PERFORMANCES OF RESISTIVE MICROMEGAS FOR THE T2K ND280 UPGRADE

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IRN Neutrino
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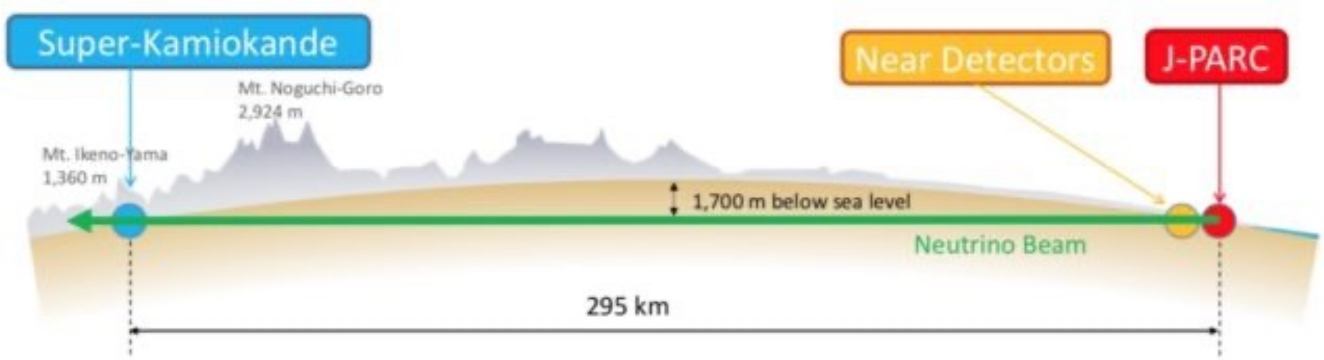
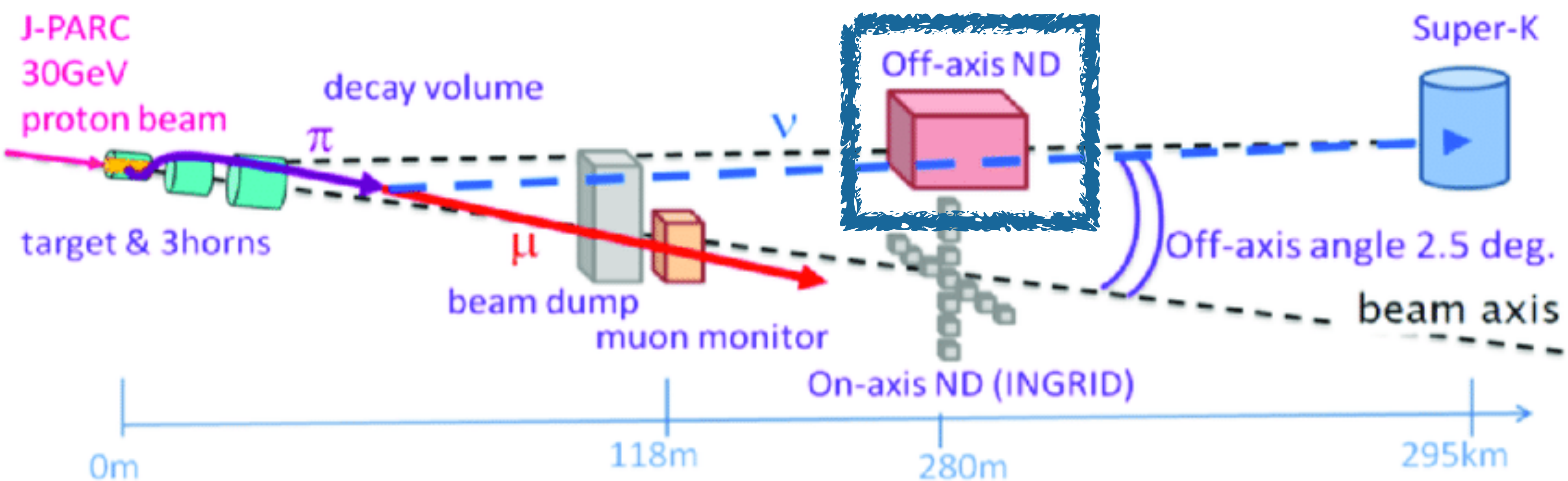
ACCELERATOR NEUTRINO EXPERIMENTS

- Accelerator ν experiments:
  - precisely controlled pure $\overset{(-)}{\nu}_\mu$ beam
  - allow to study:
    - appearance (ν_e) & disappearance (ν_μ) channel
    - neutrino & anti-neutrino oscillations

} CP violation measurements

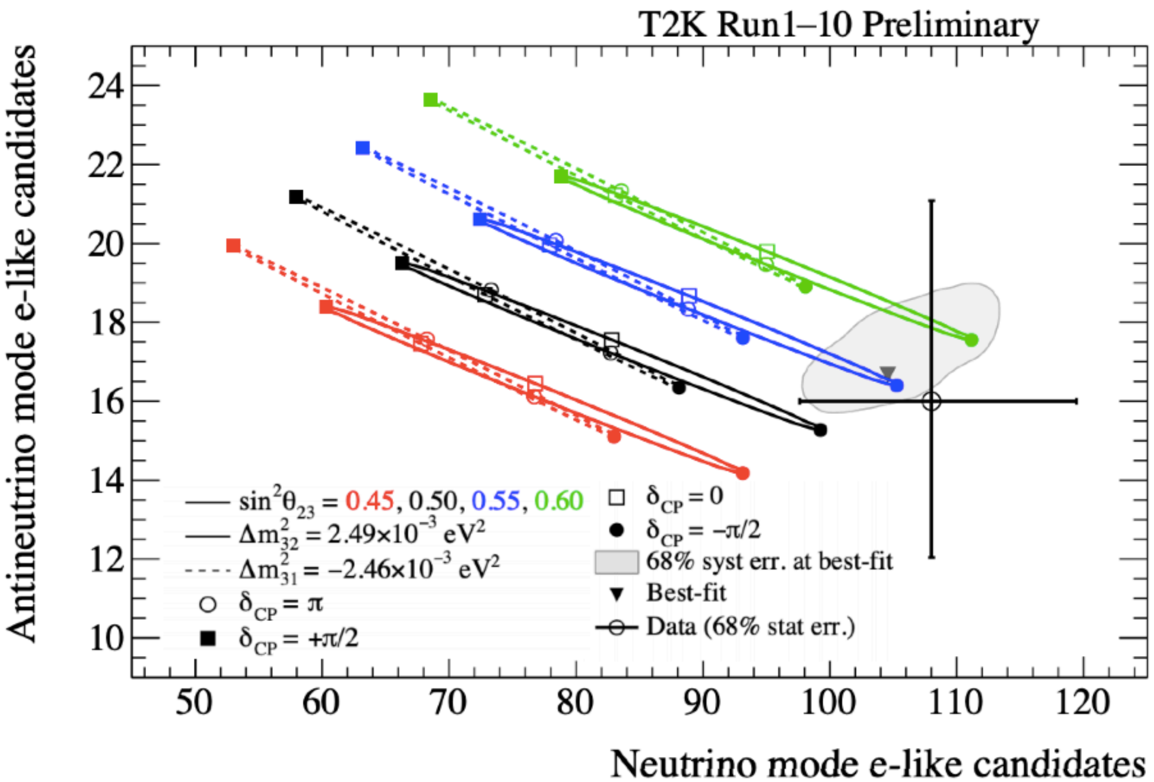


- Beam production:



ND280 UPGRADE MOTIVATION

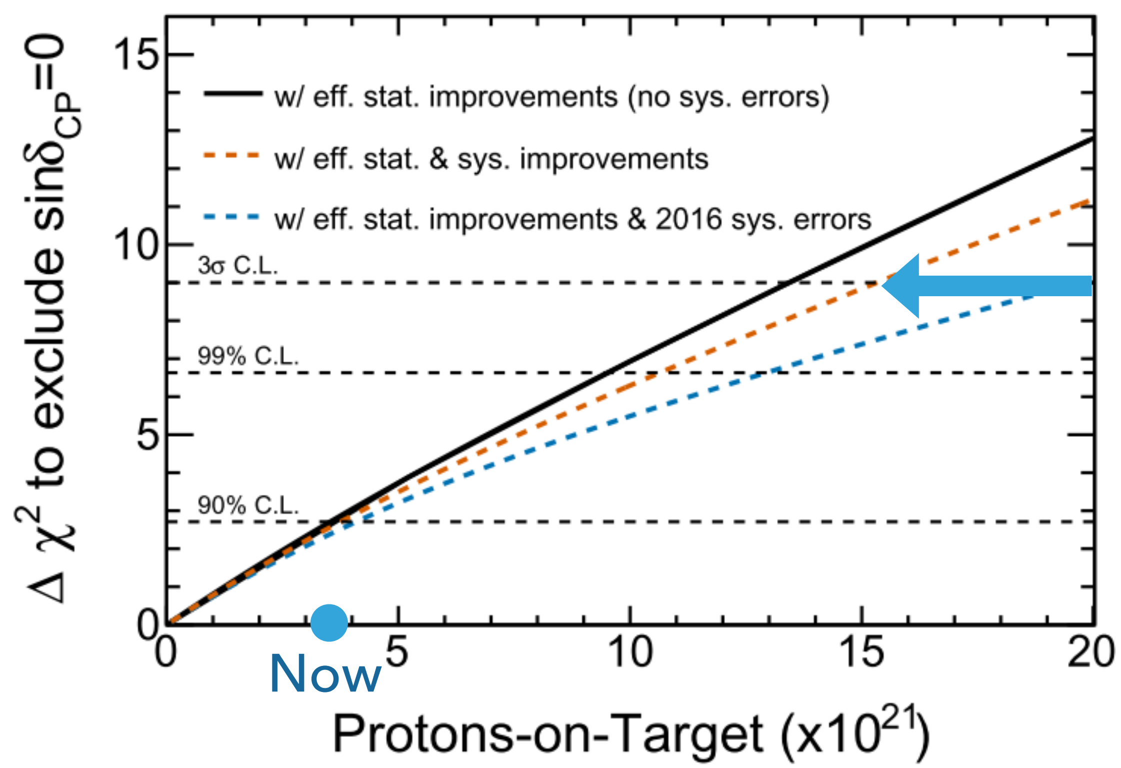
- T2K was approved to collect 20×10^{21} protons on target stat. (T2K-II stage)
  - the main goal is measurements of the δ_{CP}



$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E_\nu} - \sin 2\theta_{12}\sin 2\theta_{13}\cos\theta_{13}\sin\delta\sin^2\frac{\Delta m^2_{32}L}{4E_\nu}\sin\frac{\Delta m^2_{21}L}{4E_\nu}$$

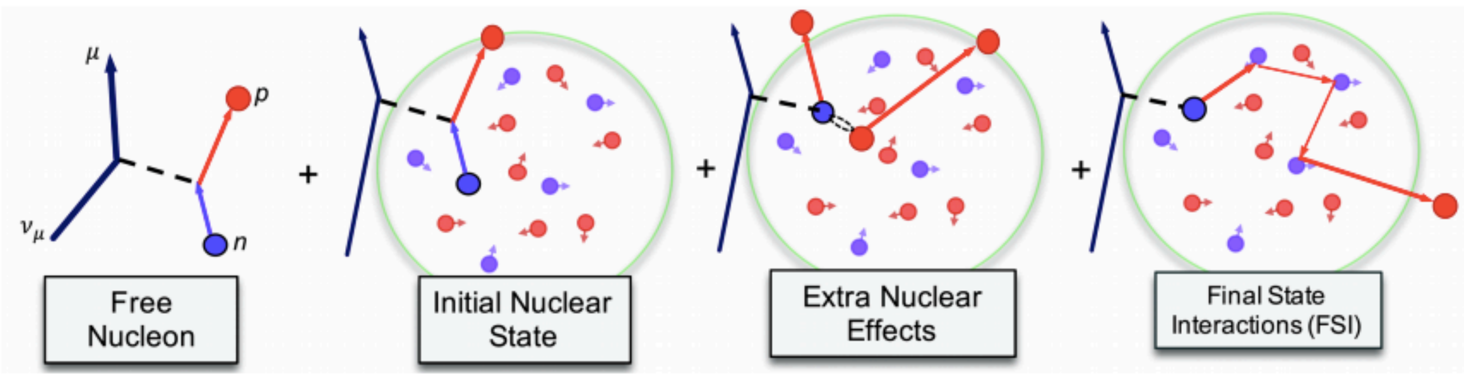
- e-like candidate observed:
  16 in $\overline{\nu}$-mode and **109** in ν-mode

- Now we are limited by statistics
- For T2K-II systematic is critical for search for CPV
  - *CPV sensitivity with current and improved systematics vs statistics*



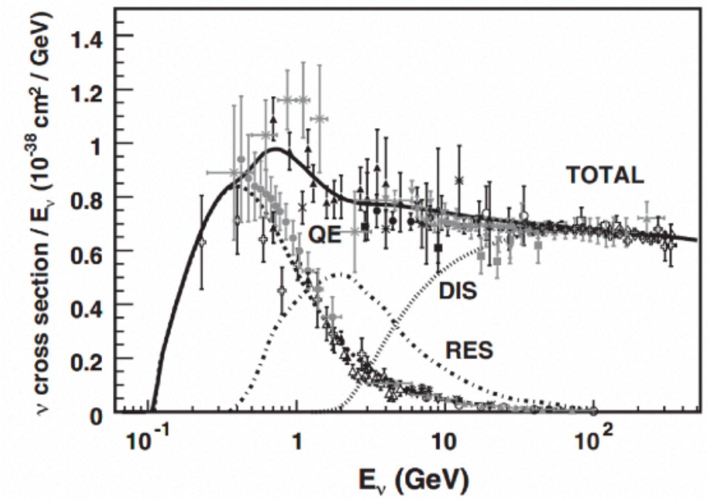
T2K SYSTEMATIC IMPROVEMENTS

- Oscillation analysis systematic is dominated by the ν interaction models uncertainties
  - Precise measurements are complicated because of poorly studied nuclear effects



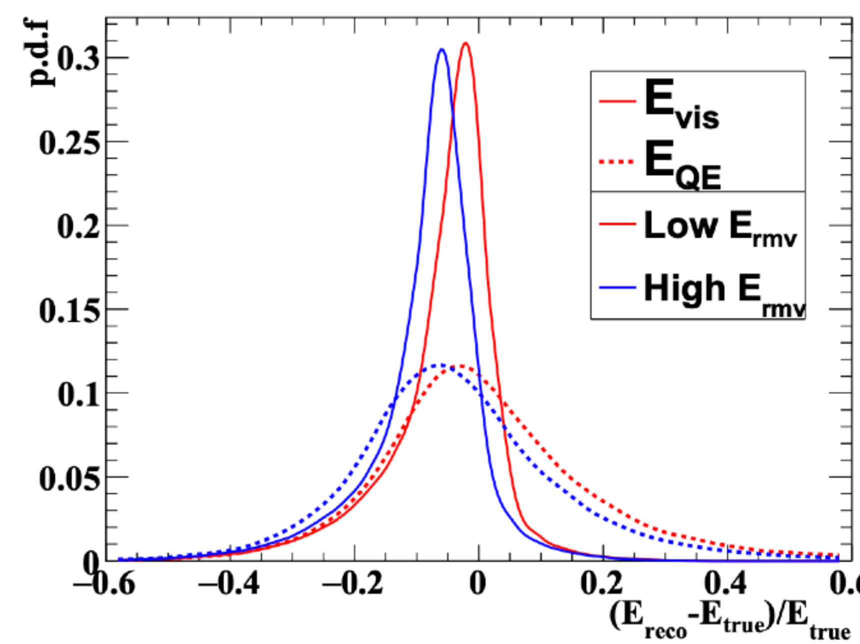
Fermi motion

e.g. 2p2h
2 nucleon interaction



- Example: Neutrino energy reconstruction in Super-Kamiokande:
  - Charge Current Quasi Elastic (CCQE) interaction on the nucleon at rest is assumed
  - E_ν is reconstructed based on the lepton kinematics only

$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

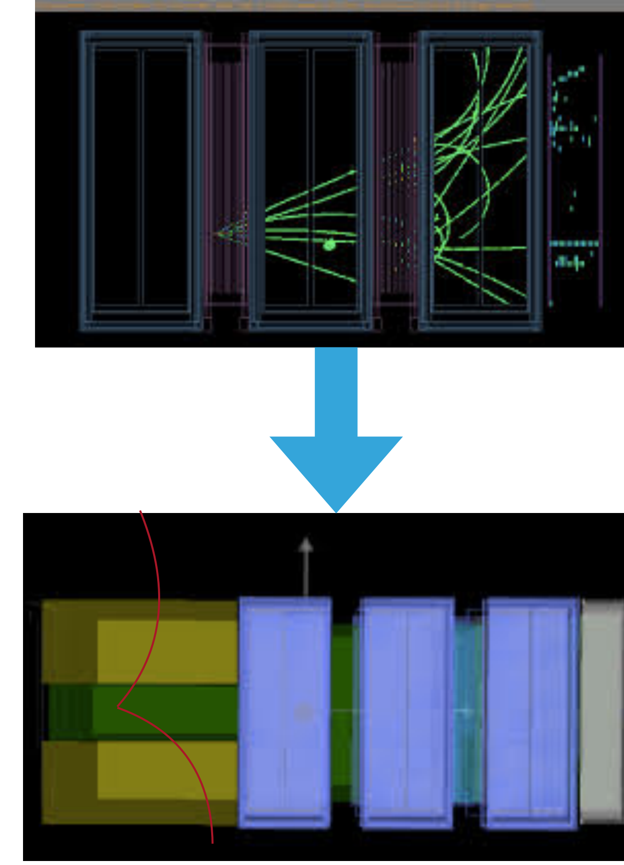


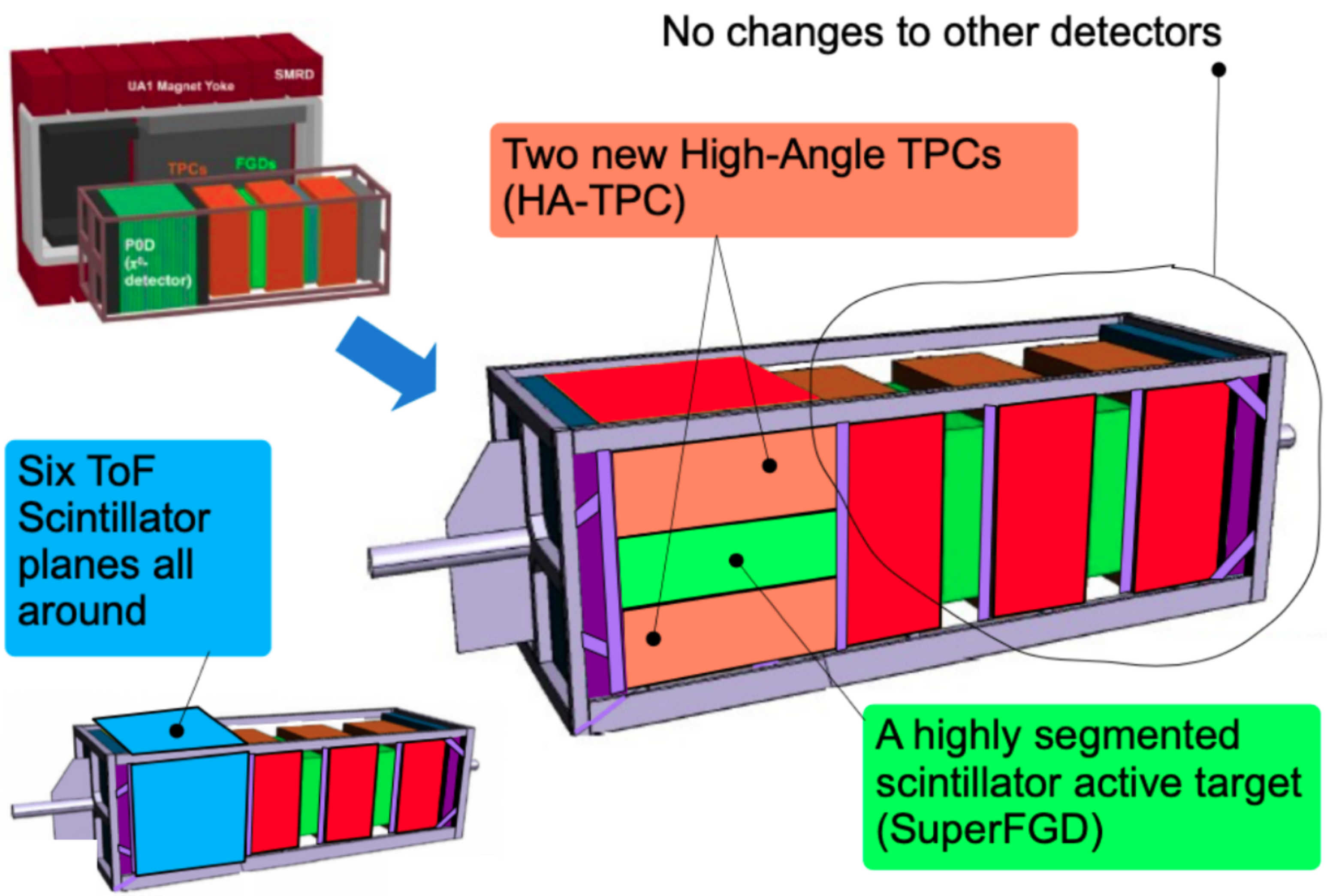
Benefits of the including nuclear information over QE assumption

- To perform more precise measurements of ν interaction:
  - new detector configuration
  - new analysis technique

ND UPGRADE CONCEPT

- Near detector upgrade project was started aiming:
  - full phase space coverage
    –> same angular acceptance as far detector
  - lower thresholds for muon, pion, proton
  - neutron detection from $\overline{\nu}$ interactions
  - e/γ conversion separation (ν_e measurements)





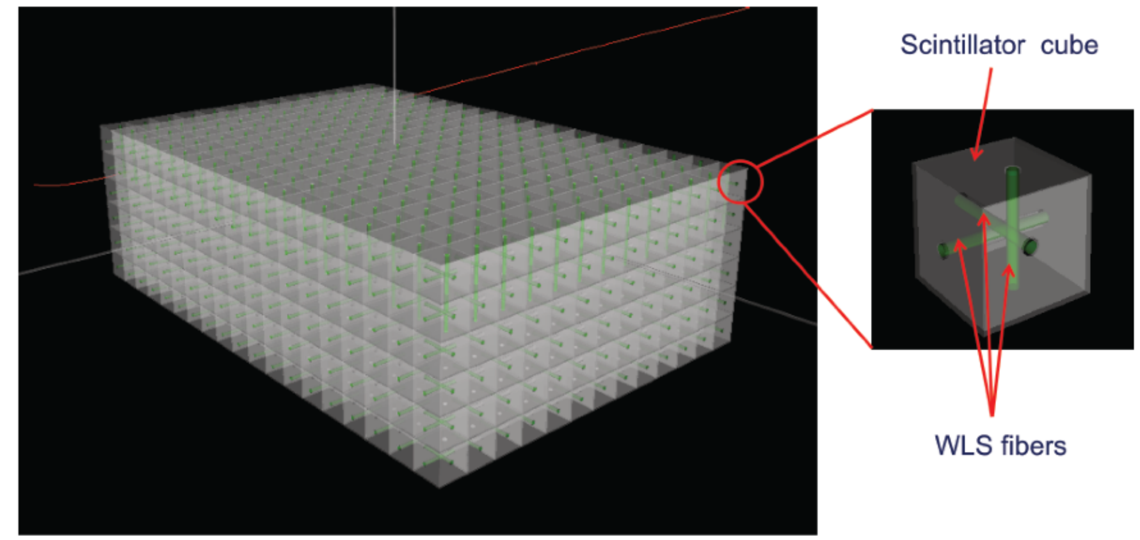
- A novel highly segmented scintillator detector
- Two new TPCs with resistive anode
- 6 time of flights panels around new sub-detectors

TDR 2019

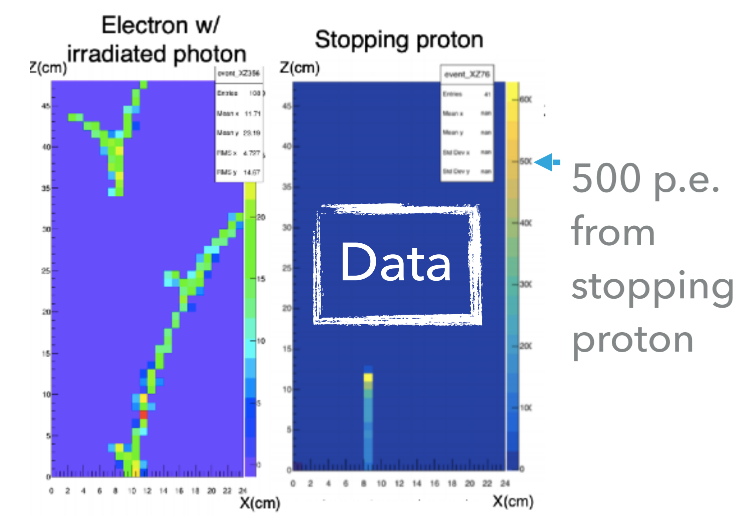
NEW SCINTILLATOR DETECTOR (SUPER FGD)

- A novel detector made from scintillator cubes
  - 1x1x1 cm^3 cube
    - *low energy thresholds*
    - *high spatial resolution*
    - *3D reconstruction*

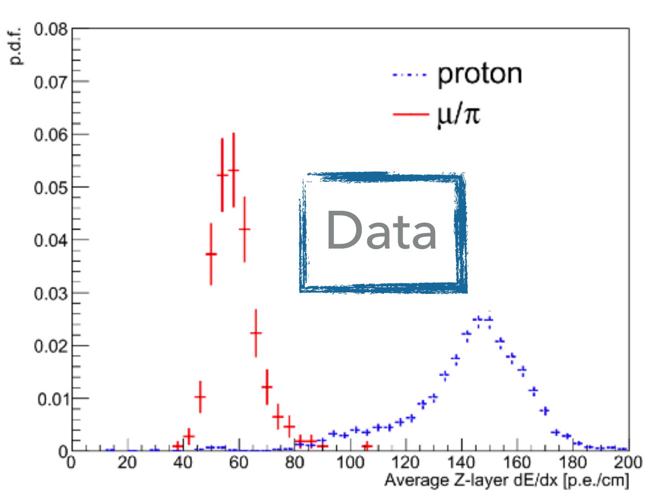
  } *Unique for scintillator detector!*



  - fully active plastic detector –> no track distortions
- Prototypes were tested at CERN (2017, 2018) and at LANL
  - e, μ, π beam at CERN (NIMA 936 (2018), JINST 15, 12 (2020))
  - Neutron beam at LANL



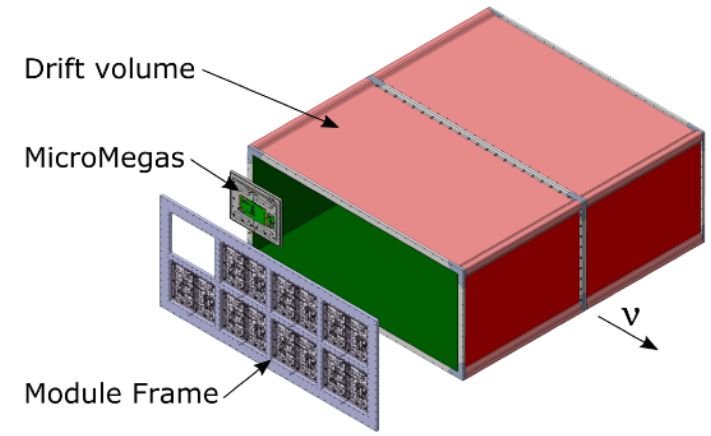
- The detector performance was measured:
  - Light yield ~50 p.e. per channel (150 p.e. per cube)
  - $\sigma_t \approx 1\ ns$ per channel



Scintillator cubes are fully produced and awaits for integration!

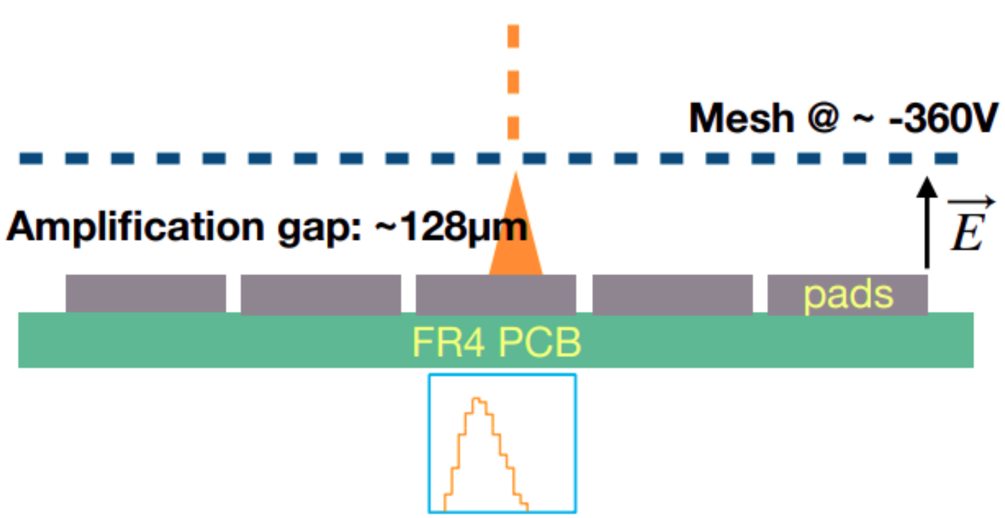
NEW TIME PROJECTION CHAMBERS

- High angle tracks from the target are tracked with 2 new TPCs
  - low material budget –> minimal track distortion at SFGD-TPC passage
  - Resistive MicroMegas (MM) modules significantly improve spatial resolution keeping pad size the same

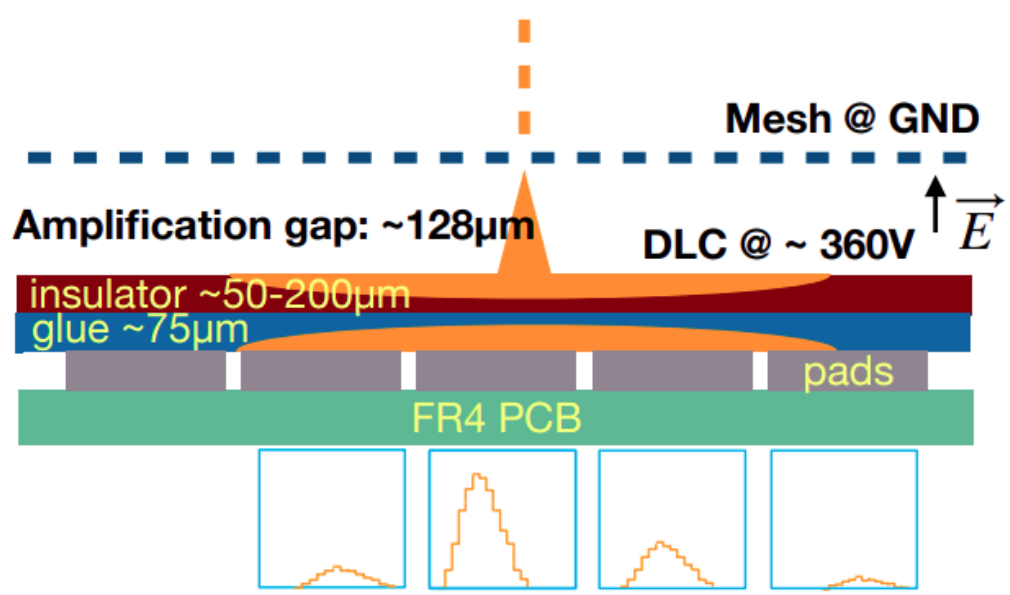


- A resistive layer on top of sensitive pads
  - charge spreading –> avalanche position is reconstructed based on information from several pads --> gain accuracy
  - charge measurements are correlated --> concerns about dE/dx resolution

bulk MicroMegas



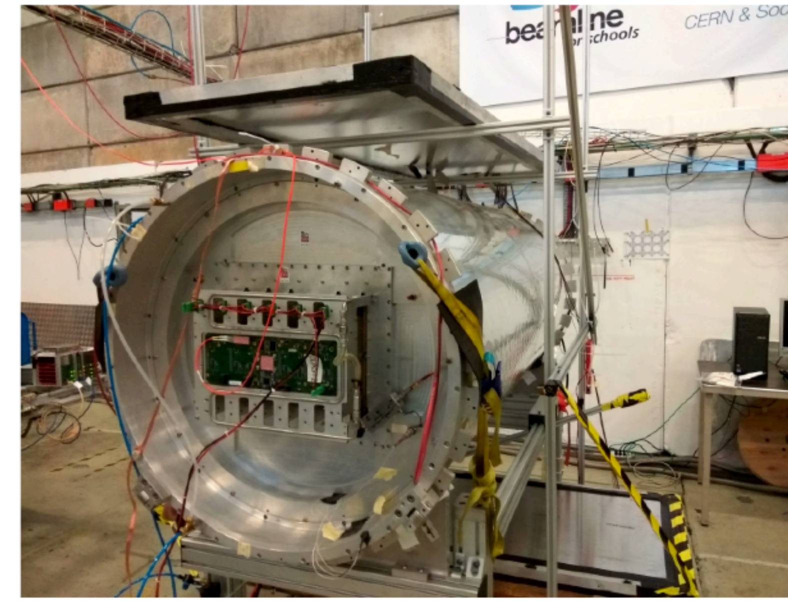
resistive anode MicroMegas

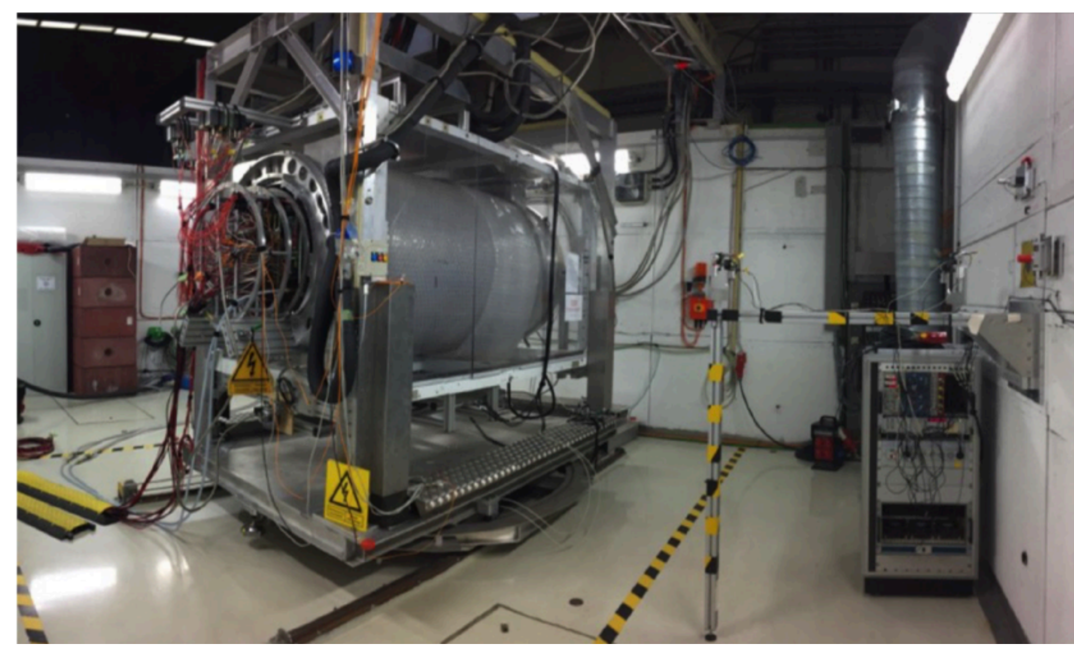


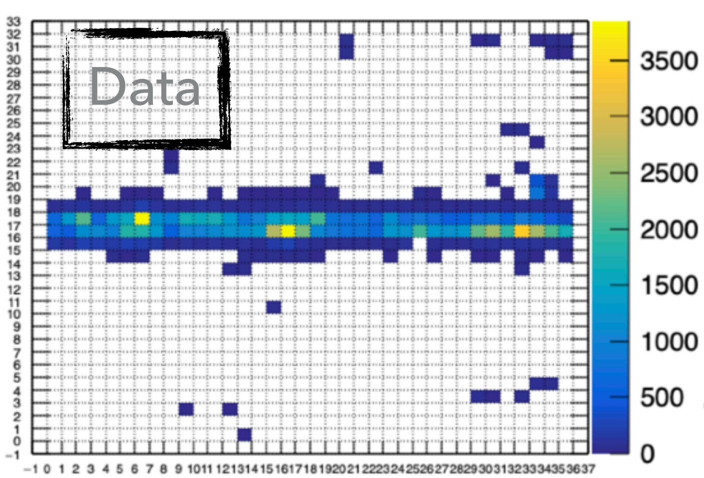
Originally designed for:

RESIDENTIAL TPC TESTS

- Several prototypes of the TPC with resistive anode were tested in:
  - CERN 2018 (10.1016/j.nima.2019.163286)
  - DESY 2020 (arXiv:2106.12634)
  - DESY 2021 (plots in the current talk)
    - *Large drift distance up to 1m*
    - *0.2 T magnetic field*
  - CERN November 2021
- The main goals of the tests are:
  - Setup stability tests
  - Spatial resolution
  - dE/dx resolution
  - Charge spread uniformity



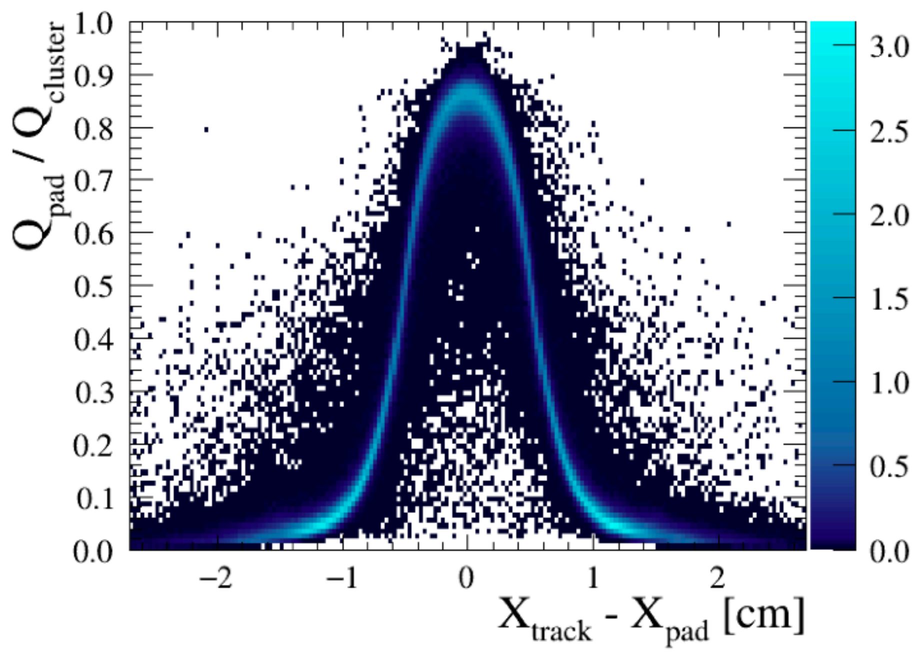




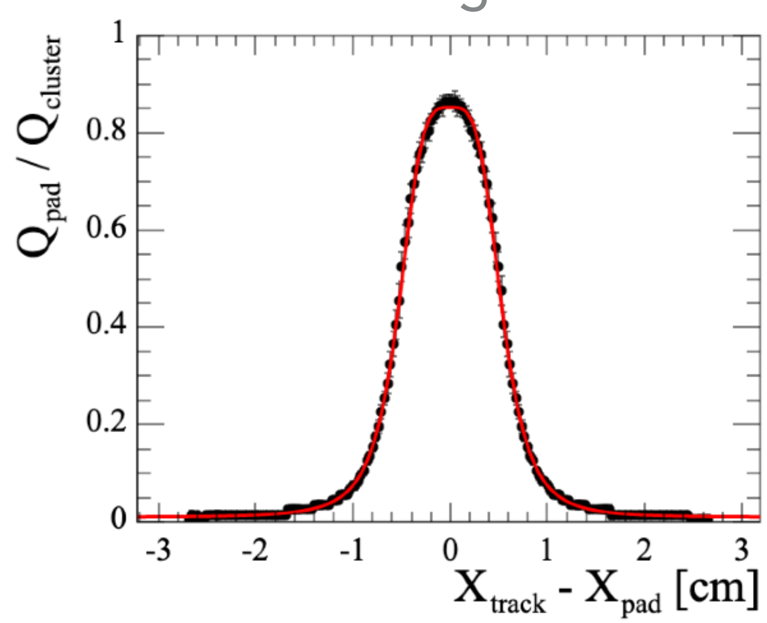
TRACK POSITION RECONSTRUCTION

- Track position was reconstructed with Pad Response Function (PRF) method
- PRF describes charge fraction $Q_{pad}/Q_{cluster}$ over the track position w.r.t. pad
- The prior position estimation is based on barycentrical method (Centre of charge)

Scatter plot

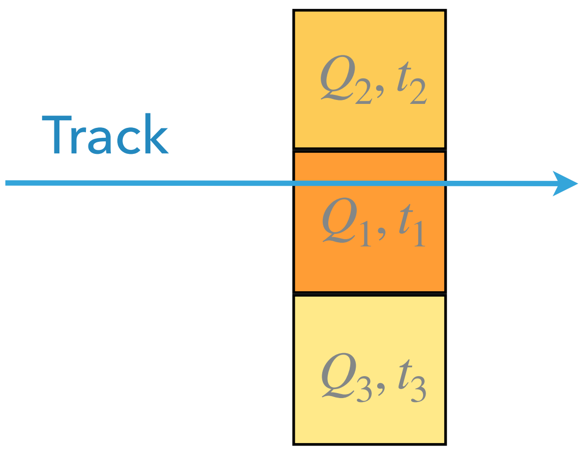


Profile along Y and fit



$$PRF\left(x,\Gamma,\Delta,a,b\right) = \frac{1 + a_2x^2 + a_4x^4}{1 + b_2x^2 + b_4x^4}$$

Charge sharing in a cluster:

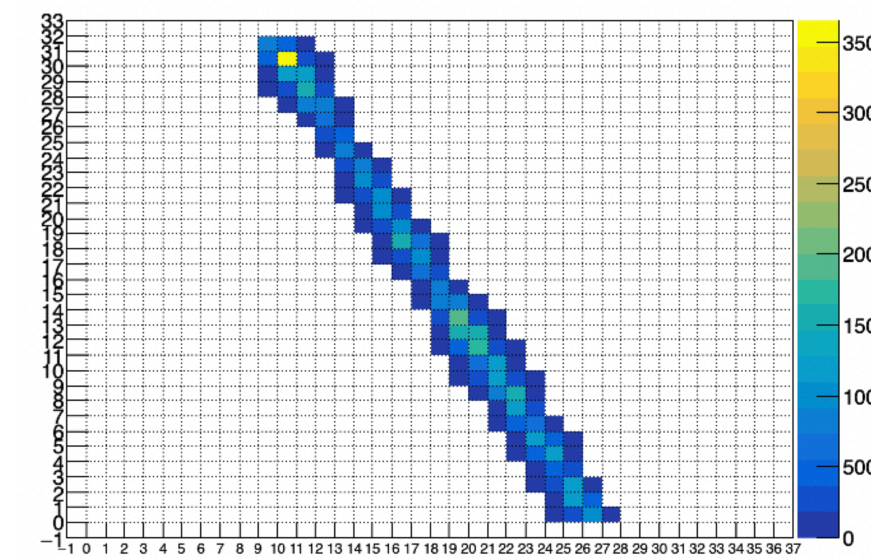


- The PRF is used in the fit to extract track position:

$$\chi^2 = \sum_{pads} \frac{Q_{pad}/Q_{cluster} - PRF\left(x_{track} - x_{pad}\right)}{\sigma}$$

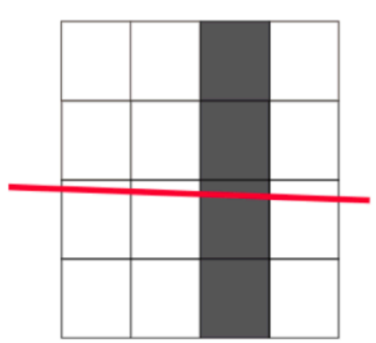
INCLINED TRACKS

- The reconstruction method is based on definition of the “cluster”
  - Inclined tracks are challenging for “cluster” definition
- Example:
  - considering column as a cluster for the inclined track will result in superposing many charge depositions –> can bias the reconstructed position

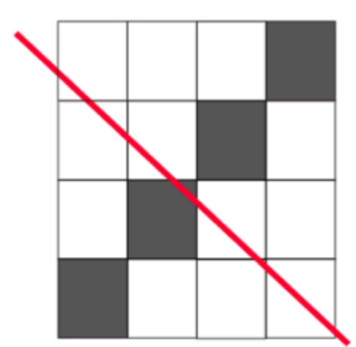


- Different “cluster” pattern was considered for the inclined tracks
  - Extract only transversal component of the charge spreading

Row/column



Diagonal

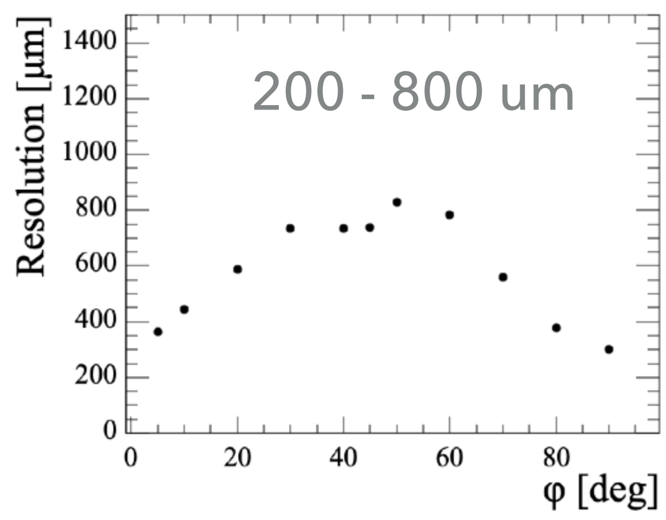


RESISTIVE TPC SPATIAL RESOLUTION

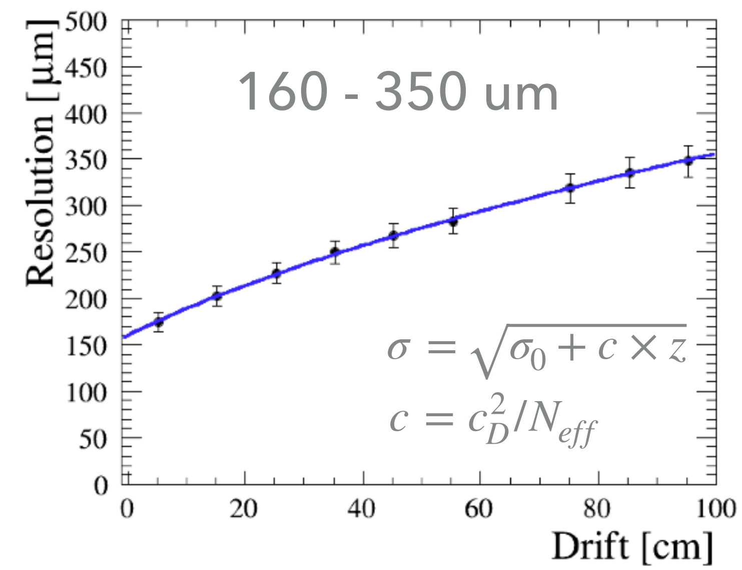
- The PRF method improves the performance over Centre of Charge
- The resistive TPCs are proved to provide better spatial resolution keeping pad size the same

Resistive Micromegas Prototypes

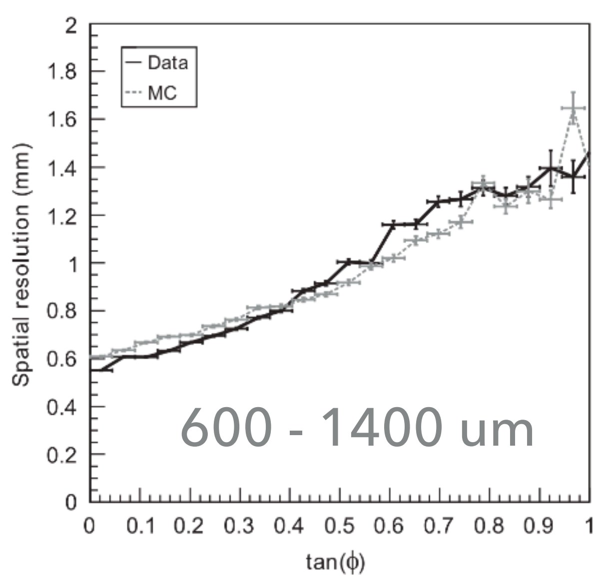
$drift = 5\ cm$

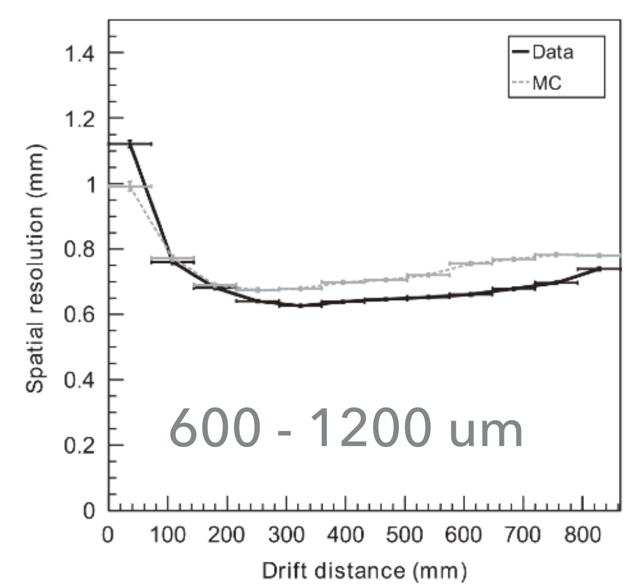


$\phi = 0°$



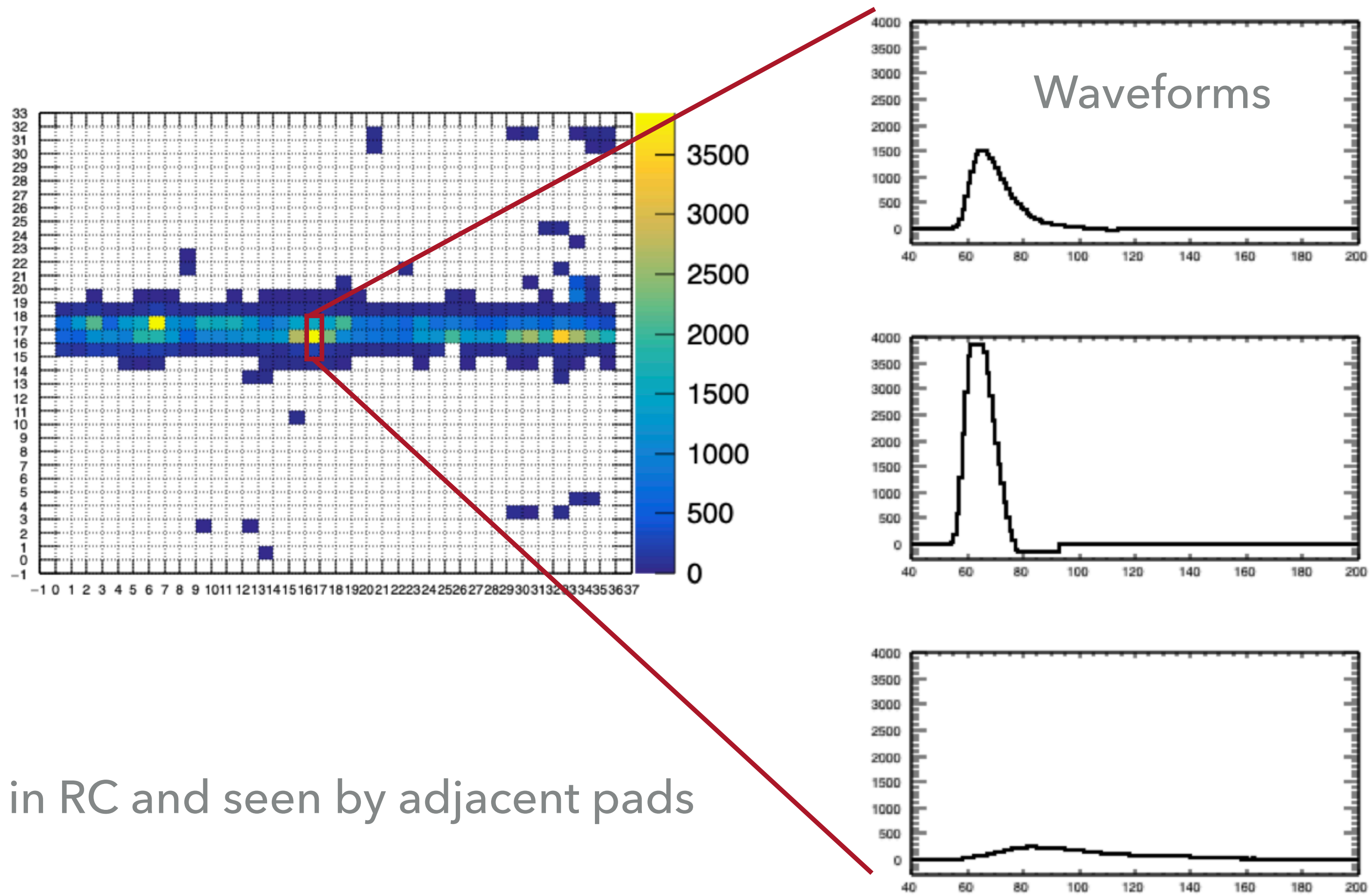
Bulk Micromegas (T2K)



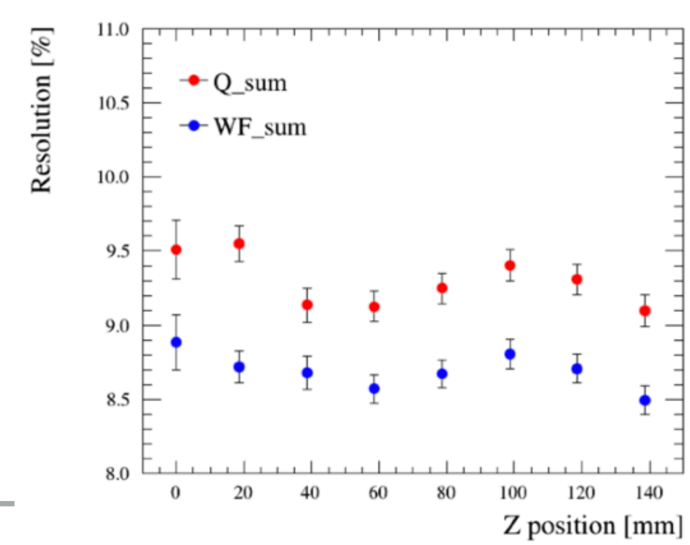


RESISTIVE TPC DE/DX RESOLUTION

- dE/dx measurements needs to be adapted for the resistive Micromegas
- The standard approach:
  - Charge in the pad is determined with maximum of the waveform
  - Charge in cluster (e.g. column) is summed up
  - Truncated mean is applied to extract average dE/dx and suppress spikes in energy deposition

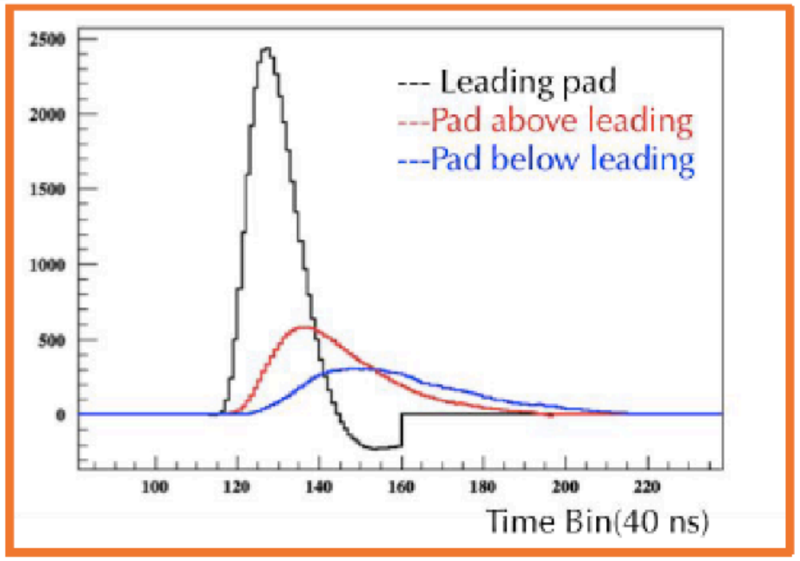


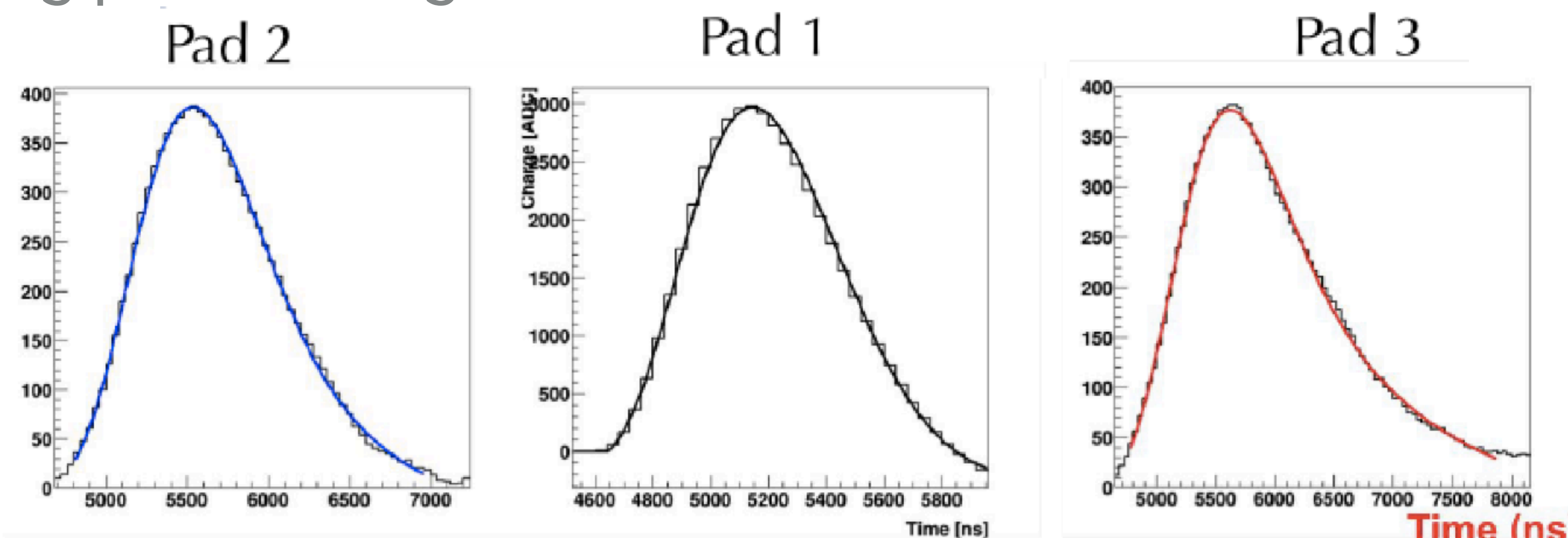
  - In resistive MM the charge is spread in RC and seen by adjacent pads –> can lead to double counting
  - Using the sum of the WFs in cluster was proved to provide a better dE/dx resolution
    - *Spread because of the diffusion is included*
    - *Spread because of resistivity is suppressed*



RC MAP

- By comparing signal in leading pad and neighbours the RC value was measured



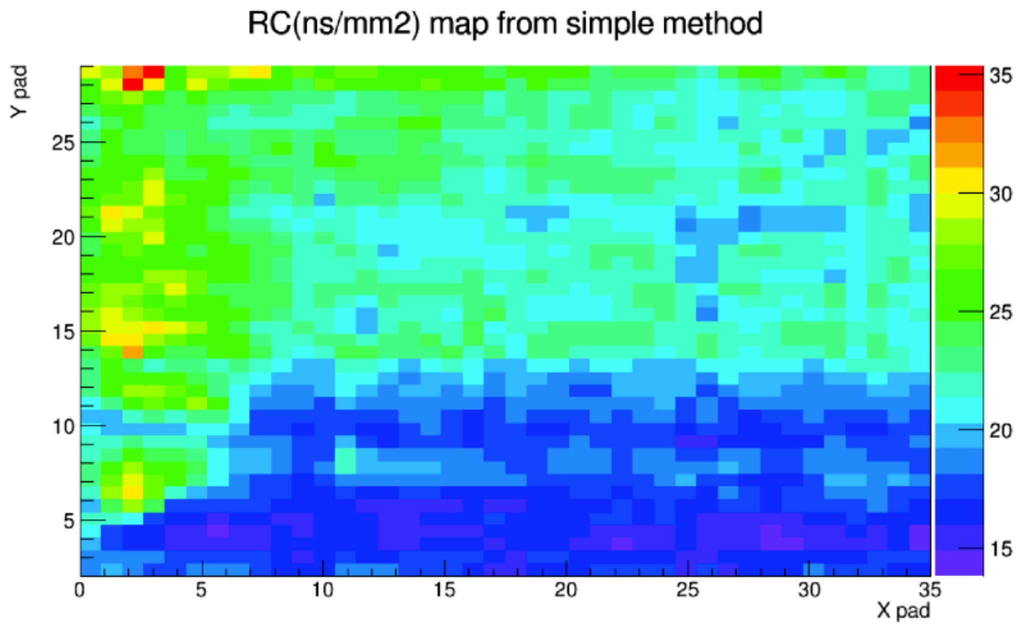


Fitted with A(t) x Q(t) | Fitted with A(t) | Fitted with A(t) x Q(t)

$$A(t) = A_{peak} \times \exp\left(-\exp\left(t - t_{peak} - a\right)/\tau_1\right)\right) \times \exp\left(\left(t - t_{peak}\right)/\tau_1\right) \times \sin\left(\left(t - t_{peak}\right)/\tau_2\right)$$

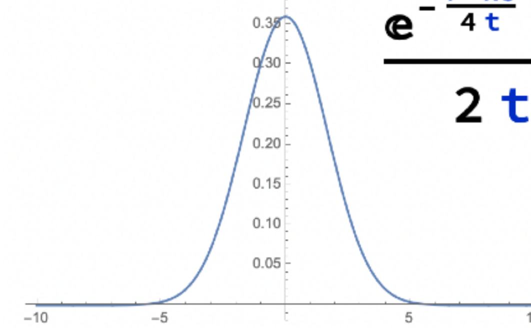
$$Q_{pad}(t) = \frac{Q}{4}\left[erf\left(\frac{x_{high} - x_0}{2\sigma(t)}\right) - erf\left(\frac{x_{low} - x_0}{2\sigma(t)}\right)\right]\left[erf\left(\frac{y_{high} - y_0}{2\sigma(t)}\right) - erf\left(\frac{y_{low} - y_0}{2\sigma(t)}\right)\right] \qquad \sigma(t) = \sqrt{\frac{2t}{RC}}$$

- **Leading pad** affected only by electronics $A(t)$
- Neighbours convolutes charge spreading with electronics $Q_{pad} \times A(t)$
- RC map was obtained from fit the equations above
  - y_0 was obtained with Pad Response Function (PRF)



SIMULATION

- The resistive foil effect can be approximated with RC chain, thus the charge spread is following the solution of diffusion equation
- To estimate charge in the pad Q(t) the integration over pad size is done



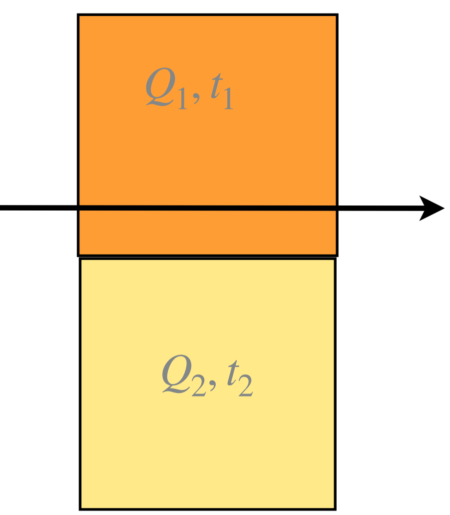
$$\frac{e^{-\frac{r^2\,RC}{4\,t}}\,RC}{2\,t}$$

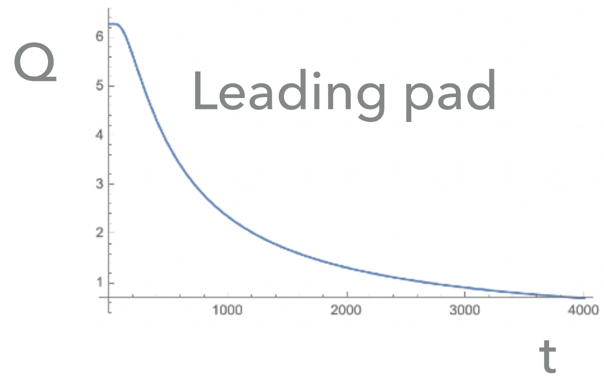
$$\frac{1}{2}\,\pi\left(\text{Erf}\left[\frac{\sqrt{RC}\;x1}{2\,\sqrt{t}}\right]-\text{Erf}\left[\frac{\sqrt{RC}\;x2}{2\,\sqrt{t}}\right]\right)\left(\text{Erf}\left[\frac{\sqrt{RC}\;y1}{2\,\sqrt{t}}\right]-\text{Erf}\left[\frac{\sqrt{RC}\;y2}{2\,\sqrt{t}}\right]\right)$$

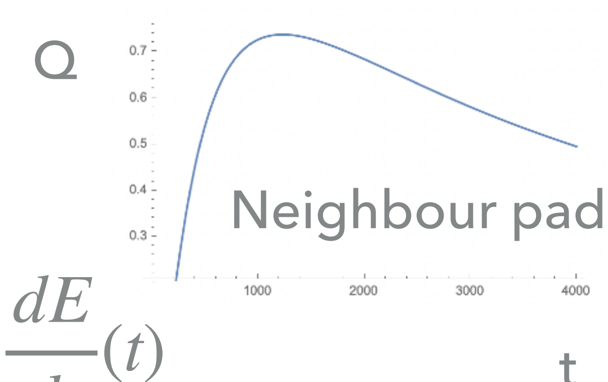
Electronics:

$$\frac{e^{-\frac{3\,\tau}{t_{shaping}}}\,\tau^3\,\text{Sin}\left[\frac{\tau}{t_{shaping}}\right]}{t_{shaping}^3}$$

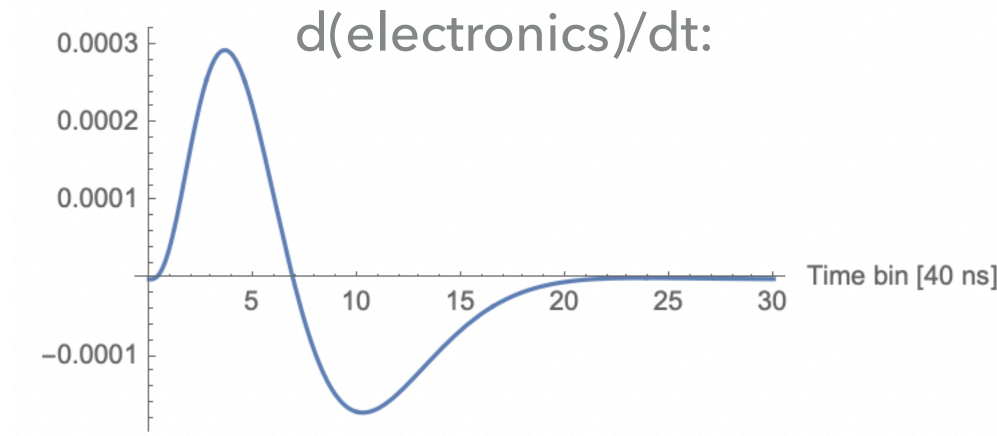
Cluster:



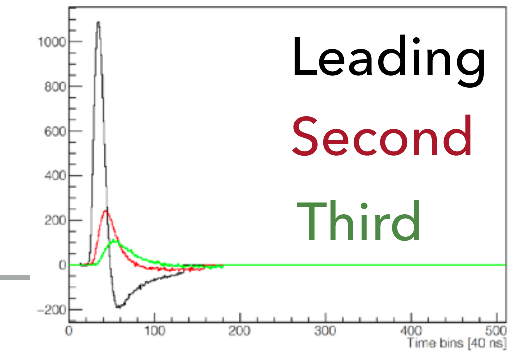




Convolution



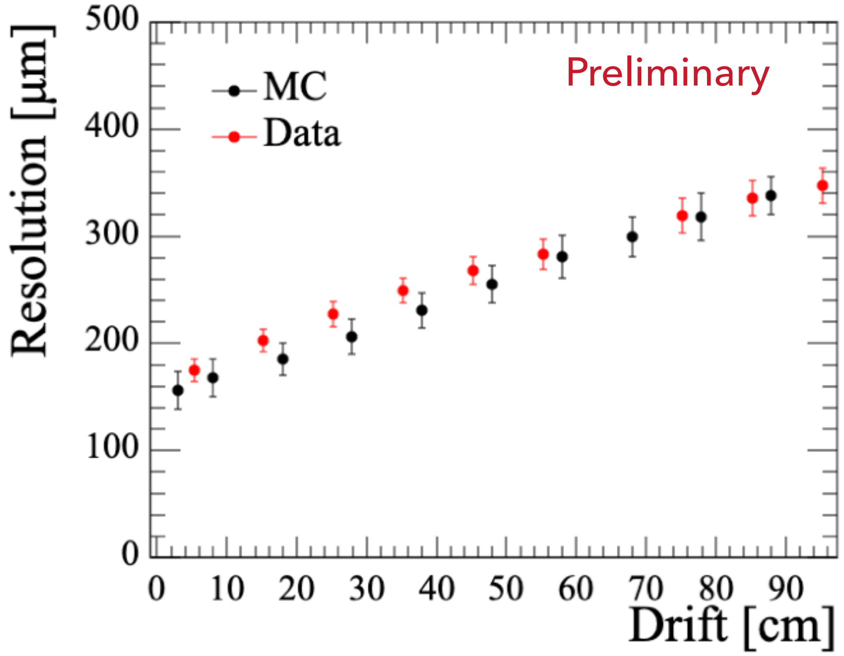
Output: waveforms

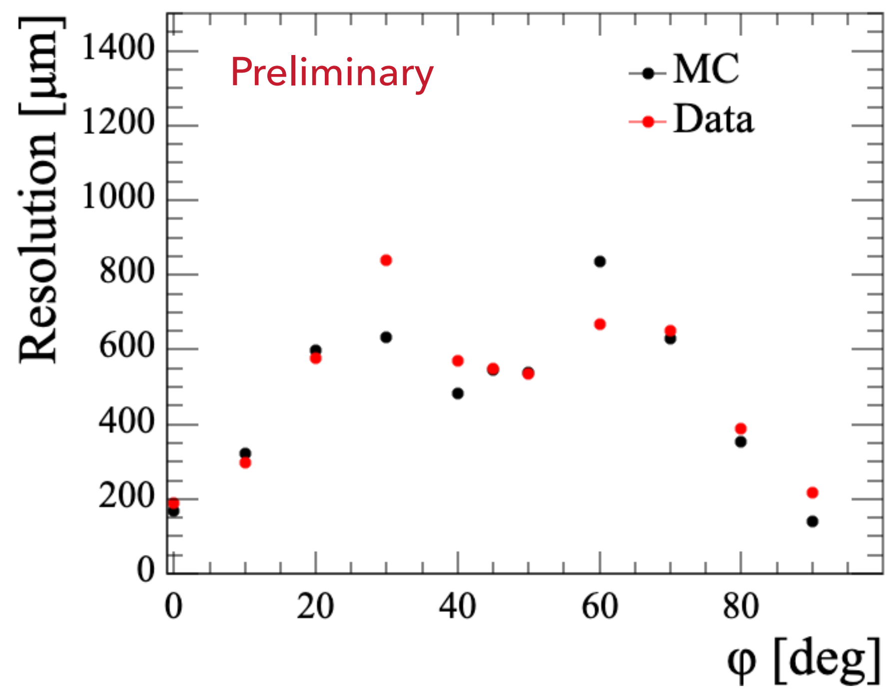


- $WF(t) = Q(t) \circledast \frac{dE}{dt}(t)$

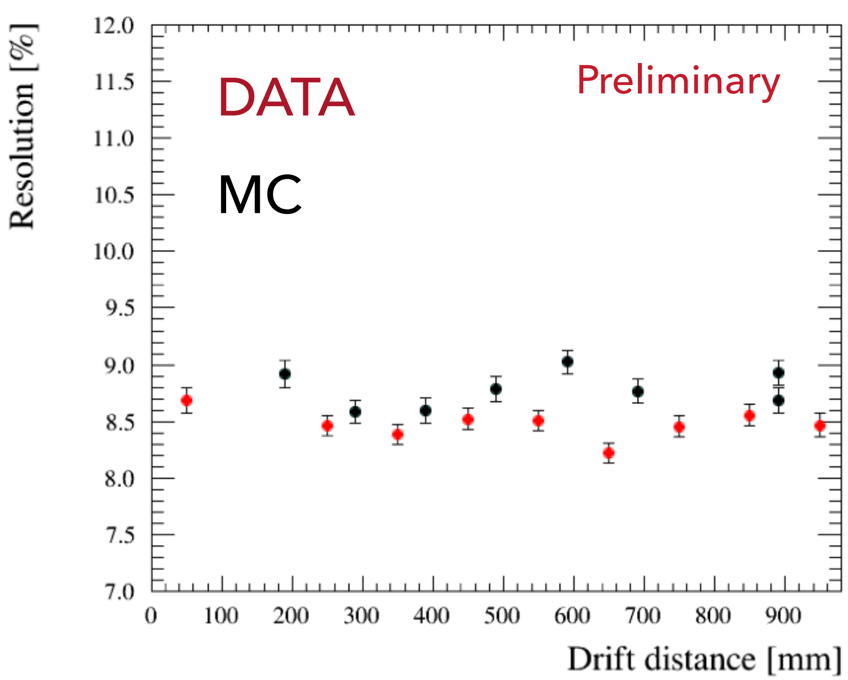
SIMULATION VALIDATION

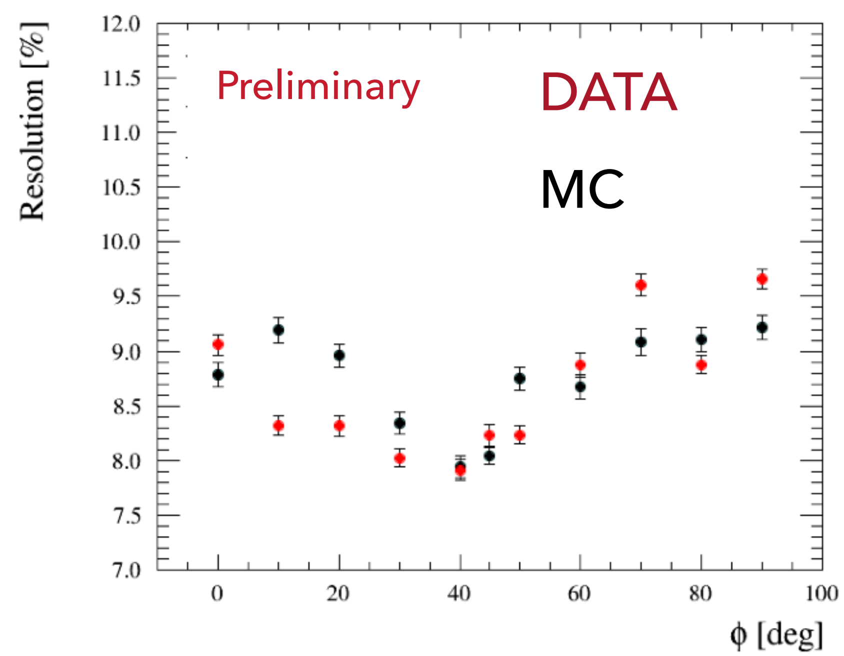
- Spatial resolution:



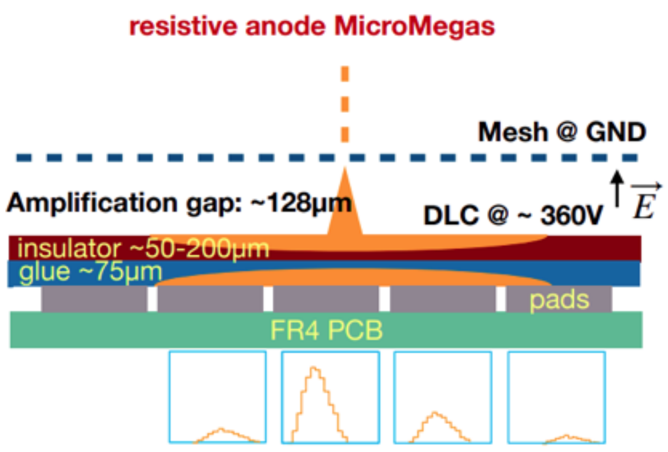


- dE/dx resolution:





SUMMARY



- Precise measurements of CP-violation in T2K experiment requires significant systematics reduction
  - Near detector upgrade program aims to reduce uncertainties in oscillation measurements 5% –> 3%

- TPC with resistive Micromegas R&D is finished and the production is ongoing
  - Various beam tests were performed
    - *Gain in detector capabilities was proved*
  - MC model of the detector was developed and validated with data
  - The physics requirements for T2K physics is met:
    - *< 9% dE/dx resolution for 1 module (< 6% for 2 modules)*
    - *< 800 um Spatial resolution (< 10% @ 1 GeV momentum resolution)*

- Detector assembly and commissioning at JPARC is scheduled in 2022

BACK UP

T2K COLLABORATION

~ 500 members, 68 Institutes, 12 countries

Canada
TRIUMF
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

CERN

France
CEA Saclay
LLR E. Poly.
LPNHE Paris

Germany
RWTH Aachen

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
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Tokyo Metropolitan U.
Tokyo U of Science
U. Tokyo
Yokohama National U.

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IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroclaw U.

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INR

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IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid

Switzerland
ETH Zurich
U. Bern
U. Geneva

United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
Royal Holloway U.L.
STFC/Daresbury
STFC/RAL
U. Glasgow
U. Liverpool
U. Sheffield
U. Warwick

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Duke U.
U. Houston
Louisiana State U.
Michigan S.U.
SLAC
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pennsylvania
U. Pittsburgh
U. Rochester
U. Washington

Vietnam
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