The TPCs of the T2K experiment

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BSM Nu Workshop

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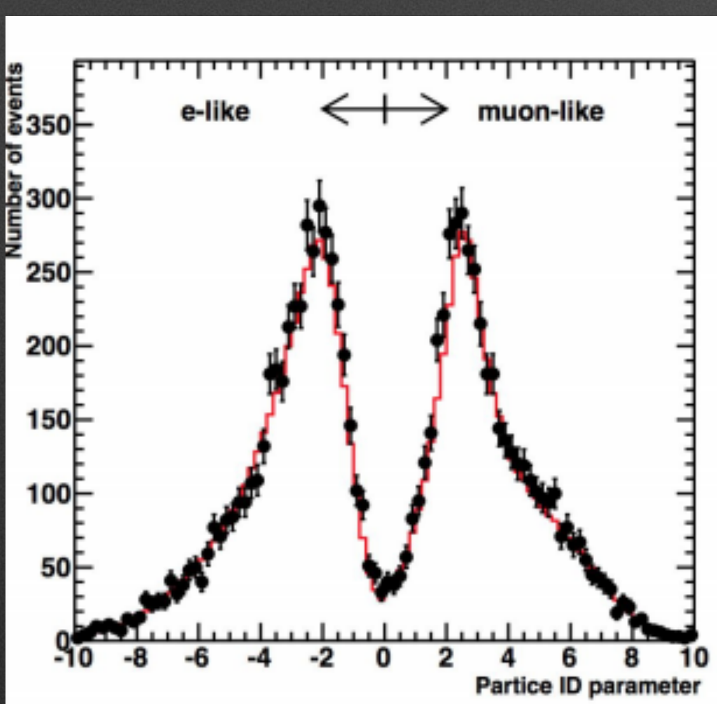
HA-TPCs

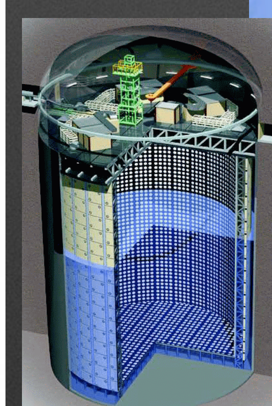
T2K - Tokai to Kamioka

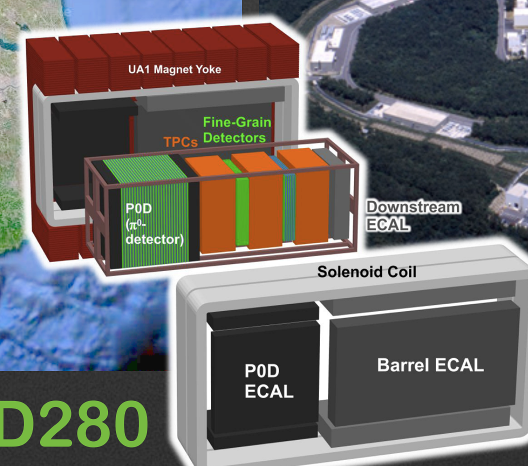
- High intensity ~600 MeV ν_μ beam produced at J-PARC (Tokai, Japan)
- Neutrinos detected at the Near Detector (ND280) and at the Far Detector, Super-Kamiokande 295 km from J-PARC
- Main physics goals:
  - Observation of ν_e and $\bar{\nu}_e$ appearance → determine θ_{13} and δ_{CP}
  - Precise measurement of ν_μ and $\bar{\nu}_\mu$ disappearance → θ_{23} and Δm^2_{32}

Super-Kamiokande

J-PARC accelerator:
Design power: 750 kW
(1.3 MW for HK)







ND280

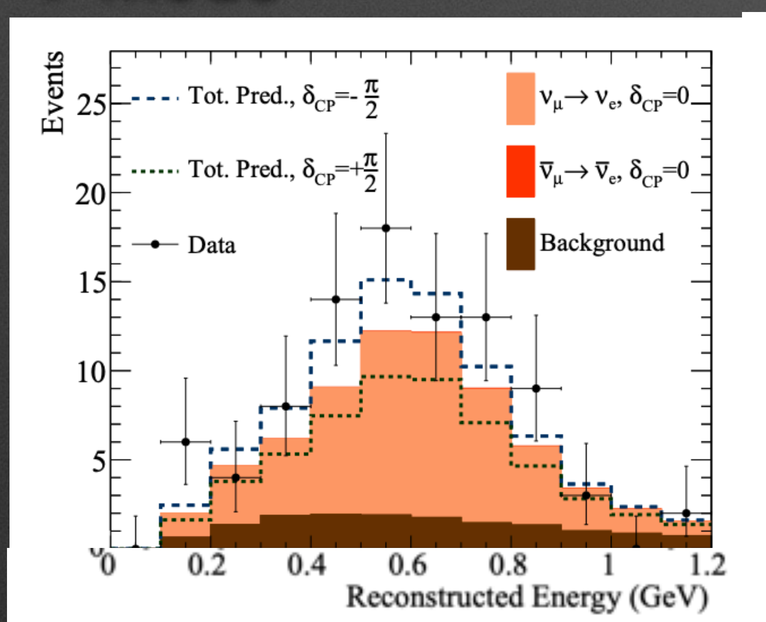
Recent T2K results

- <u>Constraint of the matter-antimatter symmetry violating phase in Neutrino oscillations</u>
  Nature Vol. 580, pp. 339-344

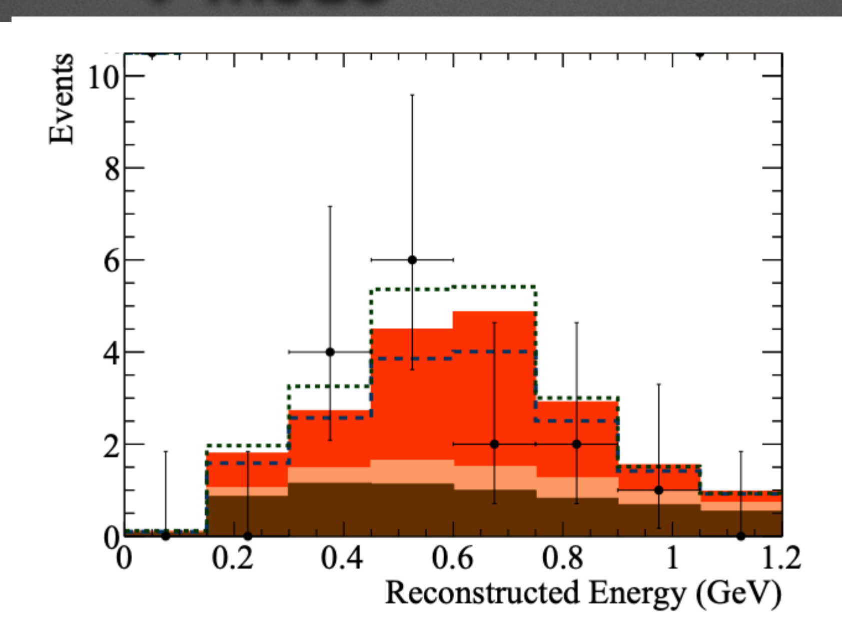
- First 3σ exclusion for 46% (65%) of the δ_{CP} values in NO (IO) with Run1-9 data

- Need more data (and smaller systematics)!

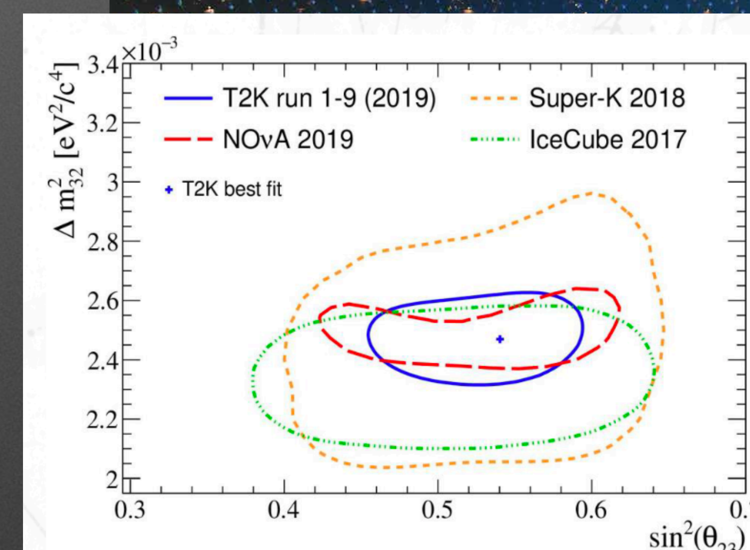
ν-mode

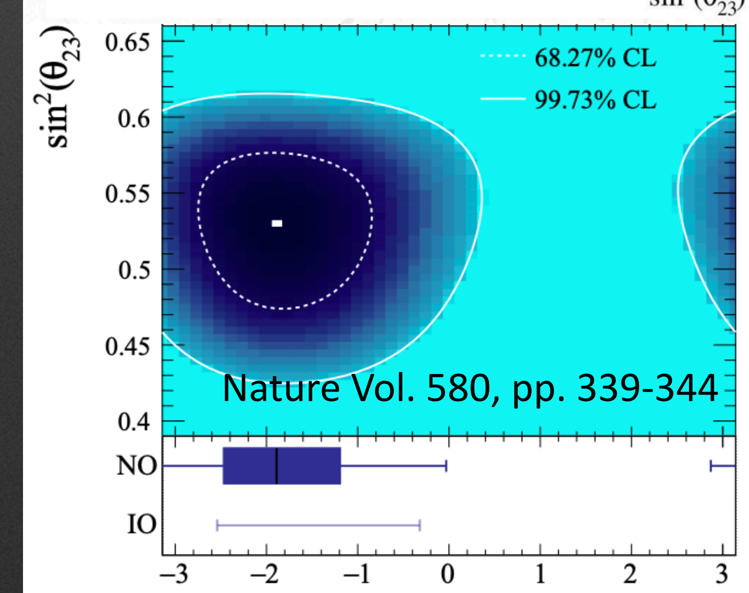


$\bar{\nu}$-mode



	ν-mode	$\bar{\nu}$-mode
Observed	**90**	**15**
Exp ($\delta_{CP}=-\pi/2$)	81.7	17.2
Exp ($\delta_{CP}=0$)	68.4	19.6



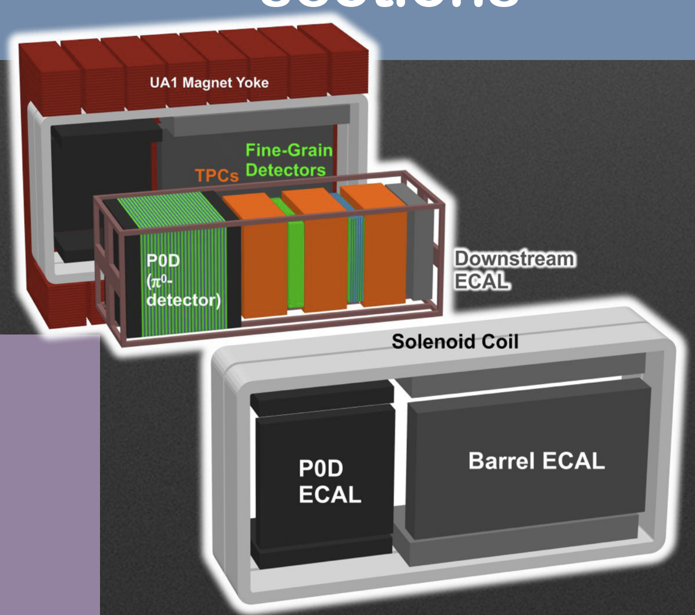


T2K Oscillation Analysis

Flux prediction:
Proton beam measurement
Hadron production (NA61 replica target data)

Prediction at the Far Detector:
Combine flux, cross section and ND280 to predict the expected events at SK

ND280 measurements:
ν_μ and $\overline{\nu}_\mu$ selections to constrain flux and cross-sections

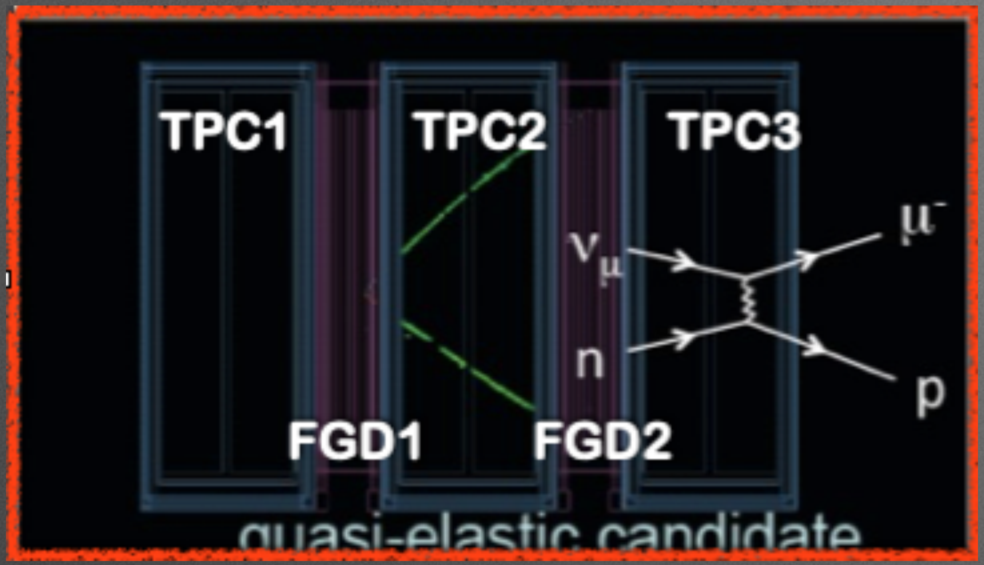


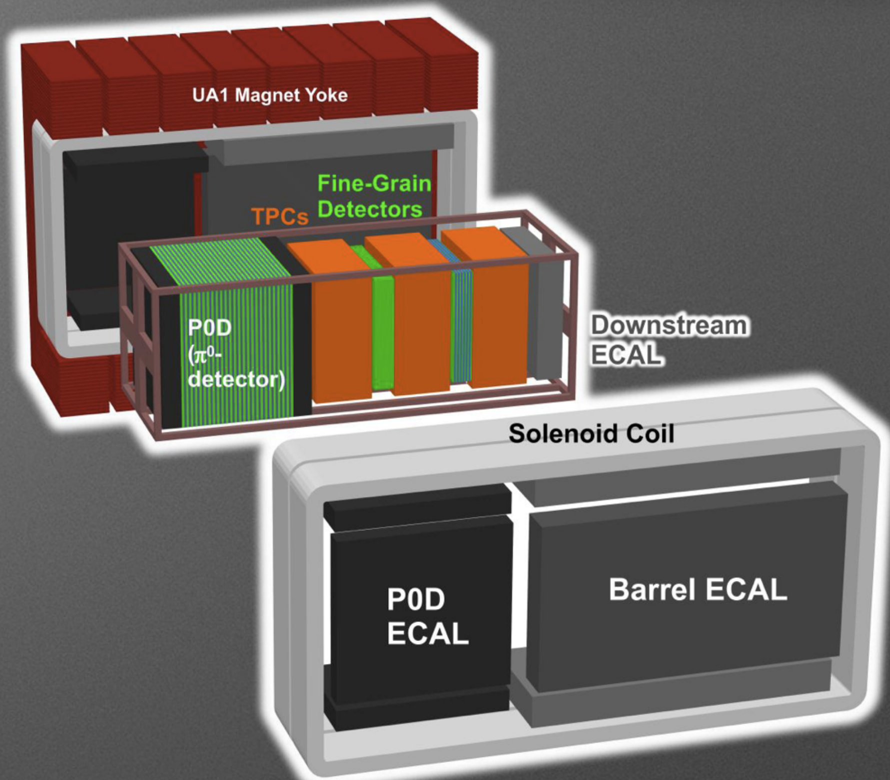
Extract oscillation parameters!

Neutrino interactions:
Cross-section models
External data

SK measurements:
Select CC ν_μ, $\overline{\nu}_\mu$, ν_e, $\overline{\nu}_e$ candidates after the oscillations

ND280

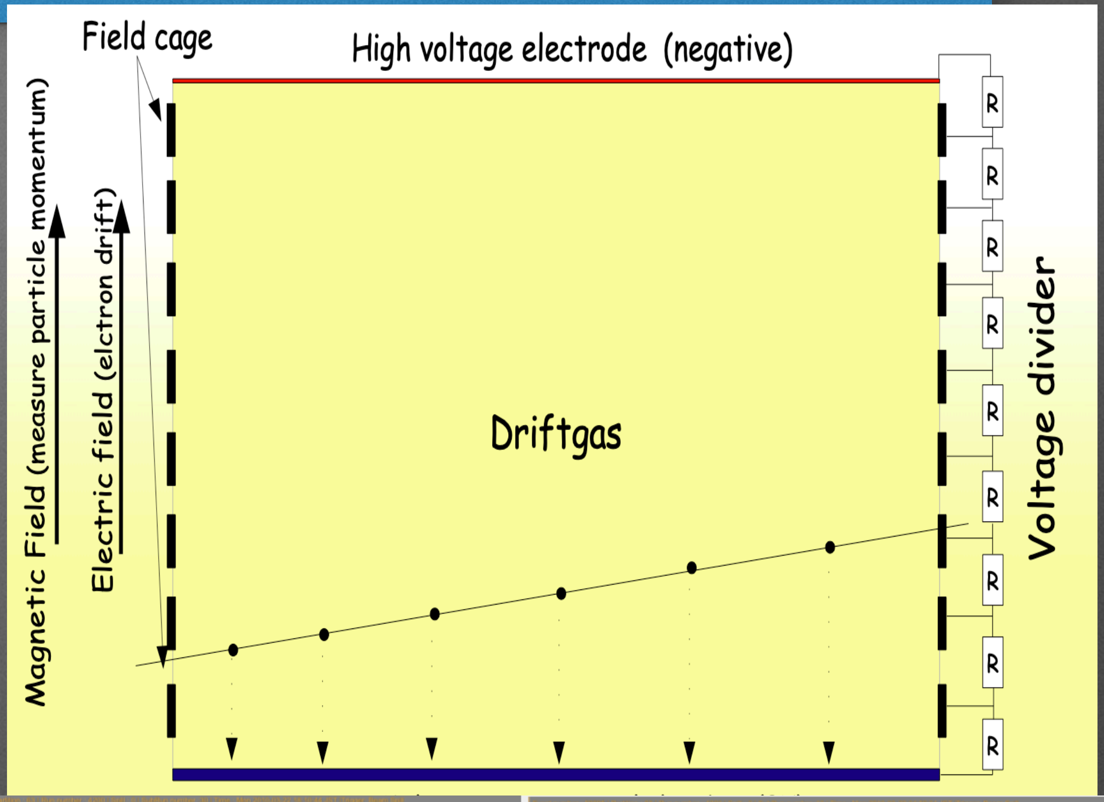


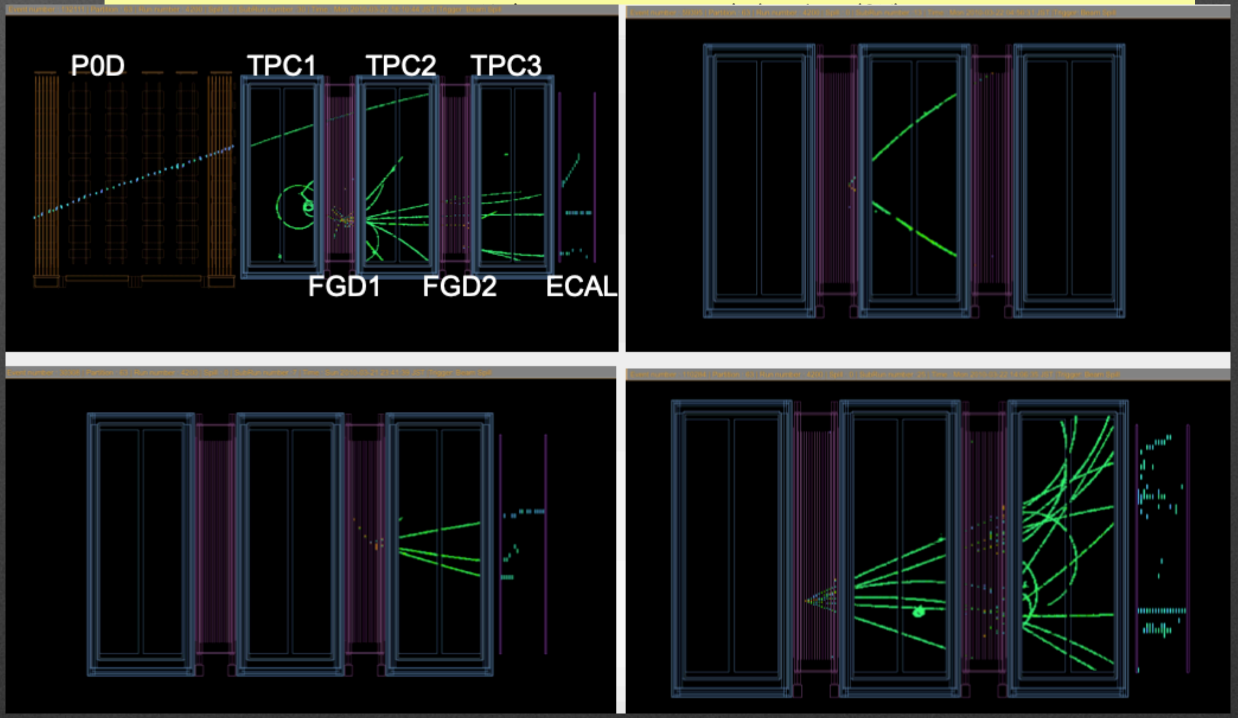


- Measure beam spectrum and flavor composition before the oscillations
- Detector installed inside the UA1/NOMAD magnet (0.2 T)
- A detector optimized to measure π^0 (P0D)
- An electromagnetic calorimeter to distinguish tracks from showers
- A tracker system composed by:
  - 2 Fine Grained Detectors (target for ν interactions). FGD1 is pure scintillator, FGD2 has water layers interleaved with scintillator
  - 3 Time Projection Chambers: reconstruct momentum and charge of particles, PID based on measurement of ionization

TPC principles

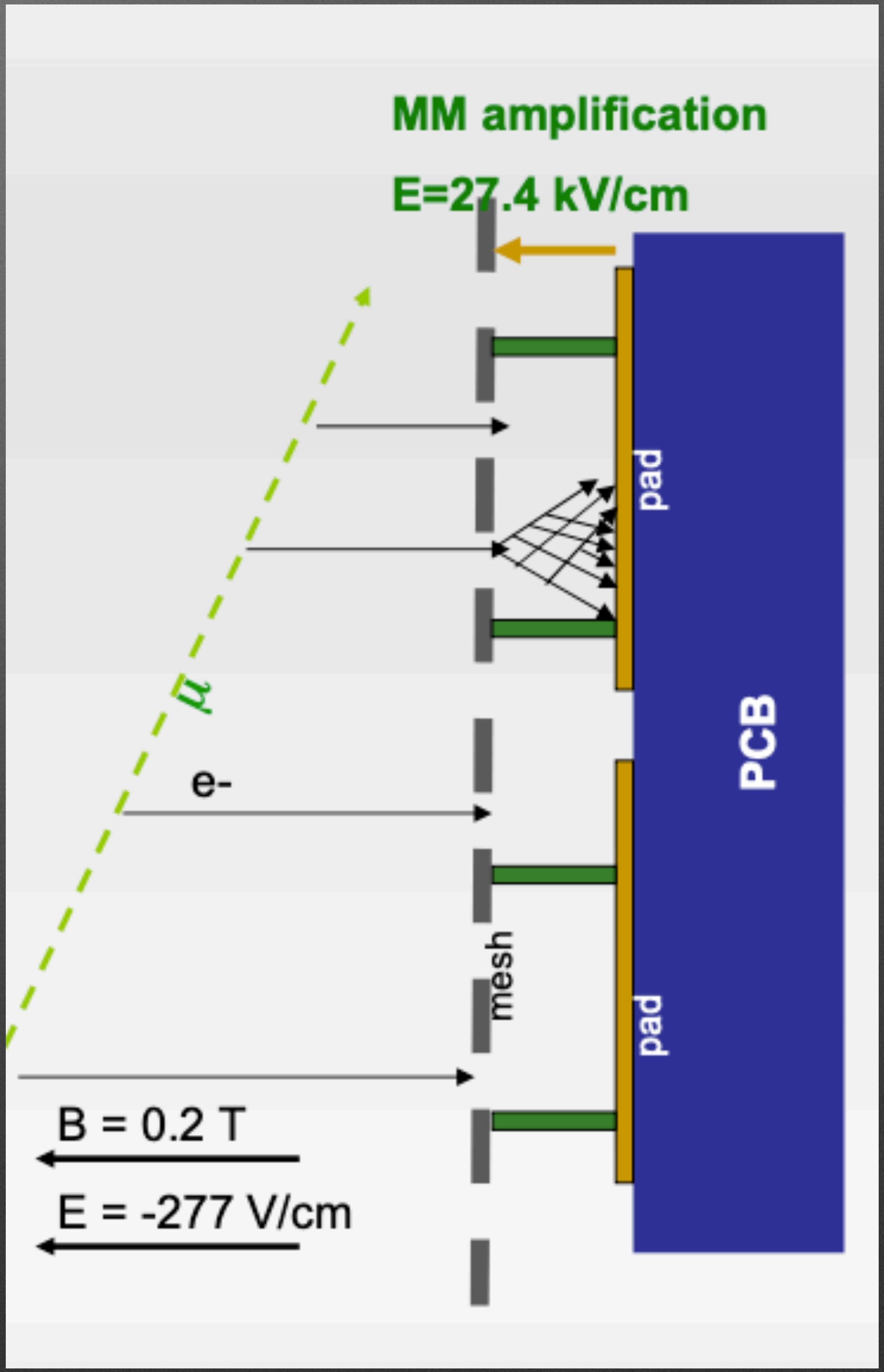
- Tracking device
- Charged particles ionise gas molecules producing free electrons
- Electrons drifted towards readout plane under the effect of an Electric field
  - 2 coordinates given by the projection on the pad plane
  - 3rd coordinate given by the drift time
- Usually TPC are immersed in a magnetic field
  - Induce curvature in the trajectory of the charged particles
  - Curvature is proportional to the particle momentum





MicroMegas principles

- T2K TPCs are instrumented with MicroMegas modules as readout system
- On the MicroMegas plane a strong electric field is applied → avalanche
  - Gain 10^3 - 10^4
  - ~100% collection efficiency
- MicroMegas are segmented into pads of ~1cm2 → high granularity, precise measurement of the track position



TPC advantages

* Gaseous TPCs are an ideal detector for Near Detector of ν experiments
  * Almost the whole volume is active
  * Minimal radiation length
  * Easy pattern recognition with continuous tracks
  * Measurement of particle momentum from curvature
  * PID from dE/dx measurements
* Doesn't provide target mass → need to be coupled with a target (FGD in our case)

T2K TPC requirements

Momentum resolution <10% at 1 GeV

$$\frac{\sigma(p_T)}{p_T} = \frac{8p_T}{0.3BL^2} \times \sigma_s$$

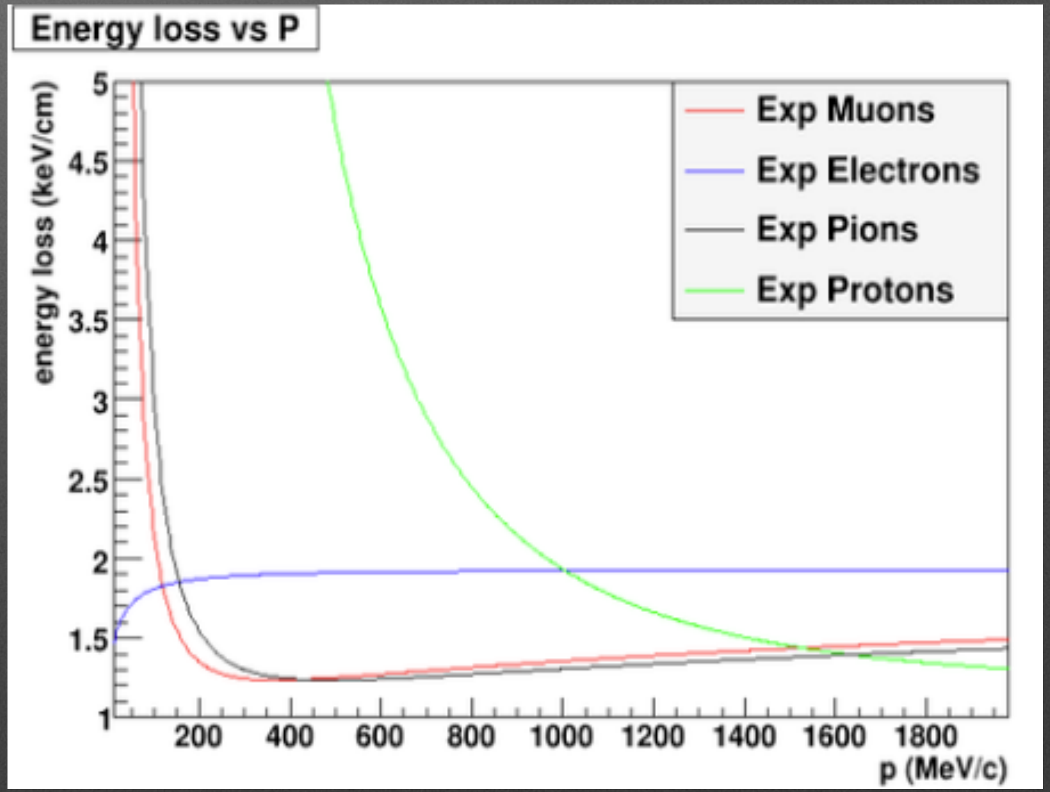
$$\sigma_s = \sqrt{\frac{A_N}{N+4}} \times \frac{\sigma_{res}}{8}$$

σ(pT)/pT proportional to spatial resolution → σ_{res}

With 72 clusters and a track length of 70 cm this results in a spatial resolution **better than 700 μm**

dE/dx resolution better than 10%

dE/dx depends on βγ = p/m (Bethe-Block formula)



Electrons and muons are separated by ~40% → 10% resolution allow to distinguish them by >3σ

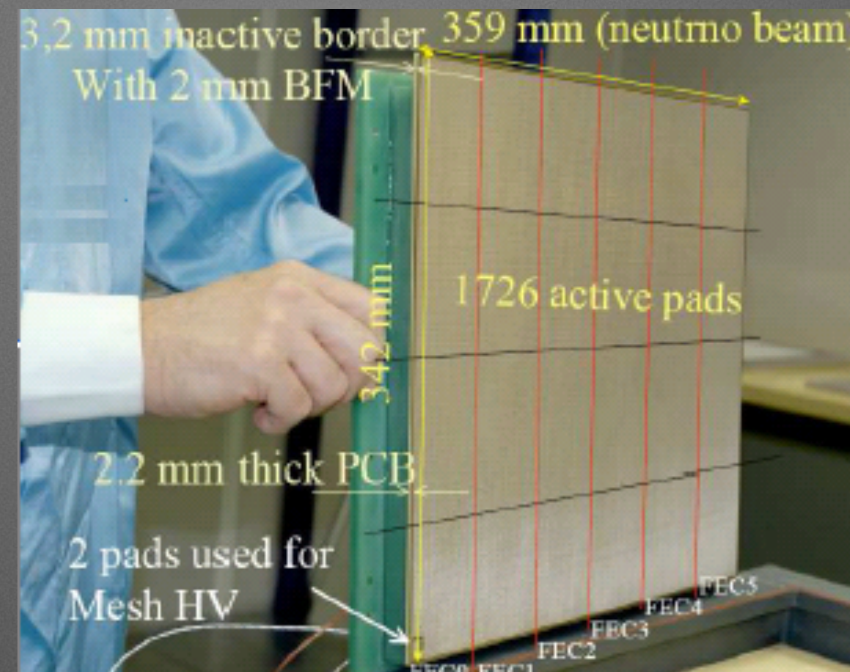
Measure ν_e contamination in the beam

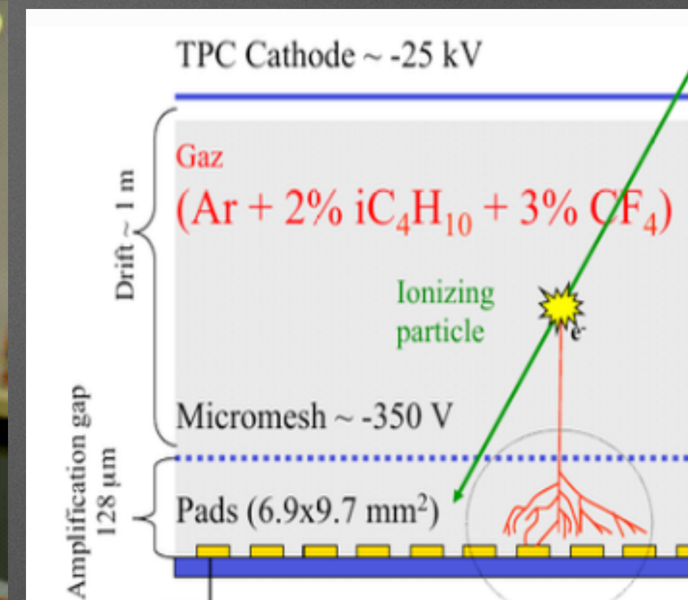
Vertical TPCs

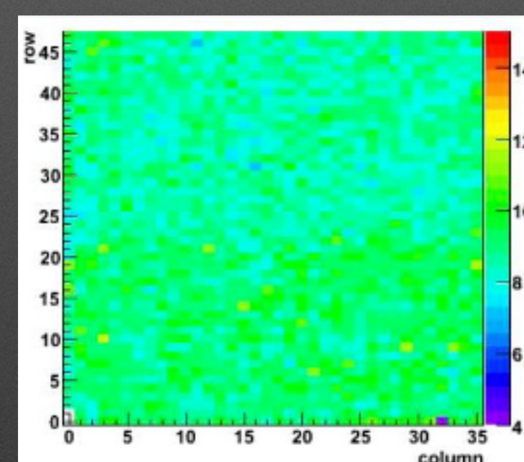
- Double wall structure
  - Inner volume walls create drift field
  - Outer volume for gas/HV insulation
  - Total active area of $9 m^2$
- Gas mixture $Ar/CF_4/iC_4H_{10}$ (95/3/2)
  - Fast (v_d~7.9 cm/μs@280 V/cm)
  - Low transverse diffusion (D_t~250 $\mu m/cm^{-1/2}$ @ 0.2 T)
- Installed at J-PARC in 2009 and continuously taking data since then → no degradations in performances observed

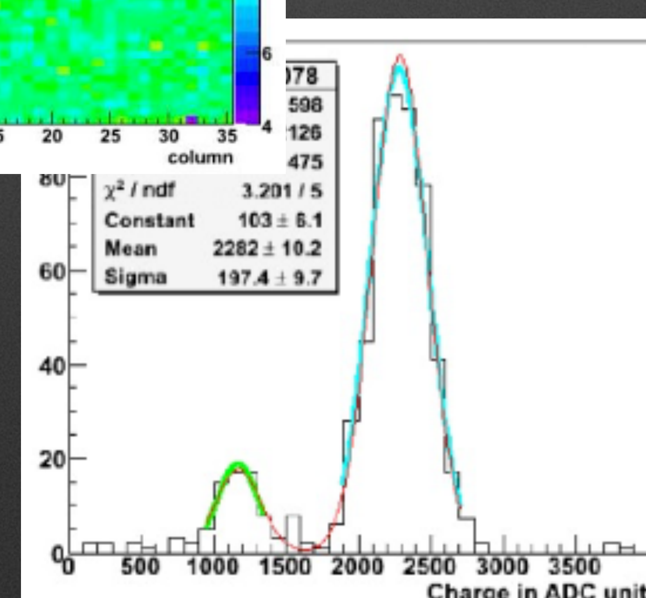
Bulk MicroMegas and Electronics

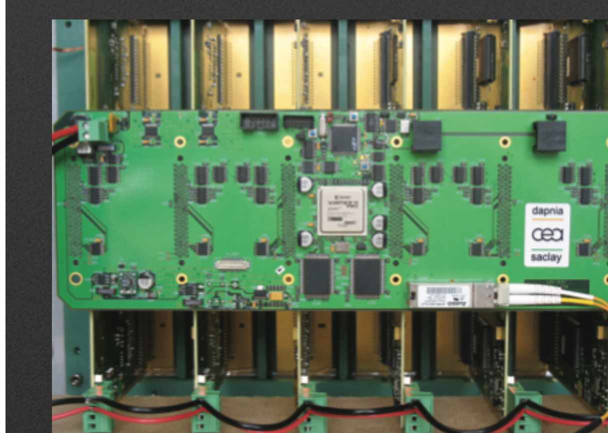
- 12 large bulk-MicroMegas on each endplate → 72 modules in total
- Each module has 1726 active pads → total of ~120000 active channels
- Readout electronics based on ASIC AFTER chips (72 channels) with programmable gain, sampling time, peaking time, …
- 6 Front-End-Cards (FEC) and 1 Front-End-Mezzanine (FEM) for each module)







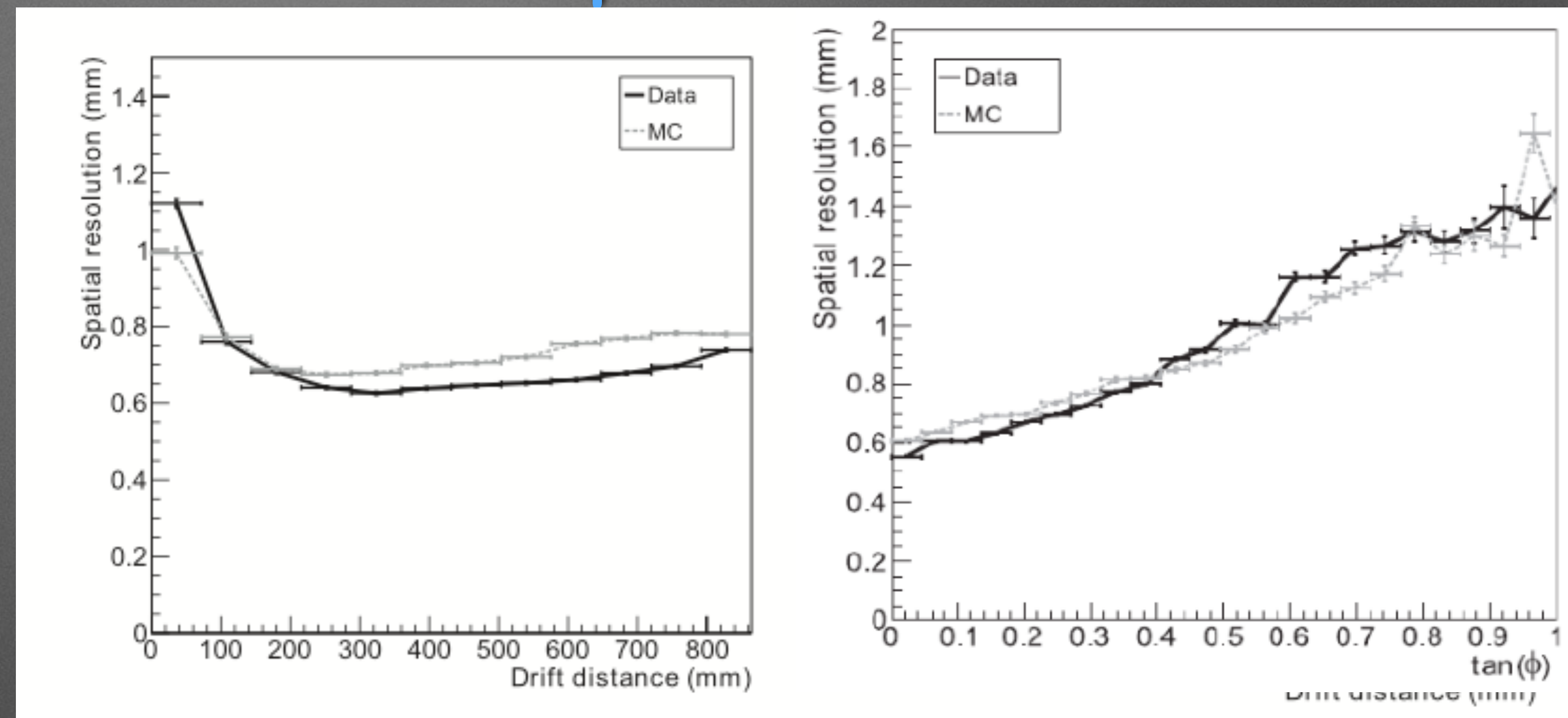




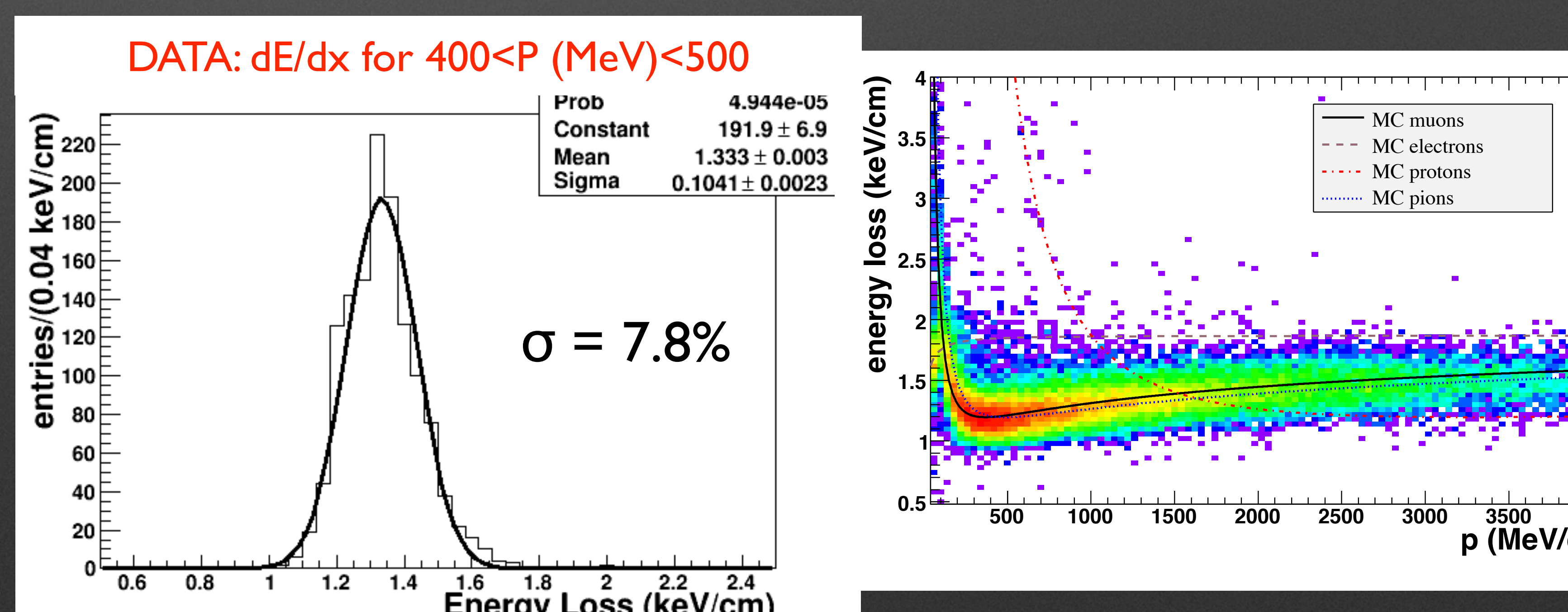
T2K TPCs performances

Spatial resolution

- Spatial resolution ~600 μm for horizontal track, 1.2 mm for diagonal tracks→ Corresponding to momentum resolution <10% at 1 GeV

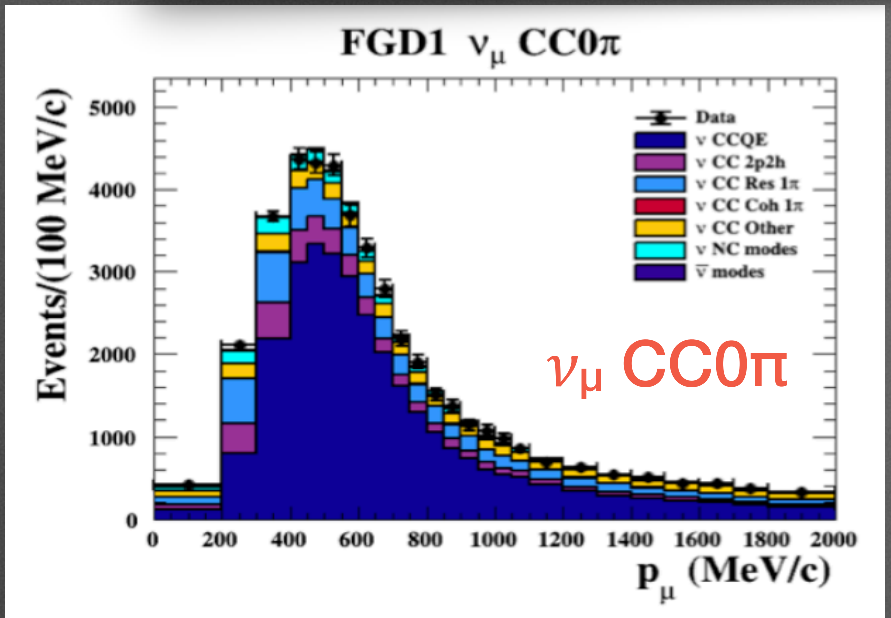


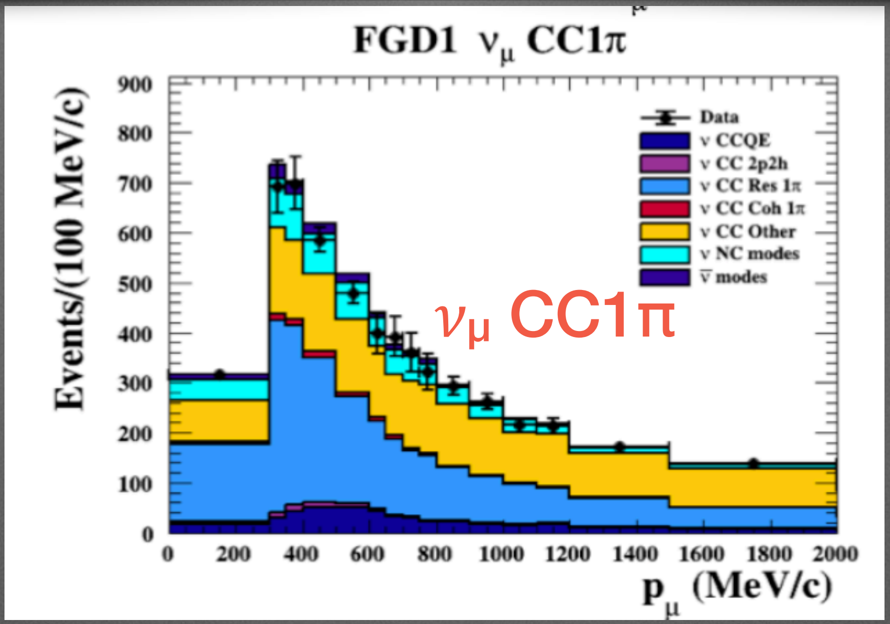
- Energy resolution < 8% → allow to distinguish electrons from muons

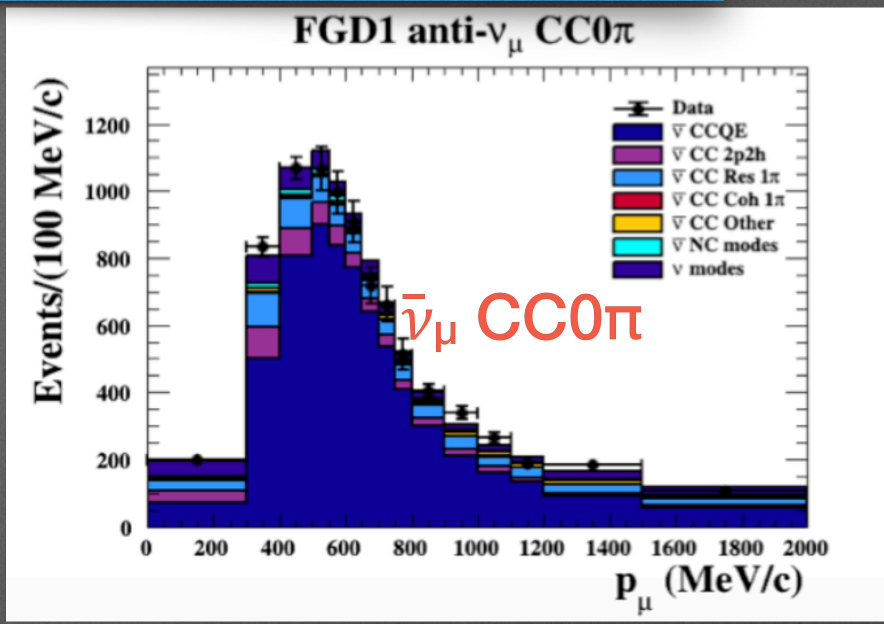


Nucl.Instrum.Meth.A 637 (2011) 25-46

ND280 selections

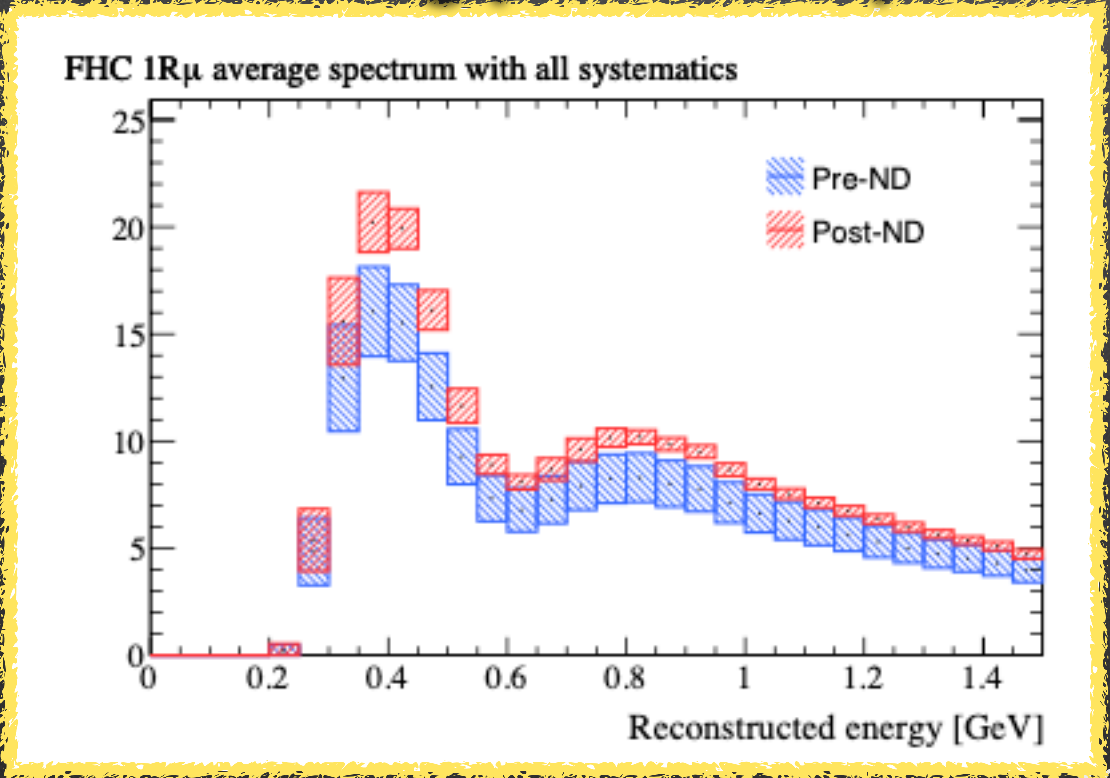




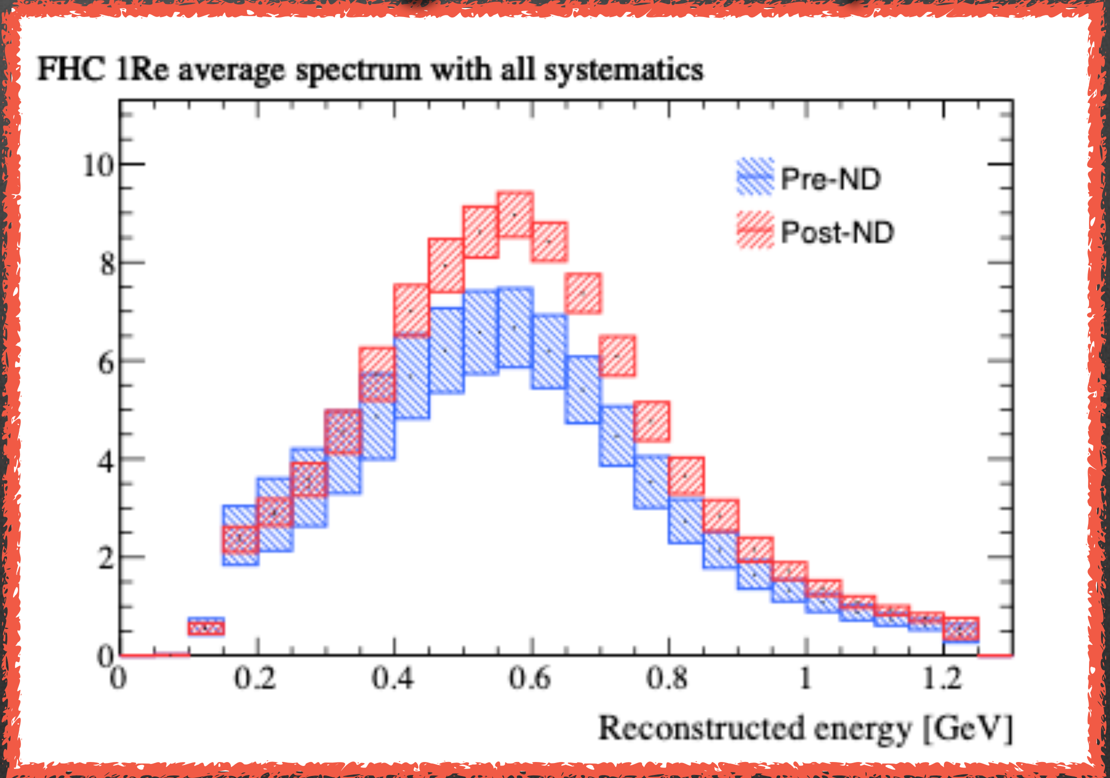


Postfit systematics uncertainties on the rate
(from flux and cross-section) ~2%

SK 1Ring μ-like sample

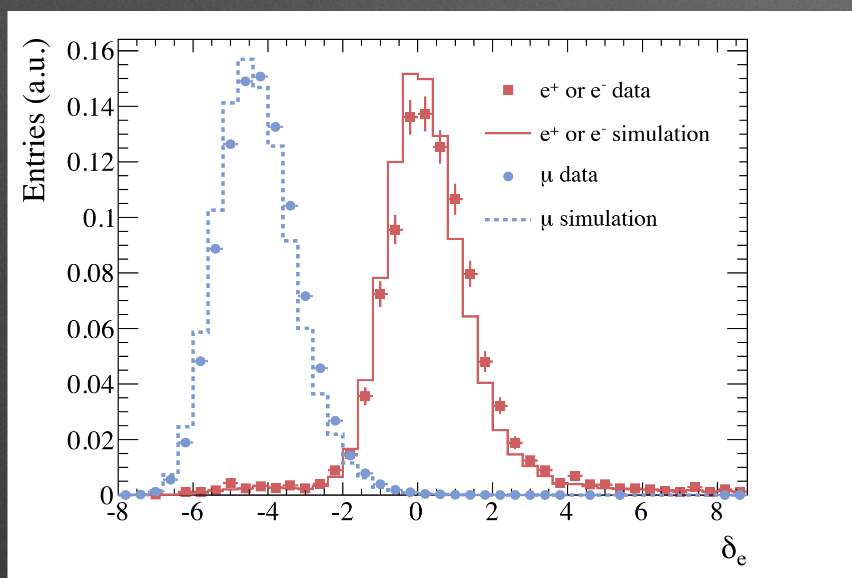


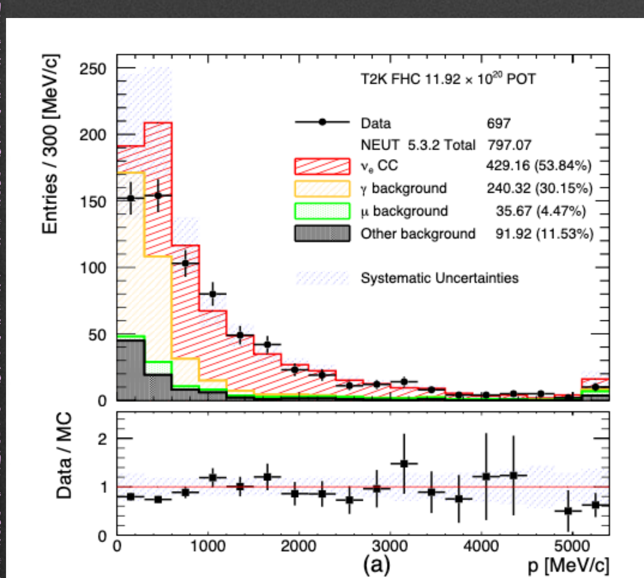
SK 1Ring e-like sample

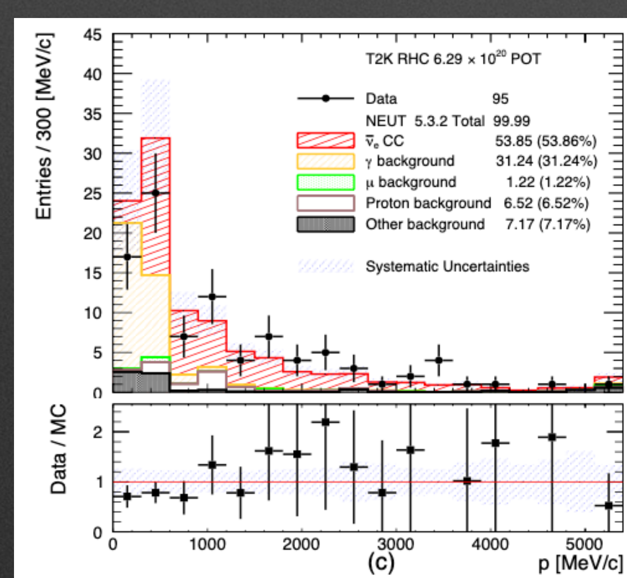


More TPCs based analyses

Distinguish e/μ by combining TPC and ECAL PID to measure ν_e and $\bar{\nu}_e$ (~1% of total ν flux)



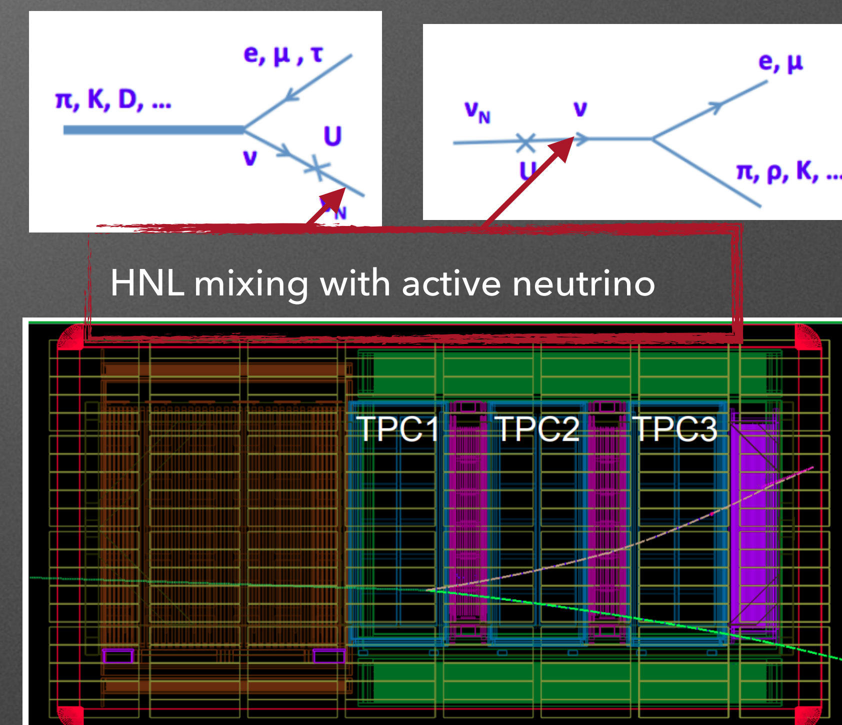




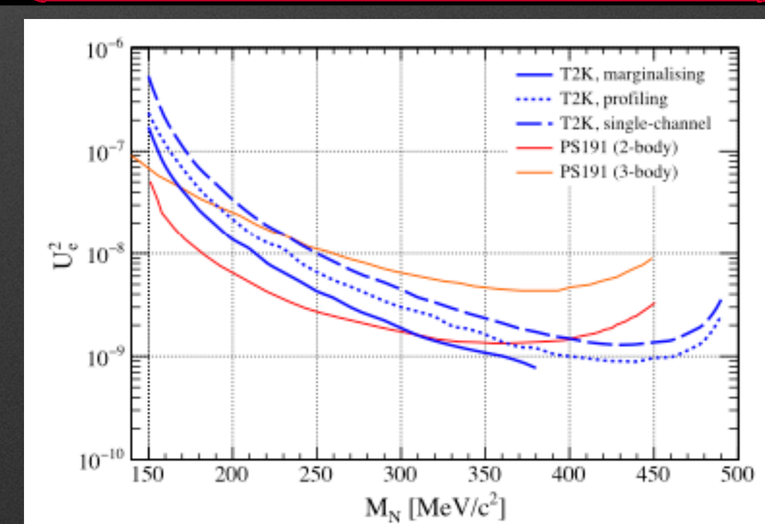
arXiv:2002.11986

Search for Heavy Neutral Leptons produced by hadrons and decaying in the TPC

HNL production in meson decay



HNL decay into SM particles

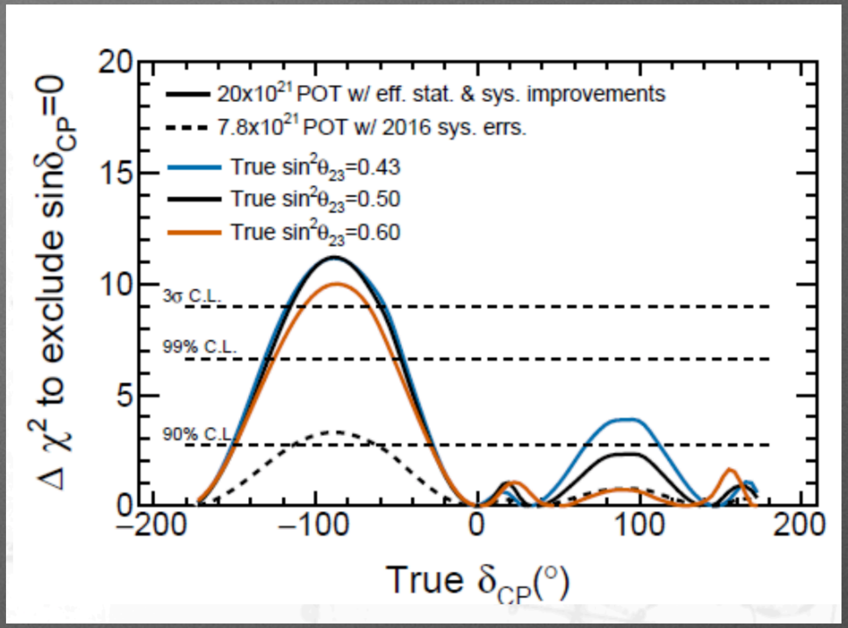


Phys.Rev.D 100 (2019) 5, 052006

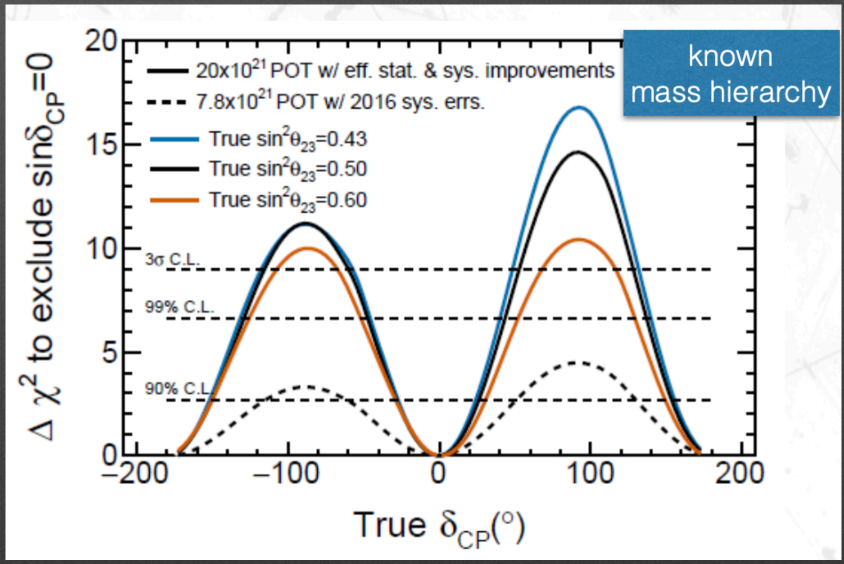
T2K-II

T2K-II

- Originally proposed exposure: 20×10^{21} POT
- Physics goals:
  - CP violation > 3σ @ $\delta_{CP}=-\pi/2$
  - $\delta\theta_{23}<1.7°$ (for maximal mixing)
  - $\delta\Delta m^2_{32}/\Delta m^2_{32} < 1\%$

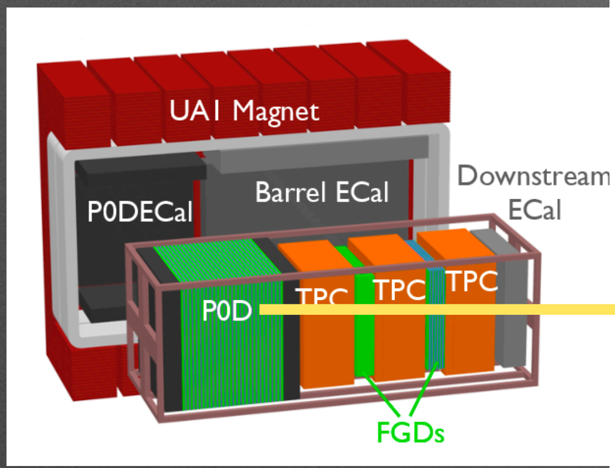


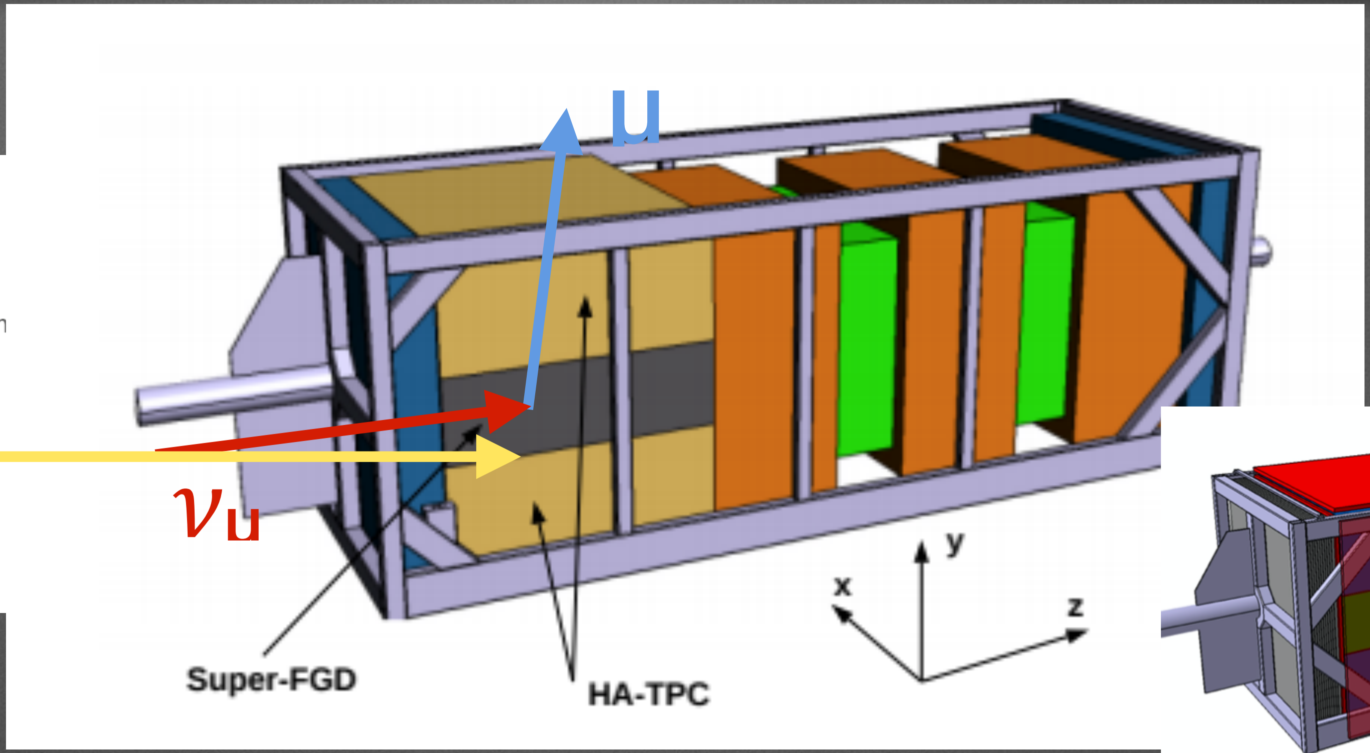
arXiv:1609.04111

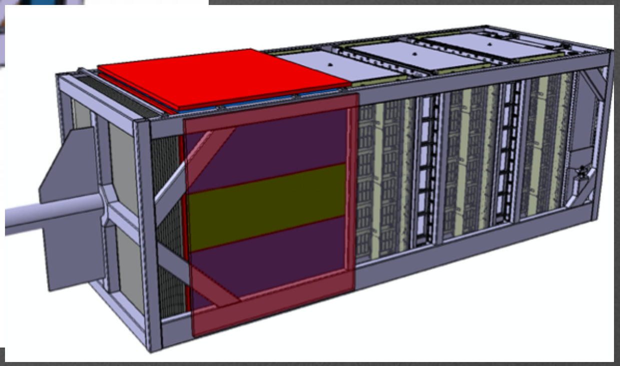


- Two hardware projects:
  - Neutrino beamline upgrade
  - Near Detector (ND280) upgrade

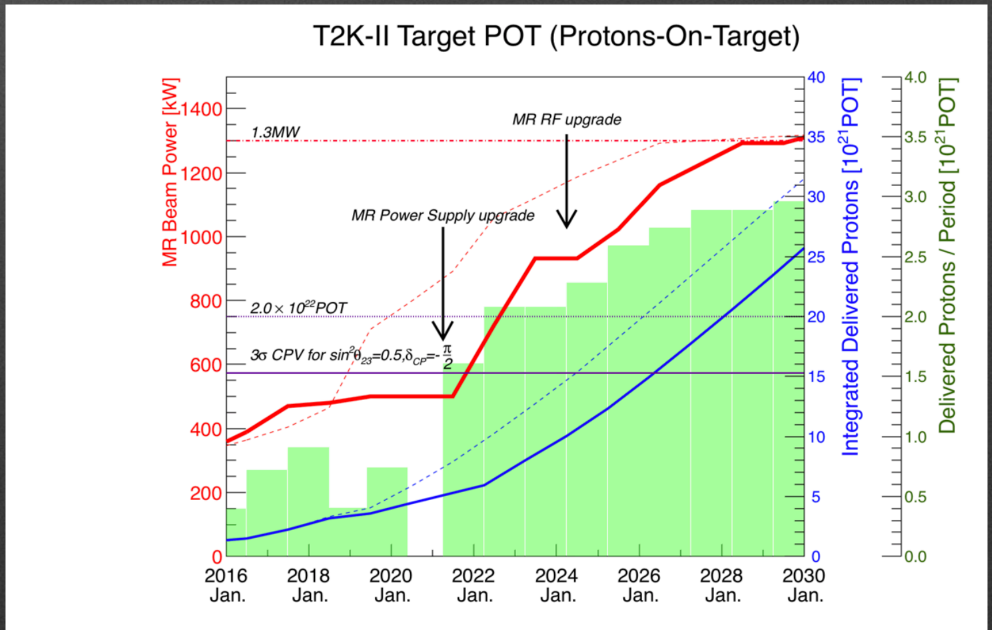
ND280 Upgrade (from 2022)



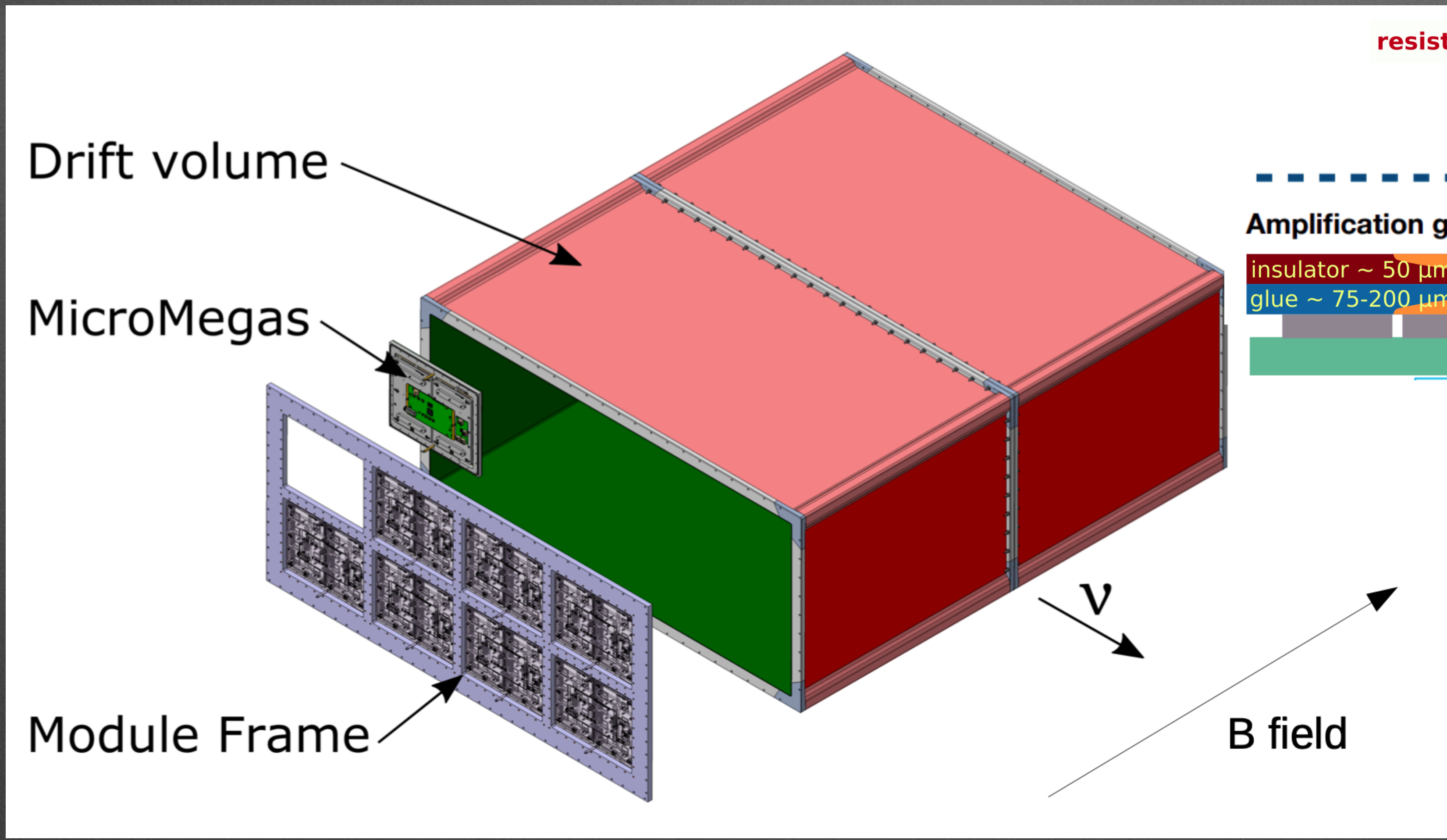


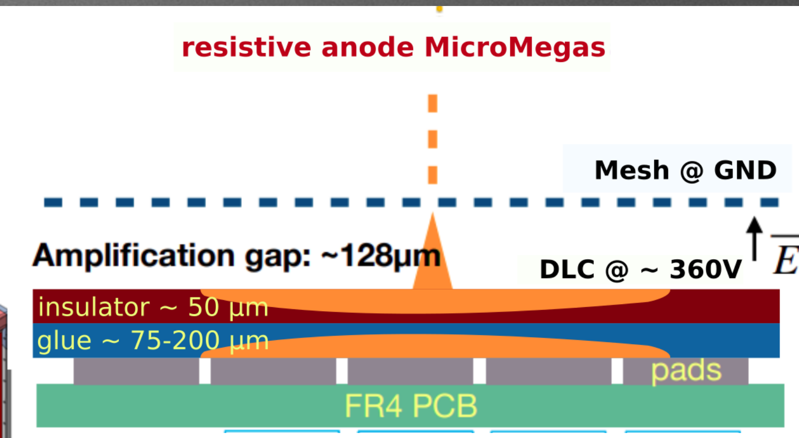


- One horizontal highly segmented target (Super-FGD) → Improve reconstruction of hadronic part of the interaction
- Two new High Angle TPCs → Improve reconstruction of high angle leptons
- 6 Time Of Flight planes → Reduce backgrounds entering from outside the Super-FGD
- After the upgrade ND280 will be a full acceptance fine grained detector with magnetic field → Measure momentum and charge of all leptons emitted in neutrino and antineutrino interactions
- Coupled with the Main Ring power supply upgrade at J-PARC in 2021 → beam power from 500 kW to 1.3 MW



HA-TPC

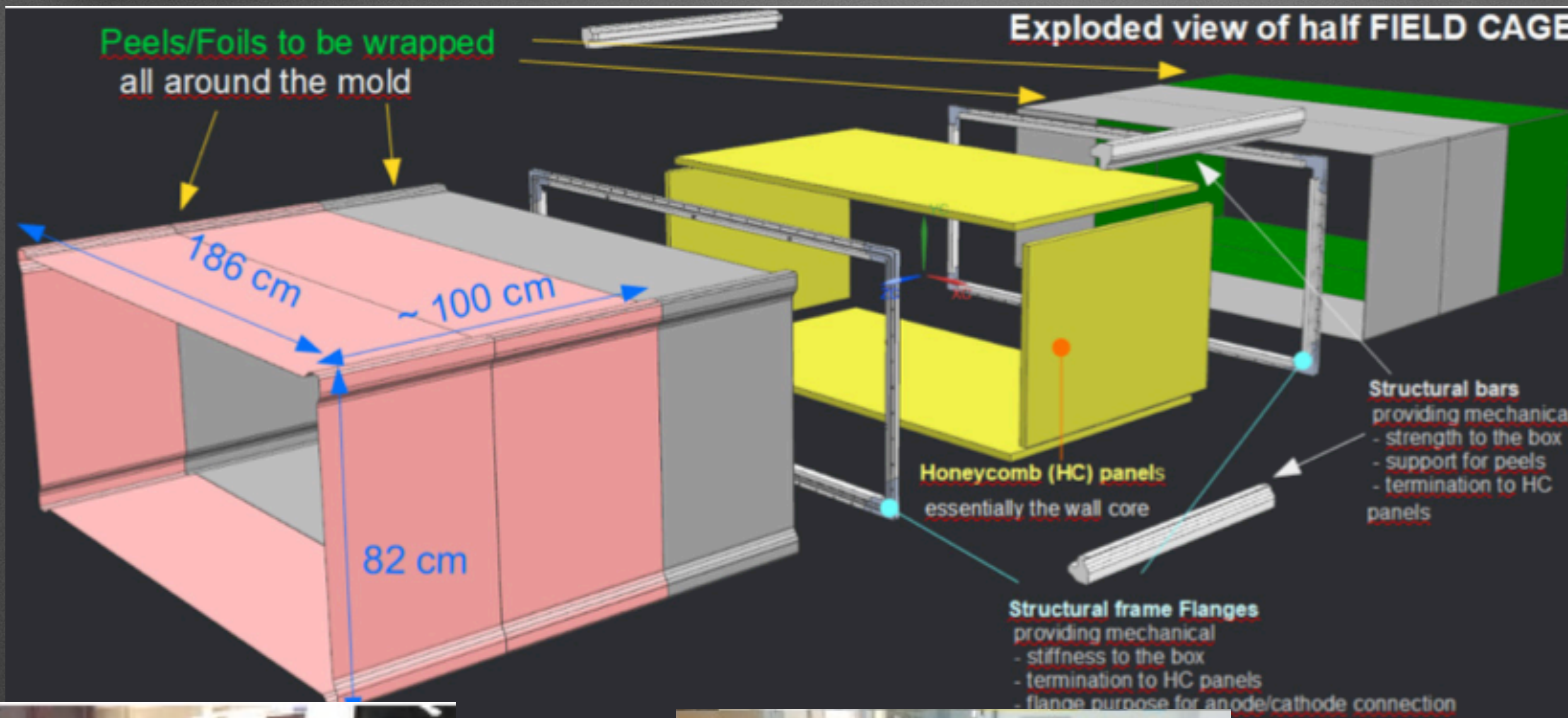




Parameter	Value
Overall x × y × z (m)	2.0 × 0.8 × 1.8
Drift distance (cm)	90
Magnetic Field (T)	0.2
Electric field (V/cm)	275
Gas Ar-CF_4-iC_4H_{10} (%)	95 - 3 - 2
Drift Velocity $cm/\mu s$	7.8
Transverse diffusion ($\mu m/\sqrt{cm}$)	265
Micromegas gain	1000
Micromegas dim. z×y (mm)	340x420
Pad z × y (mm)	10 × 11
N pads	36864
el. noise (ENC)	800
S/N	100
Sampling frequency (MHz)	25
N time samples	511

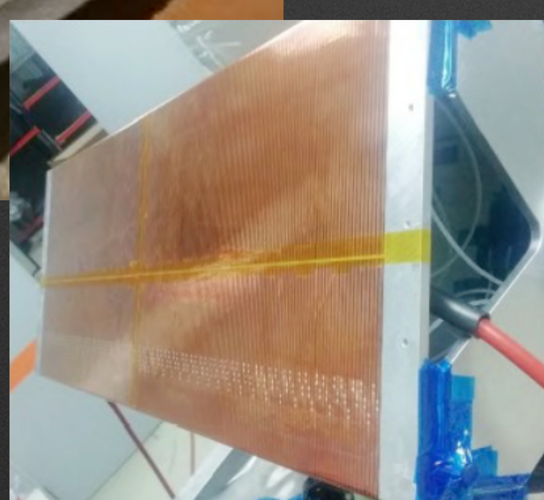
- TPC operated at atmospheric pressure
- Design similar to the one of the existing ND280 TPCs
- Main differences: use of resistive MicroMegas (ERAM modules) and thin field cage
- A gas monitor chamber will be used to monitor gain, drift velocity, …

HA-TPC Field Cage



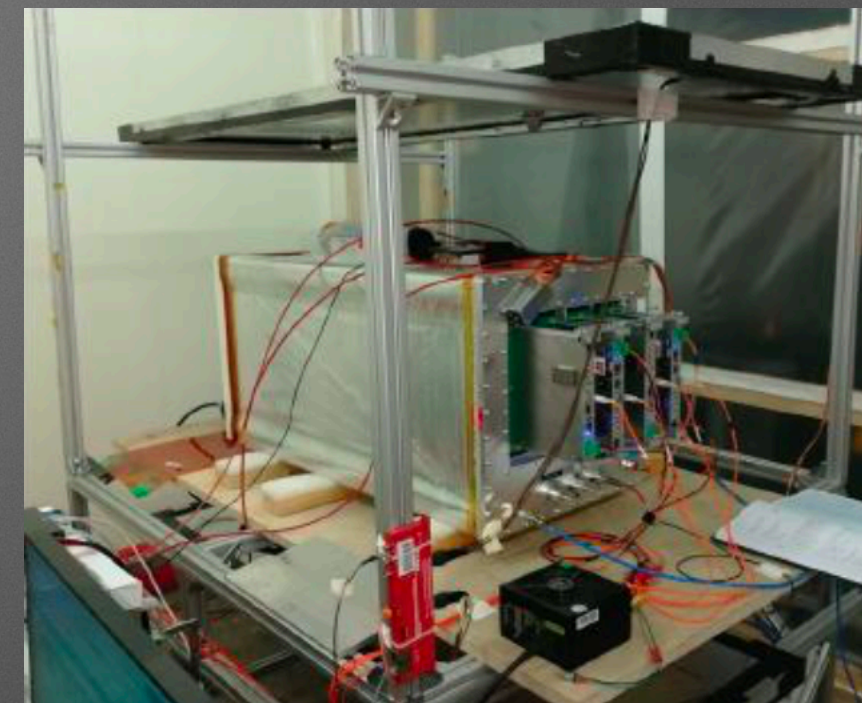
Aramide Fiber fabric based layer stack

	Material	Thickss (mm)
outer layer	Aluminum coated polymide film	~ 0.15
	Aramid Fiber Fabric (Kevlar)	2.00
	Aramide HoneyComb panel	35.00
	Aramid Fiber Fabric (Kevlar)	2.00
	Polymide film (insulation)	~ 0.10
inner layer	Strips (double later) on Kapton foil	~ 0.15
	TOTAL RADIATION LENGHT ~ 4% X0	~ 39.40

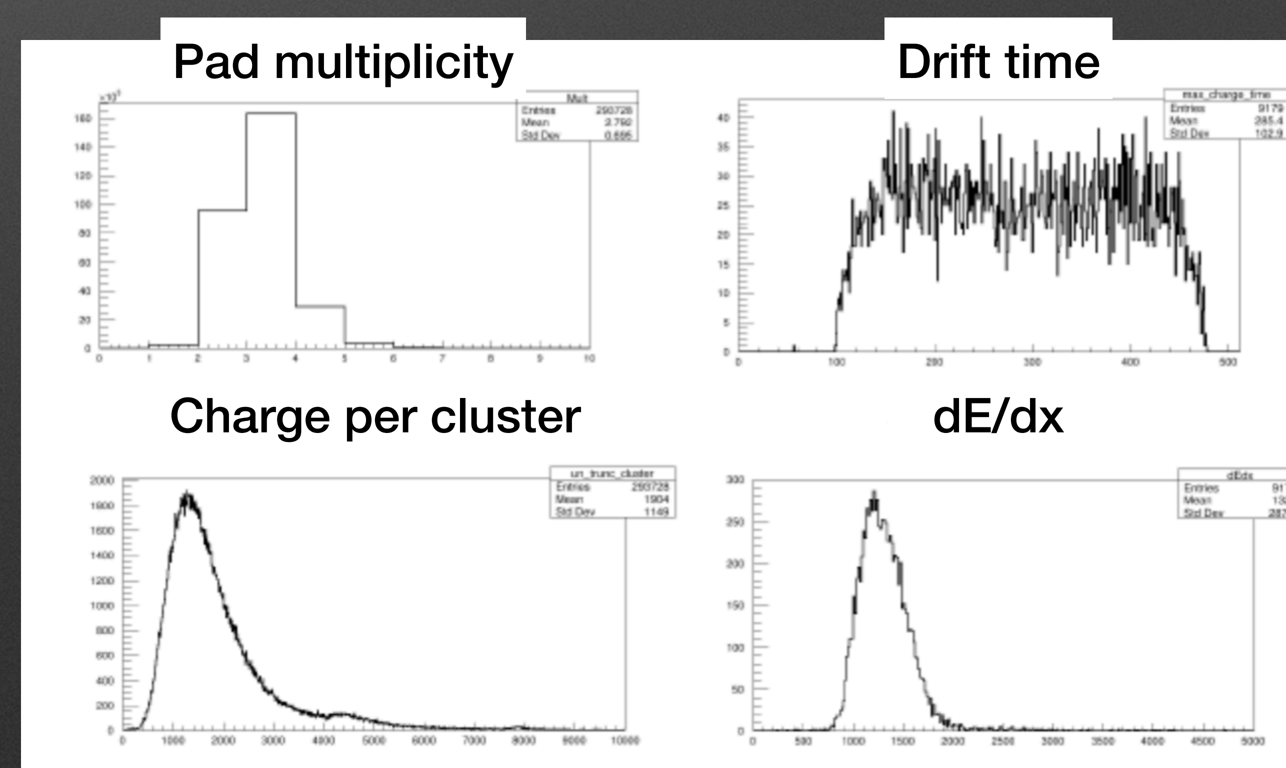


First Field Cage prototype

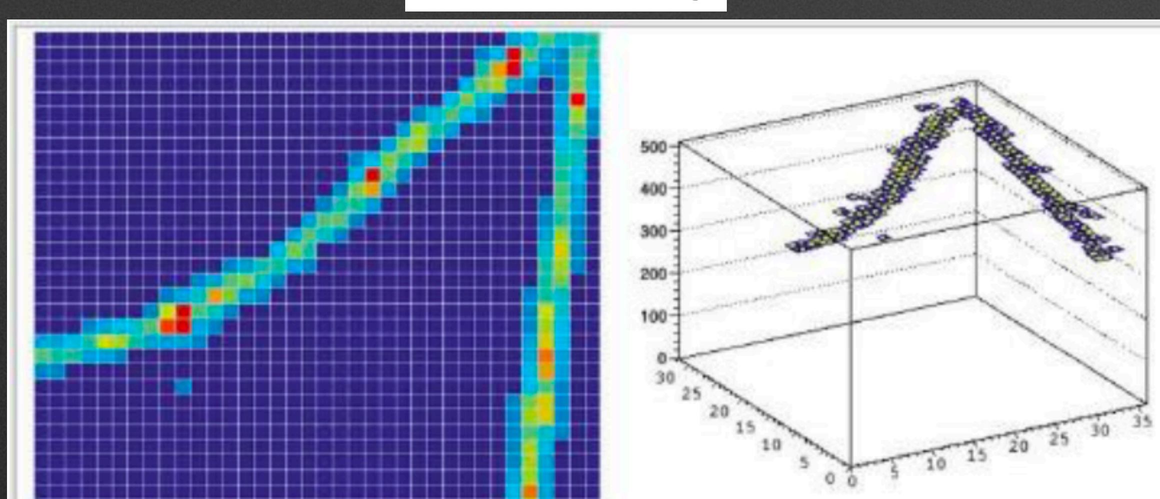
- First TPC prototype instrumented with ERAM module took cosmics data at CERN
- A second prototype is being characterized now
- First half of the TPC field cage will be shipped at CERN in May 2021
- Goal : install the detector in Japan in Summer 2022
- As readout system we will use resistive MicroMegas modules



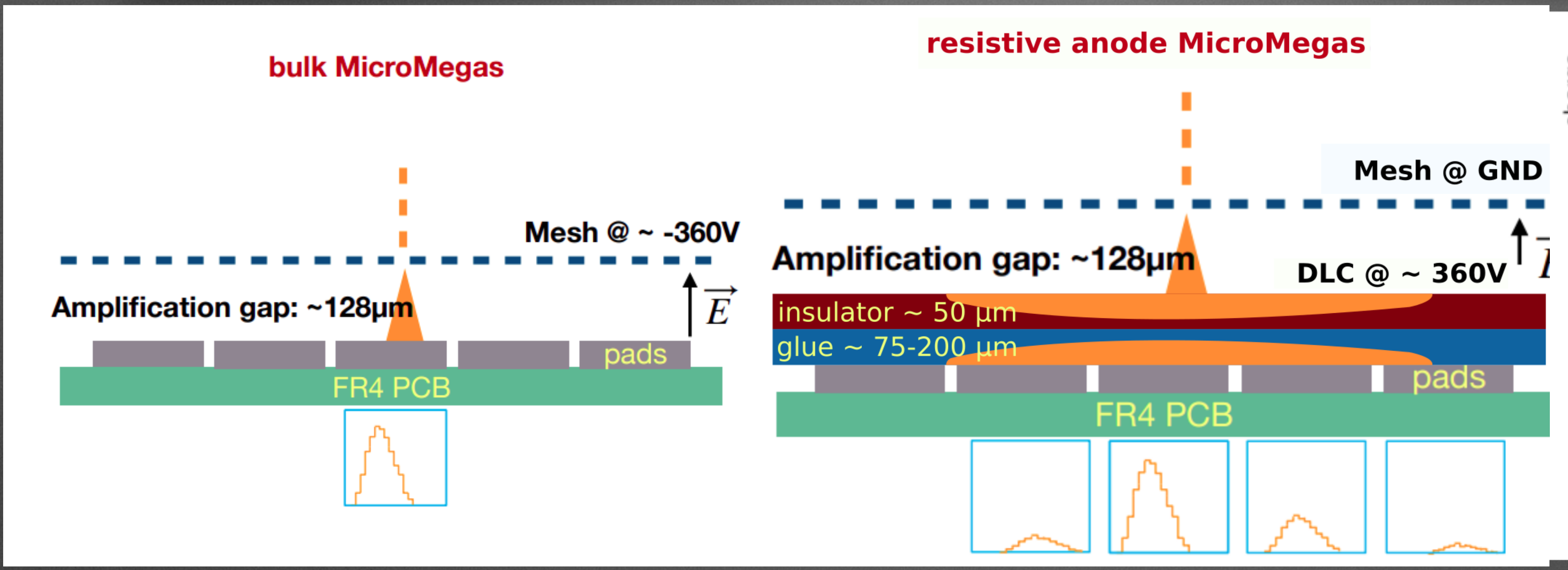
Cosmic tests at CERN

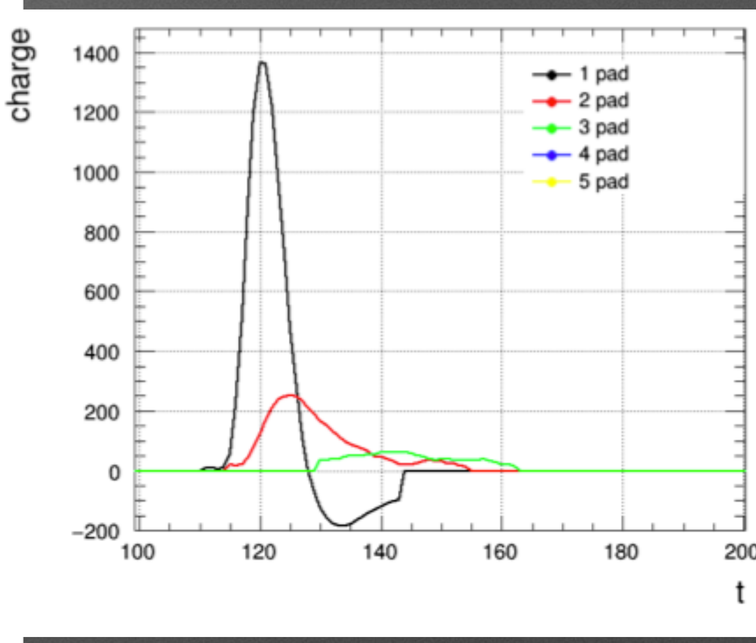


Event display



Resistive MM principles





$$\rho(\mathrm{r},\mathrm{t}) = \frac{\mathrm{RC}}{2\mathrm{t}}\exp\left[-\frac{-\mathrm{r}^2\mathrm{RC}}{4\mathrm{t}}\right]$$

R- surface resistivity
C- capacitance/unit area

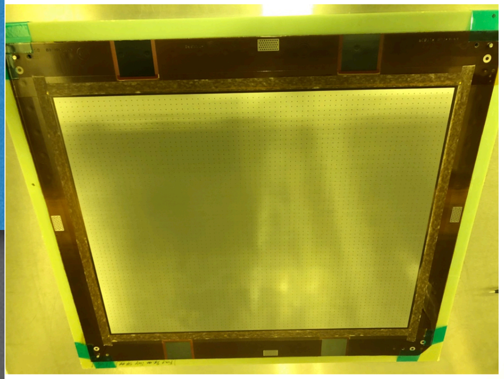
Gaussian spreading as a function of time with :

$$\sigma_r = \sqrt{\frac{2t}{RC}} \quad \begin{cases} t \approx shaping\ time\ (few\ 100\ ns) \\ RC_{[ns/mm^2]} = \dfrac{180\ R_{[M\Omega/\blacksquare]}}{d_{[\mu m]}/175} \end{cases}$$

- Encapsulated Resistive Anode Micromegas (ERAM)
- Charge spread over several pads
    - Spreading depends on RC value

- Main advantages:
    - Better spatial resolution (even with larger pads)
    - Reduced risk of sparks
    - Mesh at Ground → better electrostatic integration with TPC drift volume

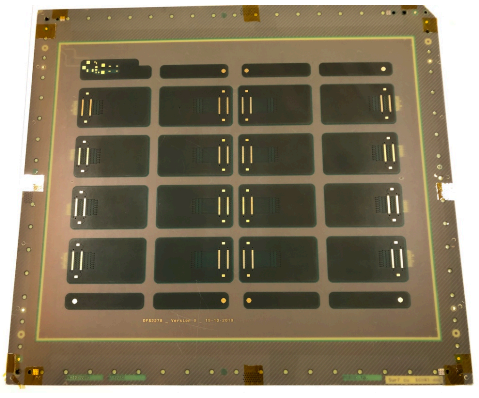
ERAM modules



Bulk-micromegas side

Resistive MicroMegas allows to reach better performances with ~30% less pads than Bulk MM

MM1-DLC2 (75 mm glue)	197 kOhm < R < 265 kOhm)
ERAM #02 (200 mm glue)	165 kOhm < R < 220 kOhm)
ERAM #03 (200 mm glue)	150 kOhm < R < 203 kOhm)



Connector side

Cosmic test in Saclay

- ERAM modules satisfactory test in test beams at CERN and DESY
- First ERAM module with the final HA-TPC design have been delivered (just before COVID…) and tested in Saclay
- Testing different glue thickness to finalize detector design and launch the production

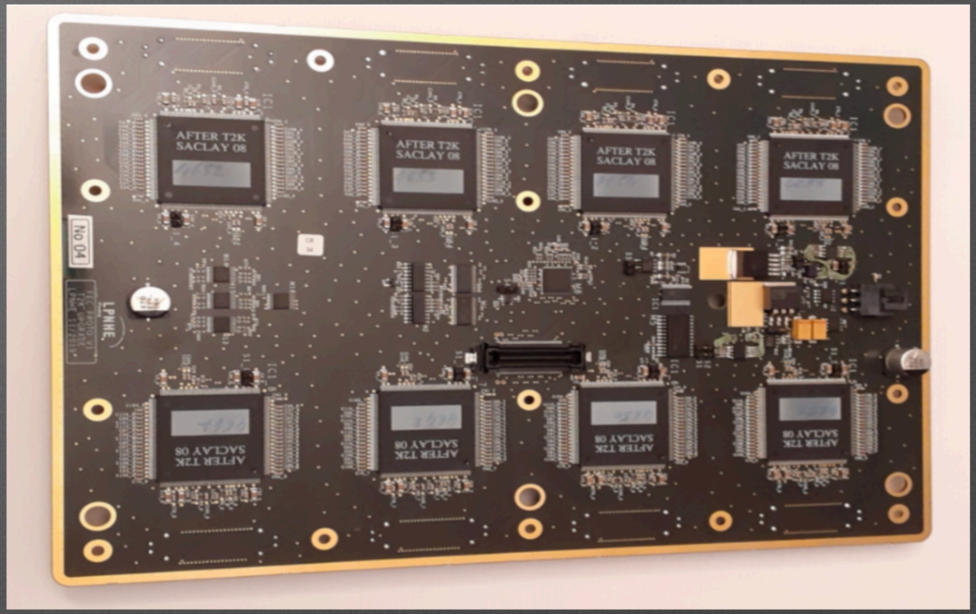
HA-TPC electronics

- Electronics is based on the AFTER chips that were designed for T2K

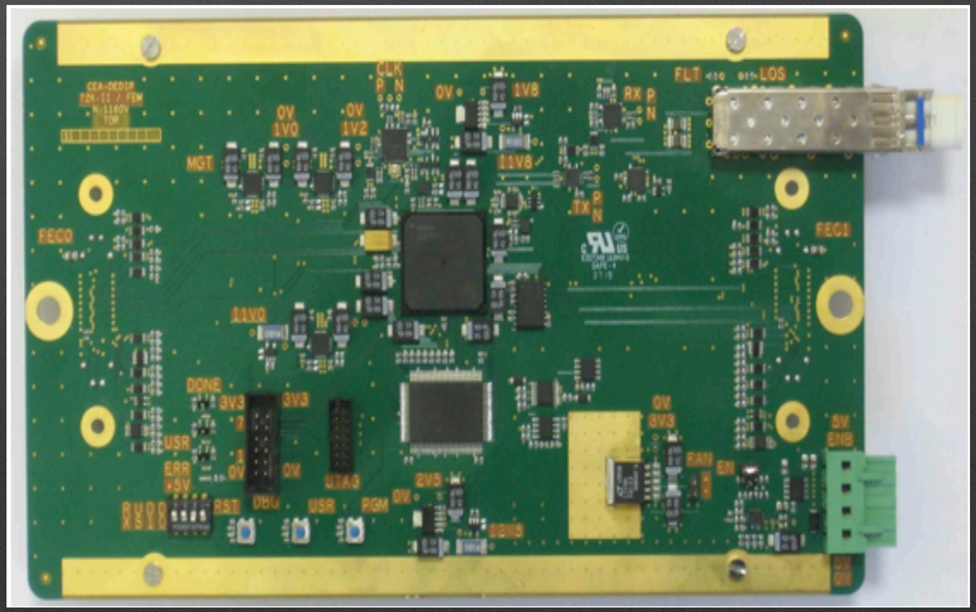
- 8 chips embedded on the Front-End-Cards that will be mounted parallel to the ERAM modules (2 FECs for each ERAM)

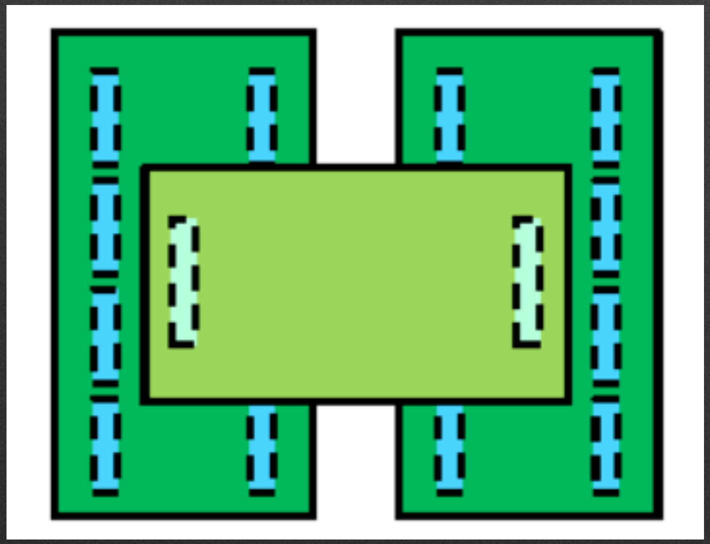
- The FECs are connected to a FEM (Front-End Mezzanine) card and then the signal is sent to the back-end electronics through optical fibers

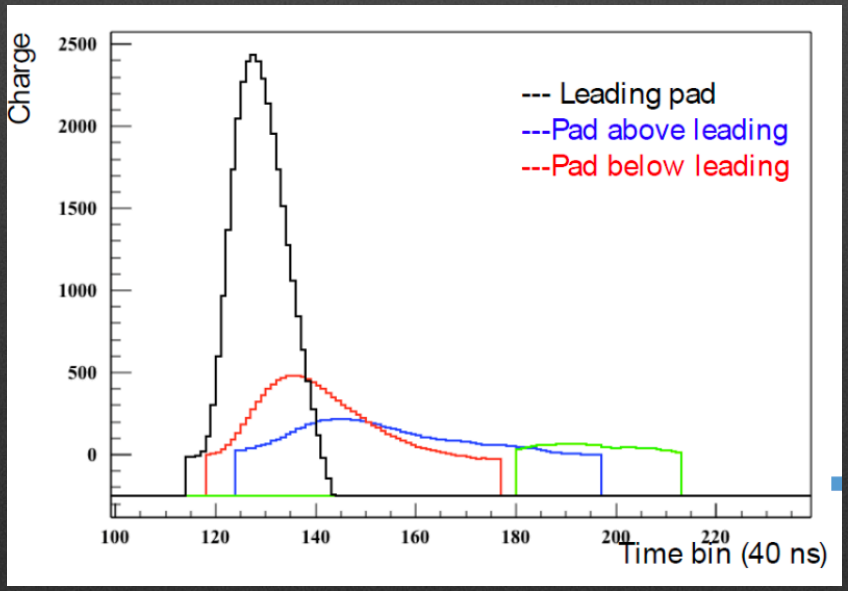
FEC



FEM

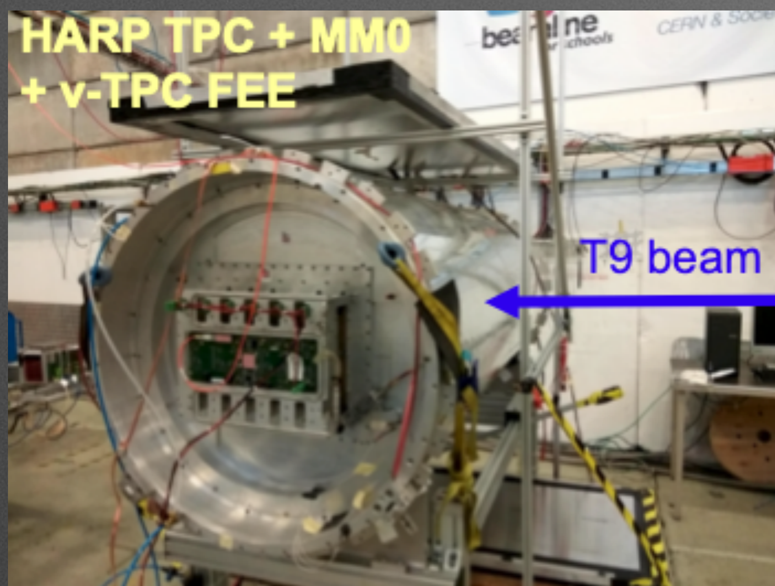


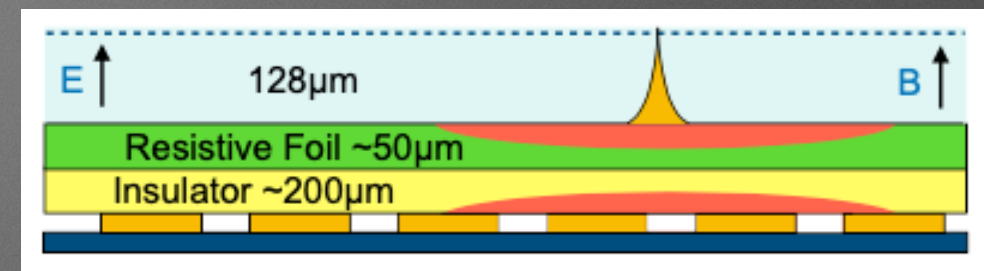




CERN Test Beam

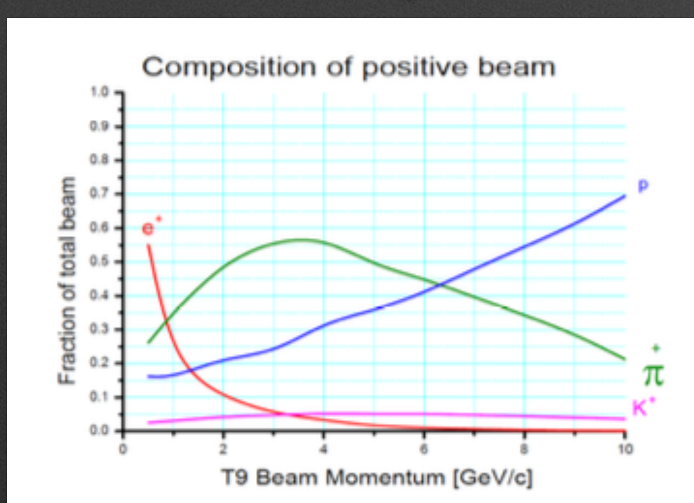
- ERAM modules have been tested at CERN in 2018

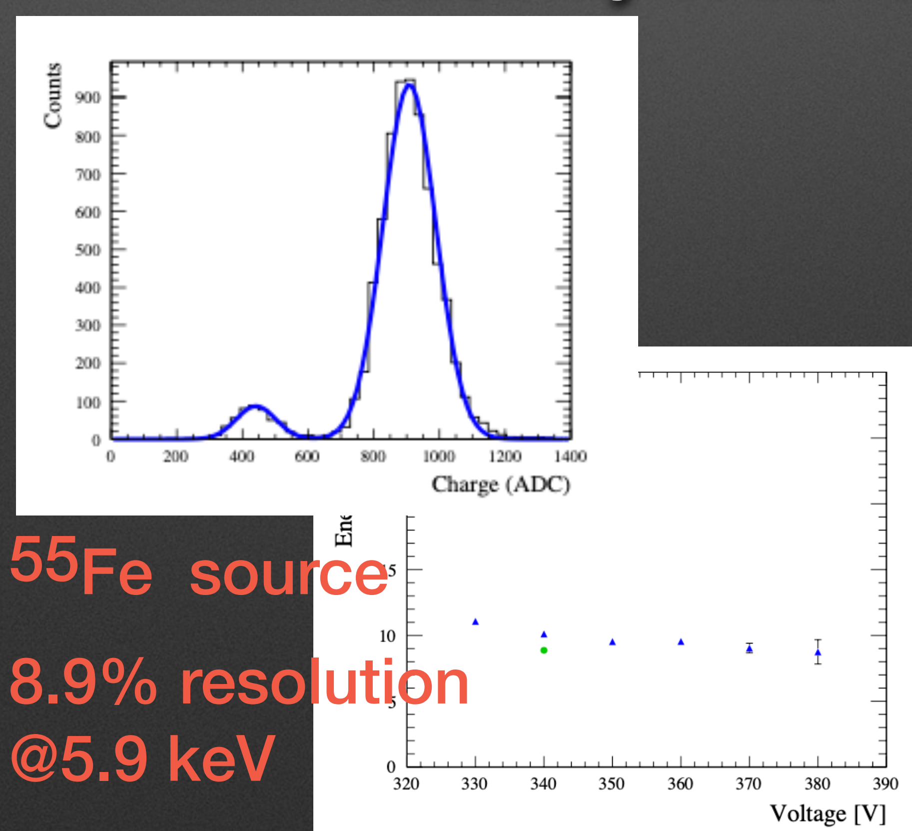




- T9 beamline, using HARP field cage
- Beam of electrons, pions and protons
- MicroMegas PCB used for current TPCs covered with 200 μm insulator and 50 μm kapton layer
- MM resistivity of 2.5 MΩ/□

Beam composition

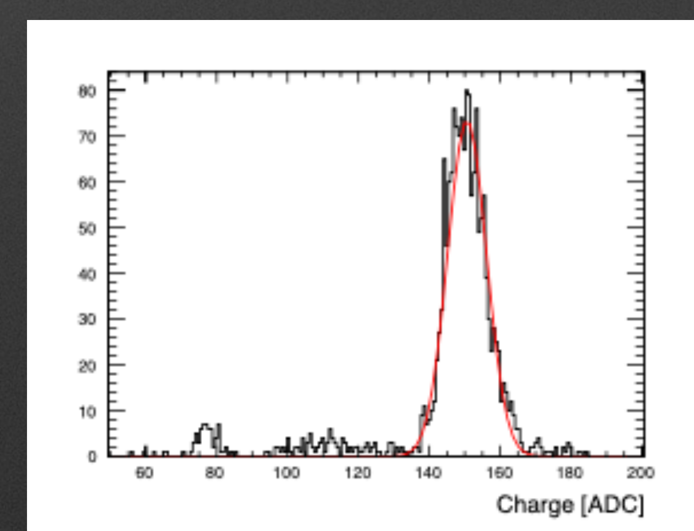




^{55}Fe source

8.9% resolution @5.9 keV

Pad gain uniformity with cosmics



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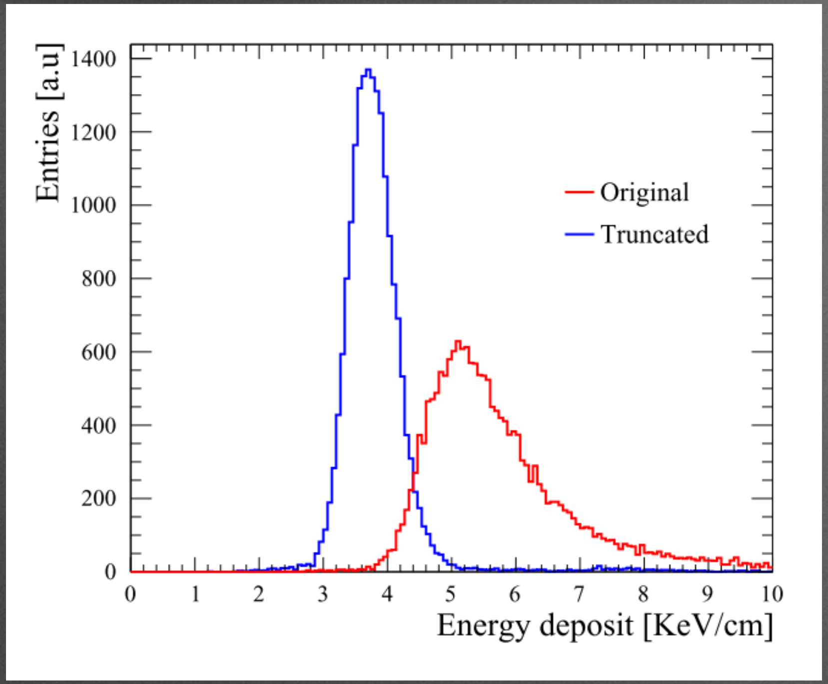
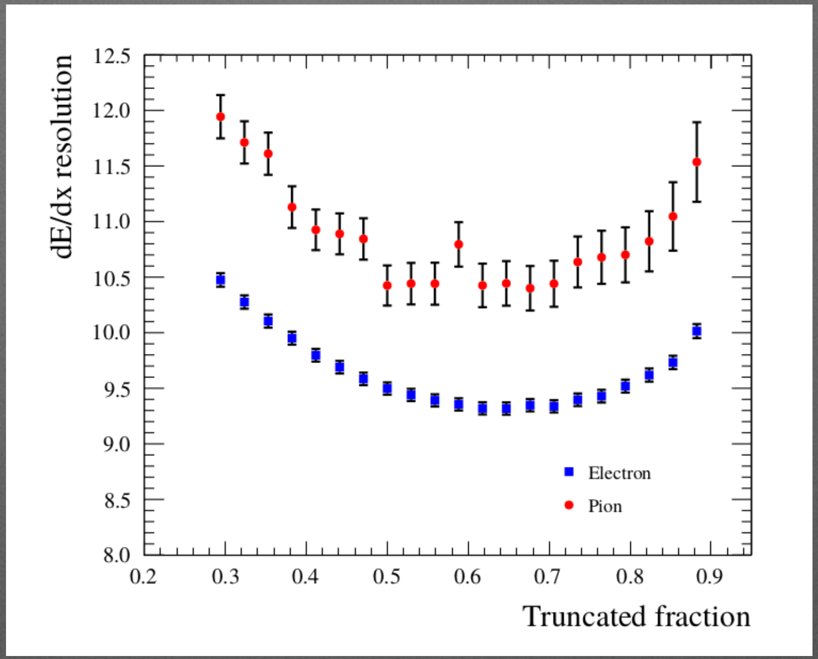
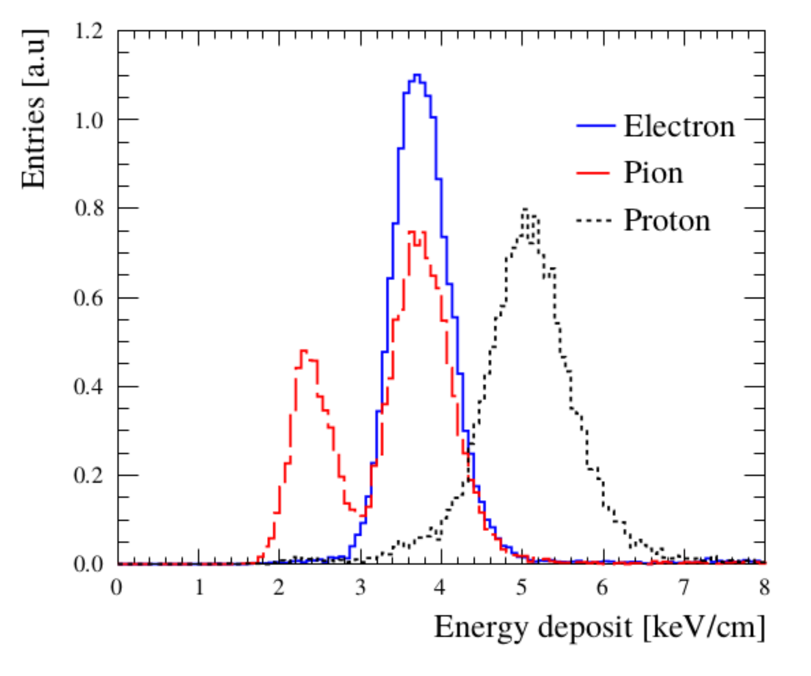
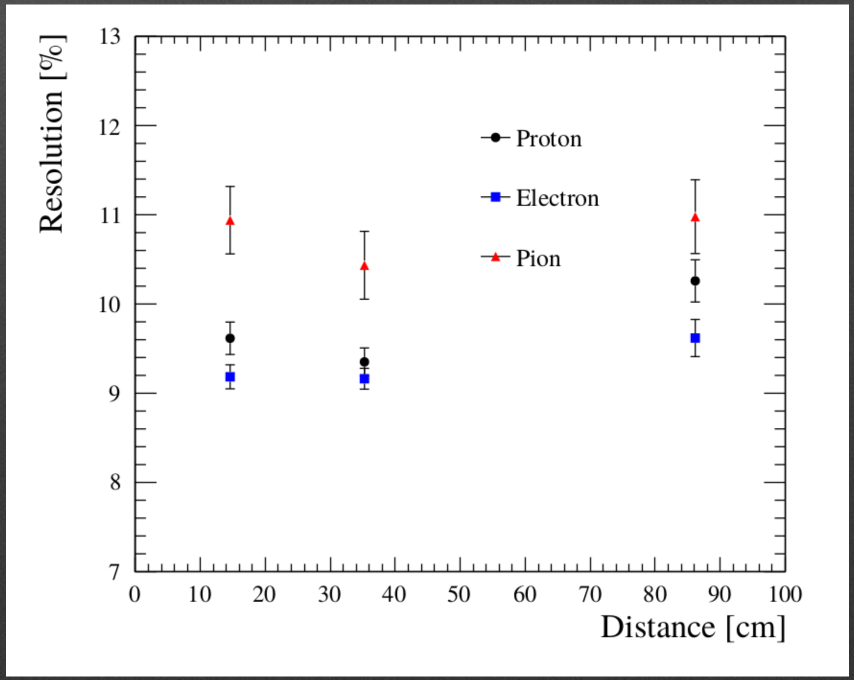
dE/dx resolution







- dE/dx resolution studied using truncated mean method
  - Clusters are sorted by charge and the ones with larger charge are removed from the computation of the mean → remove fluctuations
- <10% resolution for electrons and protons for all drift distances
- Extrapolate to ~7% for tracks crossing two ERAM modules as it will be the case in the ND280 TPCs



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Spatial resolution with PRF method

- Avalanche position can be reconstructed with Centre of charge method

$$x_{track} = \frac{\sum \left(x_{pad} \cdot Q_{pad} \right)}{\sum Q_{pad}}$$

- Better precision is reached by using the Pad Response Function

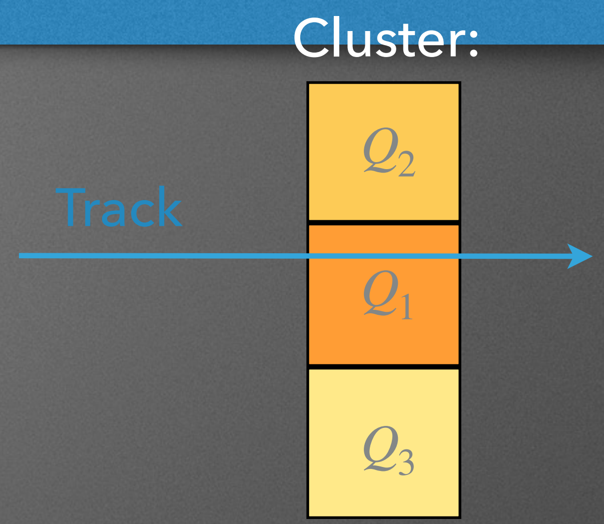
$$Q_{pad}/Q_{cluster} = PRF \left(x_{track} - x_{pad} \right)$$

- PRF is parametrized with an analytical function

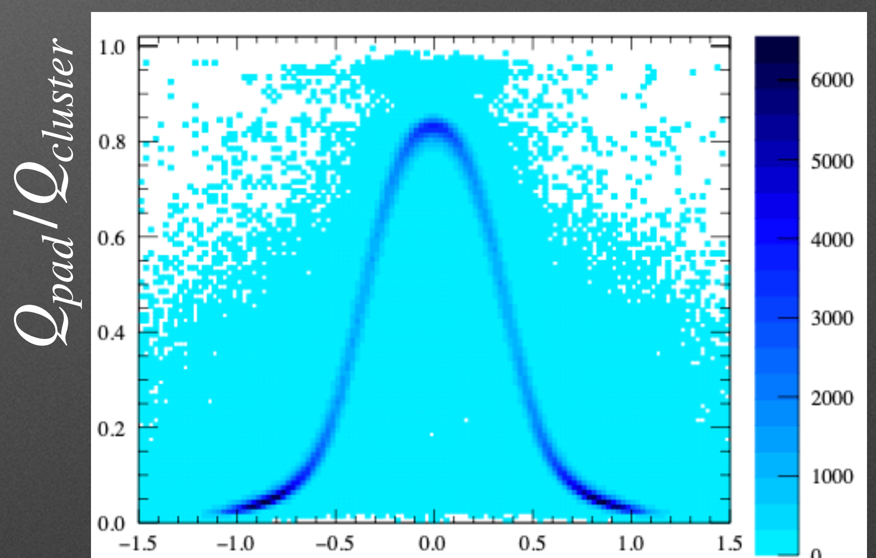
$$PRF \left(x, \Gamma, \Delta, a, b \right) = \frac{1 + a_2 x^2 + a_4 x^4}{1 + b_2 x^2 + b_4 x^4}$$

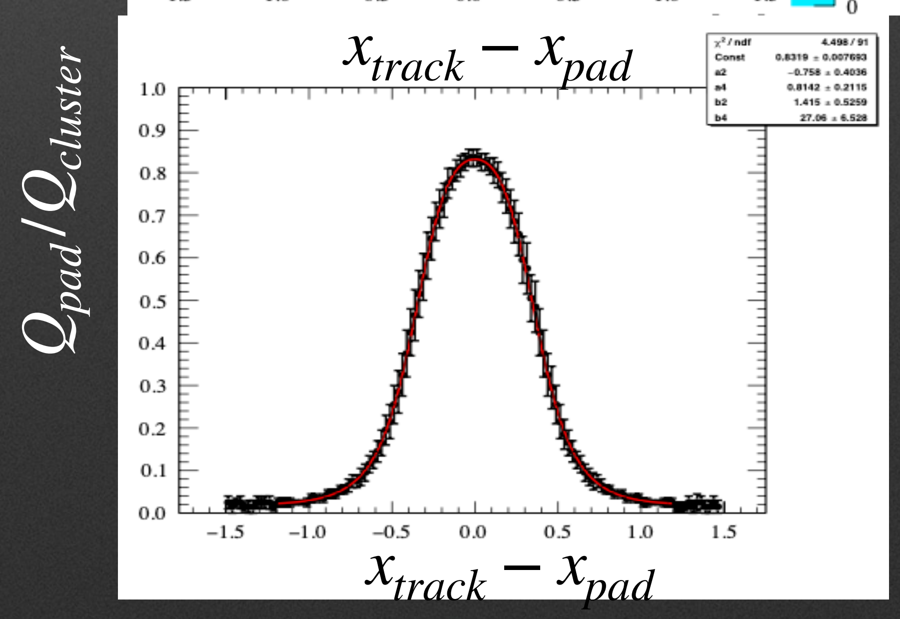
- Track position is then obtained by minimizing the χ^2

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



$$Q_{cluster} = \sum Q_i$$



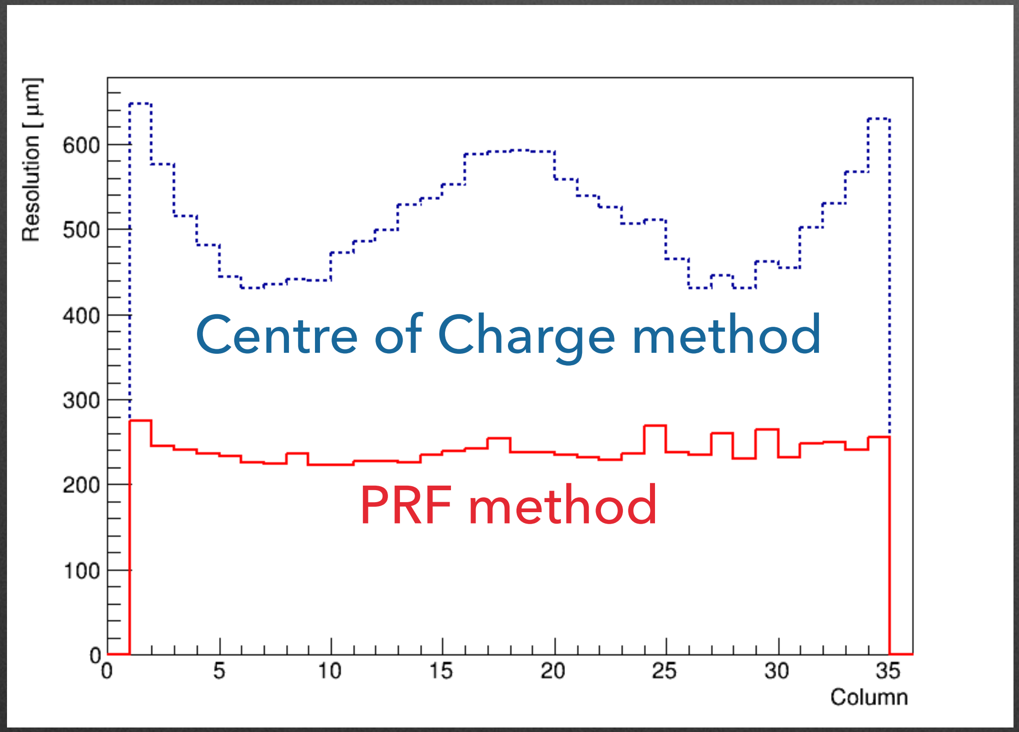


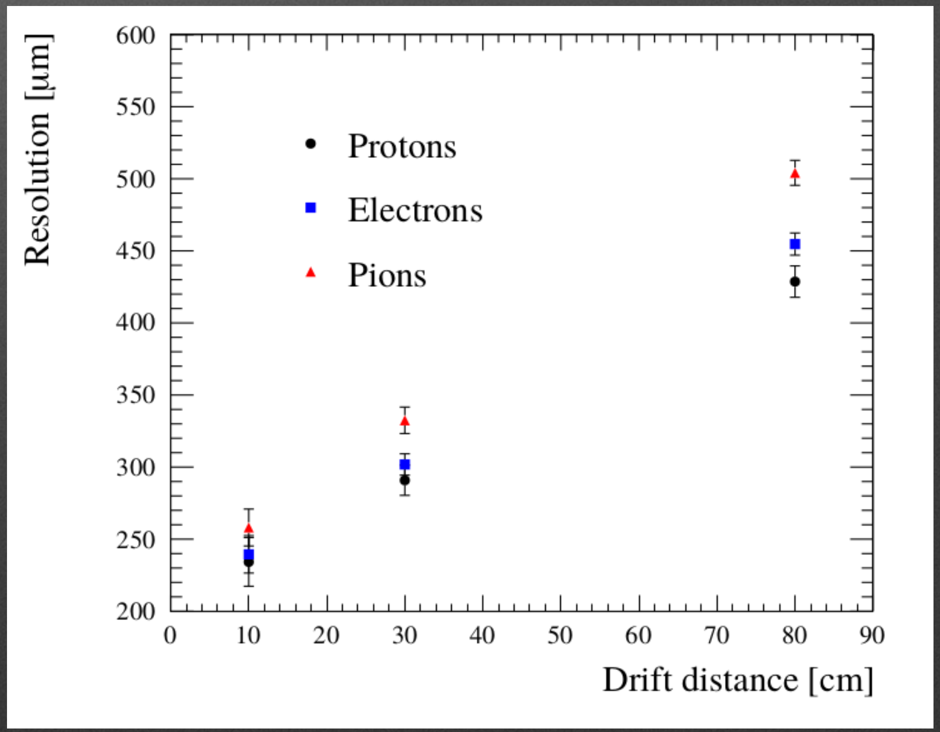
Spatial resolution

- Iterative method
  - Start with Centre of Charge → estimate PRF
  - Use PRF to extract track position → estimate new PRF

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

- We obtain a resolution of 300 μm for 30 cm drift distance and horizontal tracks (To be compared with 600 μm for Bulk MM used in current ND280 TPCs)





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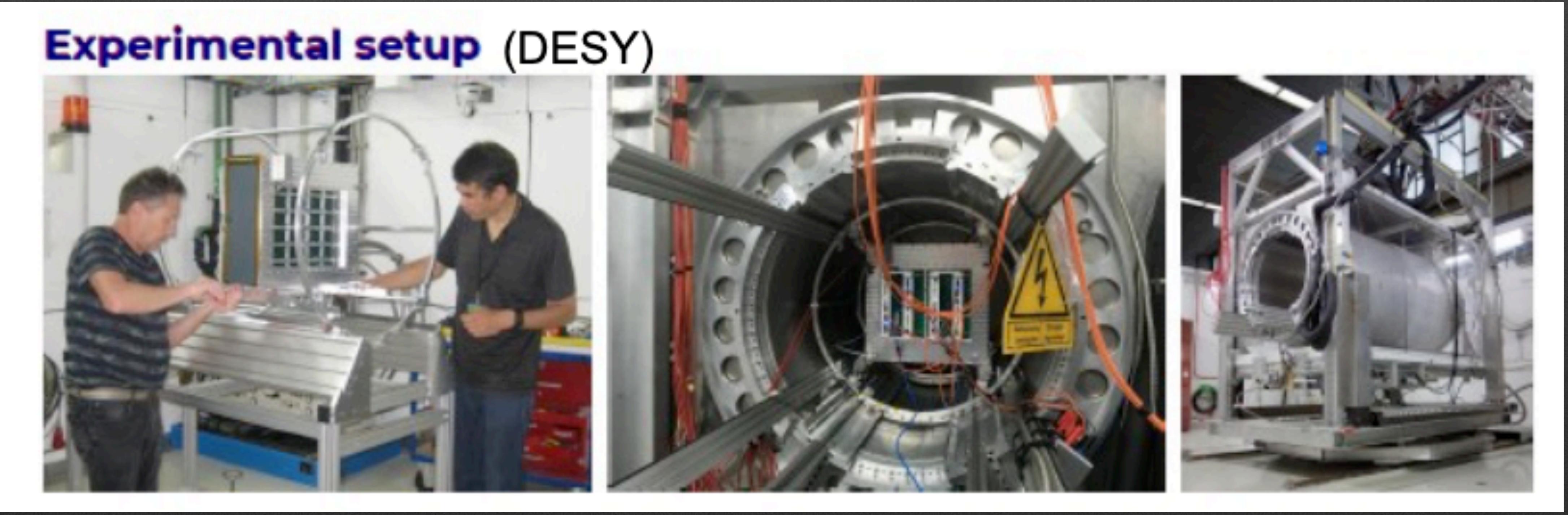
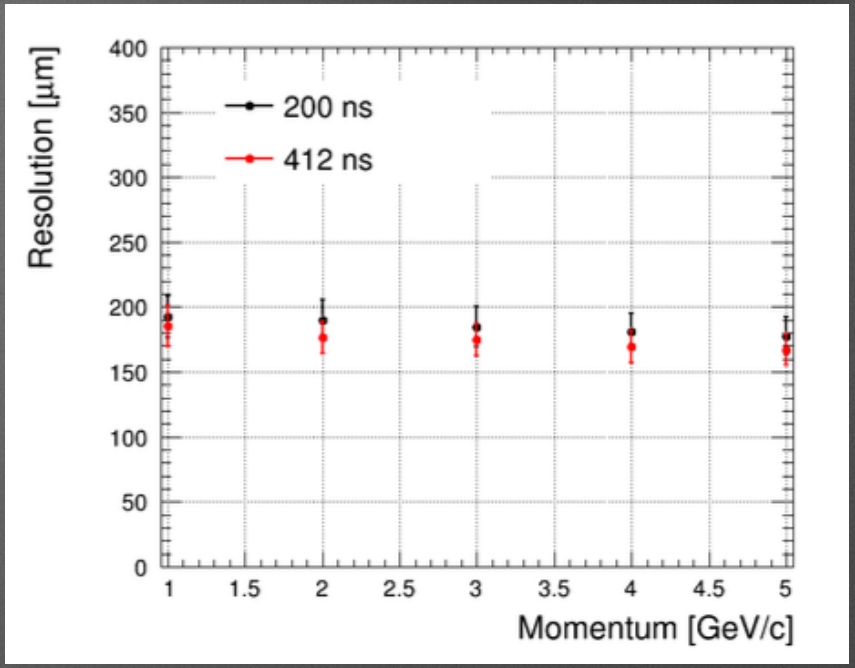
DESY Test Beam

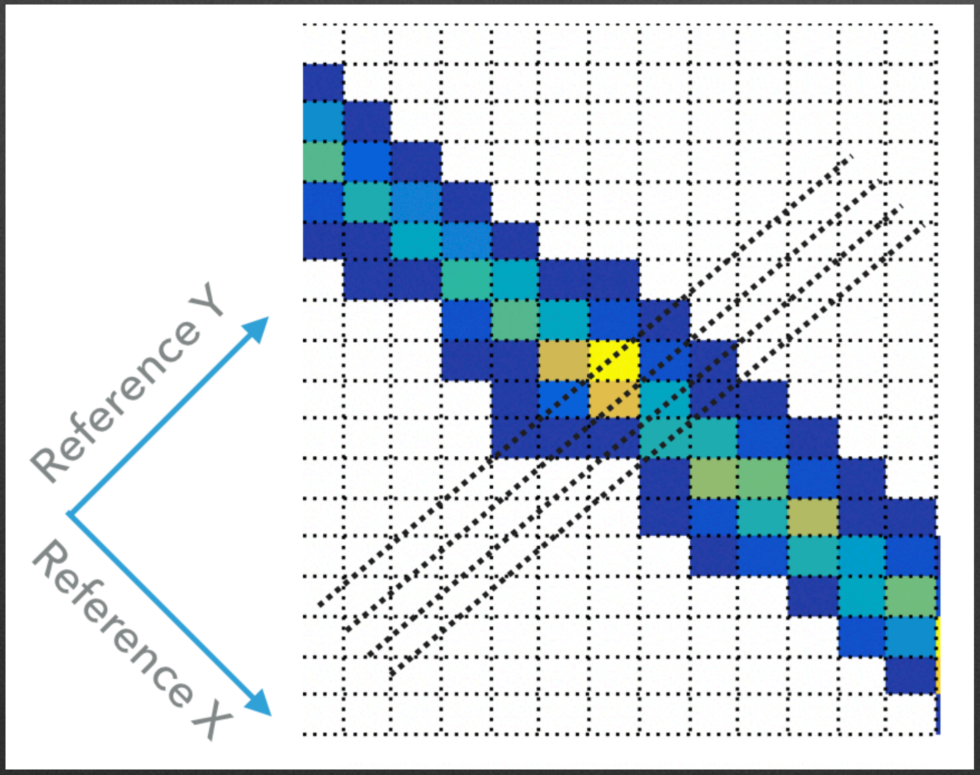
- Test Beam at DESY in Summer 2019
- Use first ERAM module prototype designed for the HA-TPC
  - 75 μm glue, 197<R (kOhm)<265
  - Pad size 1.1 x 1.0 cm
- Take data with different detector inclinations → study spatial resolution and dE/dx resolution versus the angle

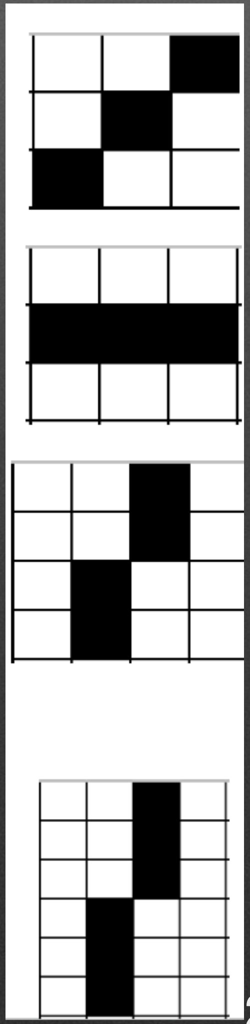


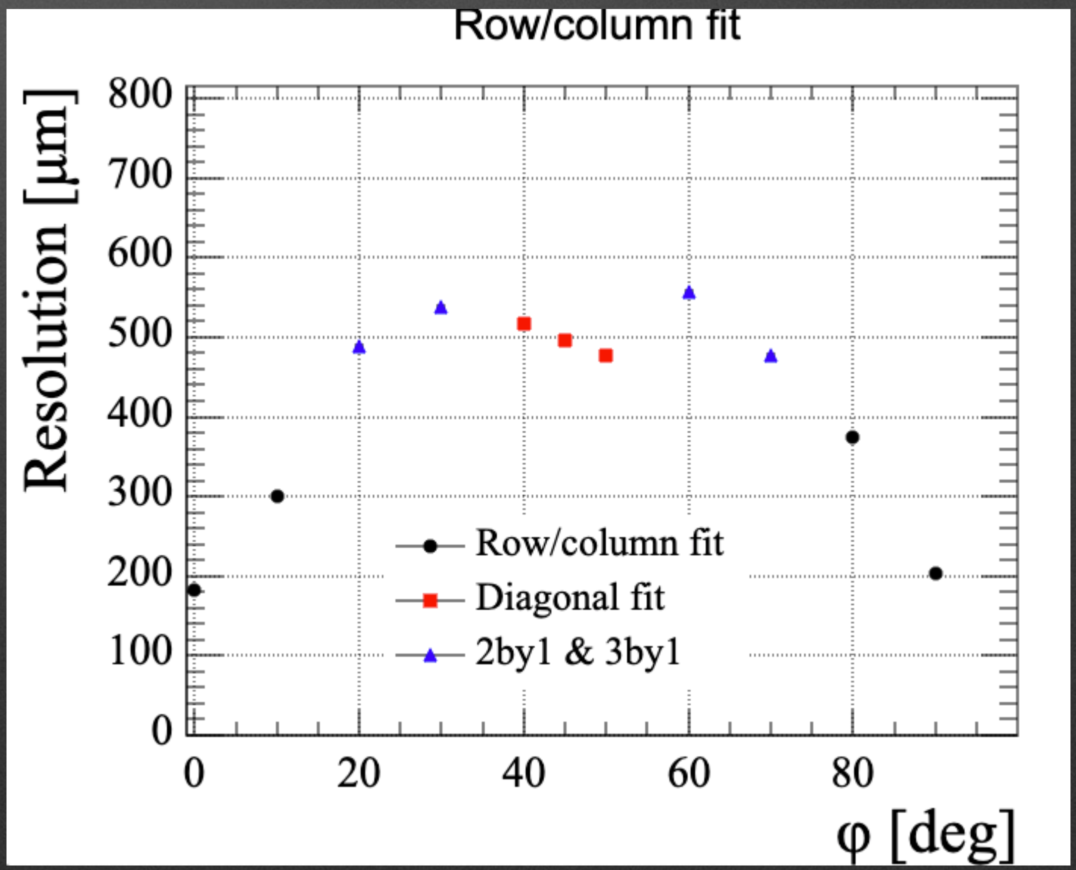
Spatial resolution

- Confirm excellent spatial resolution for horizontal tracks
- Use PRF method but using different clustering algorithm to fit inclined tracks
  - Clustering algorithm is adapted to the track angle
- Spatial resolution < 600 μm for all the angles

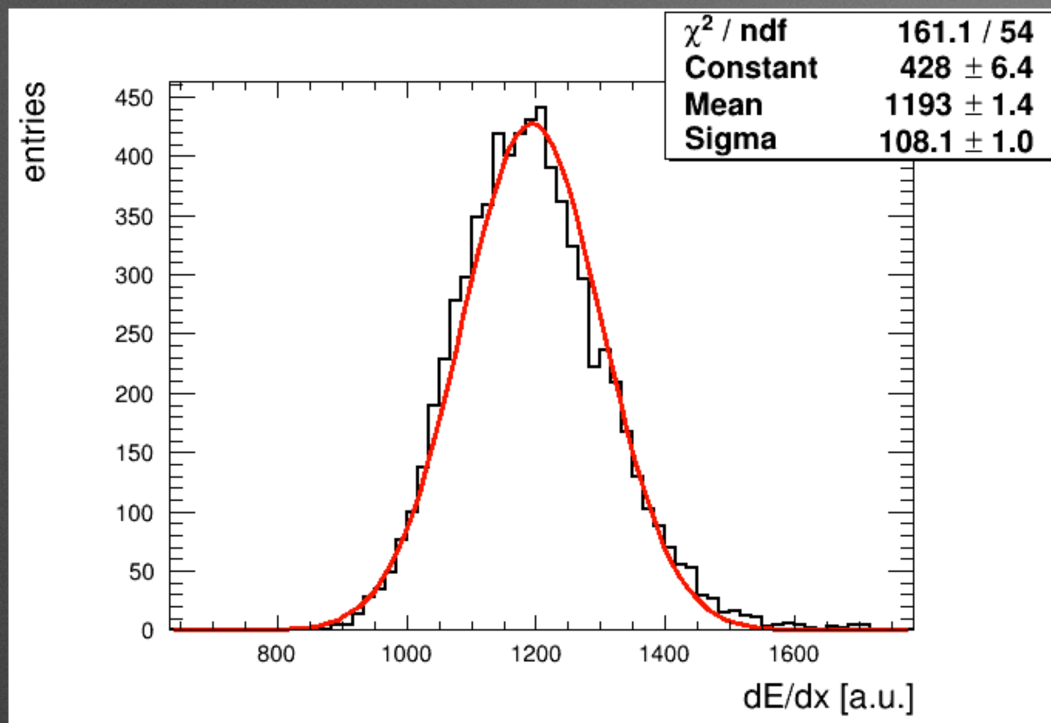


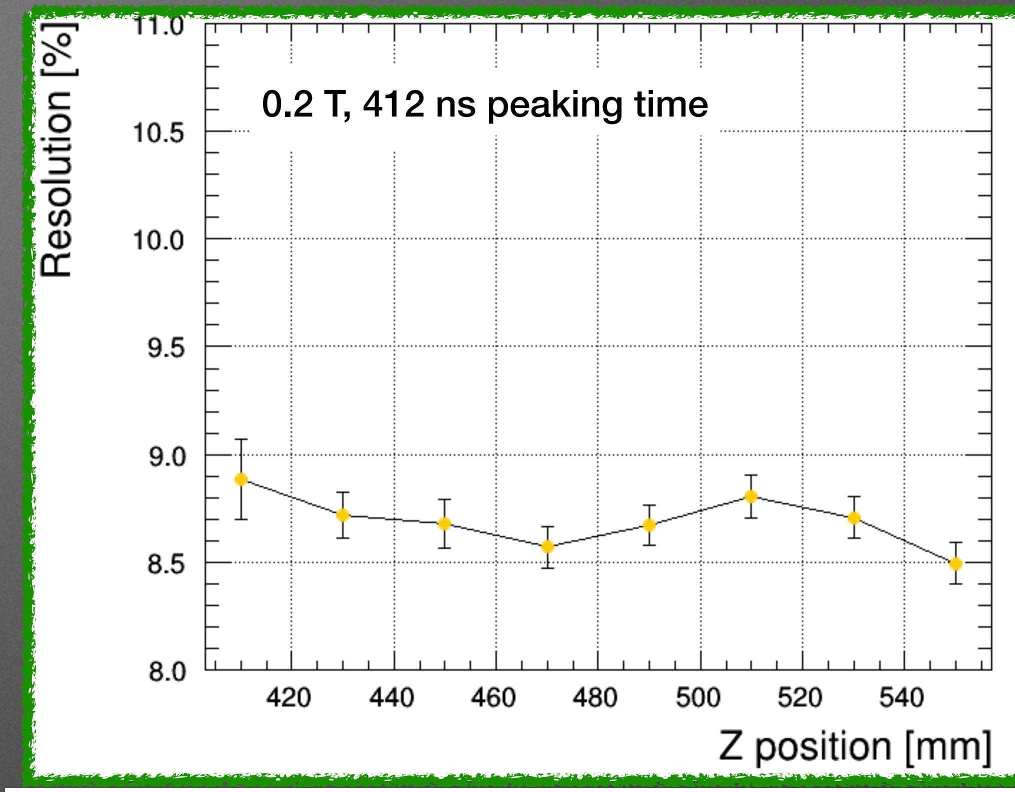


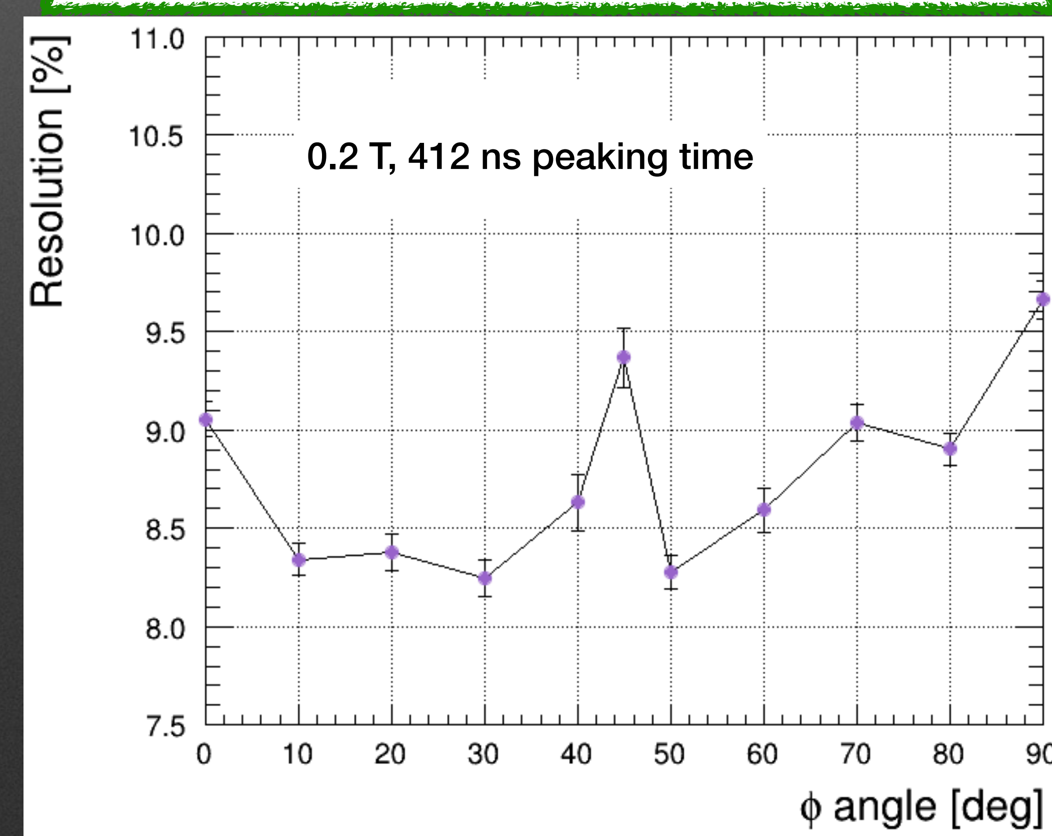




dE/dx resolution



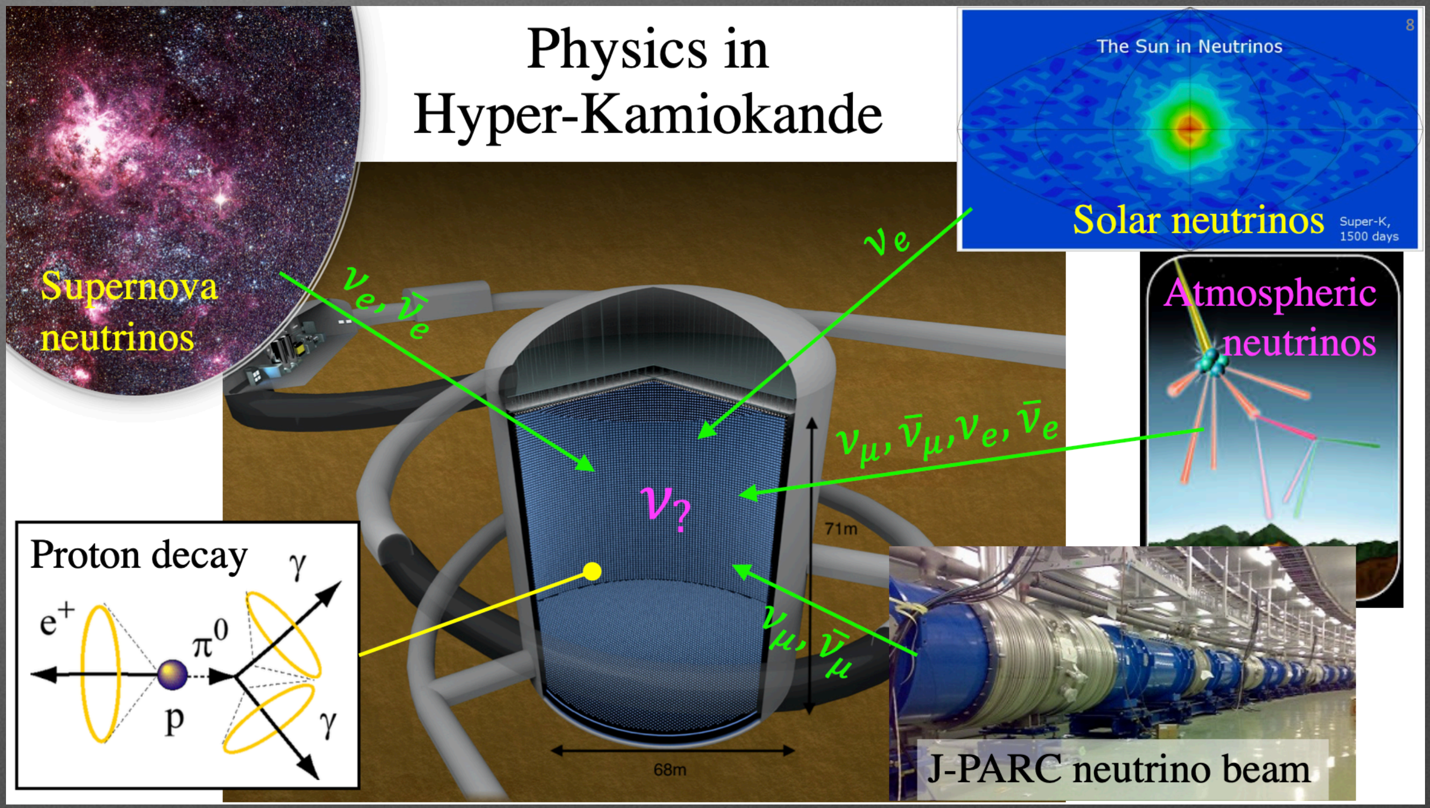


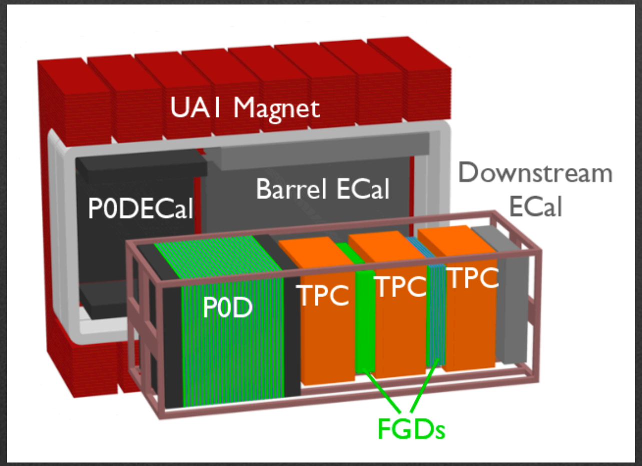


- dE/dx resolution better than 9% for horizontal tracks
  - Using only one module, expected to be <7% for tracks crossing two modules
- Good performances for all angles

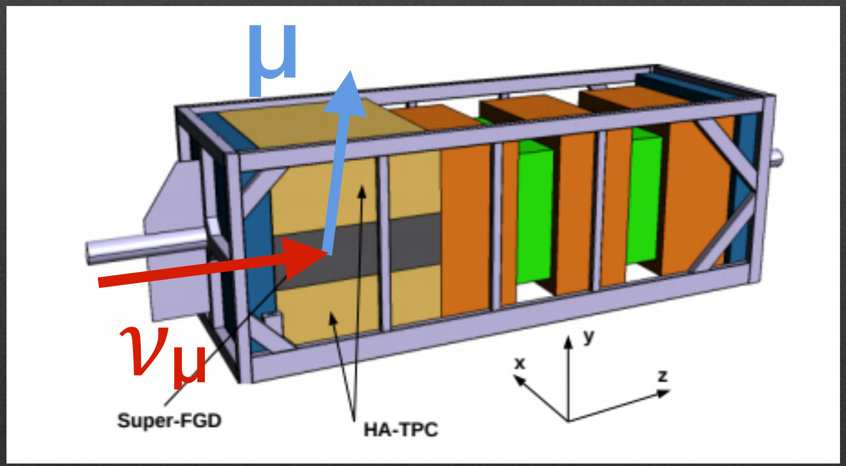
Towards Hyper-Kamiokande

- Hyper-K: Next generation Water Cherenkov detector, 8 times larger than SK
- Start construction → data taking expected in 2027
- ND280 will be part of the HK Near Detector complex
- Further upgrades of ND280 are being discussed for HK → new ideas for TPCs?

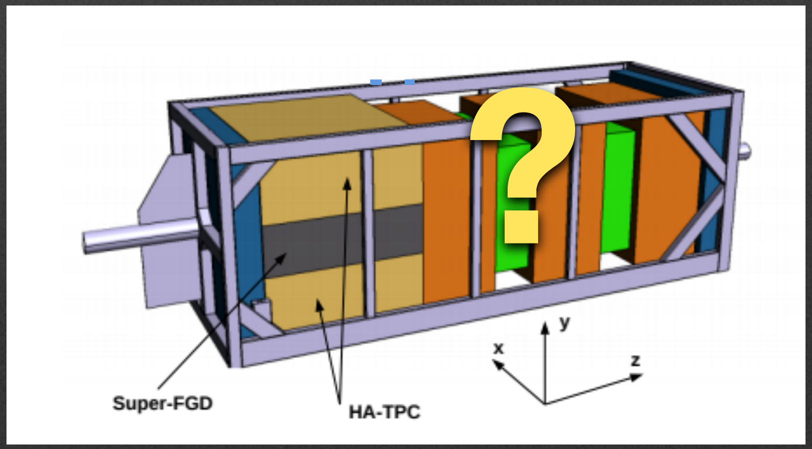




ND280 (2009)



ND280 Upgrade (2022)



ND280 for HK (2027)

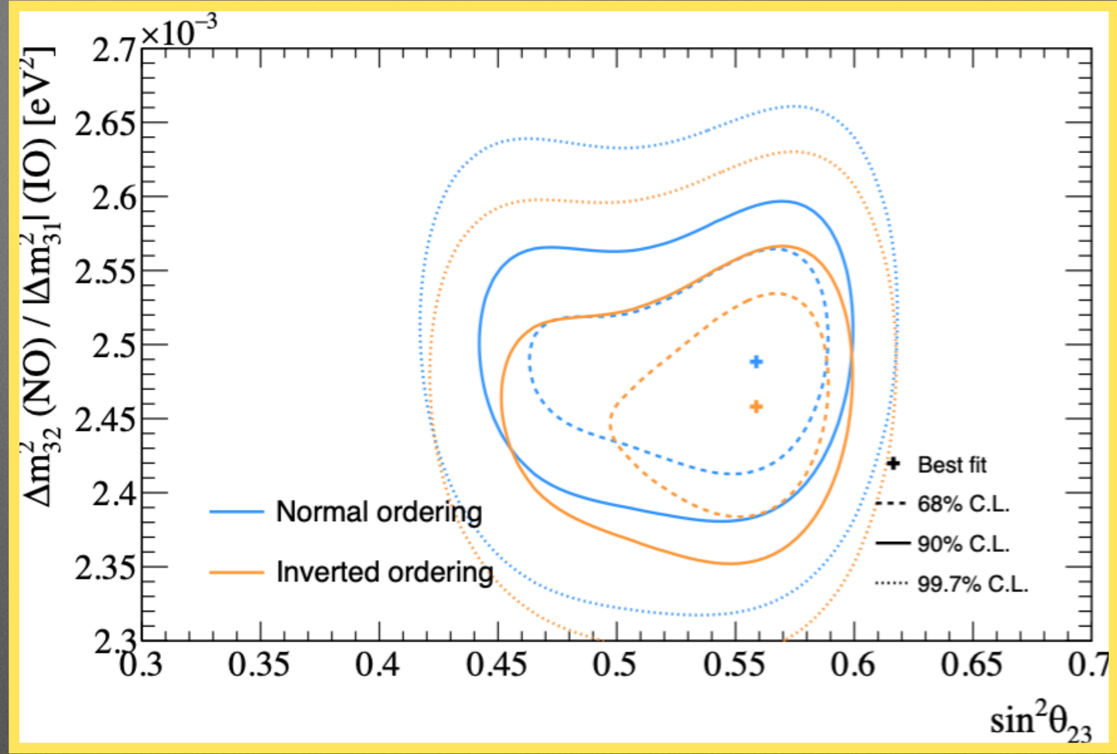
Conclusions and prospectives

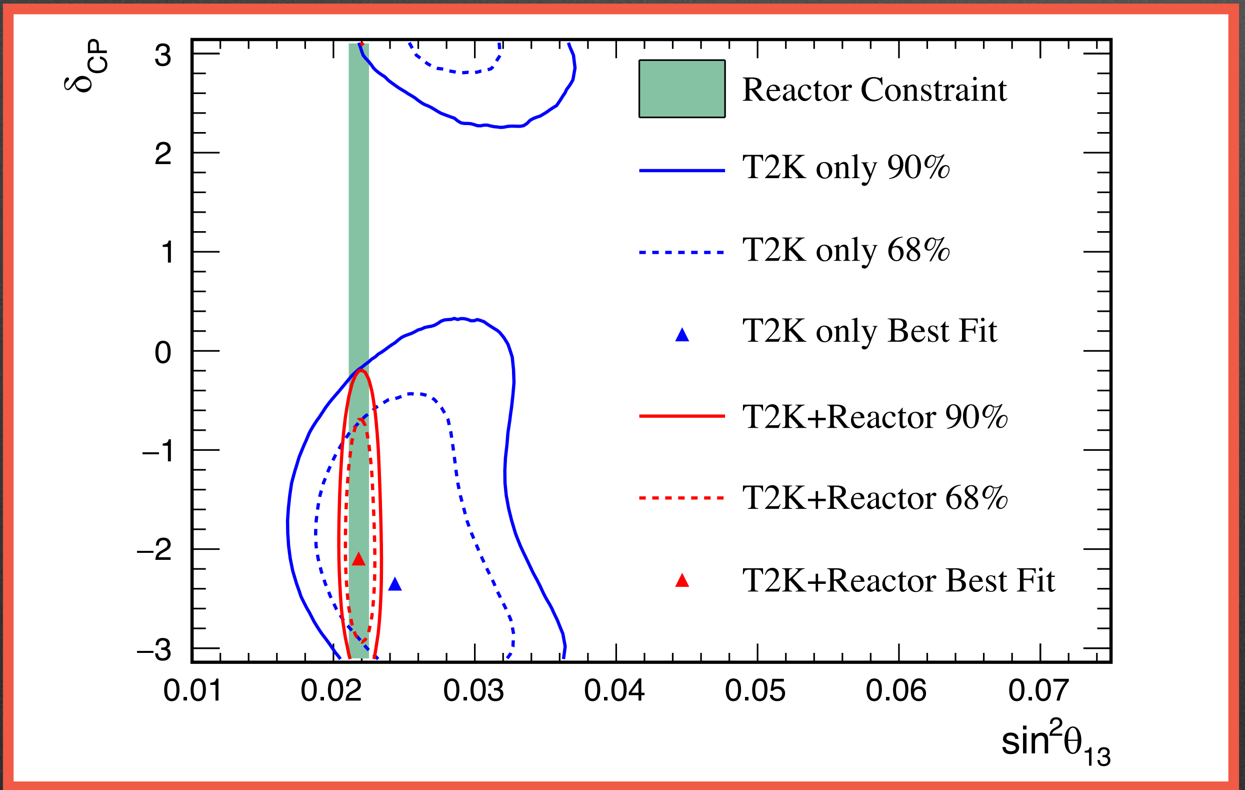
- After 10 years of data taking T2K is continuously producing world leading measurements of neutrino oscillations
- The TPCs are a vital part of the T2K Near Detector Complex
- 3 Large TPCs instrumented with Bulk MicroMegas modules installed in J-PARC since 2009
  - Taking data steadily, no sign of degradation of performances observed so far
  - Used in all the T2K Oscillation Analyses and in T2K cross-section measurements
- An upgrade of the T2K Near Detector is being built for the second phase of T2K (T2K-II) and will be installed in J-PARC in 2022
  - This upgrade will include two High-Angle TPCs instrumented with resistive MicroMegas modules
  - ERAM modules have been tested in Test Beams and show excellent performances
    - ~ 200 μm resolution for horizontal tracks
    - <9% dE/dx resolution with one module

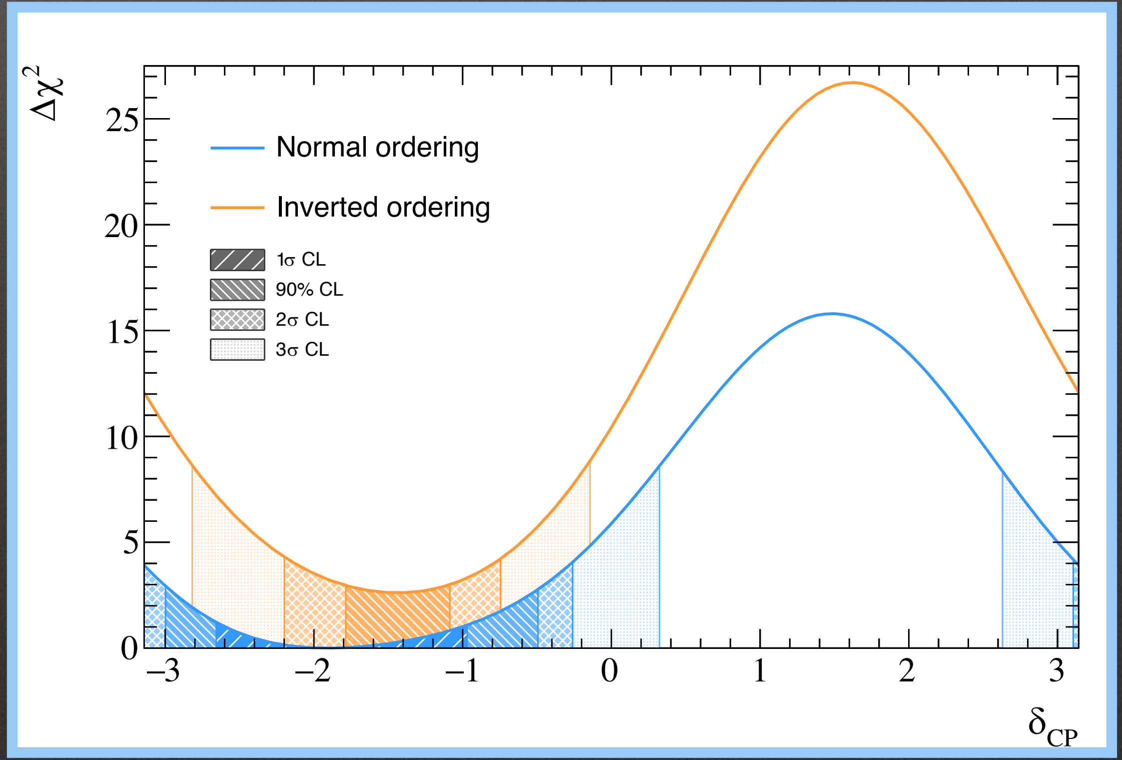
Back-up

New oscillation results

- Released at Neutrino 2020 in July
- Slight preference for non-maximal mixing with θ_{23} in the second octant
- Good agreement with reactor constraint on θ_{13}
- When combined with reactor, 35% of the values of δ_{CP} are excluded at >3σ
- CP conserving values (0,π) excluded at 90% CL

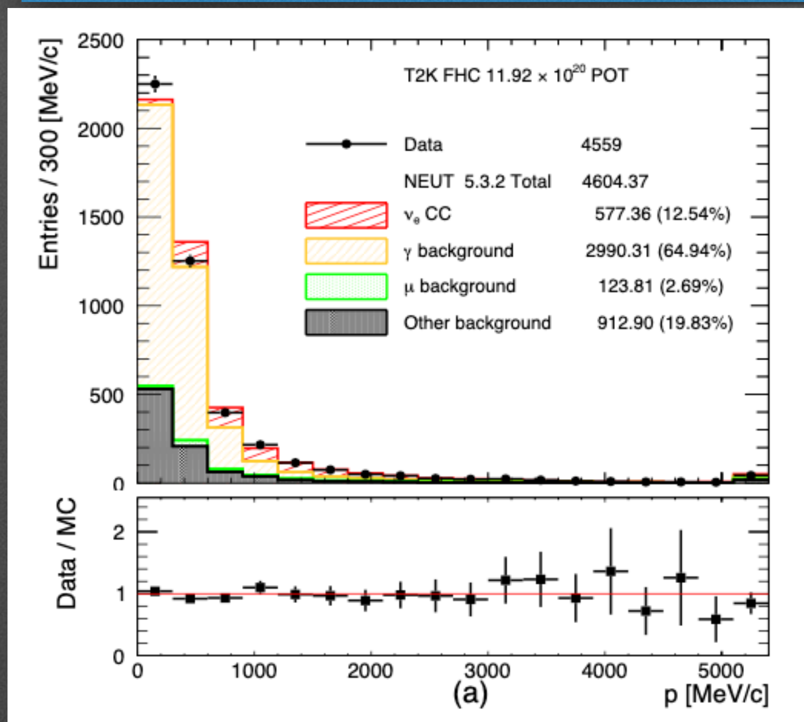


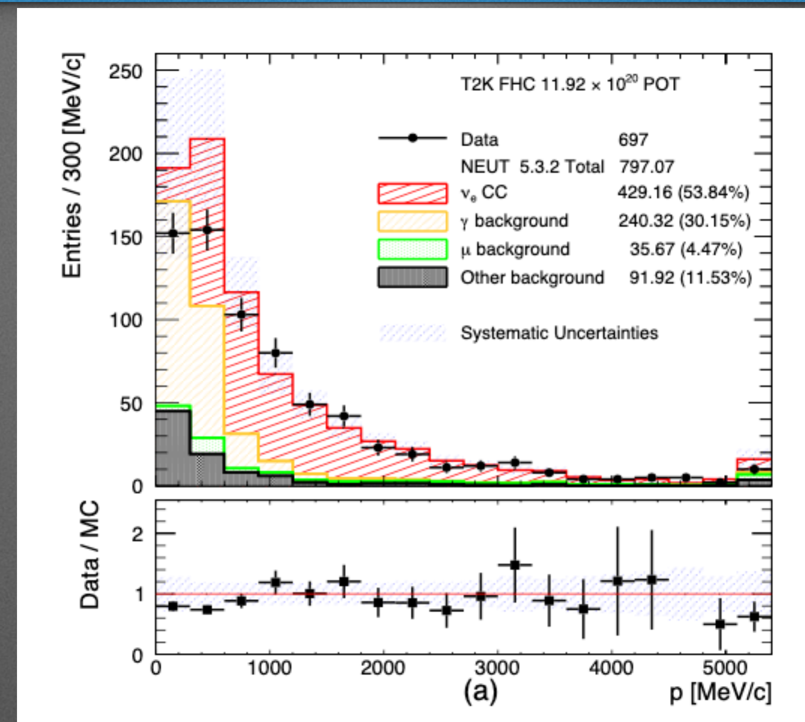




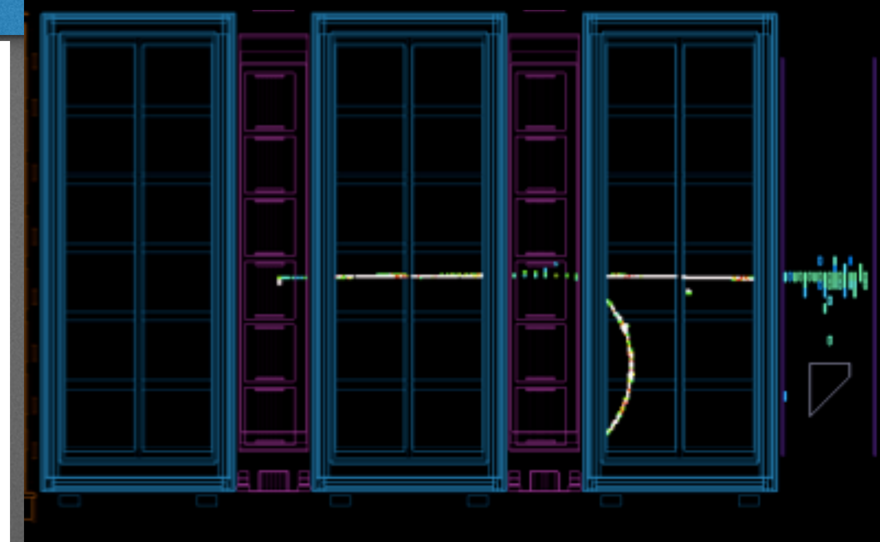
ν_e @ND280

arXiv:2002.11986



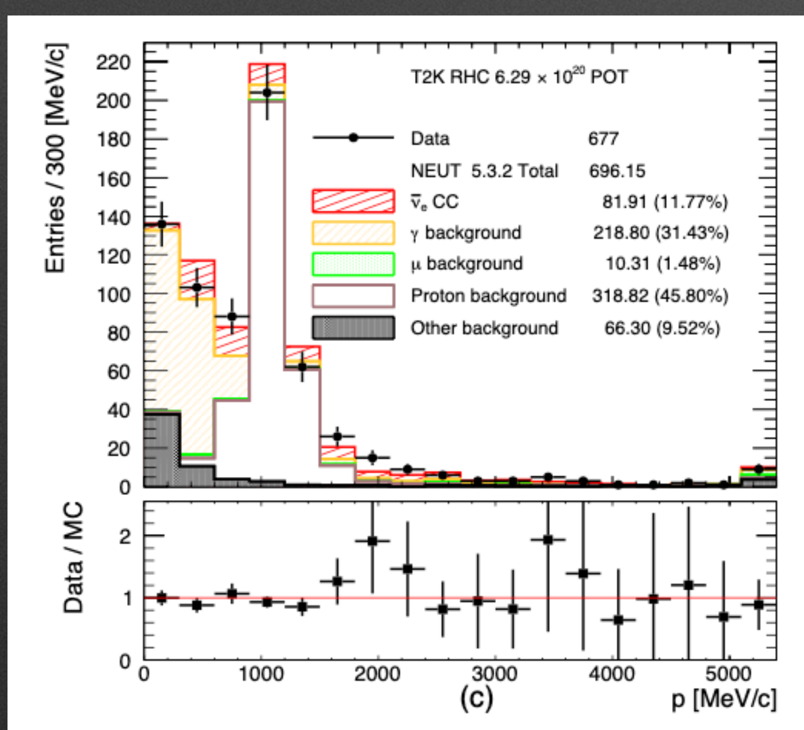


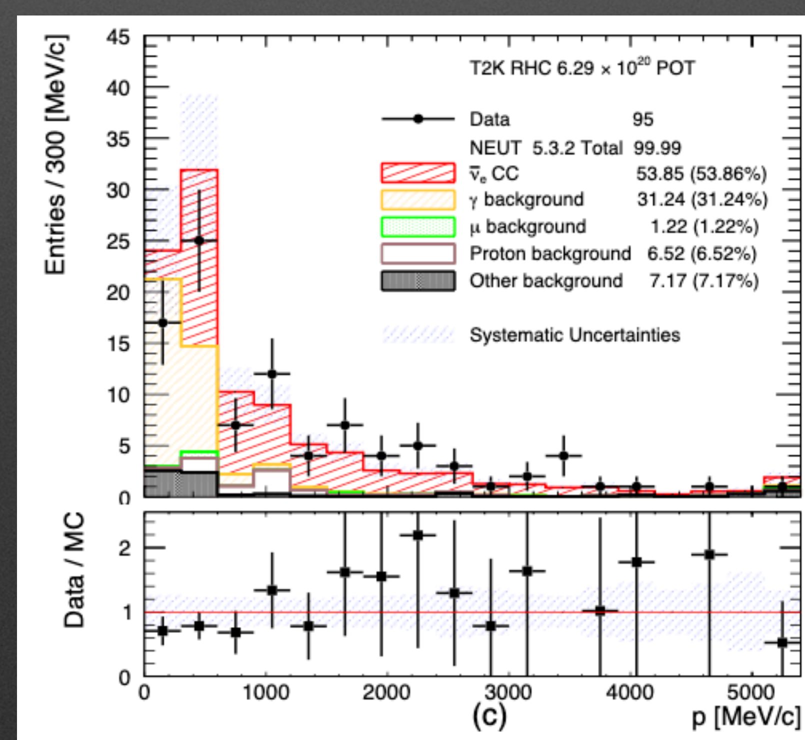
ν_e candidate with shower in ECAL

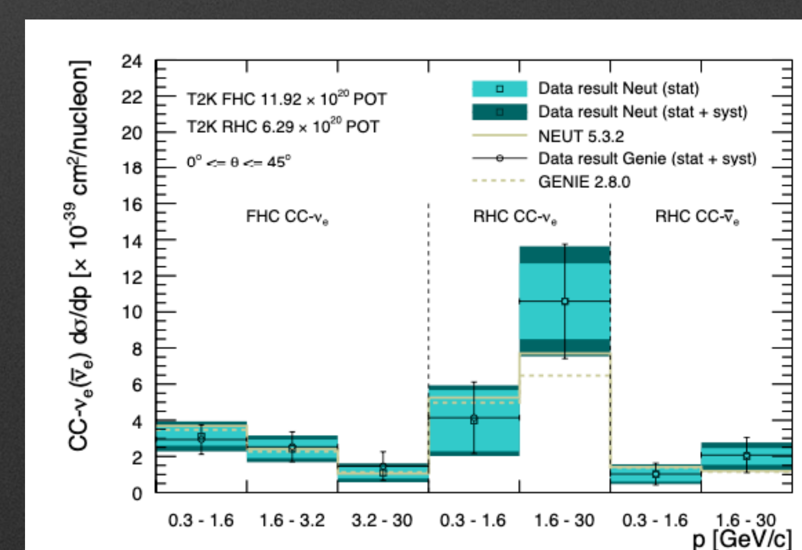


* Combining TPCs + ECAL allow to select a clean sample of electrons (1% of ν_e component expected in T2K beam)

* We recently published the first combined measurement of ν_e and $\overline{\nu}_e$ cross-section



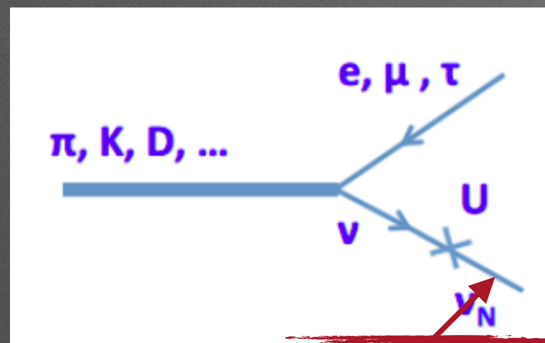


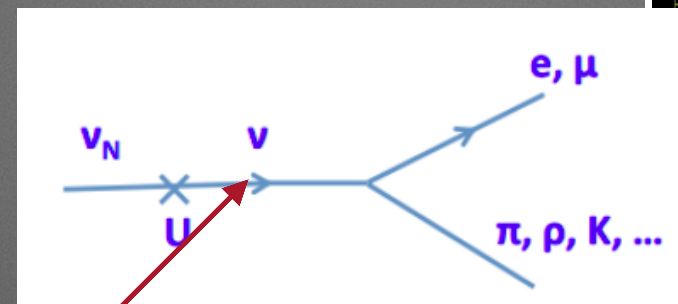


Heavy neutrinos

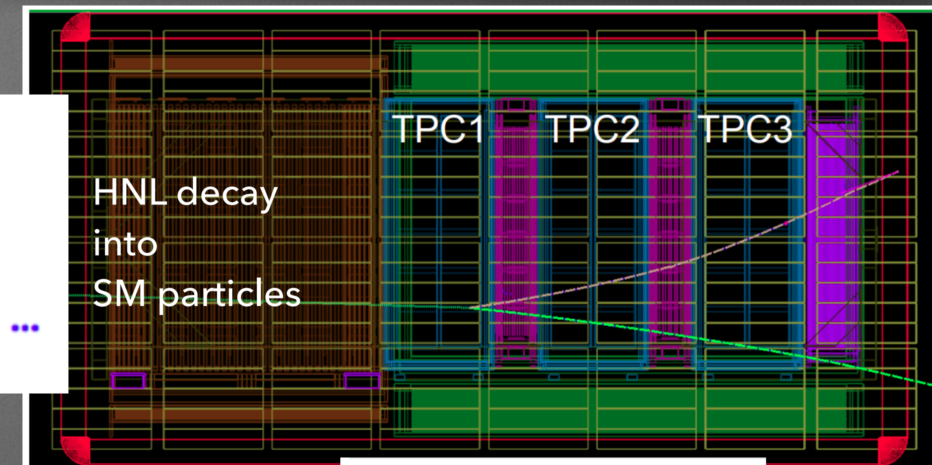
Phys.Rev.D 100 (2019) 5, 052006

HNL production in meson decay



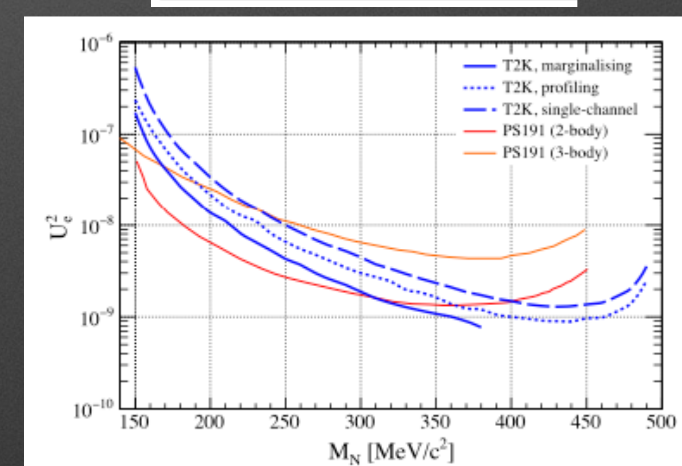


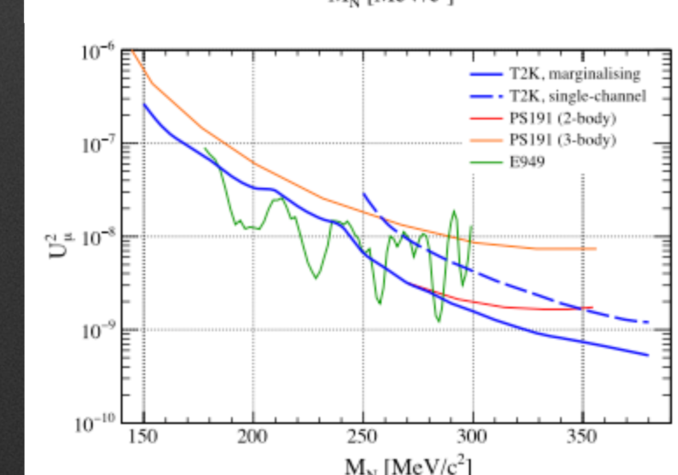
HNL mixing with active neutrino



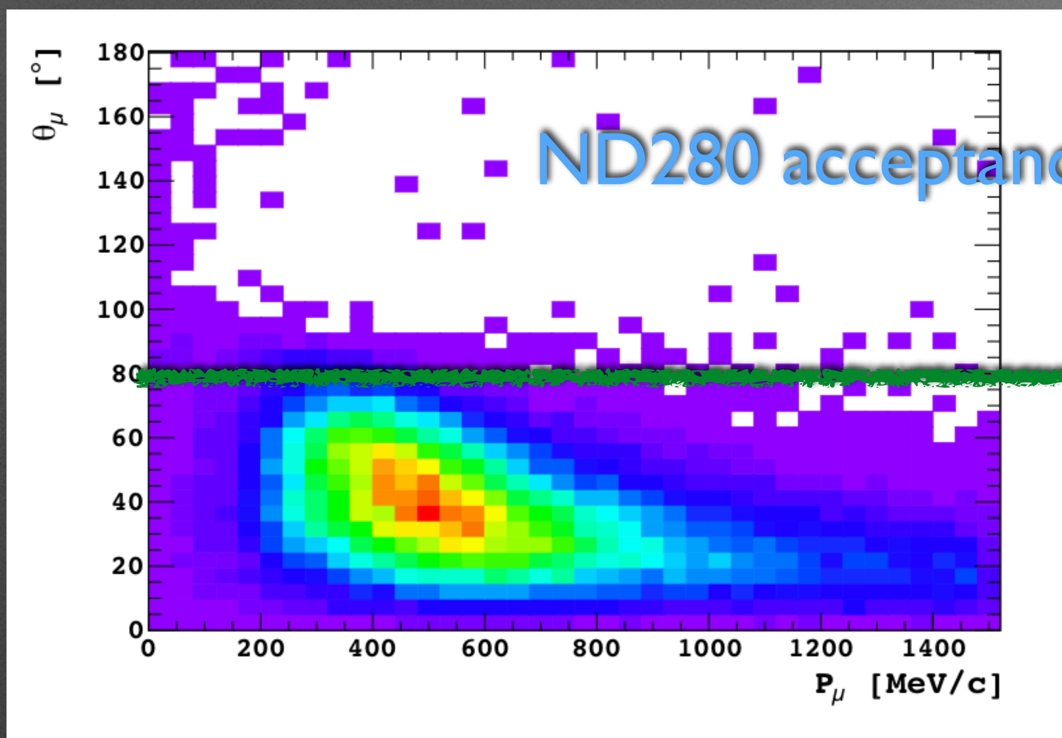
Mode	Ch.	Expected background
neutrino	$\mu^{\pm}\pi^{\mp}$	1.543
	$e^{-}\pi^{+}$	0.376
	$e^{+}\pi^{-}$	0.328
	$\mu^{+}\mu^{-}$	0.216
	$e^{+}e^{-}$	0.563
antineutrino	$\mu^{\pm}\pi^{\mp}$	0.384
	$e^{-}\pi^{+}$	0.018
	$e^{+}\pi^{-}$	0.219
	$\mu^{+}\mu^{-}$	0.038
	$e^{+}e^{-}$	0.015

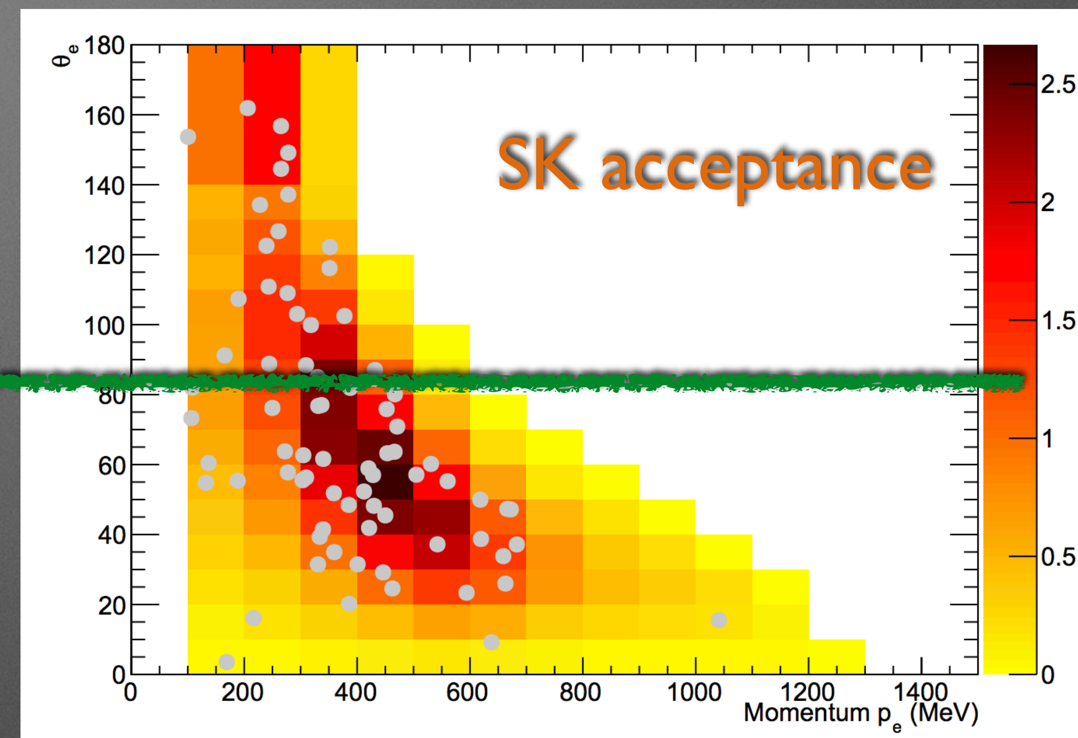
- Search for Heavy Neutral Leptons (HNL) produced by π and K decays and decaying in the TPCs
  - Very small background expected from neutrino interactions in the gas (~3 events combining all channels)
- Put limit on the mixing between HNL and active neutrinos in the mass range between 150 and 500 MeV
- Additional POT and the new TPCs of the ND280 Upgrade will allow to improve these measurements





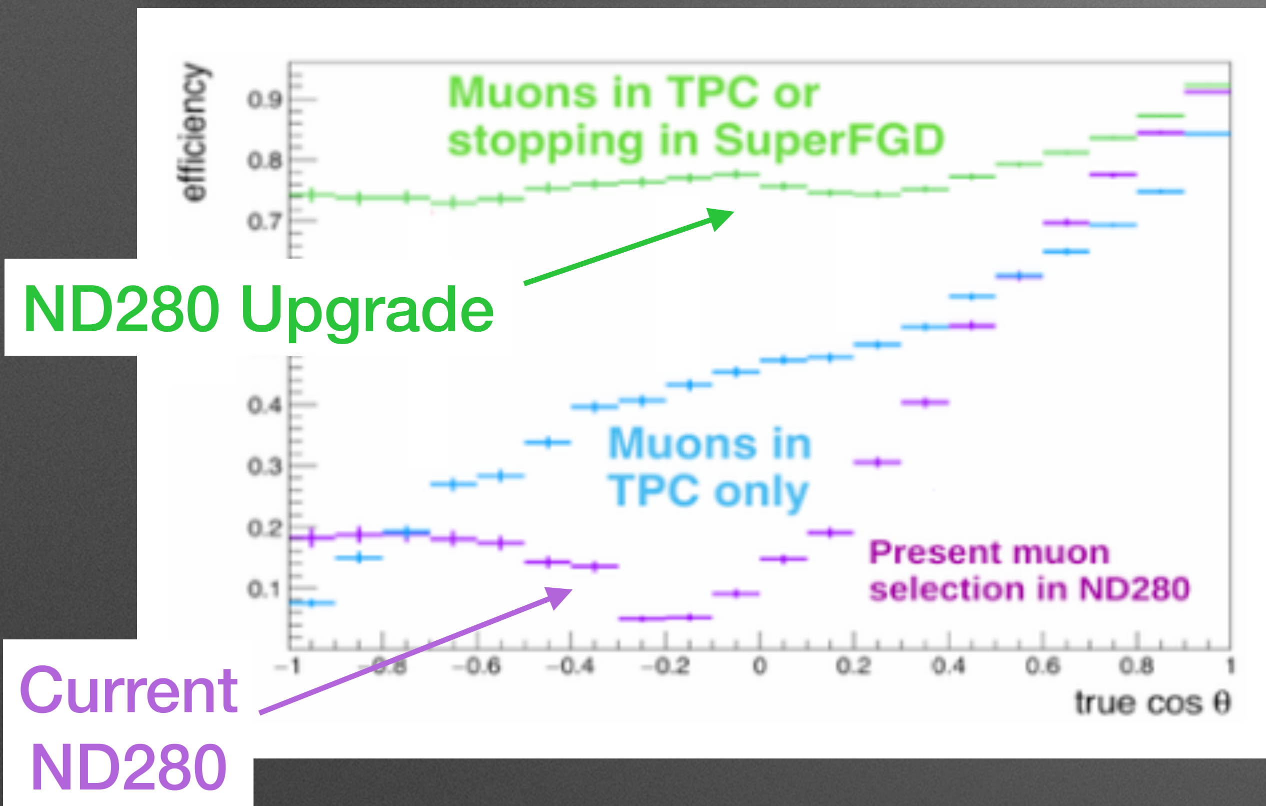
ND280 limitations

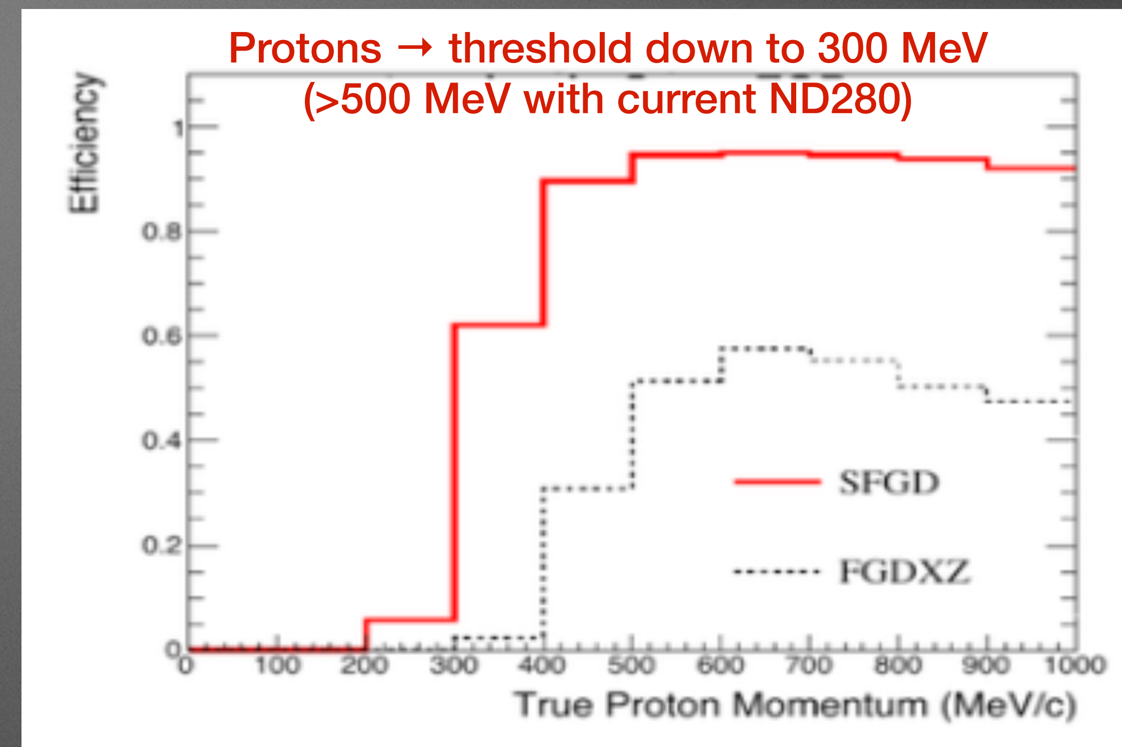




- Main strength of ND280 : magnetized detector → separate ν from $\overline{\nu}$ (cannot be done in SK)
- Main limitations:
  - Reduced angular acceptance → only forward going muons are selected with high efficiency
  - Low efficiency to reconstruct the hadronic part of the interaction → only the muon kinematics is used in the oscillation analysis

ND280 upgrade





- Larger efficiency for high angle and backward muons
- Much better performances in the reconstruction of the hadronic part of the interaction
- Larger statistics

Super-FGD

- 2 millions 1cm³ cubes **assembled in x-y layers**
- Light in each cube is collected by 3 WLS (3 views)
- Light carried by the WLS is read by **56k MPPCs** mounted on PCB
- 3D view of neutrino interactions