Detecting Dark Matter with Far-Forward Emulsion and Liquid Argon Detectors at the LHC

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B. Batell, J.L. Feng, ST, Phys.Rev.D 103 (2021) 7, 075023
B. Batell, J.L. Feng, A. Ismail, F. Kling, R.M. Abraham, ST, In preparation

ASTROCENT

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European Union European Regional Development Fund

Light thermal relic dark matter

- Light BSM sector can naturally contain a DM candidate χ

  Talk: Bhaskar Dutta

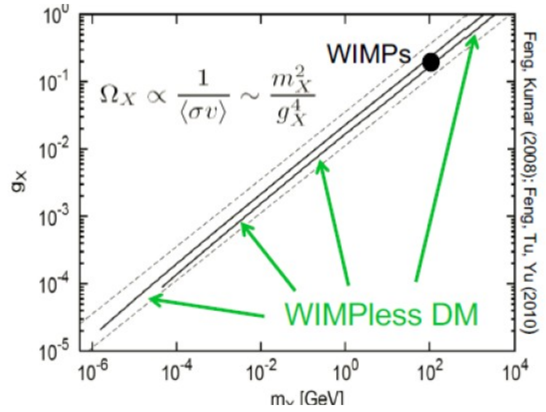
  C. Boehm, P. Fayet, hep-ph/0305261
  M. Pospelov, A. Ritz, M. B. Voloshin, hep-ph/0711.4866
  J. L. Feng and J. Kumar, hep-ph/0803.41960803.4196

- Correct thermal light DM relic density (“WIMPless” miracle)

  Talk: Tim Tait, Gordan Krnjaic

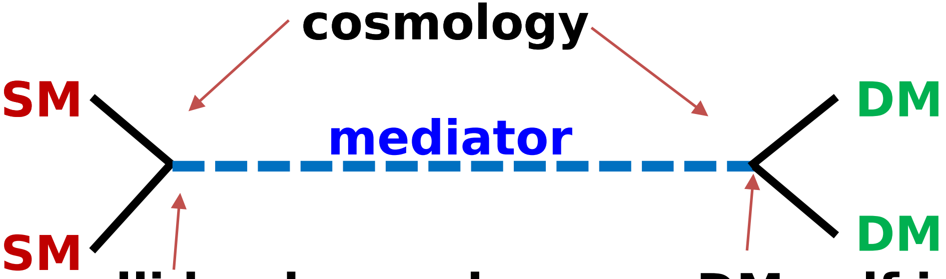
- Efficient DM annihilation in the early Universe

+ various experimental probes



Talks:
Rouven Essig
Rafael Lang
Simona Murgia
Andrew James Whiteback
...

DM direct & indirect probes, cosmology



collider, beam dumps **DM self interactions**

(e.g. long-lived mediators → SM, missing energy/momentum)

THIS STUDY

collider
DM direct detection

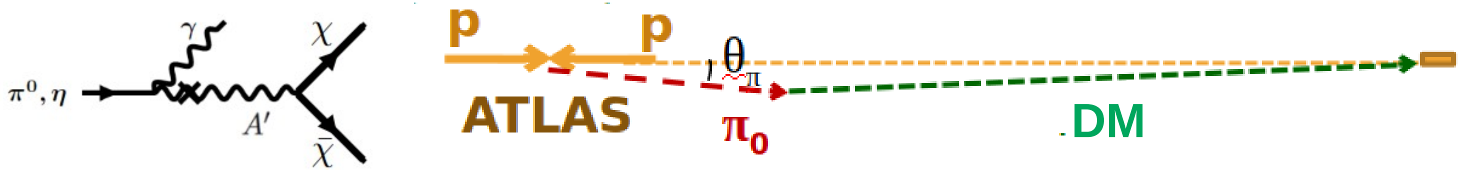
Light DM at the LHC

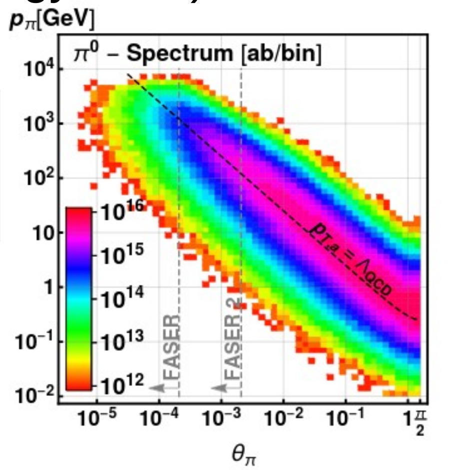
- LHC can be a very efficient light DM (LDM) factory

- LDM direct detection requires suppressing SM backgrounds – difficult in typical LHC experiments

- ...but many LDM particles will go down the beam pipe (especially high energy ones)

Example: DM production in rare decays of light mesons





other prod. modes include i.a. proton-proton bremsstrahlung

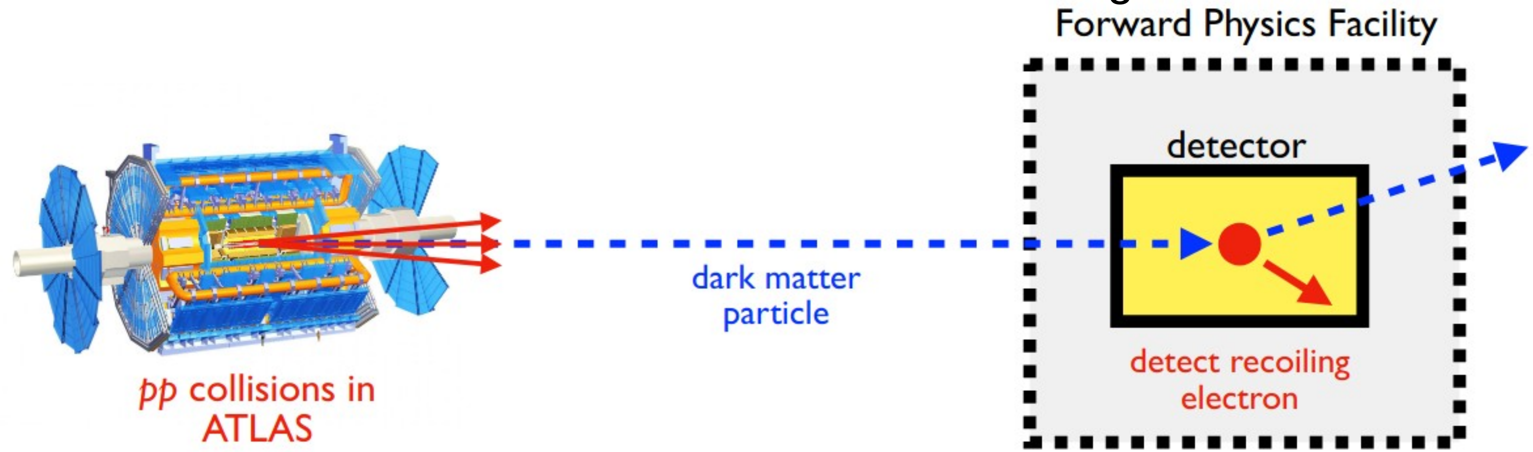
pp → pp(A' → χχ)

FASER Collaboration, hep-ph/1811.12522, hep-ex/1908.02310

- Far-forward search for light long-lived particles and studies of high-energy neutrino interactions to be initiated during Run 3 with FASER and FASERν detectors

Direct light DM detection at the LHC

- We focus on LDM particles produced in the far-forward region of the LHC & their scattering in a distance detector



credit B. Batell

- This search is highly complementary to the traditional DM direct detection searches:
  – probe of relativistic interaction rates of LDM (DM energy ~ a few hundred GeV)
  [collider-boosted DM]
  – the search is not sensitive to the precise abundance of χ DM component
  (possible variations in cosmological scenario)
  [collider-produced DM]

Example signature: DM scattering off electrons

- Signature: recoiled electron (recoil energy E_e, recoil angle θ_e wrt to the beam collision axis)
- Light mediator favors low energy electron recoil

Neutrino scattering example

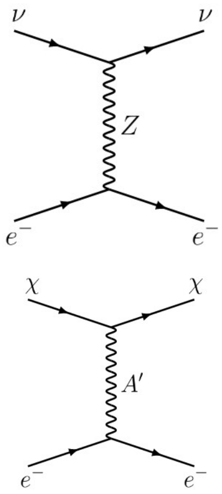
$$\frac{d\sigma(\nu_l e \to \nu_l e)}{dy} = \frac{2 m_e G_F^2 E_\nu}{\pi} \frac{1}{(1 + 2 m_e E_\nu y / M_Z^2)^2} \left(g_L^2 + g_R^2 (1-y)^2\right),$$

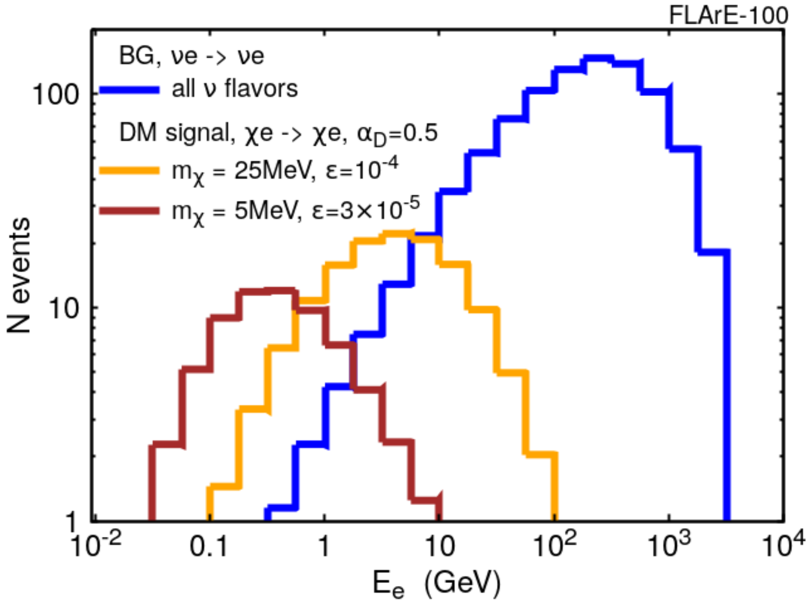
$y = E_e/(E_x,E_\nu)$

DM scattering (dark photon mediator)

$$\frac{d\sigma}{dy} \approx \frac{8\pi \epsilon^2 \alpha \alpha_D m_e E_\nu}{m_{A'}^4 (1 + 2 m_e E_\chi y / m_{A'}^2)^2}$$

$m_{A'} \ll M_Z$ ⇨ low y, soft recoils favored





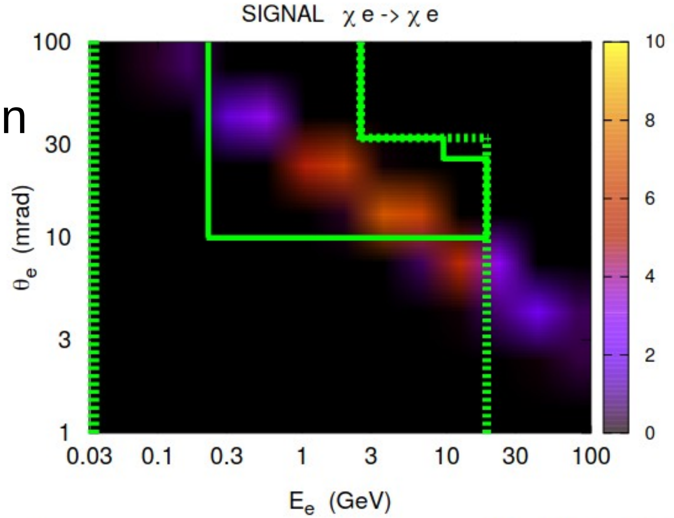
Aditional cuts

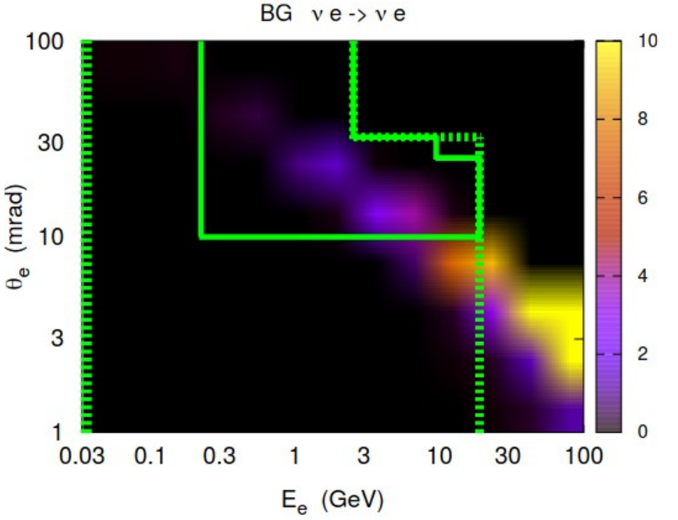
- angular cuts can further improve discrimination between DM and ν-induced backgrounds

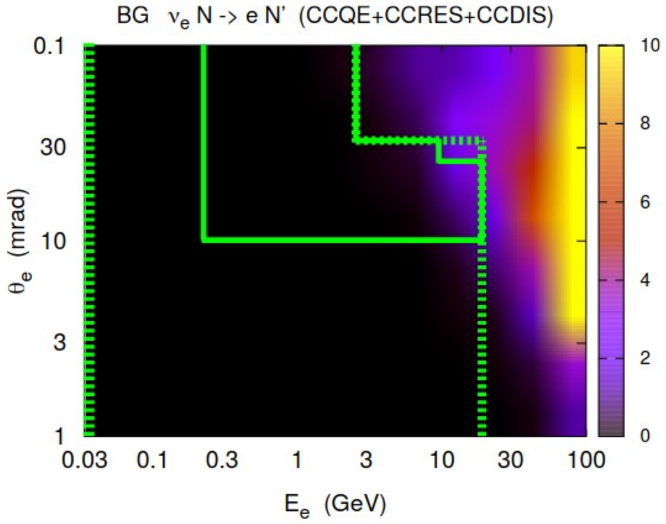
- such backgrounds can be reduced to
~10 events for the 10-tonne detector
~100 events for the 100-tonne detector
for the entire future High-Luminosity LHC era

- this depends on the detector type and geometry

- angular info also used to identify events associated with pp collisions at the distant Interaction Point







Muon-induced backgrounds

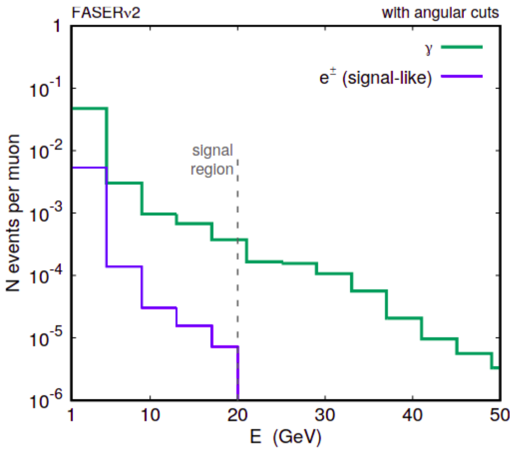
- The LHC is also the muon factory
- Most of muons are deflected by the LHC magnets so that they never reach far-forward detectors...
- ...but the remaining number of expected through-going muons is huge
  $N_\mu \sim 10^{11}$ for HL-LHC and the far-forward detector with radius~1m (on axis)
- they can be further deflected by dedicated sweeping magnets

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

- the most energetic muons can avoid deflection and be source of backgrounds

$\mu N \rightarrow \mu N \gamma$ (photon brem.) + $\gamma N \rightarrow e^+e^-N$ (pair prod.)
& e^+e^- can be misreconstructed as e^-

- event time information crucial to reject this background

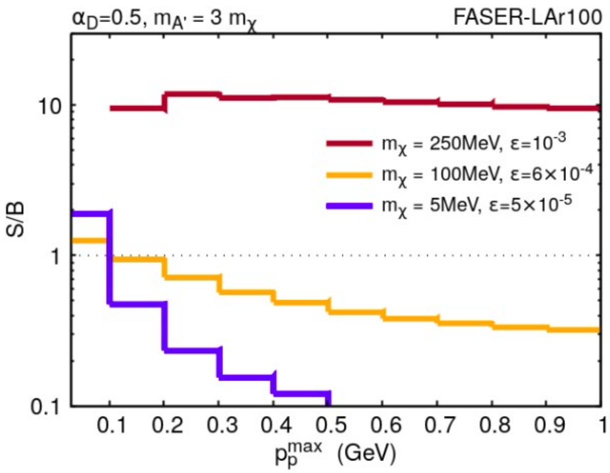


Example signature 2:
Elastic DM scatterings of protons

• elastic scatterings off protons $\chi p \to \chi p$ can lead to DM detection via observation of a single proton track

• again DM with light vector mediator favors low proton recoils

SIGNAL / BG ratio as a function of the max proton momentum cut (min cut >30 MeV)



BG can be suppressed to few tens of events for 10-tonne detectors up to few-hundred for 100-tonne detector

• both for DM signal and ν-induced BG important impact of final-state interactions (FSI) of the proton before it leaves the nucleus

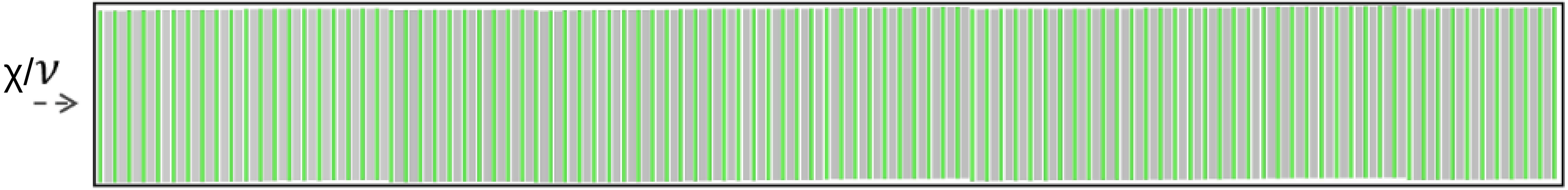
• further signatures: DM DIS events, resonant pion production

Detectors for HL-LHC (1)

Emulsion detector   FASERν2   (50cm x 50cm x 200 cm volume)

- layers of emulsion films interleaved with tungsten plates

FASER Collaboration, 1908.02310



- possible extension of the FASERν physics program (similar program SND@LHC)

(1908.02310, 2001.03073)   (2002.08722)

- experimental strategy to be tested during Run 3 (first exciting results from Run 2 already released!)

FASER Collaboration, 2105.06197

- a priori no time info – need to be interleaved with electronic tracker layers

- for soft events, reconstruction might be challenging

- readout problems if too large track density from through-going muons

Detectors for HL-LHC (2)

Forward **L**iquid-**Ar**gon **E**xperiment FLArE

- Liquid-Argon time projection chamber (TPC) + PMTs to collect scintillation light
- experimental strategy tested in MicroBooNE, …
- dynamical time information – improves background rejection capabilities
- neutrino physics program – possible detection of soft signals
- requires larger space (FLArE-10 tonne: 1m x 1m x 7m, FALrE-100 tonne: 1.6m x 1.6m x 30m)...
- ...ideally in well-shielded place like the Forward Physics Facility

F. Kling, J.L. Feng, Snowmass input https://zenodo.org/record/4059893#.YKZONiaxU5k

Talk: Felix Kling

Benchmark scenarios

- We focus on DM interactions via the dark photon portal $\mathcal{L} \supset A'_\mu (\epsilon \, e \, J^\mu_{EM} + g_D \, J^\mu_D)$

- We present the results for simple scalar and Majorana fermion DM

$$\mathcal{L} \supset \begin{cases} |\partial_\mu \chi|^2 - m_\chi^2 |\chi|^2 & \text{(complex scalar DM)} \\ \frac{1}{2}\overline{\chi} i \gamma^\mu \partial_\mu \chi - \frac{1}{2} m_\chi \overline{\chi}\chi & \text{(Majorana fermion DM)} \end{cases}$$

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

- They are characterized by p-wave annihilation cross section, avoid bounds from CMB

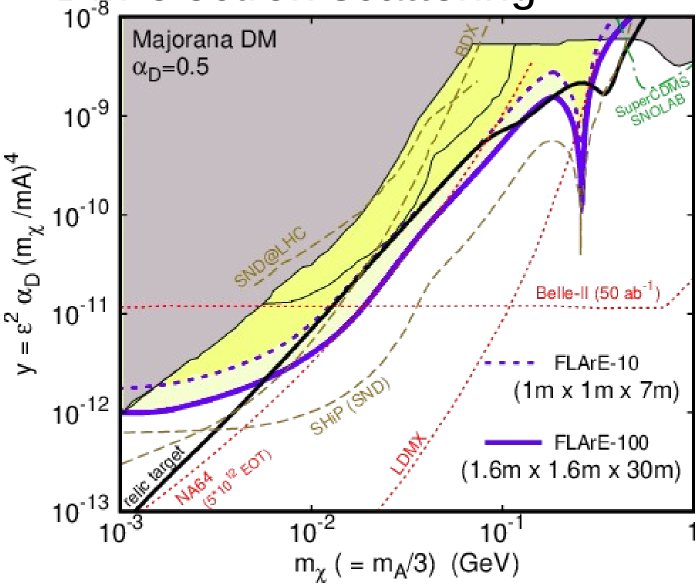
$$\sigma v \propto \alpha \, v^2 \, \frac{\epsilon^2 \, \alpha_D \, m_\chi^2}{m_{A'}^4} = \alpha \, v^2 \, \frac{y}{m_\chi^2} \, ,$$

- In the case of Majorana, non-relativistic DM direct detection rates are also suppressed

- The same can be achieved for Inelasitc Scalar DM
  (two dark species with small mass splitting)

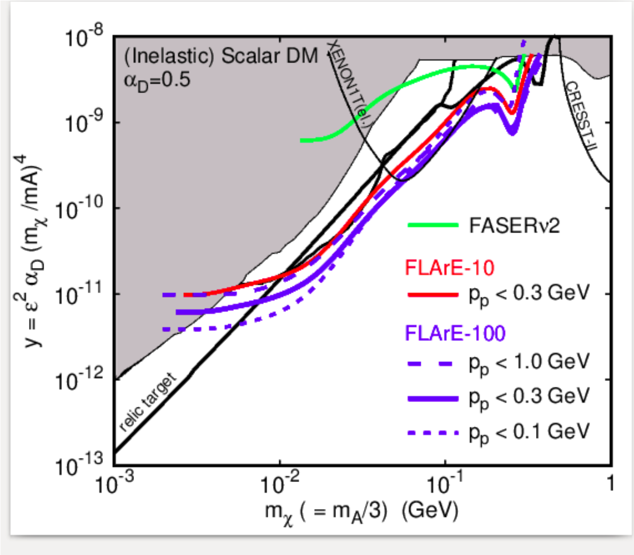
Sensitivity reach for FLArE

DM-electron scattering



DM-proton elastic scattering

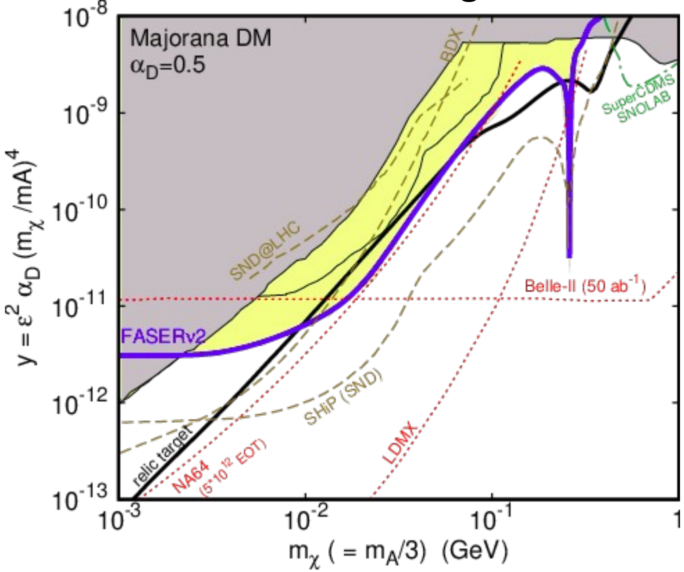
Preliminary



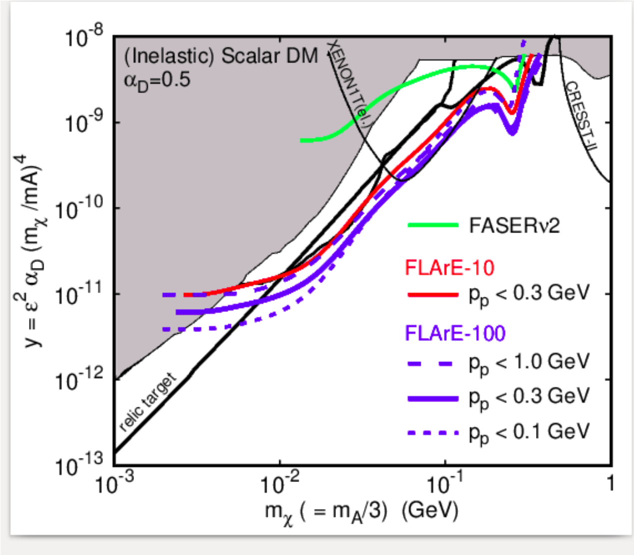
- both for Majorana and Scalar DM relic target can be probed during HL-LHC already by the 10-tonne detector FLArE-10
- complementary search strategies based on leptonic and hadronic DM couplings
- possibility to directly detect DM interactions

Sensitivity reach for FASERv2

DM-electron scattering



DM-proton elastic scattering



Preliminary

- DM-electron scattering search with similar prospects to FLArE-10 (provided than μ-induced BG is rejected)
- DM-proton scattering suffers from larger background and smaller signal rates: impact of larger energy threshold and possible misreconstruction of ν-induced BG events

Concluding remarks

• LHC can be a light DM factory, most of high-energy such dark species will go down the beam pipe and avoid detection

• DM direct detection in the far-forward LHC liquid-argon or emulsion detectors can probe important relic targets via scatterings off electron or nuclei during HL-LHC (Majorana, Inelastic scalar)

• Direct detection based on relativistic DM interactions complementary to traditional searches

• More to be studied, e.g. hadrophilic or other operators favoring relativistic scatterings)

• Backgrounds from neutrino and muon interactions
(dynamical vetoing + cuts to disentangle from DM signal)

• Rich neutrino physics program is also envisioned

• Scattterings can also lead to good detection strategies for some very long-lived new particles, see e.g. such study for HNL with dark vector portal K. Jodłowski, ST, 2011.04751 (JHEP)