MoEDAL, FASER and future experiments targeting dark sector & long-lived particles

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With many thanks to
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The lifetime frontier

- ATLAS, CMS and LHCb are mainly optimised and search for new particles that decay *promptly* ⇒ *strongly coupled*
- Strong efforts to develop new trigger/reconstruction/analysis strategies to also probe new *long-lived* particles ⇒ successful coverage of part of parameter space
- Particle lifetimes in BSM theories span a very wide range; very low masses; diverse final states (e.g. unusual charges)
- Necessary to design and build dedicated experiments for long-lived BSM particles
A new particle may be long-lived due to a very “weak” coupling with SM particles, e.g. in Higgs-portal hidden sectors, dark photons, etc.
Long-lived & decaying vs. (stable) milli-charged particles

Long-lived (neutral) particles (LLP) that decay in detector volume to charged particles
- $pp \rightarrow LLP \rightarrow tracks$
  - lifetime, coupling to SM and boost (mass)
  - angle w.r.t. beam axis; volume; distance from IP
- Case studies
  - Dark photon / dark Higgs
  - Heavy Neutral Leptons (HNLs)
  - Axion-Like Particles (ALPs)
  - $R$-parity violating supersymmetry
- Experiments

Fractionally charged particles that interact directly with the detector
- Case study: milli-charged particles
  - may or may not decay eventually (affects broader phenomenology)
  - charge is the critical parameter $\sigma \propto Q^2$
- Experiments
  - milliQan
  - MoEDAL-MAPP-mQP

Experiments
- FASER
- MoEDAL-MAPP-LLP
- CODEX-b
- MATHUSLA
- AL3X
- ANUBIS

LHC
- SHiP
- NA62
- NA64
- SeaQuest
- Solid
- ...

non-LHC

V. A. Mitsou
LHCP2020
Long-lived neutral particles decaying in detector volume

- MoEDAL-MAPP
- FASER
- CODEX-b
- MATHUSLA
- AL3X
- ANUBIS
LHC dedicated LLP experiments

MATHUSLA
milliQan

Point 3.2

Point 2

Point 3.3

Point 4

Point 5

Point 6

Point 7

Point 8

AL3X

ALICE

FASER

ANUBIS

SPS

MoEDAL-MAPP

CODEX-b

AL3X

ANUBIS

ATLAS

FASER

LHC 'B'

CODEX-b

LHC

dedicated

LLP

experiments
MAPP – MoEDAL Apparatus for Penetrating Particles

- Two subdetectors for two classes of particles
  - **MAPP-LLP:** new pseudo-stable weakly interacting *neutral* particles with *long lifetime* with the detector
  - **MAPP-mQP:** particles with charges $\ll 1e$
- Positioned at an angle of 5° w.r.t. beam axis
- To be installed for LHC Run-3

- MAPP-LLP: “Box-within-a-box” structure
- Scintillator strips in an x-y configuration read out by SiPMs
- **MAPP-2** is planned to fully occupy the UGC1 gallery and run during HL-LHC

Jim Pinfold’s talk on MoEDAL in afternoon “Upgrades & Future: Smaller LHC Experiments” session
FASER will be situated along the beam collision axis line of sight (LOS) in TI12 tunnel
- ~480 m from IP1 (ATLAS)
- after beams start to bend
- a few meters from the LHC beamline
- transverse radius of 10cm covering the mrad regime ($\eta>9.1$)

To start running after LS2

- **FASERV** (newly approved) To detect and measure collider neutrinos
- **FASER2** for HL-LHC with a larger radius of ~1 m

The detector consists of:
- Scintillator veto
- 1.5m long decay volume
- 2m long spectrometer
- EM calorimeter

Zhen Hu’s talk on FASER in afternoon “Upgrades & Future: Smaller LHC Experiments” session
A COmpact Detector for EXotics at LHCb

Expression of interest: arXiv:1911.00481

- Transverse detector at the LHC
- RPCs: fast, precise, cheap for large area
- 6 RPC layers at 4 cm intervals on each box face with 1 cm granularity
- Integration with LHCb trigger-less readout
- CODEX-β demonstrator (2×2×2 m³) plans are underway
2.6 Cosmic Ray Physics with MATHUSLA

The design of MATHUSLA is driven by the requirements of reconstructing upward-traveling displaced vertices and distinguishing them from downward-traveling cosmic rays. It therefore comes as no surprise that MATHUSLA has all the qualities needed to act as an excellent cosmic ray telescope. In fact, MATHUSLA's particular combination of robust tracking and large area allow it to make many unique measurements that could address important and long-standing questions in astroparticle physics. The study of cosmic rays is therefore an important secondary physics goal of MATHUSLA. These measurements, which in no way interfere with the primary goal of LLP discovery, represent a "guaranteed physics return" on the investment of the detector, as well as an opportunity for CERN to establish a world-leading cosmic ray physics program.

The cosmic ray physics program at MATHUSLA warrants in-depth examination beyond the scope of this work. Some initial studies will be presented elsewhere. Here we only briefly comment on the qualities that make MATHUSLA a uniquely interesting cosmic ray experiment, and outline some possible measurements that are of particular interest to the astroparticle physics community. To this end, we first review some basic facts about cosmic rays and how they are detected.

Cosmic rays, dominantly protons and heavier atomic nuclei, arrive at earth with an energy that spans some 12 orders of magnitude, from a few hundred MeV (\(10^8\) eV) to 100 EeV (\(10^{20}\) eV), see for example, Fig. 7. They are produced in violent astrophysical scenarios within our own galaxy (for energies \(E < 10^{18}\) eV) and beyond (for \(E > 10^{18}\) eV). At the highest energies, however, the origin of...
**Hidden sector**

**Heavy neutral leptons ("sterile neutrinos")**
- explain SM $\nu$ masses (seesaw), DM, BAU
- weak semi-leptonic decays of hadrons, $W, Z$

**Dark vectors ("Dark Photons")**
- adding $U(1)$ gauge group to SM, kinetic mixing with $\gamma/Z$
- light neutral meson decays, milli-charged particles

**Dark scalars ("Dark Higgs")**
- neutral singlet scalers that couple to the SM Higgs field
- produced in penguin decays of K, D, B mesons

**Axion-like particles ("ALPs")**
- solution of the strong CP problem
- generalisation of the axion model in MeV-GeV mass range

Credit: Zhen Liu, Alexander Korzenev
Minimal dark photon model

- Adding a new hidden U(1) with massive gauge field $A'_\mu$, the dark photon
- DM assumed to be either heavy or contained in a different sector
- Dark photon decays to SM states (visible decays)
- $m_{A'}$: dark photon mass
- $\epsilon$: coupling of dark photon with the standard photon
Scalar portal – dark Higgs

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DS} + \mu^2 S^2 - \frac{1}{4} \lambda_S S^4 - \epsilon_H S^2 |H|^2$$

Dark Higgs $\phi$ mixes with SM $H^0$ (mixing angle $\theta \ll 1$), leading to exotic $B \rightarrow X_s \phi$ decays with $\phi \rightarrow \ell^+ \ell^-$

Heavy Neutral Leptons

$U_{\tau N} \gg U_{eN}, U_{\mu N}$

$|V_{\alpha N}|$ controls both production and decay of the HNLs

First two generations

Green area excluded by PS191, JINR, CHARM and DELPHI
Heavy neutrino via $Z'$ production in gauged B-L model

- Pair production of RH neutrinos from the decay of an additional neutral $Z'$ boson in the gauged B-L model
  - fixed value of $M_{Z'} = 30$ GeV and $Z'$ gauge coupling $g'_1 = 10^{-3}$
- In addition to the $Z'$ and three new neutrinos $N_i$, this model also contains a singlet Higgs $\chi$ that spontaneously breaks the extra $U(1)_{B-L}$ gauge symmetry


MAPP & CODEX-b @ 300 fb$^{-1}$
MATHUSLA, FASER2, CMS, & LHCb @ 3000 fb$^{-1}$
Axion-Like Particles

Gluon dominance: assumes an ALP coupled to gluon
- \( m_\alpha \): ALP \( \alpha \) mass
- \( c_G \): \( \alpha \) coupling to gluon

CODEX-b, arXiv:1911.00481
$R$-parity violating supersymmetry

\[ W_{R} = \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^C + (\lambda'_{ijk}) \hat{L}_i \hat{Q}_j \hat{D}_k^C + \epsilon_i \hat{L}_i \hat{H}_u + \lambda''_{ijk} \hat{U}_i^C \hat{D}_j^C \hat{D}_k^C \]

Light long-lived neutralinos $\tilde{\chi}_1^0$ decay via $\lambda'_{ijk}$ couplings to charged particles.

$\tilde{\chi}_1^0 \rightarrow \text{eus, } \nu_e ds, K^\pm e^\mp$

$\lambda'_{121}$ for production; $\lambda'_{131}$ for decay.
Milli-charged particles

- milliQan
- MAPP-mQP
Proof of concept: ~1% prototype of the full detector: the milliQan demonstrator

- Background characterization
- New sensitivity for $m(mCP) > 600$ MeV

- Scintillator bars give sensitivity to small energy deposits
  - requiring in-time deposit in each layer in line-of-sight yields a strong veto
- Scintillator panels surrounding all sides of each stack identify muons and other backgrounds

Full-scale milliQan will be 4-layer, composed bundles of 2×2 bars. 9×6 bundles will form the full detector
The MAPP-mQP detector

- **100 × (10 cm × 10 cm × 75 cm) scintillator bars** in 4 lengths, 2 lengths/section readout by 4 low noise 3.1” PMTs, in coincidence
- No background from dark counts and radiogenic backgrounds
- Calibration by pulsed blue LEDs + neutral density filter

Prototype mQP installed in 2017
- 3×3 bars (~30×30 cm)
- ~10% of full detector
Millicharged particles in dark QED

Dark photon $A'$ couples to a massive dark fermion “milli-charged” $\psi$

MAPP-mQP & milliQan expect low mass (0.1-1 GeV) sensitivity to mCP with $Q = 3 \times 10^{-3} e$
Heavy neutrino with large EDM

- In several models (e.g. multiple-Higgs, flavor symmetry, leptoquarks, etc.) the electric dipole moment (EDM) of leptons scales like $m_\ell^3$
- New heavy neutrinos give rise to anomalously large EDMs → energy deposited via photons in the mQP scintillator

\[
\mathcal{L} = \mathcal{L}_{SM} + \bar{N}(i\gamma^\mu - M)N + ieD\bar{N}\sigma_{\mu\nu}\gamma_5NF^{\mu\nu} + ieD\tan\theta_w\bar{N}\sigma_{\mu\nu}\gamma_5NZ^{\mu\nu} + \frac{e}{2\cos\theta_w \sin\theta_w}Z^0_L\bar{N}\gamma^\mu N_L
\]

The heavy neutrino is assumed to be detected if it gives rise to ≥100 photons in each of the 4 sections of the detector

Ever increasing interest in long-lived particle searches at the LHC (and not only...) including the dark sector

- 7th workshop of the LHC LLP Community ☞ this week!

New ideas for additional complementary LHC experiments proposed or under construction

- FASER, MoEDAL-MAPP – aiming at start data-taking in Run3 (2021)
- MATHUSLA, CODEX-b, milliQan – expressions of interest and/or demonstrators
- ANUBIS, AL3X – new proposals

Several experiments have constructed/taken data or plan to build small-scale demonstrators to measure backgrounds and provide proof-of-concept

A different perspective – the **long lifetime** – on the dark sector is expected for LHC Run 3 and beyond
Thank you for your attention!
Spares
AL3X – A Laboratory for Long-Lived eXotics

- Reuse the L3 magnet and (perhaps) the ALICE TPC
- Use thick shield with active veto to reduce the backgrounds

AN Underground Belayed In-Shaft search experiment

- Existing geometry allows for minimal civil engineering costs
- Projective decay volume optimises acceptance for different lifetimes
- Four evenly spaced tracking stations with a cross-sectional area of 230 m² each
- Possible detector technology: Resistive Plate Chambers

Beyond LHC: beam-dump, neutrino, ... experiments

Ahdida et al, 2019 JINST14 P03025

+ many more ...
FASER location: TI12

Digging ~50cm deep trench needed to allow 5m long detector to be aligned with LOS
MAPP – MoEDAL Apparatus for Penetrating Particles

- Two subdetectors for two classes of particles
  - MAPP-LLP: new pseudo-stable weakly interacting neutral particles with long lifetime with the detector
  - MAPP-mQP: particles with charges $\ll 1e$
- Positioned at an angle of 5° w.r.t. beam axis
- Protected from cosmics by 100 m of rock overburden + active veto system
- Protected by 25-26 m of rock/concrete + forward veto from SM particles coming from IP8
- To be installed for LHC Run-3
- TDR in preparation

Jim Pinfold’s talk on MoEDAL in afternoon “Upgrades & Future: Smaller LHC Experiments” session
The MAPP-LLP detector

- “Box-within-a-box” or “Russian Doll” structure to detect charged tracks from neutral-particle decay
- The readout structure are scintillator strips in an x-y configuration readout by SiPMs
  - resolutions ~1cm × 1cm on each hit
- Using SiPM, fast scintillator and picoTDC chips MAPP plan to have 500 ps or better timing resolution
**MALL – MoEDAL Apparatus for very Long Lived particles**

- After exposure and SQUID scan, MoEDAL MMTs will be monitored for decaying *electrically charged* particles that may have been trapped in their volume
  - ATLAS & CMS similar analyses in empty bunch crossings for trapped R-hadrons decaying into jets
- Sensitive to charged particles (e, μ, had.) and to photons with energy as small as 1~GeV
- MALL planned to be installed during Run-3 at the UGC1 gallery of IP8

Estimated MALL probed lifetimes ~10 yrs
MALL – physics example

- **SuperWIMP model for cold dark matter, WIMP -> S + SWIMP**
  - S: SM particle, SWIMP=\sim G
- **SuperWIMP particles naturally inherit the desired relic density** from the late decays of metastable WIMPs & may explain the observed lithium under-abundance
- **For example,** a charged slepton NSLP in this scenario the lifetime of a \sim 150 GeV stau decaying to a \sim 100 GeV gravitino is $O(10^9 \text{ s})$ i.e. $O(10 \text{ yr})$

\[ \tilde{\tau} \rightarrow \tau \tilde{G} \]
Millicharged particles in dark QED

- Introduce new, hidden U(1) with a massless field $A'$, a “dark photon” that couples to a massive “dark fermion” $\psi'$

$$\mathcal{L}_{\text{dark-sector}} = -\frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} + i \bar{\psi}' (\gamma^\mu \partial_\mu + ie' \gamma^\mu A'_\mu + i M_{\text{mCP}}) \psi' - \frac{\kappa}{2} A'_\mu B^{\mu\nu}$$

- $\psi'$ has mass $M_{\text{mCP}}$, charge under the new U(1) of $e'$ and field strength $A'_{\mu\nu}$
- $\psi'$ couples to $\gamma$ and $Z$ with $\kappa e' \cos \theta_W$ & $-\kappa e' \sin \theta_W$, respectively
- $\psi'$ acts as a field with a charge of $ke' = e/\cos \theta_W \ll 1$ in milli-charge

Milli-charged particles are a natural consequence of extra U(1) with massless gauge field

MAPP-mQP construction started

MAPP-MALL preparation area

MAPP-mQP support structure being machined at the University of Alberta
MAPP-2 – for High Luminosity LHC

Dark Higgs scenario

- MAPP-1 (300 fb⁻¹)
- MAPP-2 (1 ab⁻¹)
- MATHUSLA (3 ab⁻¹)