Inelastic Dipole Dark Matter at FASER

Max Fieg
+ Keith Dienes, Jonathan Feng, Fei Huang, Seung J. Lee, Brooks Thomas
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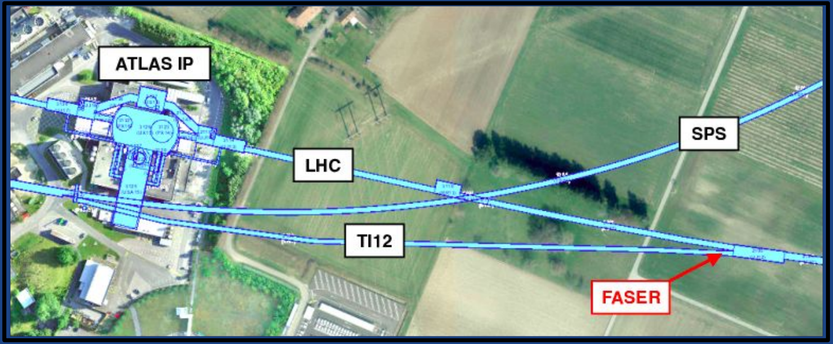
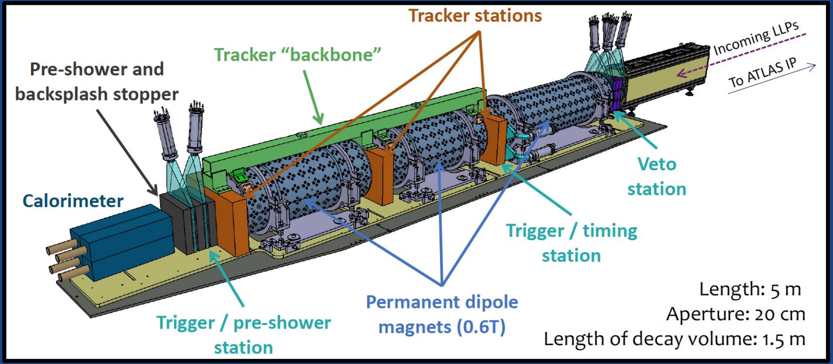
PHENO 2022

FASER : ForwArd Search ExpeRiment at the LHC

- FASER is an experiment placed 480m from the ATLAS I.P. designed to search for weakly-interacting long-lived particles (LLPs) produced in *pp* collisions
- Equipped with trackers and an EM calorimeter to identify SM particles from LLP decay
- Well-suited to search for sub-GeV visibly decaying dark photons with $\epsilon \sim 10^{-4}$, as well as ALPs and dark Higgs bosons
- Proposed upgrade, FASER2, would operate during the HL-LHC era and would feature a larger decay volume





Feng, Galon, Kling, Trojanowski (2017)
FASER TDR (2018)
FASER Reach for LLP's (2018)

Inelastic Dipole Dark Matter

- Inelastic DM features a suppressed direct detection rate due to an off-diagonal coupling between $\chi_0\,\chi_1$ and the SM. Cosmologically stable χ_0 has kinetic energies of ~10 eV:

$$E_{\rm kinetic} \sim (\frac{m_{\rm DM}}{10{\rm MeV}})(\frac{v}{10^{-3}})^2 \ {\rm eV}$$

- Starting with a neutral χ_0,χ_1 a minimal coupling to the SM can achieved by constructing a 3-point vertex to the SM photon through a dipole operator:

Ward Identity forbids vector vector coupling to photon

$$\mathcal{L} \supset \ \frac{1}{\Lambda}\ \bar{\chi_1}\sigma^{\mu\nu}(g_m + g_e\gamma^5)\chi_0 F_{\mu\nu} + {\rm h.c.}$$

- This effective operator can arise from UV theories, e.g. composite DM or theories with extra $U(1)_X$ charged particles
- Can extend this to a tower of neutral states, e.g. dynamical dark matter
  - Features cascade decays down the tower over a range of lifetimes

Curtin, Dienes, Thomas (2018)
Foadi, Frandsen, Sanning (2008)
Antipin, Redi, Strumia, Vigiani (2015)
Bagnasco, Dine, Thomas (1993) Smith, Weiner (2001)

Inelastic Dipole Dark Matter at FASER: Production

- In this model χ_0 is the DM which couples directly with the SM photon

$$\mathcal{L} \supset \frac{1}{\Lambda} \bar{\chi_1} \sigma^{\mu\nu} (g_m + g_e \gamma^5) \chi_0 F_{\mu\nu} + \text{h.c.}$$

- χ pairs are produced predominantly at the LHC from rare meson decays. $(\pi^0, \eta, \eta') \to \gamma \chi_1 \bar{\chi_0}$
  - In contrast to the dark photon scenario, χ production from vector meson decay dominates over pseudoscalar decay due to a mass^2 enhancement

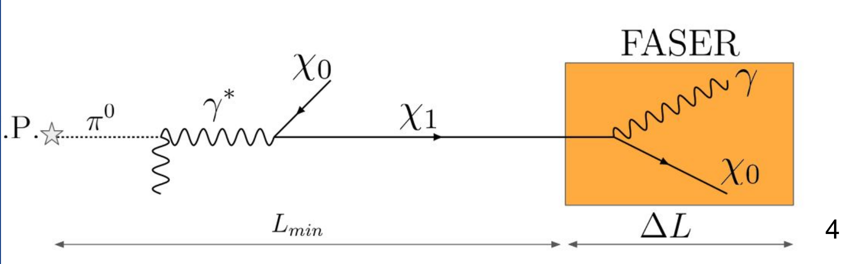
$$(\rho, \omega, \phi) \to \chi_1 \bar{\chi_0}$$

$$N_\chi \approx 10^{16} \times \text{BR}_{\text{SM}\to\chi\chi} \qquad \text{BR}_{\rho,\omega,\phi\to\chi_1\bar{\chi_0}} \sim (\frac{\text{g}}{\Lambda})^2 \text{m}^2_{\rho,\omega,\phi}$$

FPF Whitepaper (2022)

Chu, Kuo, Pradler (2020)

- Main sources of background are weak-interactions of neutrinos in the EM calorimeter and muon interactions
  - Both backgrounds can be reduced with modest event cuts



Inelastic Dipole Dark Matter at FASER: Decay

- Provides the interesting signature in FASER of a single photon from χ_1 decay which can be detected in FASER's calorimeter
  - This signature has been studied e.g. in ALP Light Shining through Wall investigations at FASER and radiative neutralino decays

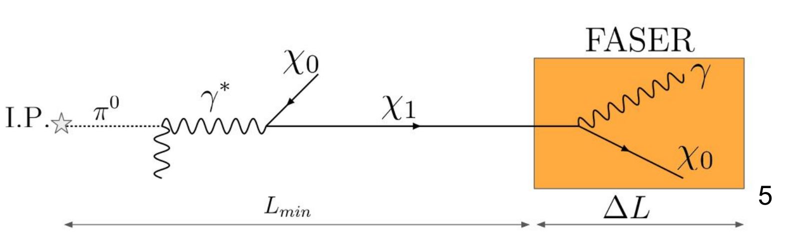
- Decay width:

$$\Gamma(\chi_1 \to \chi_0 \gamma) = \frac{g^2}{2\pi\Lambda^2}\frac{(m_1^2 - m_0^2)^3}{m_1^3} \approx \frac{g^2}{2\pi\Lambda^2}(m_0\Delta)^3 \qquad \Delta = \frac{m_1 - m_0}{m_0}$$

- Can write the decay length:

$$\bar{d} = \frac{p_1}{m_1\Gamma} \sim 100\mathrm{m} \times \left(\frac{p_1}{10^3\ \mathrm{GeV}}\right)\left(\frac{100\ \mathrm{MeV}}{m_1}\right)\left(\frac{100\ \mathrm{MeV}}{m_0}\frac{0.1}{\Delta}\right)^3\left(\frac{10^{-4}\ \mathrm{GeV}^{-1}}{g/\Lambda}\right)^2$$

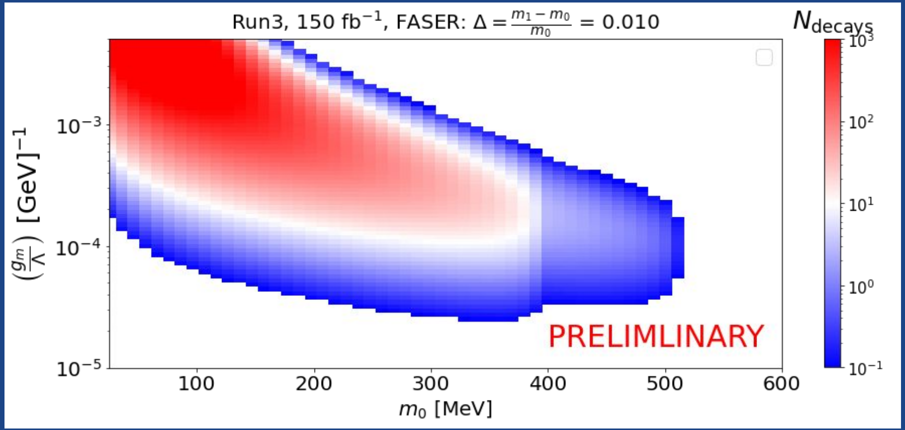
Kling, Quilez (2022)
FPF Whitepaper (2022)
Jodlowski, Trojanowski (2020)



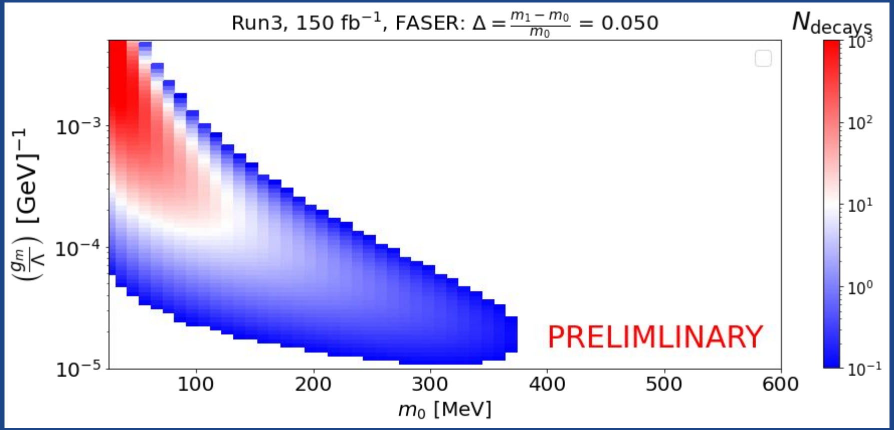
Signal Reach at FASER

$$\Gamma(\chi_1 \to \chi_0\gamma) = \frac{g^2}{2\pi\Lambda^2}\frac{(m_1^2 - m_0^2)^3}{m_1^3} \approx \frac{g^2}{2\pi\Lambda^2}(m_0\Delta)^3 \qquad \mathrm{BR}_{\rho,\omega,\phi\to\chi_1\bar{\chi_0}} \sim (\frac{\mathrm{g}}{\Lambda})^2 \mathrm{m}^2_{\rho,\omega,\phi}$$

Δ = 1%



Δ = 5%



Signal Reach at FASER

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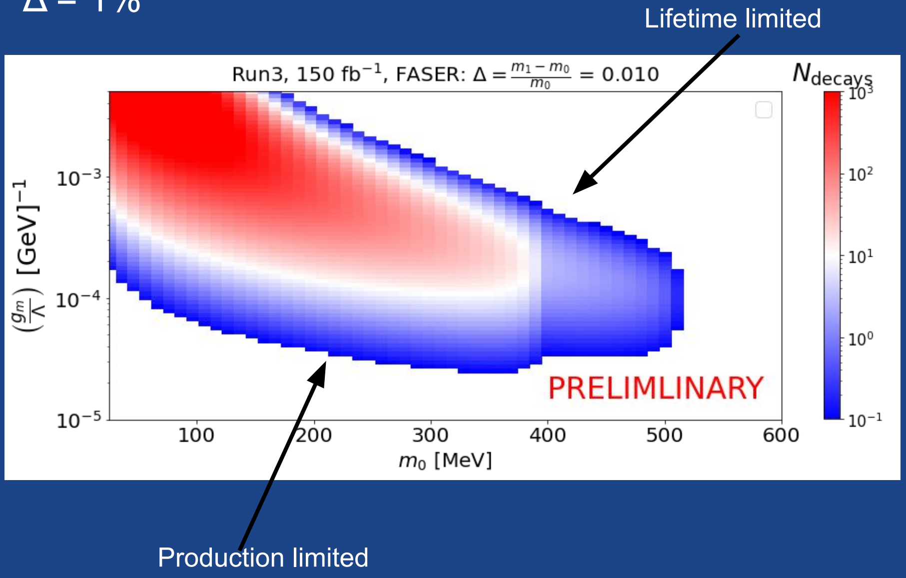
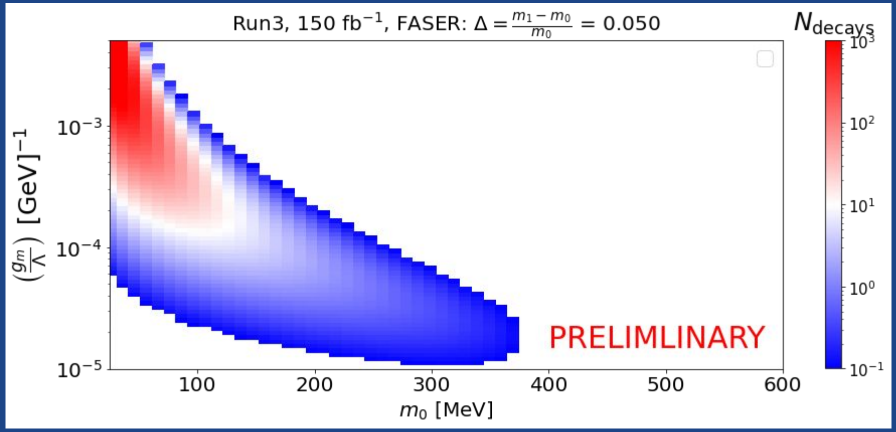


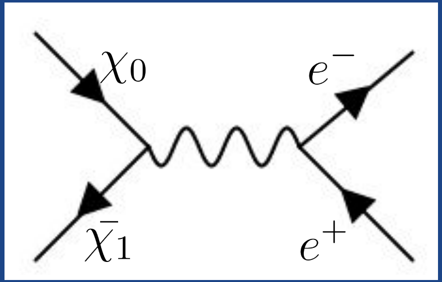
Δ = 5%



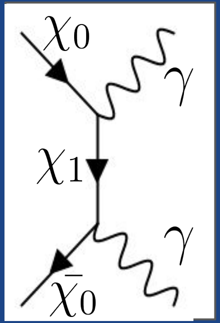
Freezeout

- Relic abundance of χ_0 can be achieved via freeze-out through s-channel coannihilation or t-channel annihilation to SM states

Izaguirre, Krnjaic, Shuve (2015)



$$\langle \sigma_{\chi_0 \bar{\chi}_1 \to \mathrm{SM}} v \rangle \sim \left(\frac{g}{\Lambda}\right)^2 \alpha \sim 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1} \times \left(\frac{\mathrm{g}/\Lambda}{10^{-4}\ \mathrm{GeV}^{-1}}\right)^2$$

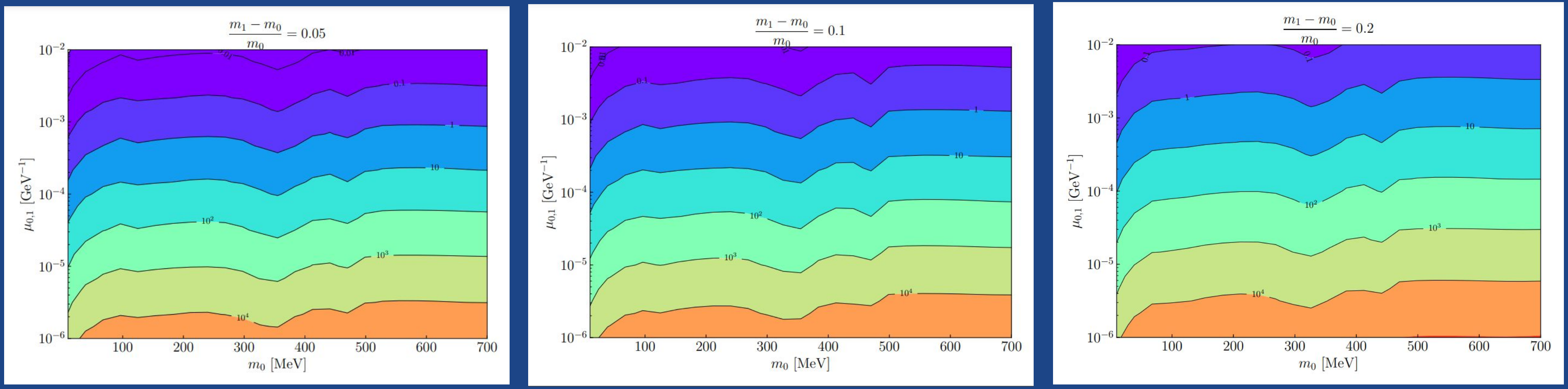


$$\langle \sigma_{\chi_0 \bar{\chi}_0 \to \mathrm{SM}} v \rangle \sim \left(\frac{g}{\Lambda}\right)^4 m_0^2 \sim 10^{-26} \mathrm{cm}^3\ \mathrm{s}^{-1} \times \left(\frac{\mathrm{g}/\Lambda}{10^{-1} \mathrm{GeV}^{-1}}\right)^4 \left(\frac{\mathrm{m}_0}{10\ \mathrm{MeV}}\right)^2$$

- For large mass splittings, primordial χ_1 abundance is Boltzmann suppressed and the t-channel becomes the dominant mode for χ_0 depletion.
- Dependence of of t-channel on g^4 demands larger couplings for correct relic abundance and is already ruled out by existing constraints

Relic contours for different delta

Contours are over/under-abundance of DM. (i.e. 1→ correct relic abundance)



Increase splitting

Existing Constraints and Benchmarks

- BaBar
  - $e^+ e^- \to \gamma \chi_0 (\chi_1 \to \chi_0 \gamma)$
  - 2 photon + missing energy signature
- E137
  - e^- nuc -> e- nuc $\chi_1 \chi_0$
  - 400m decay length
  - Scattering in detector
- nu-Cal
  - meson decay -> $\chi_0 \chi_1$
  - 80m decay length
- E141
  - e- nuc -> e- nuc $\chi_1 \chi_0$
  - 30m decay length
- Belle-II
  - $e^+ e^- \to \gamma \chi_0 (\chi_1 \to \chi_0 \gamma)$
  - With dedicated monophoton trigger, can probe similar parameter space

Existing Constraints and Benchmarks

- Can cover the target line for small splittings
- BaBar
  - $e^+ e^- \to \gamma \chi_0 (\chi_1 \to \chi_0 \gamma)$
  - 2 photon + missing energy signature
- E137
  - e^- nuc -> e- nuc $\chi_1 \chi_0$
  - 400m decay length
  - Scattering in detector
- nu-Cal
  - meson decay -> $\chi_0 \chi_1$
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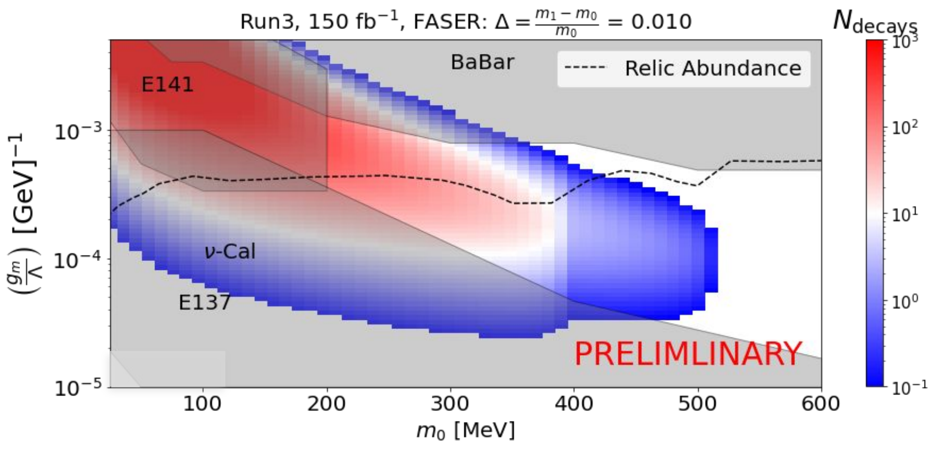
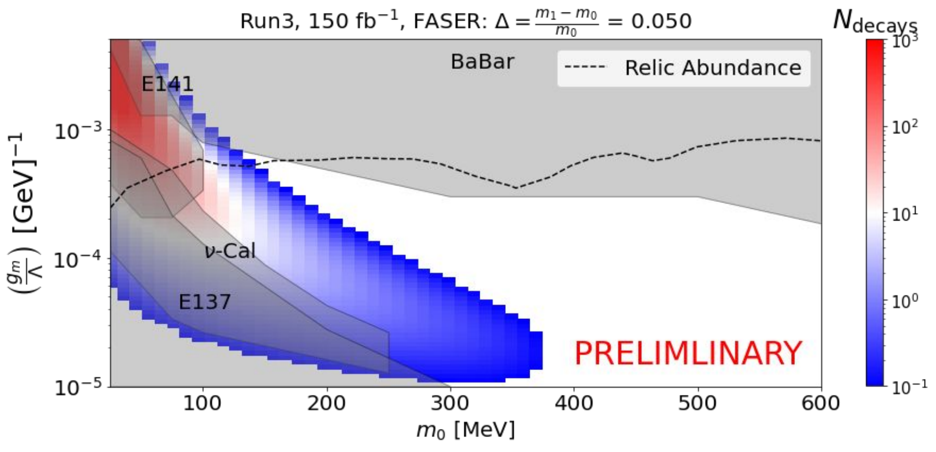




FASER2

Proposed FASER2 Upgrade:

- ~300x decay volume compared to FASER

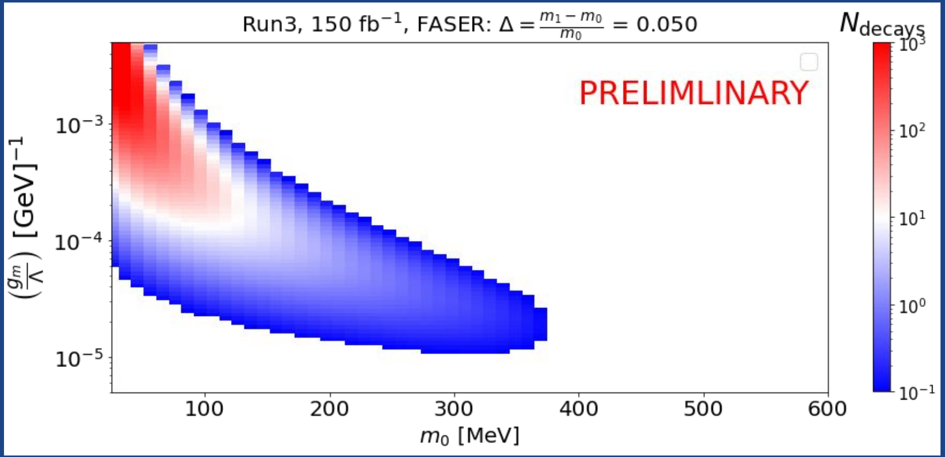
$$\text{FASER:}\quad \Delta = 1.5\ \text{m},\quad R = 10\ \text{cm},$$
$$\text{FASER2:}\quad \Delta = 5\ \text{m},\quad R = 1\ \text{m},$$

- Would operate during the HL-LHC era:
    - 20X Luminosity

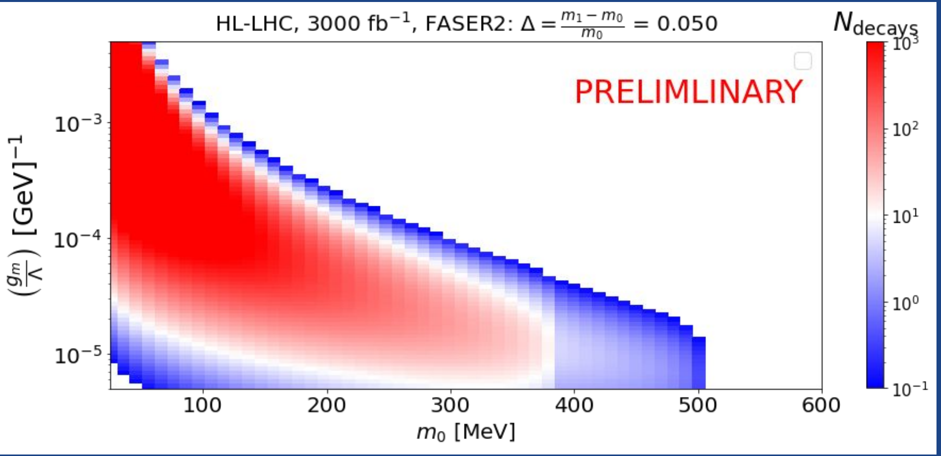
- Part of the proposed Forward Physics Facility (FPF)

Forward Physics Facility

FASER

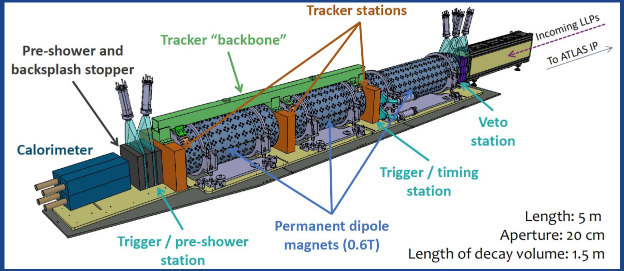


FASER2



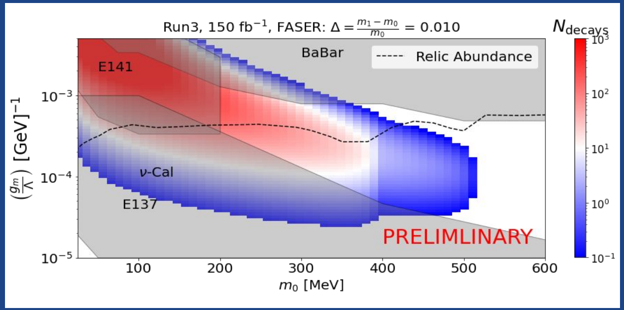
Conclusion

- FASER can search for the decay of weakly-interacting long-lived particles and is currently taking data for Run3 at the LHC
- Dipole interaction is the most minimal model choice we can make to couple 2 neutral fermions to SM
- χ pairs can be produced in the forward direction in large numbers at the LHC through vector meson decay



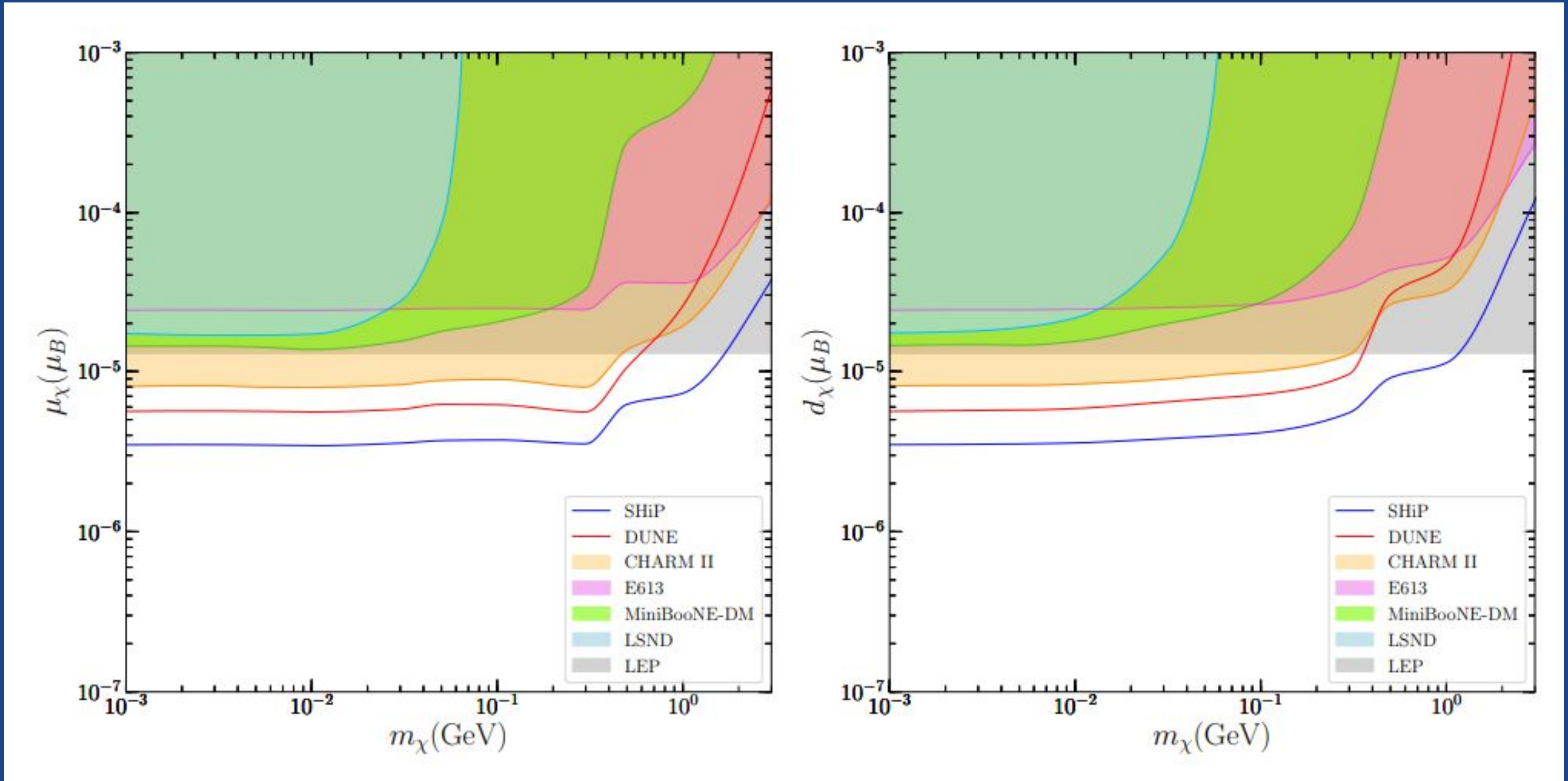
$$\mathcal{L} \supset \frac{1}{\Lambda}\bar{\chi}_1\sigma^{\mu\nu}(g_m + g_e\gamma^5)\chi_0 F_{\mu\nu} + \text{h.c.}$$

- FASER and its proposed upgrade at the forward physics facility can cover the unprobed sub-GeV thermal target
  - Thermal target moves to lower couplings with larger Δ, until Δ~1% → s-channel dominates and Boltzmann suppression is negligible
  - New parameter space will start to be probed with just 1.5 fb^{-1}



- Leading existing constraints come from E141, nu-Cal, E137 and Babar
  - Belle-II can cover comparable parameter space

Scattering rates, comparing electric and magnetic operators

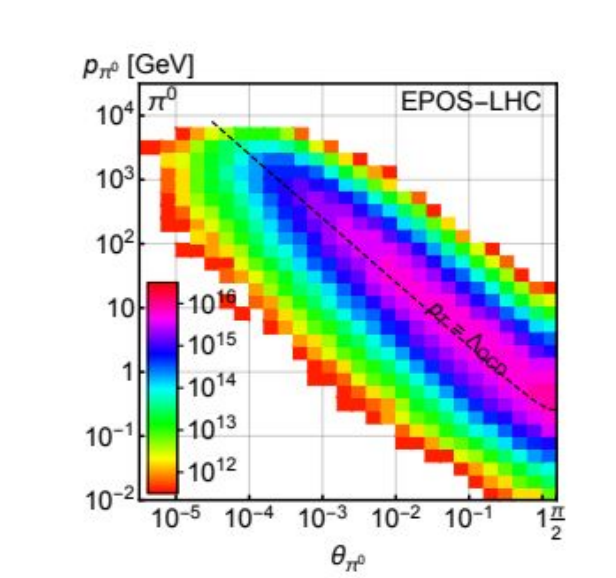


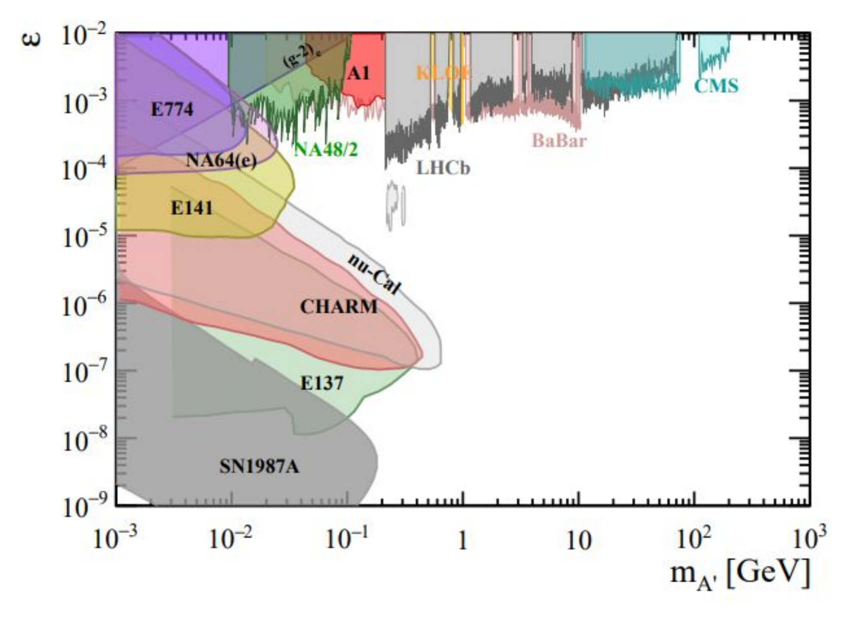
https://arxiv.org/pdf/2005.01515.pdf

Vanilla DP

$$B(\pi^0 \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \to \gamma\gamma) ,$$

$$B(\eta \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_\eta^2}\right)^3 B(\eta \to \gamma\gamma) ,$$





Feng, Galon, Kling, Trojanowski (2017)
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FPF

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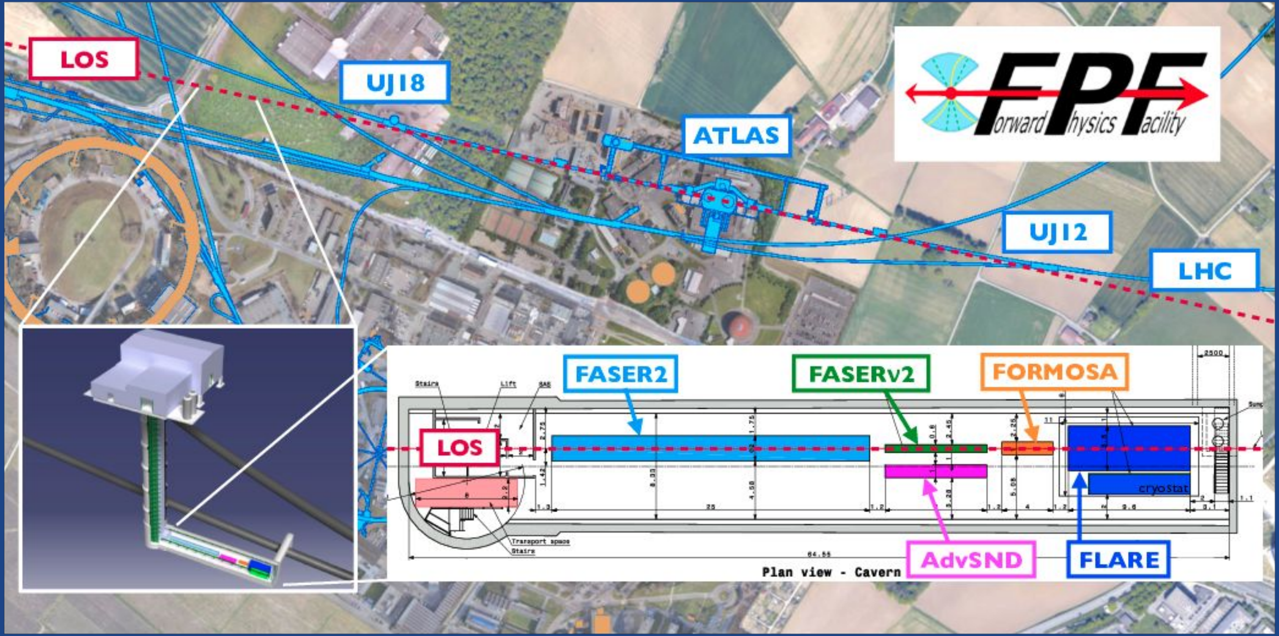

https://arxiv.org/abs/2109.10905