Light Dark Matter at the Forward Physics Facility

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with J. Feng and S. Trojanowski, to appear

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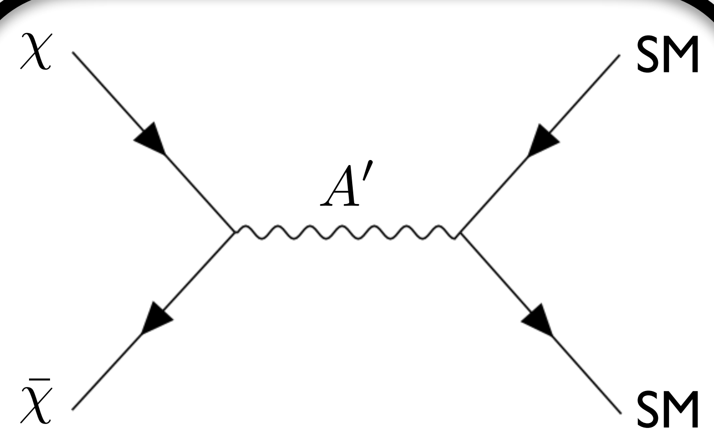
Motivation: Light Thermal Relic Dark Matter

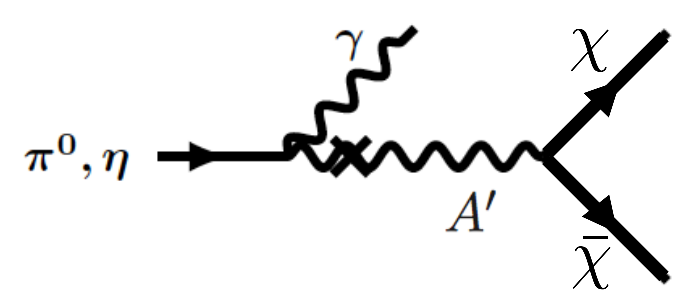
- Light dark sectors provide an interesting framework for dark matter
- Relic abundance generated via thermal freeze-out
- Extension of the WIMP below Lee-Weinberg bound

[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



DM annihilation in the early universe



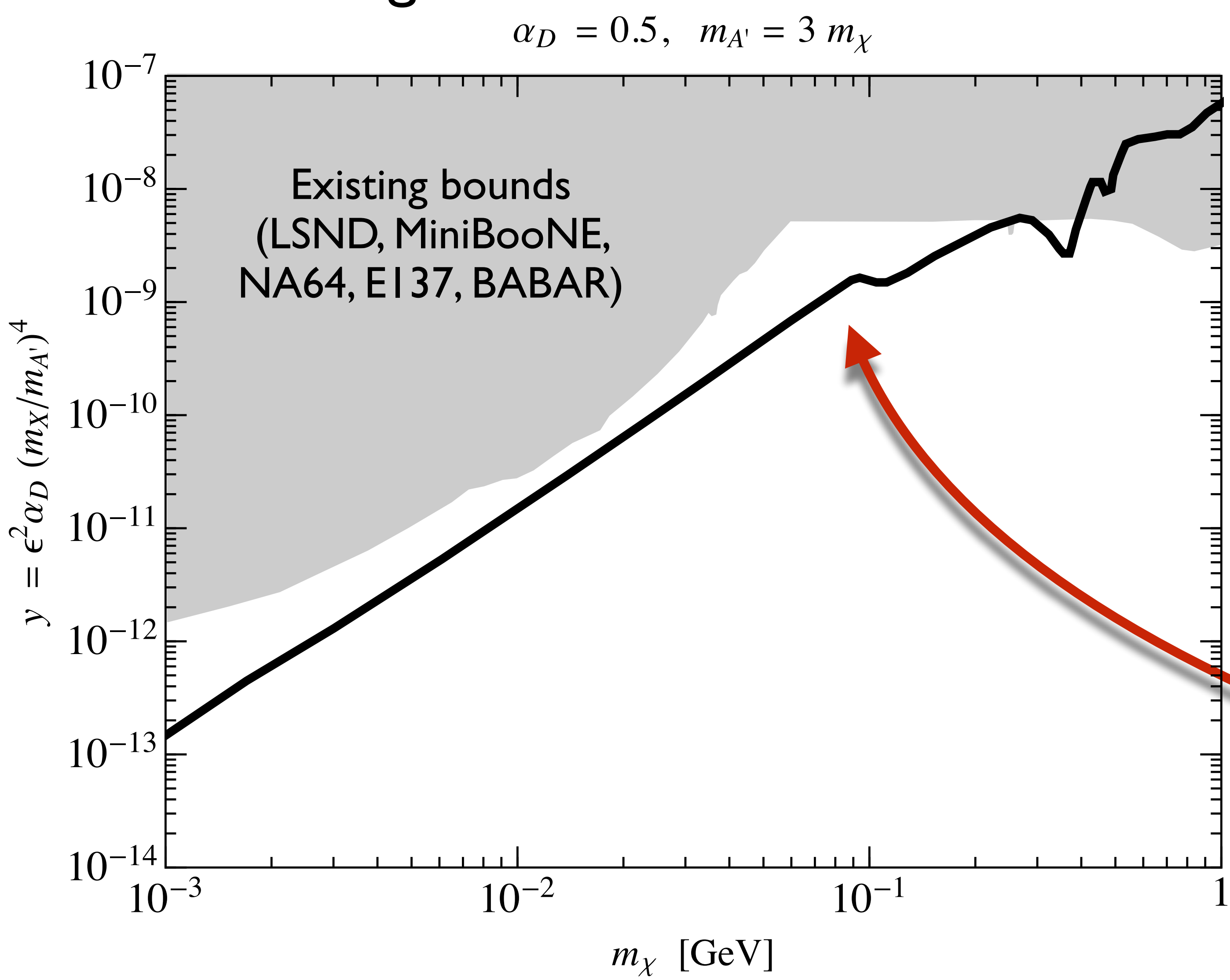
DM production in the laboratory

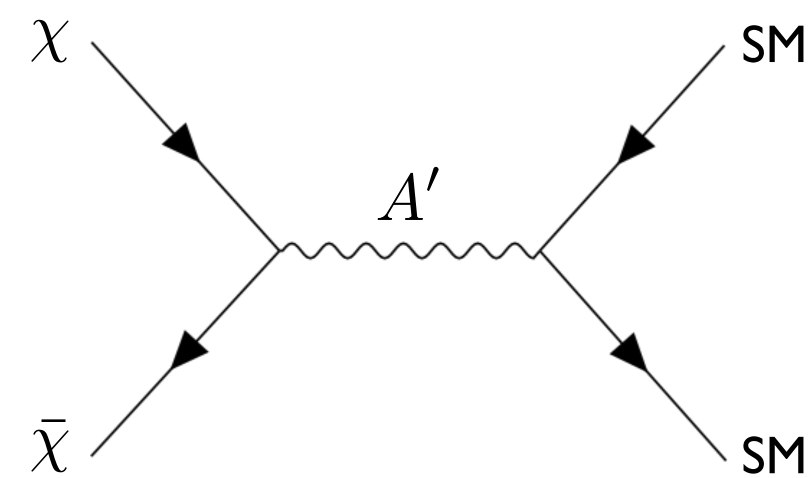
Benchmark Model: Vector Portal Dark Matter

[Holdom]
[Pospelov, Ritz, Voloshin]
[Hooper, Zurek]
[Arkani-Hamed, et al]
…

$$\mathcal{L} \supset |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4}(F'_{\mu\nu})^2 + \frac{1}{2} m_{A'}^2 (A'_\mu)^2 - \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \dots$$

- Dark photon mediates interaction 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

[Izaguirre, Krnjaic, Schuster, Toro]

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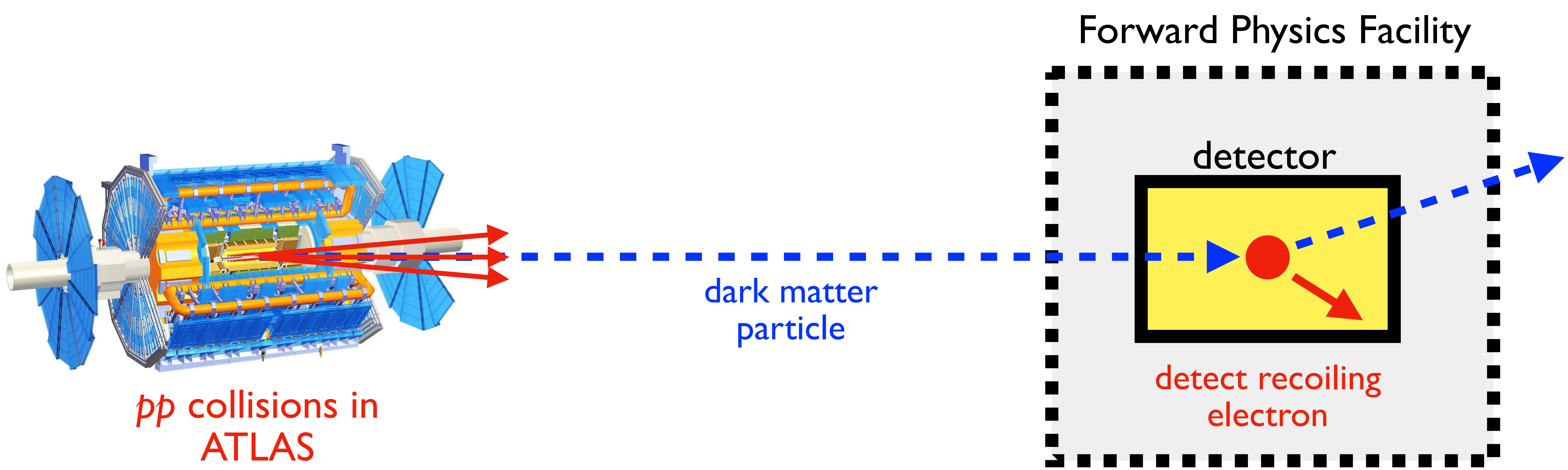
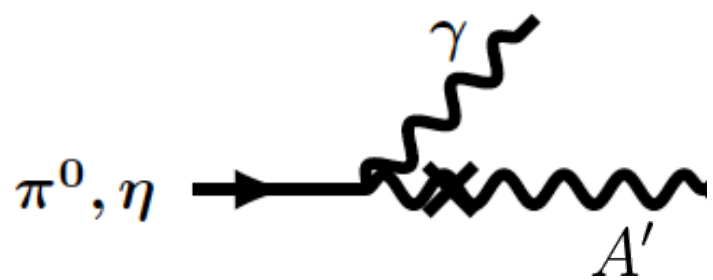


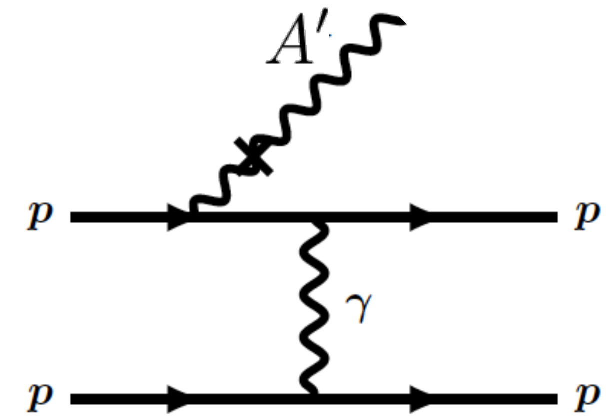
- Similar concept has been employed in fixed-target accelerator neutrino experiments [BB, Pospelov, Ritz] [deNiverville, Pospelov, Ritz] [MiniBooNE-DM '17, '18]
- Similar signature has been explored by SND@LHC [SND@LHC '20]
- Inelastic DM can also be probed at FASER via LLP signal [Berlin, Kling]
- See also talk by N. Okada for probes of Freeze-in DM

Dark Matter at Production and Detection

1. Dark photons are produced in pp collision at the ATLAS IP

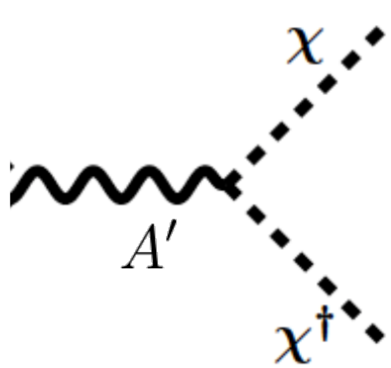


Neutral meson decays

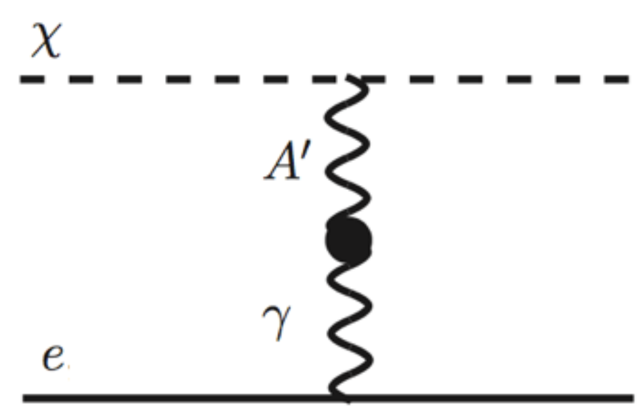


Proton Bremsstrahlung

2. Dark photon decays to dark matter particles



3. Dark matter scatters with electrons in FPF detector



Detector options:

1. Emulsion detector (FASERν-style) see talks by A. Ariga and G. De Lellis

- Layers of emulsion films interleaved with tungsten plates
- Potential to install electronic tracker layers to provide timing information
- Typical angular resolution better than 0.1 mrad
- Track momentum threshold down to 300 MeV
- Assume 10-ton scale detector; 50cm x 50cm x 200 cm volume (FASERν2)

2. Liquid argon TPC (a la MicroBooNE, …)

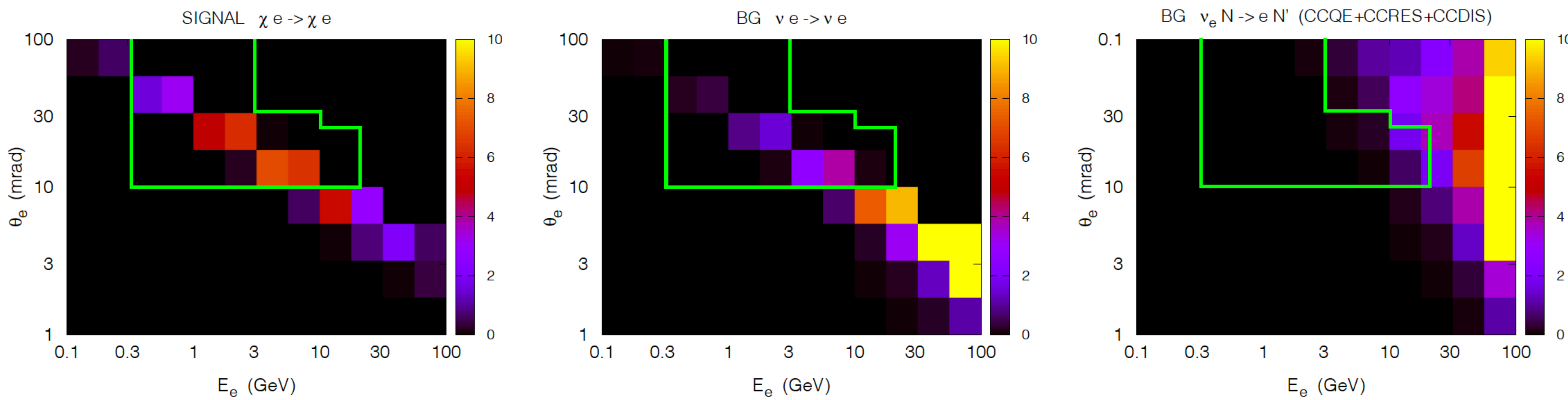
- Liquid argon medium + uniform electric field to transport ionization tracks
- PMTs collect scintillation light, providing event time information
- Wire planes detect drift electrons, providing spatial and kinematic information
- Energy thresholds down to 30 MeV
- Angular resolution of order 10s of mrad
- Assume 100-ton scale detector; 3m x 3m x 10m volume

Backgrounds from neutrino scattering

- There are several neutrino scattering processes which can potentially mimic DM-electron scattering:
  - $\nu e \to \nu e$ (neutrino-electron elastic)
  - $\nu_e n \to e^- p,$ (CCQE)
  - $\nu_e p \to e^- p\pi^+, \nu_e n \to e^- p\pi^0, \nu_e n \to e^- n\pi^+$ (CCRES)
  - $\nu_e N \to e^- X$ (CCDIS)
- We use neutrino fluxes from CERN STI team (obtained from FLUKA), which are then input to GENIE to generate neutrino scattering events
- Ultimately data driven approach to estimate flux and background rates can be employed.
- Event selection:

Electron recoil energy	$0.3\ \text{GeV} < E_e < 20\ \text{GeV}$
Electron recoil angle	$10\ \text{mrad} < \theta_e < 20\ \text{mrad for } E_e > 10\ \text{GeV}$ $10\ \text{mrad} < \theta_e < 30\ \text{mrad for } 3\ \text{GeV} < E_e < 10\ \text{GeV}$ $10\ \text{mrad} < \theta_e \text{ for } E_e < 3\ \text{GeV}$
Track visibility	no additional charged tracks with $p > 0.3$ GeV

Backgrounds from neutrino scattering



events per bin per $3ab^{-1}$

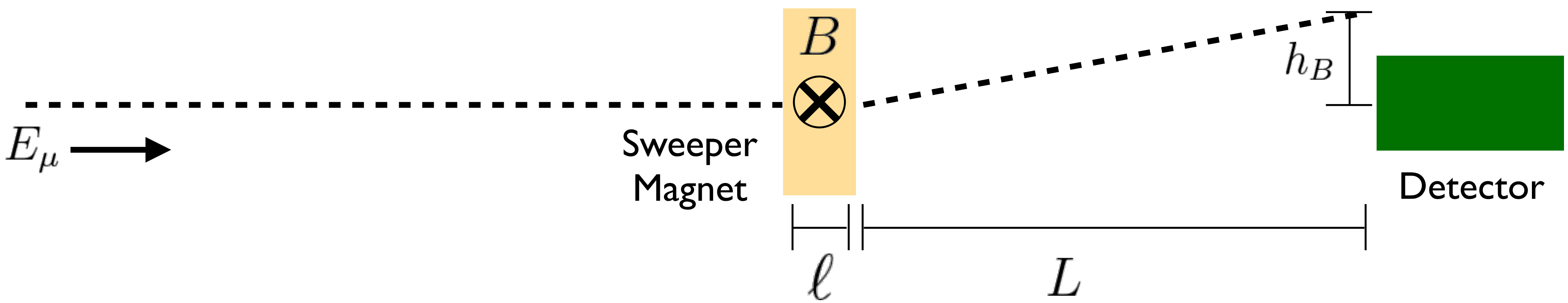
- $\nu e \longrightarrow \nu e$:
  - Energy and angular cuts provide effective discrimination
  - DM (neutrino) scattering events peaked at lower (higher) energy due to light (heavy) mediator.
  - Our estimates suggest this backgrounds can be reduced to order 1-10 event level

	NoE ($\nu e \to \nu e$)	1 GeV $< E_e <$ 20 GeV	
	$E_e > 1$ GeV	no cut on θ_e	θ_e cut (see text)
ν_e	160	5	2.3
$\bar{\nu}_e$	60	4	2.2
ν_μ	70	6	3.2
$\bar{\nu}_\mu$	44	5	2.4
ν_τ	1	0.05	0.02
$\bar{\nu}_\tau$	1	0.05	0.02
TOTAL	336	20	**10.1**

- CCQE, CCRES, CCDIS :
  - Cut on additional activity associated with the nuclear interaction
  - Our estimates suggest these backgrounds can be reduced to the order 1 event level

Muon-induced backgrounds

- Large flux of muons produced in the IP or TAN traverse the detector. These can radiate an energetic photon, which can then convert to an e^+e^- pair
- Such processes could provide a background if
  1. one of the e- or e+ has energy below the 300 MeV detection threshold, and
  2. the other has correct energy and direction to fall within the signal region
- One option to help mitigate this background is to install a sweeper magnet along the collision axis upstream of the detector see also talk by A. Ariga

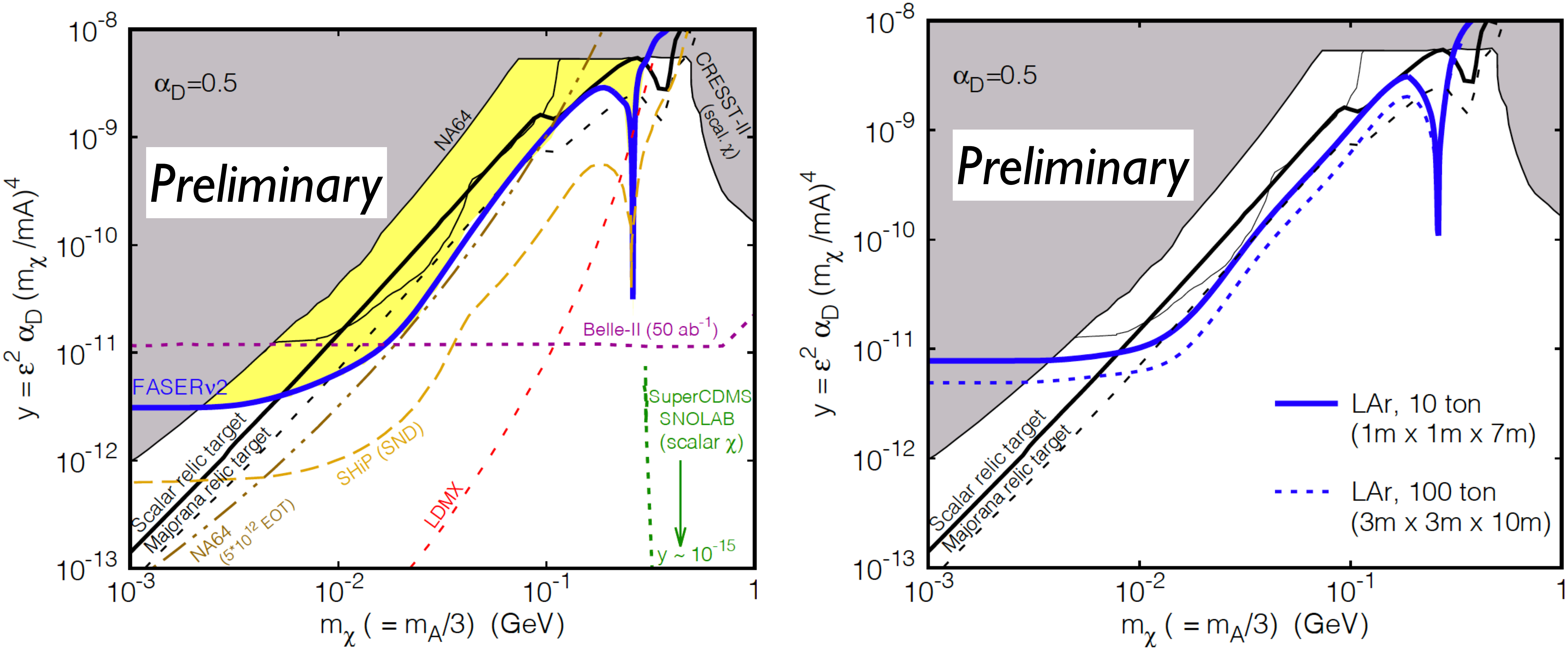


$$h_B \approx \frac{ecL}{E_\mu} B\ell = 60 \text{ cm} \left[\frac{100 \text{ GeV}}{E_\mu}\right] \left[\frac{L}{200 \text{ m}}\right] \left[\frac{B \cdot \ell}{\text{T} \cdot \text{m}}\right]$$

(horizontal displacement)

- Another option is to employ an active muon veto using event timing information:
  - Interleave electronic timing layers within emulsion detector
  - LArTPC + muon trigger outside detector

Projected Sensitivity



- Can test thermal target over a broad mass range (few MeV - few hundred MeV)
- Complementary to other existing or proposed experiments
    - Probes different production mechanisms and mediator couplings
    - Directly detects the produced dark matter through re-scattering
    - May have superior sensitivity to other dark matter models (e.g., hadrophilic couplings)

Outlook

- FASER and FASERν will soon embark 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.
- FASERν2 (10 ton-scale detector) or 10-100 ton LArTPC detector can probe thermal relic dark matter in minimal vector portal DM model over broad mass range.
- Neutrino backgrounds appear to be manageable (event topology + kinematic cuts).
- Muon induced backgrounds could pose a challenge — ideas to mitigate this include muon sweeper magnet and active muon veto using event time information.
- Looking forward…
  - We find large event rates for neutrino-electron elastic, CCQE, CCRES, …These should be investigated in more detail as part of FASER neutrino physics program
  - Feasibility of the LArTPC concept for the Forward Physics Facility?
  - It would be interesting to explore other dark sector / dark matter models

Questions and feedback are very welcome!