Looking forward to photon-coupled sub-GeV long-lived particles

Light Dark World 2023

19-21 September

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Based on:

KJ, 2305.16781

Intensity frontier BSM searches

Light, weakly interacting particles

Weak couplings → large luminosities required

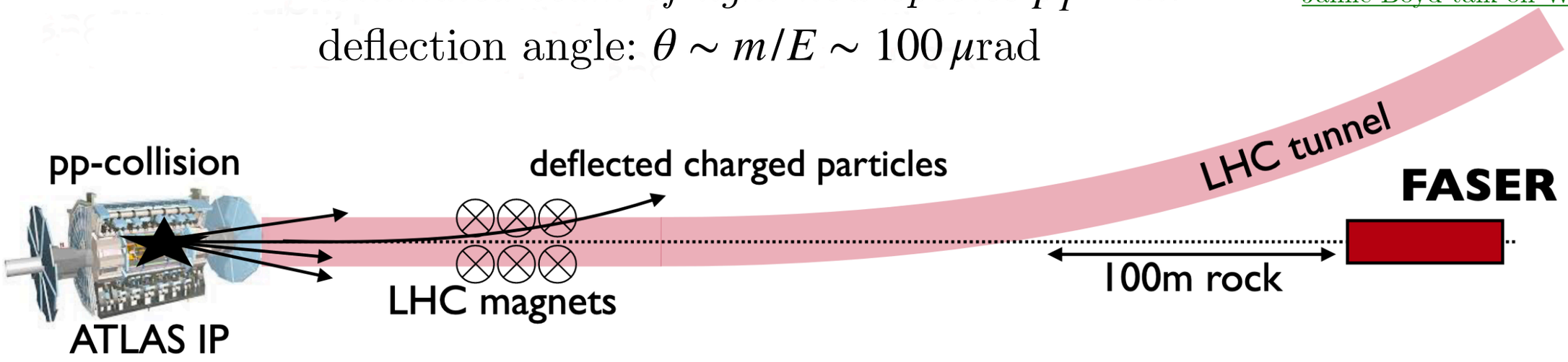
$$N_{signal} \sim \mathrm{Lum} \times \sigma_{prod} \times \mathrm{P}_{det}$$

- Beam dump experiments (proton, electron)
  - Small energies of beam
  - Huge number of collisions on target

- FASER at LHC → use "wasted" luminosity as a *collimated beam of light new species* $p_T \sim m$.
  deflection angle: $\theta \sim m/E \sim 100\,\mu\mathrm{rad}$

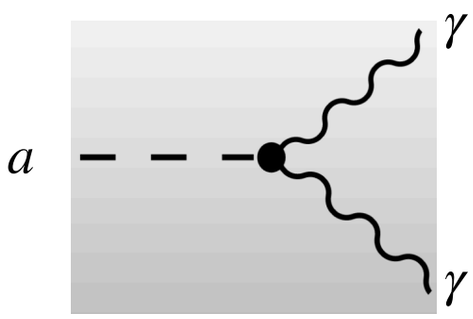
ForwArd Search ExpeRiment, 1708.09389

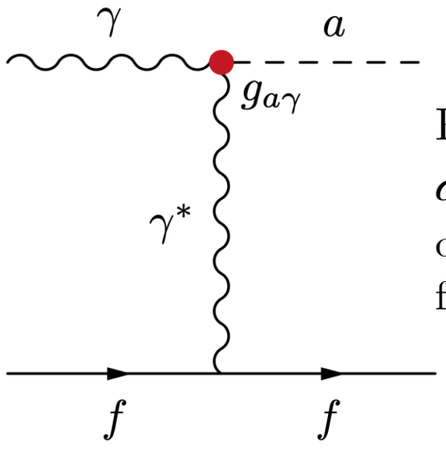
Jamie Boyd talk on Wed



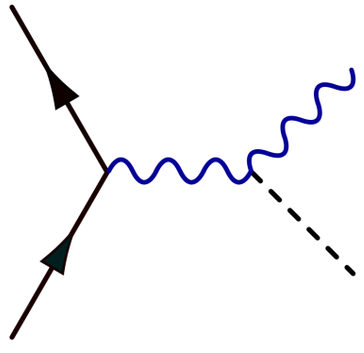
PBC benchmark 9
photon-coupled ALP

$$\mathscr{L} \supset \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



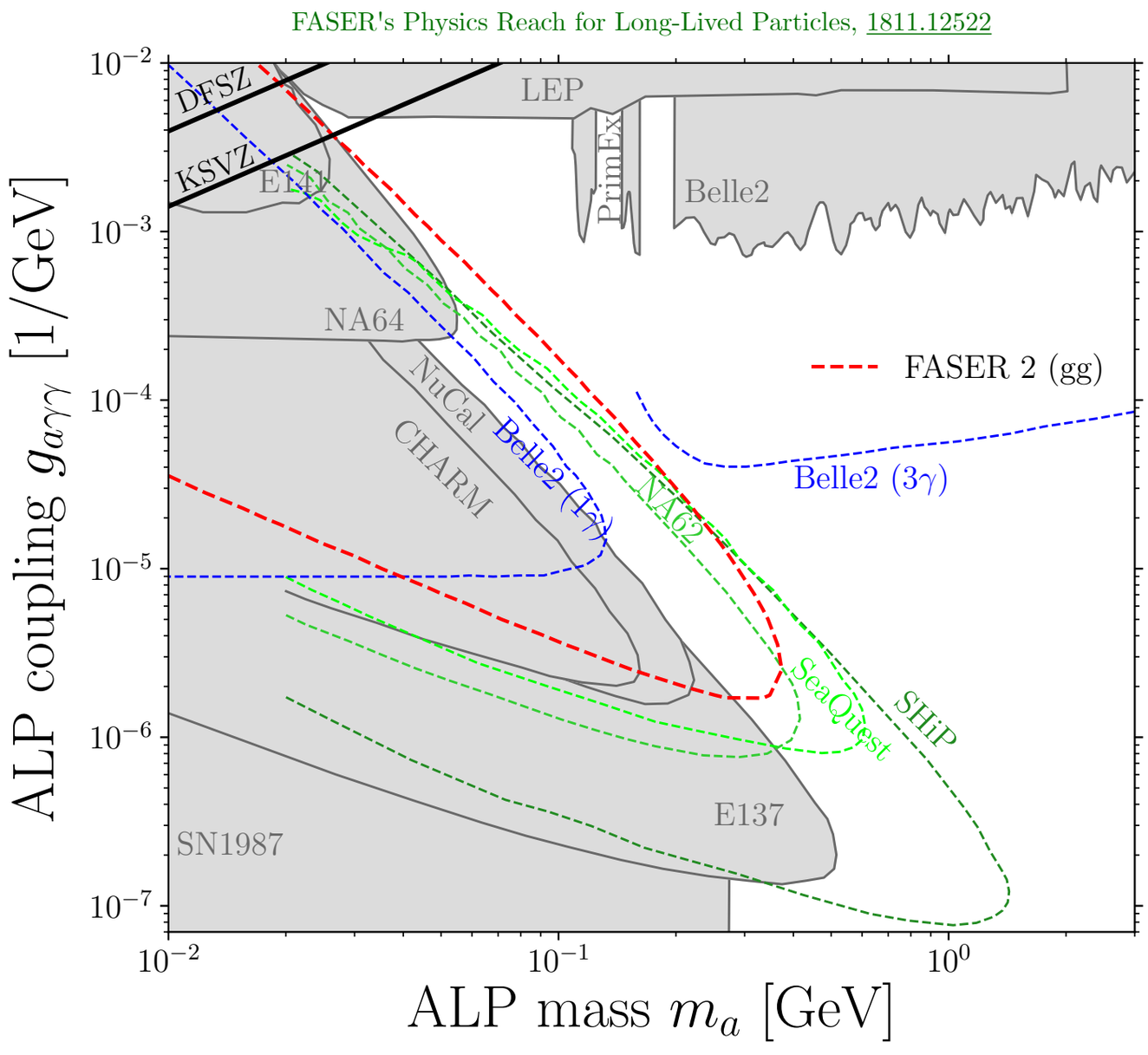


Primakoff scattering
$\sigma_{\gamma N \to aN} \propto \alpha_{em} g_{a\gamma\gamma}^2 Z^2$
dominant production mode
for ALP, spin-2 mediator, ...



Drell-Yan/vector meson decays
dominant for *single-photon couplings*

FASER's Physics Reach for Long-Lived Particles, 1811.12522



$$d_a \sim 100\,m \times \left(\frac{E}{100\,GeV}\right)\left(\frac{0.1\,GeV}{m_a}\right)^4 \left(\frac{1.05\times10^{-5}}{g_{a\gamma\gamma}}\right)^2$$

Sub-GeV LLPs coupled to a photon

- *Massive spin-2 mediator* decays into two photons

$$\mathscr{L} \supset g_\gamma G^{\mu\nu}\left(\frac{1}{4}\eta_{\mu\nu}F_{\lambda\rho}F^{\lambda\rho} + F_{\mu\lambda}F_{\nu}{}^{\lambda}\right) - i\sum_l \frac{g_\ell}{2} G^{\mu\nu}\left(\bar{l}\gamma_\mu D_\nu l - \eta_{\mu\nu}\bar{l}\gamma_\rho D^\rho l\right)$$

- *Dark ALP* decays into to a photon and a dark photon

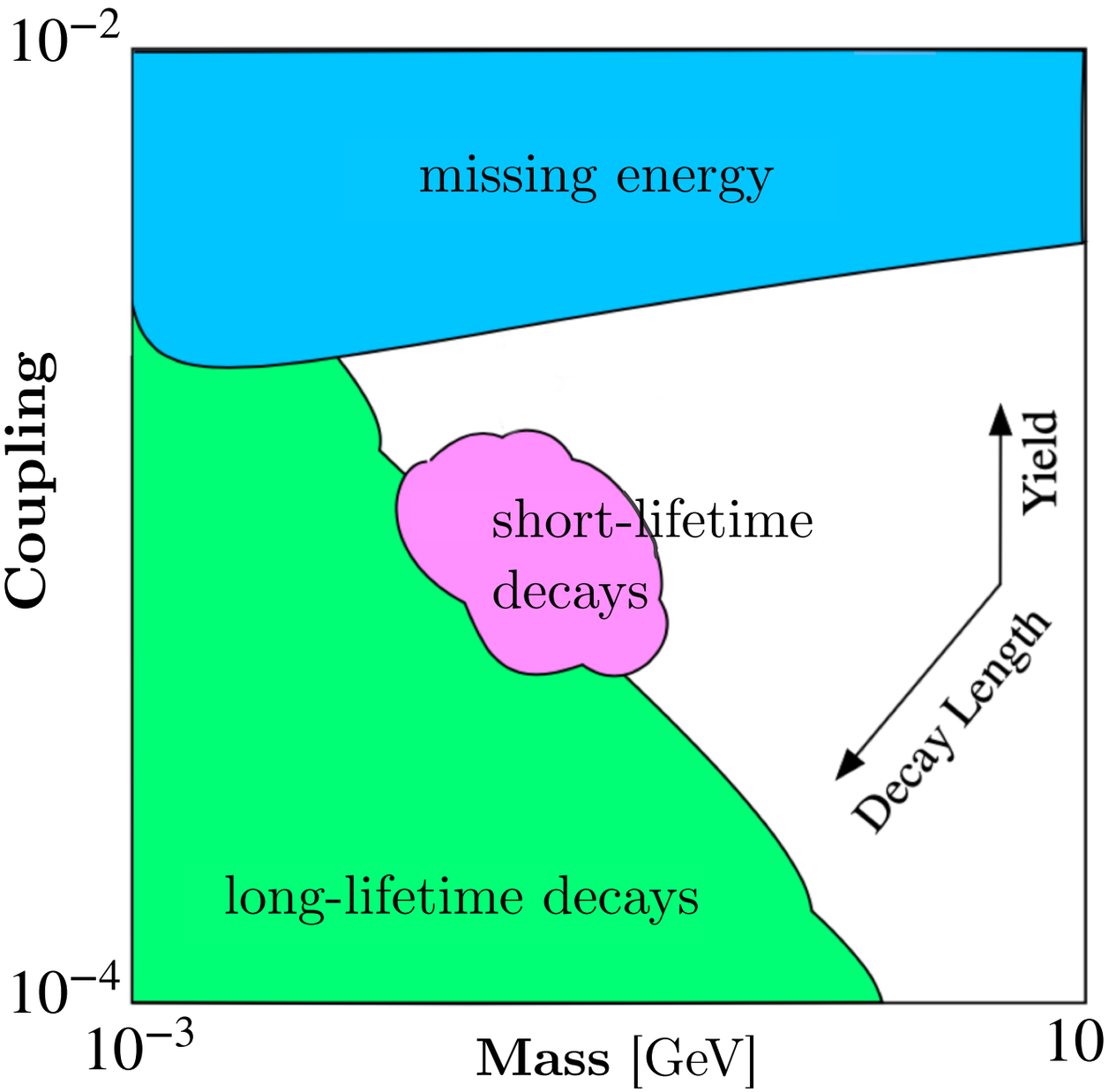
$$\mathscr{L} \supset \frac{g_{a\gamma\gamma'}}{4} a F^{\mu\nu}\tilde{F}'_{\mu\nu}$$

- SUSY - *neutralino* decays into a photon and the LSP:
  - ALPino $\quad \mathscr{L} \supset \frac{\alpha_{\text{em}} C_{a\gamma\gamma}}{16\pi f_a}\tilde{a}\gamma_5\left[\gamma^\mu,\gamma^\nu\right]\tilde{\gamma}F_{\mu\nu}$
  - gravitino $\quad \mathscr{L} \supset -\frac{1}{4M_{\text{Pl.red.}}}\bar{\psi}_\mu\sigma^{\rho\sigma}\gamma^\mu\lambda F_{\rho\sigma}$

- *Inelastic DM* with EM form factors - heavier state decays into SM and a stable dark fermion
  - dim 5 - magnetic/electric dipole moment $\quad \mathscr{L} \supset \frac{1}{\Lambda_m}\bar{\chi}_1\sigma^{\mu\nu}\chi_0 F_{\mu\nu} + \frac{1}{\Lambda_e}\bar{\chi}_1\sigma^{\mu\nu}\gamma^5\chi_0 F_{\mu\nu}$
  - dim 6 - anapole moment/charge radius op. $\quad \mathscr{L} \supset -a_\chi\bar{\chi}_1\gamma^\mu\gamma^5\chi_0\,\partial^\nu F_{\mu\nu} + b_\chi\bar{\chi}_1\gamma^\mu\chi_0\,\partial^\nu F_{\mu\nu}$

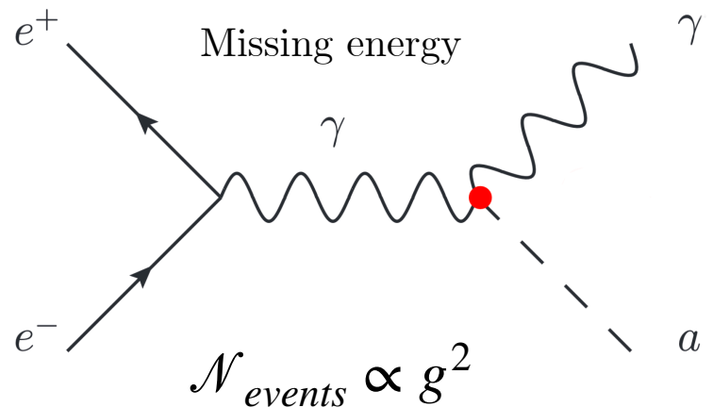
LLP signatures

determined by yield and lifetime



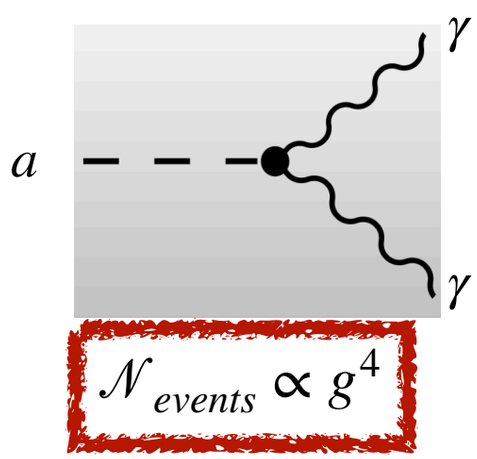
Similar dependence for many models:
i) dark photon, ii) dark Higgs, iii) ALP, ...

$d \lesssim 10$ m → invisible decays/missing energy
10 m $\lesssim d \lesssim$ 10 km → displaced decays
$d \gtrsim 10$ km → astrophysics/cosmology



Large $\mathcal{N}_{events}$ with large backgrounds

Displaced decays

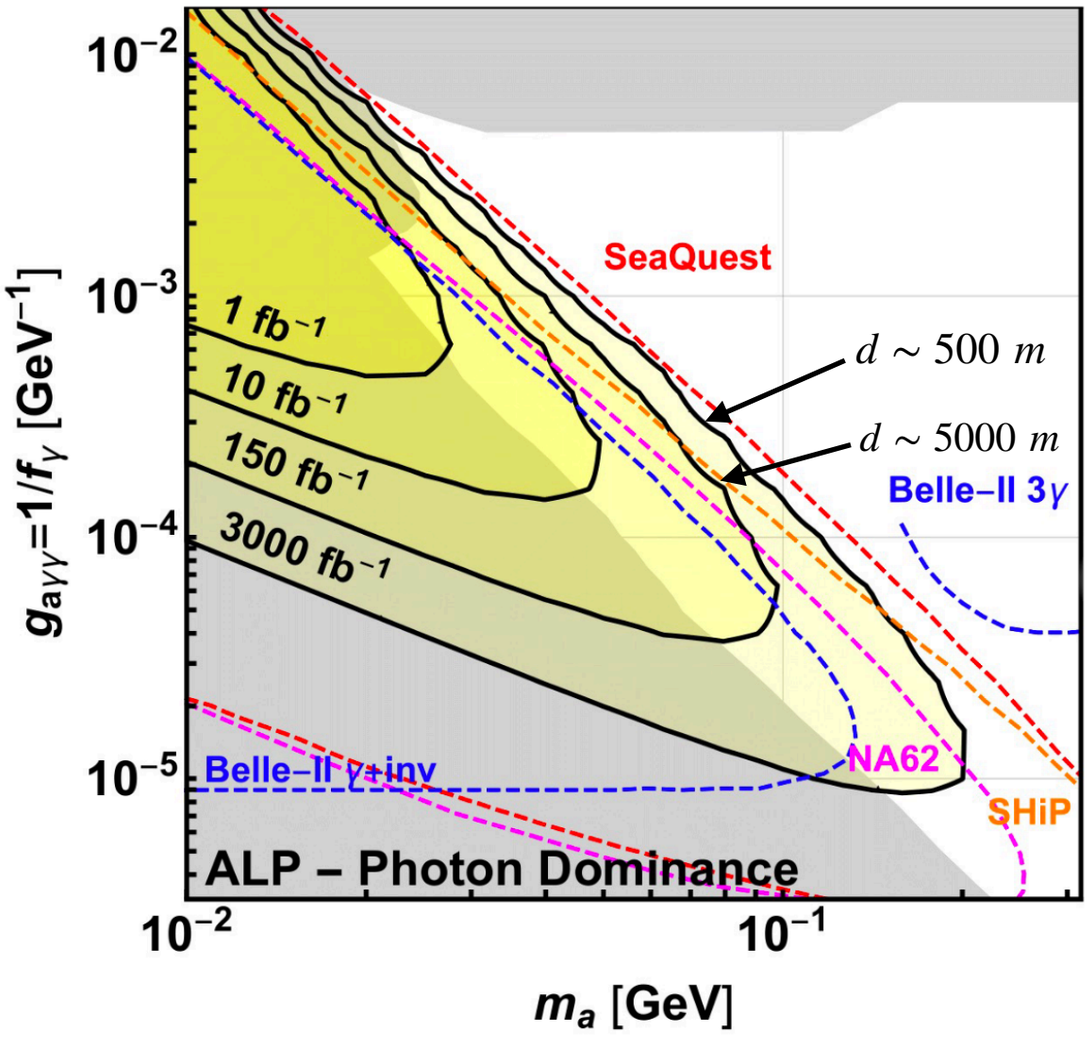


Small $\mathcal{N}_{events}$ with essentially no background

ALP decays at beam dumps

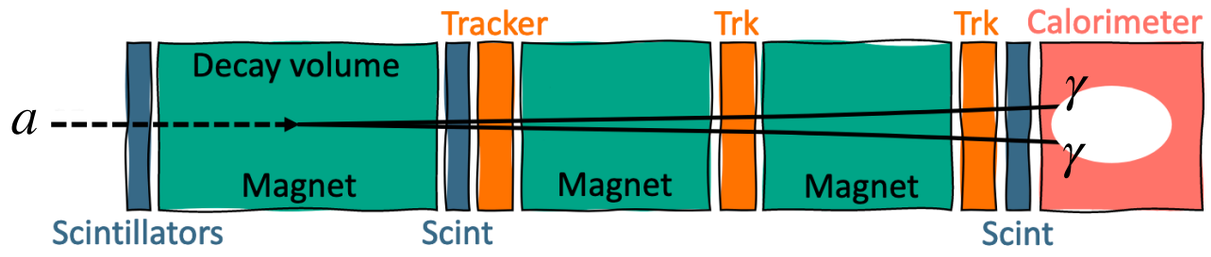
$$\mathscr{P}_{decay} = \exp\left(-\frac{L_{min}}{d}\right) - \exp\left(-\frac{L_{max}}{d}\right) = \begin{cases} \dfrac{L_{max} - L_{min}}{d} \equiv \dfrac{\Delta}{d} & : \text{ for } d \gg L_{min} \\ \exp(-L_{\min}/d) & : \text{ for } d \ll L_{min} \end{cases} \quad \rightarrow d \text{ is } \underline{\textbf{exponentially sensitive}} \text{ to } L_{min}$$

Distance to the decay vessel L_{min} determines the scale of LLP decay length d, which can be probed.



FASER's Physics Reach for Long-Lived Particles, 1811.12522

ALP: $d = c\tau\gamma \sim 100\ \text{m} \times (100\ \text{MeV}/m_a)^2 \times (10^{-5}/g)^2$



Displaced vertex → essentially *zero background* search

$$\mathscr{N}_{events} = \text{production} \times \text{solid angle} \times \text{decay inside detector}$$

$$= \mathscr{L}_{lumi} \cdot g^2 \times \left(\frac{r}{L_{\max}}\right)^2 \times \mathscr{P}_{decay} \propto g^2/d \propto g^4$$

Good detector is:

- *big* - large radius r and decay length Δ
- *close* to production point - small L_{min}
- placed in the *forward direction* of the production point

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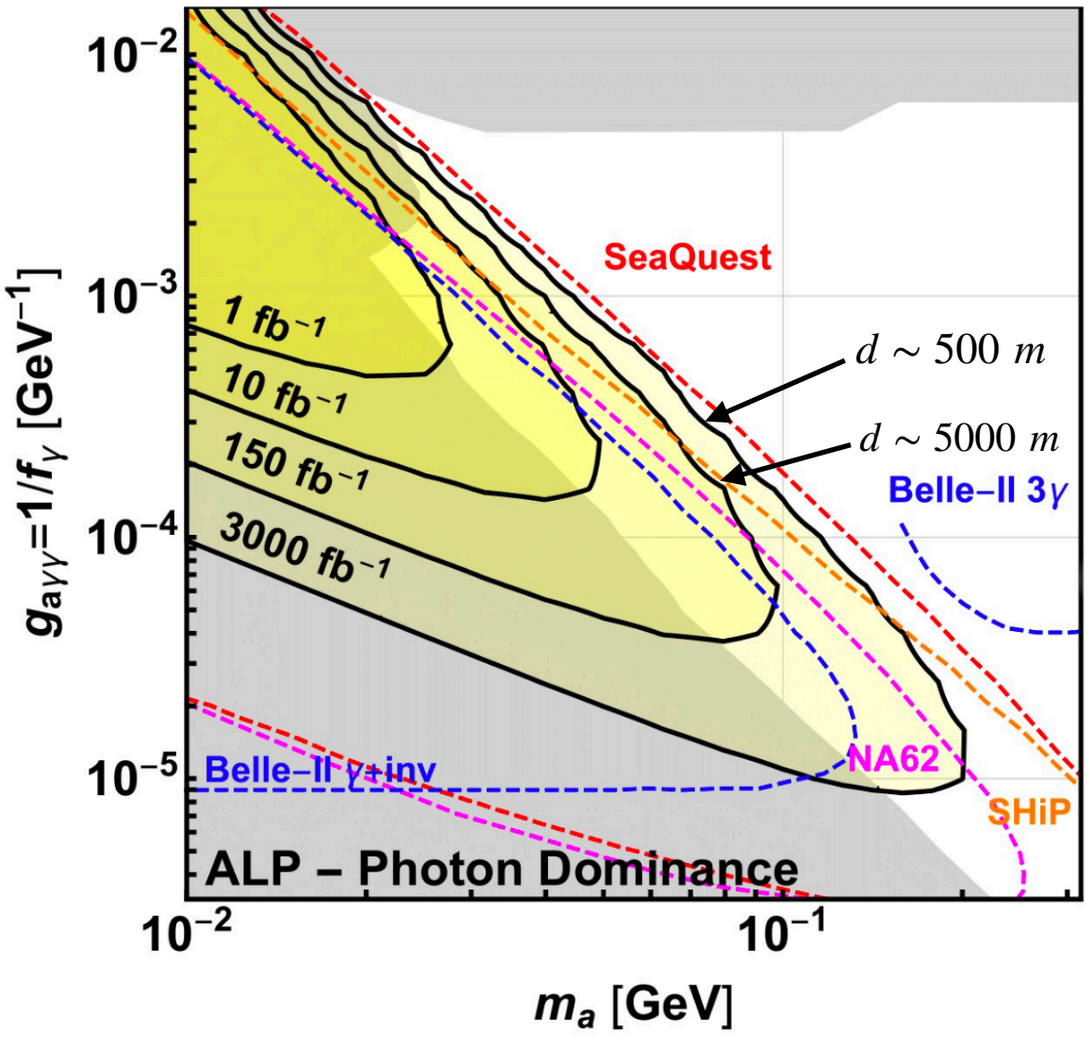

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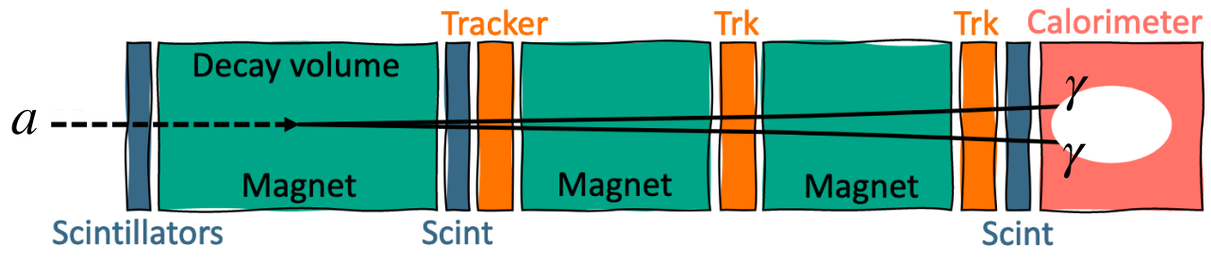

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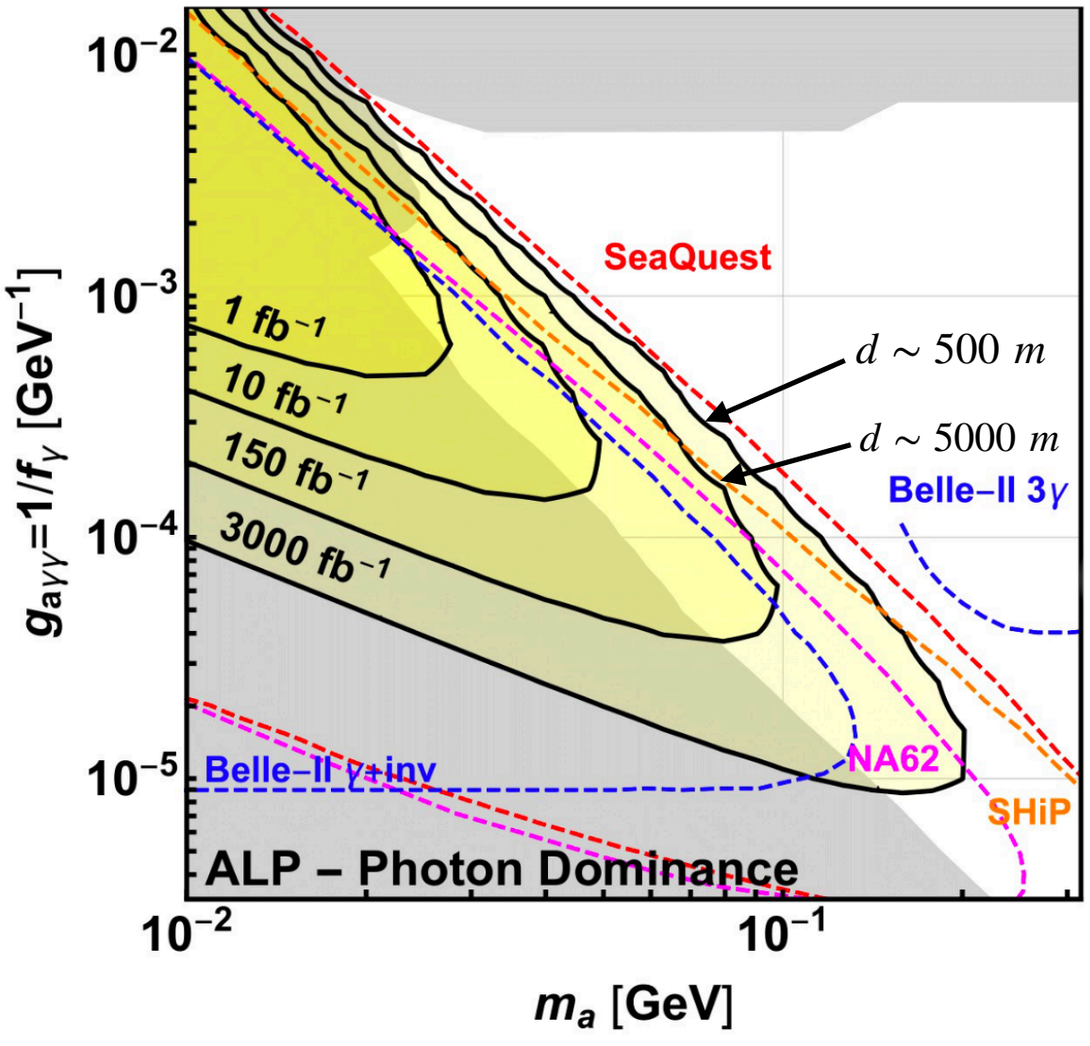

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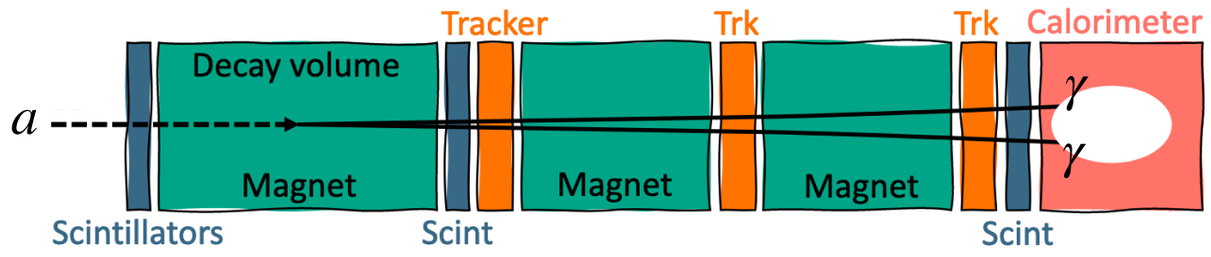

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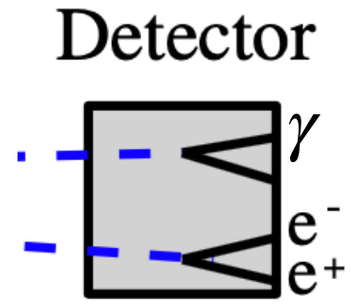
LLP signatures at FASER/FPF



- **LLP signal inside the decay vessel – $\gamma\gamma$ or $\gamma + X$**
  - $E_{vis} > 100$ GeV
  - $\gamma\gamma$, e^+e^- search: negligible background due to high energies of LLP's
  - γ search: KJ, S. Trojanowski, 2011.04751; The FASER W-Si High Precision Preshower Technical Proposal, CERN-LHCC-2022-006
    - neutrino-induced BG minimized by preshower put in front of the calorimeter
    - BG from muon-induced photons vetoed by scintillators detecting a time-coincident muon going through the detector → *excess of single-photon events unaccompanied by any muon indicative of new physics*

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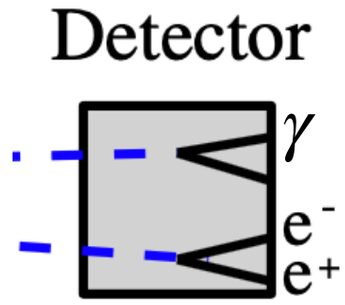

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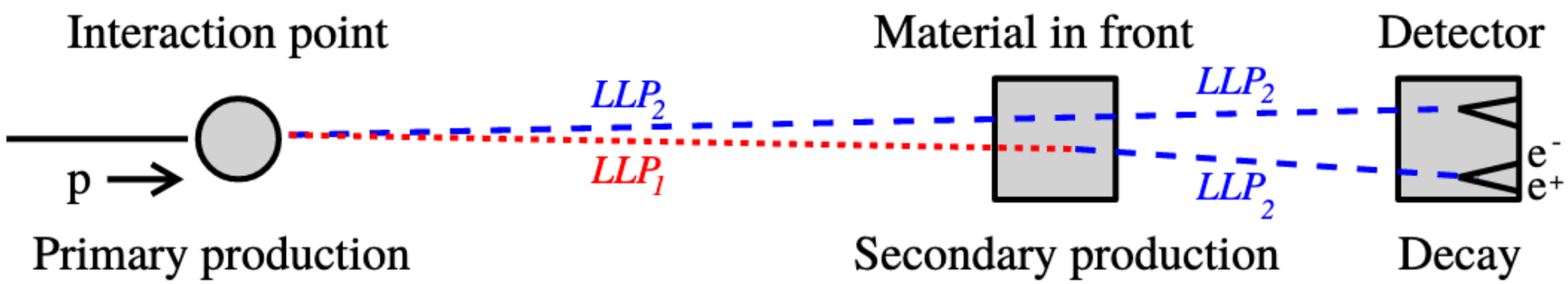
- **Scattering off electrons**
  - new-physics-induced neutrino scatterings off electrons producing electron recoils inside the neutrino detector.
  - *Energy and angular cuts:* Batell, Feng, Trojanowski, 2101.10338 (FLArE)
    - Electron energy and angular cuts following the DM scattering signature
    - The cuts have been designed to minimize the neutrino-induced BG to the level of $O(10)$ such expected events in FASERν2/FPF.
- **Secondary LLP production**



Inelastic DM with EM form factors

- Inelastic DM with EM form factors - heavier state decays into SM and the LSP
  - dim 5 - magnetic/electric dipole $\mathscr{L} \supset \frac{1}{\Lambda_m}\bar{\chi}_1\sigma^{\mu\nu}\chi_0 F_{\mu\nu} + \frac{1}{\Lambda_e}\bar{\chi}_1\sigma^{\mu\nu}\gamma^5\chi_0 F_{\mu\nu}$ $\rightarrow$ decay: $\chi_1 \rightarrow \chi_0\gamma$
  - dim 6 - anapole/charge radius $\mathscr{L} \supset -a_\chi\bar{\chi}_1\gamma^\mu\gamma^5\chi_0\,\partial^\nu F_{\mu\nu} + b_\chi\bar{\chi}_1\gamma^\mu\chi_0\,\partial^\nu F_{\mu\nu} \rightarrow$ decay: $\chi_1 \rightarrow \chi_0 e^+e^-$

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- Relic density set by co-annihilations and decay (dim-5 iDM was discussed in Dienes et al, 2301.05252)

$$\frac{dY_0}{dx} = -\lambda\left(Y_0Y_1 - Y_0^{\rm eq}Y_1^{\rm eq}\right)\left\langle\sigma_{01\to \rm SMSM}v\right\rangle - \lambda\left(Y_0 - Y_1\frac{Y_0^{\rm eq}}{Y_1^{\rm eq}}\right)\left\langle\sigma_{0e^-\to 1e^-}v\right\rangle + \tilde{\lambda}\left(Y_1 - Y_0\frac{Y_1^{\rm eq}}{Y_0^{\rm eq}}\right)\left\langle\Gamma_{1\to 0e^+e^-}\right\rangle$$

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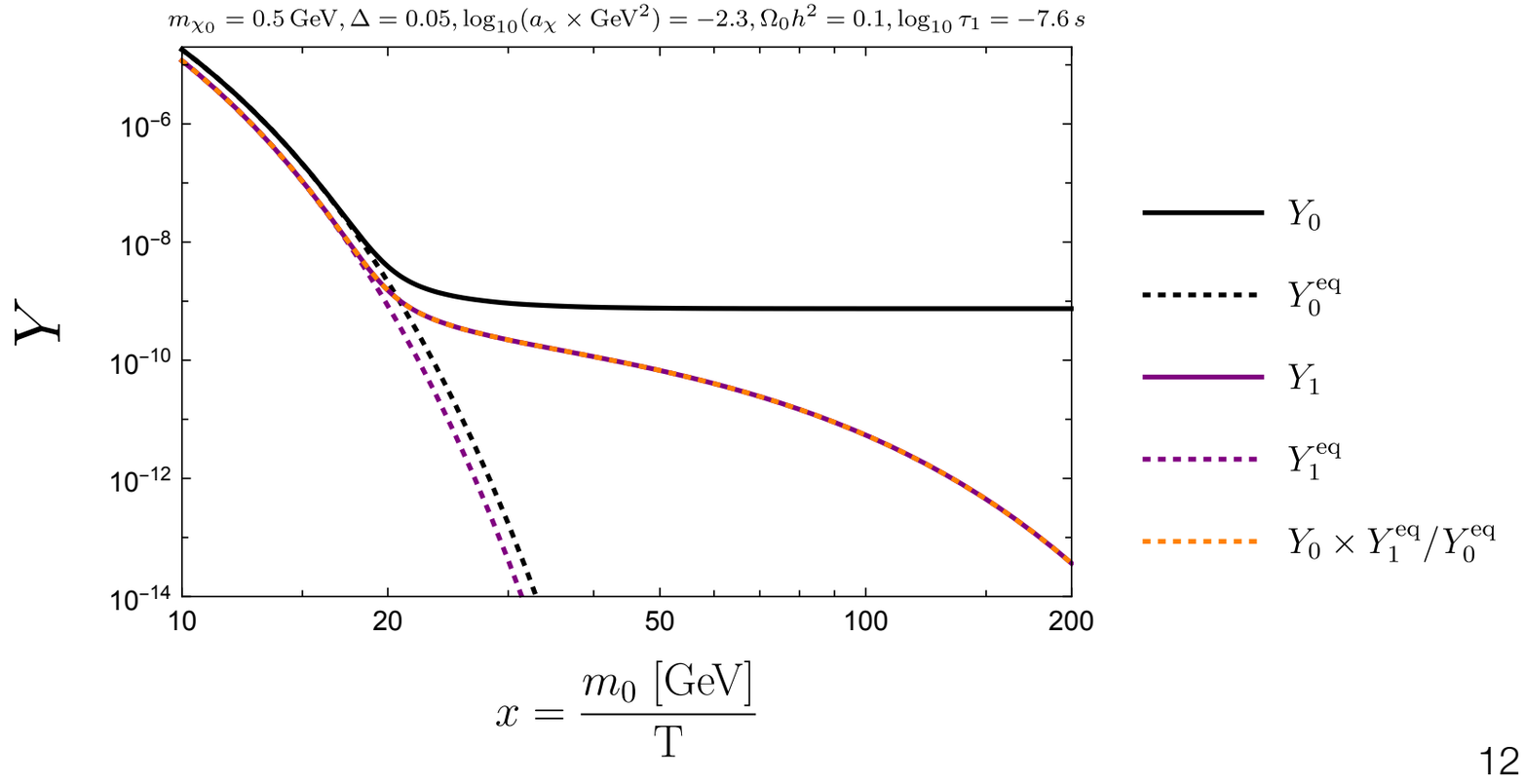
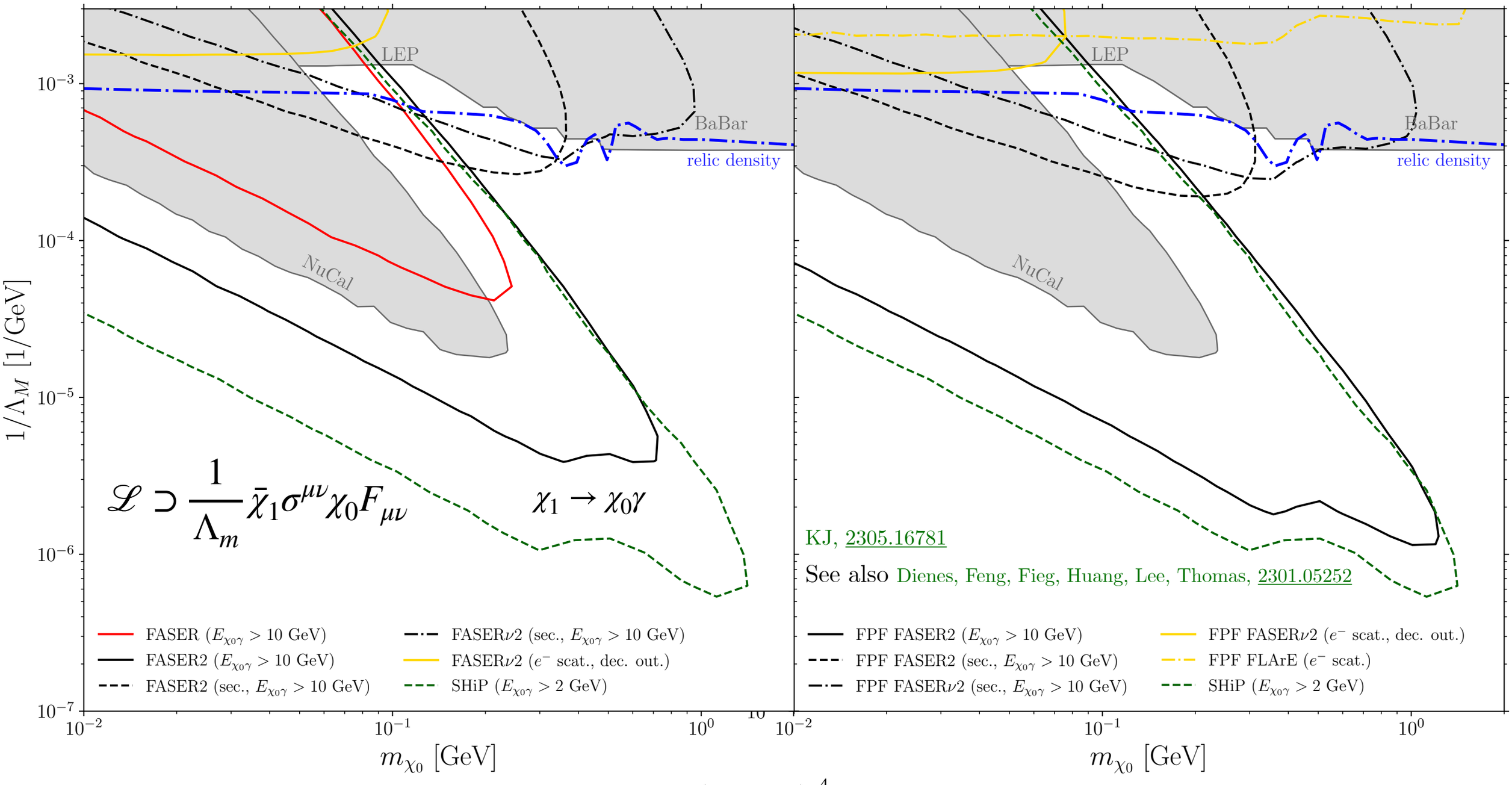
- The mass splitting is bounded, $0 < \Delta \equiv \frac{m_1 - m_0}{m_0} \lesssim O(0.5)$, because $\left\langle\sigma_{\text{co-an.}}v\right\rangle \propto \exp(-x\cdot\Delta)$
- $\Omega_0 h^2 \simeq 0.1$, $\Omega_1 h^2 \simeq 0$ due to decays and down-scatterings → $Y_1(x) \simeq Y_0(x)\frac{Y_1^{\rm eq}(x)}{Y_0^{\rm eq}(x)}$.



Magnetic dipole iDM

Secondary production allows to cover the $d \sim O(1)\, m$ regime. The low mass regime is also covered by electron scatterings - sec. prod. is more efficient than e^- scattering thanks to the Z^2 enhancement.



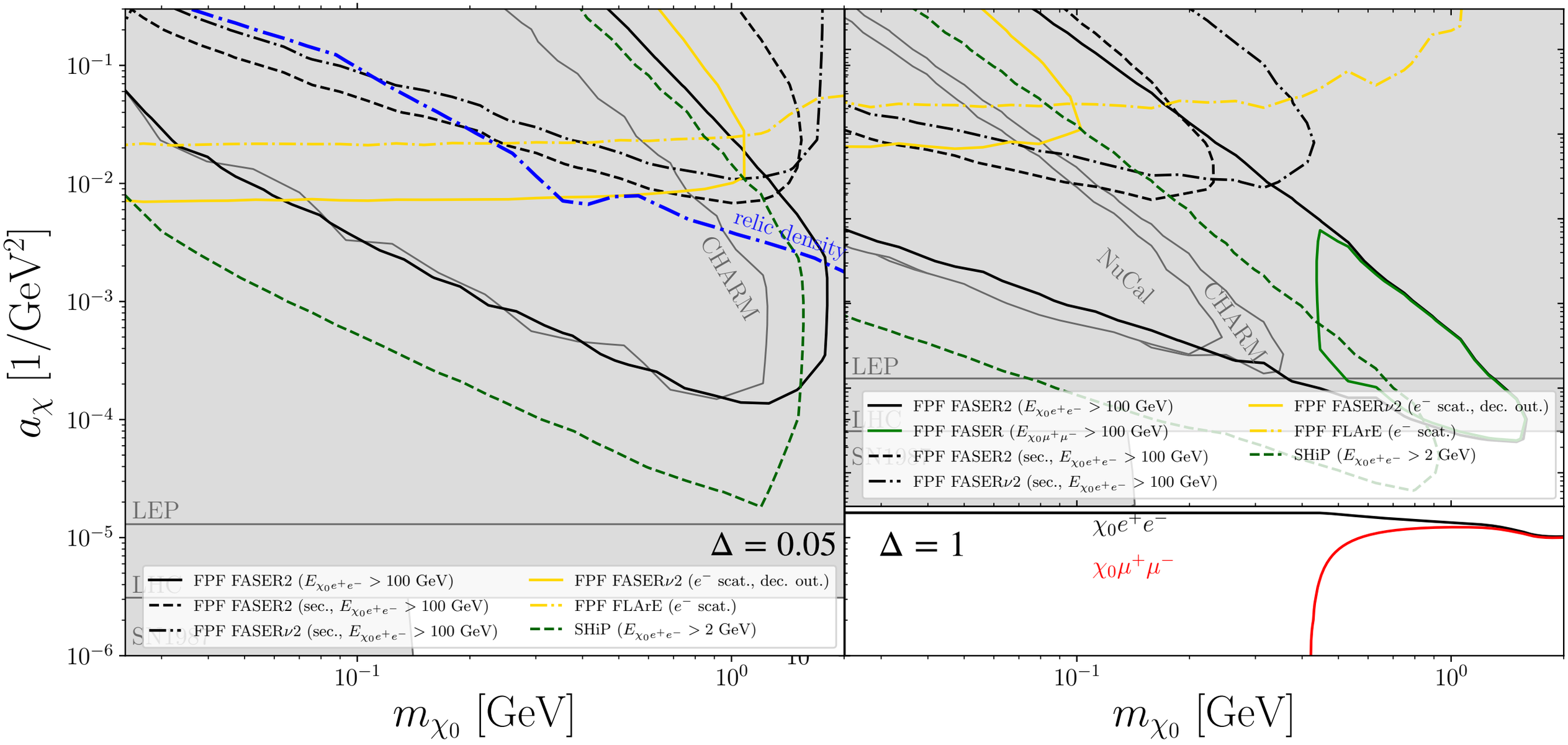
KJ, 2305.16781

See also Dienes, Feng, Fieg, Huang, Lee, Thomas, 2301.05252

$$d_{\chi_1} \simeq 100\, m \times \left(\frac{E}{1000\, GeV}\right) \left(\frac{0.1\, GeV}{m_{\chi_0}}\right)^4 \left(\frac{0.05}{\Delta}\right)^3 \left(\frac{\Lambda}{2.55 \times 10^3 GeV}\right)^2$$

Anapole moment iDM

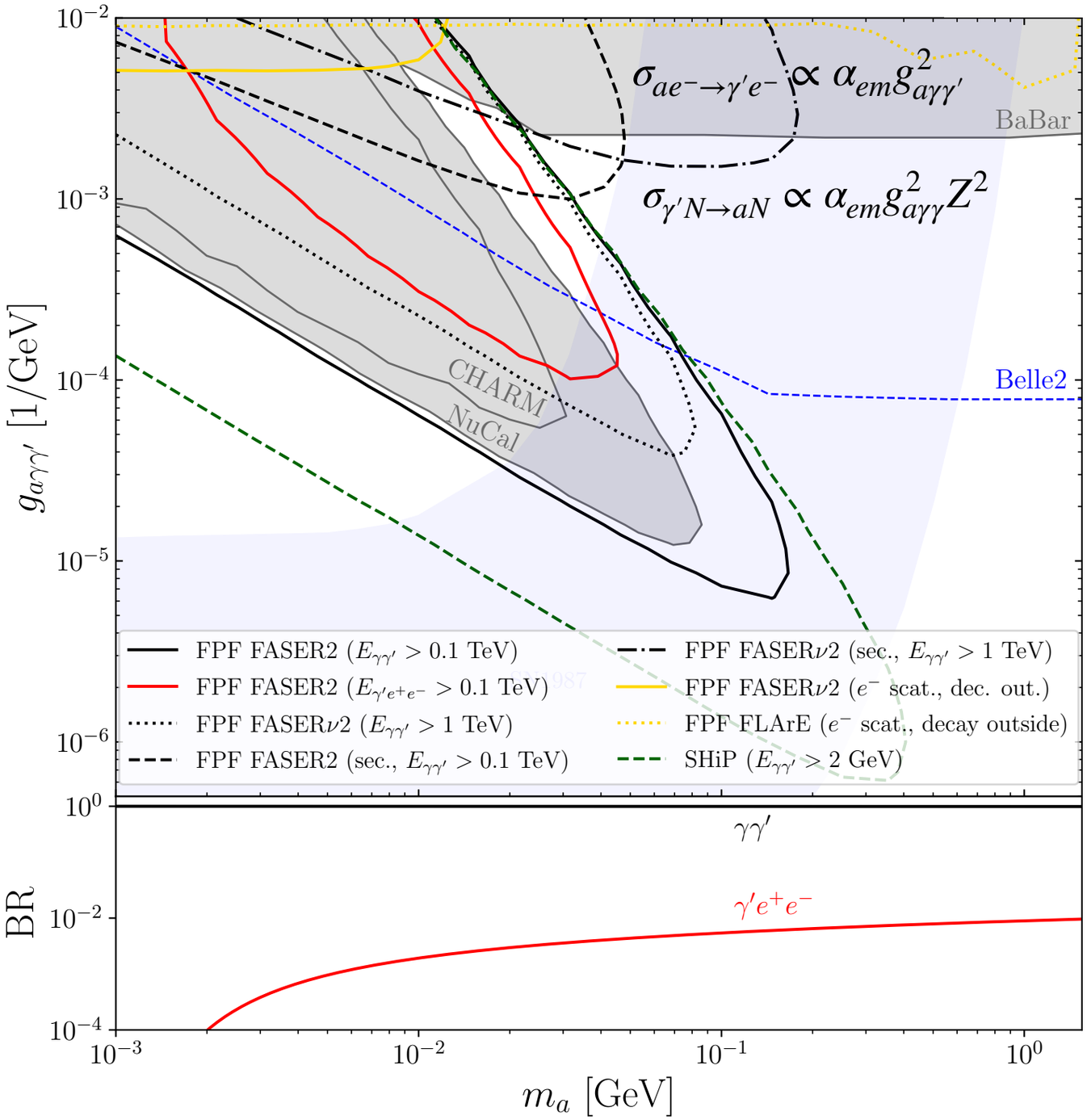
$\chi_1 \to \chi_0 e^+ e^-$ $\qquad$ $\mathscr{L} \supset -a_\chi \bar{\chi}_1 \gamma^\mu \gamma^5 \chi_0 \, \partial^\nu F_{\mu\nu}$



$$\Gamma_{\chi_1 \to \chi_0 e^+ e^-} = \frac{a_\chi^2 \alpha_{em} \Delta^5 m_{\chi_0}^5}{5\pi^2} \qquad d_{\chi_1} \simeq 100\, m \times \left(\frac{E}{1000\,\text{GeV}}\right) \left(\frac{0.1\,\text{GeV}}{m_{\chi_0}}\right)^4 \left(\frac{0.05}{\Delta}\right)^3 \left(\frac{7.65 \times 10^{-3}\text{GeV}^{-2}}{a_\chi}\right)^2$$

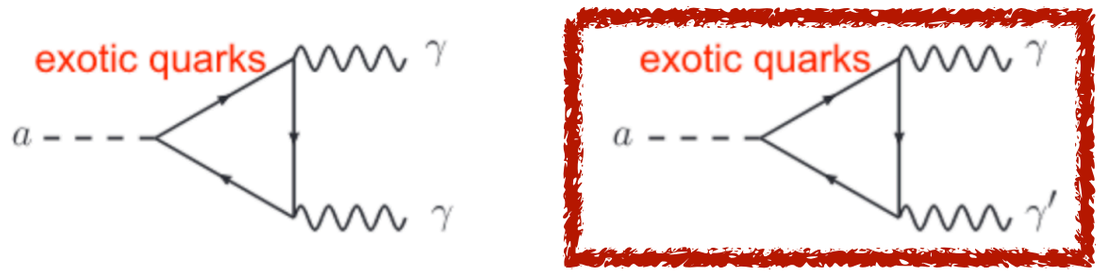
Dark ALP at Forward Physics Facility

BaBar/Belle: $\gamma + X \to m_{LLP} < 1\,\text{MeV}$ too long-lived → covered by FLArE/FASERν



$$\mathscr{L}_{\text{dark axion portal}} = \frac{g_{a\gamma\gamma'}}{2} a F_{\mu\nu} \tilde{F}'^{\mu\nu}$$

Kunio Kaneta, Hye-Sung Lee, Seokhoon Yun, 1611.01466



a is the LLP: $m_{\gamma'} \ll m_a$

$$d_a \simeq 100\,m \times \left(\frac{E}{1000\,\text{GeV}}\right)\left(\frac{0.1\,\text{GeV}}{m_a}\right)^4 \left(\frac{4\times 10^{-5}}{g_{a\gamma\gamma'}}\right)^2,$$

Conclusions

- FASER2/FPF will explore a range of models predicting sub-GeV long-lived particles coupled to a photon by dim-5 or -6 operators.

- FASER is a particularly suitable to cover a large part of available parameter space for i) *dark ALP portal, ii) neutralino coupled to axino or gravitino, iii) iDM with EM form factors, and iv) massive spin-2 mediator.*

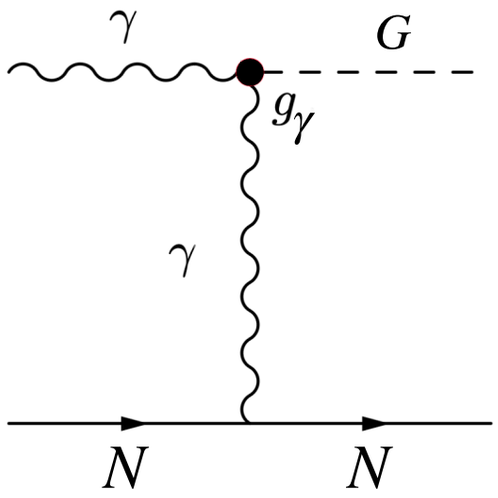
- Secondary LLP production via Primakoff-like upscattering of the LSP on tungsten FASERν2, will allow to *cover the* $d_{LLP} \sim 1\,m$ *region of parameter space.*

- Monte Carlo simulation is implemented in an extended version of FORESEE

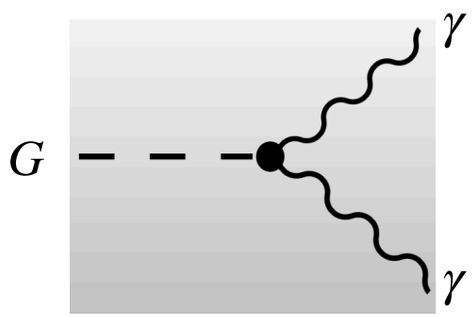
Massive spin-2 mediator at FPF

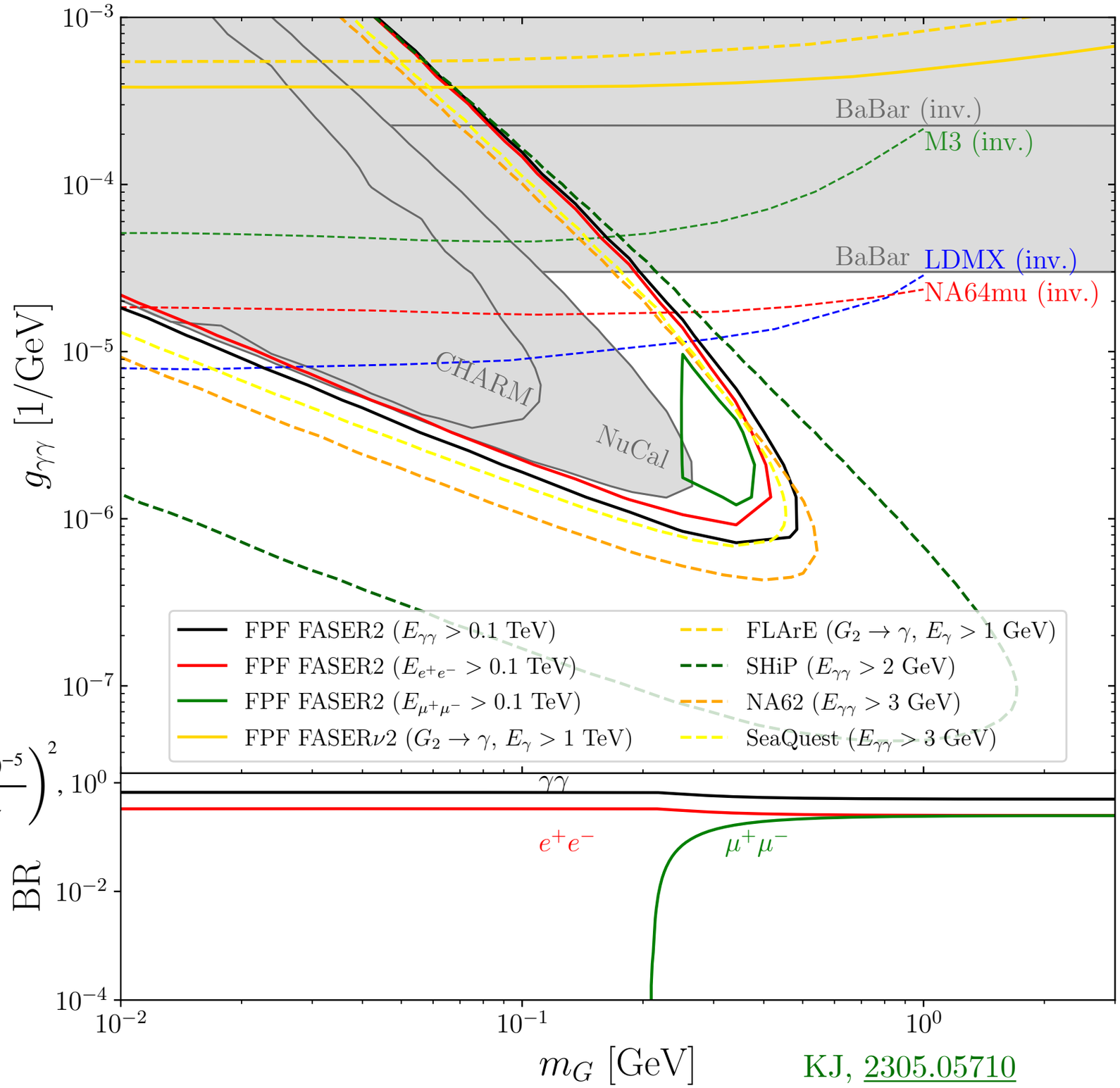
$$\mathscr{L} \supset g_\gamma G^{\mu\nu}\left(\frac{1}{4}\eta_{\mu\nu}F_{\lambda\rho}F^{\lambda\rho} + F_{\mu\lambda}F_\nu{}^\lambda\right) - i\sum_l \frac{g_\ell}{2} G^{\mu\nu}\left(\bar{l}\gamma_\mu D_\nu l - \eta_{\mu\nu}\bar{l}\gamma_\rho D^\rho l\right)$$

$$\sigma_{\gamma N\to GN} \simeq \frac{\alpha_{em} g_{G\gamma\gamma}^2 Z^2}{2}\left(\log\left(\frac{d}{1/a^2 + t_{max}}\right) - 2\right)$$



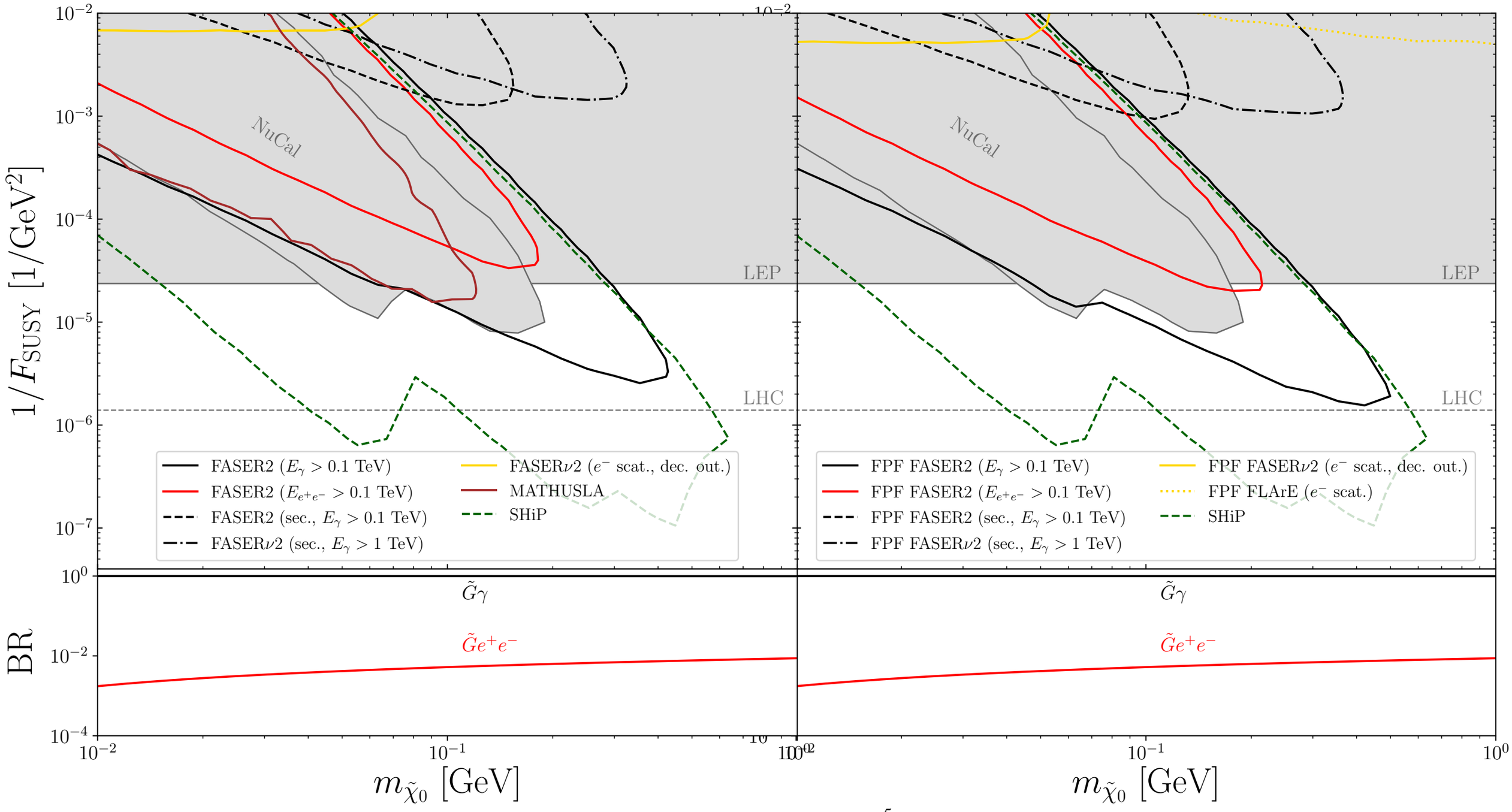
$$d_G = c\tau\beta\gamma \simeq 100\,m \times \left(\frac{E}{1000\,GeV}\right)\left(\frac{0.1\,GeV}{m_G}\right)^4\left(\frac{5\times10^{-5}}{g_{G\gamma\gamma}}\right)^2,$$





Neutralino-gravitino at FASER

- Neutralino is NLSP, gravitino is LSP $\tilde{\chi}_0 \to \tilde{G}\gamma$



$$d_{\tilde{\chi}} \simeq 100m \times \left(\frac{E}{1000\,\text{GeV}}\right)\left(\frac{0.1\,\text{GeV}}{m_{\tilde{\chi}}}\right)^5\left(\frac{F_{\rm SUSY}}{(60\,\text{GeV})^2}\right)^2$$