Extending the reach of FASER, MATHUSLA, and SHiP towards smaller lifetimes using secondary particle production

Krzysztof Jodłowski

Narodowe Centrum Badań Jądrowych
National Centre for Nuclear Research
ŚWIERK

19/11/2020

Based on:

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

Related work:

KJ, S. Trojanowski, 2011.04751

Intensity frontier

Experimental signatures

Look for:

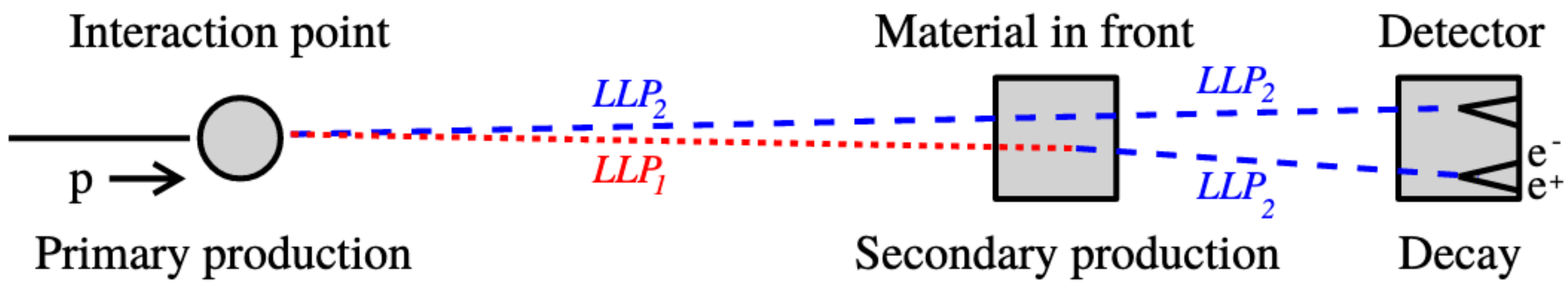
- highly-displaced decay signatures of light **long-lived particles** (LLPs) in a **distant detector** that is **well-shielded from SM background**
- missing energy in invisible decays
- …

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

Physics Beyond Colliders, 1901.09966

Going beyond long lifetime regime

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

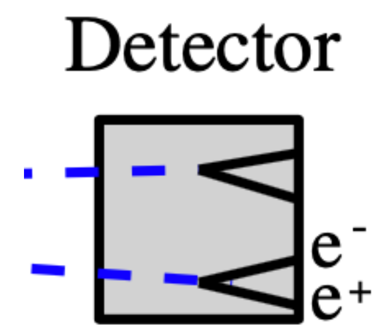
$$\mathscr{P}_{decay} = \exp\left(-\frac{L_{min}}{\bar{d}}\right)\left[1 - \exp\left(-\frac{L_{max} - L_{min}}{\bar{d}}\right)\right],$$

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

- **Secondary production**
  - Signal due to $\mathrm{LLP}_2 \to \mathrm{LLP}_1 + e^- + e^+$ or $\mathrm{LLP}_2 + e^- \to \mathrm{LLP}_2 + e^-$

Experimental signatures of new physics

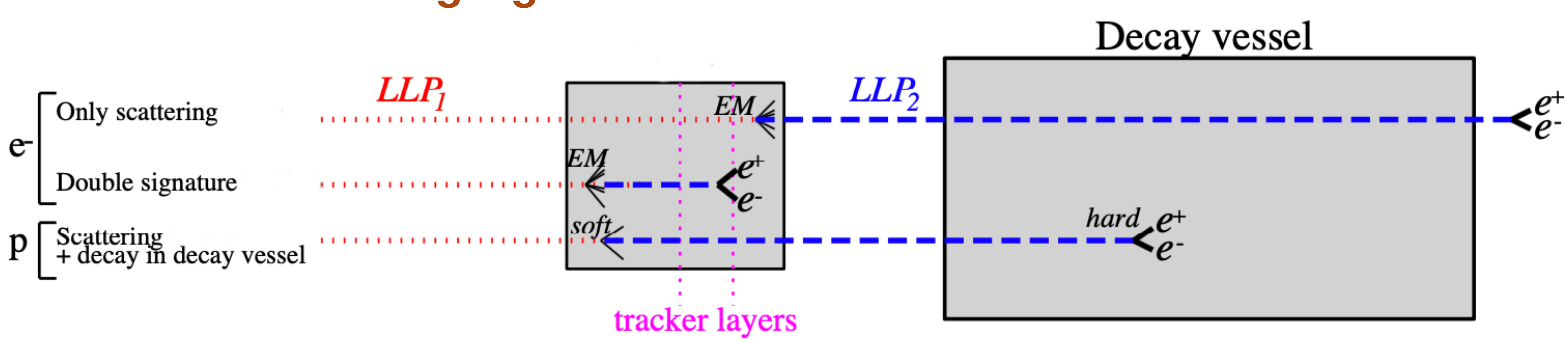
- **LLP decay signal inside the decay vessel – e^+e^-**
  - $E_{vis} > 100$ GeV (FASER)
  - e^+e^- search - negligible background due to high energies of LLP's



- **Scattering off electrons**
  - new-physics-induced 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

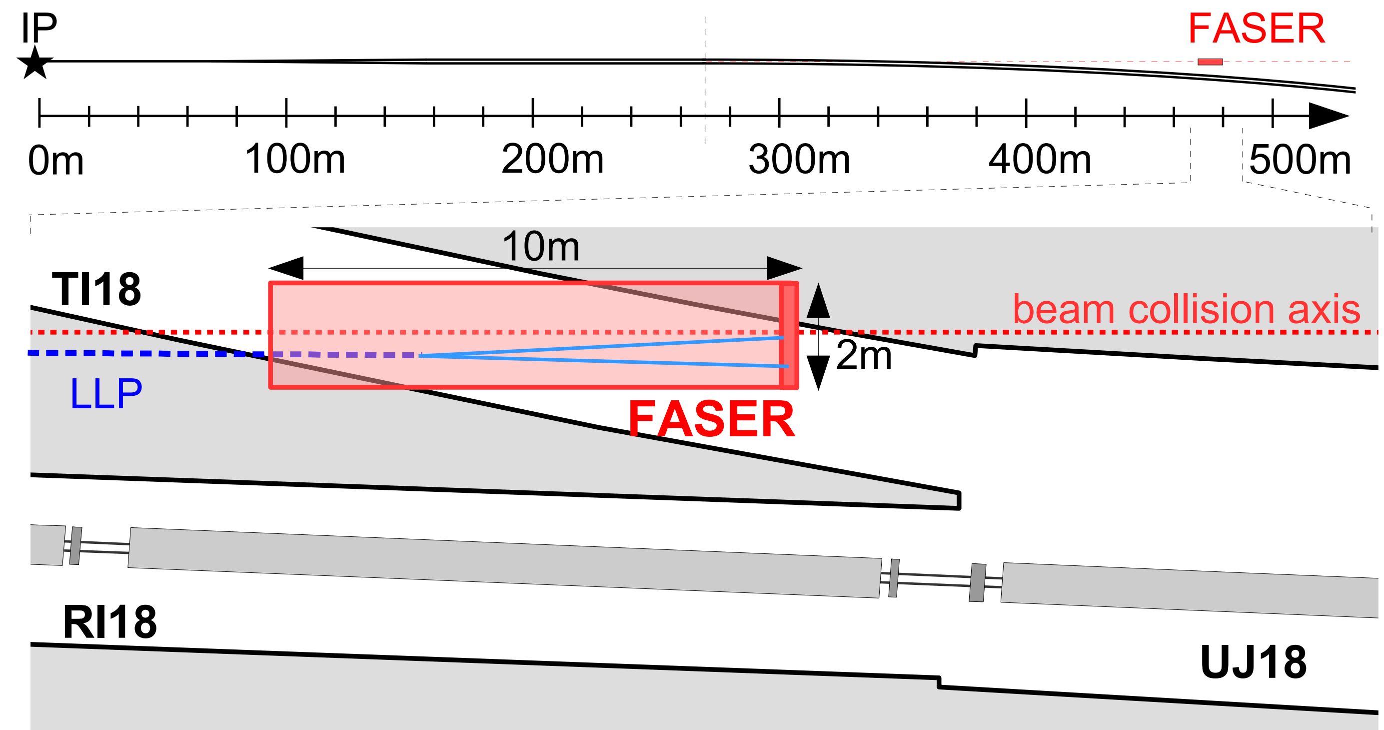
Batell, Feng, Trojanowski, 2011.xxxxx
Technical Proposal: A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case, 1504.04855
Sensitivity of the SHiP experiment to light dark matter, 2010.11057

- **Collinear double-bang signature**



ForwArd Search ExpeRiment

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

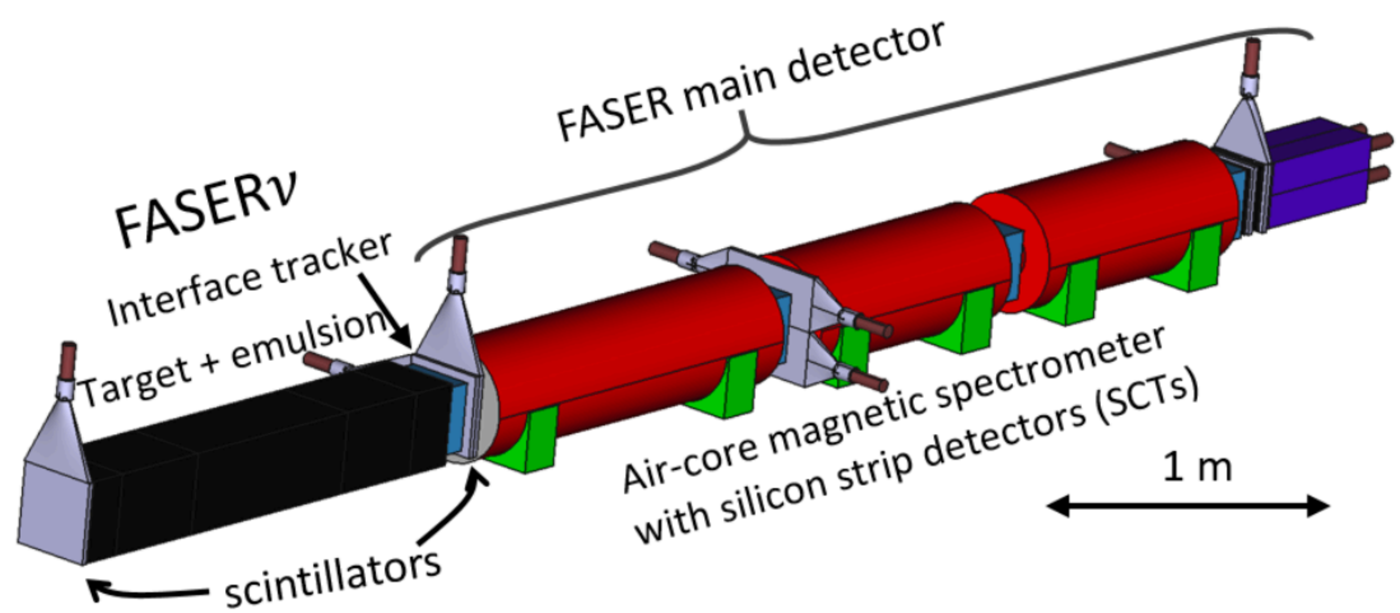


Feng, Gallon, Kling, Trojanowski, 1708.09389
Letter of Intent for FASER: ForwArd Search ExpeRiment at the LHC, 1811.10243
Technical Proposal for FASER: ForwArd Search ExpeRiment at the LHC, 1812.09139

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

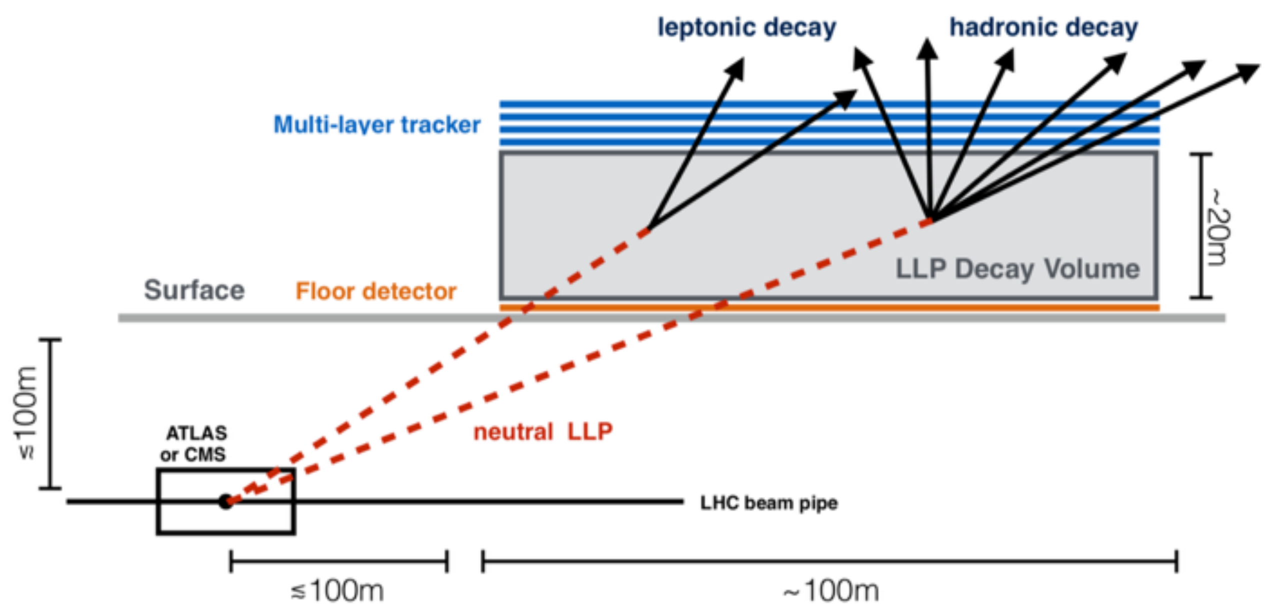
→ *probing high energy neutrinos and short-lifetime regime*



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

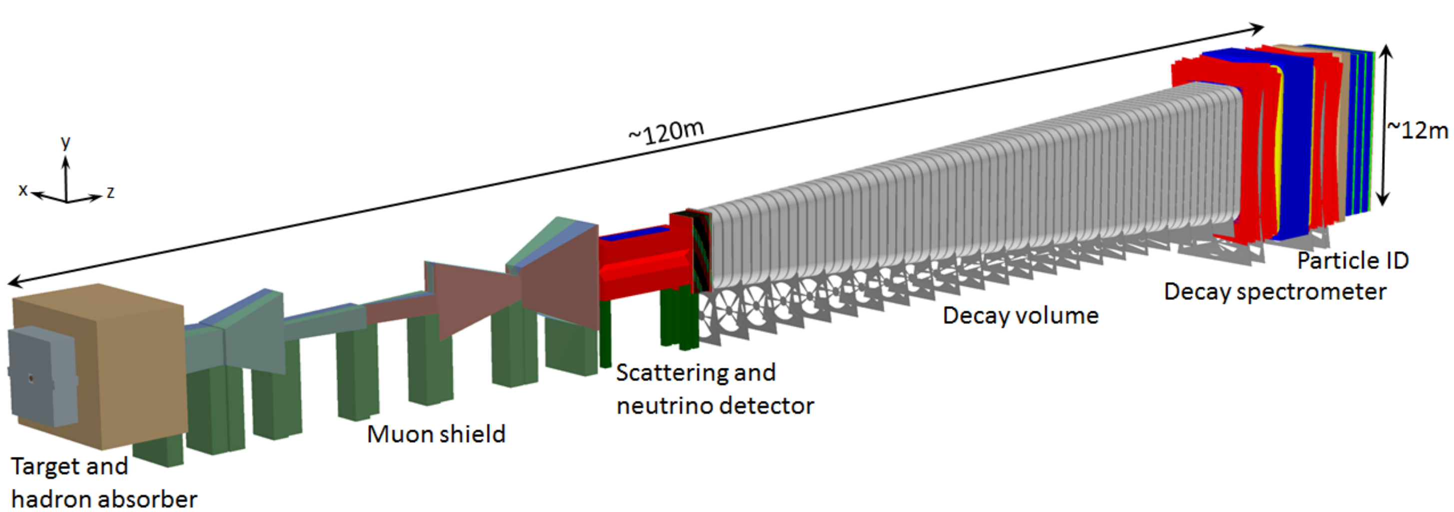
MATHUSLA - start with HL LHC (proposed)



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

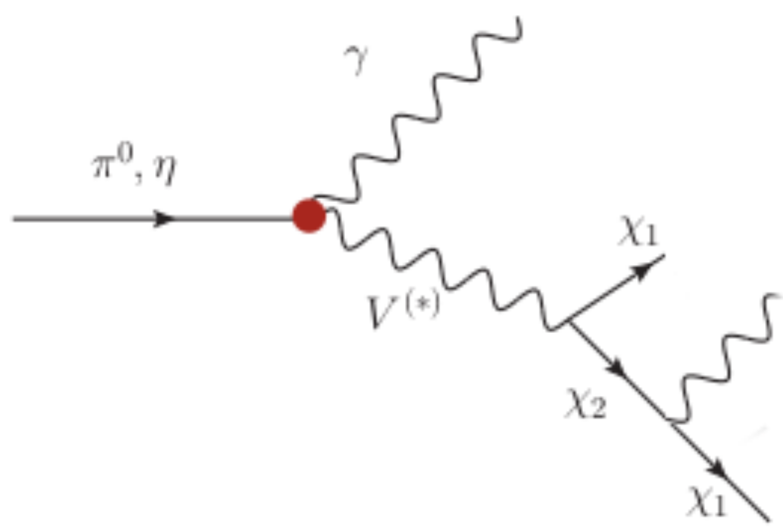
SHiP Experiment PROGRESS REPORT, November 2018

Inelastic DM

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

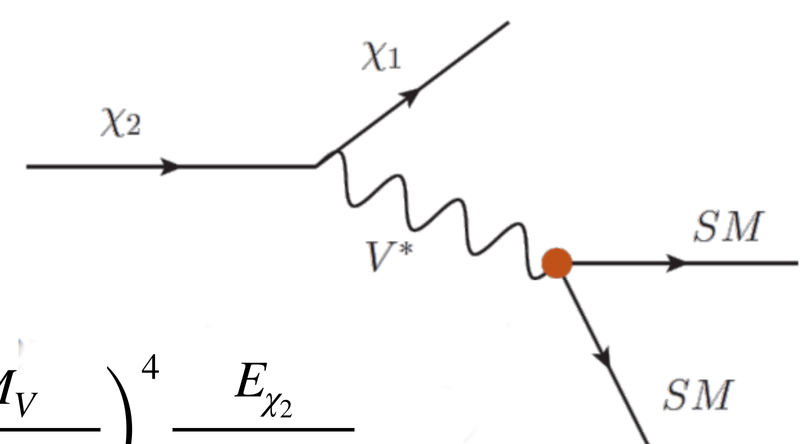
Smith, Weiner, 0101138

- 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

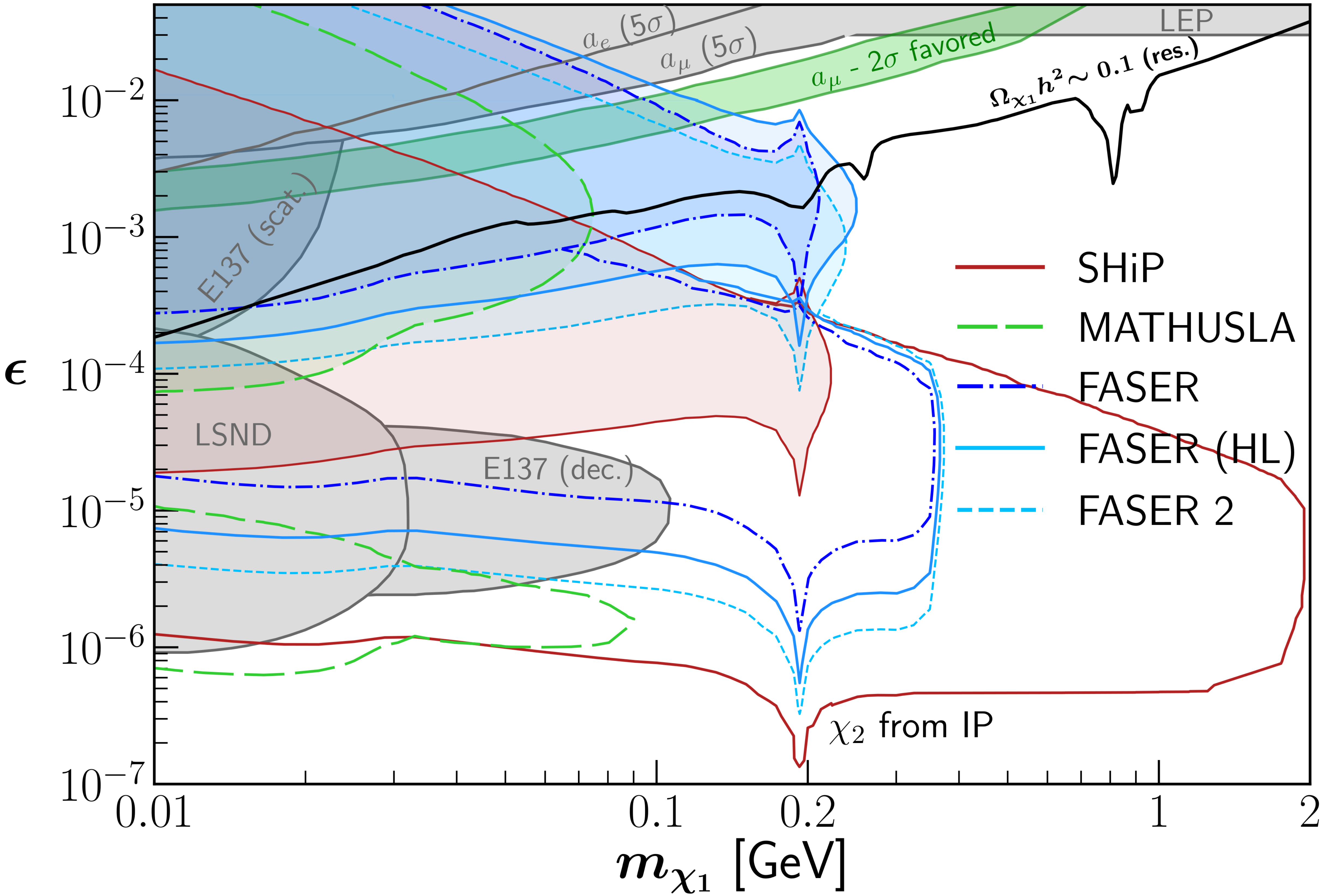
$$m_{\chi_1} : m_{\chi_2} : m_{A'} \sim 1 : 3 : 4$$



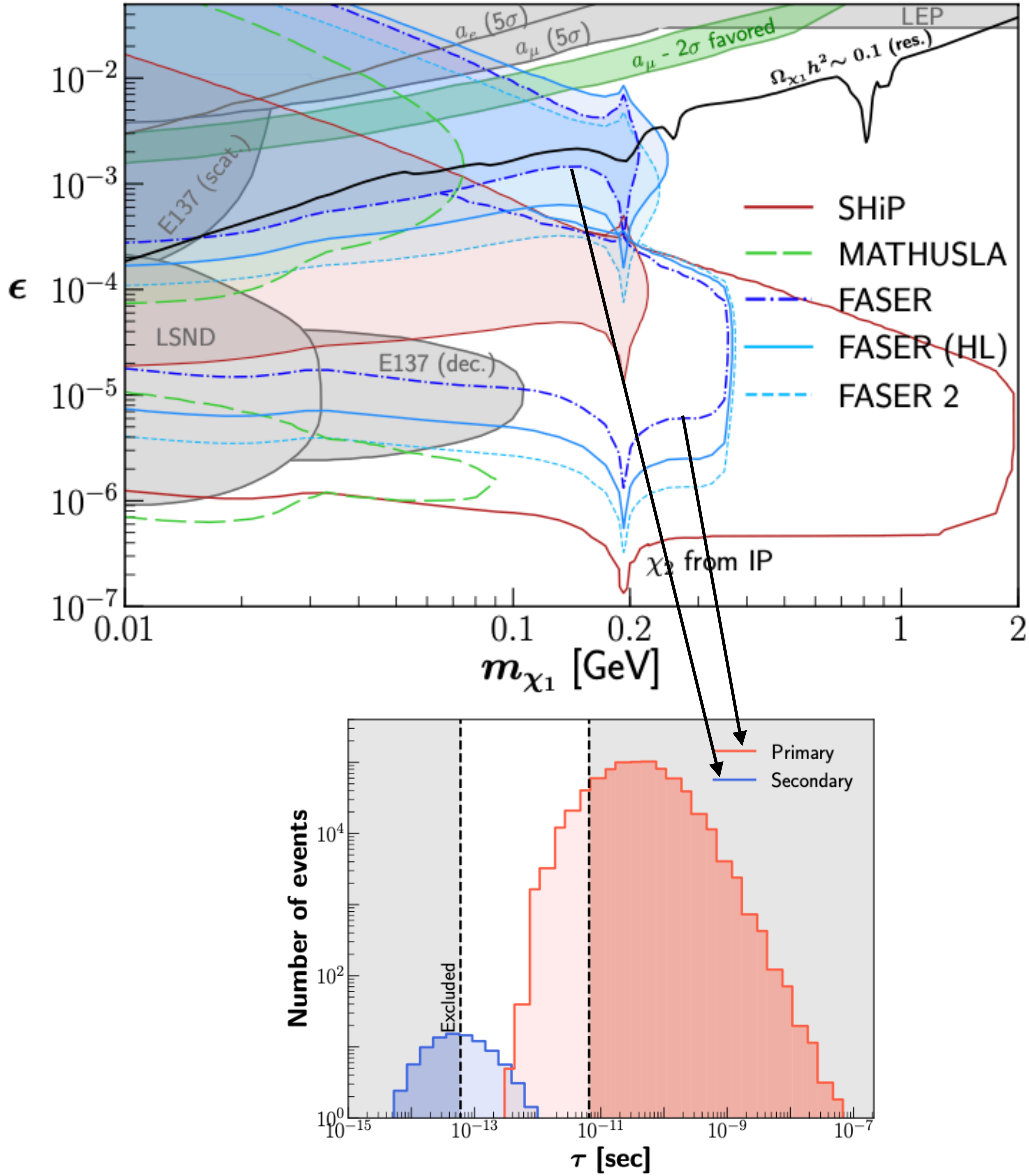
- Typical lifetime

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

Results: iDM



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



LEP
a_e (5σ)
a_μ (5σ)
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]

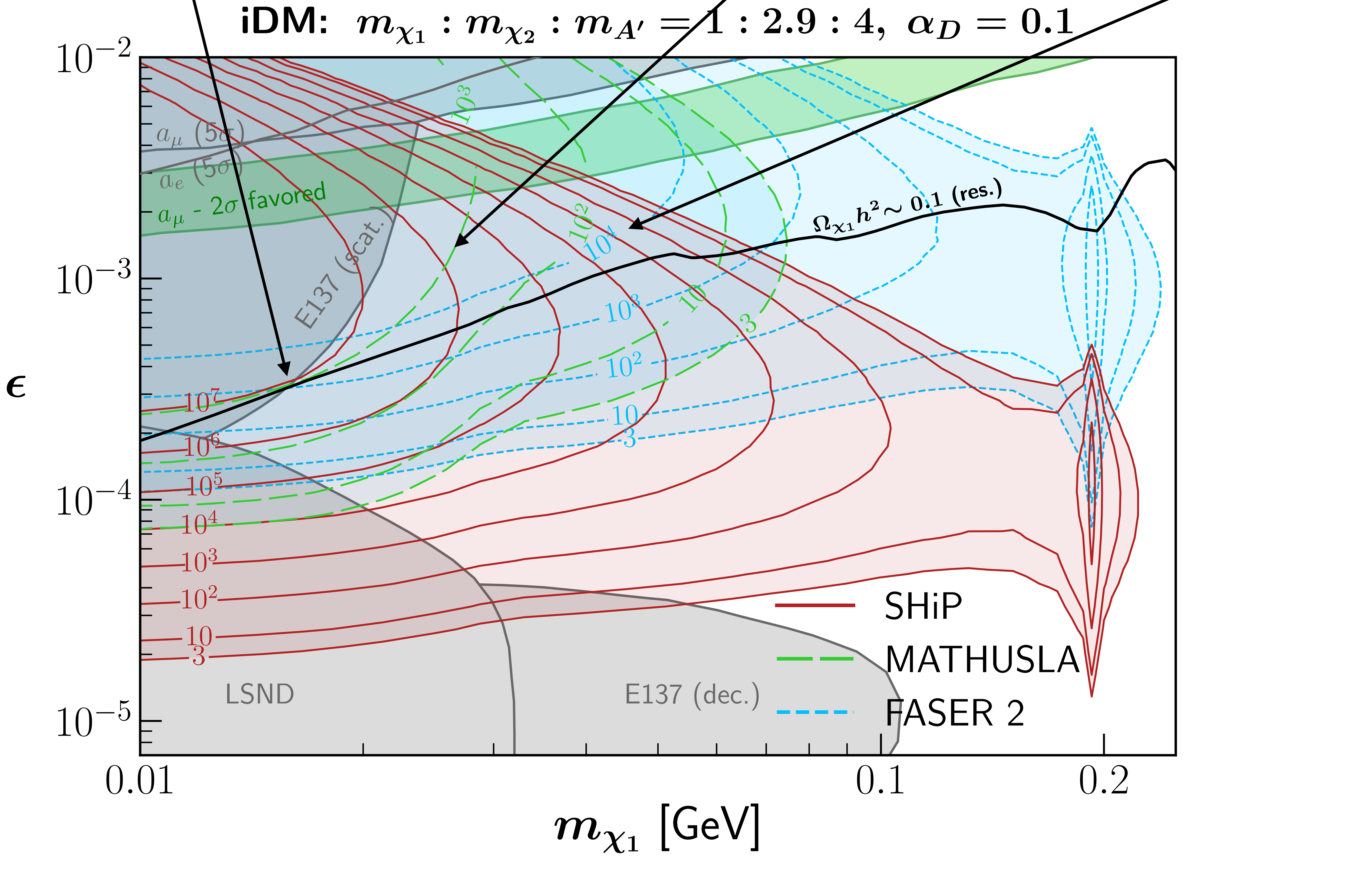
Secondary production

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

up to 10^7 events for SHiP

up to 10^3 events for MATHUSLA

up to 10^5 events for FASER2



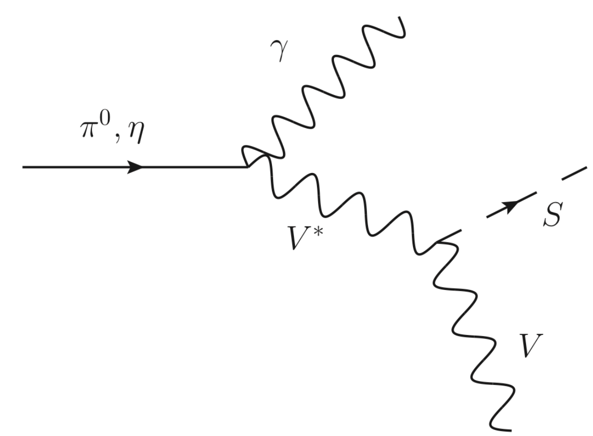
Dark Higgs mechanism

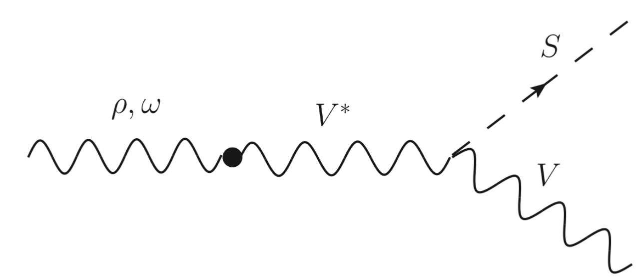
- Need mechanism to give mass to the dark photon
- Simplest solution: dark Higgs mechanism:

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

- 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

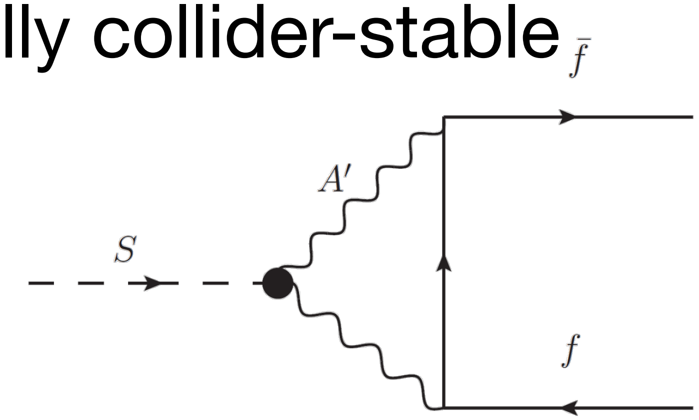
Batell, Pospelov, Ritz, 0906.5614
Darmé, Rao, Roszkowski, 1806.06036





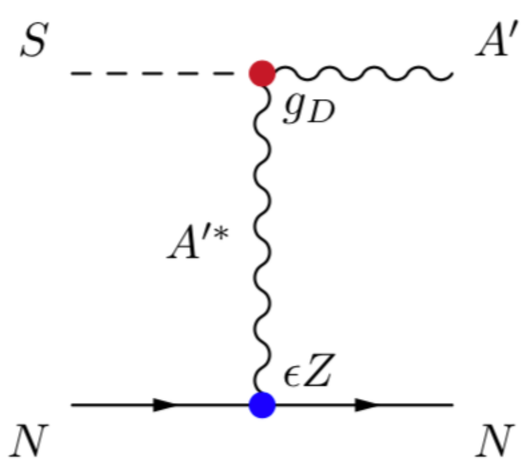
- If the dark Higgs is to be light, it is naturally collider-stable

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

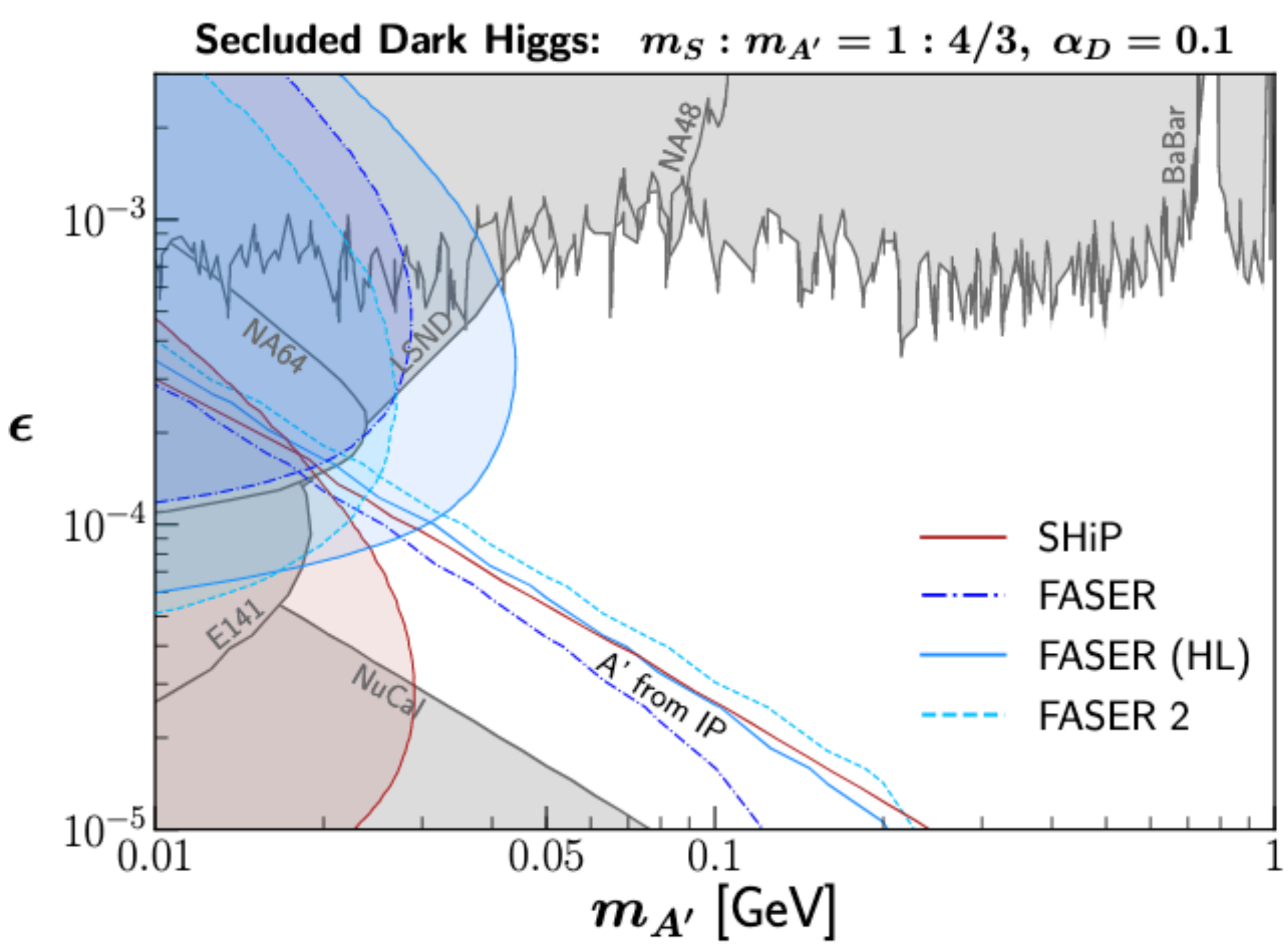


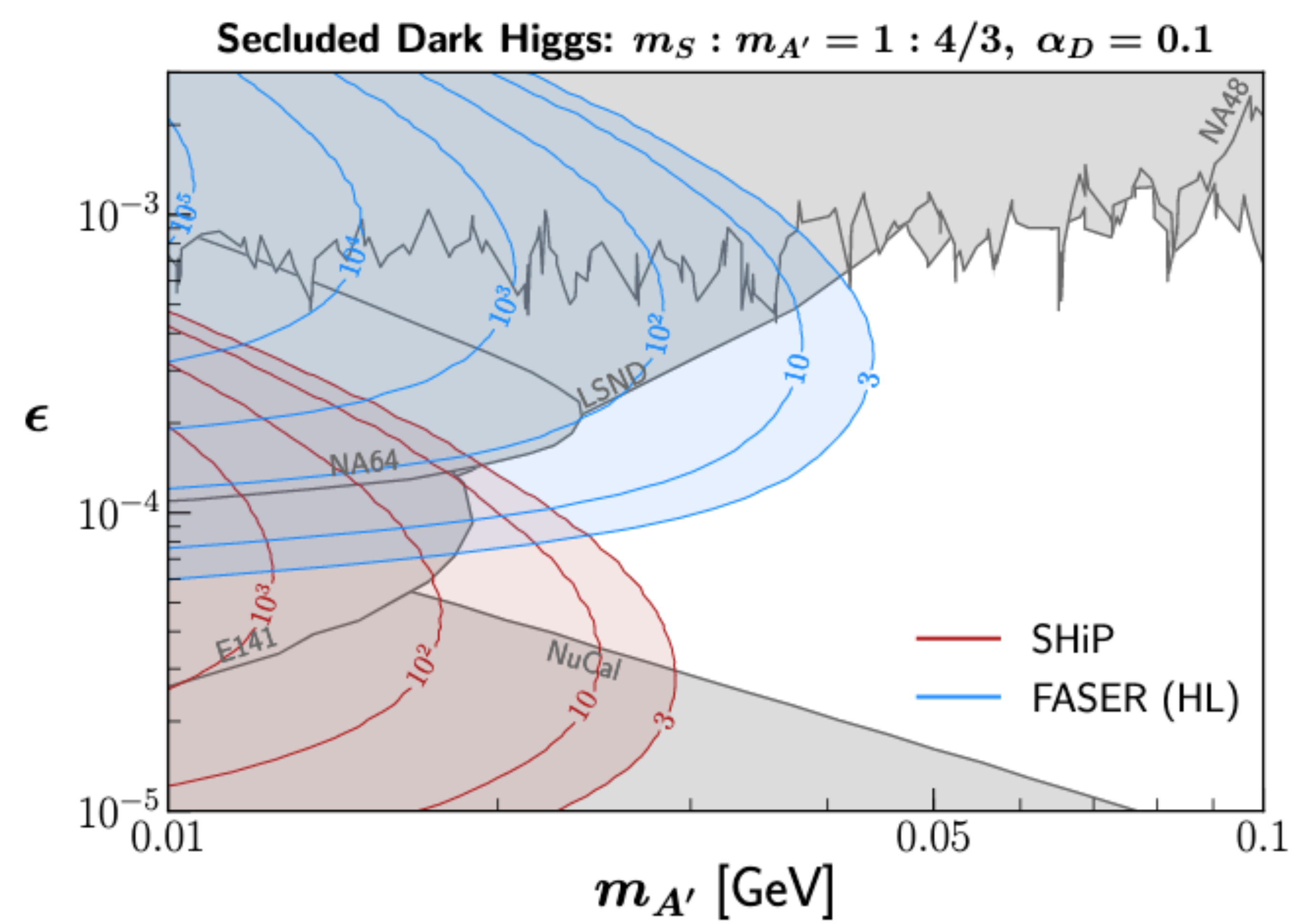
$$m_S : m_{A'} = 1 : 4/3$$

Dark Higgs



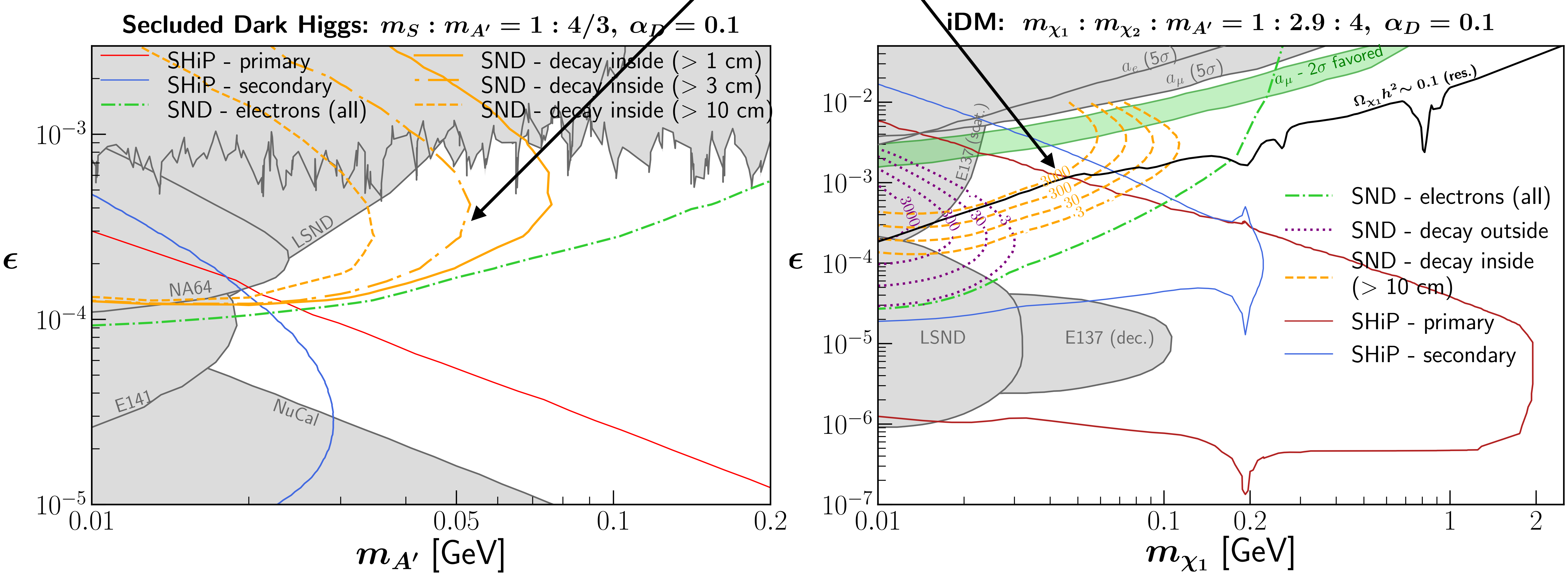
- Long-lived dark Higgs scatters in front of the detector, producing dark photon which decays in the detector to SM



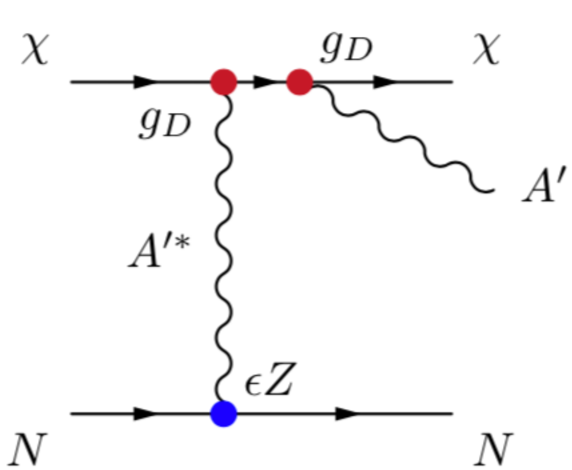


Electron scattering events at SND@SHiP

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



Dark Bremsstrahlung



Dark photon mediator to light DM

$$\mathcal{L} \supset \bar{\chi}\left(i\not{D} - m_\chi\right)\chi$$

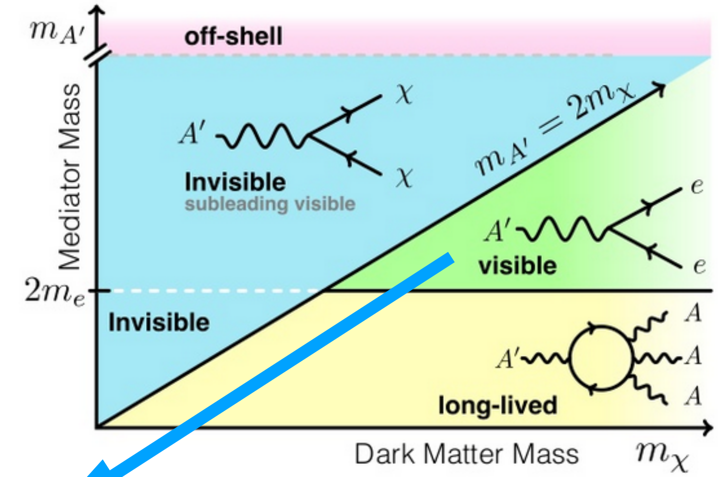
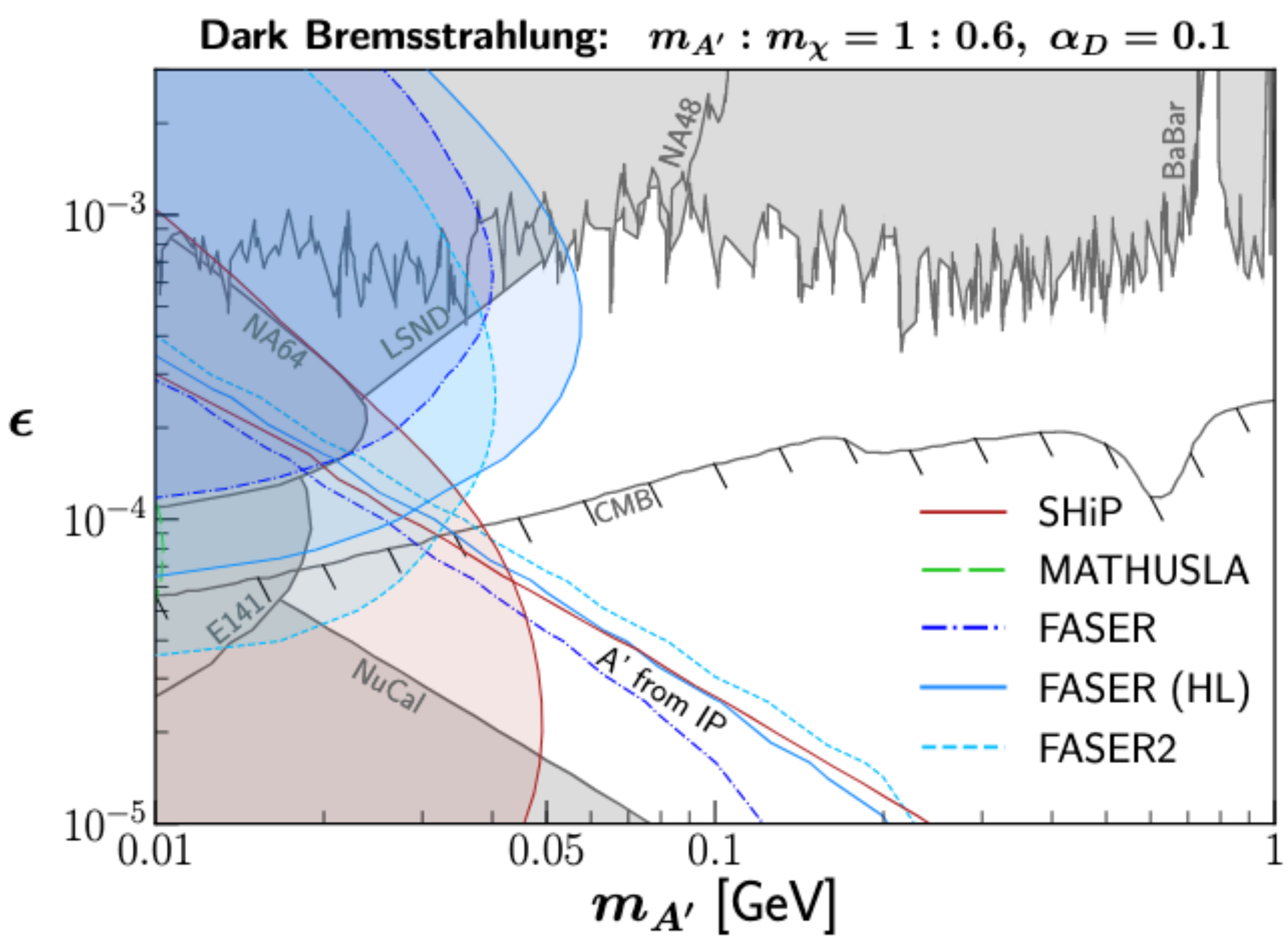
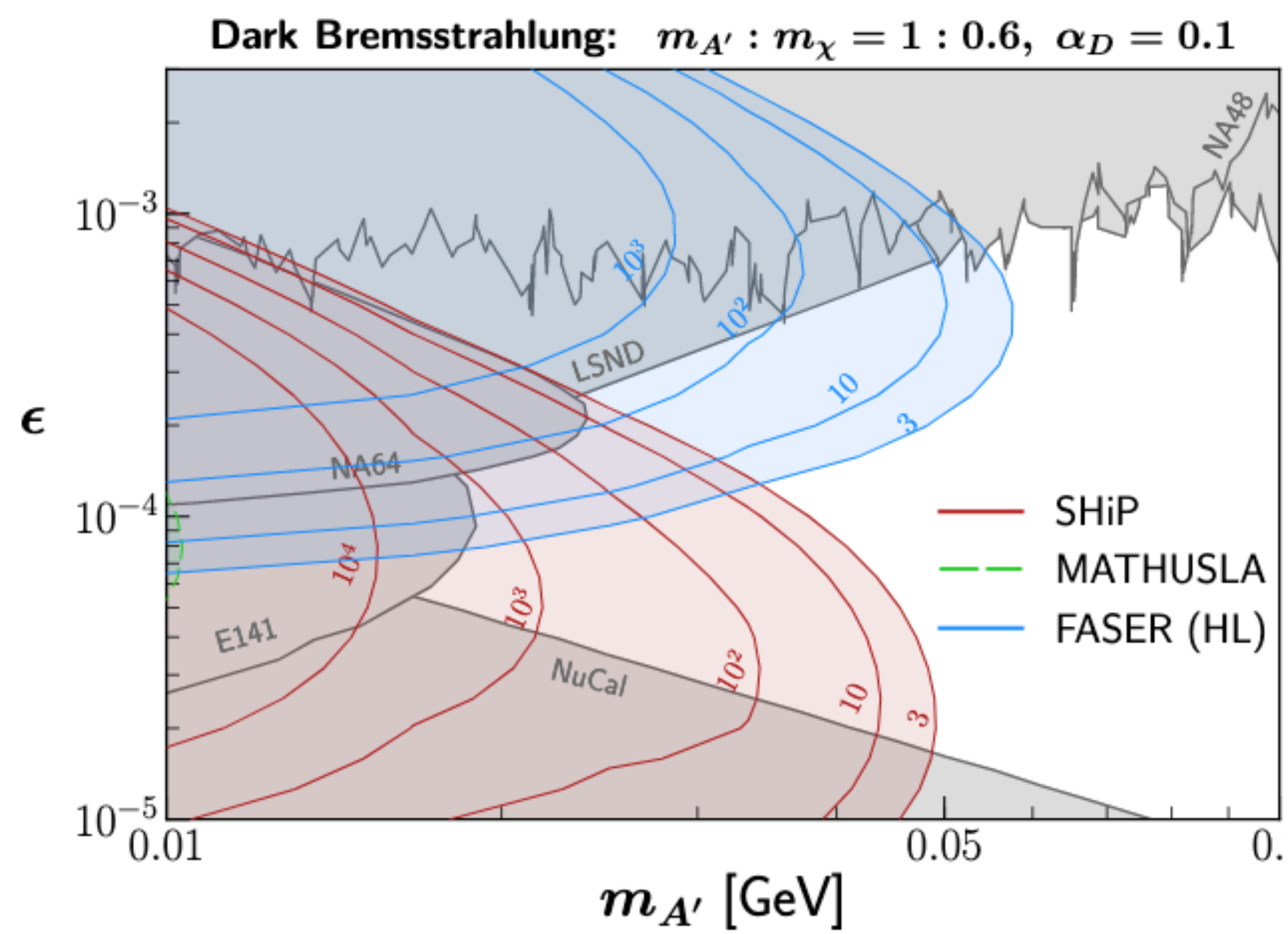


Figure by F. Tanedo

$m_\chi : m_{A'} = 0.6 : 1$ Regime where $m_\chi < m_{A'} < 2m_\chi$





Conclusions

- Realistic BSM scenarios often predict more than a single light new particle
- **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 **FASER**, **MATHUSLA** and **SHiP** detectors for nonminimal models featuring dark photon - inelastic DM, dark brehmstrahlung and dark photon together with dark Higgs mechanism

See also talk by S. Trojanowski: New directions in BSM searches at FASER and beyond

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