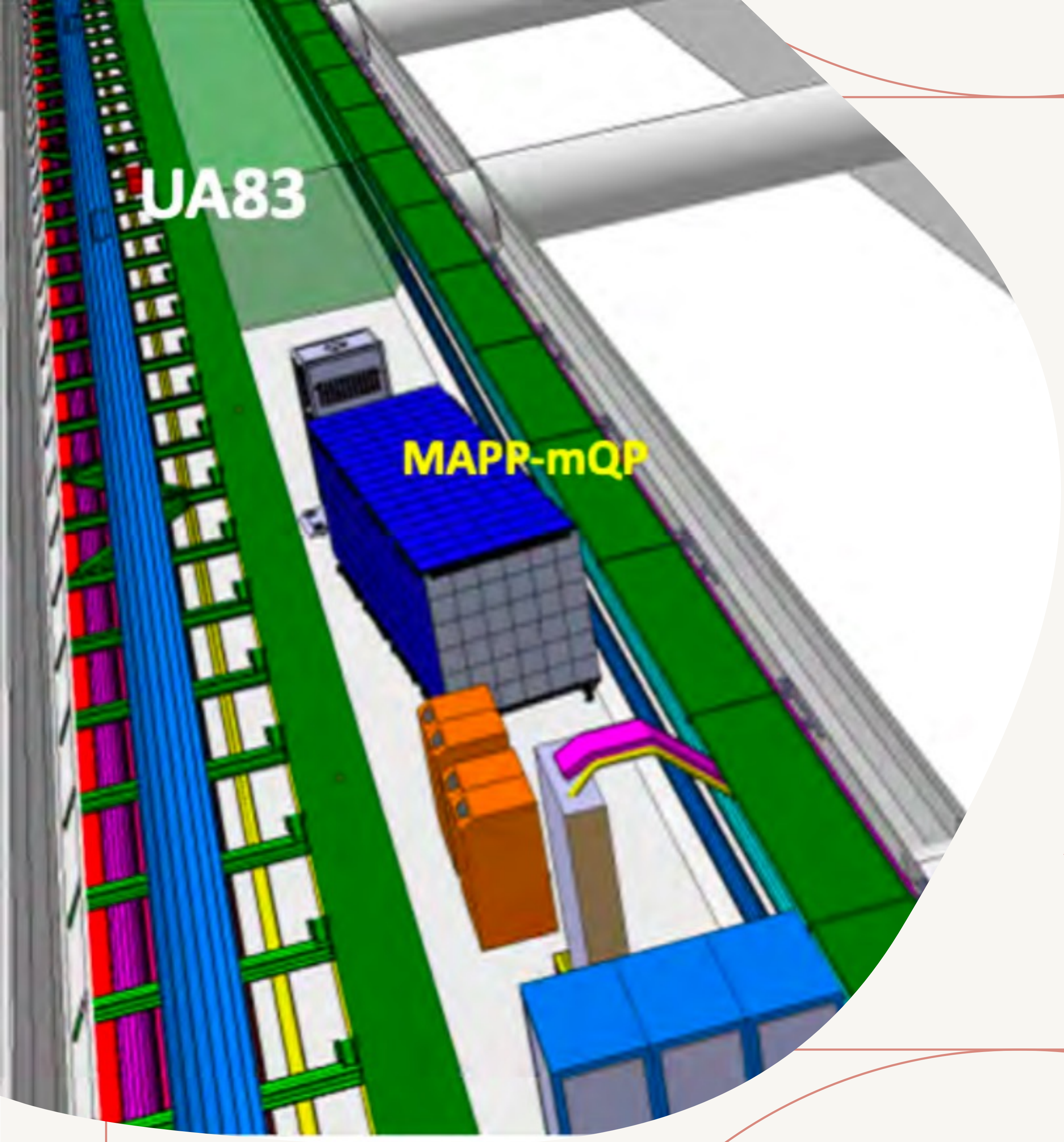


Geant4 simulations

Cosmic Muon Background at UA83 & mQP's G4 model

Aditya Upreti

LHCC Meeting on MAPP

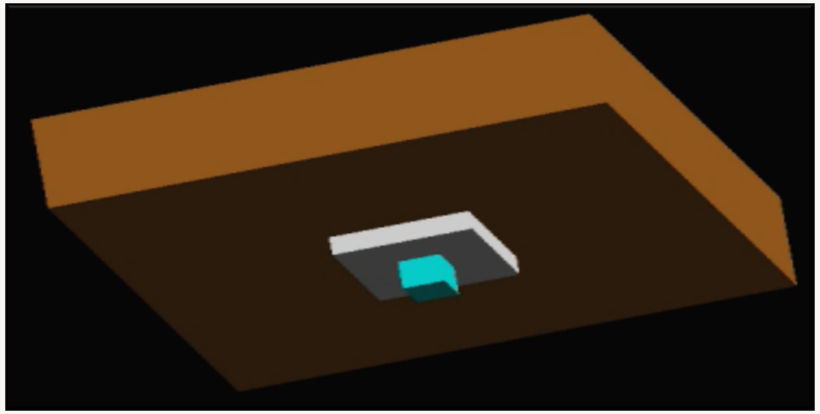
16th November 2021

MAPP MoEDAL

THE UNIVERSITY OF ALABAMA

G4 Geometry & Material content

- The 100m thick Rock Overburden (dimensions – 400m x 400m x 100m) above UA83.
- Material content (limestone – $MgCO_3$ (10%)+ $CaCO_3$ (90%))
- Material density = 2.71 g/cm^3
- The Physics list used in the model is QGSP_BERT_HP.



- Additional regions in the model.
- Scoring region (100m x 100m x 20m) with Air
- Sensitive Detector Volume (30m) with plastic scintillators (1m x 1m x 1.2m)
- Scintillator Material – Vinyl toluene plastic scintillators in G4.
- The figure shows the G4 geometry as seen from below.

Sampling Angular distribution of Cosmic muons

- The theta (angle of incidence – zenith angle) distribution of cosmic muons is based on the Muon distribution function defined in. (arXiv:1606.06907)

International Journal of Modern Physics A | Vol. 33, No. 30, 1850175 (2018) | Research Papers

Energy and angular distributions of atmospheric muons at the Earth

Prashant Shukla and Sundaresh Sankrith

- The Phi distribution is uniform.

- G4 General Particle Source (GPS) uses this distribution to provide the initial (θ, ϕ) the muons.

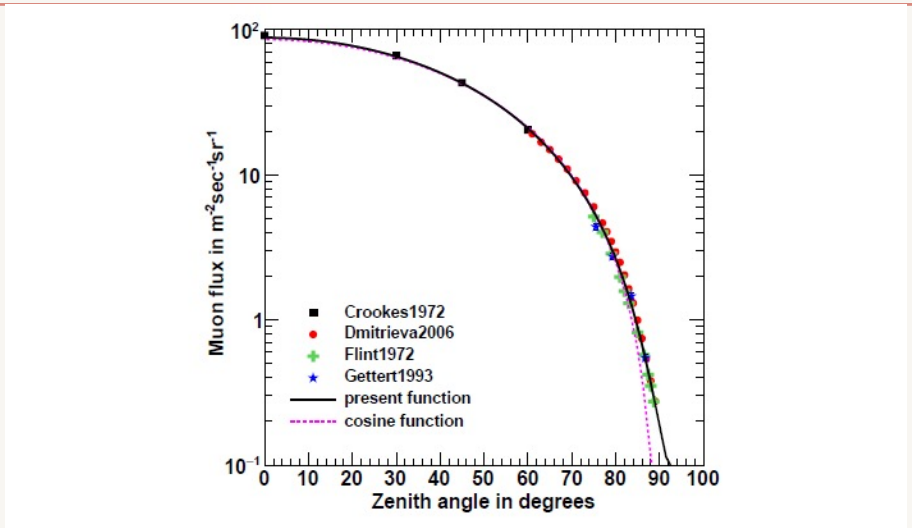
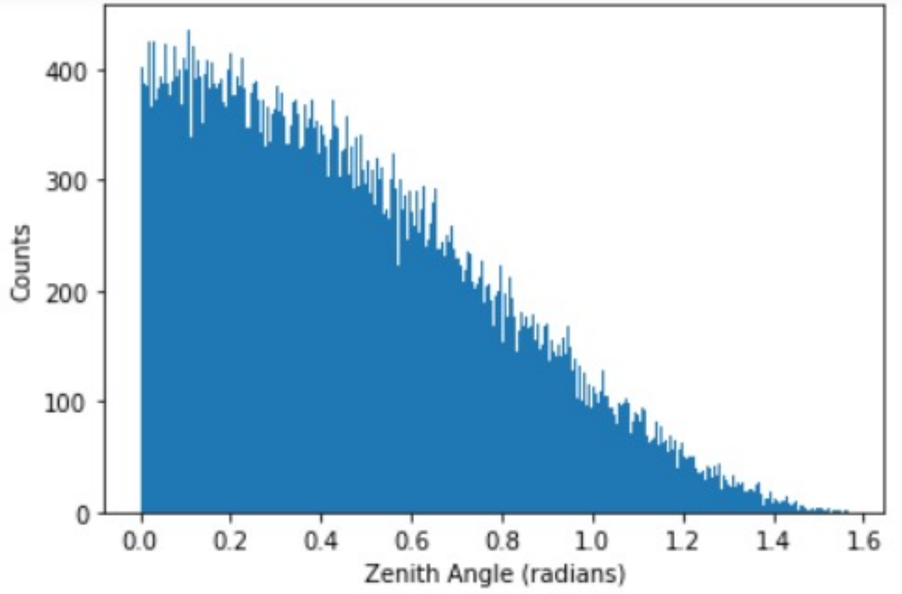
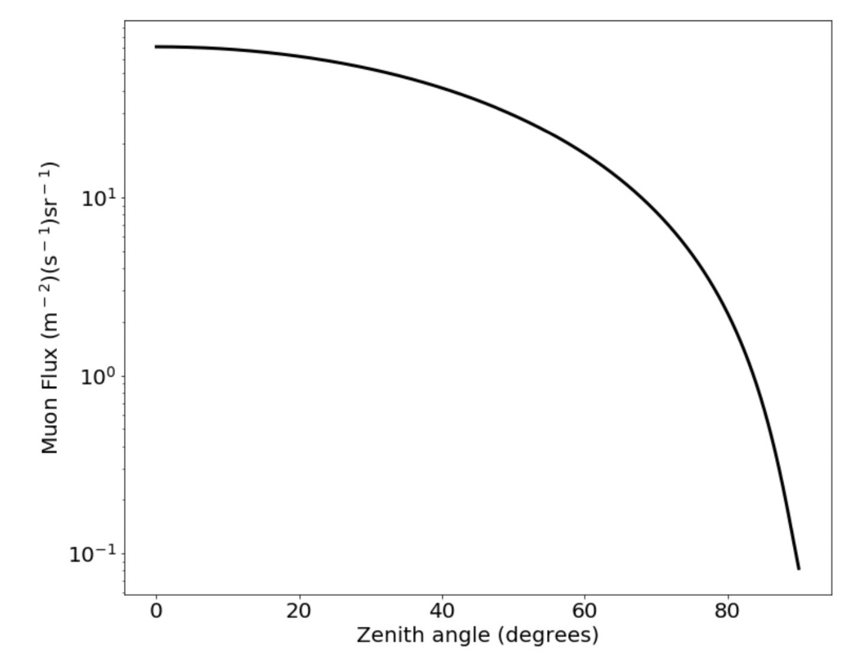


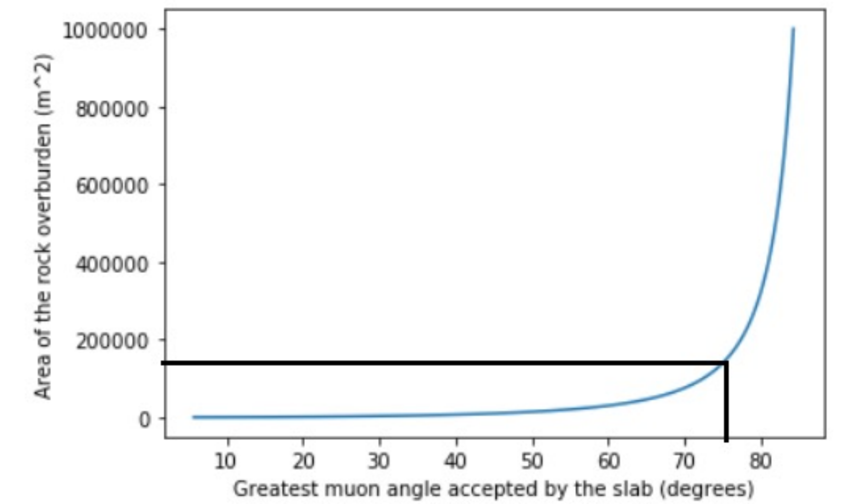
Fig. 9. Muon flux as a function of zenith angle[21] at sea level fitted with Eq. 9 and Eq. 11



Qualitative understanding of the size of rock slab

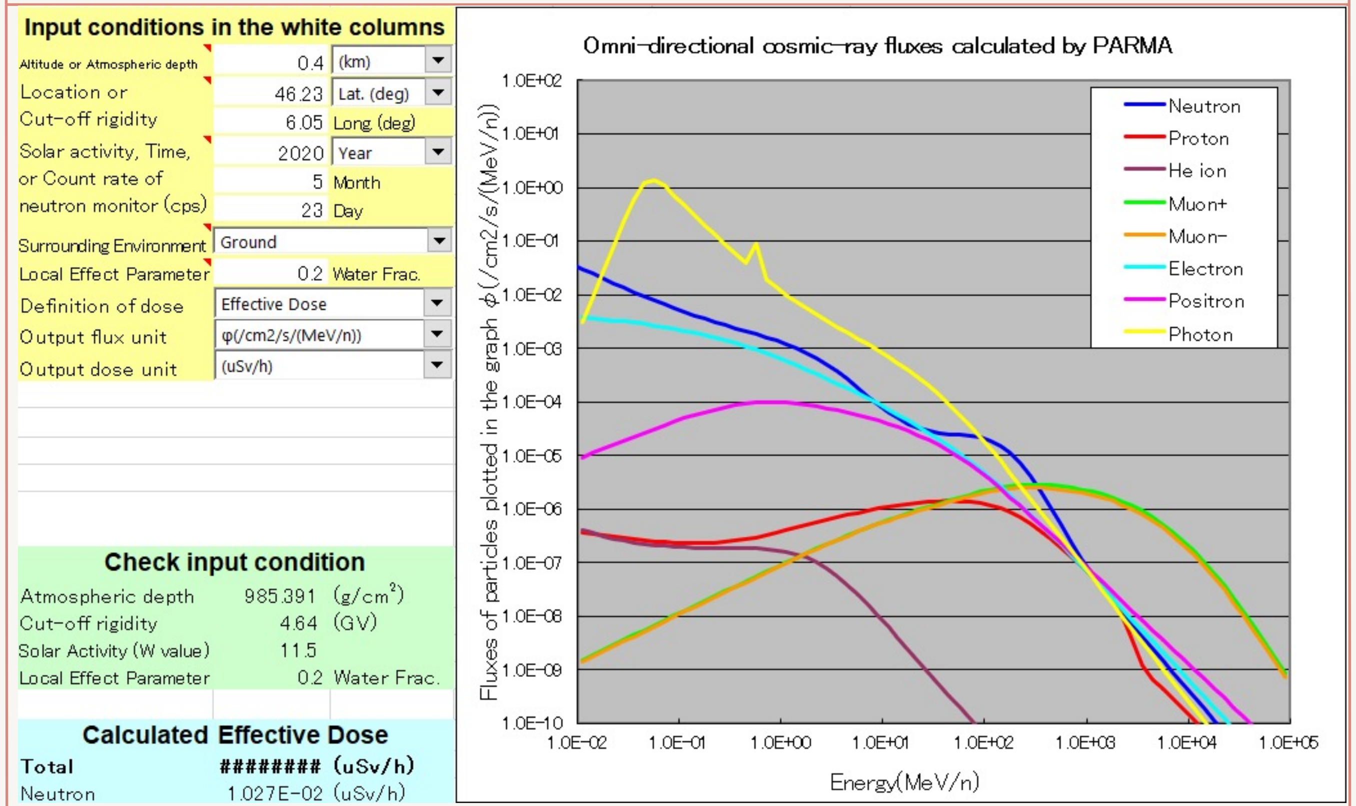
- For a slab area 160000m^2 (400m x 400m) – Greatest Muon angle accepted – 75.964°
- An exponential increase in rock area for every additional degree.

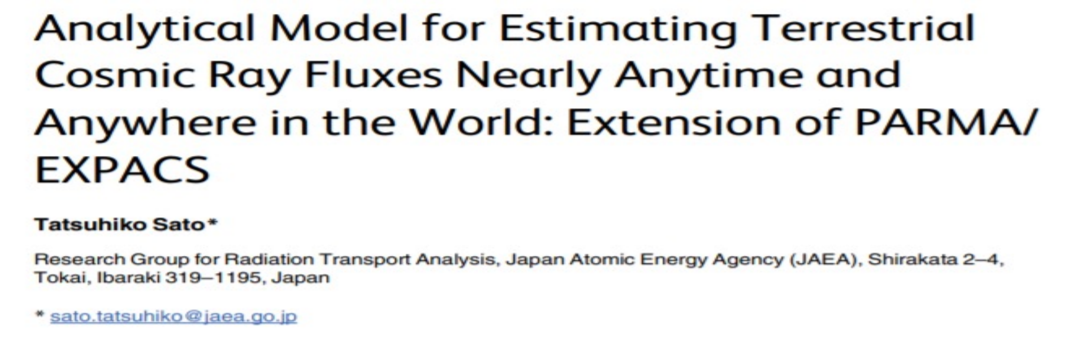




Energy distribution of Cosmic muons

- Using EXPACS - PARMA 4.0 for estimating cosmic ray fluxes (used in G4 simulations on MATHUSLA)
- EXPACS - EXcel-based Program for calculating Atmospheric Cosmic-ray Spectrum
- PHITS-based Analytical Radiation Model in the Atmosphere: PARMA
- https://journals.plos.org/plosone/article/file?id=10.1371/journal.pone.0144679&type=printable





Analytical Model for Estimating Terrestrial Cosmic Ray Fluxes Nearly Anytime and Anywhere in the World: Extension of PARMA/EXPACS

Tatsuhiko Sato*

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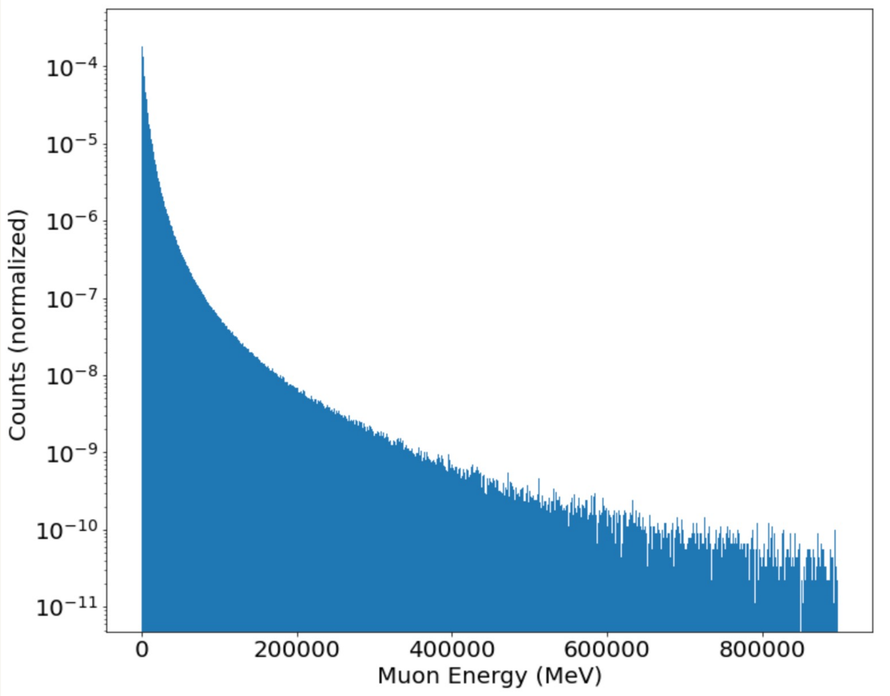
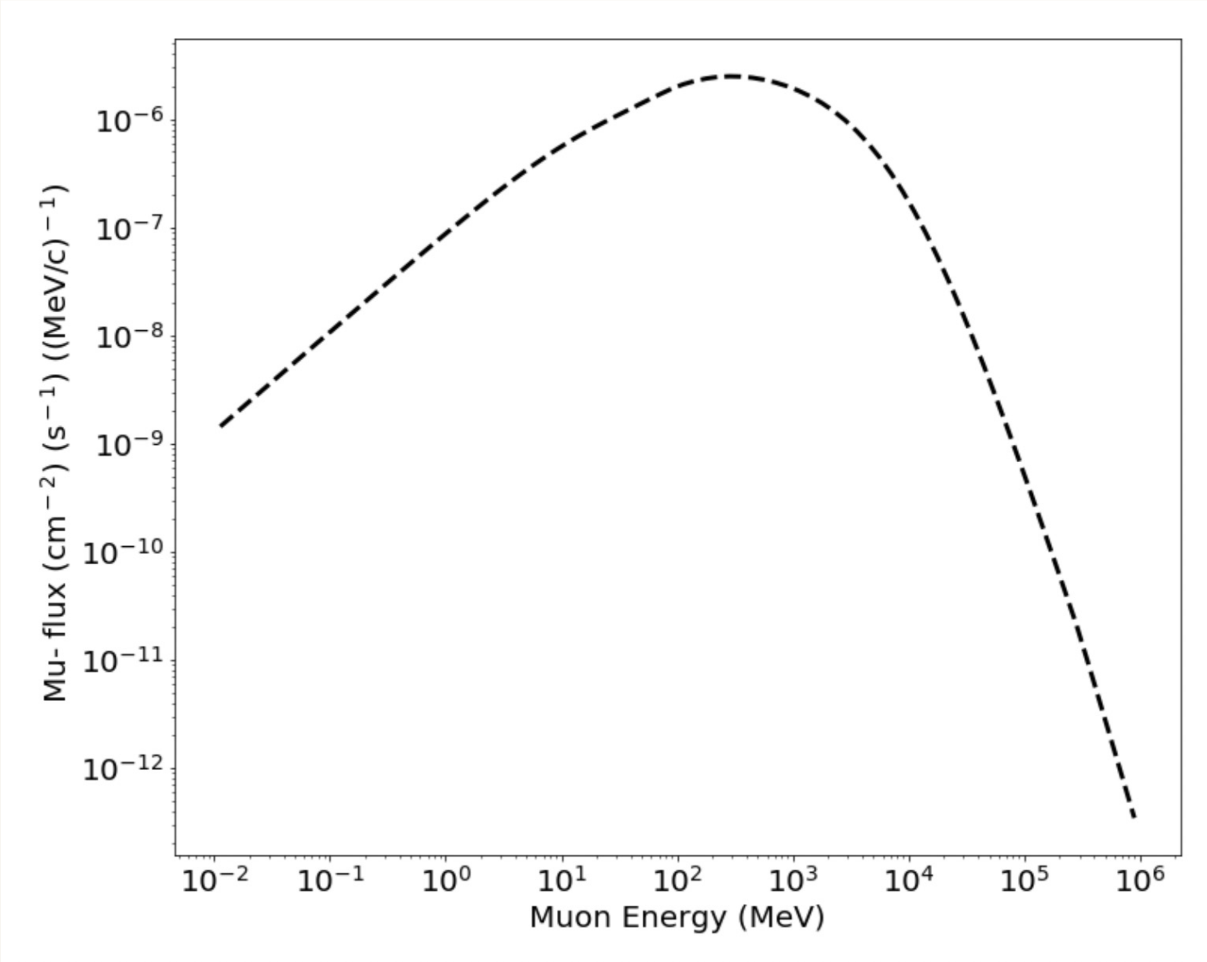
Sampling energies from the distribution predicted by PARMA

The energy distribution at the surface at CERN (altitude 400m above sea level)
is provided in the Geant4 GPS which gives the initial energy distribution of Cosmic Muons.





Particle fluxes out of the Rock Overburden

- Muon & secondary particle flux using PARMA muon distribution using 1000 muon runs for 10^7 events each.
- Particle flux through 100m thickness of Rock Volume.
- Total Incoming Muons (all runs) = 1000*1e7 = 1e10
- Integrated flux at rock surface – 0.55 muons per square centimeter per minute – using PARMA dist.
- 1 minute – 8.8e8 muons incoming.
- Currently ~ 11 minutes statistic.

Table 1: Flux of primaries and secondaries through the rock overburden.

Type of Flux	Flux (cm^{-2} sec^{-1})
Total	$(5.49 \pm 0.07) \times 10^{-03}$
Mu-	$(4.04 \pm 0.06) \times 10^{-05}$
Electron	$(3.11 \pm 0.05) \times 10^{-05}$
Gamma	$(1.53 \pm 0.01) \times 10^{-04}$
Positron	$(5.12 \pm 0.02) \times 10^{-06}$
Mu+	$(6.45 \pm 0.25) \times 10^{-10}$
Alpha	$(4.47 \pm 0.21) \times 10^{-12}$
Neutron	$(8.22 \pm 0.09) \times 10^{-07}$
Proton	$(3.02 \pm 0.17) \times 10^{-08}$
Deuteron	$(2.43 \pm 0.15) \times 10^{-10}$
Muon Neutrino	$(3.45 \pm 0.05) \times 10^{-03}$
Muon Anti Neutrino	$(1.52 \pm 0.04) \times 10^{-05}$
Electron Neutrino	$(1.48 \pm 0.04) \times 10^{-05}$
Electron Anti Neutrino	$(1.78 \pm 0.04) \times 10^{-03}$

Mu- flux at the top surface of rock (400m altitude) = $(9.2 \pm 0.9) \times 10^{-3}\ cm^{-2}s^{-1}$ (PARMA)

Mu- flux exiting the –Z face of 100 m rock overburden = $(4.04 \pm 0.06) \times 10^{-5}\ cm^{-2}s^{-1}$

Muon flux – the takeaways.

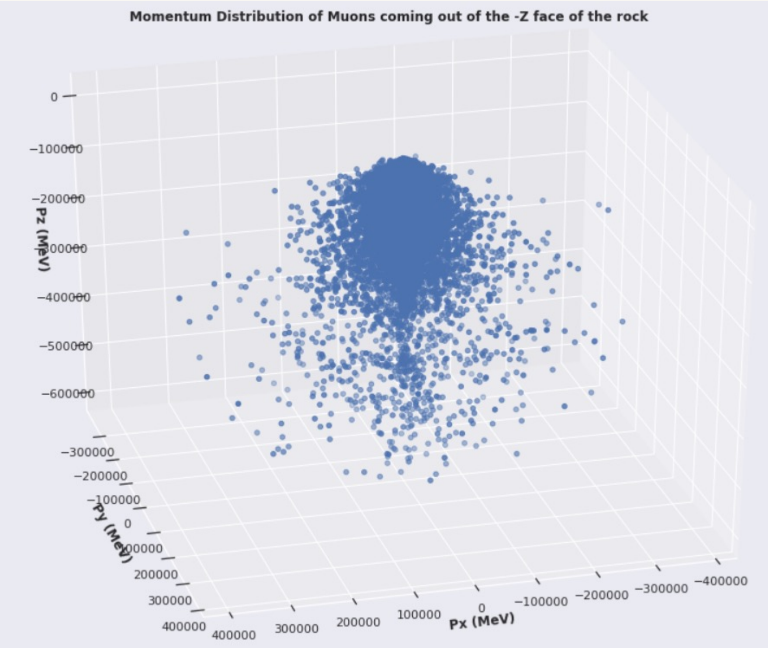
- Mu- flux at the top surface of rock (400m altitude) = $(9.2 \pm 0.9) \times 10^{-3}\, cm^{-2} s^{-1}$ (PARMA)
- Mu- flux exiting the –Z face of 100 m rock overburden = $(4.04 \pm 0.06) \times 10^{-5}\, cm^{-2} s^{-1}$

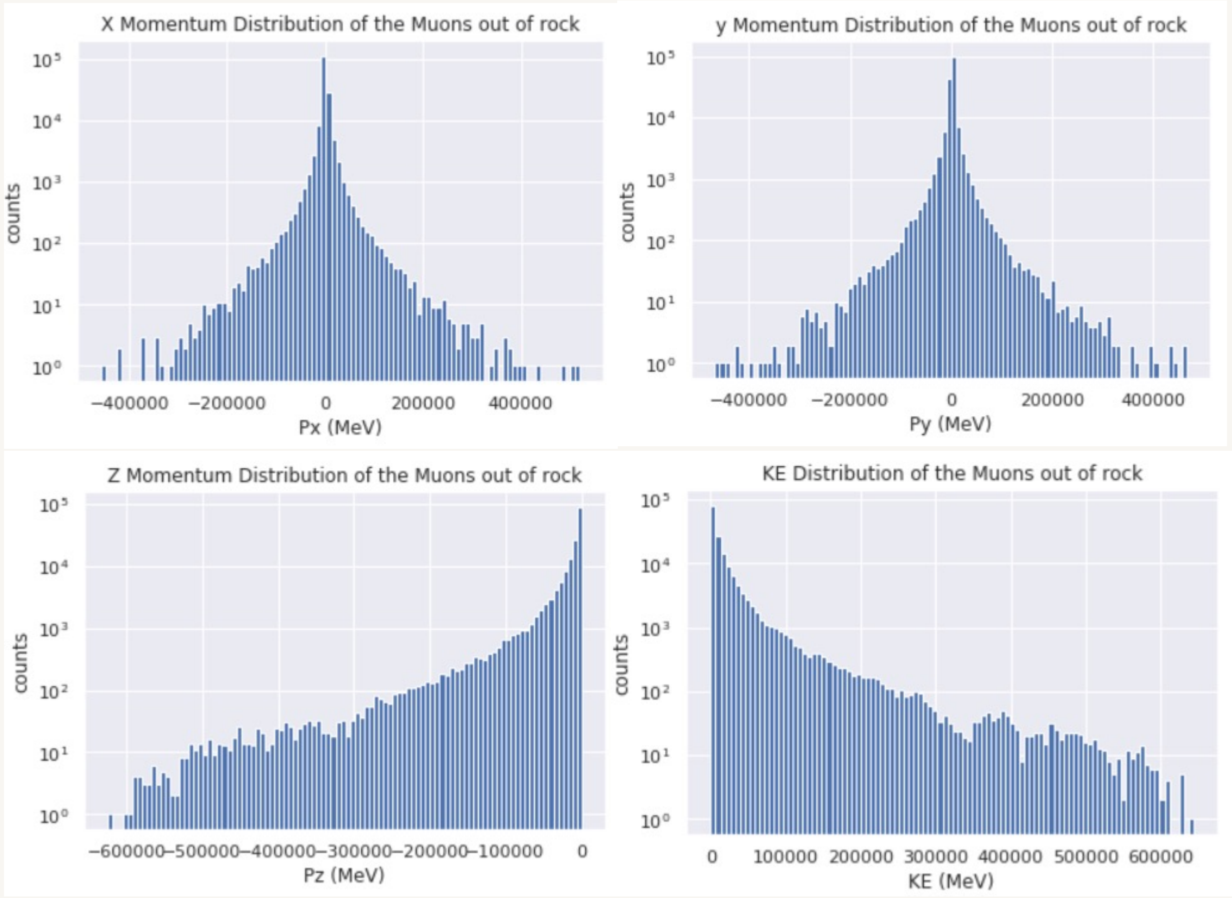
- The top area of the detector is 4.4×10^{4} cm^2
- # of muons crossing per second = (4.4×10^{4} cm^2) x (4.04×10^{-5} cm^{-2} s^{-1}) = 1.78 muons/sec
- This rate will be further reduced by the veto panels.

Cosmic muons coming out of the rock

Energy/momenta distribution at the last step in boundary (coming out of rock)

Selecting outgoing muon events from the bottom edge of rock overburden





Muon events sampled from this distribution to further propagate particles through the full MAPP geometry.

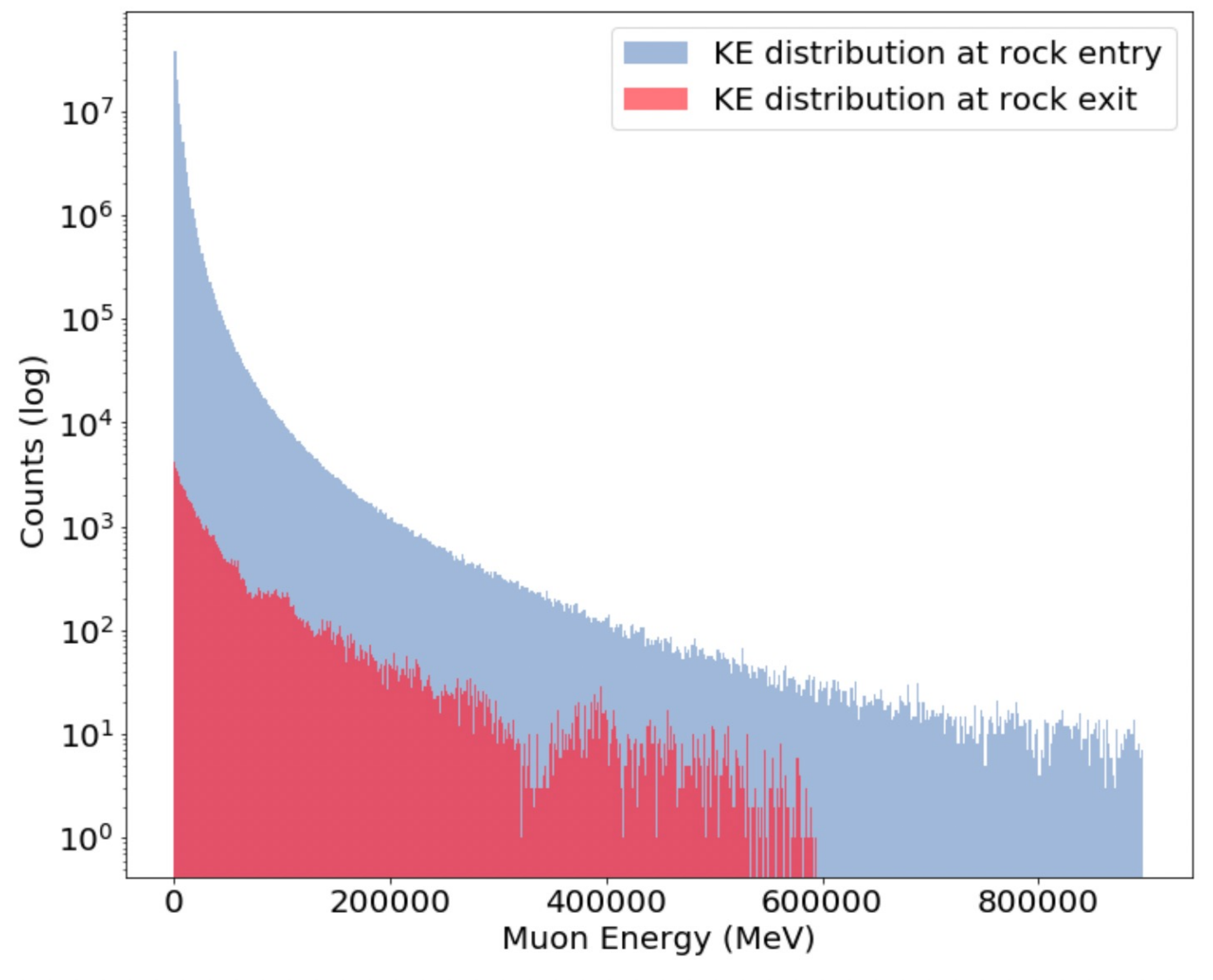
Kinetic energy distribution of muons

- ..before and after passing through the rock overburden of 100m thickness.

- Ratio of Muons exiting

$$= \frac{\#\ of\ Muons\ exiting\ the\ bottom\ surface\ of\ rock}{\#\ of\ Muons\ simulated\ from\ the\ top\ surface}$$

$$= (4.2 \pm 0.6) \times 10^{-3}$$



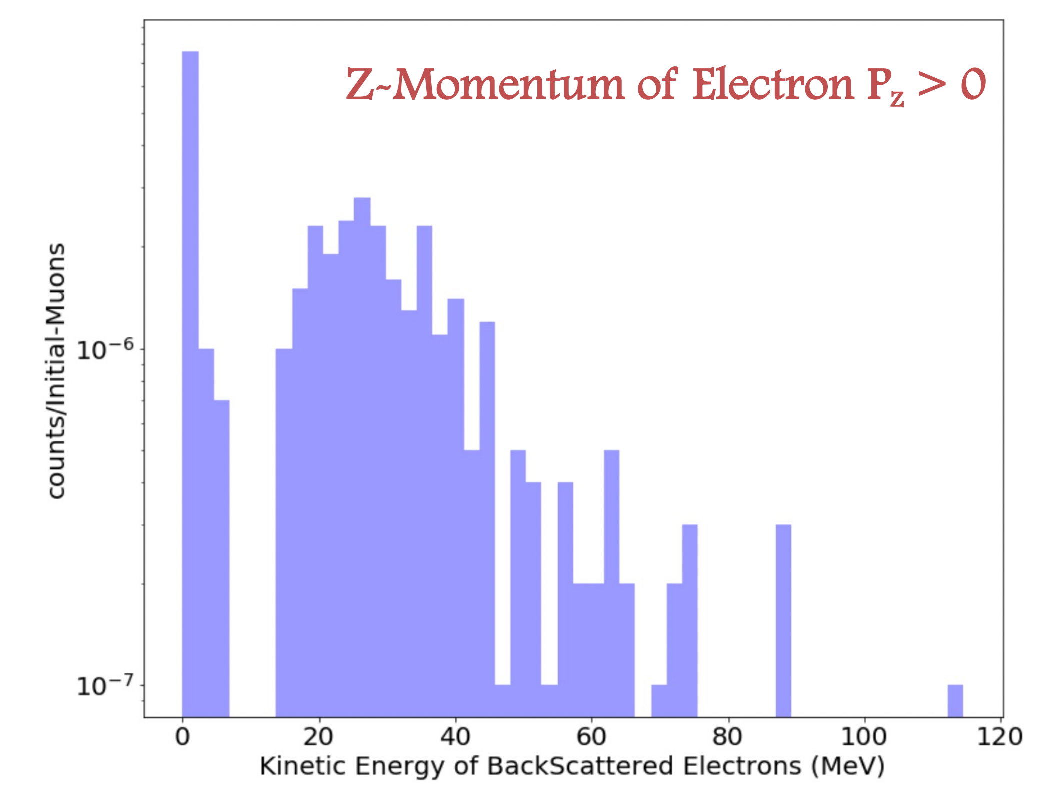
Rate of inelastic backscattering from cosmic muons

- Rate of Backscattered electrons – 10^6 muons simulated
- condition **Z-Momentum of Electron $P_z > 0$ (upward going)**
- Rate of backscattered electrons

$$= \frac{\#\ of\ upward\ tracks}{\#number\ of\ downward\ incident\ cosmic\ muons}$$

$$= (\mathbf{3.1} \pm \mathbf{0.5}) \times \mathbf{10^{-5}}$$

The spectrum and multiplicity of back-scattered secondary electrons produced from initial muon spectrum through the detector region.



Comparing with MATHUSLA ->

$$R_{\text{up-to-down}} = \frac{(\text{Number of upward tracks})_{\text{data, no beam}}}{(\text{Number of downward tracks})_{\text{data, no beam}}} = (7.0 \pm 0.2) \times 10^{-5}$$

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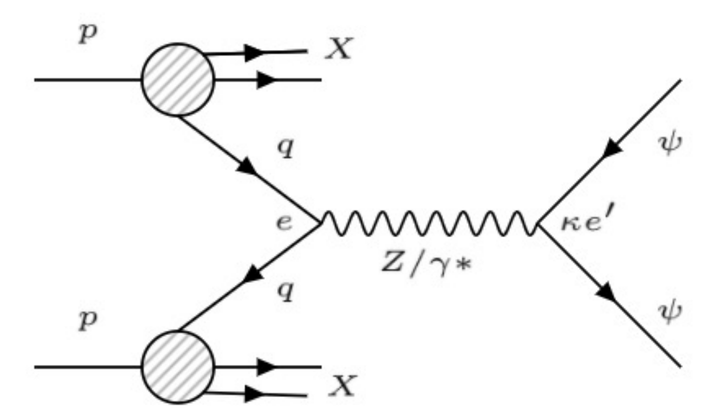
In summary

- Initial results of the same order of magnitude for primary, secondary and backscattered flux.

- NEXT STEPS
- Integrating with Matti's Geant4 model of MAPP arena.
- Simulations for secondary particles including Neutrons.
- Full simulation with cosmic muons using the complete MAPP geometry for final results.

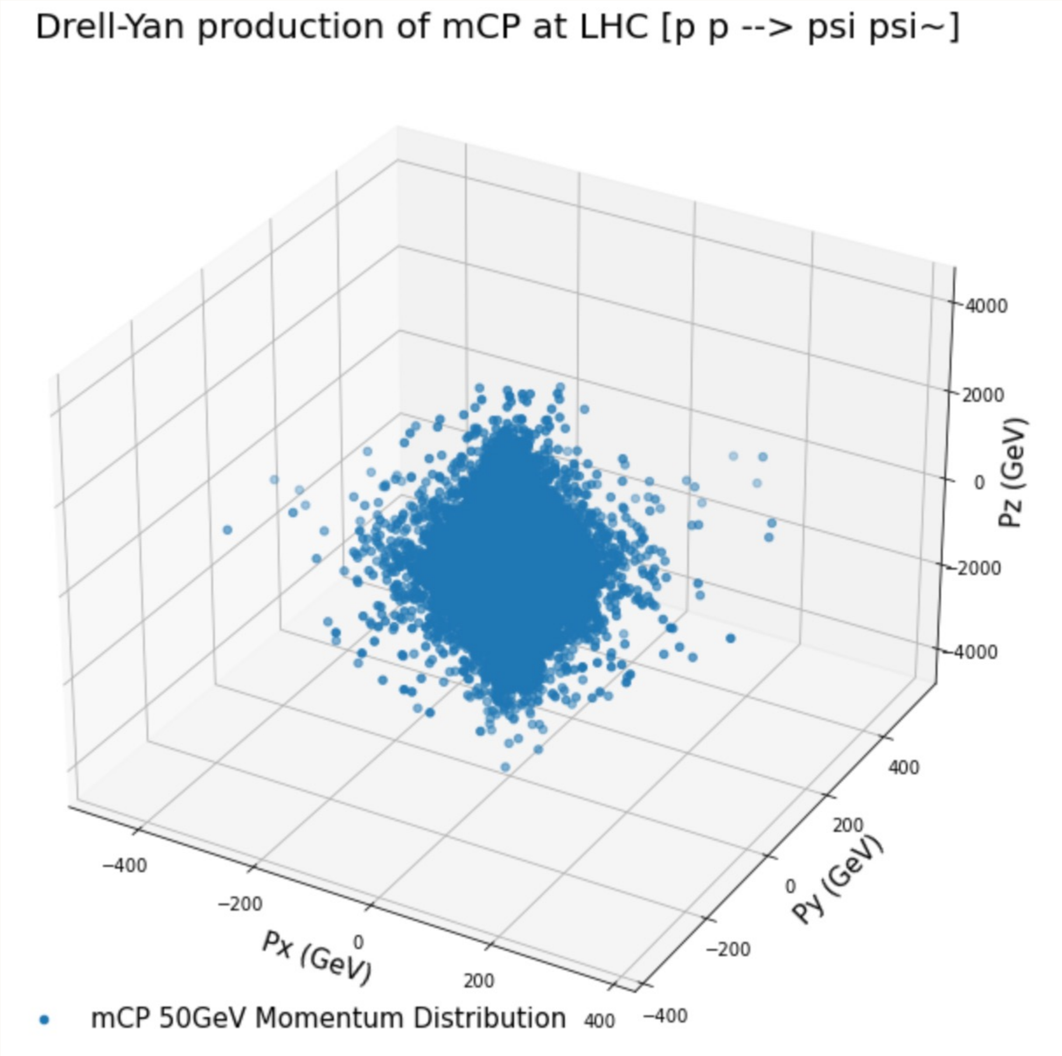
mQP's in Geant4

- Kinematics of mQPs produced in p-p collisions via the Drell-Yan mechanism
- Derived from Madgraph model for mQPs.
- (more details about the model in Michael's talk)



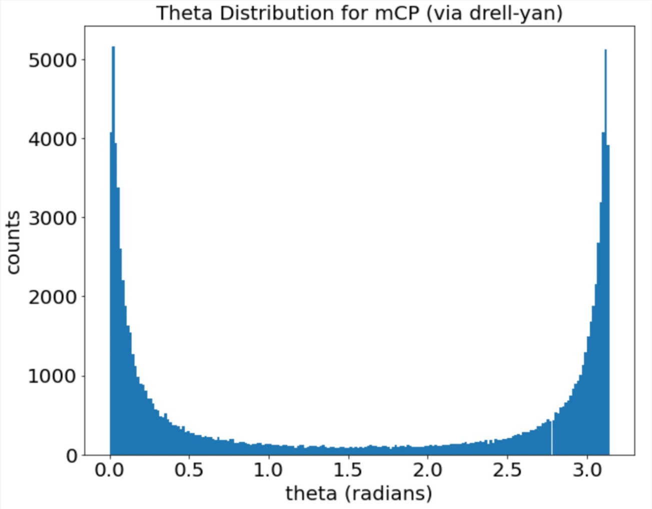
- 100k events were generated.

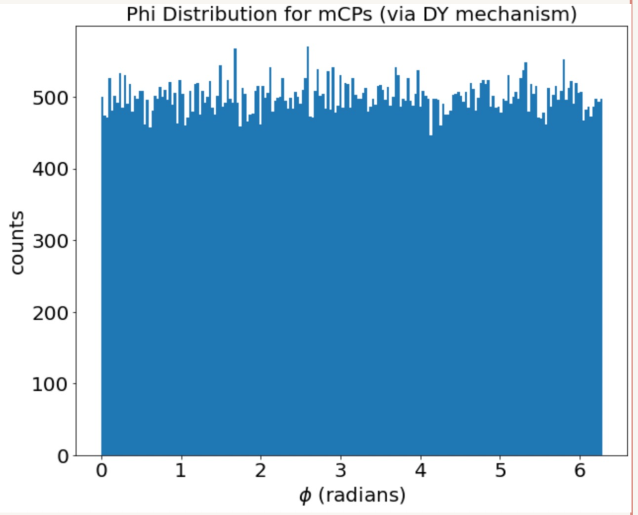
- Momentum distribution of mCPs ->

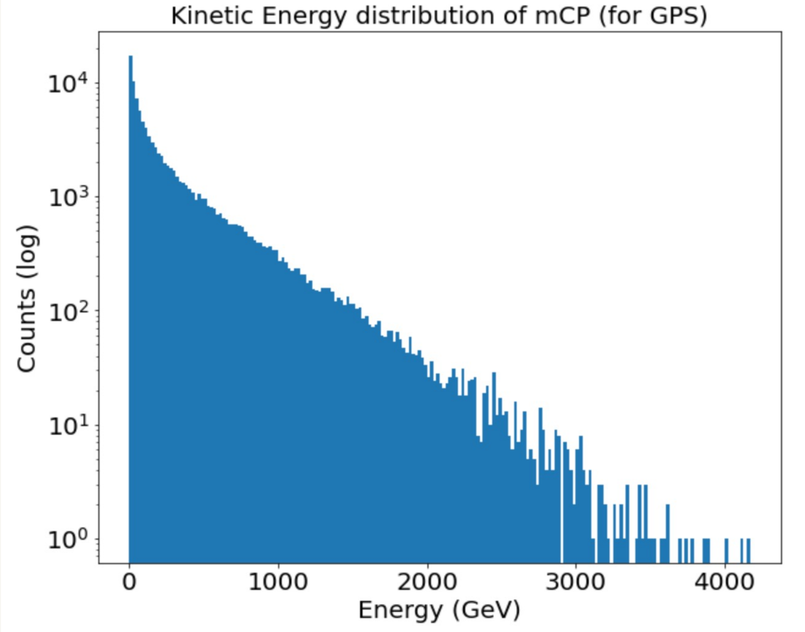


Angular & Energy distribution of DY produced mCPs

- The angular and kinetic energy distribution was converted into a Geant4 macro
- to propagate particles in G4 using General Particle Source (GPS).







mQP Physics in Geant4

Modeling energy loss of mQPs in Geant4

- Defining the mQP particle properties in G4
- Defining the Physics list corresponding

to the physics processes.

- mQPs model modified from the standard

G4 Muon Model

Simulation of energy loss of fractionally charged particles using Geant4

Full Record | References (43) | Other Related Research

JOURNAL ARTICLE:

Free Publicly Available Full Text

Accepted Manuscript (DOE)

Publisher's Version of Record
https://doi.org/10.1016/j.nima.2020.164114

OTHER AVAILABILITY

Abstract

Over the years several rare-event search experiments have shown increasing interest to search for Fractionally Charged Particles (FCPs) within the data acquired in those experiments. This, in turn, has required the need for a framework to calculate accurately the energy loss expected from FCPs as they pass through the detector material. We have developed Monte Carlo methods within Geant4 to simulate for the first time energy loss of FCPs through different physics processes. The program can be used to calculate energy deposition distributions, a major component of any FCP search analysis, as they interact with detector material. We discuss the implementation and validation of the energy loss of FCPs using a typical detector material.

Authors: Banik, S. [1]; Kashyap, V. K. S. [1]; Kelsey, M. H. [2]; Mohanty, B. [1]; Wright, D. H. [3]

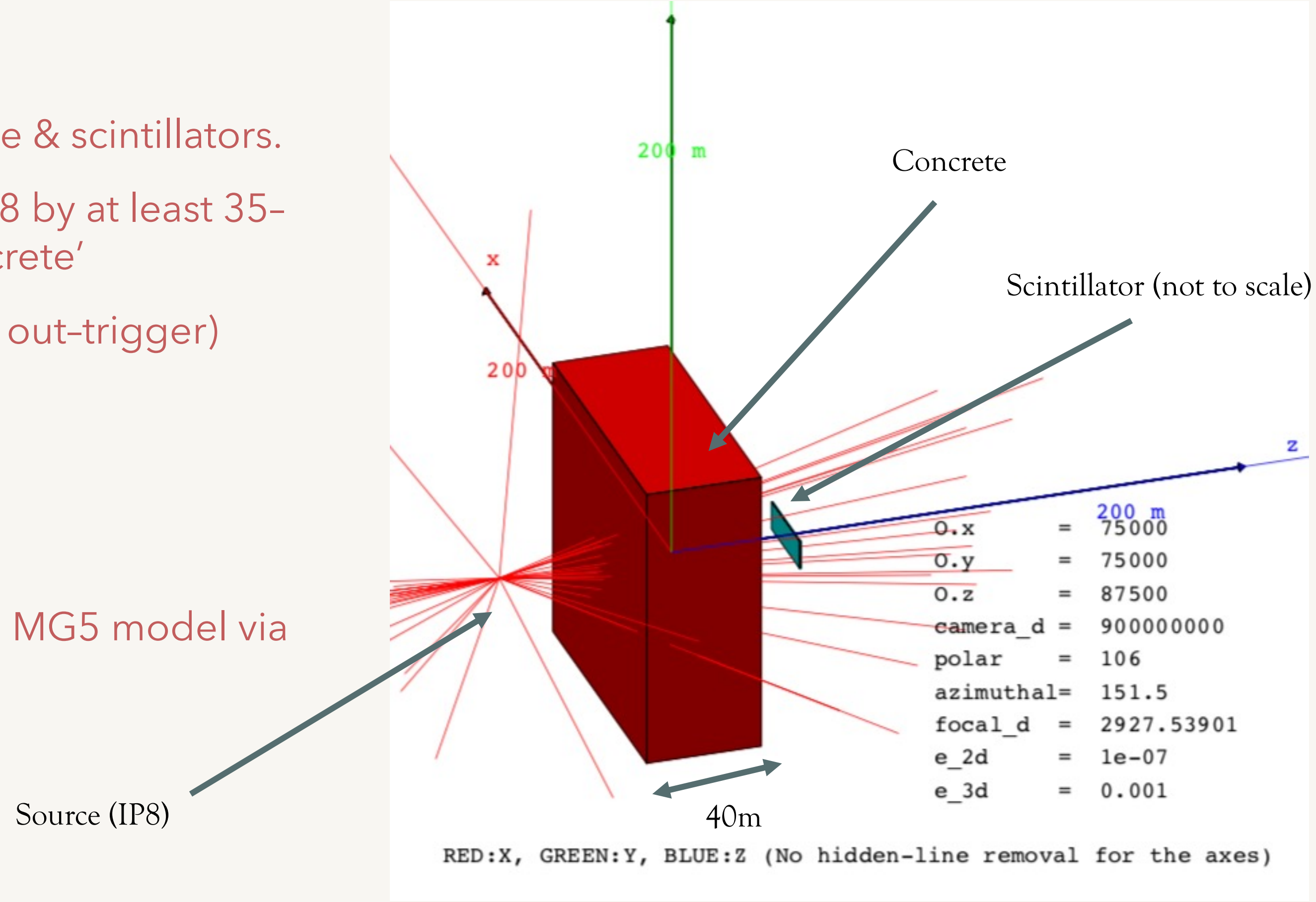
https://www.osti.gov/pages/biblio/1637466

- mQP class defined in Geant4
- Modified from G4MuonMinus class.
- Separate classes for positively (mQP+) and negatively (mQP–) charged mQPs.
- mQP– charge defined as –> "–fabs(*charge*)**eplus*" where *charge* is fractional, *eplus = 1*e*.
- PDG ID set as 90 (arbitrary).
- Mass variable (0.1 GeV to 100 GeV)
- STABLE – True, lifetime = 0 (do not decay).
- SHORTLIVED – False
- Default charge = 0.01e
- Default mass = 1 GeV
- (mass & charge can be changed using Physics Messenger in G4)

A rough initial geometry in Geant4 to test the model (in progress)

- Basic geometry was developed with air, concrete & scintillators.
- UA83 is protected from SM background from IP8 by at least 35-40m of concrete. – G4Material – 'ShieldingConcrete'
- Scintillator dimensions (for deploying in hole as out-trigger)
- 30cm x 60cm x 5cm (or 30cm x 30cm x 5cm)
- World material – G4Air

- mCPs were simulated using the kinematics from MG5 model via GPS.



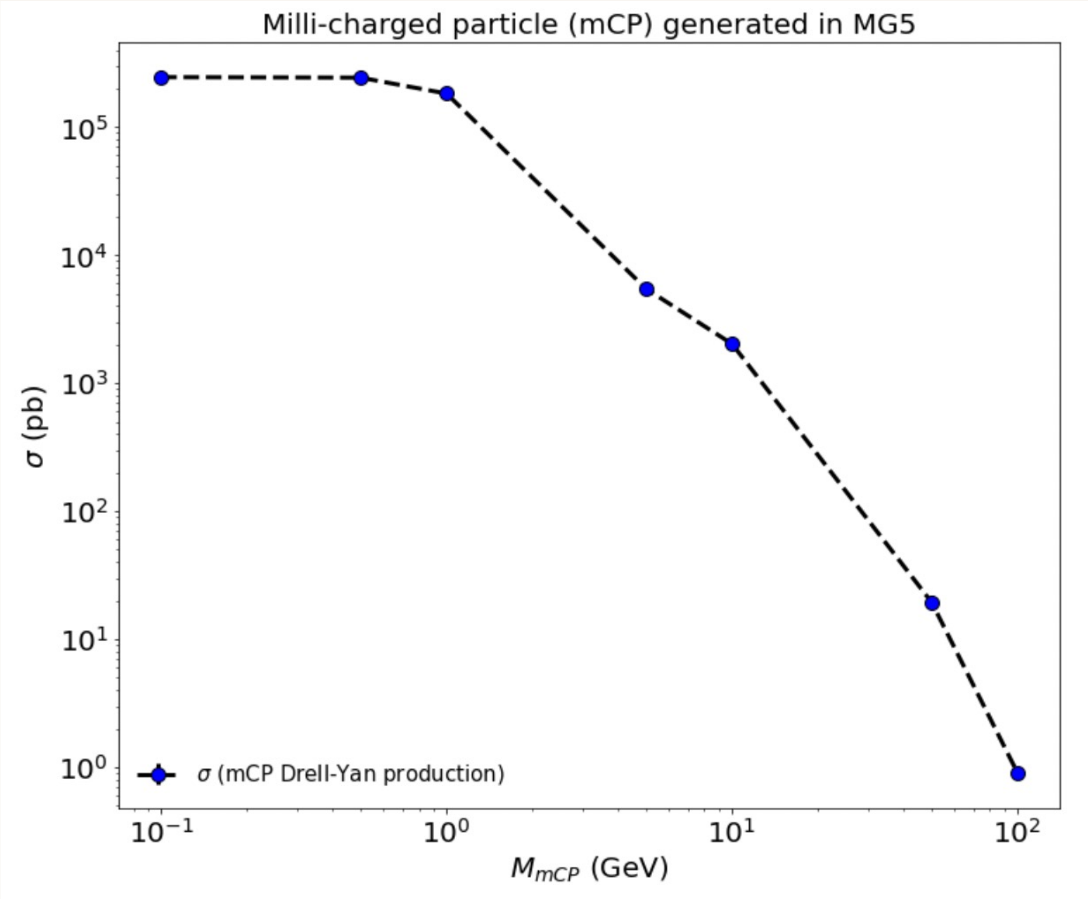
Summary of the milli charged particle G4 model

S.No.	Implemented in Model	Yet to be implemented/ongoing
1.	mCP+ and mCP- physics definition (default charge/mass)	Calculating the # of scintillation photons per event (ongoing) Precise values for MAPP scintillator optical parameters
2.	mCP physics processes	Comparison (with a basic model) & validation of the model.
3.	Basic detector model (scintillators) + concrete	Simulations for varying charges and masses and subsequent energy losses
4.	Madgraph kinematic model of mCPs via Drell-Yan mechanism	Detailed MAPP geometry (Matti)
5.	G4 General Particle Source to propagate particles with arbitrary energy/angular distribution	
6.	Sensitive detector volumes and flux scorers of primary (mCPs) and secondaries. G4OpticalPhysics for counting optical photons in scintillator	**Timescale for the completion of study – Mid-January**
7.	ROOT NTuples saving the energy loss, track length in sensitive volume, outgoing flux of primary, secondaries, number of secondaries.	

Thank you!

Questions & comments…

Additional slides



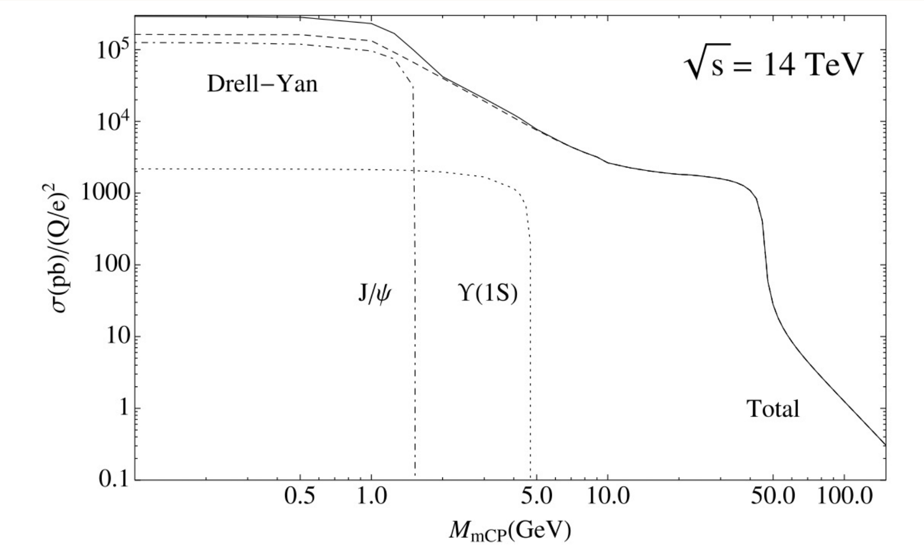


Fig. 2. Cross-section at the LHC for the process $pp \to \psi\bar{\psi} + X$ as a function of the mCP mass. As described in the text, the combined cross-section (solid) is obtained through Drell–Yan (dashed), $\Upsilon(1s) \to \psi\bar{\psi} + X$ (dotted), and $J/\psi \to \psi\bar{\psi} + X$ (dot-dashed). The enhancement for $M_{\mathrm{mCP}} < m_{Z^0}/2$ is due to the Z^0-mediated contribution.

Looking for milli-charged particles with a new experiment at the LHC

Andrew Haas [a], Christopher S. Hill [b], Eder Izaguirre [c,*], Itay Yavin [c,d]

[a] Department of Physics, New York University, New York, NY, USA
[b] Department of Physics, The Ohio State University, Columbus, OH, USA
[c] Perimeter Institute for Theoretical Physics, Waterloo, ON, Canada
[d] Department of Physics, McMaster University, Hamilton, ON, Canada

MILLI CHARGED PARTICLES GENERATED IN MADGRAPH

G4 Physics Lists + GPS

- The Physics lists for Muons – G4MuBetheBlochModel, G4MuBremsstrahlungModel, G4MuPairProductionModel, G4MuMultipleScattering are modified to account for mCP charge and mass to compute mCP energy losses. (list of modifications –> next slide)
- G4EmStandardPhysics – standard module is included to simulate the secondaries generated by the interaction of the mCPs in material.

- G4GeneralParticleSource is linked to the Geant4 model to simulate particles using the energy and angular distributions produced via Madgraph

Modifications in the physics list

1. **G4MuBetheBlochModel** –

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

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

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.

```
G4double dedx = 0.0;
if (kineticEnergy <= lowestKinEnergy) return dedx;

G4double tmax = kineticEnergy;
G4double cut  = std::min(cutEnergy,tmax);
if(cut < minThreshold) cut = minThreshold;
```

```
G4double loss =
  ComputMuBremLoss((*theElementVector)[i]->GetZ(), kineticEnergy, cut);

dedx += loss*theAtomicNumDensityVector[i];
```

```
inline
void FCPBremsstrahlungModel::SetParticle(const G4ParticleDefinition* p)
{
  if(!particle) {
    particle = p;
    mass = particle->GetPDGMass();
    charge = particle->GetPDGCharge();///eplus;
    rmass=mass/CLHEP::electron_mass_c2 ;
    cc=CLHEP::classic_electr_radius/rmass ;
    coeff= 16.*charge*charge*CLHEP::fine_structure_const*cc*cc/3. ;
  }
}
```

Modifications in the physics list (2)

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

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

$$\alpha = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{\hbar c}$$

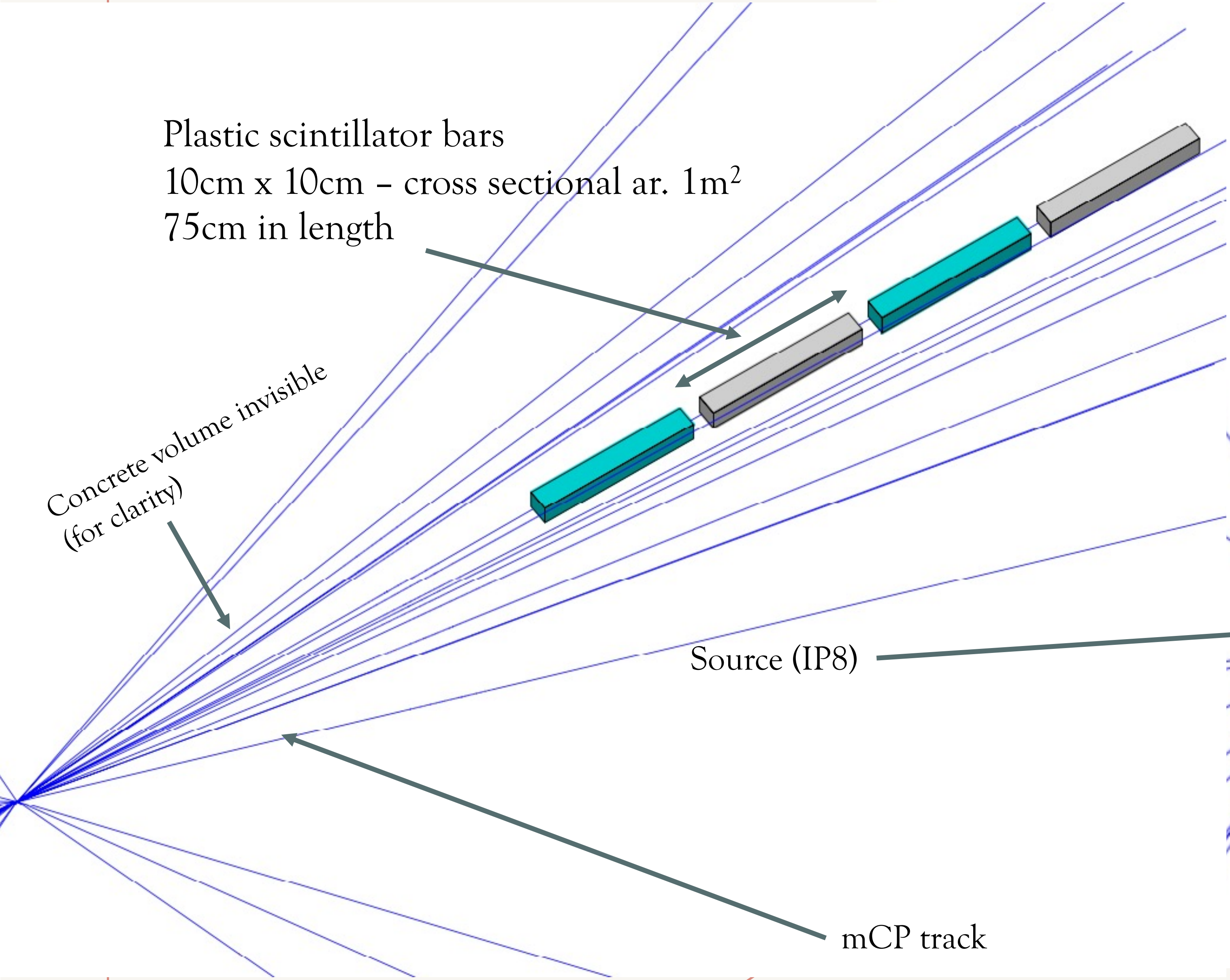
4. **G4MuMultipleScattering** –

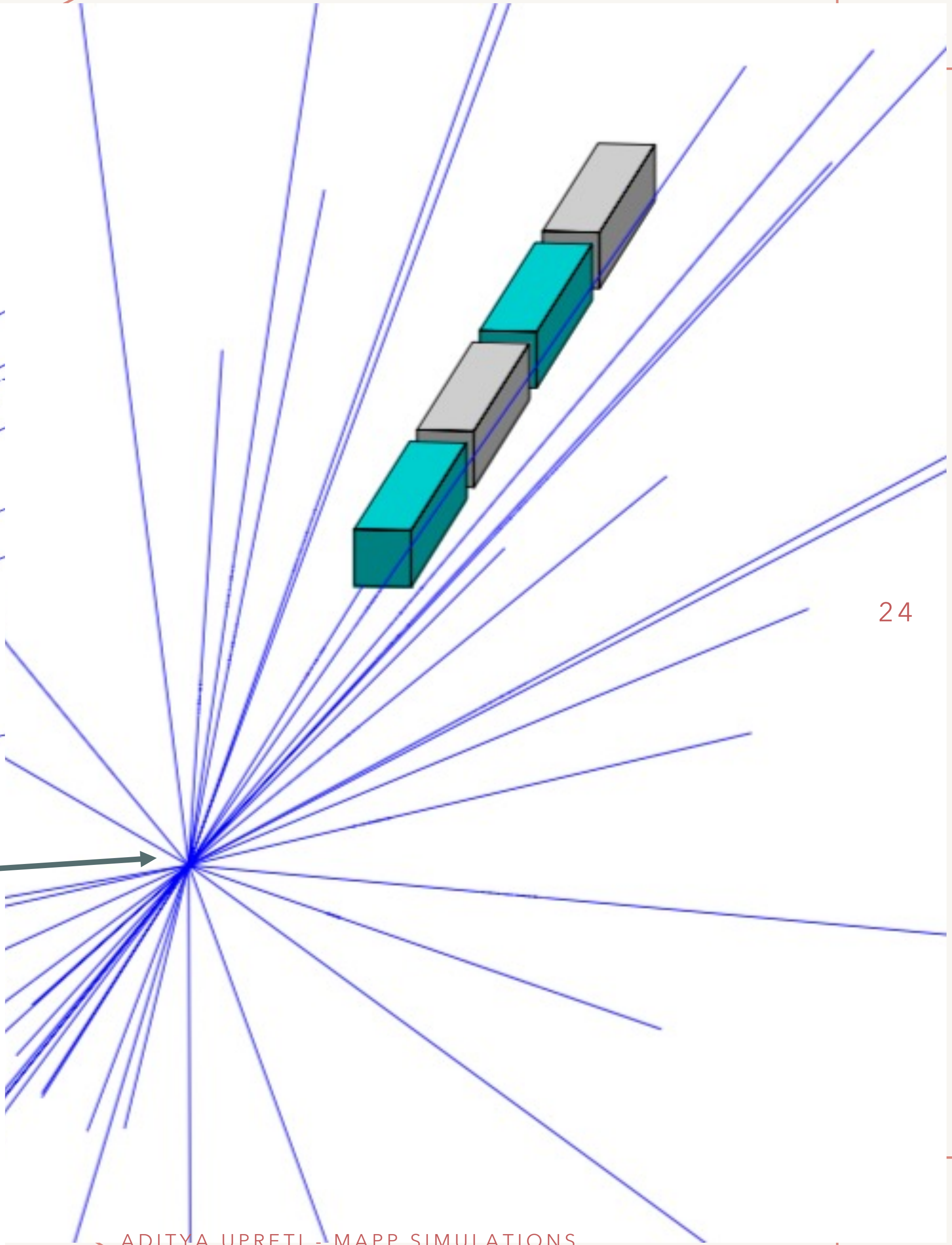
- Replaced UrbanMsc Model95 by WentzelVI Model
- (original source code for Muons includes headers for UrbanMsc and WentzelVI but uses only UrbanMsc)

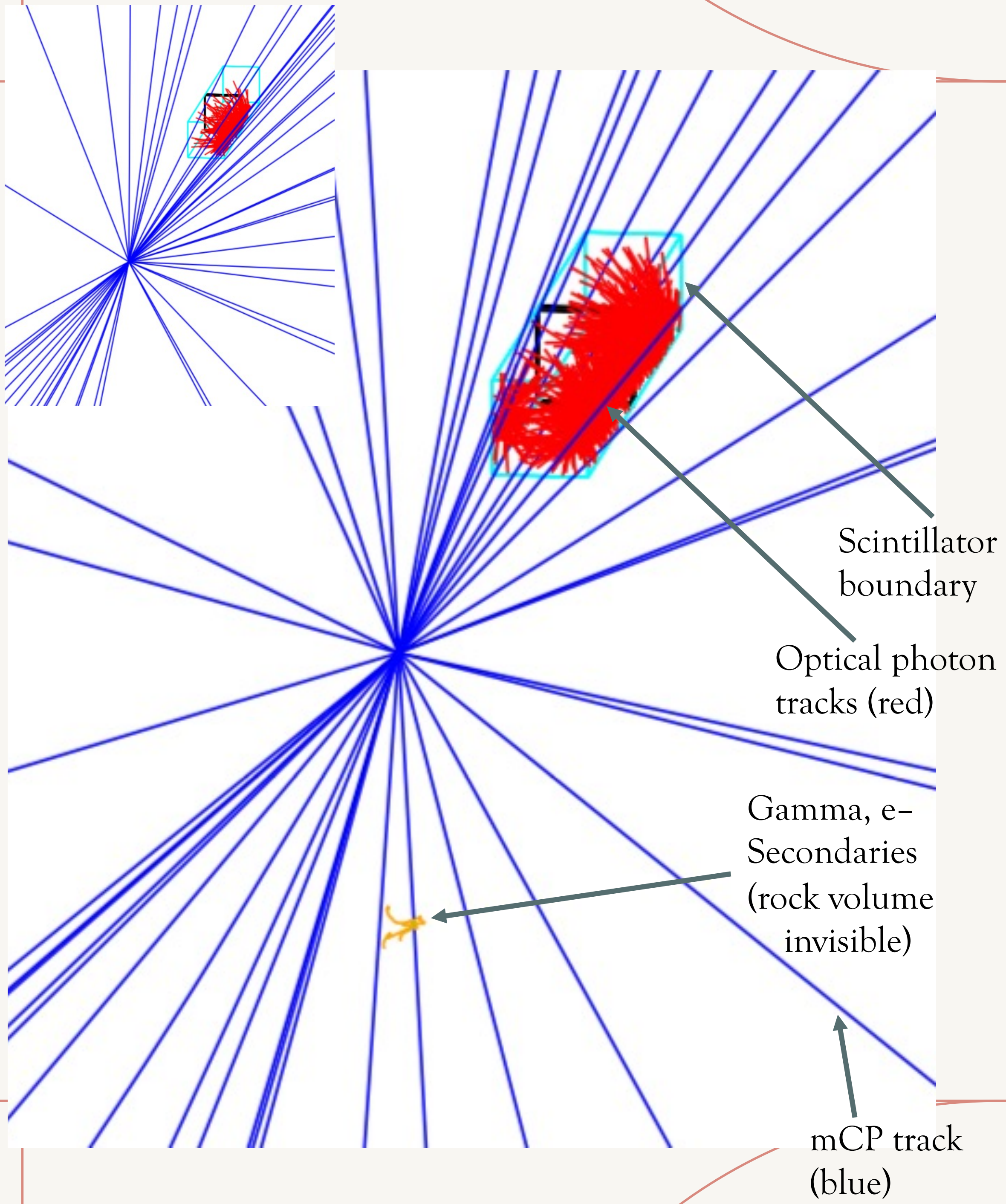
WentzelVI

- **emstandardWVI** new physics constructor for validation of combined WentzelVI and Single Scattering models. The corresponding physics constructor includes following modifications on top of *G4EmStandardPhysics.cc*:
  - *G4WentzelVIModel* for multiple scattering combined with *G4eCoulombScatteringModel* for large angle scattering is used for electrons, positrons, muons, pions, kaons, protons, and anti-protons.

Four adjacent scintillator bars







Implementing G4OpticalPhysics

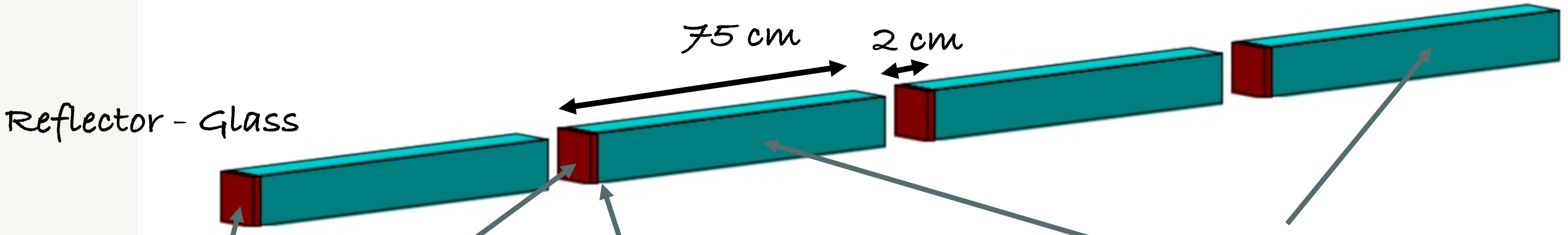
- For calculating the number of optical photons produced in the scintillators by the milli charged particles.

- Optical properties
- – Refractive Index, Absorption Length, Scintillation Yield, Resolution Scale, Fast Time Constant, Yield Ratio (using default values in G4)

- (position of source closer for testing the model and visualization)

Adding details to scintillator geometry

Scintillator - Plastic Scintillator BC408
Cross sectional area - 10 cm*10 cm
Base – Polyvinyl toluene



Scintillator Optical properties
Ref. Index = 1.58
Absorption Length = 250 cm
Scintillation yield = 11136 (photons/MeV)
Emission peak = 425 nm
Slow/fast yield = 0.27
Fast decay time = 2.1 ns
Slow decay time = 14.2 ns

Reflector Optical Properties
Ref. Index = 1.49
Absorption Length = 420 cm
Density = 1.032 g/cm^3

Optical surface
Type – Dielectric metal
Model – Glisur
Finish – Polished

Particle fluxes in other units.

Type of Flux	Total Particles coming out of -Z face of rockburden	Flux (particles/m^2)
Total Flux	5.99e+09	(3.74 ± 0.02) e+4
Mu- Flux	4.40e+07	(2.75 ± 0.17) e+2
Electron Flux	3.40e+07	(2.13 ± 0.14) e+2
Gamma Flux	1.67e+08	(1.04 ± 0.03) e+3
Positron Flux	5.59e+06	(3.50 ± 0.5) e+1
Mu+ Flux	7.04e+02	(4.40 ± 0.06) e-3
Alpha Flux	4.88e+00	(3.05 ± 0.5) e-5
Neutron Flux	8.97e+05	(5.60 ± 0.07) e+0
Proton Flux	3.29e+04	(2.06 ± 0.01) e-1
Deuteron Flux	2.65e+02	(1.66 ± 0.04) e-3
Mu Neutrino Flux	3.76e+09	(2.35 ± 0.01) e+4
Mu Anti-Neutrino Flux	1.66e+07	(1.04 ± 0.1) e+2
Electron Neutrino Flux	1.61e+07	(1.10 ± 0.1) e+2
Electron Anti-Neutrino Flux	1.94e+09	(1.21 ± 0.01) e+4