DOUBLE-HIT SIGNATURE OF MILLICHARGED PARTICLES IN 3D SEGMENTED NEUTRINO DETECTOR

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OUTLINE

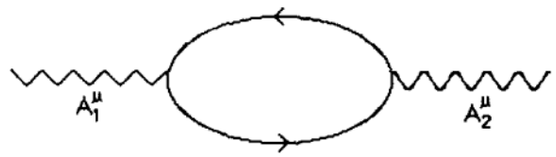
- MCP phenomenology

- Design of the new 3D scintillator neutrino detector

- Sensitivities studies

MILLICHARGED PARTICLES

- **M**illi**C**harged **P**article (MCP) are hypothetical particles carrying the fractional charge $O(10^{-3})e$



  - Extension of the SM (Phys. Lett. 138, (115). 1984)
  - additional symmetries in high energy scale (Phys. Rev. B 166, 2 (196). 1986)
  - Possible contribution to the dark matter (Phys. Rev. D 85, 101302(R). 2012)

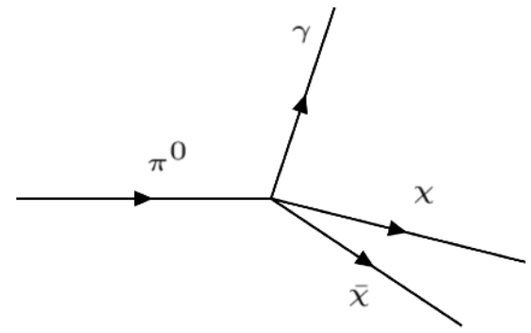
- Neutrino experiments are expected to have good sensitivity to MCP detection (Phys. Rev. Lett. 122, 071801. 2019)

- In particular, we found a brand-new 3D scintillator detector SuperFGD to have a good performance for MCP search

MCP PRODUCTION

- MCP (χ) are characterised with mass (m_χ) and effective charge (ϵ)

- Scalar meson (π^0, η, η') can decay only through 3-body decays:
  $X \to Y\chi\bar{\chi}$
  e.g. $\pi^0 \to \gamma\chi\bar{\chi}$ $\quad$ $\eta \to \gamma\chi\chi$



- The branching ratios of these processes are described with:

$$\mathrm{Br}(X \to Y\chi\bar{\chi}) = \epsilon^2 \cdot \mathrm{Br}(X \to Y\gamma) \cdot \frac{2\alpha}{3\pi} f_{X\to Y} \int_{4m_\chi^2}^{m_X^2} \frac{dm_{\chi\chi}^2}{m_{\chi\chi}^2} \left(1 + 2\frac{m_\chi^2}{m_{\chi\chi}^2}\right) \left(1 - 4\frac{m_\chi^2}{m_{\chi\chi}^2}\right)^{\frac{1}{2}}$$
$$\times \left(\left(1 + \frac{m_{\chi\chi}^2}{M_X^2 - M_Y^2}\right)^2 - 4\frac{m_{\chi\chi}^2 M_X^2}{(M_X^2 - M_Y^2)^2}\right)^{\frac{3}{2}} \left|F_{XY}(m_{\chi\chi}^2)\right|^2 ,$$

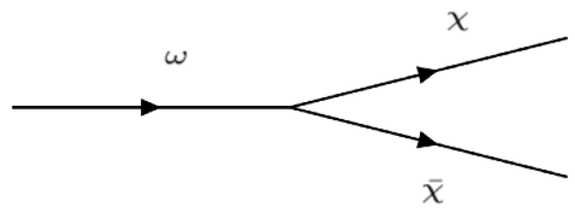
$$X \to Y \in \{\pi \to \gamma, \eta \to \gamma, \eta' \to \gamma, \omega \to \pi^0, \phi \to \pi^0, \phi \to \eta\}$$
$$f_{\pi\to\gamma} = f_{\eta\to\gamma} = f_{\eta'\to\gamma} = 1\,, \quad f_{\omega\to\pi^0} = f_{\phi\to\pi^0} = f_{\phi\to\eta} = \frac{1}{2}$$

MCP PRODUCTION

- Vector meson (ρ, ω, ϕ) can decay through 2-body $V \to \chi\bar{\chi}$

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

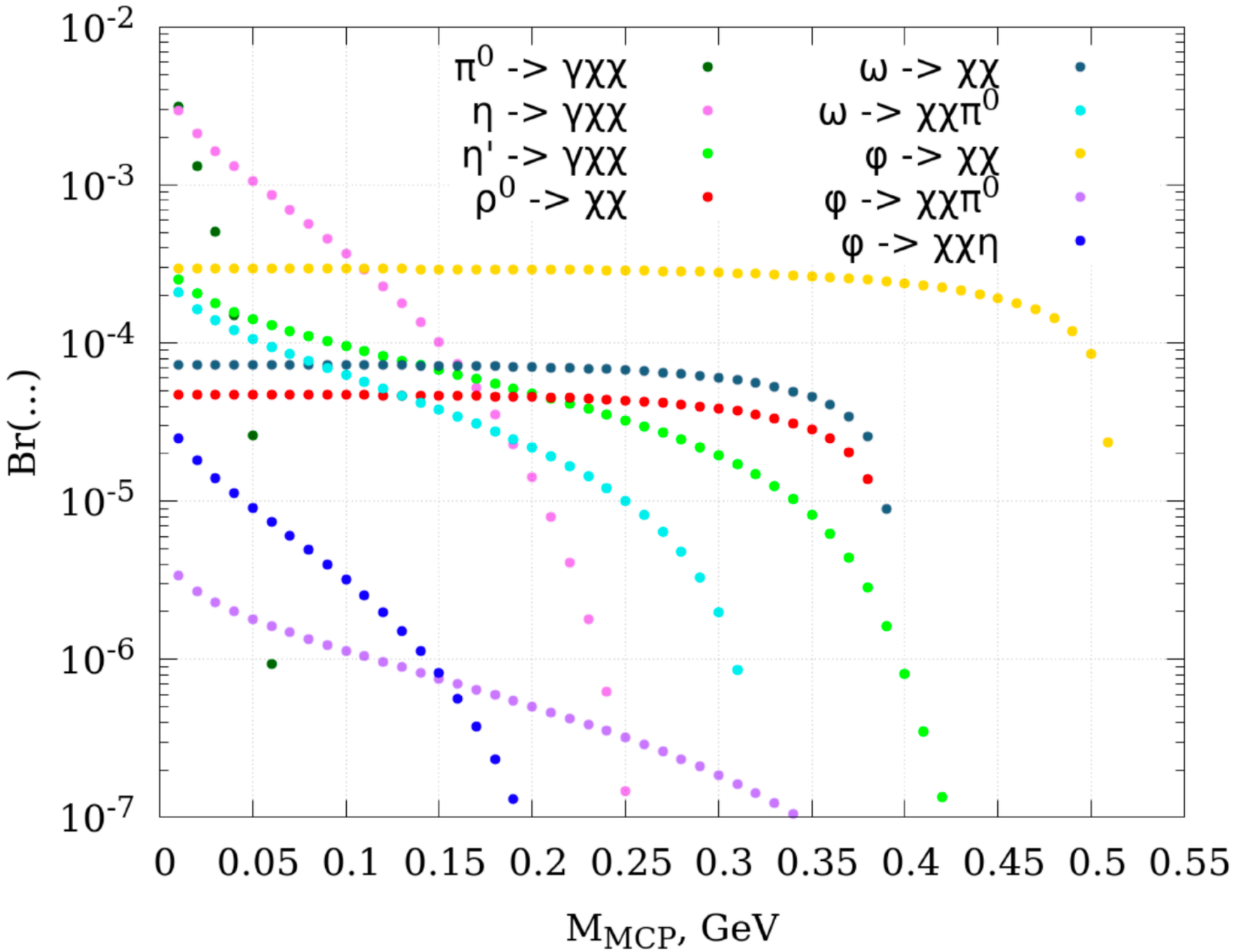
While 3-body channel is also possible: e.g. $\omega \to \pi^0\chi\bar{\chi}$



- Comparing 2 and 3-body decays modes:
  - 3-body decay modes are less probable
  - scalar mesons are more likely to be produced in proton-target collision

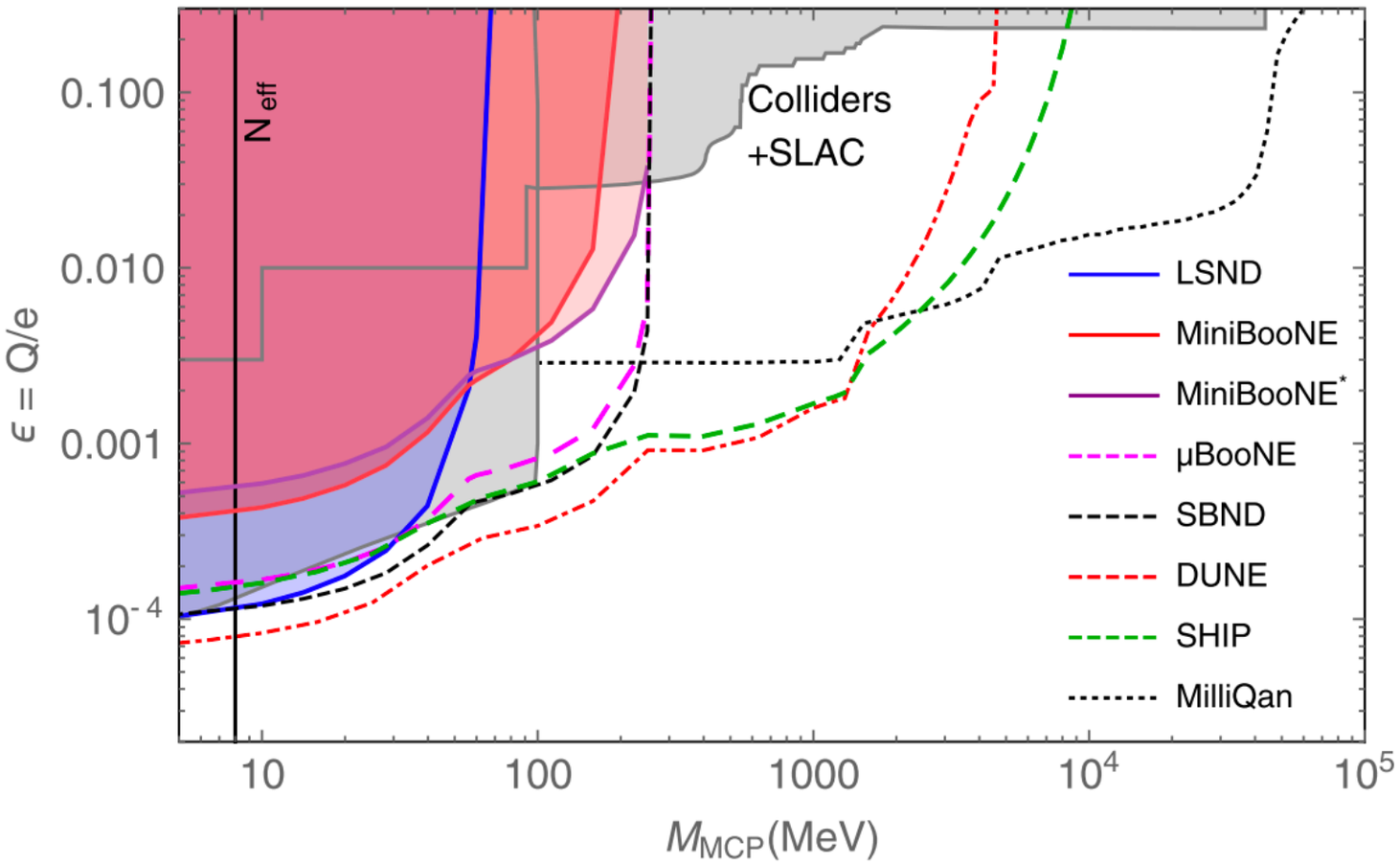
MCP PRODUCTION

- The MCP productions branching ratios, assuming $\epsilon = 1$



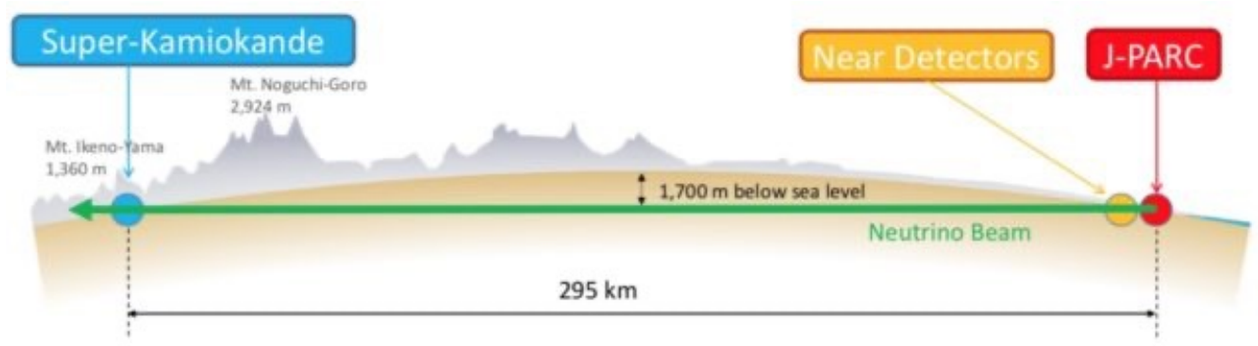
MCP DETECTION

- There are few channels for the MCP detection:
  - Small dE/dx e.g. in the long scintillator bars
  - Single high energy delta-electron production. (arXiv:2011.08153)
  - **Coincidence of 2 delta-electron production**. (JHEP 07 (2019) 170)
- Various neutrino experiments already performed such a study + sensitivities studies –> constraints on ϵ

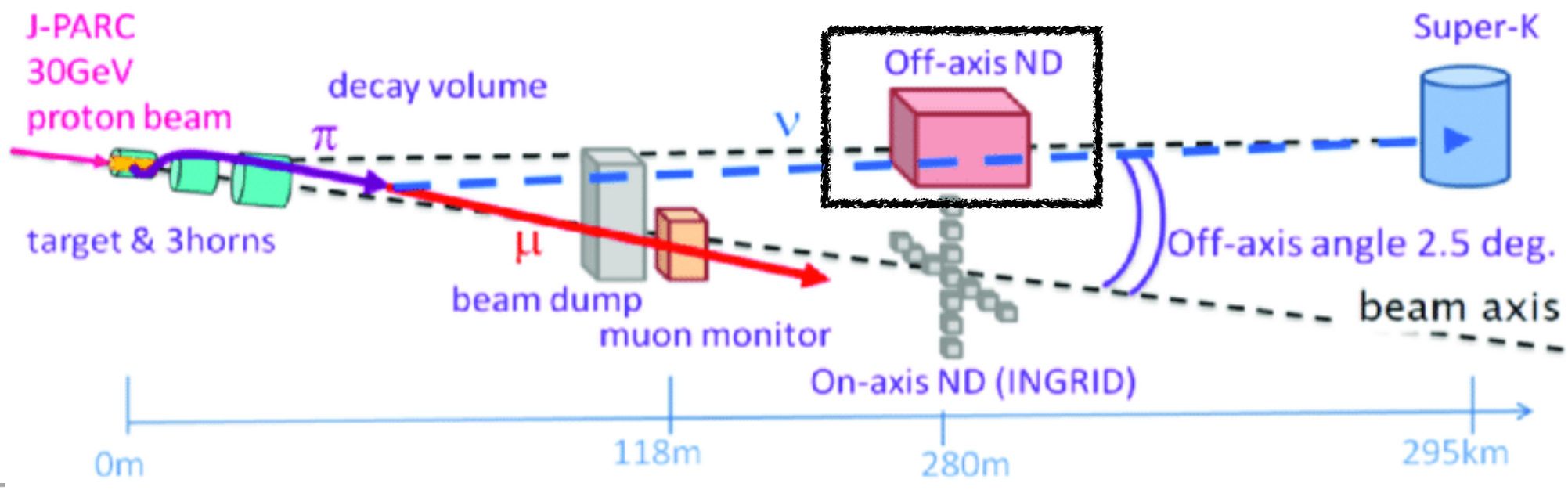


T2K EXPERIMENT

- Tokai-to-Kamioka (T2K) is a long-baseline accelerator neutrino experiment
  - Precise measurements of the neutrino oscillation parameters
  - Search for the CP-violation in ν oscillations

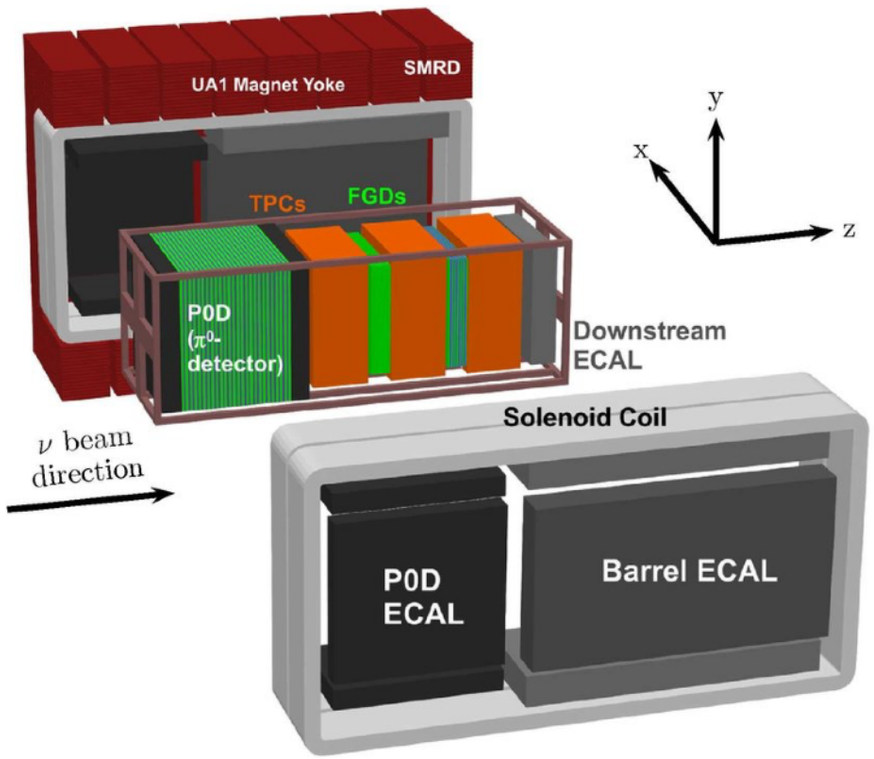


- J-PARC accelerator provides intense 30 GeV proton beam
  - Beam hits the Carbon target producing various mesons
  - Charged mesons are focused and further decay into neutrinos
  - **Intense meson beam could be used for MCP search in the near detector**

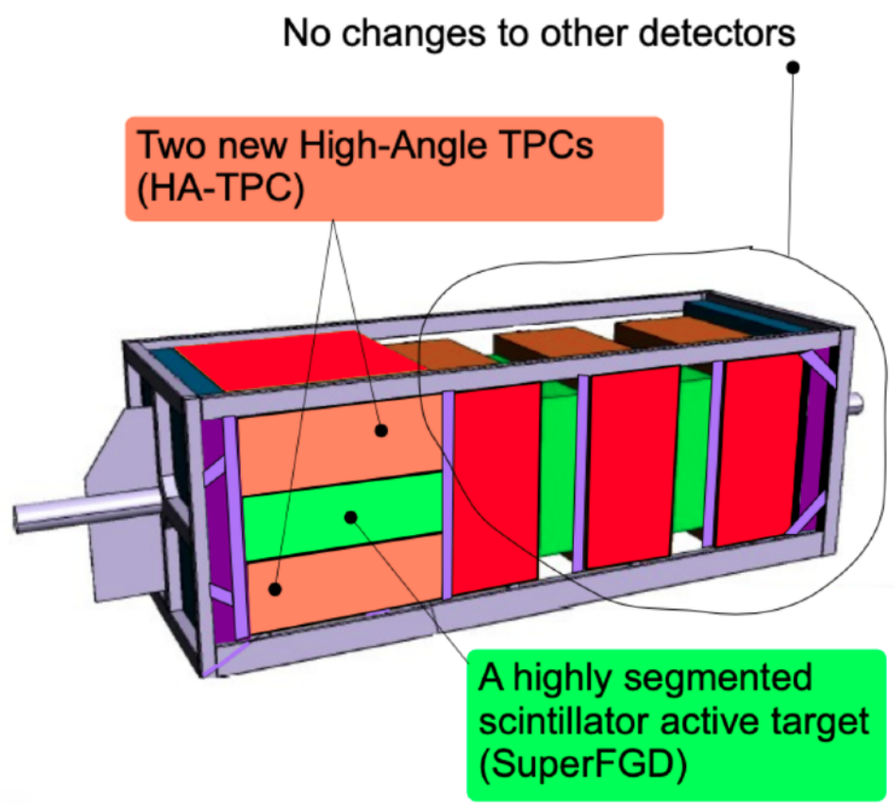


T2K NEAR DETECTOR

- Near neutrino detector (ND280) is a magnetised complex detector
  - Measurements of the flux × cross-section
  - Reduction of the systematic uncertainties of the oscillation analysis



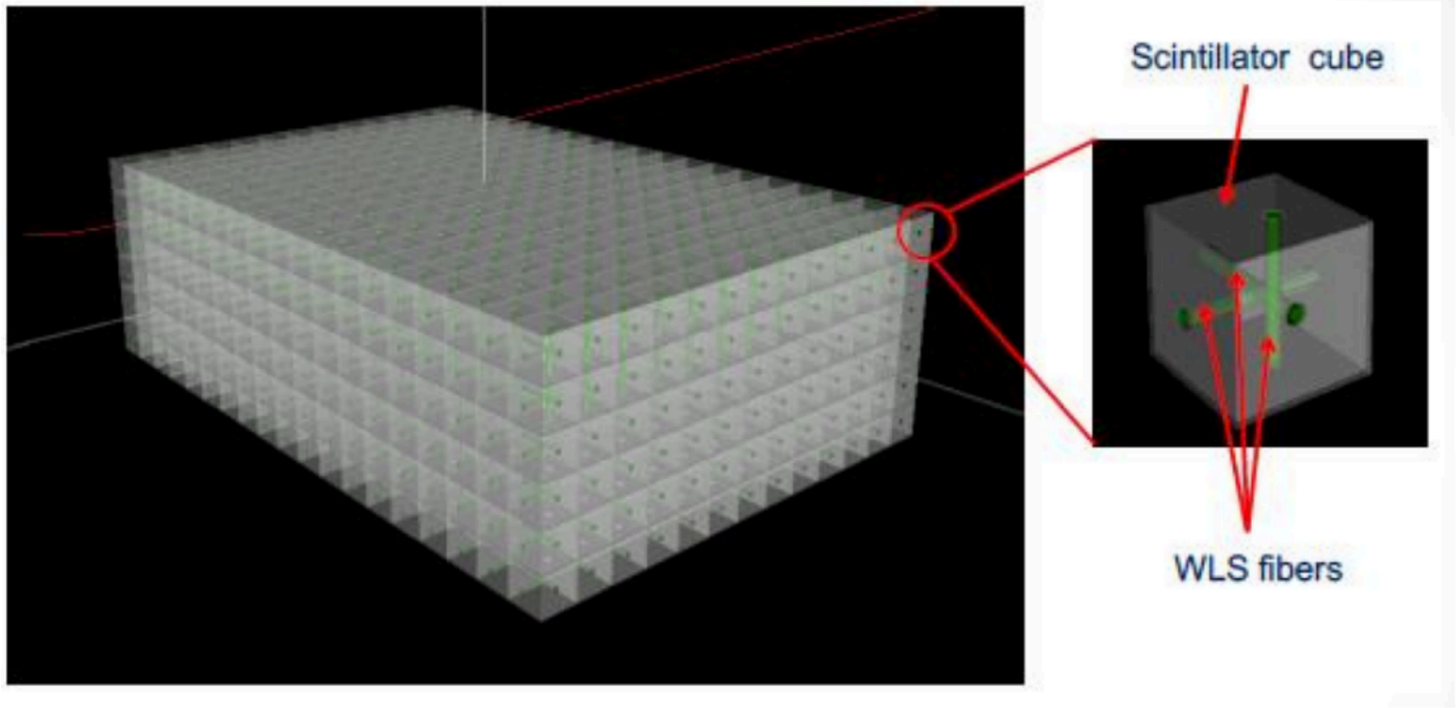
Upgrade scheduled for 2022



- The upgrade of the TK experiment is scheduled for the next year (2022)
  - Near detector will be upgraded with a new neutrino target (SuperFGD)
  - arxiv:1901.03750

3D SEGMENTED NEUTRINO DETECTOR

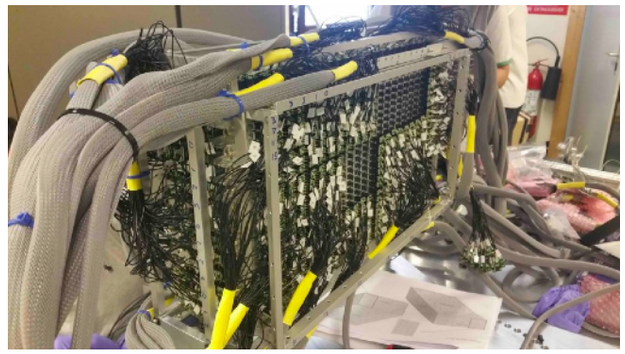
- SuperFGD is built with 1x1x1 cm^3 scintillator cubes
  - The detector dimensions are 192 x 184 x 56 cm
  - The total mass is ~2 tonns
  - 2M cubes and 60k cnahhels



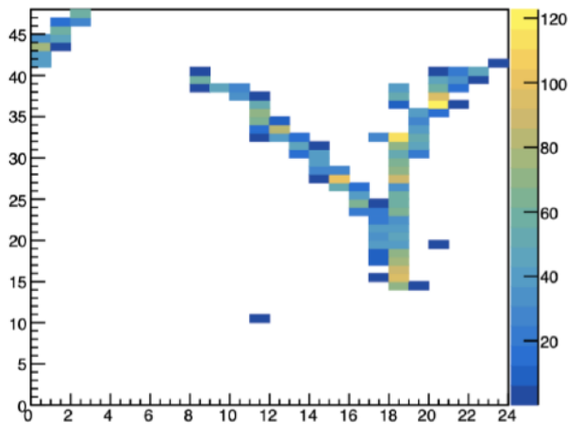
- The readout is done with WLS fibers read by MPPCs
- Benefits for the MCP search:
  - Fine granularity (1cm)
  - Low energy threshold (40 photo-electrons per channel per MIP)
  - Low MPPC dark rate (0.5 kHz)
  - Good time resolution (~1ns)

[NIM A 923, 134–138 (2019)](#)
[JINST, 15(12).2020](#)

Detector prototype



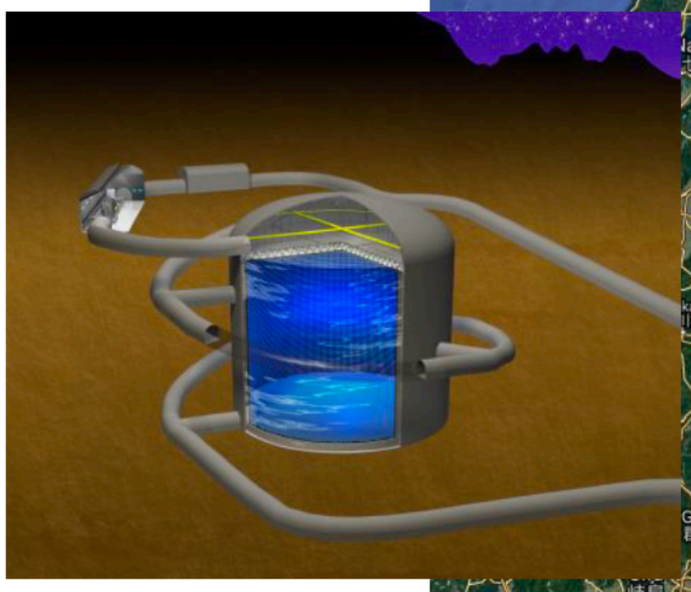
Event display
for photon conversion



T2K FUTURE

- T2K was approved to collect 20×10^{21} Protons on Target (POT) by 2027
  - 0.5×10^{22} POT with the new SuperFGD detector
- Afterwards it will be replaced with Tokai-to-Hyper-Kamiokande (T2HK) experiment
  - The completely new far detector will be used
  - The same accelerator and near detector are considered to be used
    - *The MCP study will continue data accumulation!*
    - *The gaol is* 2.7×10^{22} *POT*

Hyper-K



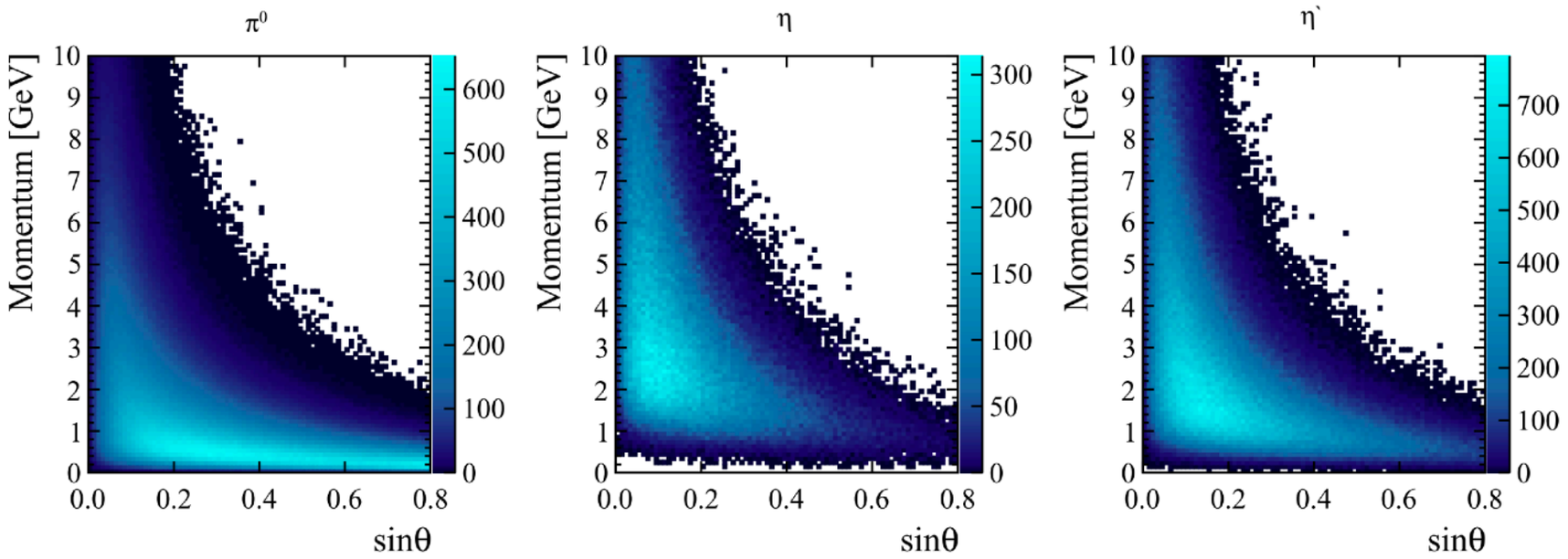
J-PARC

T2K SIMULATIONS

- We estimated the meson outcome from proton collisions with T2K target
  - For these studies PYTHIA is commonly used
  - Not applicable for T2K case:
    - *30 GeV is below PYTHIA validated kinematics region*
    - *Secondary interactions are omitted - critical for the meson production*
- Geant4 was used
  - T2K target geometry was considered (Carbon cylinder ~1 m long)
  - Various physics lists were tested –> meet agreement about the charged meson production with QGSP_BERT
    - *Not obligatory a sign of a robust neutral meson outcome, but no other reliable metric is there*
    - *No precise measurements of the neutral meson production at given energy scale*

Outcome for initial 30 GeV proton:

Meson	#/proton
π^0	3.12
η	0.40
η'	0.15
ρ	0.21
ω	0.12
ϕ	0.0051



MCP IN SUPERFGD

- We expect to see 2 hits from delta-electrons
  Probability for 2 MCP scattering with electron kick out with $E_e > E_r^{min}$:

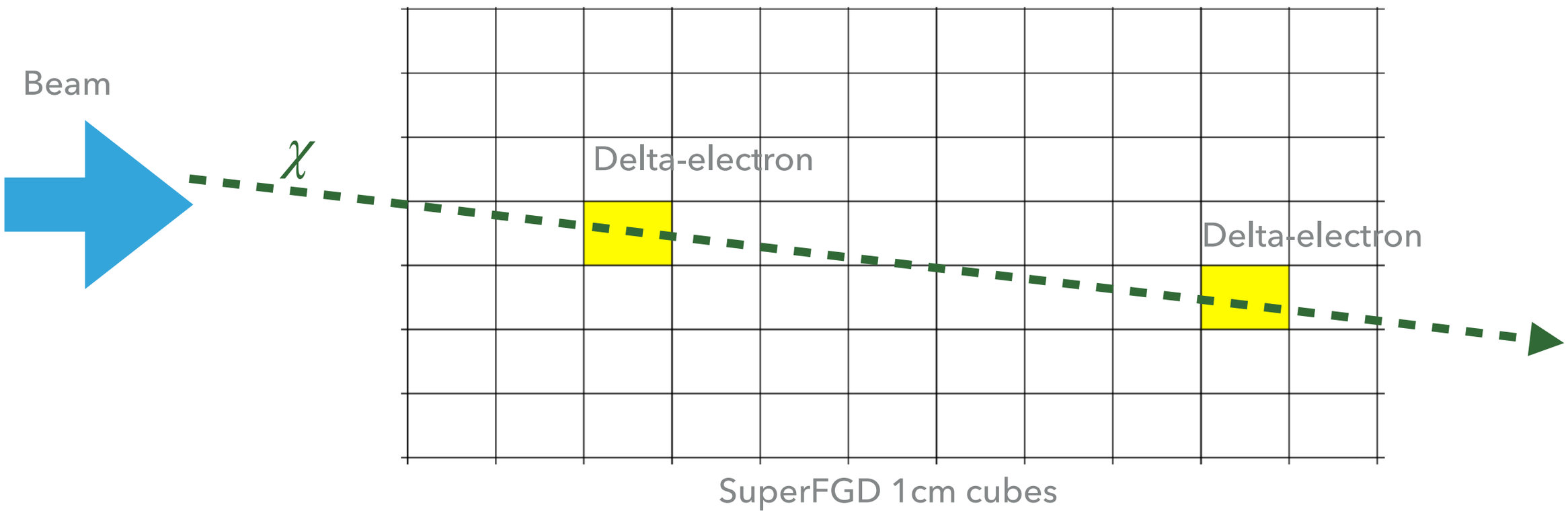
Detector length

$$P_{2h} = \frac{1}{2}\left(\xi\,\frac{L}{\lambda}\right)^2 = \frac{1}{2}\left(\frac{\left(\frac{\xi}{0.92}\right)\,1.84\,\mathrm{m}}{\left(\frac{10^{-2}}{\epsilon}\right)^2\left(\frac{E_r^{min}}{100\,\mathrm{keV}}\right)14\,\mathrm{km}}\right)^2 \approx 0.29\times10^{-8}\times\left(\frac{\epsilon}{10^{-3}}\right)^4$$

Detection efficiency

MCP free-path $\propto \epsilon^{-2}$

Electronics threshold is 1.5 p.e.
We estimated threshold at 100 keV as we expect ~2-3 p.e. per channel
the detection efficiency is estimated as 92%



T2K SIMULATIONS

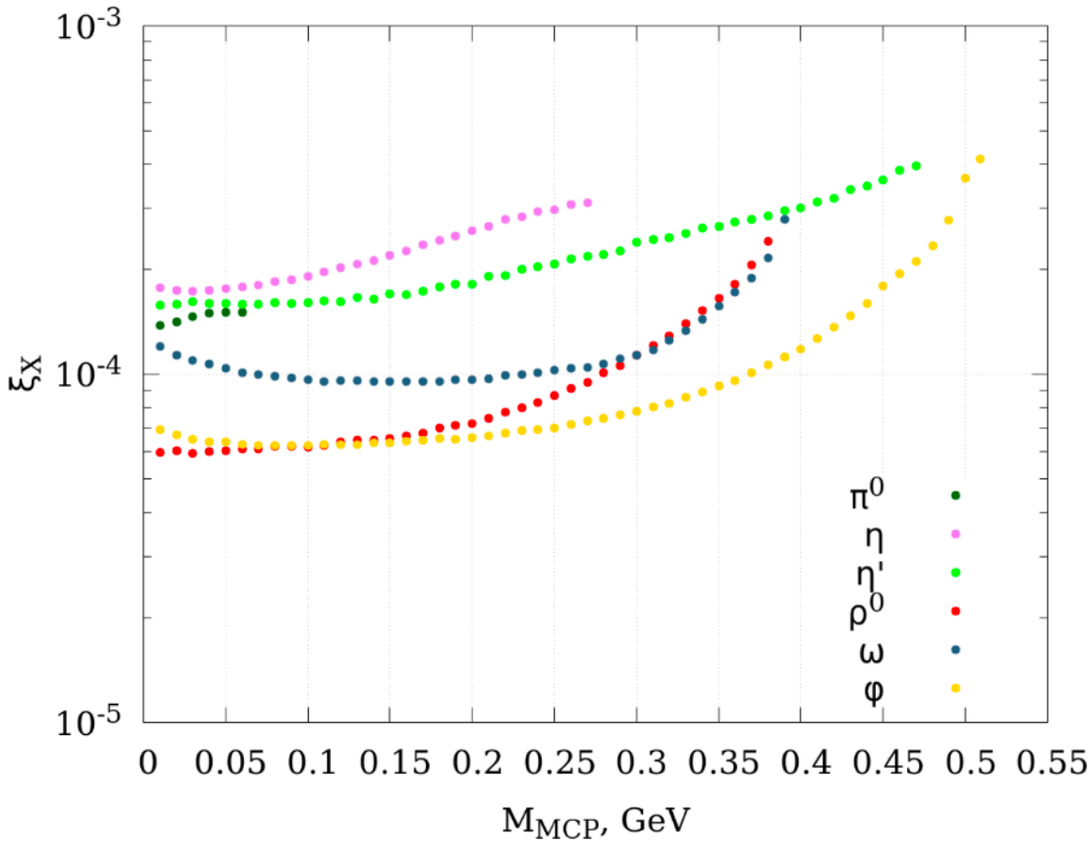
- The decay kinematics of each meson was simulated
  - Isotropic meson decay to MCP is considered
    and the boost towards parent meson direction is applied

- The off-axis position has a small effect on the detector acceptance
  - Mainly limited be the detector surface area 56 x 196 cm

- Distance from target to detector 280 m

- Benefit from meson kinematics
  - MCP are boosted towards the beam direction

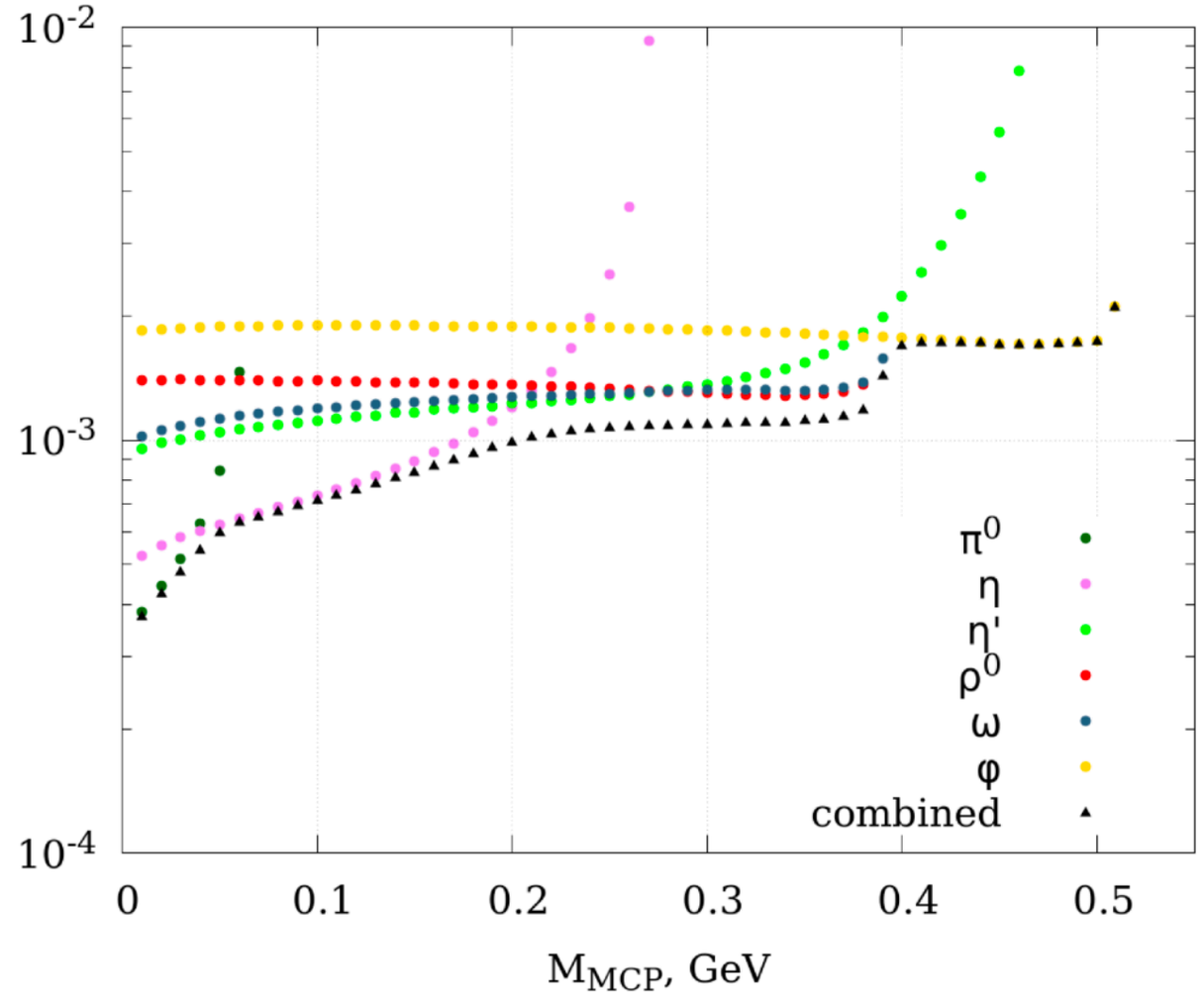
SuperFGD geometrical acceptance



SENSITIVITIES

- Possible background source:
  - MPPC dark rate:
    Number of coincidence of two dark rate "hits" pointed to the beam target
    $\approx 2.5 \times 10^{-2}$ in case 2 fibres used for each hit
    $\approx 10^{-4}$ in case all 3 fibres are used per each hit
    for the whole T2K statistics (10^8 s 2.7×10^{22} POT)
  - Neutrino interactions:
    expected to leave a long
    (>5 cubes) track
  - Low-energy backgrounds
    to be studied during the data taking

- Based on expected $N_{events}(\epsilon)$
  the sensitivities on ϵ could be set
  based on the expectation
  of 3 events



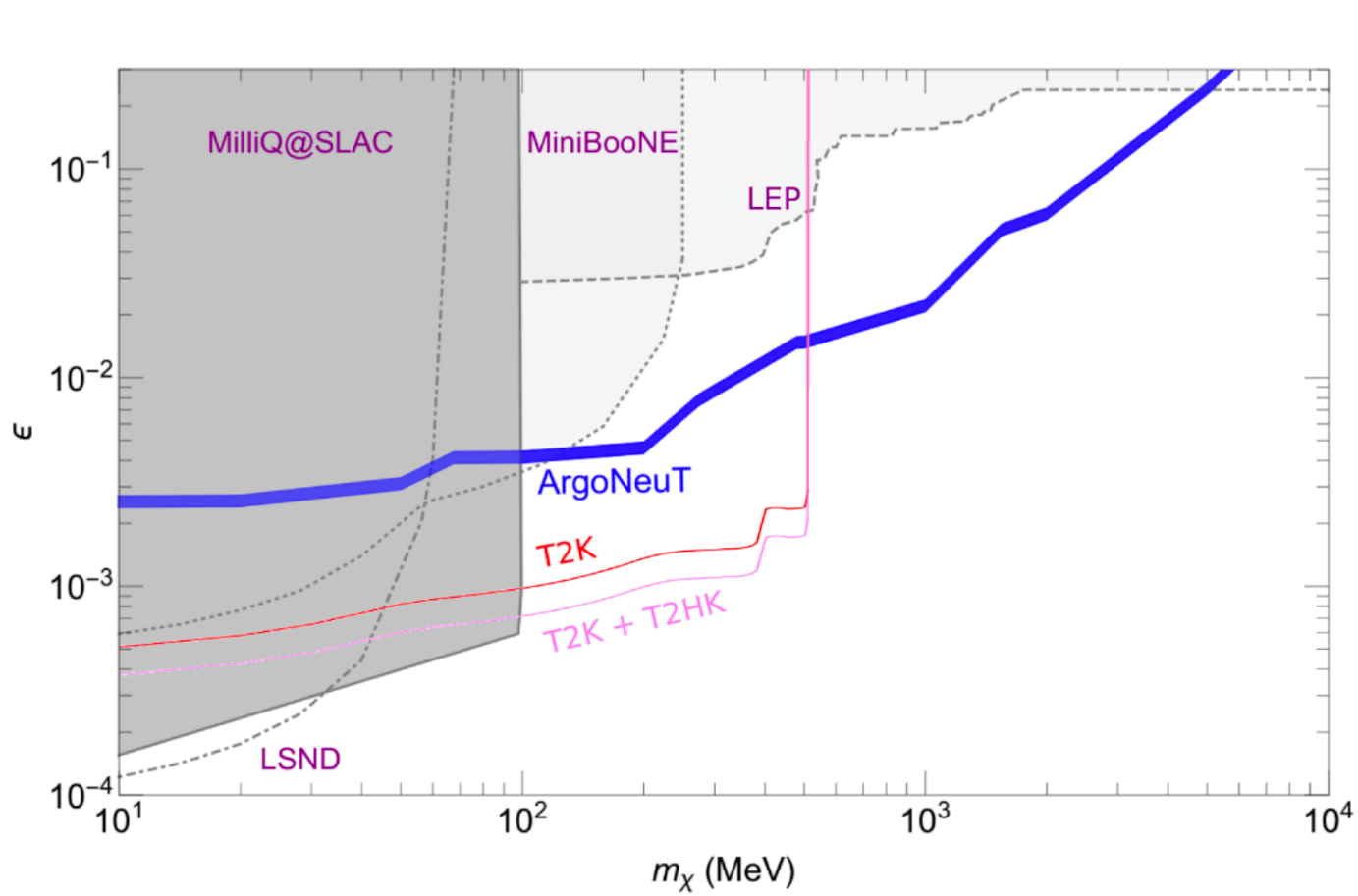
SUMMARY

- MilliCharged Particles are perspective window towards physics beyond SM

- Neutrino experiments have large potential for MCP search with large meson outcome

- SuperFGD is very sensitive to the MCP:
  - Fine granularity –> direction reconstruction
  - Low thresholds
  - Low MPPC dark rate –> low background

- Preprint is available arxiv:2103.11814



BACK UP

MCP DETECTION

- Free path:

$$\lambda = \frac{1}{Z n_{det} \sigma(E_r^{min})} = \epsilon^{-2} \frac{m_e E_r^{min}}{2\pi\alpha^2 Z n_{det}}$$

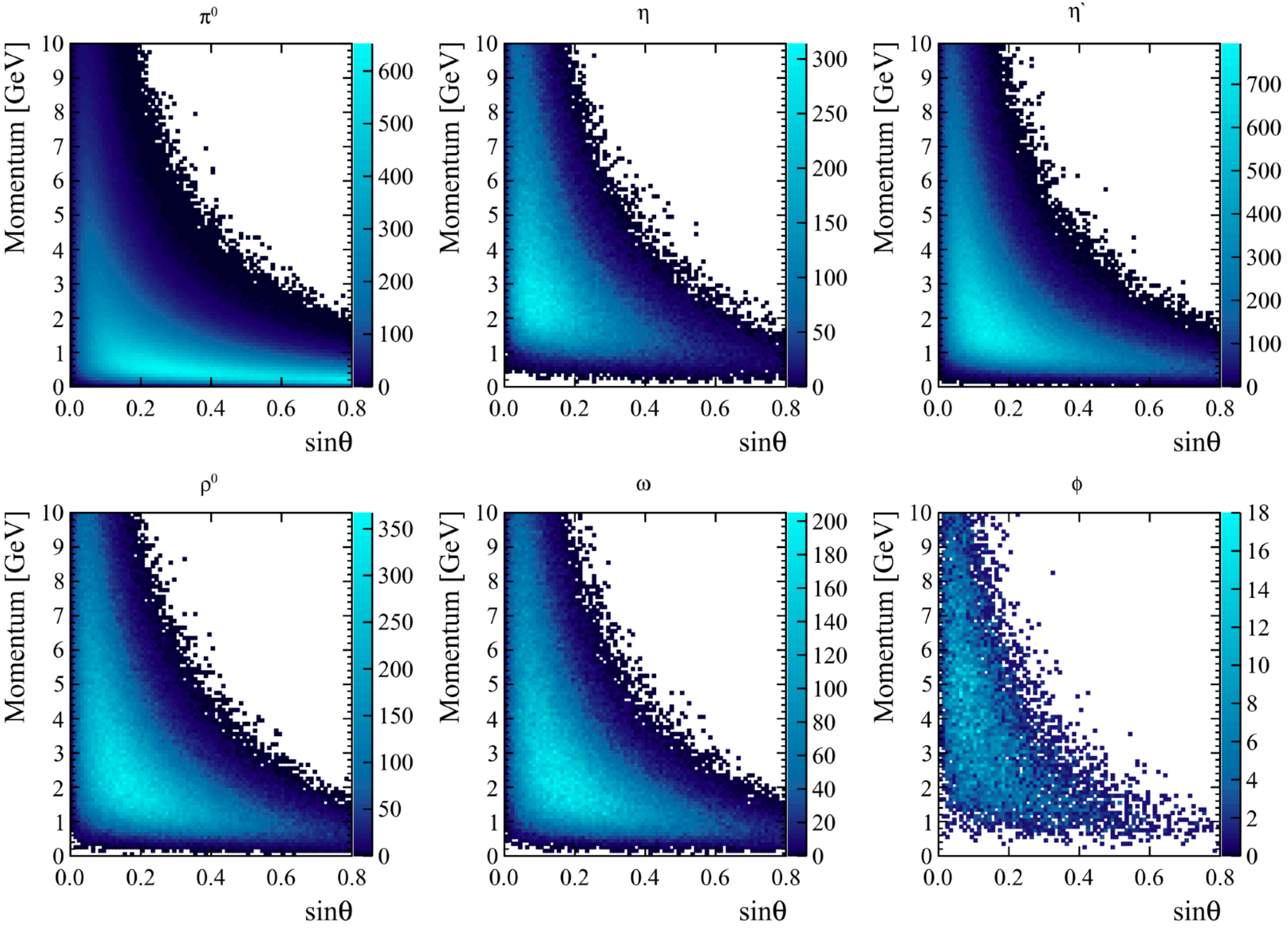
- With SuperFGD material:

$$\lambda \approx 1.2 \times 10^4 \times \left(\frac{10^{-3}}{\epsilon}\right)^2 \times \left(\frac{E_r^{min}}{100\,\mathrm{keV}}\right) \mathrm{m}$$

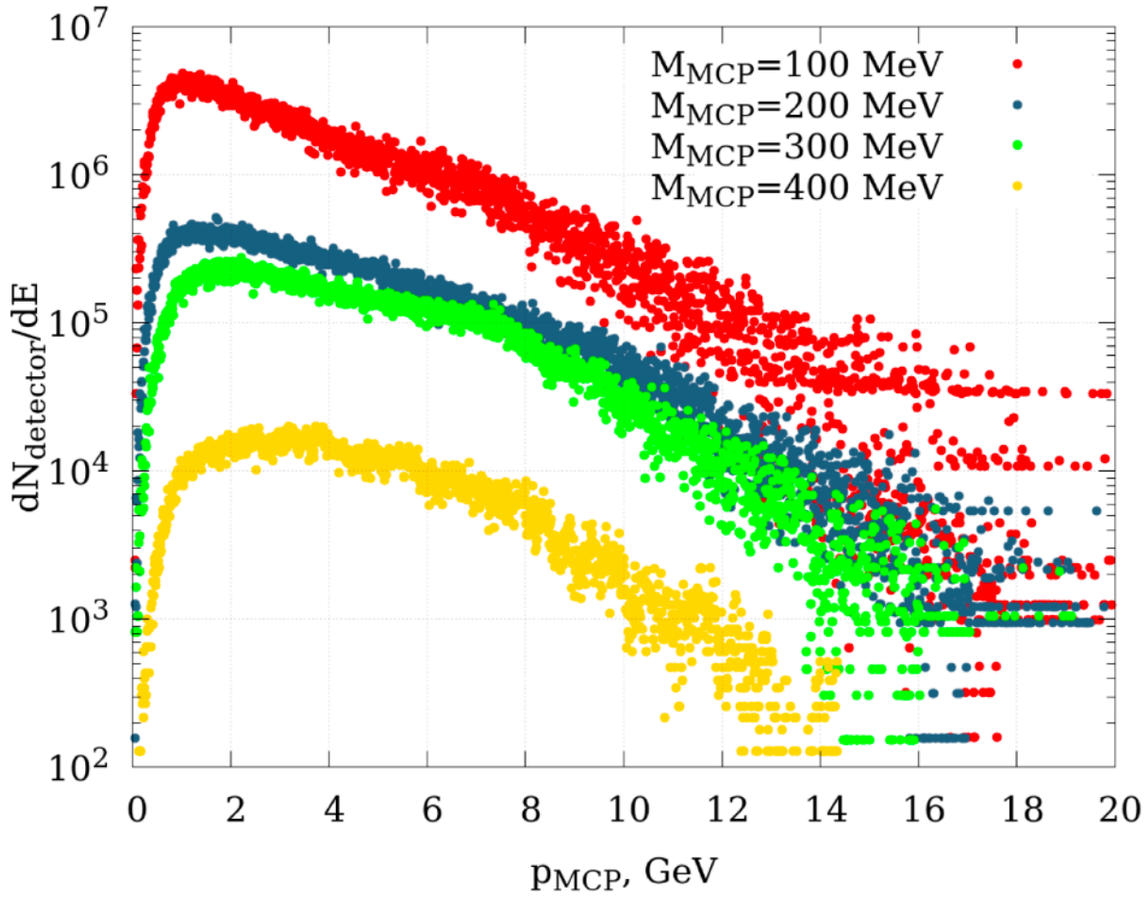
- Coincidence of two hits above threshold:

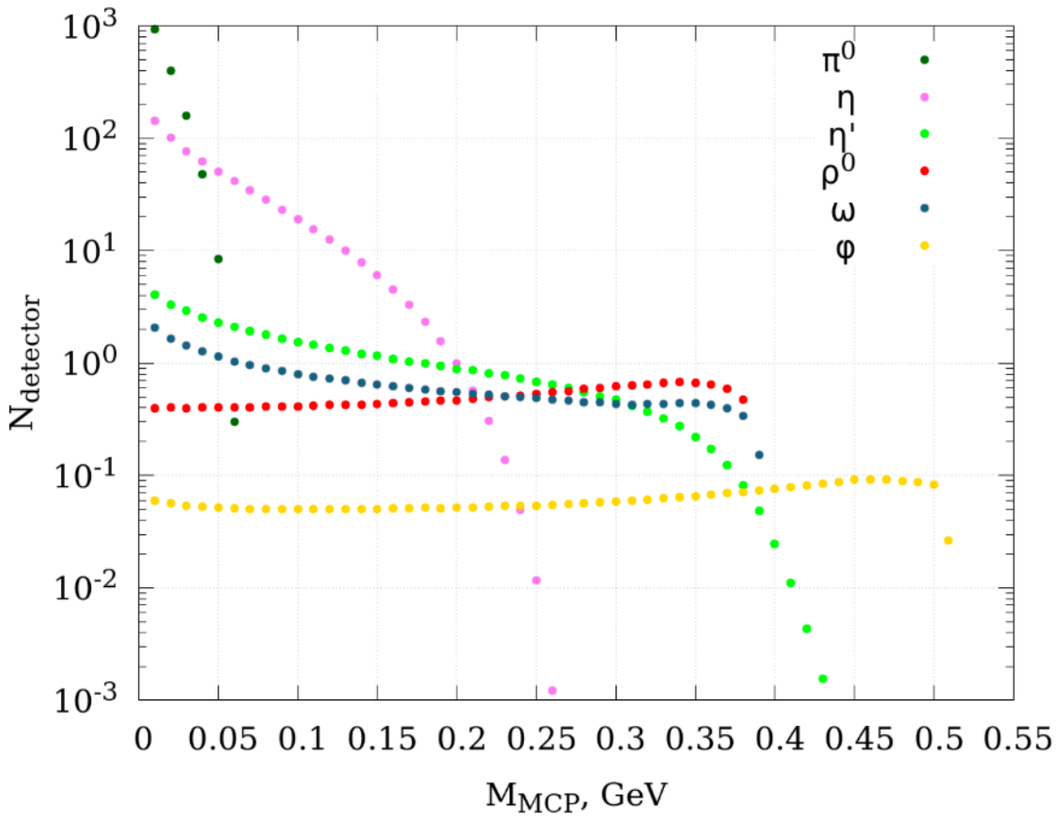
$$P_{2h} = \frac{1}{2}\left(\xi \frac{L}{\lambda}\right)^2 = \frac{1}{2}\left(\frac{\left(\frac{\xi}{0.92}\right) 1.84\,\mathrm{m}}{\left(\frac{10^{-2}}{\epsilon}\right)^2 \left(\frac{E_r^{min}}{100\,\mathrm{keV}}\right) 14\,\mathrm{km}}\right)^2 \approx 0.29 \times 10^{-8} \times \left(\frac{\epsilon}{10^{-3}}\right)^4$$

PRODUCED MESONS



- Number of double hits events in SFGD
  For $\epsilon = 10^{-3}$ and 2.27×10^{22} POT





- MCP spectra at SuperFGD
  for $\epsilon = 10^{-3}$ and 2.27×10^{22} POT