FPF Whitepaper status
Search for Dark Matter Scattering

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Talks (Monday)

ASTROCENT

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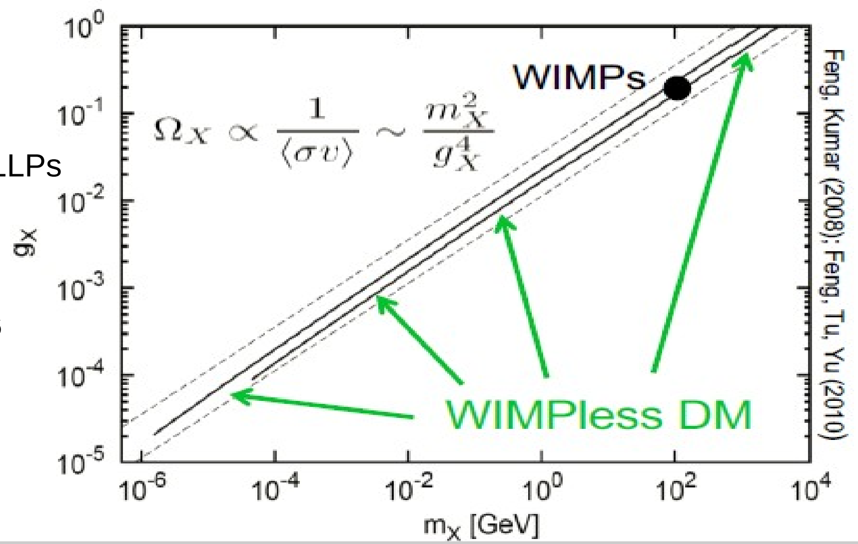
Dark matter – beyond the WIMP paradigm

- Lack of heavy WIMP DM signal
  Increasingly improving bounds

→ but thermal DM production remains a very attractive mechanism

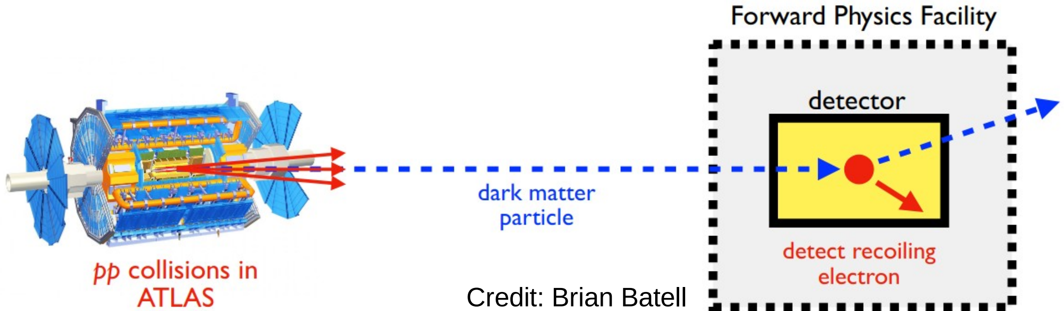
Generalization, LLPs →

C. Boehm and P. Fayet, hep-ph/0305261
M. Pospelov, A. Ritz, and M. B. Voloshin, hep-ph/0711.4866
J. L. Feng and J. Kumar, hep-ph/0803.4196



- Possible small-scale structure problems
- Other tensions in ΛCDM

Search for DM scattering in the FPF



Credit: Brian Batell

- Probing DM interactions in the relativistic regime
- Signal rate depends differently on the coupling constants than in traditional DM direct detection searches

DM searches at the FPF

Search for LLP mediators
decays in the FPF
Talk: Ahmed Ismail

Direct search for DM scattering
THIS TALK

Milli-charged particles
can be a small fraction of DM < 0.4%
Talk: Yu-Dai Tsai

FPF searches – comprehensive approach & complementarity; specific examples:

- visible LLP decays + DM **scattering**

  e.g., hadrophilic DM models

  B. Batell etal, hep-ph/2111.10343

  [either, or]

- Milli-charged particle search at FORMOSA (scintillation) & FLArE (**scattering**)

  [simultaneous]

- Semi-stable new particles can also be probed via **scatterings**

  e.g., dipole or vector portal between neutrinos and HNLs

  [scattering but not DM]

  K. Jodłowski, ST, hep-ph/2011.04751
  A. Ismail, S. Jana, R.M. Abraham, hep-ph/2109.05032

Dark photon mediator

Contribution: Brian Batell, ST

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu + A'_\mu(\varepsilon\, e\, J^\mu_{EM} + g_D\, J^\mu_\chi), \qquad (144)$$

where $m_{A'}$ is the dark photon mass, ε is the kinetic mixing parameter, $g_D \equiv \sqrt{4\pi\alpha_D}$ is the $U(1)_D$ gauge coupling, J^μ_{EM} is the SM electromagnetic current, and J^μ_χ is the current for the DM particle χ, with mass denoted by m_χ. For our DM candidates, we will study two cases: (1) complex scalar DM and (2) Majorana fermion DM, with respective currents given by

$$J^\mu_\chi = \begin{cases} i\chi^* \overleftrightarrow{\partial}_\mu \chi & \text{(complex scalar DM)} \\ \frac{1}{2}\bar{\chi}\gamma^\mu\gamma^5\chi & \text{(Majorana fermion DM)}\,. \end{cases} \qquad (145)$$

Both scalar and Majorana DM can be produced in the early universe through simple thermal freeze-out with the correct relic density. Notably, for $m_{A'} > 2m_\chi$, DM annihilates directly to SM fermions through s-channel dark photon exchange, $\chi\chi \to A'^{(*)} \to f\bar{f}$, with an annihilation cross section given by (for $m_{A'} \gg m_\chi$)

$$\sigma v \propto \alpha\, v^2 \frac{\varepsilon^2\, \alpha_D\, m^2_\chi}{m^4_{A'}} = \alpha\, v^2 \frac{y}{m^2_\chi}\,, \qquad (146)$$

where α is the SM electromagnetic fine structure constant and $y \equiv \varepsilon^2\alpha_D(m_\chi/m_{A'})^4$, following

useful parameter

Light dark photon couples to both the SM and DM ($m_{A'}=3m_\chi$, $\alpha_D=0.5$)

$A' \to \chi\chi$ (invisible decays)

Complex scalar DM ↔ DM DD

Majorana DM ↔ non-relativistic scat. rates suppressed

DM annihilations $\chi\chi \to$ SM+SM
- suppressed DM indirect detection
- avoid bounds from CMB

Scattering signatures

depositions in the detector. This can be seen from the approximate expression for the differential electron scattering cross section valid in the limit of the large incident DM energy, $E_\chi \gg m_\chi$, and large electron recoil energy, $E_e \gg m_e$,

$$\frac{d\sigma}{dE_e} \approx \frac{8\pi\,\epsilon^2\,\alpha\,\alpha_D\,m_e}{(m_{A'}^2 + 2m_eE_e)^2}\,. \tag{147}$$

The relevant scattering rate is dominated by events characterized by $2m_eE_e \lesssim m_{A'}^2$. For $m_{A'} \lesssim 100$ MeV, this corresponds to $E_e \lesssim 10$ GeV. This allows for a sensitive search for DM through its *electron scatterings*, $\chi e \to \chi e$, by employing a cut favoring low recoil energy events.

- Electron scattering

– favors low recoil energies

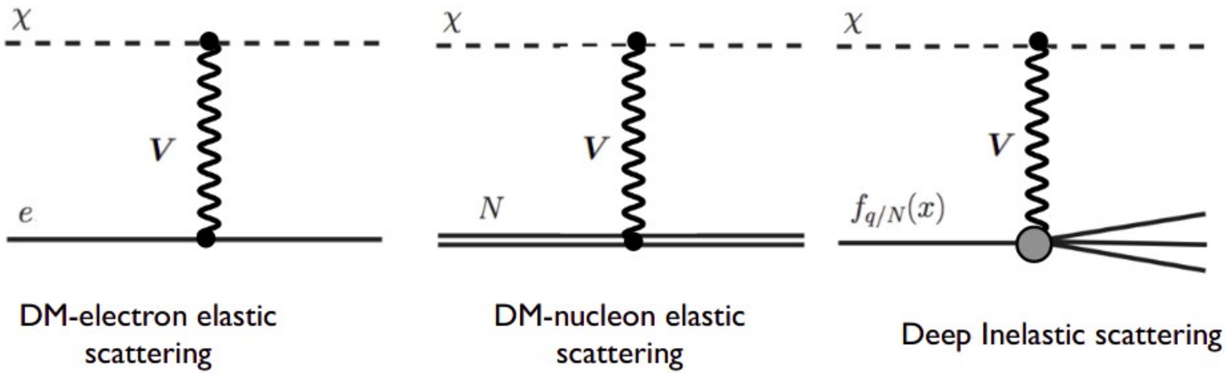
– ν-induced BG can be suppressed to O(10) events (10-tonne detector)

- Scattering with nucleus

a) elastic proton scattering

– ν-induced BG O(100) events

– finite efficiency for $\chi p \to \chi p$ events (GENIE)



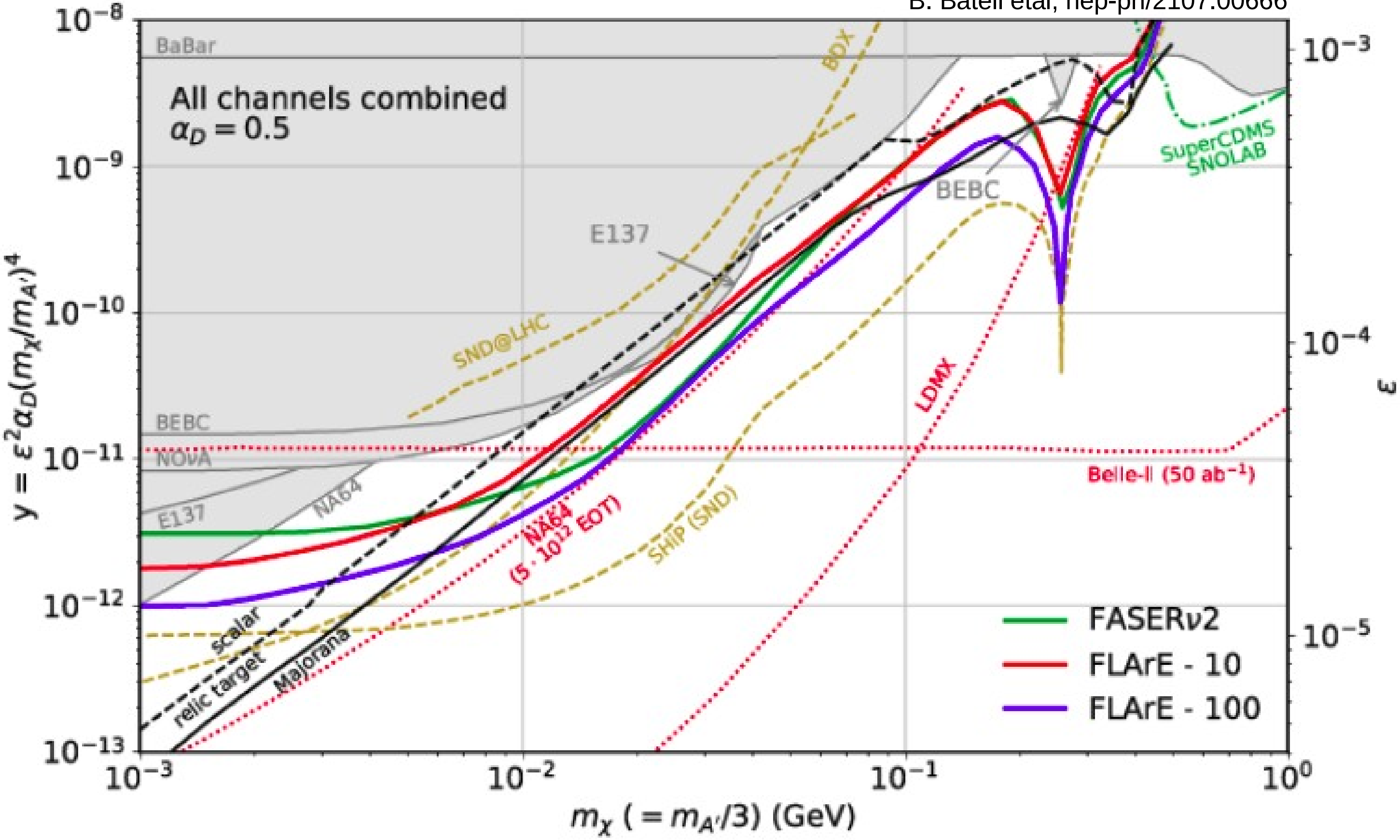
b) DIS regime

– ν-induced BG O(1000) events

– bounds at a partonic level: 1 GeV < E_{had} < 15 GeV, 1 GeV < $p_{T,had}$ < 1.5 GeV

Sensitivity

B. Batell etal, hep-ph/2107.00666



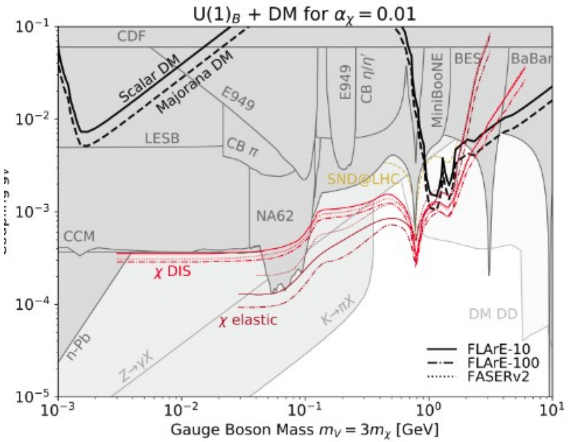
These lines take into account ν-induced BG and assume that μ-induced BG can be rejected

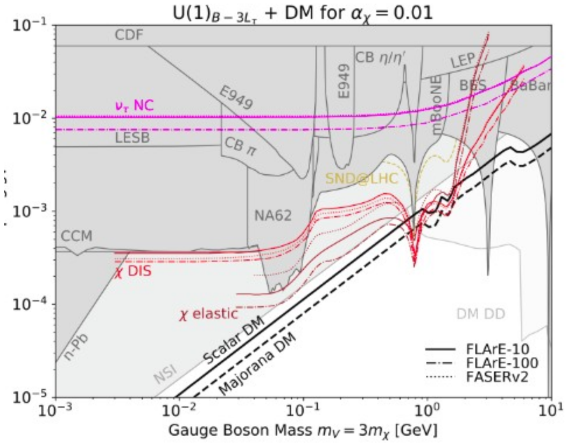
FASERν2 – μ BG rejection will require going beyond the currently planned design

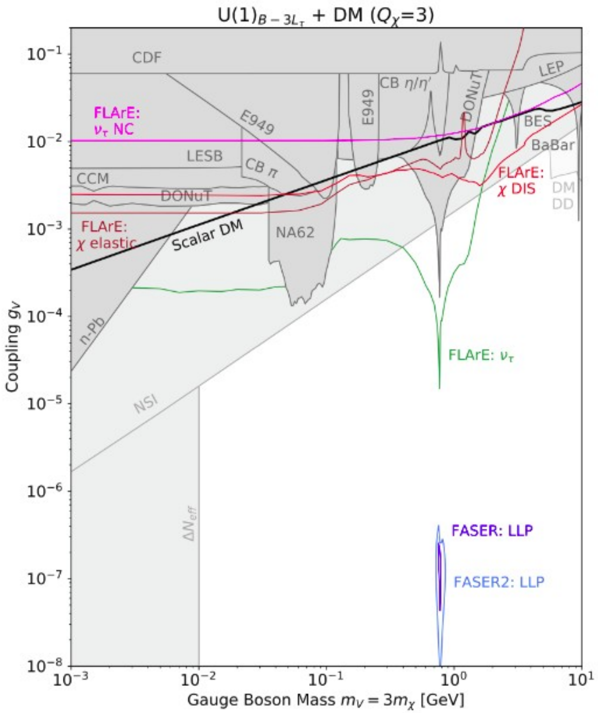
Hadrophilic DM – multiple signatures

Talk: Brian Batell

- $U(1)_B$ gauge boson can also Mediate DM-SM interactions
- Coupled to baryon number – attractive for LHC
- Subject to anomaly constraints (might also be due to DM DD)
- Anomaly-free version $U(1)_{B-3L\tau}$
- Here additional bounds from ν Non-standard interactions (NSI)
- In both case multiple signatures Possible:
  – LLP decays
  – DM scattering
  – enhanced ν scat. rates







DM search at Advanced SND@LHC

Contribution: Alexey Boyarsky, Alex Mikulenko, Maksym Ovchynnikov, Lesya Shchutska

● Sensitivity reach shown for SND@LHC (Run 3) and for AdvSND1 and AdvSND2 (FPF)

	target cross section	distance l_{min}	η	target mass
SND@LHC	$39 \times 39\,\mathrm{cm}^2$	480 m	[7.2,8.6]	800 kg
AdvSND1	$100 \times 40\,\mathrm{cm}^2$		≈[7.2,8.4]	5 tons
AdvSND2	$100 \times 100\,\mathrm{cm}^2$	50 m	≈[3.9,4.5]	

● Two scattering signatures:

– elastic χp → χp scatterings

– excess NC/CC scatterings

Scatterings. We consider here two scattering signatures: elastic – an excess of neutrino-like elastic scatterings over the SM yield due to $\chi + p$ process, and inelastic – an excess of the ratio of neutral-to-charged current-like events, $r = N_{\mathrm{NC}}/N_{\mathrm{CC}}$, over the SM prediction $r \approx 0.31$ due to $\chi +$ nucleus deep inelastic scattering (DIS). SND@LHC allows measuring the r ratio with the accuracy $(\Delta r/r)_{\mathrm{SND@LHC}} = 10\%$. We assume that the accuracy of the advanced configurations will be improved, and consider $(\Delta r/r)_{\mathrm{AdvSND}} = 1\%$ as the reference value.

● For the elastic signature, sensitivity plotted for $N_{\mathrm{DM,ev}} = 10$

● For the NC/CC signature it is required that

$$N_{\mathrm{events}} > 2\sqrt{N_{\mathrm{NC}} + (0.01 \cdot N_{\mathrm{NC}})^2},$$

which is $\simeq 450$ for AdvSND1 and $\simeq 30$ for AdvSND2.

● μ-induced BG assumed to be rejected

DM search at Advanced SND@LHC (2)

Intuitive rescaling

$$\alpha_{B,\text{lower}}^{\text{AdvSND1}} \sim \alpha_{B,\text{lower}}^{\text{SND@LHC}} \left(\frac{\mathcal{L}_{\text{Run 3}}}{\mathcal{L}_{\text{HL}}} \times \frac{\epsilon_{\text{azimuthal}}^{\text{SND@LHC}}}{\epsilon_{\text{azimuthal}}^{\text{AdvSND1}}} \right)^{1/4} \simeq 0.3 \cdot \alpha_{B,\text{lower}}^{\text{SND@LHC}}, \qquad (159)$$

with $\mathcal{L}$ being the luminosity. Here the scaling 1/4 comes from the scaling of the signal and background $N_{\text{events}}/\alpha_B^2, N_{\text{NC}} \propto \epsilon_{\text{azimuthal}}\mathcal{L}$ in Eq. (158). The number of events at AdvSND2 is lower due to the geometric acceptance and the cross section, which is only partially compensated by $\simeq 10$ times lower number of background events. Therefore, AdvSND2 has worse sensitivity.

need to make sure that our current bounds agree

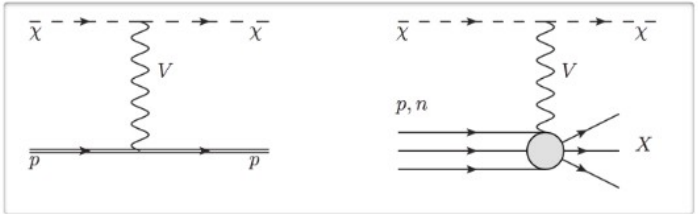
AdvSND1 > AdvSND2 > SND@LHC

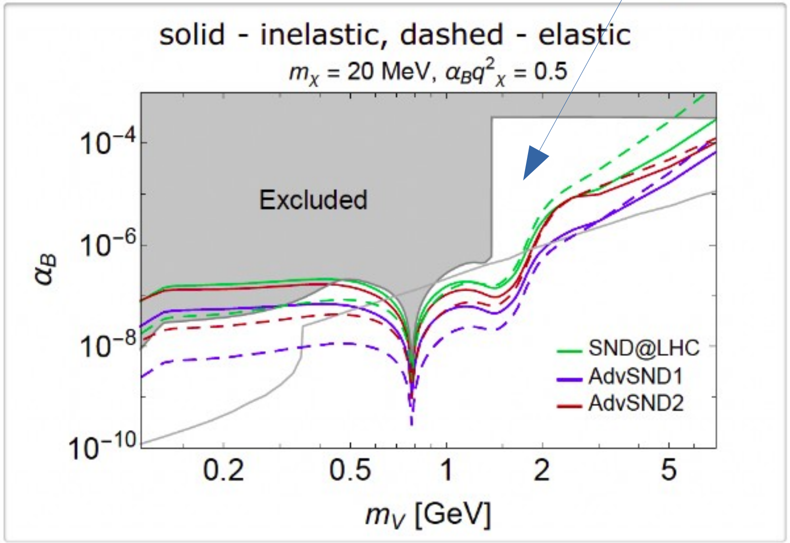
Talk: Antonia Di Crescenzo

1. Scattering

Production: scalar χ particle coupled to the Standard Model via a leptophobic portal

Detection: χ elastic/inelastic scattering off nucleons of the target

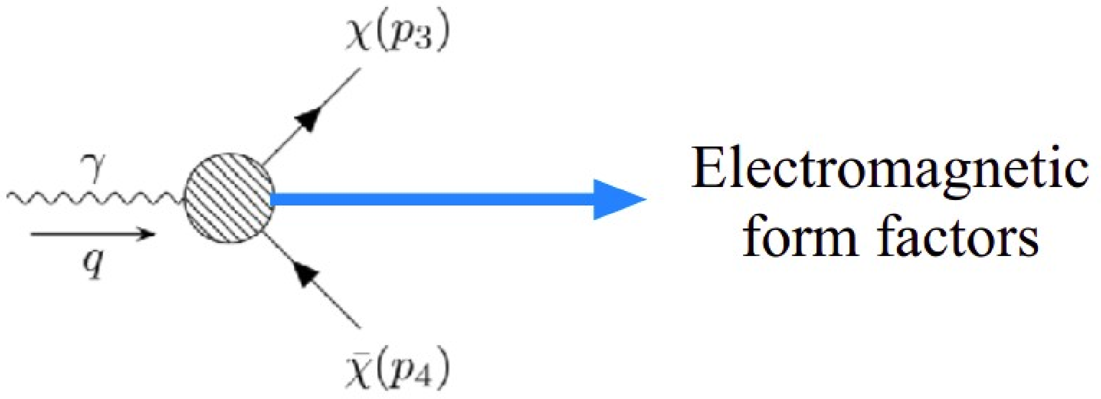




Dark matter with EM form factors

Contribution: Jui-Lin Kuo etal (also talk on Monday)

- How dark is the dark sector?
- Mediator between dark sector and SM sector: SM photon ← at low energy effective "photon portal"
- Dark sector particles are electromagnetic neutral (or millicharged)
- Talk to photons with higher-dimensional operators



Dark matter with EM form factors (2)

millicharge (ϵQ):	$\epsilon e\, \bar{\chi}\gamma^{\mu}\chi A_{\mu}$,	**Dimension-4**
magnetic dipole (MDM):	$\frac{1}{2}\mu_{\chi}\, \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$,	**Dimension-5**
electric dipole (EDM):	$\frac{i}{2}d_{\chi}\, \bar{\chi}\sigma^{\mu\nu}\gamma^{5}\chi F_{\mu\nu}$,	
anapole moment (AM):	$a_{\chi}\, \bar{\chi}\gamma^{\mu}\gamma^{5}\chi\partial^{\nu}F_{\mu\nu}$,	**Dimension-6**
charge radius (CR):	$b_{\chi}\, \bar{\chi}\gamma^{\mu}\chi\partial^{\nu}F_{\mu\nu}$.	

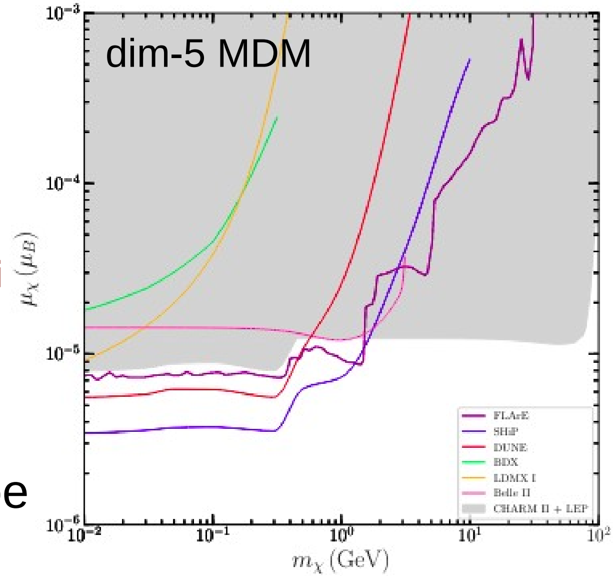
- DM-electron scattering signature
  `a-la DM`

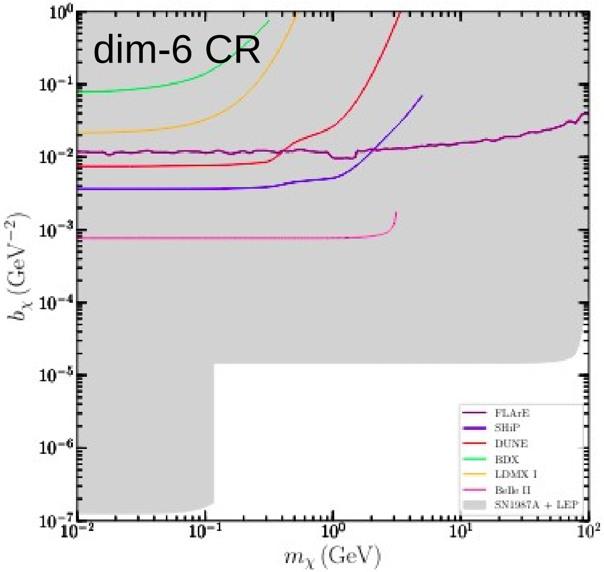
- milli-charged particles can be nicely probed by scatterings in FLArE

  Talk: Yu-Dai Tsai

- dim-5 MDM case:
  FLArE can cover a small allowed region

- dim-6 operators more difficult to probe
  Missing-energy searches comptitive





Outlook

Many thanks for all the contributions !

- Search for DM scattering – important extension of the neutrino physics program of the FPF
- Complementarity between different experiments and signatures
- Thermal targets of important benchmark scenarios can be probed
- Discussions: suppression of μ-induced BG
  (sweeper magnet, interplay between different detectors)

THANK YOU !!!