Simulation of MAPP-1 Detector in GEANT4

Abhinab Mukhopadhyay

Supervisor: James Pinfold

University of Alberta

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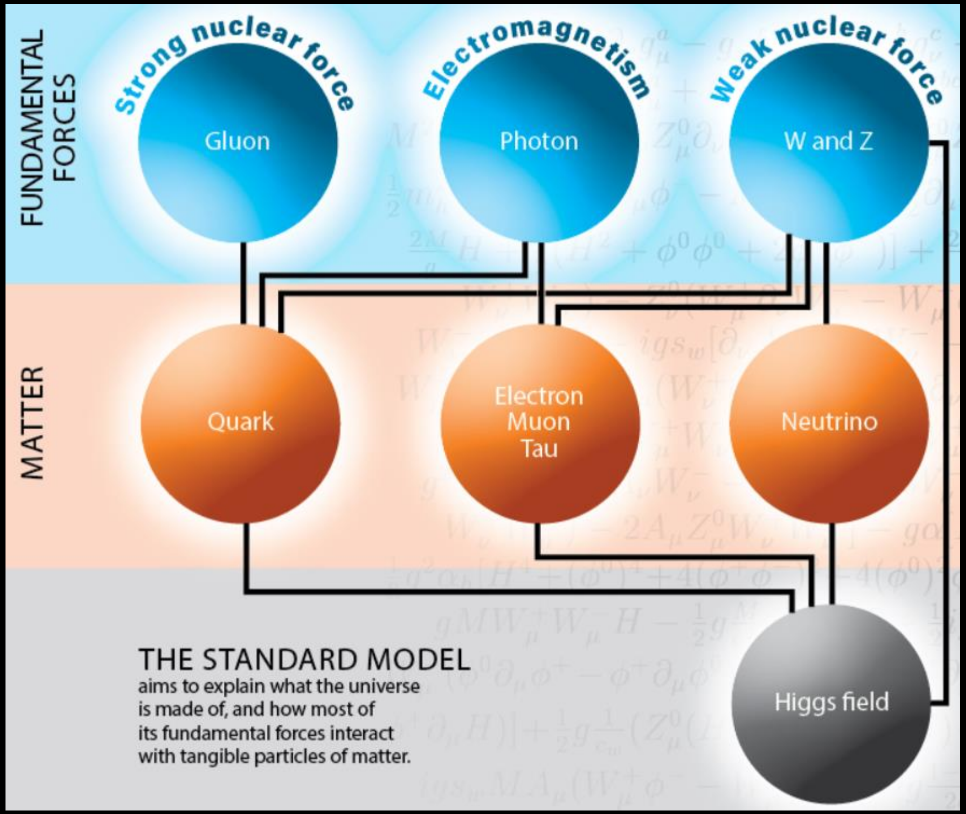
Limitations of Standard Model

SM doesn’t provide any insights to :

- Charge quantization – Why is charge quantized ? "What is the mechanism of electric charge quantization?
- Doesn’t explain Anti-matter matter asymmetry
- Doesn’t explain Dark Matter (DM) and the nature of DM. Where are the DM particle candidates?



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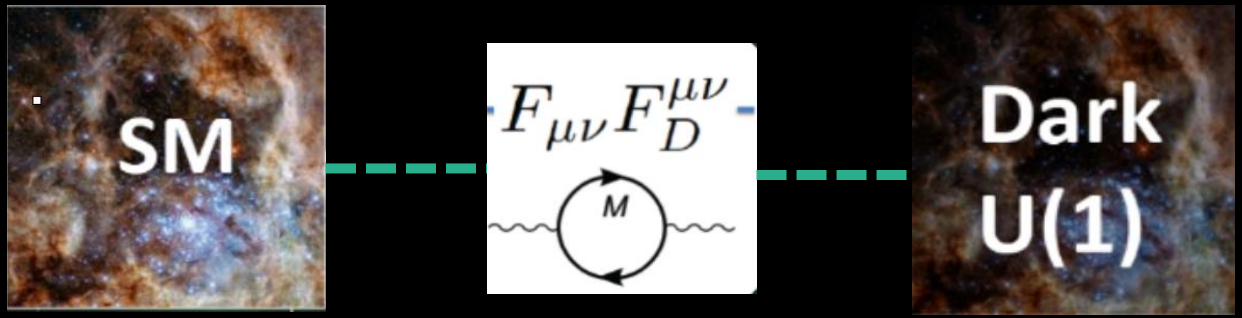
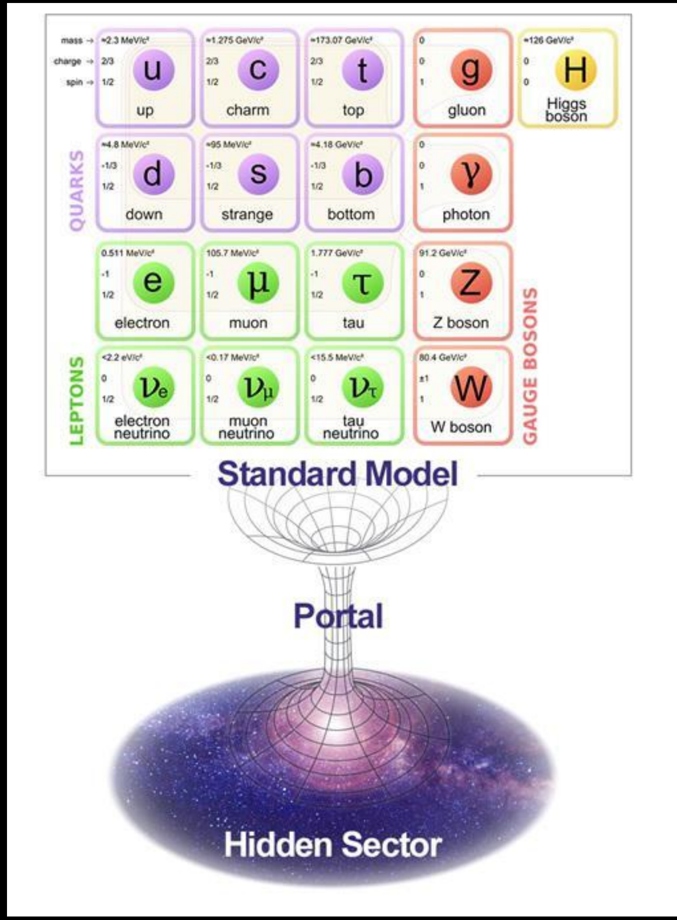
Milli-Charged Particles and Portals

- Beyond Standard Model Theories: A Dark Sector
- Interactions between two sectors are via mediator particles through so-called “portal interactions” - in this case vector portal



- Feebly Ionizing Particles(FIPs) such as Milli-charged particles (mCPs) arising from Dark Sector models can provide a possible solutions and insight to these problems
- mCP Hypothetical non-SM particles that have an effective charge with typical order of 10^{-3} ***e***



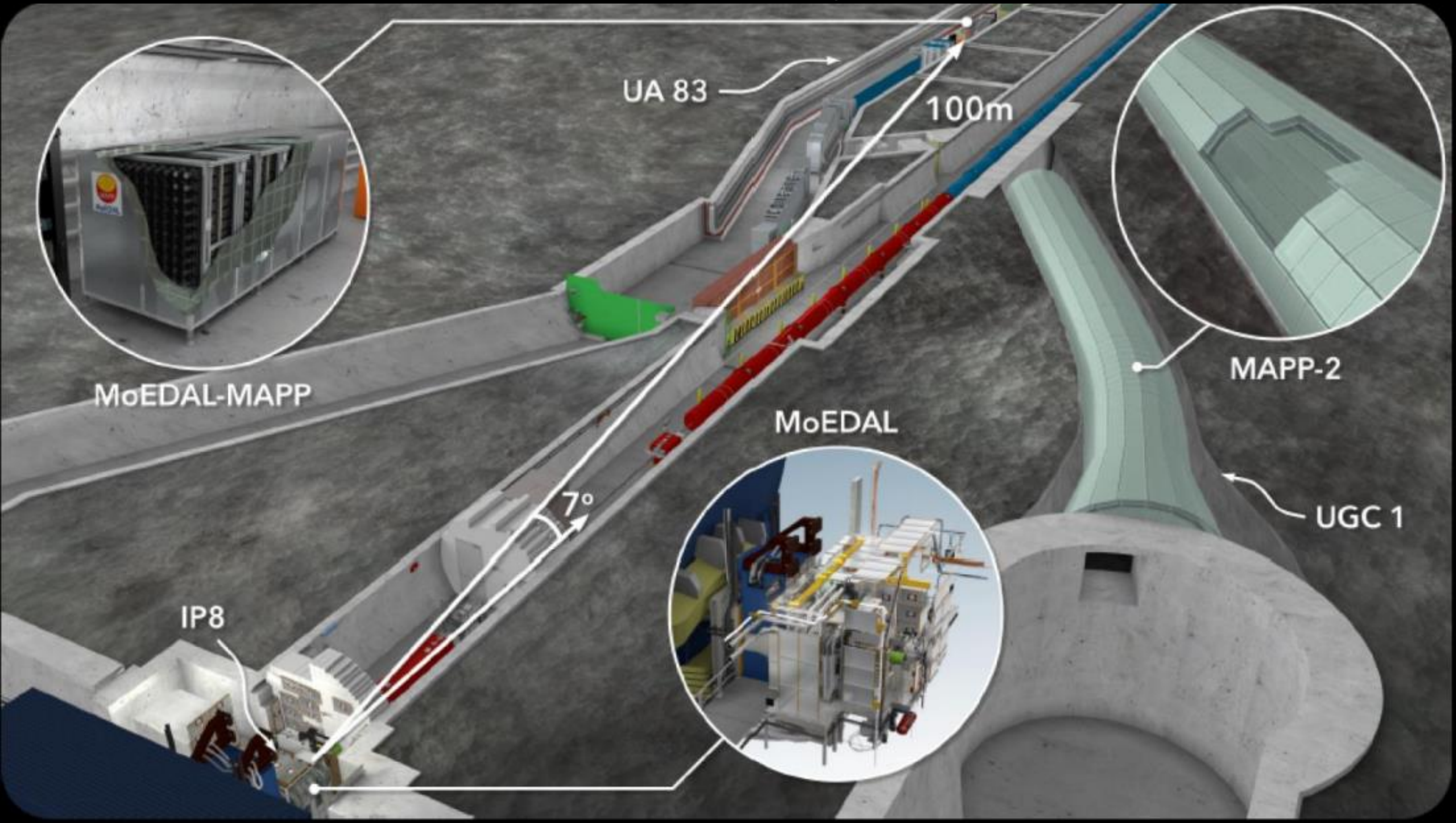
Kunio Kaneta et al, Physical Review Letters (2017)

Why do we need a dedicated search Experiment ?

- Major experiments such as ATLAS, CMS, ALICE and LHCb have limitations when searching for such exotic particles as they are not optimized for these searches
- For example, ATLAS is unable to see mCPs below charge of 1/3e[1]
- Since mCPs will deposit very little energy, they will not register at the LHC detectors sub-components
- Hence you would need dedicated experiment designed to search for FIPs such as mCPs

[1] https://cds.cern.ch/record/2872119/files/ATL-GEN-PUB-2023-001.pdf

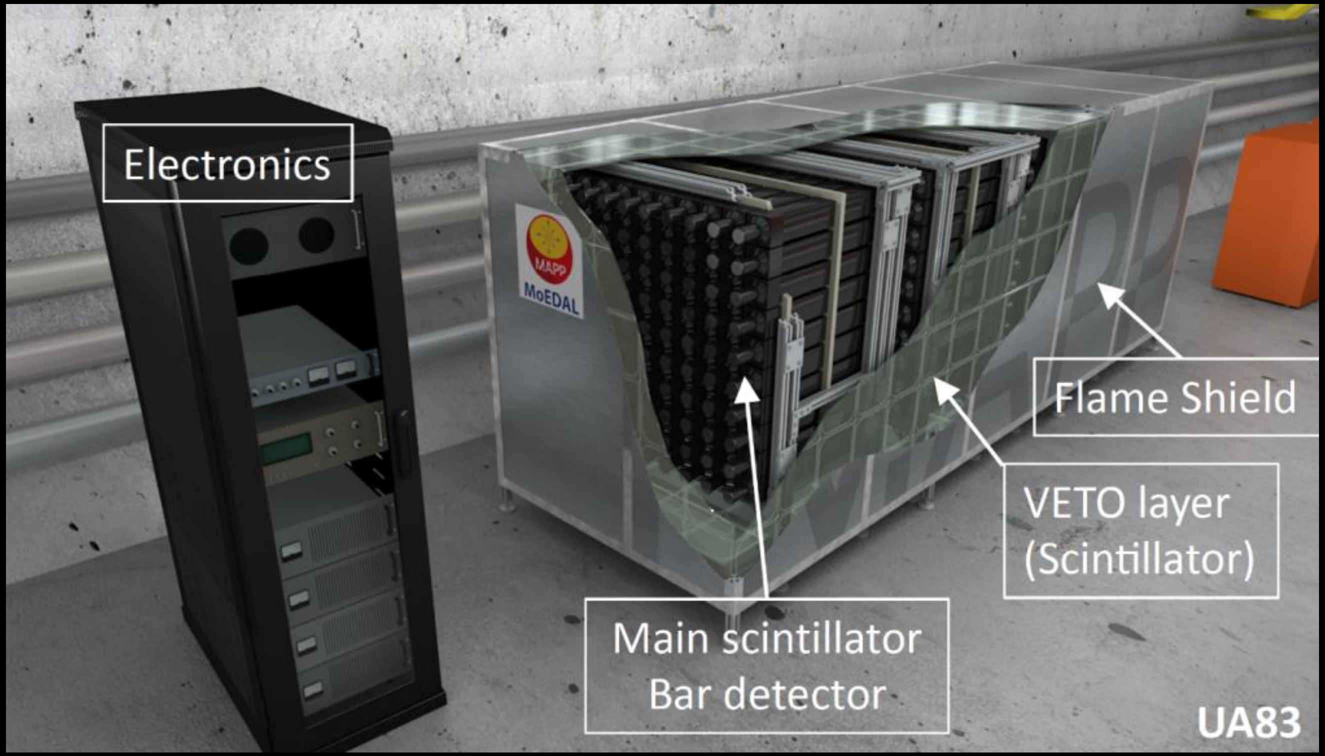
MoEDAL-MAPP Experiment



Phase 1: MoEDAL (In place)
Phase 2: MAPP-1 (Planned for Run 4)
Phase 3: MAPP-2 (Design stage)

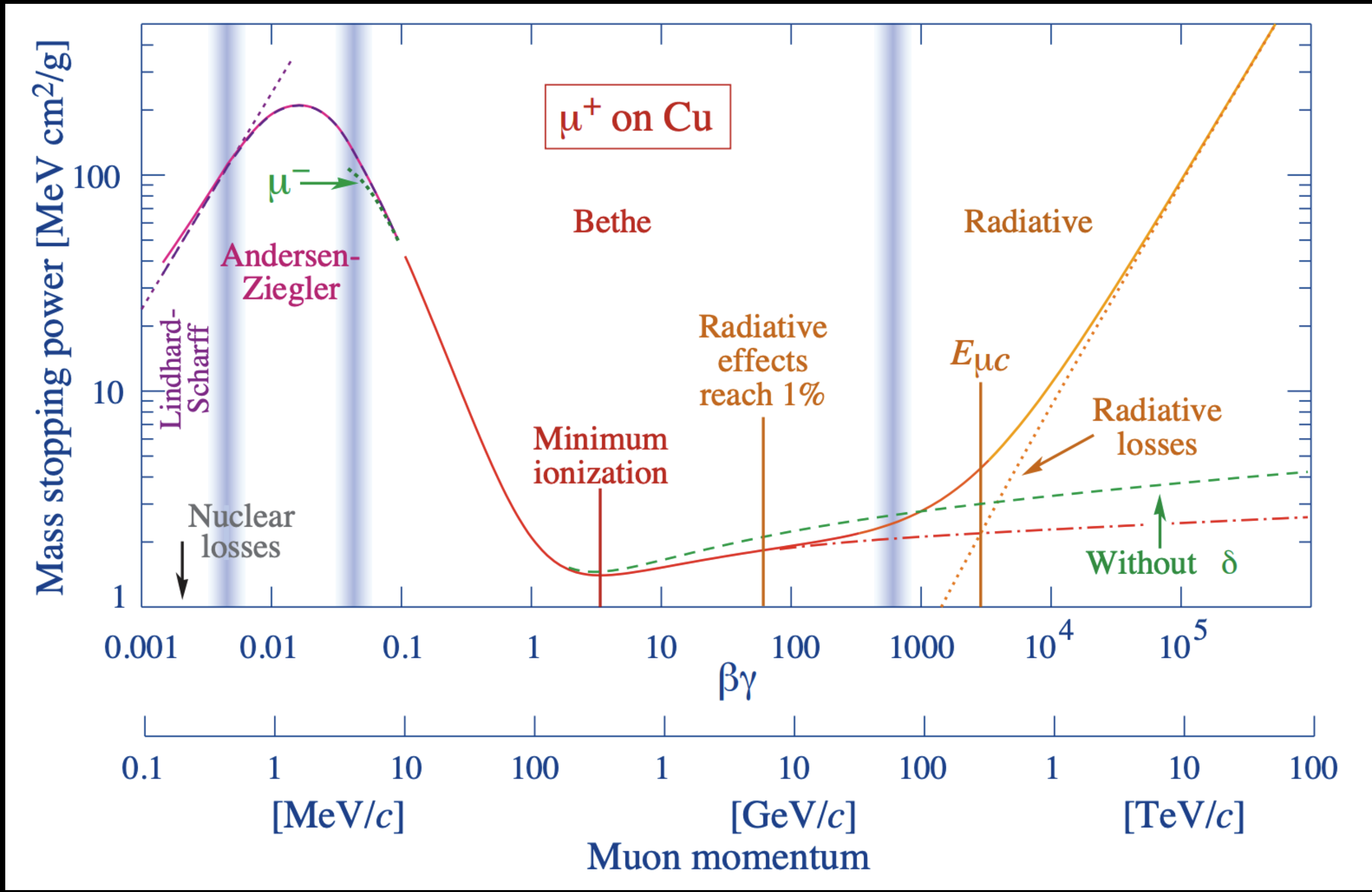
MAPP-1 Detector

- Located at U83 Gallery which benefits from 110m of rock overburden, providing substantial protection from Cosmic ray
- It is also protected from collision-related background by approximately 50m of rock
- Each scintillator bar unit of size 10 cm x 10 cm x 75 cm coupled directly to low noise photomultiplier tube (PMT)
- Design provides four-fold coincidence to reduce false signal events
- Outer layer is veto layer to veto out any cosmic muon and background events



Modelling Energy loss of Milli-Charged Particle

- Energy loss of mCP it is generally treated as muon with fractional charge [1]
- Hence all equations for energy loss such as Bethe-Bloch for ionization is scaled with mCP charge → cross-section multiplied with ratio of charge of mCP squared
- Radiative energy loss process such as Bremsstrahlung and Pair production are included. Their respective cross-section is also scaled by taking ratio of charge of mCP squared



Mass stopping power of positive muons in Copper [Taken from PDG "passage of particles"]

Experimental Method Simplified

Collisions are produced in LHC
[p-p collisions …]

Data Acquisition takes place in main collision points [ATLAS, CMS, LHCb, ALICE]

Event Reconstruction
[ORCA, ATHENA]

Event Generators generate physics events for targeted particles-[MADGRAPH]

Detector Simulation – Detector response to physics events [**GEANT4 - SUMMA** ,
GEANT4 MAPP-1 Optical Model]

Modified Event Reconstruction:
Implementation of GEANT4 processes for Optical detector response [**GEANT4 MAPP-1 Optical Model**]

Physics Analysis
ROOT, Python …

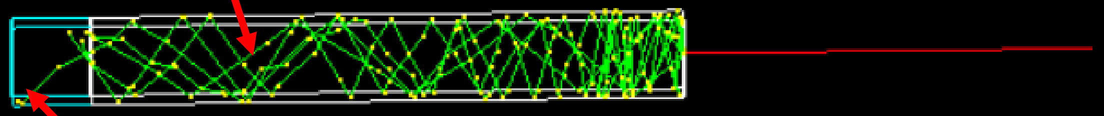
My current focus

Optical Model of MAPP-1 component – Scintillator Units (Preliminary)

- The Plastic scintillator was wrapped with Tyvek in custom GEANT4 optical library
- Silicone light guide was initialized as sensitive detector and attached to end of SP32 Plastic scintillator bar to record number of optical photons reaching end of the bar.
- Optical photon boundary interaction between Tyvek, Plastic Scintillator and Silicone was defined

Now with optical model we can estimate our detector sensitivity !

Plastic Scintillator with Tyvek Wrapping



pseudo-detector [Silicone]

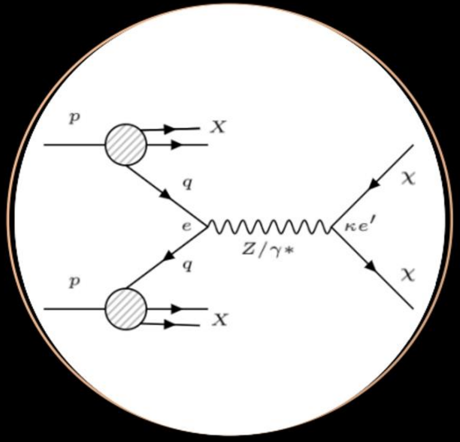
Image above is Scintillator unit with Scintillator yield reduced significantly to show optical photon propagation inside the unit

Estimating detector sensitivity by incorporating optical simulations

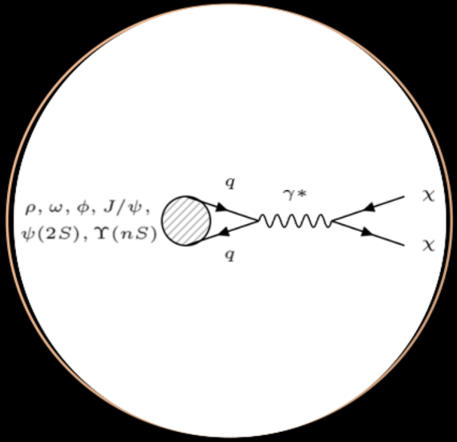
- The sensitivity of the MAPP-1 detector to mCPs for LHC-HL run was determined based on the following formulas [1]:

$$N_{\text{sig}} = N_\chi \times A \times P \qquad P = \left(1 - \mathrm{e}^{-N_{\text{PE}}}\right)^n \qquad N_{\text{PE}} \propto \epsilon^2 N_\gamma \text{QE}$$

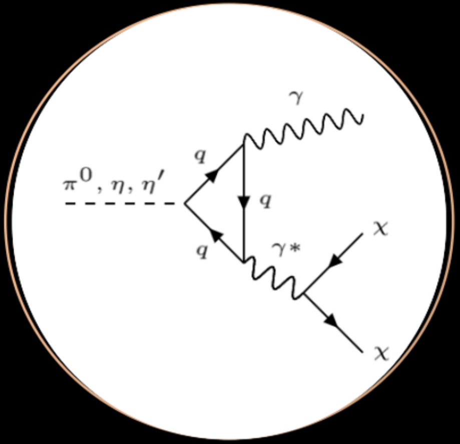
- Where ***Nχ*** is the number of mCPs produced, ***A*** is geometric acceptance of the detector, and ***P*** is detection probability of charged particles with ***n*** scintillator bars
- ***Nχ*** values are determined by calculating the accumulative contributions from different production mechanism for mCP using MadGraph. The mCP production considered for this study is shown:



via the **Drell-Yan Process**



via **direct decays of vector mesons**



via **Dalitz decays of pseudoscalar mesons**

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[1] https://doi.org/10.1007/JHEP04(2024)137

Estimating detector sensitivity by incorporating optical simulations

$N_{\mathrm{sig}} = N_{\chi} \times A \times P$ $\quad P = \left(1 - \mathrm{e}^{-N_{\mathrm{PE}}}\right)^n$ $\quad N_{\mathrm{PE}} \propto \epsilon^2 N_{\gamma} \mathrm{QE}$

- Number of Photoelectrons (***N_{PE}***) is computed based on the Quantum Efficiency (QE) of the XP72B20 PMT which taken to be 25% [1].
- Number of Optical Photons given by Nγ reaching the silicone light guide from 1 GeV muon was obtained and converted to photoelectrons.
- The charge scaling was used to determine number of photoelectrons of mCP with effective charge ***ϵ*** passing through the MAPP-1 scintillator unit.

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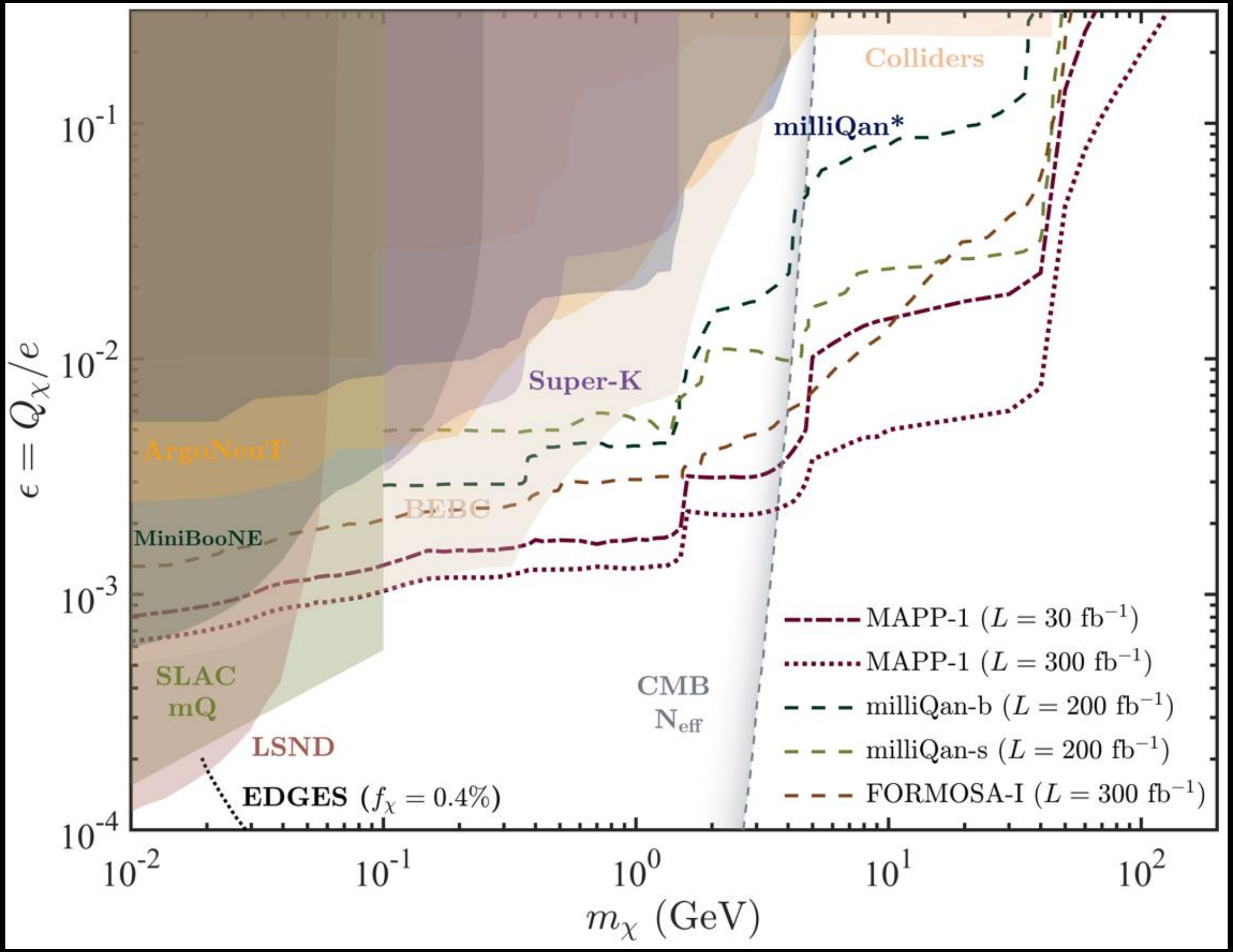
[1] https://doi.org/10.1016/j.nima.2021.165347

Projected exclusion limits



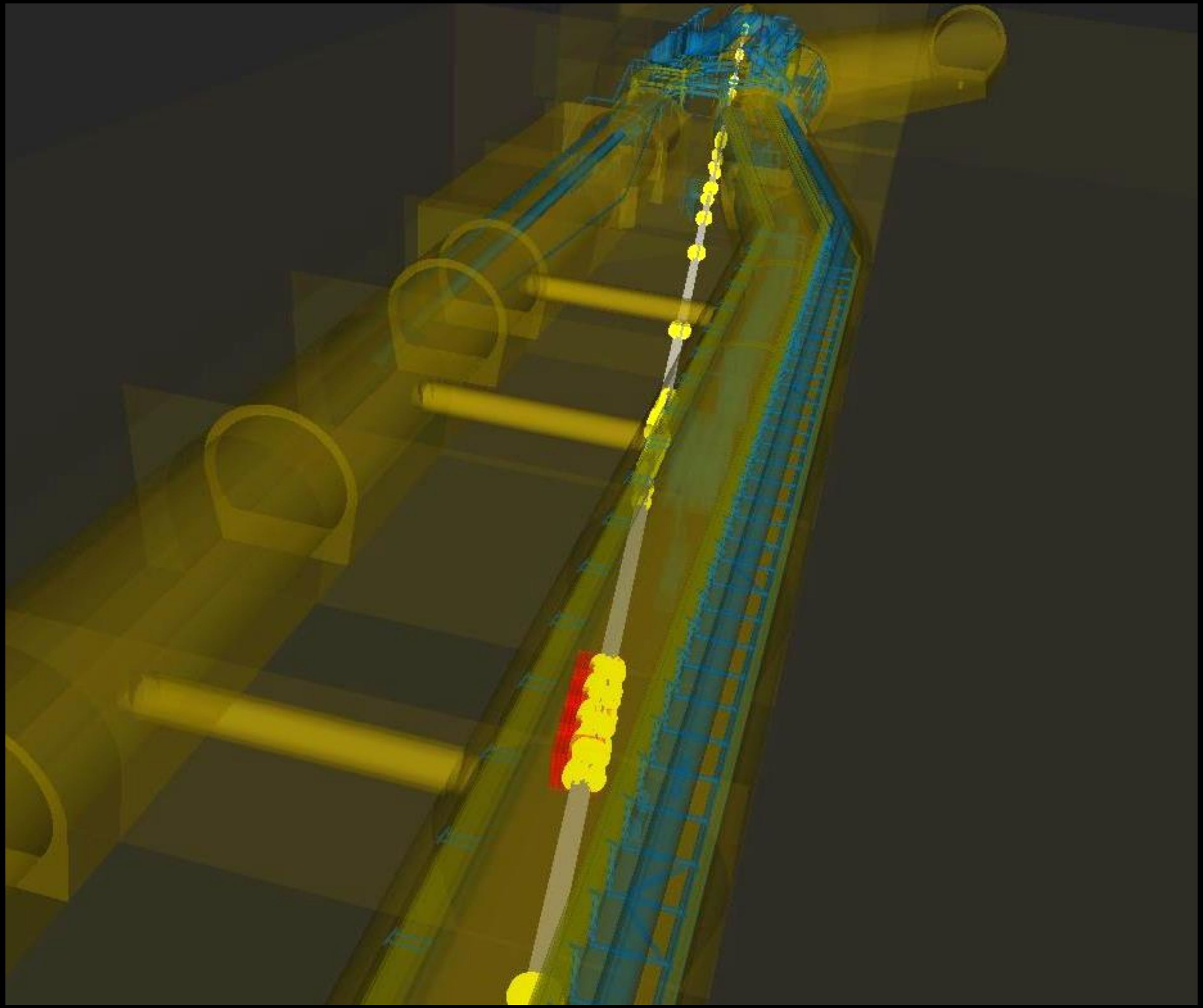
The projected 95% confidence level (CL) Background free exclusion limits for MAPP-1 compared to other experiments

The plots show both respective luminosity for Run-3 and upcoming high luminosity run.

References:
MAPP-1: arXiv:2307.07855; J. High Energ. Phys. 2024, 137 (2024).
milliQan: Phys. Lett. B 746, 117–120 (2015); Phys. Rev. D 104, 032002 (2021).
FORMOSA: Phys. Rev. D 104, 035014 (2021).

SimUlation of the MoEDAL-MAPP Arena (SUMMA) Model

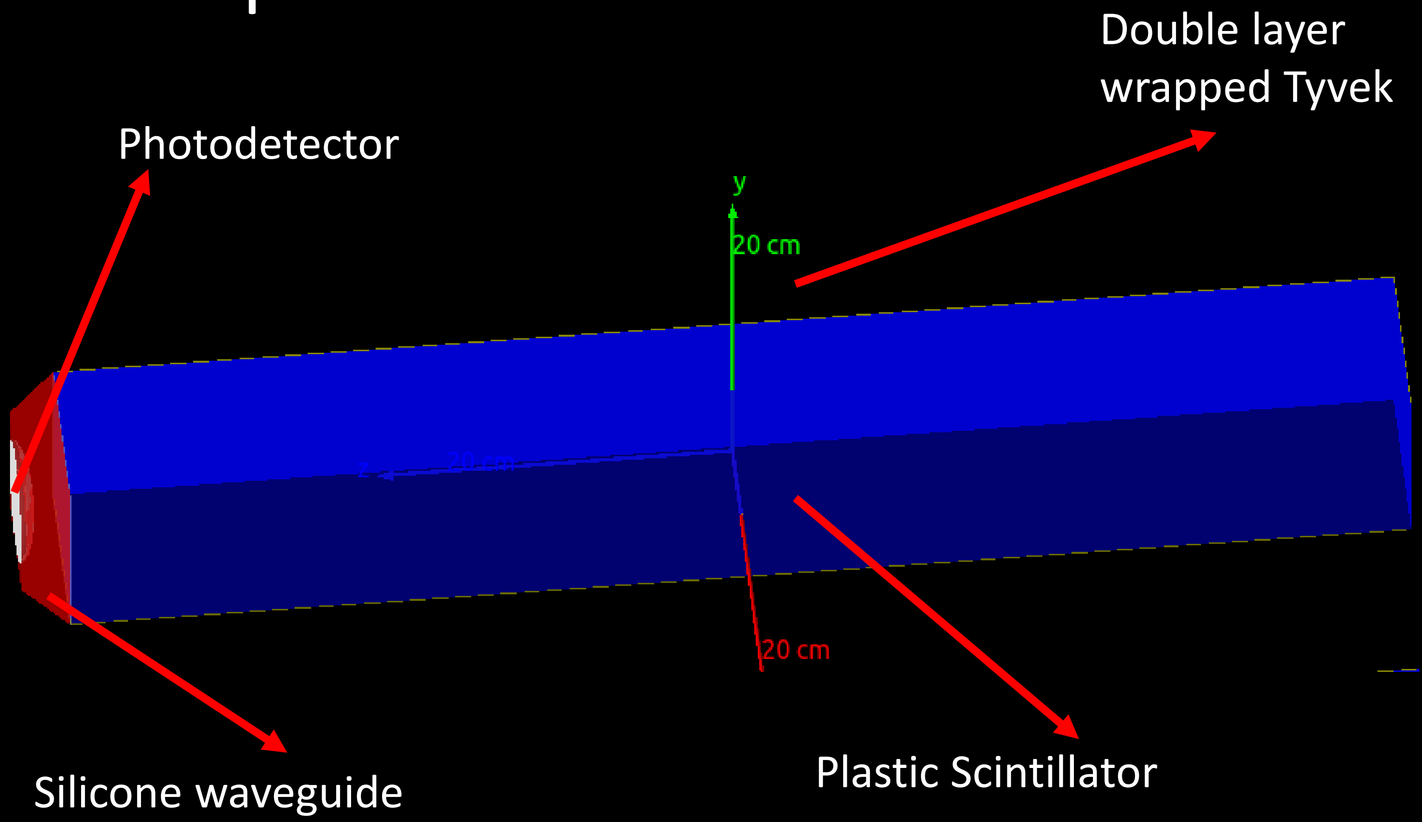
- A full SUMMA Model has been developed to get a more realistic simulation of MAPP-1 Detector
- Includes all the interaction material from IP8 to MAPP-1 detector
- Is to be interfaced with the Optical Model to get a more realistic sensitivity of MAPP-1 to mCPs
- Takes account of the attenuation and scattering of mCPs as it traverses through material from IP8 to MAPP-1



MAPP-1 Optical Model Updated

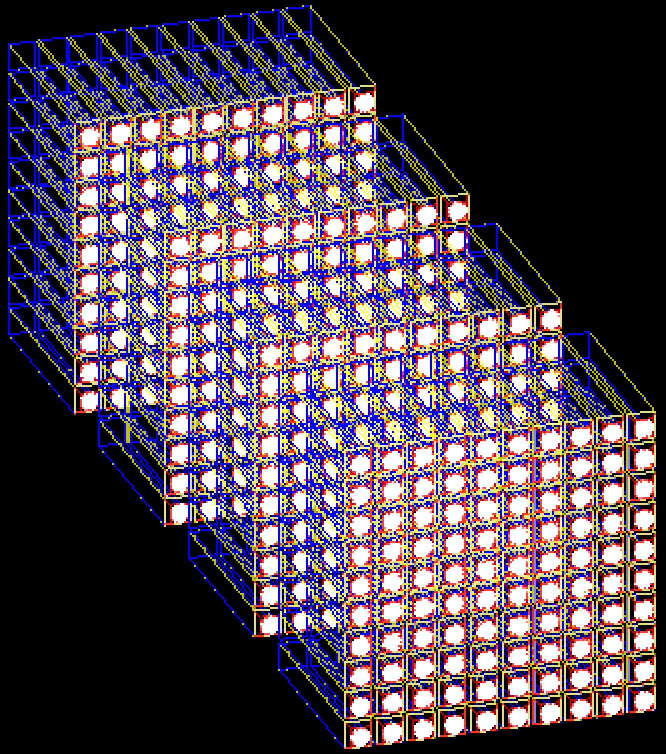
What's new?

- More realistic implementation of MAPP-1 plastic scintillators (SP32). Includes modified Birk coefficient , optical parameters such as relative emission spectrum of SP32 model.
- Accurate geometric shapes - Silicone light guide and PMTs
- **Implementation of PDE (Photo Detector Efficiency) in PMT: Photoelectrons are produced based on the absorption spectrum of photons that reach the PMT.**



Summary and Future

- Preliminary Optical Model was used to get preliminary exclusion plots of MAPP-1 detector to mCPs
- By combining the SUMMA Model and MAPP-1 Optical Model we can more realistically and accurately simulate the MAPP-1 Detector reach for mCPs
- Get realistic detector response to mCPs with different mass and charges using High Performance Computing
- Plan is also to extend simulation for sensitivity analysis for Long Lived Particles (another exotic type of particles arising from Dark Sector)



Rendered GEANT4 image of MAPP-1 Detector with all its optical component

THANK YOU !

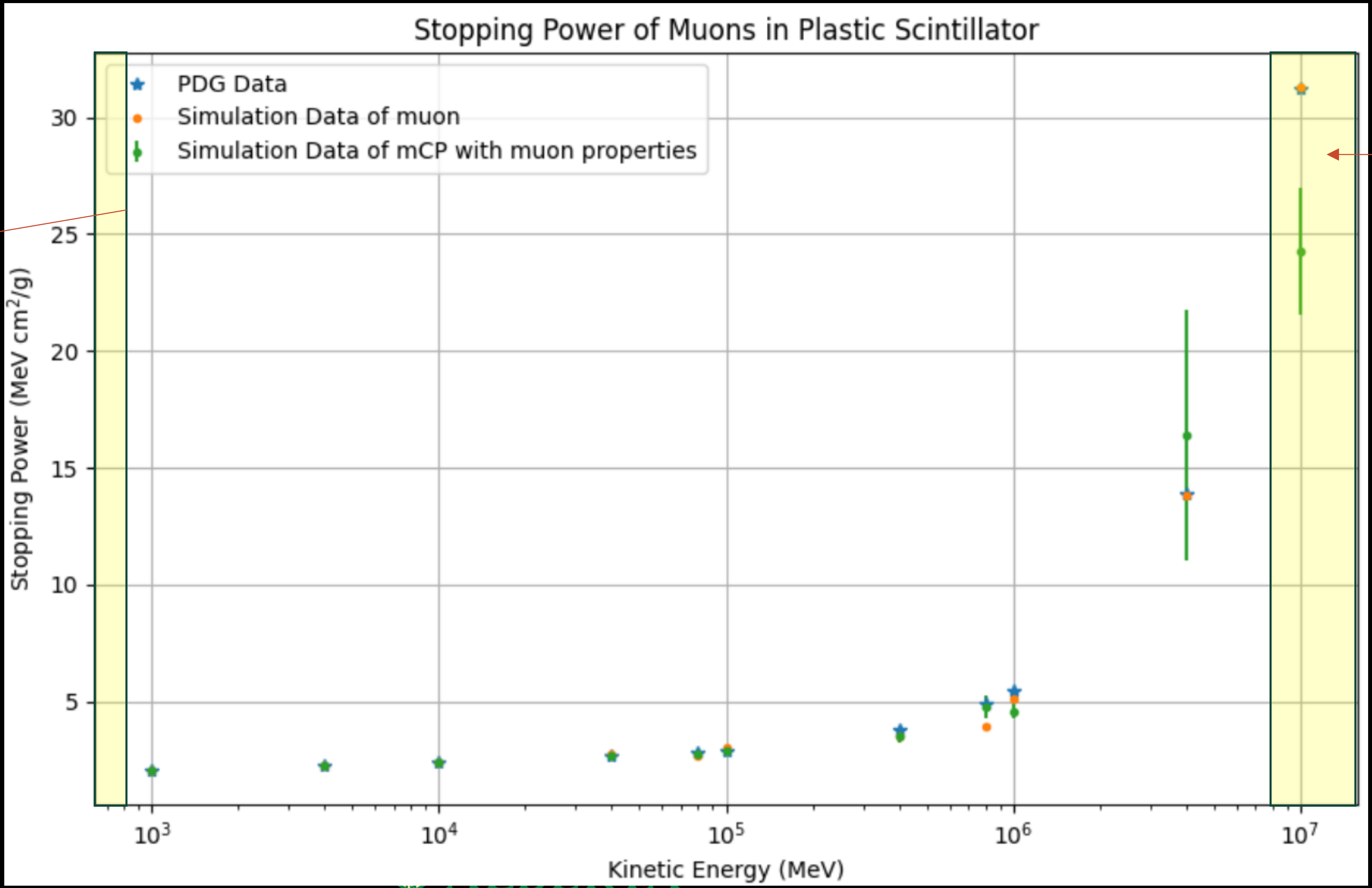
Main Collaborators:

Dr. James Pinfold	[University of Alberta]
Dr. Michael Staelens	[Okanagan College]
Dr. Matti Kalliokoski	[University of Helsinki]
Dr. Pierre-Philippe A. Ouimet	[University of Regina]

BACKUP SLIDES

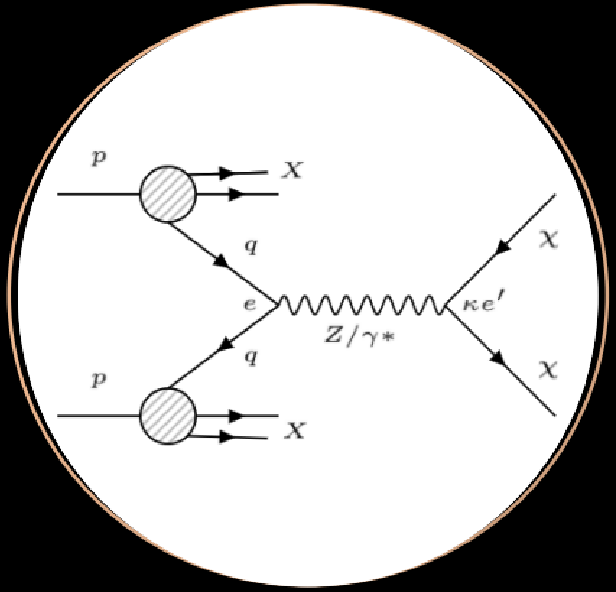
Energy loss validation

Nuclear stopping model not implemented yet

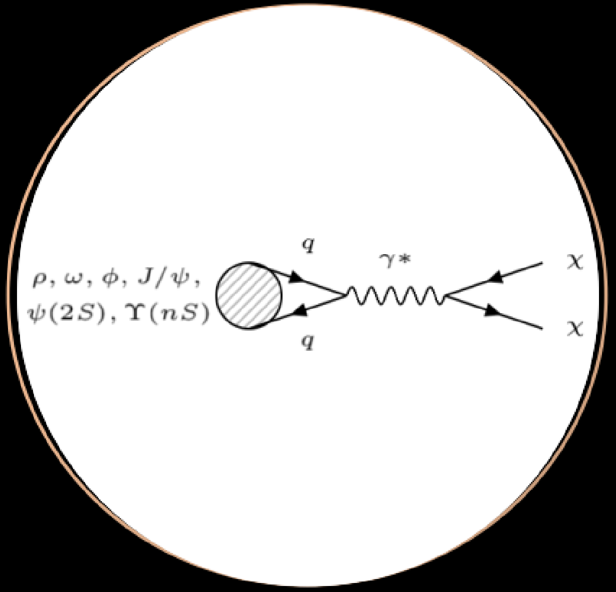


Photonuclear energy loss model not implemented

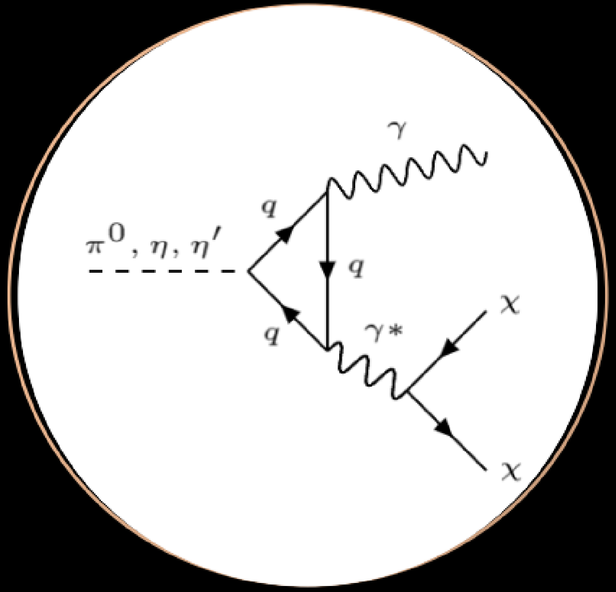
Production mechanism of mCPs at CERN



via the **Drell–Yan Process**

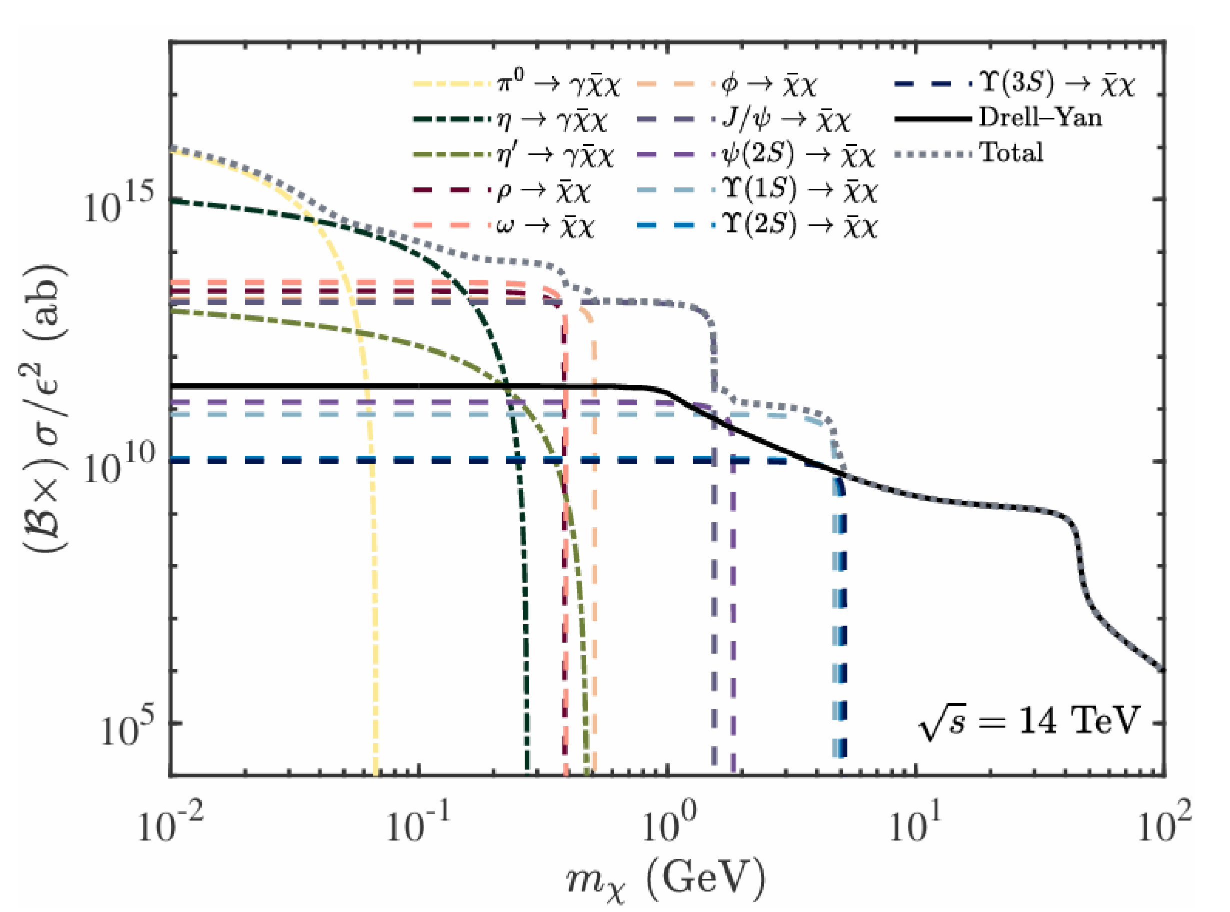


via **direct decays of vector mesons**



via **Dalitz decays of pseudoscalar mesons**

Cross – sections computed via MadGraph



Charge-normalized minicharged particle production cross-sections at √s = 14TeV for all processes considered in this study. Results corresponding to meson decays are scaled by their respective branching ratios

Physics changes

1. **G4MuBetheBlochModel** –

- multiplying the cross section per electron by mCP charge squared.
- multiplying the dE/dX per volume by mCP charge squared.

$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

2. **G4MuBremsstrahlungModel** –

- minThreshold changed from 1keV to 50eV
- lowestKinEnergy changed from 1GeV to 100eV
- While setting particle as mCP,

'coeff' multiplied by charge squared,

used in Compute Microscopic Cross section,

referenced by Bremsstrahlung energy loss.

3. **G4MuPairProductionModel** –

- Lowest limit for pair production dependent on particle mass (limit = mass*8)
- Lowest KE = limit , Max KE = 10 TeV.
- multiplying the dE/dX per volume by mCP charge squared.
- multiplying cross section per atom by mCP charge squared

$$\sigma_{pair} = Z^2 \alpha r_e^2 \frac{2\pi}{3} \left(\frac{k-2}{k} \right)^3 \left(1 + \frac{1}{2}\rho + \frac{23}{40}\rho^2 + \frac{11}{60}\rho^3 + \frac{29}{960}\rho^4 \right)$$

Energy loss [Continued…]

The differential cross section for muon bremsstrahlung (in units of $\text{cm}^2/(\text{g GeV})$ can be written as

$$\frac{d\sigma(E,\epsilon,Z,A)}{d\epsilon} = \frac{16}{3}\alpha N_A(\frac{m}{\mu}r_e)^2\frac{1}{\epsilon A}Z(Z\Phi_n+\Phi_e)(1-v+\frac{3}{4}v^2)$$
$$= 0 \quad \text{if} \quad \epsilon \geq \epsilon_{\text{max}} = E-\mu,$$

where μ and m are the muon and electron masses, Z and A are the atomic number and atomic weight of the material, and N_A is Avogadro's number. If E and T are the initial total and kinetic energy of the muon, and ϵ is the emitted photon energy, then $\epsilon = E - E'$ and the relative energy transfer $v = \epsilon/E$.


CODEX-b
MATHUSLA
ANUBIS
MilliQan
MoEDAL
AL3X
=0
Transverse
0 < η < 1.5
η=0.5
η=1
η=1.5
MAPP-2
MAPP-1
Intermediate
1.5 < η < 4
η=2
η=2.5
η=3
η=4
Forward
η > 4
FPF
Forward Physics Facility
FASER- 2, FASERnu2, advSND, FORMOSA, FLARE
FORMOSA
FASER
SND
FACET

Background Considerations:

- MAPP-1 is naturally shielded from cosmic muons by 110 m rock overburden and 47 m of materials (concrete) from IP8 to its location.
- Background from muons originating from IP8 and its subsequently generated secondaries to be 1 out of 40,000 bunch-crossings
- Dark current in the PMTs can also result in signal-like events; however, the four-fold coincidence design employed essentially eliminates this BG source
- We assume a mean DCR of 500 Hz based on PMT Specifications. Assuming a 3-year trigger live time, a negligible result of 0.008 total signal-like events is obtained.

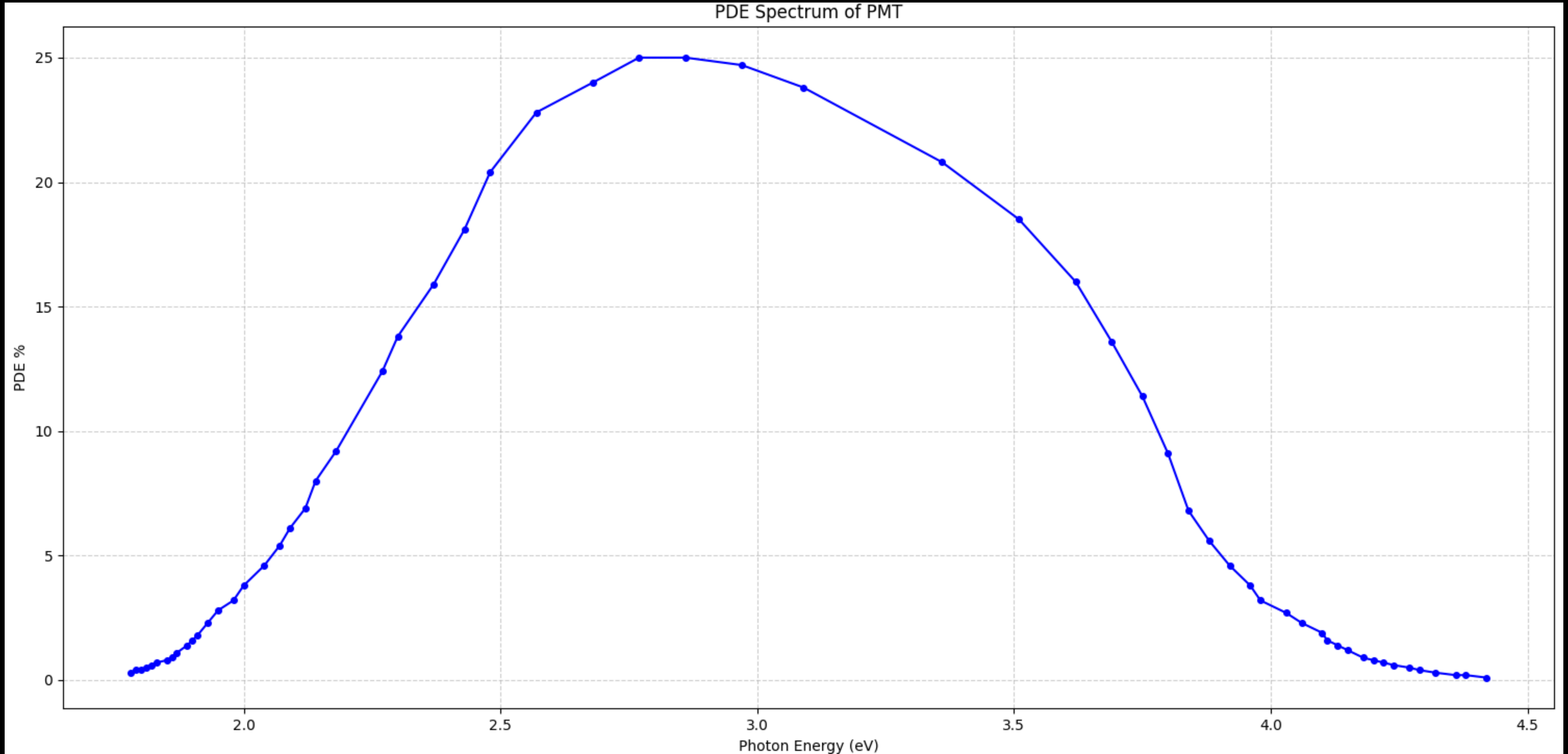
Physics changes

```
// create particle
//
//    Arguments for constructor are as follows
//               name             mass          width         charge
//             2*spin           parity  C-conjugation
//          2*Isospin       2*Isospin3       G-parity
//               type   lepton number  baryon number   PDG encoding
//             stable         lifetime     decay table
//             shortlived      subType     anti_encoding
anInstance = new G4ParticleDefinition(
        name, mass, 0,  +fabs(charge)*eplus,
        1,               0,                0,
        0,               0,                0,
        "lepton",        -1,                0,       -90,
        true,             0,             NULL,
        false,           "FCP"
        );
```

Optical Parameters [Extended]

Birk Law: Birk's coefficient quantifies the quenching effect in scintillators especially organic scintillator. It refers to loss of linearity is due to recombination and quenching effects between the excited molecules and the surrounding substrate.

PDE Plot for Photodetector



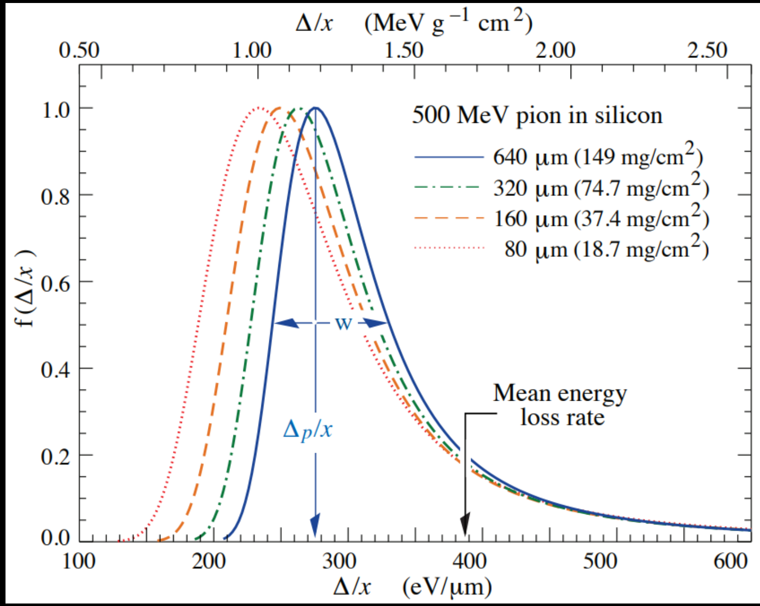
Energy Fluctuations

- For detectors of moderate thickness such as plastic scintillators the energy loss probability distribution function is adequately described by highly-skewed Landau distribution [1]
- The mean energy loss in absorber is influenced by the rare, high-energy-transfer collisions pushing it into the tail of the distribution.
- Hence for such thickness of detectors mean given by Bethe equation is thus ill-defined experimentally and instead Landau-Vavilov most probable energy loss function should be used.

The Key questions then arises are

1] Is this applicable to exotic particle such as mCPs ?

2] How can we implement this in GEANT4 for our case?



[1] Groom, Donald E., and S. R. Klein. "Passage of particles through matter." The European Physical Journal C-Particles and Fields 15, no. 1-4 (2000): 163-173.

Landau-Vavilov

- The most probable energy loss equation for moderate thickness ***x*** detector for given in PDG [1] :

$$\Delta_p = \xi \left[\ln \frac{2mc^2\beta^2\gamma^2}{I} + \ln \frac{\xi}{I} + j - \beta^2 - \delta(\beta\gamma) \right]$$

- Here ***ξ*** is Landau parameter in MeV , ***j*** is a correction term [dimensionless] and $\boldsymbol{\delta(\beta\gamma)}$ is density correction. ***I*** is mean excitation energy in MeV.
- Expression for ***ξ*** is given is:

$$\xi = (K/2)\,\langle Z/A\rangle\, z^2(x/\beta^2)$$

- Where ***K*** is Coefficient for dE/dx, 0.307075 MeV $\text{mol}^{-1}\,\text{cm}^2$, ***Z/A*** is ratio of Atomic and Mass number of detector material, ***z*** is charge of the incident particle and ***x*** is the detector thickness detector in gcm^{-2}
- "Moderate thickness" of detector is ***G*** value described by Rossi $G \le 0.05 - 0.1$ which is same as Vavilov's ***κ*** parameter[1][2]
- In that regime the fluctuations would be prominent and Landau-Vavilov should be used.

[1] B. Rossi, High Energy Particles, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1952.
[2] P. V. Vavilov, Sov. Phys. JETP 5, 749 (1957), [Zh. Eksp. Teor. Fiz.32,920(1957)].

Vavilov parameter

- We need to assess the Vavilov parameter for our case to determine if we can use fluctuation model
- Vavilov parameter $\boldsymbol{\kappa}$ is given by [1]

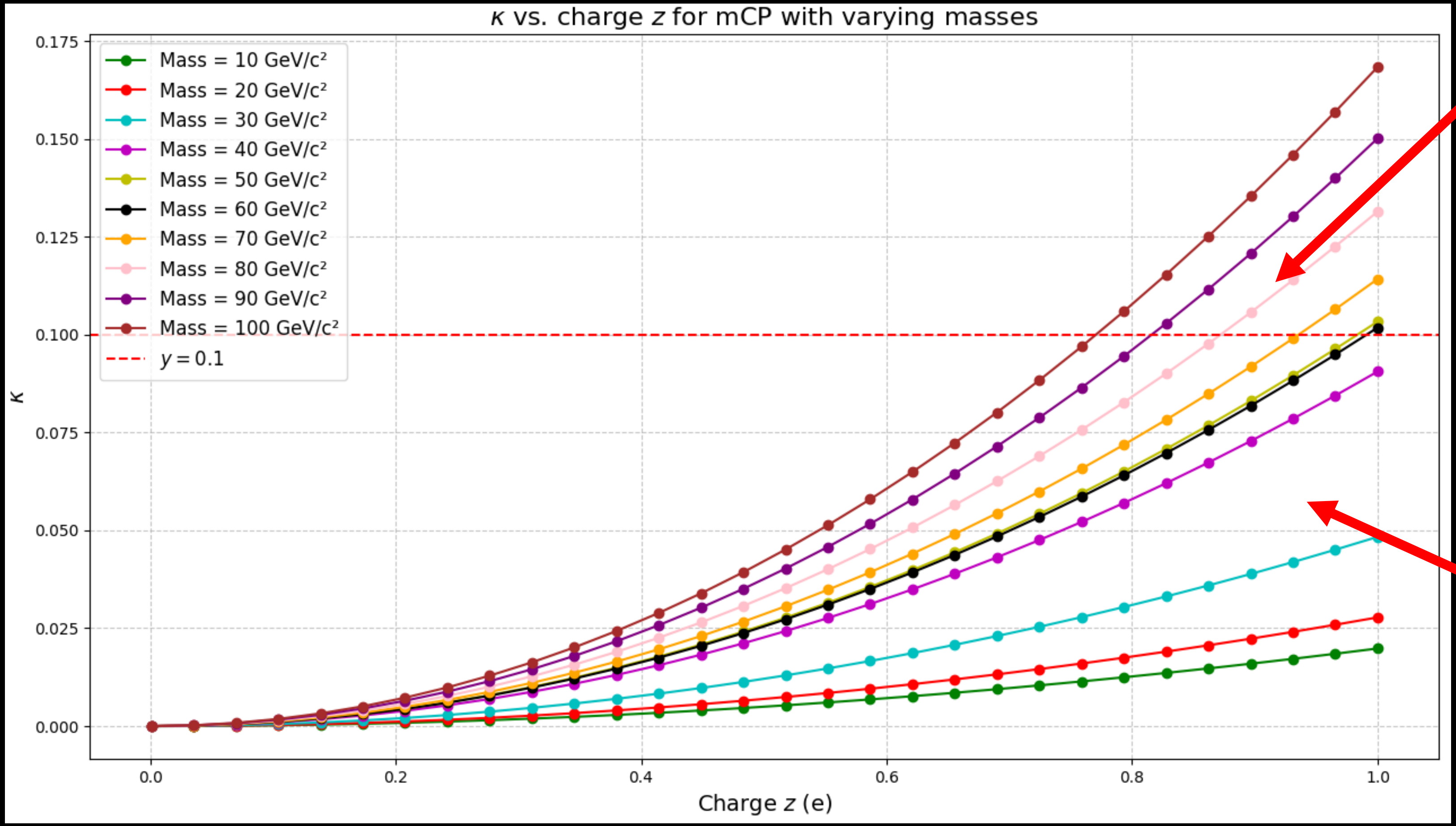
$$\kappa = \xi / E_M \ ,$$

$$E_M = Mc^2\beta^2\gamma^2 / [(M/2m) + (2m/M) + \gamma]$$

- $\boldsymbol{E_m}$ is the Maximum possible energy transfer to an electron in a single collision. $\boldsymbol{M}$ is incident particle mass and $\boldsymbol{m}$ is mass of electron.
- Hence, we can then compute $\boldsymbol{\kappa}$ for mCP with varying charges, masses and $\boldsymbol{\beta}$.
- The mCPs in the direction of MAPP-1 detector were found to have relativistic and ultra-relativistic $\boldsymbol{\beta}$ and each $\boldsymbol{\beta}$ per respective mass was calculated
- Hence with this simplification we can compute $\boldsymbol{\kappa}$ for varying charge based on mass of mCP and respective $\boldsymbol{\beta}$.

[1] H. Bichsel, Rev. Mod. Phys. 60, 663 (1988)

Vavilov parameter



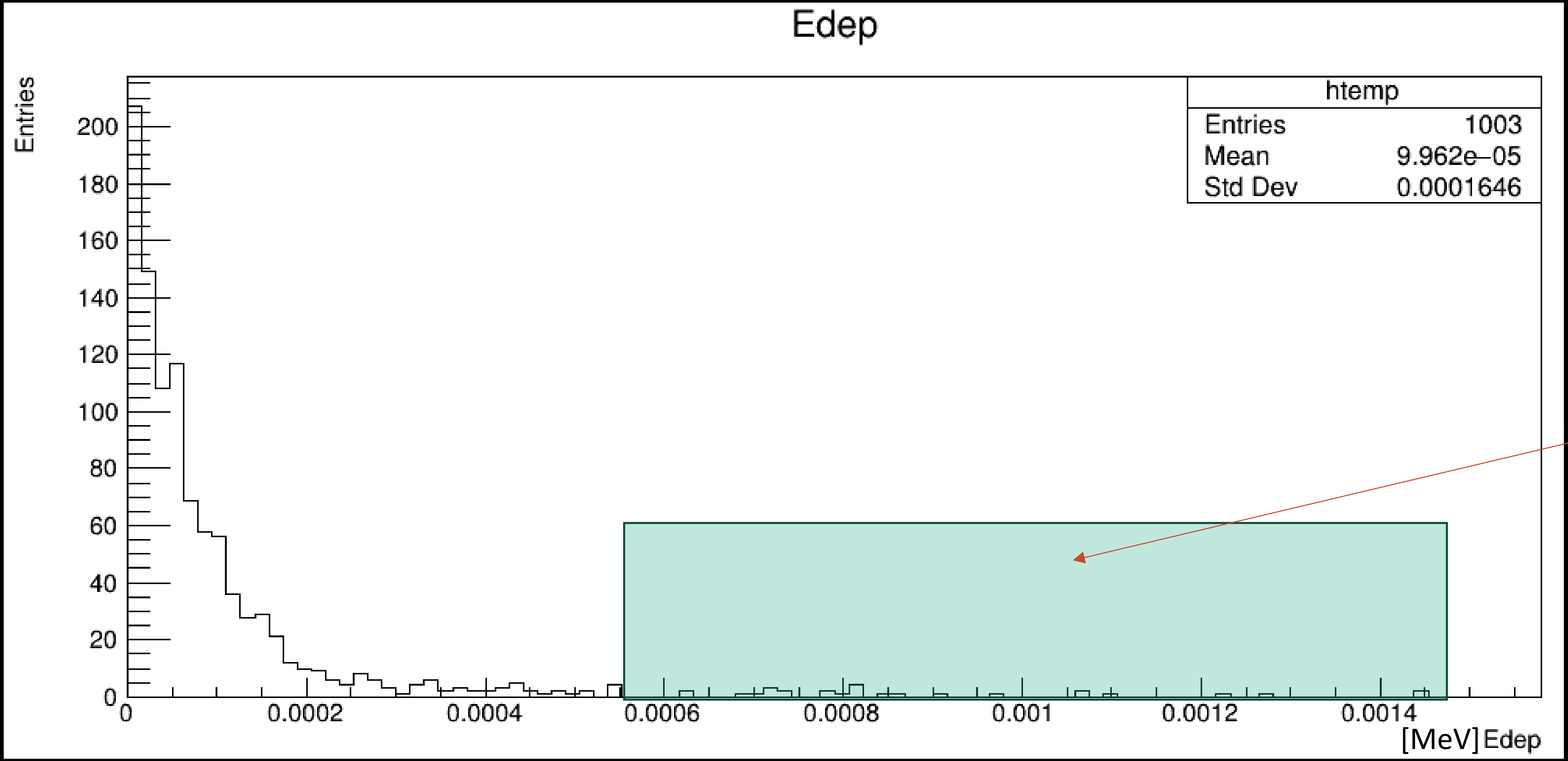
Landau Model is not [Thick detector]

Considered Moderate absorber -> Landau Model is dominant

Energy Fluctuations

- GEANT4 default physics list includes both low-energy and high energy loss fluctuation models
- However, since we are building the modified physics list, the fluctuation models are not automatically included.
- Looking at GEANT4 source code for Energy Loss Fluctuations, the GEANT4 implements via $G4V$ $EmFluctuationMode$l
- G4UniversalFluctuation model is used like the one used in default GEANT4 ionization source for muons.
- It automatically takes account for charge and mass of the particle hence it is applicable to any defined exotic particle [1]

[1] Geant4. (n.d.). *Geant4/source/processes/electromagnetic/standard/SRC/g4universalfluctuation.cc at master · GEANT4/GEANT4*. GitHub. https://github.com/Geant4/geant4/blob/master/source/processes/electromagnetic/standard/src/G4UniversalFluctuation.cc



Edep in Plastic scintillators in MAPP-1 for mCP 0.001e charge 30 GeV Mass generated at IP8

High end fluctuations that fall on Landau tail

Geometric Acceptance of MAPP-1 detector

- For a positive signal we consider geometric acceptance of mCP as it hits all 4 colinear plastic scintillators.
- For Background free case we require a minimum of 3 hits(signals) for clear discovery at the 95% confidence level [credits: Michael]