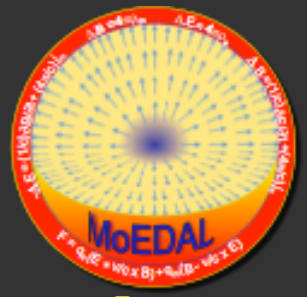


The MoEDAL-MAPP Detector: Physics Performance Benchmarks

2020 Winter Nuclear and Particle Physics Conference. Banff, Alberta.

Friday, February 14 2020

Supervised by: James Pinfold & Jack Tuszynski

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

Shedding Light on the Dark Sector with the New MoEDAL-MAPP Detector

Overview

MoEDAL (Monopole & Exotics Detector @ LHC)

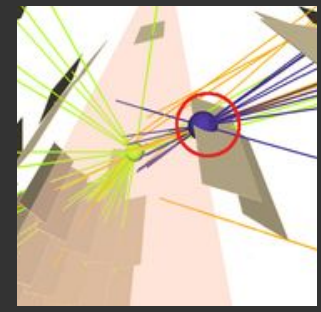
A Brief Overview

Upgrading MoEDAL into a multi-purpose detector

MAPP (MoEDAL's Apparatus for Penetrating Particles)

mCPs @ MoEDAL

Sensitivity of MAPP to Mini-Charged Particles in Dark QED



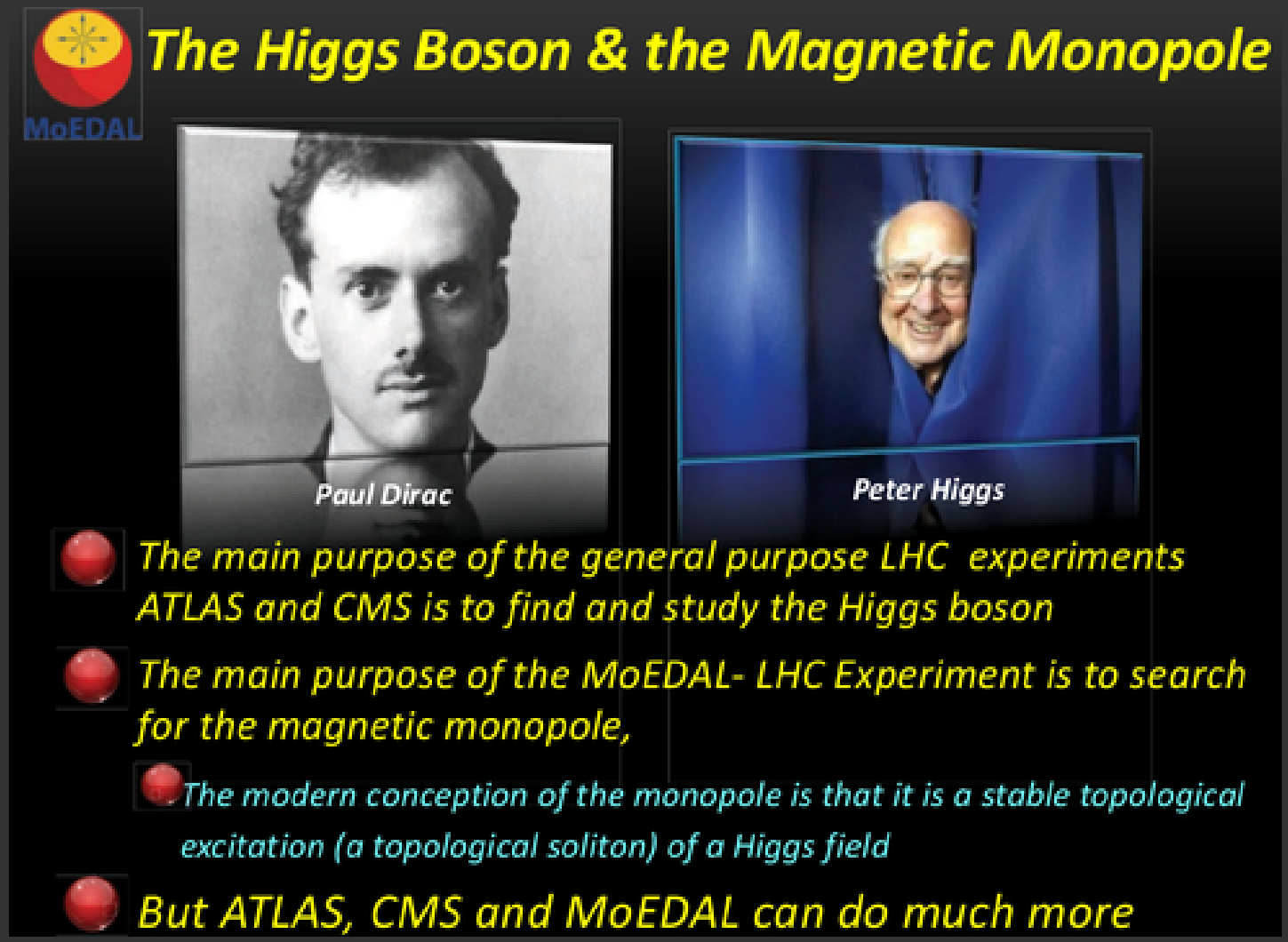
LLPs @ MoEDAL

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

The MoEDAL Experiment

(Now 70 physicists Contributing)

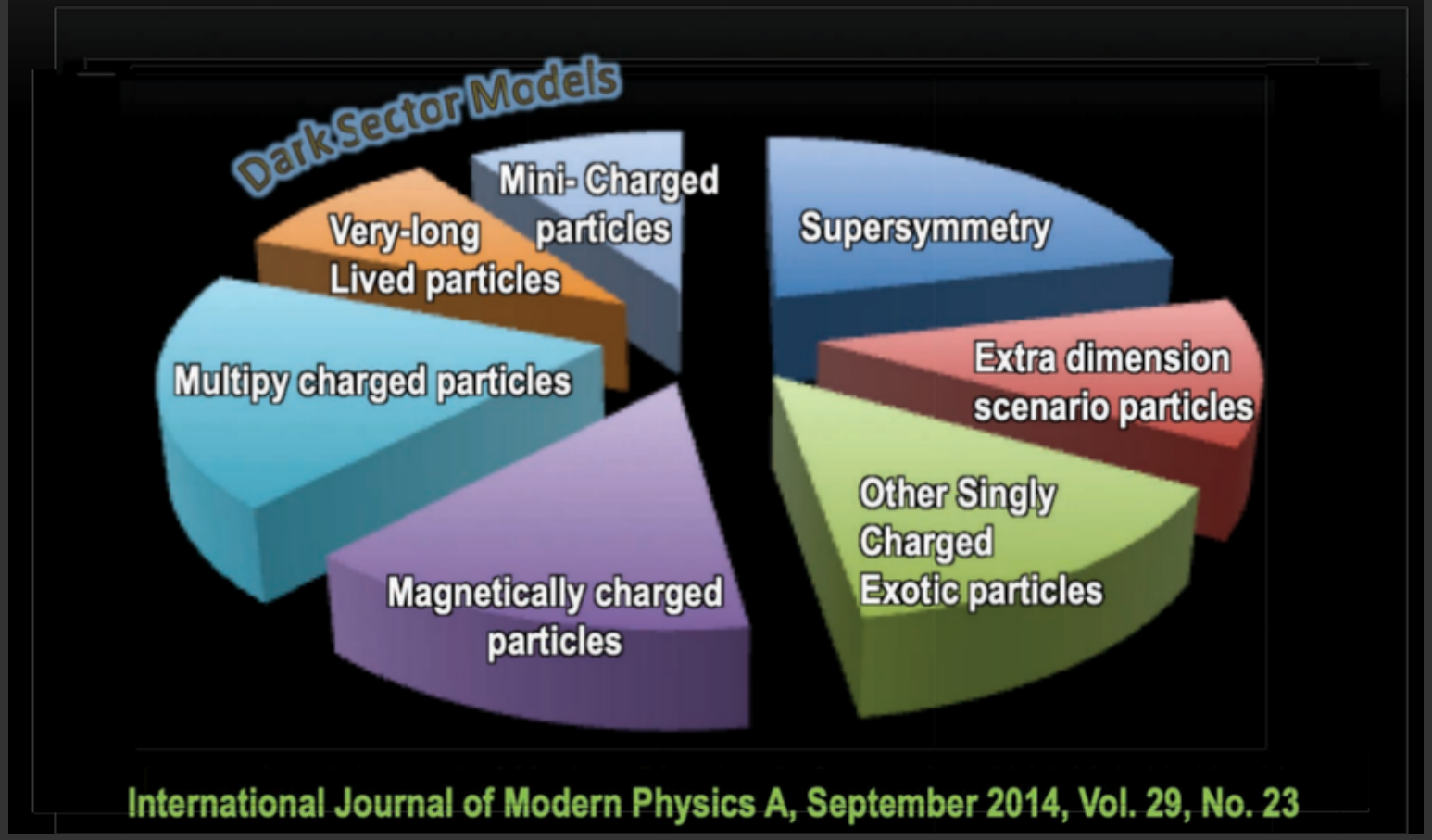
MoEDAL has taken data in p-p collisions at 8 TeV and 13 TeV Collision Energy as well as in heavy-ion collisions



Recent calculations predict a MM mass on the order of *a few TeV!*
(c.f. “The Price of an EW Monopole”, J. Ellis, N. Mavromatos, T. Yu)

MoEDAL Physics Program

Sensitive to over 40 new physics scenarios

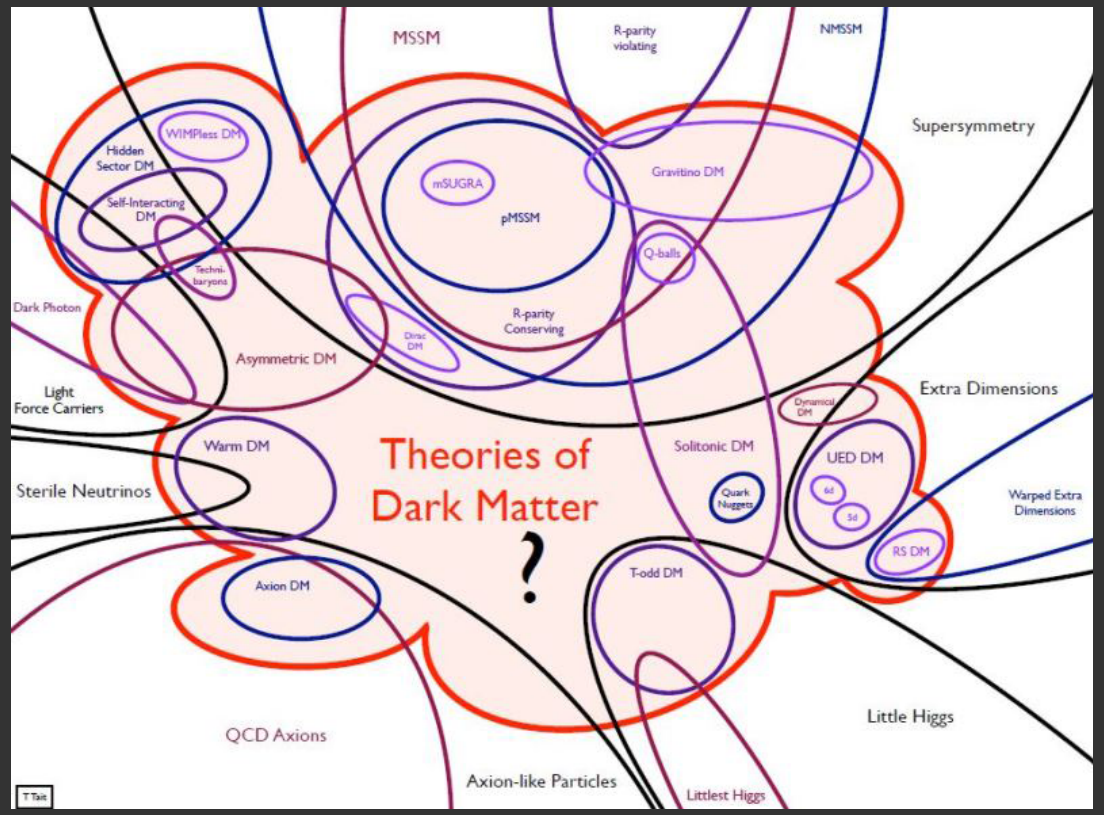


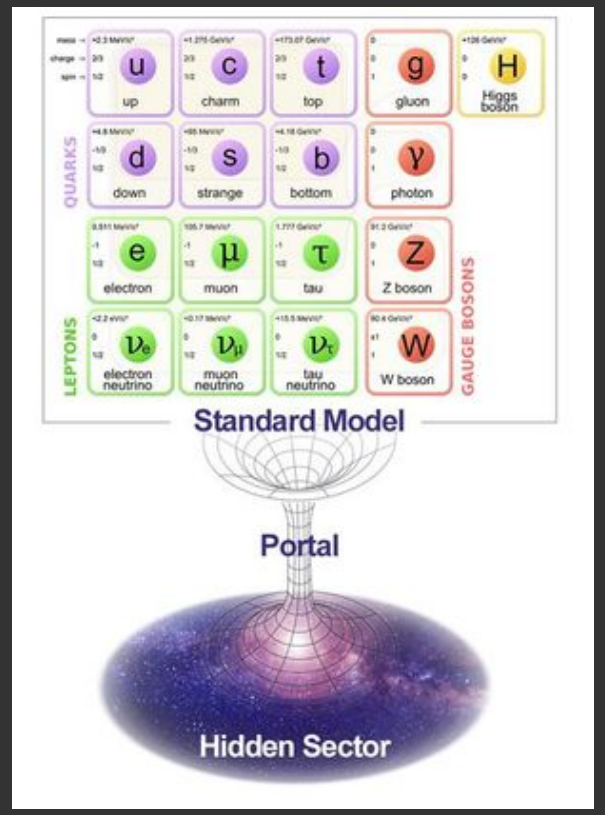
N.B. This is MoEDAL's program, including MAPP.

Upgrading MoEDAL:
The MAPP Detector

(MoEDAL Apparatus for Penetrating Particles)

Motivation: DM & Hidden Sectors





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

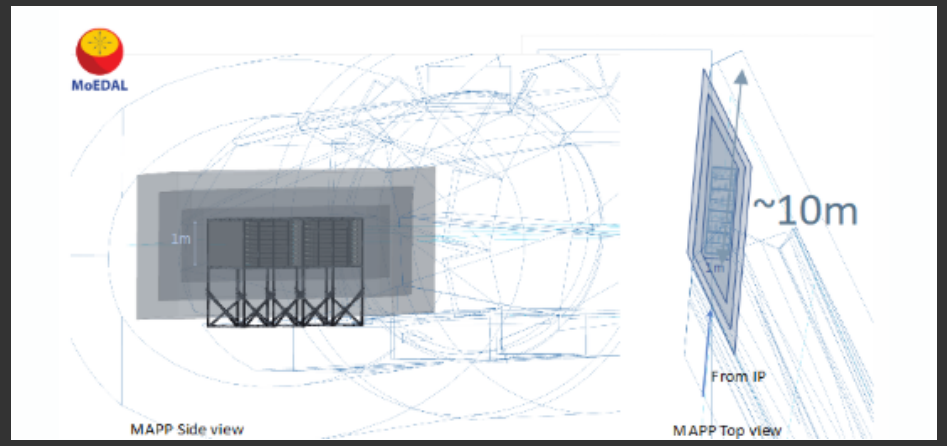
The Present Physics Program of MAPP

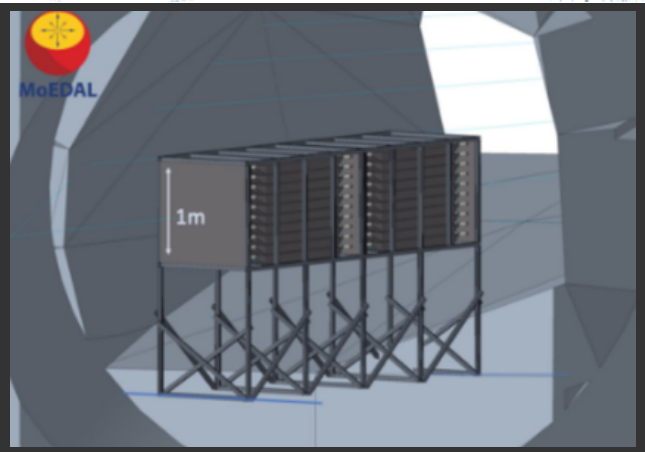
Physics Model	Signal	**MAPP-1 Run-3** (30fb^{-1})	**MAPP-1 HL-LHC** (300fb^{-1})	**MAPP-2 HL-LHC** (300fb^{-1})
mCP in Dark QED	Frac. Ionization	✓	✓	✓
Heavy Neutrinos with a Large EDM[1]	Anomalous Ionization	✓	✓	✓
LL Dark Photon	Decay $A' \to l^+l^-$	✗	?	?
LL Dark Higgs	Decay $\phi_h \to l^+l^-$	✓	✓	✓
LL RH Majorana Neutrinos in $Z_{(B-L)}$[2]	$N \to l + l-$	✗	✓	✓

1 - Phys. Lett. B Vol. 802, 10 March 2020, 135204 (https://arxiv.org/abs/1909.05216)
2 - https://arxiv.org/abs/1905.11889

MAPP - MoEDAL Apparatus for Penetrating Particles

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



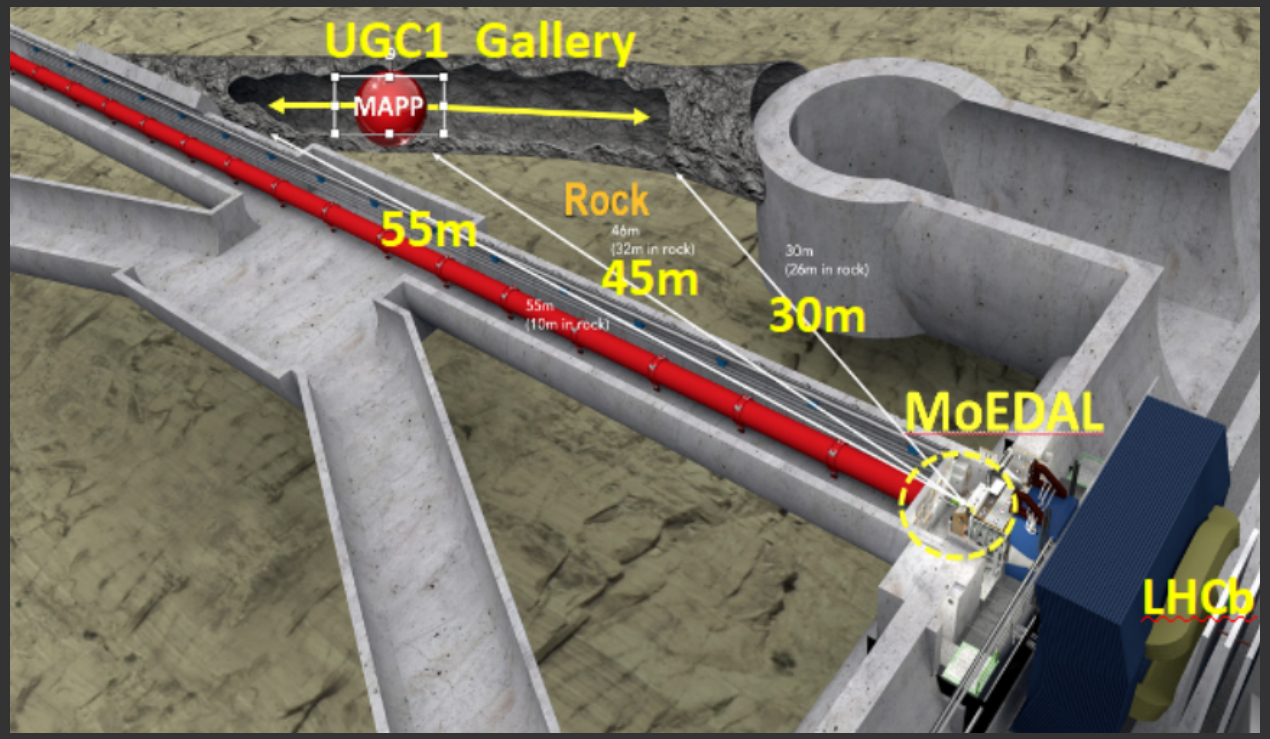


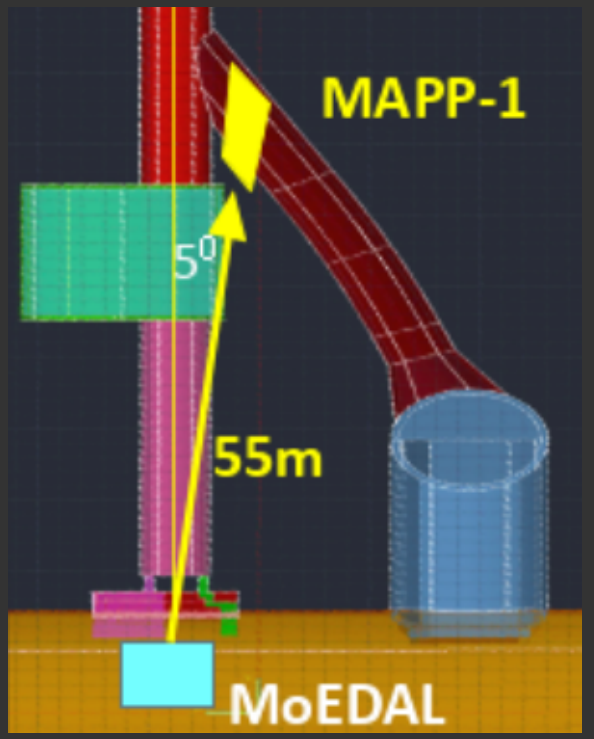
- Search for fractionally charged particles (q<<1e) (MAPP-mCP)

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

- Search for new pseudo-stable neutral particles with long lifetimes (MAPP-LLP)

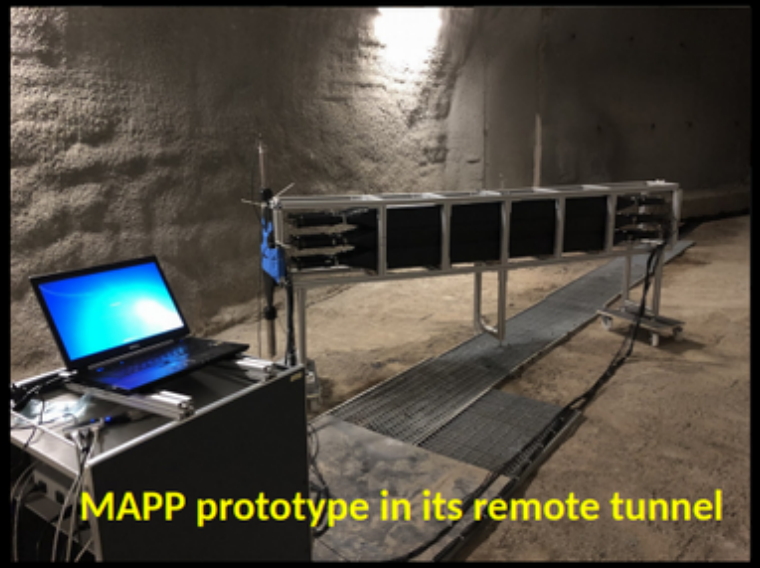
MAPP-1 Location @ The LHC

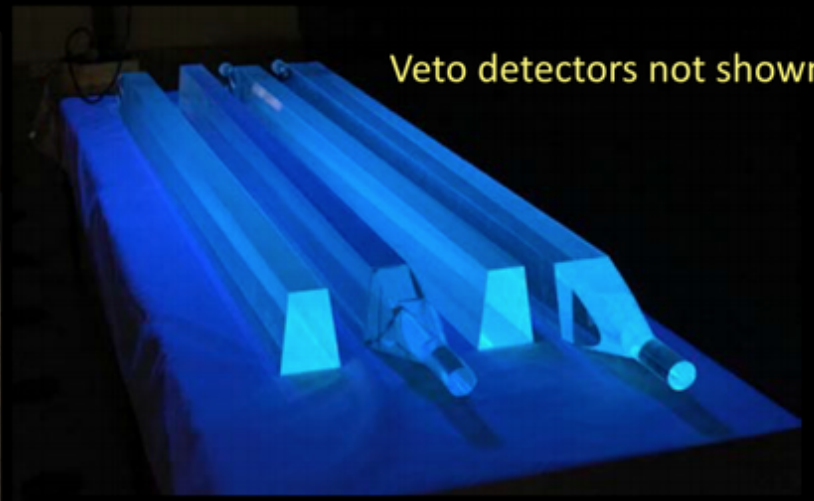




MAPP-1 will be placed at the position 5 degrees from the beam line shown here.
For the remainder of this talk, all results and plots shown use the position.

The MAPP Prototype Installed in 12/2017

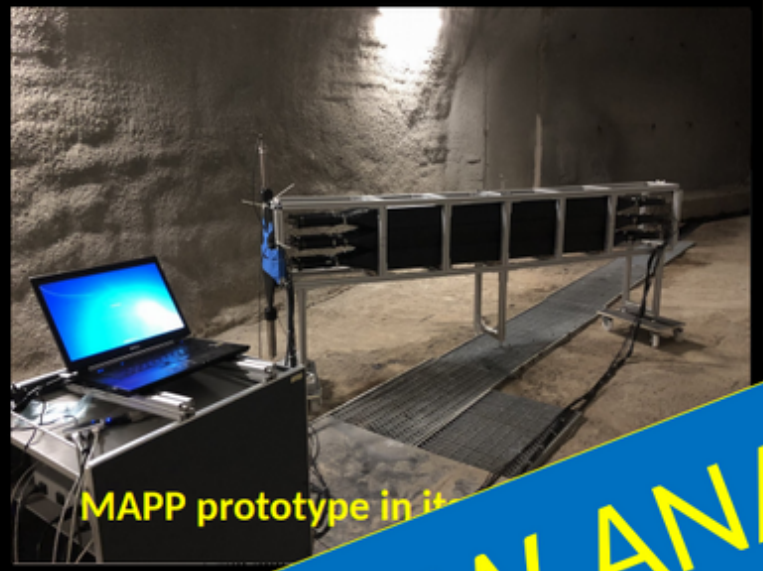

MAPP prototype in its remote tunnel


Veto detectors not shown

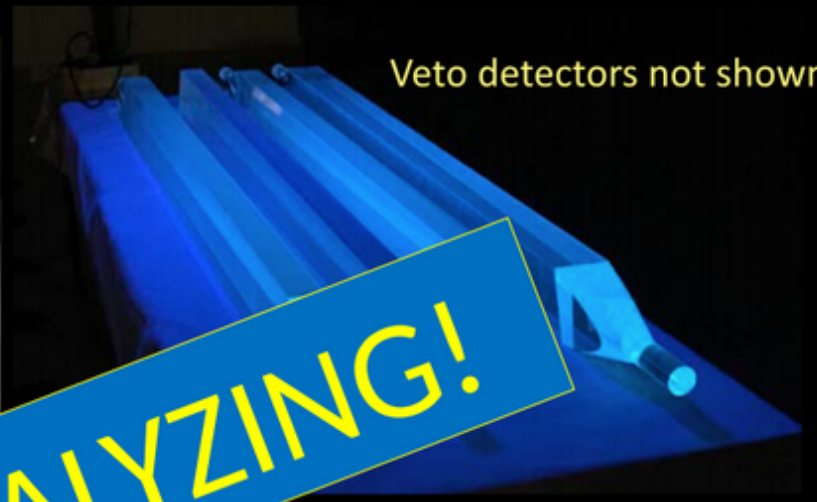
Electronics


MAPP prototype in its remote tunnel

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
Physics Performance

MAPP: Establishing Physics Benchmarks

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

2. Create MadGraph5 model using Mathematica + FeynRules. (.fr --> ufo files)

3. Implement model into MadGraph5 OR Pythia8 if hadronization is also required.

4. Validate model using a combination of analytic\numeric calculations and the literature available.

   Fix model if necessary and test again..

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

Mini-Charged Particles (mCP) in Dark QED

Dark QED scenario Introduce an extra U(1) gauge field,

A' that mixes with the SM U(1) gauge group. Reformulate this such that the new Dirac fermion ψ couples to the U(1) hypercharge gauge field.

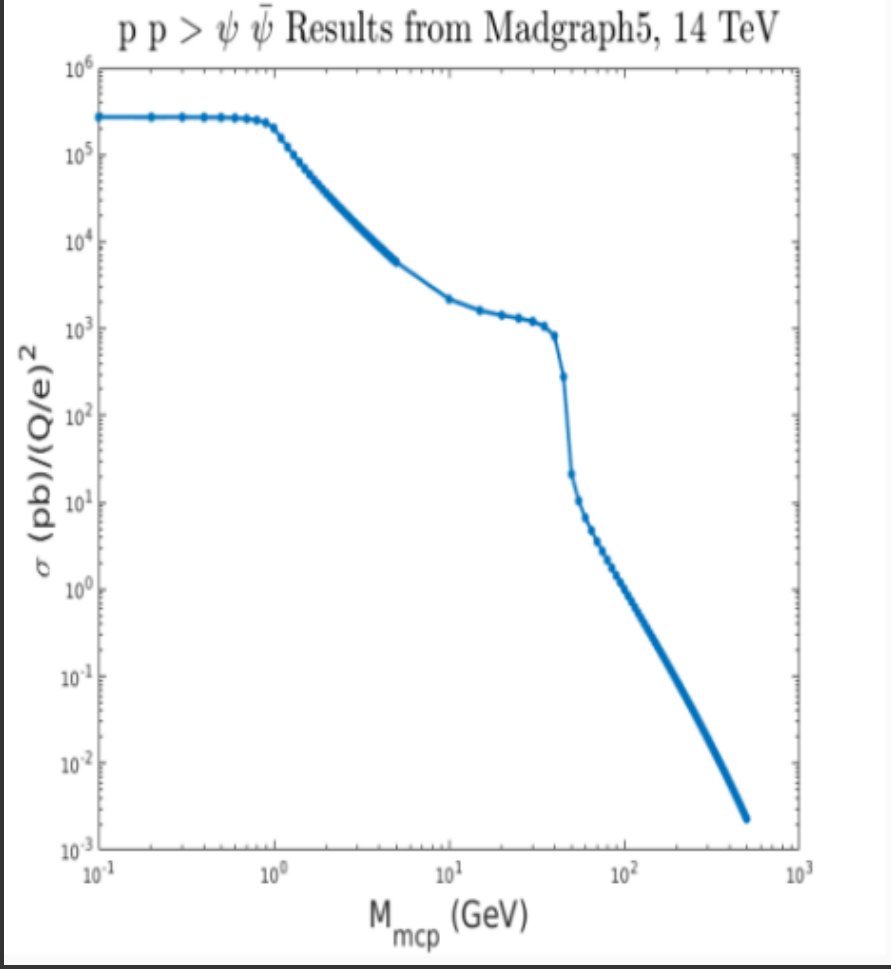
$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} + i\bar{\psi}(\partial\!\!\!/ + ie' A\!\!\!/' - i\kappa e' B\!\!\!/ + iM_{mcp})\psi$$

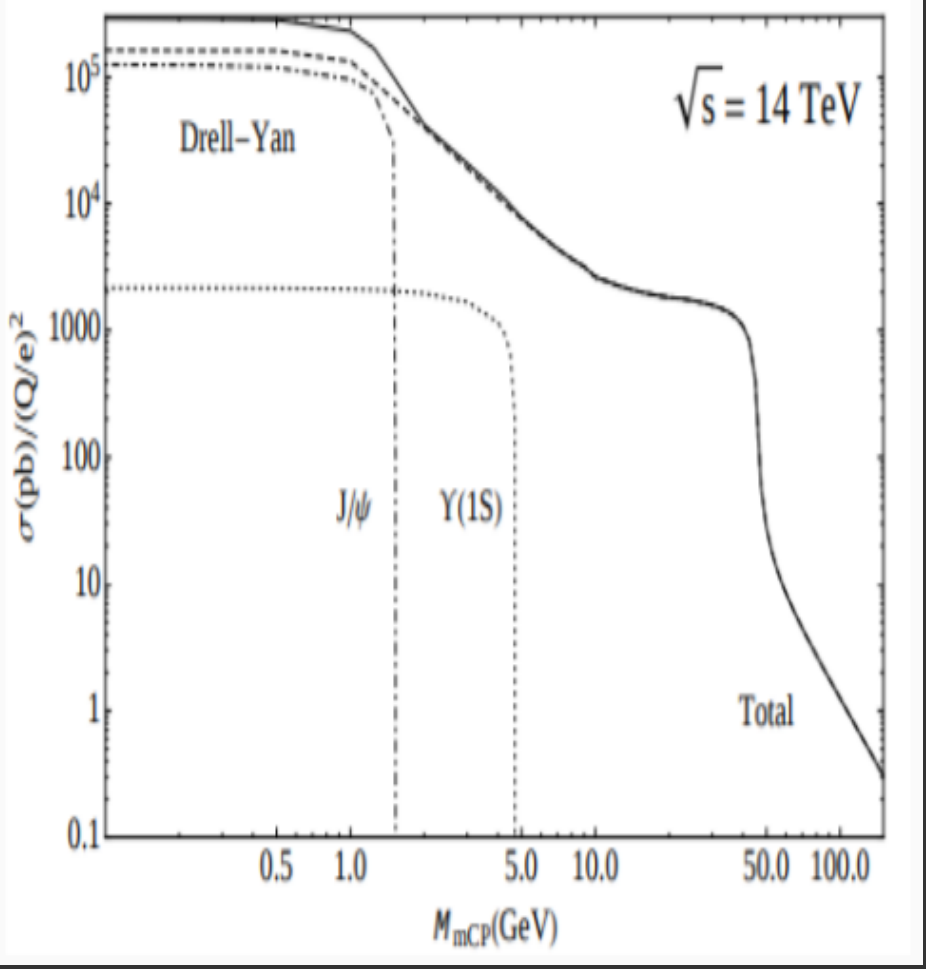
ψ acts a field with a charge of $\kappa e' = \dfrac{e\epsilon}{\cos\theta_w}$

Phys. Lett. B 166, 196 (1986)

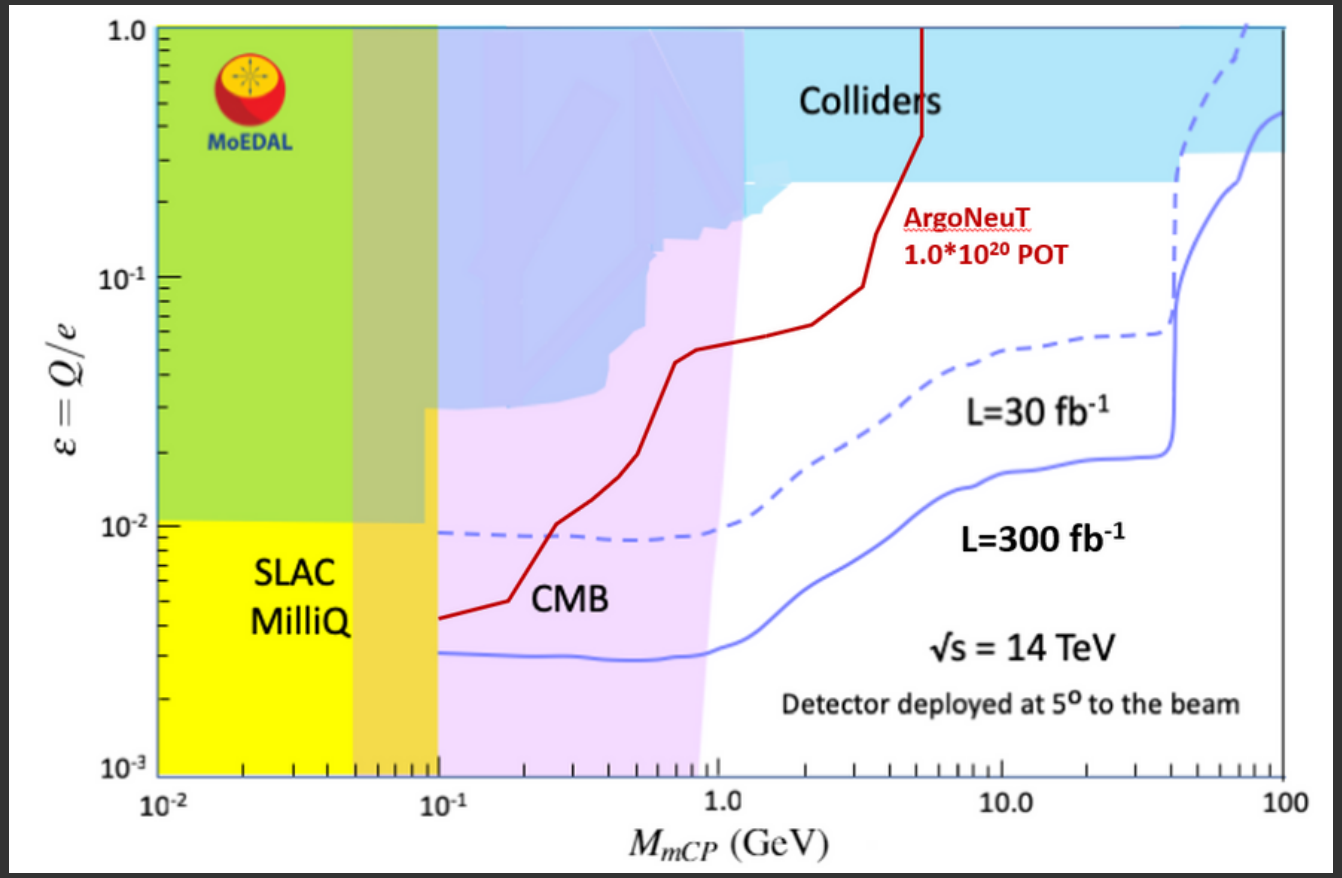
MG5 Cross-Section Results

Drell-Yan Pair Produced mCP





Sensitivity of MAPP-1 to mCP (95% C.L.)



Both blue curves were produced assuming 10% overall detector efficiency.

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

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

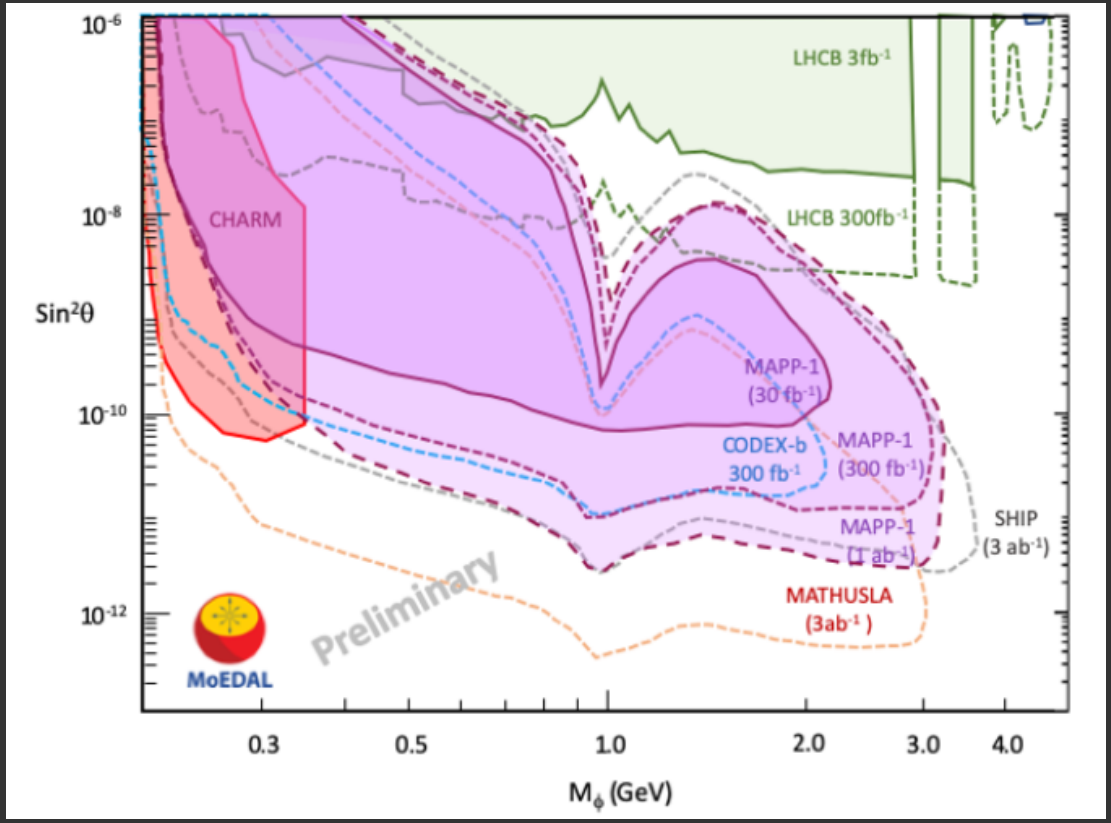
We look at dark Higgs production in rare B decays:

$B \to k\ \phi$

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

- MAPP-1 is sensitive to mCP with masses between 0.1-100 GeV and down to charges of ~e/100 (RUN-3).

  For the HL-LHC MAPP-1's limits push down to ~e/500.

- For the other benchmark shown, MAPP-1 is sensitive to a new LL Dark Higgs with masses between 0.1-2 GeV and a large range of mixing angles. (RUN-3).

- In both cases MAPP-1 can place new constraints on significant portions of virgin parameter space.

- Currently establishing MAPP's Sensitivity to other models models. (e.g. Dark Photon/Vector Portal)

  Nearly complete!

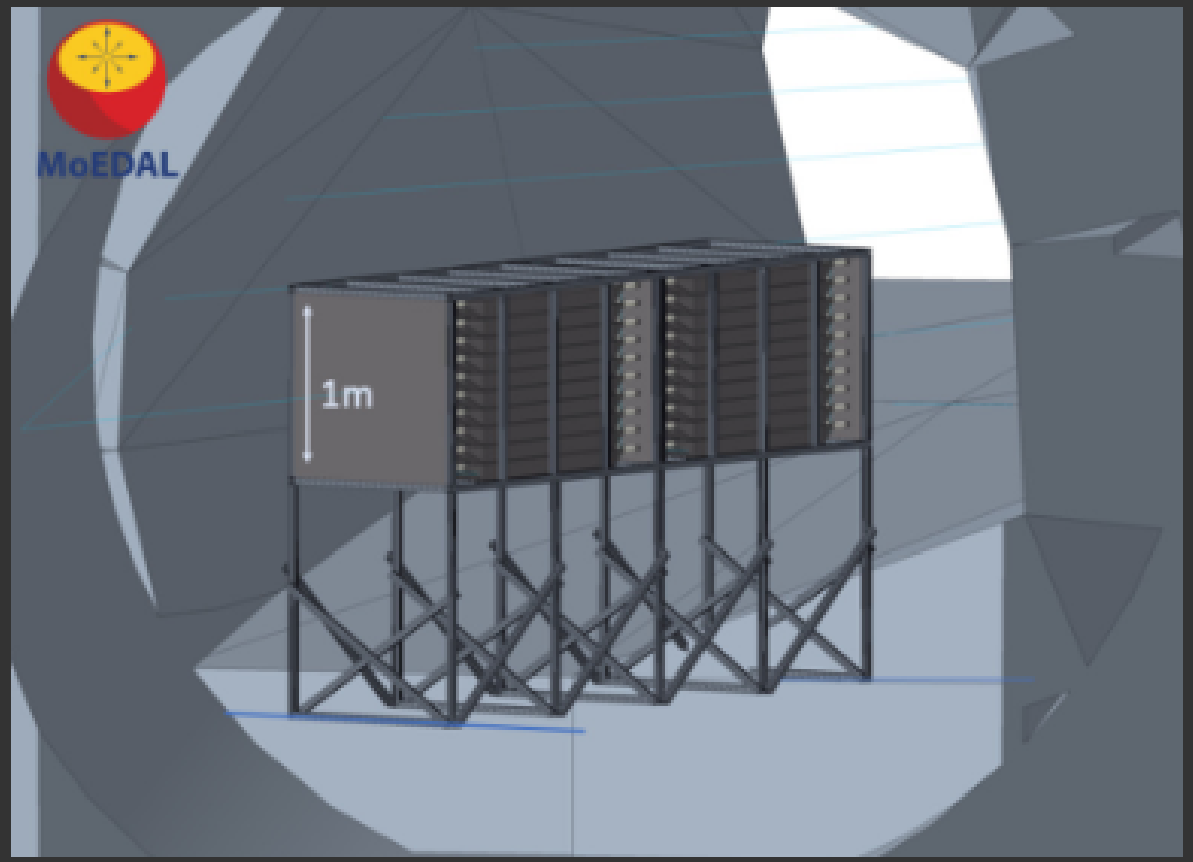
- Full Analysis & Simulation of the Background @ MAPP is a WIP

  Full GEANT4 Model of the detector and surrounding region + materials is now completed.

Thank you!

Backup Slides

MAPP-mCP



mCP Field Redefinition

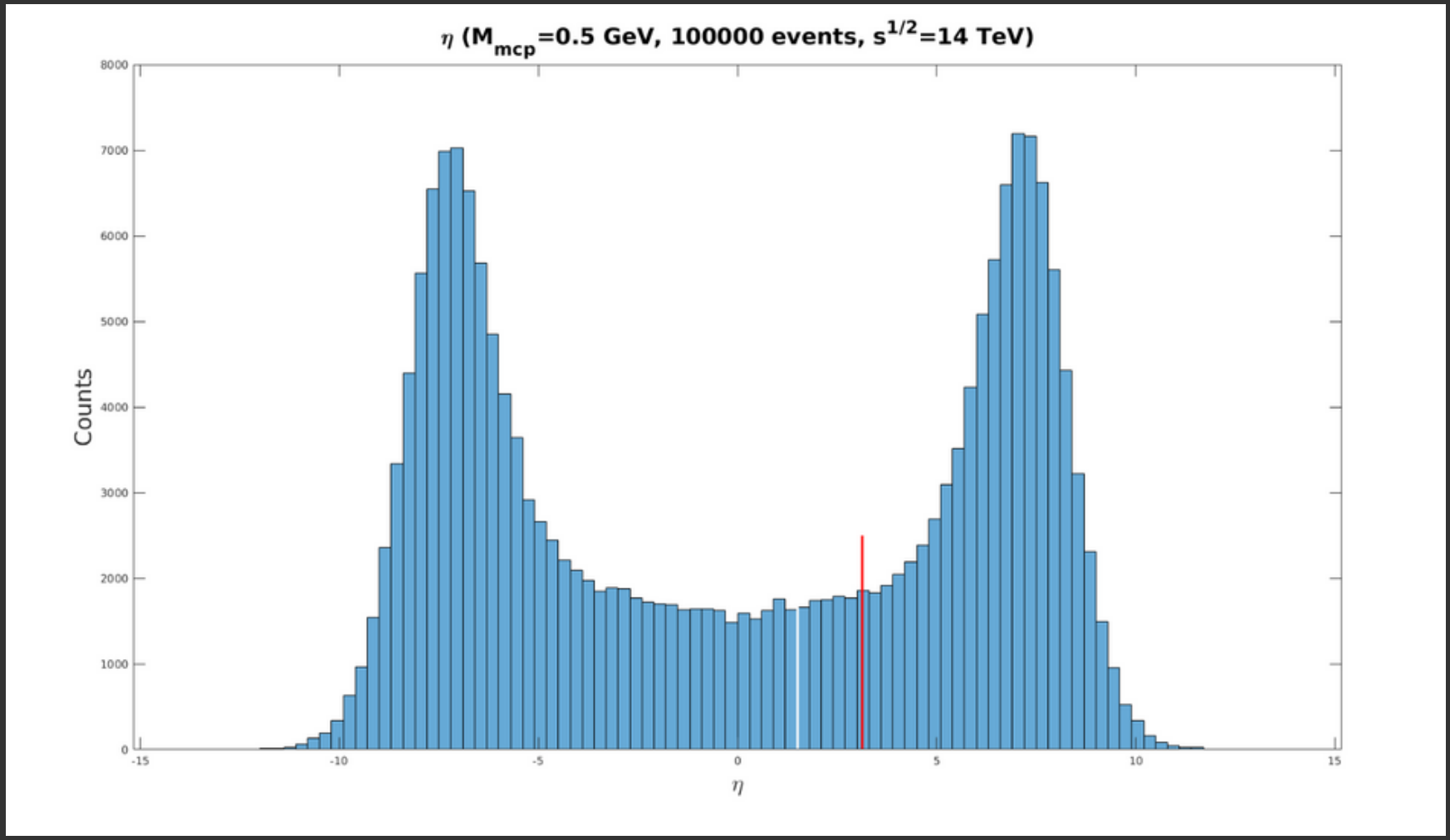
Extra info regarding the change of varaibles that go from U(1) hypercharge mixing with new U(1), to new fermion coupling to U(1) hypercharge.

$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} + i\bar{\psi}(\partial\!\!\!/ + ie' A\!\!\!/' + iM_{mcp})\psi + \frac{\kappa}{2} A'_{\mu\nu} B^{\mu\nu}$$

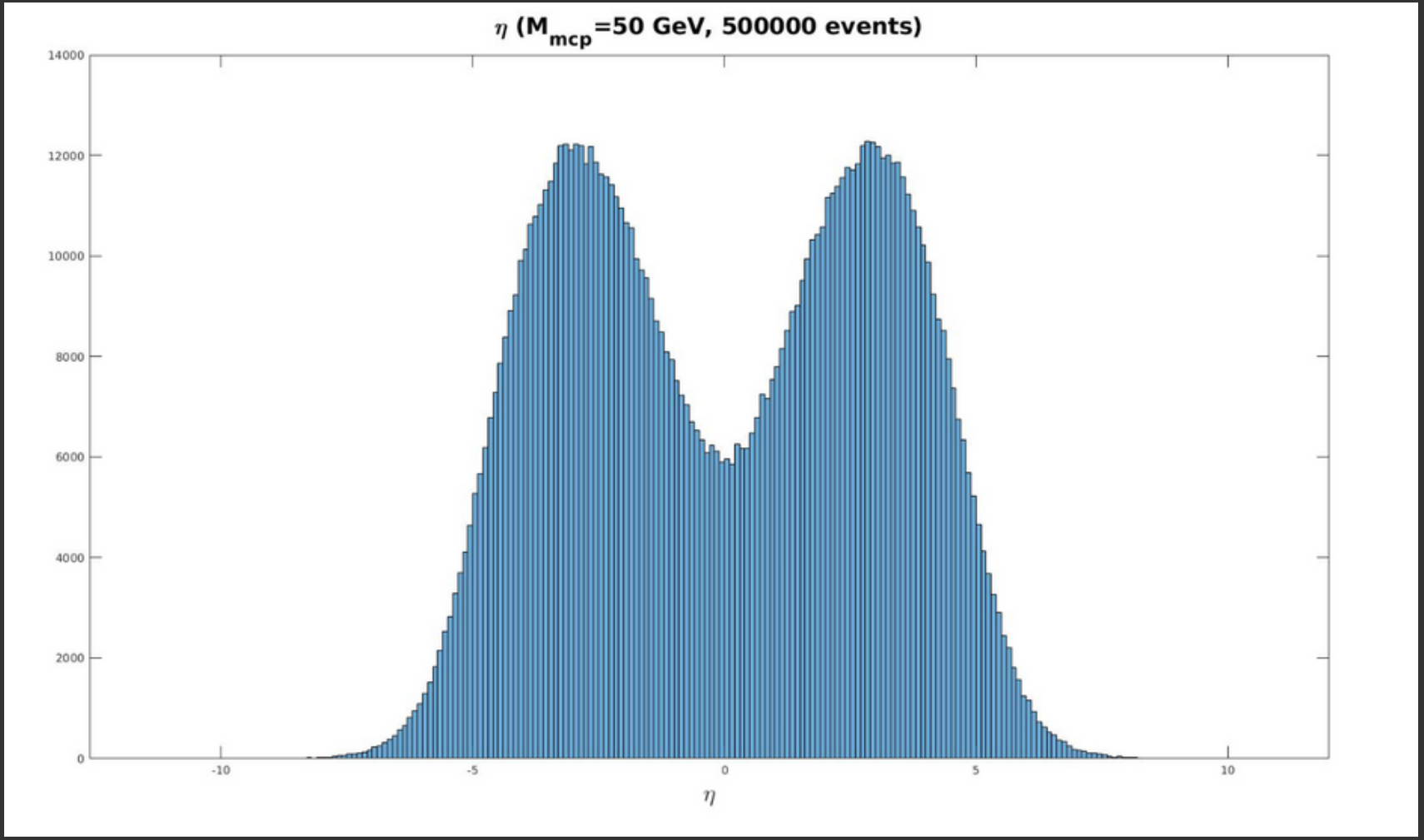
The last term is a kinetic mixing term between the field strength of the new gauge boson and that of hypercharge. Redefining $A'^{\mu} = A'^{\mu} + \kappa B_{\mu}$, yields the equation on slide 10.

Reference: Haas

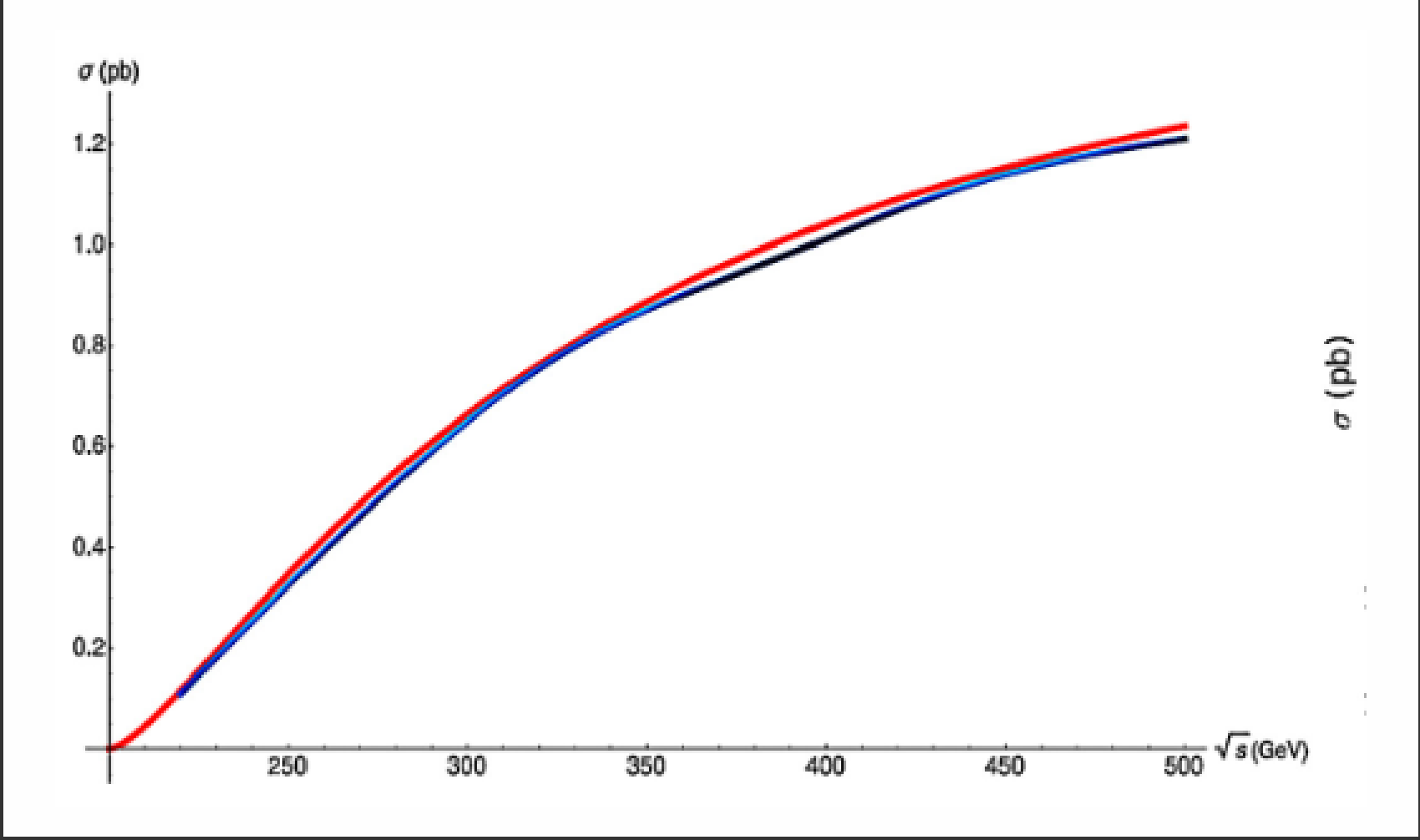
mCP Pseudorapidity Distribution (Low mass)



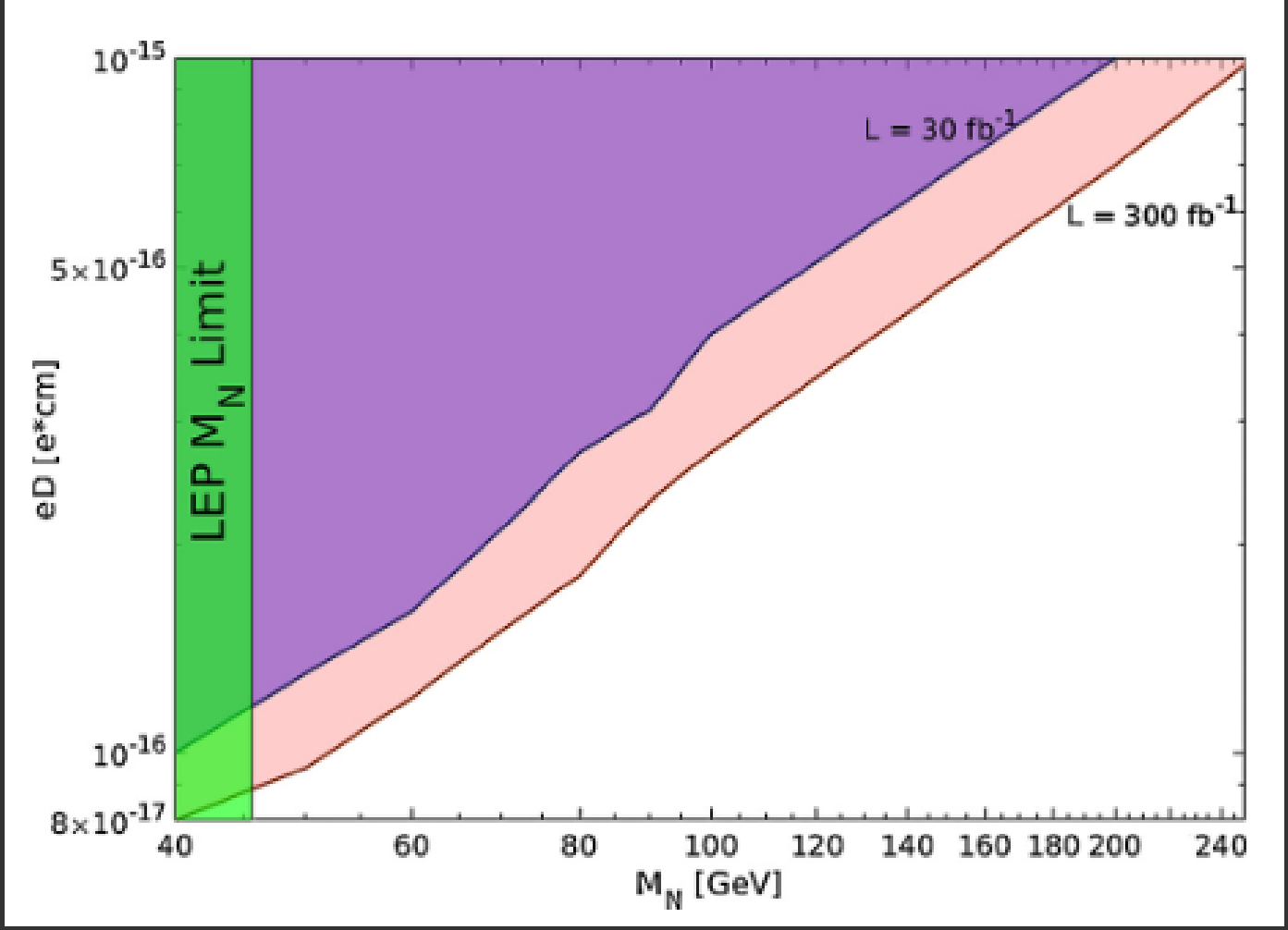
mCP Pseudorapidity Distribution (High Mass)



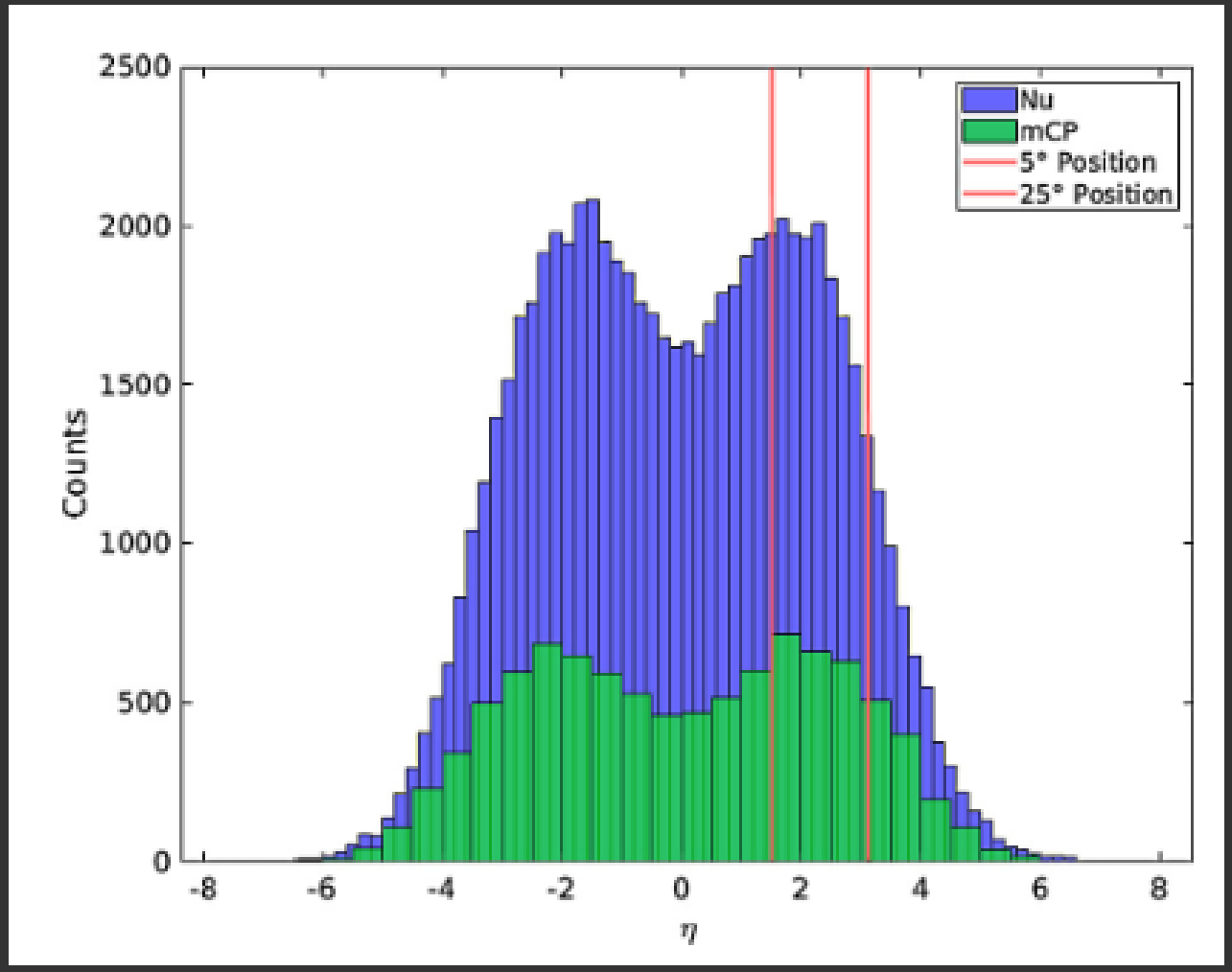
Hvy Nu Model Validation



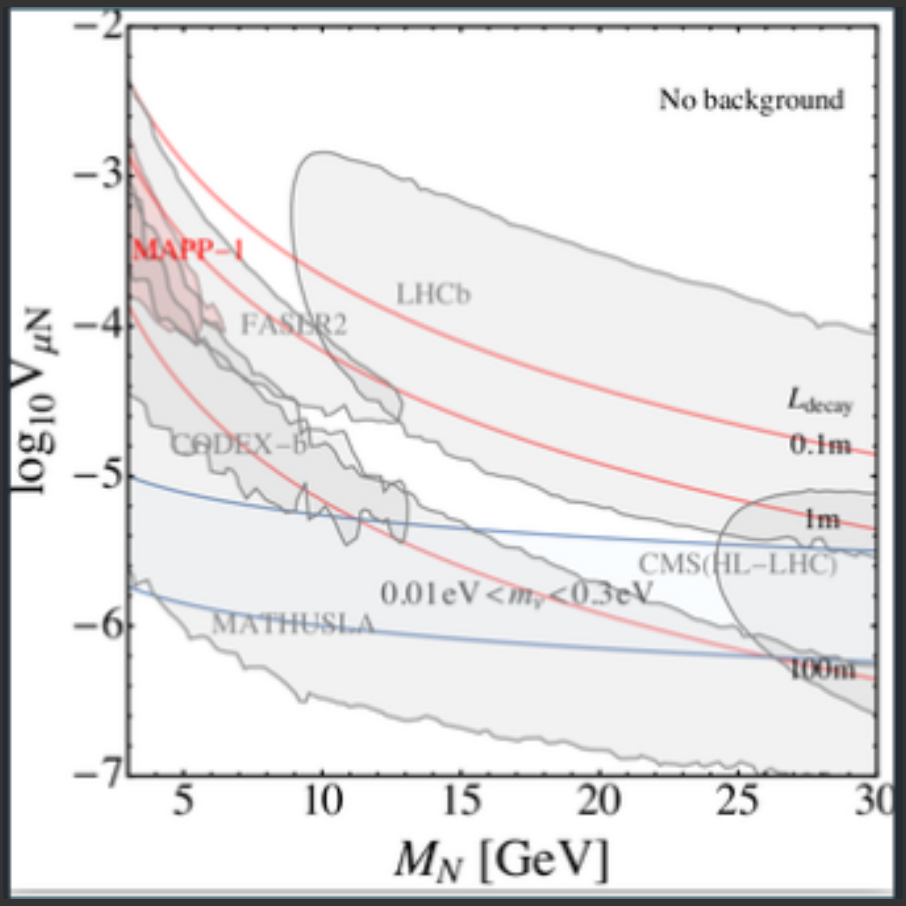
Heavy Nu (95% C.L.)



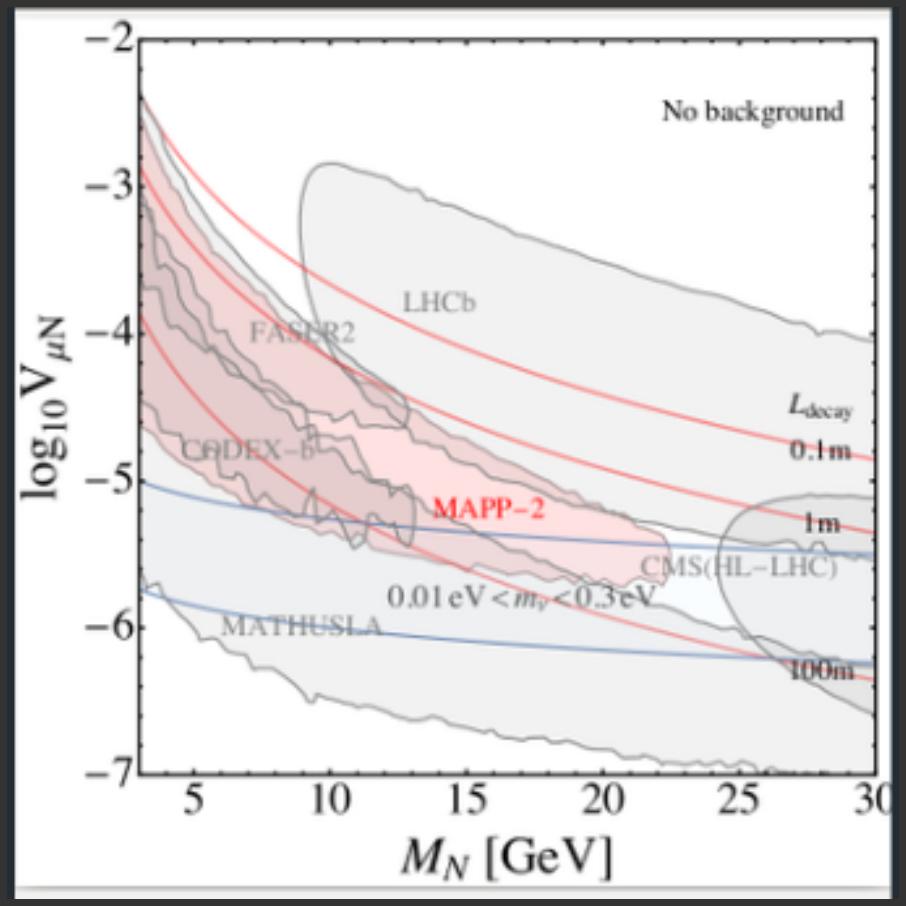
Backup 1


Nu
mCP
5° Position
25° Position
Counts
η
2500
2000
1500
1000
500
0
-8
-6
-4
-2
0
2
4
6
8

Z_(B-L) Model - LL RH Majorana Neutrinos @ MAPP-1

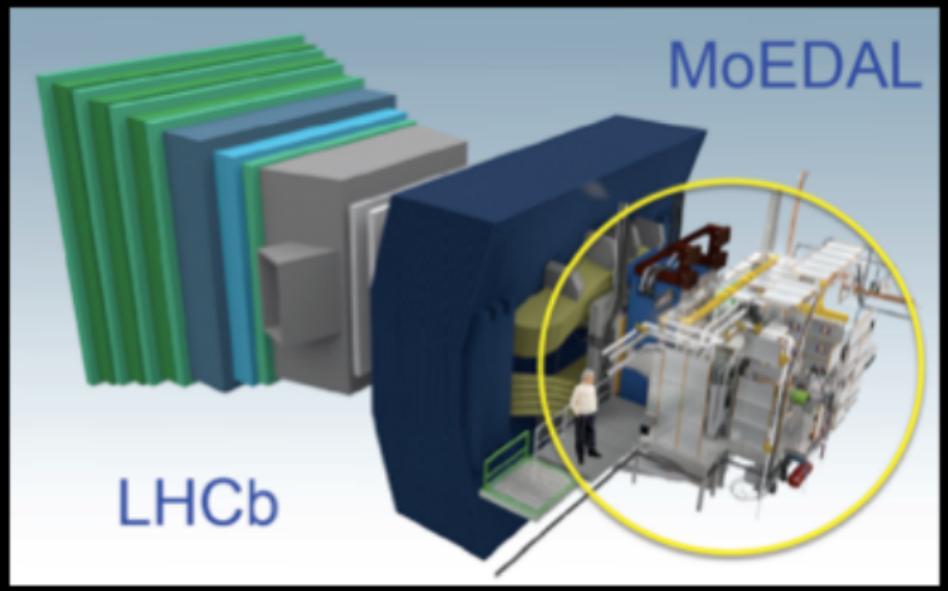


Z_(B-L) Model - LL RH Majorana Neutrinos @ MAPP-2



The MoEDAL Detector in a Nutshell

Permanent Physical record of new physics



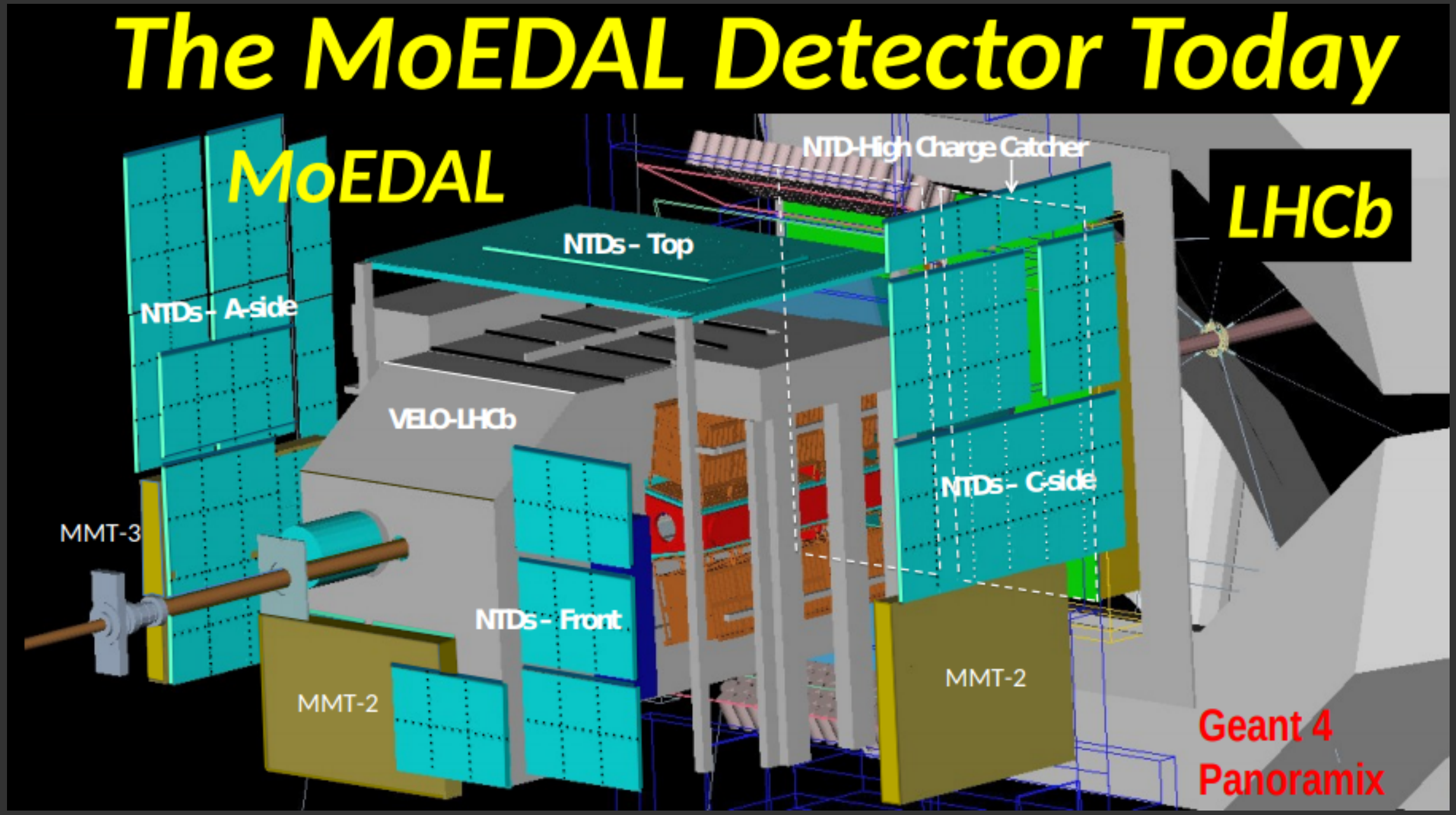
No Standard Model Physics Backgrnds

MoEDAL is largely passive and made up of three detector systems

NUCLEAR TRACK DETECTOR
Plastic array (~200 sqm)
– Like a Giant Camera

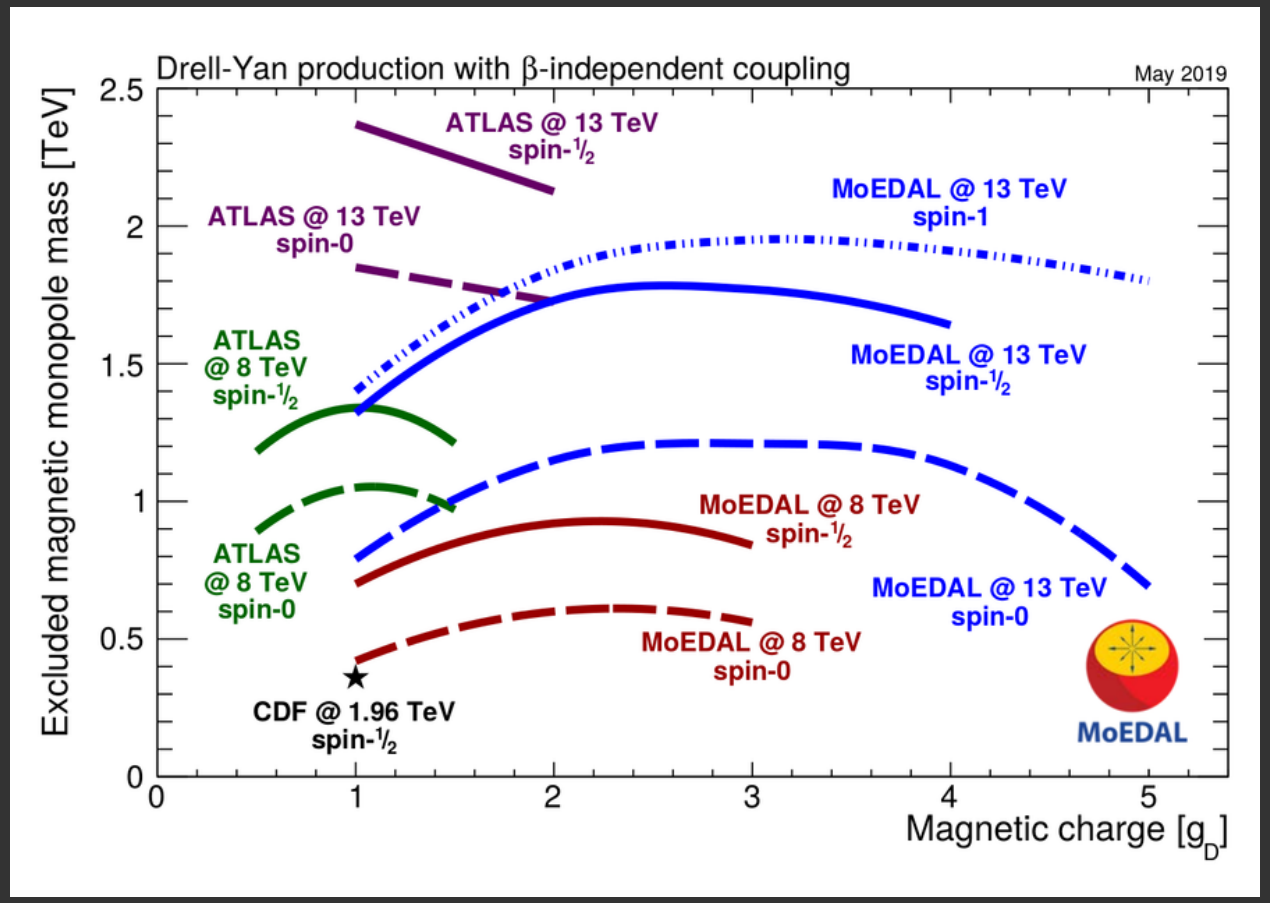
TRAPPING DETECTOR ARRAY
A tonne of Al to trap Highly Ionizing Particles for analysis

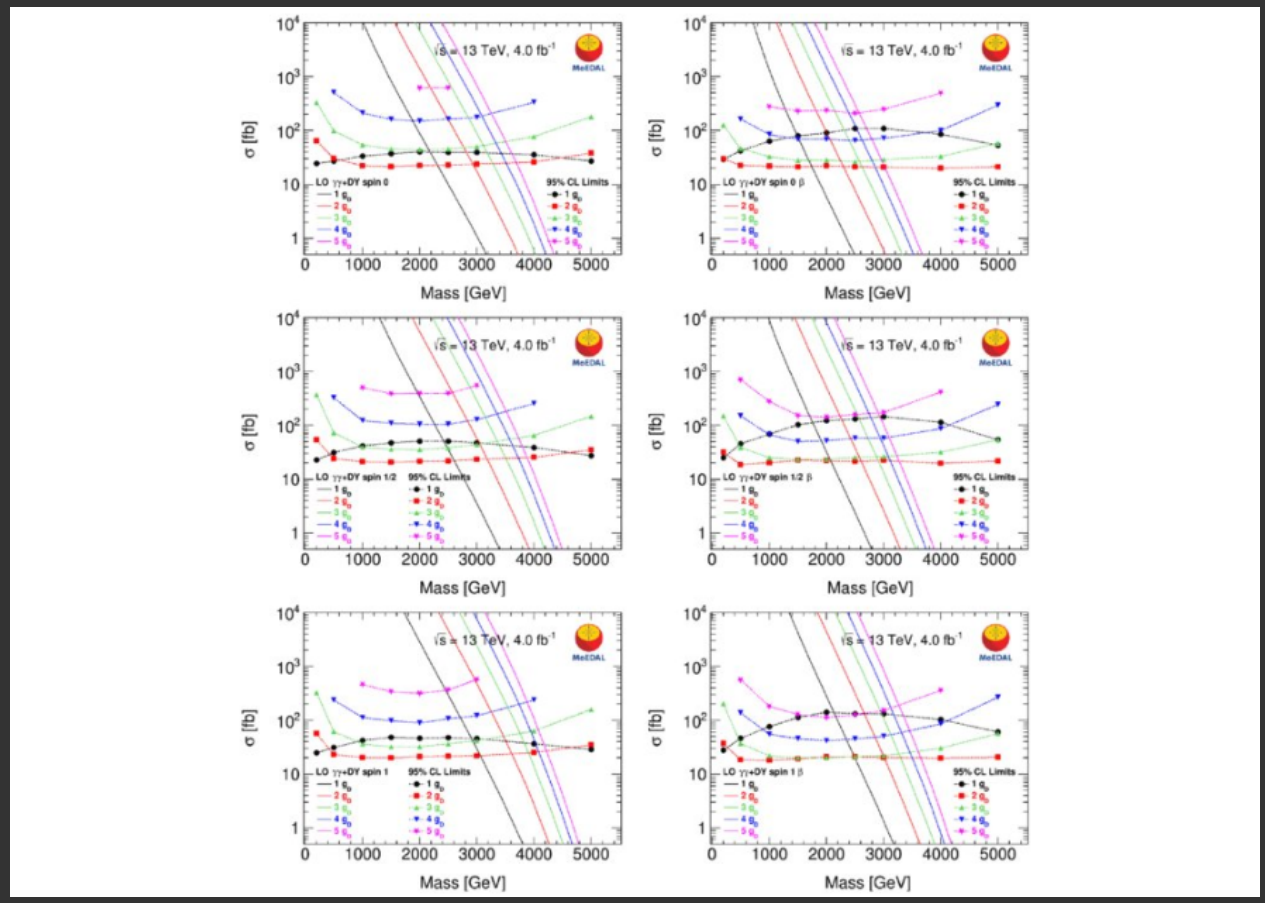
TIMEPIX Array a digital Camera for real time radiation monitoring


The MoEDAL Detector Today
MoEDAL
NTD-High Charge Catcher
LHCb
NTDs - Top
NTDs - A-side
VELO-LHCb
NTDs - C-side
MMT-3
NTDs - Front
MMT-2
MMT-2
Geant 4
Panoramix

MoEDAL's Latest Limits on MM Production @ LHC

Published in PRL July 2019. Including Photon-Photon Fusion for the 1st time @ the LHC.





Spin-1 MM considered for the 1st time @ LHC which corresponds to Lee-Yang Field Theory (Monopole obeys a gauged KG eqn.)