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

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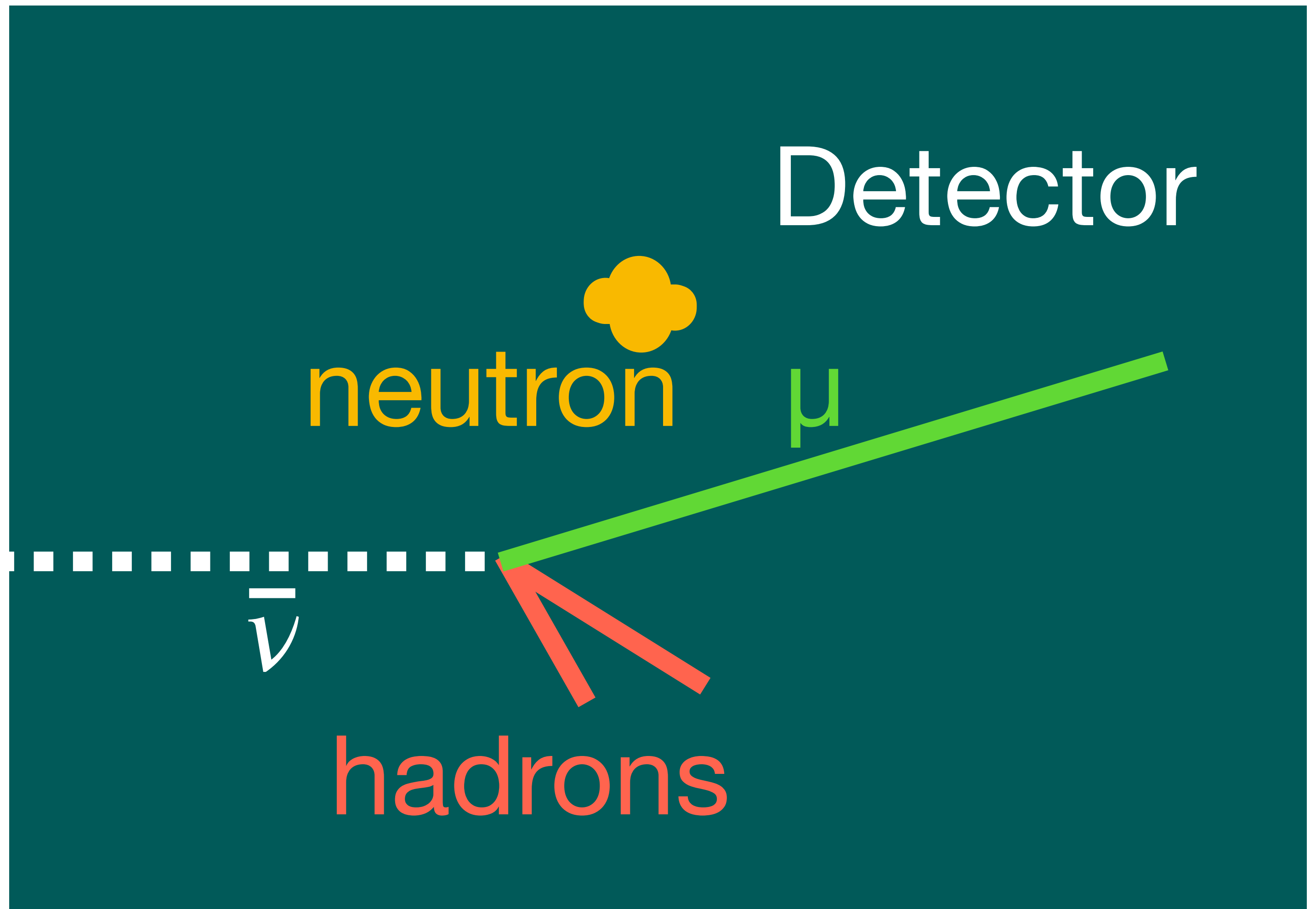
Motivations

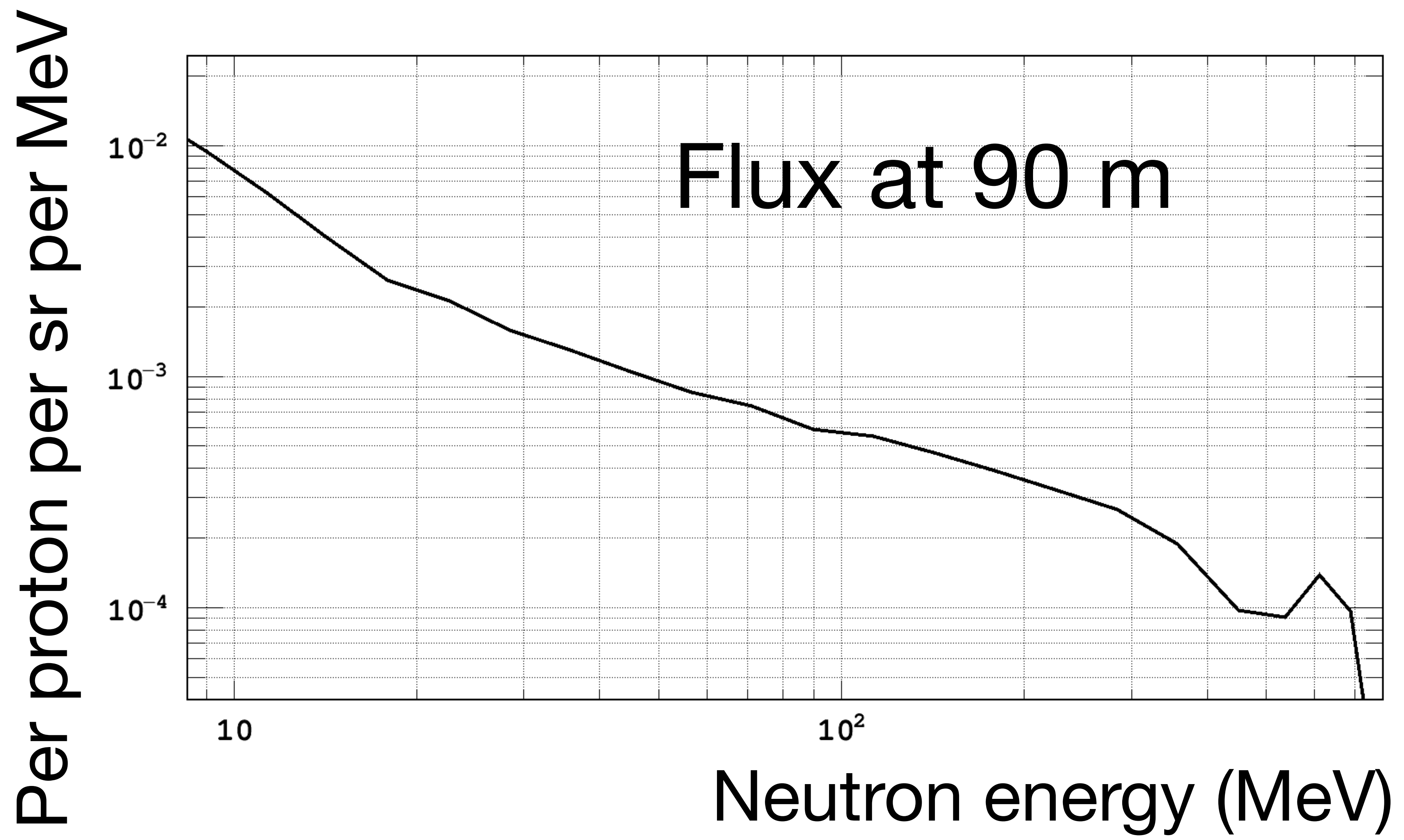
- A novel 3D-projection scintillator detector, called SuperFGD, will be the tracker of the upgraded near detector of T2K (see Aoi Eguchi's talk)
- Neutron detection and kinematic reconstruction among the different improvements it promises
  - Neutron kinematics is one of missing piece for (anti)neutrino energy reconstruction but not accessible to current LBL detectors
  - High precision needed in future LBL experiments and measuring neutron kinematics helps in this direction
- Neutron detection and kinematic reconstruction capabilities were studied exposing a prototype to a neutron beam at LANL

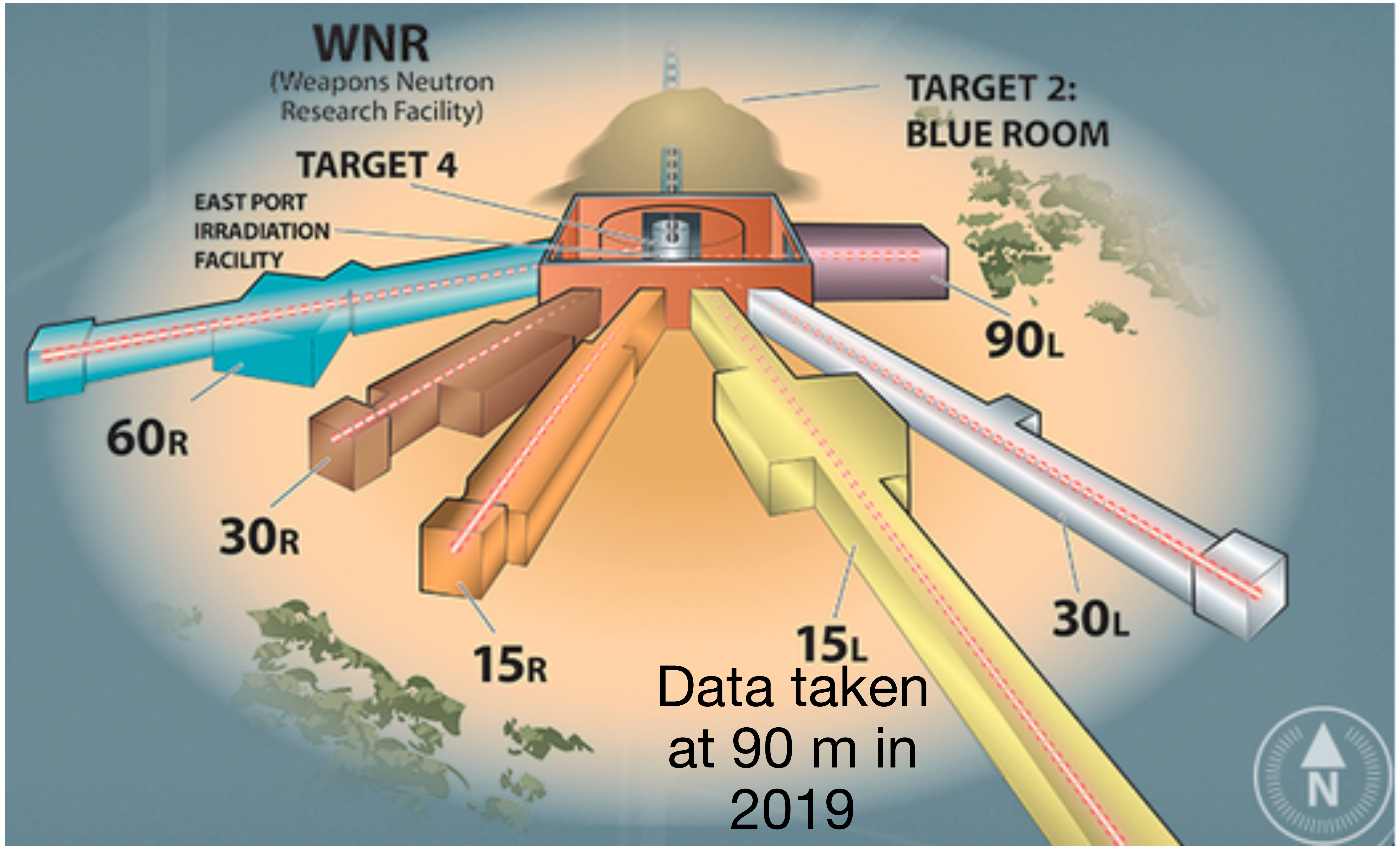


Simplified drawing of a (anti)neutrino interaction

LANL facility

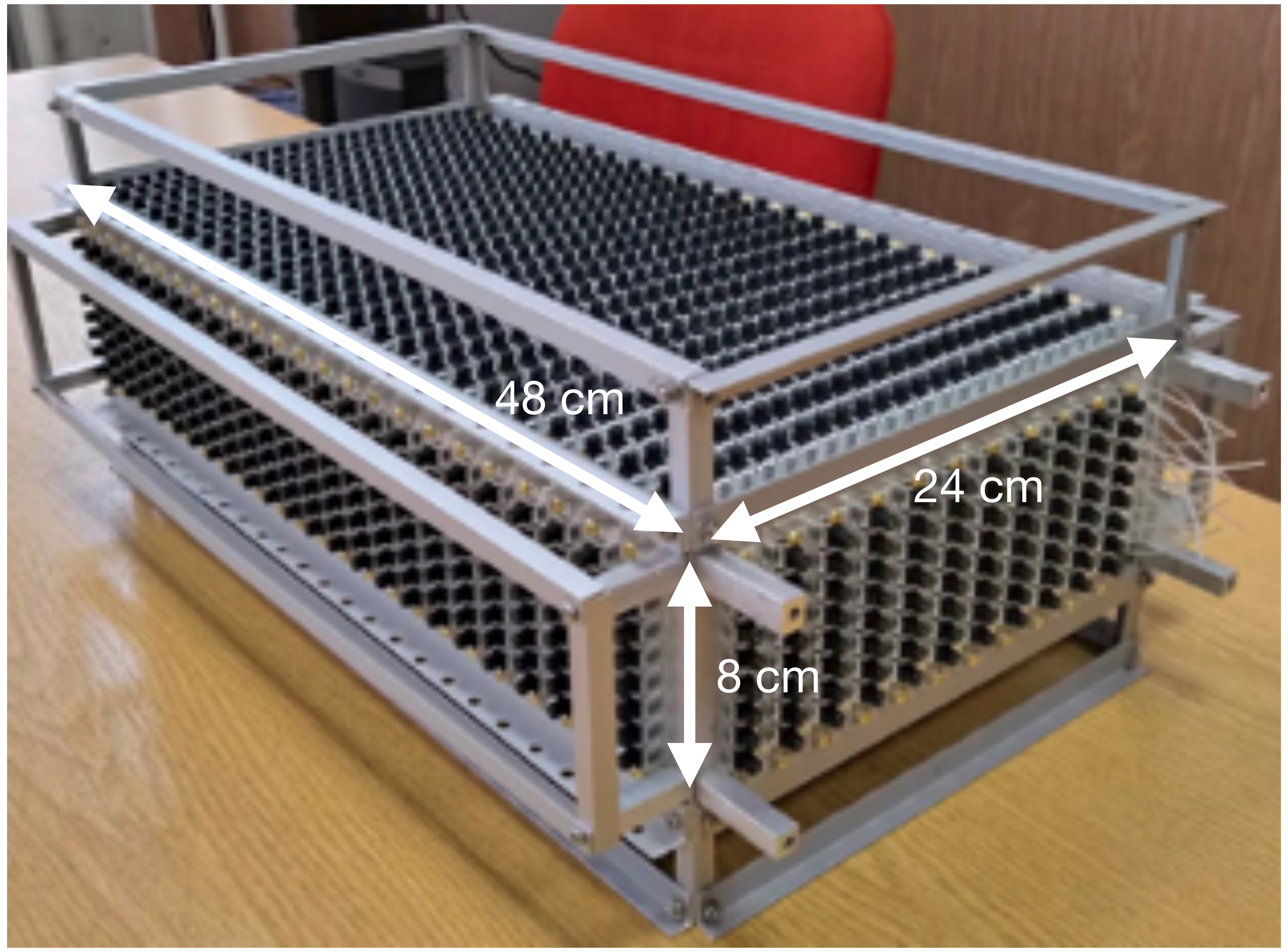
Weapons Neutron Research Facility at LANL provides neutron beam ranged from 0-800 MeV





SuperFGD Prototype

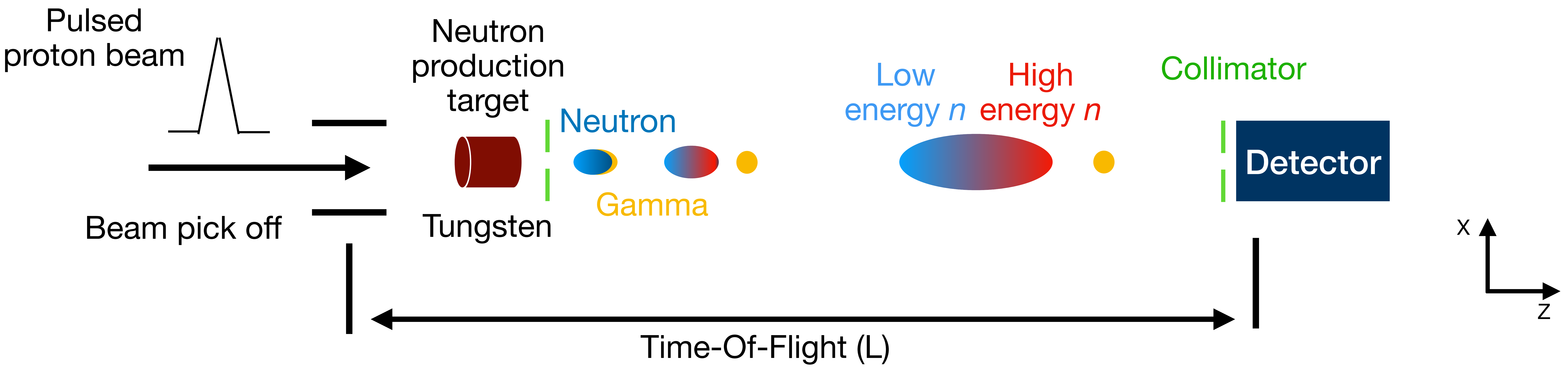
Super-FGD prototype exposed to neutron beam



Already used for the charged particle beam test at CERN and published here

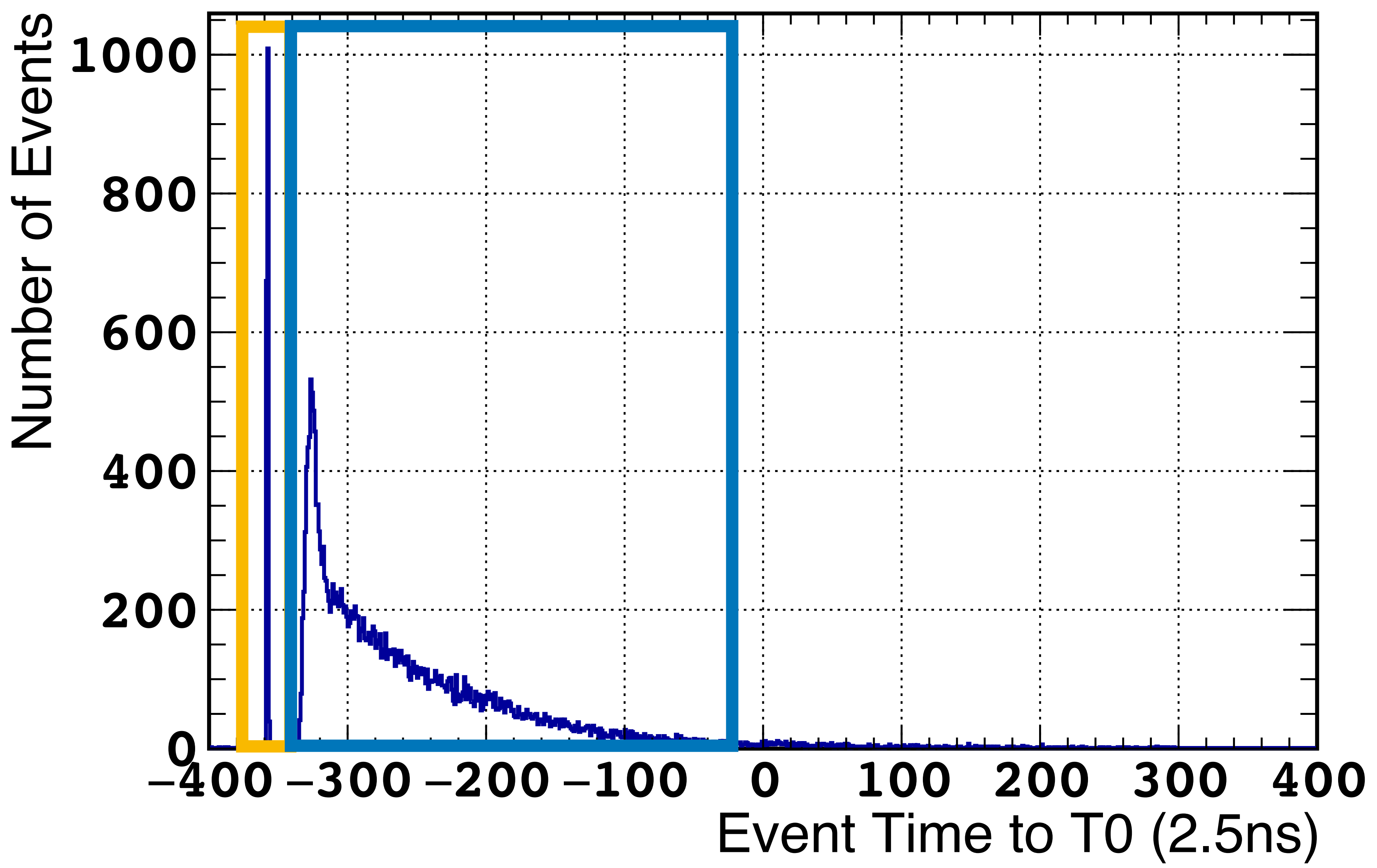
- Three different types of MPPC used
- Gain calibration
  - LED runs taken at LANL in 2019
  - Gain extracted for each channel and temperature variation included
- Light yield calibration
  - Dedicated cosmic samples selected
  - PE per MeV obtained for each channel
- Light attenuation measured at CERN

Neutron beam



A gamma flash comes before the neutron

The neutron energy is measured using the time-of-flight.



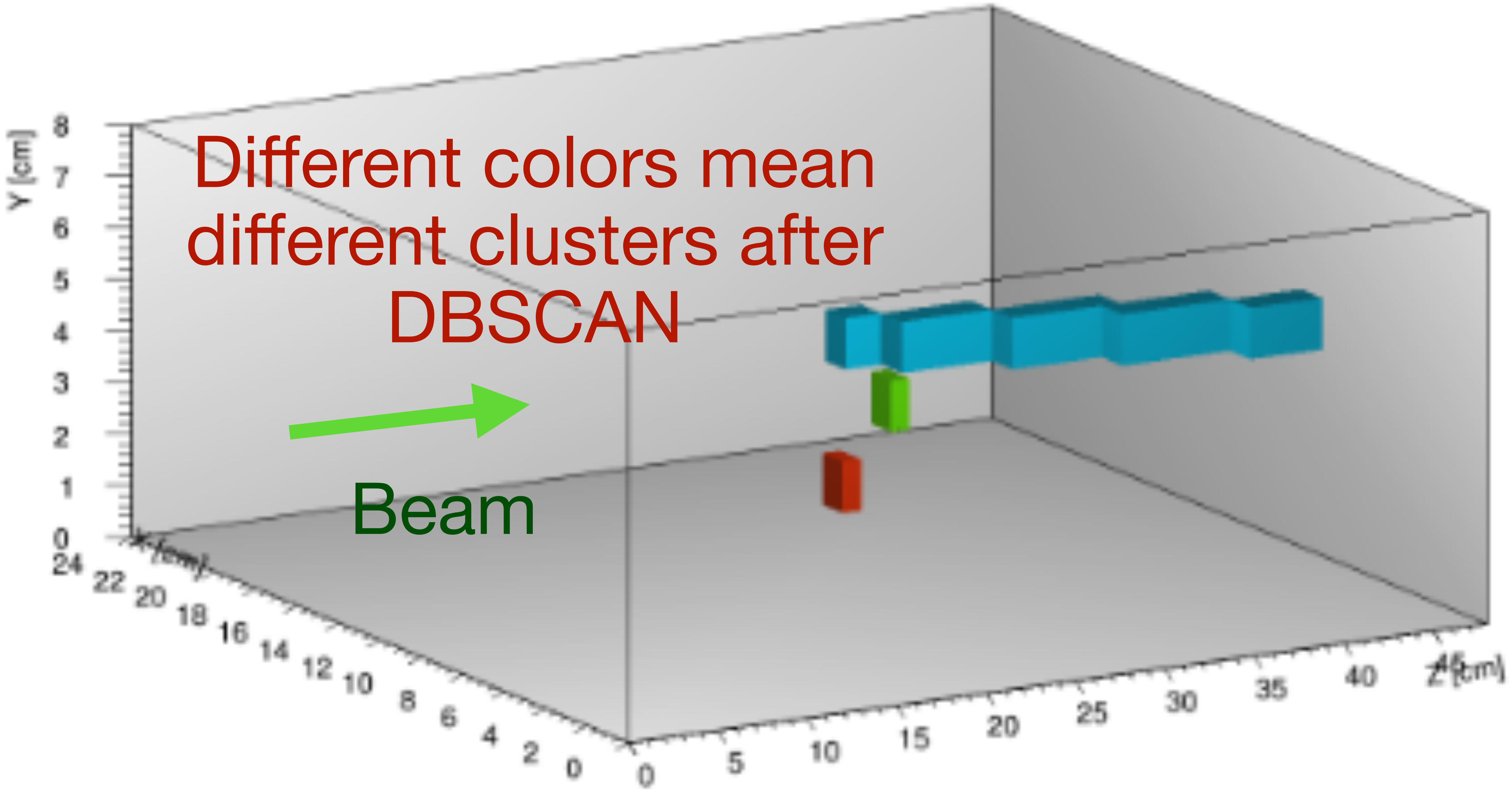
*Simplified drawing

Total n-CH cross section

- Total cross section on CH has been extracted using data taken in 2019 and has been submitted on ArXiv recently. The extraction strategy is the following:
  - Neutron flux decreases as a function of depth in the detector due to neutron interactions with CH
  - The total neutron-CH cross section can be extracted from the attenuation of the beam $N_0 e^{-T\sigma z}$
  - The attenuation can be measured by choosing a particular event topology and measuring the change in the rate of this particular process as a function of depth in the detector
  - We assume that the fraction of the total cross section that results in the chosen topology does not change as a function of depth
  - We have chosen events with single reconstructed tracks as topology

Event reconstruction

- Neutron interaction time window: -326 ns < Hit time < 340 ns
- Require #hits > 3 each with PE > 20
- Time clustering: if $t_{hit}(i+1) - t_{hit}(i) < 17.5$ ns then hits belong to same cluster
- Voxelization: three 2D-view matching of time-clustered hits
- DBSCAN is used to group voxels into clusters
  - Any voxels within 1.8 cm ($\sqrt{3}$) cm of each other are grouped into the same cluster
  - 1 voxel by itself is considered a cluster

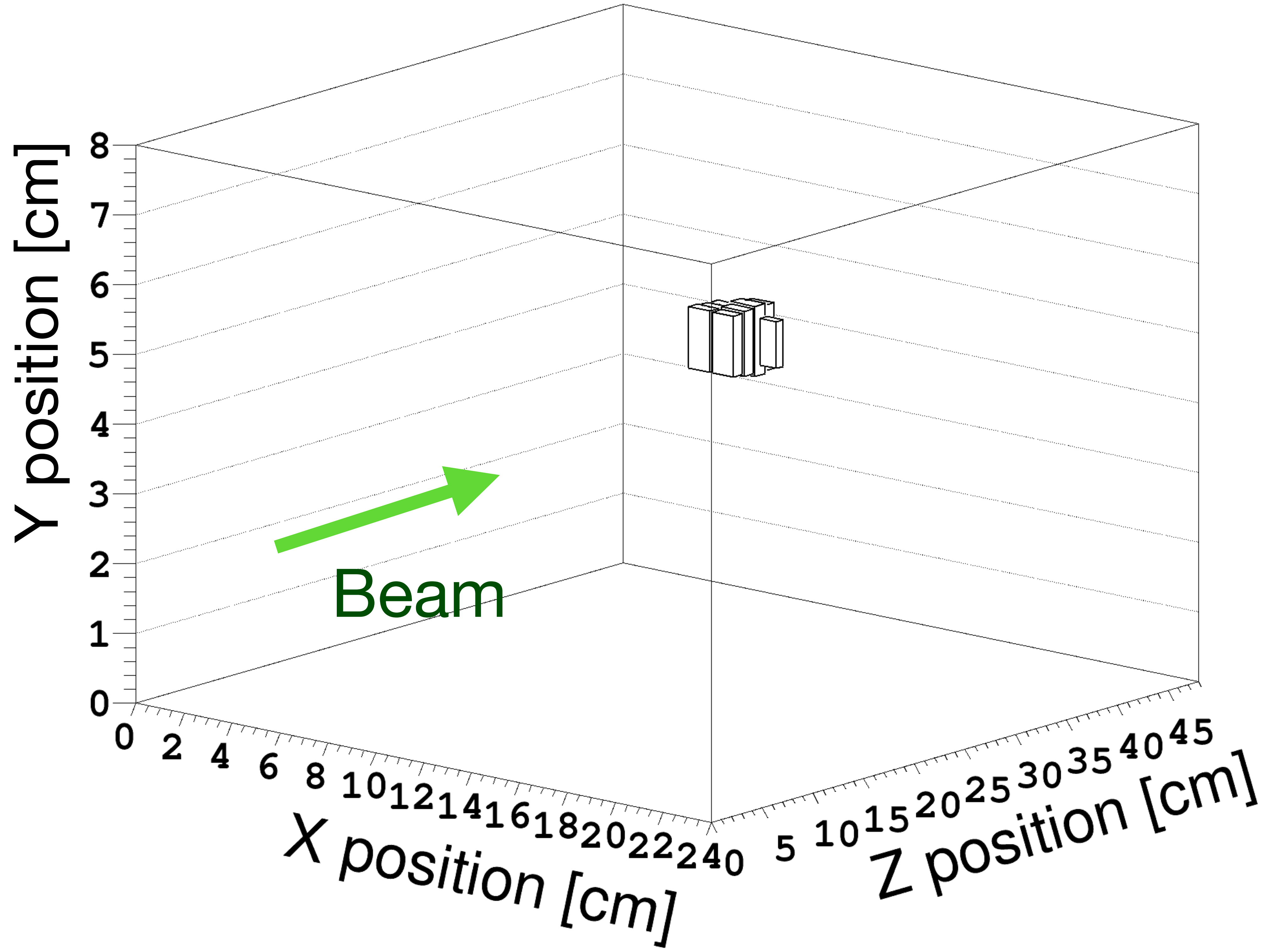


Single track selection

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)
PCA-derived	Cut that reject blob-like event using a variable that measure the development of the cluster along the best-fit
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)

PCA-derived cut

- For each cluster a matrix that encodes the distance between each voxel and the center of the cluster is defined as: $M_{ij} = \sum \frac{(\overrightarrow{v} - \overrightarrow{c})_i(\overrightarrow{v} - \overrightarrow{c})_j}{N}$
- 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
- Reject blob-like events

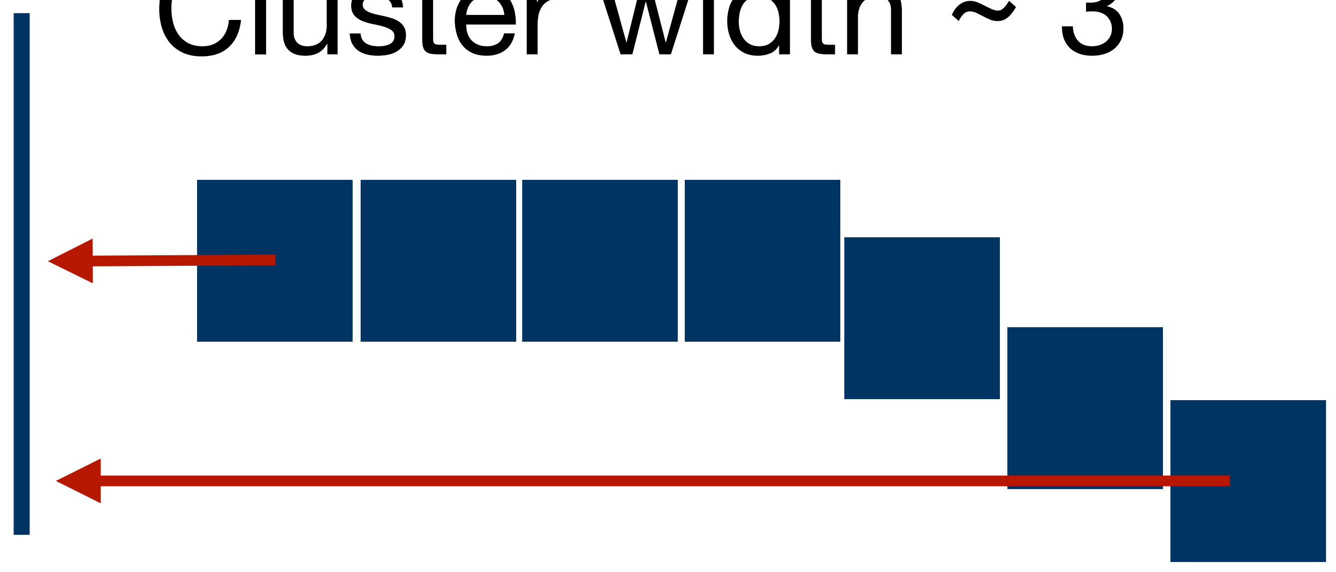


Max cluster width

- 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 principal 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

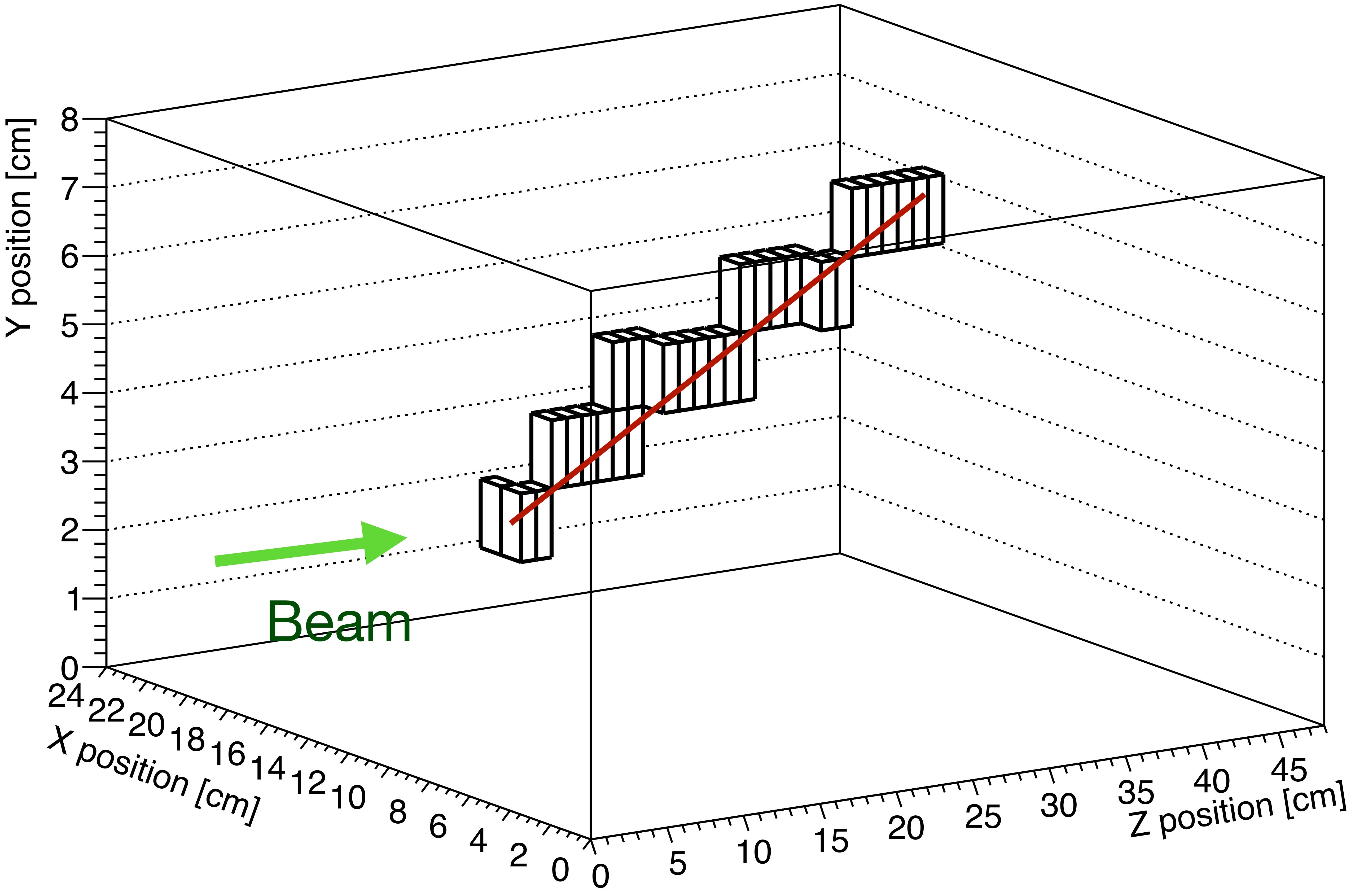
Cluster width = 0

Cluster width ~ 3



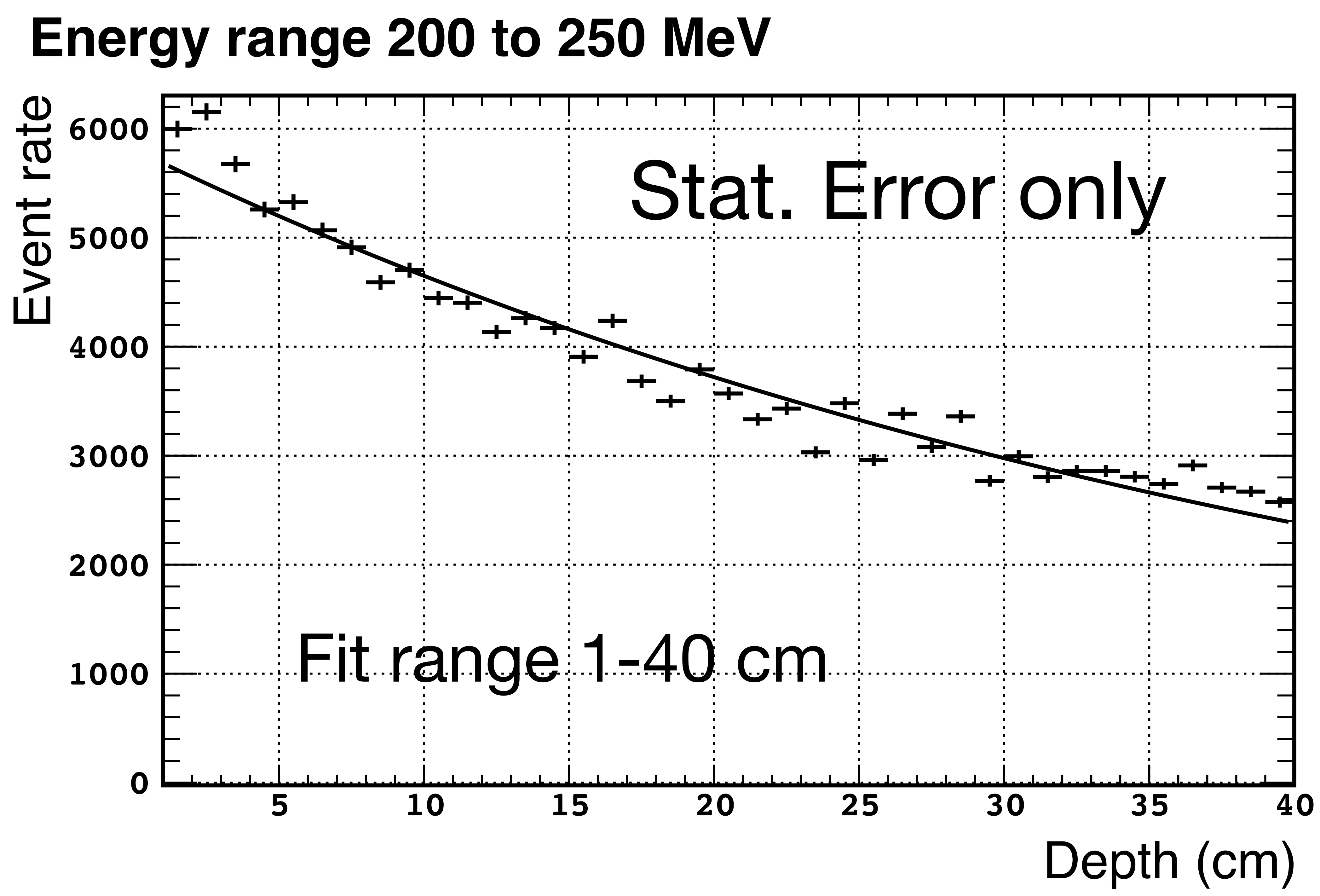
3D line-voxel max distance

- 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



Neutron cross-section

- Fill an histogram for every energy (from ToF between production point and vertex) bin, which is the distribution of the number of events as function of the depth (z-layer)
- Energy binning optimized taking into account the time resolution (1.37 ns)
- Energy restricted to be between 98 and 688 MeV. Below 98 MeV tracks not long enough and neutron elastic scattering dominates, above 688 MeV gammas dominates and less statistics
- Fit with the exponential $N_0e^{-T\sigma z}$
- Extract the cross section for every bin from the exponential fit



Systematic uncertainties

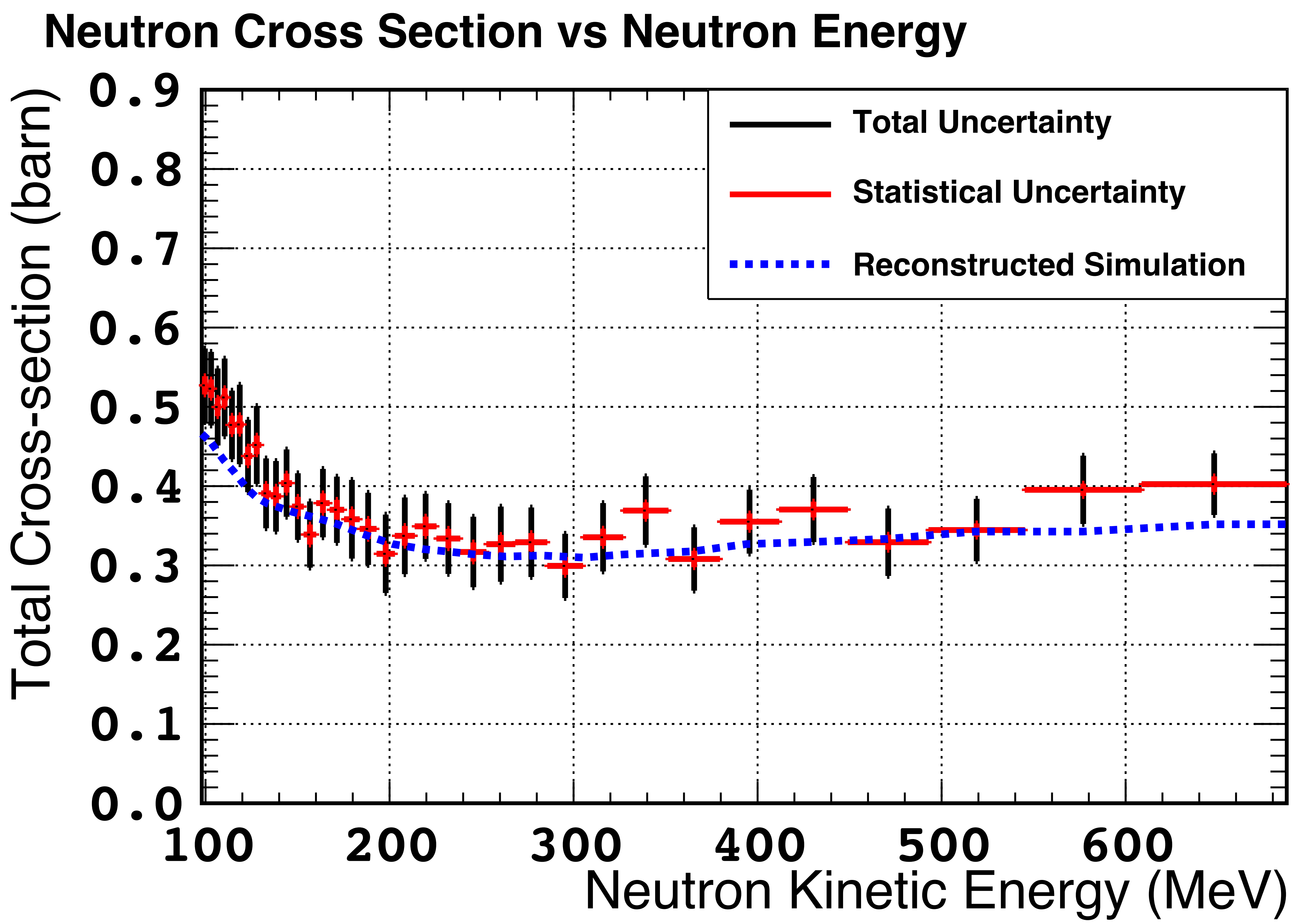
- **Detection systematic (dominant):** cube, MPPC and passive material non-uniformity
- **Invisible scattering:** missed primary interaction vertex
- **Geometric acceptance:** location dependent acceptance due to limited detector size: multi-tracks event can look like a single track close to the edge
- **Light yield:** variation for each channel measured using cosmic rays
- **Time resolution:** measured using the gamma flash and CERN data
- **Collimator interactions:** neutrons interacting with the collimator before entering the detector

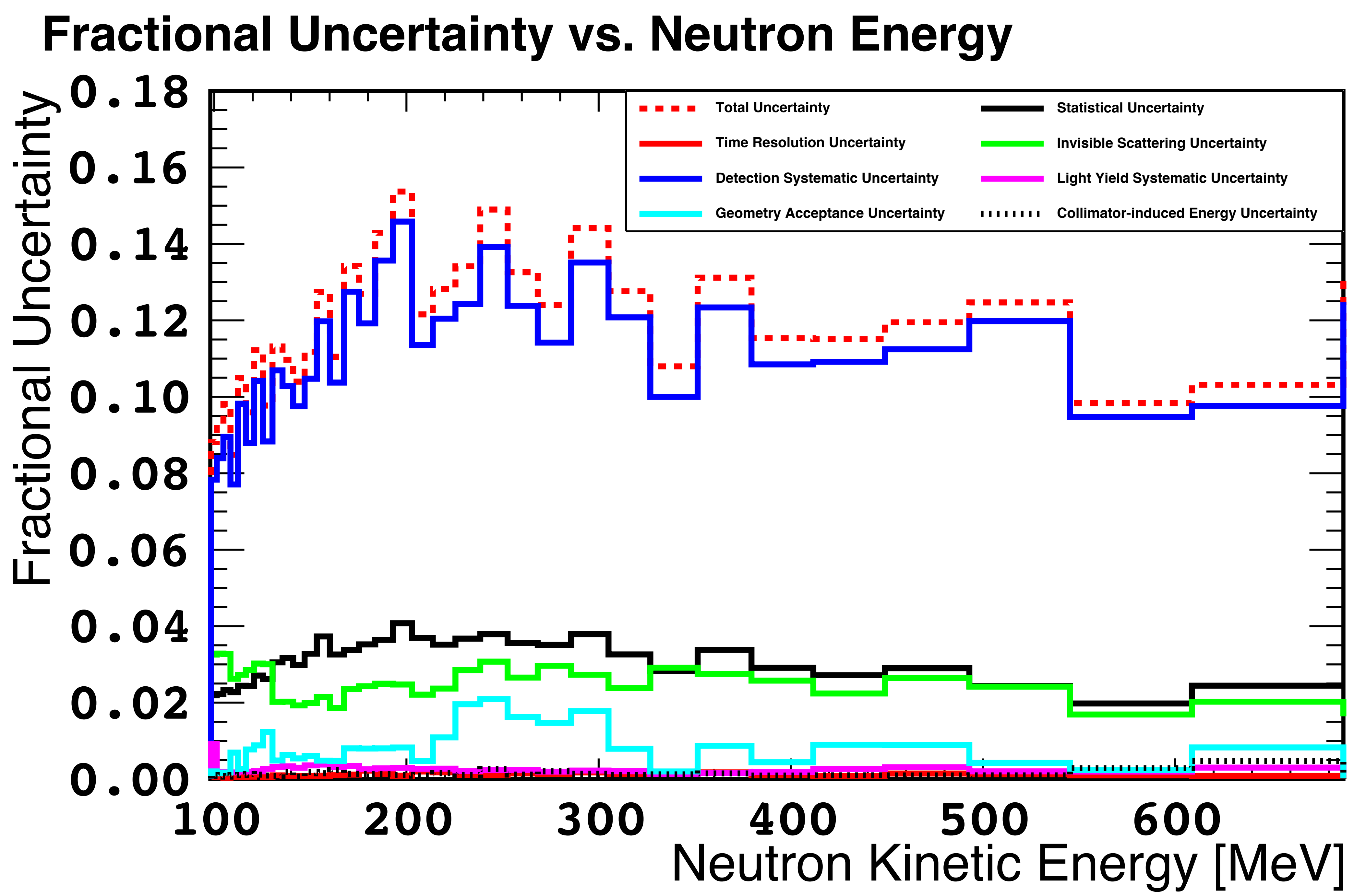
Error propagation

- The systematics that change the number of events in each z-layer are propagated in the following way:
    - Fit with the exponential $N_0 e^{-T\sigma z}$ the distribution obtained after every gaussian variation of the number of events in every z-layer and energy bin
    - Fill an histogram with every value of the cross section
    - The systematic uncertainty is the RMS of this distribution
- Time resolution and the uncertainty due to collimator interactions changes the energy distribution (shape-like systematics) all the others change the normalization (#events in each z-layer)
- The total systematic uncertainty is the sum in quadrature of the single one
- Statistical uncertainty given by square root of number of events in every z-layer

Final result

Total of 20h of data analyzed. The total rate is about 1e6 events (total interactions are ~1e8 and efficiency is ~1e-2)





The energy-integrated (98-688 MeV) cross section is 0.36 ± 0.05 barn with a $\chi 2$/d.o.f. of 22.03/38

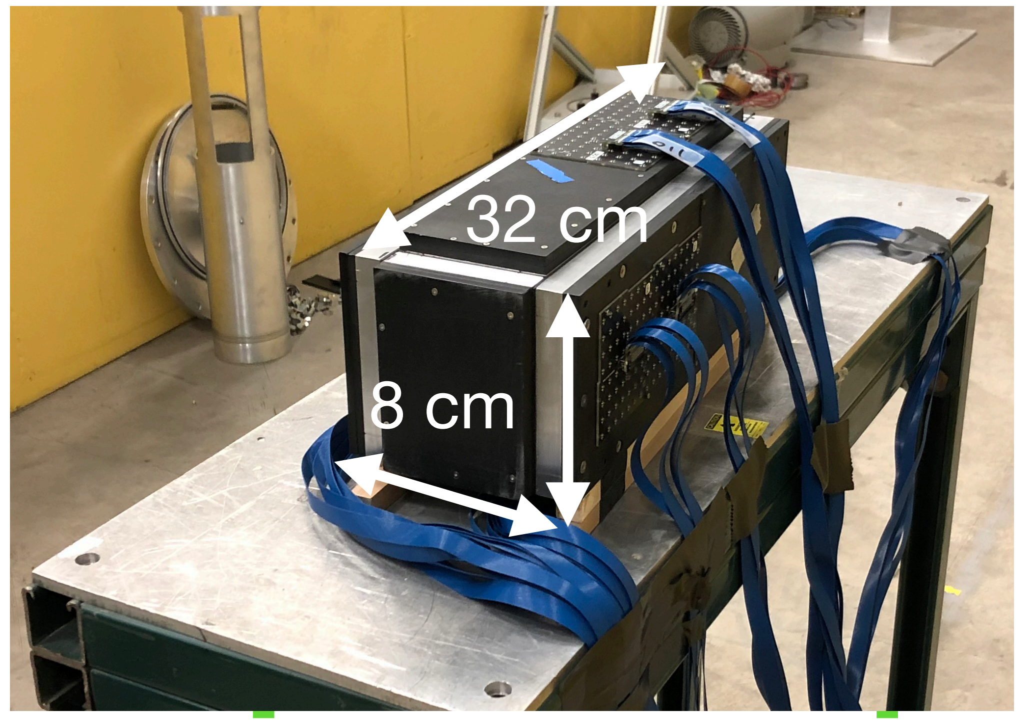
Future studies

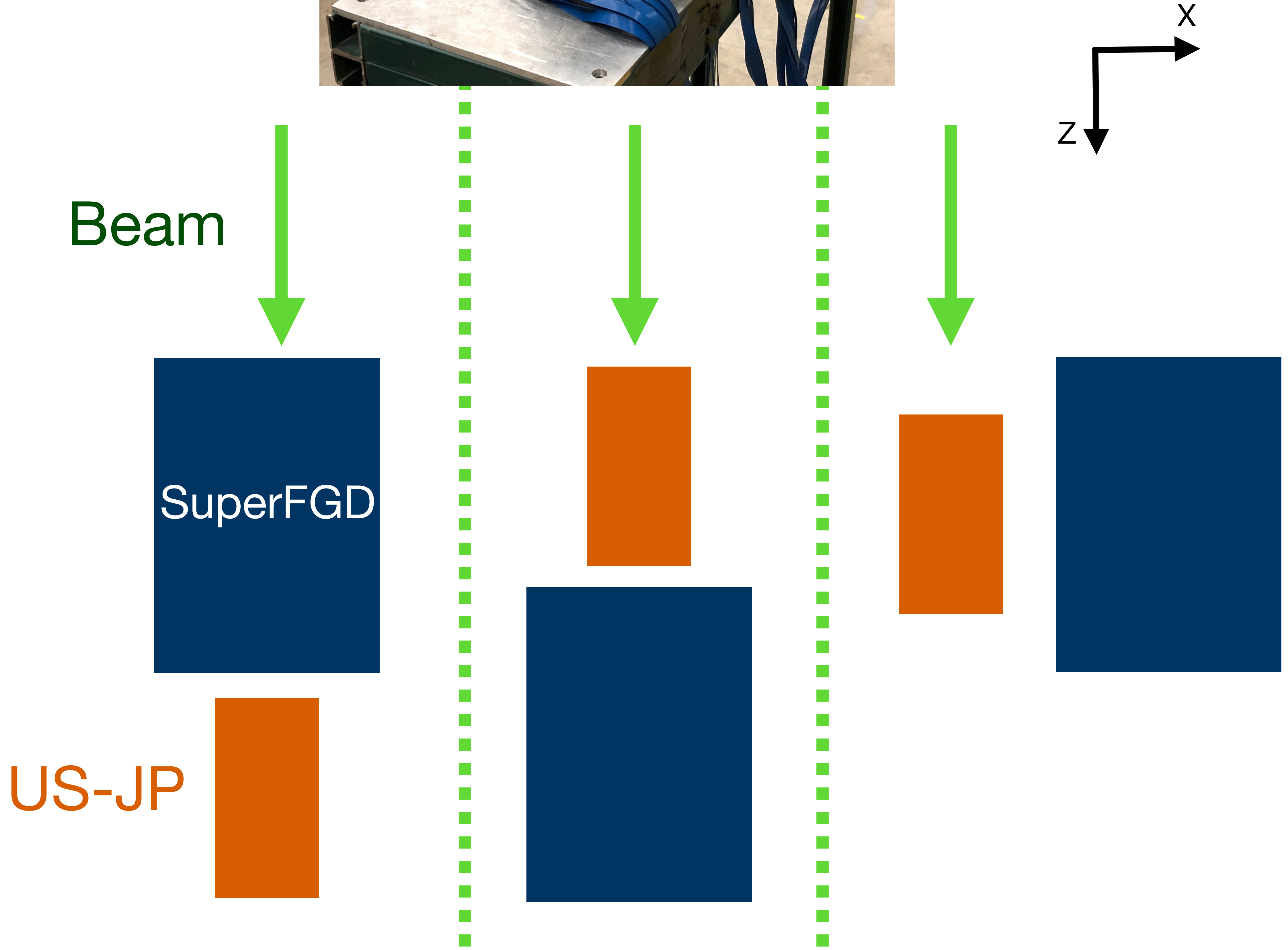
- In 2020, the SuperFGD and a smaller prototype called US-Japan prototype, were exposed to the neutron beam for 2 weeks (location 15L - 90 m from the production point)

- Different prototypes configurations, collimator size and beam configurations allowing for various studies

- Studies of neutron secondary interactions, MC studies and comparison with data, elastic vs inelastic scattering, investigate possibility to constrain invisibile scattering

US-Japan prototype





Conclusions

- The total n-CH cross-section measurement has been submitted on ArXiv recently and is the first physics results of the technology developed for SuperFGD
- It demonstrates that SuperFGD is capable of detecting neutrons!
- Lessons learned are the starting point for neutron reconstruction in SuperFGD
- Additional data have been collected with SuperFGD and US-Japan prototypes in 2020 and analysis of them will continue
- A lot of interesting physics topics will be studied in the near future

Thank you!

3D Projection Scintillator R&D group
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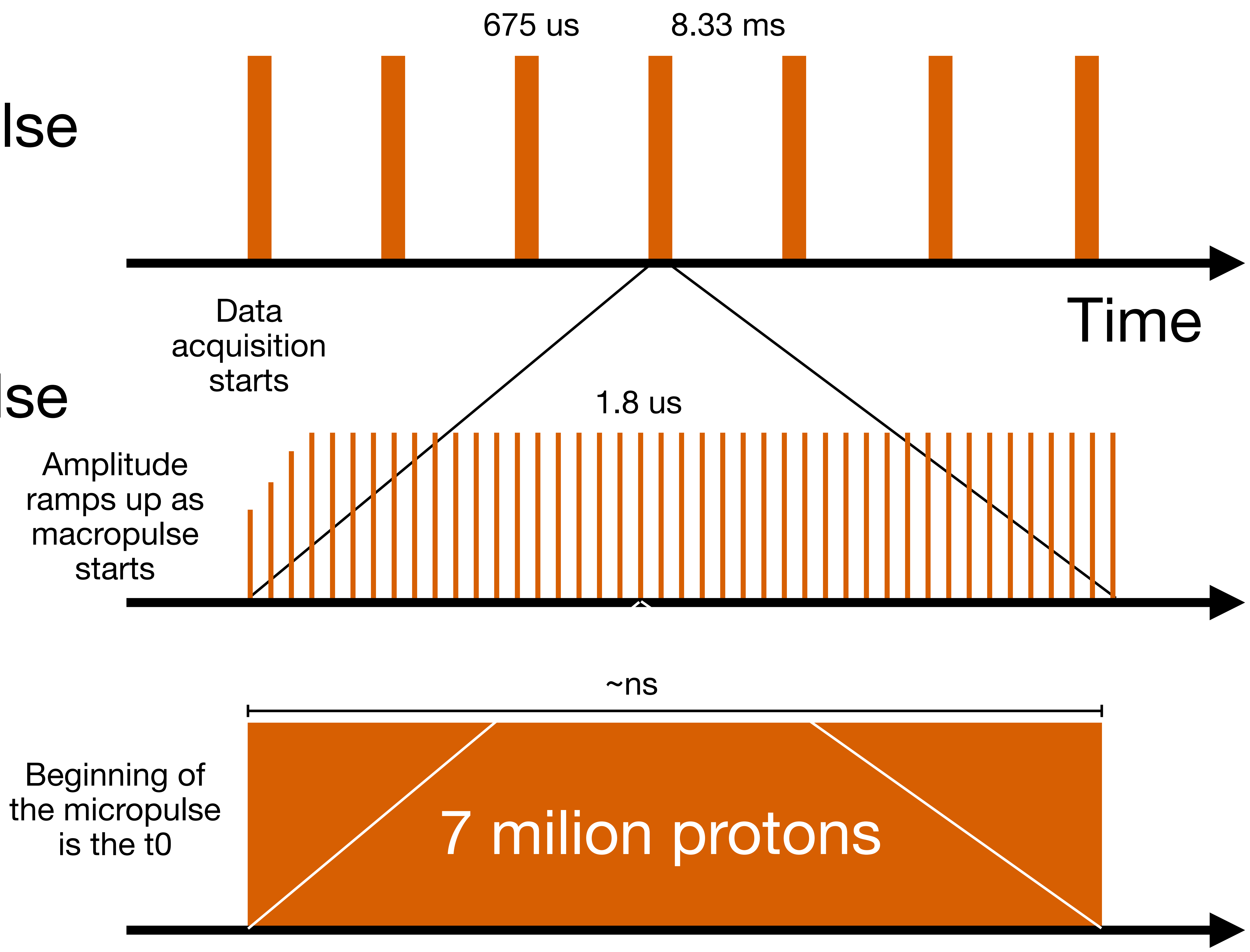
Imperial College, UK
Institute for Nuclear Research (INR), Russia
University of Kyoto, Japan
Louisiana State University
University of Pennsylvania
University of Pittsburgh
University of Rochester
South Dakota School of Mines and Technology
Stony Brook University
University of Tokyo, Japan

Backup

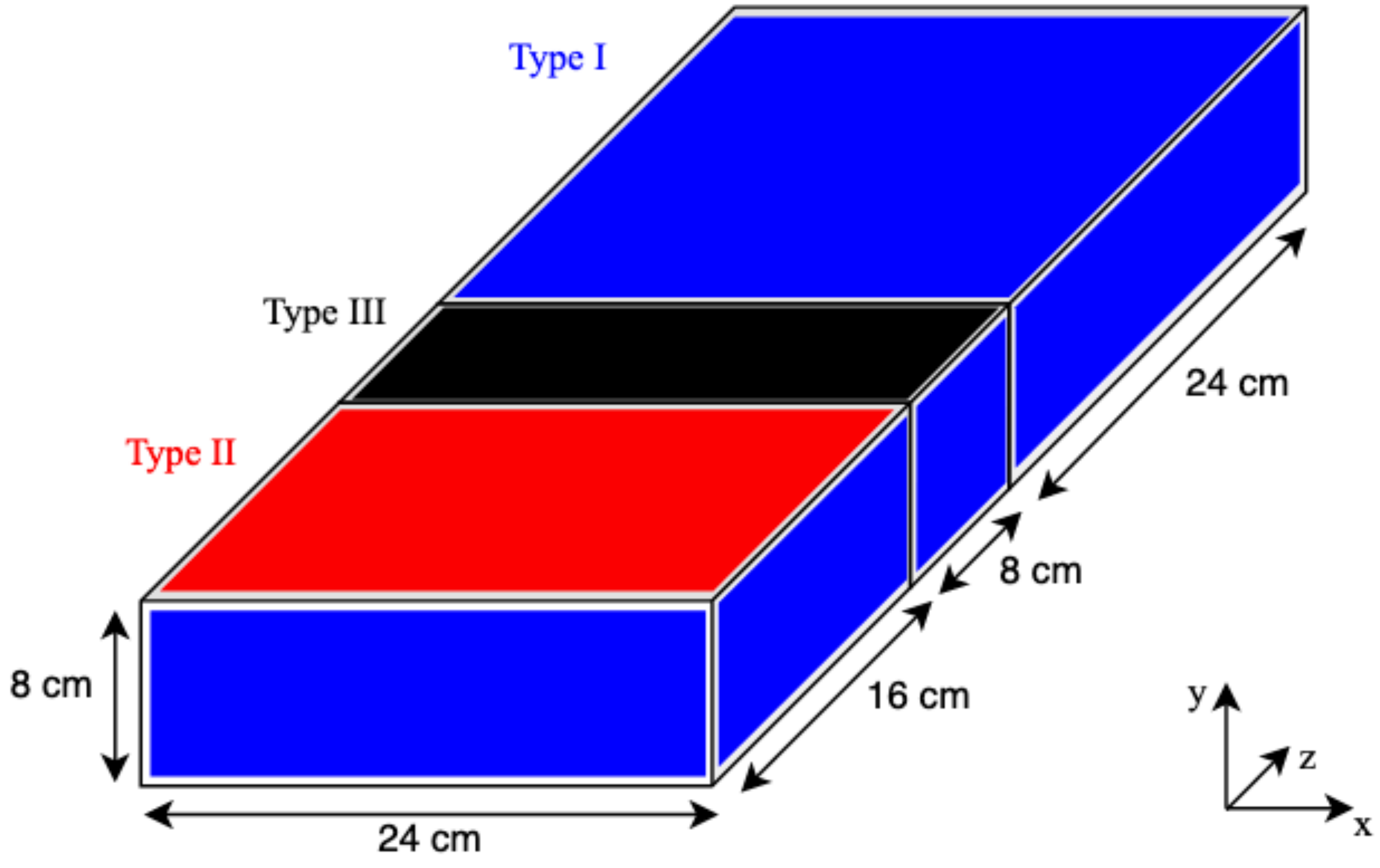
Beam structure



Protons impinge on the target and produce neutrons and gammas.

MPPC type

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



Detection Systematics

Major causes:

- Cube misalignment: In MC, systematically shifting every 5 layers by 1 mm makes the events rate at z changes up to 10%.
- MPPC anisotropy: Relatively small as the YZ and XZ view results are very similar.
- Cut vs no-cut ratio gives the systematics