8th International conference on particle physics and astrophysics (ICPPA-2026)

Probing Pion-Nucleon and Proton-Nucleon Production Channels for Millicharged Particles in the SuperFGD Detector at T2K

Nikita Mashin[1, 2, 3], Nataliya Skrobova[2, 3]

[1]Moscow Institute of Physics and Technology, Moscow Region, Dolgoprudny, Russia
[2]The Lebedev Physical Institute, 119991 Moscow, Russia
[3]Institute for Nuclear Research of the Russian Academy of Sciences, 117312 Moscow, Russia

This work was supported by RSF grant #24-72-10089

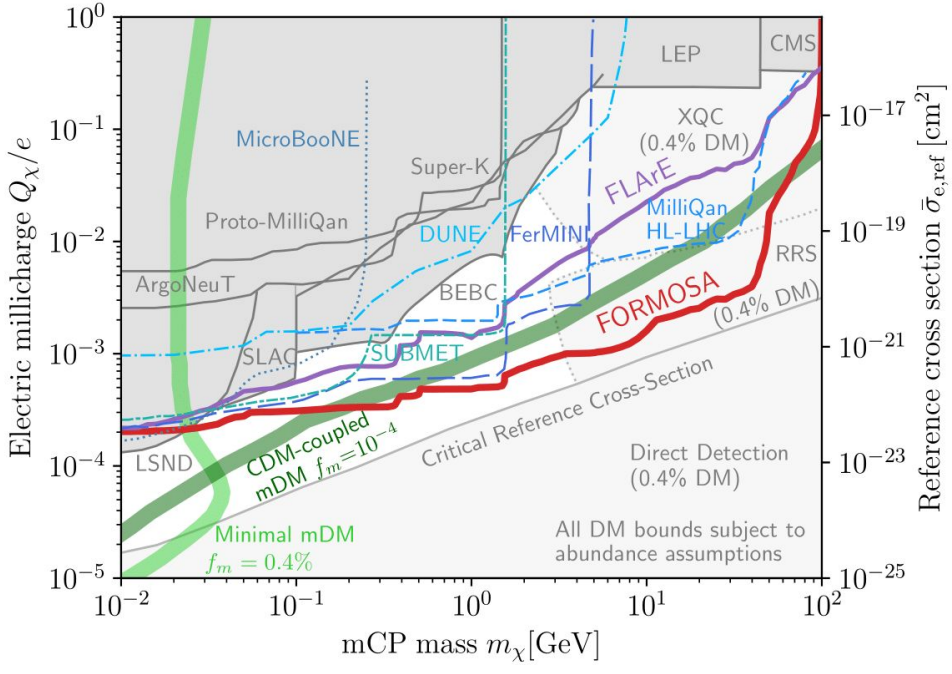
October 28, 2026
Moscow

MilliCharged Particles (mCP)

- MilliCharged Particles (mCP) are hypothetical particles carrying the fractional charge O(10^{-3})e
  - Extension of the SM
  - Additional symmetries in high energy scale
  - Possible contribution to the dark matter
- The phenomenology of mCPs is determined by their coupling to the electromagnetic field A_μ, and for the fermionic mCP χ with mass m_χ the interaction is described by the Lagrangian:

$$\mathcal{L} \supset \epsilon e A_\mu \bar{\chi} \gamma_\mu \chi, \quad \epsilon \ll 1$$

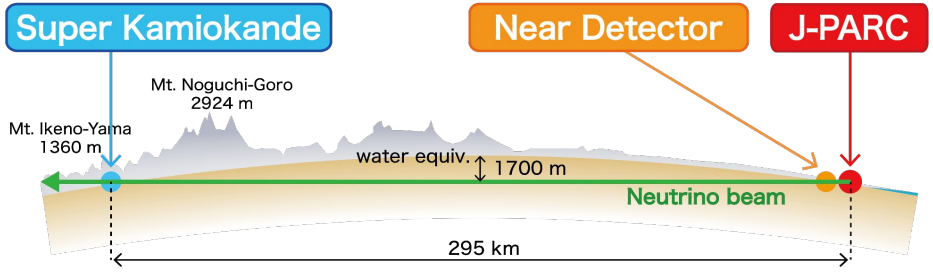
J.Phys.G 50 (2023) 3, 030501

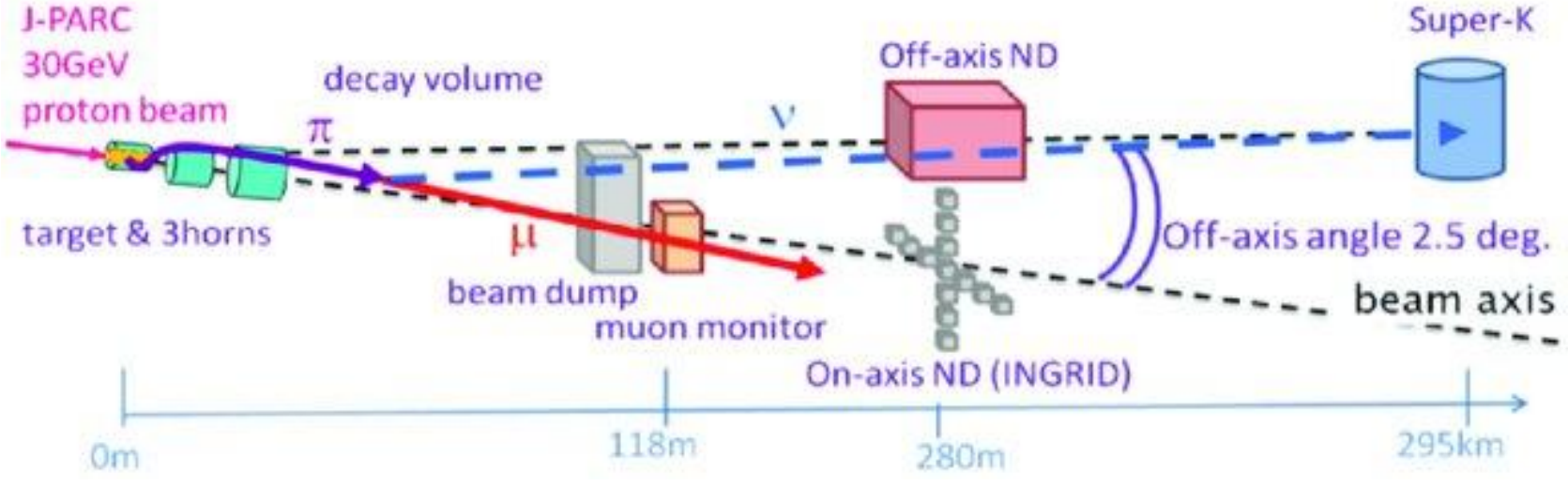


- Neutrino experiments are expected to have good sensitivity to mCP detection
- In particular, new 3D scintillator detector SuperFGD of the T2K experiment seems to have a good performance for mCP search (10.1016/j.physletb.2021.136641)

T2K Experiment

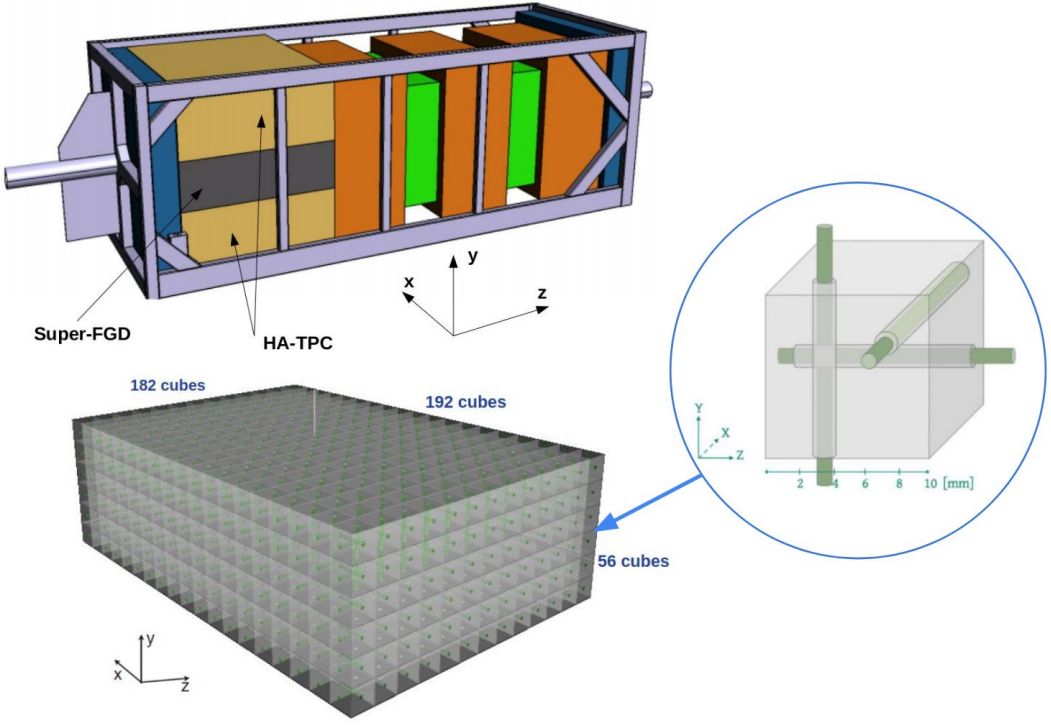
- Tokai-to-Kamioka (T2K) is a long-baseline accelerator neutrino experiment
  - Precise measurements of the neutrino oscillation parameters
  - Search for the CP-violation in neutrino oscillations
- J-PARC accelerator provides intense 30 GeV proton beam
- Beam hits the carbon target producing various mesons
- Charged mesons are focused and further decay into neutrinos (primarily muon neutrinos/antineutrinos)





T2K Near Detector

- Near neutrino detector (ND280) is a magnetised complex detector located 280 meters from the target
  - Measurements of the flux × cross-section
  - Reduction of the systematic uncertainties of the oscillation analysis
- In 2023–2024 the Near Detector upgraded with a new neutrino detector SuperFGD [1, 2, 3], two High-angle TPCs and TOF planes.



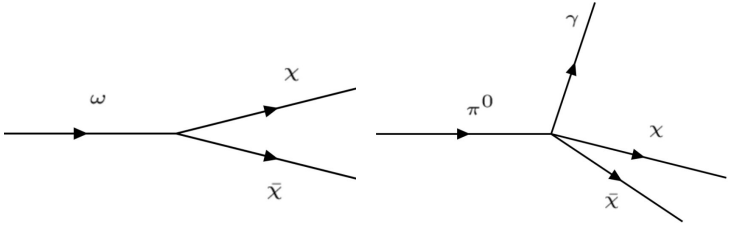
- SuperFGD is built with ~ 2 mln 1 × 1 × 1 cm^3 scintillator cubes
- The detector dimensions are 192 × 56 × 182 cm
- The total mass is ~2 tons
- The readout is done with WLS fibers read by MPPCs (~60k channels)
- 40 photo-electrons per channel per MIP
- Low MPPC dark rate (0.5 kHz)
- Good time resolution (~1 ns)

[1] Blondel, A. [et al.]. A fully active fine grained detector with three readout views // JINST. 2018. V. 13: P02006.
[2] Chvirova A. [et al.]. Commissioning of 3D-Segmented Neutrino Detector SuperFGD in the T2K Neutrino Beam // Phys. Atom. Nucl. 2025. V. 88(2). P. 260–268.
[3] S. Abe [et al.] The super fine-grained detector for the T2K neutrino oscillation experiment// Nucl.Instrum.Meth.A 1092 (2026) 171882

MCP production at J-PARC: primary channels

- In J-PARC mCPs can be produced in:
  - **Decays of scalar (π^0, η, η') and vector (ρ, ω, ϕ) mesons: primary mechanism**
  - J/ψ meson decays, Drell-Yan processes, and proton bremsstrahlung: minor contribution
- Scalar meson (π^0, η, η') can decay only in 3-body mode: X → Yχχ (e.g. π^0 → γχχ, η → γχχ)
- Vector meson (ρ, ω, ϕ) can decay in 2-body (X → χχ) mode, 3-body channels are also possible, e.g. ω → π^0χχ

$$\mathrm{Br}(V \to \chi\bar{\chi}) = \epsilon^2 \mathrm{Br}(V \to e^+e^-)\left(1 + 2\frac{m_\chi^2}{M_V^2}\right)\sqrt{1 - \frac{4m_\chi^2}{M_V^2}}, \quad V \in \{\rho, \omega, \phi\}$$



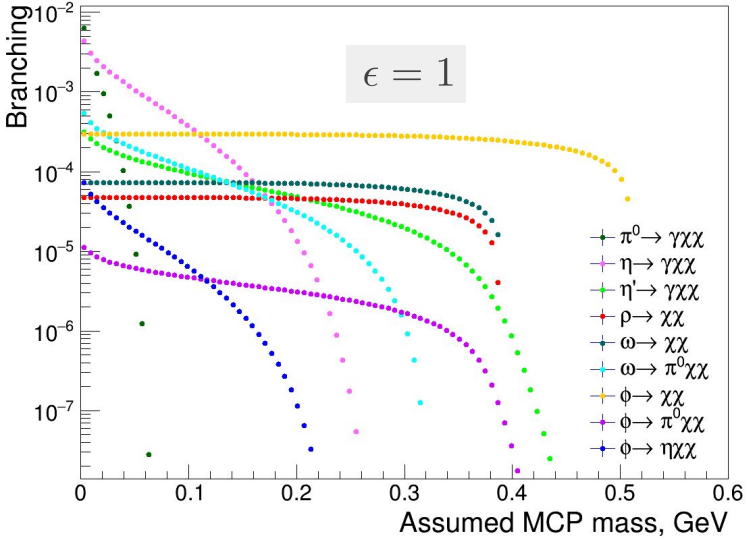
$$\mathrm{Br}(X \to Y\chi\bar{\chi}) = \epsilon^2 \mathrm{Br}(X \to Y\gamma) \times$$

$$\times \frac{2\alpha}{3\pi} f_{X\to Y} \int_{4m_\chi^2}^{m_X^2} \frac{dm_{\chi\chi}^2}{m_{\chi\chi}^2}\left(1 + 2\frac{m_\chi^2}{m_{\chi\chi}^2}\right)\left(1 - 4\frac{m_\chi^2}{m_{\chi\chi}^2}\right)^{\frac{1}{2}} \times$$

$$\times \left(\left(1 + \frac{m_{\chi\chi}^2}{M_X^2 - M_Y^2}\right)^2 - 4\frac{m_{\chi\chi}^2 M_X^2}{\left(M_X^2 - M_Y^2\right)^2}\right)^{\frac{3}{2}} \left|F_{XY}(m_{\chi\chi}^2)\right|^2$$

$$X \to Y \in \{\pi^0 \to \gamma, \eta \to \gamma, \eta' \to \gamma, \omega \to \pi^0, \phi \to \pi^0, \phi \to \eta\}$$

$$f_{\pi\to\gamma} = f_{\eta\to\gamma} = f_{\eta'\to\gamma} = 1, \qquad f_{\omega\to\pi^0} = f_{\phi\to\pi^0} = f_{\phi\to\eta} = \frac{1}{2}$$

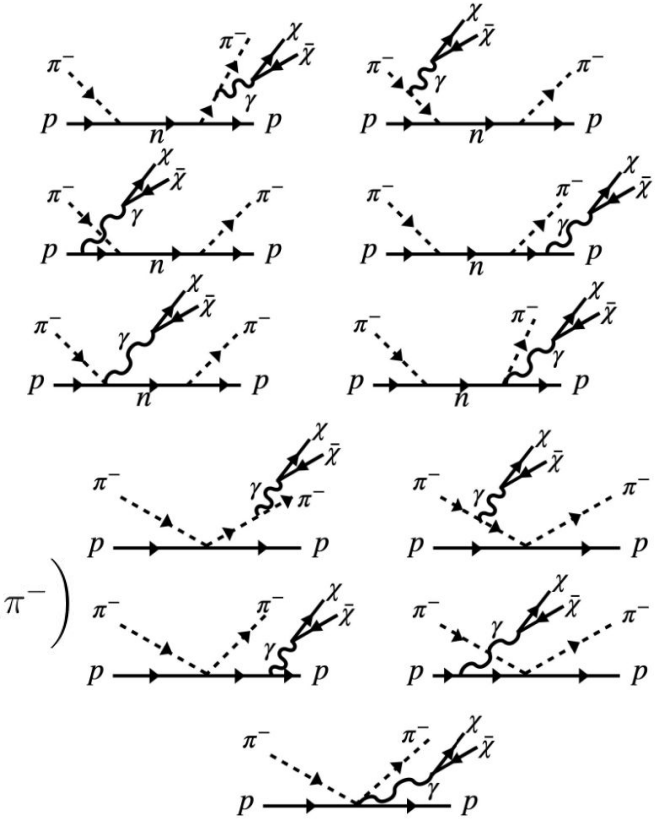


MCP production at J-PARC: additional channels

- Another potential source of MCPs is **πN and pN scatterings**
- Consider a model where a fermionic MCP χ with mass mχ has electric charge Q = eϵ, with e = √4πα the QED gauge coupling and ϵ ≪ 1. The MCP therefore couples to the SM photon Aμ through the Lagrangian

$$\mathcal{L}_{\chi\bar{\chi}} \supset \bar{\chi}(i\gamma^\mu\partial_\mu - m_\chi)\chi + Q\bar{\chi}\gamma^\mu\chi A_\mu + \mathcal{L}_{\pi N} + \mathcal{L}_{\pi NA}$$

where LπN and LπN A are pion-nucleon and pion-nucleon-photon Lagrangians described by **chiral perturbation theory (ChPT)**. (see Phys.Rev.D 110 (2024) 9, 095029)

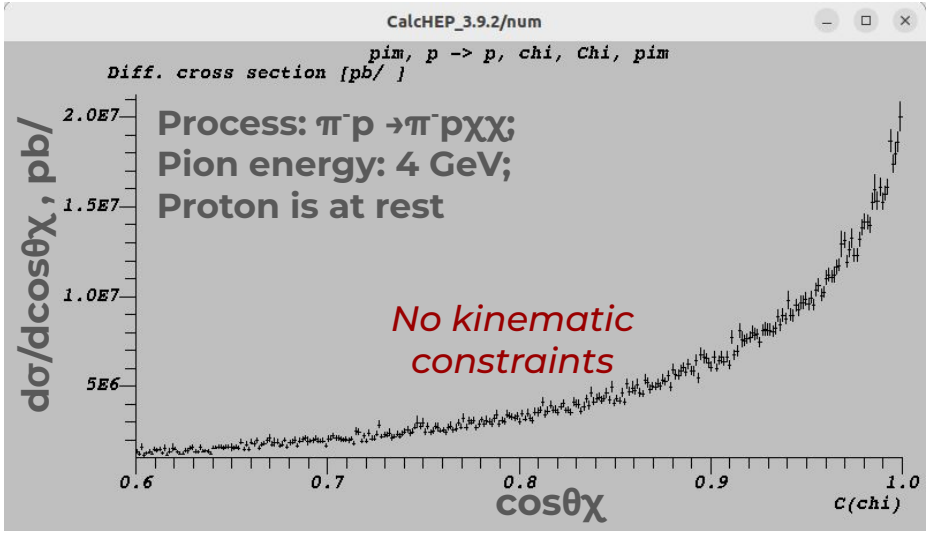


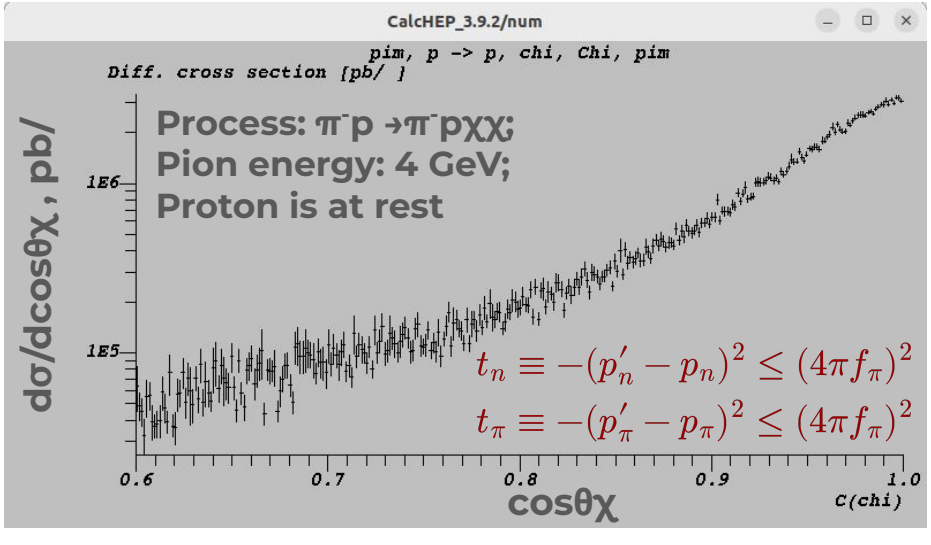
$$\mathcal{L}_{\pi N} \supset \frac{g_A}{2f_\pi}\left(\bar{p}\gamma^\mu\gamma^5 p\partial_\mu\pi^0 - \bar{n}\gamma^\mu\gamma^5 n\partial_\mu\pi^0 + \sqrt{2}\bar{p}\gamma^\mu\gamma^5 n\partial_\mu\pi^+ + \sqrt{2}\bar{n}\gamma^\mu\gamma^5 p\partial_\mu\pi^-\right)$$
$$+\frac{i}{4f_\pi^2}\left(\bar{p}\gamma^\mu p(\pi^+\partial_\mu\pi^- - \pi^-\partial_\mu\pi^+) + \bar{n}\gamma^\mu n(\pi^-\partial_\mu\pi^+ - \pi^+\partial_\mu\pi^-)\right.$$
$$\left.+\sqrt{2}\bar{n}\gamma^\mu p(\pi^-\partial_\mu\pi^0 - \pi^0\partial_\mu\pi^-) + \sqrt{2}\bar{p}\gamma^\mu n(\pi^0\partial_\mu\pi^+ - \pi^+\partial_\mu\pi^0)\right)$$

$$\mathcal{L}_{\pi NA} \supset ieA_\mu\left(\pi^-\partial^\mu\pi^+ - \pi^+\partial^\mu\pi^-\right) + e^2A_\mu A^\mu\pi^+\pi^- + eA_\mu\bar{p}\gamma^\mu p + \frac{ieg_A}{\sqrt{2}f_\pi}A_\mu\left(\bar{n}\gamma^\mu\gamma^5 p\pi^- - \bar{p}\gamma^\mu\gamma^5 n\pi^+\right)$$
$$+\frac{e}{2f_\pi^2}A_\mu\left(\bar{n}\gamma^\mu n\pi^+\pi^- - \bar{p}\gamma^\mu p\pi^+\pi^- + \frac{1}{\sqrt{2}}\bar{n}\gamma^\mu p\pi^0\pi^- + \frac{1}{\sqrt{2}}\bar{p}\gamma^\mu n\pi^0\pi^+\right)$$

πN and pN cross sections: LanHEP + CalcHEP approach

- We need cross-sections for mCP signal events calculation from πN and pN scattering
- **LanHEP** for deriving Feynman rules in our ChPT (lanhep)
  - INPUT: ChPT Lagrangian
  - OUTPUT: Model composition and Feynman rules
- **CalcHEP** for numerical calculation of cross-sections and mCP angular distributions (calchep)
  - INPUT: Model composition and Feynman rules
  - OUTPUT: Differential cross-sections
- **ChPT limitations:** To remain within the regime of validity of leading-order ChPT, we impose the momentum-transfer cuts as phase-space restrictions

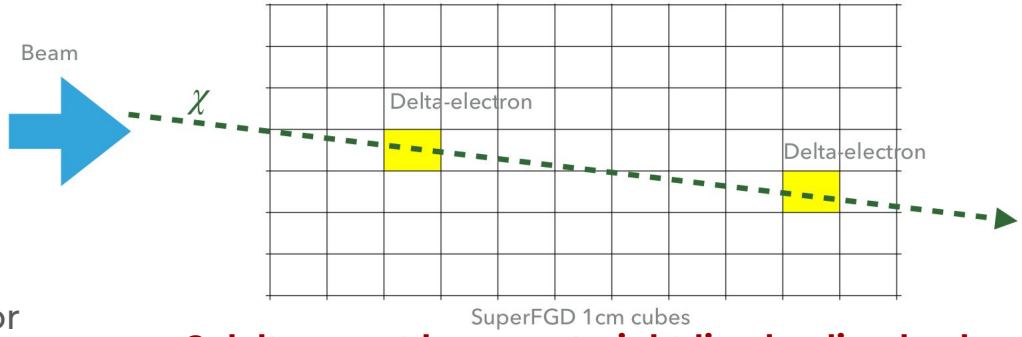




These constraints lead to a conservative estimate of the cross-section, and therefore of the overall final sensitivity.

Signal events in SuperFGD: detection principle

- mCP detection:
  - **Coincidence of 2 delta-electron production.**
  - Single high energy delta-electron production.
    Limitation: Challenging background rejection.
  - Small dE/dx e.g. in the long scintillator bars. (MilliQan) Limitation: Sub-threshold signal.



2 deltas must be on a straight line leading back to the production point (target alignment)

- The number of signal events from **neutral meson decays** is:

$$N_S^{\text{decays}} = 2N_{POT} \sum_{\text{vol.}} \sum_{X} \left(\frac{N_X}{N_{\text{sim}}} \right)_{\text{vol.}} \sum_{i} \text{Br}_i(X \to \ldots)\, \xi_{X,i,\text{vol.}}\, P_{2h}\, \varepsilon_{\text{tot}},$$

Number of protons | Meson outputs | Branching fractions | Acceptances | Double-hit probability | Detection efficiency

Probability for mCP double-scattering with electron kick out with Er > Er^{min}:

$$P_{2h} = \frac{1}{2}\left(\frac{L}{\lambda}\right)^2$$

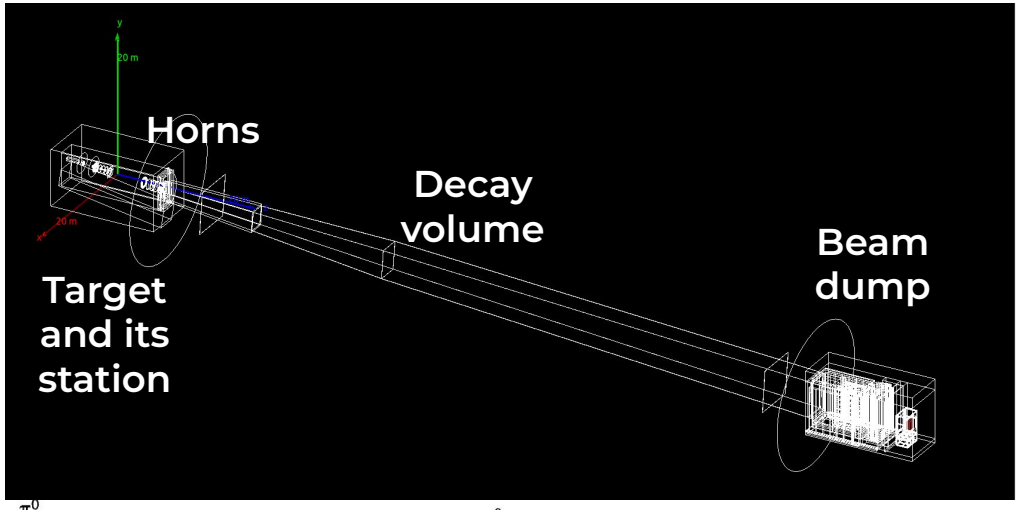
- The exact formula for the number of signal events from **pion-nucleon scatterings**:

$$N_{\pi^\pm N} = 2\rho\frac{N_A}{A}N_{p(n)}\frac{N_{POT}}{N_{\text{sim}}} \sum_{i\in\text{all pions}} \int_{\text{det. surf.}} d\Omega \int_0^{l(E_\pi = m_\pi)} dl\, \frac{d\sigma_{\pi^\pm N}}{d\Omega}\,(E_i(l), \cos\theta_i)\, P_{2h}\varepsilon_{\text{tot}}.$$

Nucleon density | Scaling factor | Sum over all pions in sample | Diff. cross-section | Energy parametrization against traveled distance | Angle between meson momentum and direction to detector

Beamline simulation: output of neutral mesons

- Fully **Geant4** simulation
- Geometry from **T2K G4JNUBEAM** software
  - Magnetic horns are included
  - Accurate description of target and beam dump volumes
  - Realistic description of surrounding sand (Concrete instead of ground
- Physics List: **QGSP_BERT**



Meson	Output
π^0	11.83
η	0.62
η'	0.25
ρ	0.51
ω	0.44
ϕ	0.0091

Table: Neutral meson outputs per POT (for the whole beamline)

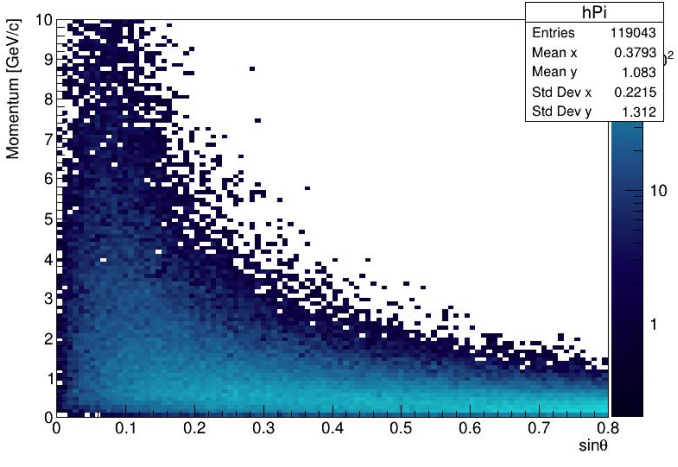


Figure: π^0-meson kinematics

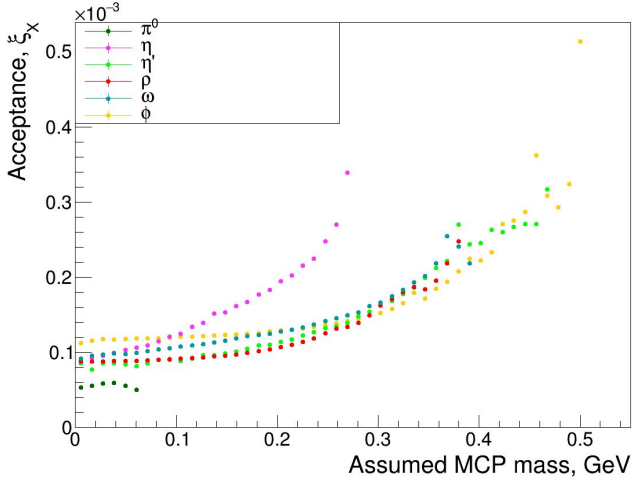


Figure: Geometrical acceptances for relevant meson types.

Charged pions and protons in T2K target

- Geant4 simulation for charged pions and protons production
- All tracks with start or end in target are saved

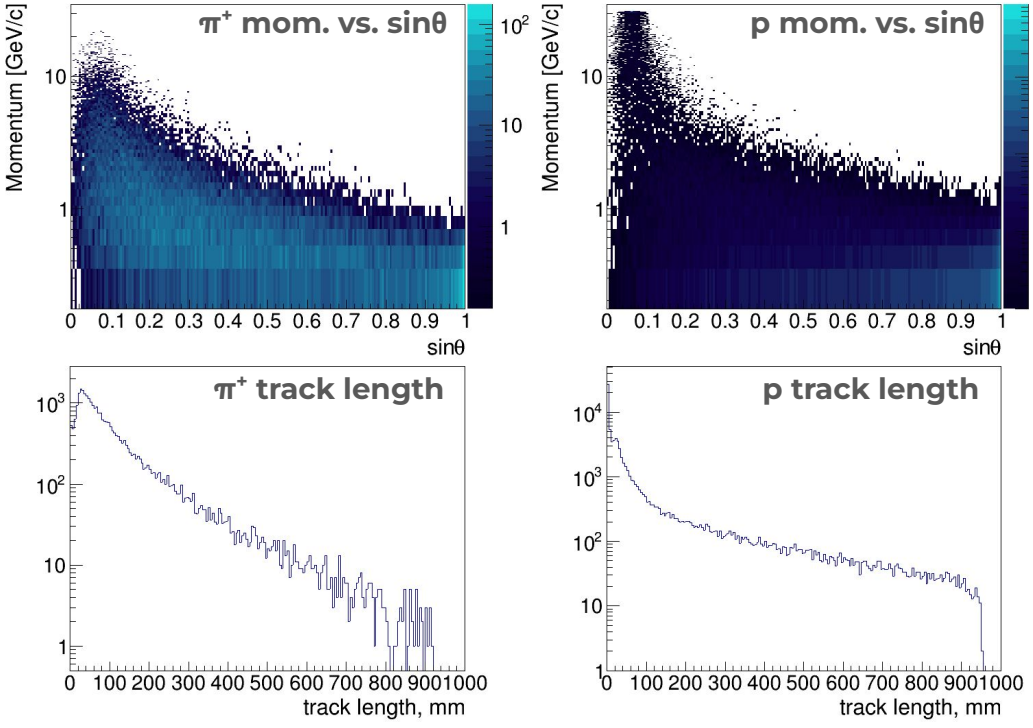


Fig.: Kinematic distributions for π^+ and protons (upper row). Track length distributions inside the target for π^+ and protons (lower row).

- Pion (proton) momentum, cosθ and track length are saved
- Track length are calculated only inside the target

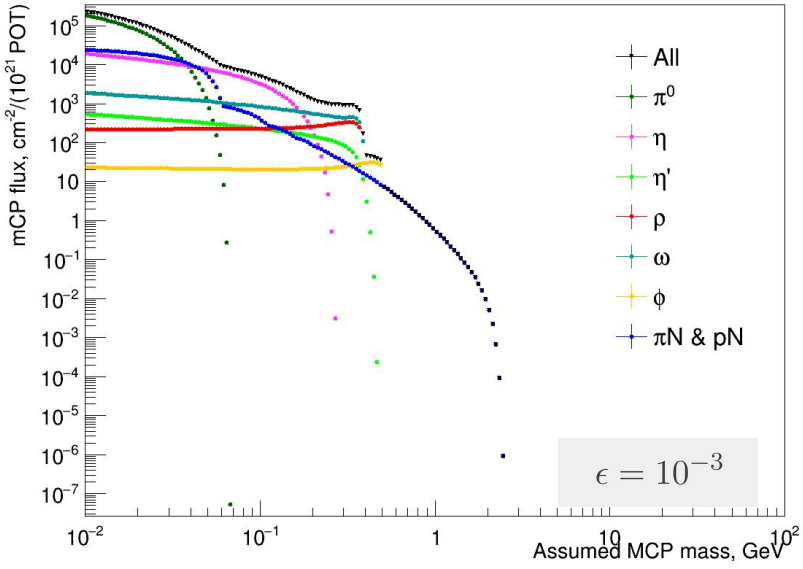


Fig.: The integral flux of millicharged particles near SuperFGD as a function of the mCP mass.

In the region below 0.5 GeV, the increase in flux due to πN and pN reactions is about 10%. Nevertheless, these channels extend the mass range up to 2.5 GeV

Signal selection: from low-activity events to aligned pairs

The expected signature is two small clusters produced by recoil electrons from an mCP crossing the detector **(cluster = several adjacent hits, hit = "fired" cube)**

Stage 1: Select low-activity events

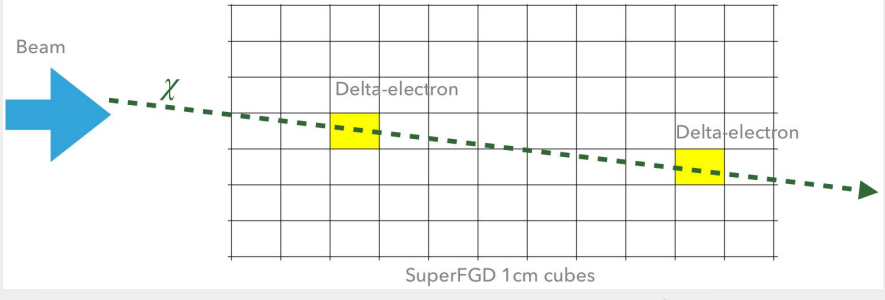
- Cut 1: No tracks in SFGD (Reject tracks and clusters with > 5 hits)
- Cut 2: Number of clusters in SFGD < 3
- Cut 3: Total charge of SFG hits < 500 p.e.
- Cut 4: No activity in P0DECAL
- Cut 5: No activity in UsECAL
- Cut 6: SFGD Veto cut (No hits near the edges of SFGD)

Stage 2: Search for small clusters in selected events

- Clusters with ≤ 5 hits are selected
- Their coordinates, time, and energy are recorded.

Stage 3: Search for a pairs aligned with the target

- Reconstruct pairs of small clusters.
- Extrapolate the line connecting the clusters back to the target.
- Require consistency with the target position.



$$\chi^2 = \frac{(\text{int}_x - \text{trg}_x)^2}{\sigma_x^2} + \frac{(\text{int}_y - \text{trg}_y)^2}{\sigma_y^2}$$

$$\chi^2 < n_\sigma^2, \quad n_\sigma = 3 \text{ (adjustable parameter)}$$

- Apply cut on a minimum distance between the clusters.

Monte Carlo strategy: background and signal efficiency

Background model

NEUT MC ⇨ Event selection ⇨ Background estimate

- NEUT MC for neutrino interactions (interactions occur both in the detector and in surrounding materials)
- The full selection is applied to the events
- Looking for double coincidences

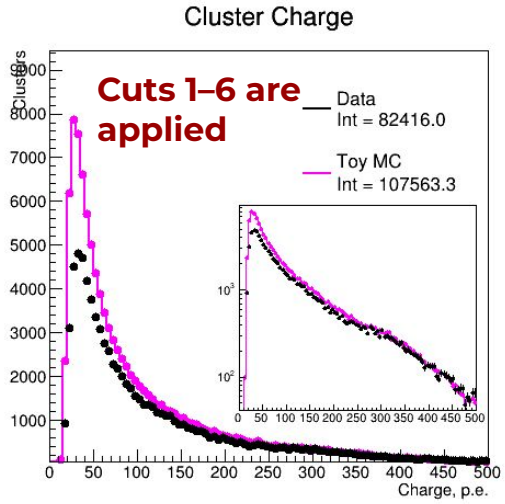
Signal efficiency

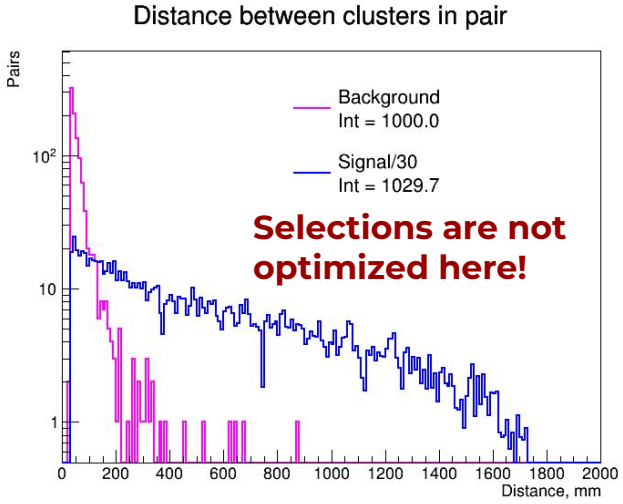
NEUT MC + Signal MC ⇨

Spill overlay ⇨ Event selection ⇨ Signal efficiency

- This approach allows one to estimate the total efficiency (including efficiency of recoil electron detection, efficiency of selecting events with low activity, efficiency of geometric cuts)

$$\varepsilon_{\text{tot}} = \frac{N^{\text{found}}_{\text{pairs}}}{N^{\text{all}}_{\text{pairs}}}$$





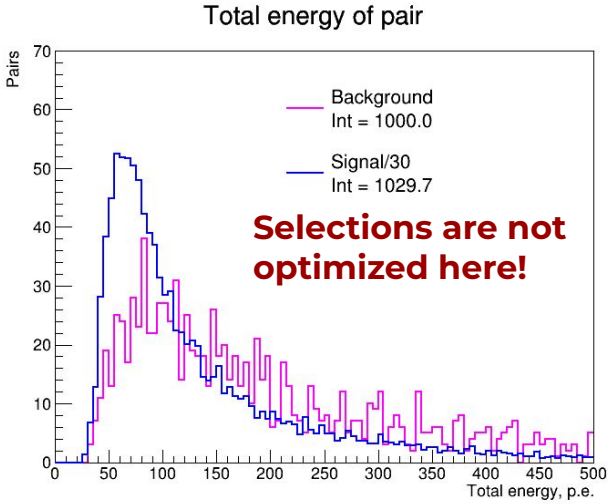
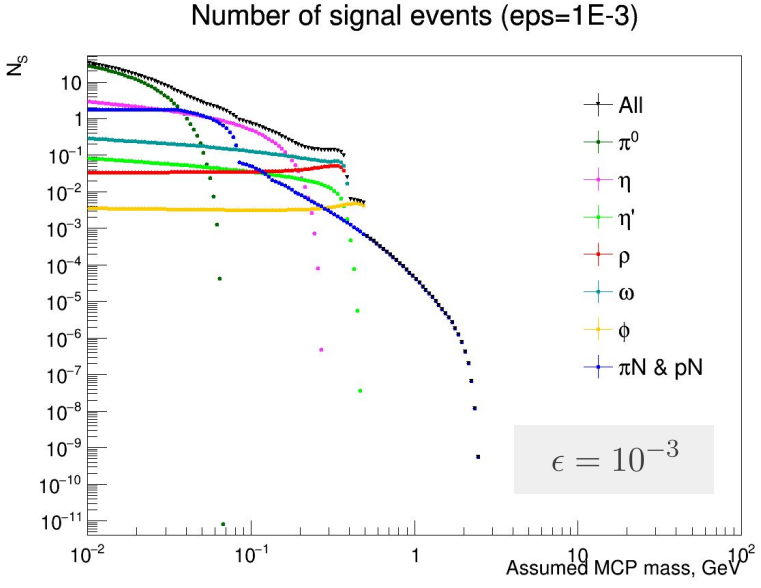


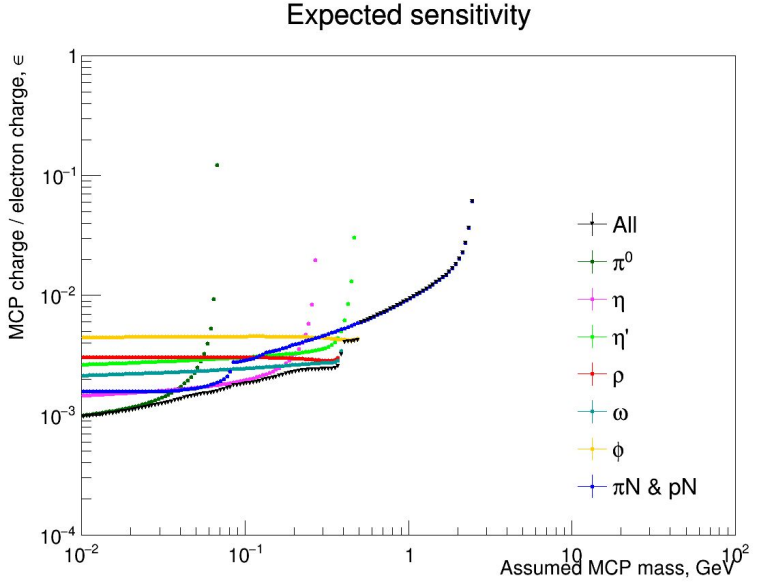
Fig.: Charge of single clusters in data and in MC. Data and MC are normalized to the same POT.

Fig.: Distance between clusters (left) and total charge of two clusters (right) in the found pairs (in the background MC and in the signal MC)

Sensitivity estimate

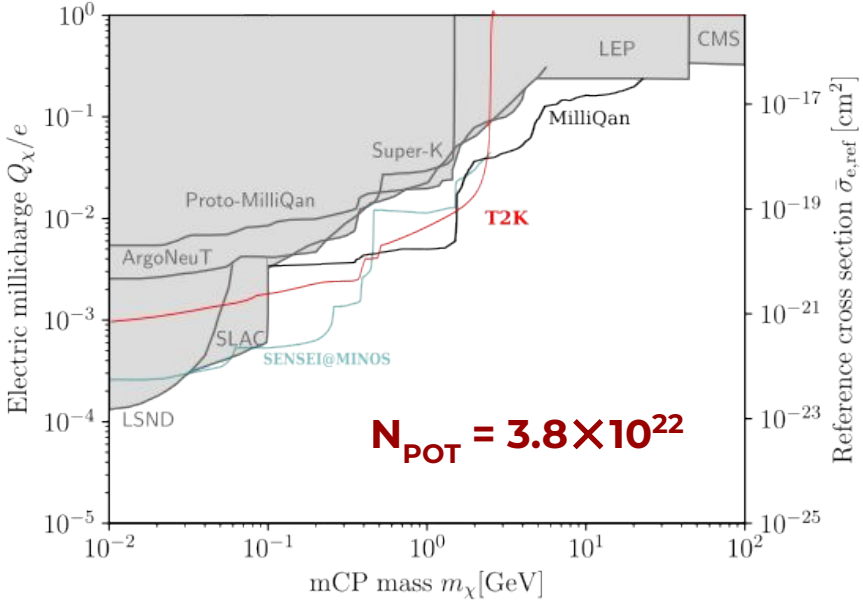
- After optimization of selections:
  - Total signal detection efficiency: **0.8 %**
  - Total expected background for the experiment full statistics ($N_{POT} = 3.8 \times 10^{22}$): **179 events**

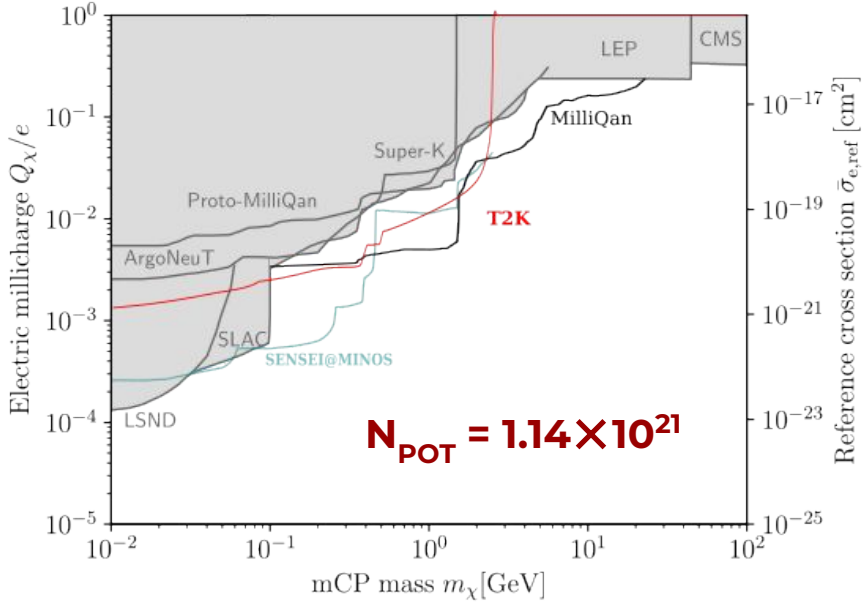




- The **Feldman-Cousins** approach is used to estimate the sensitivity.
- mCP signal events from pion-nucleon and proton-nucleon reactions were added to main contribution from neutral meson decays
- **Left:** Number of signal events from all channels for ϵ = 1E-3. Pion-nucleon channel is blue.
- **Right:** Expected sensitivity within all channels

Limits for full T2HK and current statistics





- Regions shaded in gray are experimentally excluded.
- The region above the turquoise line is also excluded by the recent SENSEI study, while the region above the solid black line is excluded by the MilliQan experiment.
- **Left panel:** Projected T2K sensitivity for the full planned exposure of $N_{POT} = 3.8 \times 10^{22}$ (10 years of data taking);
  Right panel: Sensitivity for the currently accumulated exposure of $N_{POT} = 1.14 \times 10^{21}$.

Conclusions

- The potential of the SuperFGD detector for searching for millicharged particles was investigated.
- Decay channels of scalar (π^0, η, η') and vector (ρ, ω, ϕ) mesons, **as well as scattering processes of pions and protons in the target material**, was considered as sources of mCPs. The cross sections of pion-nucleon and proton-nucleon reactions were estimated from chiral perturbation theory.
- Full simulation of the neutrino beamline is used to estimate the yields of neutral mesons, as well as charged pions and protons.
- A study of backgrounds and signal event detection efficiencies has been performed using Monte Carlo.

  The developed selection criteria yield **179 background events** for the full experimental statistics ($N_{POT} = 3.8 \times 10^{22}$) and a **signal selection efficiency of 0.8%**.

  - The main contribution to the efficiency comes from the reconstruction efficiency of clusters from recoil electrons. For electrons with energies above 50 keV, this efficiency is ~3.4%.
- **The additional channels make it possible to achieve sensitivity in the range from 0.5 to nearly 2.5 GeV, previously uncovered by the T2K experiment.**

Thank you for your attention!

BACKUP

LanHEP

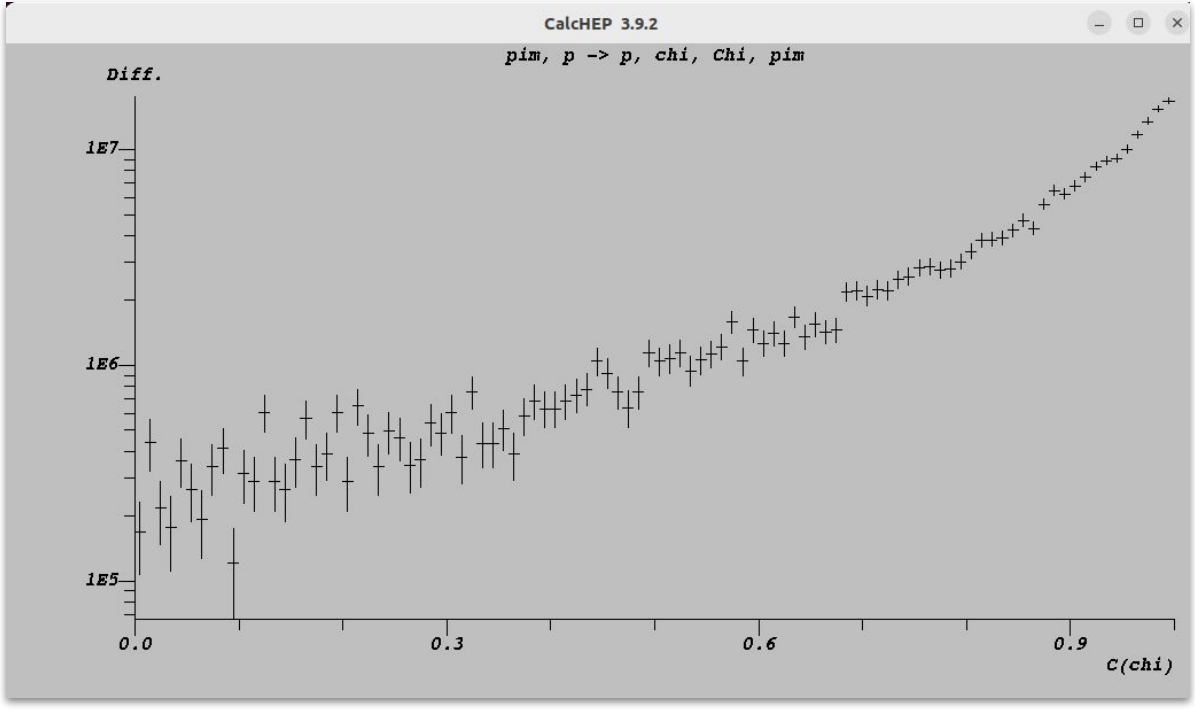
- INPUT: ChPT Lagrangian
- OUTPUT: Model composition and Feynman rules

```
Chiral pion-nucleon model with MCP
 Particles
Full   Name     | P | aP|  number  |spin2|mass|width|color|aux| LaTeX(A)       |  LateX(A+)         |
photon          |A  |A  |22        |2    |0   |0    |1    |G  |A               |A                    |
proton          |p  |P  |2212      |1    |Mp  |Wp   |1    |3  |p               |\bar{p}              |
neutron         |n  |N  |2112      |1    |Mn  |Wn   |1    |0  |n               |N                    |
mcp             |chi|Chi|666       |1    |Mchi|0    |1    |3  |\chi            |\bar{\chi}           |
pi_plus         |pip|pim|211       |0    |Mpi |Wpi  |1    |3  |\pi^{+}         |\pi^{-}              |
neutral_pion    |pi0|pi0|111       |0    |Mpi0|Wpi0 |1    |0  |\pi^{0}         |\pi^{0}              |
```

```
Chiral pion-nucleon model with MCP
 Lagrangian
P1   |P2   |P3   |P4   |>   Factor                                  <|> dLagrangian/ dA(p1) dA(p2) dA(p3)
A    |pim  |pip  |     |EE                                           |m1.p3-m1.p2
Chi  |chi  |A    |     |EE*epsM                                      |G(m3)
N    |n    |pi0  |     |i*gA/(2*Fpi)                                 |G(p3)*G5
N    |p    |pim  |     |-i*Sqrt2*gA/(2*Fpi)                          |G(p3)*G5
P    |n    |pip  |     |-i*Sqrt2*gA/(2*Fpi)                          |G(p3)*G5
P    |p    |A    |     |EE*epsM                                      |G(m3)
P    |p    |pi0  |     |-i*gA/(2*Fpi)                                |G(p3)*G5
A    |A    |pim  |pip  |2*EE^2                                       |m1.m2
N    |n    |pim  |pip  |1/(4*Fpi^2)                                  |G(p4)-G(p3)
N    |p    |A    |pim  |i*EE*Sqrt2*gA/(2*Fpi)                        |G(m3)*G5
N    |p    |pi0  |pim  |Sqrt2/(4*Fpi^2)                              |G(p3)-G(p4)
P    |n    |A    |pip  |-i*EE*Sqrt2*gA/(2*Fpi)                       |G(m3)*G5
P    |n    |pi0  |pip  |Sqrt2/(4*Fpi^2)                              |G(p4)-G(p3)
P    |p    |pim  |pip  |1/(4*Fpi^2)                                  |G(p3)-G(p4)
```

CalcHEP

- INPUT: Model composition and Feynman rules
- OUTPUT: Differential cross-sections



- Process: $\pi^- p \rightarrow \pi^- p \chi\chi$
- Pion energy: 4 GeV
- Proton is in rest
- Output distribution is cosθ of mCP relative to pion momentum
- Vertical axis: diff. cross-section in pb/

- Cross sections are calculated for grid in pion momentum and mCP mass space

Signal events in SuperFGD

The exact formula for event numbers from **pion-nucleon scatterings**:

$$N_{\pi^\pm N} = \rho \frac{N_A}{A} N_{p(n)} \times \frac{N_{POT}}{N_{sim}} \times \sum_{i \in \text{all pions}} \int_{\text{det.surf.}} d\Omega \int_0^{l(E_\pi = m_\pi)} dl \frac{d\sigma_{\pi^\pm N}}{d\Omega} (E_i(l), \cos\theta_i) \times P_{2h} \times \epsilon_{\text{tot}}$$

Nucleon density

Scaling factor

Sum over all pions in sample

Diff. cross-section

Energy parametrization against traveled distance

Angle between meson momentum and direction to detector

We can simplify this formula.

- Averaging over the track length is replaced with using the mean energy and multiplying by the track length.
- Integration over the detector surface is replaced with multiplication by the solid angle corresponding to the front surface of the detector.

$$N_{\pi^\pm N} = 2\rho \frac{N_A}{A} N_{p(n)} \frac{N_{POT}}{N_{\text{sim}}} \sum_{i \in \text{all pions}} \frac{1}{2\pi} \frac{d\sigma_{\pi^\pm N}}{d\cos\theta} (E_{i,\text{mean}}, \cos\theta_i) \, l_{\text{track},i} \frac{S_{\text{det}}}{L_i^2} P_{2h} \varepsilon_{\text{tot}}.$$

Similar formula for proton-nucleon scattering:

$$N_{pN} = 2\rho \frac{N_A}{A} N_{p(n)} \frac{N_{POT}}{N_{\text{sim}}} \sum_{i \in \text{all protons}} \frac{1}{2\pi} \frac{d\sigma_{pN}}{d\cos\theta} (E_{i,\text{mean}}, \cos\theta_i) \, l_{\text{track},i} \frac{S_{\text{det}}}{L_i^2} P_{2h} \varepsilon_{\text{tot}}.$$

Optimization of Cluster Pair Search Criteria

At this stage, event selection criteria for low-activity events are fixed. Optimization is performed only for parameters directly related to pair searching:

- Allowed deviation from the target direction (n_sigma)
- Minimum distance between clusters

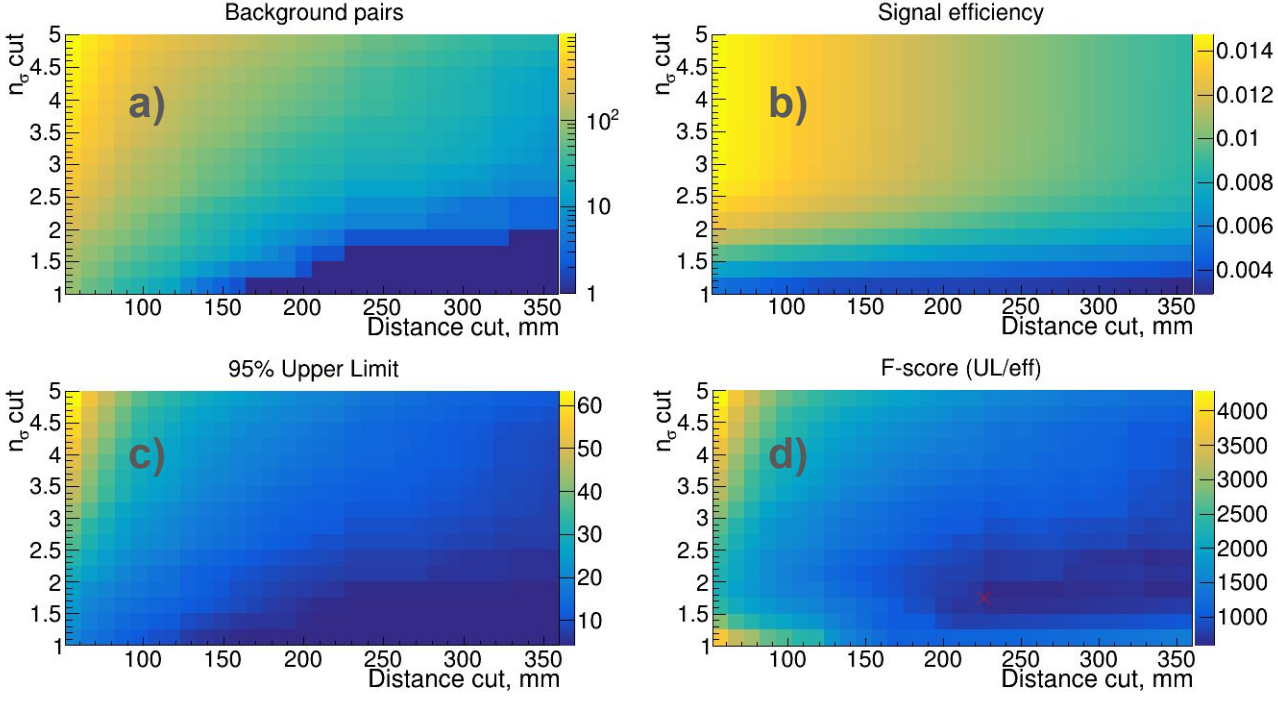


Fig.: Results of the parameter scan: (a) – number of background pairs; (b) – signal-pair selection efficiency; (c) – upper limit on the number of signal events corresponding to the given background level; (d) – figure of merit.

$$N_{\text{sig}} = C(m_\chi)\varepsilon_{\text{sig}}\epsilon^6,$$

$$\epsilon_{\text{lim}} \propto \left(\frac{N_{\text{UL}}^{95}}{\varepsilon_{\text{sig}}}\right)^{1/6}$$

$$F = \frac{N_{\text{UL}}^{95}(N_{\text{bkg}})}{\varepsilon_{\text{sig}}}$$

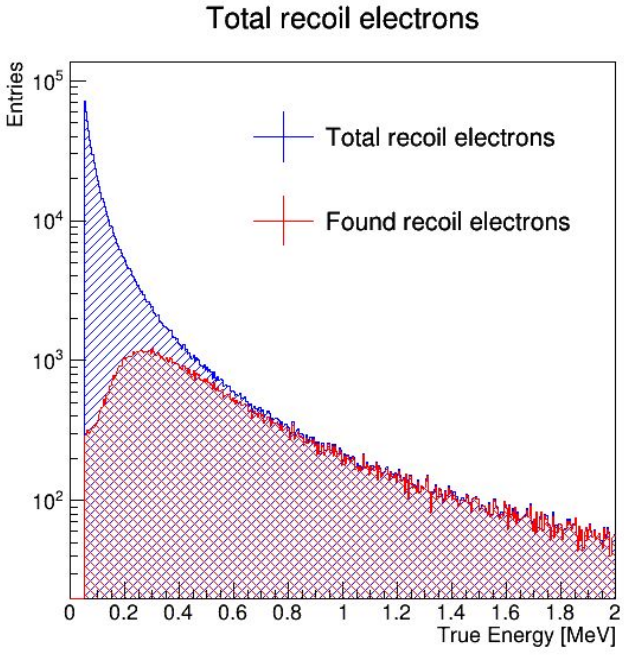
Maximizing sensitivity corresponds to minimizing F. Upper limit is calculated by Feldman-Cousins method.

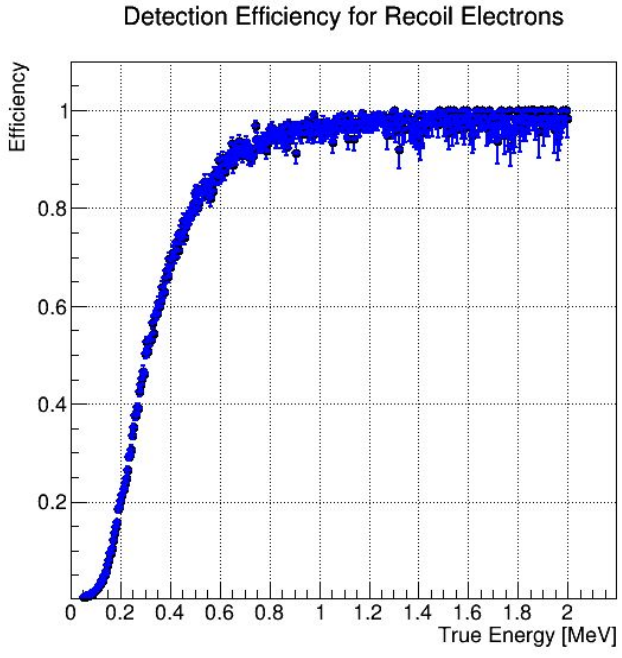
Optimal parameters are:

- **n_sigma = 1.8**
- **min_dist = 226 mm**

- **Total detection efficiency: 0.8%**
- **Expected background for the full statistics: 179 double coincidences**

Recoil electrons detection efficiency



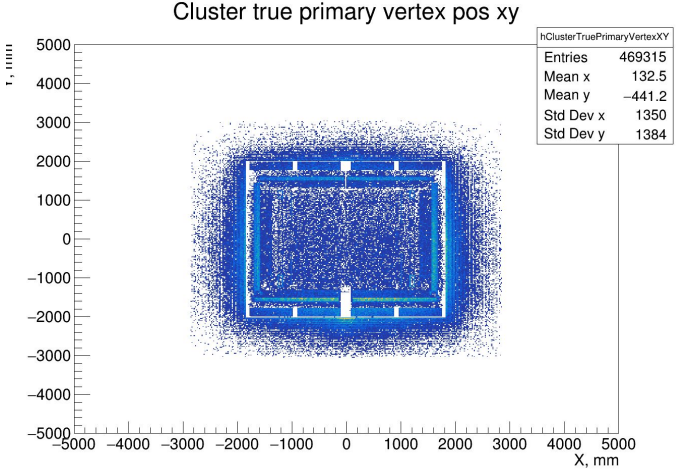


Averaging the efficiency over the typical recoil electron spectrum from mCPs gives an average efficiency of 18.5%. Thus, the efficiency for the simultaneous detection of two recoil electrons with energy above 50 keV is 3.4%. This efficiency is the main factor determining the overall signal signature detection efficiency.

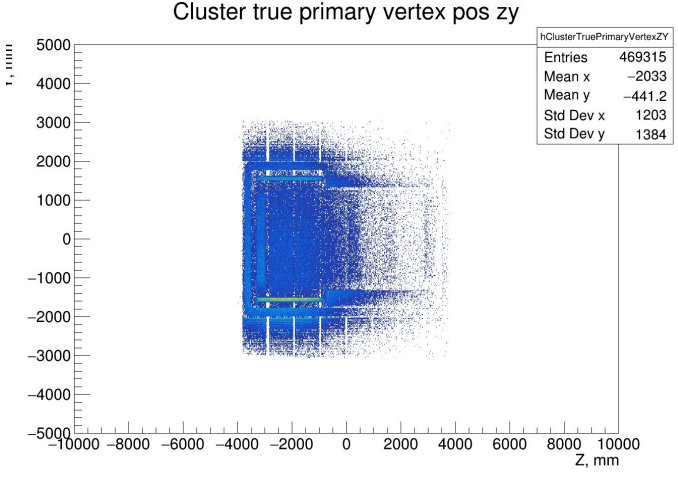
Fig.: (Left) The true recoil electron spectrum from mCPs and the spectrum of recoil electrons for which a cluster associated with this electron was successfully reconstructed. (Right) The dependence of the recoil electron detection efficiency on energy.

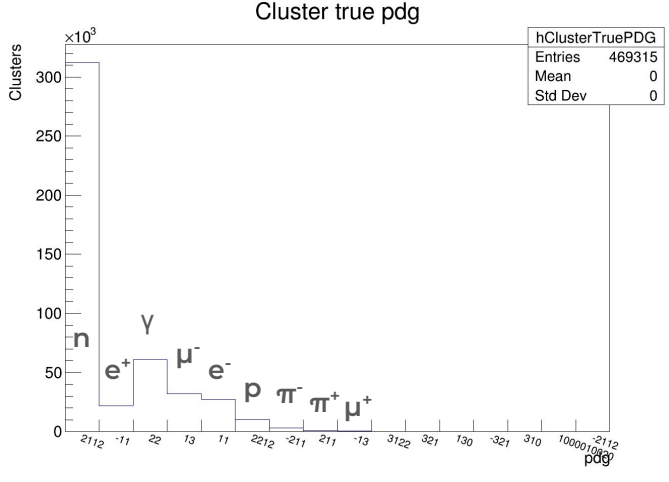
$$\xi \equiv \frac{\int \varepsilon(E_r)\frac{d\sigma}{dE_r}dE_r}{\int \frac{d\sigma}{dE_r}dE_r}, \qquad \frac{d\sigma}{dE_r} \sim \frac{1}{E_r^2}$$

Background studies: Magnet MC production

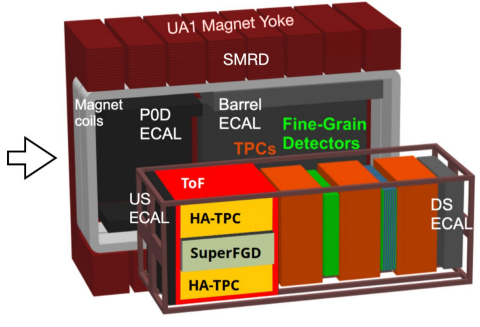


- Simulate neutrino interactions in ND280 magnet, using NEUT and the beam flux; output is list of output particles from each neutrino interaction (in nRootracker format).
- Use the list of output particles as input to nd280mc Geant simulation; then do the elecSim, oaCalib, Recon and analysis steps.

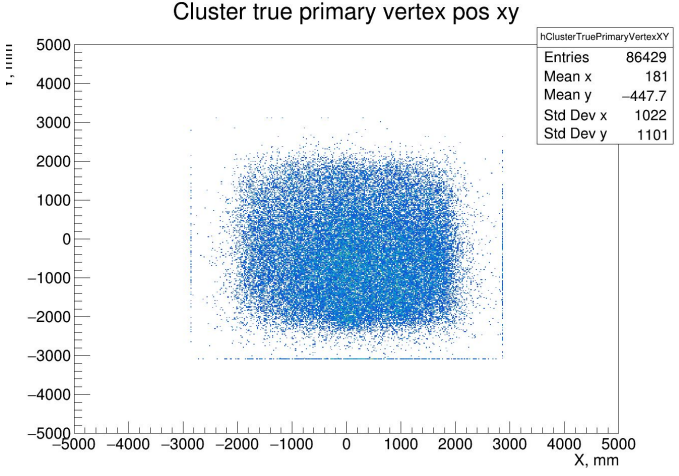




The target is the detector itself and the magnet

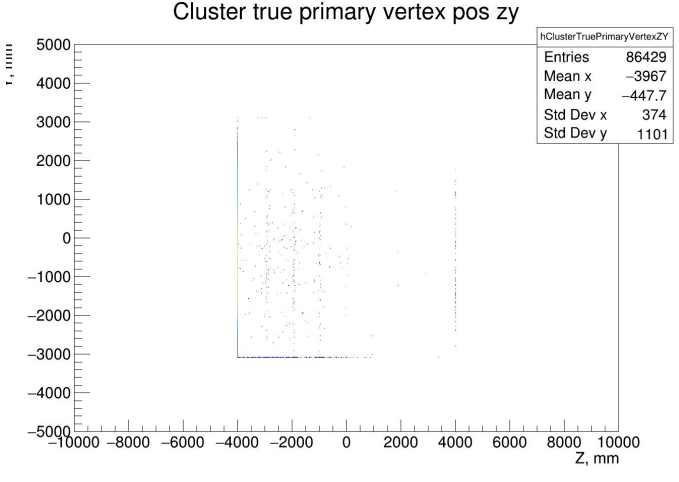


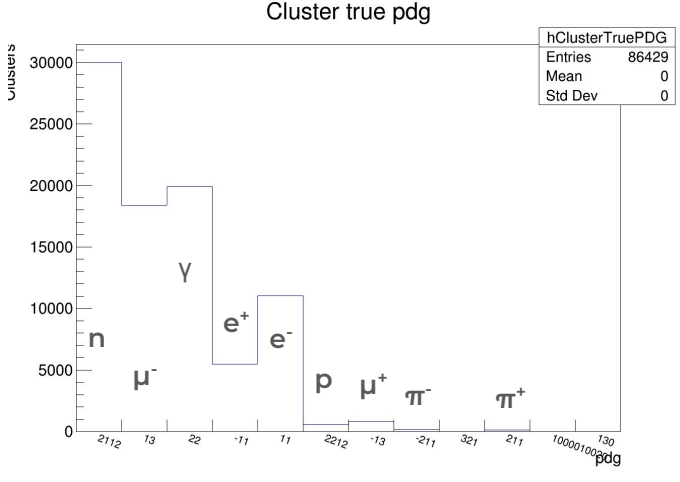
Background studies: Sand MC production

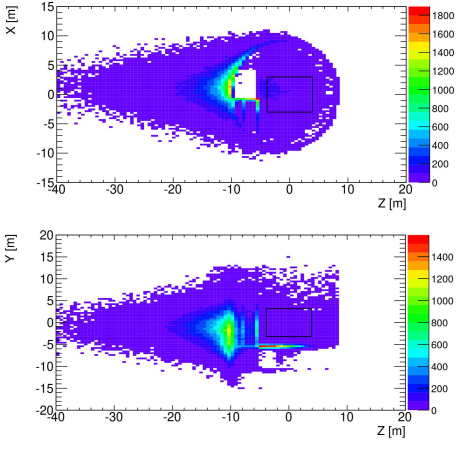


1. Simulate neutrino interactions in sand around ND280, using NEUT and the beam flux; output is list of output particles from each neutrino interaction (in nRootracker format).
2. Use a separate program (called sandPropage) to propagate the outputs from stage 1 to the edge of the ND280 magnet; output is again in Rootracker format.
3. Use the list of particles at edge of magnet as input to nd280mc Geant simulation; then do the elecSim, oaCalib, Recon and analysis steps.

The target is the sand surrounding the detector

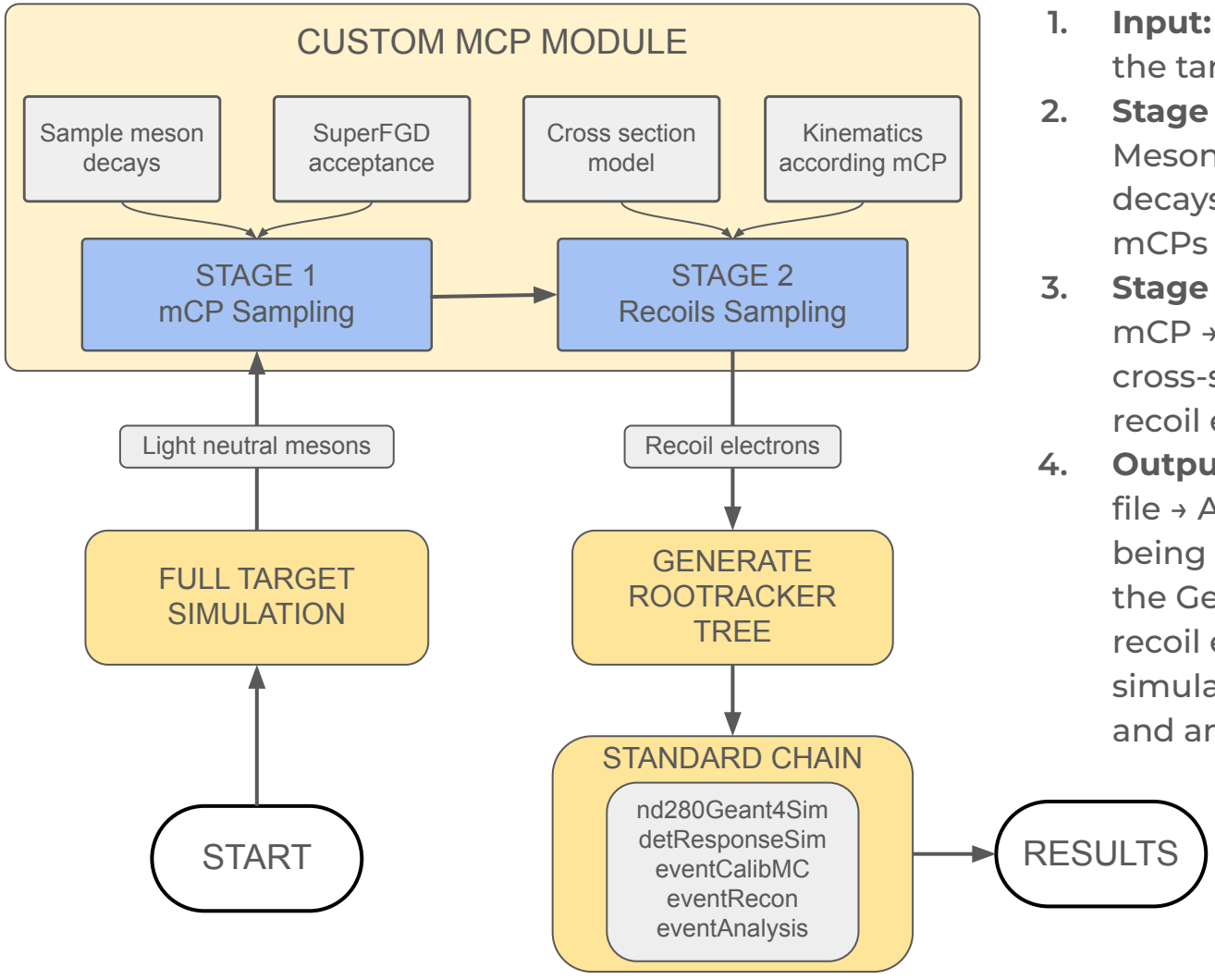






*In the Sand MC, those clusters were discarded that, in the chain of parent particles, have a neutron coming from outside the detector.

Custom module for mCP signal simulation



1. **Input:** GEANT4 → Full simulation of the target bombarded by protons.
2. **Stage 1 (My Module):** Neutral Mesons Kinematics → Sampling of decays into mCPs → Filtering of mCPs that hit the SuperFGD.
3. **Stage 2 (My Module):** For each mCP → Using analytical cross-section → Sampling of two recoil electrons.
4. **Output:** Generation of a rootracker file → A standard simulation chain is being performed, which includes the Geant4 physics simulation of recoil electrons, detector response simulation, event reconstruction, and analysis.