# Journées de Rencontre des Jeunes Chercheurs 2022: Search of the coherent neutrinoless muon to electron convertion with the COMET experiment at J-Parc

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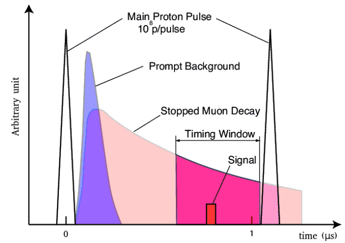
# Muon to electron conversion without neutrinos

| Experiment | Sensitivity limit | Date |
|---|---|---|
| $(\mu; Au) \to (e; Au)$ (SINDRUM II) | $7 \times 10^{-13}$ | 2006 |
| $(\mu; Al) \to (e; Al)$ (COMET) | $3 \times 10^{-15} (2.6 \times 10^{-17})$ | 2024 |

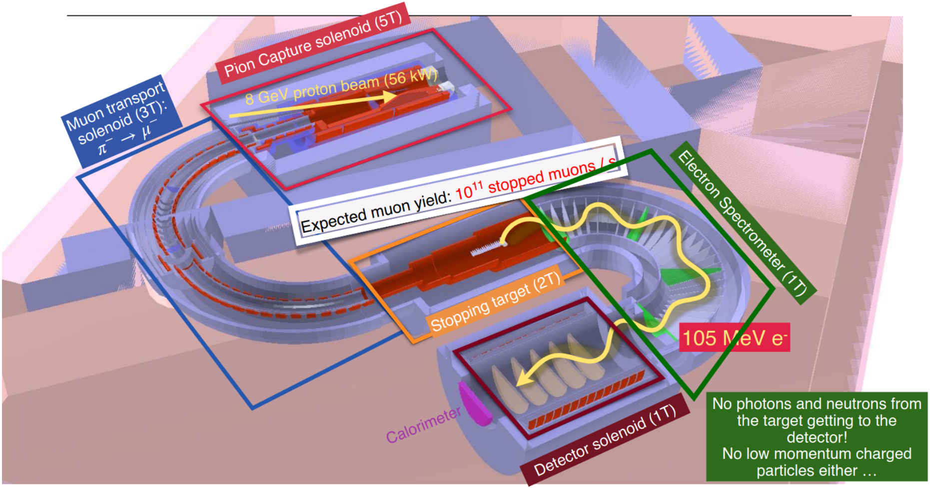
| Initial state | Interaction processes | |
|---|---|---|
| muonic Al (1s) | Decay In Orbit (DIO) | $\mu \to \nu\nu e$ |
| | Nuclear muon capture | $\mu + N(A,Z) \to \nu + N'(A, Z-1)$ |
| | Other processes ? | |

$E_{\mu e} = m_\mu - B - \Delta = 105 MeV$




- $\tau$(muonic Al (1s)) $= 864 ns$
- timing window : $0.7 - 1.17 \mu s$
- time between 2 proton pulses : $1.17 \mu s$
- $CR(\mu + Al \to e + Al) \approx \frac{1}{f_{cap}.A_e.N_\mu}$
  $\Rightarrow N_\mu = 10^{16} (2 \times 10^{18})$ ($A_e = 0.04$ (detector acceptance) and $f_{cap} = 0.6$ (fraction of captured muons in Al))

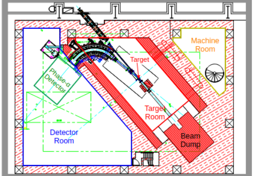
# COherent Muon to Electron Transition (COMET)

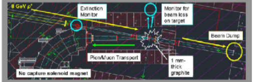


# The COMET experiment schedule

## Phase α

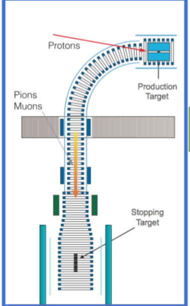
2023




- Low intensity run (260 W) without Pion Capture Solenoid
- Thin graphite p-target
- Proton beam diagnostic detectors
- Secondary particle detectors

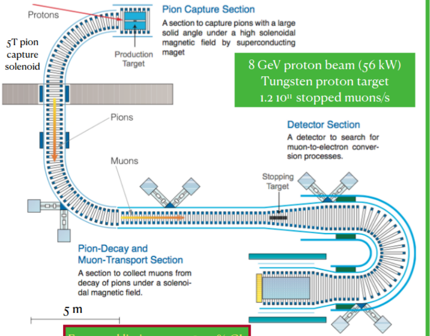
## Phase I




8 GeV proton beam (3.2 kW)
Graphite proton target
1.2 $10^9$ stopped muons/s

Expected limit : 7 $10^{-15}$ @ 90% CL
Total background: 0.01 events
Running time: 0.4 yrs (1.2 $10^7$ s)

## Phase II




8 GeV proton beam (56 kW)
Tungsten proton target
1.2 $10^{11}$ stopped muons/s

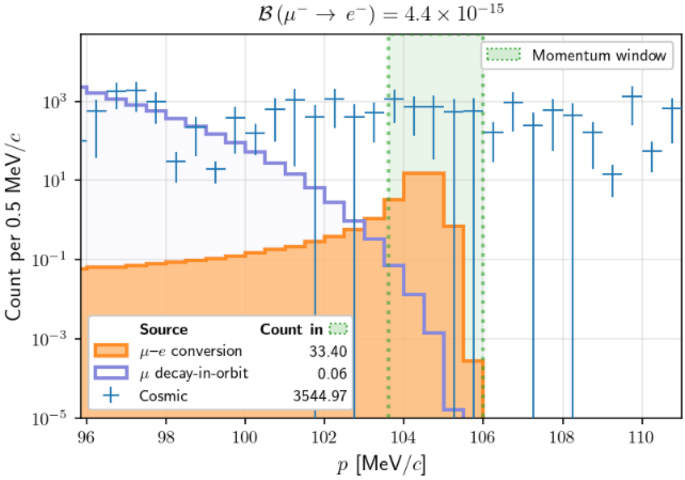
Expected limit : 7 $10^{-17}$ @ 90% CL
Total background: 0.32 events
Running time: 1 yr (2 $10^7$ s)

# Experiment's background noises

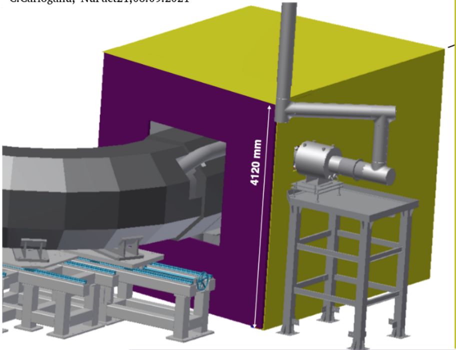
Summary of the estimated background events for a single-event sensitivity of $3 \times 10^{-15}$

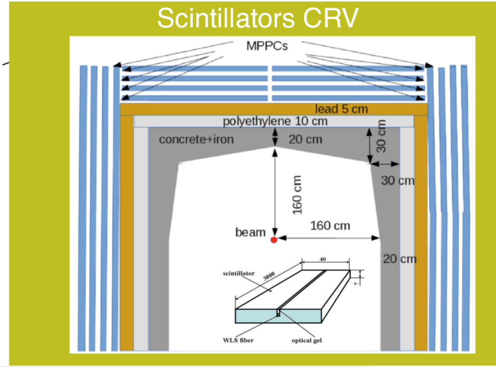
| Type | Background | Estimated events |
| --- | --- | --- |
| Physics | Muon decay in orbit | 0.01 |
| | Radiative muon capture | 0.0019 |
| | Neutron emission after muon capture | $< 0.001$ |
| | Charged particle emission after muon capture | $< 0.001$ |
| Prompt Beam | * Beam electrons | |
| | * Muon decay in flight | |
| | * Pion decay in flight | |
| | * Other beam particles | |
| | All (*) Combined | $\leq 0.0038$ |
| | Radiative pion capture | 0.0028 |
| | Neutrons | $\sim 10^{-9}$ |
| Delayed Beam | Beam electrons | $\sim 0$ |
| | Muon decay in flight | $\sim 0$ |
| | Pion decay in flight | $\sim 0$ |
| | Radiative pion capture | $\sim 0$ |
| | Antiproton-induced backgrounds | 0.0012 |
| Others | Cosmic rays$^{\dagger}$ | $< 0.01$ |
| Total | | 0.032 |

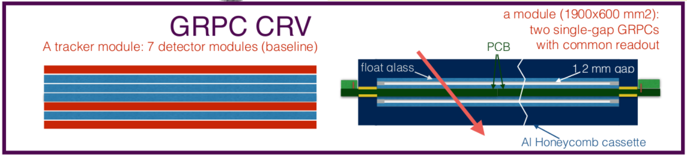
**Cosmic muons** can interact and produce **signal-like events**



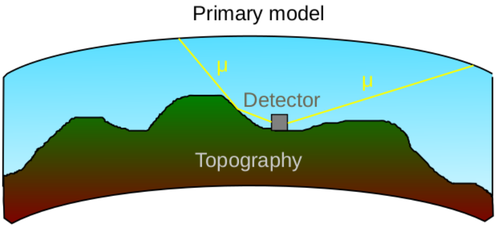
C.Carlogânu, NuFact21,08.09.2021

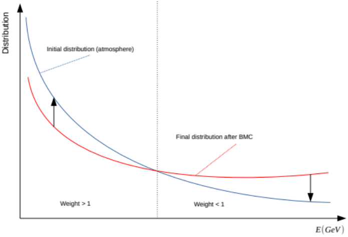


# Backward Monte Carlo (BMC)




- Small detector compared to the source ⇒ **backward propagation** from the detector to the source ;
- BMC → **stochastic process** ⇒ propagating N times the same muon :
  - $\bar{\Phi} = \sum_{i=1}^{N} w_i \Phi_{0,i}$, $w_i$ the weight and $\Phi_{0,i}$ the initial flux ;
  - $\sigma^2_{\bar{\Phi}} = \frac{1}{N-1} \sum_{i=1}^{N} w_i^2 \Phi_{0,i}^2 - \frac{N}{N-1} \bar{\Phi}^2 \propto o(\frac{w_i^2}{N}) \rightarrow$ if $w_i < 1$ so $\sigma_{\bar{\Phi}}$ is small and if $w_i \geq 1$ so N have to be "big enough" to have a small $\sigma_{\bar{\Phi}}$.

# Staps to estimate the muon flux by simulations

- **Resolution to distinguish anisotropies**. Radiation length, $X_0 \rightarrow$ energy loss :
  - **High** $X_0 \Rightarrow$ high energy loss $\Rightarrow$ **lack of muons** ;
  - **Low** $X_0 \Rightarrow$ low energy loss $\Rightarrow$ **small variation** in the muon flux ;

  $\Rightarrow$ **Scan the geometry**
- **Lot of simulated muons and high resampling** $\Rightarrow$ **good estimation of the muon flux** :
  - Muon **distribution over the detector has no gap** with the above resolution $\rightarrow$ **number of muons : ok** ;
  - Muon **distribution in the atmosphere** after BMC process has **no gap** with the above resolution $\rightarrow$ **resampling : ok**.

Estimation of the global mean flux :

$$\bar{\Phi} = 0.00163(s.m^2.sr.GeV)^{-1}$$
$$\sigma_{\Phi} = 0.00377(s.m^2.sr.GeV)^{-1}$$

# From the BMC to the expected number of cosmic muons

$$N(\alpha,\beta) = \int\int_S \int_{E_{min}}^{E_{max}} A(\alpha,\beta)\epsilon\bar{\Phi}(\alpha,\beta,E)\mathrm{dEdSdt}$$

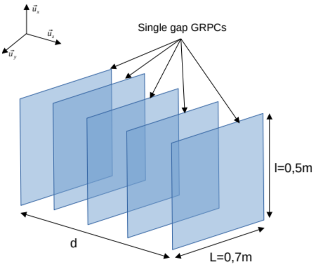
- $\bar{\Phi}(\alpha,\beta,E)$ : mean flux in $(s.m^2.sr.GeV)^{-1}$ depending on the direction we are looking at and the energy ;
- $\epsilon$ : efficiency of the detector ;
- $A(\alpha,\beta)$ : geometrical acceptance of the detector depending on the direction we are looking ;
- $\int_{E_{min}}^{E_{max}} dE$ : integral over the energy range used for simulation ;
- $\int_S dS$ : integral over the surface of the detector ;
- $\int dt$ : integral over the time.

Perfect detector = $A(\alpha,\beta) = \epsilon = 1$ :

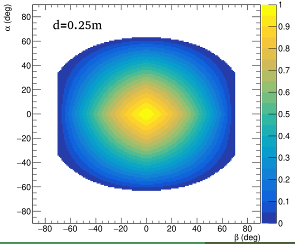
$$\frac{dN}{dt} = \frac{d}{dt}\left(\int_\Omega N(\alpha,\beta)d\Omega\right) = 42.0min^{-1}$$

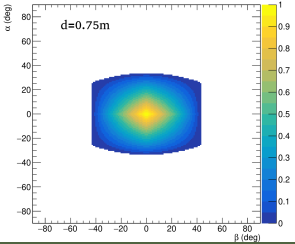
$$\sigma_N = 96.6min^{-1}$$

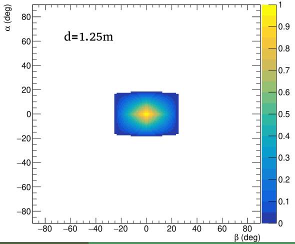
# Telescope's geometrical acceptance $A(\alpha, \beta)$



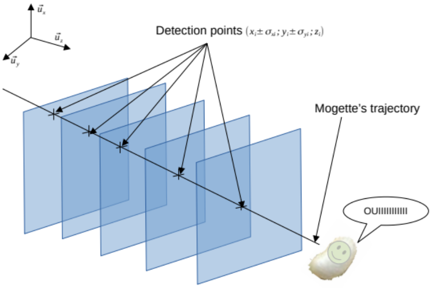

$$A(\alpha,\beta) = cos(\alpha)cos(\beta)max\left(0; 1 - \frac{d \times tan(\beta)}{L}\right) max\left(0; 1 - \frac{d \times tan(\alpha)}{l \times cos(\beta)}\right)$$



# Trajectory reconstruction with the telescope - I



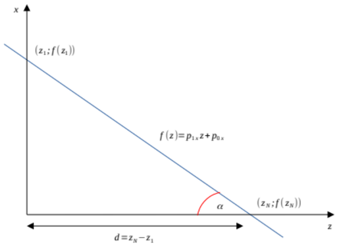

Trajectory reconstruction is based on $\chi^2$ minisation :

- xOz and yOz are independant projection :

  $$\chi^2 = \chi^2_x + \chi^2_y = \sum_{i=1}^{N} \left(\frac{x_i - x(z_i)}{\sigma_{x,i}}\right)^2 + \sum_{i=1}^{N} \left(\frac{y_i - y(z_i)}{\sigma_{y,i}}\right)^2$$

- Linear interpolation of the trajectory :
  - $x(z_i) = p_{1x} z_i + p_{0x}$
  - $y(z_i) = p_{1y} z_i + p_{0y}$

# Trajectory reconstruction with the telescope - II




- Equidistant planes and same error along each axis, with $\bar{x} = \sum_{i=1}^{N} x_i$ and $\bar{x_w} = \sum_{i=1}^{N} i x_i$ (same goes for y) :
  - $p_{1x} \pm \sigma_{p_{1x}} = \frac{12}{d(N+1)} \left( \bar{x_w} - \frac{N+1}{2} \bar{x} \right) \pm \frac{(N-1)\sigma_x}{d\sqrt{N}(N+1)}$
  - $p_{0x} \pm \sigma_{p_{0x}} = 6 \left( \frac{N-1}{N+1} \right) \left( \frac{2(N+2)}{3} \bar{x} - \bar{x_w} \right) \pm \left( 1 - \frac{3}{2(N+1)} \right) \frac{\sigma_x}{2\sqrt{N}}$
- Reconstruction of $\alpha$ and $\beta$ :
  - $\alpha \pm \sigma_\alpha = arctan(-p_{1x}) \pm \frac{\sigma_{p_{1x}}}{p_{1x}^2 + 1}$
  - $\beta \pm \sigma_\beta = arctan(-p_{1y}) \pm \frac{\sigma_{p_{1y}}}{p_{1y}^2 + 1}$

# Futur perspective

- Perspective before Phase $\alpha$ :
  - Analyse the simulations (still running) to have the resolution ;
  - Increase the number of simulated muons ;
  - Estimate the direction of the observation to measure anisotropies ;
  - Detector calibration and data taking at J-Parc $\rightarrow$ comparison with the simulations ;
- Phase I CRV and background reduction :
  - Design, construction and test of the GRPCs for the CRV ;
  - Analysis on the cosmic muons dicrimination by the CRV $\rightarrow$ update of the CRV rejection and the total cosmic rays events for Phase I ;

"The Nature has be kind with us for now. But she has no reason to let us discover all her secrets" Dario AUTERIO

Thanks for your attention

# BACKUPS

# Errors on the estimators

$$\sigma_{\bar{\Phi}} = 3.54 \times 10^{-12} (s.m^2.sr.GeV)^{-1}$$

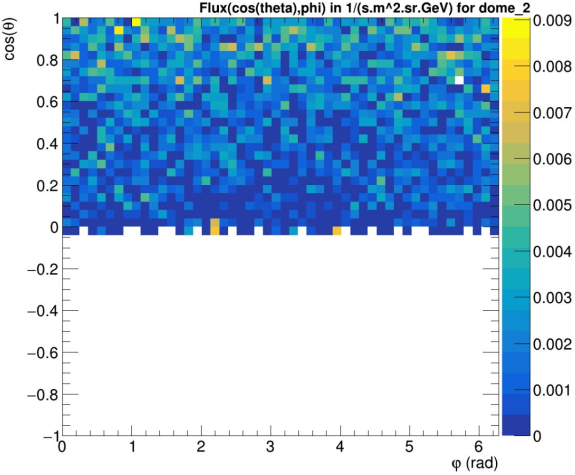
$$\sigma_{\sigma_\Phi} = 2.94 \times 10^{-12} (s.m^2.sr.GeV)^{-1}$$

$$\sigma_R = 2.20 \times 10^{-14} min^{-1}$$

$$\sigma_{\sigma_R} = 1.17 \times 10^{-14} min^{-1}$$

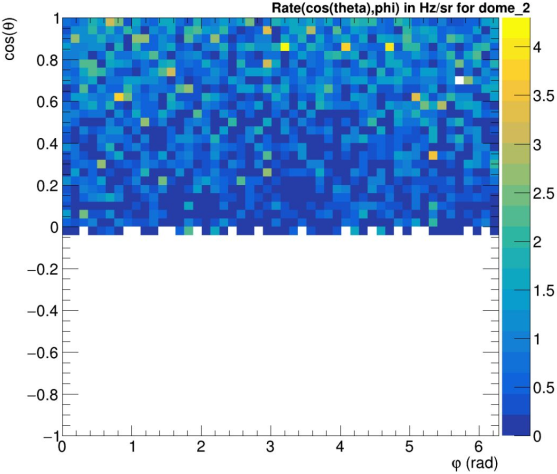
# Flux map depending on azimuthal and zenithal angles

No particular anisotropy



# Differential rate map depending on azimuthal and zenithal angle

Same kind of anisotropie at $cos(\theta) = 0.5$



# Differential rate depending on the kinetic energy