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
Light thermal relic dark matter

• Light BSM sector can naturally contain a DM candidate $\chi$
  
  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/0803.4196

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

• Efficient DM annihilation in the early Universe
  + various experimental probes

Talks:
Knut Moraa
Joseph Bramante
Natalia Toro

DM direct & indirect probes, cosmology

collider, beam dumps

DM self interactions

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

\[ \pi^0, \eta \rightarrow A' \rightarrow \chi \chi \]

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

\[ pp \rightarrow pp(A' \rightarrow \chi \chi) \]

• Far-forward search for light long-lived particles and studies of high-energy neutrino interactions to be initiated during Run 3 with FASER and FASER\nu 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
- 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)
  - the search is not sensitive to the precise abundance of $\chi$ DM component
    (possible variations in cosmological scenario)

credit B. Batell
Example signature: DM scattering off electrons

• Signature: recoiled electron (recoil energy $E_e$, recoil angle $\theta_e$ wrt to the beam collision axis)

• Light mediator favors low energy electron recoil

Neutrino scattering example
\[
\frac{d\sigma(\nu_e \rightarrow \nu_e)}{dy} \approx \frac{2m_eG_F^2E_\nu}{\pi} \frac{1}{(1 + 2m_eE_\nu y/M_Z^2)^2} \left( g_L^2 + g_R^2(1 - y)^2 \right),
\]
\[y = E_e/(E_\chi E_\nu)\]

DM scattering (dark photon mediator)
\[
\frac{d\sigma}{dy} \approx \frac{8\pi e^2 \alpha \alpha_D m_e E_\nu}{m_{A'}^4 (1 + 2m_eE_\chi y/m_{A'}^2)^2}
\]

$m_{A'} \ll M_Z \Rightarrow$ low $y$, soft recoils favored
Additional 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
  \[ h_B \approx \frac{c c d}{E_\mu} B \ell = 60 \text{ cm} \left[ \frac{100 \text{ GeV}}{E_\mu} \right] \left[ \frac{d}{200 \text{ m}} \right] \left[ \frac{B \cdot \ell}{T \cdot \text{m}} \right] \]

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

\[ \mu N \rightarrow \mu N \gamma \text{ (photon brem.)} \quad + \quad \gamma N \rightarrow e^+ e^- N \text{ (pair prod.)} \]
Example signature 2: 
Elastic DM scatterings of protons

- elastic scatterings off protons $\chi p \rightarrow \chi p$ 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 $\nu$-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

• Convenient location: Forward Physics Facility (FPF) – tunnel to host several far-forward experiments

• Considered detector types:

  – emulsion detector FASERv2 (50cm x 50cm x 200 cm)
  Similar detection strategies to be tested during Run 3: FASERv (1908.02310, 2001.03073), SND@LHC (2002.08722)
  Consists of layers of emulsion films interleaved with tungsten plates + electronic tracker layers for timing
  Requirements: good soft track reconstruction and readout in presence of numerous muon tracks

  – Forward Liquid Argon Experiment (FLArE-10 tonne: 1m x 1m x 7m, FLArE-100 tonne: 1.6m x 1.6m x 30m)
  Similar to MicroBooNE, ...
  Liquid-Argon time projection chamber (TPC) + PMTs to collect scintillation light
  Dynamical time information
  Requirements: larger space, well-shielded place ➔ FPF

• Sample results for two benchmark models: dark photon mediator & Majorana or (inelastic) complex scalar DM

\[ \mathcal{L} \supset A'_\mu(e e J_{EM}^\mu + g_D J_D^\mu) \]

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

\[ J_D^\mu = \begin{cases} i\chi^* \partial_\mu \chi & \text{(complex scalar DM)} \\ \frac{1}{2} \chi i\gamma^\mu \gamma^5 \chi & \text{(Majorana fermion DM)} \end{cases} \]
Sensitivity reach for FLArE

• 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 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.

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

• Rich neutrino physics program is also envisioned.

• Scatterterings 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).

(VERY) SCHEMATIC FAR-FORWARD DETECTOR CAPABILITIES

Current bounds
Secondary production
(1911.11346, 2011.04751)
Search for LLP decays
FASER(2): 1708.09389, 1811.12522...
SND@LHC: 2104.09688

Anomalies (g-2), ?, DM mediators

Scattering detectors: FASERv(2), SND@LHC, FLArE

DM, ν physics, very long-lived new particles

THIS TALK