Total neutron cross-section measurement on CH with a novel 3D-projection scintillator detector

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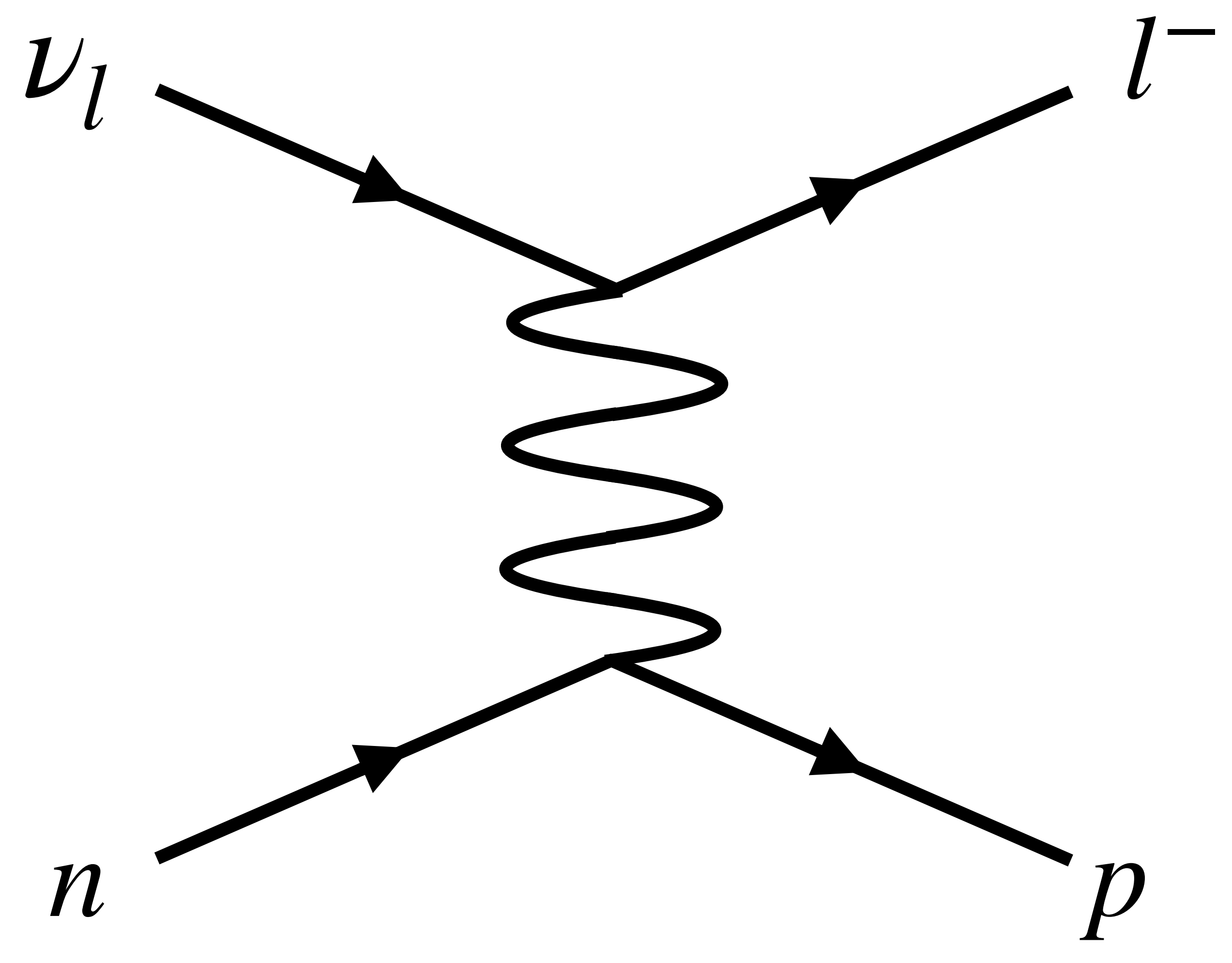
On behalf of 3D-Projection Scintillator R&D group

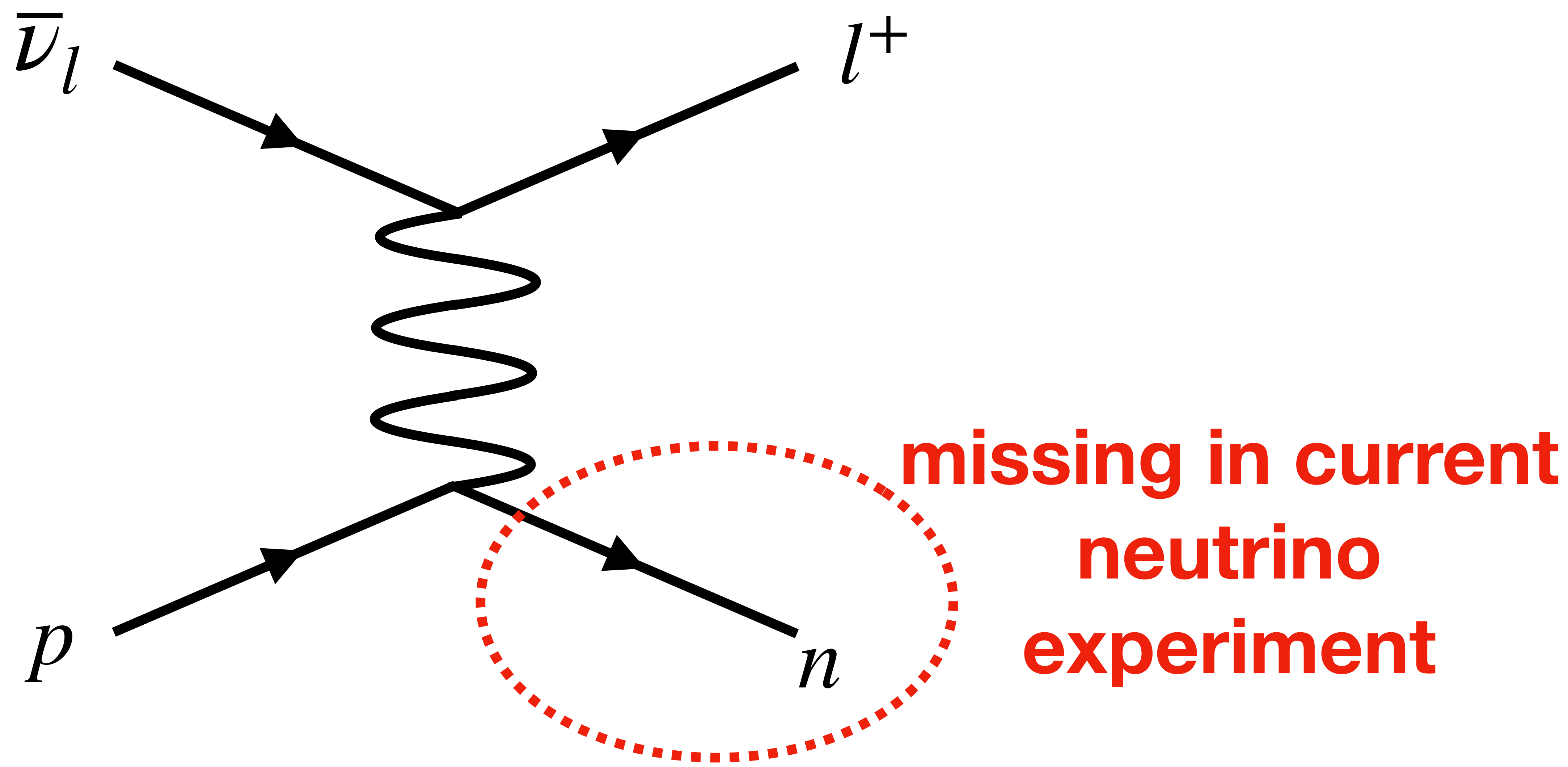
Motivation

- CP violation measurement is one of the most important measurements in long-baseline neutrino experiments.
  - CP violation is measured by comparing neutrino and anti-neutrino oscillation probability.

- The precise reconstruction of the energy of the (anti)neutrino is needed to discern the oscillation phenomena.
  - The proton from neutrino interaction can be detected, but neutron kinematic reconstruction from anti-neutrino interaction is missing.



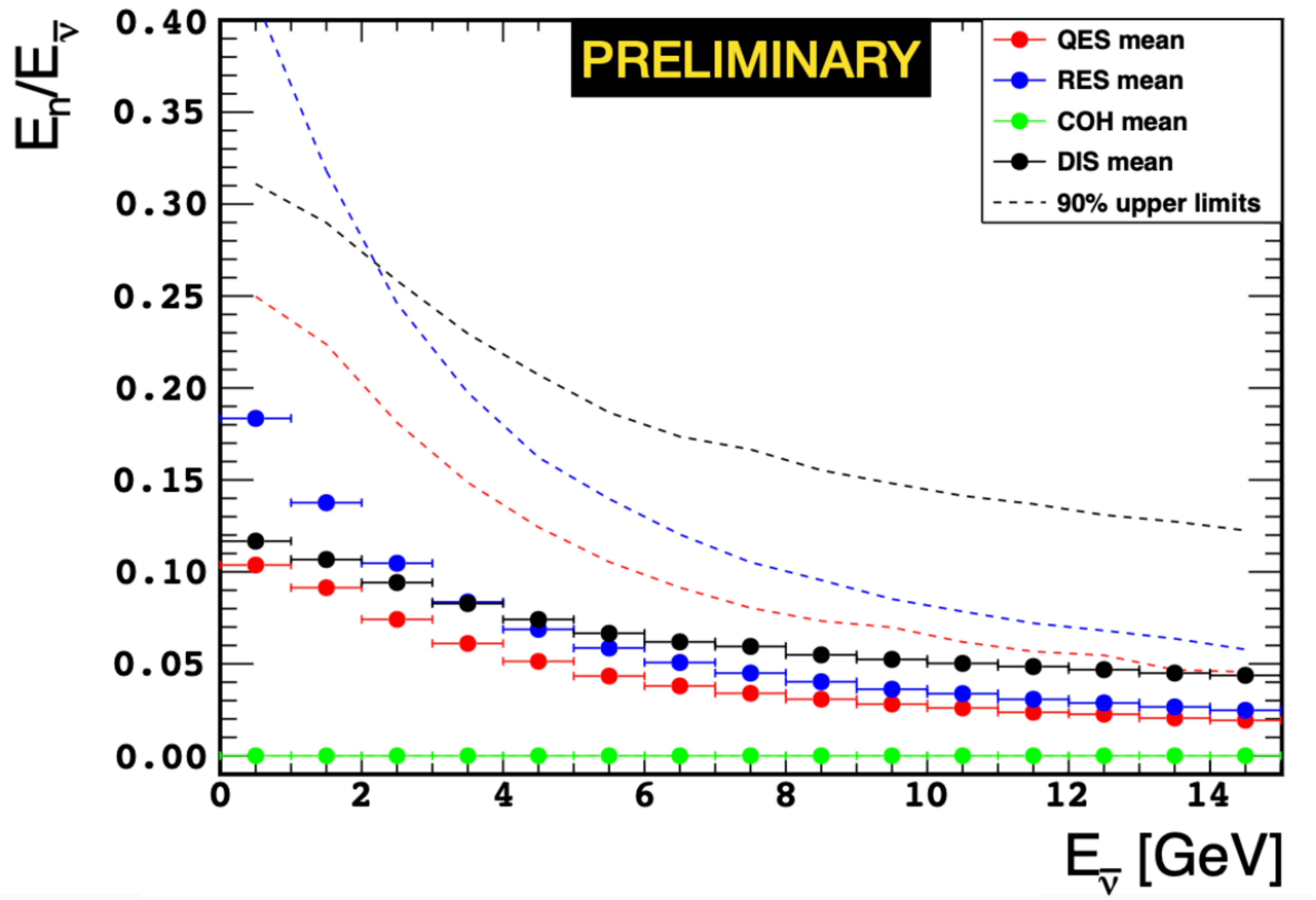
neutrino CCQE interaction



anti-neutrino CCQE interaction

Motivation

- In the current long-baseline neutrino experiment, neutron kinematic detection in the neutrino interaction is missing.

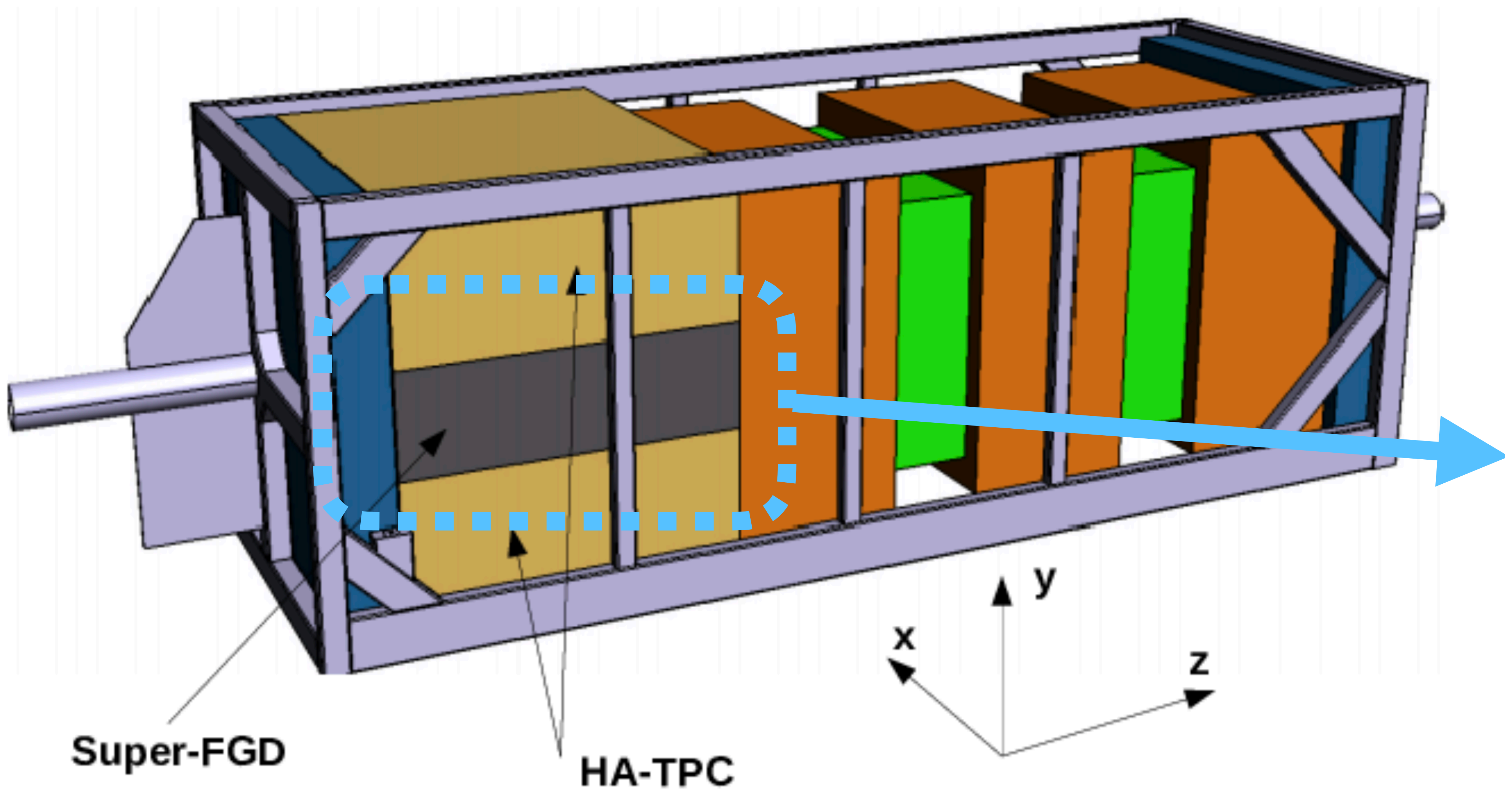


antineutrino interaction on CH target generated by GENIEv3

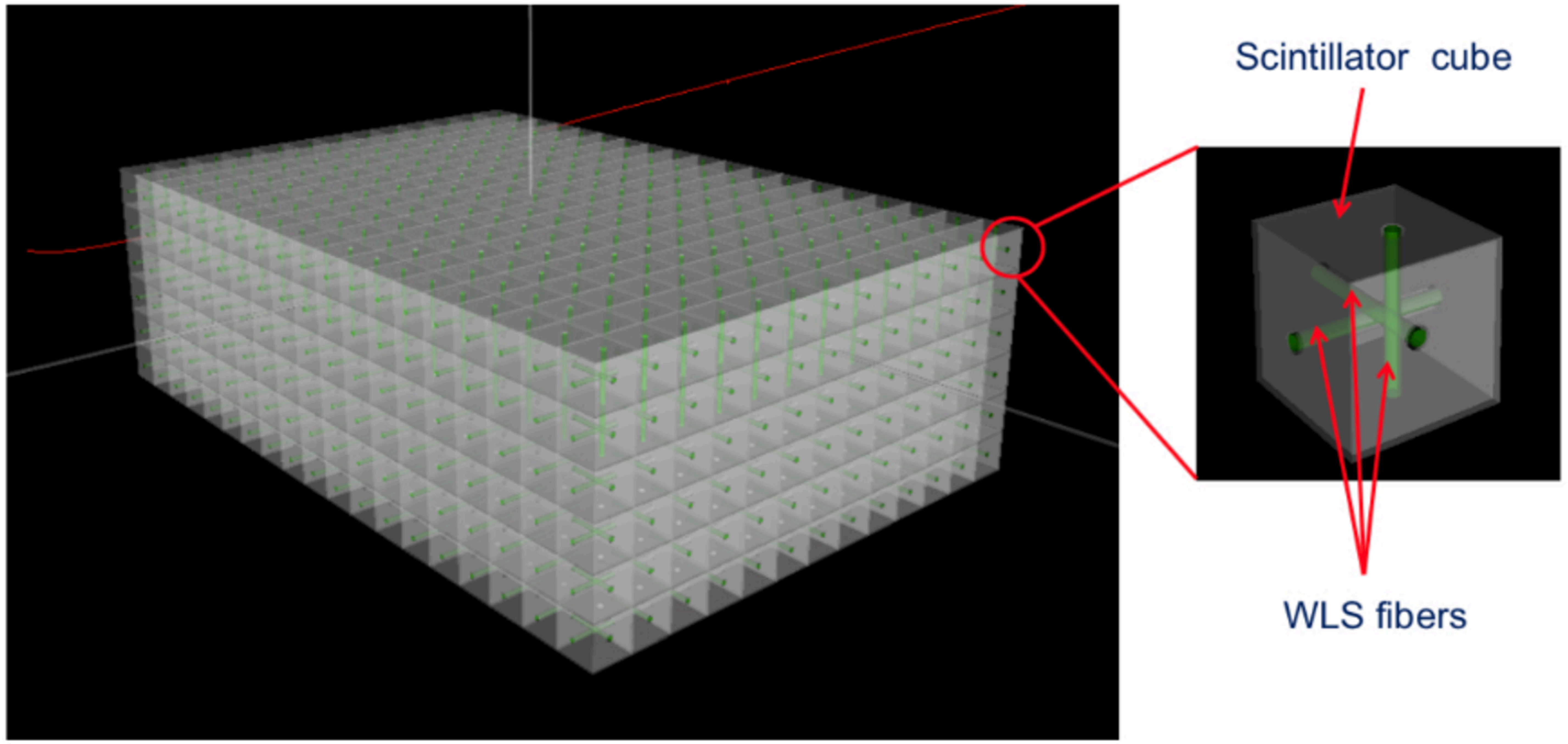
- The portion of the neutrino energy carried by the neutron in the antineutrino interaction
- The dashed lines show the 90% upper limit on the proportion of neutrino energy carried by the neutron.
- For example, in CCQE interactions, there can be up to 25% loss of neutrino energy by the neutron.

SuperFGD detector

- A novel 3D-projection scintillator detector, called SuperFGD, will be the tracker of the upgraded near detector of T2K.

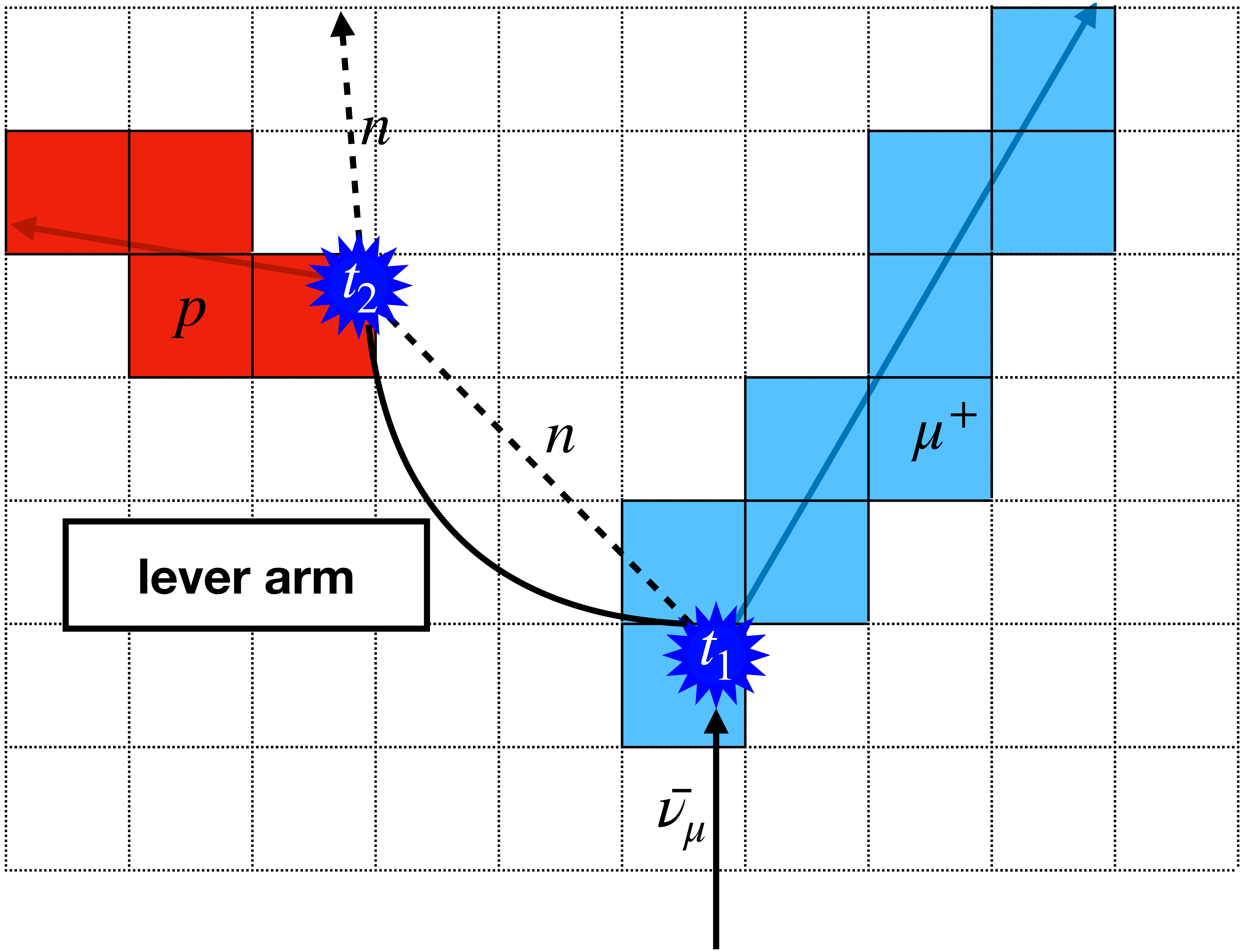


T2K ND280 upgrade



- It consists of two millions 1cm³ plastic (CH) scintillator cubes. The cubes are optically isolated, and scintillation light is read out by three orthogonal wavelength shifting fibers (WLS).

Neutron kinematic detection on an event-by-event basis

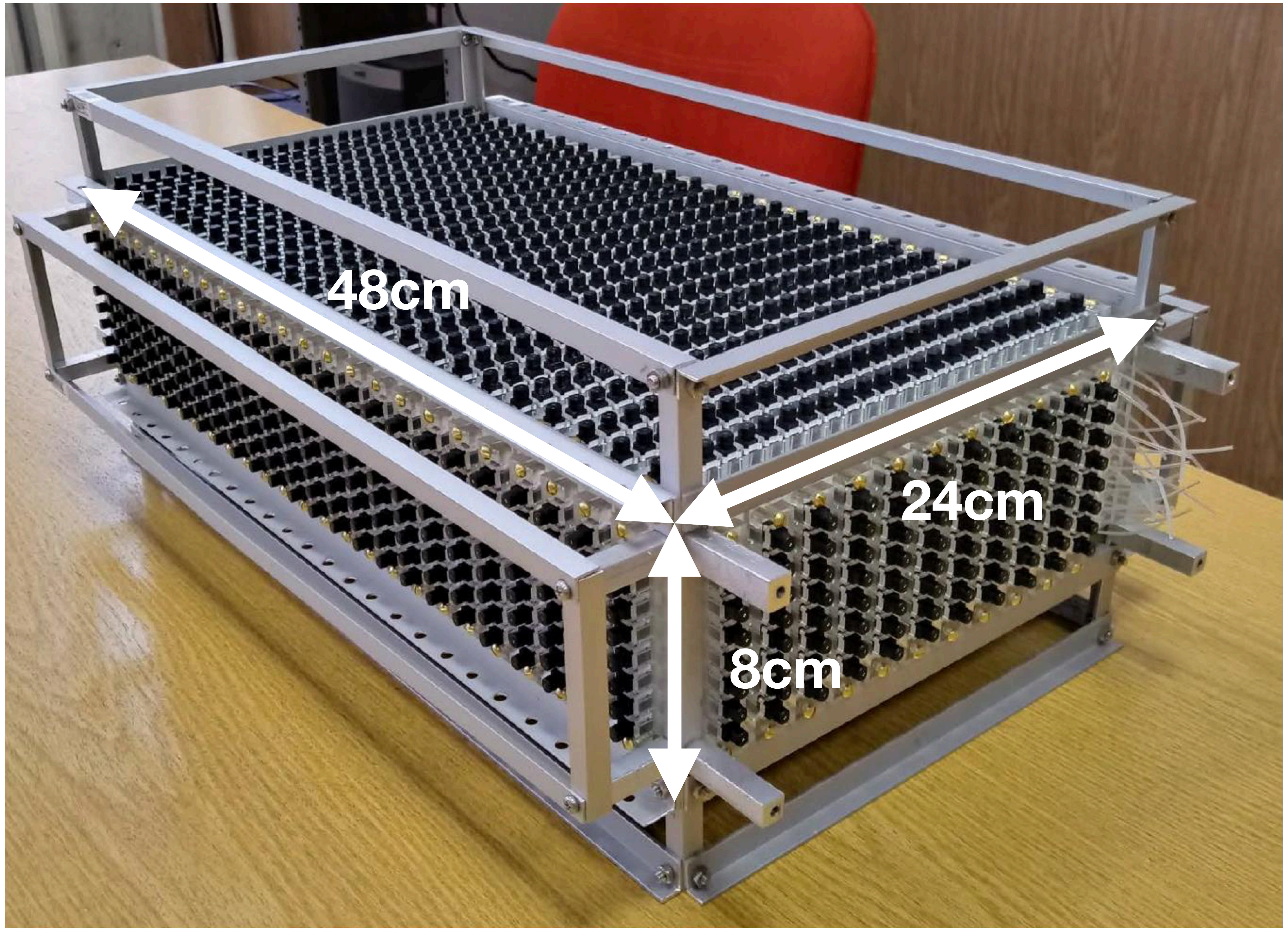


2D view of $\bar{\nu}_\mu$ CCQE interaction in the detector

- The neutron's kinetic energy can be measured by time-of-flight (ToF) and lever arm.
- The detector has the following features to enable the ToF technique.
  - good timing resolution
  - fine granularity
  - fully active target
  - 4π solid angle acceptance

Prototyping

- SuperFGD prototype was built to demonstrate this new technology, and it was exposed to charged particle beam at CERN to characterize the detector: JINST15, P12003 (2020).

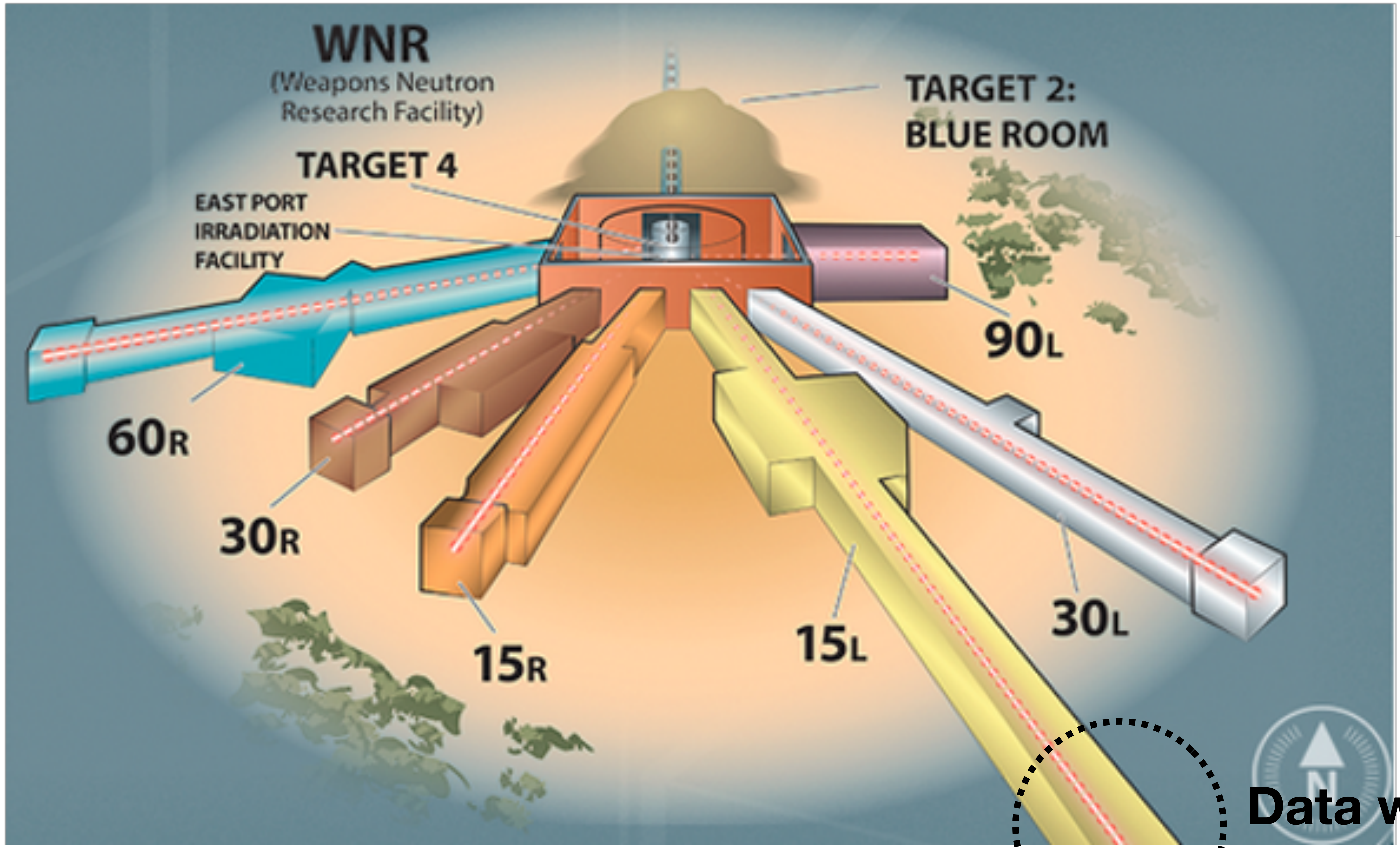


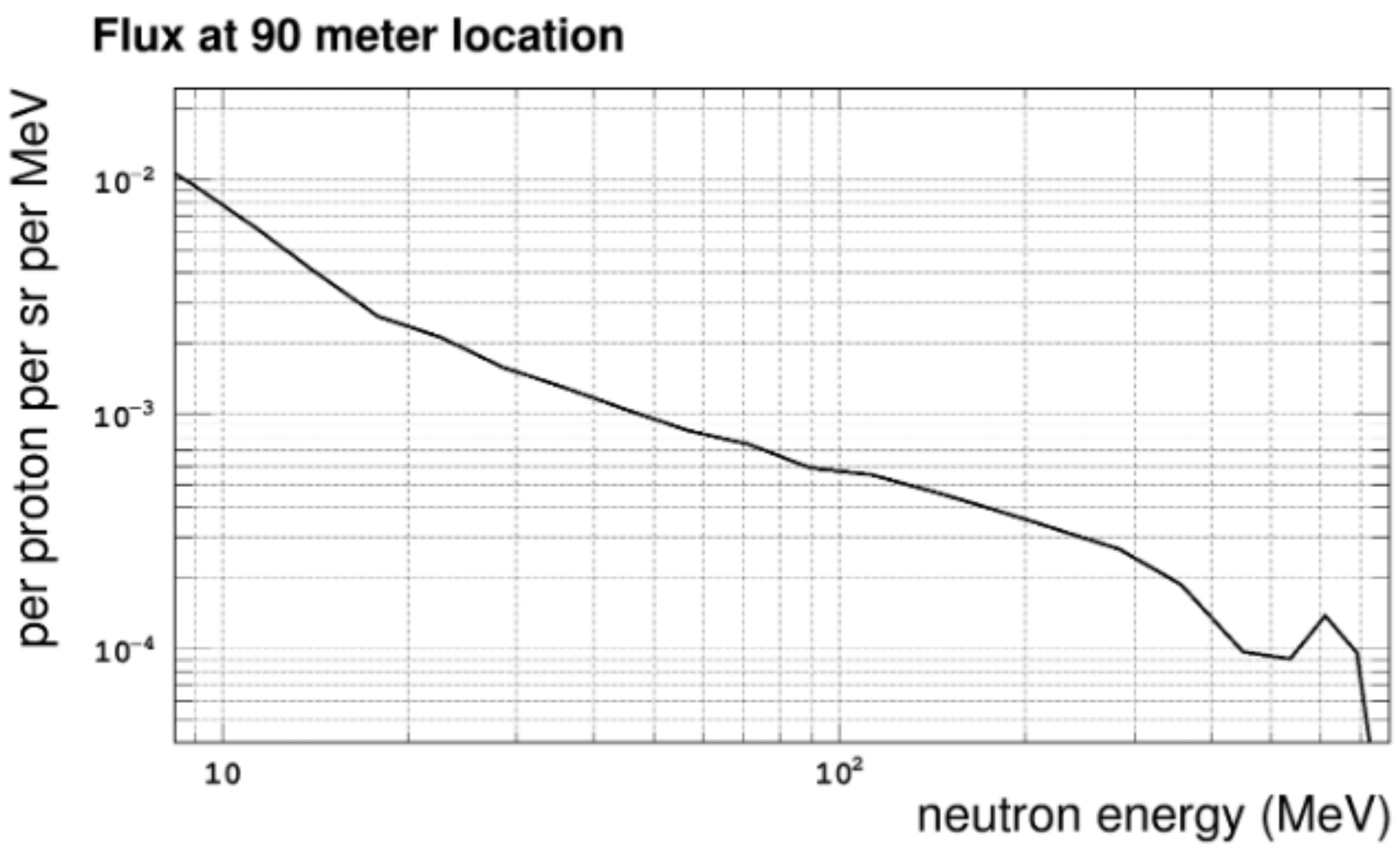
SuperFGD prototype

- Three different types of MPPC used
- Gain calibration
  - LED runs taken at LANL in 2019
  - Gain extracted for each channel and temperature variation included
- Light yield calibration
  - Dedicated cosmic samples selected
  - PE per MeV obtained for each channel
- Light attenuation measured at CERN

Neutron beam facility

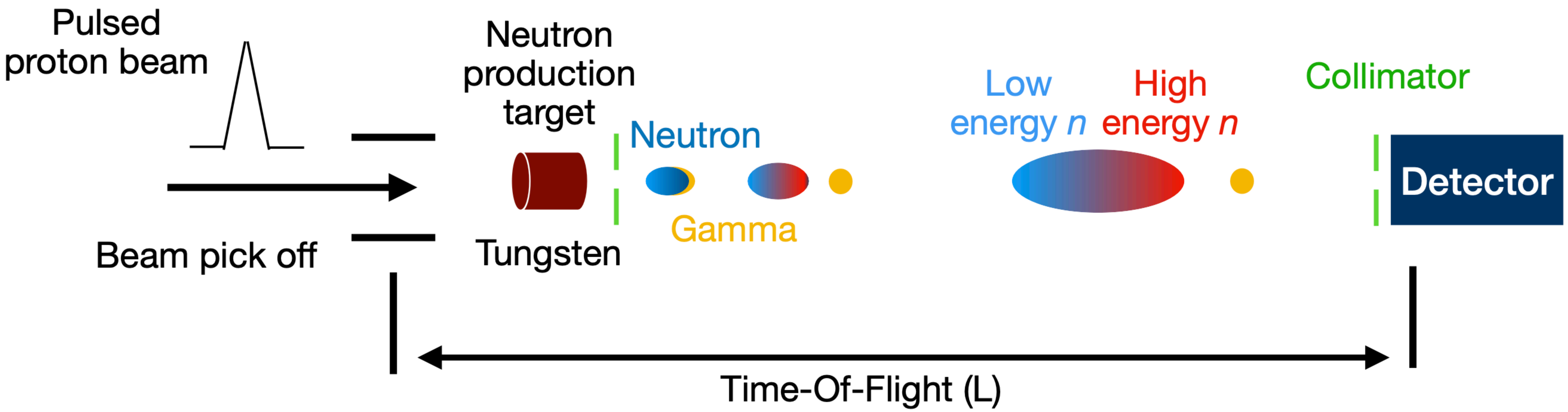
- The Super-FGD prototype was exposed to neutron beam.
- Weapons Neutron Research Facility at LANL provides neutron beam ranging from 0-800 MeV.

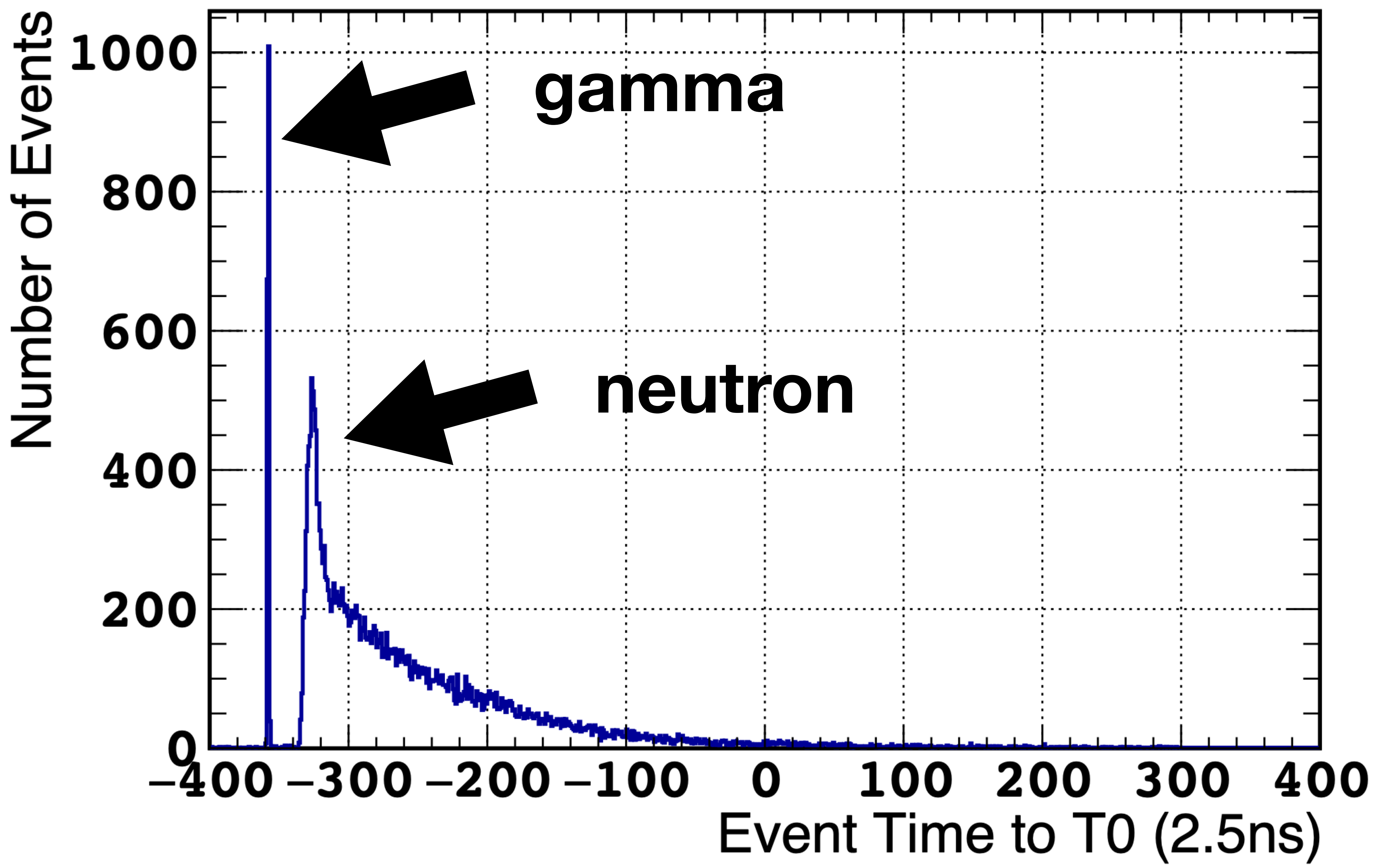




Data was taken at 90 m in 2019

Neutron beam time structure





- When the proton hits the target, it produces photons and neutrons along with other hadrons that are swept away by a magnetic field.
- In each pulse, gamma arrives earlier. It is a kind of a trigger.
- The neutron's kinetic energy is measured by time-of-flight technique.

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A total cross-section measurement

- The total cross section on CH has been extracted using the extinction method:

$$N(z) = N_0 \times \exp(-T\sigma_{total} z)$$

nuclear density — total cross section — depth along the detector layer

- If we measure the attenuation of the event rate as a function of depth in the detector, we can extract the total cross section.
- The attenuation can be measured by choosing a particular event topology.
- We assume that for each layer, the cross-section ratio of particular topologies is constant
- We have chosen events with single reconstructed tracks as topology since it's the cleanest event and simple to select the vertex point.

Event reconstruction

2D hits	3D voxel	clusters
Time cut on hits: the time window defined by gamma flash. PE cut on hits: to reduce noise and cross talk. Number of hits: more then three hits Time clustering hits: to reduce hit pile up	3D view matching of time-clustered hits XY, XZ, YZ 3 hits sharing the same XYZ coordinates Attenuation correction with variable PE cut	Voxel clustering (DBSCAN) is used to group voxels into clusters Any voxels within 1.8 cm ($\sqrt{3}$ cm, the diagonal distance between cubes) of each other are grouped into the same cluster

Single track selection

Cut name	Cut description and value
#clusters	Select events with only one time and spatial cluster
#voxel	3 - 8 voxels in single cluster (reduce dependence on geometric acceptance)
linearity	We performed a PCA with the voxels we extract the variable which we call linearity, to reject short and blob-like tracks.
Max cluster width	Width of the projection of the voxel position on the direction perpendicular to the best fit line < 1.4 cm
3D line-voxel max distance	Max distance between 3D best fit line and voxels in a cluster must be < 1.2 cm
Vertex in FV	Vertex (first voxel in Z) must be in 1.5x1.5 cm^2 FV (build around the beam center)

Systematic uncertainties included

Dominating !

- **Detector**: A geometrical and electronics non-uniformity. Cube misalignment, different MPPC types.
- **Invisible scattering**: Invisible scattering includes elastic scattering as well as any interactions that do not produce visible tracks above the threshold.
- **Geometric acceptance**: Due to the limited detector size, less ability to distinguish between the single-track and multi-track events in the downstream part of the detector.
- **Light yield**: Light yield variation for each channel is essentially the non-uniformity of the detector material.
- **Time resolution**: The finite timing resolution results in an uncertainty on the neutron ToF and consequently its reconstructed kinetic energy.
- **Collimator interaction**: If the neutron interacts with the upstream collimator before entering the detector, it will lose energy.

Error propagation

- Time resolution and the uncertainty due to the collimator interactions change the energy distribution (shape-like systematics), and all the others change the normalization (#event in each z-layer).

- The systematics that change the number of events in each z-layer are propagated in the following way:
  - Fit with the $N_0 \times \exp(-T\sigma_{total}z)$ distribution obtained after every gaussian variation of the number of events in every z-layer and energy bin
  - Fill a histogram with every value of the cross section
  - The systematic uncertainty is the RMS of this distribution.

- The total systematic uncertainty is the sum in quadrature of the individual uncertainties.

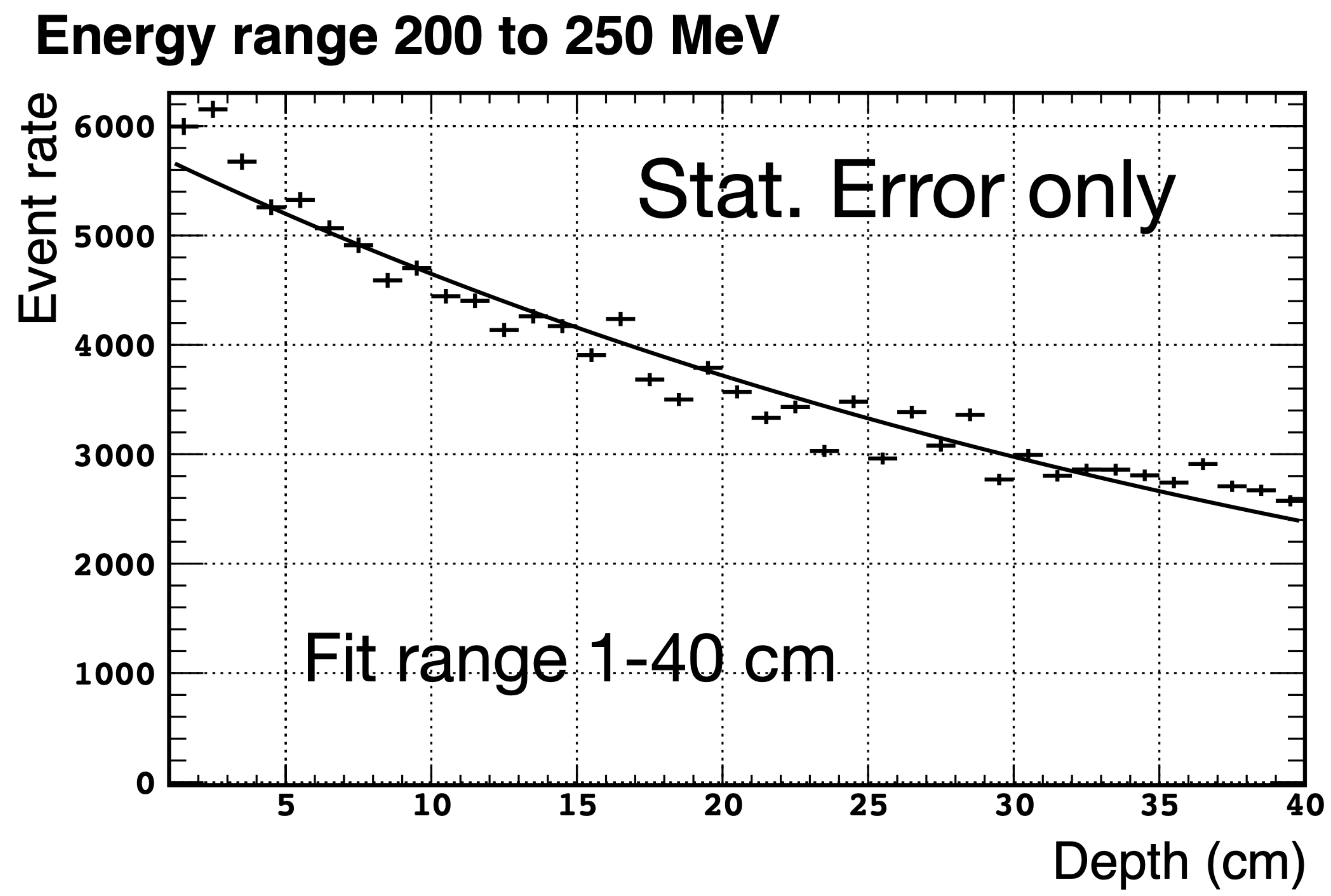
- Statistical uncertainty is given by the square root of the number of events in the z-layer.

- for each energy bin the measurement is effectively independent and systematic uncertainties are considered uncorrelated across energy bins.

Neutron cross section

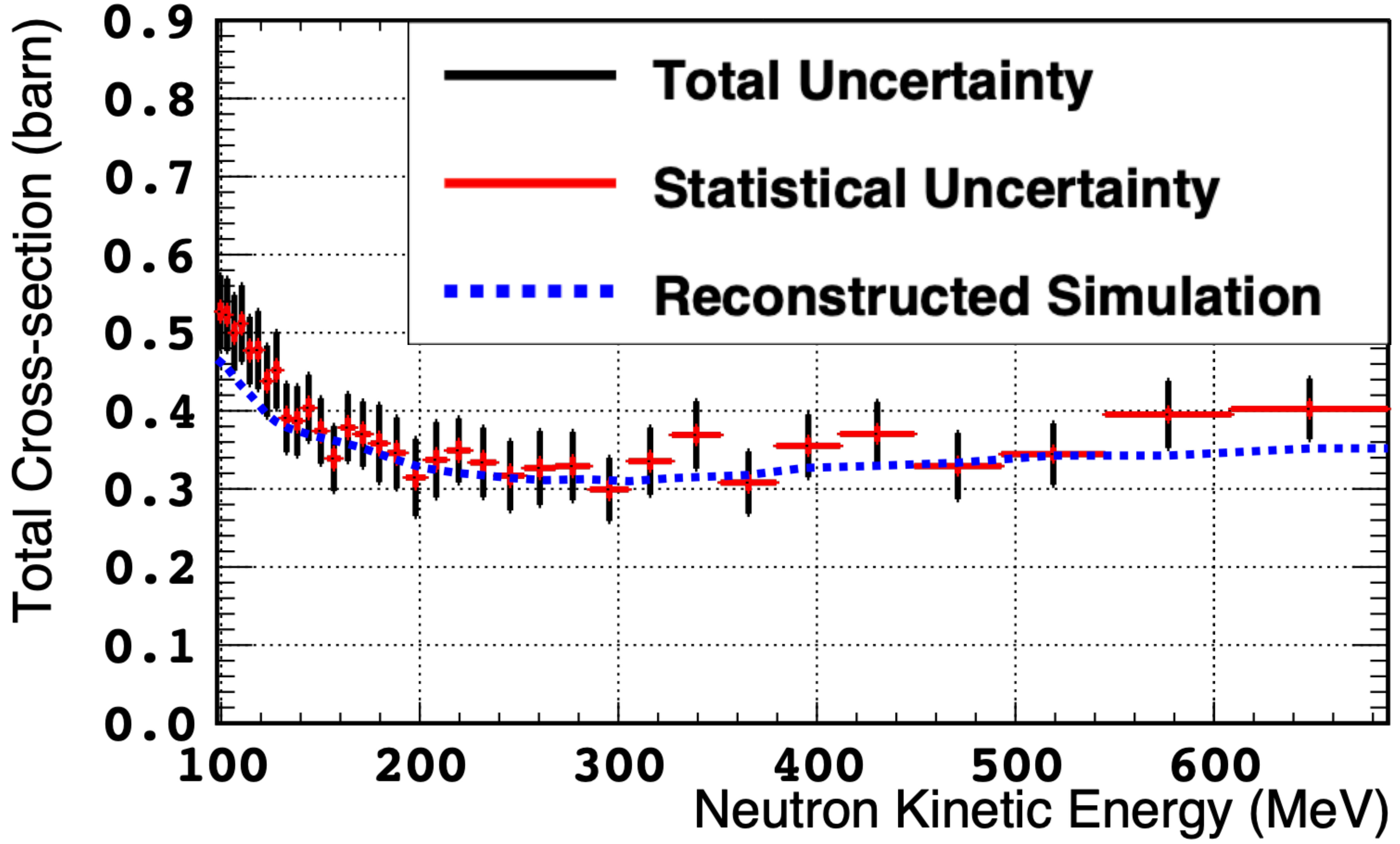
- Neutron-CH total cross section from 98 MeV to 688 MeV
  - Below 98 MeV tracks are not long enough, and invisible scattering uncertainty will be larger.
  - Above 688 MeV gammas dominates and less statistics.

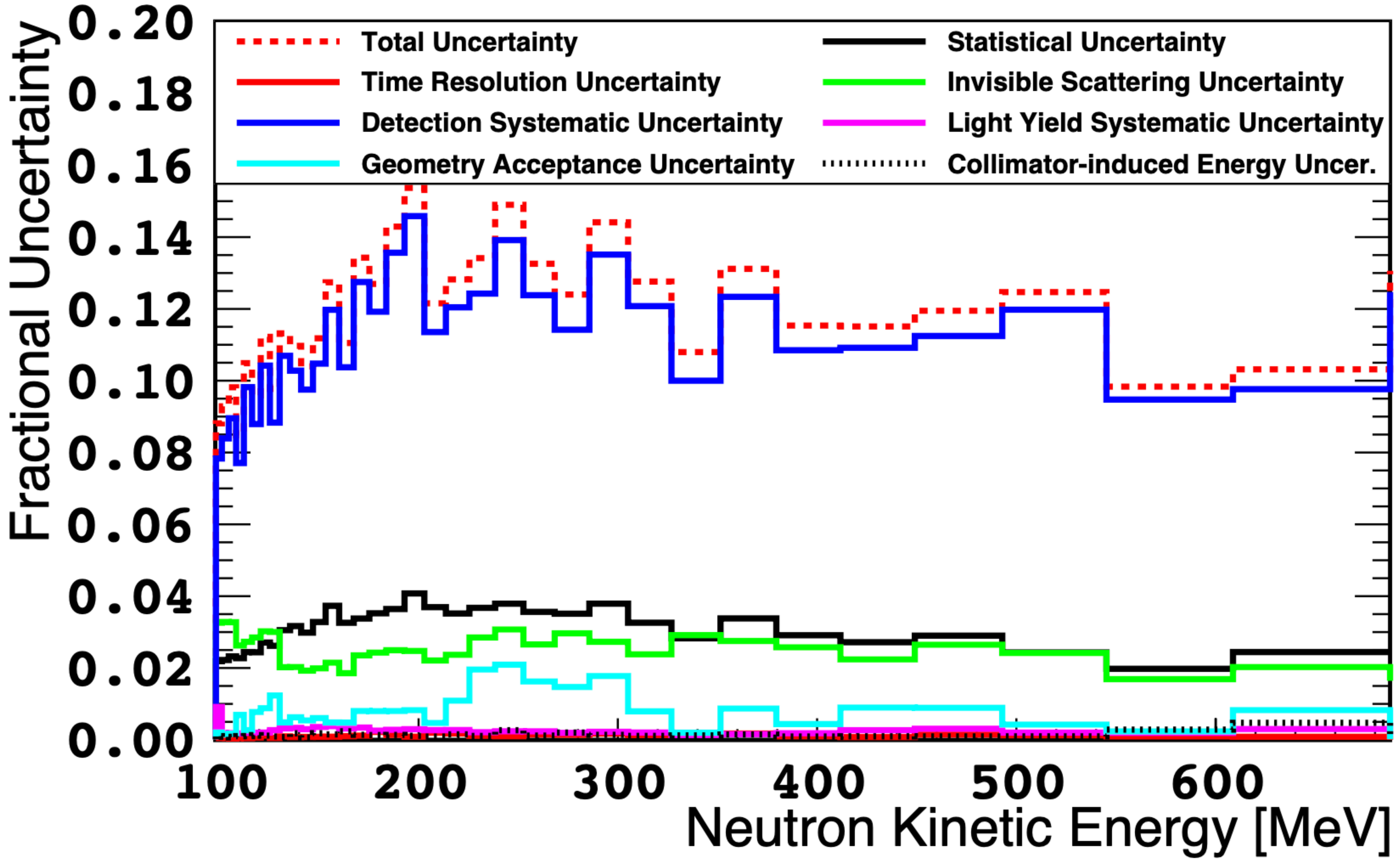
- Fitting an exponential function to the Z layer distribution for each energy range (optimized considering the time resolution).



- The fit range is 1-40cm:
  - The first z layer is rejected to reject particles from interactions in the upstream material and collimator.
  - The last eight layers are rejected to reduce the geometric acceptance uncertainty.

Total cross section result





Total of 20h of data was analyzed. The selected rate is about 4e6 events (total interactions are about 6e7 and efficiency is about 7%)

The energy-integrated (98-688 MeV) cross section is 0.36 ± 0.05 barn with a $\chi2$/d.o.f. of 22.03/38

Summary

- Not only tagging, SuperFGD can measure neutron kinematics.
- A total n-CH cross-section measurement has been completed, and it demonstrates SuperFGD is capable of detecting neutron kinematics: arXiv:2207.02685 [physics.ins-det]
- Additional data have been collected with SuperFGD and another prototype (US-Japan prototype) in 2020, and analysis of them will continue:
  - Exclusive n-CH cross-section measurements such as proton production and pion production
  - Neutron elastic and inelastic scattering fraction study
  - Exclusive neutron detection efficiencies for different topologies as a function of the neutron energy

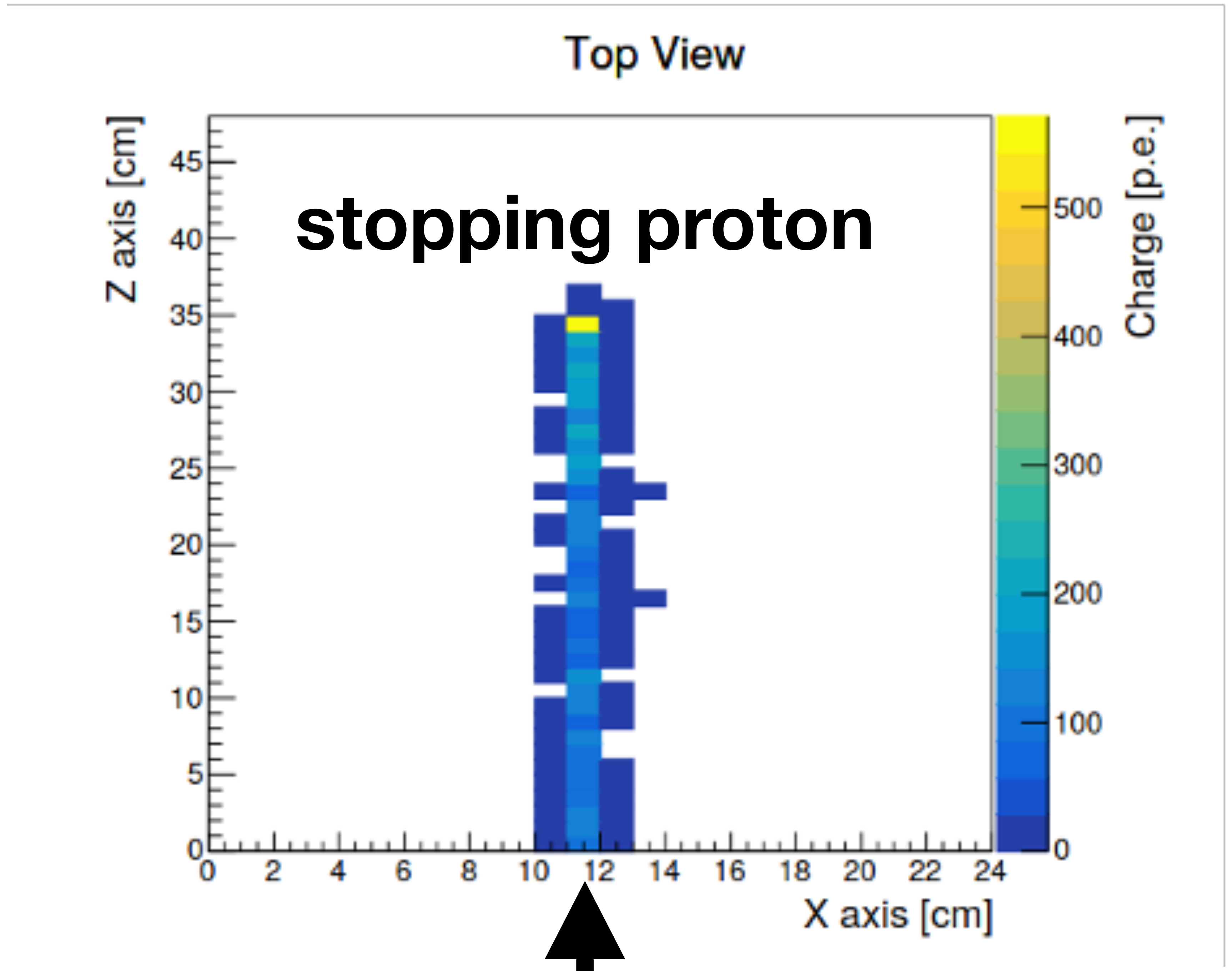
3D-Projection Scintillator R&D group

CERN
Chung-Ang University, South Korea
ETH Zurich, Switzerland
University of Geneva, Switzerland
High Energy Accelerator Research Organization (KEK), Japan
IFAE (Spain)
Imperial College, UK
Institute for Nuclear Research (INR), Russia
University of Kyoto, Japan
Louisiana State University, USA
University of Pennsylvania, USA
University of Pittsburgh, USA
University of Rochester, USA
South Dakota School of Mines and Technology, USA
Stony Brook University, USA
University of Tokyo, Japan

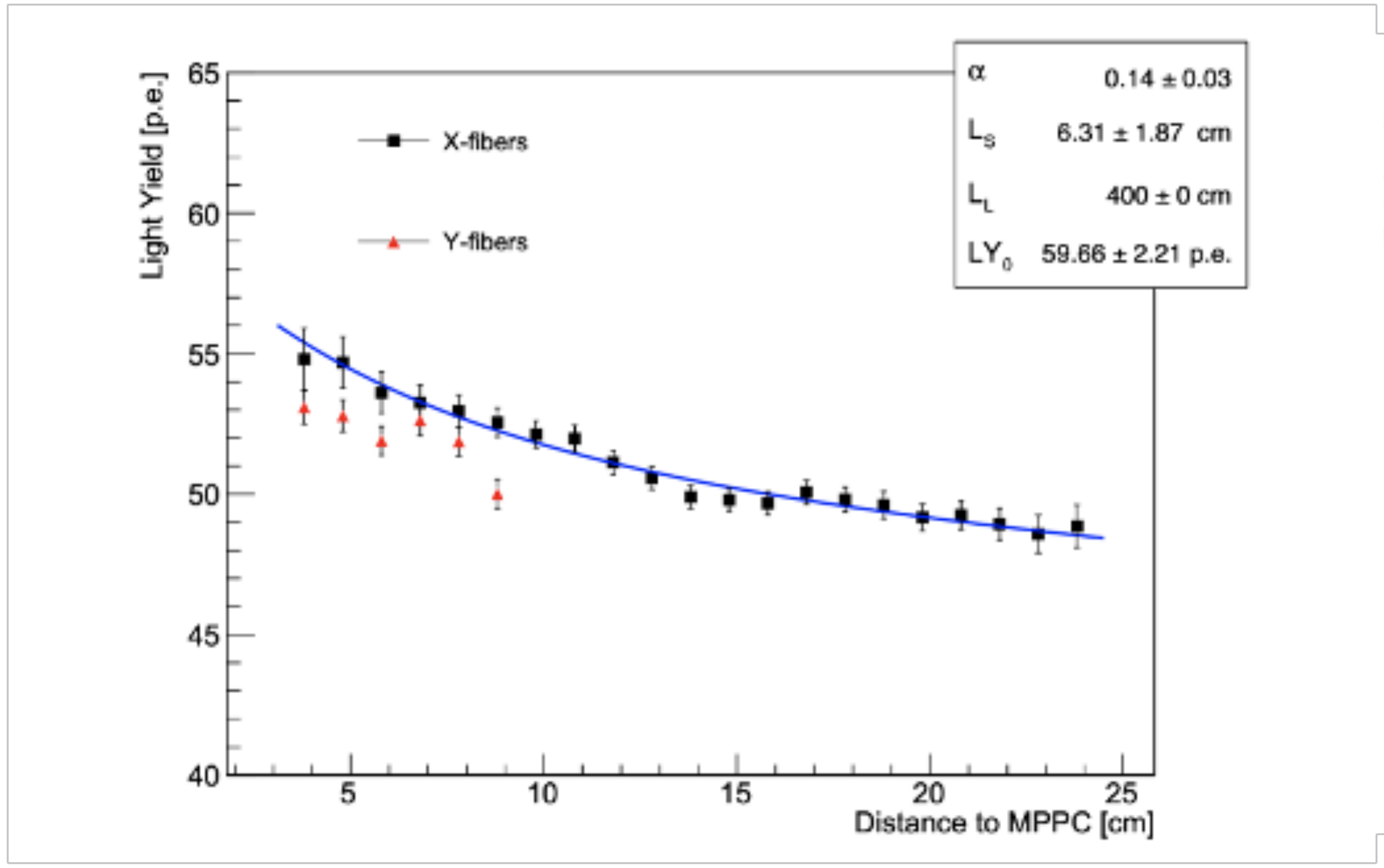
Back up

SuperFGD prototype at CERN charged beam facility

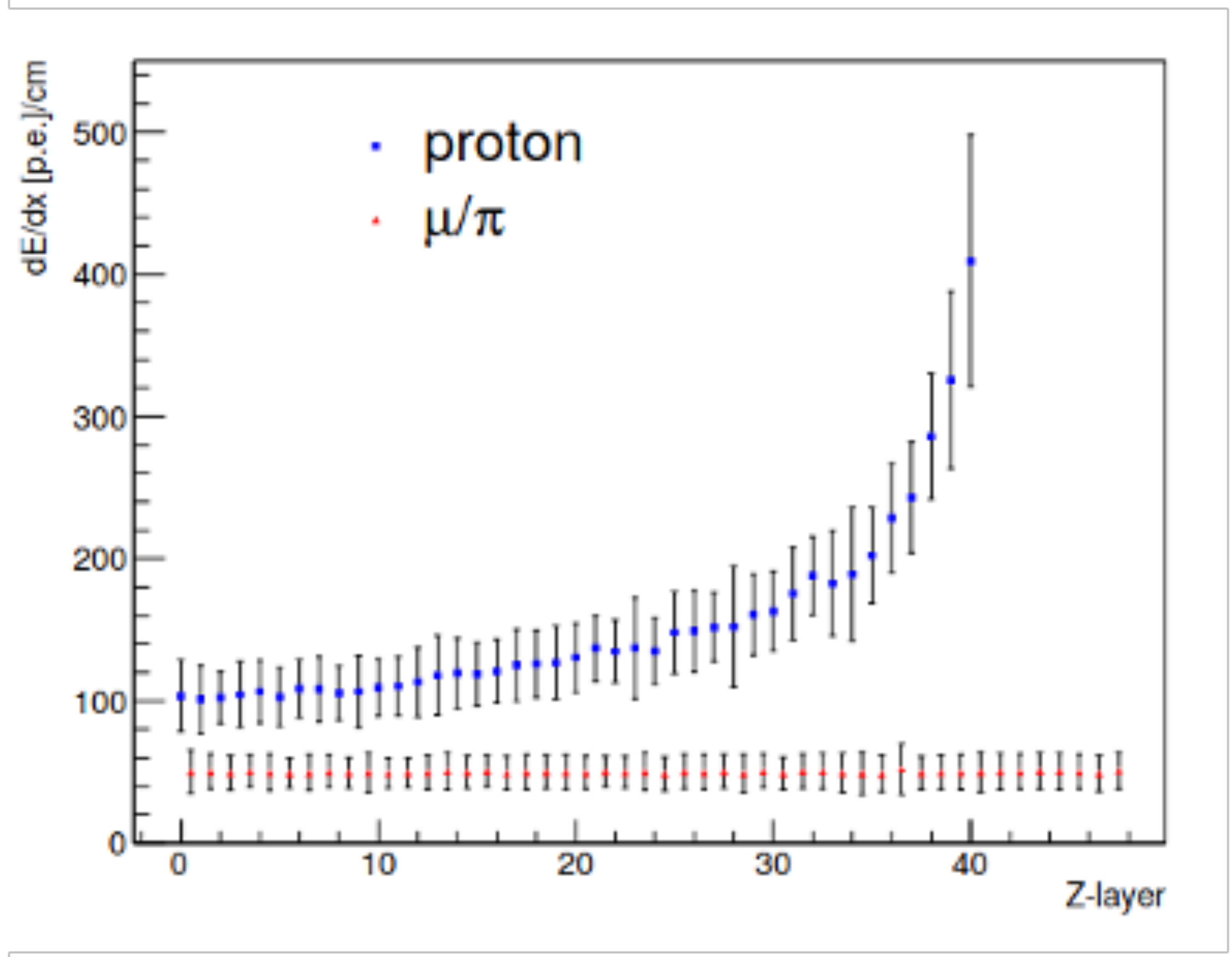
- A thorough understanding of the detector response to charged particles such as proton, muon, pion, gamma conversion: JINST 15 (2020) 12, P12003



beam direction



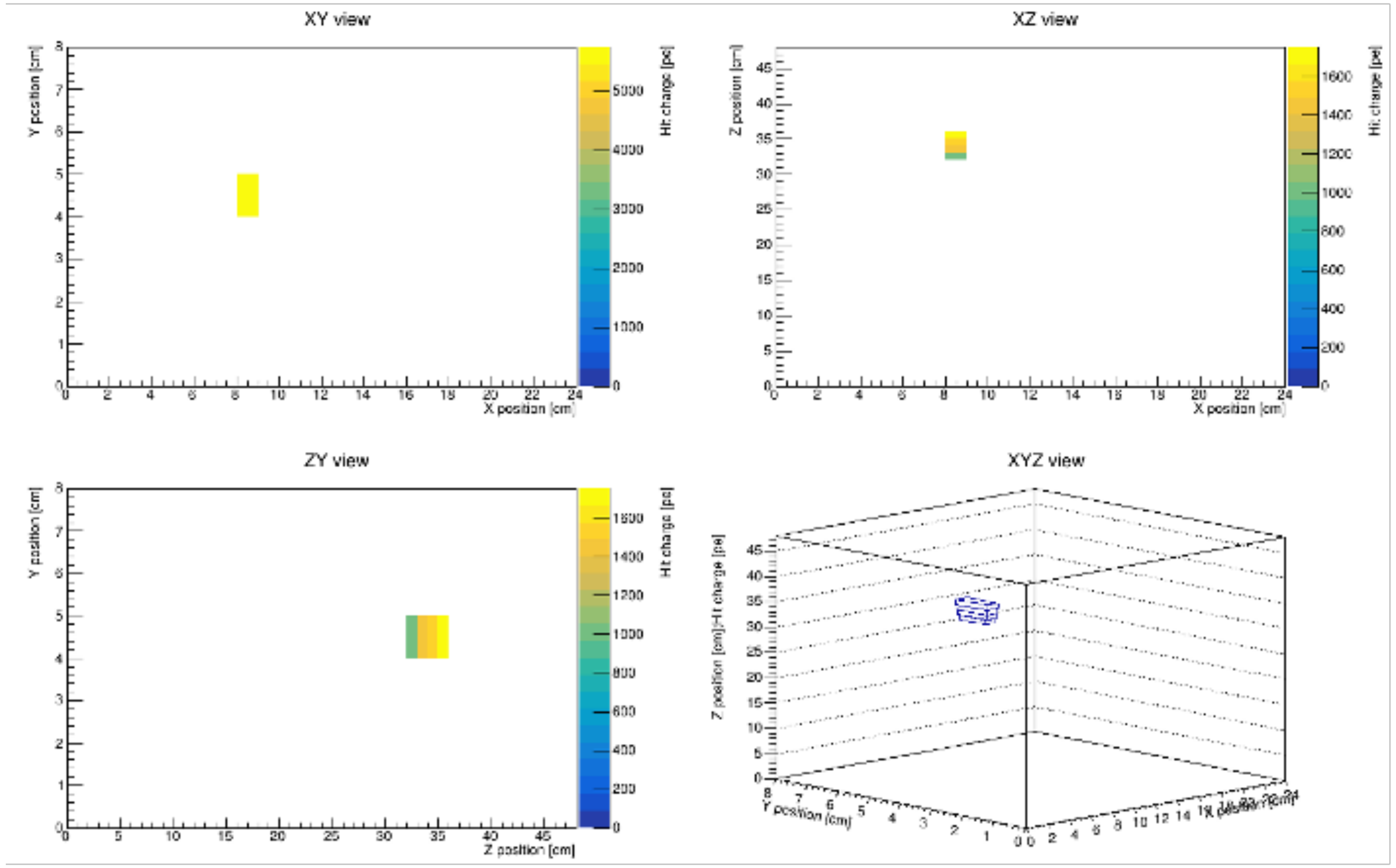
Light yield and attenuation



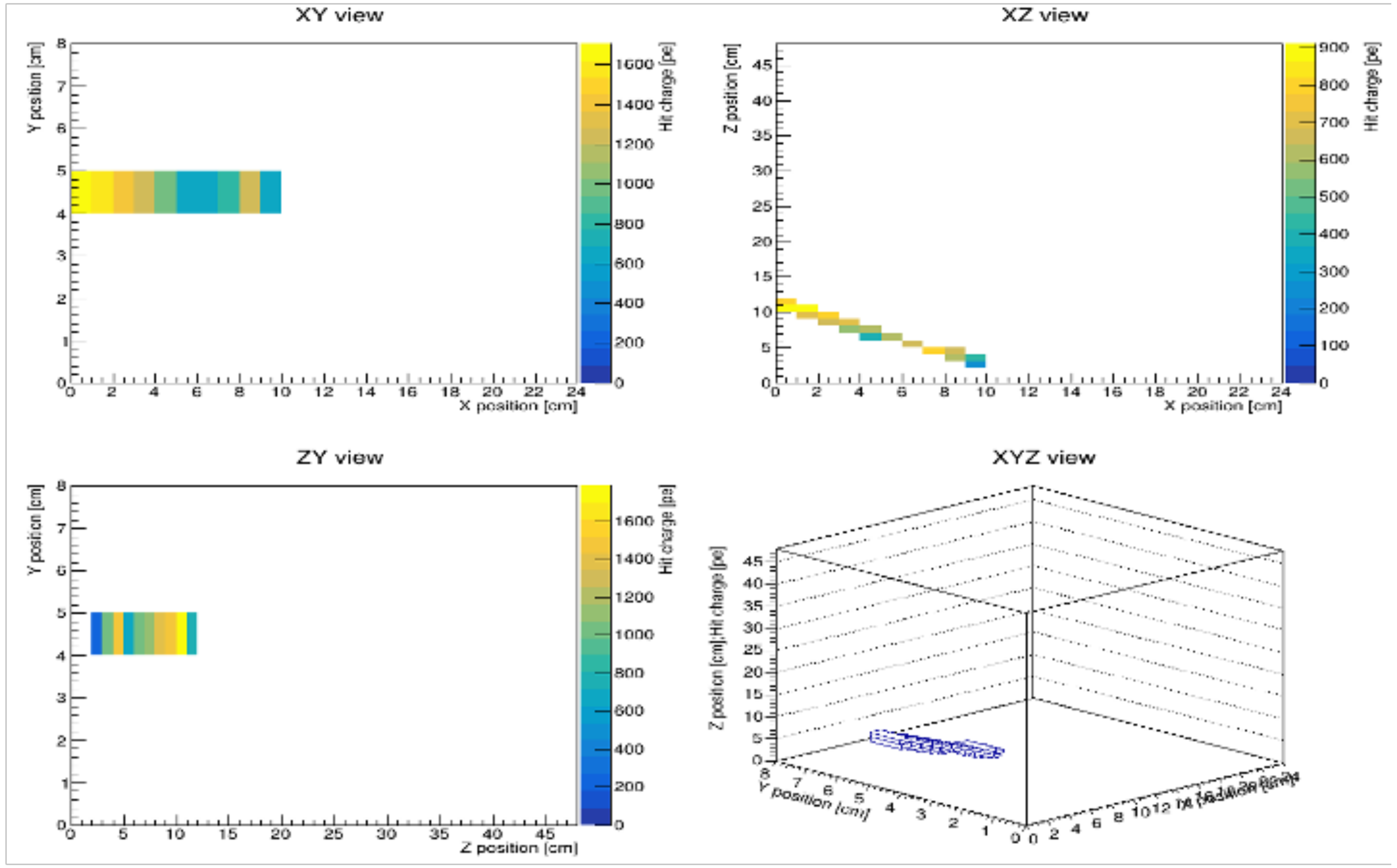
PID

Individual neutron events

65 MeV neutron with 60 MeV deposit energy



193 MeV neutron candidate with 123 MeV deposit energy



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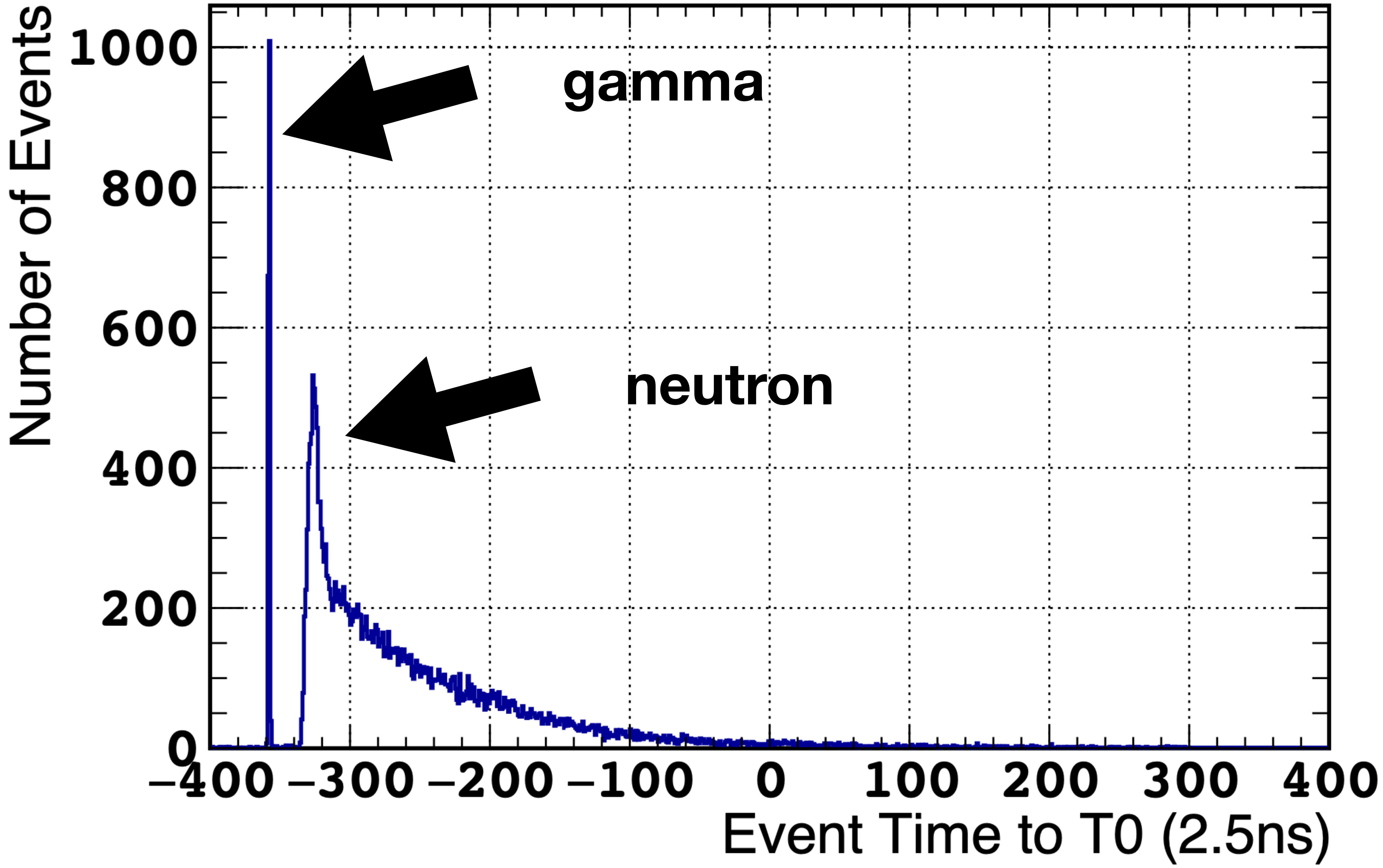
Neutron beam time structure



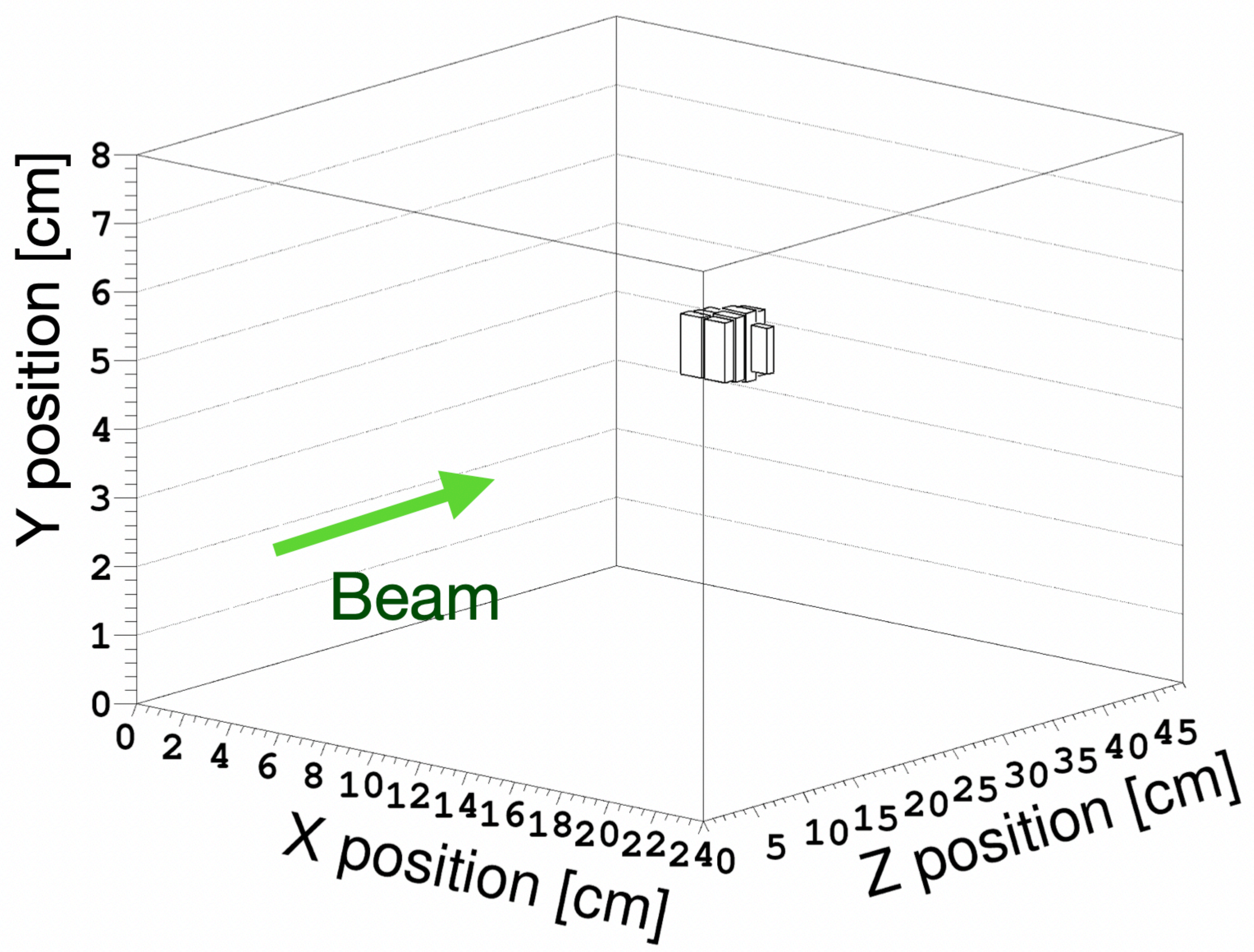
- The t_0 is the received proton bunch trigger time. The signal transit time in the cable is included.
- 2.5ns is the sampling rate of the electronics (CITIROC ASICs in the Baby MIND experiment) that we used for this prototype.

Attenuation correction with variable PE cut

- The neutron beam is not perfectly aligned; It has a small angle.
- The particle traveling through different cubes has different travel lengths, especially for the first and last cubes.

Linearity

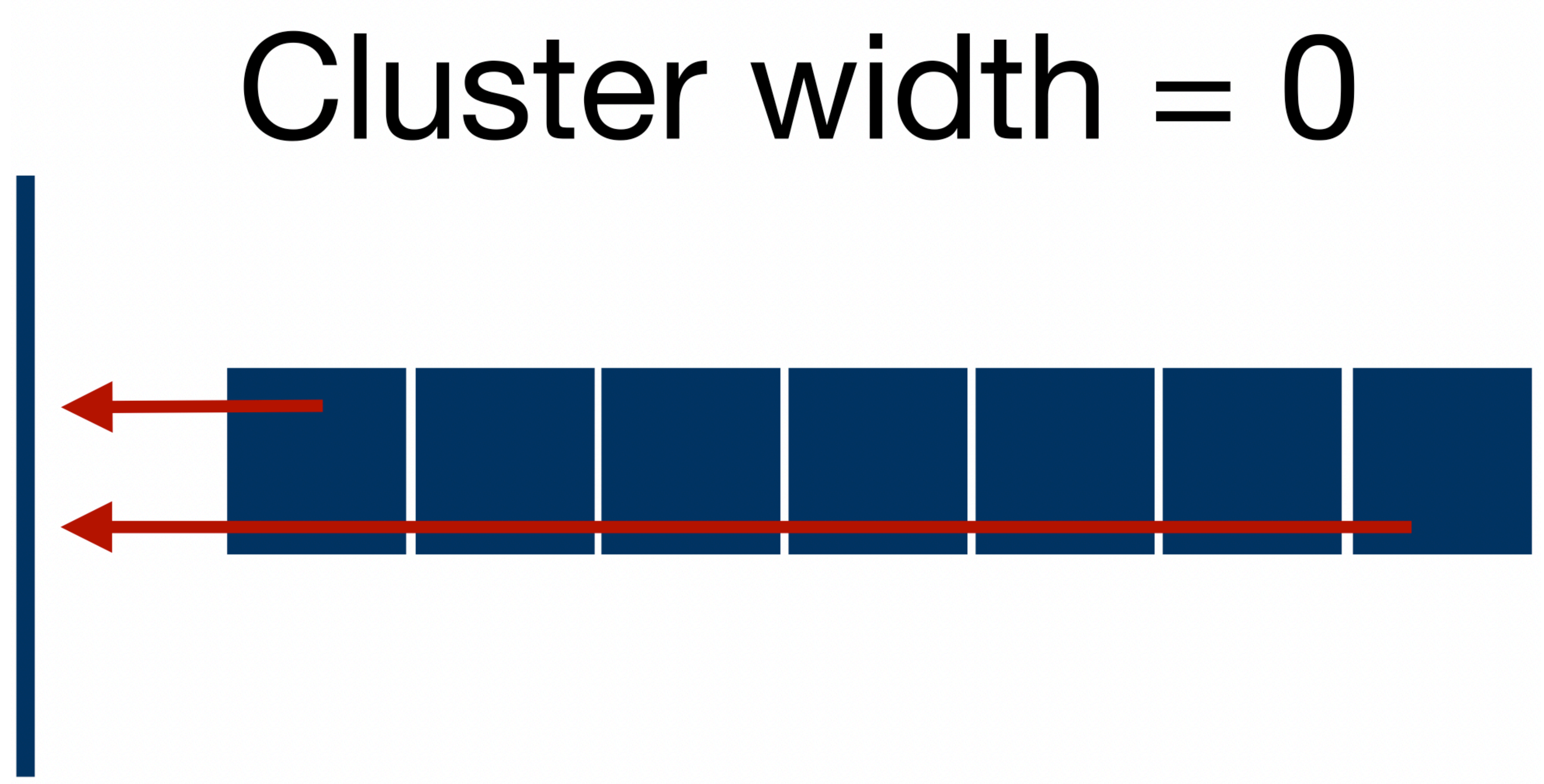
- For each cluster, a matrix that encodes the distance between each voxel and the center of the cluster is defined as: $M_{ij} = \Sigma \frac{(\vec{v} - \vec{c})_i (\vec{v} - \vec{c})_j}{N}$
- A PCA of this matrix is performed.
- The following quantity can be extracted $L = (\lambda_1 - \lambda_2)/\lambda_1$ where λ_i are the eigenvector of the matrix M_{ij}.
- If L is lower than 0.7 the event is rejected.
- Recject blob-like events.

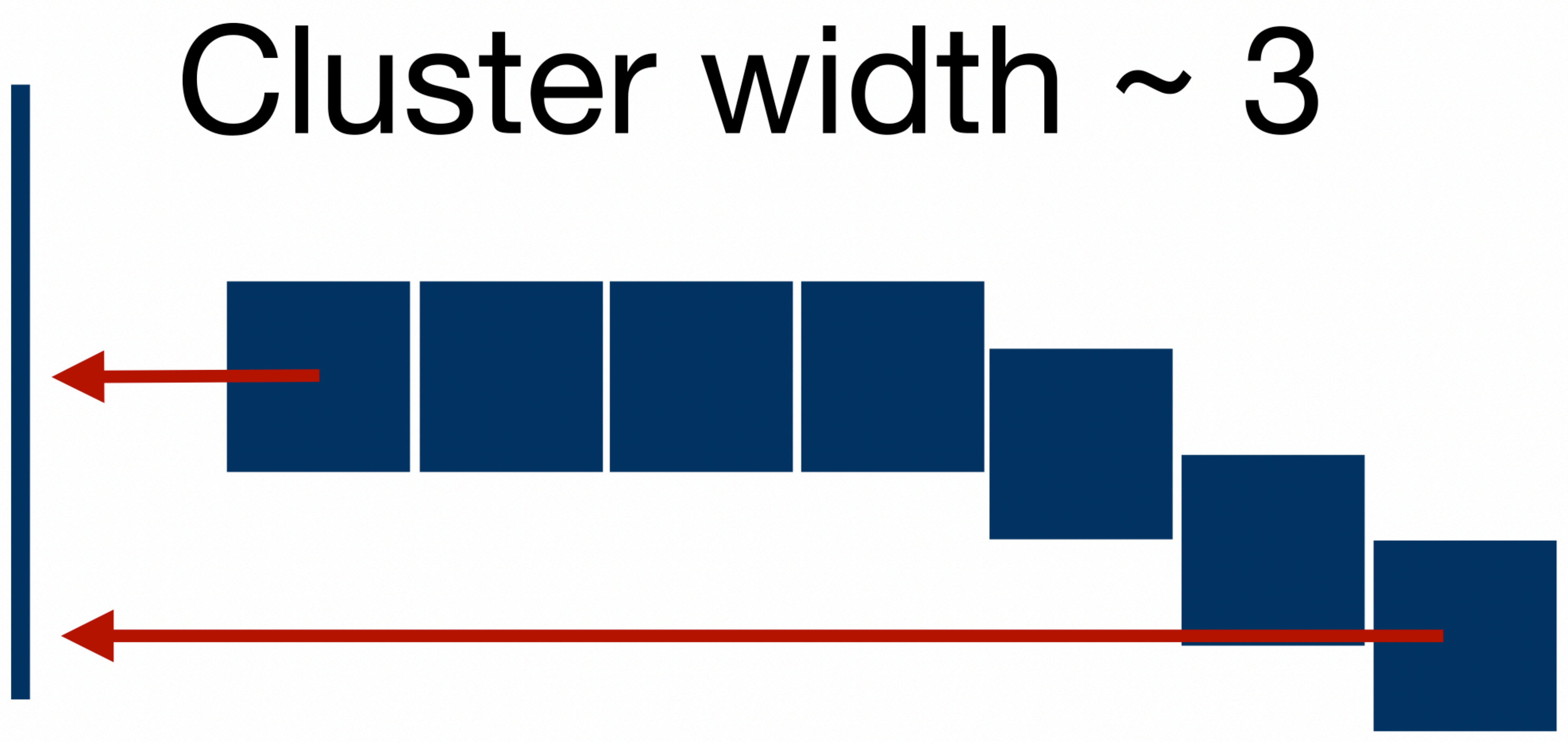


Max cluster width

- To improve track-like events selection, we compute the following quantity: $d_i = \overrightarrow{e}_2 \cdot (\overrightarrow{v}_i - \overrightarrow{c})$ which is the projected distance between one voxel and the center of mass of the cluster on the second principle vector.

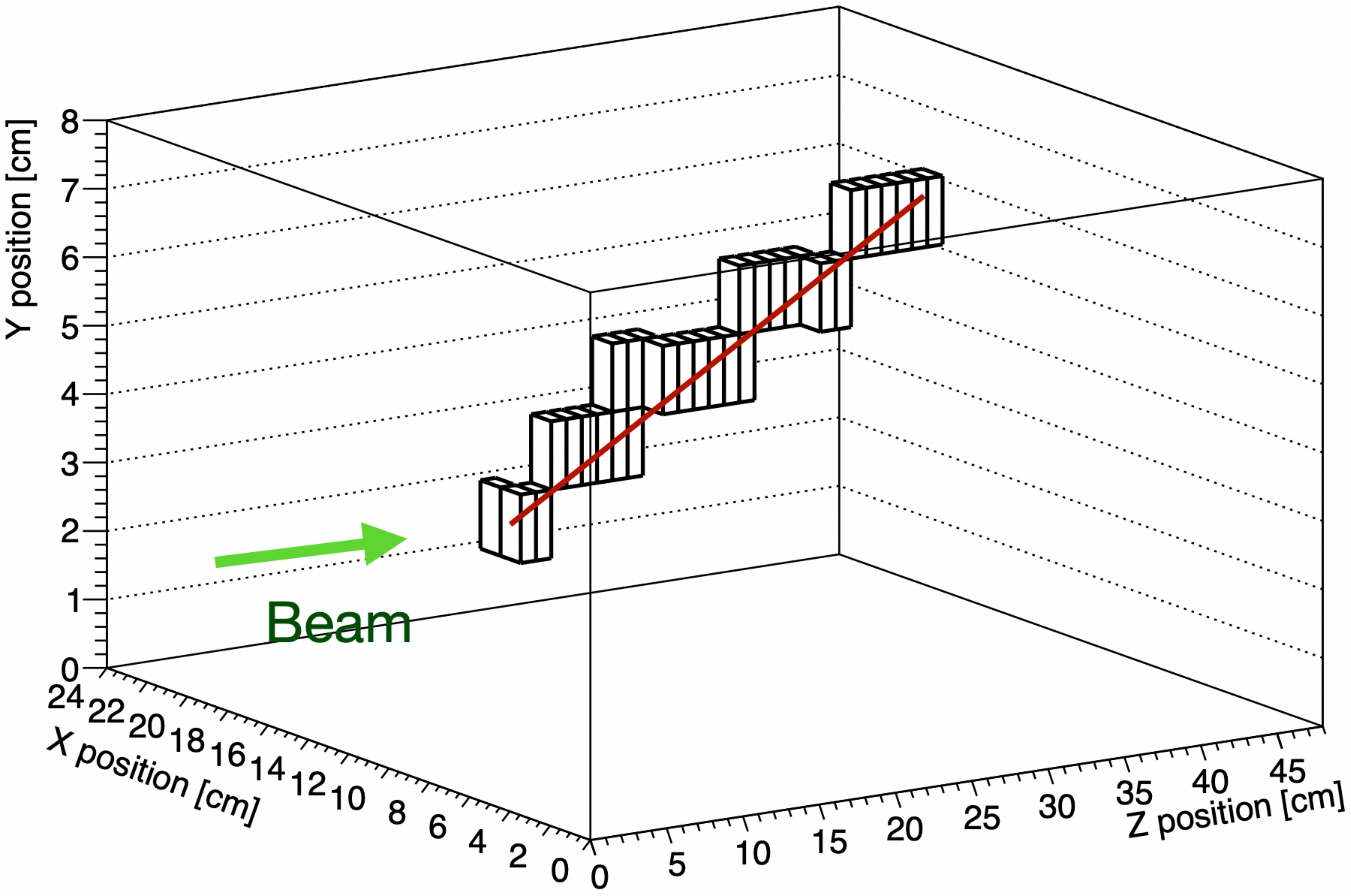
- We calculate the distance between the 2 voxels furthest away from each other $d = d_{max} - d_{min}$, and this must be lower than 1.4 cm.





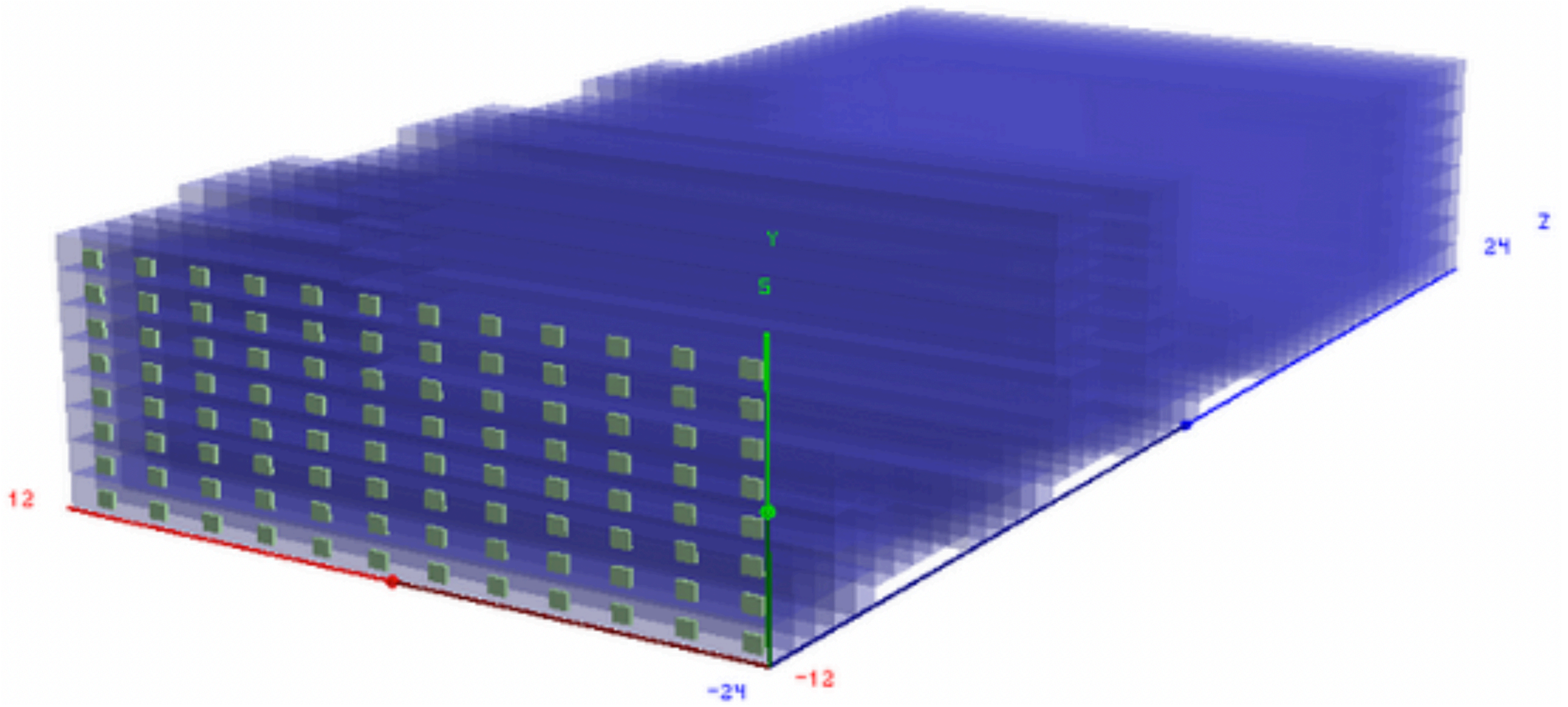
3D line-voxel max distance

- The principal vector of a cluster represents the direction of 3D line with origin in first voxel in z of the cluster (red line in figure)
- Compute the distance between the voxel and the best fit line
- If the maximum distance is larger than 1.2 cm the event is rejected.
- Helps to reject tracks with kinks

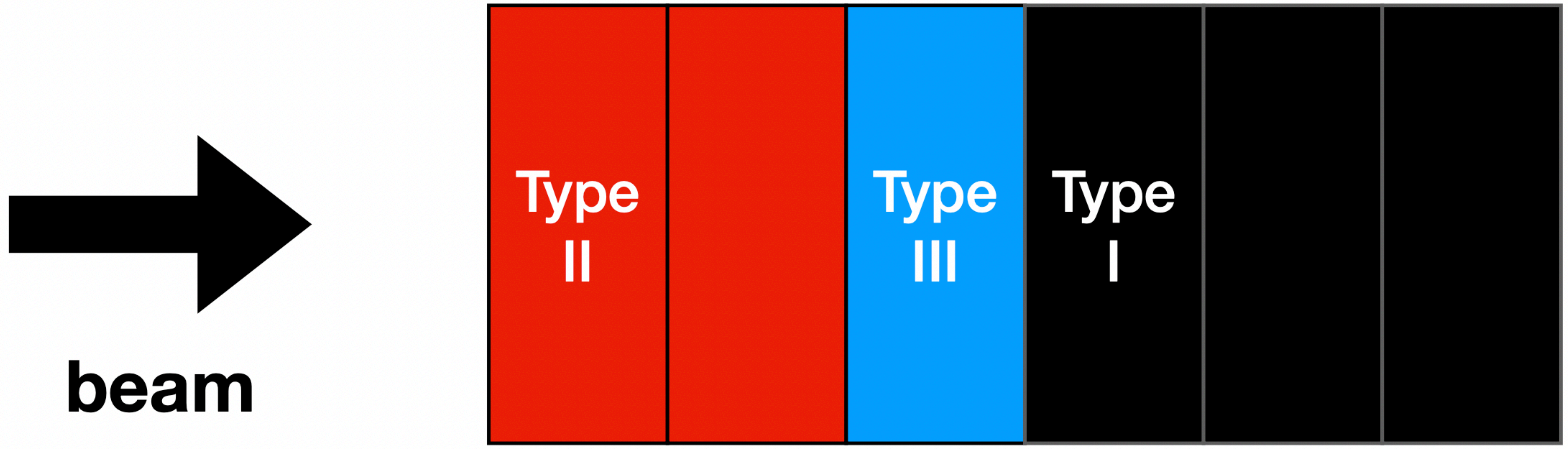


Detector systematic

- Cube misalignment:



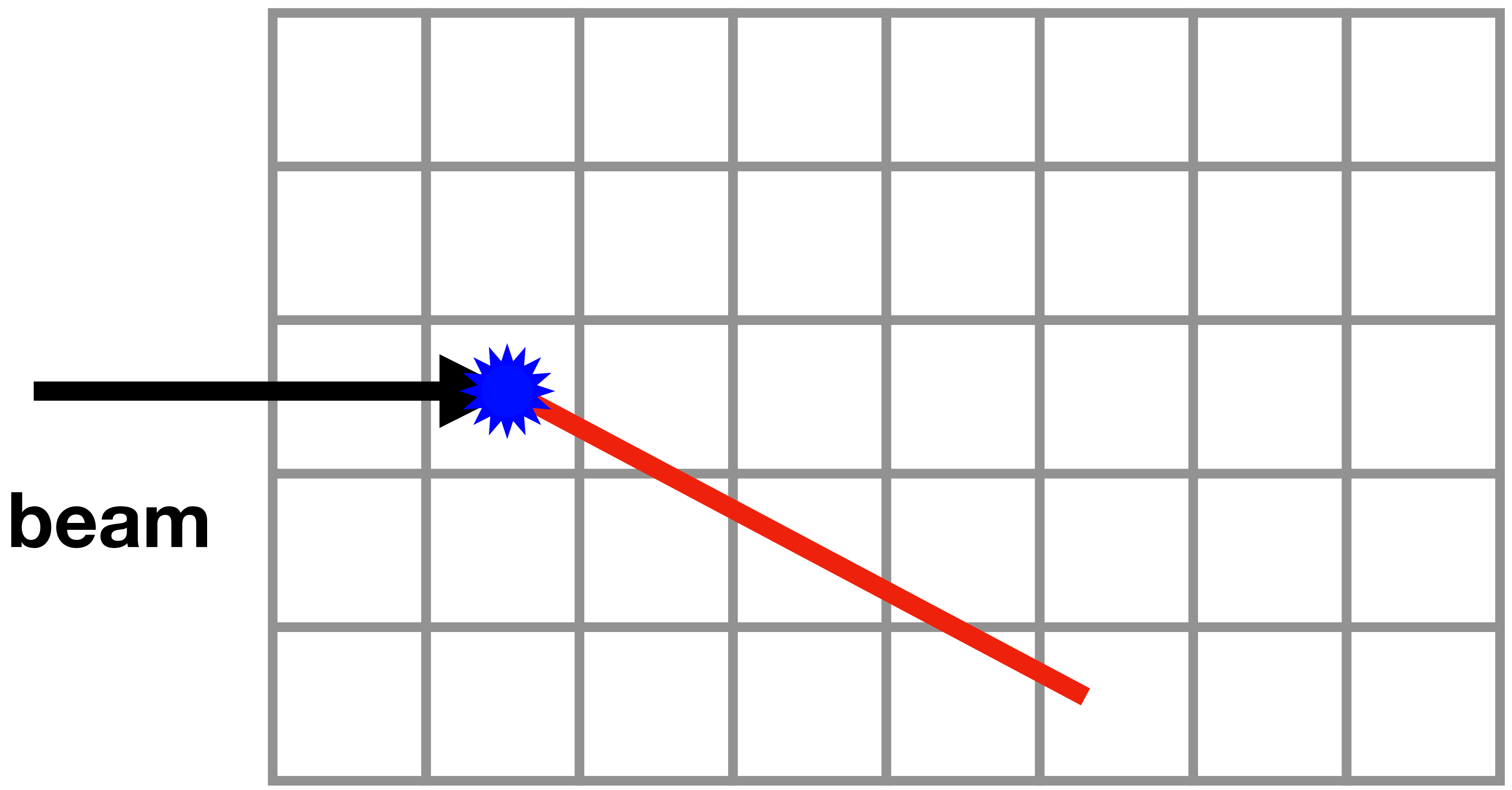
- Different MPPC types: relatively small compared to the cube misalignment.

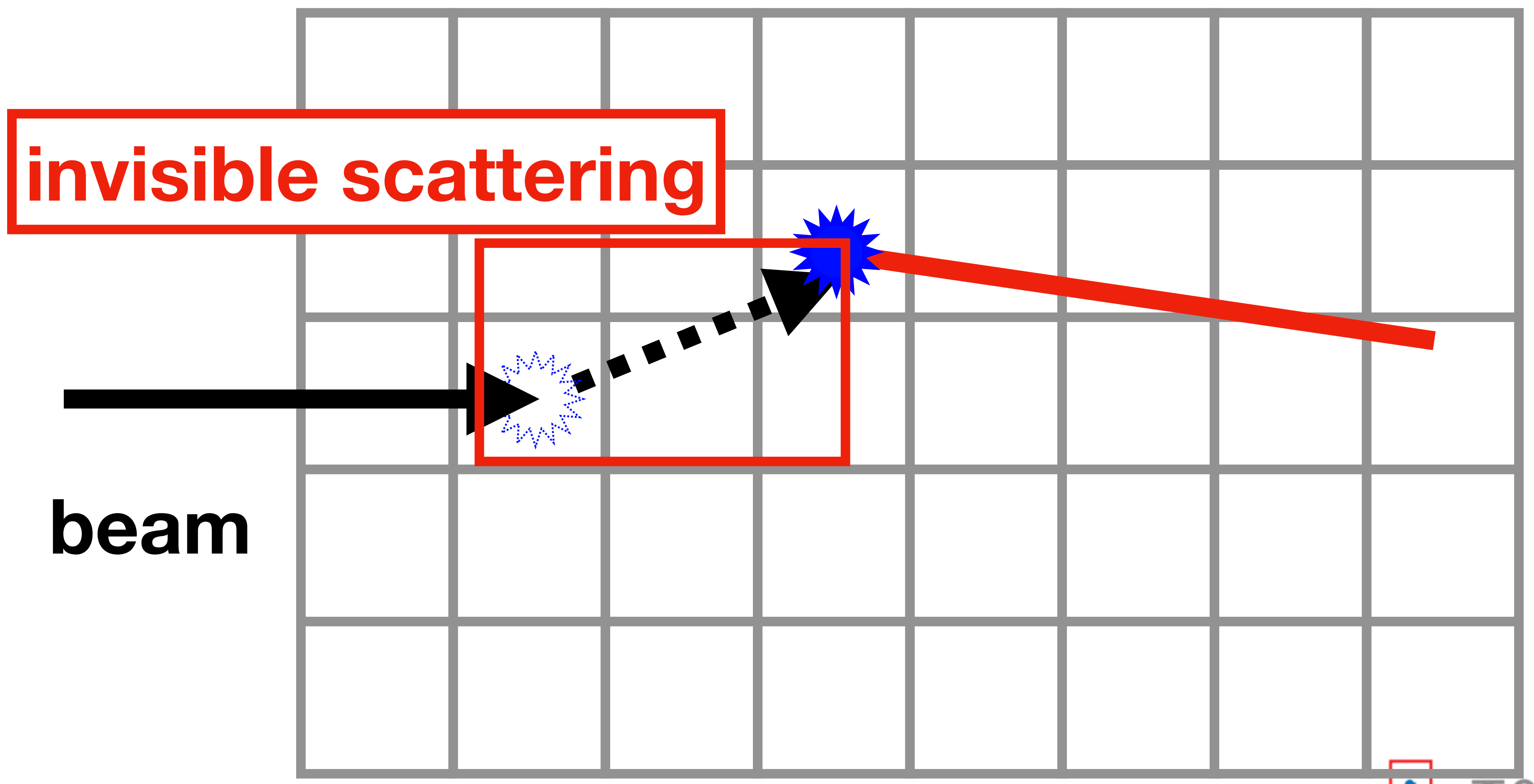


Description	Type I	Type II	Type III
Manufacturer ref.	S13360-1325CS	S13081-050CS	S12571-025C
No. in Prototype	1152	384	192
Pixel pitch [μm]	25	50	25
Number of pixels	2668	667	1600
Active area [mm^2]	1.3×1.3	1.3×1.3	1.0×1.0
Operating voltage [V]	56–58	53–55	67–68
Photon detection eff. [%]	25	35	35
Dark count rate [kHz]	70	90	100
Gain	7×10^5	1.5×10^6	5.15×10^5
Crosstalk probability [%]	1	1	10

Invisible scattering

- We conservatively assumed all of the transverse spread comes from invisible scattering, tuned the simulations to match the spread seen in data, and calculated the change in the reconstructed neutron cross section.
- The impact of the invisible scattering with our conservative assumption is as large as 10% below 100 MeV but limited to a few percent above 100 MeV.
- The difference between the cross section results with and without the invisible scattering is taken as a systematic uncertainty.

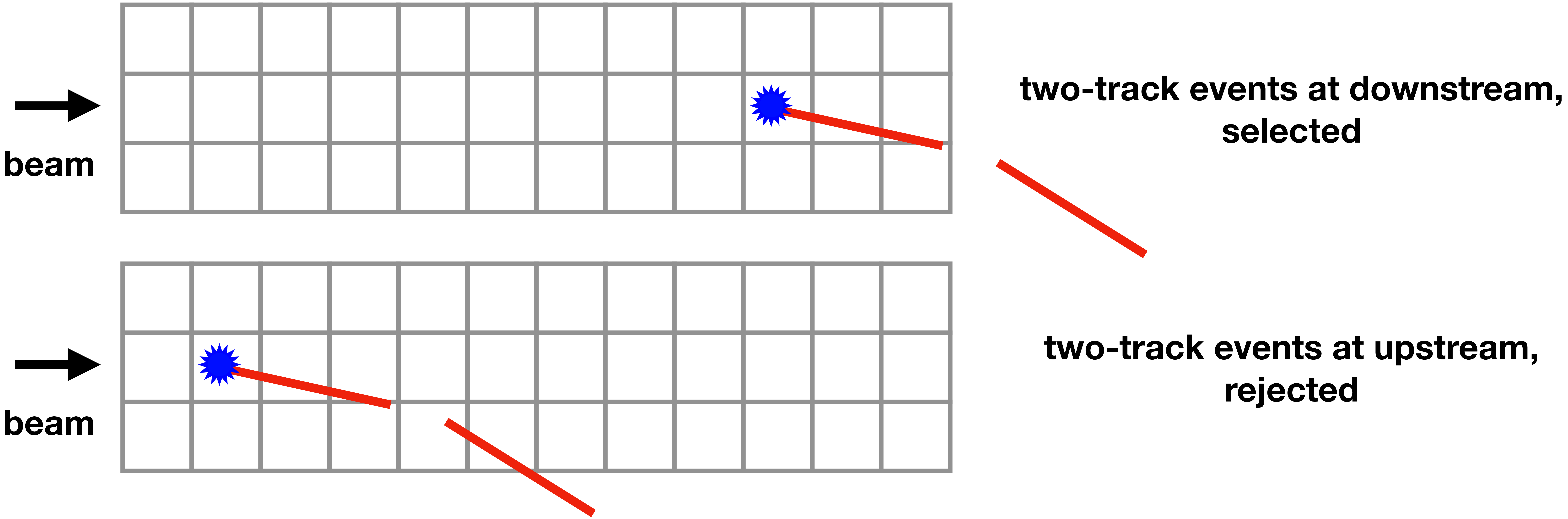




Geometric acceptance

- The same topology may have different selection acceptance depending its z location.

example) two-track events



Light yield

- In order to evaluate the light yield variation, for each channel, the light yield fluctuation estimated by the cosmic muon track fitting is propagated through the reconstruction with a simulated neutron interaction sample, providing the uncertainty on the vertex location induced by light yield fluctuations.