Searching for New Physics with MoEDAL's MAPP-1 and MAPP-2 Detectors

Emanuela Musumeci (IFIC, Valencia)

on behalf of the

MoEDAL-MAPP collaboration

SUSY 2024
Theory meets Experiment

14/06/2024

MoEDAL-MAPP COLLABORATION

Currently ~60 physicists contributing!

19 institutions

- UNIVERSITY OF ALABAMA
- UNIVERSITY OF ALBERTA
- INFN & UNIVERSITY OF BOLOGNA
- UNIVERSITY OF BRITISH COLUMBIA
- UNIVERSITÉ DE GENÈVE
- UNIVERSITY OF HELSINKI
- UNIVERSITY OF MONTREAL
- CERN
- CONCORDIA UNIVERSITY
- IMPERIAL COLLEGE LONDON
- KING'S COLLEGE LONDON
- NATIONAL INSTITUTE OF TECHNOLOGY, KURUKSETRA
- TECHNICAL UNIVERSITY IN PRAGUE
- QUEEN MARY UNIVERSITY OF LONDON
- INSTITUTE OF SPACE SCIENCE, ROMANIA
- CENTER FOR QUANTUM SPACETIME, SEOUL
- TUFT'S UNIVERSITY
- IFIC VALENCIA
- UNIVERSITY OF VIRGINIA

MoEDAL APPARATUS for PENETRATING PARTICLES

MoEDAL baseline detector optimised for detection of (meta)stable **highly ionising particles** (HIPs)

- high charges (**high z**)
  - magnetic ➜ **monopoles**
  - electric ➜ High Electric Charge Objects (**HECOs**)
- slow moving (**low β**) ⇒ massive

See Oscar Vives' talk

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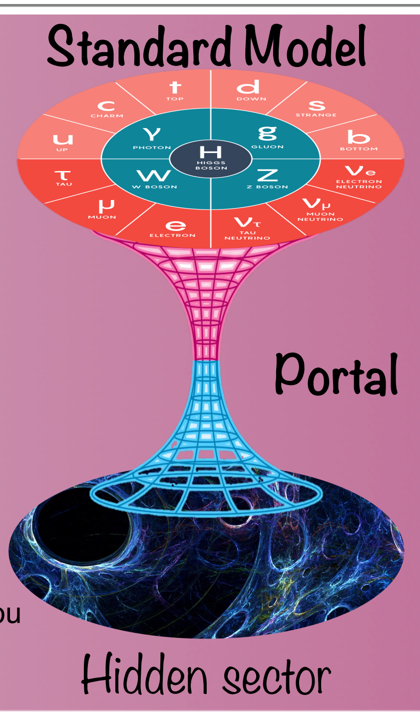
Extending the physics program

MAPP designed to expand the search for *new physics* at the LHC

Feebly Interacting Particles (**FIPs**)

- miniCharged Particles (**mCPs**)
- Long-Lived electrically neutral Particles



Courtesy of V.Mitsou

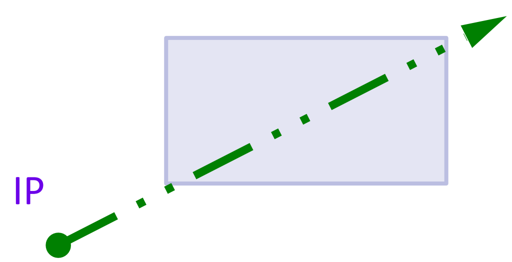
MoEDAL APPARATUS for PENETRATING PARTICLES

The installation of *MAPP* was unanimously approved by the LHCC in 2021

2 Phases

❖ *MAPP-1* for Run3 (*UA83 gallery*)

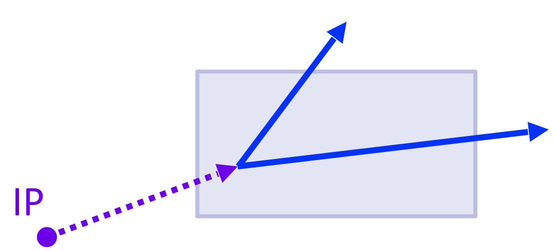
- sensitive to low ionisation induced by millicharged particles (charges $\ll 1e$)



❖ *MAPP-2* for HL-LHC (UCG1 gallery)

- sensitive to very long-lived weakly interacting neutral particles through visible decay products

  ➡displaced vertices



MoEDAL gets a new detector

The new detector, known as MAPP, will increase the physics reach of the MoEDAL experiment and the Large Hadron Collider

28 MARCH, 2022 | By Ana Lopes

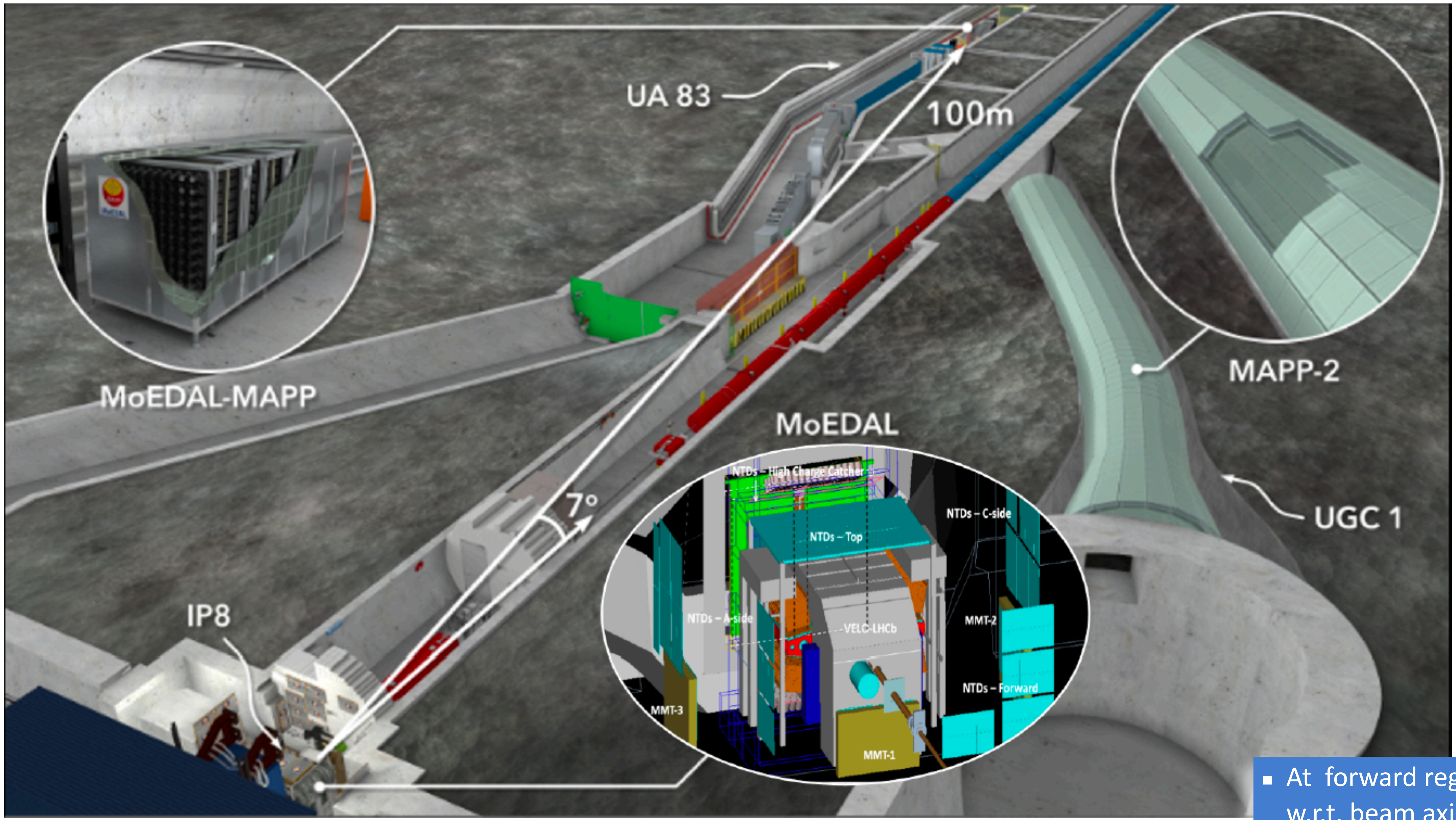
Installation of the support structure for the MAPP detector components. (Image: CERN)

The MoEDAL collaboration at the Large Hadron Collider (LHC) is adding a new detector to its experiment, in time for the start of the next run of the collider this coming summer. Named as the MoEDAL Apparatus for Penetrating Particles, or MAPP for short, the new detector will expand the physics scope of MoEDAL to include searches for minicharged particles and long-lived particles.

MoEDAL-MAPP flythrough: http://www.physixel.com/JLP_MAPP/MAPP_FlyOver1.mp4

MoEDAL contribution to Snowmass, arXiv:2209.03988
Pinfold, Phil.Trans.Roy.Soc.Lond.A 377 (2019) 20190382

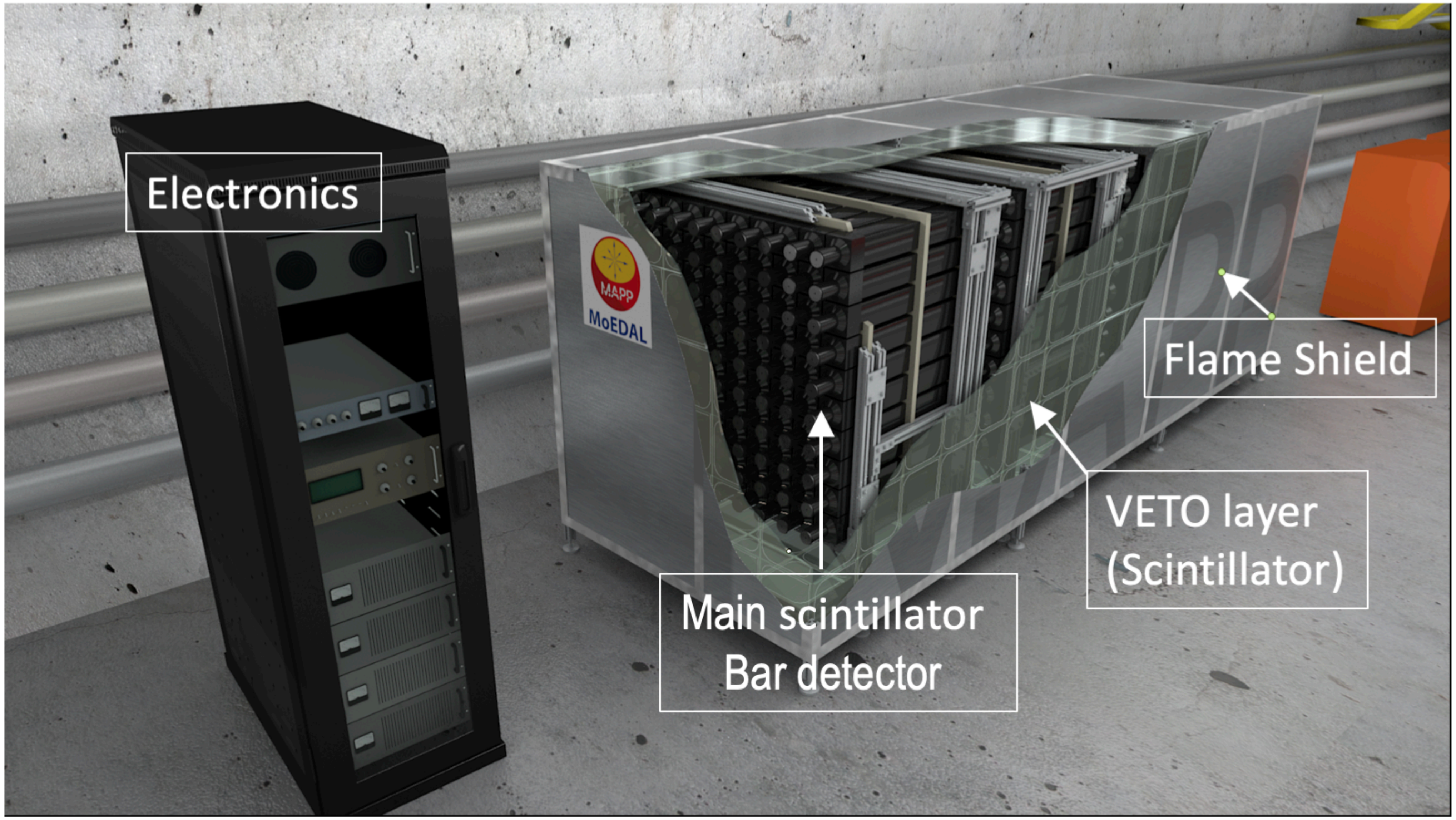
MAPP LOCATIONS



- At forward region w.r.t. beam axis
- Protected by ~100 m of rock overburden

MAPP MoEDAL

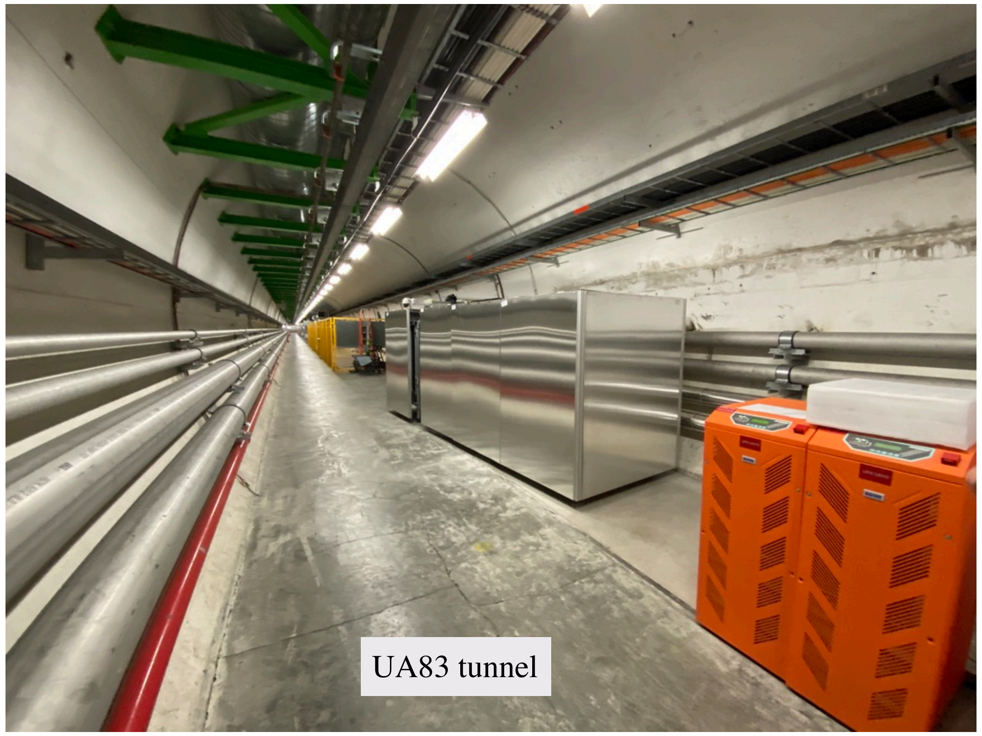
THE MAPP DETECTOR



- 400 scintillator bars (10×10×75 cm³) in 4 sections readout by PMTs
- Main support structure is comprised of generic T-bar extruded aluminium construction bars
- Bars protected by a hermetic VETO counter system
- MAPP detector and VETO layer are enclosed in an aluminium flame shield (1.3 m × 1.5 m × 4 m)

MAPP-1 INSTALLATION


Initial stages of the installation


UA83 tunnel

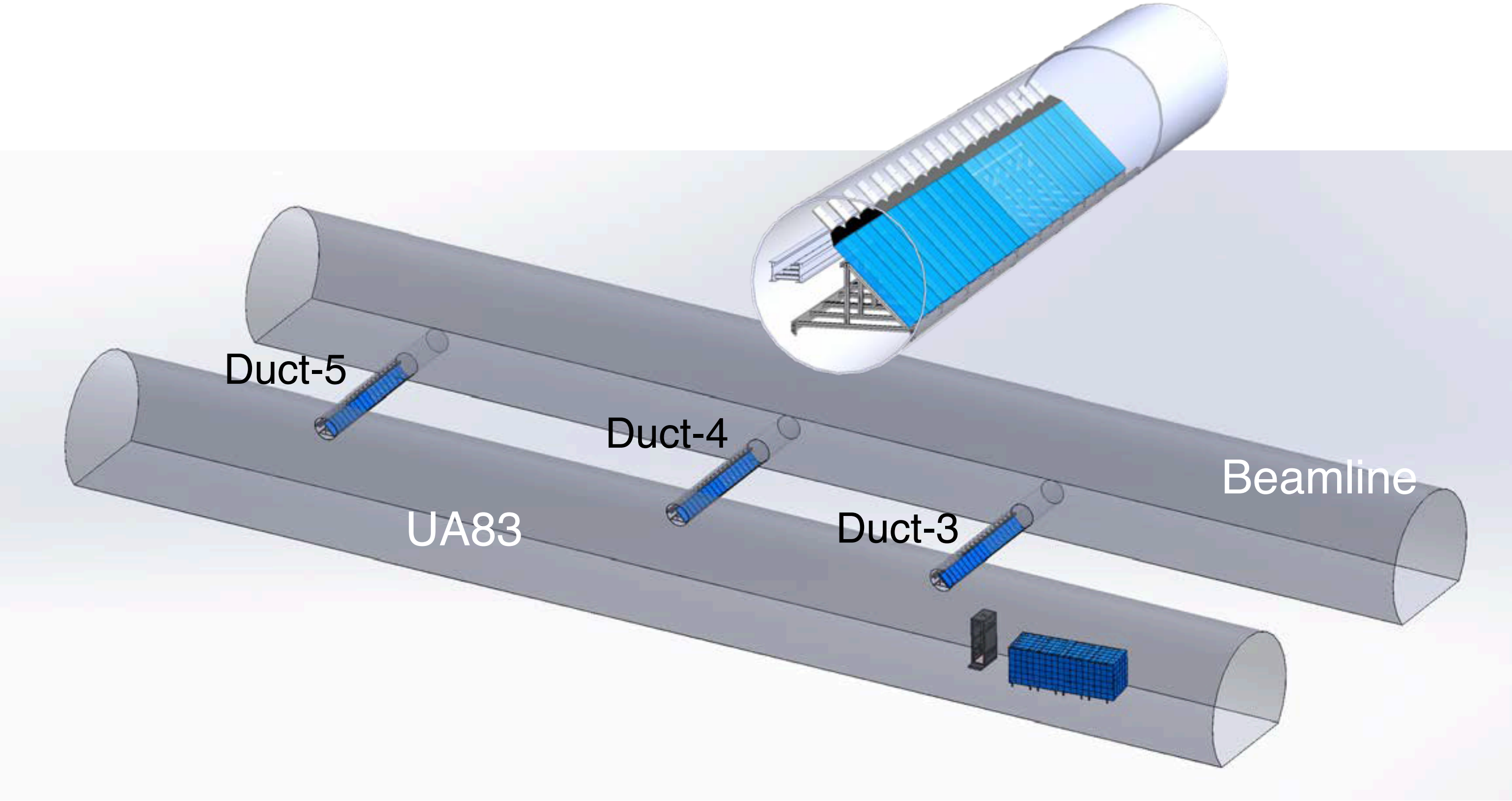

UA83, November 2023

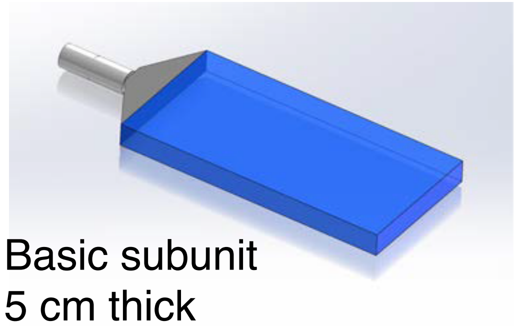

YETS, Nov 2023


YETS, Nov 2023

The MAPP-1 Outrigger Detector

- To increase the acceptance of MAPP-1 at higher mass and larger fractional charge (~ 0.01e)
- Size of the scintillator "planks" 6m × 0.6m × 5cm, inclined at 45º
- ~120 m from IP8; covers from ~2–6º
- Four-fold coincidence between the PMTs in each layer





MAPP MoEDAL

MAPP *PHYSICS PROGRAM* - *miniCharged Particles*

- Predicted by various theories beyond the Standard Model
- We consider class of FIPs that has a mill-charge as small as $10^{-3}e$ or lower
- mCPs connect naturally to the dark sector (via the vector portal/dark photon)

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

U'(1) gauge field (*Dark Photon*) — Massive Dark Fermion — mixing term

Holdom, B., *Phys. Lett. B* 166(2), 196–198 (1986)

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U'(1) gauge field (*Dark Photon*)

Massive Dark Fermion

mixing term

$$A'_\mu \rightarrow A'_\mu + \kappa B_\mu$$

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

minicharge

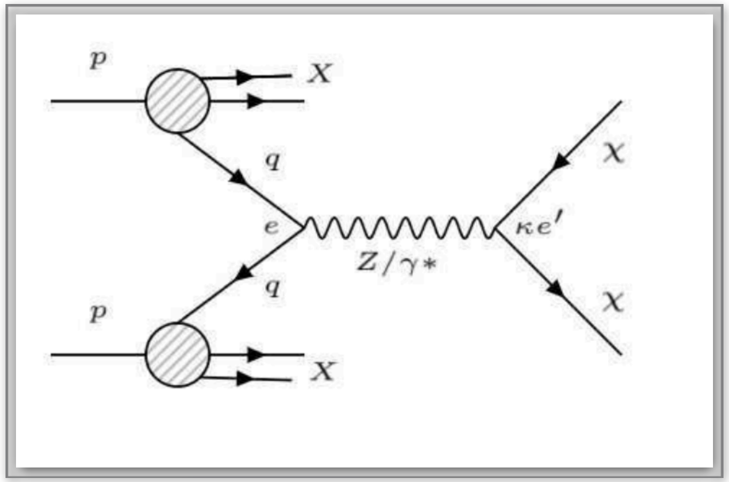
Fractional charge $\epsilon = \dfrac{\kappa e' \cos\theta_W}{e}$

Holdom, B., *Phys. Lett. B* 166(2), 196–198 (1986)

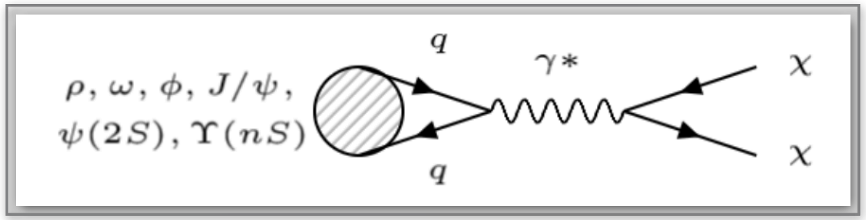
MAPP *PHYSICS PROGRAM* - *miniCharged Particles*

Production mechanisms at colliders

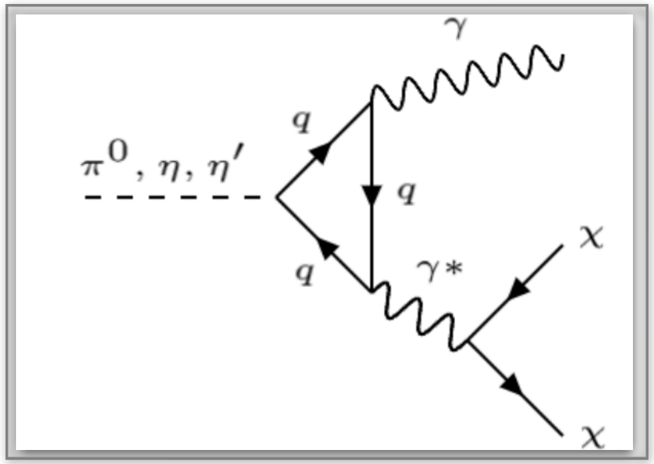
Drell–Yan



Direct decays of vector mesons



Dalitz decays of pseudo-scalar mesons



MAPP PHYSICS PROGRAM - miniCharged Particles

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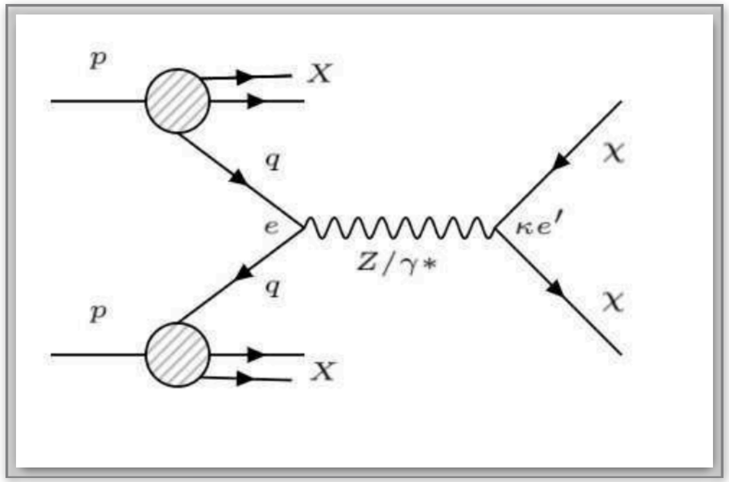
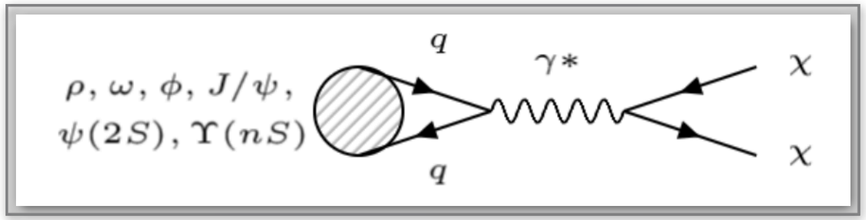


Direct decays of vector mesons



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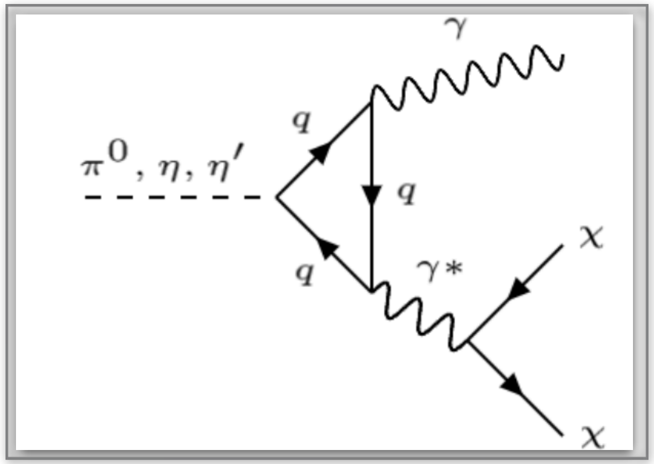
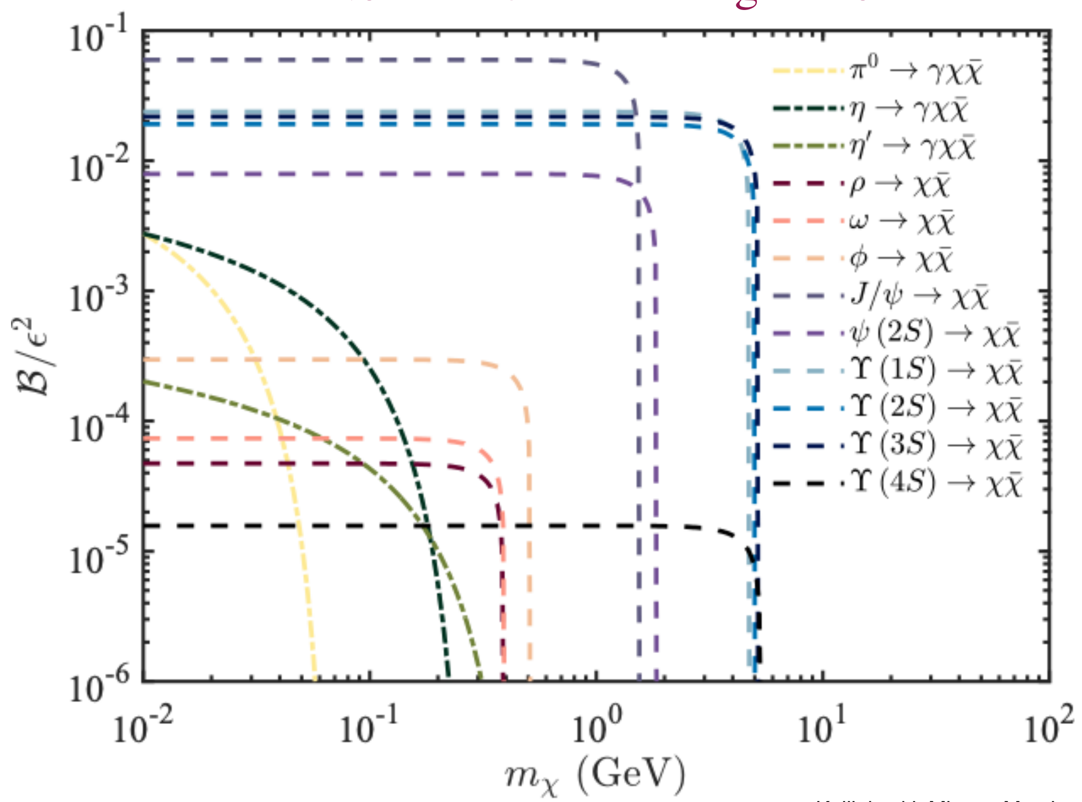
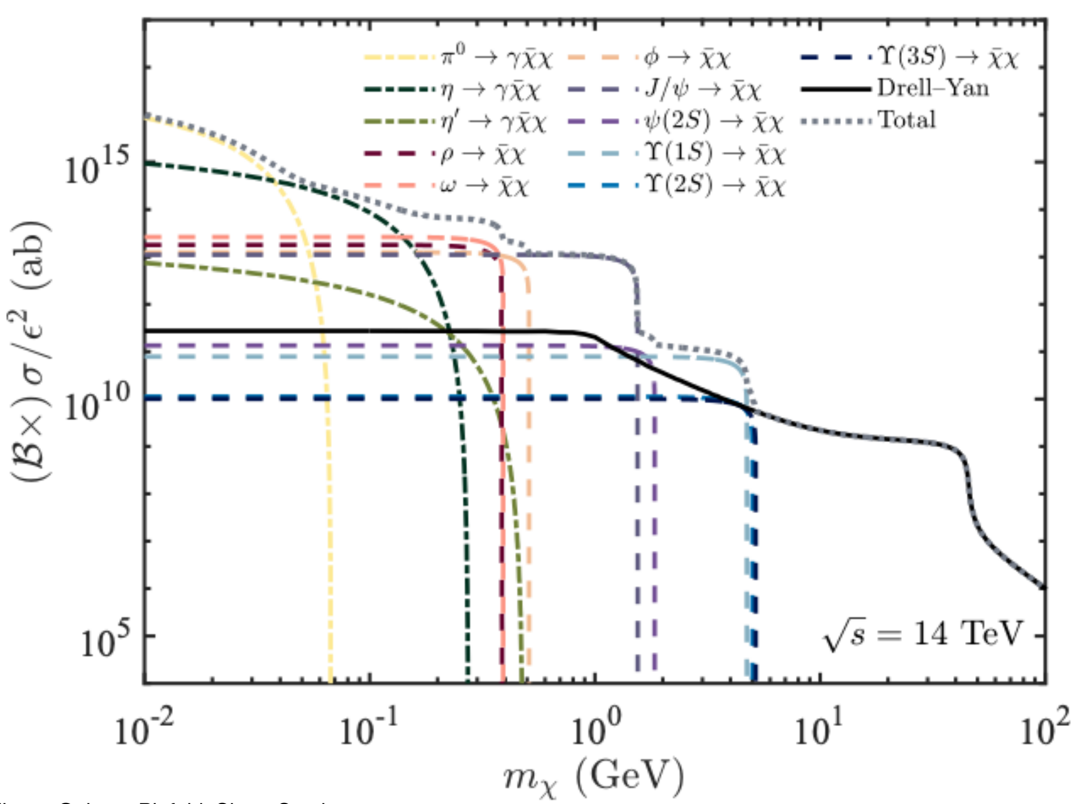


Normalised Branching Ratios



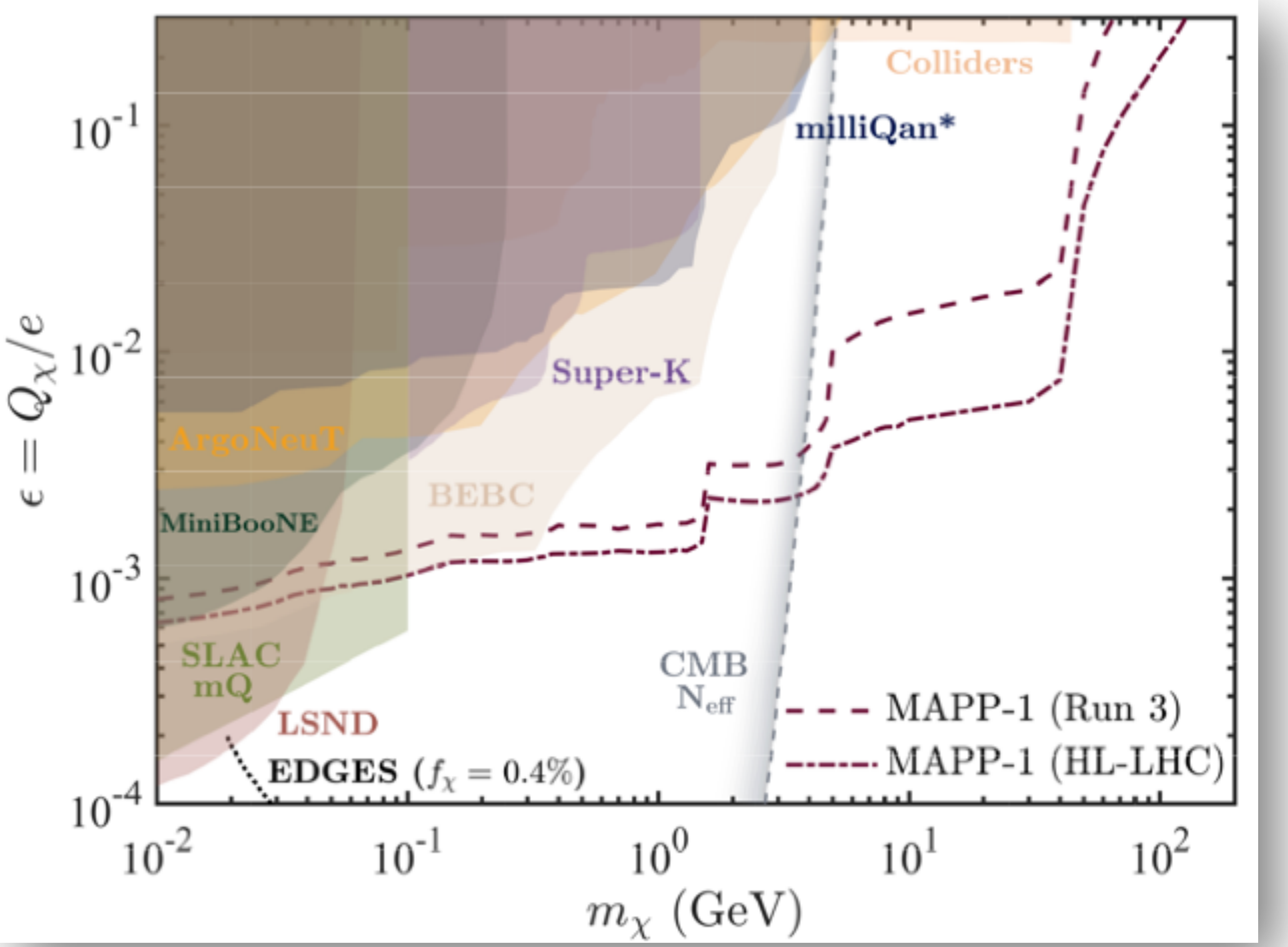
mCP Prod. X/S Estimates in *pp* Collisions



Kalliokoski, Mitsou, Montigny, Mukhopadhyay, Ouimet, Pinfold, Shaa, Staelens,
J. High Energ. Phys. 2024, 137 (2024)

MAPP PHYSICS PROGRAM - miniCharged Particles

95% C.L. for pair-produced mCPs in pp collisions



Kalliokoski, Mitsou, Montigny, Mukhopadhyay, Ouimet, Pinfold, Shaa, Staelens, JHEP 04 (2024) 137

- BG-free limits set at the 95 % c.l.
- Active veto significantly reduces background
- Signal efficiency estimates included
- 0.008 signal-like events expected in 3-yr operation
- The outrigger will significantly enhance the sensitivity to higher masses, particularly those around 1 GeV (limit plot update forthcoming)

MAPP *PHYSICS PROGRAM* - *LLPs*

- *Dark Higgs* mixing portal admits exotic inclusive B decays $B \to X\phi_H$
- ϕ_H is a light CP-even scalar that mixes with the SM Higgs ($\theta \ll 1$)
- A simple Lagrangian that includes this new dark Higgs mixing is

$$\mathcal{L} = \mathcal{L}_{\text{Kin}} + \mathcal{L}_{\text{DS}} + \mu_s^2 S^2 - \frac{\lambda_S}{4} S^4 + \mu^2 |H|^2 - \lambda |H|^4 - \epsilon_h S^2 |H|^2$$

- The signal we look for in MAPP-LLP is $\phi_H \to l^+ l^-$

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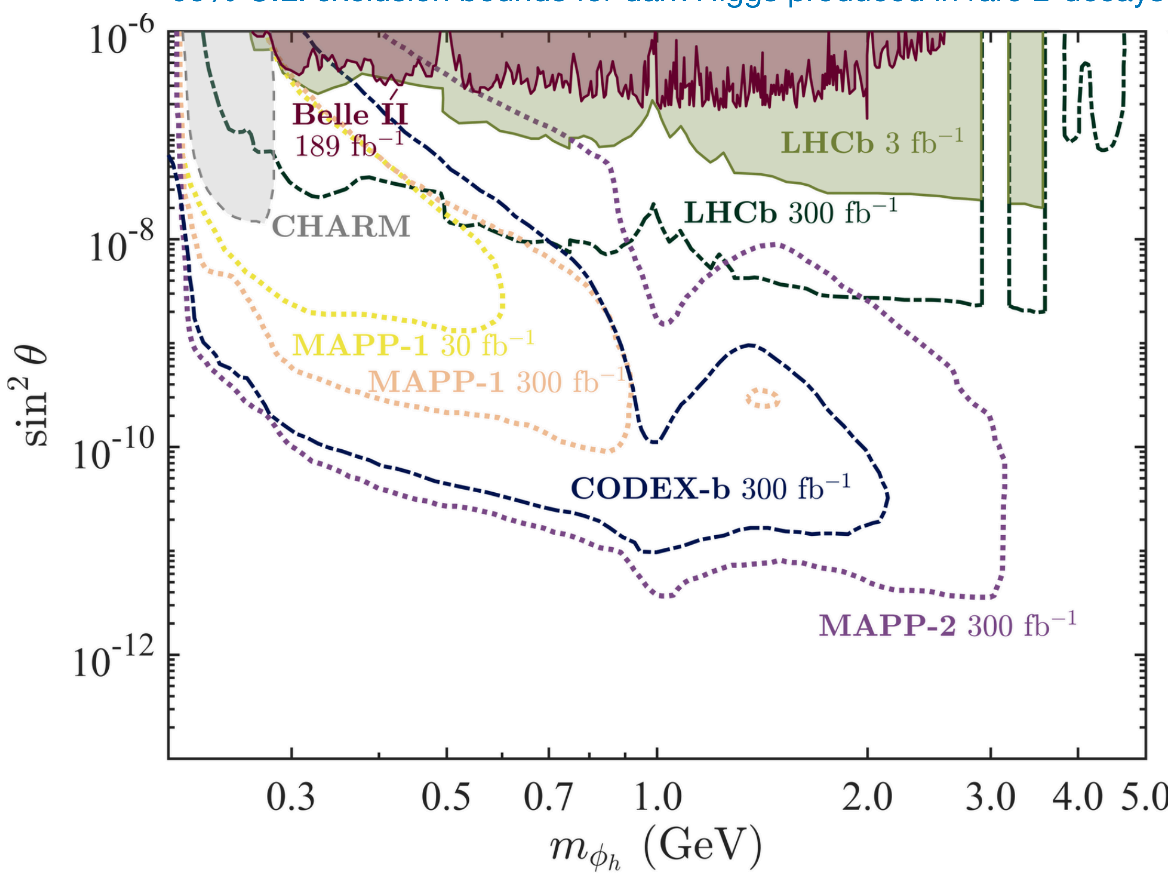
95% C.L. exclusion bounds for dark Higgs produced in rare B decays



V.Gligorov et al., *PRD* **97,**015023 (2018)

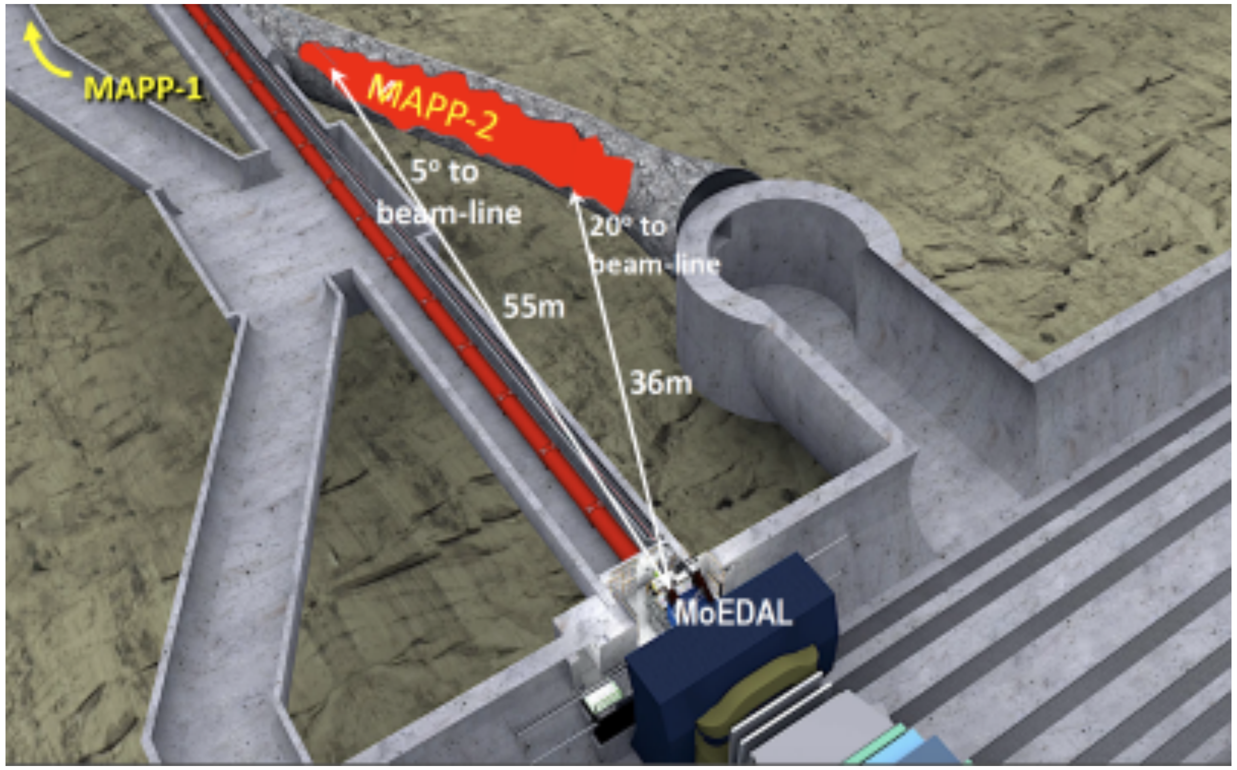
- A '*hit*' is defined as a dark Higgs decay to muons inside the MAPP-LLP detector volume
- The number of expected hints in MAPP

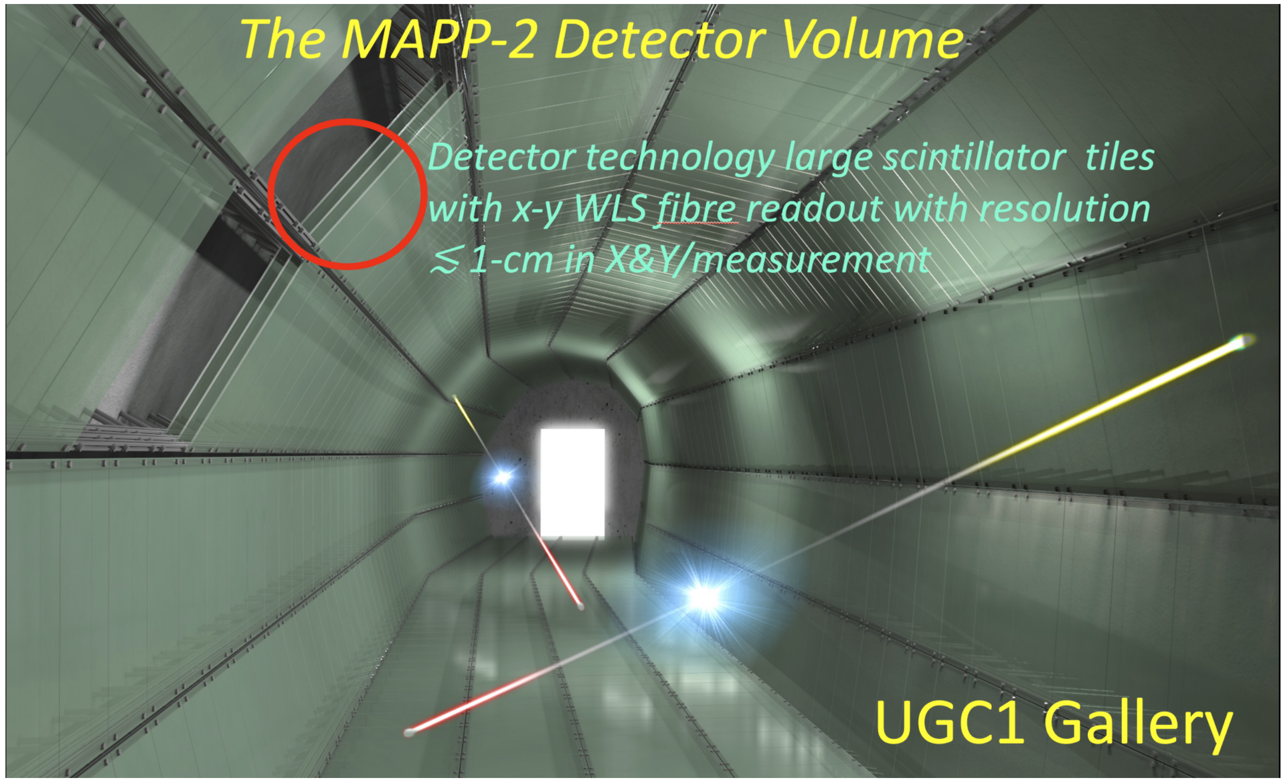
$$N_{ev} = \sigma_{B\bar{B}} \times L^{int}_{LHCb} \times B_{B \to X_s \phi_h} \times \epsilon_{fid}$$

- Fiducial efficiency of MAPP obtained by performing MC simulations of B decays to dark higgs

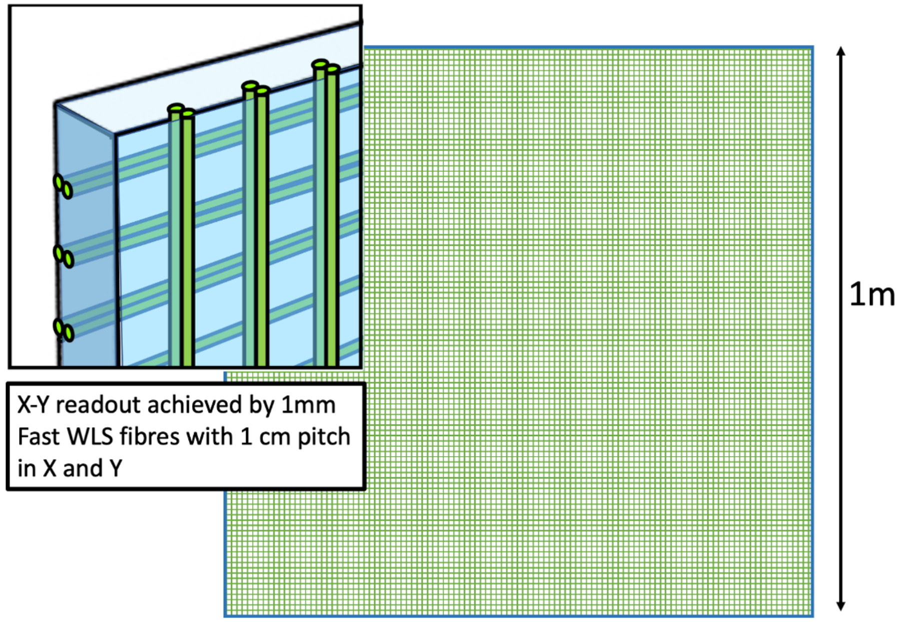
MAPP MoEDAL

MAPP-2 upgrade for HL-LHC





- The UGC1 gallery will be prepared during Long Shutdown prior to HL-LHC
- MAPP-2 extends to the full length of the UGC1 gallery (~1200 m^3)
- Detector technology: large scintillator tiles with readout by Wave Length Shifting fibres attached to silicon photomultipliers (SiPMs)
- An X-Y grid of fibres will give position sensitivity
- Tracking detectors formed by 3 or 4 hermetic containers – one within the other – lining UGC1 walls
- A layer of lead incorporated before innermost layer of scintillator to give sensitivity to photons with energy as low as ~100 MeV



BASIC MAPP-2 Tile – Position determination to better than 1 cm in X and Y

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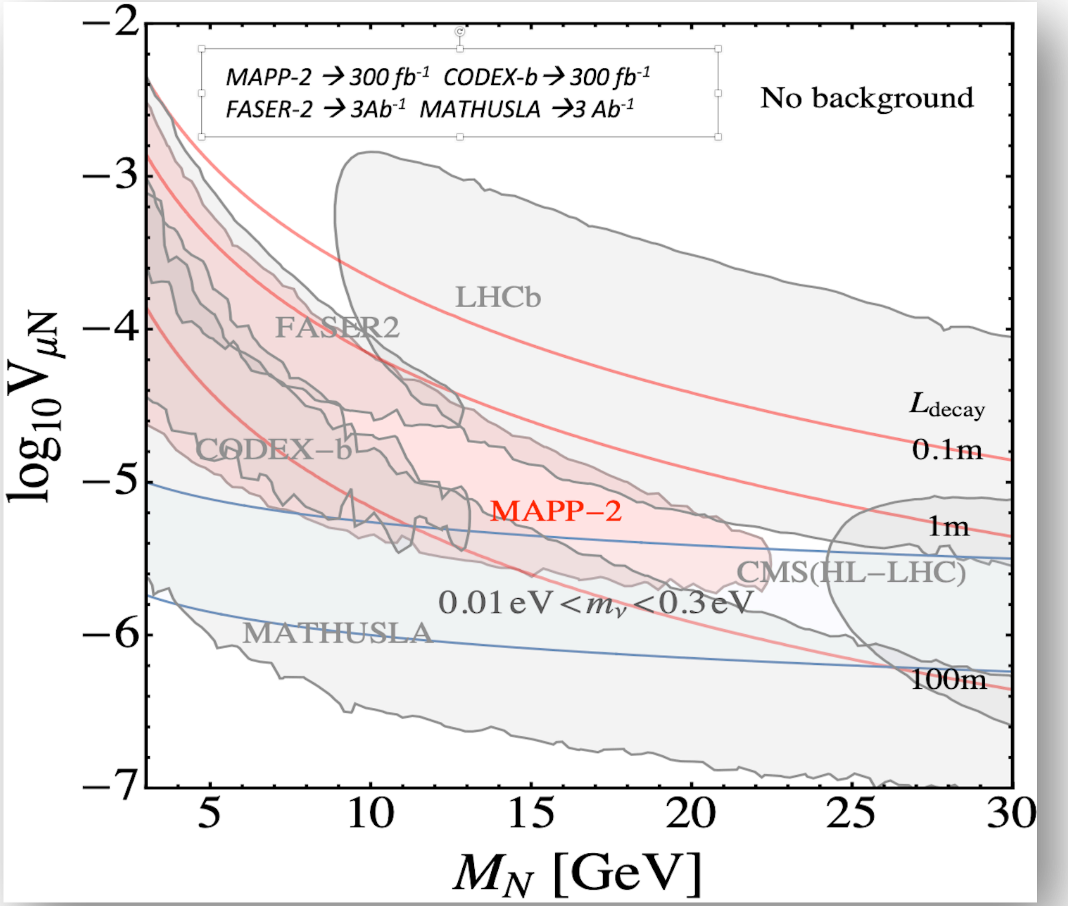
MAPP2– Physics Program

Heavy neutral leptons

$U(1)_{B-L}$ HNL scenario

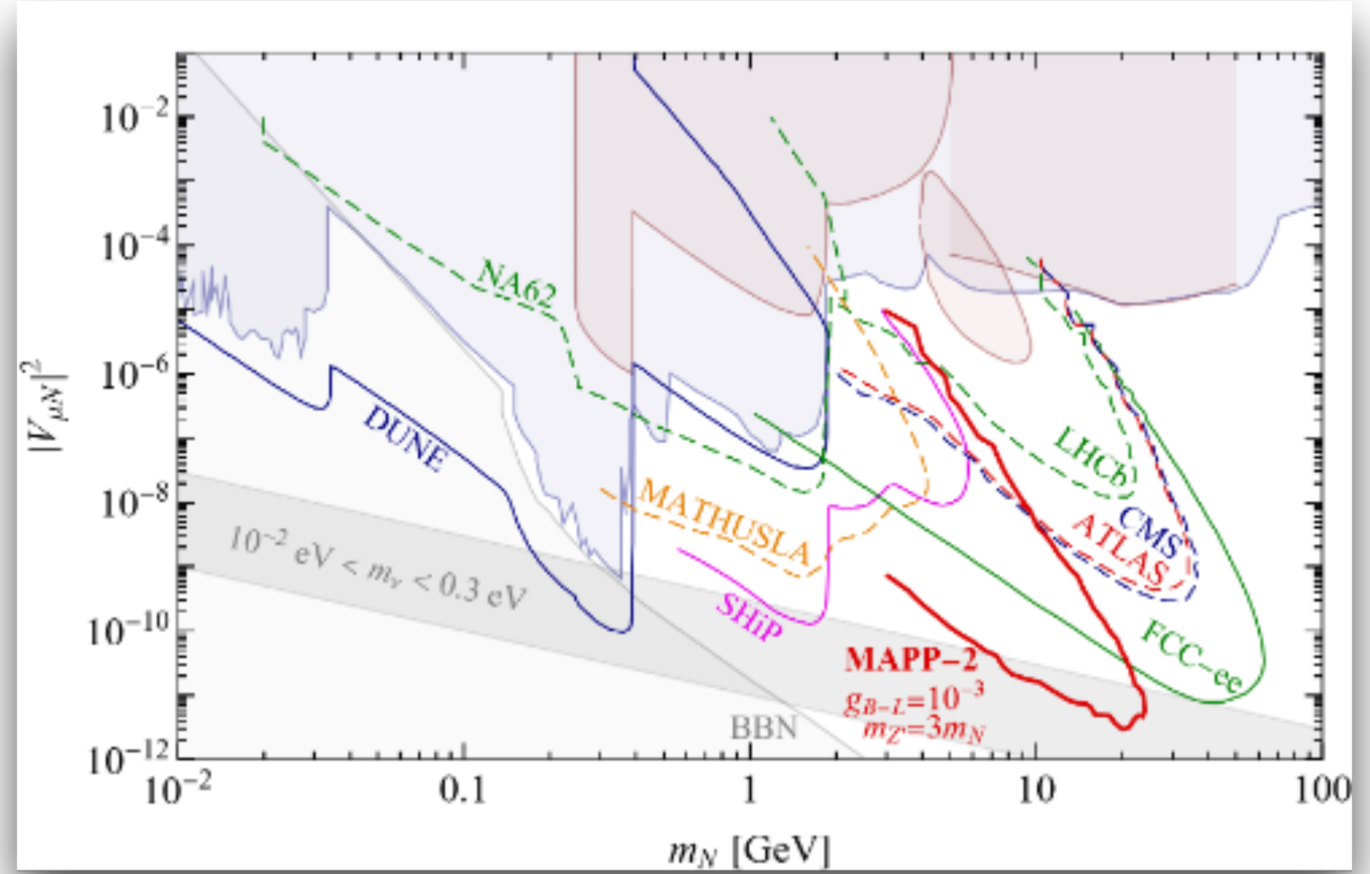


Pair production of RH neutrinos from decay of additional neutral Z' boson in gauged *B-L* model

MoEDAL Snowmass paper, arXiv:2209.03988

See also, Deppisch et al, PRD 100 (2019) 035005

Sterile neutrinos

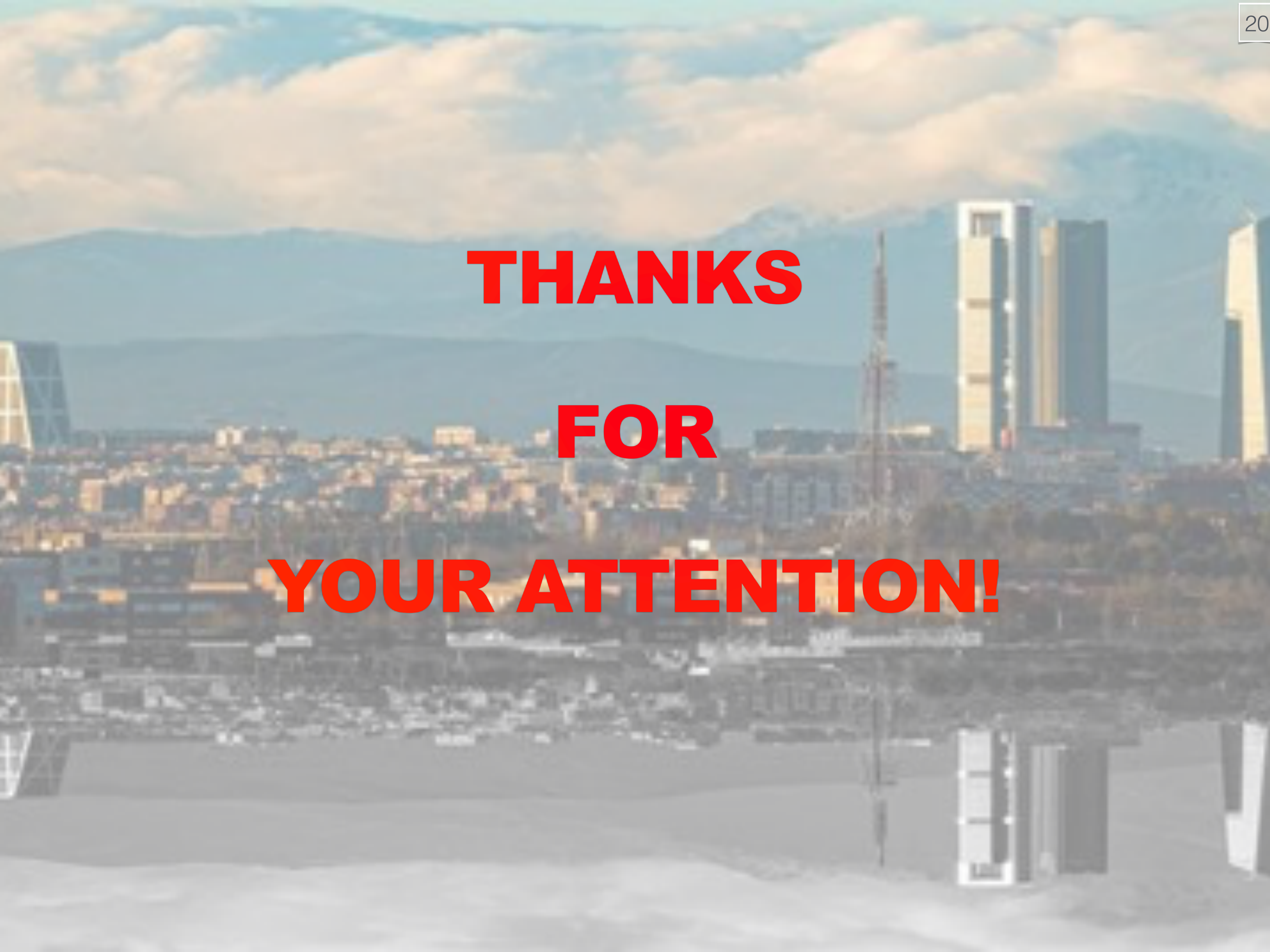


Minimal scenario: interactions are purely mediated by W- and Z-bosons via active-sterile neutrino mixing

F. Deppisch, S. Kalkarni, W. Liu 2311.01719

SUMMARY & OUTLOOK

- Dedicated experiments are needed to detect New Physics signals
- MoEDAL-MAPP experiment provides a complementary expansion of the LHC's discovery horizon by providing sensitivity to scores of new physics scenarios, that involve FIPs and LLPs
- Numerous phenomenological studies have already been conducted
- The MAPP-1 upgrade to the MoEDAL detector is currently being installed in the UA83 gallery some 100 m from IP8
- MAPP-2 will be installed in the UGC1 gallery before the HL-LHC



THANKS

FOR

YOUR ATTENTION!

Backup

slides

DETECTOR SENSITIVITY ESTIMATES

Method to obtain limit curves at the 95% confidence level

The number of signal events , N_{sig}, can be estimated as

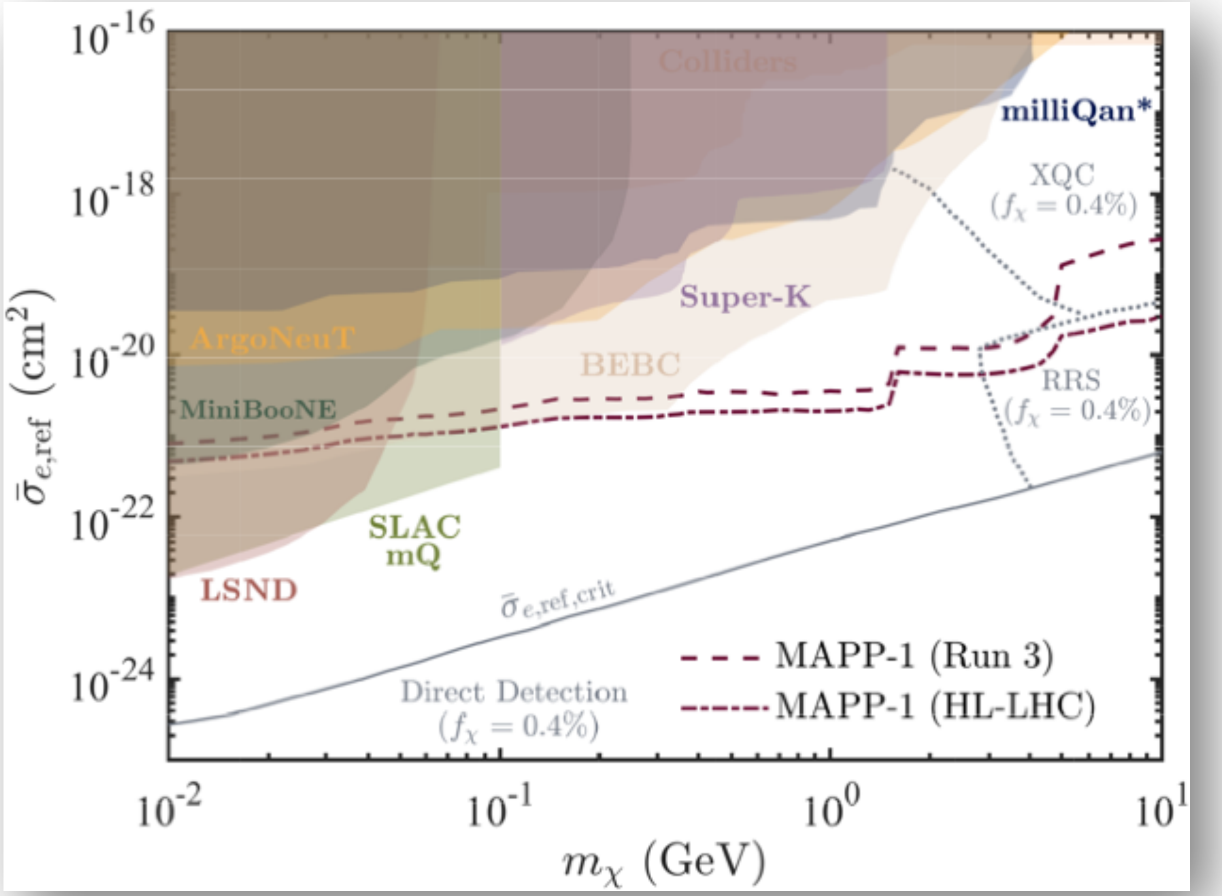
$$N_{sig} = N_{\chi} \times A \times P$$

- N_{χ} is the number to mCPs produced by a given process
- A is the acceptance of the detector to mCPs produced by such process
- P is the Poisson distribution associated with the number of photoelectrons produced

mCPs & strongly interacting DM

- mCPs can account for a fraction of dark matter abundance
- mSIDM characterised by a large "reference cross section"
- Particle flux attenuated through interactions in the Earth's atmosphere and crust
- Can escape detection by conventional underground direct-detection detectors

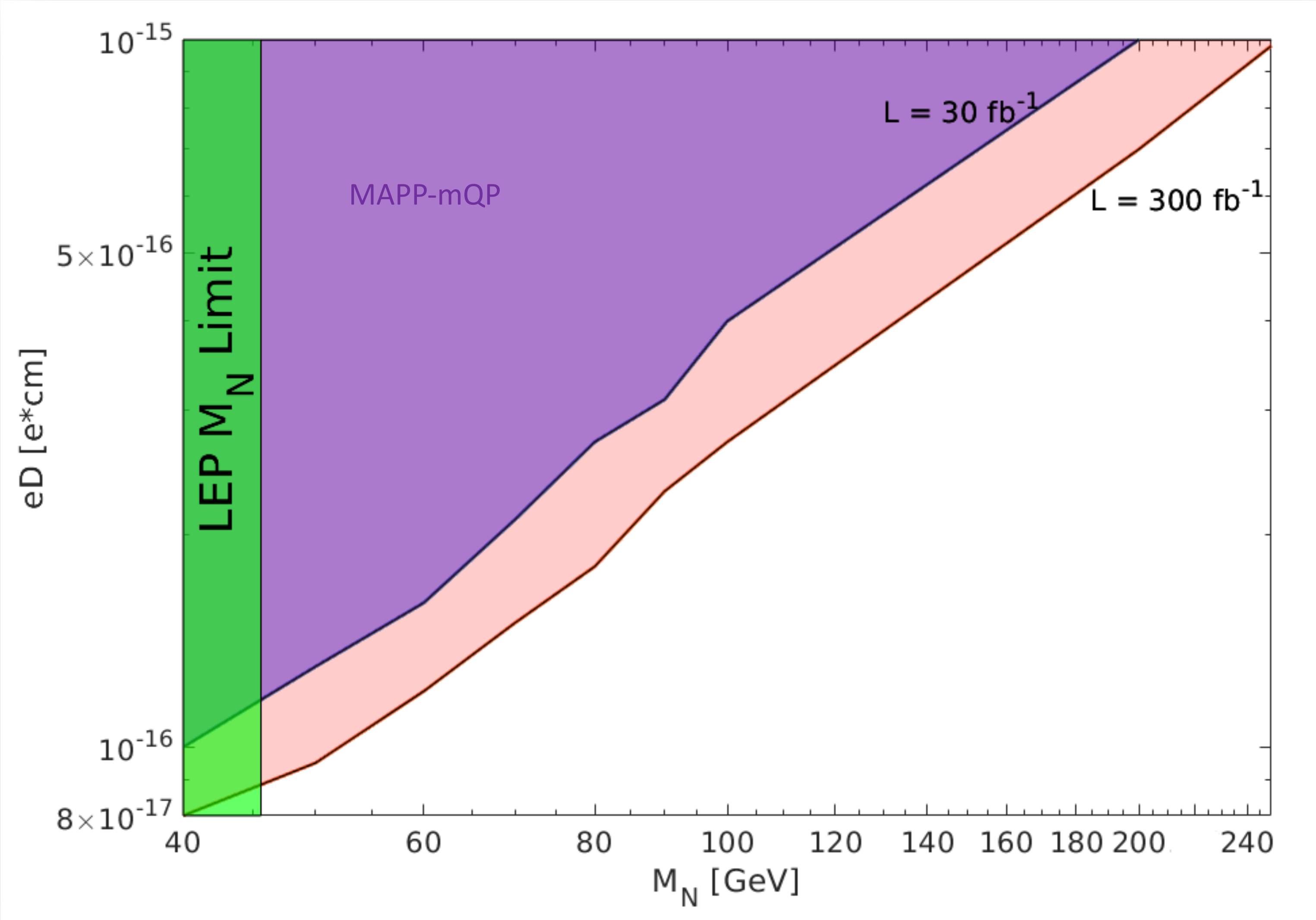
Emken, Essig, Kouvaris, Sholapurkar, JCAP 09 (2019) 070
Foroughi-Abari, Kling, Tsai, PRD 104 (2021) 035014



Kalliokoski, Mitsou, Montigny, Mukhopadhyay, Ouimet, Pinfold, Shaa, Staelens, arXiv:2311.02185 [hep-ph]

MAPP *PHYSICS PROGRAM* - *Heavy neutrinos with large EDM*

Limits that MAPP can place on heavy neutrino production with large EDM at Run-3 and HL-LHC at IP8

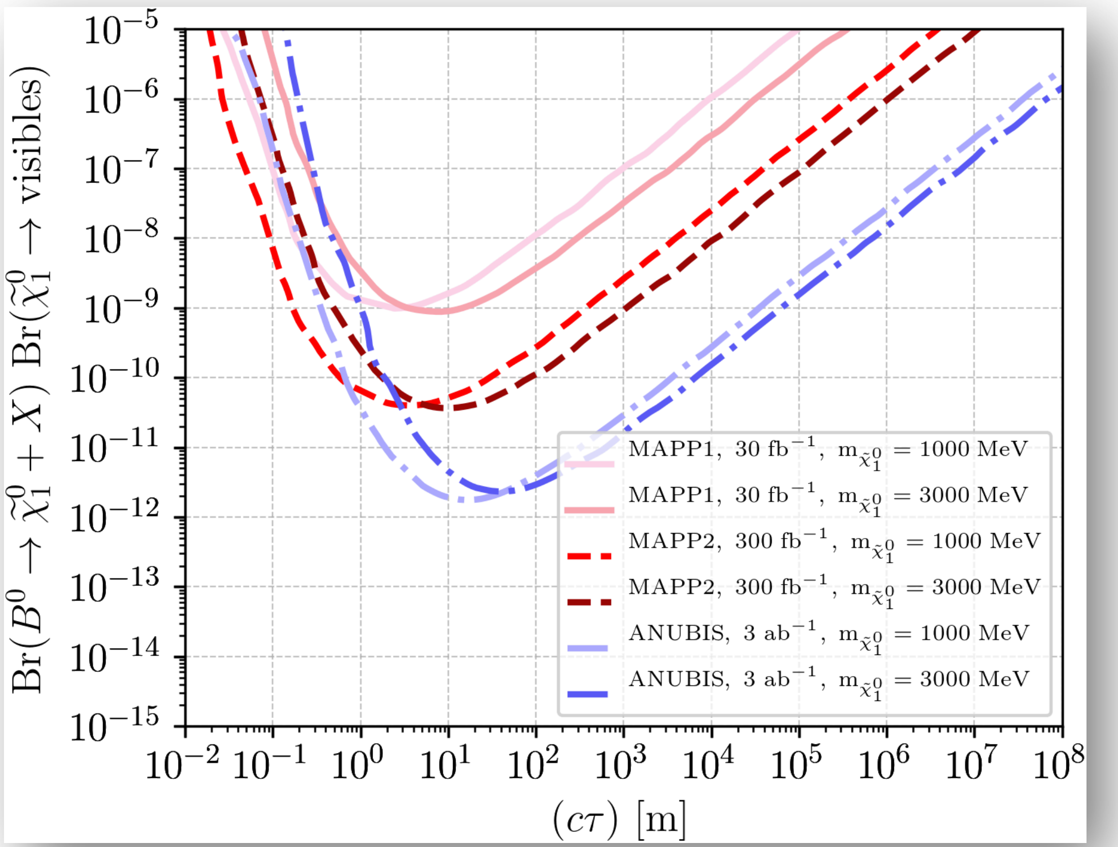


Frank et al, Phys.Lett.B 802 (2020) 135204

MAPP2– Physics Program

R-parity violating (RPV) supersymmetry

If RPV coupling, λ, λ’, λ’’ small enough, the (N)LSP may be long lived



Dreiner, Günther, Wang, PRD 103 (2021) 075013

$\tilde{\chi}_1^0 \to$ charged

λ'_P for production	λ'_{131}
λ'_D for decay	λ'_{112}
Produced meson(s)	B^0, $\bar{B}^0$
Visible final state(s)	$K^\pm + e^\mp$, $K^{*\pm} + e^\mp$
Invisible final state(s) via λ'_P	None
Invisible final state(s) via λ'_D	$(K_L^0, K_S^0, K^*) + (\nu_e, \bar{\nu}_e)$

} RPV couplings

Sensitivity of LLP experiments, such as MAPP, to sterile neutrinos recast to obtain bounds on RPV couplings associated with light neutralino

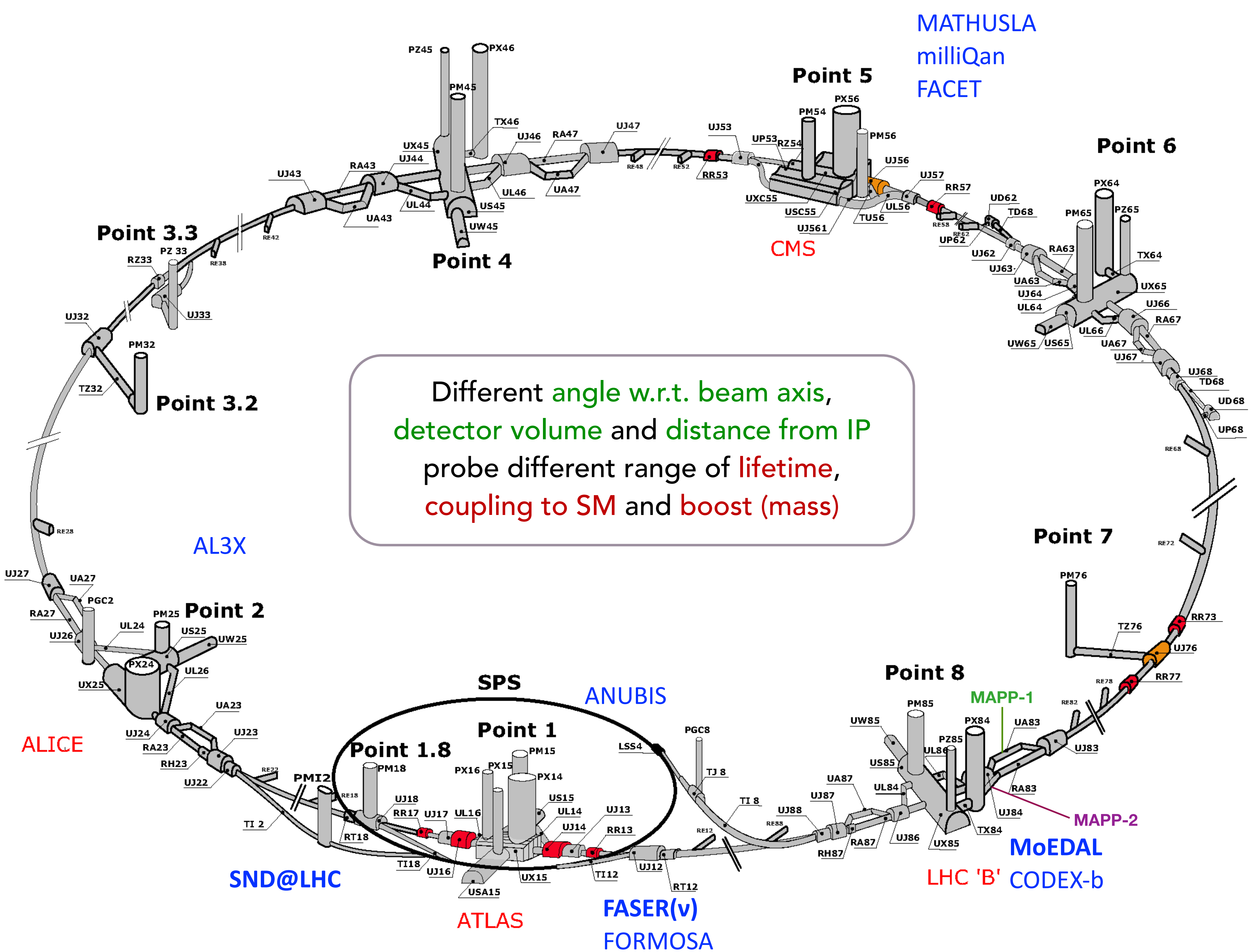
⬇

improvement on current bounds on RPV couplings by up to 3–4 orders of magnitude

Dreiner, Köhler, Nangia, Schürmann, Wang, JHEP 08 (2023) 058

MAPP MoEDAL

LHC dedicated LLP experiments



Different angle w.r.t. beam axis, detector volume and distance from IP probe different range of lifetime, coupling to SM and boost (mass)