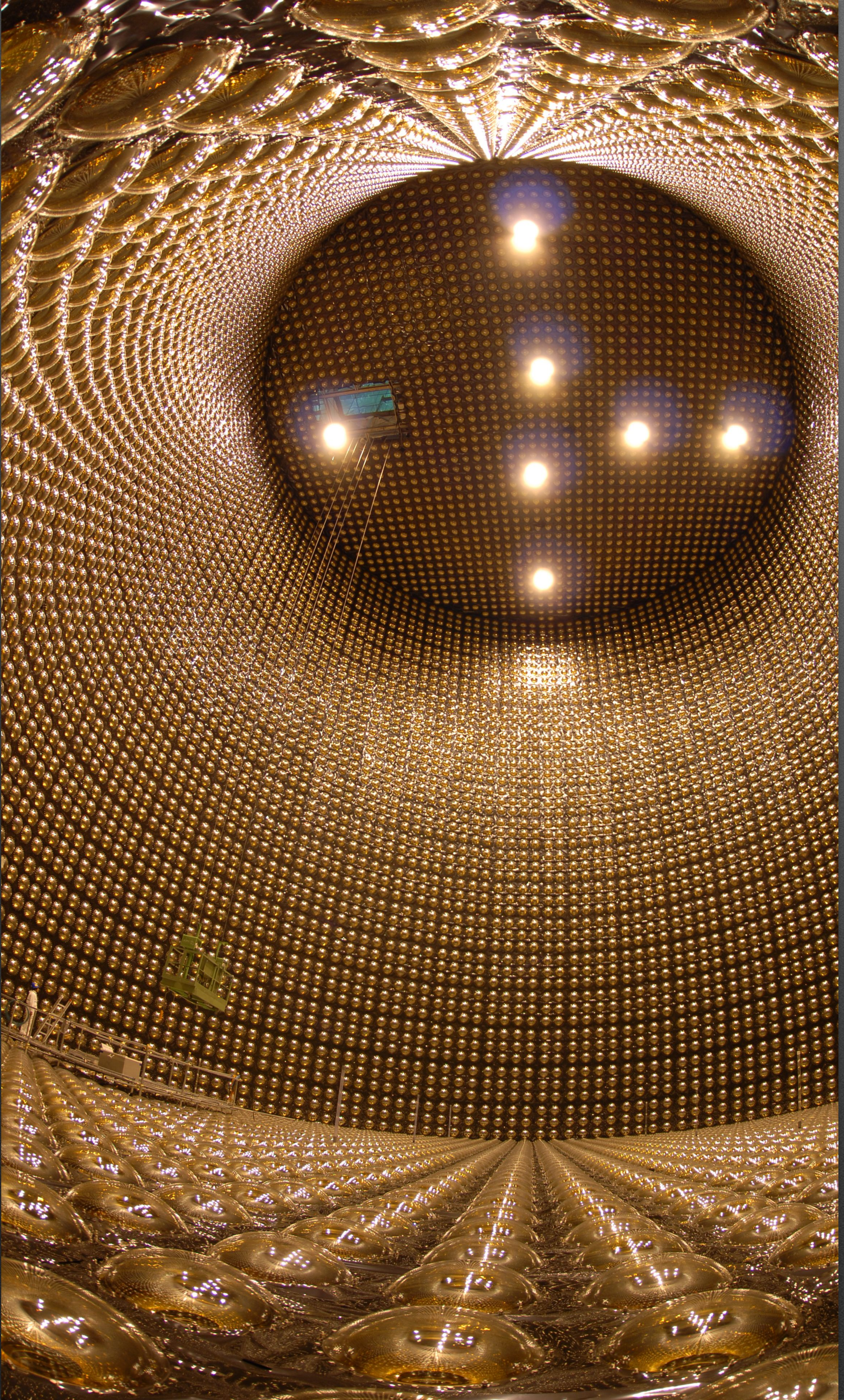


Search for CP violation in the T2K long baseline neutrino oscillation experiment

NGUYEN Quoc Viet

Comité de thèse - 1ère réunion

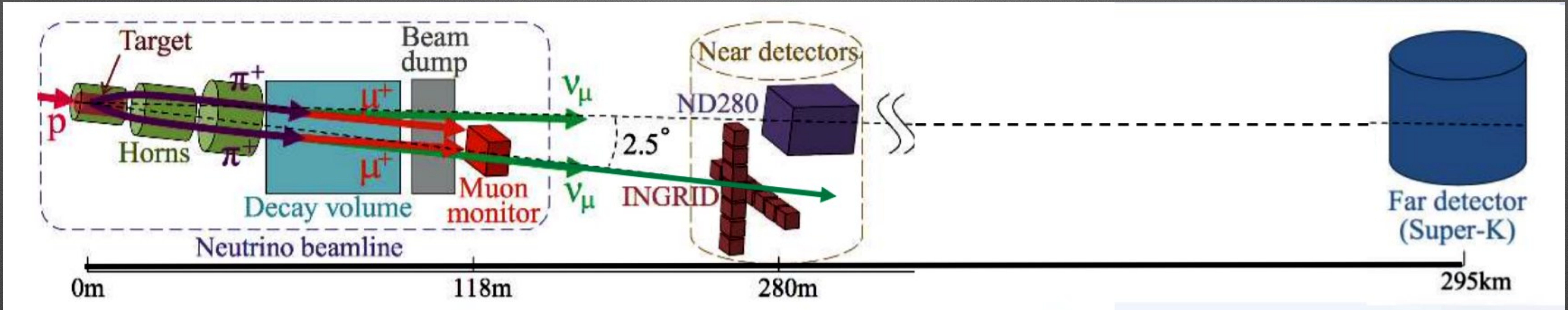
12/05/2020

Content

To save time:
some of the results are in back up

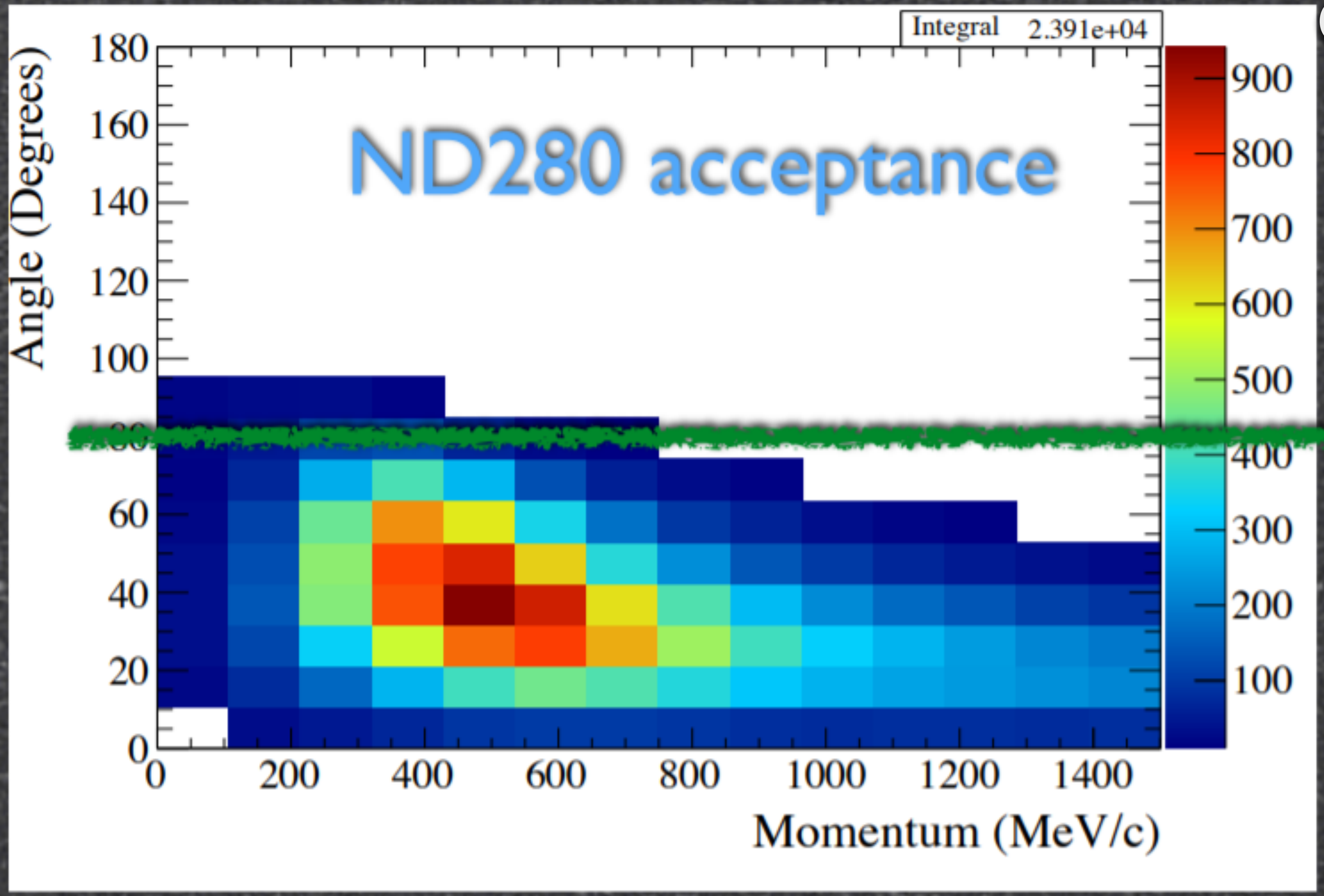
- T2K introduction
- Near detector (ND280) upgraded program, motivation
- High Angle TPC (HA-TPC) desy test beam analysis:
  -dE/dx resolution studies.
  -Gain and time uniformities.
  -Drift velocity.
- Physics studies for ND280 upgrade, Quantitative sensitivities to neutrino-nuclei interaction mode.
  -Studying the sensitivity of neutrino-nucleus interaction models to key parameters' errors
- Future plan + Courses and Training

T2K experiment

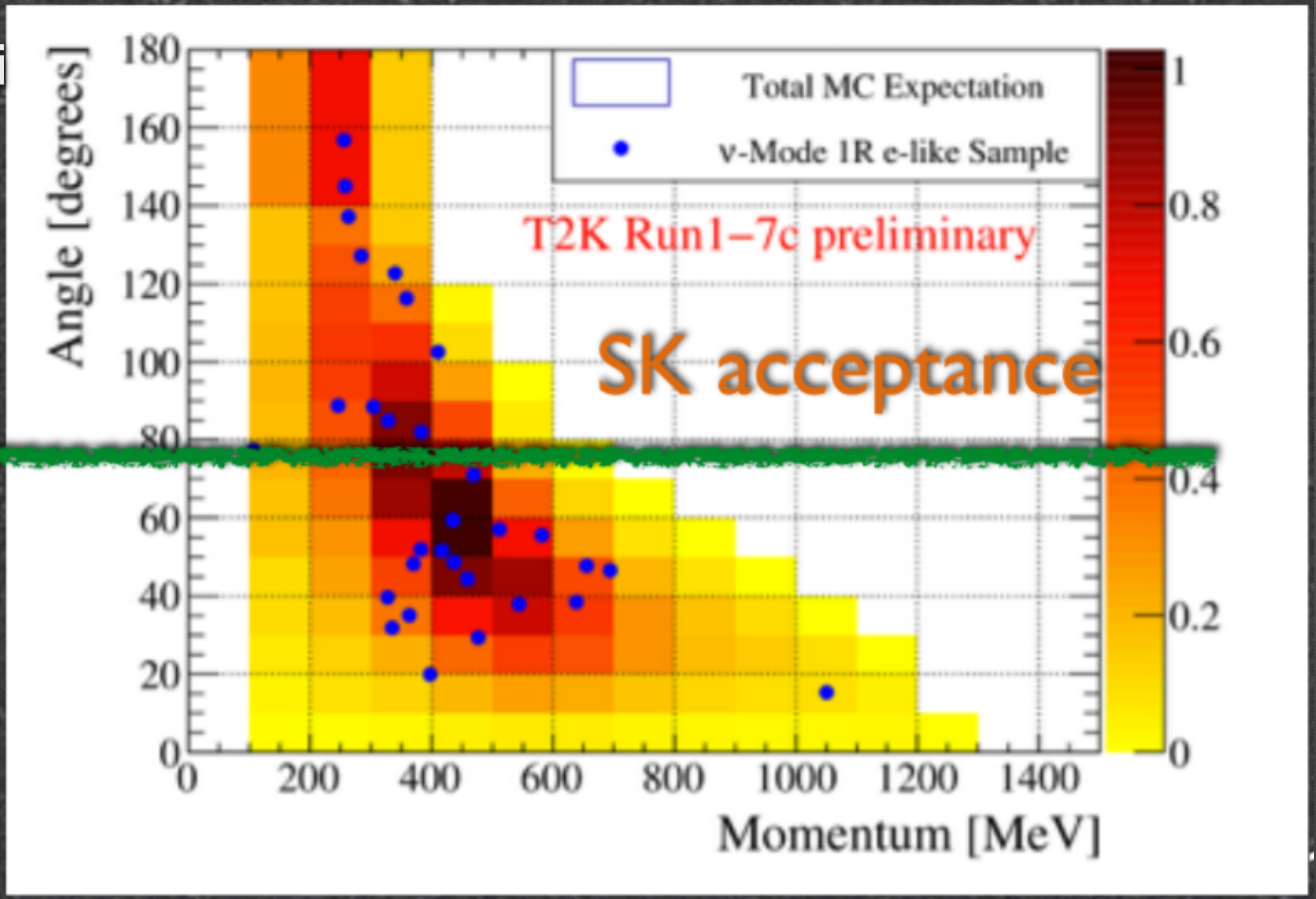


- T2K (Tokai to Kamioka) is a long-baseline neutrino experiment in Japan, and is studying neutrino oscillations.
- The current goal of T2K is searching for the CP violation in the lepton sector by comparing the appearance probabilities of neutrino and antineutrinos. (By changing the direction of magnetic field in the horn, we are able to create whether neutrino beam or anti-neutrino beam later.)
- T2K is under an upgrade program for the near detector ND280 (upgraded ND280)

ND280 upgrade motivation



C. Giganti



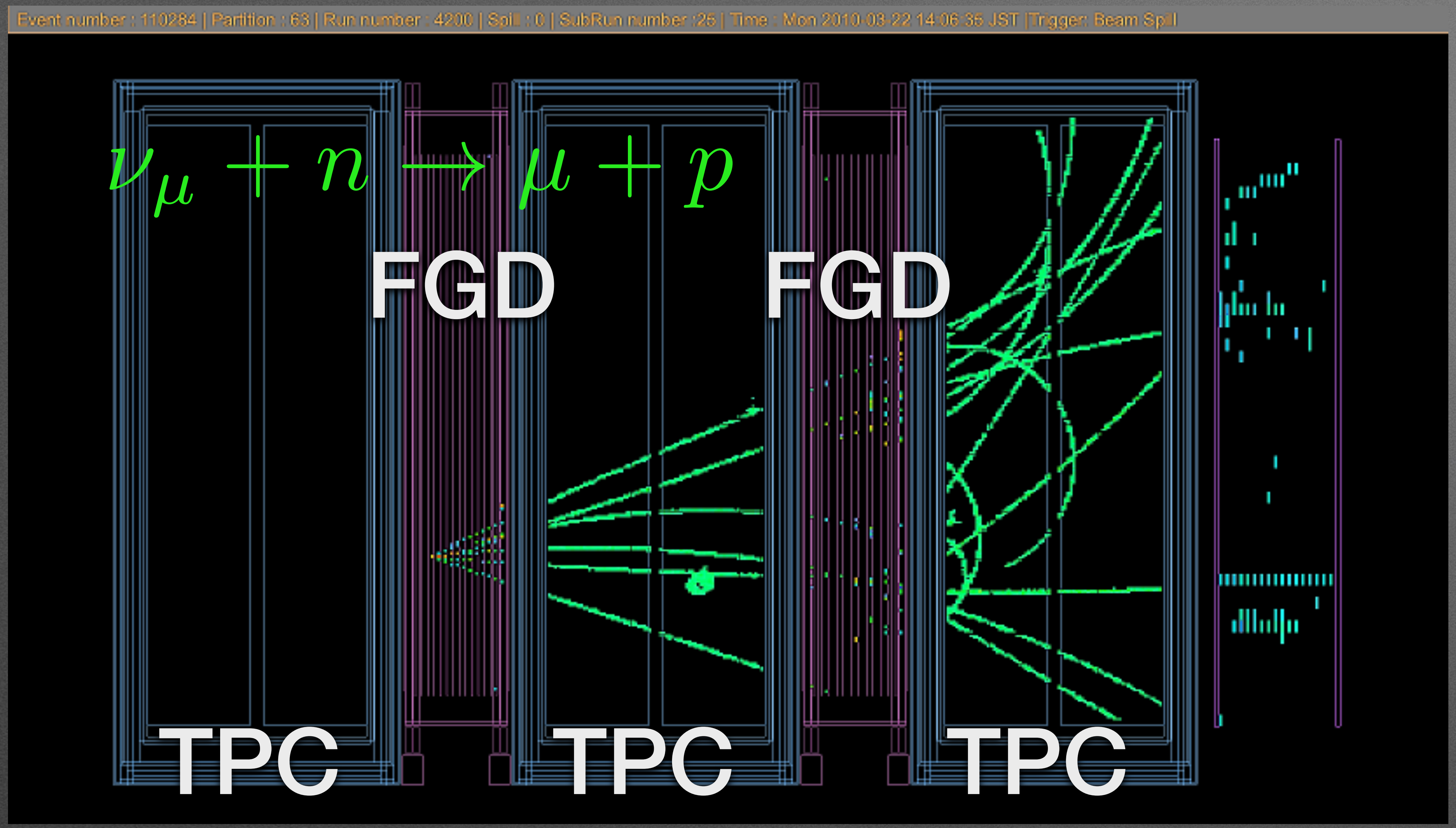
T2K ND280 upgrade aim:

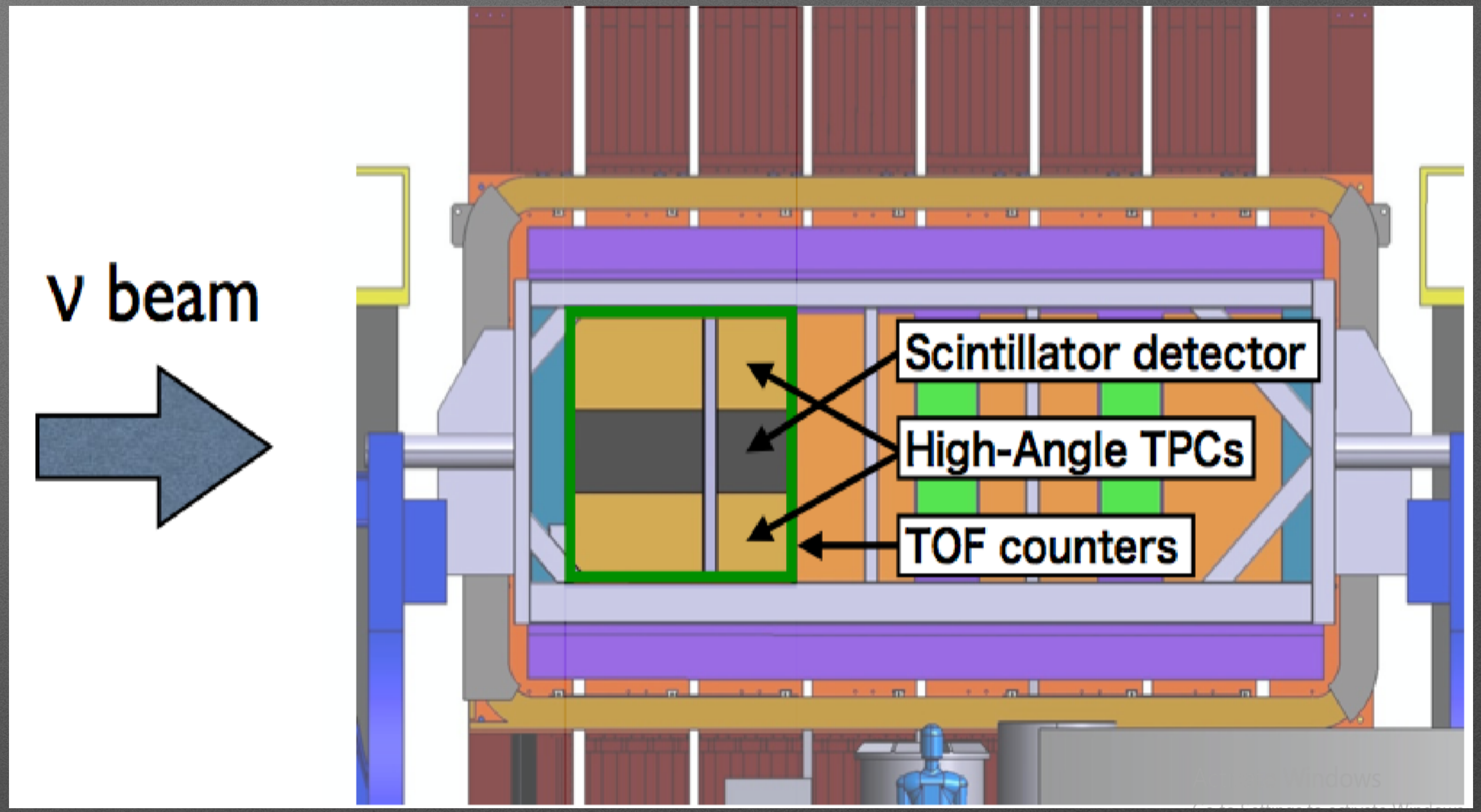
- Cover the full polar angle for the out going charge leptons.
- Measure ν_μ and ν_e cross-sections.
- Address the issue of nuclear effects and their impact on energy reconstruction.

new design with efficiency is comparable with SK and reduce the uncertainties.

SK: Super Kamiokande

Upgraded near detector ND280



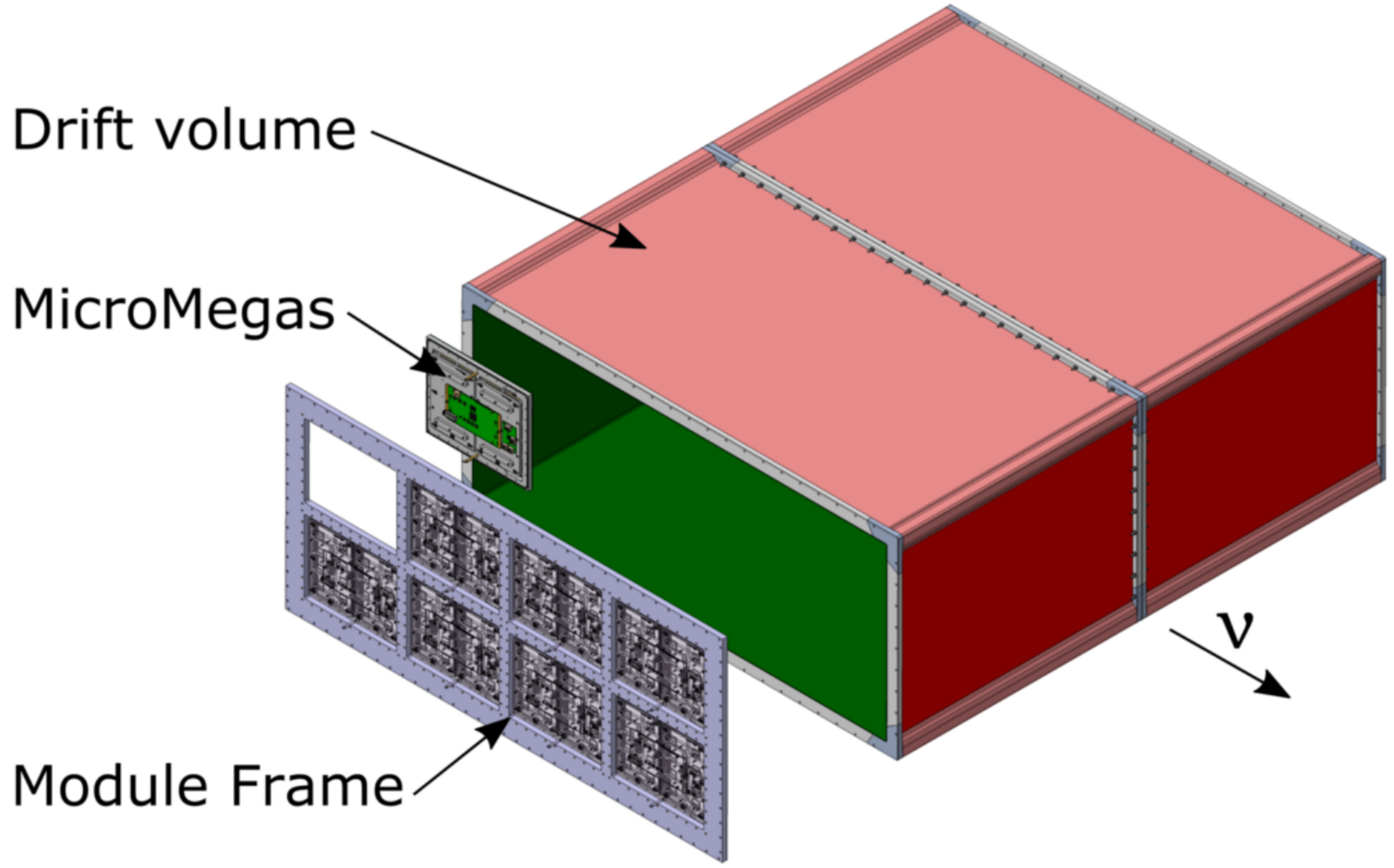


FGD: Fine Grain Detector
TPC: Time Projection Chamber

- Near Detector is used to determine the neutrino flux (normalization and energy spectrum) and neutrino cross section.
- In order to have better coverage in the new configuration => Need to add High-Angle TPCs to measure the large angle tracks

DESY test beam analysis for High Angle TPC (HA-TPC)

This work is following what I did in the Master 2 internship with CERN Test Beam for which results have been published in Nucl.Instrum.Meth.A 957 (2020) 163286

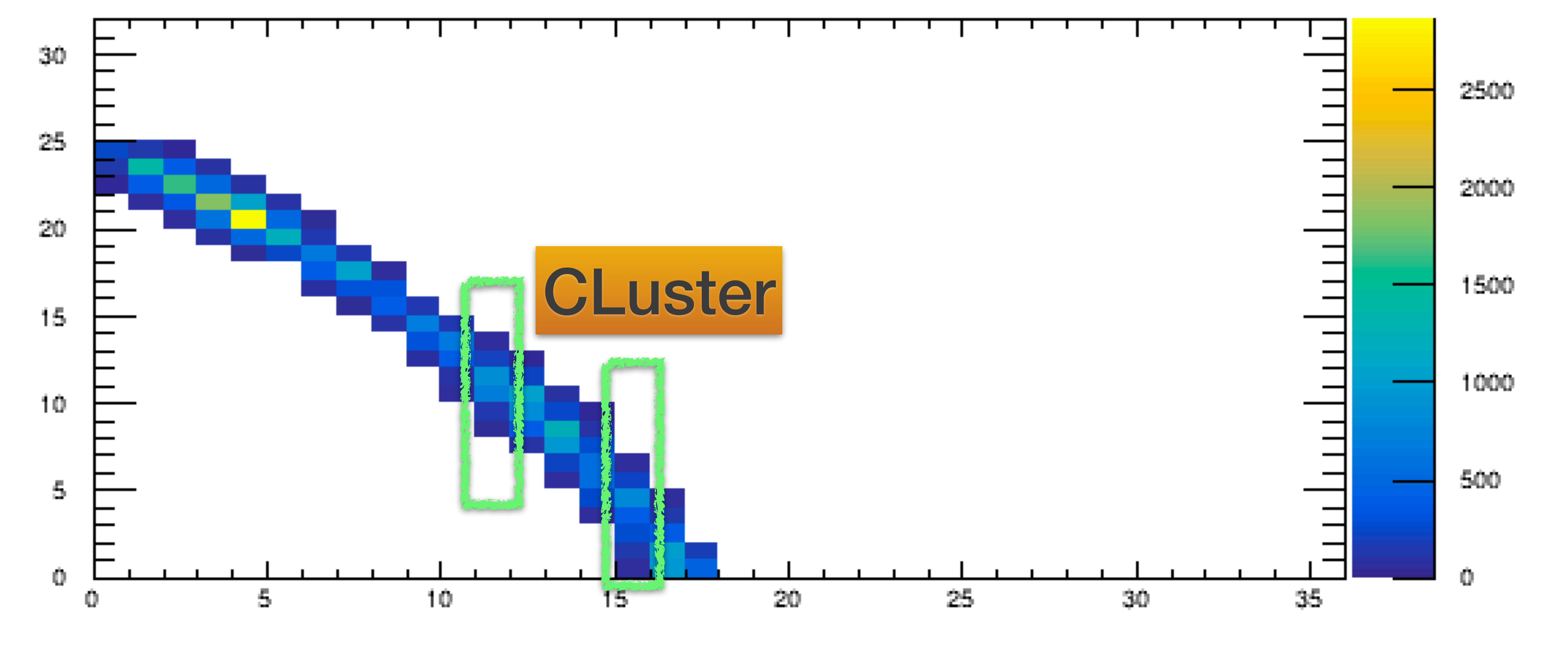


High-Angle TPC contains a new type of detector which is the Resistive MicroMegas.

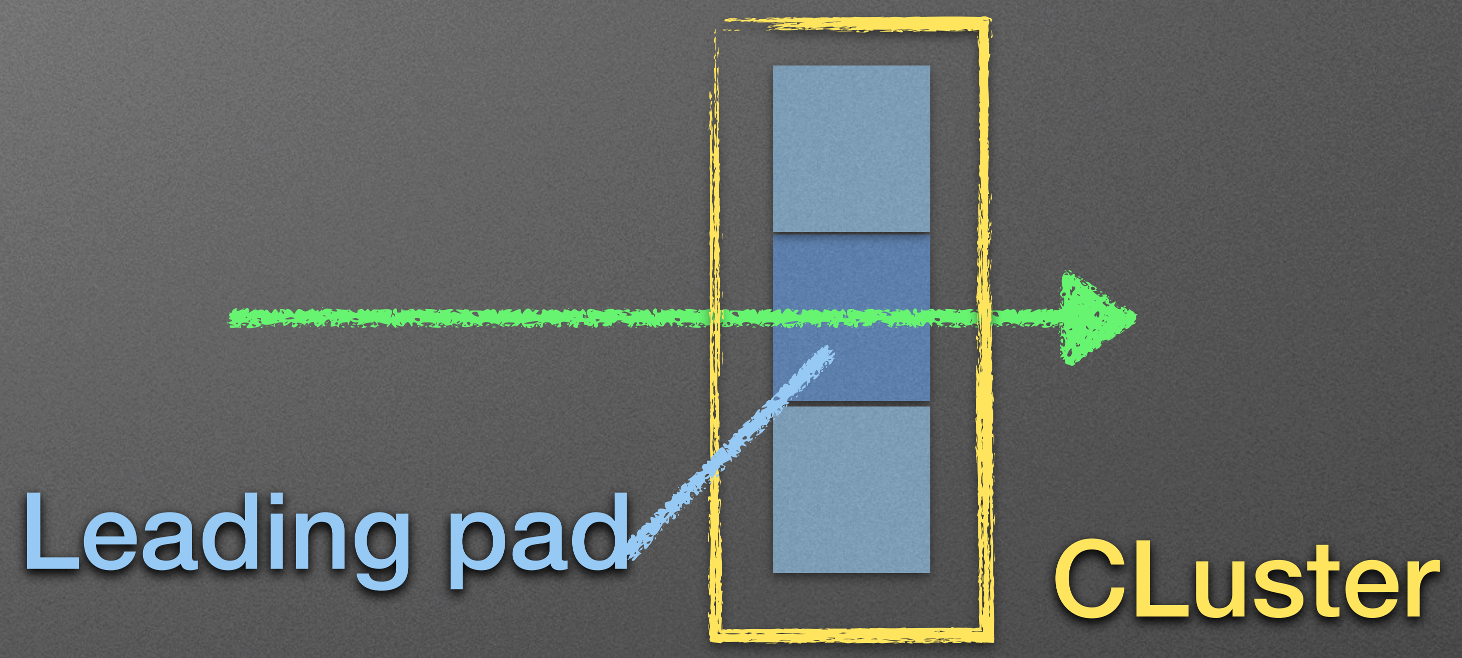
In Summer 2019, a TPC prototype has been tested by using beams from DESY.

- Test beam was high energy electron beam (1-5GeV), short chamber (15 cm drift distance)
- Scan in in the detector plane and along drift distance
- Scan in angle: 0, 20, 30, 45, 60, 80 degree MicroMegas rotation

dE/dx studies

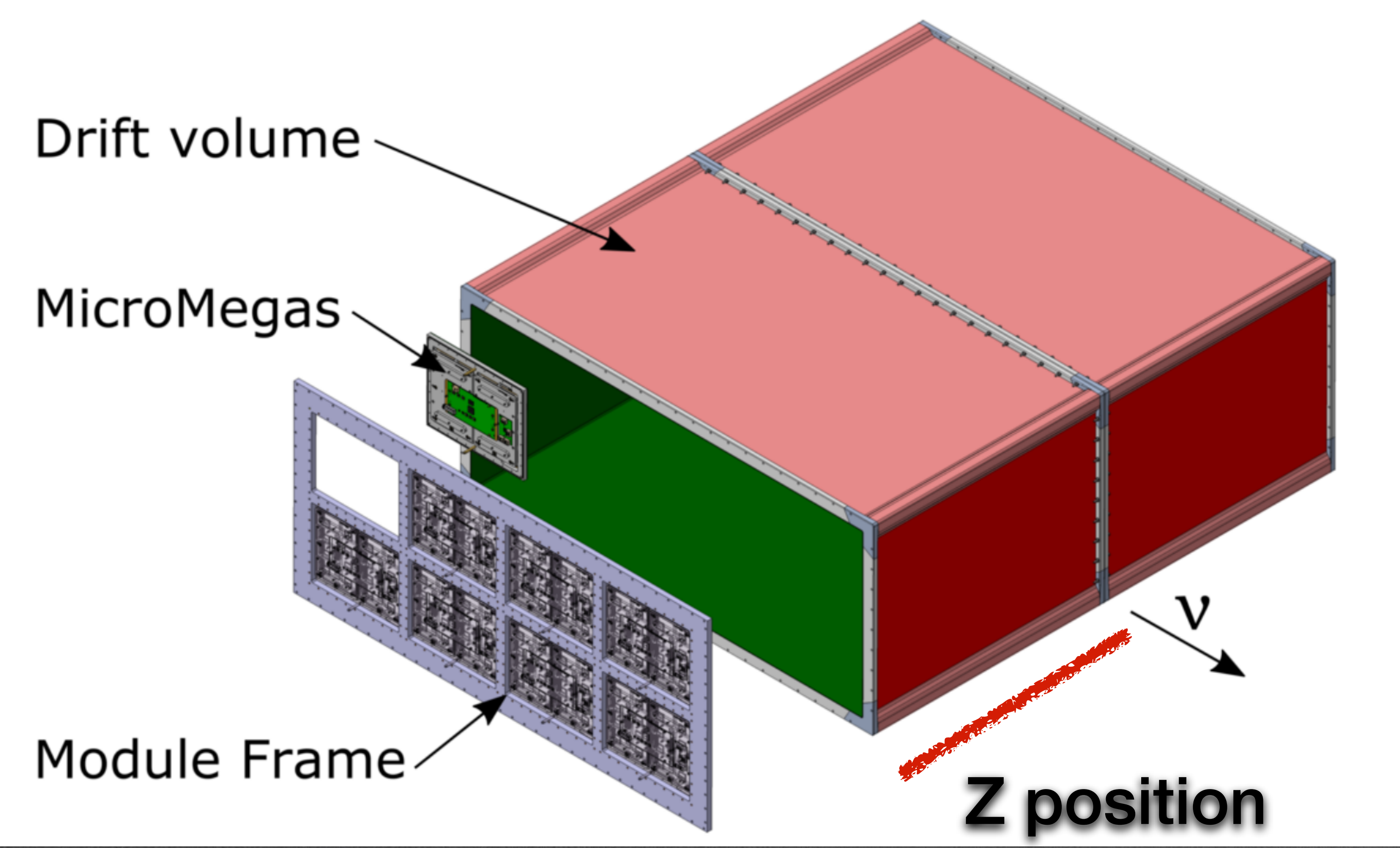


There are 36*32 pads

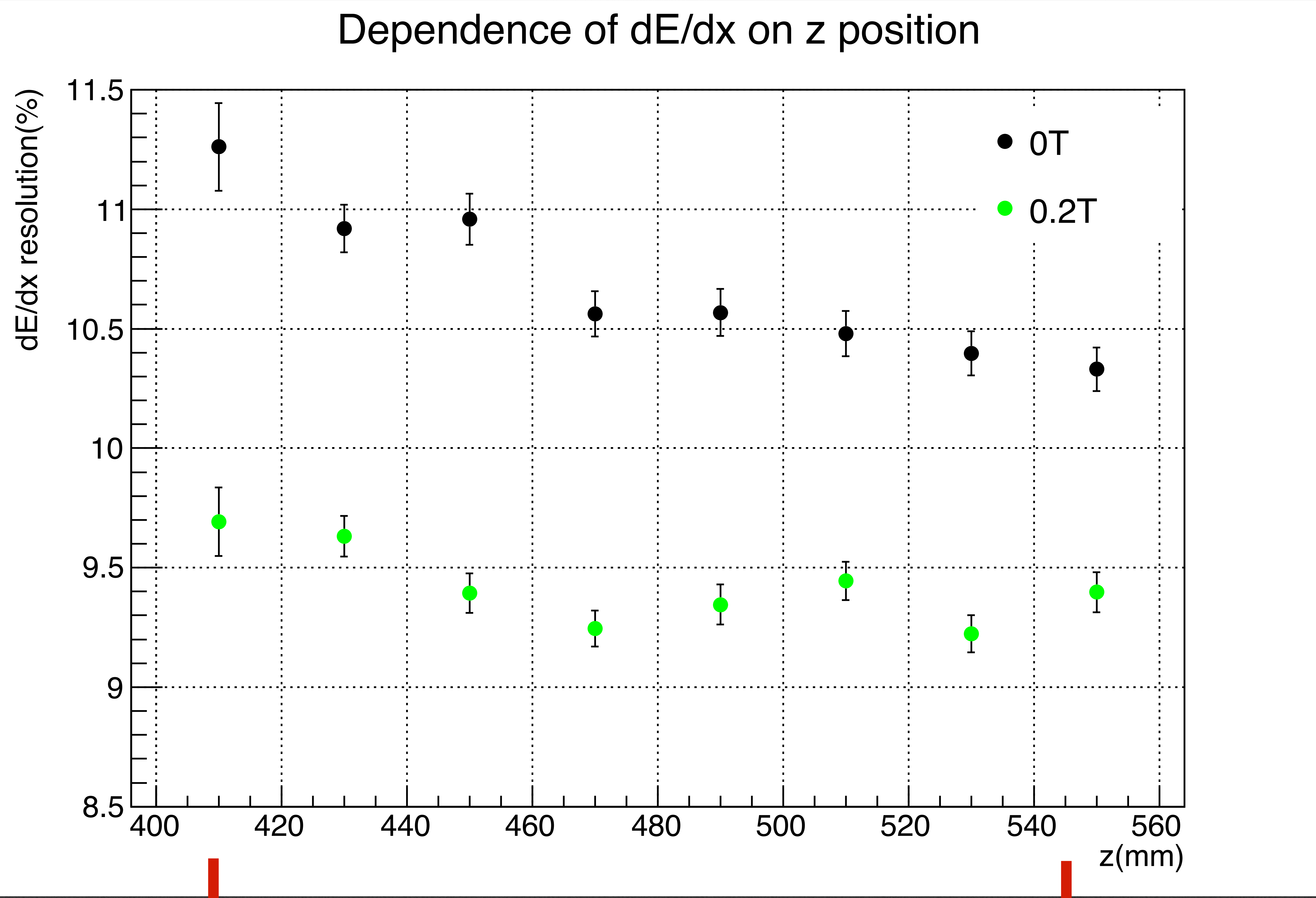


- The charge deposited not only in one pad but in surrounding pads too. Thus we consider cluster of pads to calculate charge => There are 36 clusters.
- Eliminate the very high deposited charge, due to fluctuation and can bias our mean value, by using truncated method (simply cutting an amount of clusters with highest charge, for example the truncated fraction is 0.8 means that we cut 20% of the highest charged clusters).
- Then calculate the dE/dx resolution.

dE/dx resolution wrt on z position and magnetic field



Z position: position of the test tracks wrt MicroMegas module



dE/dx resolutions are supposed to be the same with different z position. We must ignore the ones at the beginning and ending due to the border effect.

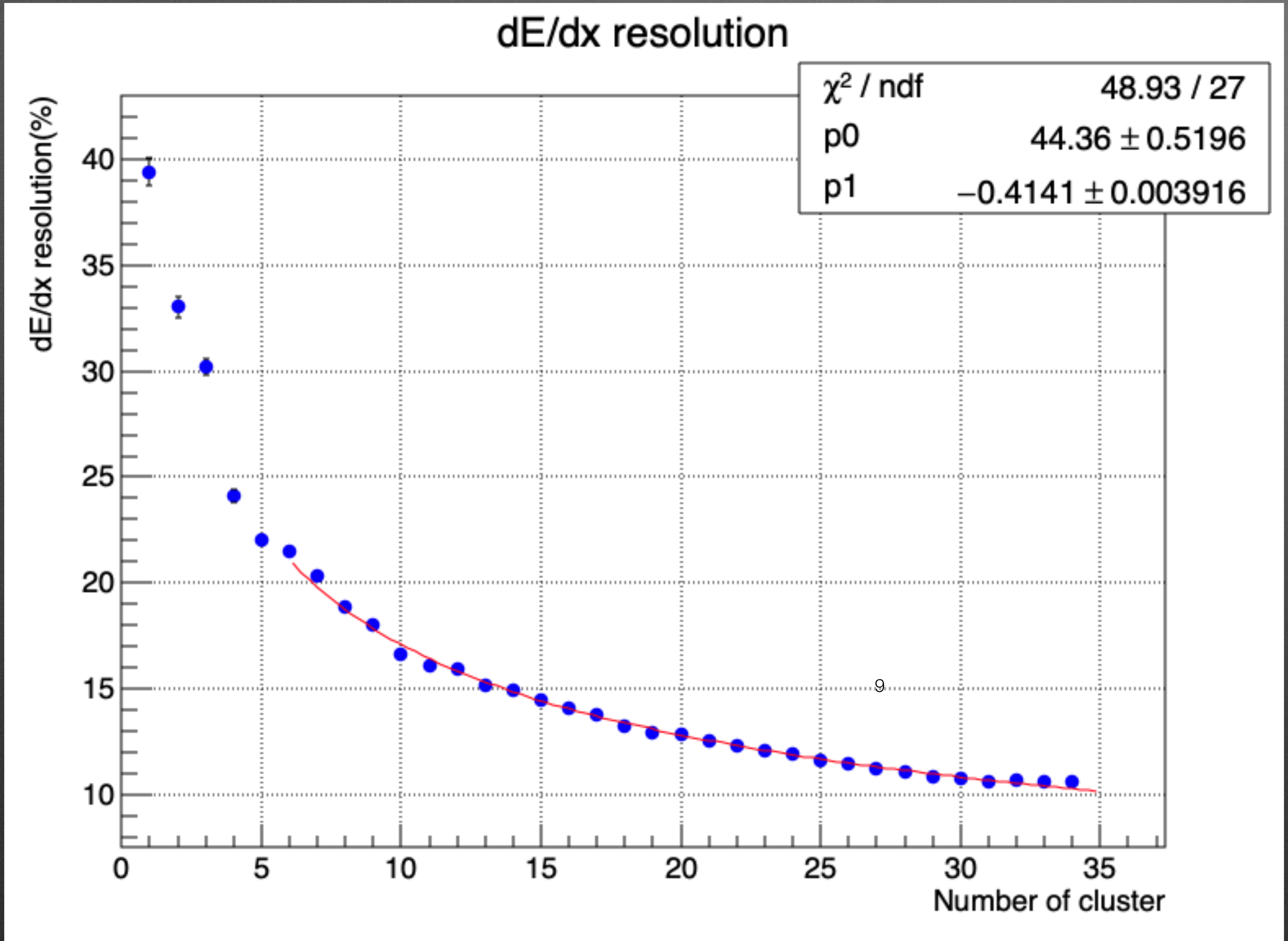
dE/dx resolutions with magnetic field are better than without magnetic field, because of the less diffusion

Distance ~ 0cm to Micromegas

The test was done with
0T: Without magnetic field
0.2T: The current magnetic field applied for ND280

Distance ~ 15cm to Micromegas

dE/dx resolution wrt number of clusters

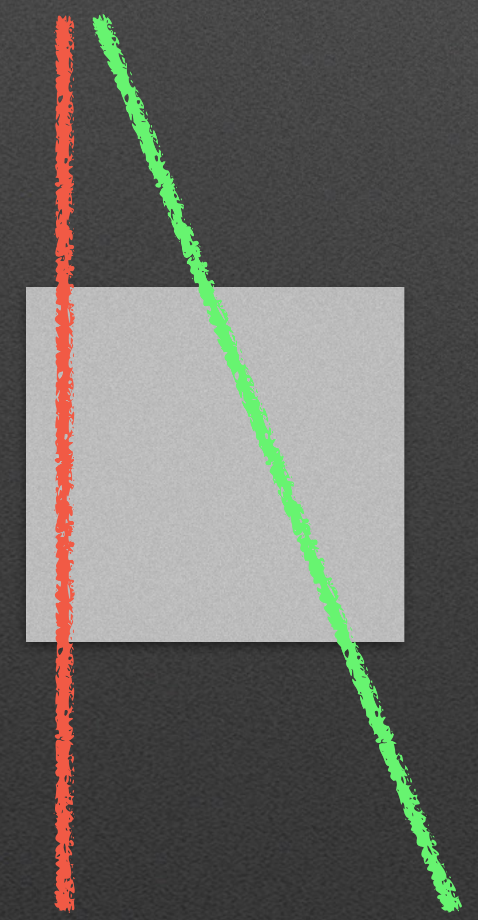


Number of cluster

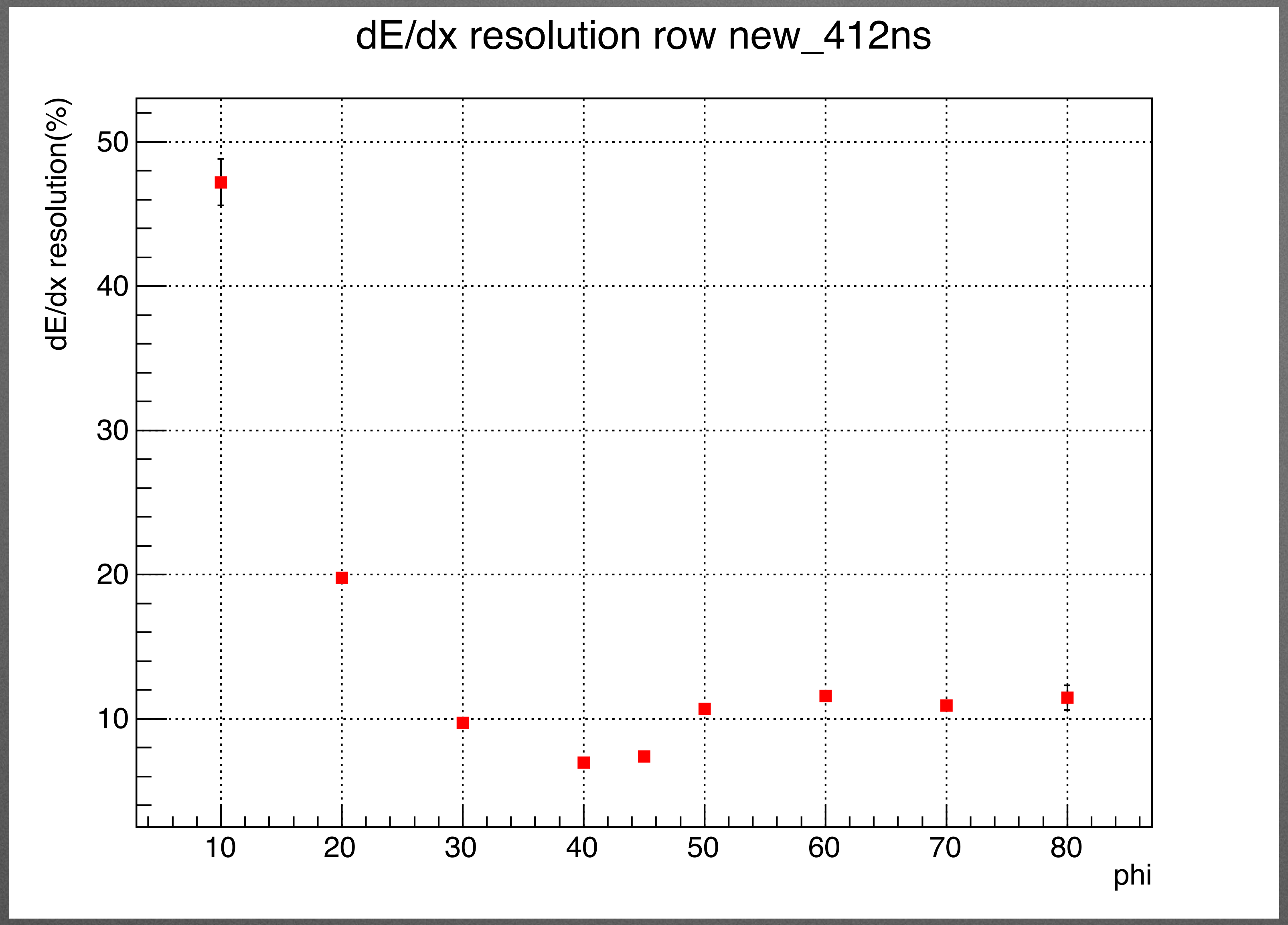
dE/dx resolution wrt number of clusters.
This plot helps to extrapolate the resolution for the bigger MicroMegas with more clusters.

dE/dx wrt angles

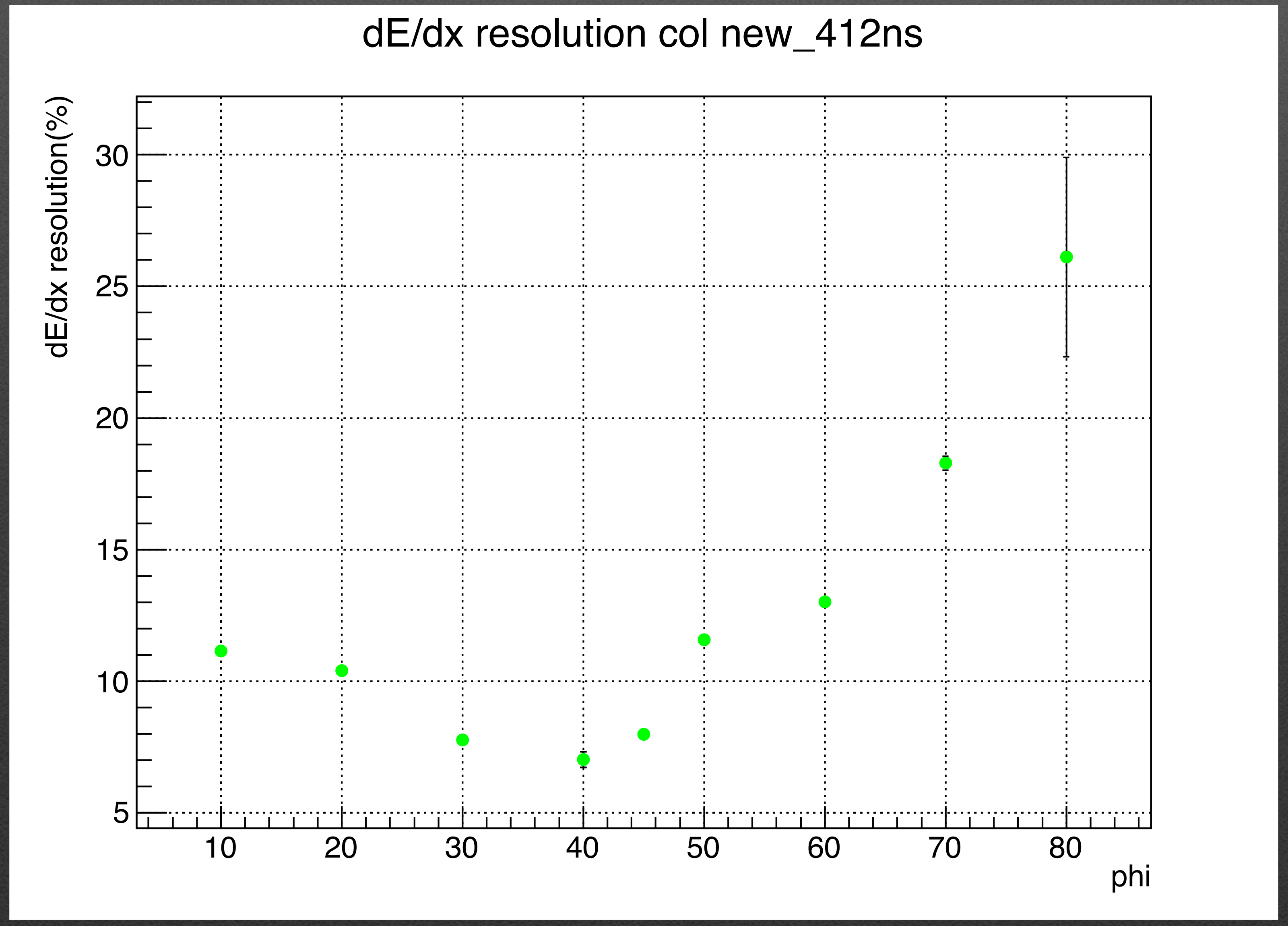
Why need to test with angles?



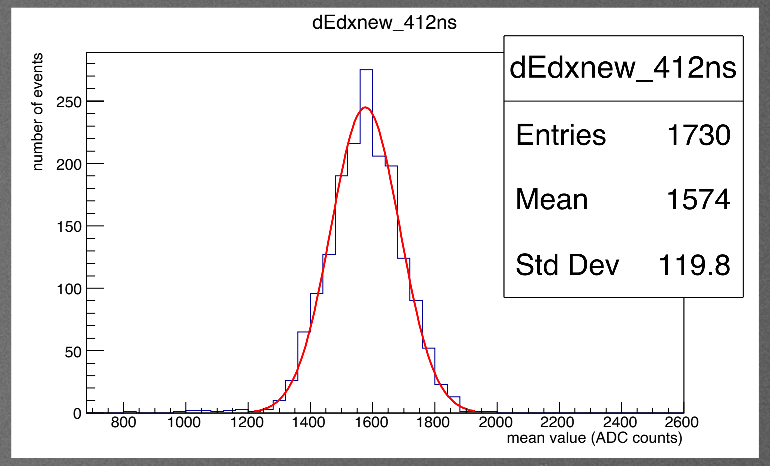
Pad receive more charge with green track

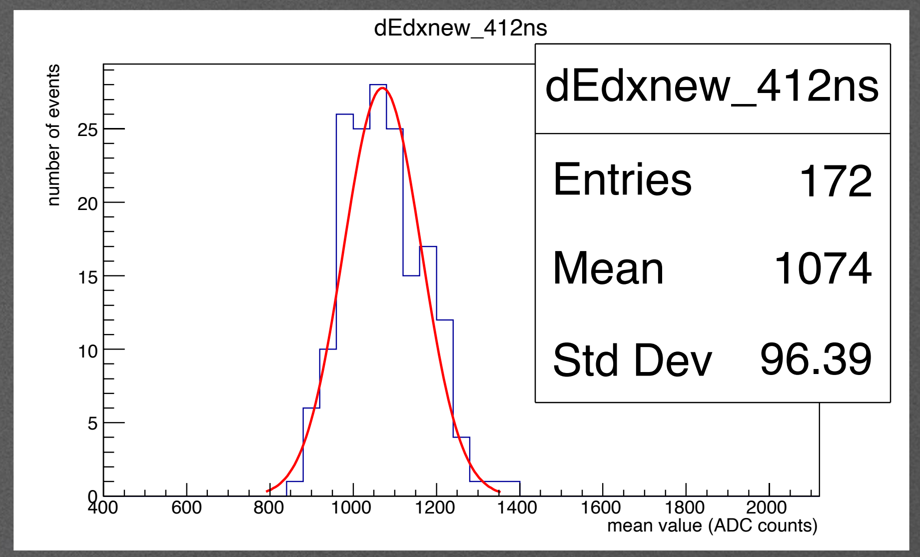


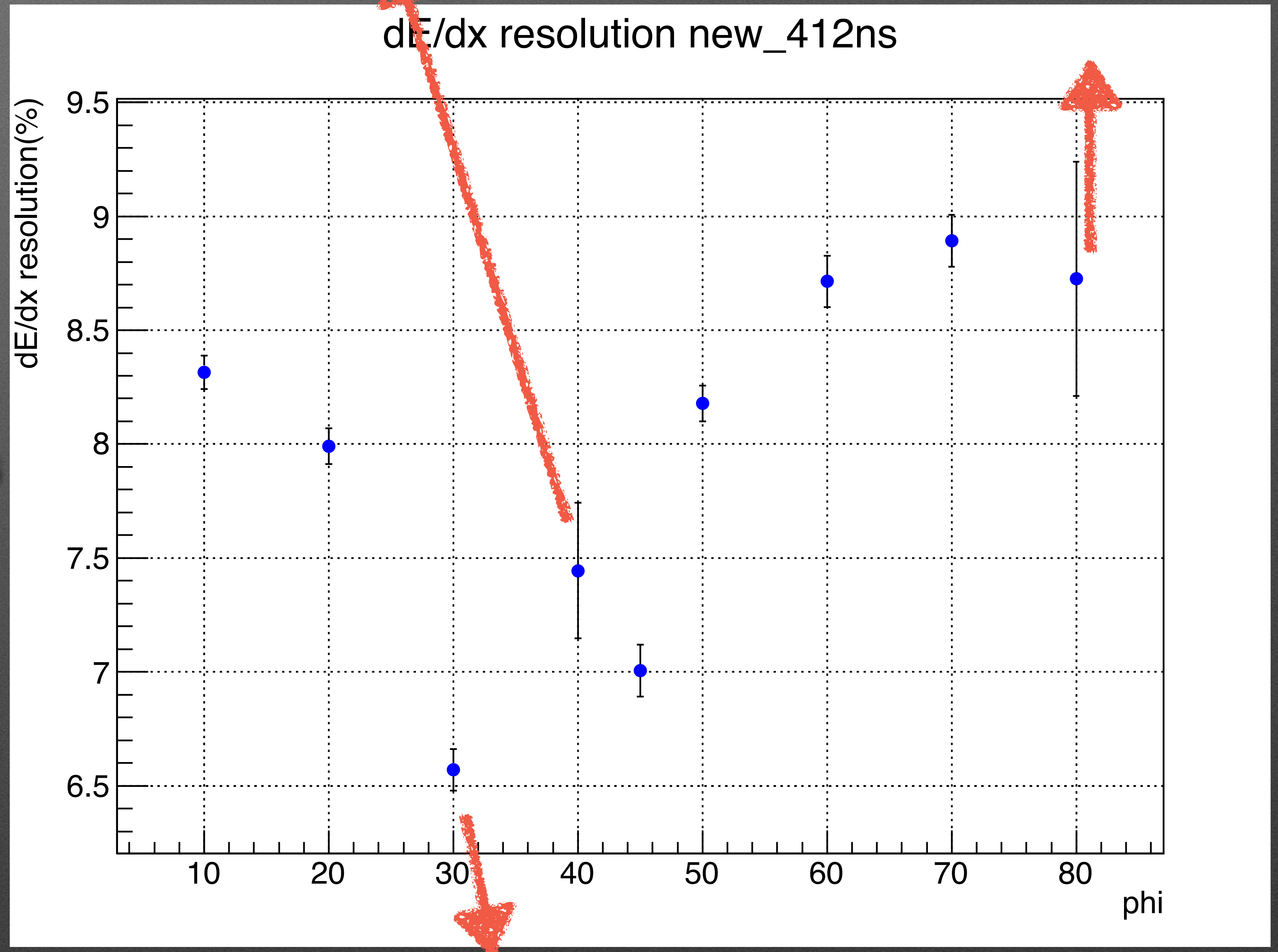
dE/dx resolution when we divide tracks into rows

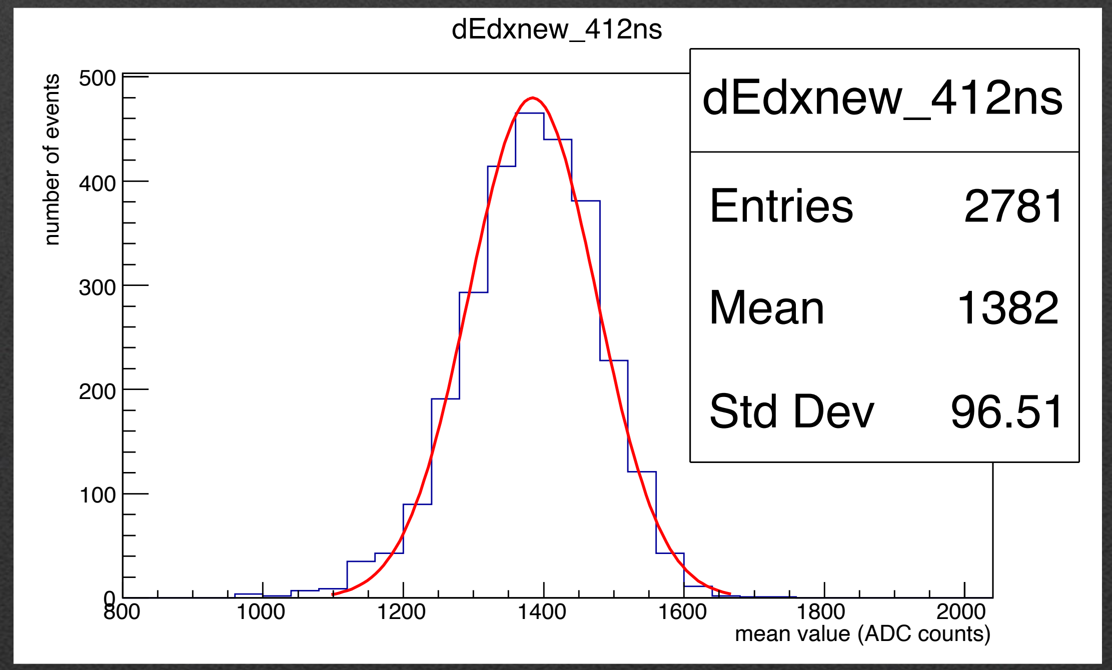


dE/dx resolution when we divide tracks into columns





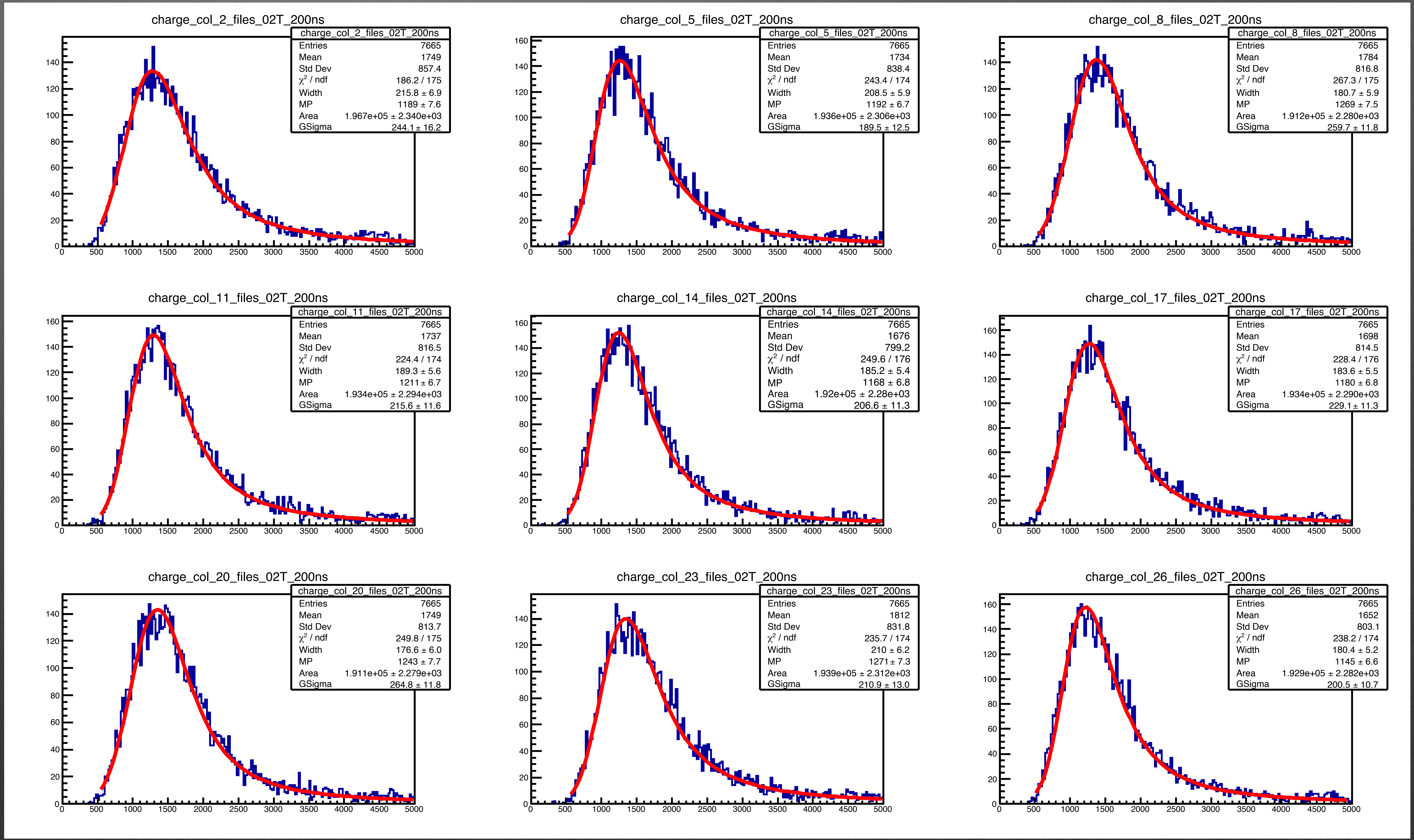




dE/dx resolution when we treat tracks either as vertical or horizontal tracks.

Gain uniformity for clusters

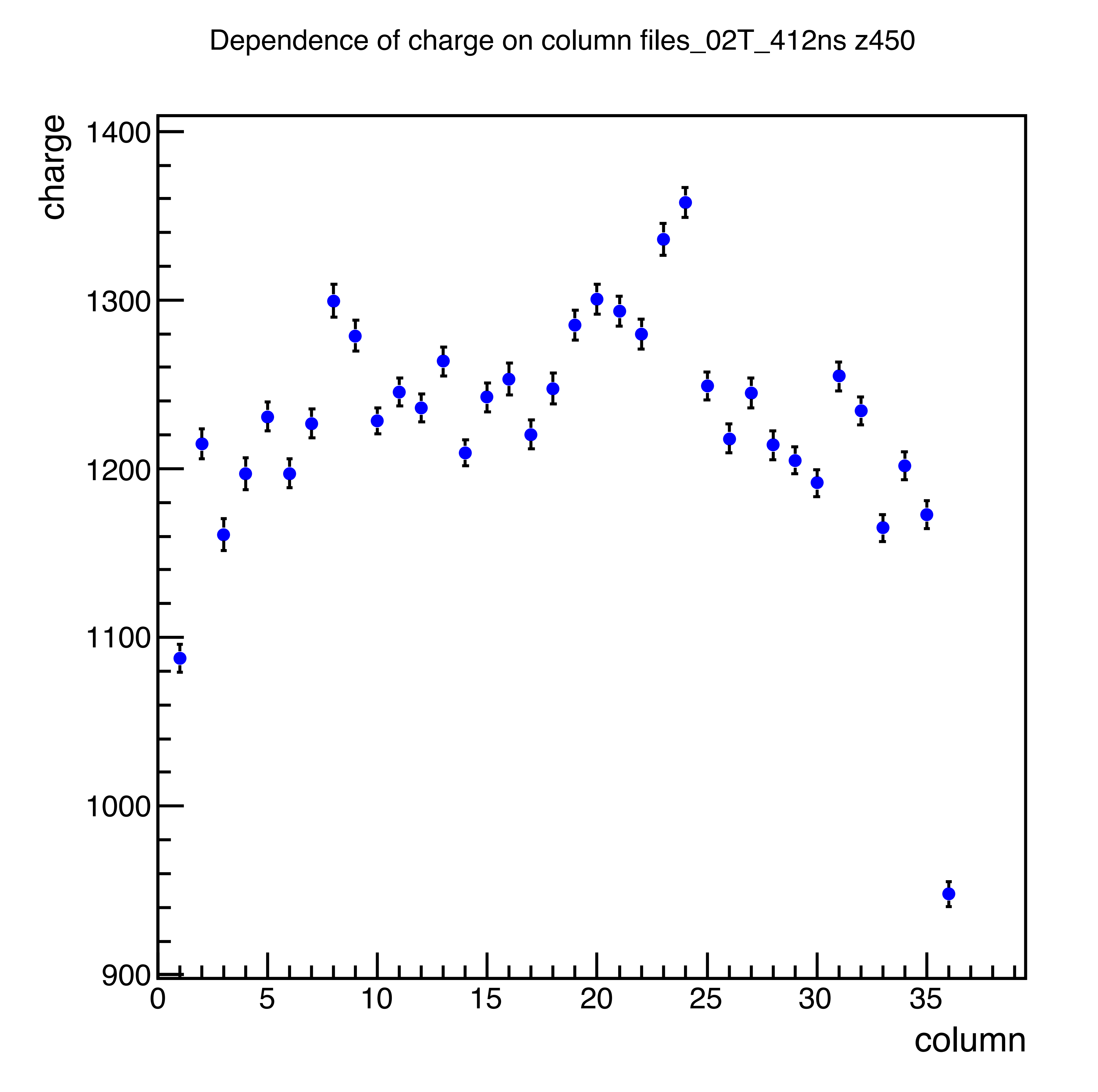
- I calculated the received charge for each cluster
- The amount of charge may be large, on rare occasions it will be very large so that it can bias the mean values. This kind of distribution was modelled by Landau and was name after him.
  => Fit it with Landau function
- Draw the Most Probable (MP) values and Width/MP ratio.

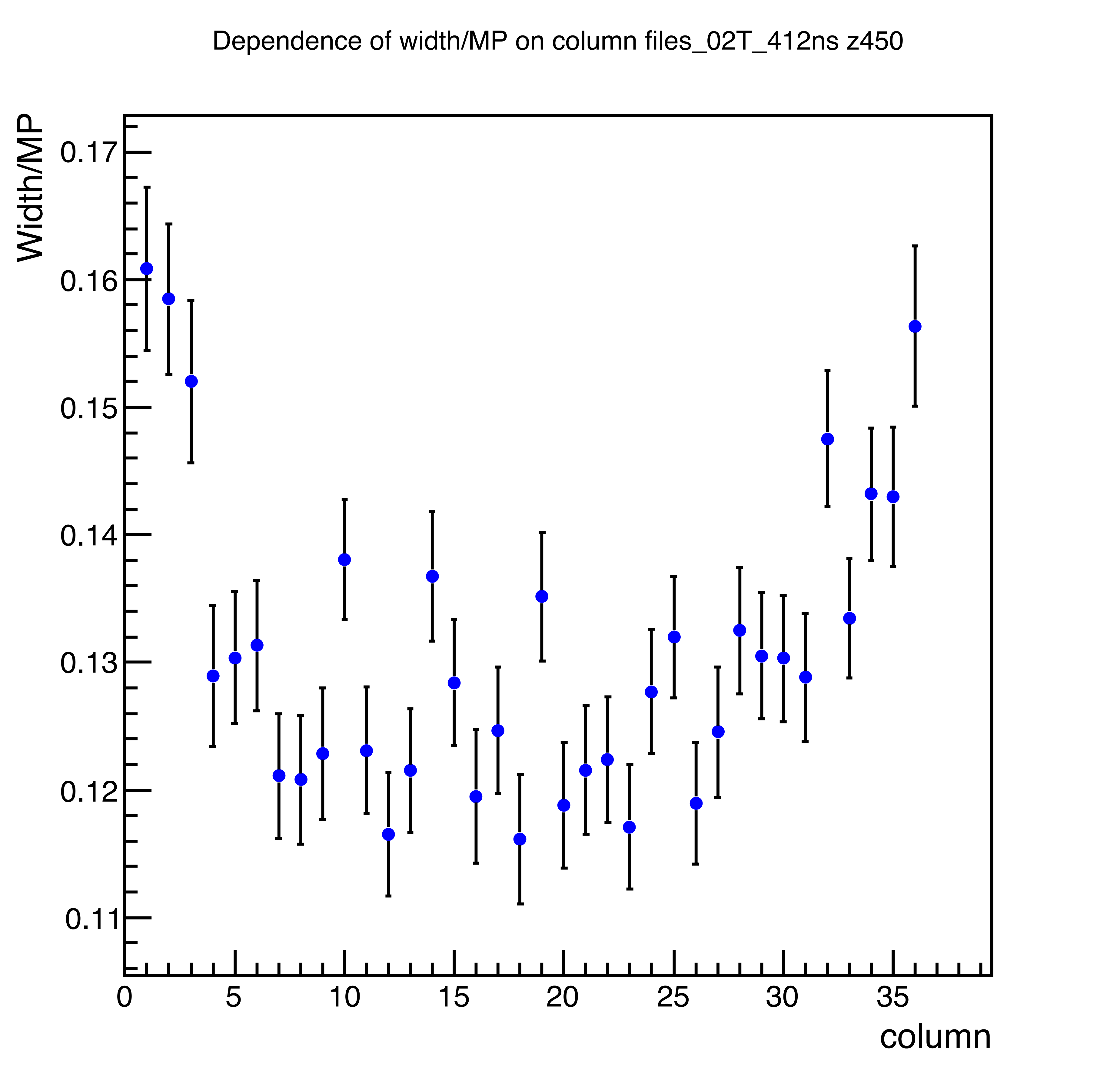


Received charge for each cluster in Landau distribution

Gain uniformity for clusters

- Pads in the border of the MicroMegas gain less than the others (border effect)
- Pads in the middle seem to have better so-called "resolution"

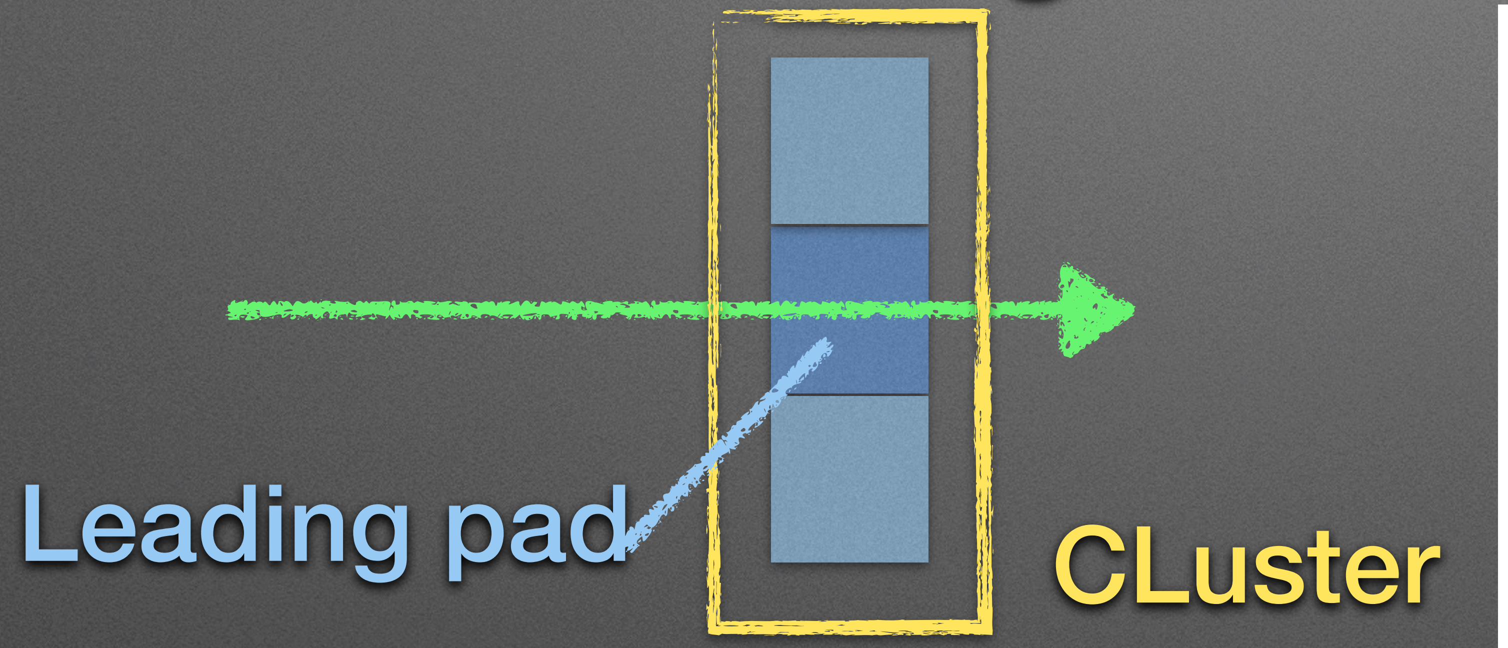




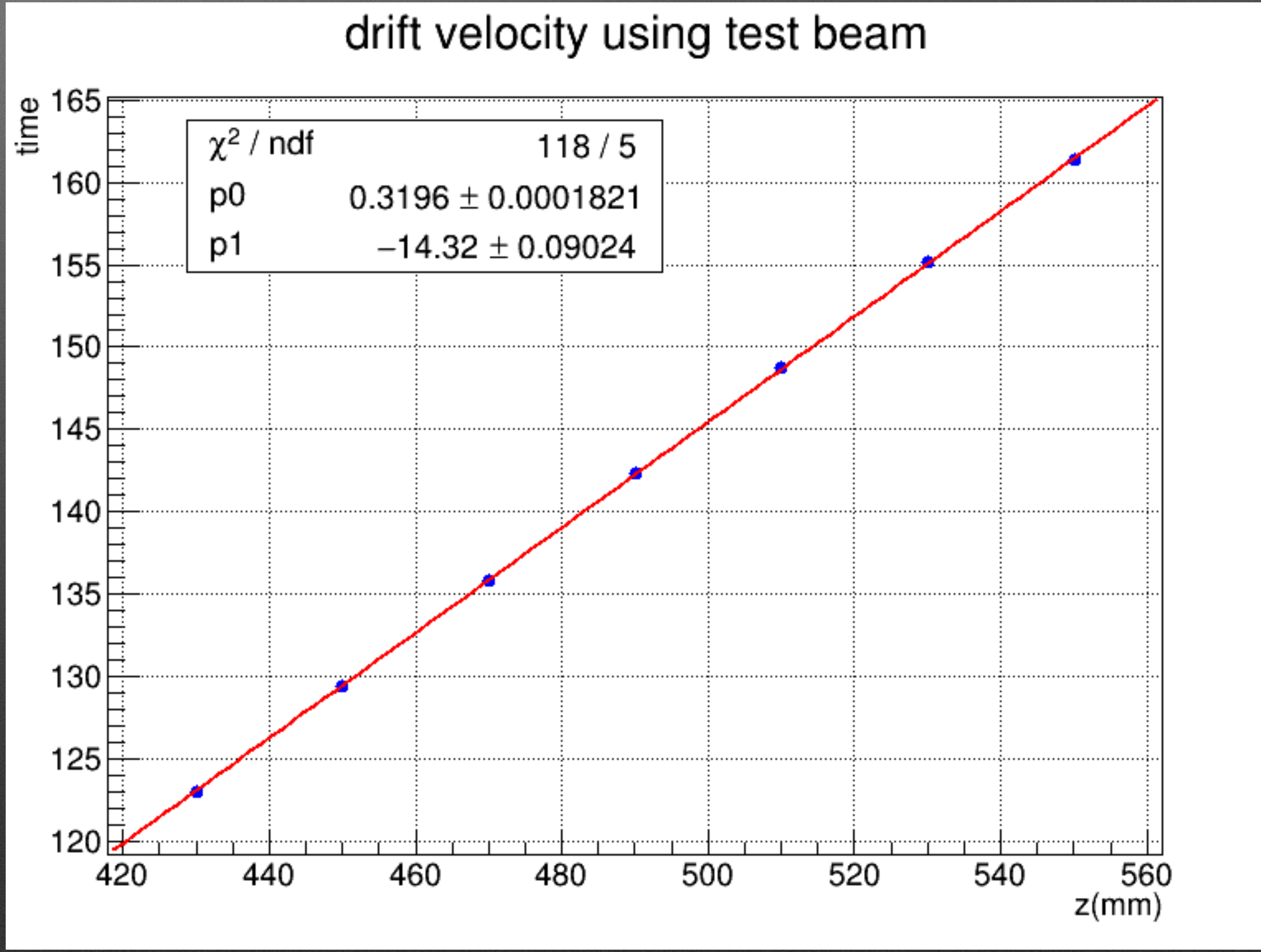
- Most Probable (MP) values
- Width/MP ratio (pseudo-resolution)

Drift velocity results

I calculated the average time when the leading pad receive the charge.



Fit function $time = p_0 * z + p_1$



Uncertainty of z (mm)	Drift velocity $cm/\mu s$	χ^2/ndf
0	7.8229 ±0.0044	118.0/5.0
0.1	7.8273 ±0.0086	30.09/5.0
0.2	7.8159 ±0.0153	9.378/5.0

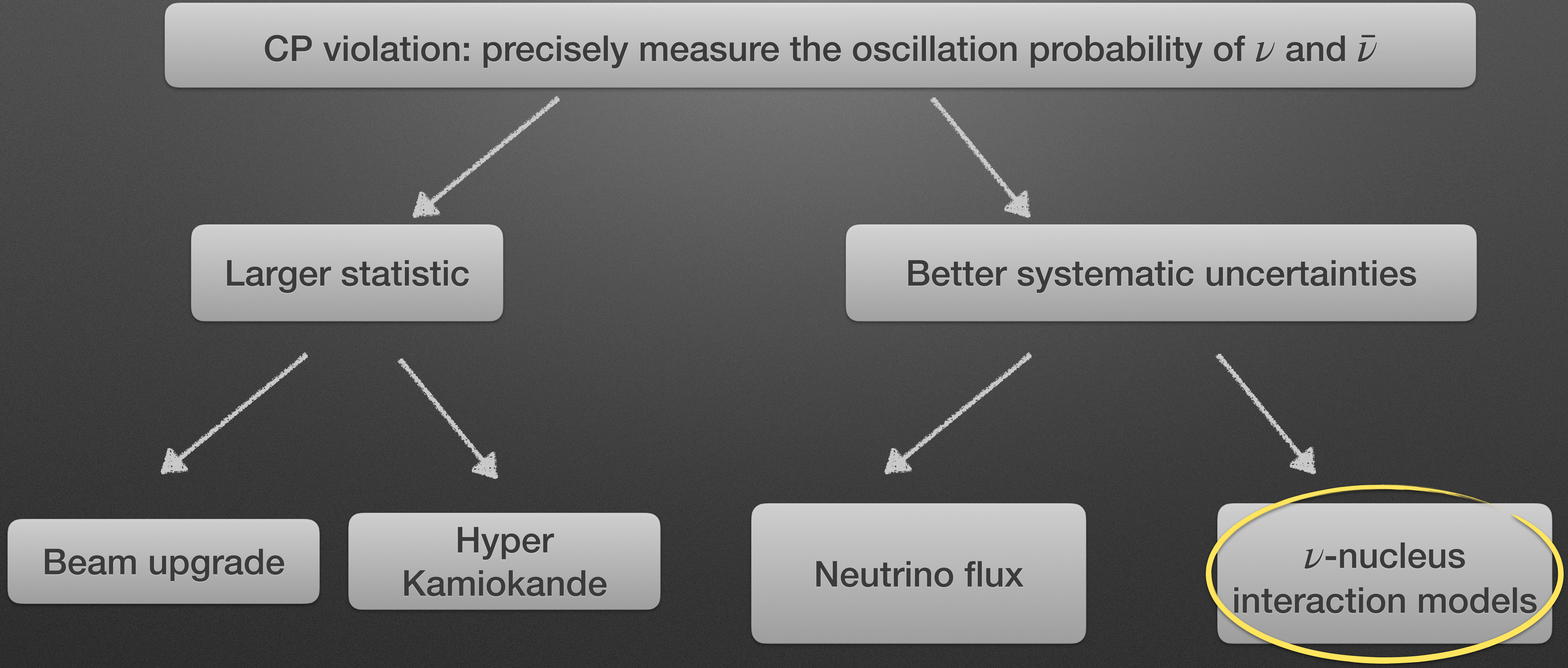
High angle TPC summary

- The dE/dx studies show that the dE/dx resolution is below 10%, which is totally meet the requirements of T2K collaboration.

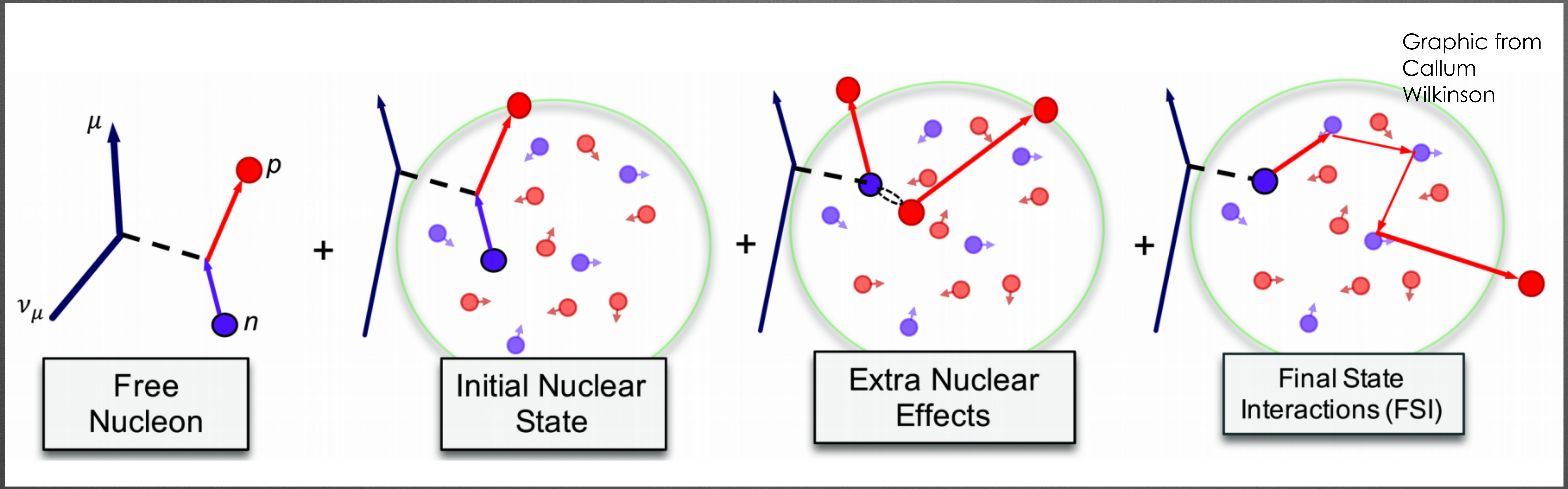
- -dE/dx resolution studies.
  -Gain uniformities.
  -Time uniformities.
  -Drift velocity with different methods.
  Most of these results show the good performance of High Angle TPC

- The HA TPC have many advantages. It provides better spatial resolution, also provide a good coverage at high angle, which will help a lot to catch the low momentum neutrino interaction events and then constrain the nuclei models.

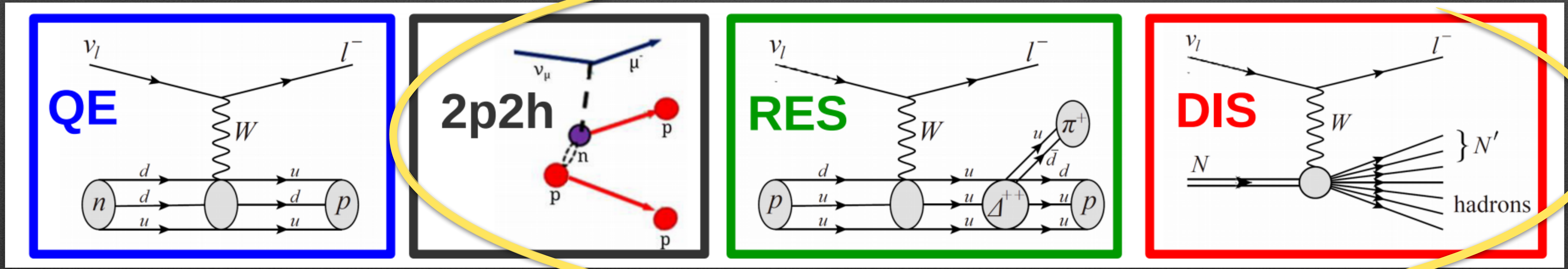
Second project: Physics Studies for ND280 Upgrade
Quantitative sensitivities to neutrino-nuclei interaction mode



Neutrino-nucleus interaction



Final State Interactions (FSI): Particles in the final state re-interact before going out of the nucleus.



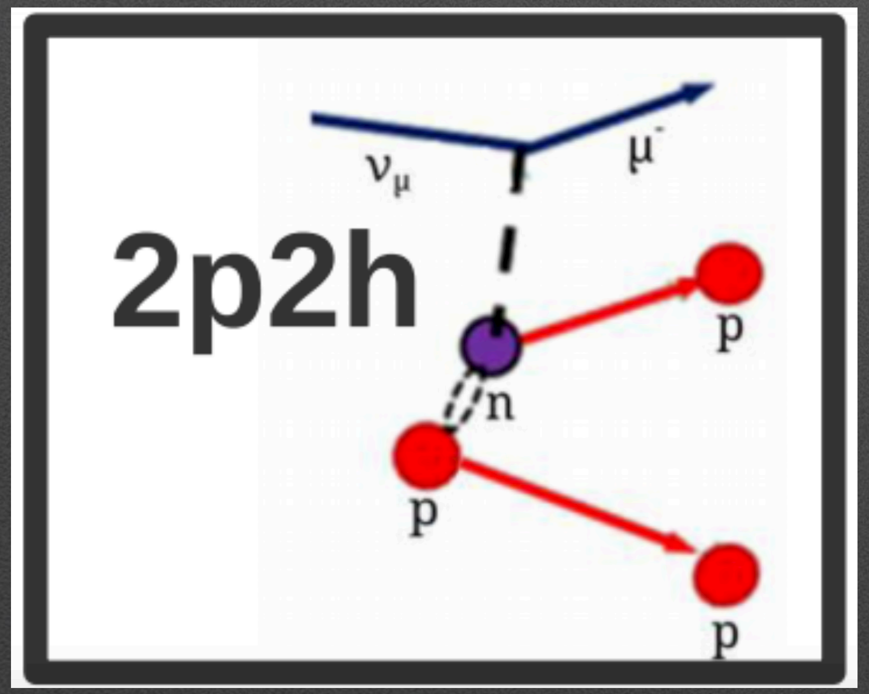
Neutrino energy reconstruction is based on the Charge Current Quasi-Elastic (CCQE) kinematics

These modes also contribute to reconstructed quasi-elastic events

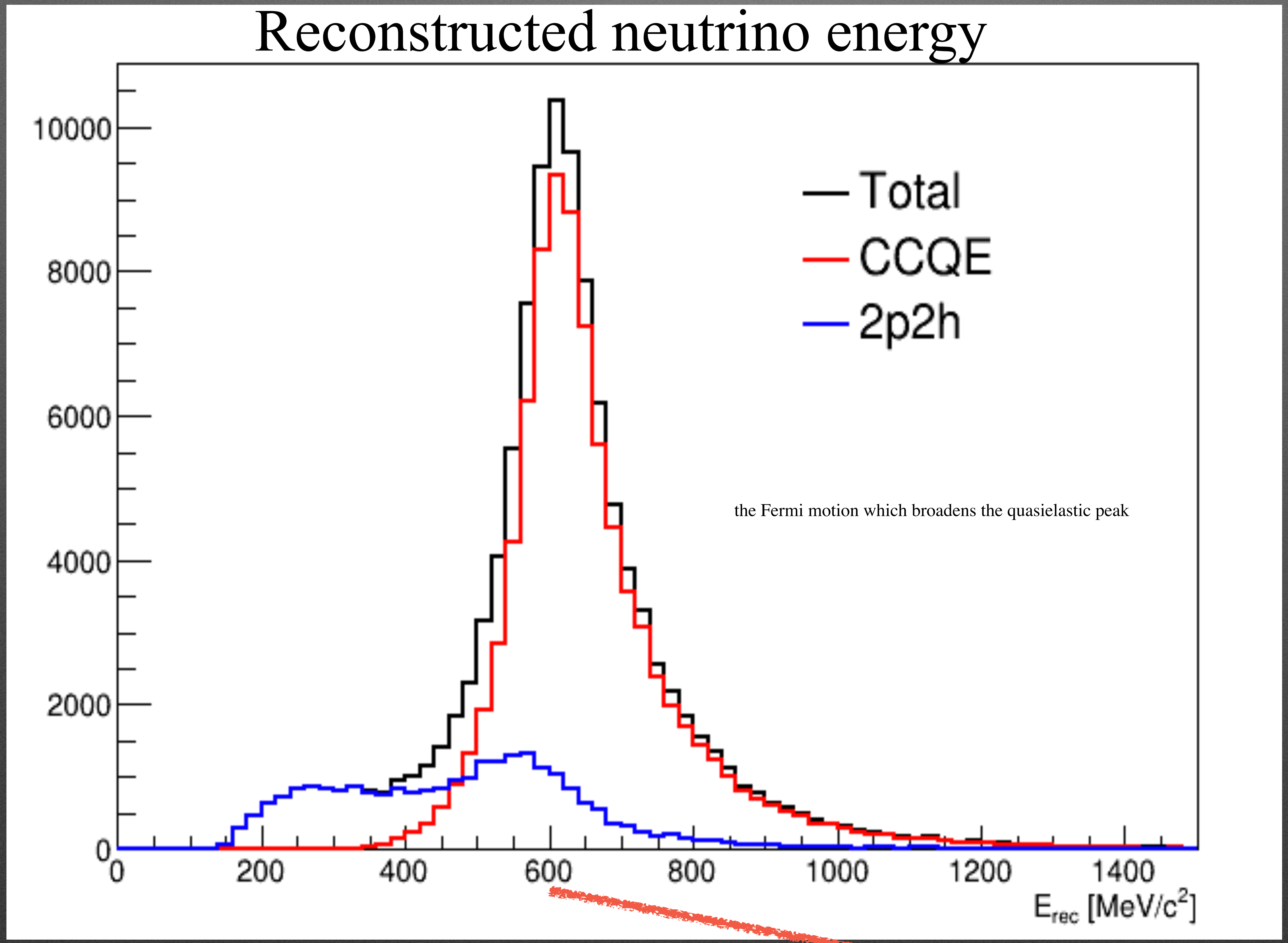
Focus on CC0π events
CC0π=1p1h + 2p2h + 1π(+abs)

No pion in the final state

Why should we know precisely the 2p2h component?



2p2h = 20±20%



2p2h component will bias the reconstructed neutrino energy over lower value

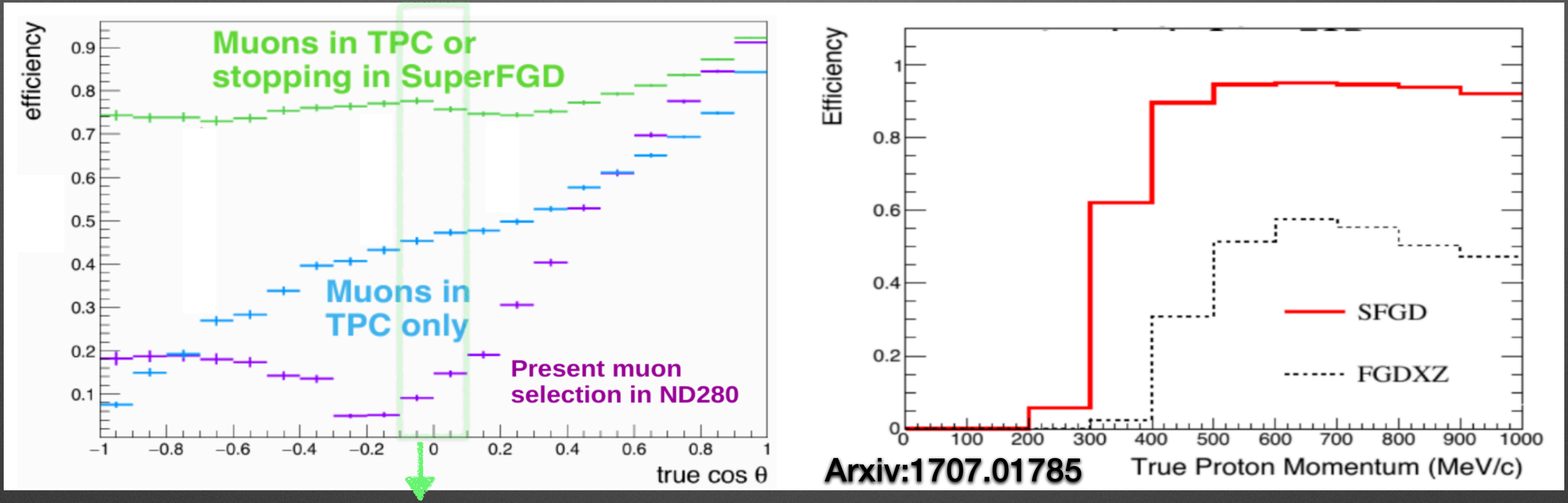
Neutrino energy using by T2K

Neutrino oscillation probability

$$P(\nu_\mu \rightarrow \nu_e)$$
$$= \sin^2(2\theta_{13})\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

=> Bias measurements of neutrino oscillation parameters

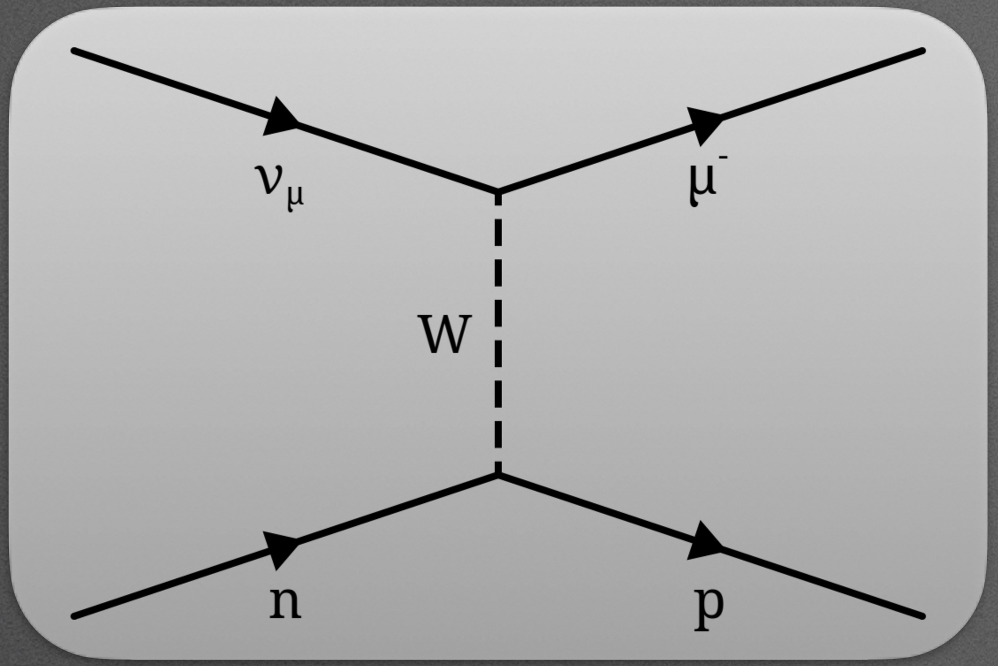
Why upgraded ND280 can help? ->Better efficiency



High angle tracks: ~$\pm 90^o$

- To study neutrino-nucleus interaction, we need low momentum process where incoming neutrino's energy does not dominate the Fermi momentum of the nucleons inside target nucleus.
- For low momentum neutrino interaction, the particles in the final state have more isotropic direction and lower momentum.
- Upgraded ND280 helps to better measure high angle tracks, lower momentum particles, and better use the traverse variables.

Why upgraded ND280 can help?



- Limitation: We only use the kinematic of outgoing lepton from ν interaction.

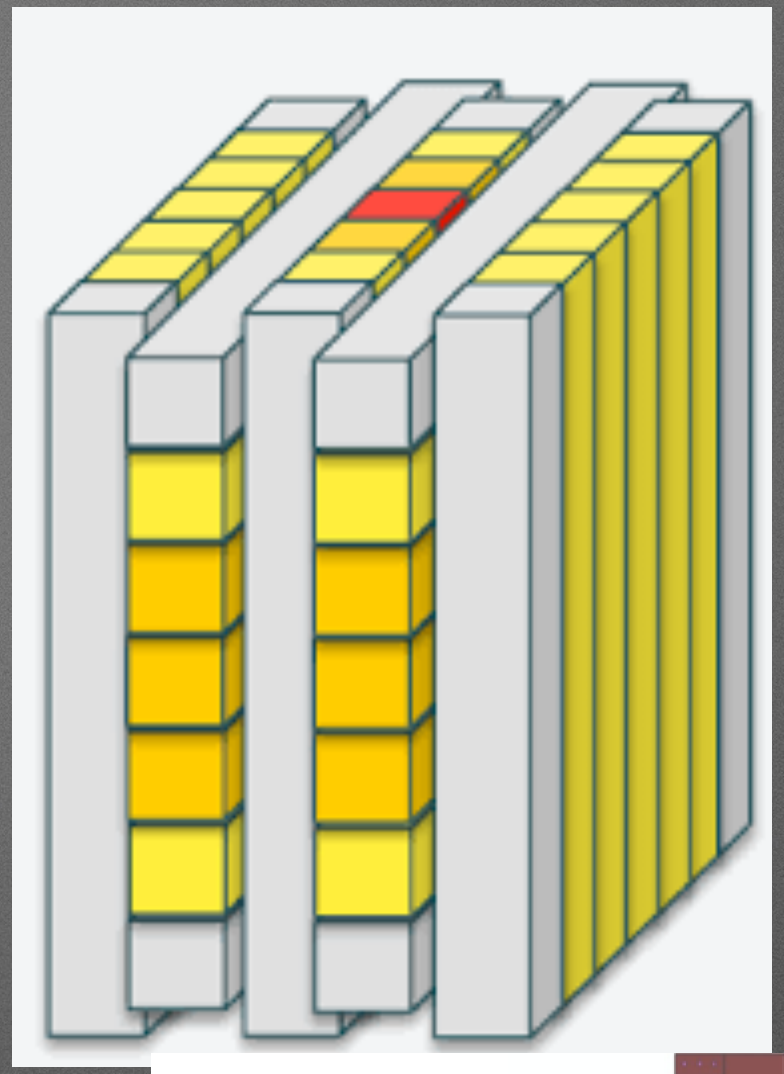
- Things affect the oscillation measurements

  1. Fermi momentum of initial nucleus.

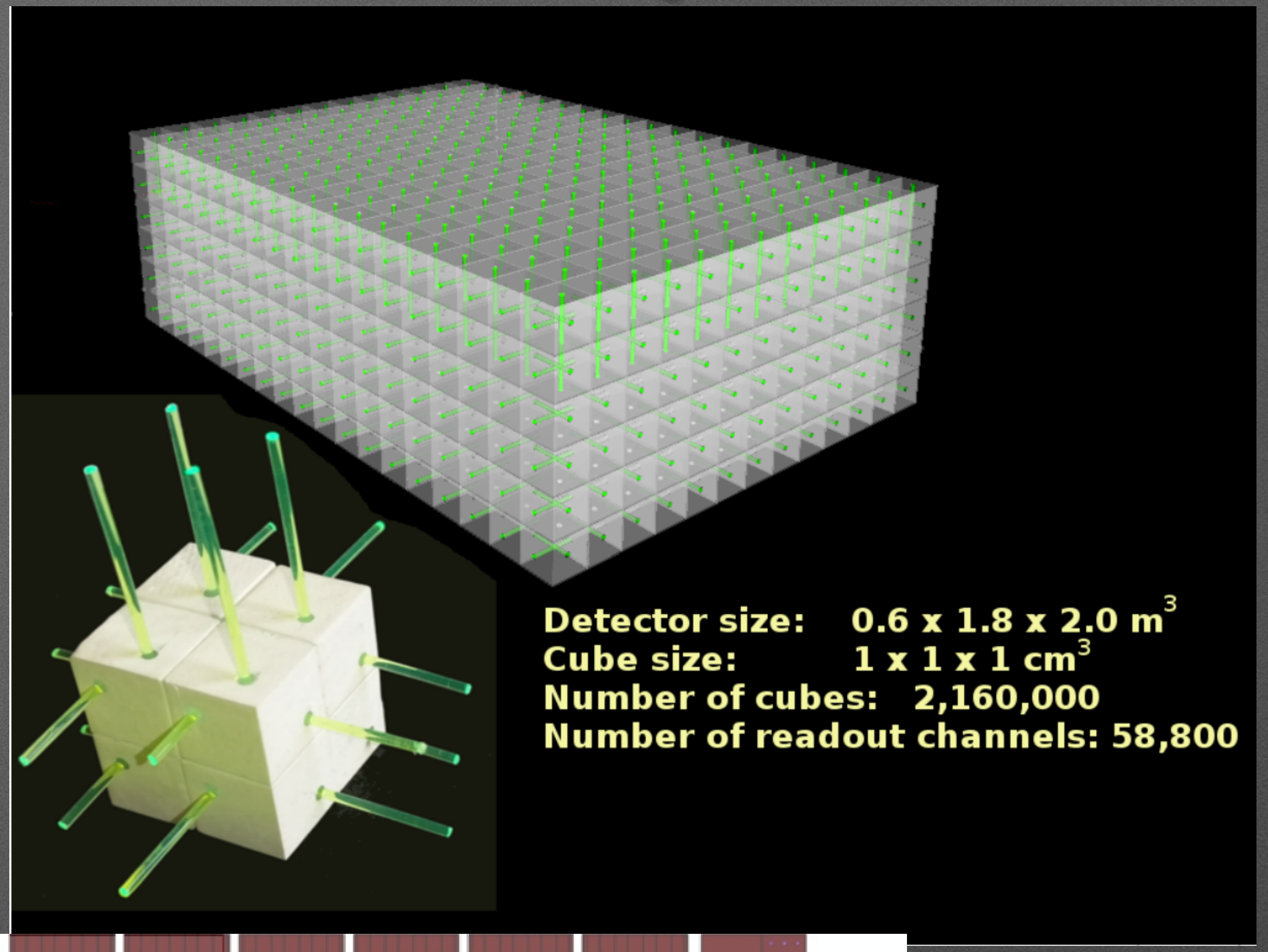
  2. Binding energy to extract nuleon from target nucleus.

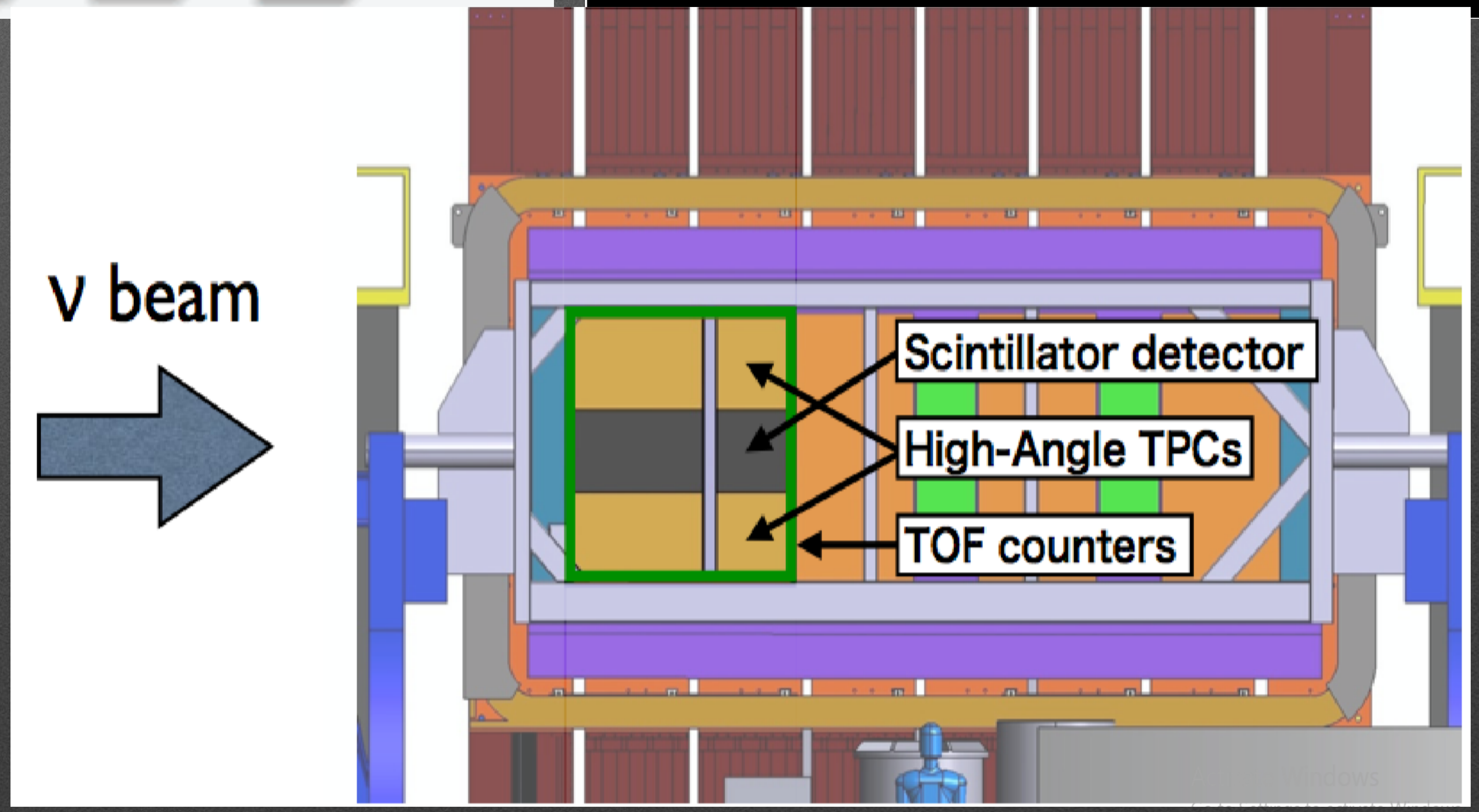
  3. Component of non quasi-elastic events without pion in the final state.

Old FGD



New super FGD





With the help of new Super FGD and High Angle TPC, New upgrade can measure better the low-momentum particles produced in the neutrino interactions (ie protons)
⇒ Constrains the Nuclear models

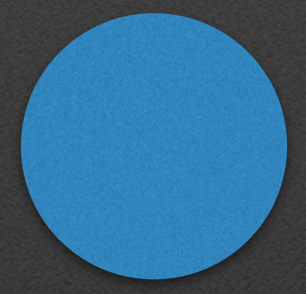
Introduction to simple fitter code

- In order to reduce the systematic uncertainty for the neutrino oscillation parameters, we need to know better the neutrino-nucleus interaction model, and obtain better precision for interaction modes (CCQE, 2p2h, other).

- The fitter code helps us to figure out the fraction of all interaction mode components. We are using the fake data, so their values should be one for all as input of the fake data simulation, but then we care more about the errors of CCQE, 2p2h,…

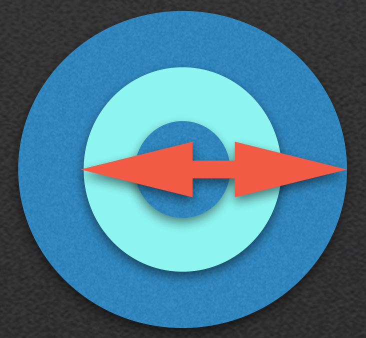
- The Monte Carlo is generated by NEUT generator for 3 models: Relativistic Fermi Gas (RFG), Local Fermi Gas (LFG) and Spectral Function (SF).

  - Relativistic Fermi Gas: all nucleons have the same binding potential



  - Local Fermi Gas: binding potential depends on the radial position of a nucleon.

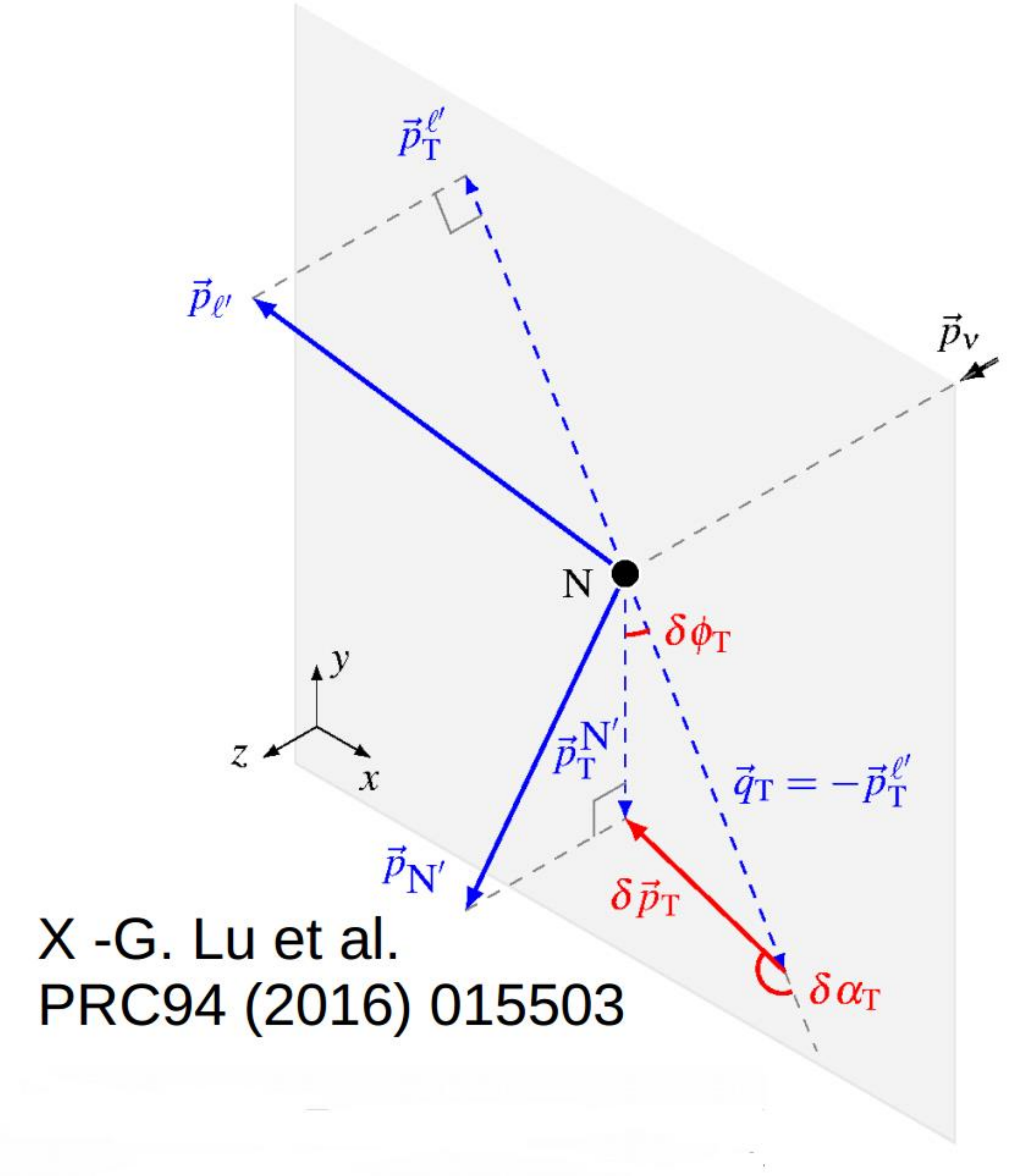
  - Spectral function: nucleons are treated as interacting fermions.



Input, output

Input

- 2D histograms of Single Transverse Variables dalphaT and dpT or dalphaT and nucleon fermi momentum (pn)
- These are pseudo-reconstructed variables



X -G. Lu et al.
PRC94 (2016) 015503

Fitter code

Output
Value and precision of

- 2p2h_c1 0-600MeV
- 2p2h_c2 (>600MeV)
- CCQE_c1 0-100MeV
- CCQE_c2 100-200MeV
- CCQE_c3 200-300MeV
- CCQE_c4 300-500MeV
- pion Absorption FSI norm
- pion Background FSI norm
- norm syst
- proton FSI
- Eb/25 (for easy plot since other parameter values are 1)

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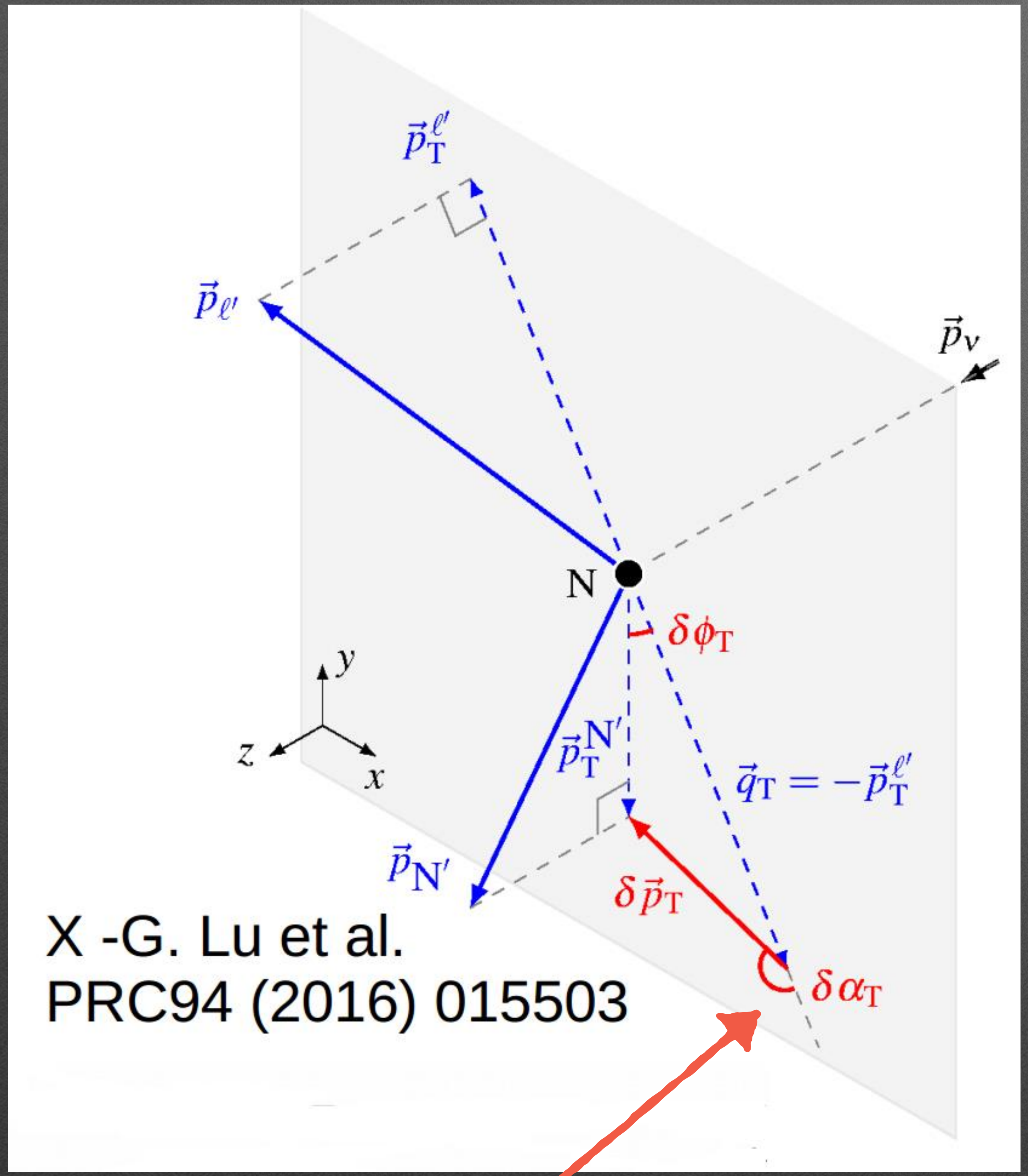
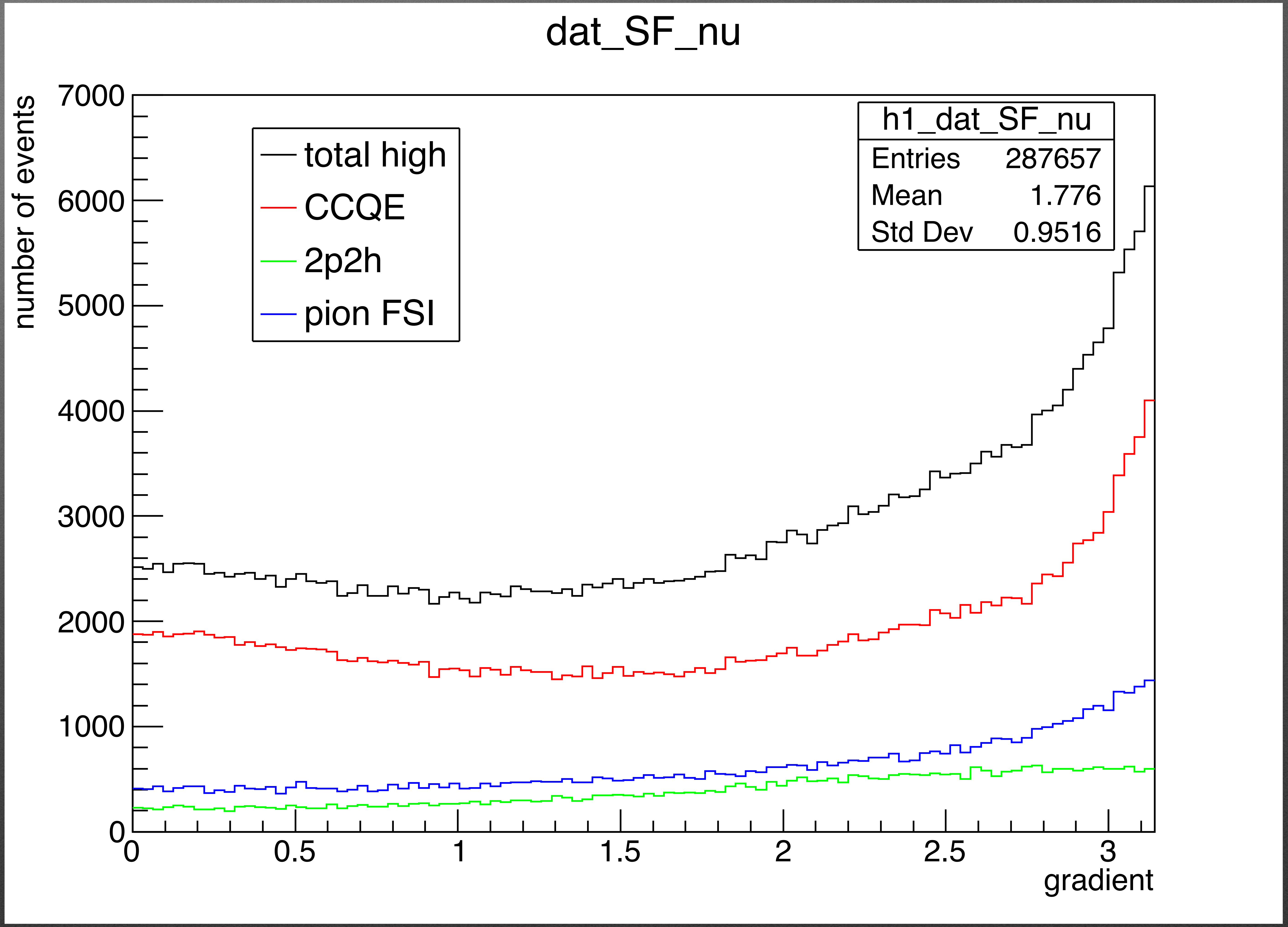
Input for fitter ($\delta\alpha_T$)



$$\delta\alpha_T = \arccos\left(-\frac{\mathbf{p}_T^{\mu} \cdot \delta\mathbf{p}_T}{p_T^{\mu}\delta p_T}\right),$$

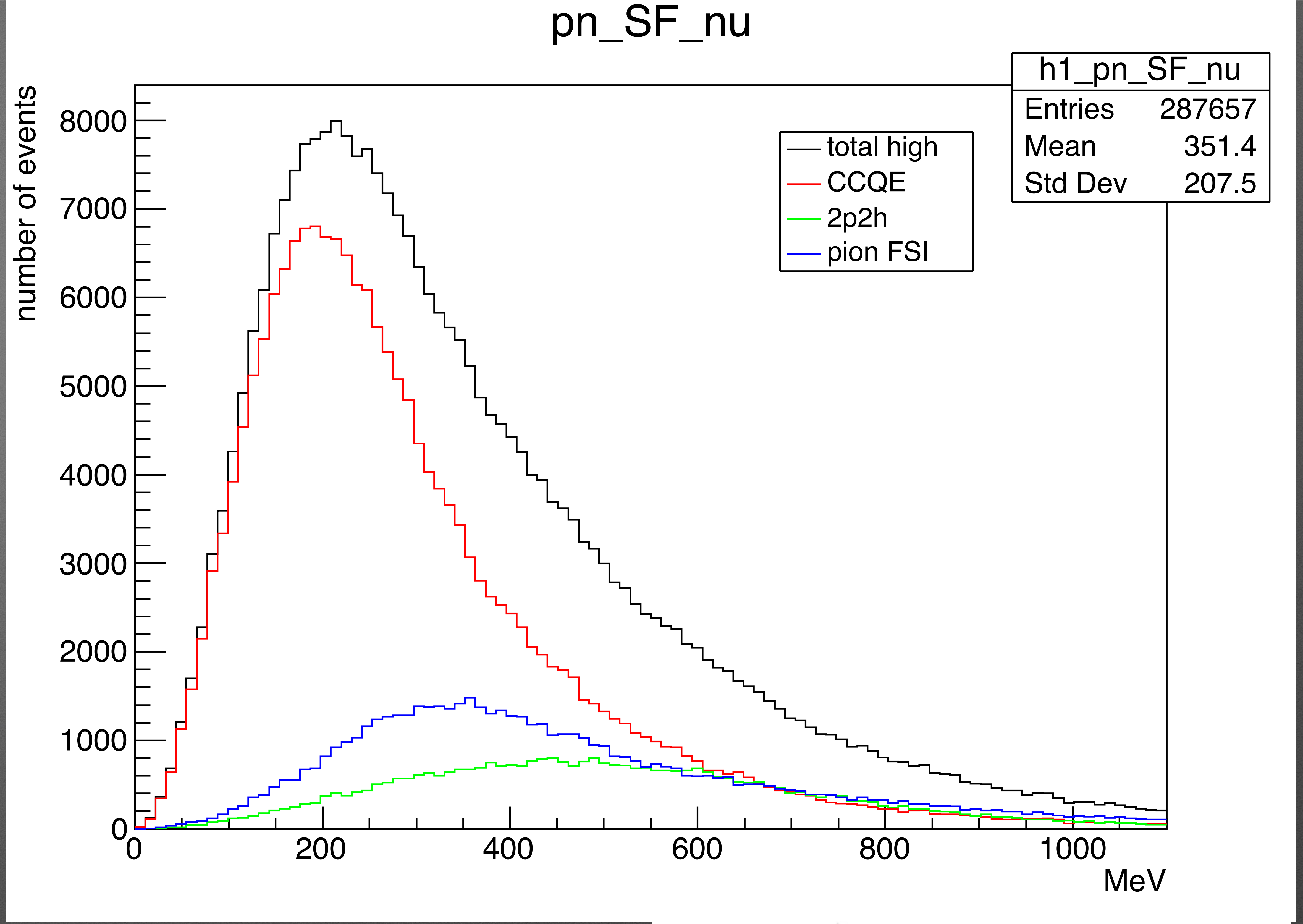


$\delta\alpha_T$ distribution for Spectral Function model

Input for fitter (pn)

pn is the Fermi momentum of initial nucleon

$$p_n = \sqrt{\delta p_L^2 + \delta p_T^2}$$



Longitudinal component of the Fermi momentum

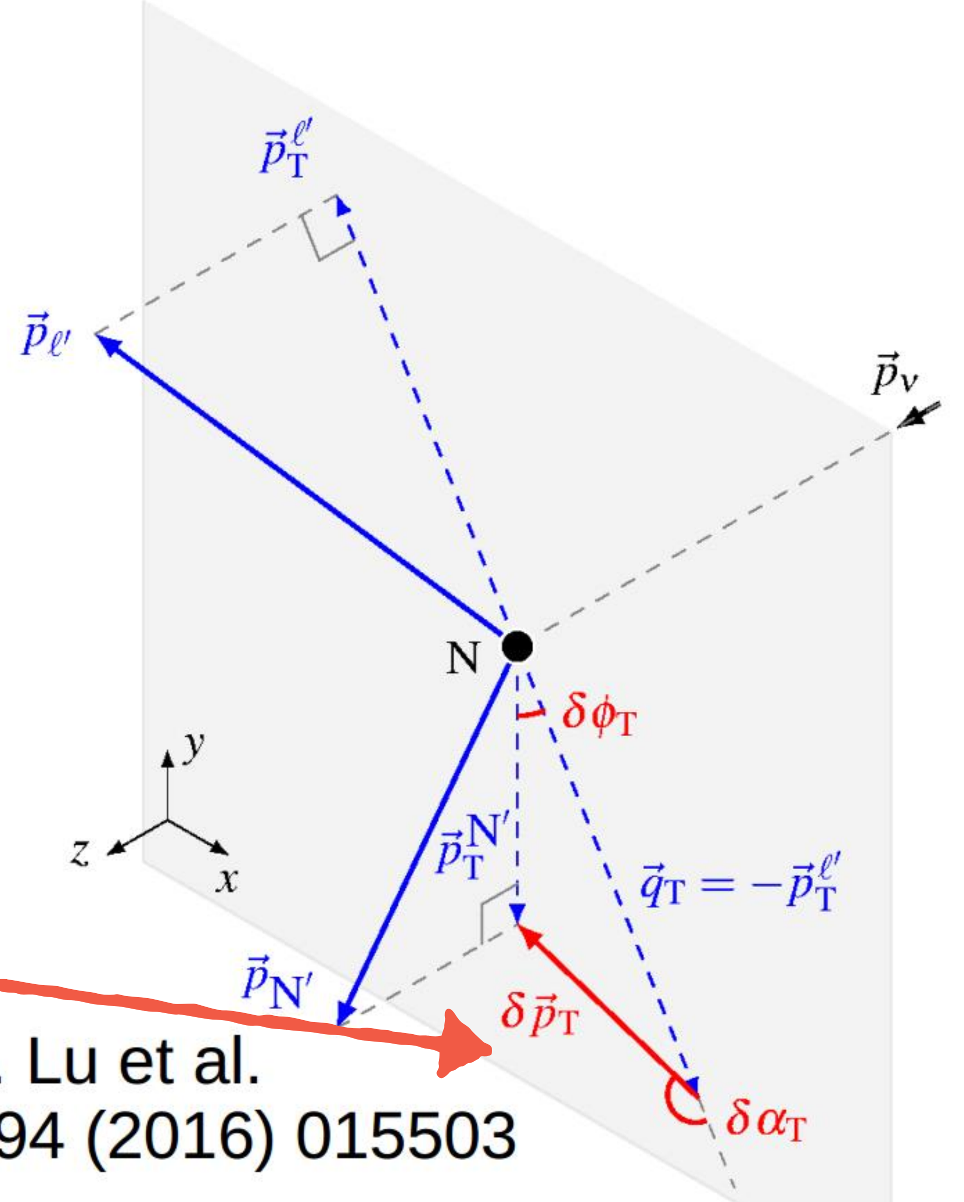
$$\delta p_L = \frac{1}{2}R - \frac{M_{A-1}^2 + \delta p_T^2}{2R}, \text{ where}$$

$$R = M_A + p_L^\mu + p_L^n - E^\mu - E^n$$

$$M_{A-1} = M_A - M_n + E_b$$

Transverse component of the Fermi momentum: momentum difference between muon and proton in the transverse plane

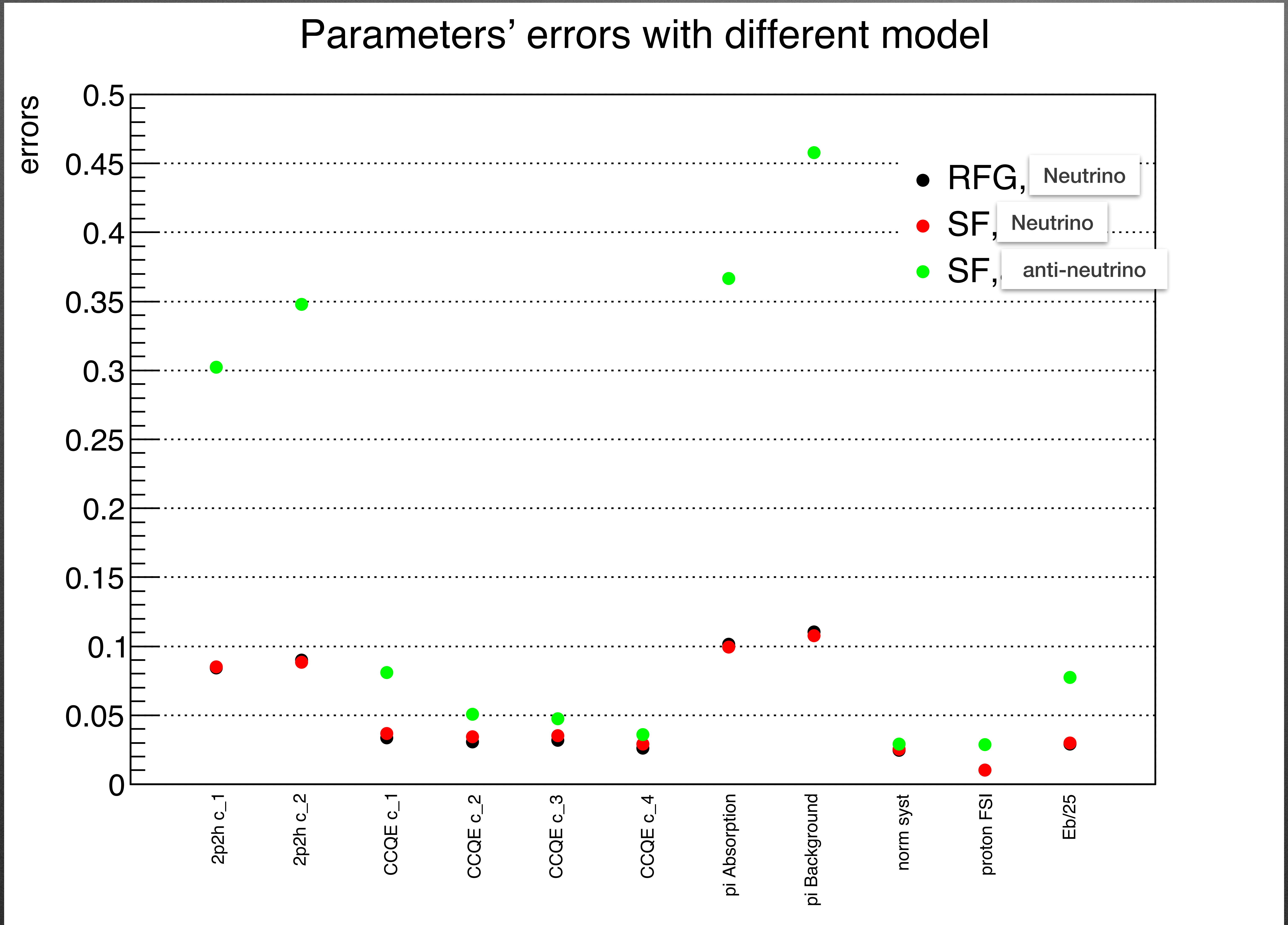
$$\delta p_T = \left| \mathbf{p}_T^\mu + \mathbf{p}_T^p \right|$$



X -G. Lu et al.
PRC94 (2016) 015503

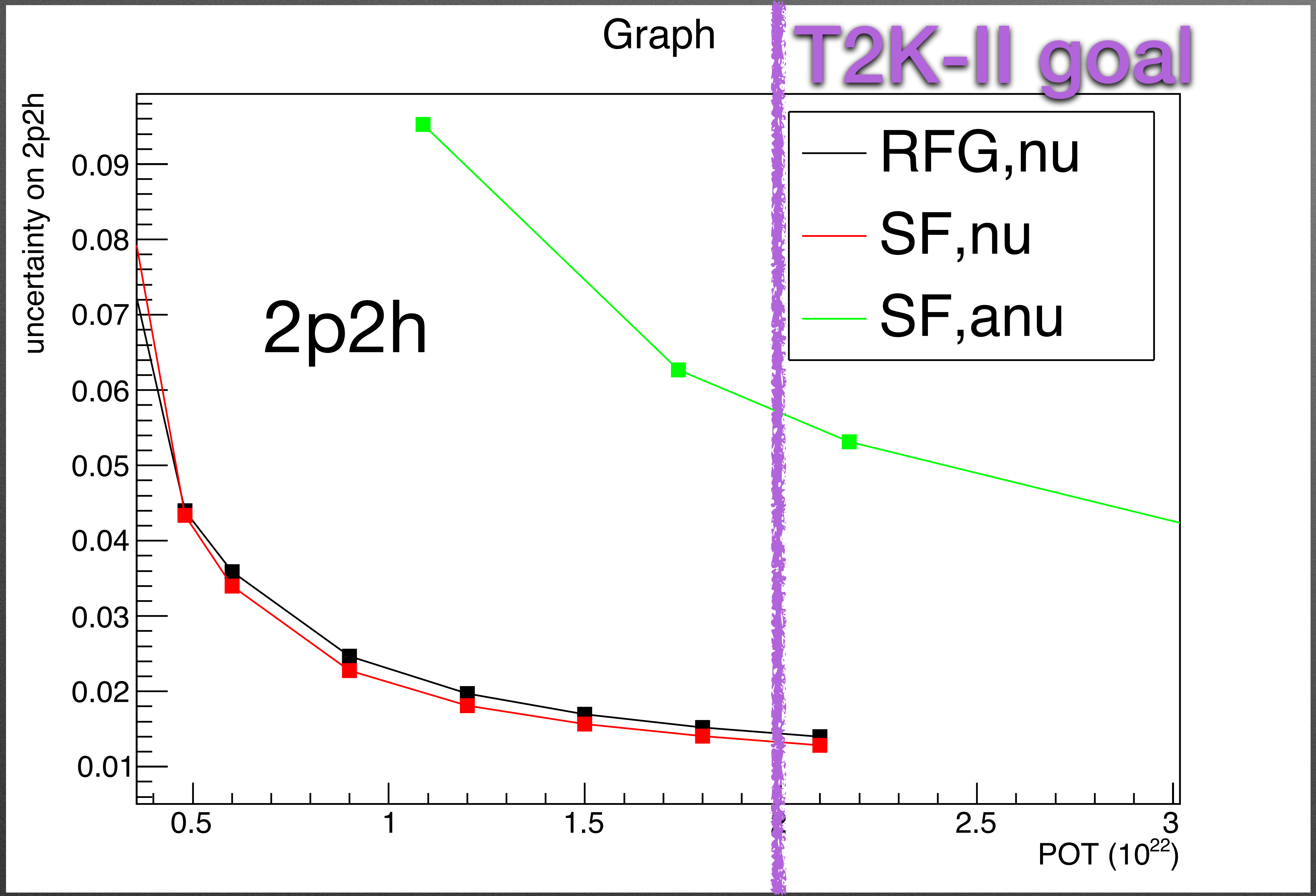
n is the nucleon that (anti-)neutrino interact with.
n is neutron (nu case) or proton (anu case)
M_A is mass of target nucleus.

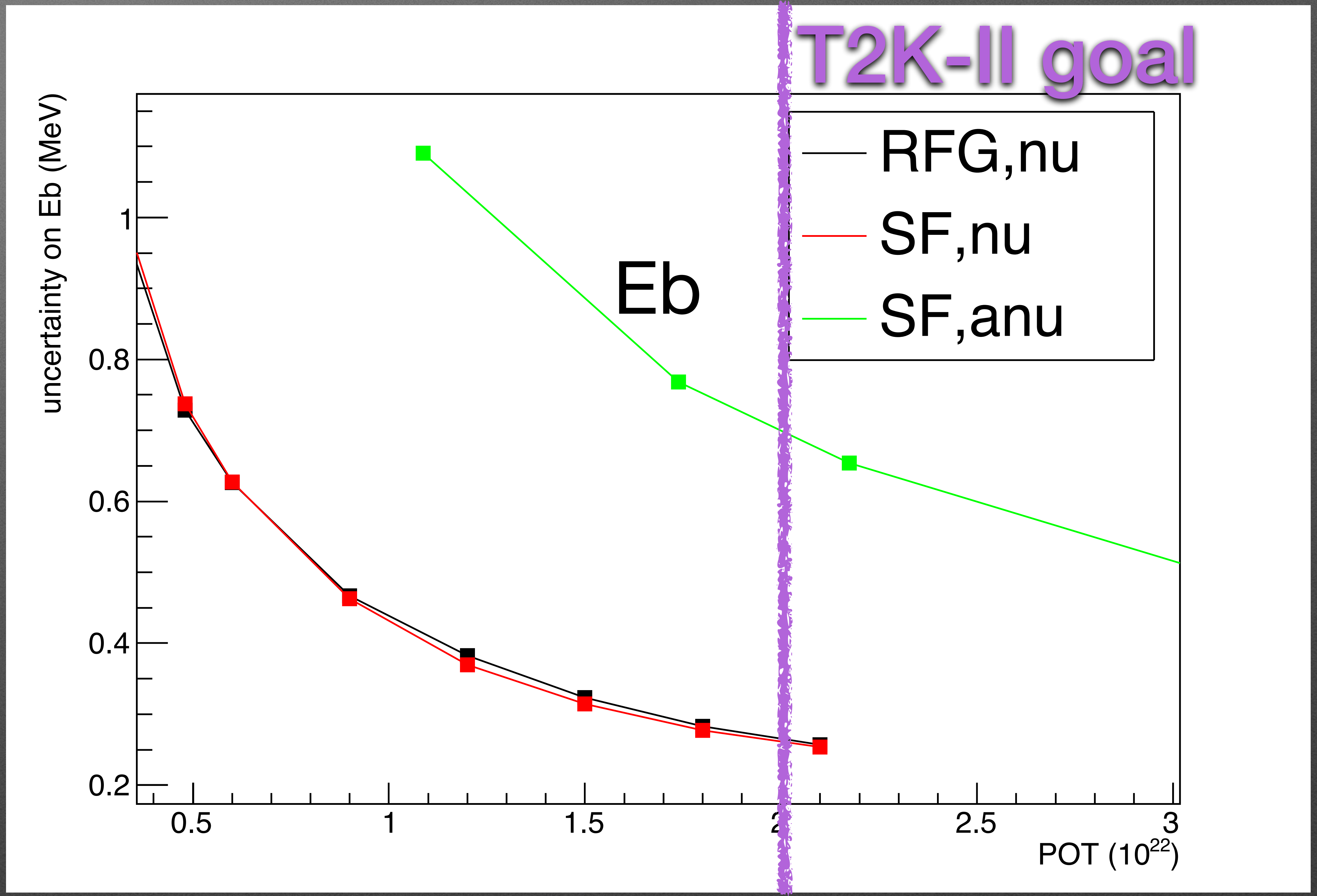
Results after the fit



- The scales for all cases are modified to have the same Proton On Target (6×10^{21}POT). => the anti-neutrino precision is worse than that of neutrino due to the smaller cross-section (less events eventually)
- The CCQE have better errors compared to 2p2h and pion FSI since CCQE is the dominated process.
- The parameter errors behave similarly for RFG and SF in neutrino case.

2p2h and Eb precision





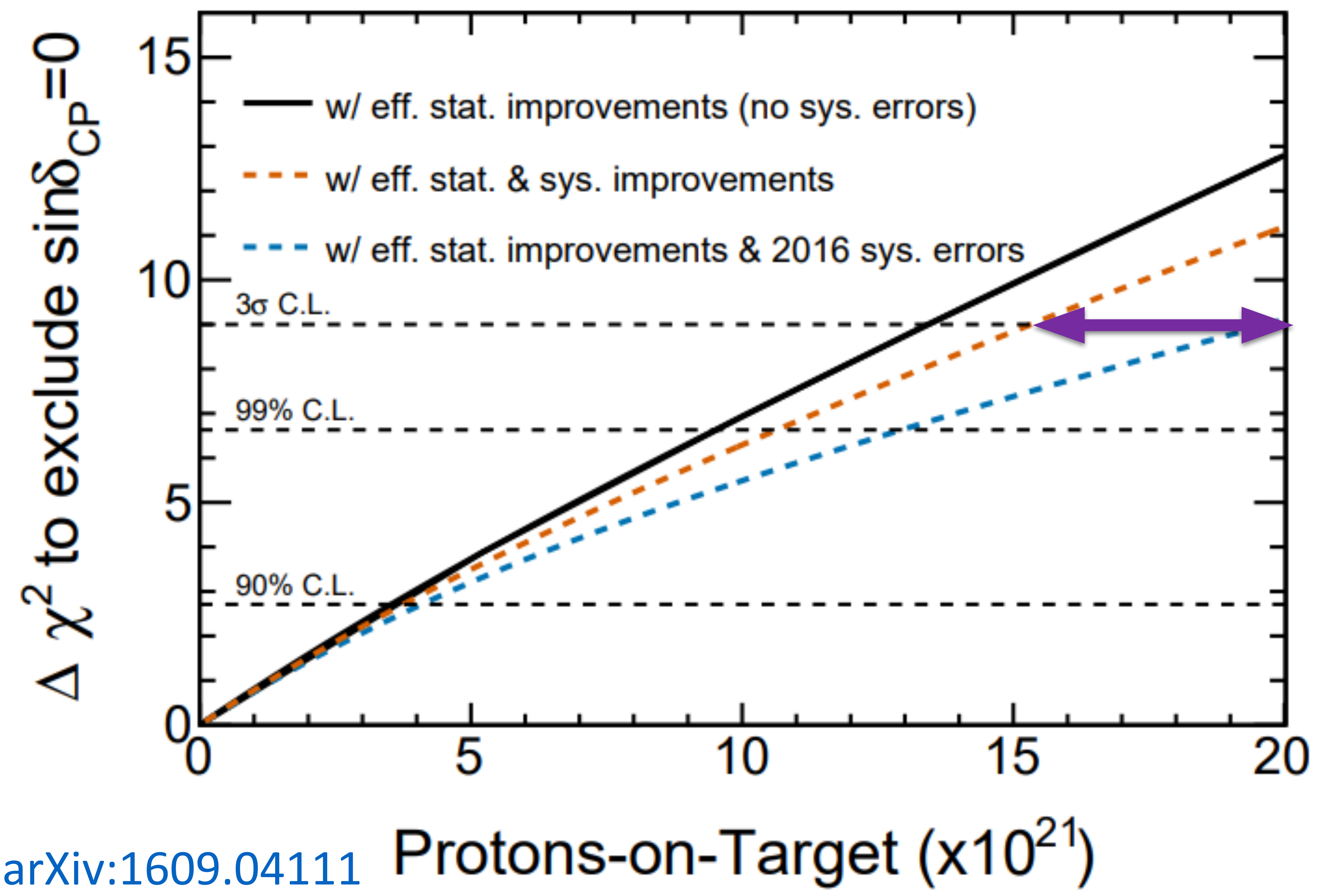
Current 2p2h precision: 100%
After fit: <10%

Error for binding energy at the end: <1MeV

Very good errors for 2p2h and Eb eventually

Quantitative contribution of ND280 upgrade physics

- 5×10^{21} Protons on Target (POT) is the difference between with and without systematic improvements to reach 3σ exclusion.
- The current accumulated POT of T2K is about 3.7×10^{21}



arXiv:1609.04111

Physics studies for ND280 upgrade summary

- Physics study for near detector ND280 upgrade: bi-weekly meeting.
  This will be the main thing for my thesis, the ND280 physics study team and I obtained promising results for the errors of interaction modes (for example the error of 2p2h mode was improved from 100% to <10%). I’ve given talks every meeting up to now.
  - Results were compare with different nuclear models, different type of neutrino was taken into account.
  - Check the results with different rebin, uncorrelated uncertainties, with different type of input (Back up).

Plan for future

- I want to have a major contribution for analysis of next High Angle-TPC test beam on Octorber/2020.
- Physics study for ND280 upgrade project:
  - My current work will hopefully first converge with an assessment of ND280 Upgrade sensitivity to the main systematics in the oscillation analysis.
  - Second, considering the role of the additional uncertainties that must be taken into account when measuring hadron kinematics.
  - Then I could fit all my parameters to T2K and MINERvA measurements of dpt, dat and pn. From this, we could extract tunes to our generators and quantify a real uncertainty on each of the parameters for future upgrade oscillation analyses and ongoing cross-section analyses.
  - Move from simple fitter to more complete fitter, this would form near detector fits for current T2K oscillation analyses. Basically means we are trying to do an upgrade-like oscillation analysis using the current ND280
  - Hopefully, the upgrade program will be on time (end of 2021), then I can use the real data to constrain neutrino-nucleus interaction models.
- The current situation prevents me to go to Japan for the qualification tasks, so I can not be a co-author of T2K's publications.

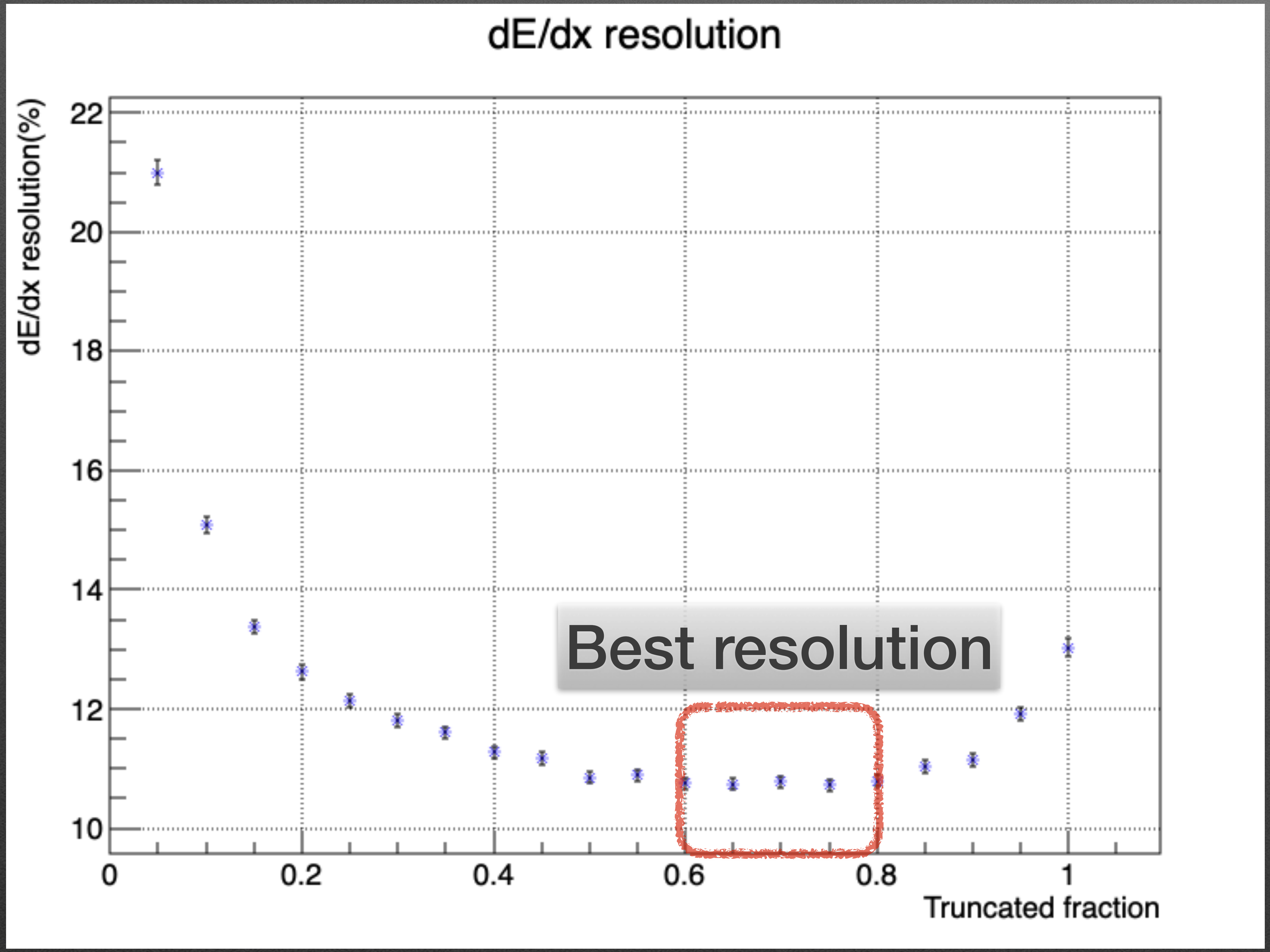
Courses and training

- French course A1: 1 point
- Elements of statistics: 3 points
- How to make a poster: 1 point
- CDD organisation: 1 point
- On plan: Particle acceleration in astrophysics: 3 points
- Accumulated points for 1st year: 9/15

Thank you for your listening

Back up HA-TPC test beam analysis

dE/dx resolution

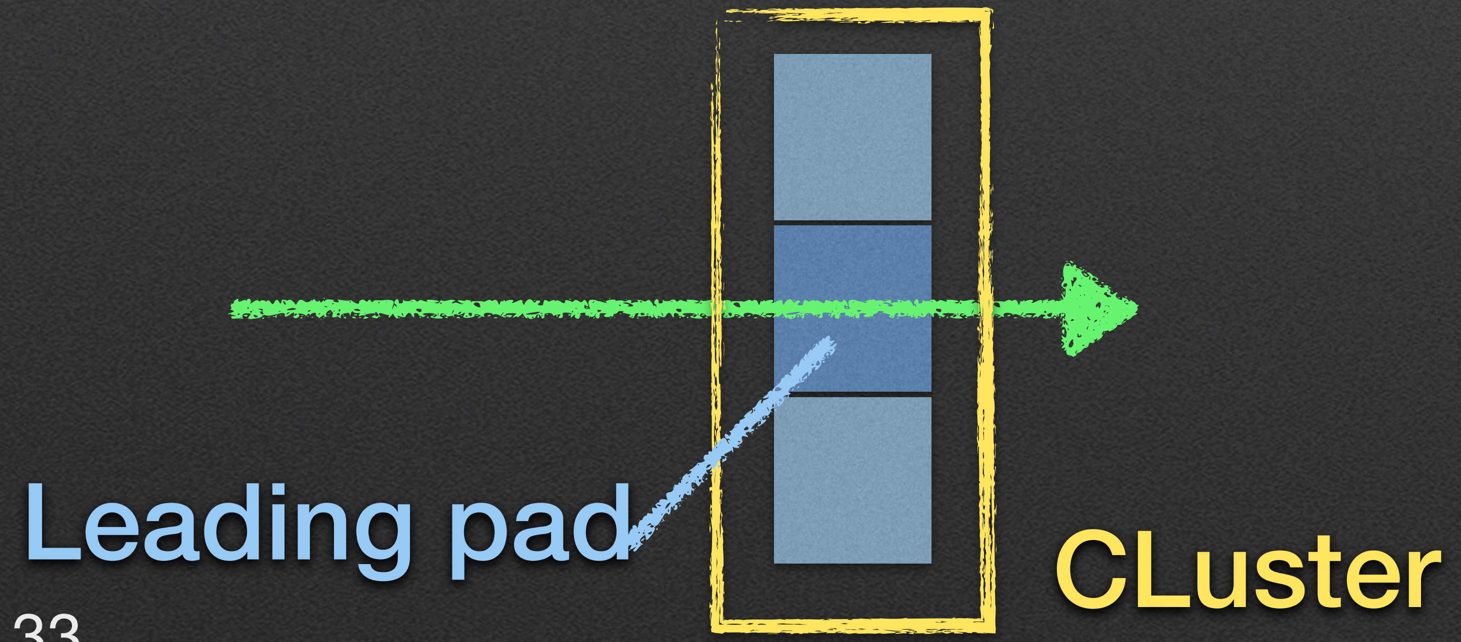


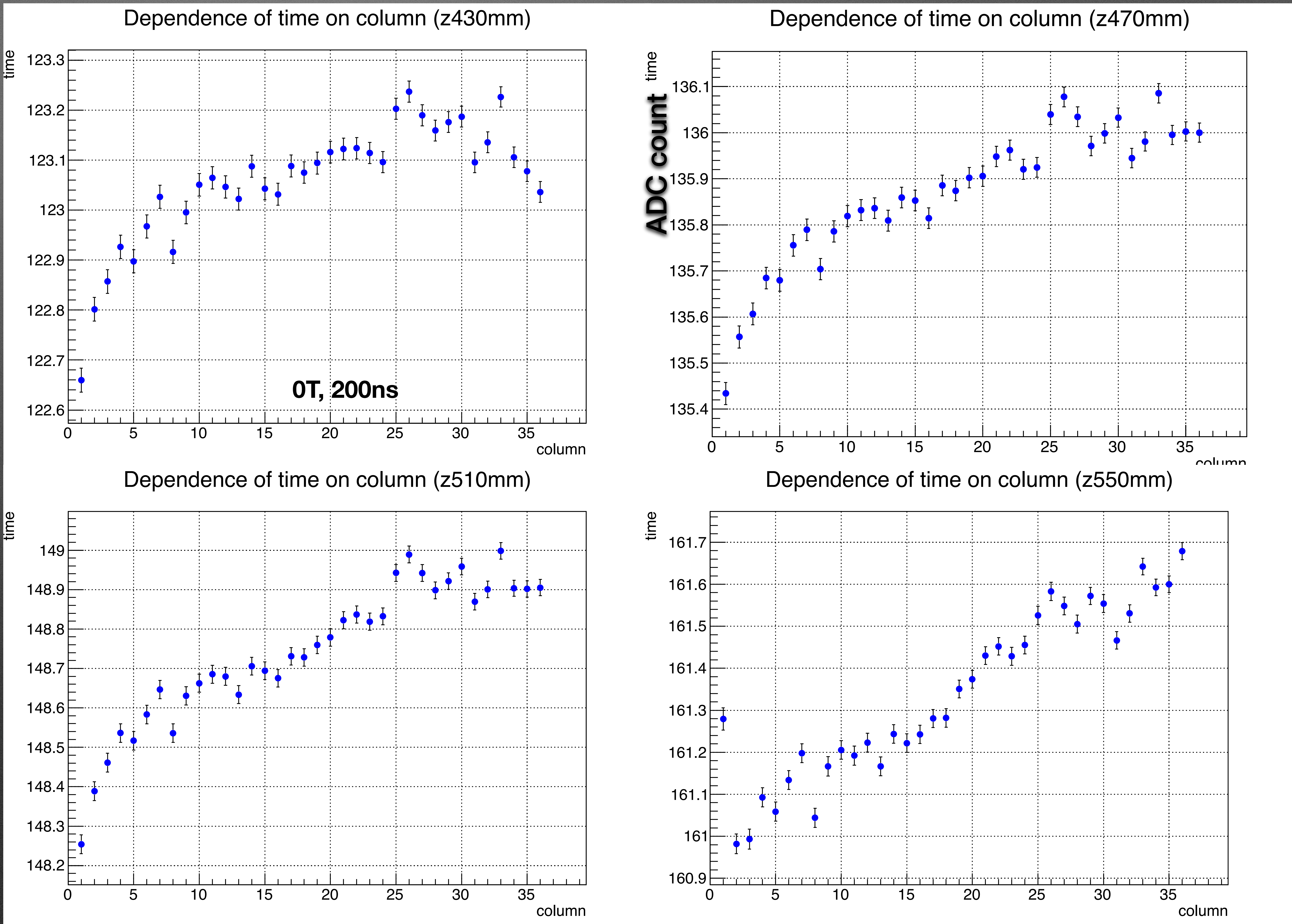
dE/dx resolution wrt truncated fraction

The range for truncated fraction to obtain the best dE/dx resolution is ~ (0.6, 0.8)

Uniformity in time

- In this analysis, I calculated the time that the leading pads received the charge for each columns.
- Data information: without magnetic field, 200ns peaking time. And testing with many z position



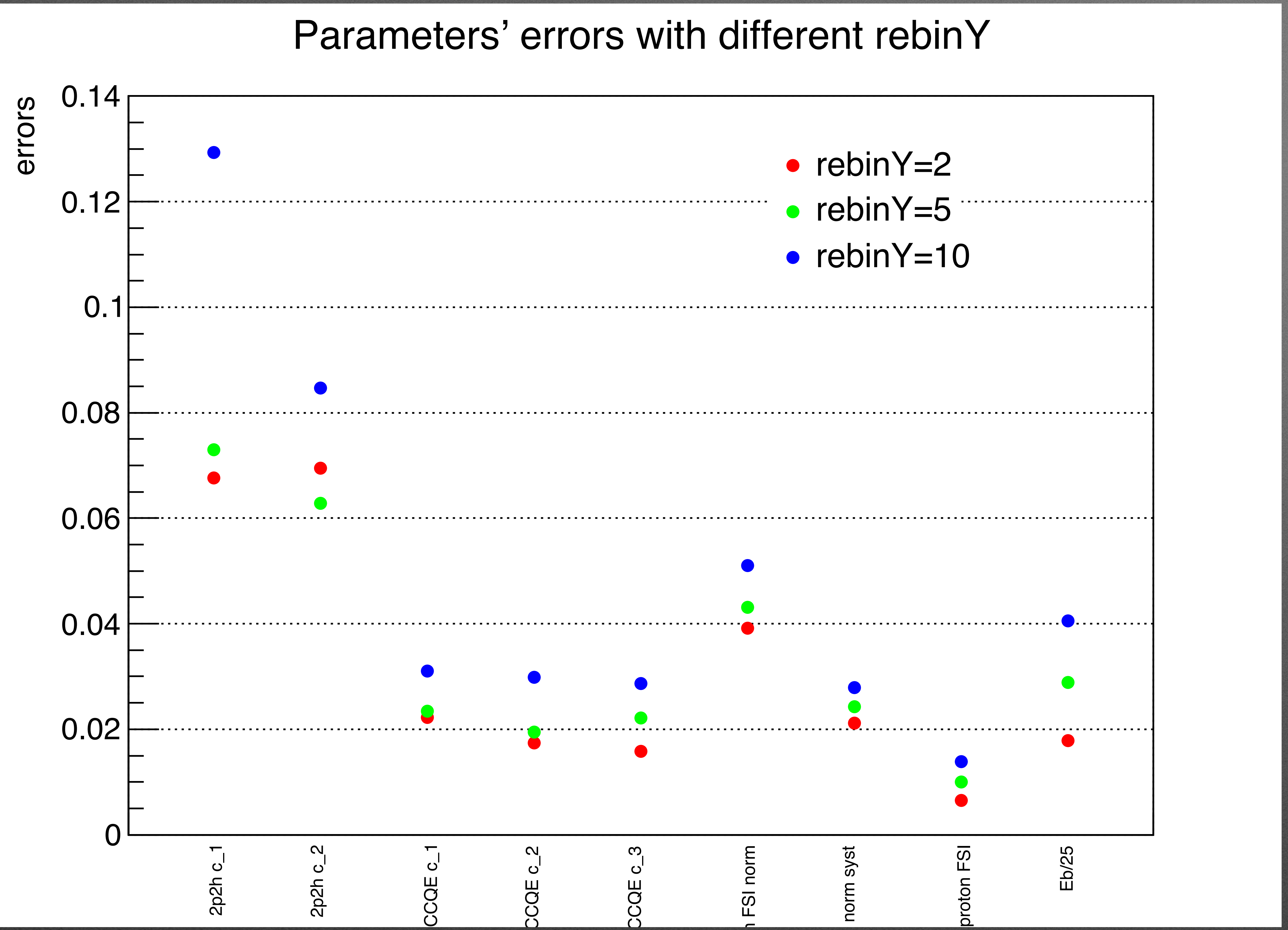


Back up physics study for ND280 upgrade

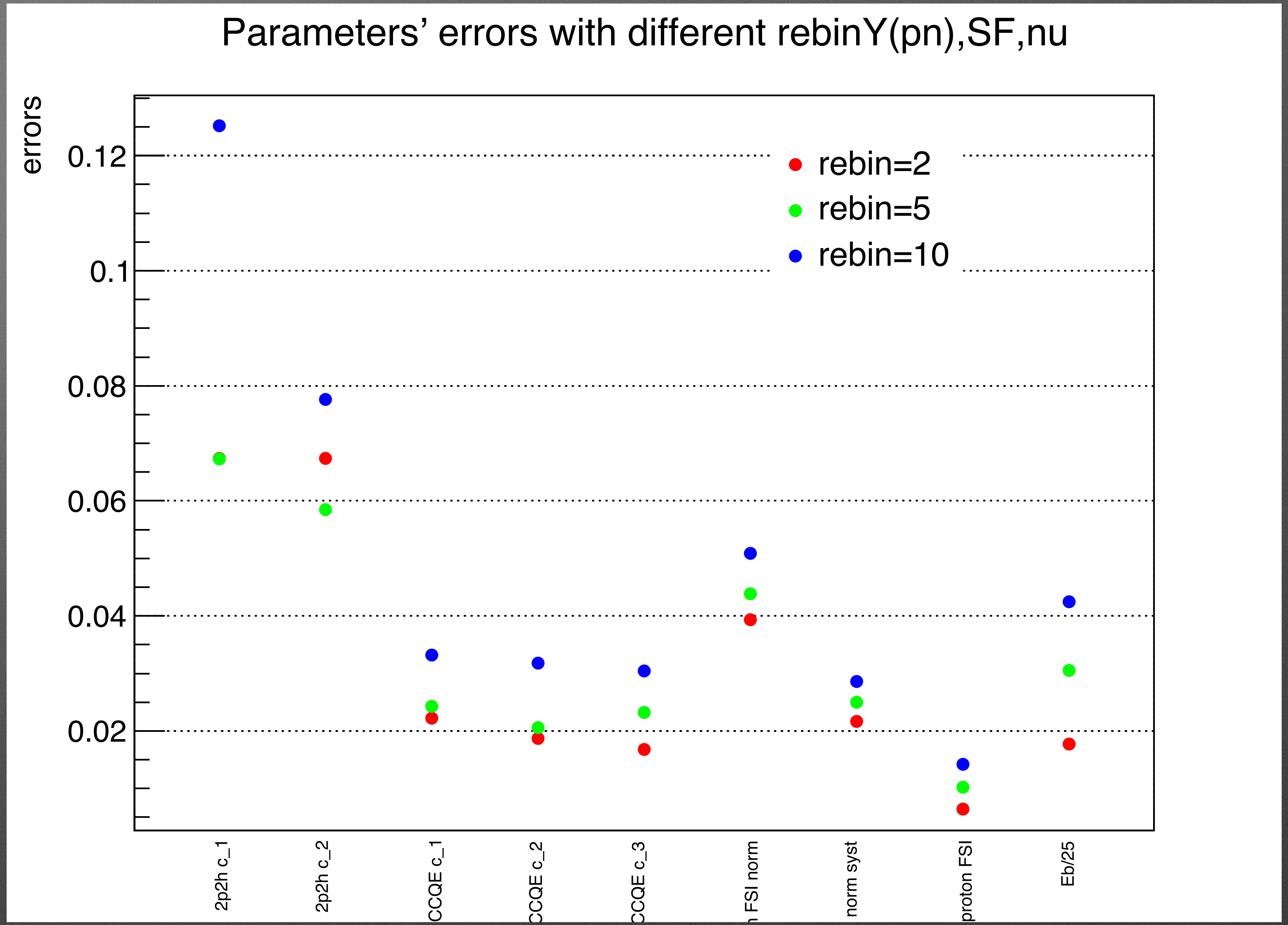
Second project: Physics Studies for ND280 Upgrade
Quantitative sensitivities to neutrino-nuclei interaction mode

- Neutrino oscillation physics is in the precision era.
- There are two main sources of systematic uncertainty in T2K experiment: neutrino flux and neutrino-nucleus interaction model.
- New upgrade can measure better the low-momentum particles produced in the neutrino interactions
  ⇒ Constrains the Nuclear models

Rebin on nucleon momentum (pn)



Relativistic Fermi Gas



Spectral Function

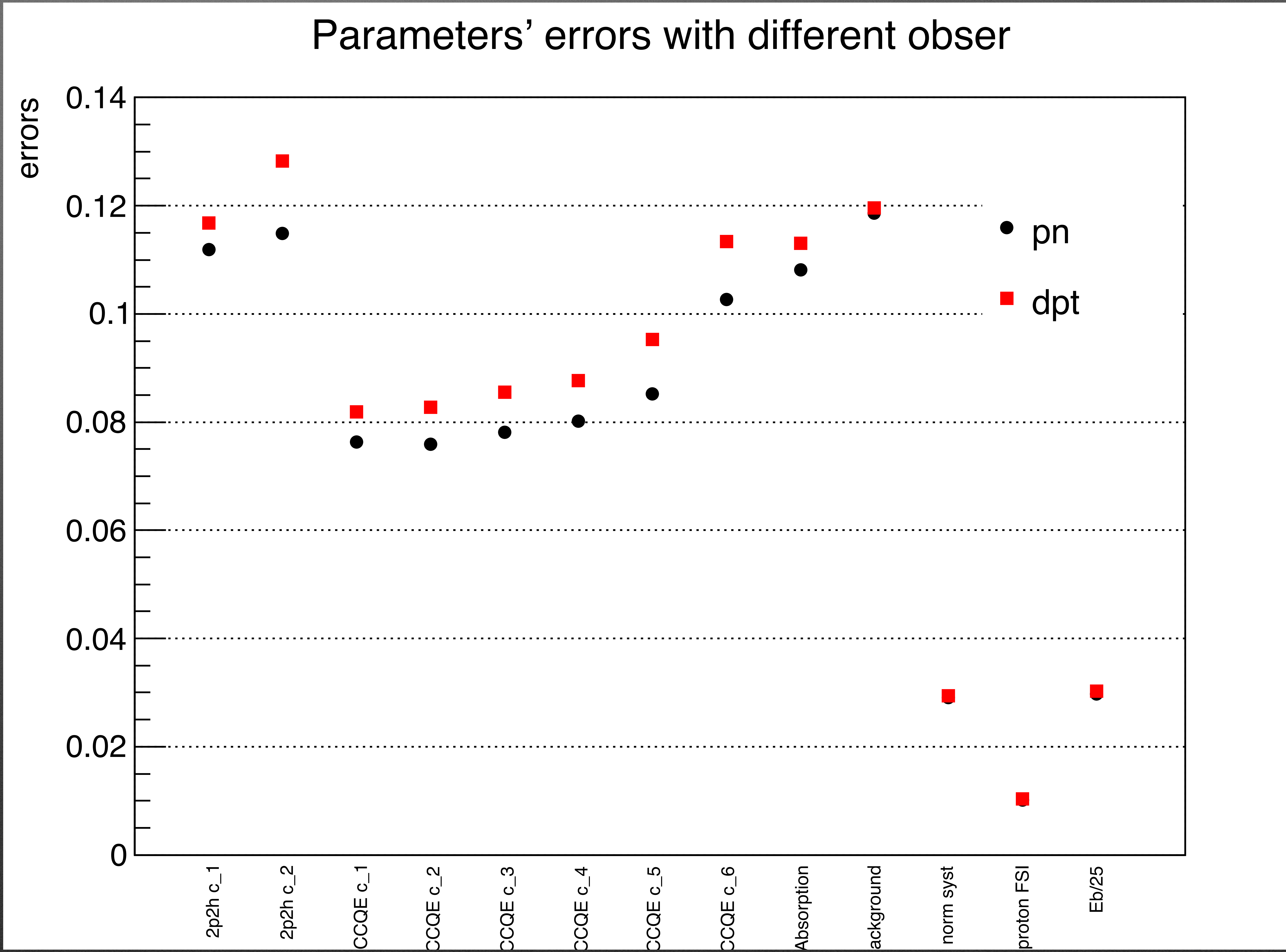
-The CCQE components have better precision compared to 2p2h, and there is no big differences between the 3 parameters of CCQE.
-The precision for all parameters are not good if we rebin to much. So the reasonable value is 5.
-The total bin is 100 before rebin.

Compare results for dpT and pn as observables

Pn: the Fermi momentum of initial nucleon

dpT (δp_T): Transverse component of the Fermi momentum

Using pn as observables results in better errors for key parameters

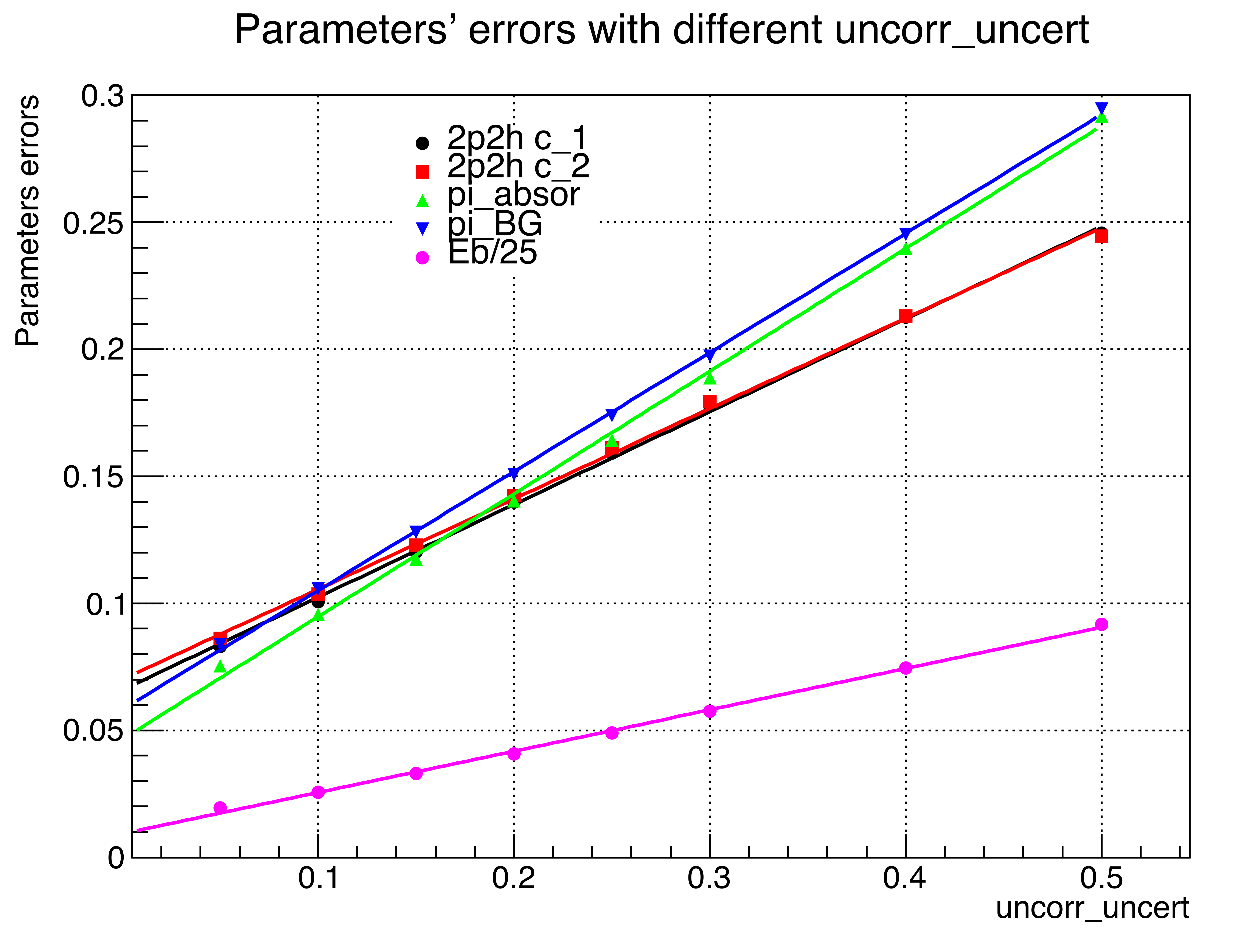


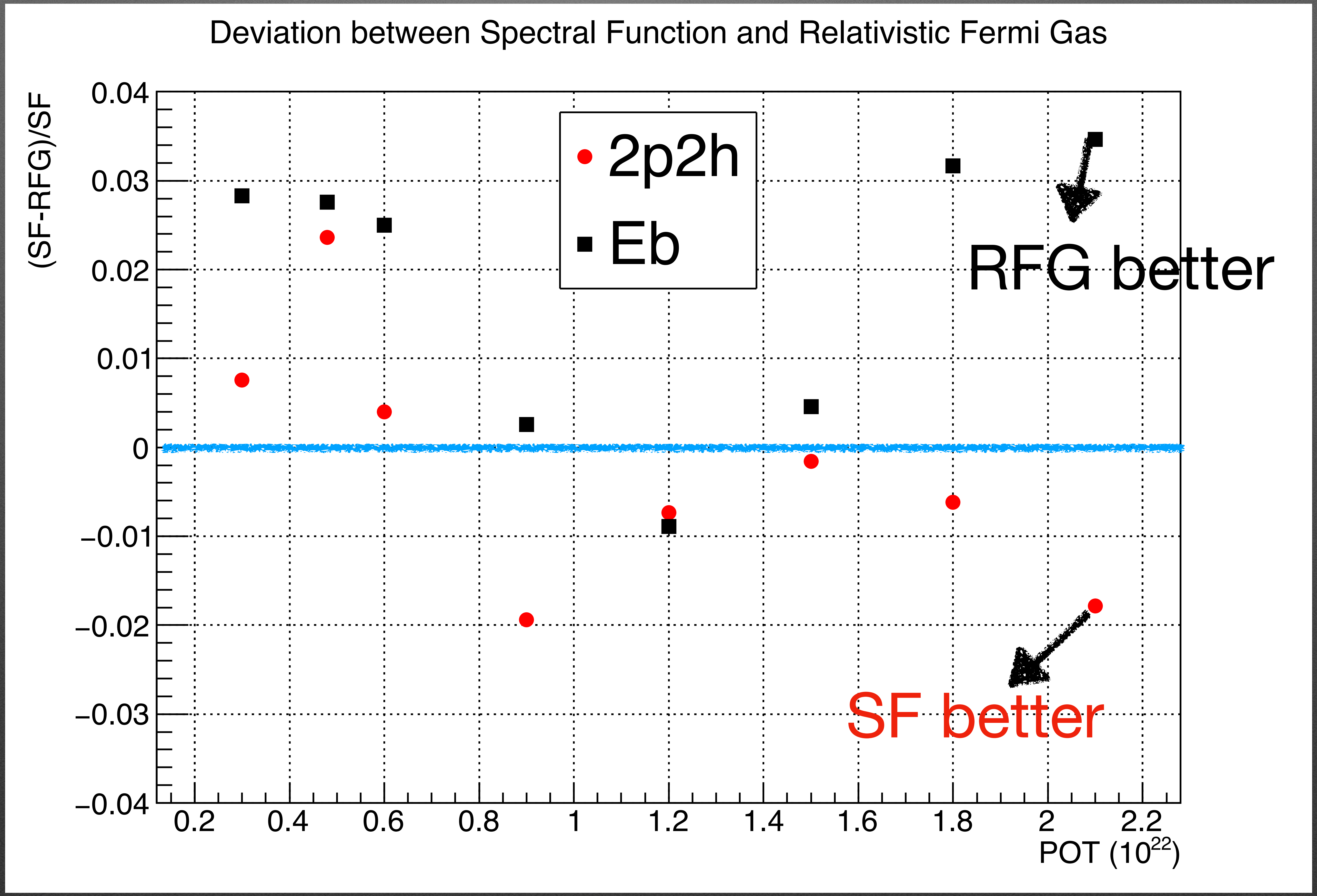
Uncorrelated uncertainty check

Bin-by-bin uncorrelated uncertainty: simulating the impact of flux, detector and background systematics

The parameter errors increase with the uncorrelated uncertainty as a linear function.

But with different slopes





(uncert_SF-uncert_RFG)/uncert_SF
Neutrino case