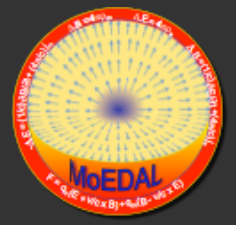


Physics Performance Benchmarks For The New MoEDAL-MAPP Detector

2020 Virtual CAP Congress, PPD Energy Frontier

Tuesday, June 9 2020

Supervised by: James Pinfold & Jack Tuszynski

Michael Staelens (On Behalf of the MoEDAL Collaboration) staelens@ualberta.ca

Studying Dark Matter and CP-Violation with the New MoEDAL-MAPP detector

via exotic new physics @ the LHC! :)

Overview

MoEDAL (Monopole & Exotics Detector @ LHC)

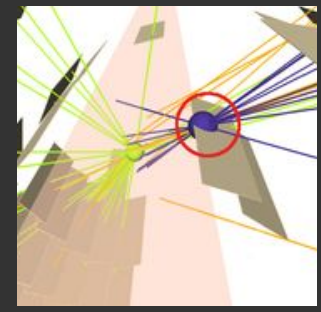
A Quick Overview

MAPP (MoEDAL's Apparatus for Penetrating Particles)

Upgrading MoEDAL into a multi-purpose detector

mini-Ionizing Particles (mIPs) @ MoEDAL

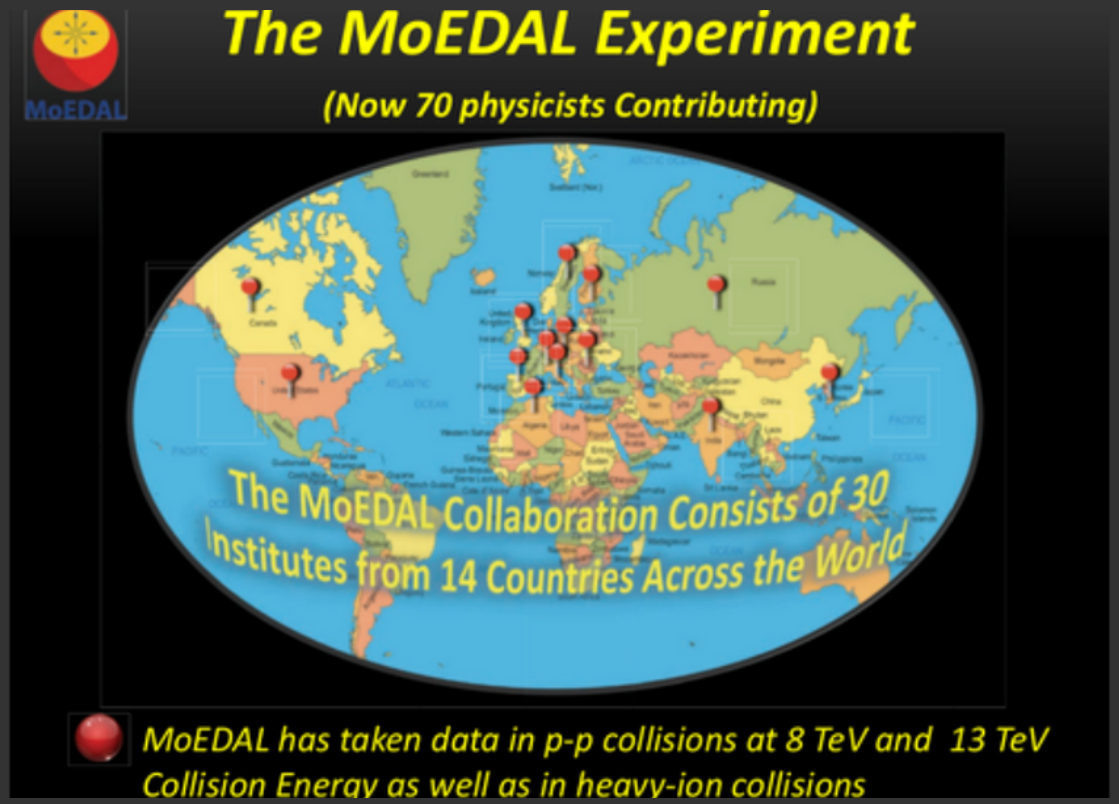
Sensitivity of MAPP to Mini-Charged Particles & Heavy Neutrino EDMs

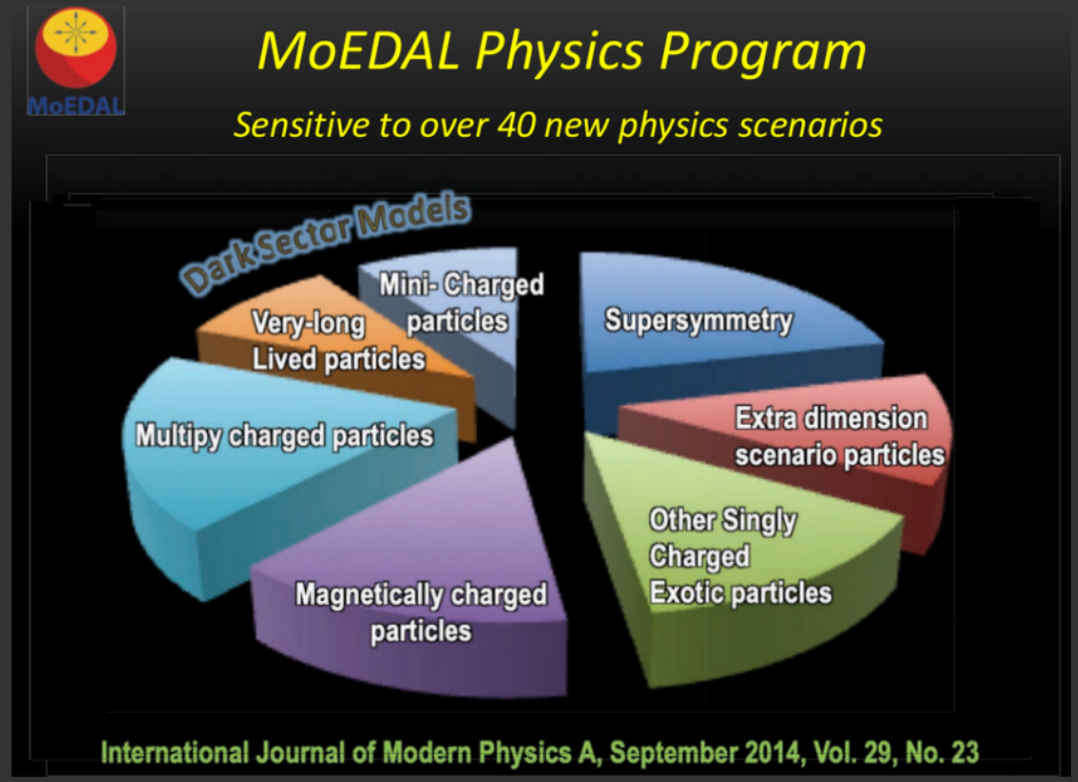


Long-Lived Particles (LLPs) @ MoEDAL

Sensitivity of MAPP to a Long-Lived New Light Scalars/Vectors (mixed w/ SM Higgs)

The Monopole and Exotics Detector at the LHC



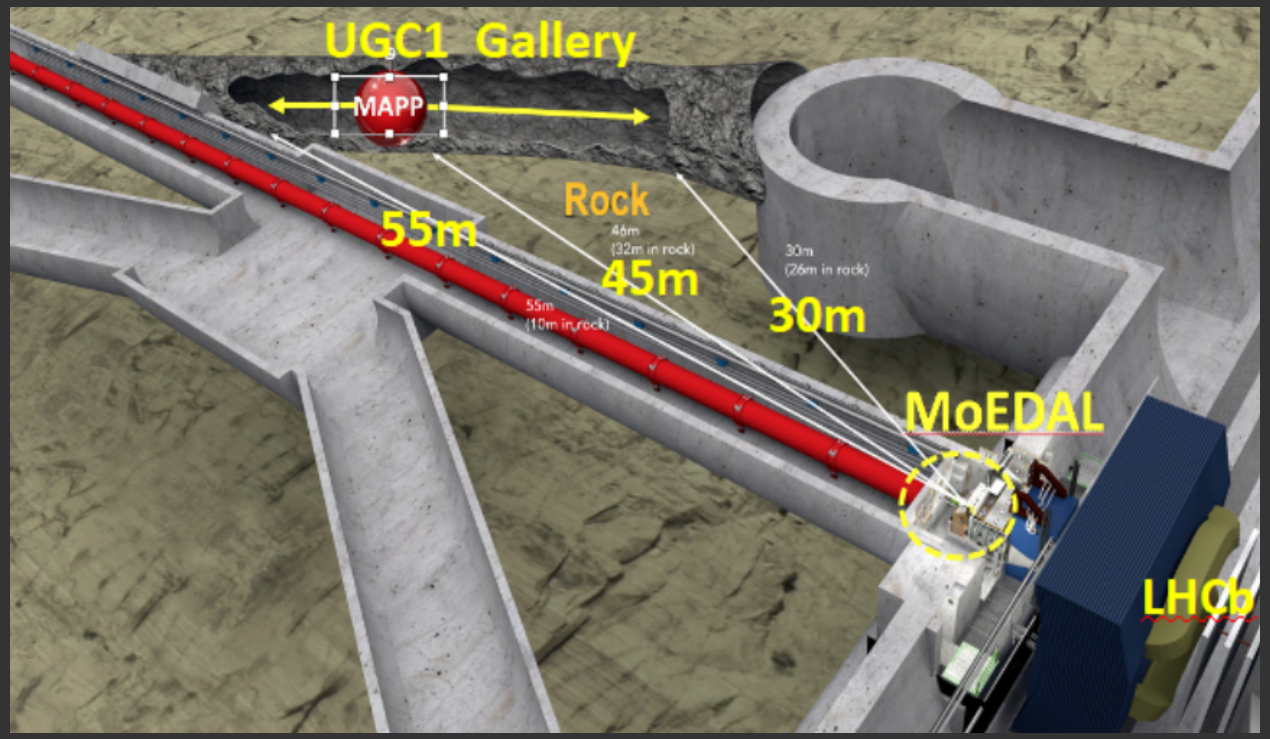


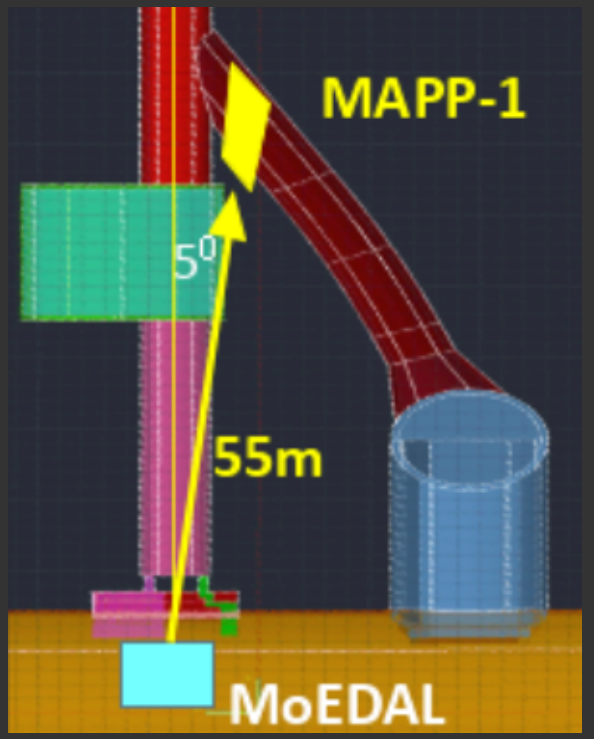
N.B. This is MoEDAL's program, including MAPP (Dark Sector Models).

Upgrading MoEDAL:
The MAPP Detector

(MoEDAL Apparatus for Penetrating Particles)

MAPP-1: Location @ The LHC

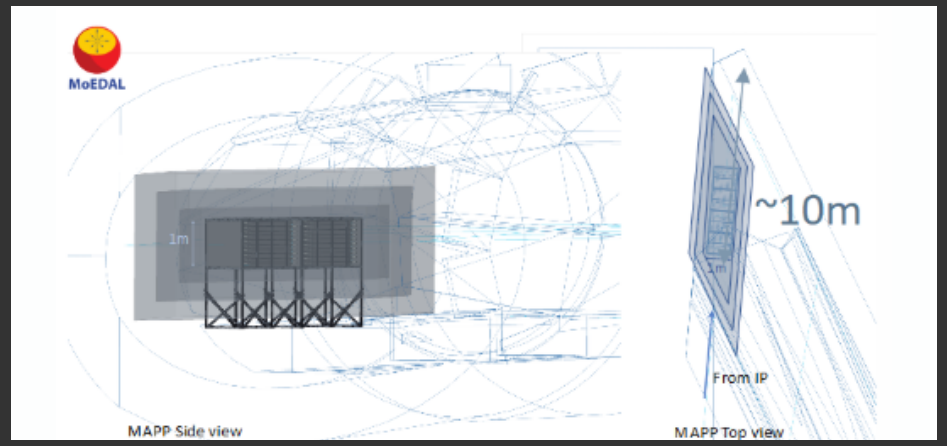


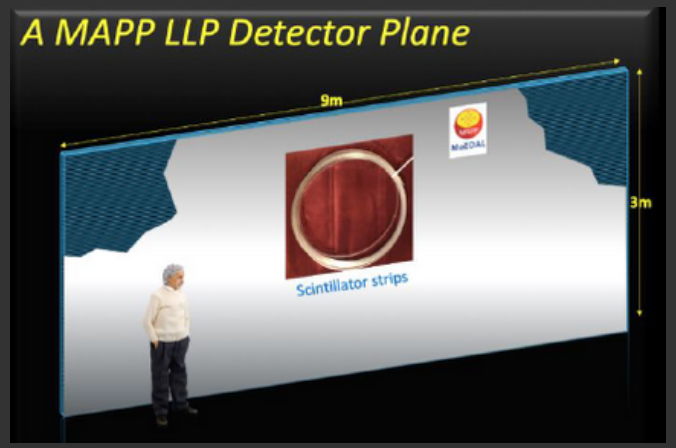


MAPP-1 will be placed at the position 5 degrees from the beam line shown here.
For the remainder of this talk, all results and plots shown use this position.

MAPP - MoEDAL Apparatus for Penetrating Particles

A scintillation based active detector which aims to search for new anomalously penetrating particles.





- Search for fractionally charged particles (q<<1e) (MAPP-mCP) (1m x 1m x 3m)

  Note: Atlas and CMS are limited to ~e/3 or greater.

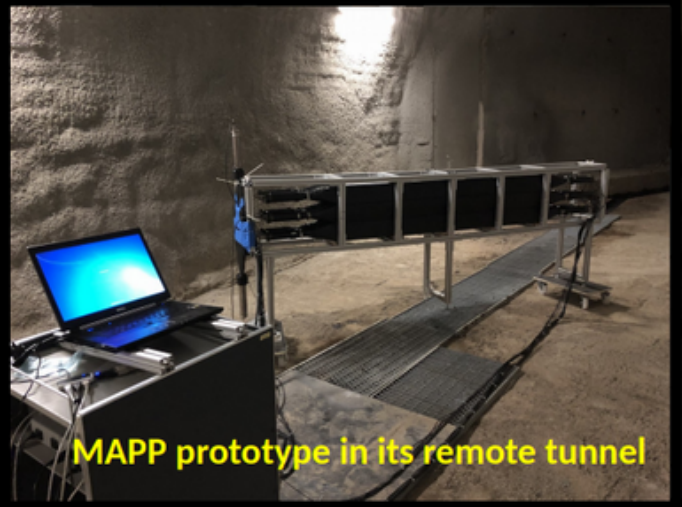
- Search for new pseudo-stable neutral particles with long lifetimes (MAPP-LLP) (5m x 3m x 9m)

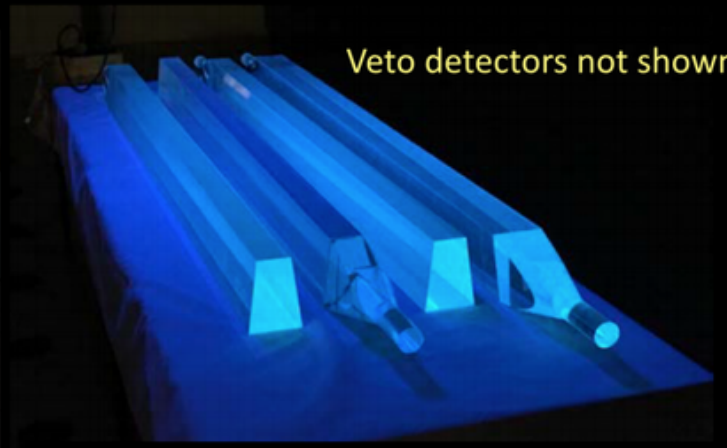
  Nested Fine Grain Hodoscope Detector Planes with SiPMs arranged along the planes. **Timing resolution of ~500 ps & spatial resolution of ~1cm.** Full efficiency study is currently underway.

- MAPP-mCP is planned for deployment in 2021, at the start of the LHC's Run-3

  Deployment of MAPP-LLP will be phased throughout RUN-3.

The MAPP Prototype Installed in 12/2017


MAPP prototype in its remote tunnel

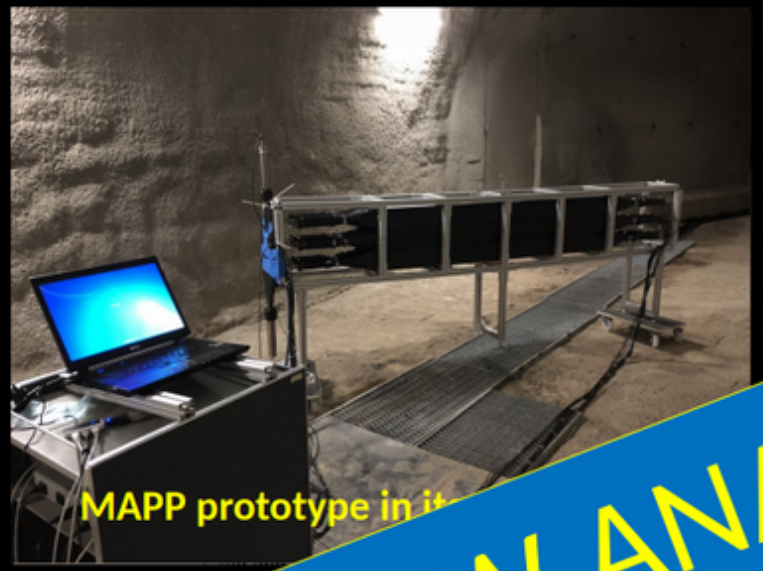


Electronics

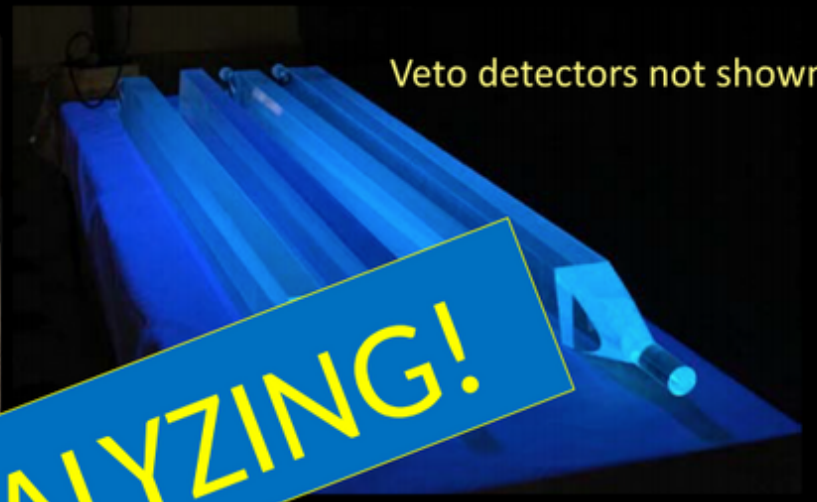

MAPP prototype in its remote tunnel

Acquired several fb-1 of data during LHC's Run-2

The MAPP Prototype Installed in 12/2017



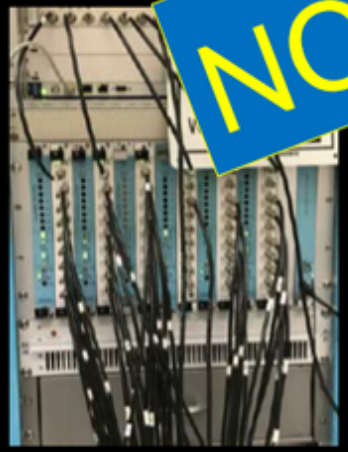
MAPP prototype in it



Veto detectors not shown

NOW ANALYZING!

Electronics



MAPP prototype in its remote tunnel

MAPP-1
LHC Physics Performance

MAPP: Establishing Physics Benchmarks

1. Explore BSM scenarios from various theories and models that MAPP may be sensitive to.

2. Implement models into various MC Event generator SW. (Madgraph5, Pythia8)

3. Validate model using a combination of analytic & numeric calculations and the literature available.

   Fix model if necessary and test again..

4. Finally, generate N ~ L * σ Monte-Carlo events with the validated model and, simulating the MAPP detector, establish 3 hit sensitivity (95% C.L.) limit curves over the parameter space of interest.

   Cuts may also be placed throughout this process.

MAPP-mCP

Mini-Ionization @ The LHC via Heavy Neutrino EDMs

Motivation: Matter/AntiMatter Asymmetry

CP-Violation and Electric Dipole Moments

- The observed matter-antimatter asymmetry in the universe suggests a significant amount of CP violation in the universe.

  While the weak interactions in the SM may violate CP, the amount of CP violation is still small. **Is there any CP violation present in QED/QCD?**

- The generation of EDMs of neutral leptons requires CP violating processes.

  A simple way to incorporate CP-violation into QED/QCD.

- In many models, such as the MSSM, EDMs of leptons scale linearly with the mass.

- However, in a number of models, such as some multiple-Higgs, leptoquark, and flavor symmetry models, the EDM scale as the cube of the lepton mass.

  There is some model dependence here, and it is KEY that the neutrino be heavy; to yield sizeable EDMs accessible to MAPP (and sizeable CP-violation).

New Heavy Neutrinos with Large EDMs: Model

We add one vector-like doublet (w/ LH and RH components) and its mirror to the SM lepton REPns.
We are particularly interested in the interaction of neutrinos (new neutral Dirac fermions) in the model.

The following effective Lagrangian is used to cast a wide net in modeling the heavy neutrinos,

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{N}(i\partial\!\!\!/ - M)N + ieD\bar{N}\sigma_{\mu\nu}\gamma_5 NF^{\mu\nu}$$
$$+ ieD\tan\theta_w \bar{N}\sigma_{\mu\nu}\gamma_5 NZ^{\mu\nu} + \frac{e}{2\cos\theta_w \sin\theta_w} Z^0_\mu \bar{N}_L \gamma^\mu N_L$$

- eD is the magnitude of the EDM in units of [e*cm]

  We use 10^-15 e*cm as our upper bound (set by unitarity & mass range).

- N is the field describing the new, non-SM heavy neutrino

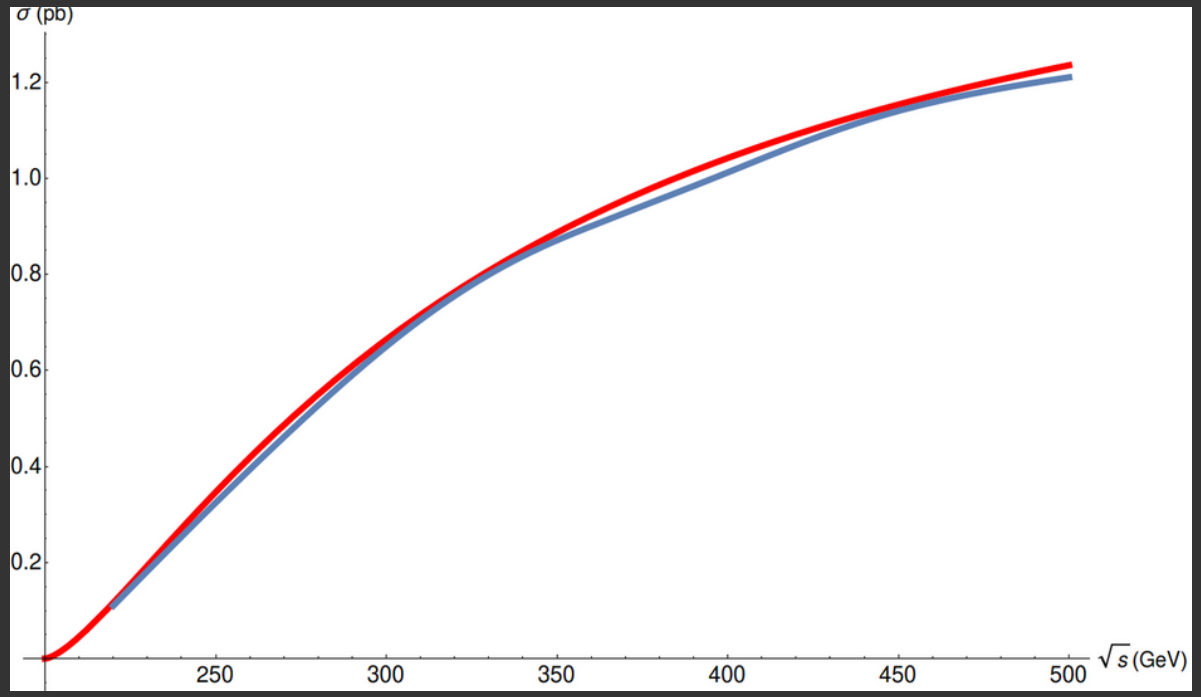
  Z and A are the usual gauge fields for the Z boson and photon.

Heavy Neutrinos with Large EDMs: Model Validation

Comparison **of e+ e–** heavy neutrino production cross section in MadGraph (blue) with analytic expressions (red).

$$\mathscr{L}_{\text{interaction 1}} = ieD\bar{N}\sigma_{\mu\nu}\gamma_5 NF^{\mu\nu}$$

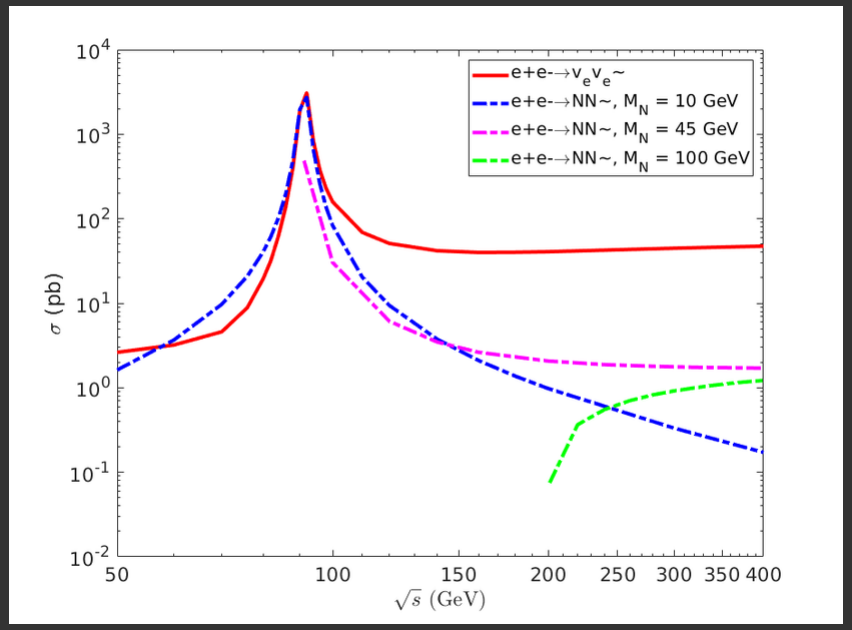
$$\left(\frac{d\sigma}{d\Omega}\right)_\gamma = \frac{1}{4}\alpha^2 D^2 \left(1 - \frac{4M_N^2}{s}\right)\sqrt{1 - \frac{4M_N^2}{s}}\sin^2\theta$$



Heavy Neutrinos with Large EDMs: Model Validation

Comparison of heavy neutrinos (dashed) with SM neutrinos (solid) for e+e- -> NN. The blue, magenta, and green curves correspond to MN = 10, 45, and 100 GeV respectively.

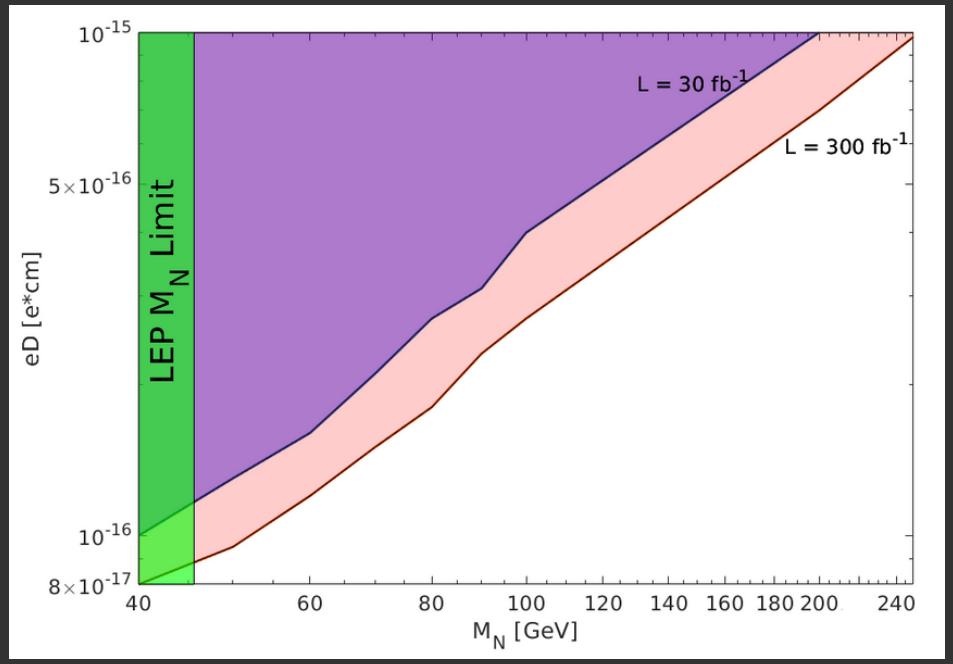
$$\mathscr{L}_{\text{interaction 2}} = \frac{e}{2\cos\theta_W \sin\theta_W} Z^0_\mu \bar{N}_L \gamma^\mu N_L$$



Taking the heavy neutrino mass to 0 recovers the SM neutrino behavior.

Sensitivity of MAPP-1 to Heavy Neutrino EDMs

Considering Drell-Yan pair production (pp --> NN~) of heavy neutrinos at a COM Energy of 14 TeV.



Compared to the usual Bethe Formula, the Ionization Energy loss profile of a neutral particle EDM is different.

$$\left\langle \frac{dE}{dx} \right\rangle = \pi N Z \frac{e^2}{4\pi\epsilon_0} D\gamma$$

N.B. We assume that the heavy neutrino could be detected due to its EDM if it gives rise to **100 photons or more in each of the 4 sections of the detector for a total of at least 400 photons**.

To convert energy deposition into number of photons in the scintillator we assume that **10000 photons are produced per MeV** of energy deposited in the plastic scintillator.

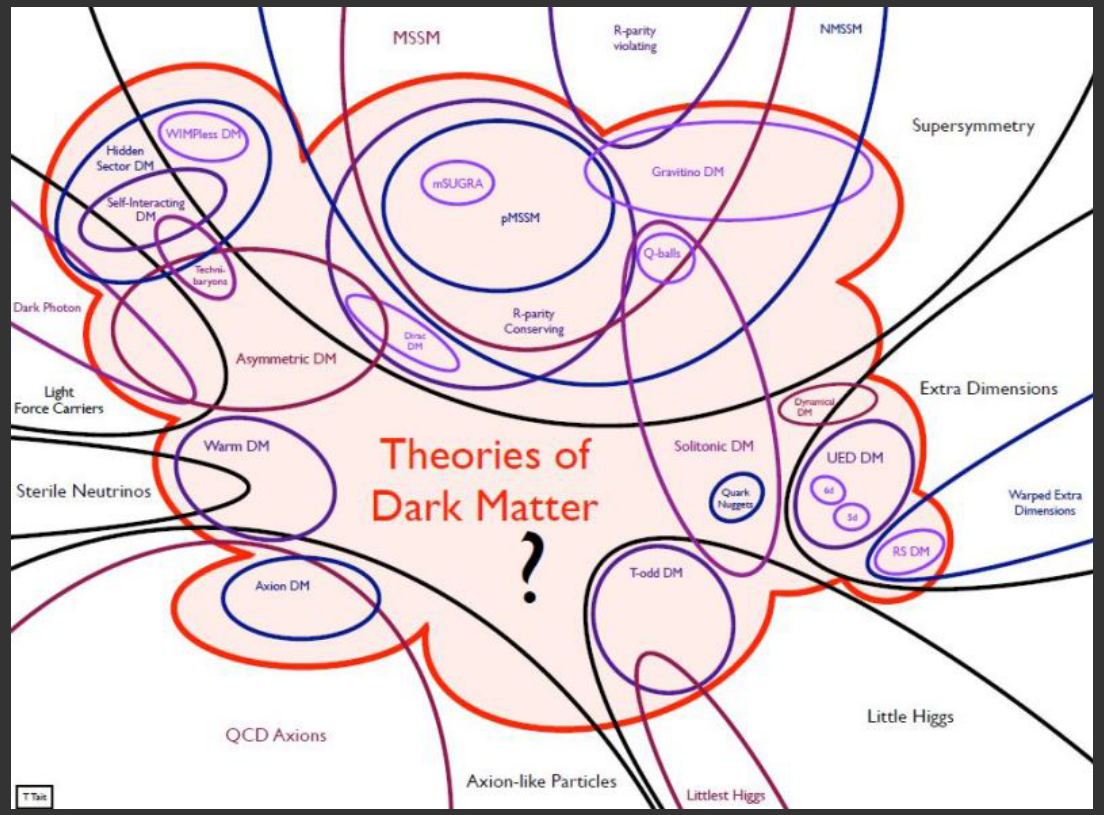
Tracking efficiency is assumed to be 100% for ease of comparison.

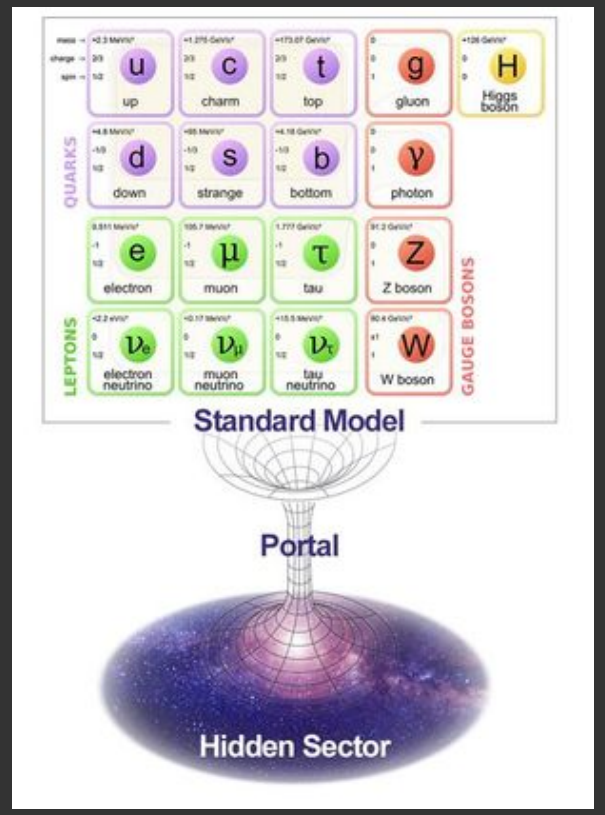
MAPP-LLP

Long Lived Particles at the LHC

Motivation: DM & Hidden Sectors

Portal Models





- Vector-Like Portal
  $\epsilon_\gamma A^{\mu\nu} A'_{\mu\nu}$
- Higgs/Scalar Portal
  $\epsilon_h |h^2||\phi^2|$
- Neutrino Portal
  $\epsilon_\nu L h \psi$

Long-Lived New Light Scalar (Dark Higgs)

Here the portal between the dark sector and SM is given by a new scalar particle S, coupled to the SM Higgs. A possible Lagrangian including this new dark Higgs is given by:

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

Mixing occurs between SM Higgs and dark scalar via S^2 term. The resulting physical fields are the SM Higgs and a scalar particle ϕ, the dark Higgs.

Arxiv: 1811.12522

Long-Lived Dark Higgs

This coupling between the SM Higgs and dark Higgs induces new Yukawa-like couplings between SM fermions and the dark Higgs. Can write this effective Lagrangian as

$$\mathscr{L}_{eff} = -m_\phi^2\phi^2 - \sin\theta\frac{m_f}{v}\phi\bar{f}f - \lambda v h\phi\phi + ...$$

We look at dark Higgs production in rare B decays:

$B \to k\ \phi$

The signal in MAPP is a charged lepton from dark Higgs decay, $\phi \to l+l-$, hitting at least 2 consecutive planes.

Arxiv: 1811.12522

Long-Lived Dark Higgs

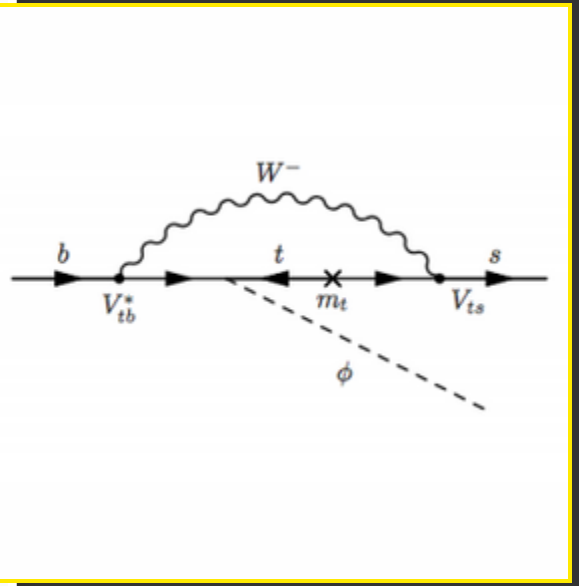
This coupling between the SM Higgs and dark Higgs induces new Yukawa-like couplings between SM fermions and the dark Higgs. Can write this effective Lagrangian as

$$\mathscr{L}_{eff} = -m_\phi^2\phi^2 - \sin\theta\frac{m_f}{v}\phi\bar{f}f - \lambda v h\phi\phi + \ldots$$

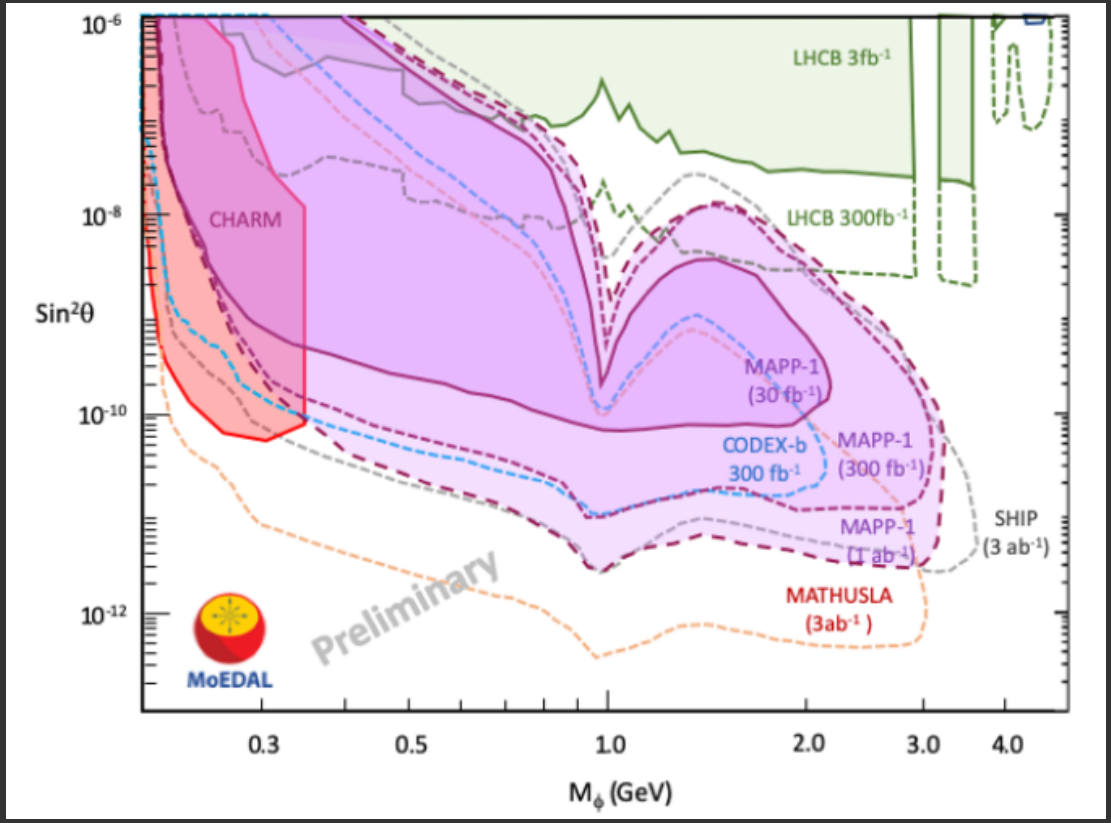
We look at dark Higgs production in rare B decays:
$B \to k\ \phi$

The signal in MAPP is a charged lepton from dark Higgs decay, $\phi \to l+l-$, hitting at least 2 consecutive planes.

Arxiv: 1811.12522



Sensitivity of MAPP-1 Long-Lived Dark Higgs (95% C.L.)



For ease of comparison, here we assume 100% tracking efficiencies. (Estimates currently place MAPP-1's tracking at ~80% efficiency.)

Conclusions & Future Directions

- In both cases MAPP-1 can place new constraints on significant portions of unexplored parameter space.
- MAPP's Sensitivity to other models has also been established: Dark Photon/Vector Portal (Pre-lim), Heavy Neutral Leptons (HNLs), and minicharged particles (mCPs).

  Study of Axion-Like Particles (aLPs) to come later this year.
- Full Analysis & Simulation of the Background @ MAPP-1 is a WIP.

  Full GEANT4 Model of the detector and surrounding region + materials is now completed. This study will also come later this year.

Thank you!

NSERC
CRSNG

Canadian Association
of Physicists

Association canadienne
des physiciens et physiciennes