2026/05/27 NPN2026

Analysis Status of the 2025-2026 NINJA Physics Run

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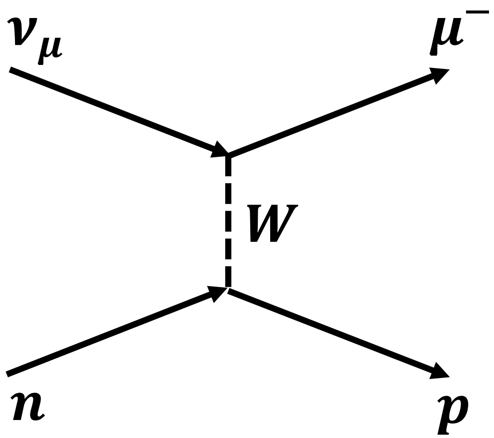
on behalf of the NINJA collaboration

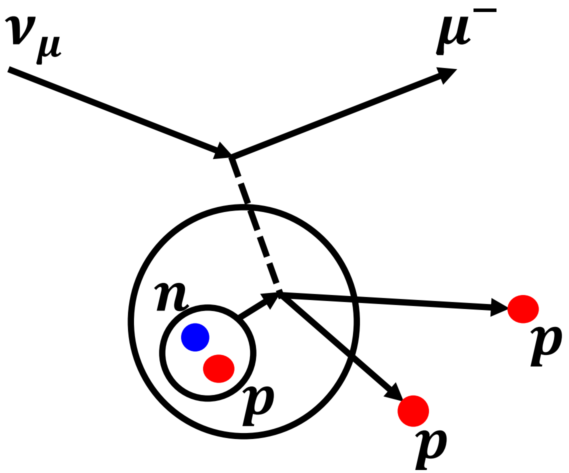
The uncertainty of the neutrino interaction models

- **A major source of the systematic errors in the T2K experiment** (neutrino oscillation experiment)
- In particular, the uncertainty of **2p2h**, which serves as a background to the primary signal mode **CCQE**, is significant
- The detection of **low-momentum protons produced from 2p2h** is difficult
  →**There have not been sufficient measurements of protons from 2p2h**



CCQE

$(\nu_\mu + n \rightarrow \mu^- + p)$



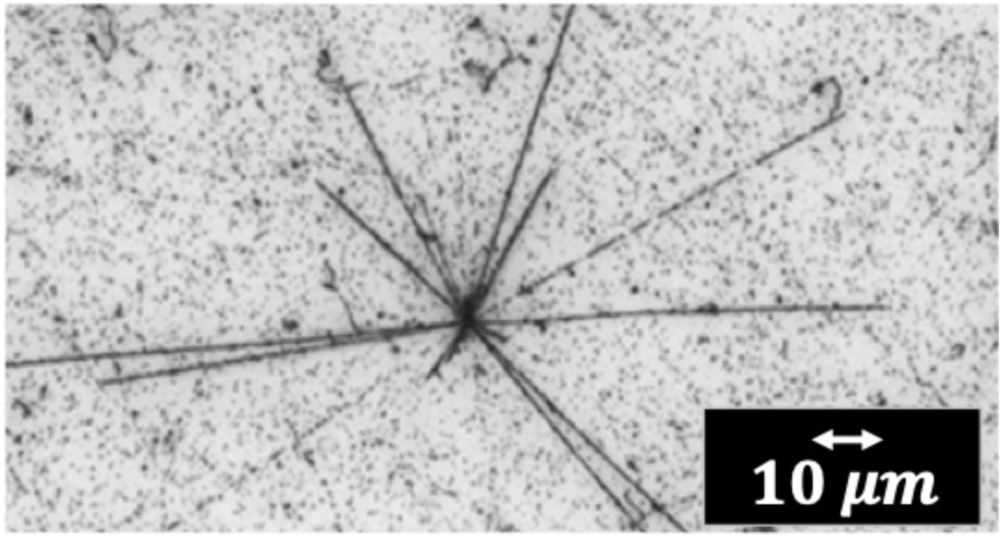
2p2h ※10~20% of CCQE

$(\nu_\mu + n + p \rightarrow \mu^- + p + p)$

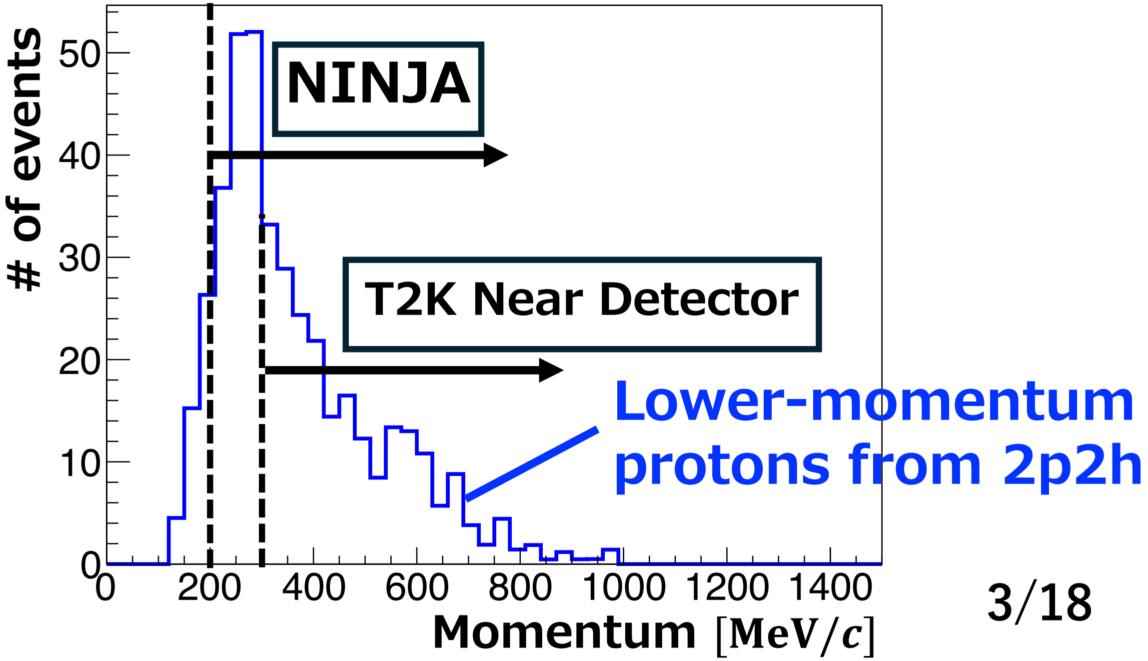
NINJA Experiment

Neutrino Interaction research with Nuclear emulsion and J-PARC Accelerator

- Precisely measure neutrino interactions with water target **using nuclear emulsion**
- **Nuclear emulsion**: a tracking detector **with sub μm position resolution**
  →Can detect short tracks from low-momentum protons ($> 200\ \mathrm{MeV}/c$)
- Aim to reduce the uncertainty of the neutrino interaction models
  (a major source of the systematic errors in T2K)

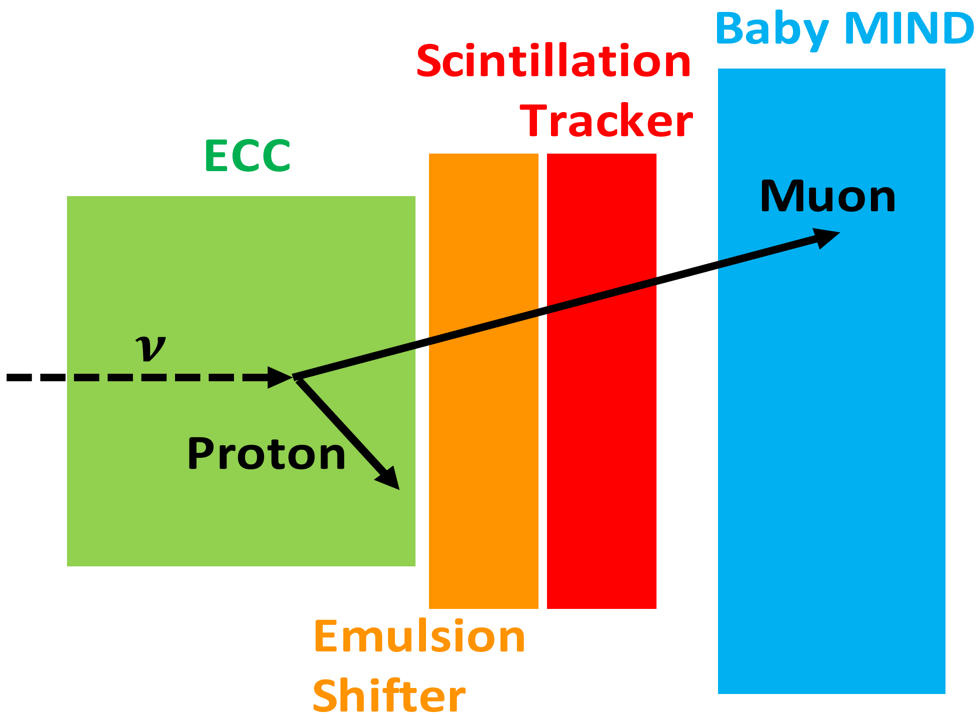


Microscopic view of tracks in a nuclear emulsion



NINJA Experiment: Detector setup

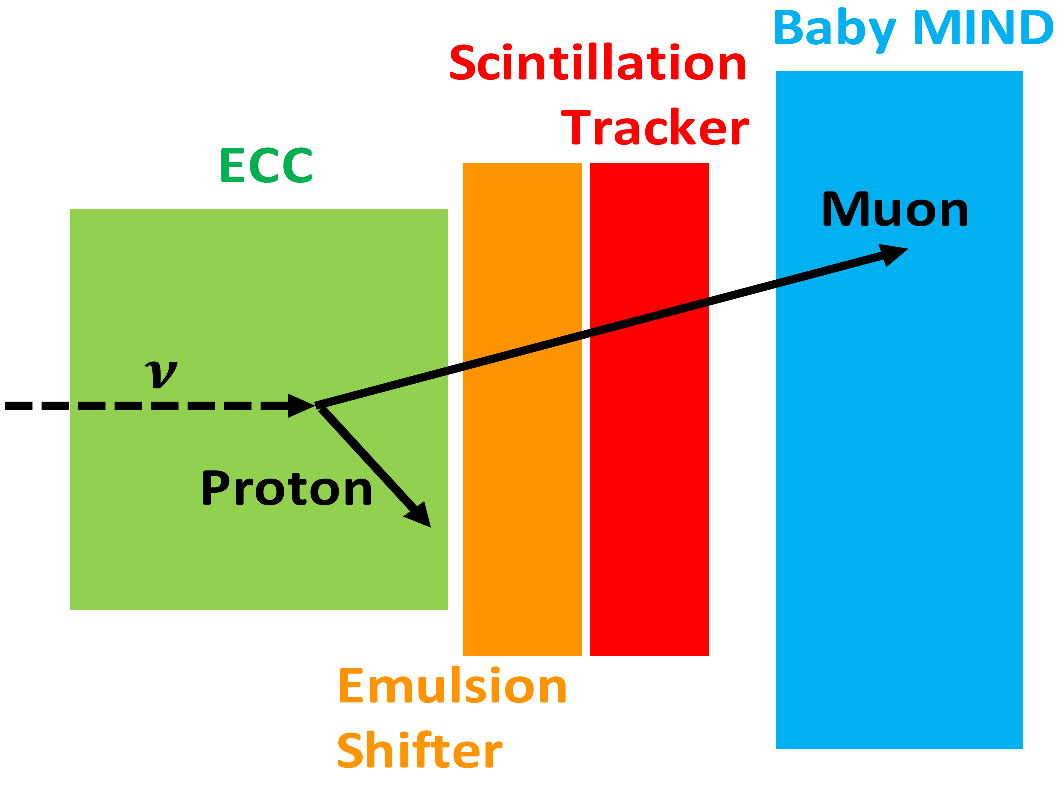
- **ECC**: alternating layers of nuclear emulsion films and water targets
- **Baby MIND**: muon range detector
- **Emulsion Shifter**: provides rough timing information using moving nuclear emulsion films
- **Scintillation Tracker**: provides timing information using plastic scintillator



Detector	Position resolution	Time resolution
ECC	$\mathcal{O}(\mu\mathrm{m})$	∞
Emulsion Shifter	$\mathcal{O}(\mu\mathrm{m})$	$\mathcal{O}(\mathrm{min} - \mathrm{hour})$
Scintillation Tracker	$\mathcal{O}(\mathrm{mm})$	$\mathcal{O}(\mathrm{ns})$
Baby MIND	$\mathcal{O}(\mathrm{cm})$	$\mathcal{O}(\mathrm{ns})$

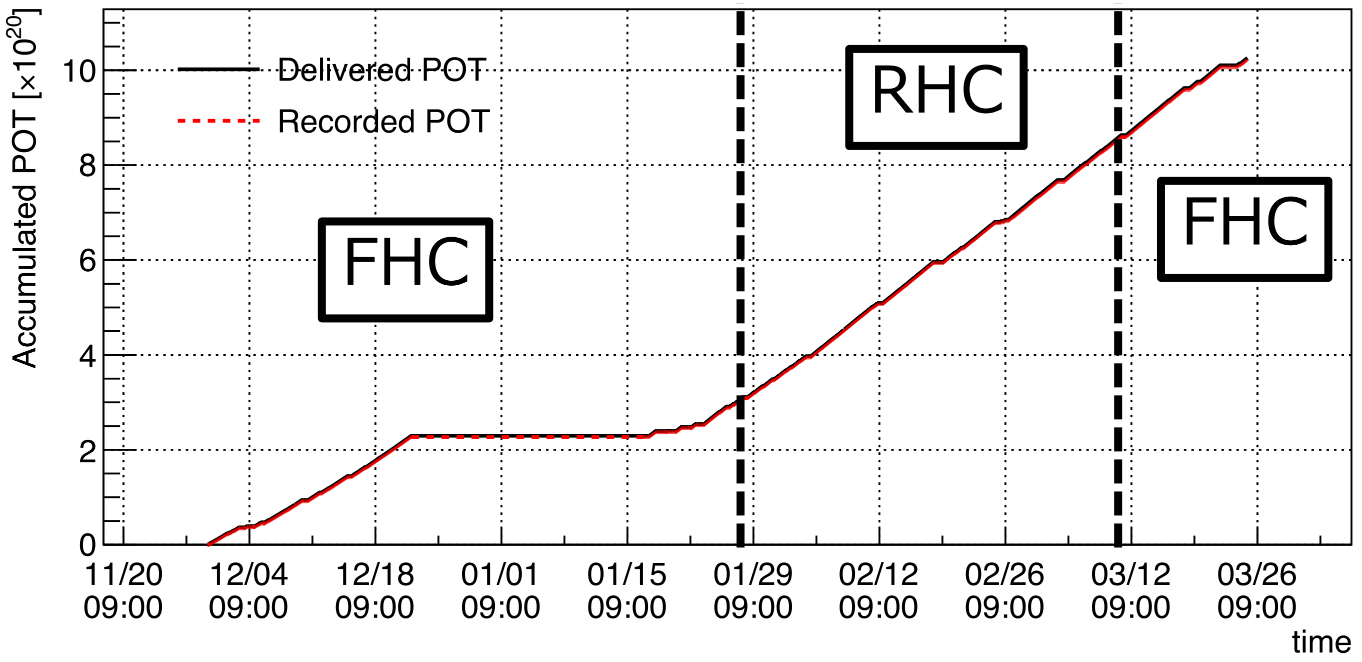
2025-2026 physics run (3rd physics run)

- We acquired 7.7×10^{20} POT in two physics runs (2019-2020, 2023-2024)
- But **insufficient statistics** **(goal: 1.0×10^{21} POT)**
  →Conducted 3rd physics run (2025-2026)
- Detector updates in 3rd physics run:
  - **3×3 ECCs→ 3×4 ECCs**
    (Water target mass: 75 kg→100 kg)
  - **New Emulsion Shifter**
    Size: 1.0 m×1.0 m→1.2 m×1.4 m
    Time resolution: 4 hours→10 mins
  - **New Scintillation Tracker (FROST)**
    Size: 1.0 m×1.0 m→1.3 m×1.4 m
    Position resolution: 2.5 mm→~1.5 mm



Operation summary

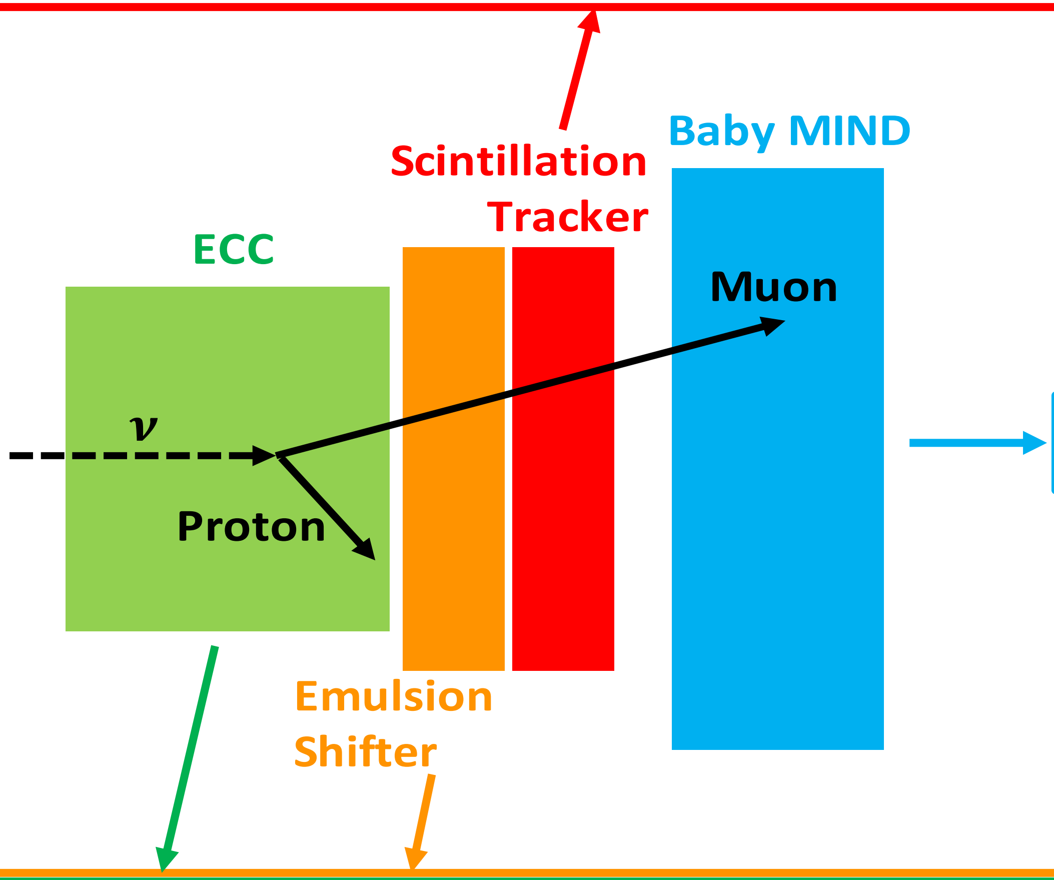
Period	Mode	Delivered POT	FROST recorded POT	Efficiency
2025/11/29~12/22, 2026/1/16~1/28, 2026/3/11~3/25	FHC	4.74×10^{20}	4.72×10^{20}	99.44%
2026/1/28~2026/3/11	RHC	5.52×10^{20}	5.50×10^{20}	99.73%
Total		10.26×10^{20}	10.22×10^{20}	99.59%



- Acquired **1.24×10^{21} POT in FHC** **(> 1.0×10^{21} POT)** over physics runs
- First RHC-mode data taken during the physics run

Analysis status: overview (1)

Position reconstruction and
track matching with Baby MIND completed



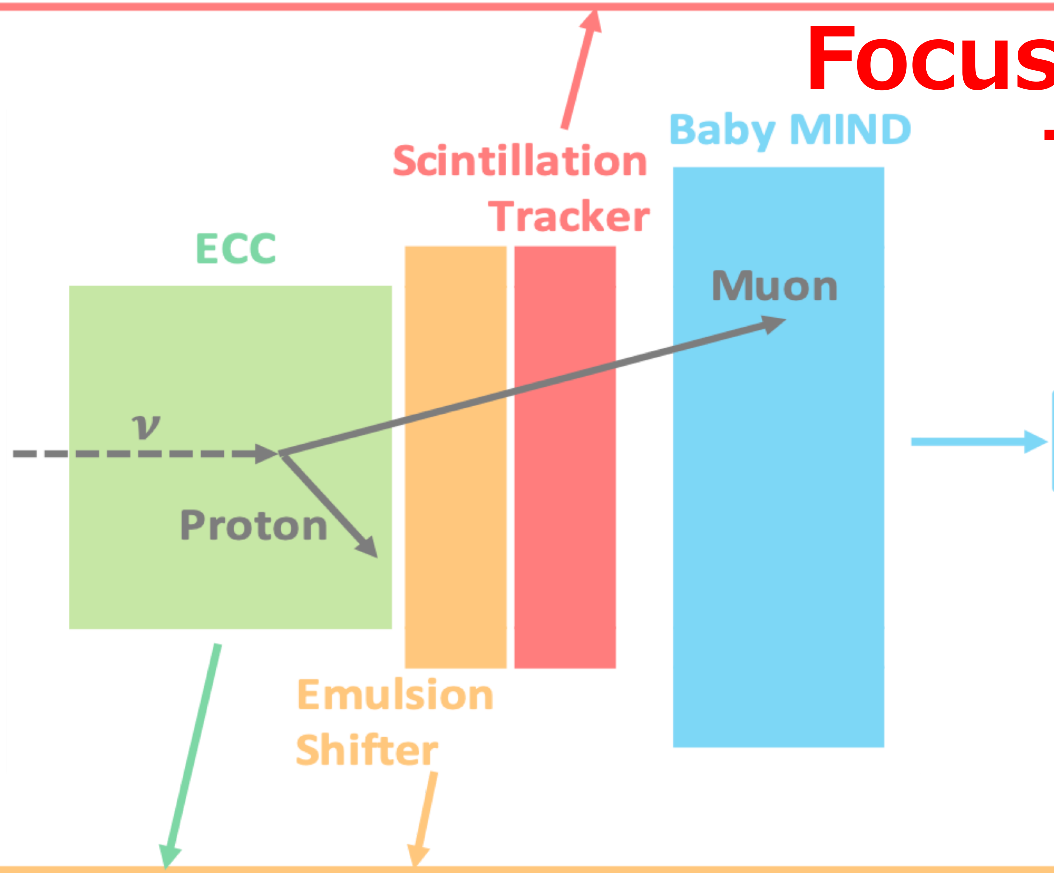
Track reconstruction has been completed

Emulsion film development is in progress (70% completed)

Analysis status: overview (2)

Position reconstruction and track matching with Baby MIND completed

Focus on FROST (New Scintillation Tracker) analysis status

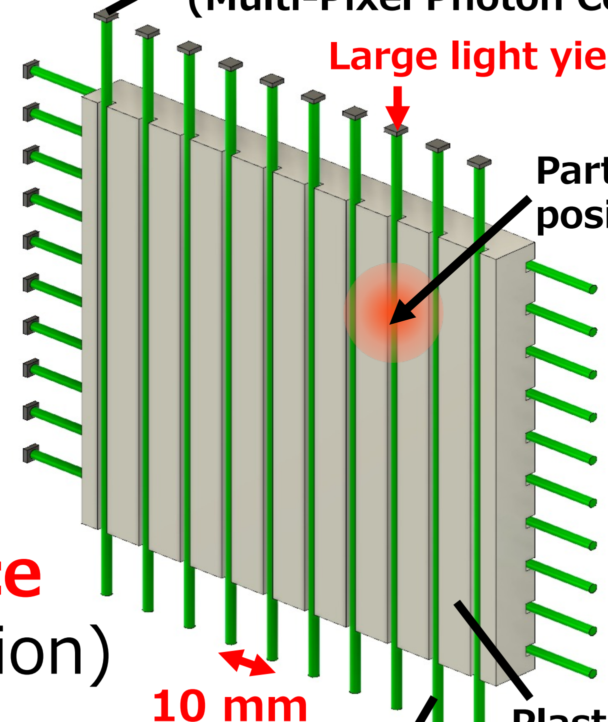


Track reconstruction has been completed

Emulsion film development is in progress (70% completed)

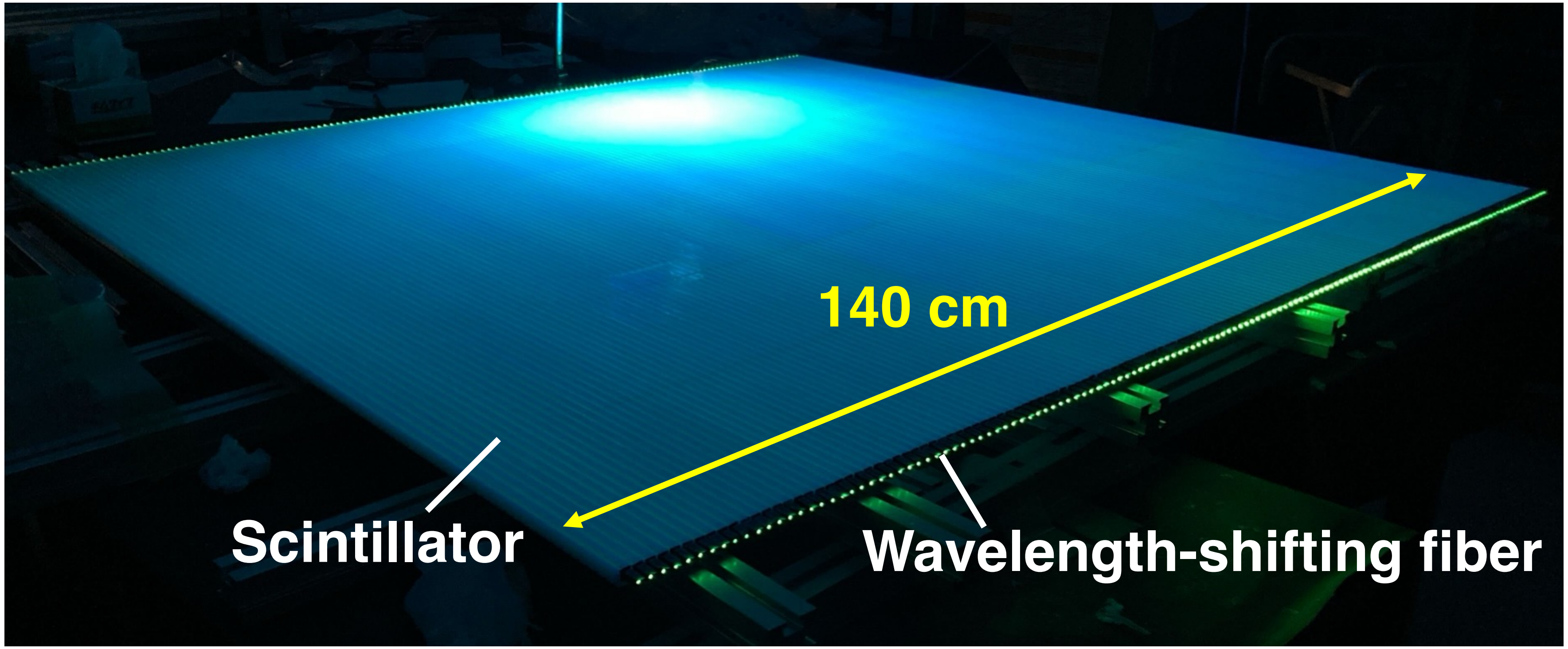
The introduction of FROST (1)

- **F**iber-**R**eadout m**O**nolithic and **S**catterer-embedded scintillator **T**racker
- Assign beam timing information to emulsion tracks
- **Monolithic wide plastic scintillator plane** including **scatterers**
- **Scatterers** in the plastic scintillator **localize the scintillation light**
- Scintillation light is read out by wavelength-shifting fibers and MPPCs
- Position is reconstructed using **light yield balance** (Larger light yield near the particle crossing position)



The introduction of FROST (2)

- Required position resolution is **4.6 mm**
- Simulated position resolution is estimated to be **1.5 mm** (considering stat. error only)

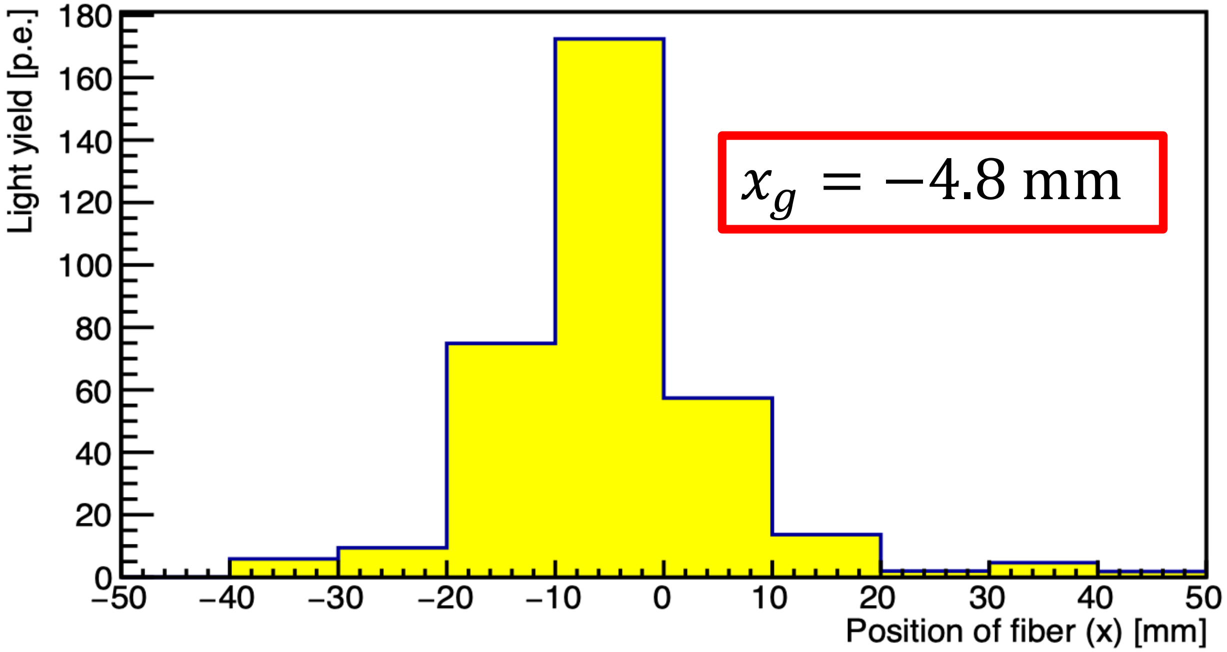


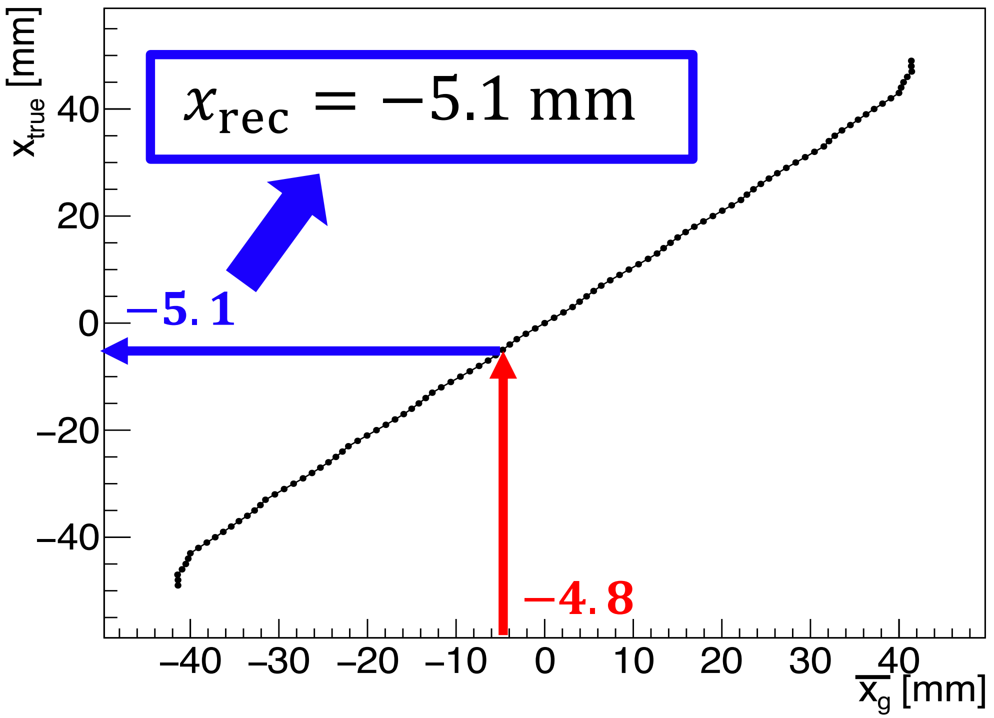
arXiv: https://arxiv.org/abs/2604.03107

Position reconstruction method (1)

①Single-particle hits

- Position reconstruction using **the weighted center of light yield x_g** and **the MC-derived relation b/w x_{true} and $\overline{x_g}$**

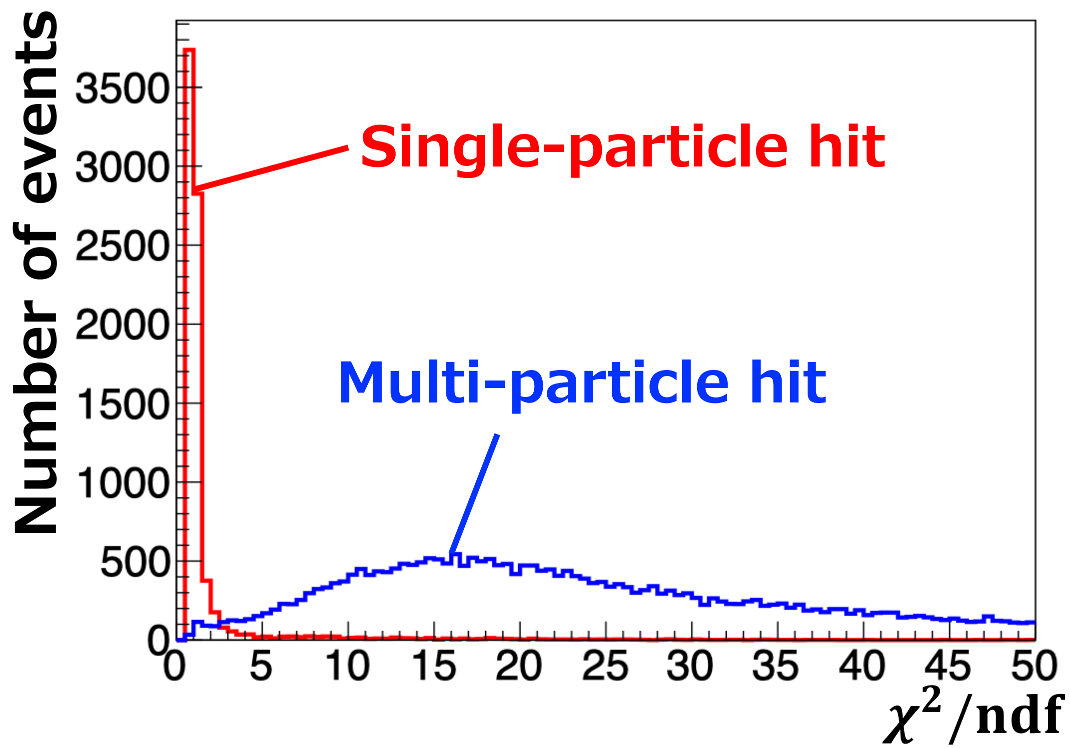


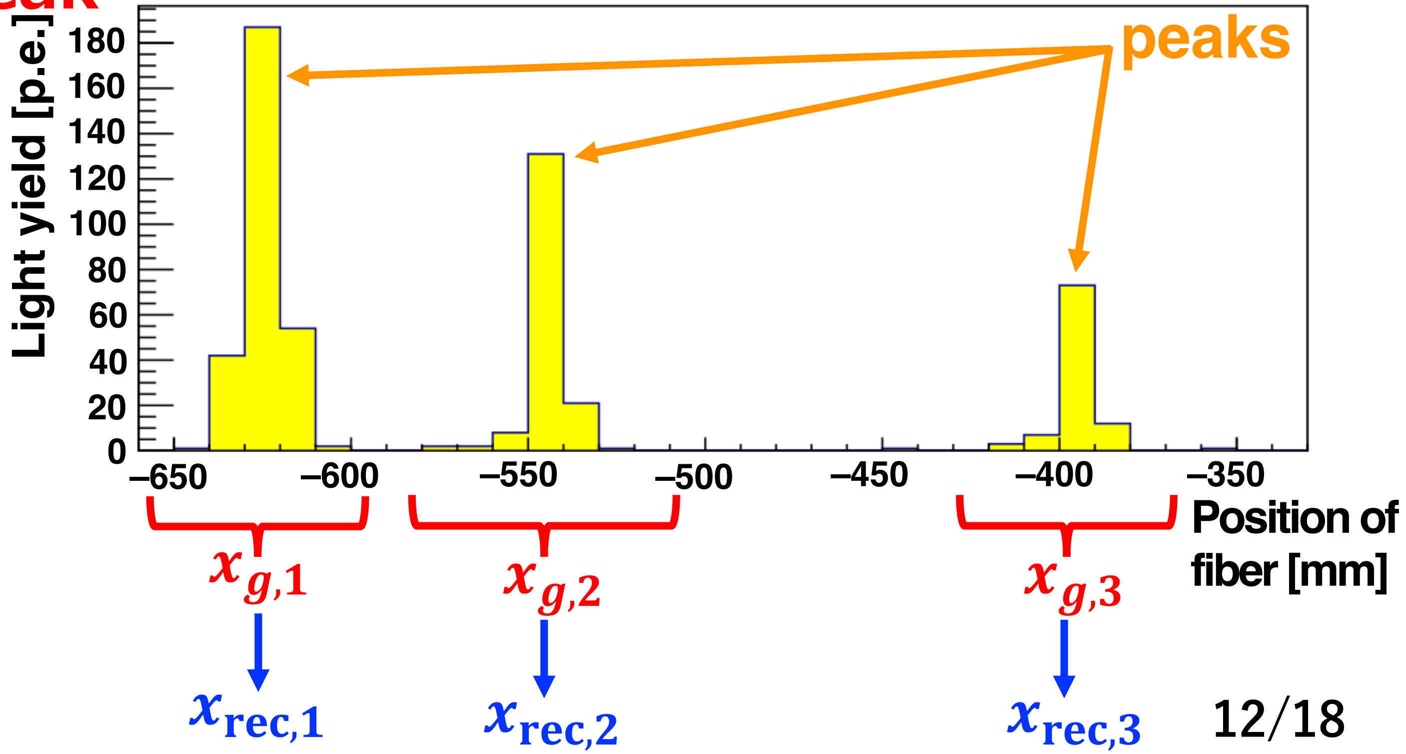


Position reconstruction method (2)

②Including multi-particle hits

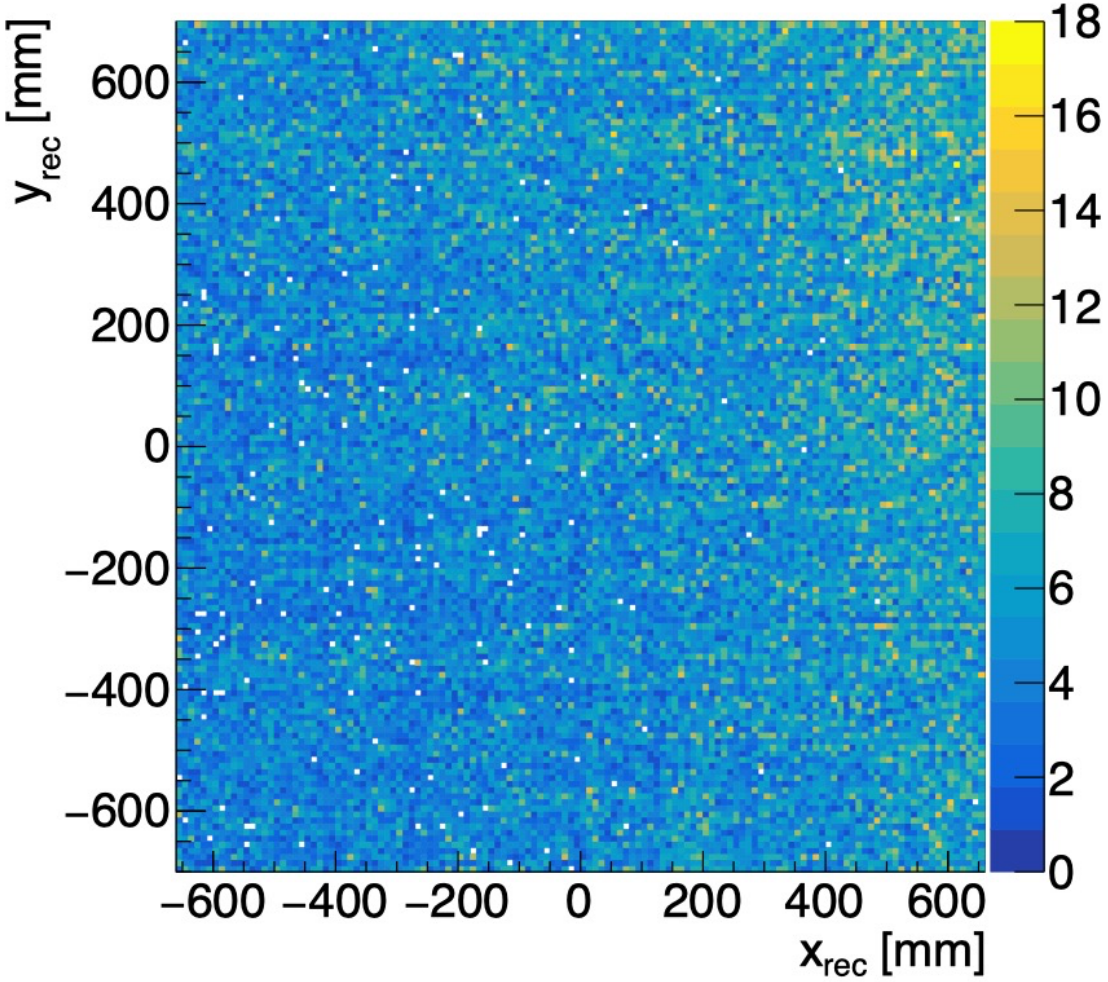
1. **Distinguish single- and multi- particle hits using χ^2** under the single-particle-hit hypothesis
2. For single-particle hits, reconstruct the position with the method ①
3. For multi-particle hits, reconstruct the position from **the weighted center of light yield around each peak**





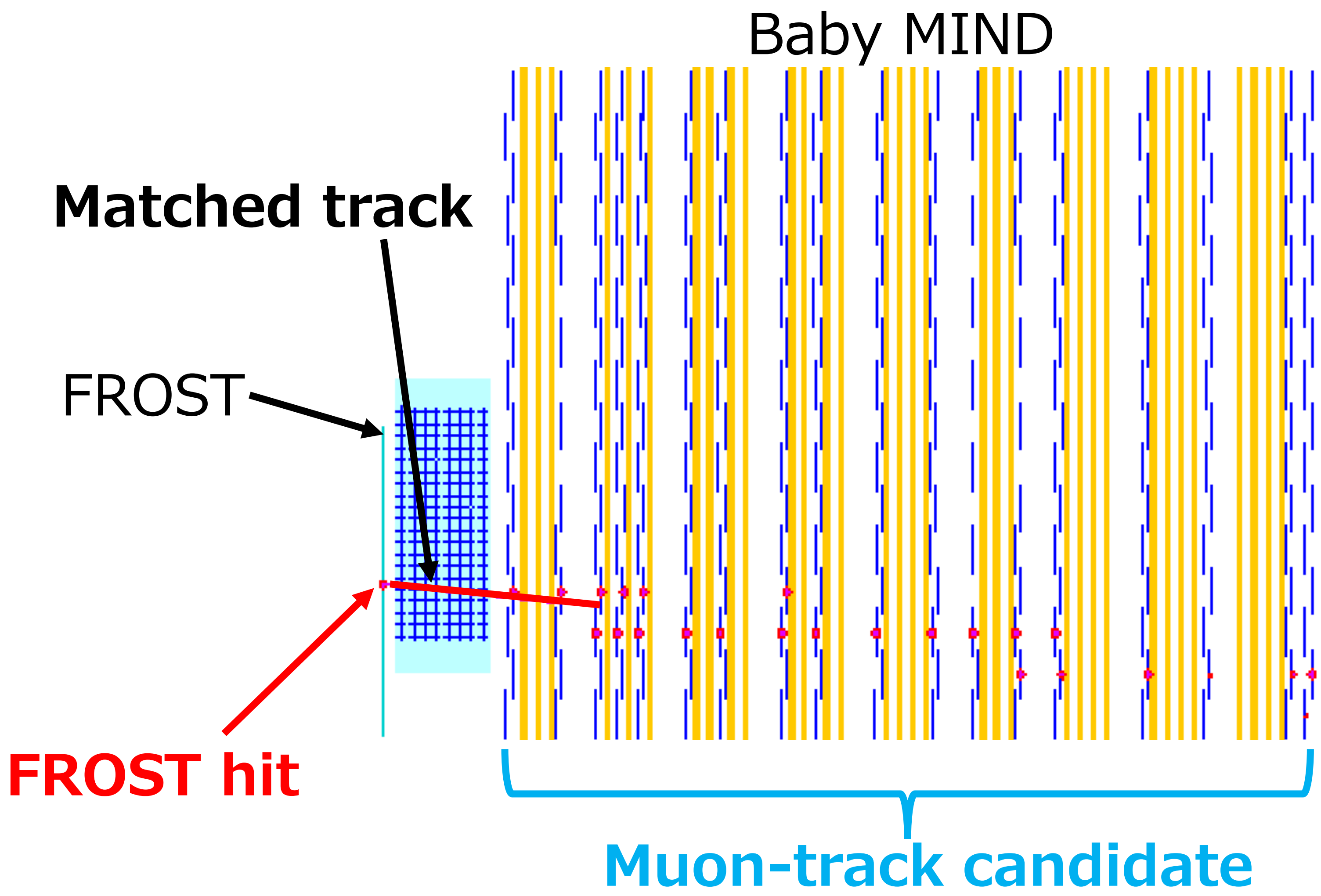
Reconstructed position distribution

- **As expected** (Almost uniform and more events in x>0, y>0 because the beam axis is located at x>0,y>0)

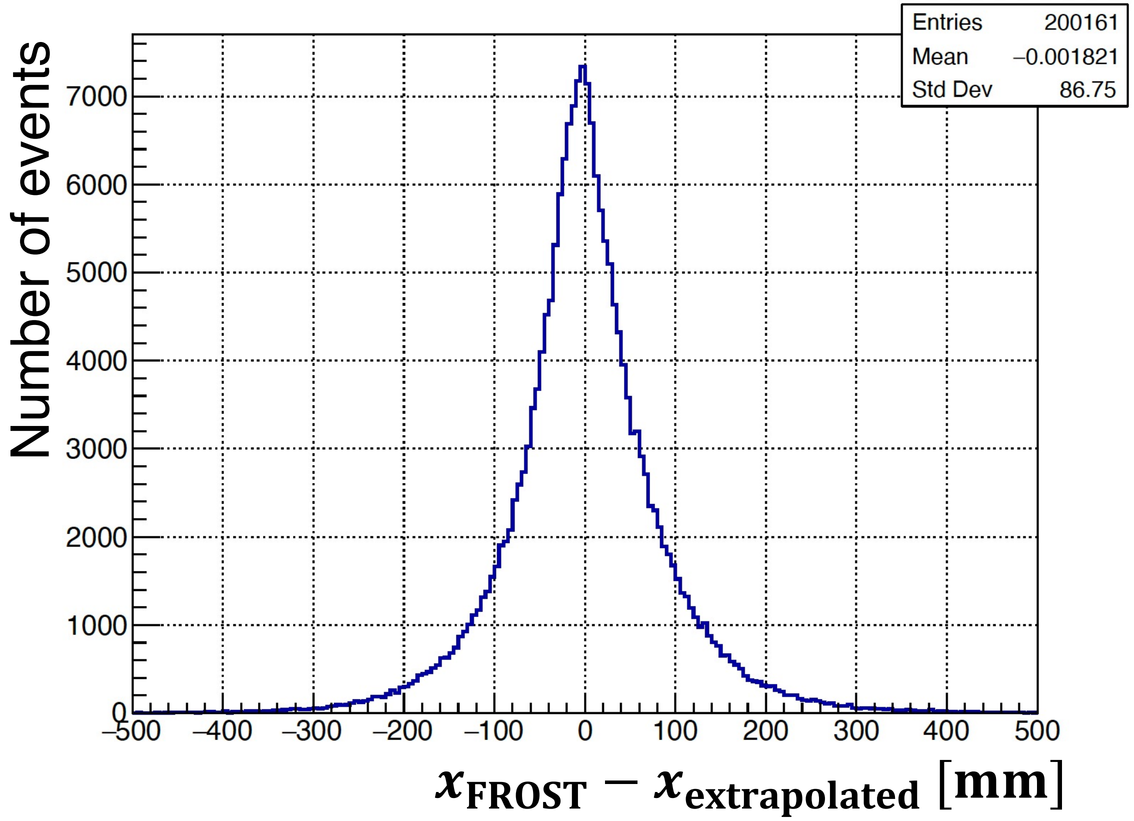


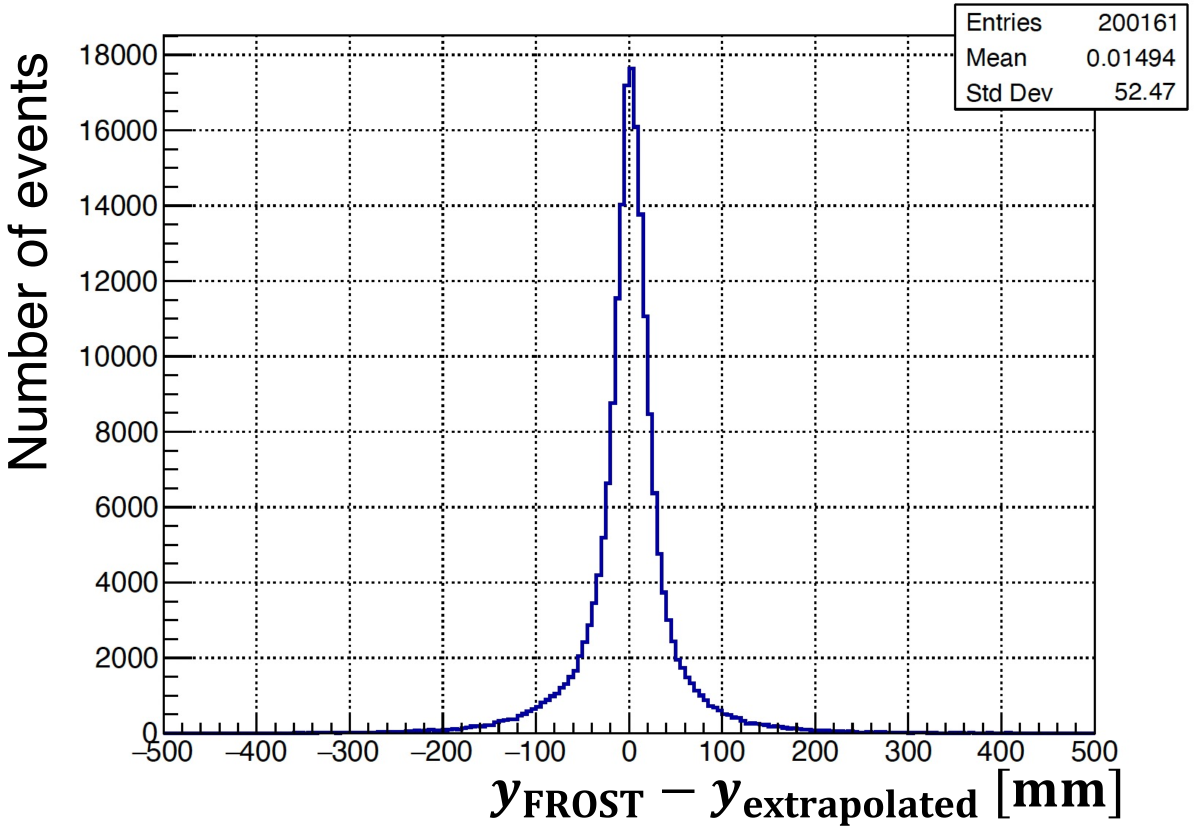
Muon track matching b/w FROST and Baby MIND

- Match **muon-track candidates in Baby MIND** with the time-matched **FROST hits**



Distribution of the difference b/w FROST position and the extrapolated position from Baby MIND

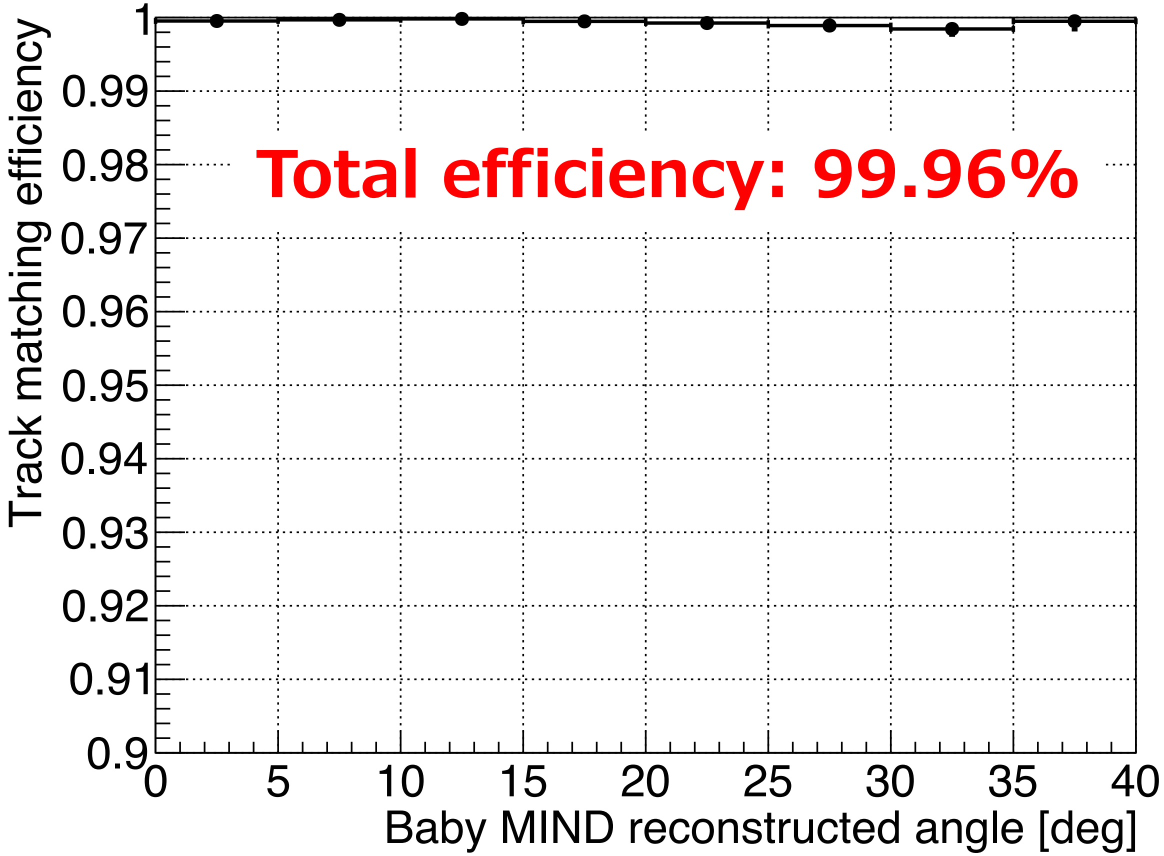




- The width of the residual distribution is **mainly driven by the Baby MIND resolution ($\mathcal{O}(\mathrm{cm})$)**

Evaluation of matching efficiency (hit efficiency)

- Evaluate the matching efficiency (=FROST hit efficiency) using sand muons from neutrino interactions in the upstream wall of the detector hall
- **Matching efficiency≡** $\frac{\text{(\# of matched tracks)}}{\text{(\# of sand muon tracks in the FROST central region)}}$

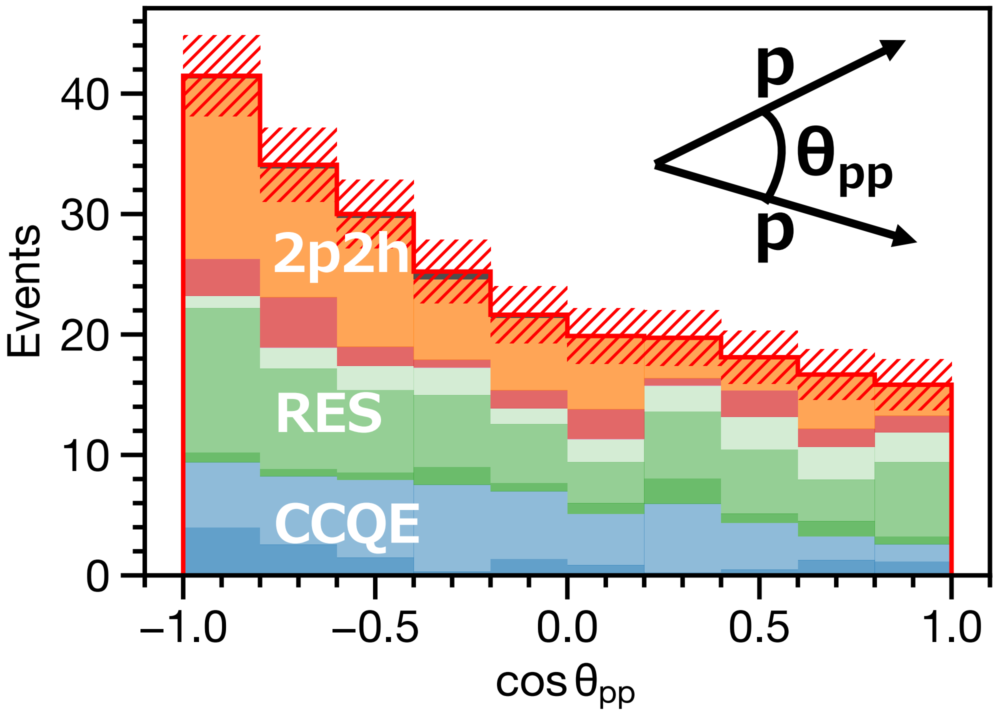


Prospects of the physics results

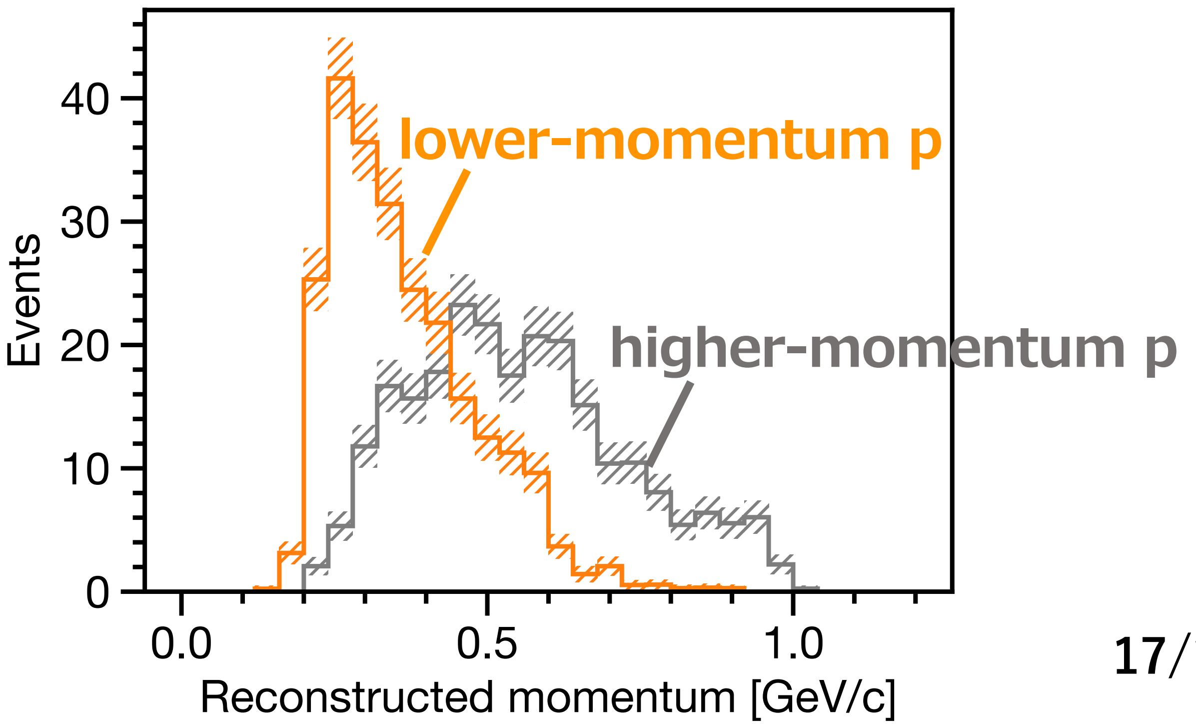
- We expect 200-300 $\nu_\mu \mathrm{CC0\pi 2p}$ events out of ~4000 $\nu_\mu \mathrm{CC}$ events across all physics runs
- **2p2h interaction tends to have a large opening angle of 2 protons**
  →Key to constraining 2p2h interaction model

$\nu_\mu \mathrm{CC0\pi 2p}$ events

cos(p-p angle)



p momentum



Summary

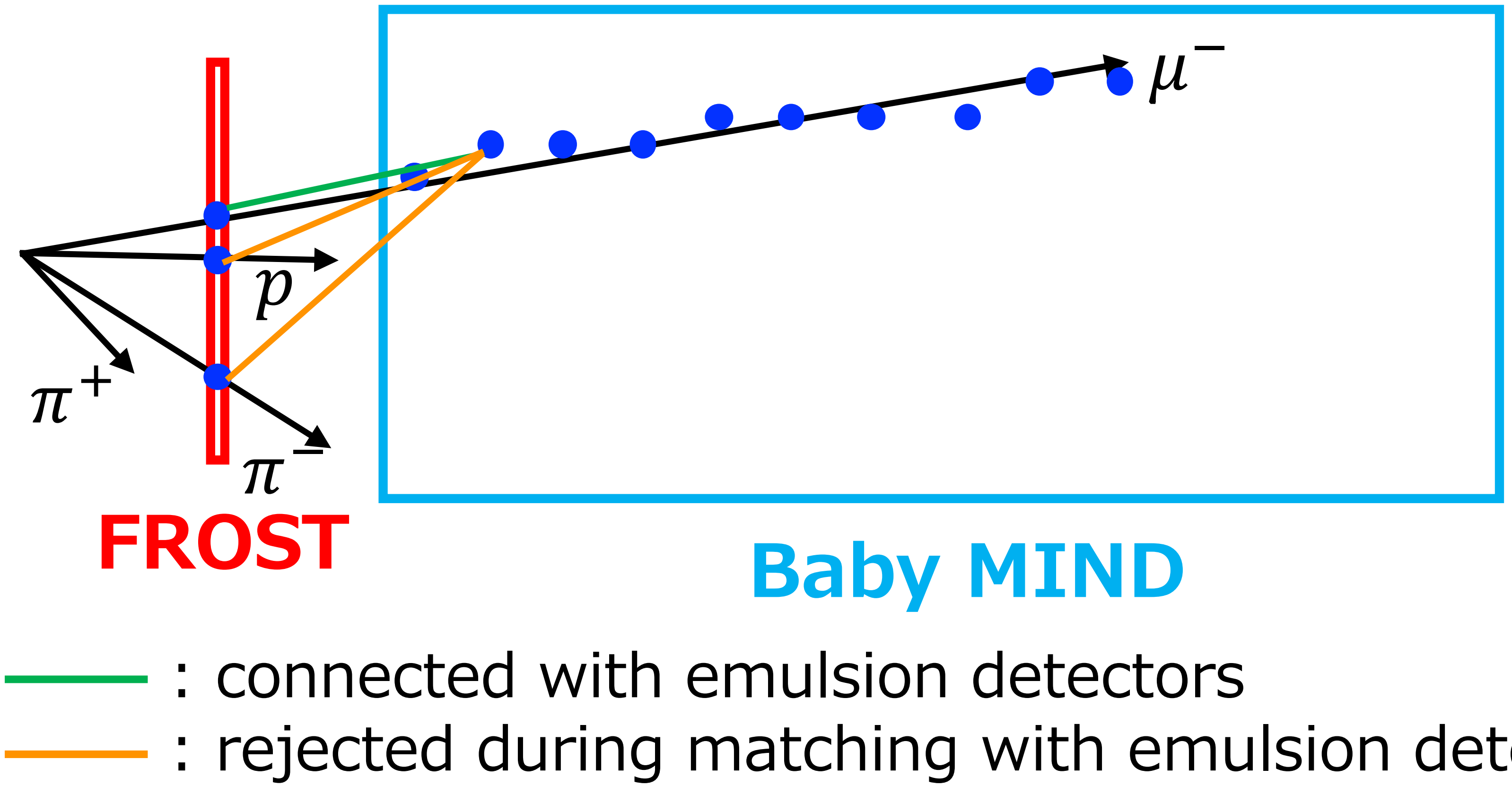
- **The NINJA experiment** precisely measures **neutrino interactions** with water target **using nuclear emulsion**
- **Conducted 3rd physics run** and achieved the NINJA target statistics of **1.0×10^{21} POT in FHC**
- In the 3rd physics run, **New Scintillation Tracker (FROST)** was introduced
- Track matching b/w FROST and Baby MIND (muon detector) completed
- **99.96% track matching efficiency** (=FROST hit efficiency)
- We expect **200-300 ν_μCC0π2p events out of ~4000 ν_μCC events** across all physics runs, **aiming to constrain neutrino interaction models**

Thank you for your attention!

Backup

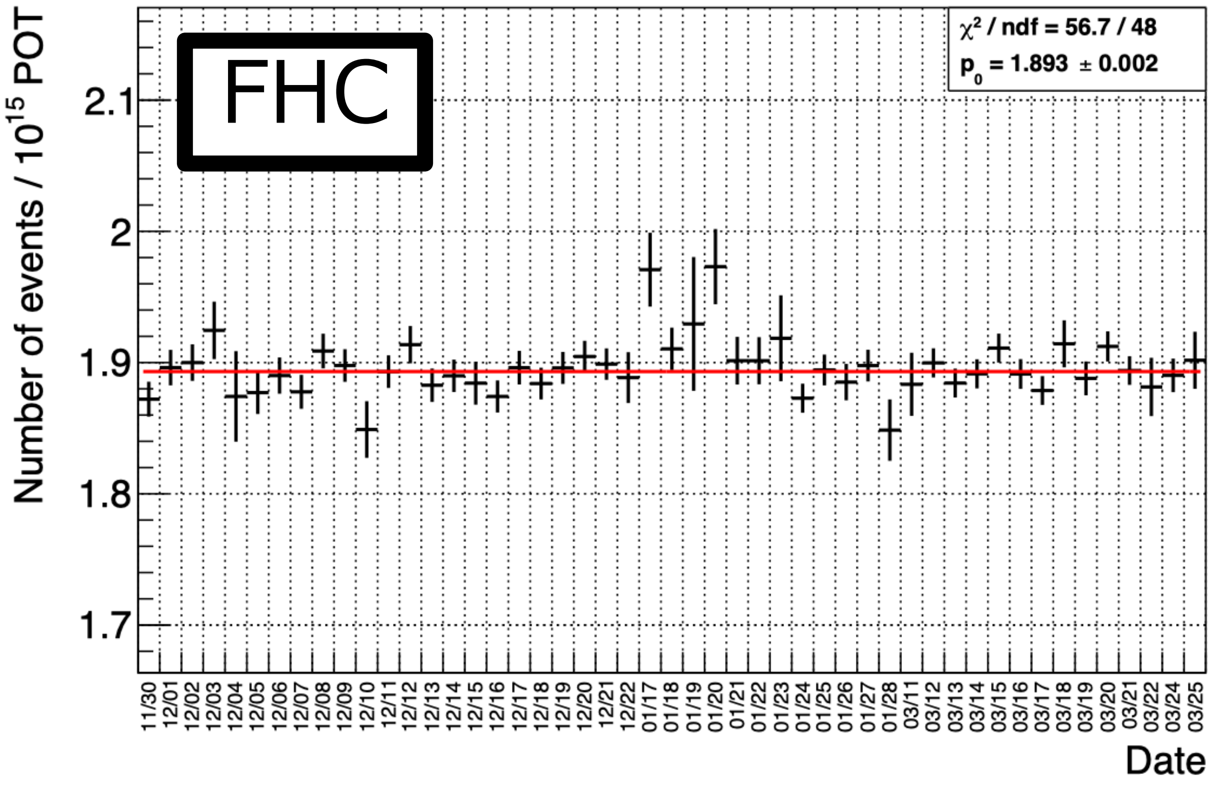
Multi-particle hits treatment

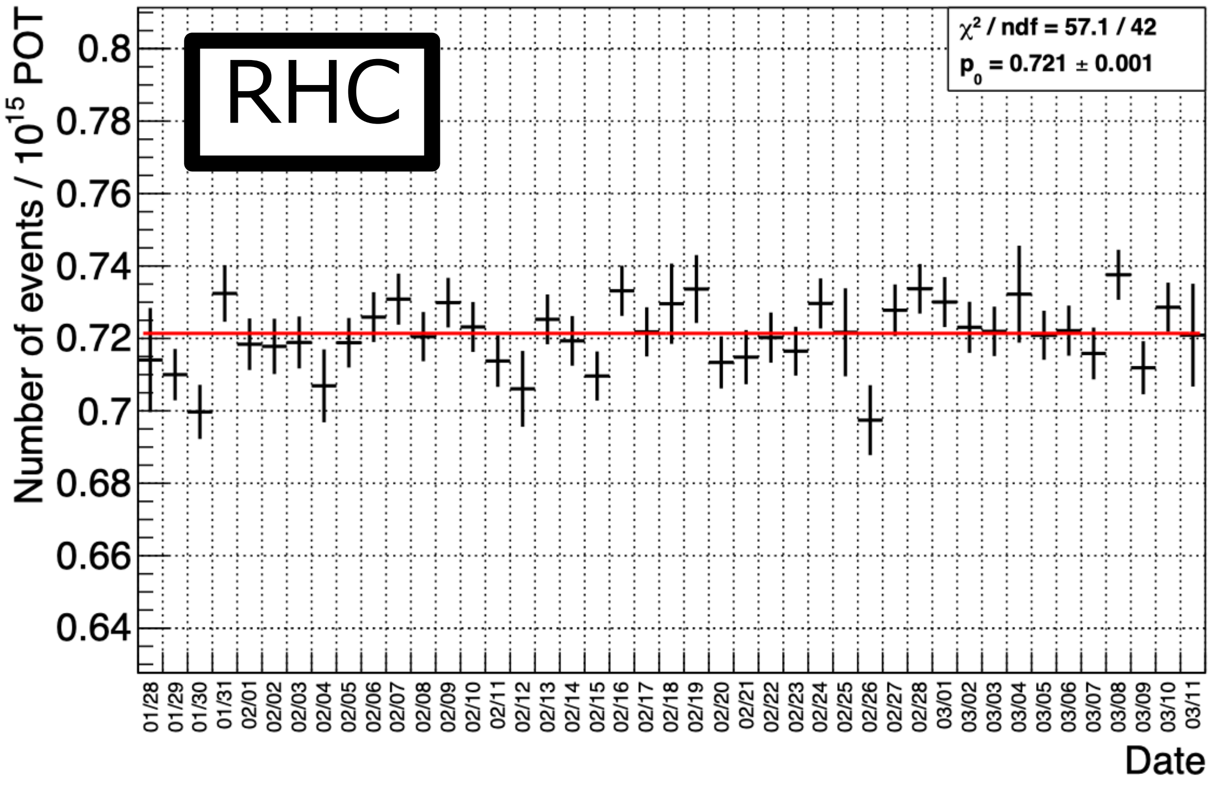
- If multiple position candidates are found in FROST, **all candidates are retained** at this stage and matched with the Baby MIND track
- **Misconnected tracks can be rejected in matching with Emulsion detectors** thanks to their much higher position and angular resolutions



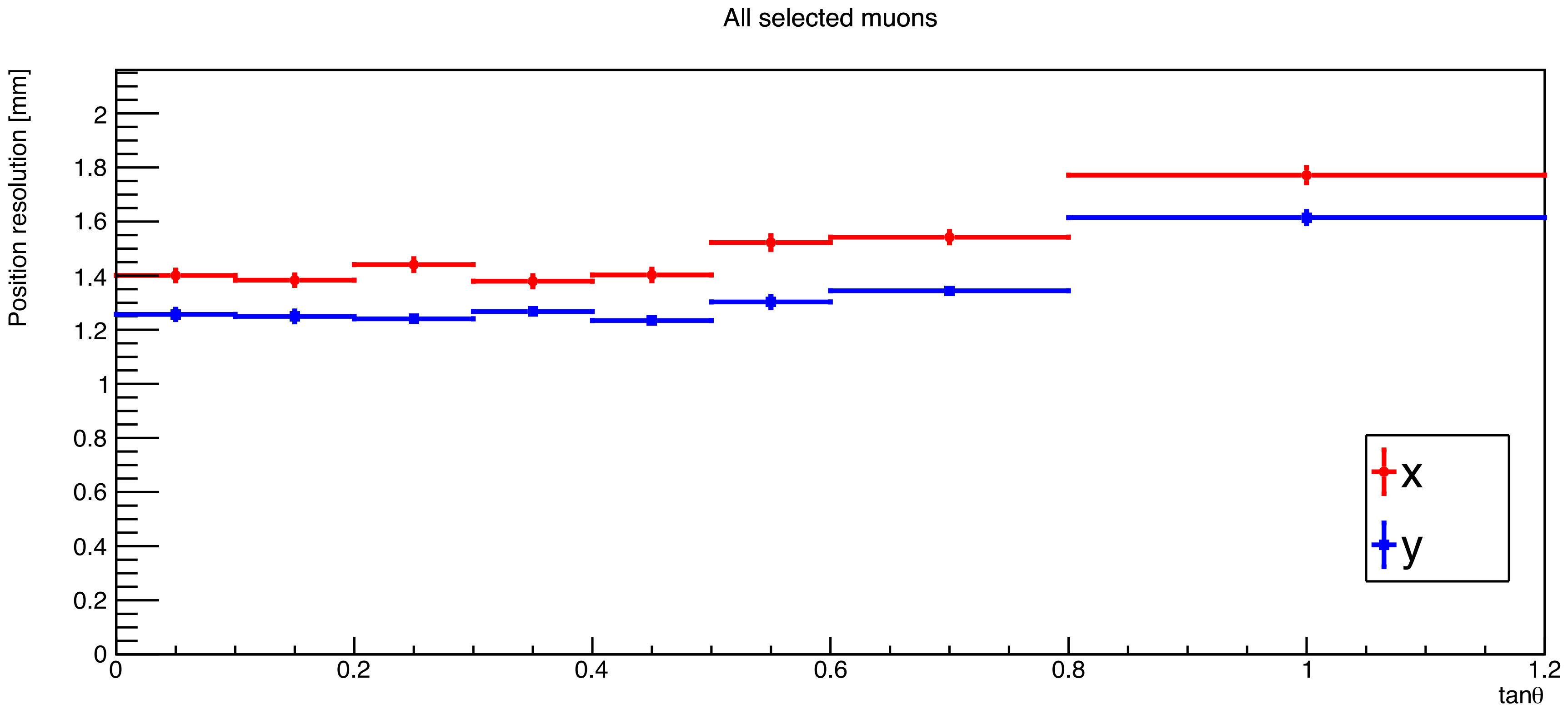
FROST event rate

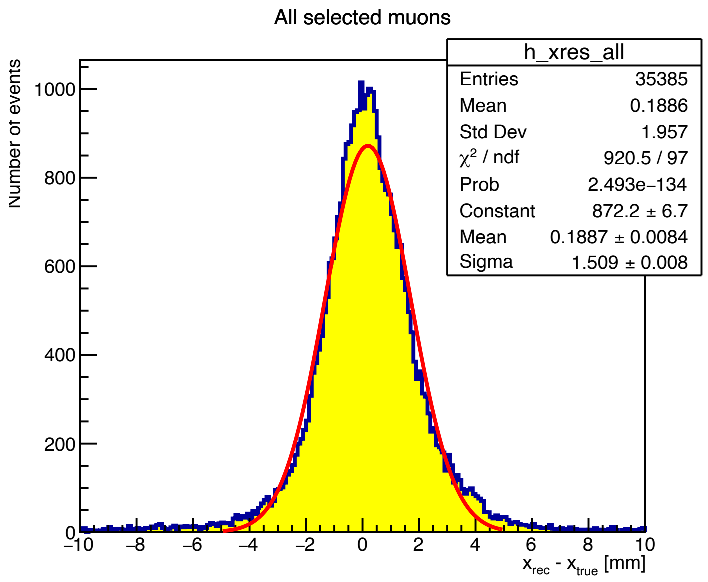
- Event rate was stable

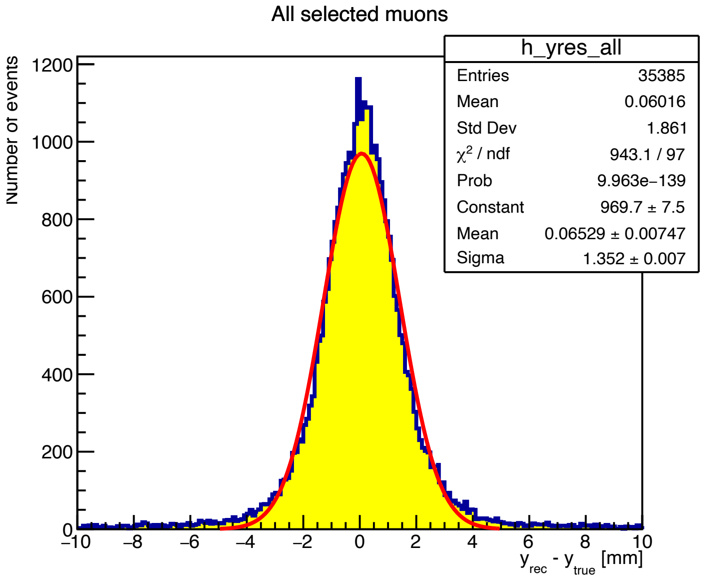




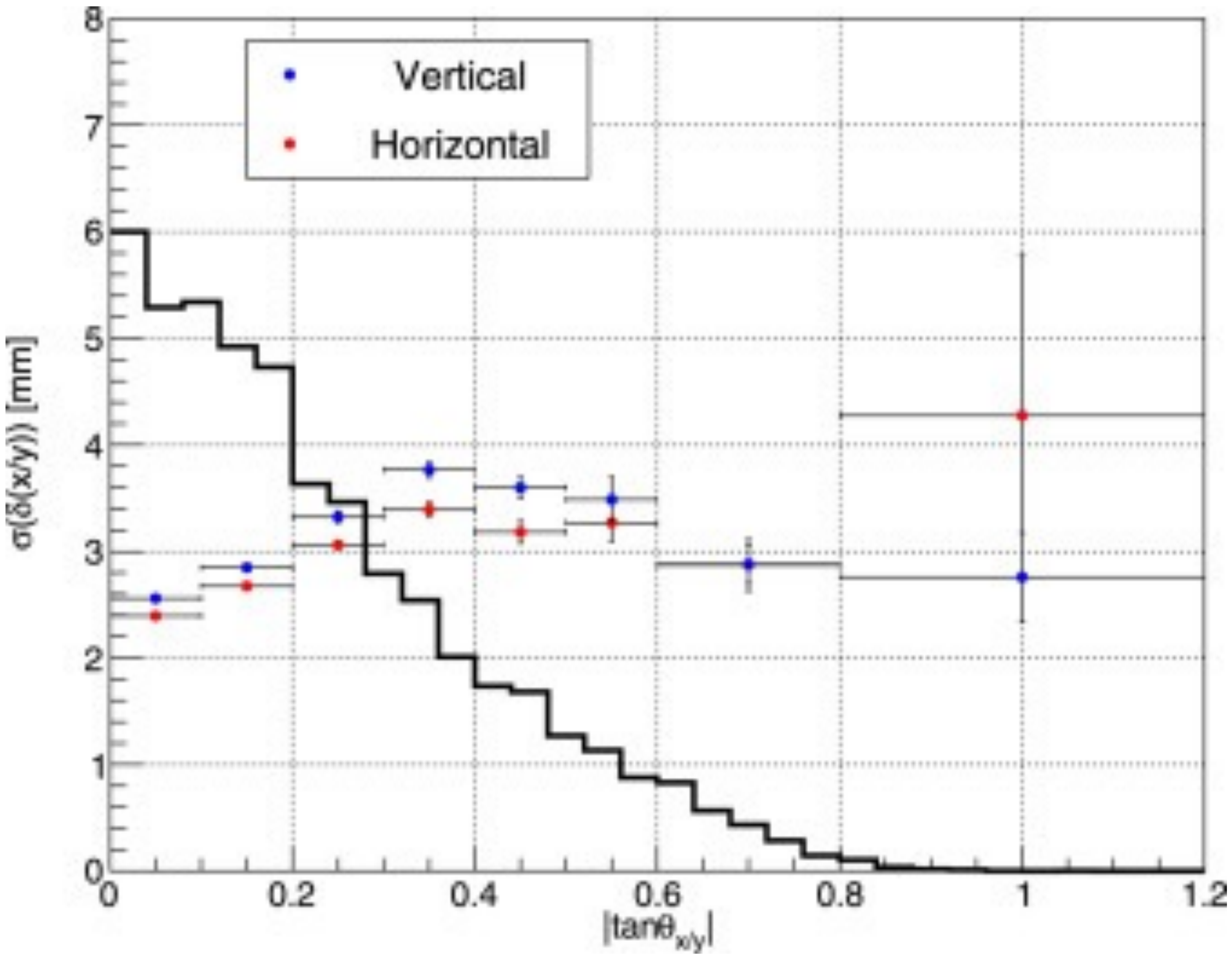
Simulated position resolution of FROST



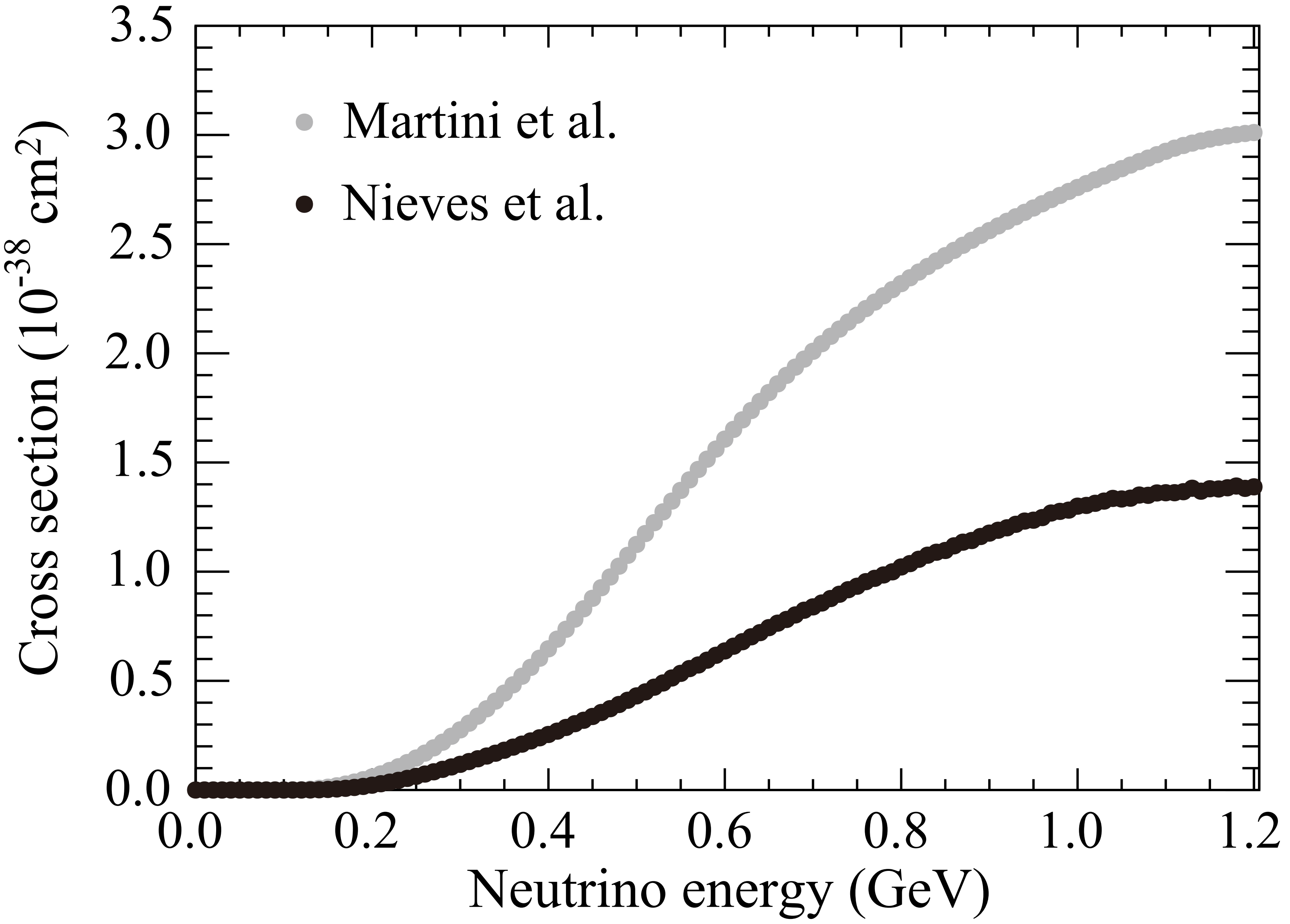




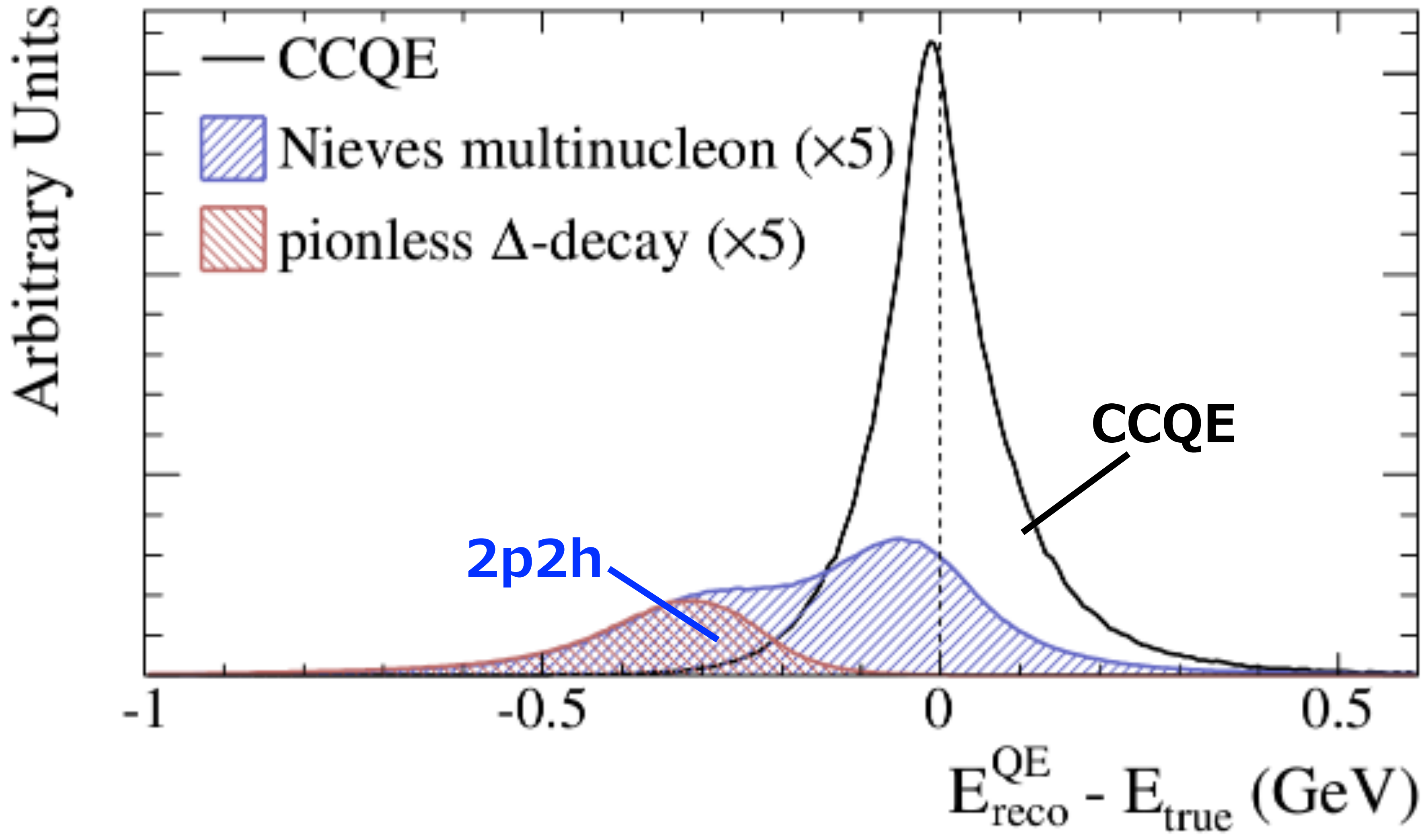
Position resolution of Previous Scintillation Tracker



2p2h: Model dependence of Xsec

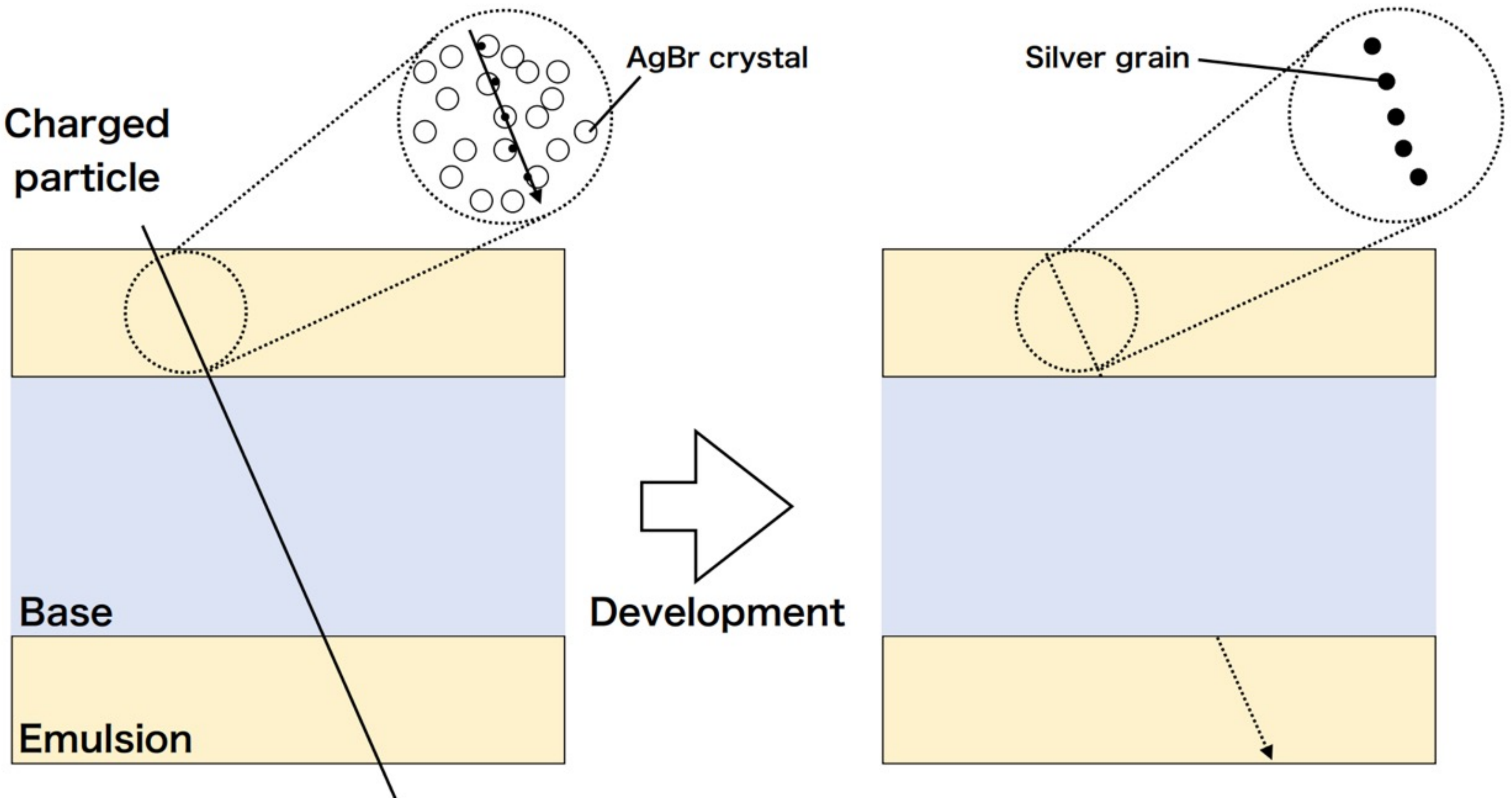


2p2h: Difference b/w reconstructed and true neutrino energy assuming CCQE



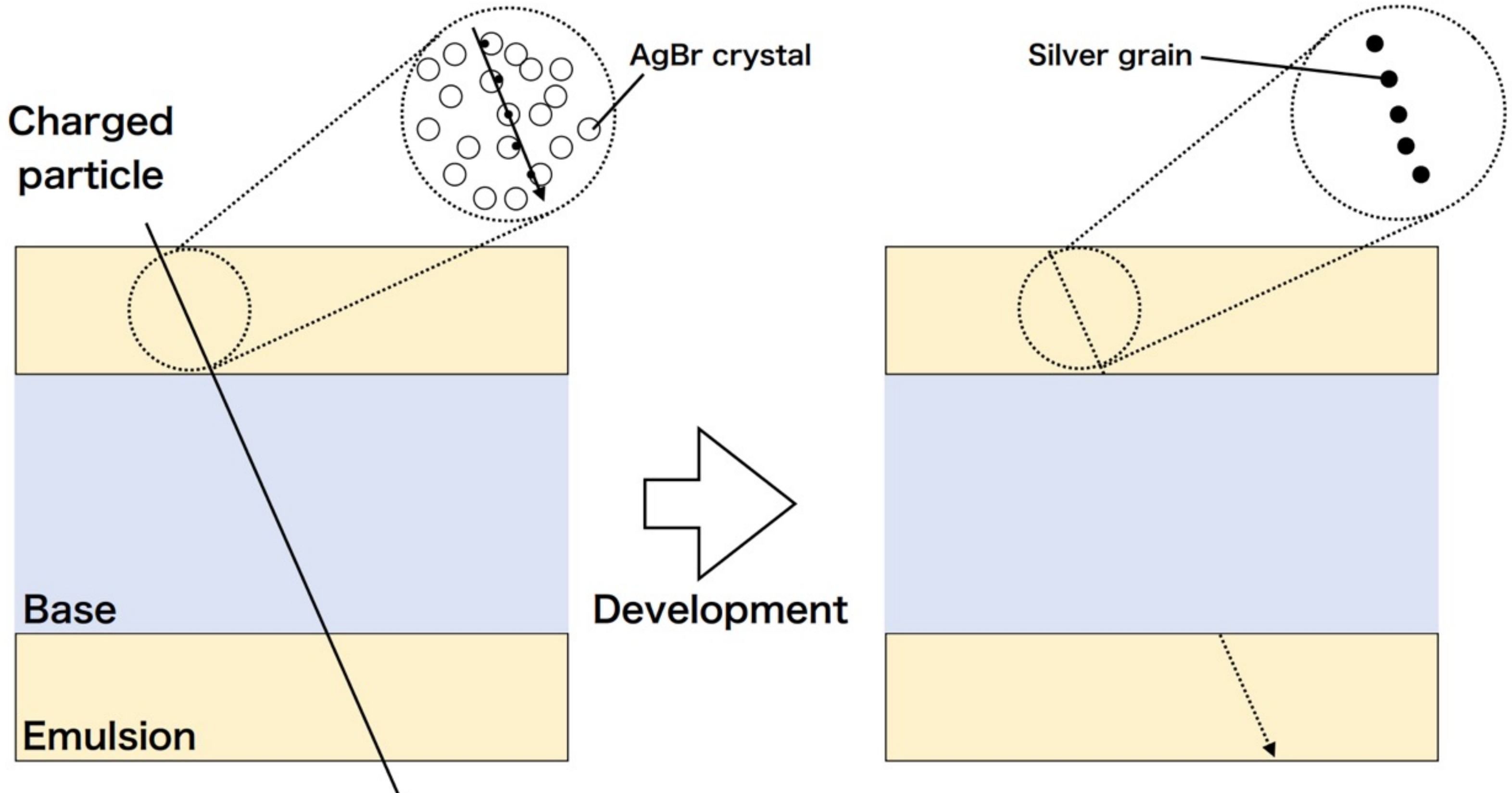
Nuclear emulsion (1)

- The nuclear emulsion is made by silver bromide (AgBr) crystals dispersed in gelatin
- The trajectories of charged particles get visible as a latent image after a development process
- Since each silver grain functions as a detector element, it has a very high granularity and can record short tracks three-dimensionally



Nuclear emulsion (2)

- When a charged particle passes through the emulsion, electrons are generated and captured in the lattice defects of the surface of the crystals
- The negatively charged crystals make silver atoms by deoxidizing silver ions around them
- More than three silver atoms are gathered to make a latent image
- All silver ions are deoxidized to make a silver grain in the development process
- The size of grains: sub-μm



ECC (Emulsion Cloud Chamber)