Searching for Light Dark Matter at the Forward Physics Facility

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arXiv: 2101.10338, 2107.00666, 2111.10343

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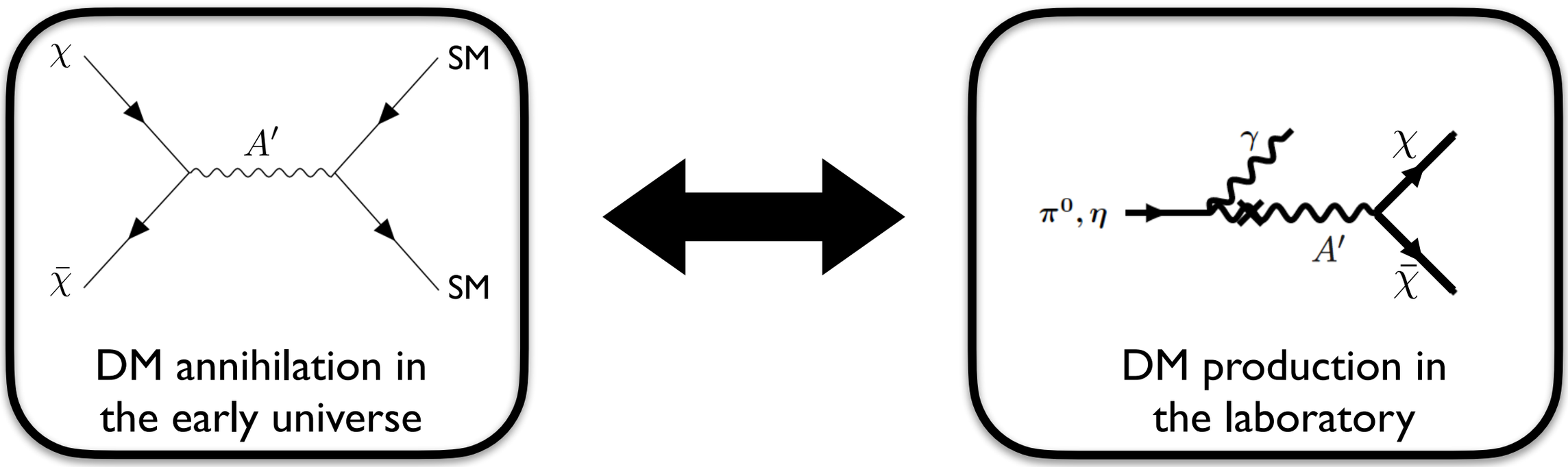
Motivation: Light Thermal Relic Dark Matter

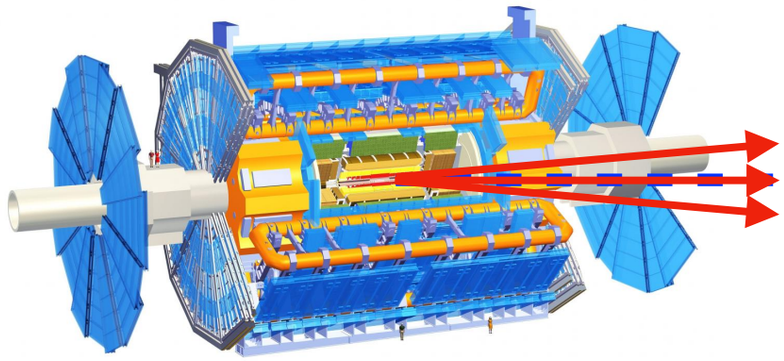
- Light dark sectors provide an interesting framework for dark matter
- Relic abundance generated via thermal freeze-out
- Extension of the WIMP below Lee-Weinberg bound

[Boehm, Fayet]
[Pospelov, Ritz, Voloshin]
[Feng, Kumar]

- Direct DM annihilation to SM leads to predictive targets for experiment
- Same interaction governs DM annihilation and laboratory DM production



Dark Matter Scattering at the Forward Physics Facility



pp collisions in ATLAS

dark matter particle

Forward Physics Facility

detector (e.g. FLArE)

recoiling electron, nucleon, or DIS

[BB, Feng, Feig, Ismail, Kling, Abraham, Trojanowski]
[2101.10338, 2107.00666, 2111.10343]

[See also Kelly, Kling, Tuckler, Zhang '21]

- Along with dark matter scattering, dark sector models can lead to a variety of additional phenomena and signatures at the Forward Physics Facility, e.g.,
  - LLP decays of the mediator at FASER(2) [Feng, Galon, Kling, Trojanowski '17]
  - Enhanced neutrino production [Kling '20]
  - Modified neutrino scattering rates

FLArE — Forward Liquid Argon Detector

See talk by Jianming Bian

[BB, Feng, Trojanowski - 2101.10338]

Proposed Liquid Argon Time Projection Chamber at Forward Physics Facility

- Liquid argon medium + uniform electric field to transport ionization tracks
- PMTs collect scintillation light, providing event time information
- Wire planes detect drift electrons, providing spatial and kinematic information
- Energy thresholds down to 30 MeV, angular resolution down to 10 MeV
- Liquid Krypton option also being considered
- Consider two detector options:
  - FLArE-10 : 10-ton scale; 1m x 1m x 7m volume
  - FLArE-100 : 100-ton scale; 1.6 m x 1.6 m x 30 m volume

Neutrino backgrounds discriminated with kinematic and topological cuts

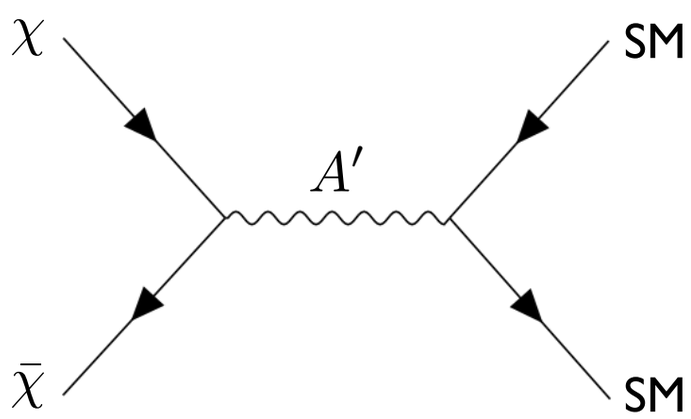
LArTPC timing capabilities critical in mitigating muon-induced backgrounds

DM scattering search can also potentially be done in future emulsion detectors, such as FASERν2, Advanced-SND

Vector portal dark matter

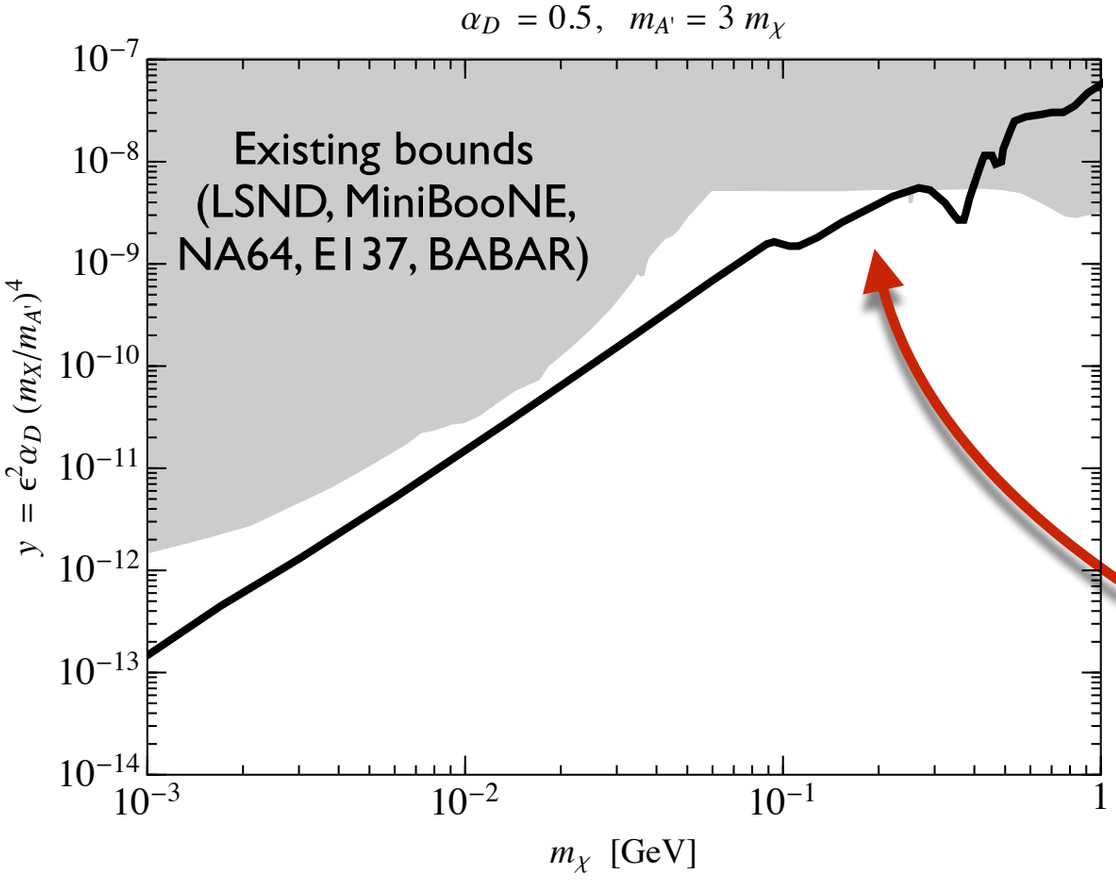
$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu + A'_\mu(\varepsilon\, e\, J^\mu_{EM} + g_D\, J^\mu_\chi) \qquad J^\mu_\chi = \begin{cases} i\chi^* \overleftrightarrow{\partial_\mu} \chi & \text{(complex scalar DM)} \\ \frac{1}{2}\overline{\chi}\gamma^\mu\gamma^5\chi & \text{(Majorana fermion DM)} \end{cases}$$

- Simple, well motivated, popular dark sector model
- Dark photon couples to charge and mediates interactions between DM and SM
- 4 new parameters $m_\chi, m_{A'}, \alpha_D, \epsilon$
- Thermal target:



$$\langle\sigma v\rangle \sim \frac{\epsilon^2\,\alpha_D\,\alpha\,m_\chi^2}{m_V^4} \sim \frac{y^2}{m_\chi^2}$$

$$y \equiv \epsilon^2\alpha_D(m_\chi/m_{A'})^4$$



Observed DM relic abundance predicted along this line

Hadrophilic Dark Sector

[BB, Feng, Feig, Ismail, Kling, Abraham, Trojanowski]

[See also Boyarsky et al, 2104.09688]

- LHC is pp collider — particularly sensitive to hadrophilic mediators
- We consider two models for concreteness:

1. Gauged baryon number $U(1)_B$
   - Minimal hadrophilic mediator (all couplings to leptons are suppressed)
   - Gauge anomalies lead to important bounds from flavor changing meson decays

   [Dror, Lasenby, Pospelov]

2. Gauged $B - 3L_\tau$, $U(1)_{B-3\tau}$
   - Anomaly free, suppressed couplings to electrons and muons
   - Important bounds from neutrino NSI [Han, Liao, Liu, Marfatia '19; Heeck '19]

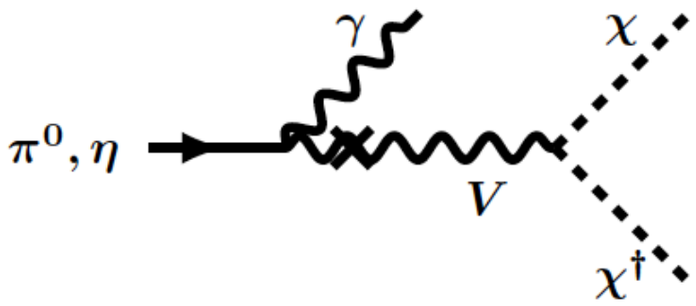
$$\mathcal{L} \supset -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + V_\mu(J^\mu_{\rm SM} + g_V Q_\chi J^\mu_\chi)$$

$$J^\mu_{\rm SM} = g_V[J^\mu_B - 3x(\overline{\tau}\gamma^\mu\tau + \overline{\nu}_\tau\gamma^\mu P_L\nu_\tau)] + \varepsilon\, e\, J^\mu_{\rm EM}$$

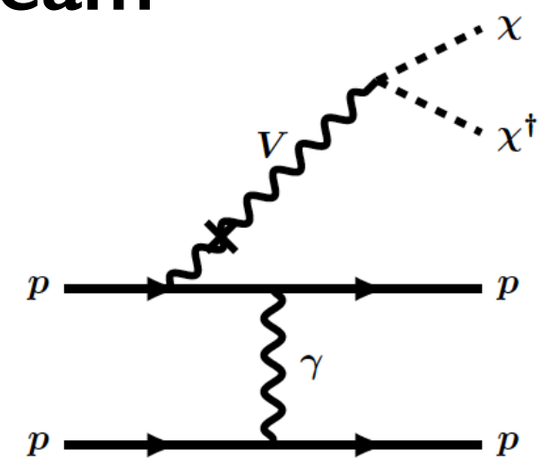
$$J^\mu_\chi = \begin{cases} i\chi^* \overleftrightarrow{\partial_\mu}\chi & \text{(complex scalar DM)} \\ \frac{1}{2}\overline{\chi}\gamma^\mu\gamma^5\chi & \text{(Majorana fermion DM)} \end{cases}$$

- Predictive dark matter thermal targets exist
- Several additional interesting signatures predicted FPF experiments

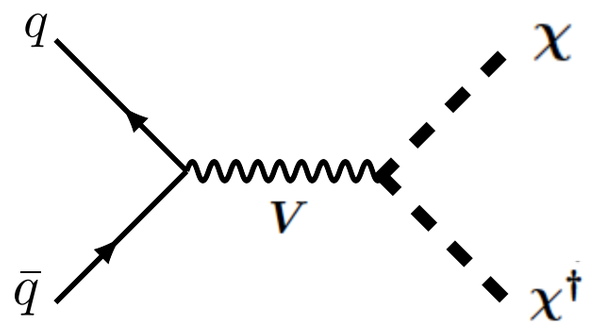
Production of the DM beam



Neutral mesons decays

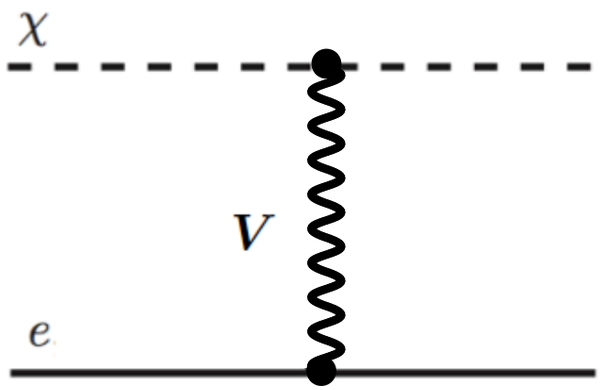


Proton bremsstrahlung

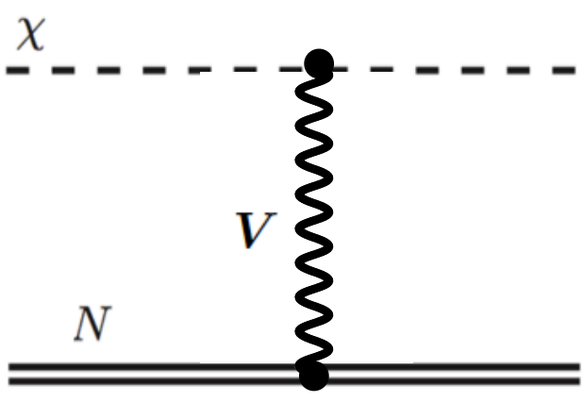


Drell-Yan

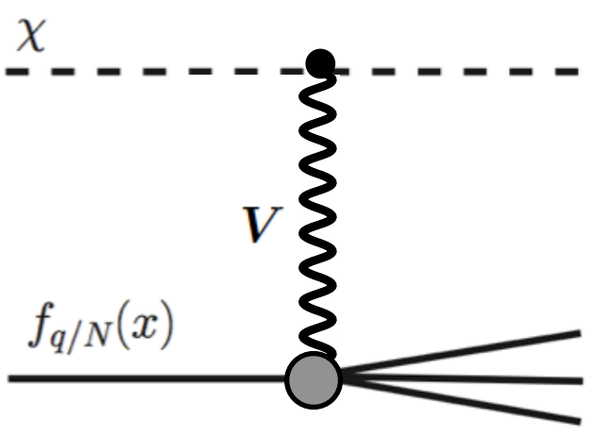
Detection of DM via scattering



DM-electron elastic scattering

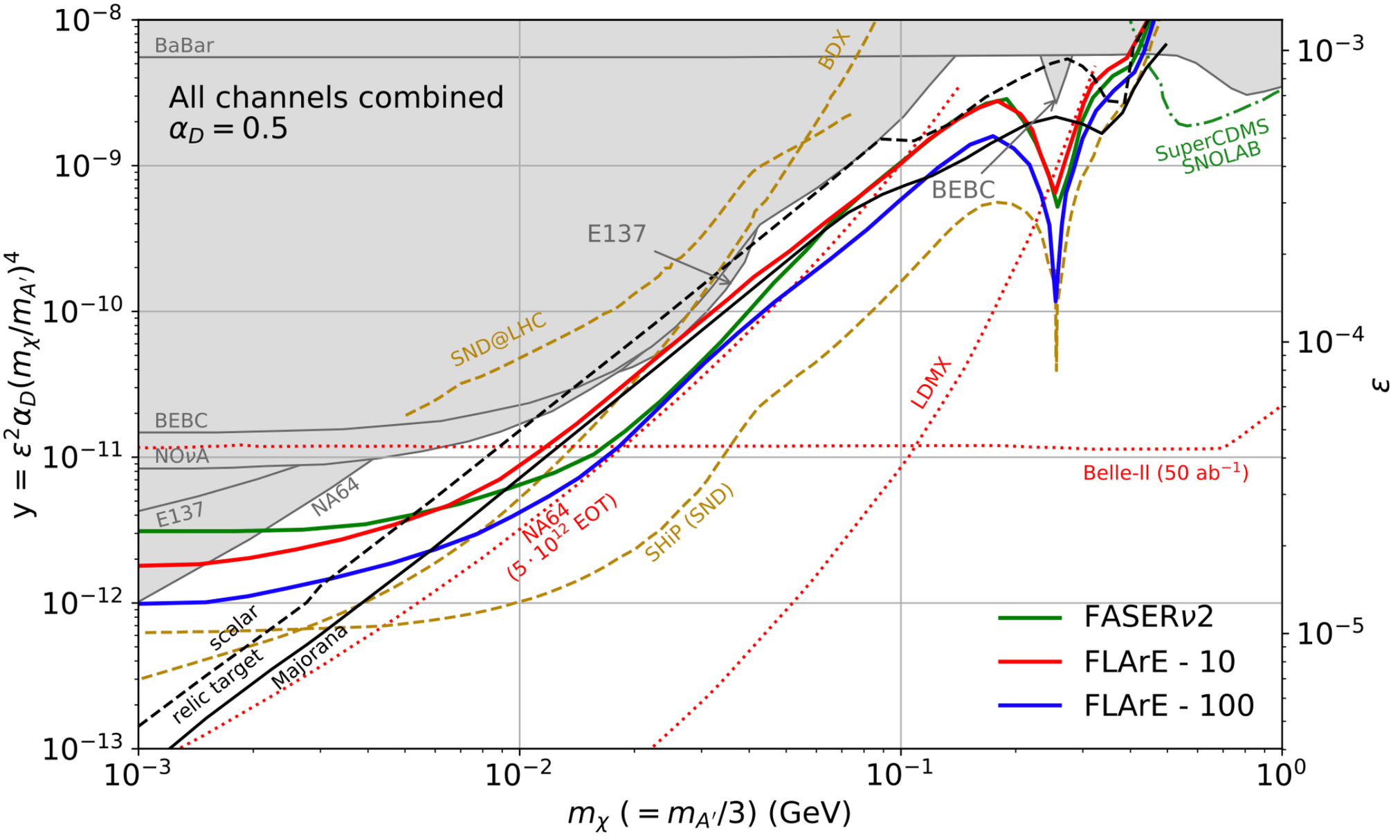


DM-nucleon elastic scattering

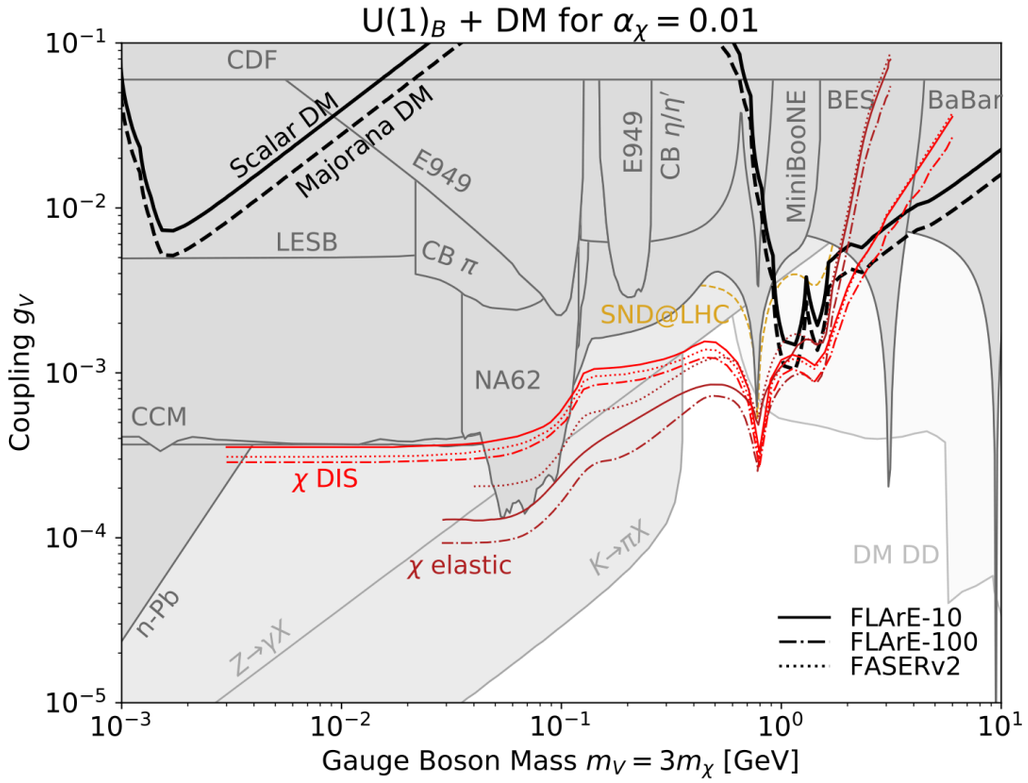


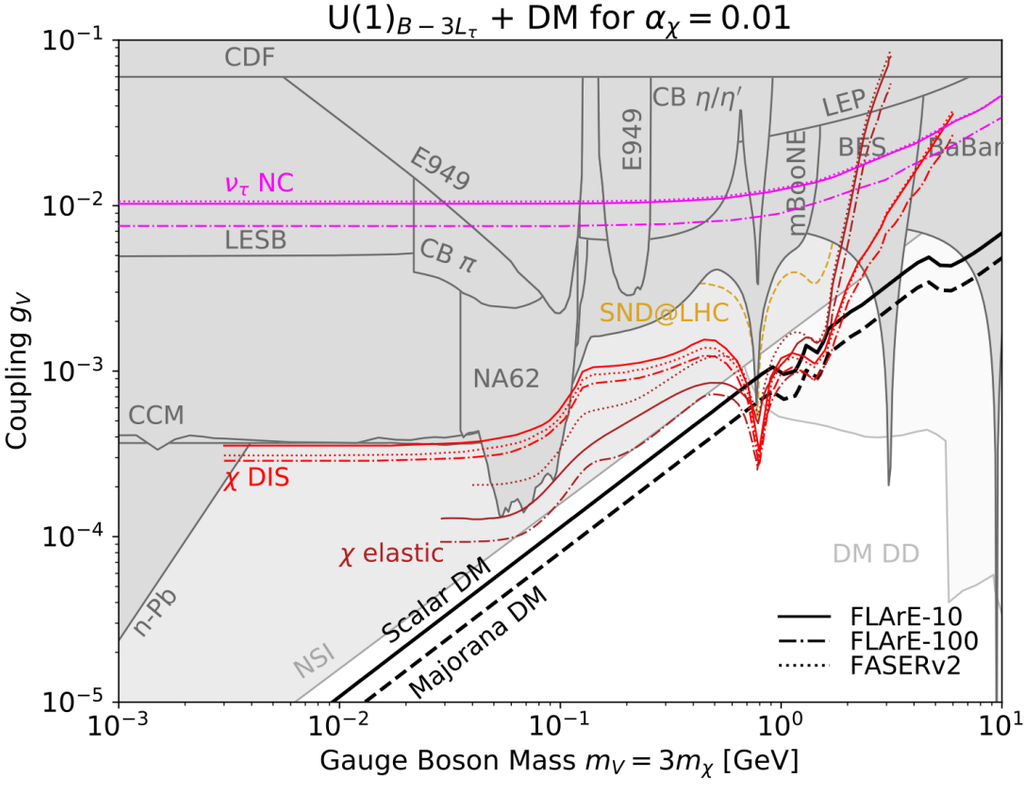
Deep Inelastic scattering

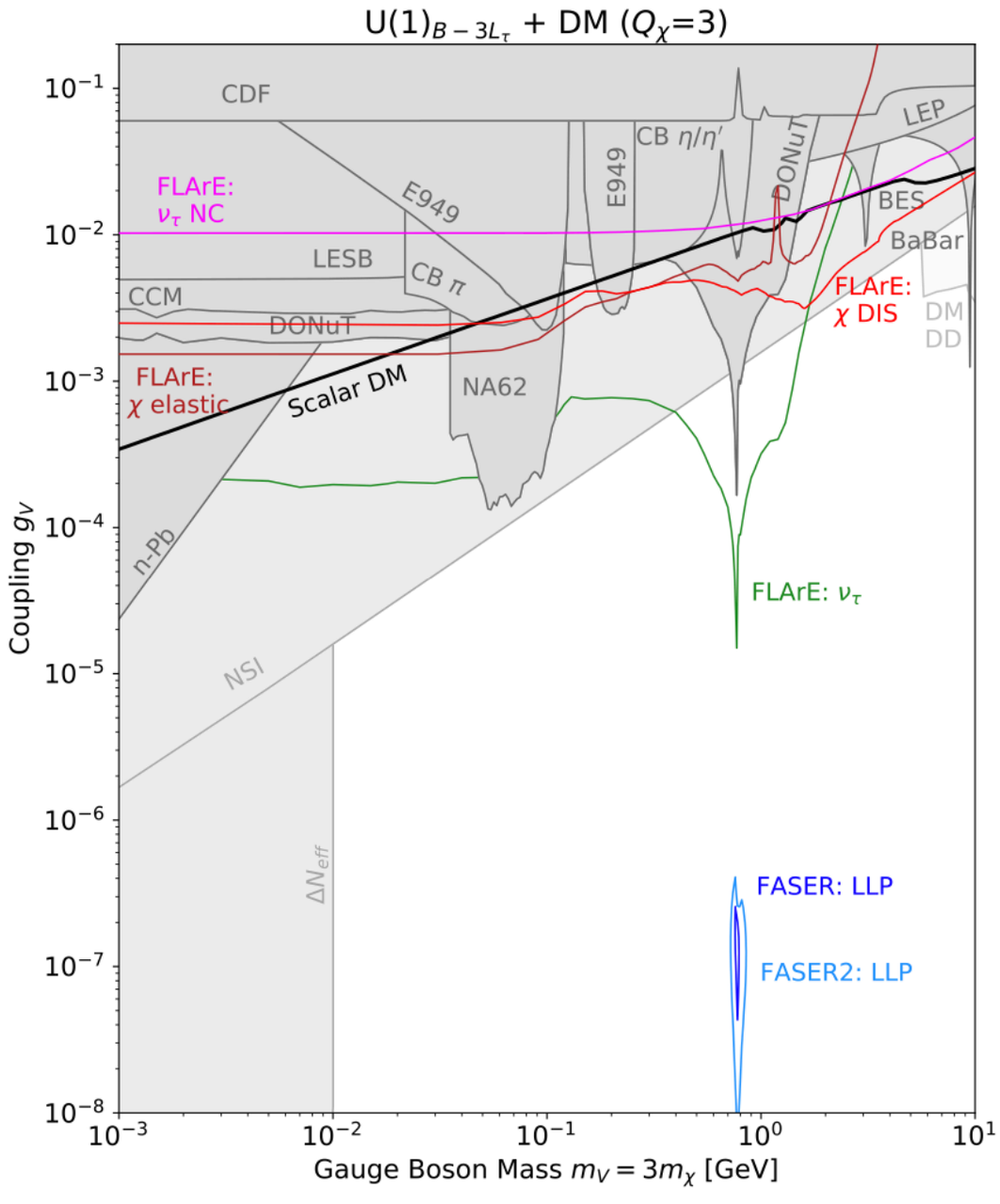
FPF detector sensitivities to vector portal dark matter



FPF detector sensitivities to hadrophilic dark sectors







Outlook

- FASER and FASERν are embarking on an exciting physics program exploiting the large forward pp cross section at the LHC.

- One interesting target for these experiments is light sub-GeV dark matter and dark sectors.

- The FLArE LArTPC detector can probe thermal relic dark matter in both the minimal vector portal DM model and hadrophilic models over broad mass range.

- Along with the search for dark matter scattering, light dark sectors predict a range of other interesting signatures (LLP decay, modified neutrino production and scattering).

Here's looking forward to dark matter at the FPF!