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

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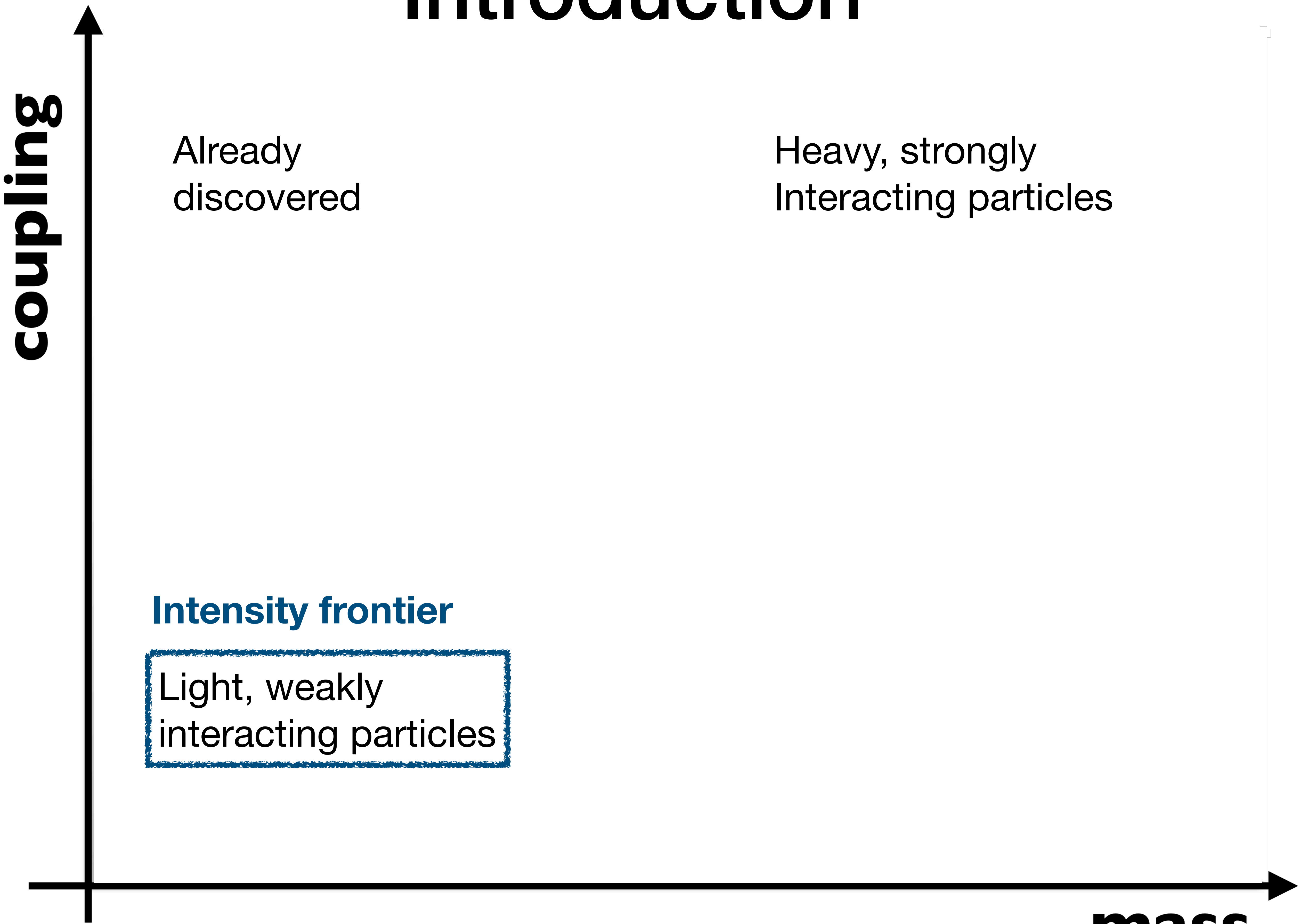
Based on:

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

KJ, S. Trojanowski, 2011.04751

Introduction

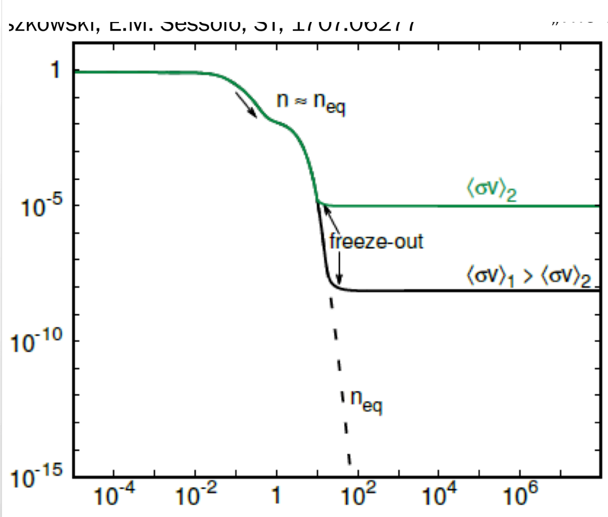


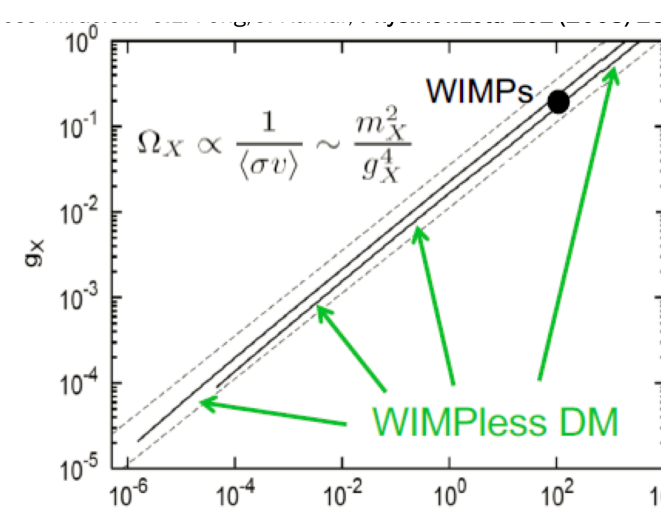
Introduction

coupling

Already discovered

Heavy, strongly Interacting particles





Weak couplings → large luminosities required

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

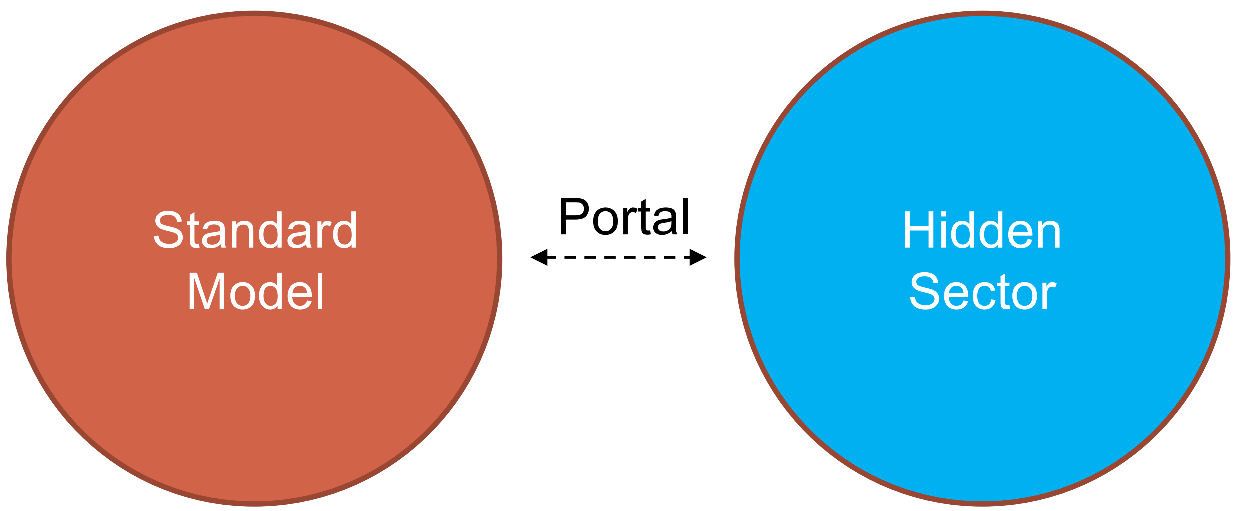
Intensity frontier

Light, weakly interacting particles

mass

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:

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

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

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

Intensity frontier

Experimental signatures

Look for:

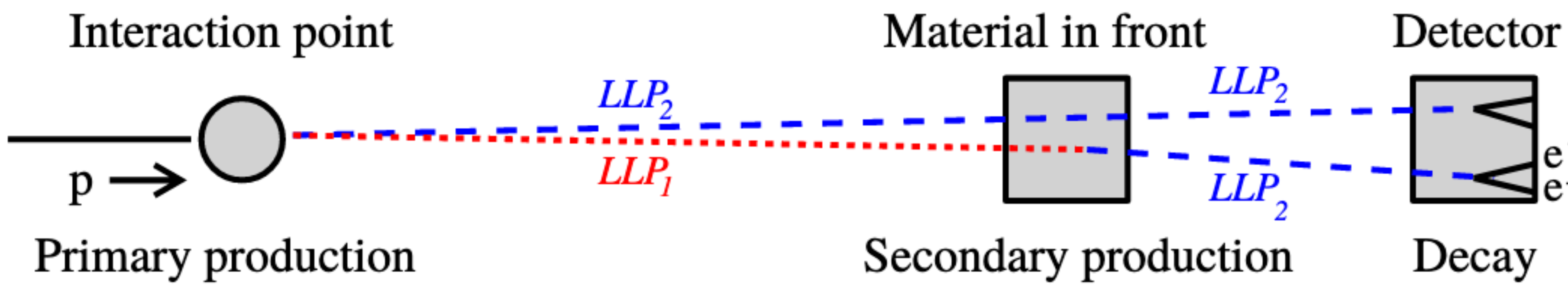
- highly-displaced decay signatures of light **long-lived particles** (LLPs) in a **distant detector** that is **well-shielded from SM background**
- missing energy in invisible decays
- …

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

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

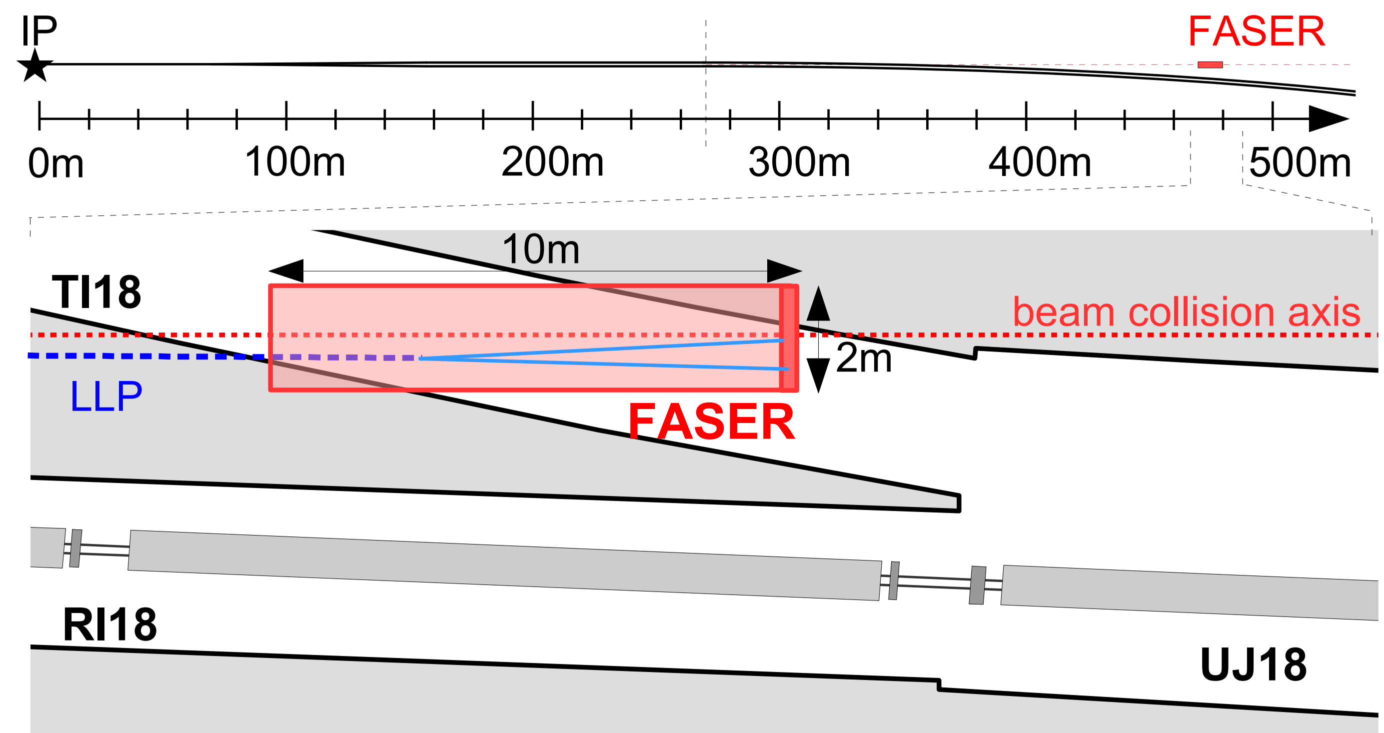
$$N_{\mathrm{sig}} \propto \begin{cases} \mathcal{L}^{\mathrm{int}}\,\epsilon^2\,e^{-L_{\min}/\bar{d}} & \text{for} \quad \bar{d} \ll L_{\min} \\ \mathcal{L}^{\mathrm{int}}\,\epsilon^2\,\frac{L_{\max}-L_{\min}}{\bar{d}} & \text{for} \quad \bar{d} \gg L_{\min} \end{cases}$$

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

ForwArd Search ExpeRiment

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

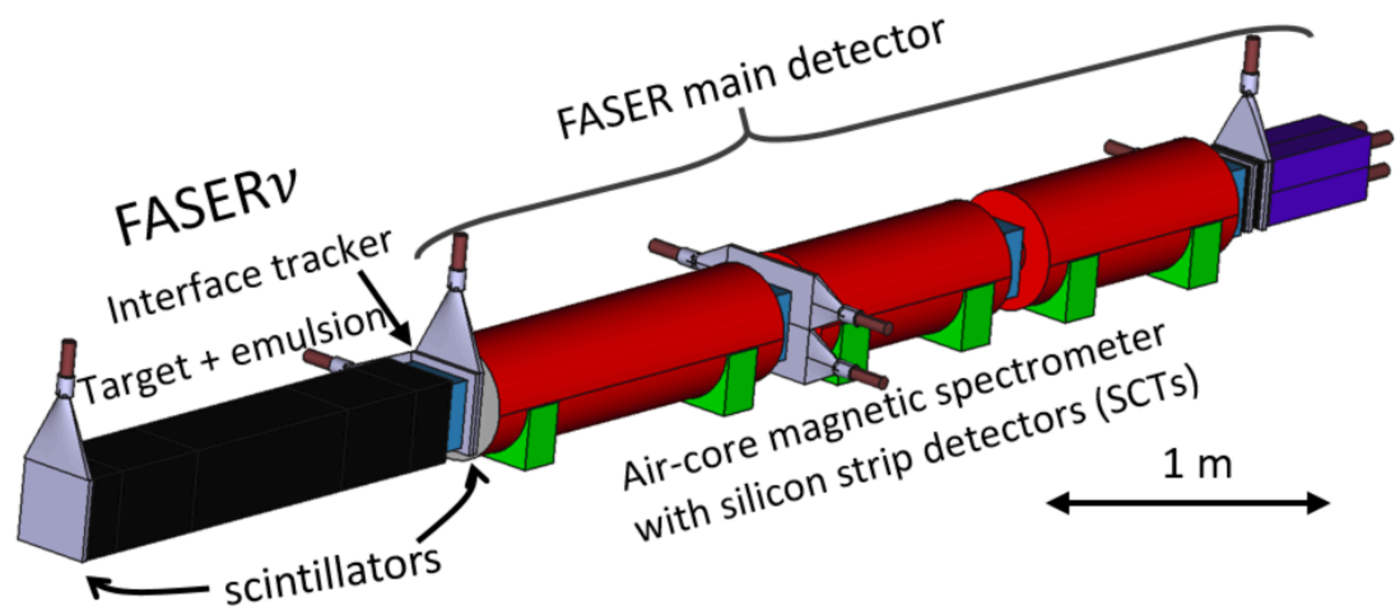
Feng, Gallon, Kling, Trojanowski, 1708.09389
Letter of Intent for FASER: ForwArd Search ExpeRiment at the LHC, 1811.10243
Technical Proposal for FASER: ForwArd Search ExpeRiment at the LHC, 1812.09139



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

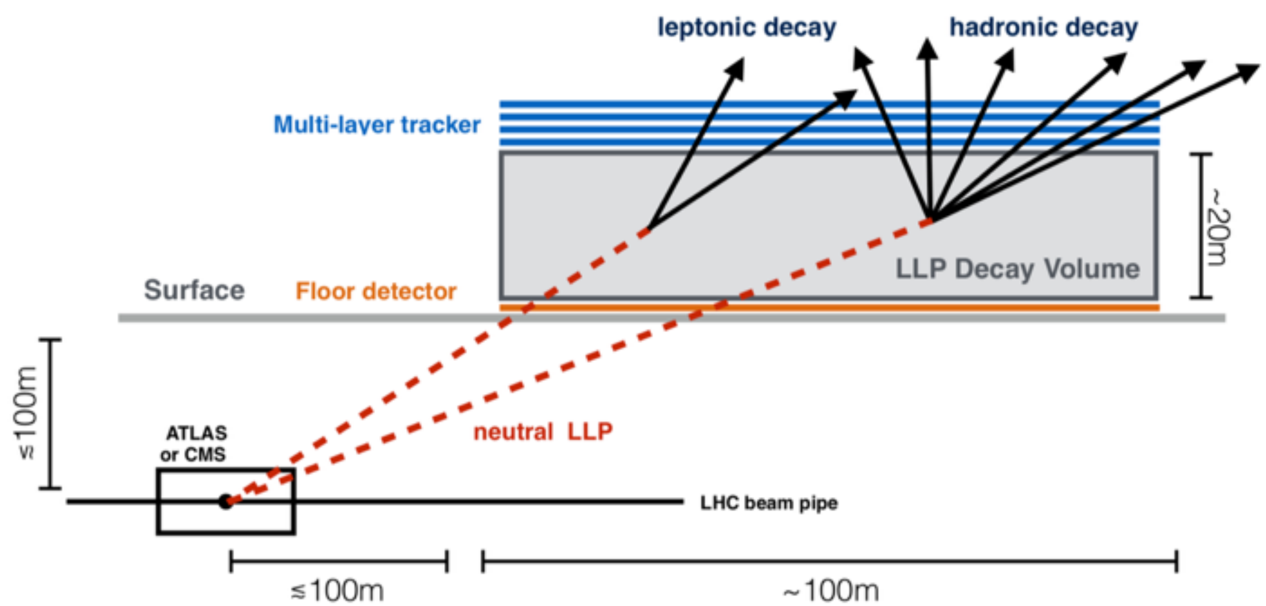
→ probing high energy neutrinos and short-lifetime regime



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

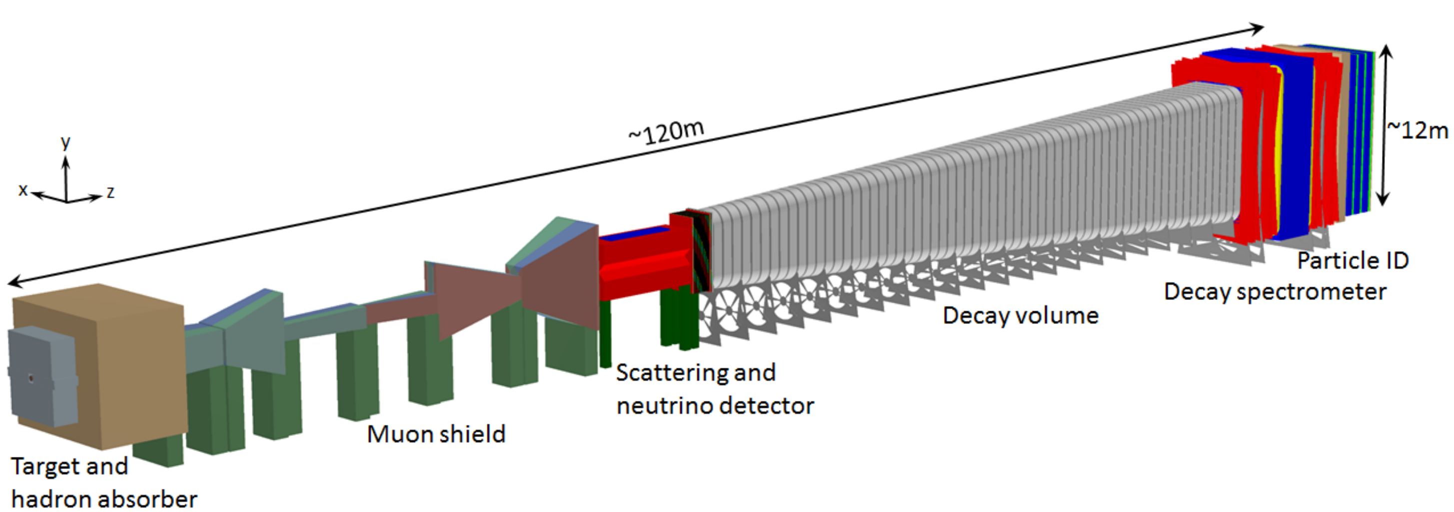
MATHUSLA - start with HL LHC (proposed)



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

From E. Torró for the MATHUSLA Collaboration, July 2019

SHiP - start about HL LHC (proposed)

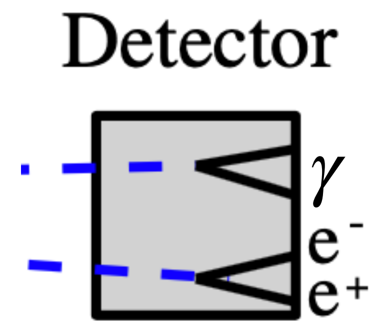


Technical Proposal: A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case, 1504.04855
SHiP Experiment PROGRESS REPORT, CERN-SPSC-2019-010 / SPSC-SR-248
Sensitivity of the SHiP experiment to light dark matter, 2010.11057

SHiP Experiment PROGRESS REPORT, November 2018

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 $\rightarrow$ <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

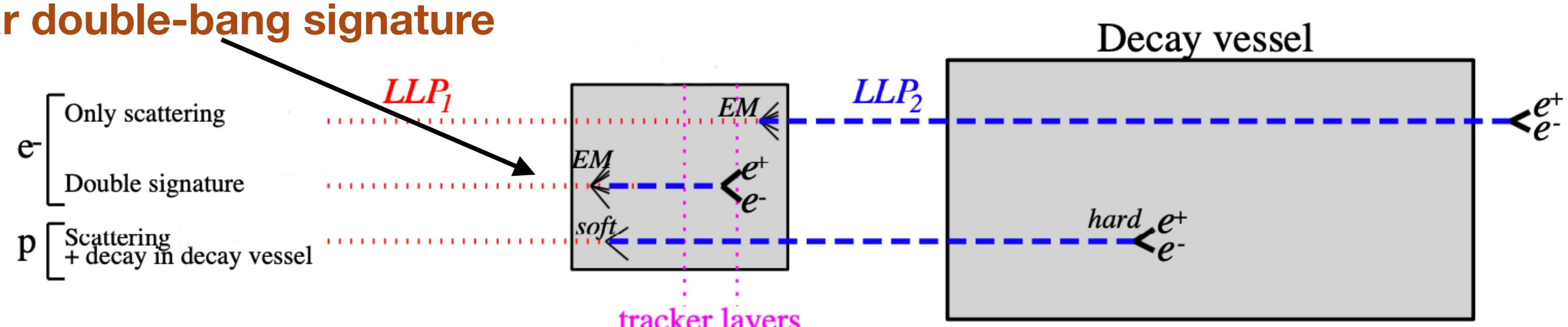
- **Scattering off electrons** *See also talk by S. Trojanowski* Detecting Dark Matter with Far-Forward Emulsion and Liquid Argon Detectors
  - new-physics-induced neutrino scatterings off electrons producing detectable electron recoils inside the neutrino detector.
  - **Energy and angular cuts**:
    - Electron energy and angular cuts following the DM scattering signature

      Batell, Feng, Trojanowski, 2011.xxxxx

      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**



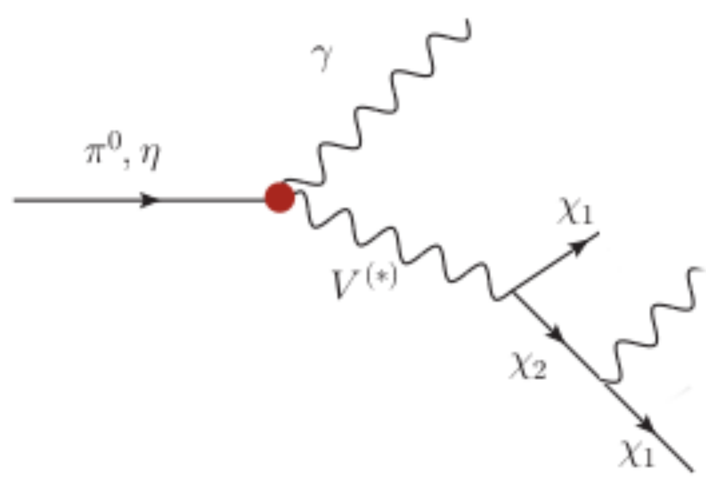
KJ, F. Kling, L. Roszkowski and S. Trojanowski, 1911.11346

Inelastic DM (iDM)

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

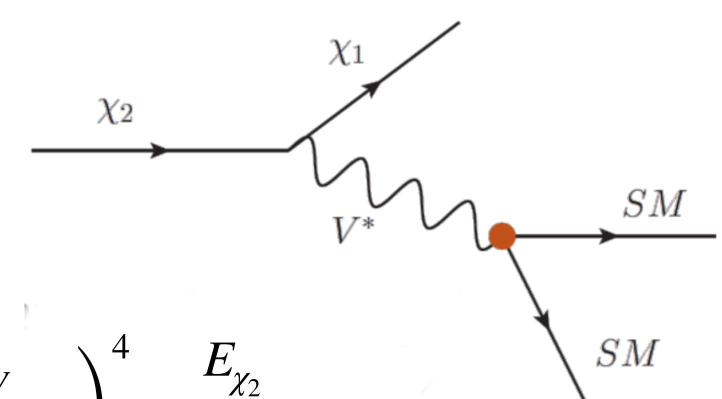
Smith, Weiner: 0101138

- 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

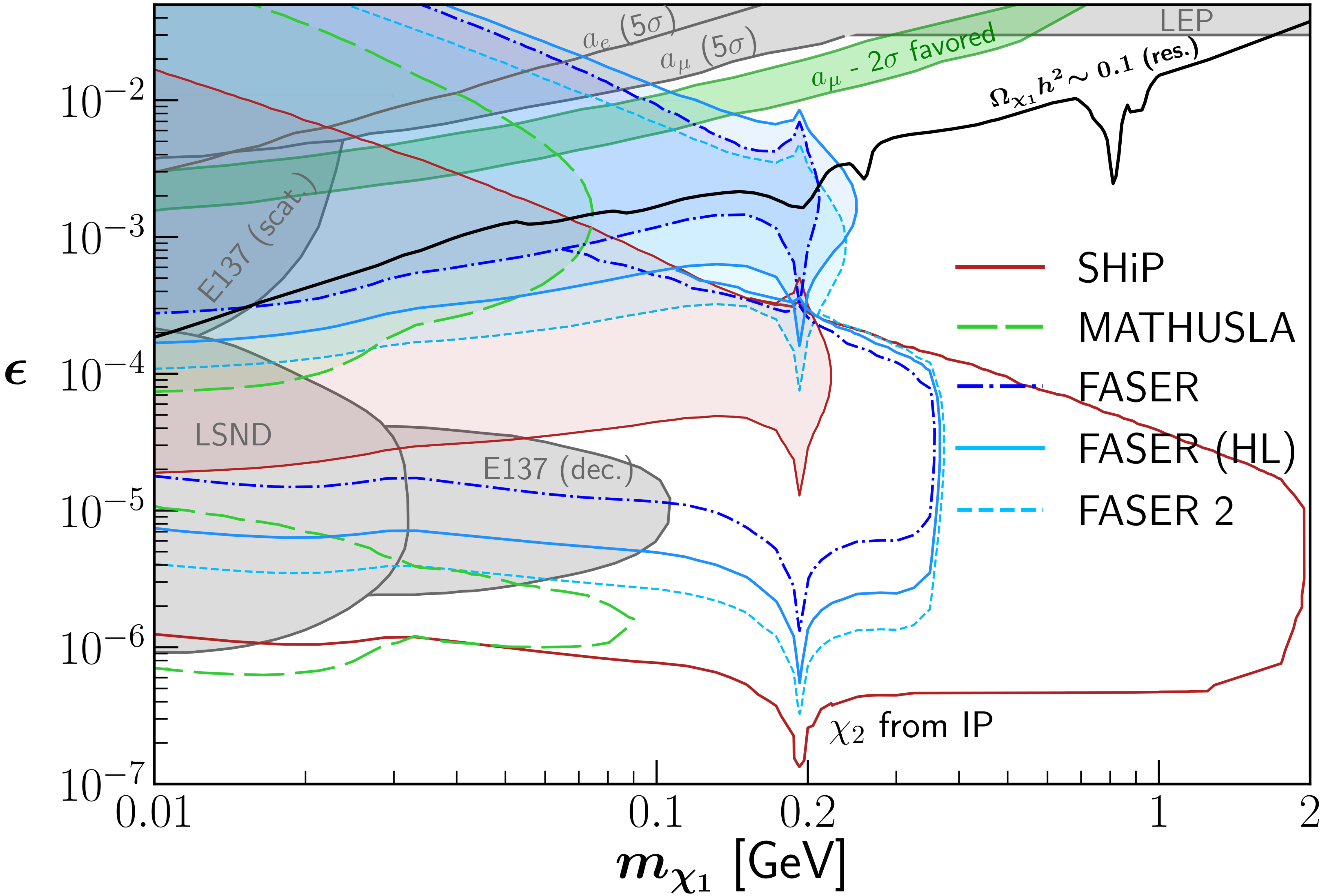
$$m_{\chi_1} : m_{\chi_2} : m_{A'} \sim 1 : 3 : 4$$



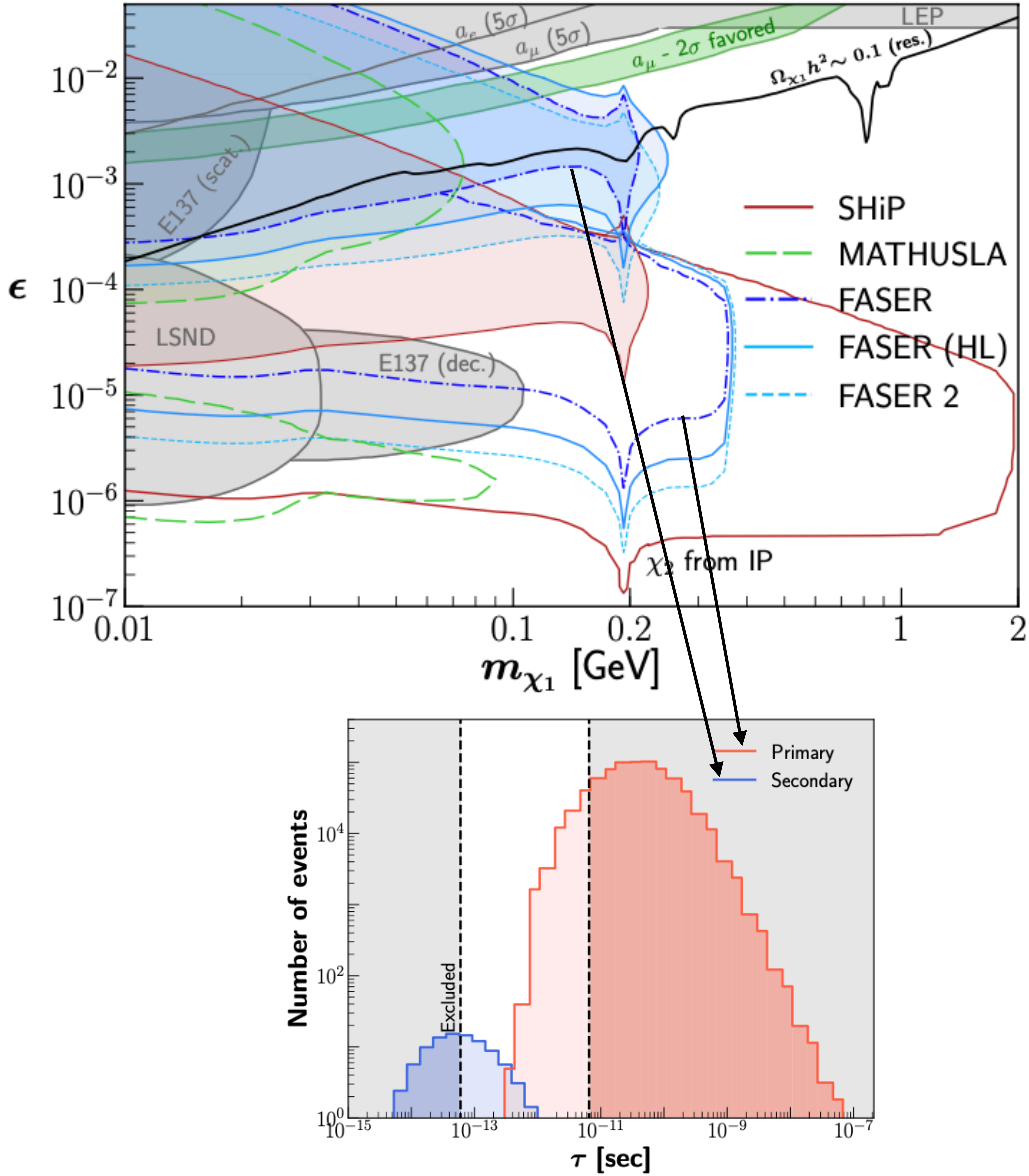
- Typical lifetime

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

Results: iDM



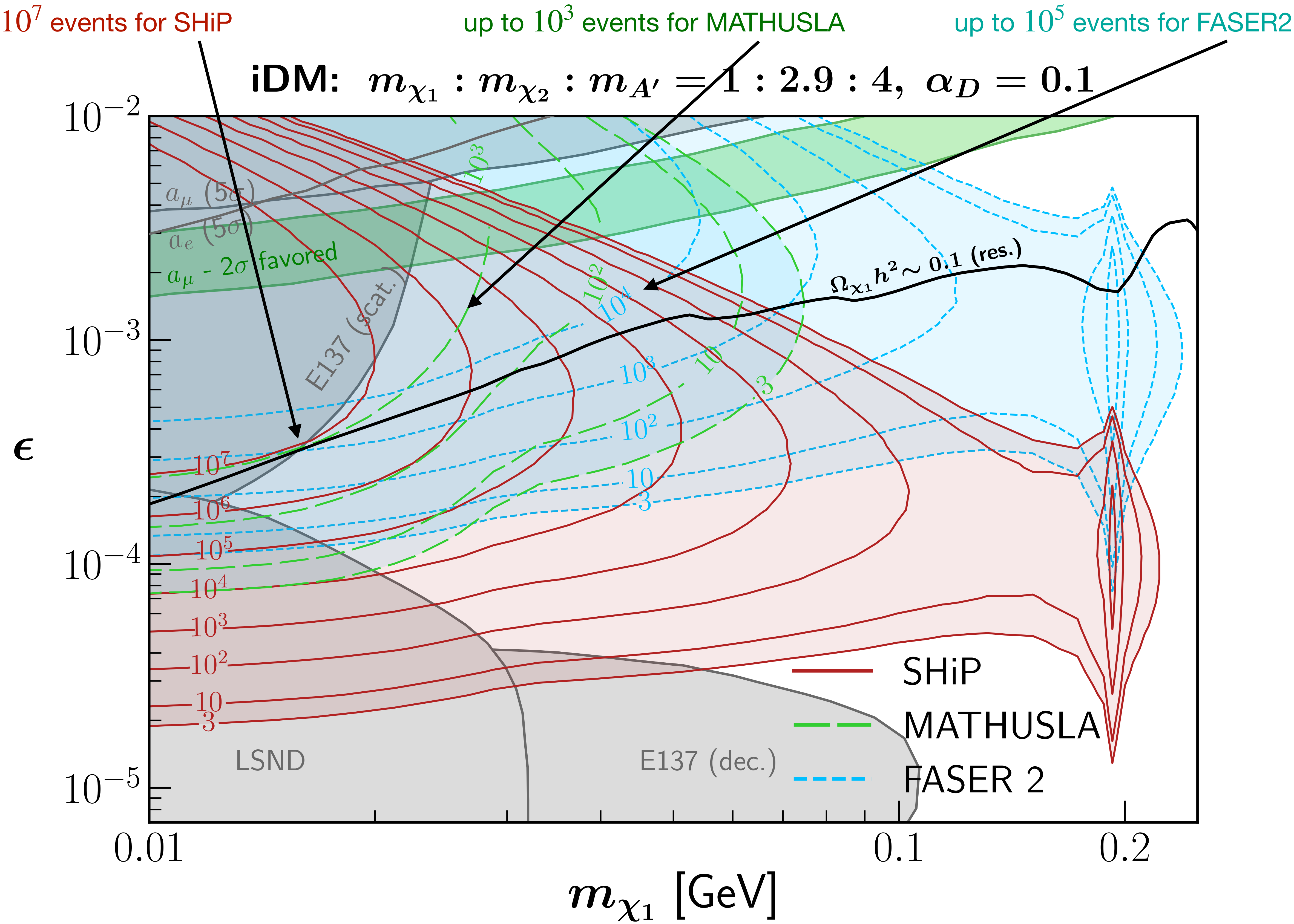
KJ, F. Kling, L. Roszkowski and S. Trojanowski, 1911.11346



a_e (5σ)
a_μ (5σ)
LEP
a_μ - 2σ favored
$\Omega_{\chi_1} h^2 \sim 0.1$ (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

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



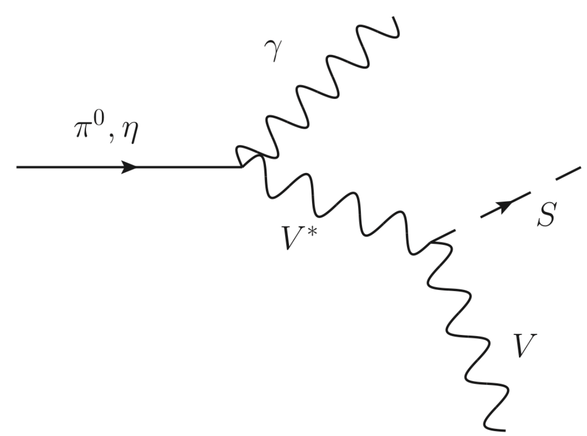
Dark Higgs mechanism

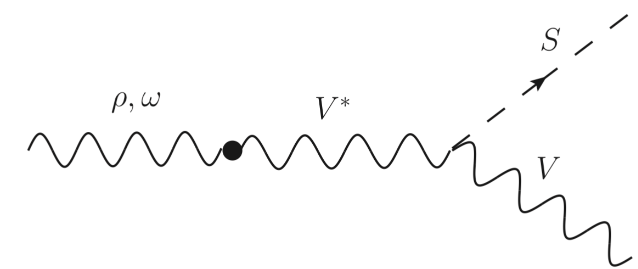
- Need mechanism to give mass to the dark photon
- Simplest solution: dark Higgs mechanism:

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

  - 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

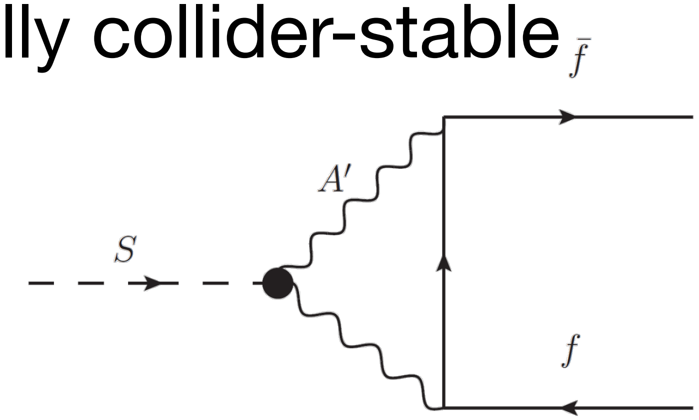
Batell, Pospelov, Ritz, 0906.5614
Darmé, Rao, Roszkowski, 1806.06036





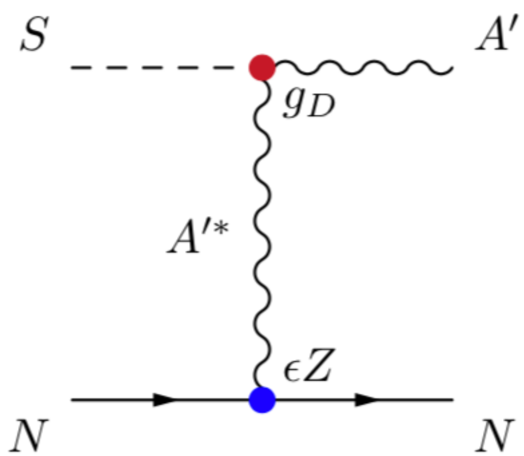
  - If the dark Higgs is to be light, it is naturally collider-stable

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

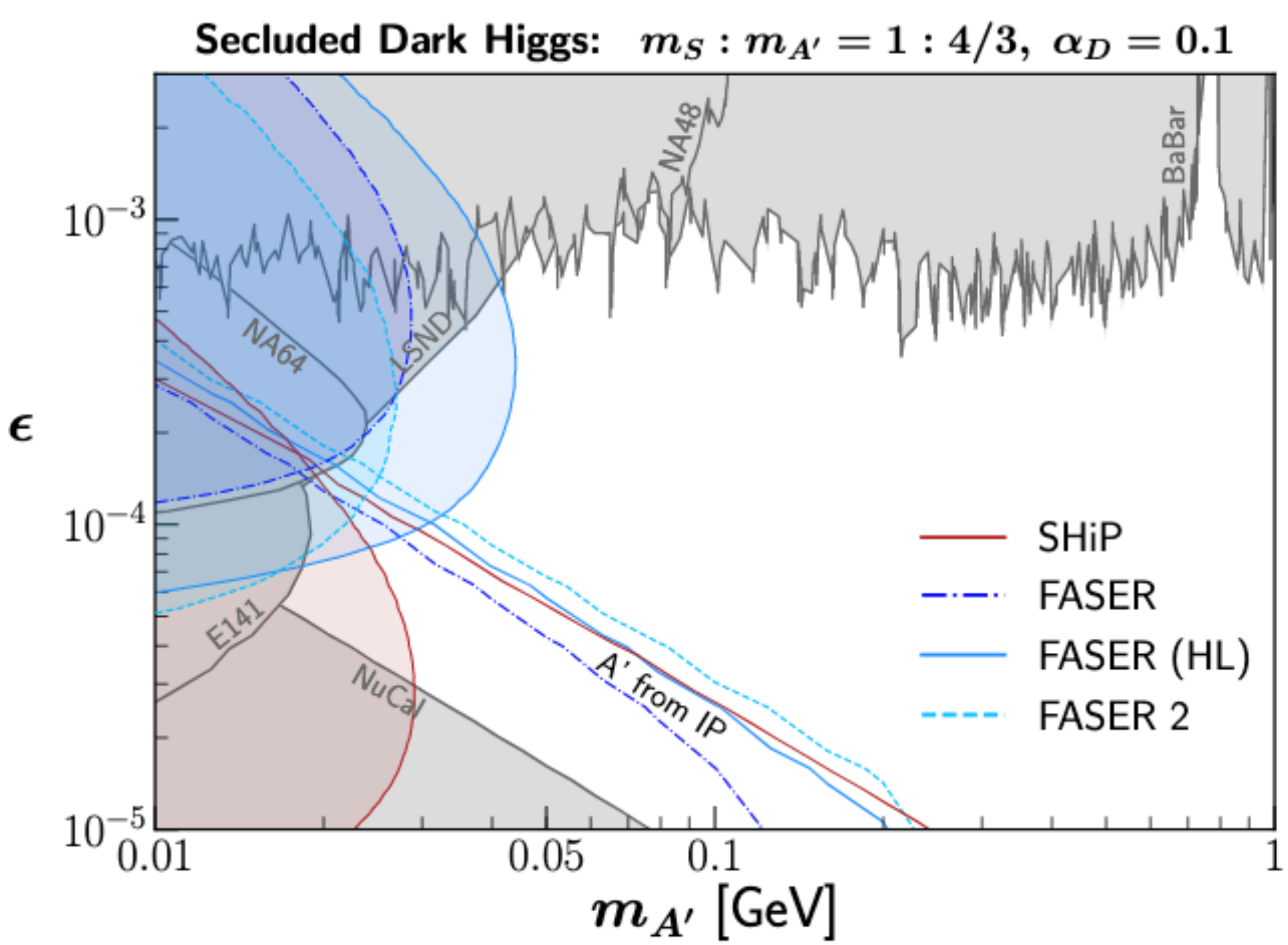


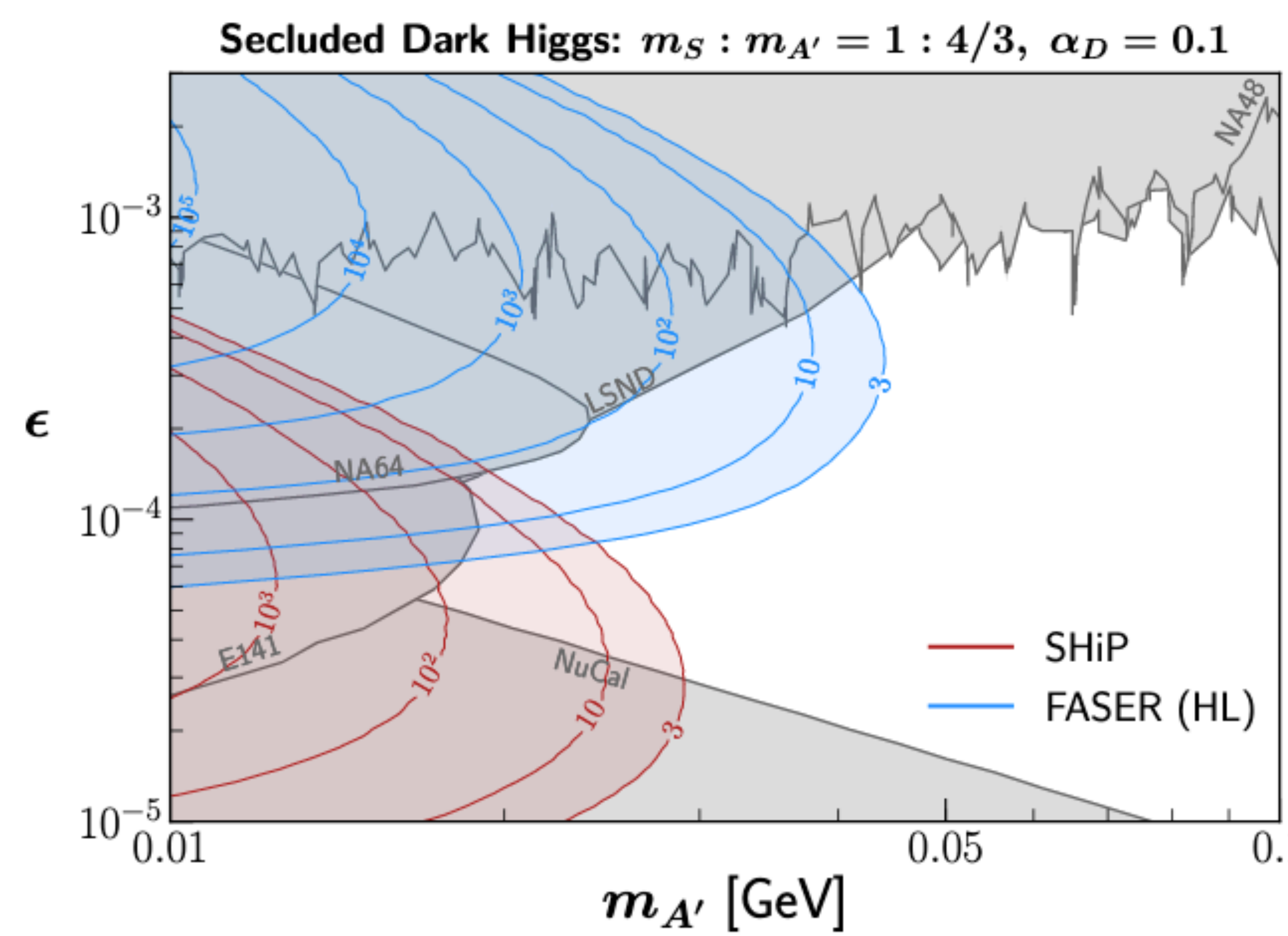
$$m_S : m_{A'} = 1 : 4/3$$

Dark Higgs



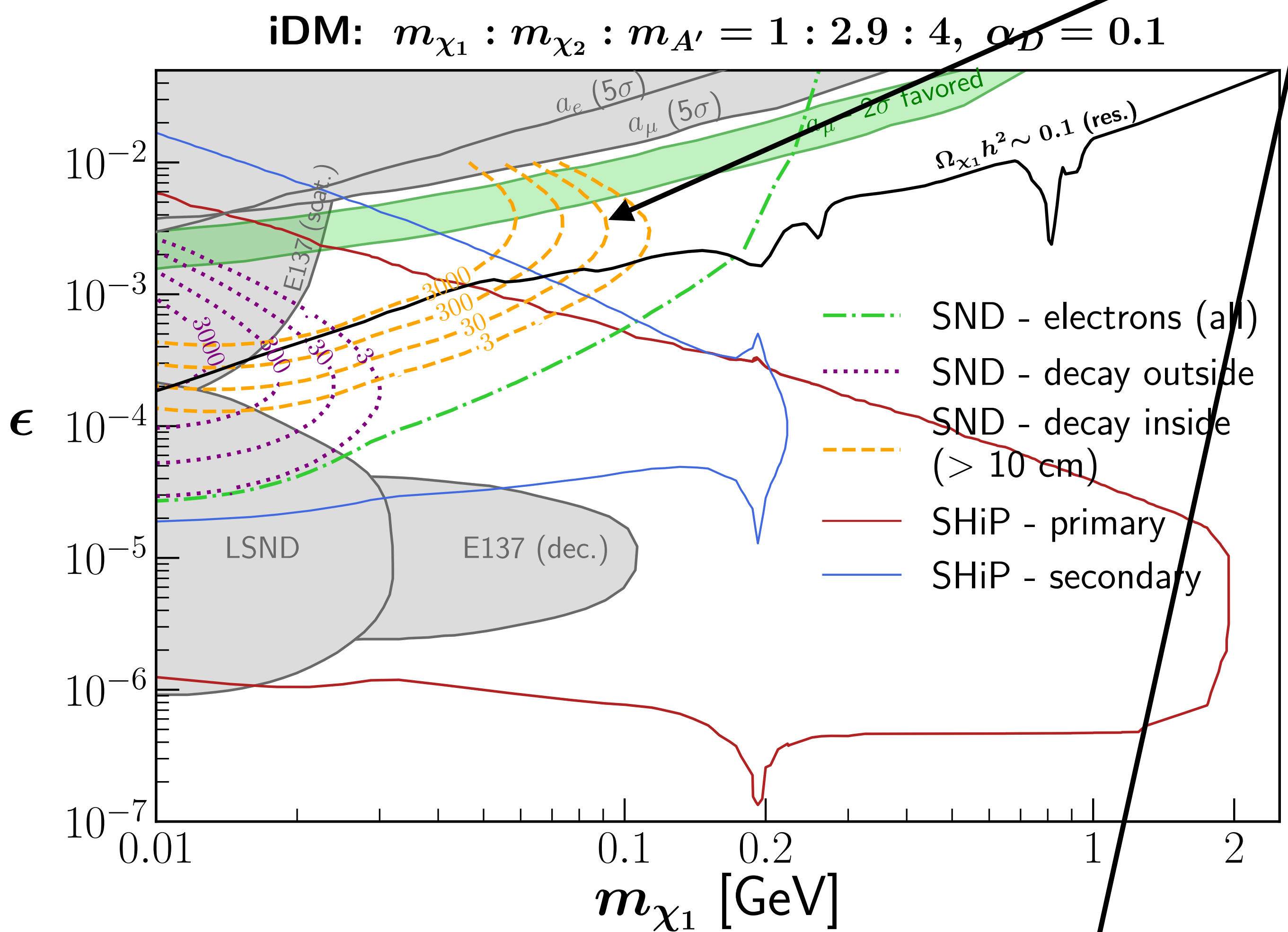
- Long-lived dark Higgs scatters in front of the detector, producing dark photon which decays in the detector to SM

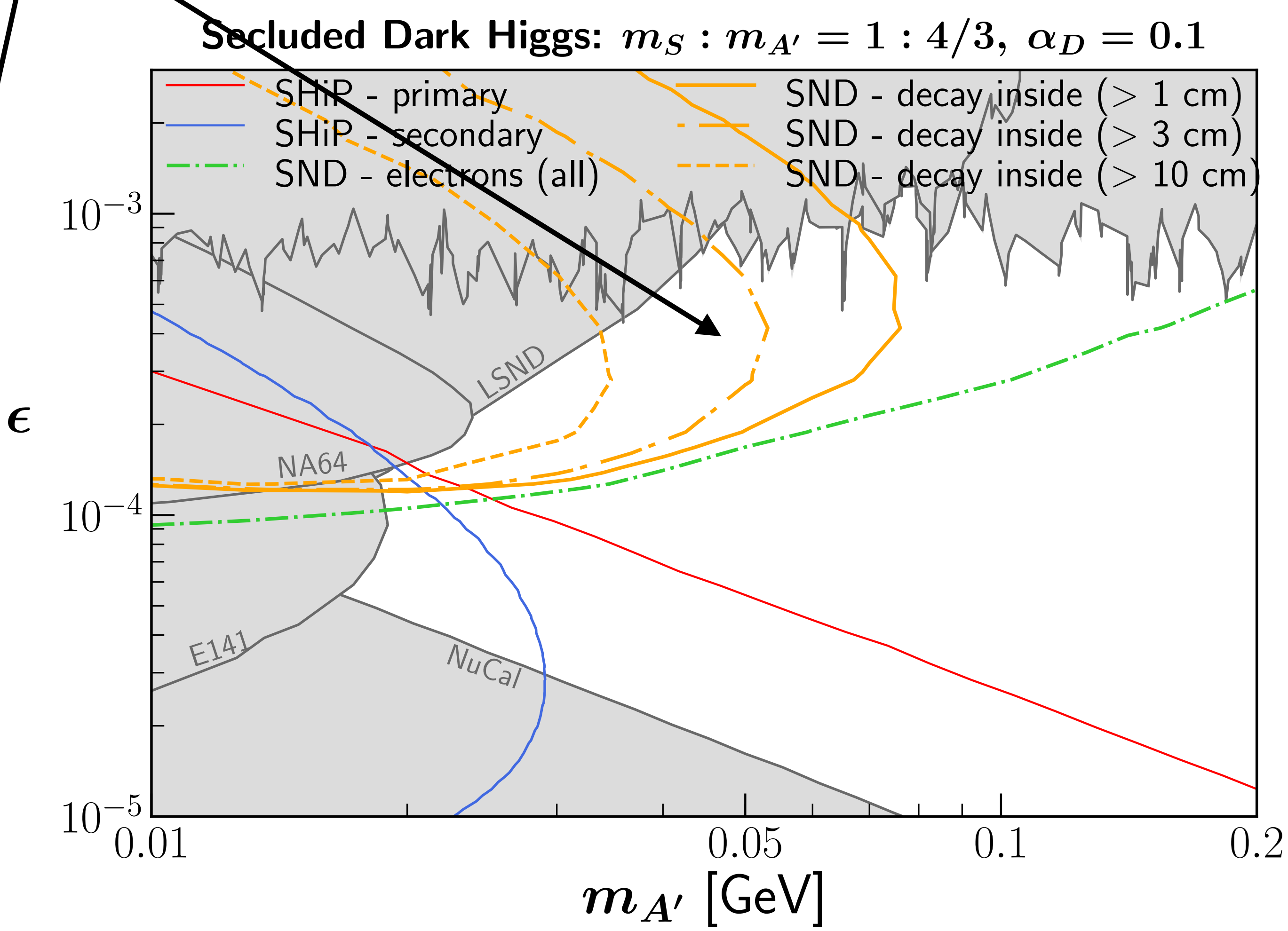


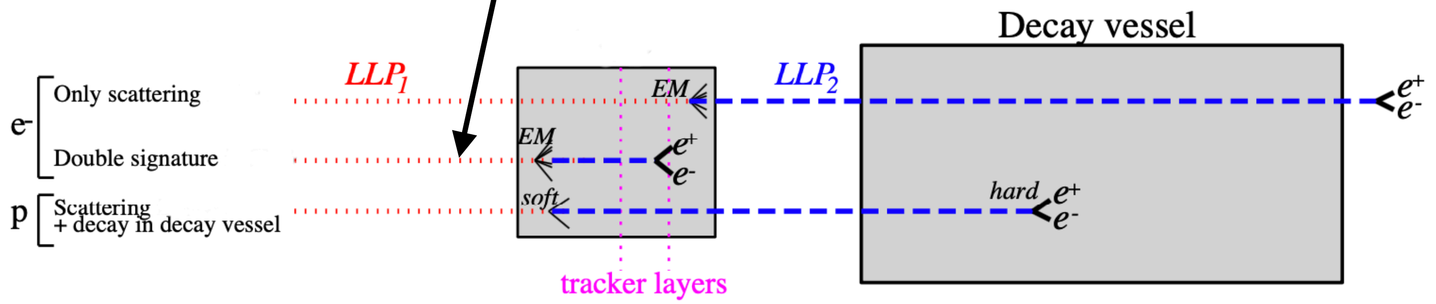


Electron scattering events at SND@SHiP

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





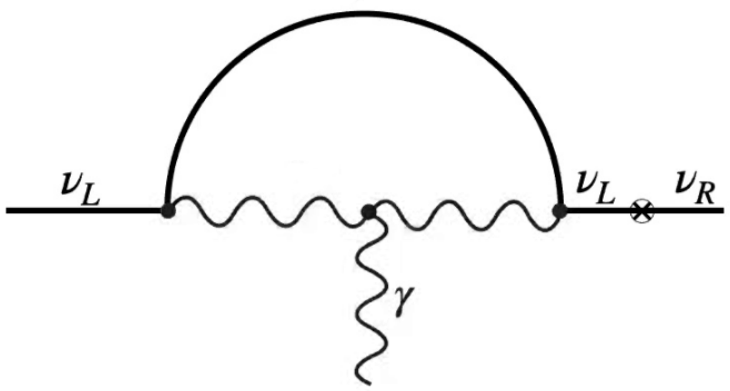


Neutrino non-standard interactions

- *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 $\mu_\nu < 10^{-19}\mu_B$, where $\mu_B \equiv \frac{\sqrt{4\pi\alpha}}{2m_e} \simeq 300\ \text{GeV}^{-1}$

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

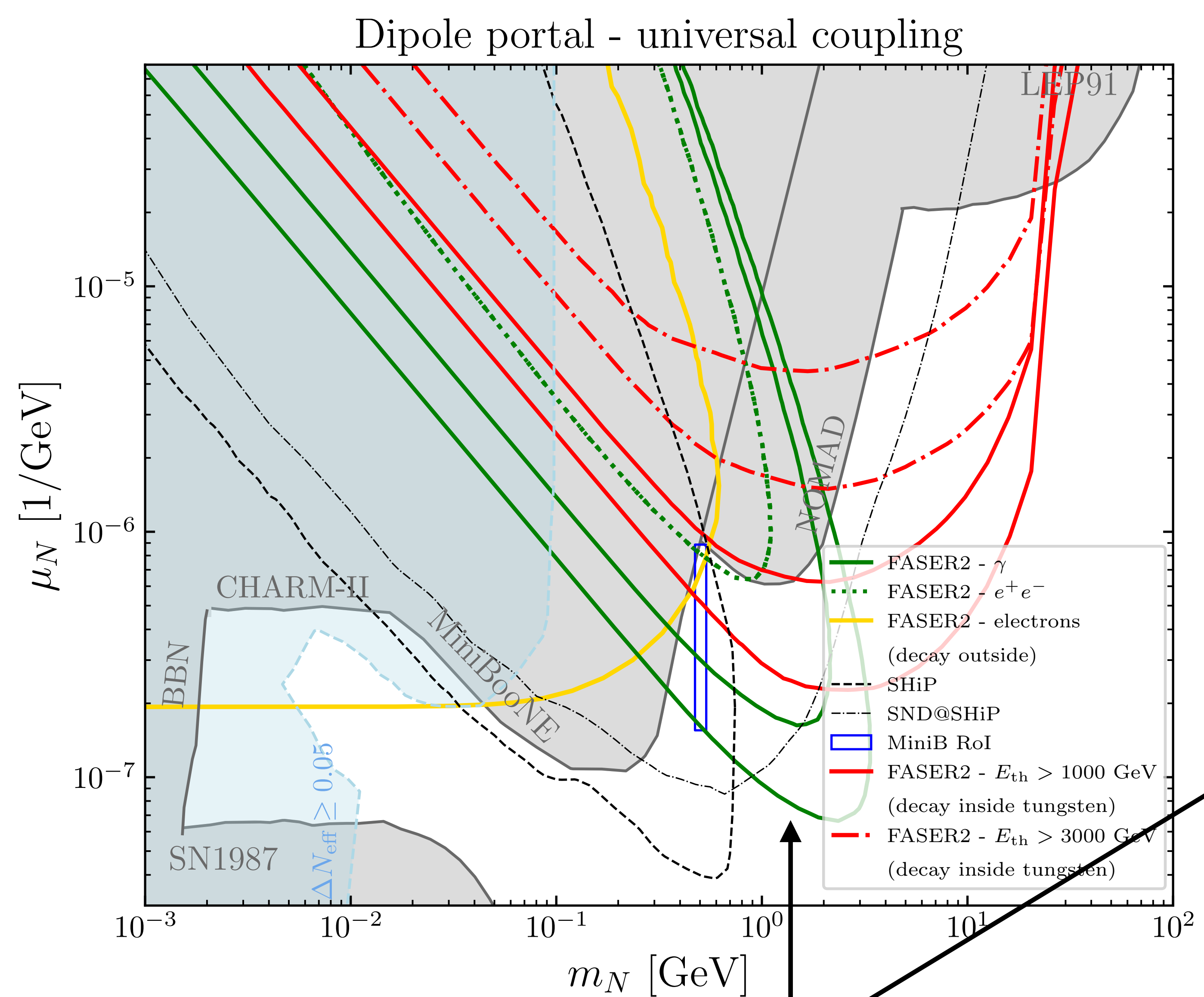
- Light Z_D mediator from dark gauge group $U(1)_D$ - *dark neutrino model*

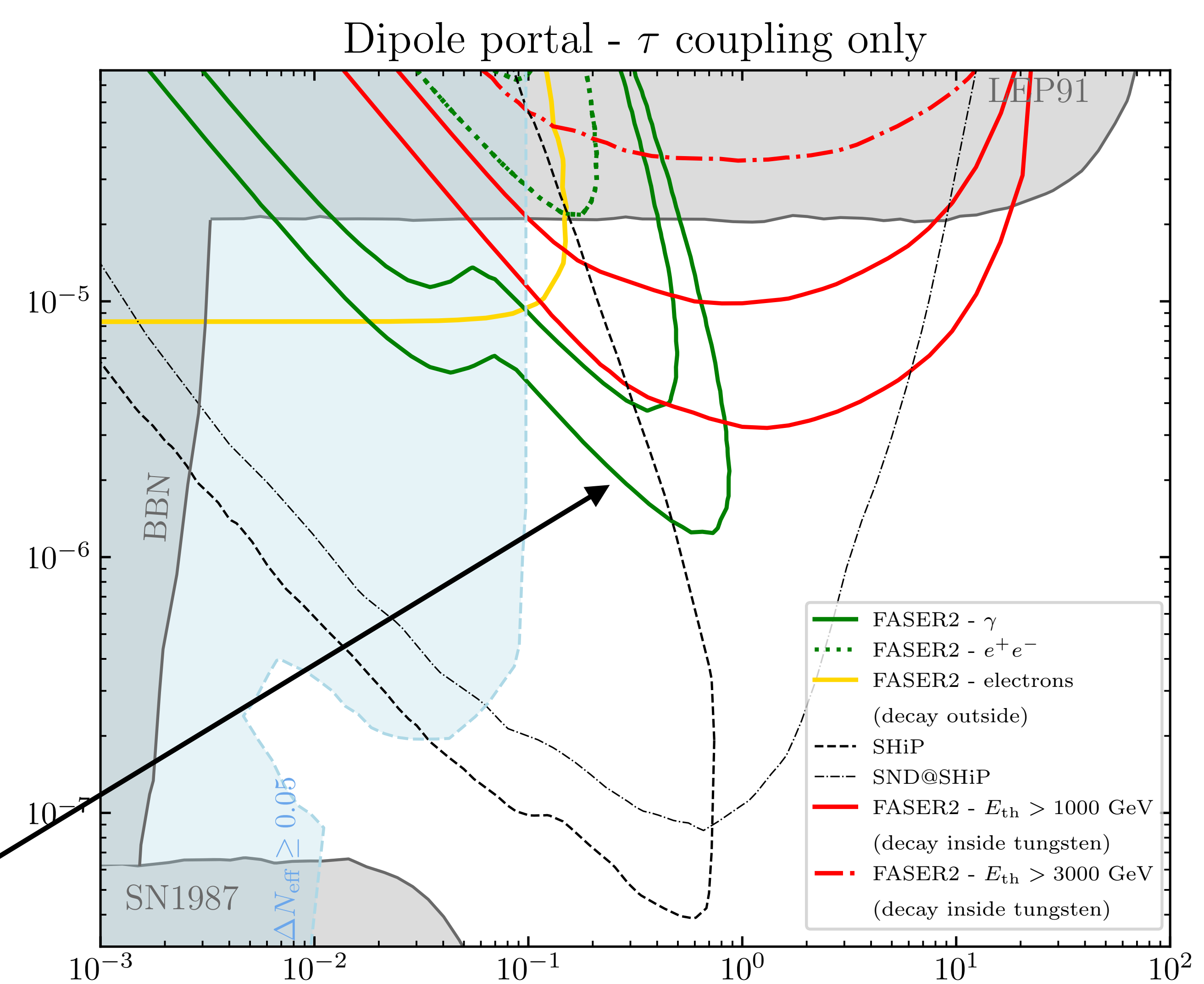
$$\mathscr{L}_D \supset \frac{m_{Z_D}^2}{2} Z_{D\mu} Z_D^\mu + g_D Z_D^\mu \bar{N} \gamma_\mu N + e\epsilon Z_D^\mu J_\mu^{\text{em}},$$

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

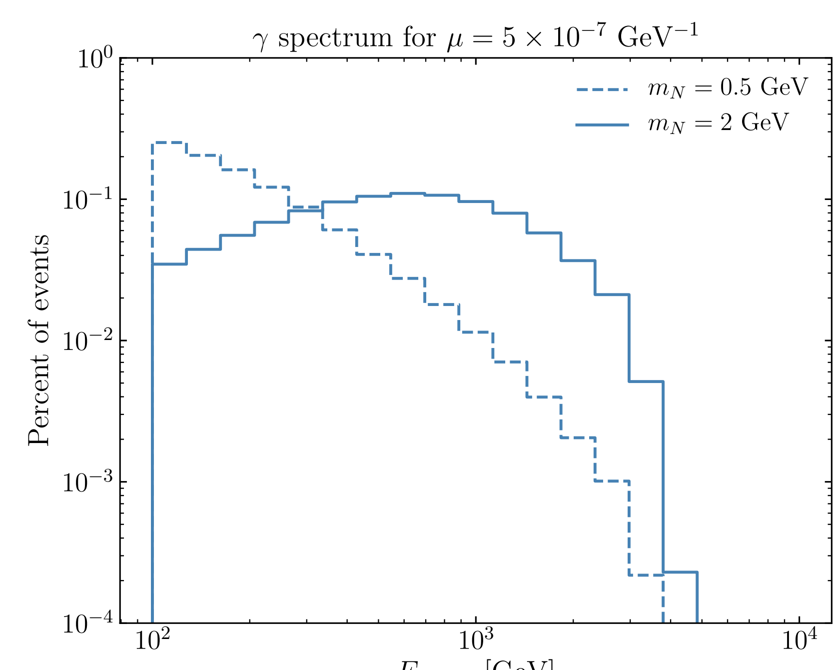
Neutrino magnetic moment



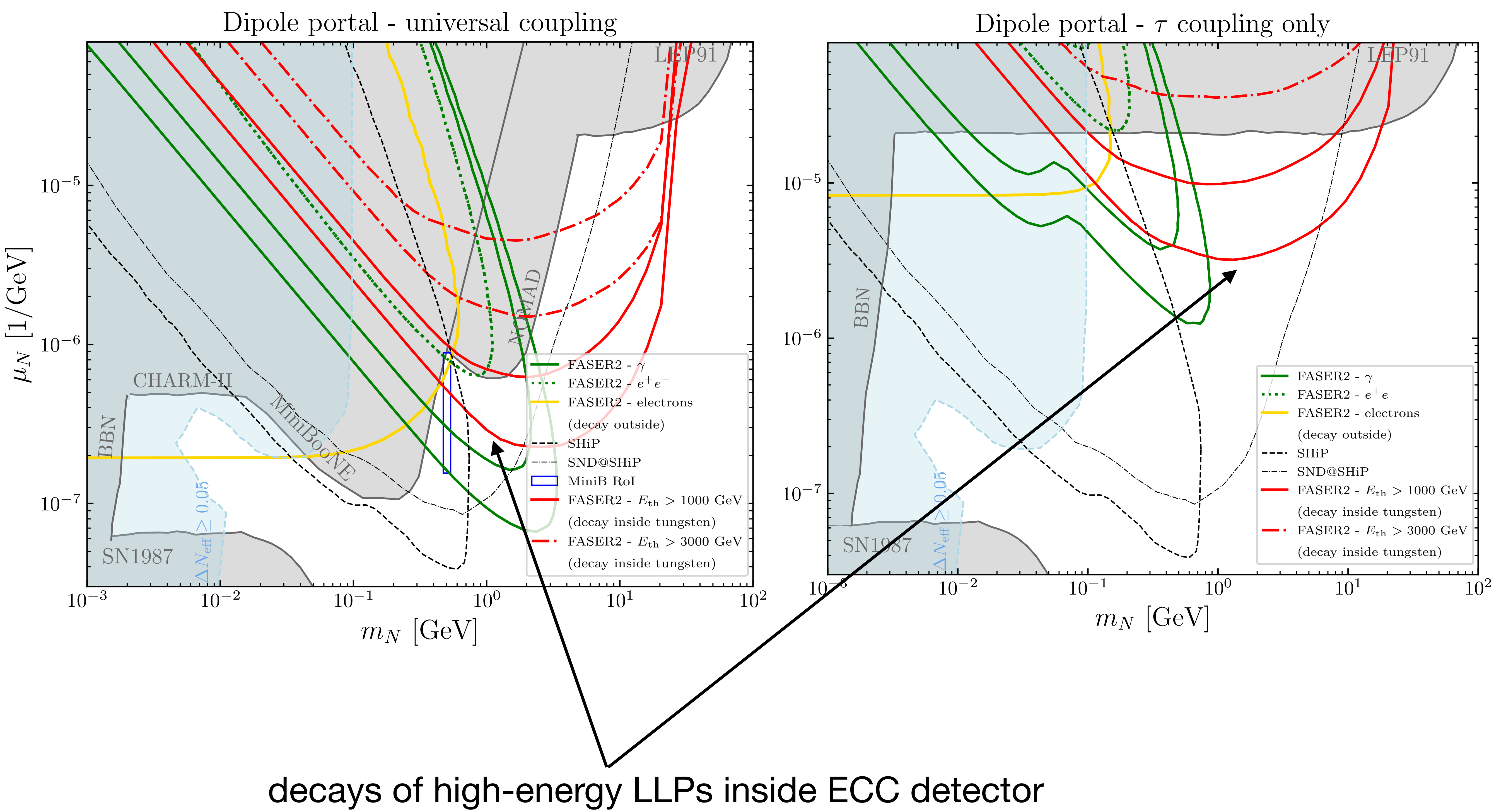


Upscattering $\nu X \to N X$ followed by LLP signal inside decay vessel $N \to \nu\gamma$

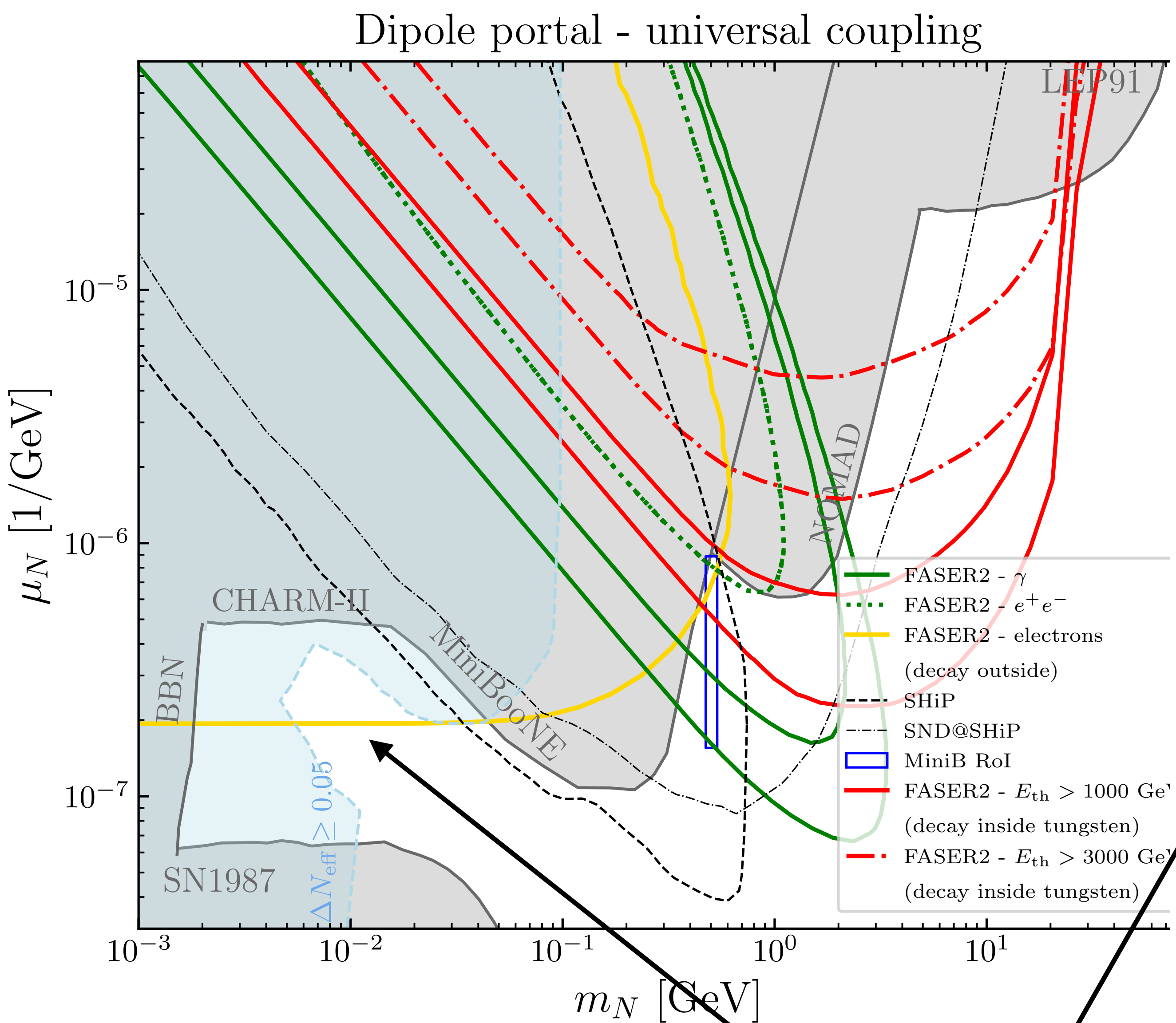
Spectrum of high-energy photons in the decay vessel

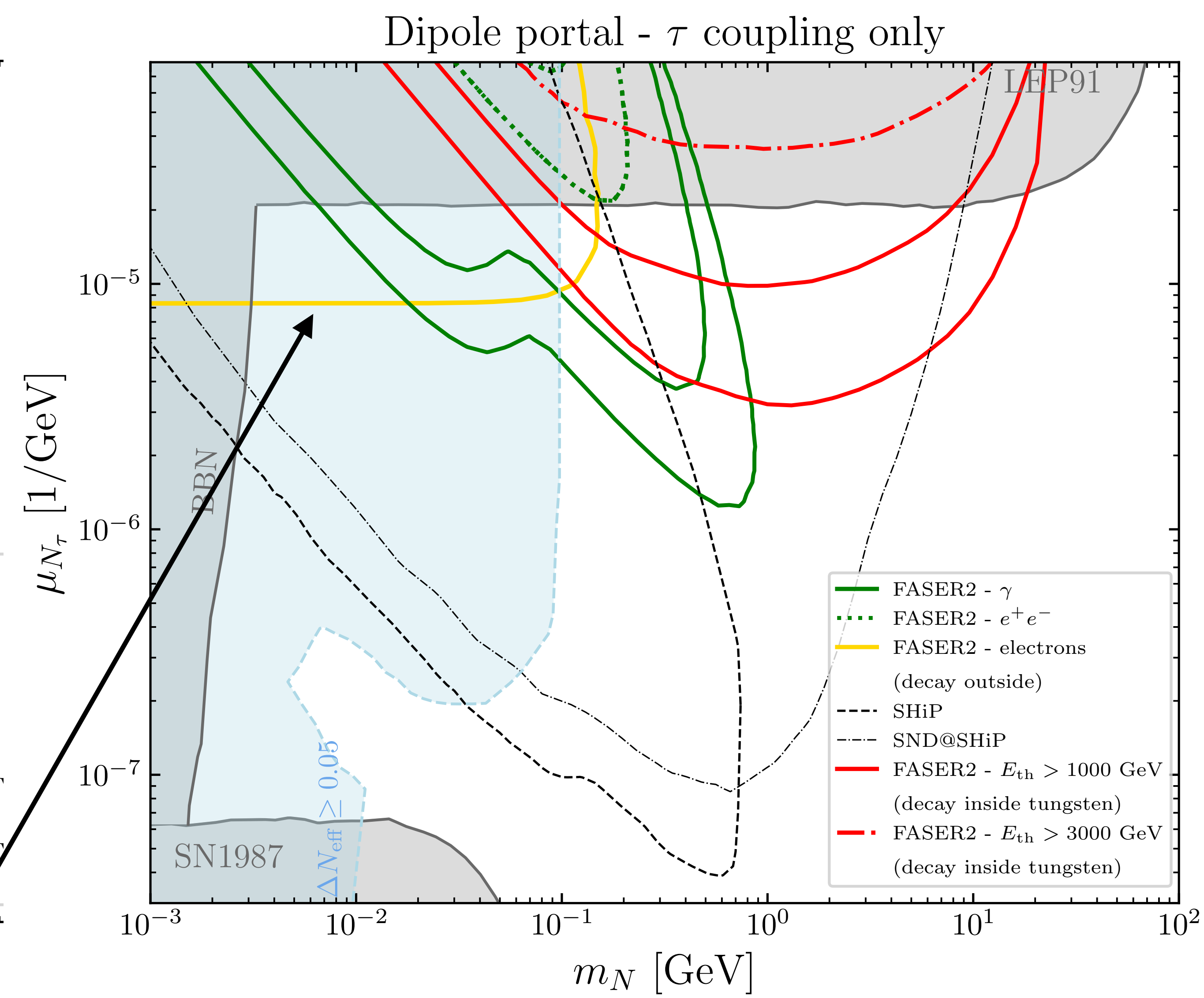


Neutrino magnetic moment



Neutrino magnetic moment





scattering off electrons

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

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 idea 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 both 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

Vector Portal - Dark Photon

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

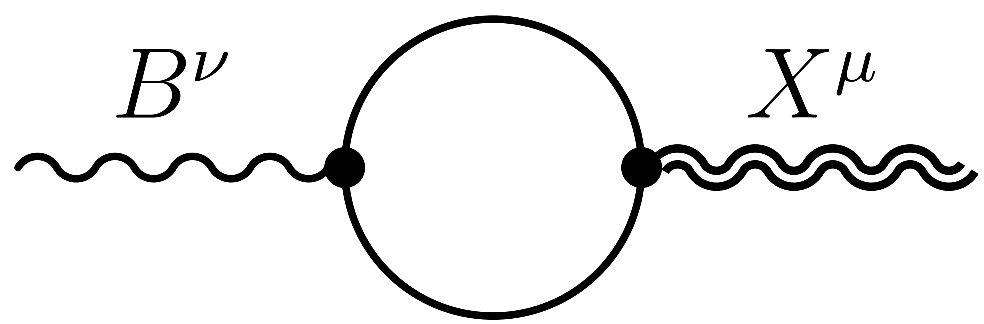
$$\mathscr{L} \supset -\frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}F^{\mu\nu'}F'_{\mu\nu} - \frac{\epsilon}{2}B^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_A^2 A'^{\mu}A'_{\mu}$$

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

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

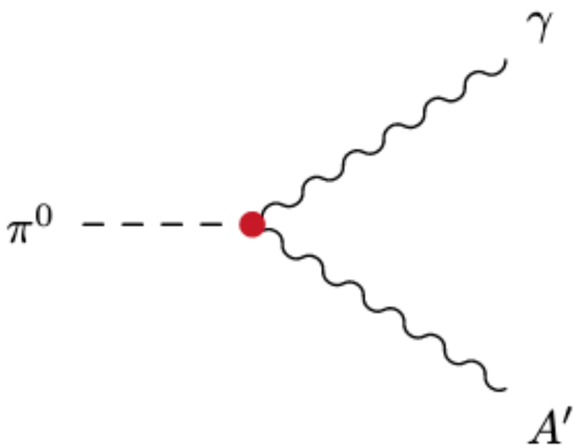
- Even if $\epsilon = 0$ at tree level, non-zero value induced by loops

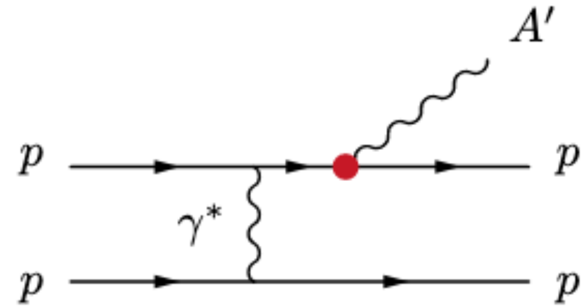
$$\epsilon \sim \frac{g_D g_Y}{16\pi^2} \sim 10^{-3}$$



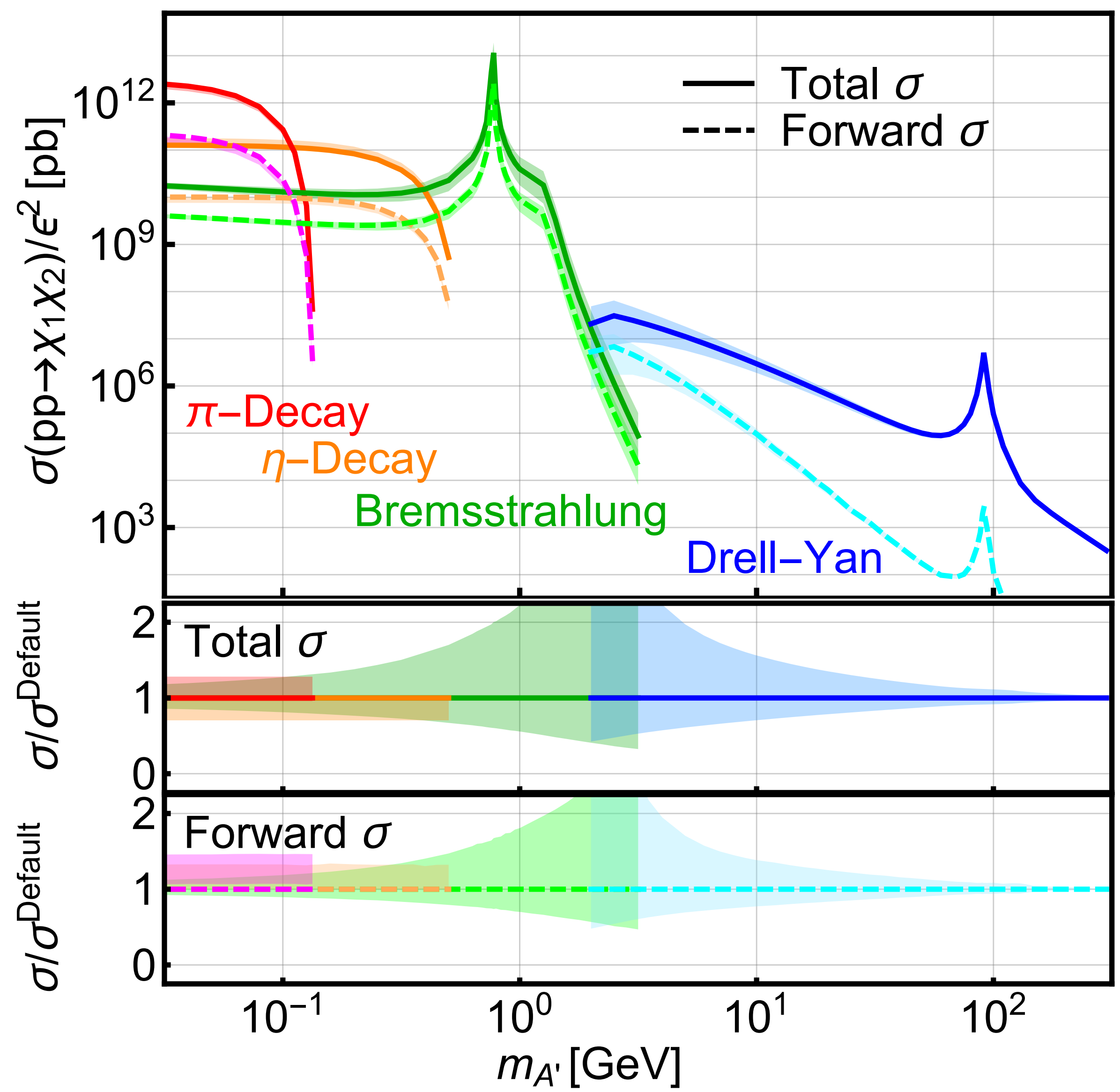
Production of Dark Photon

- Mesons decay
- Bremsstrahlung

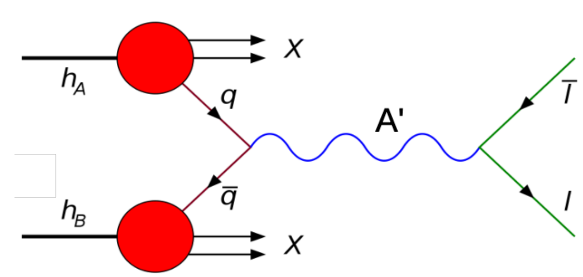




Asher, Kling: 1810.01879



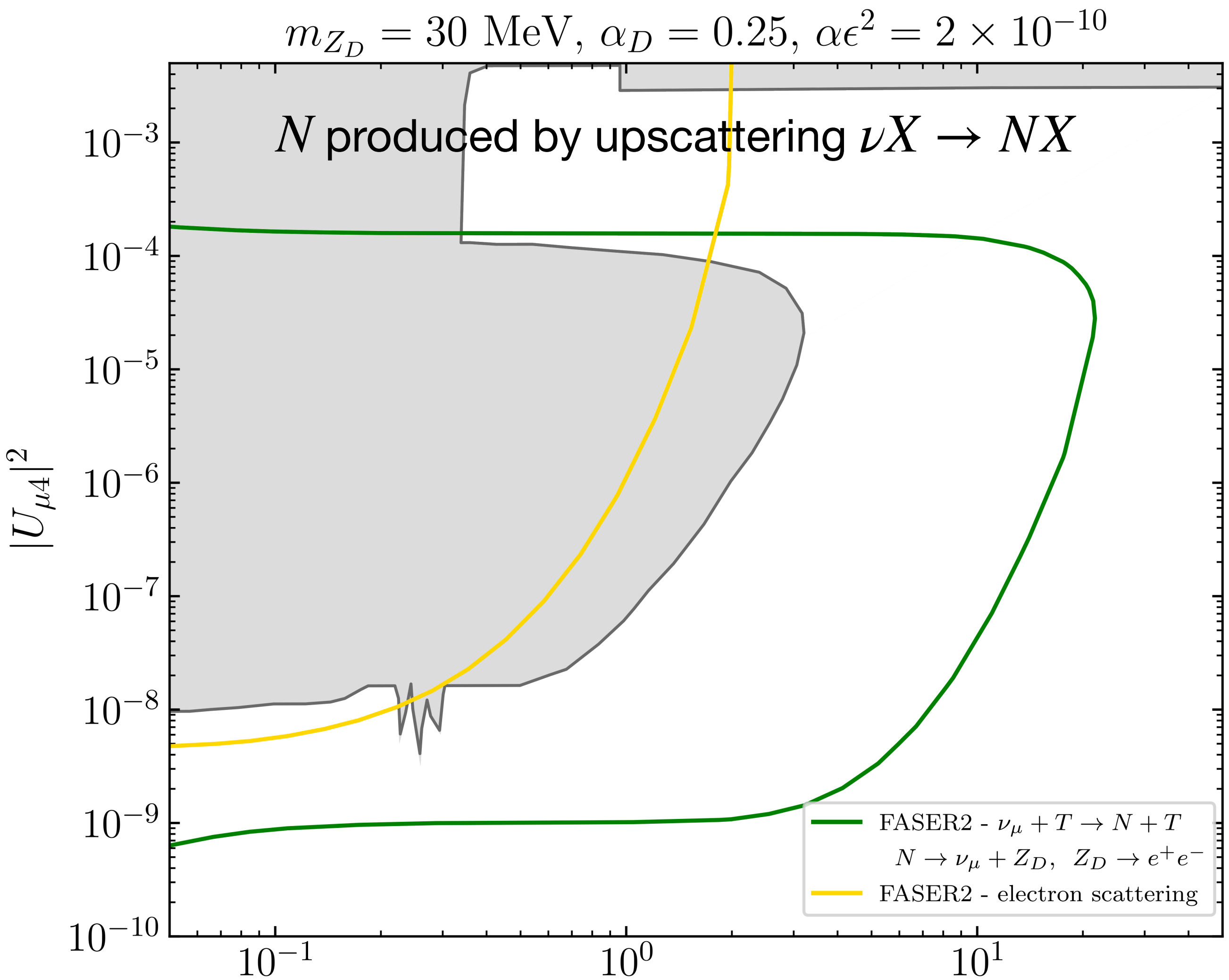
- Drell-Yan

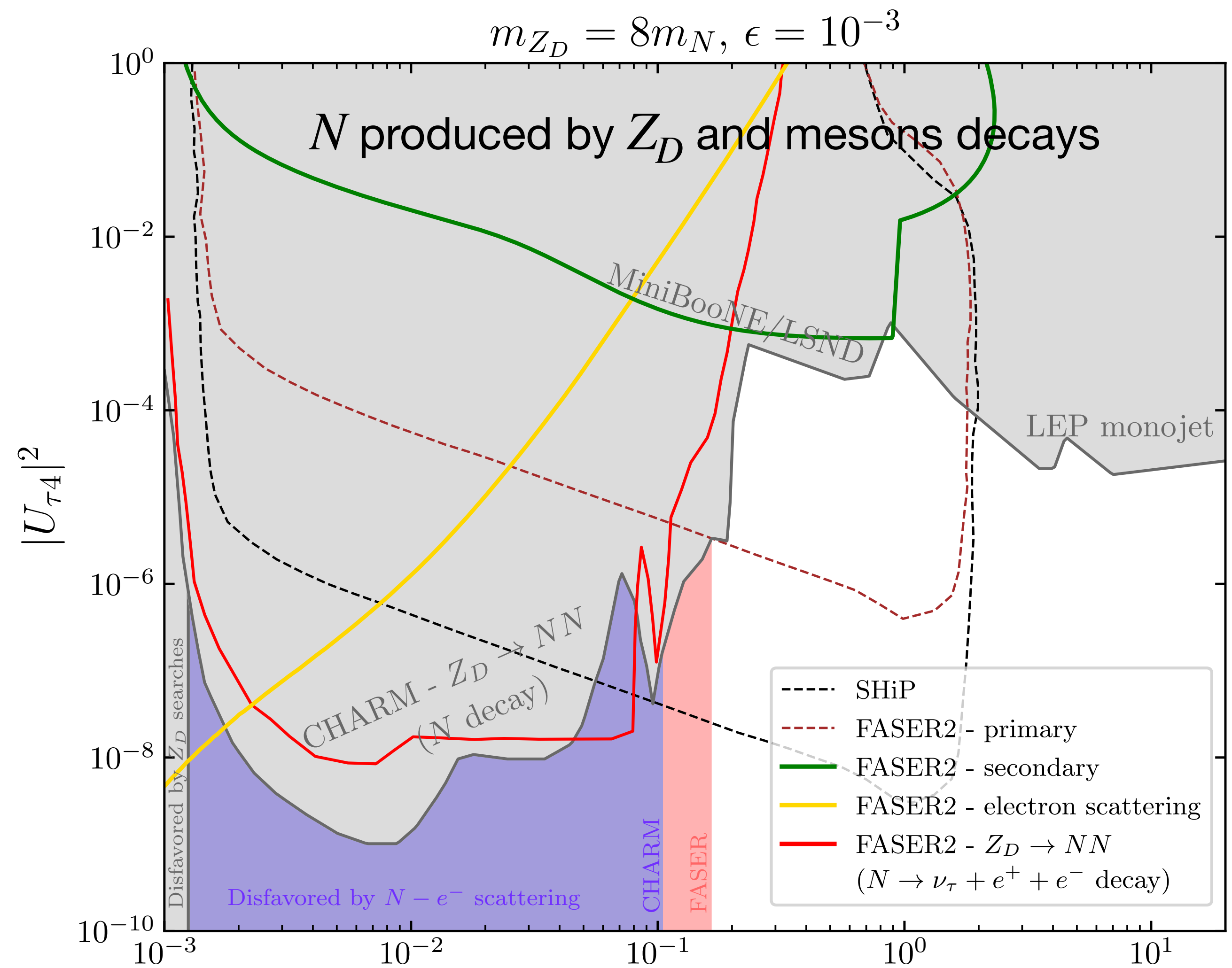


Production contributions for masses of interest only weakly dependent on Dark Sector matter specification

Light Z_D mediator

$m_{Z_D} < m_N$ ← → $m_{Z_D} > m_N$





electron scattering: $Ne^- \to Ne^-$ and $\nu e^- \to Ne^-$