High granularity near detectors for long baseline experiments

and a short introduction to systematic uncertainties for neutrino oscillation

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CERN
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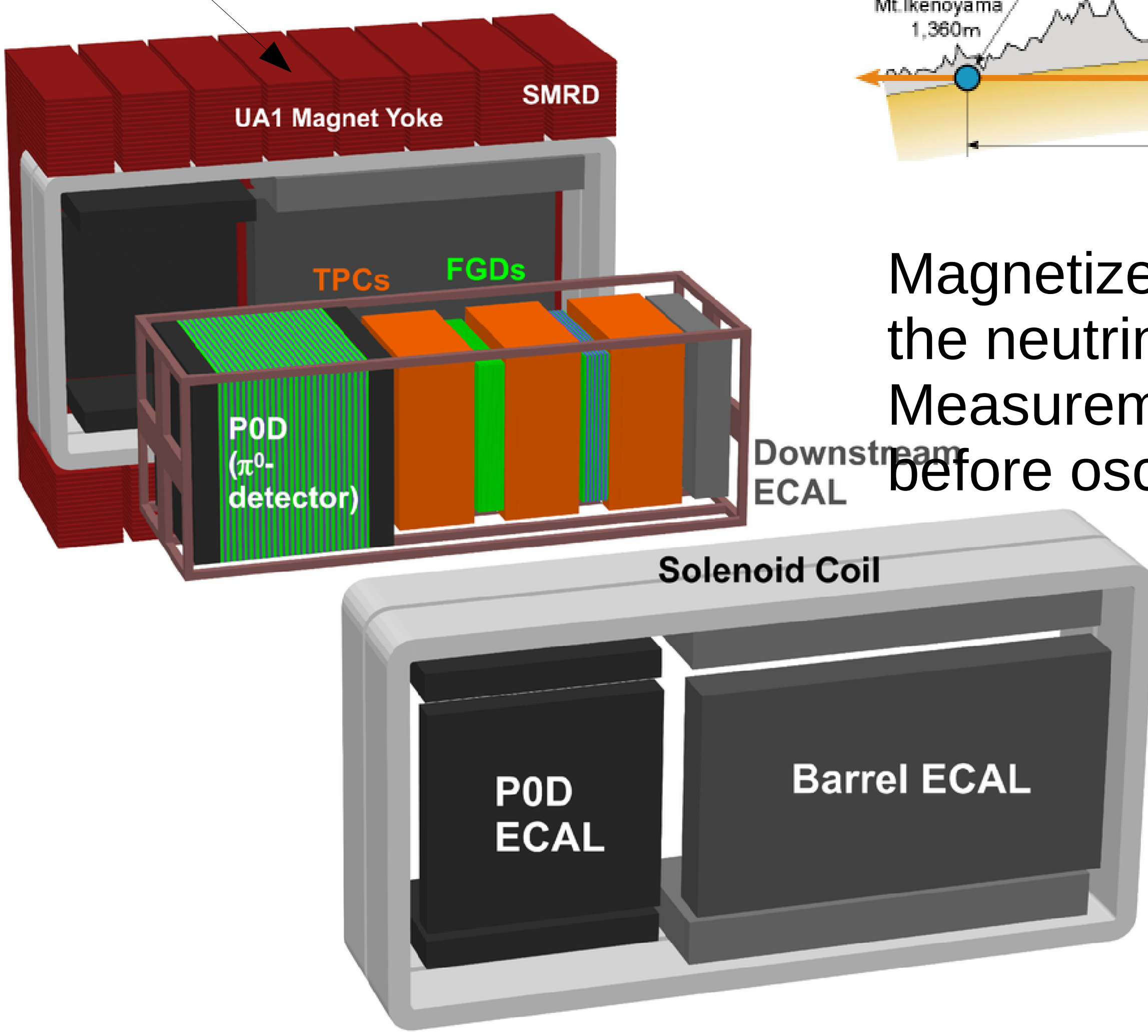
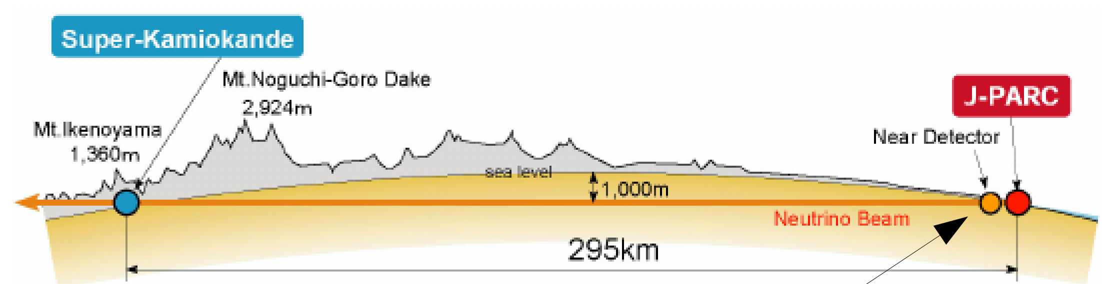
Outline

- Near detectors and systematic uncertainties
- Challenges for future long baseline exp.
- The experience with the T2K ND280 and the ND280 Upgrade
- A word on DUNE ND and the HPTPC

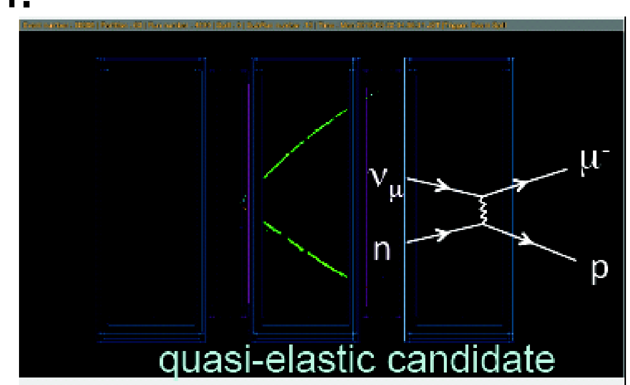
The T2K ND280 Near Detector

CERN donation

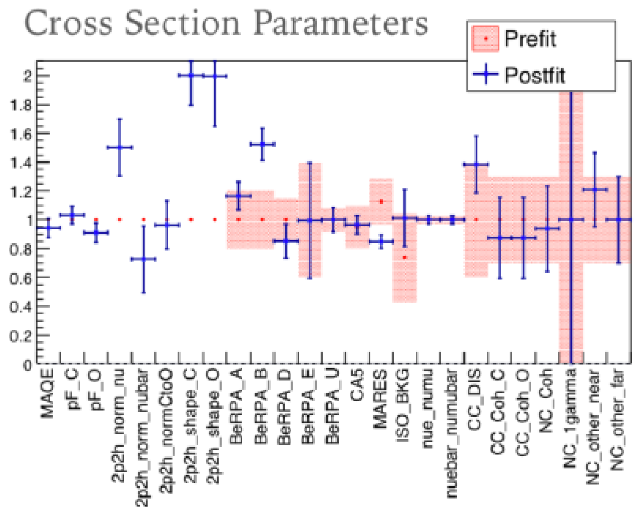




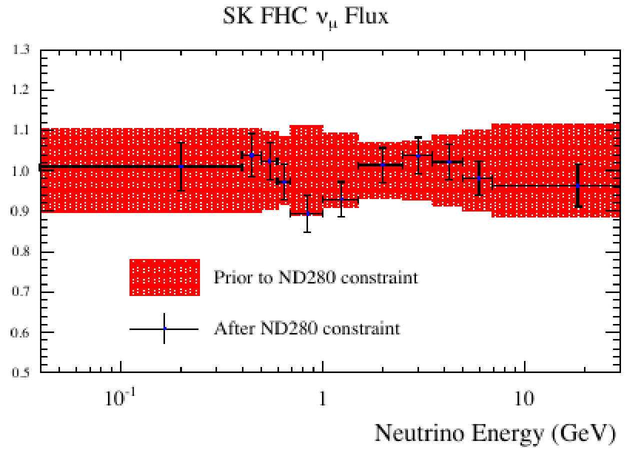
Magnetized near detector at 280m from the neutrino production point (target). Measurement of the interaction rates before oscillation.

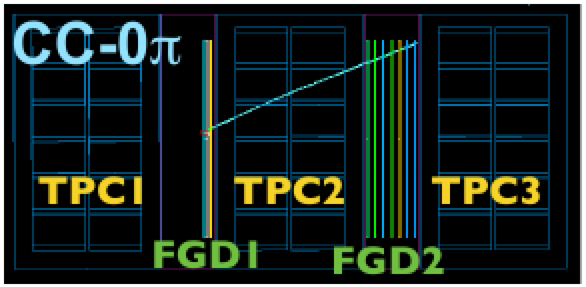


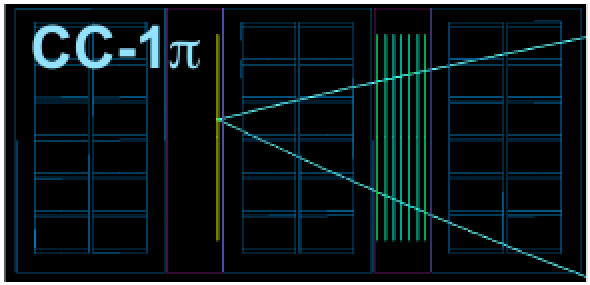
T2K ND280 at work

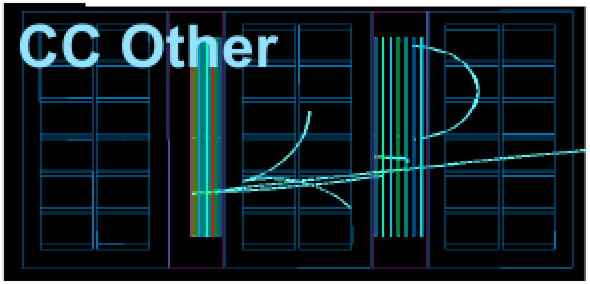


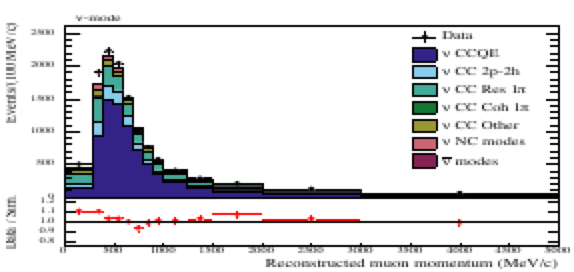
- Select events with vertices in the scintillator detectors (FGD) and charged particles in the TPC
- Class them in various topologies
- Fit of flux and cross-section parameters

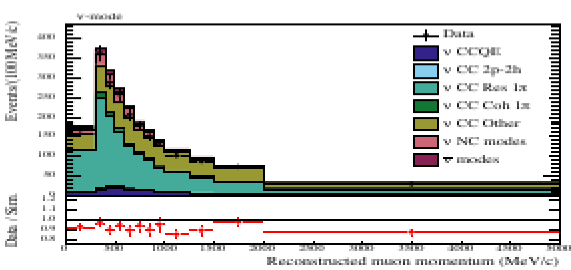


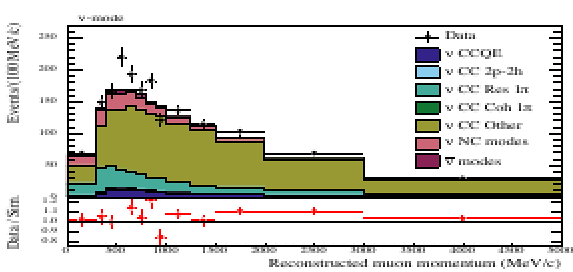




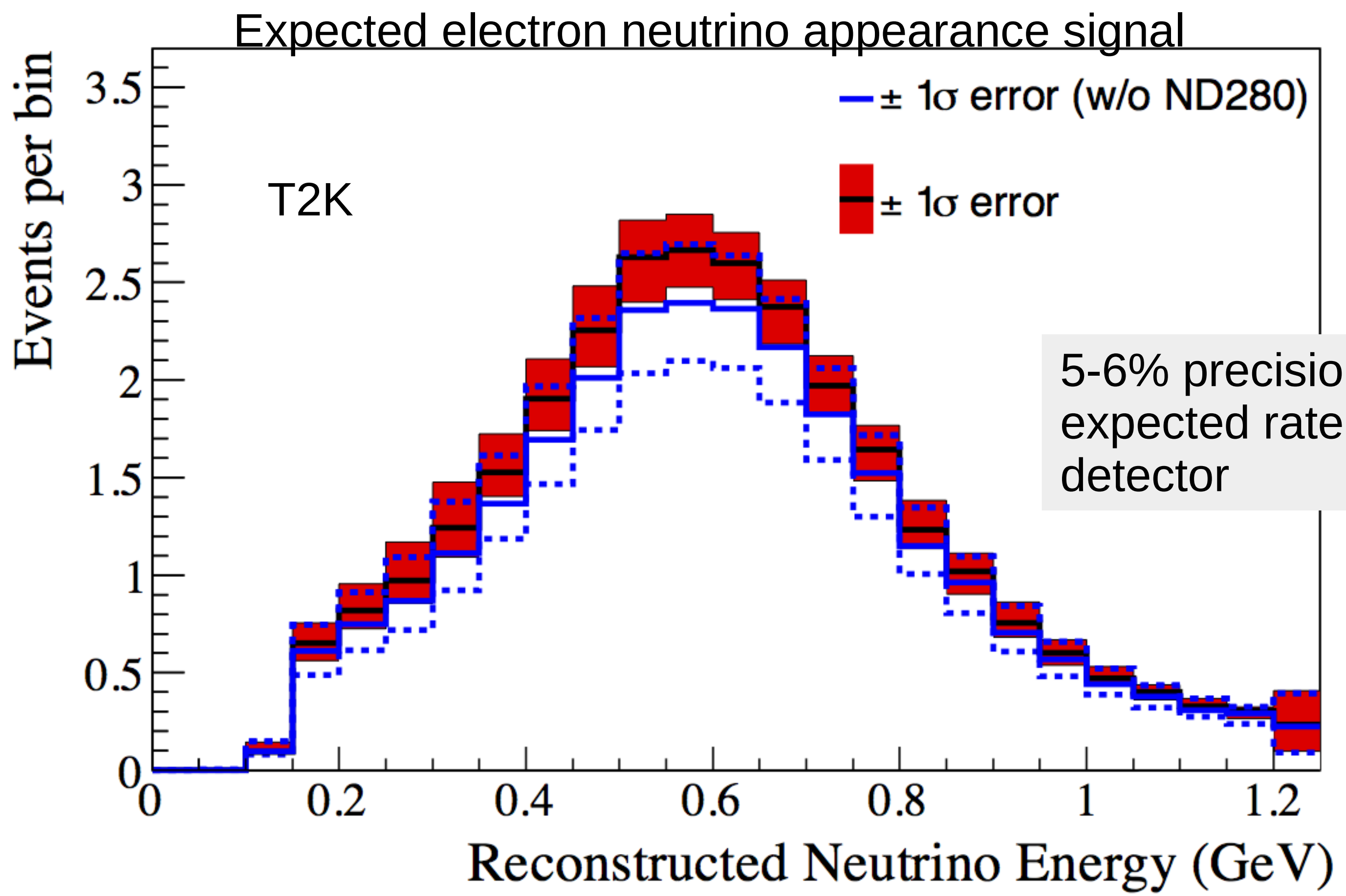








Role of the ND280 near detector



5-6% precision on the expected rate at the far detector

- Measure the neutrino interaction rates (flux.times.cross-section) in various channels
- Strongly constrain the expected rates at SuperKamiokande for precision oscillation analyses
- Measure neutrino nucleus cross-sections in several channels

Issues

However, there are two major issues

1) for a ν_e sample of ~2000 events (HK) we need to push the precision down to the 2-3 % level

2) The neutrino-nucleus interaction model at ~1 GeV energy is not yet fully developed

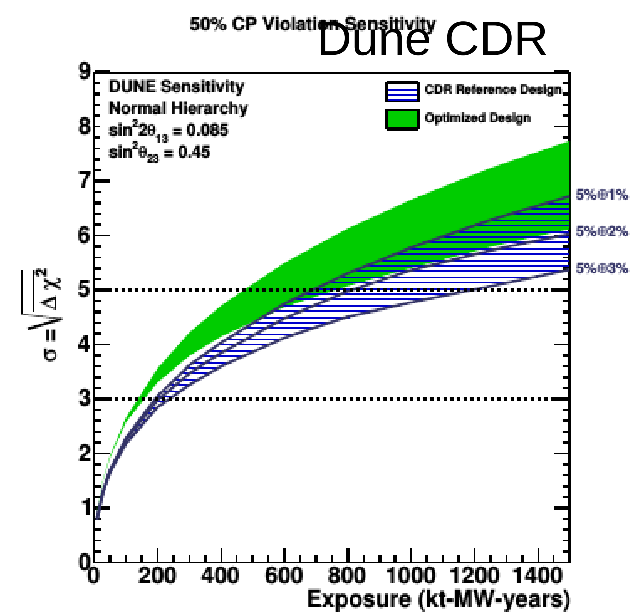
Systematic uncertainties

Systematic uncertainties on the number of ν_e events in the far detector.

	T2K	HK	DUNE
Flux and xsec ND const.	4.2%	3%	2%
ND ind xsec	2.5% (FSI+SI)	0.5%	2%
FarDet	2.4%	0.7%	1%
Total	5.5%	3.2%-3.9%(nueb)	3.6%

Ex

Dune CDR



Source:
DUNE CDR
T2K 2017
HK DR 2018

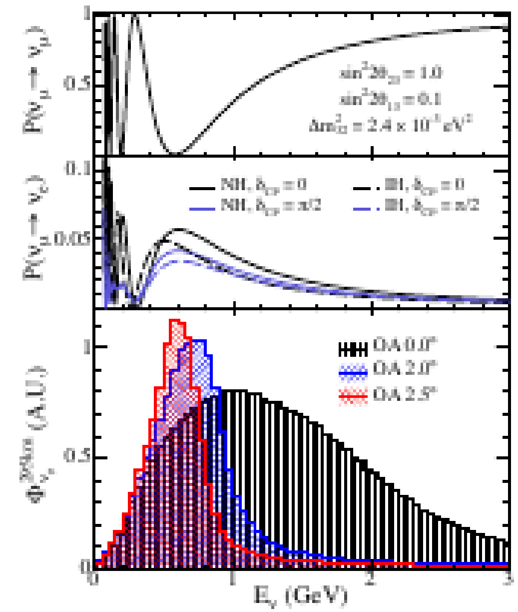
Near Detectors for Long Baseline

Far Det $$N_k(p_k,\theta_k)=\sum_i^{E_{true}bins}\sum_j^{\nu\ species}\Phi_j^{far}(E_i^{true})P_{\nu_i\to\nu_k}(E_i^{true})\sigma_k^A(E_i^{true},p_k,\theta_k)\epsilon_{FD}$$

Near Det $$N_j(p_j,\theta_j)=\sum_i^{E_{true}bins}\Phi_j^{near}(E_j^{true})\sigma_j^A(E_i^{true},p_j,\theta_j)\epsilon_{ND}$$

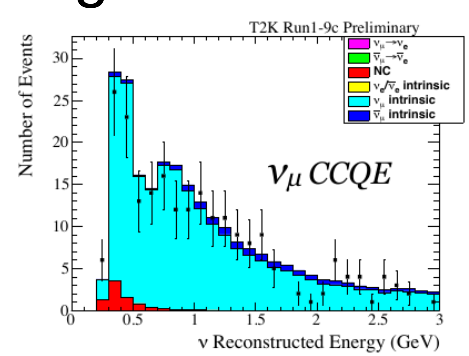
The naive assumption that far/near ratio simply cancel out all flux and cross-section is not correct for several reasons

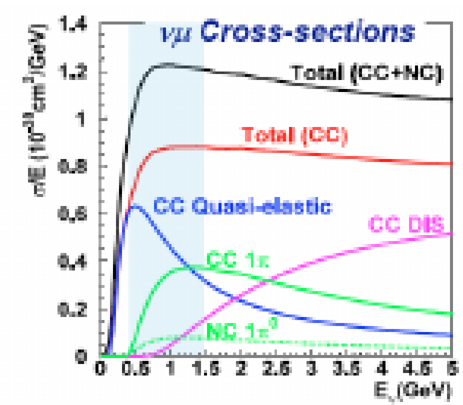
1) New neutrino species due to oscillation
2) Target nucleus
3) Oscillation (maximal disappearance at far site!)
4) No monochromatic beam, smearing of reconstructed energy



=> a complex entanglement of flux, cross-sections and detector effects

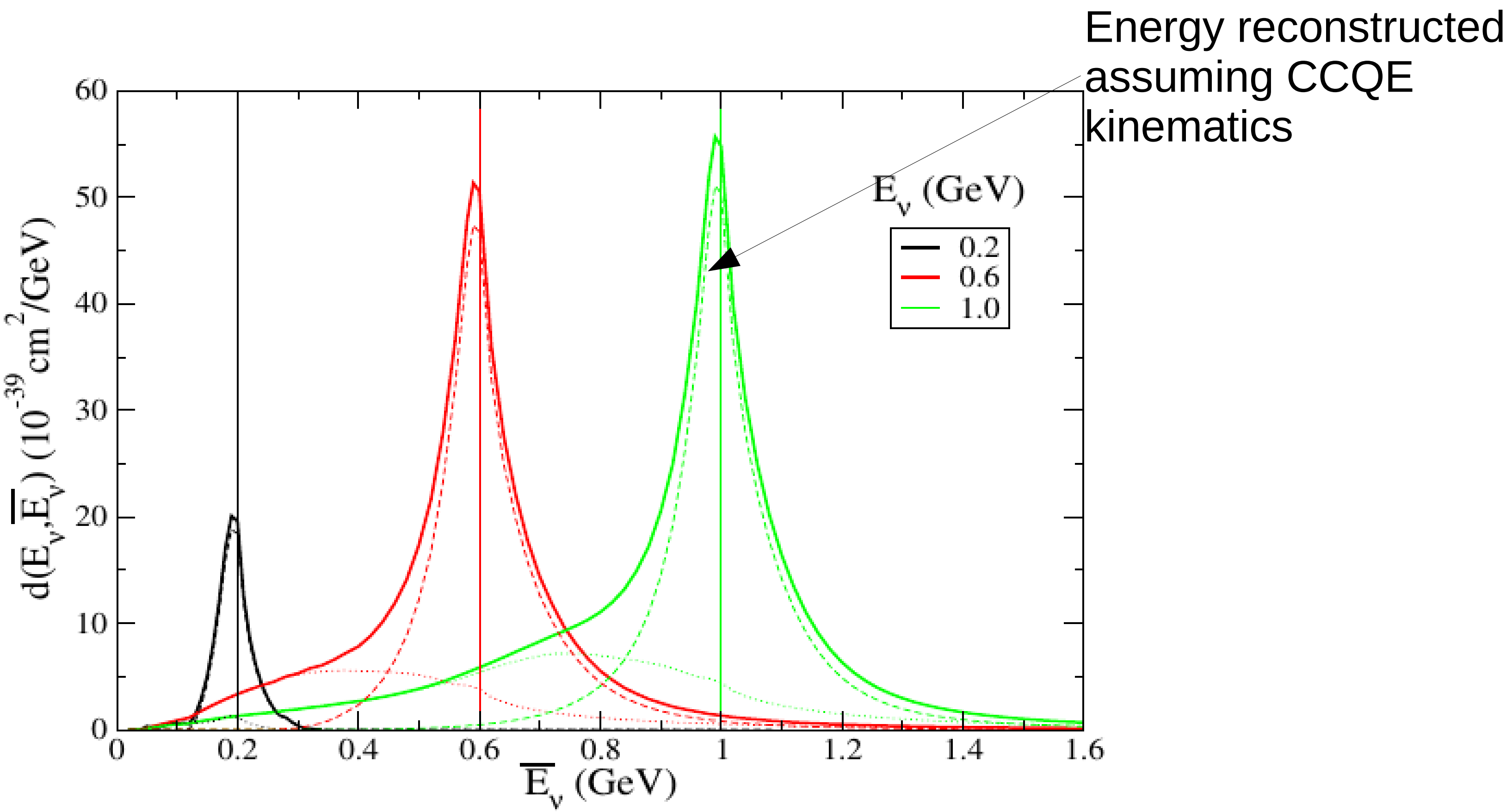
NB even a calorimetric measurement is not immune of these effects, as the resolution depends on the hadronic content (neutrons)!





Martini et al 1211.1523

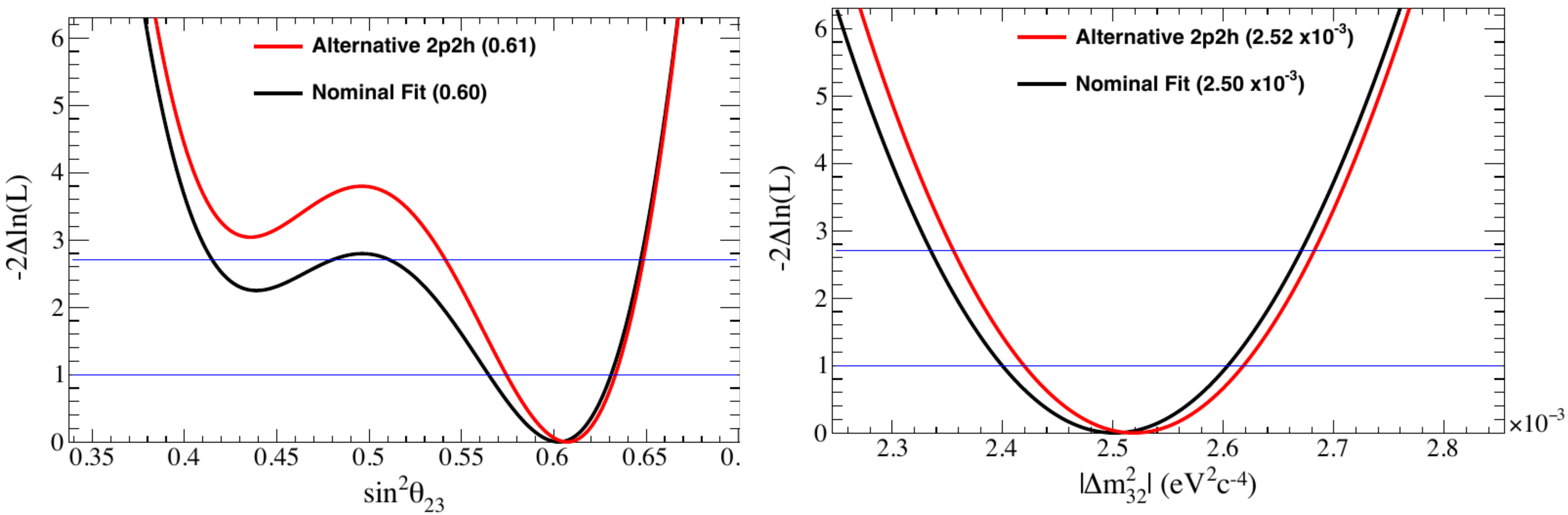
Energy reconstruction effects



The scattering on correlated pair of nucleons (2p-2h) rather than on a single nucleon affects the kinematics of the events, but in many detectors (and certainly in Water Cerenkov) it is impossible to distinguish between CCQE and 2p2h. Reconstructing the neutrino energy from the lepton momentum requires understanding the full kinematic of the interaction

T2K PHYSICAL REVIEW D 96, 092006 (2017)

Impact of cross-section model on precision measurements



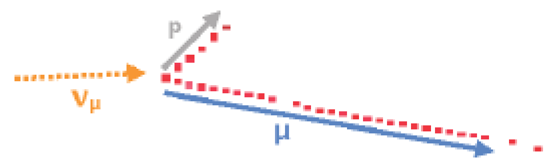
At the moment the bias is a fraction of the statistical uncertainty, but we will need soon to do a much better job

See also P. Coloma P Huber 2013

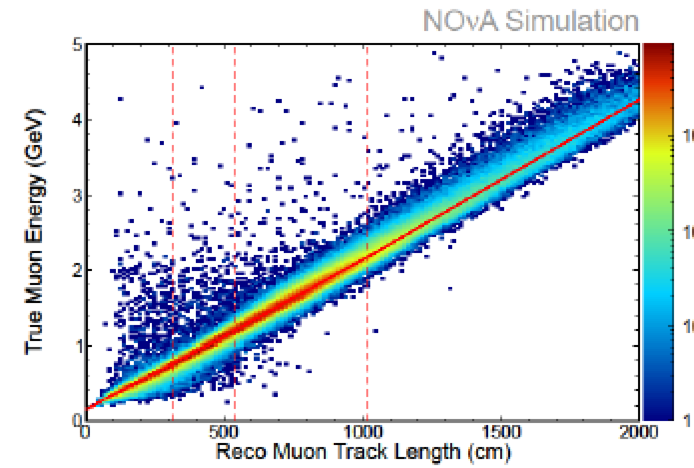
Plots from E. Smith talk at NUFACT 2018

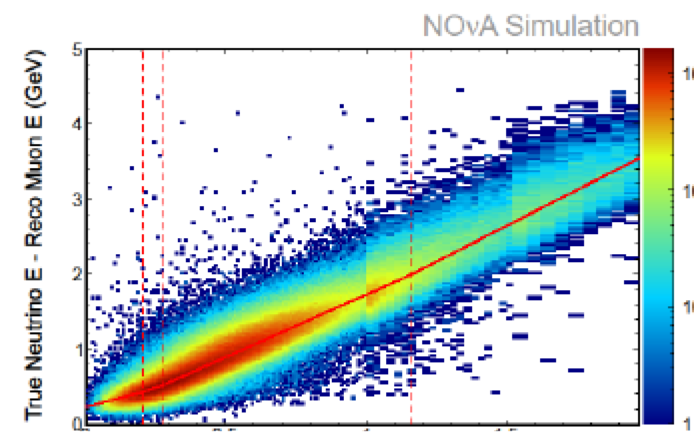
Calorimetric measurements: NOVA, DUNE

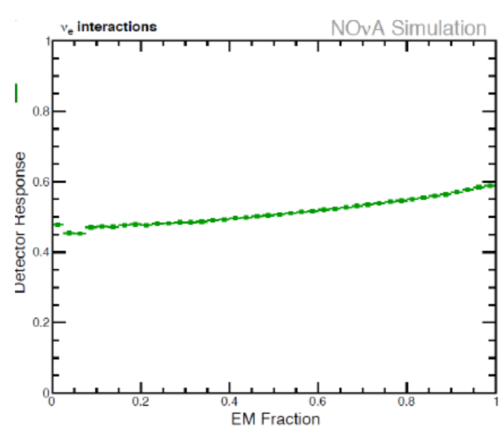
- Even total calorimetric detectors, with ND similar in detection technique to the FD are affected
- $E_\nu = E_\mu + E_{had}$

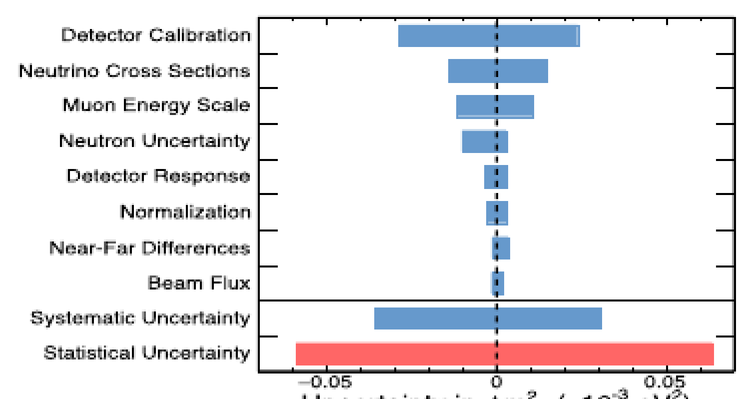


- Depends on the content of the hadronic system
- Detector response, neutrons
- Importance of detector calibration







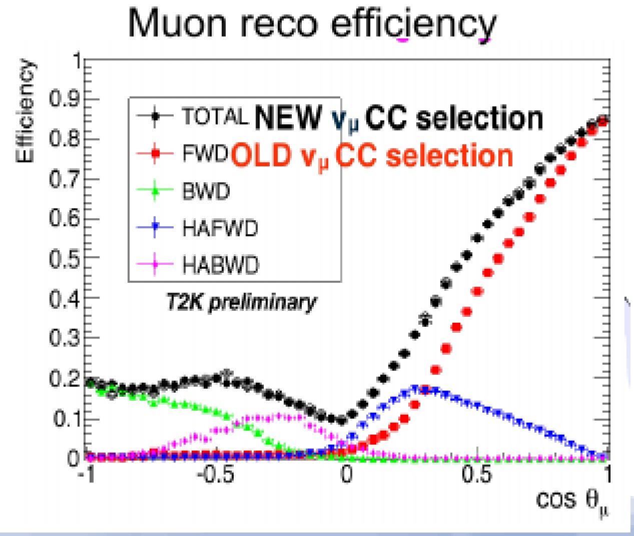


How to make progress ?

- No single easy solution !
- Keep increasing the precision of flux measurements
- Nuint/NUSTEC have produced a roadmap towards a more reliable neutrino interaction model
- While additional data-set like NUSTORM, ENUBET, NuPRISM-like measurements could be valuable, a state of the art near detector is mandatory
- Both Hyper-Kamiokande and DUNE are planning for a magnetized ND
- New experimental techniques might help disentangling the various effects

ND280 limitations

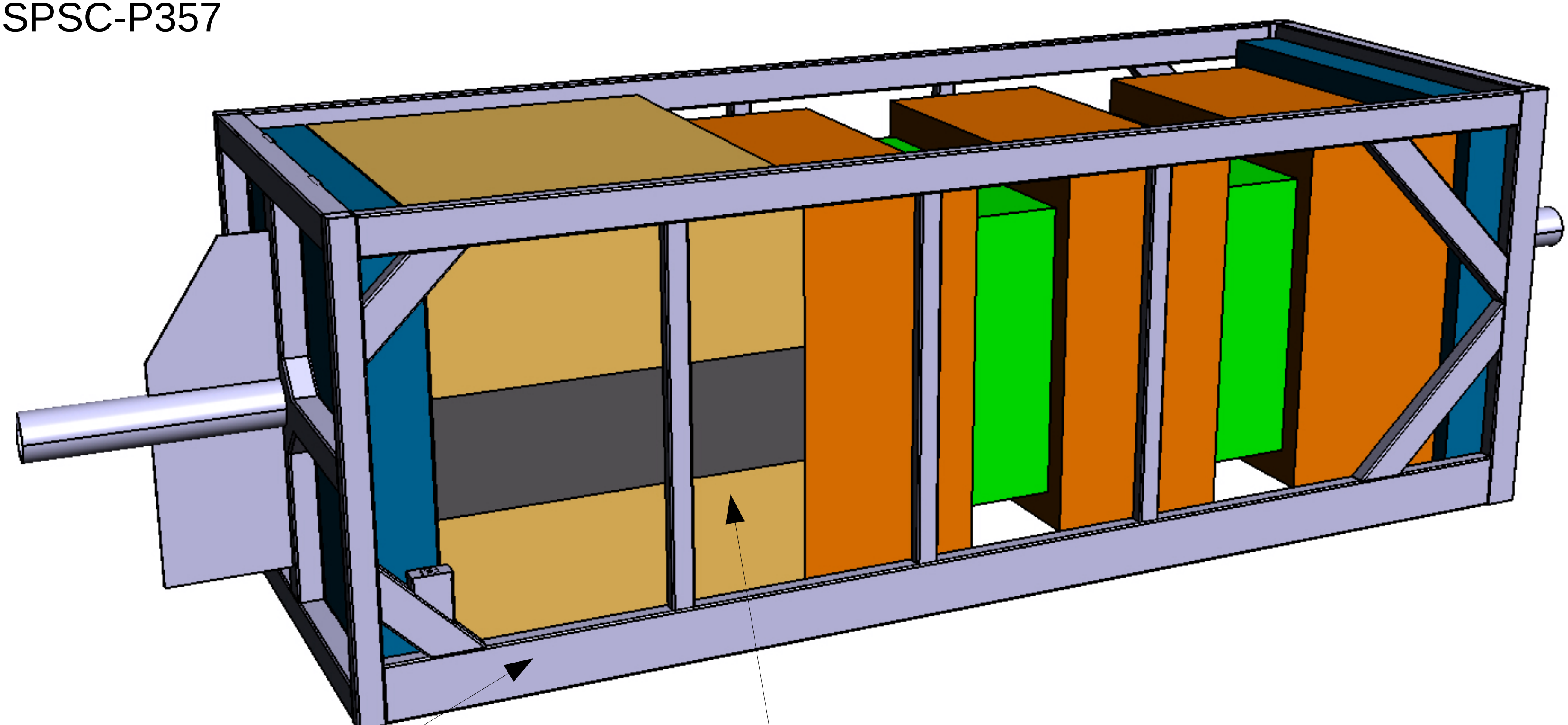
- One of the main limitations of the ND280 data used for the oscillation analyses is that they mainly cover the forward region while SK has a 4π acceptance
- Model dependence when extrapolating to the full phase space
- The neutrino-nucleus cross-section is not well known, an upgrade is necessary to reduce the systematic errors for T2K-II



Strong support from CERN Neutrino Platform for the test beams and the detector design

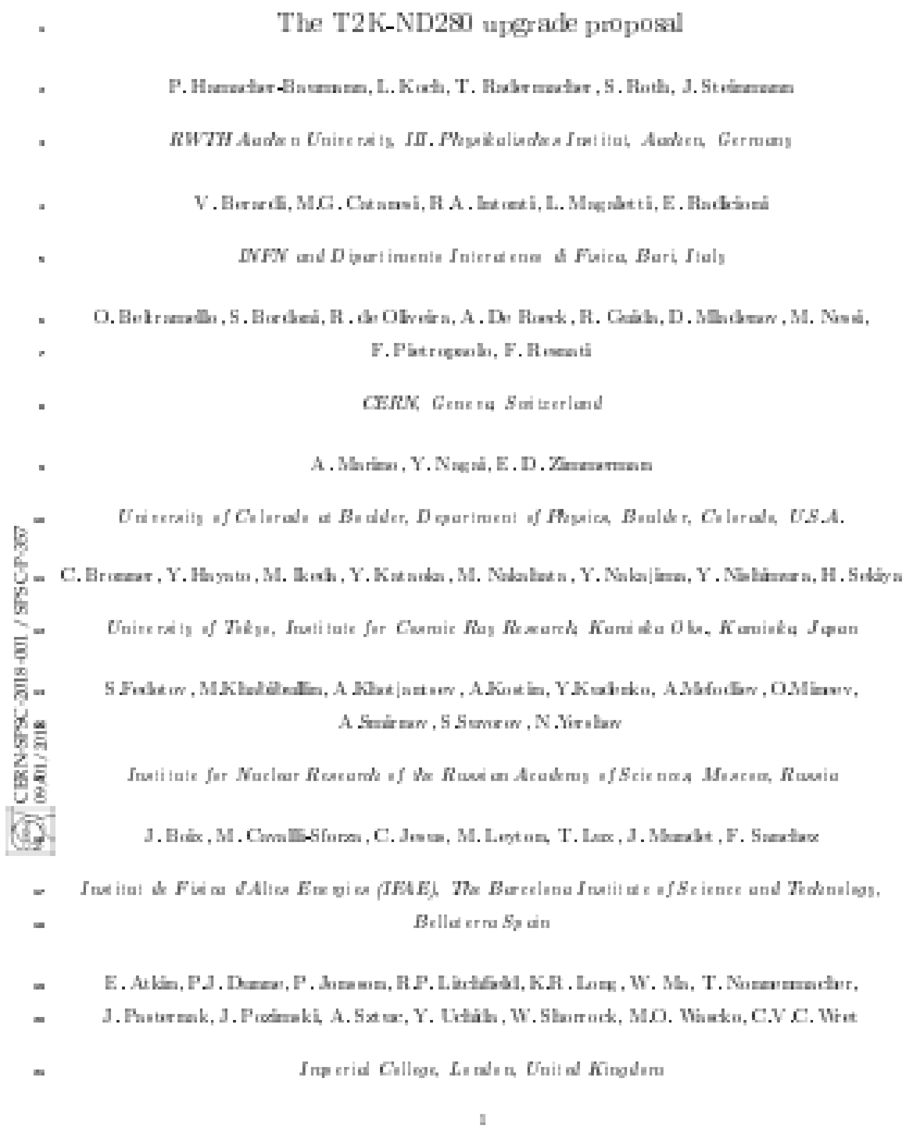
The ND280 upgrade detector

SPSC-P357



Two new High-Angle TPCs
A highly segmented Scintillator Detector (SuperFGD)
TOF planes all around
Collaborating groups: Europe (France, Spain, Italy, Poland, Russia, Germany, CERN),
Japan, USA + support from the full T2K collaboration

The ND280 Upgrade Proposal


CERN-SPSC-2018-001 / SPSC-P-357
09/01/2018

The T2K-ND280 upgrade proposal

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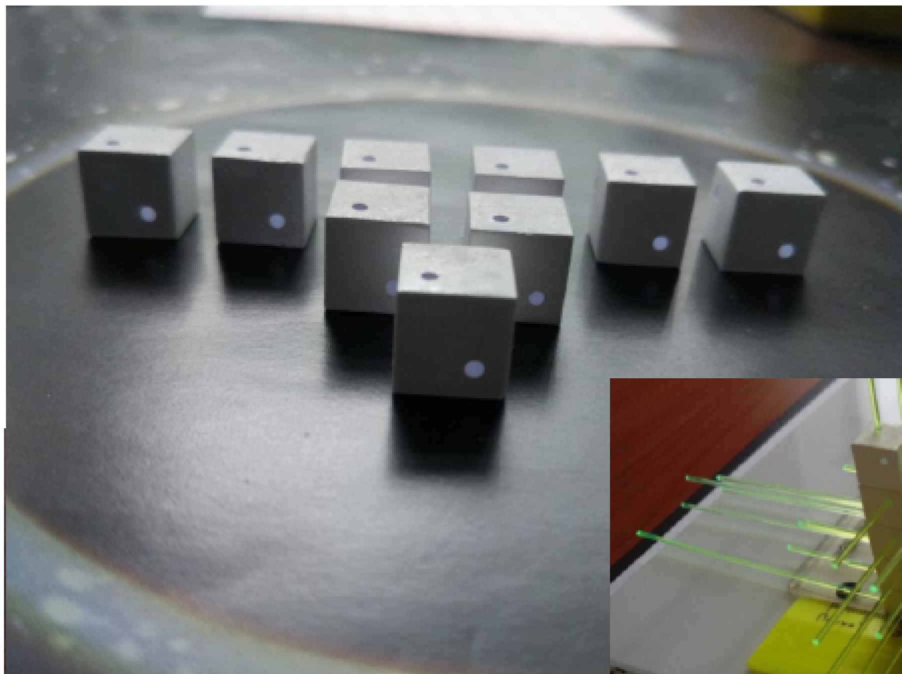
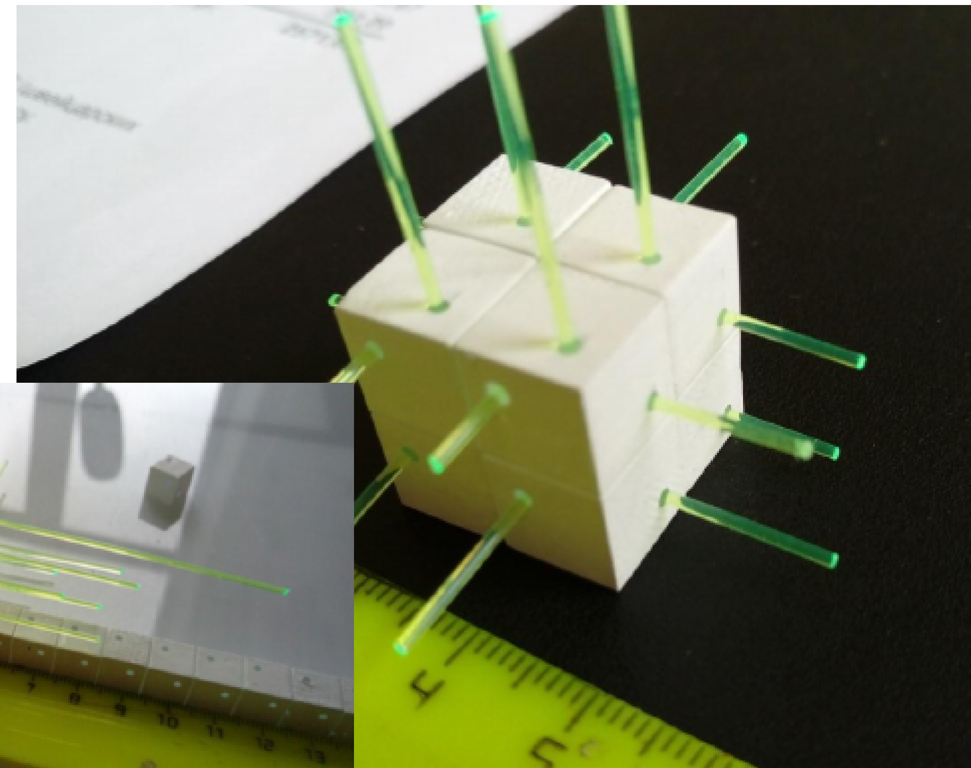
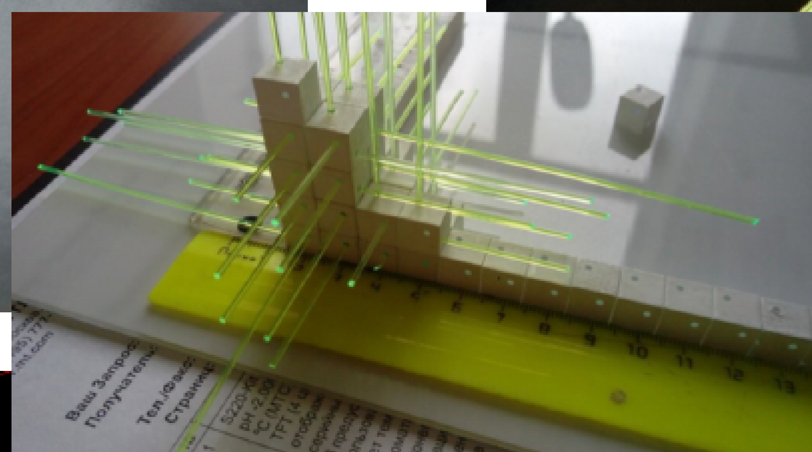
- Proposal submitted to CERN SPSC and JPARC PAC in January 2018
- CERN-SPSC-P357
- 214 authors
- TDR in preparation (due November 2018)

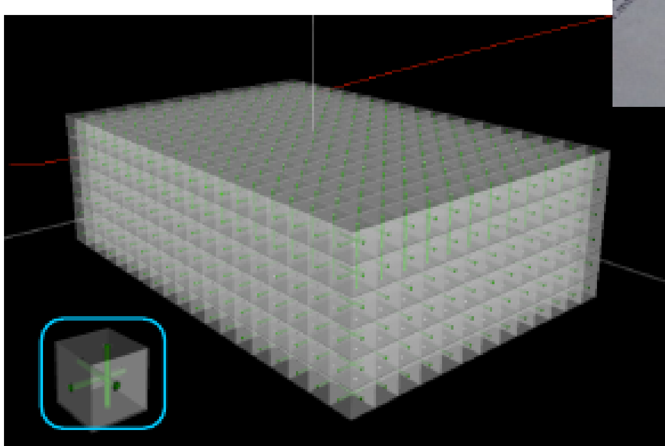
Super-FGD

arXiv:1707.01785



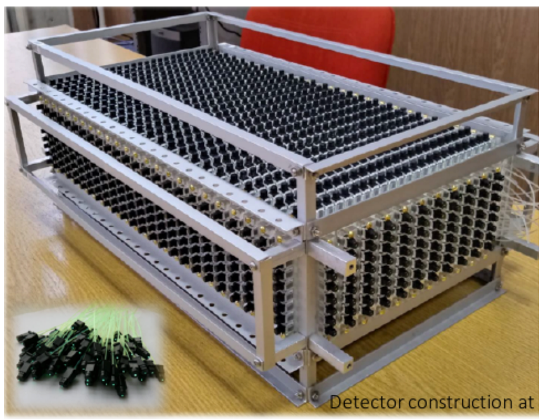


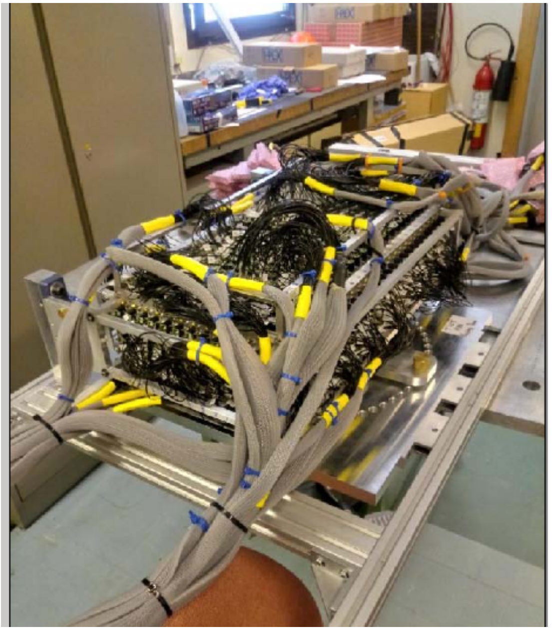


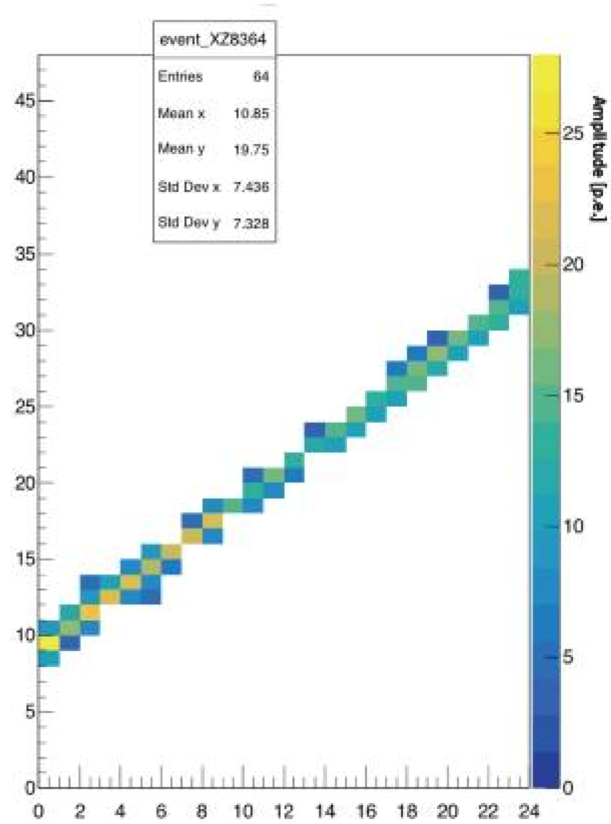


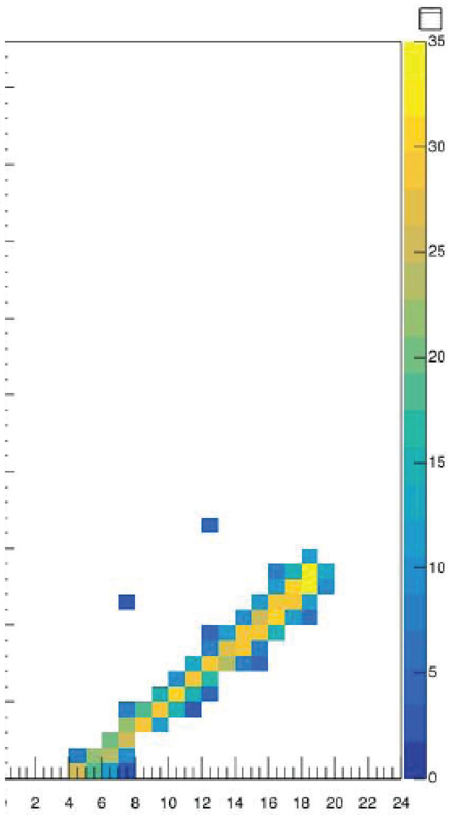
1x1x1 cm^3 plastic scintillator cubes with 3 fibers readout
Several prototypes up to 24x8x48 cm^3

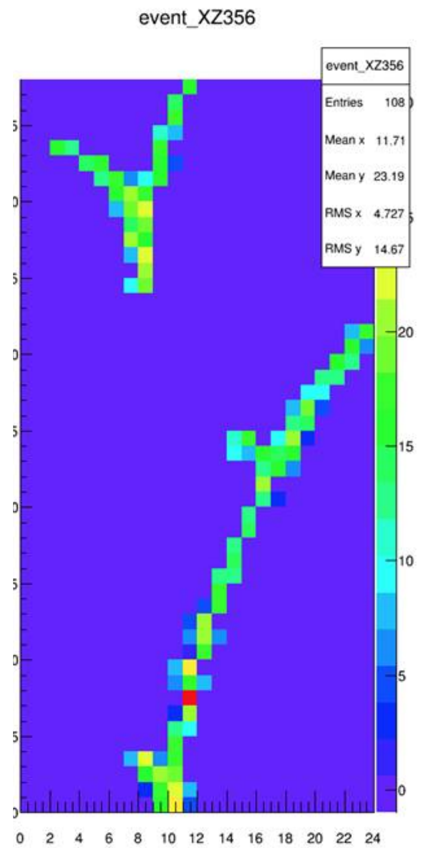
SFGD test beam in 2018



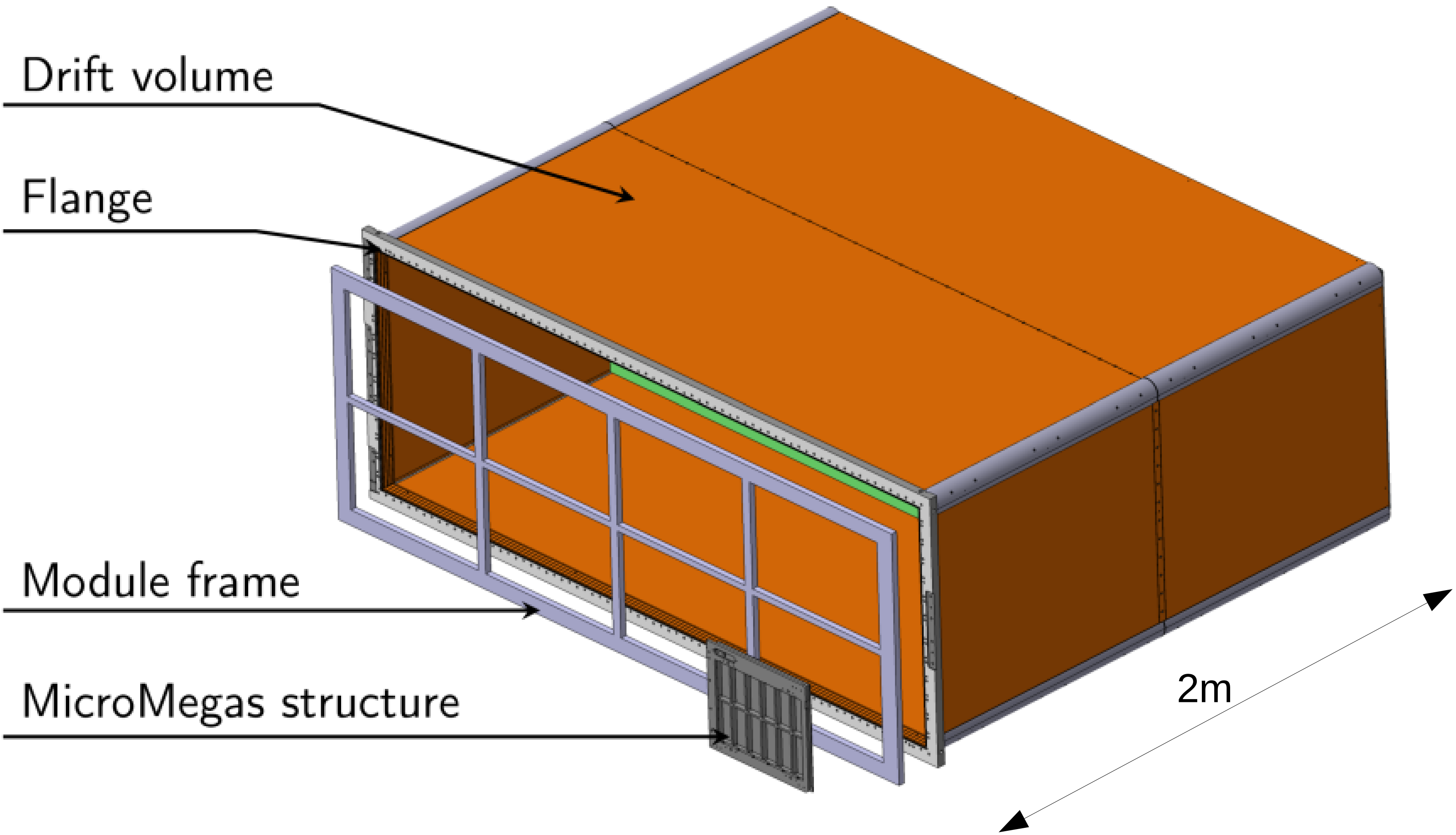




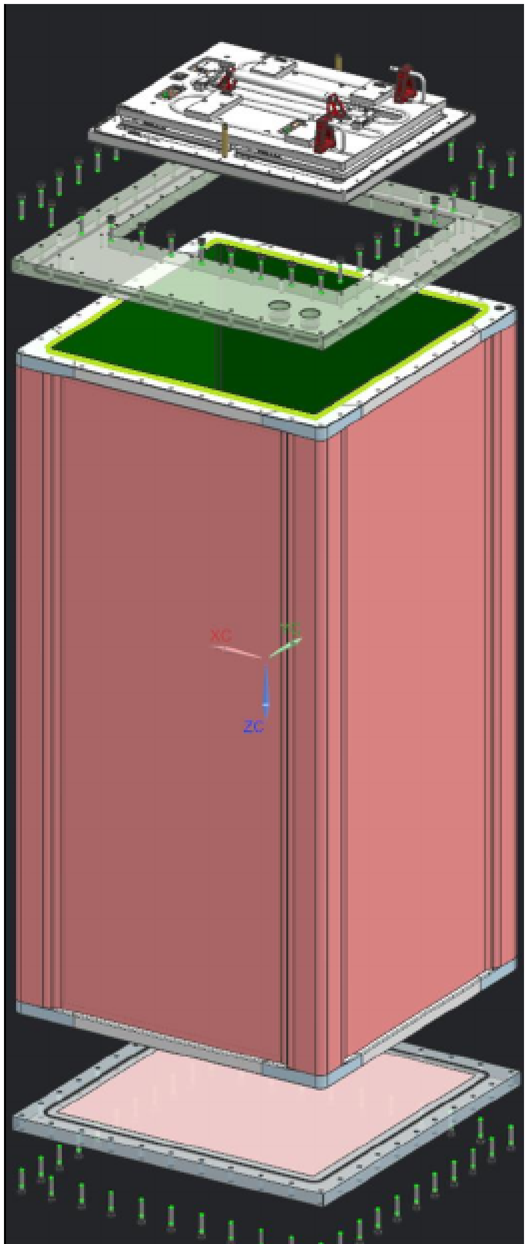




High Angle-TPC



ND280 Upgrade TPC Field Cage

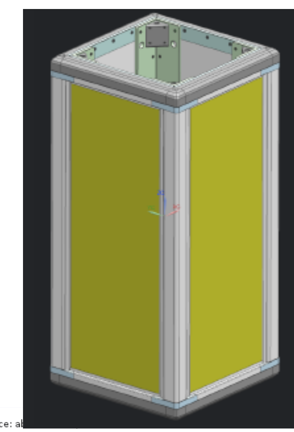


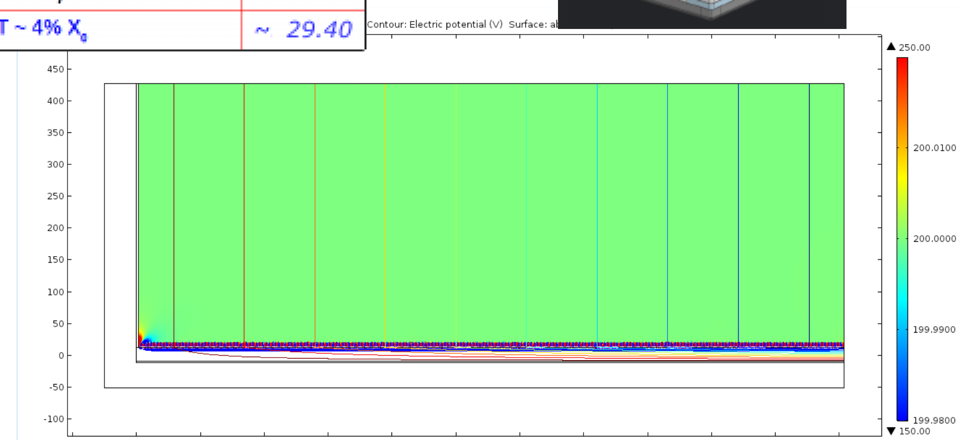
- Thin composite field cage based on Aramid fiber
- Complete technical design ready for the prototype
- Double strip system shaping the E field

Aramide Fiber fabric based layer stack

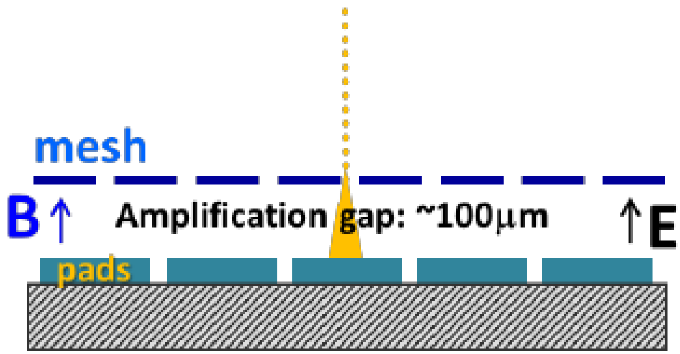
outer layer ↑ inner layer

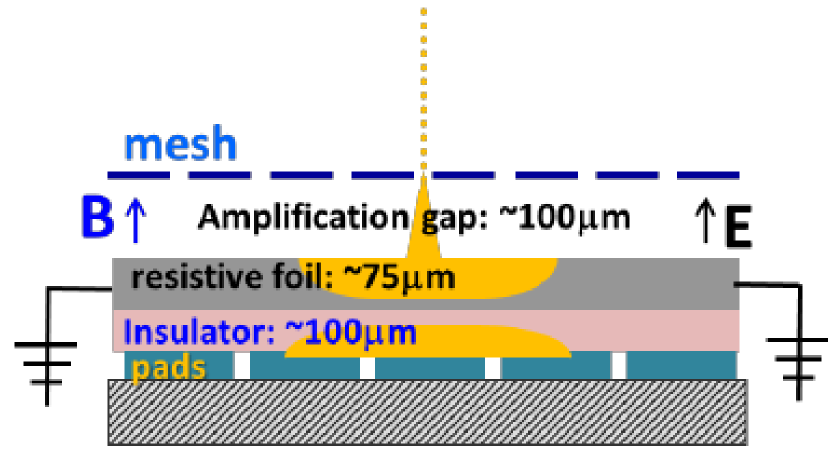
Material	Thickss (mm)
Copper coated polymide film	*~ 0.15*
Aramid Fiber Fabric (Kevlar)	*2.00*
Aramide HoneyComb panel	*25.00*
Aramid Fiber Fabric (Kevlar)	*2.00*
Polymide film (insulation)	*~ 0.10*
Strips (double later) on Kapton foil	*~ 0.15*
TOTAL RADIATION LENGHT ~ 4% X_0	*~ 29.40*

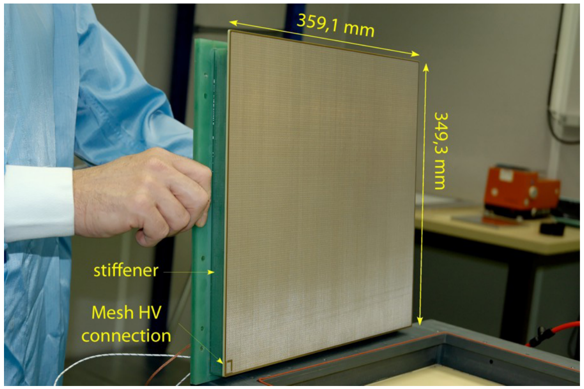


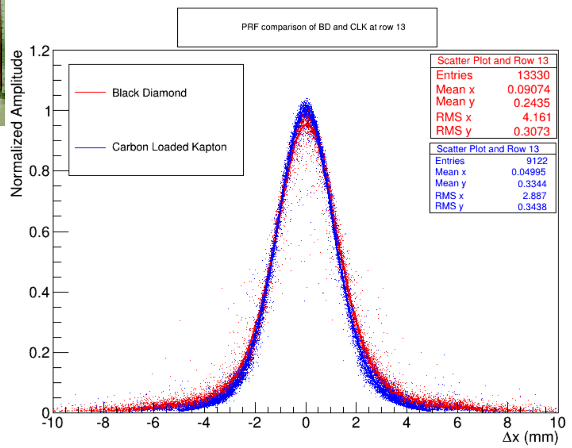


Bulk resistive Micromegas





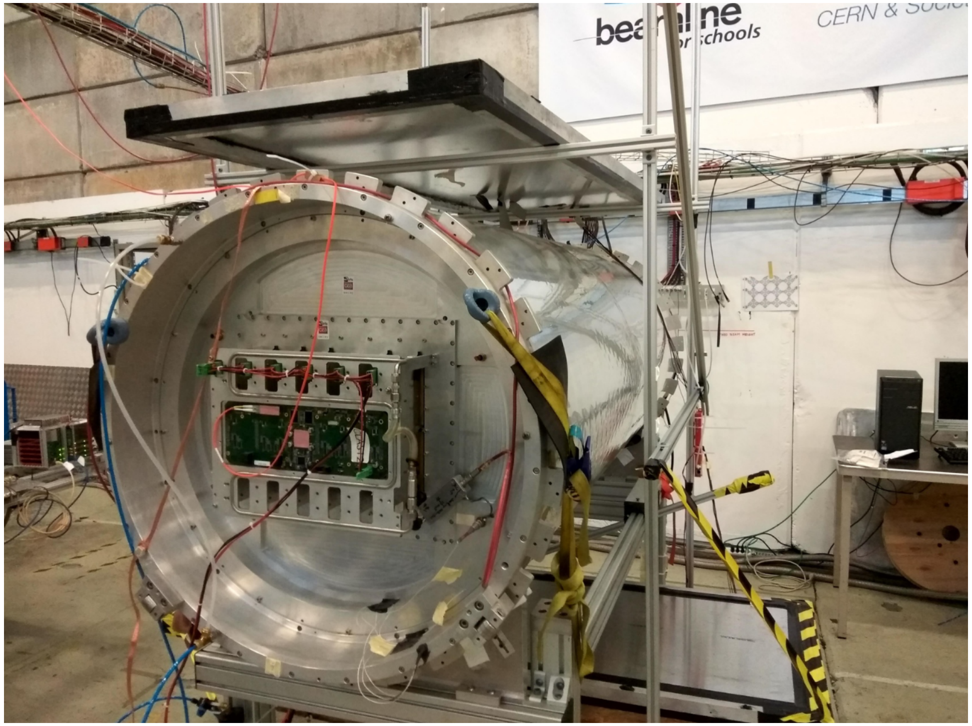


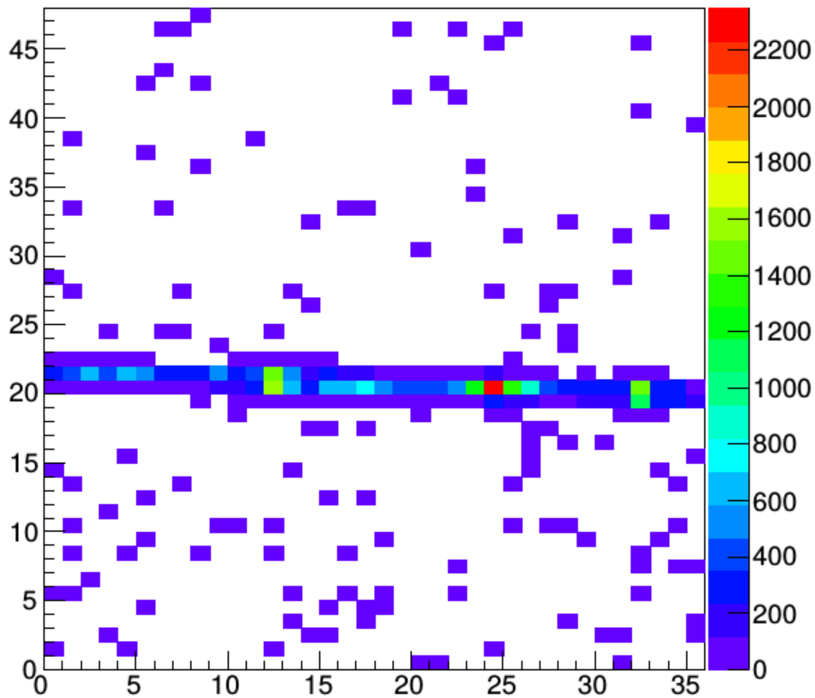


- We will equip the TPC with bulk resistive Micromegas
- Built by covering the pads with a Diamond-Like-Carbon resistive foil
- Optimal resistivity: 400 kOhm/square
- R&D already conducted within the ILC TPC and RD51 collaborations
- Advantages: naturally quench the sparks, spread the charge to neighboring pads
- Large improvement in space point resolution
- No negative impact observed on dE/dx

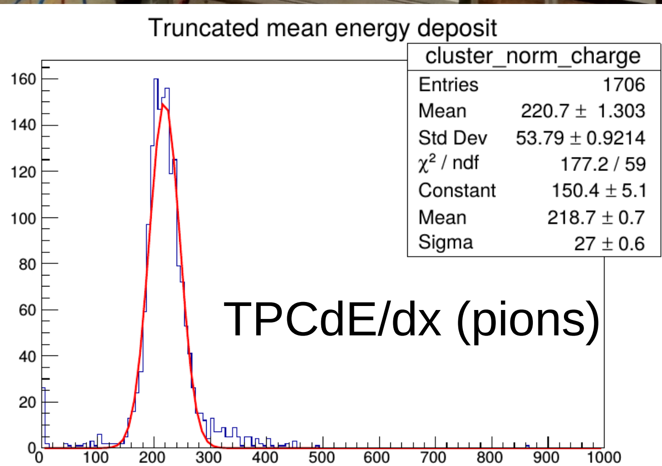
TPC test beams

Successful test beams on CERN PS T9 line end of August



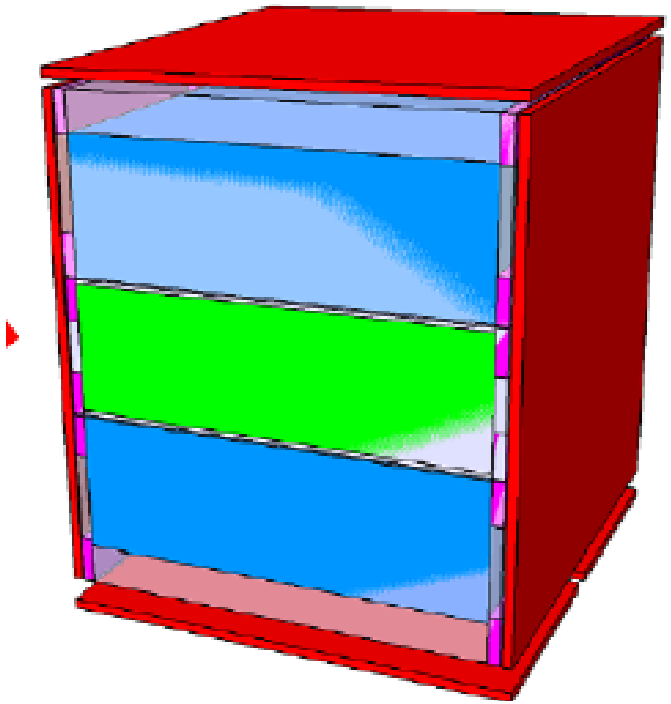


MM event displays

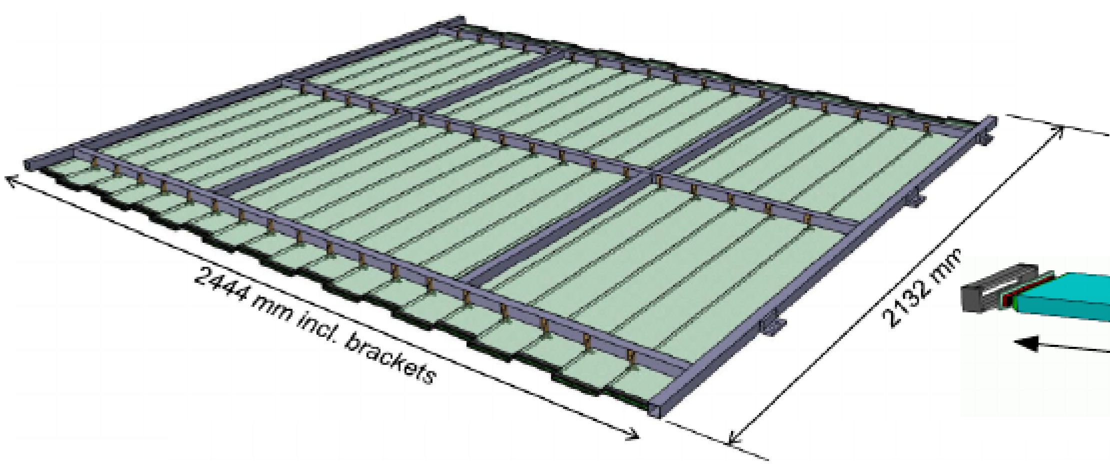


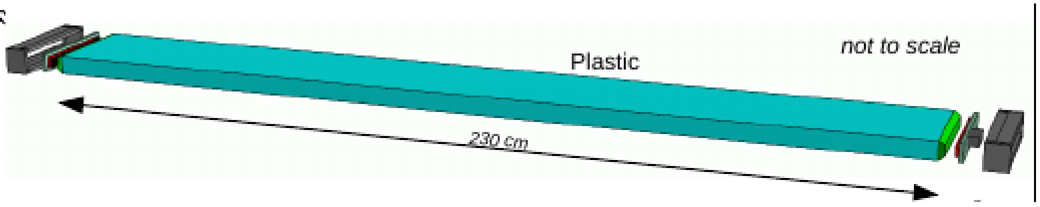
TPCdE/dx (pions)

Time of Flight



- Large surface to be instrumented on the six faces of the detectors : ~2x2 m^2
- ~ 100 ps time resolution
- Allows to distinguish ingoing/outgoing tracks
- Help TPC PID
- Cast scintillators coupled to SiPM (from SHIP R&D)

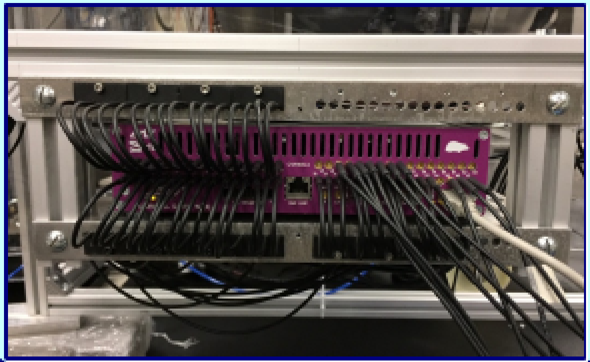




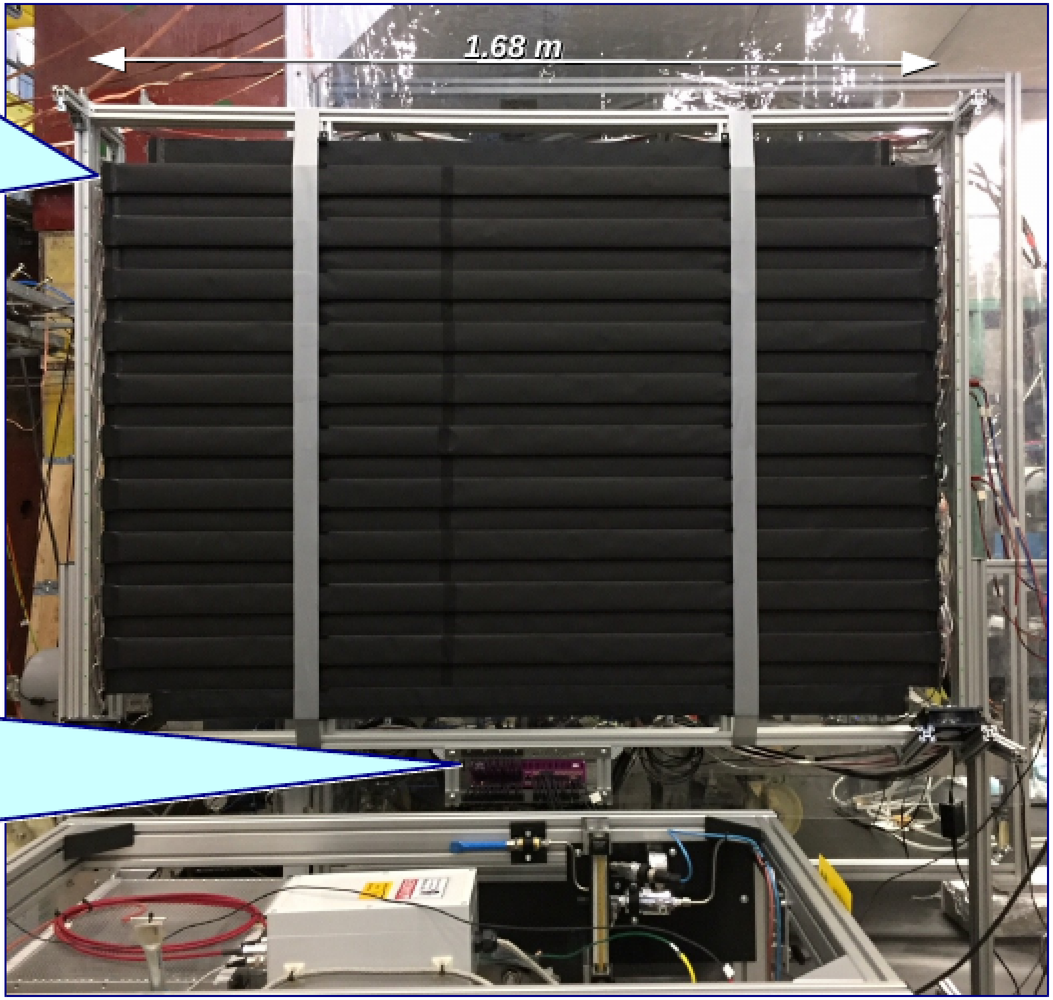
Large TOF prototype in testbeam

Readout by SiPM-arrays

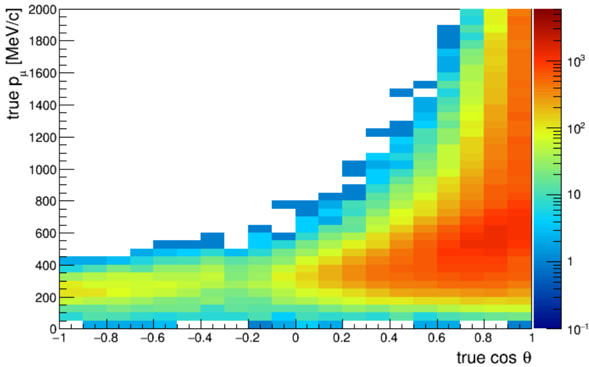
64ch SAMPIC module

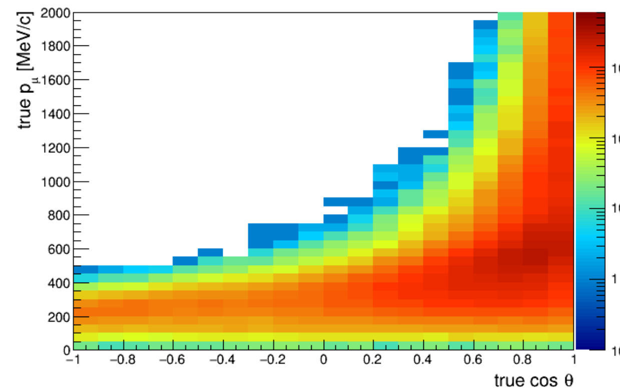


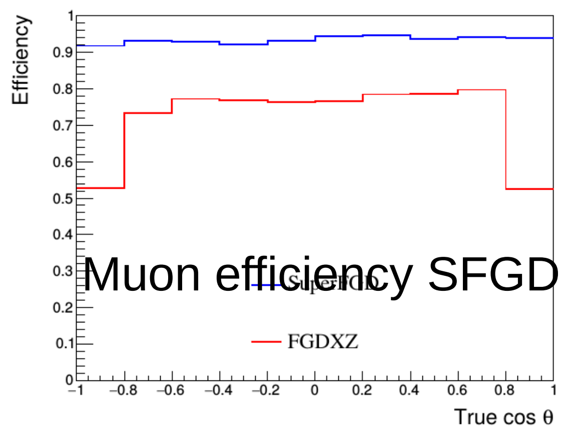
Testbeam Aug 15 – Sep 19, East hall T10 of CERN PS

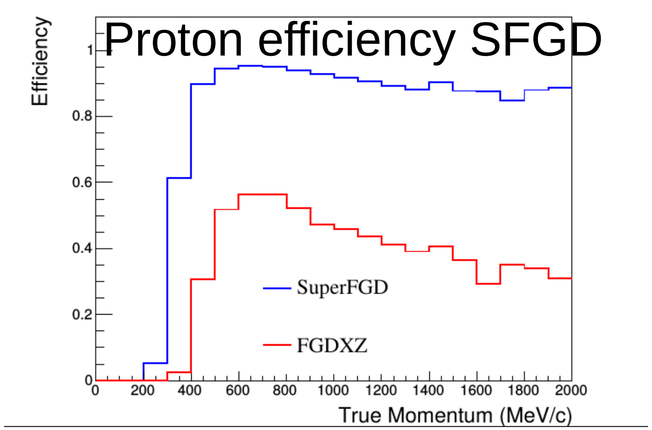


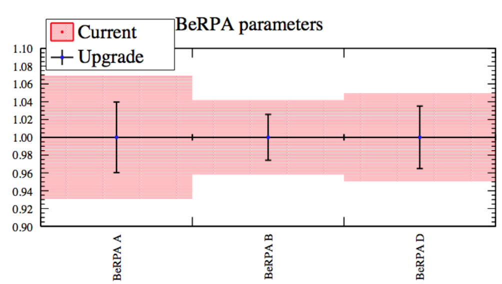
T2K ND280 Upgrade: improvement for acceptance and efficiencies







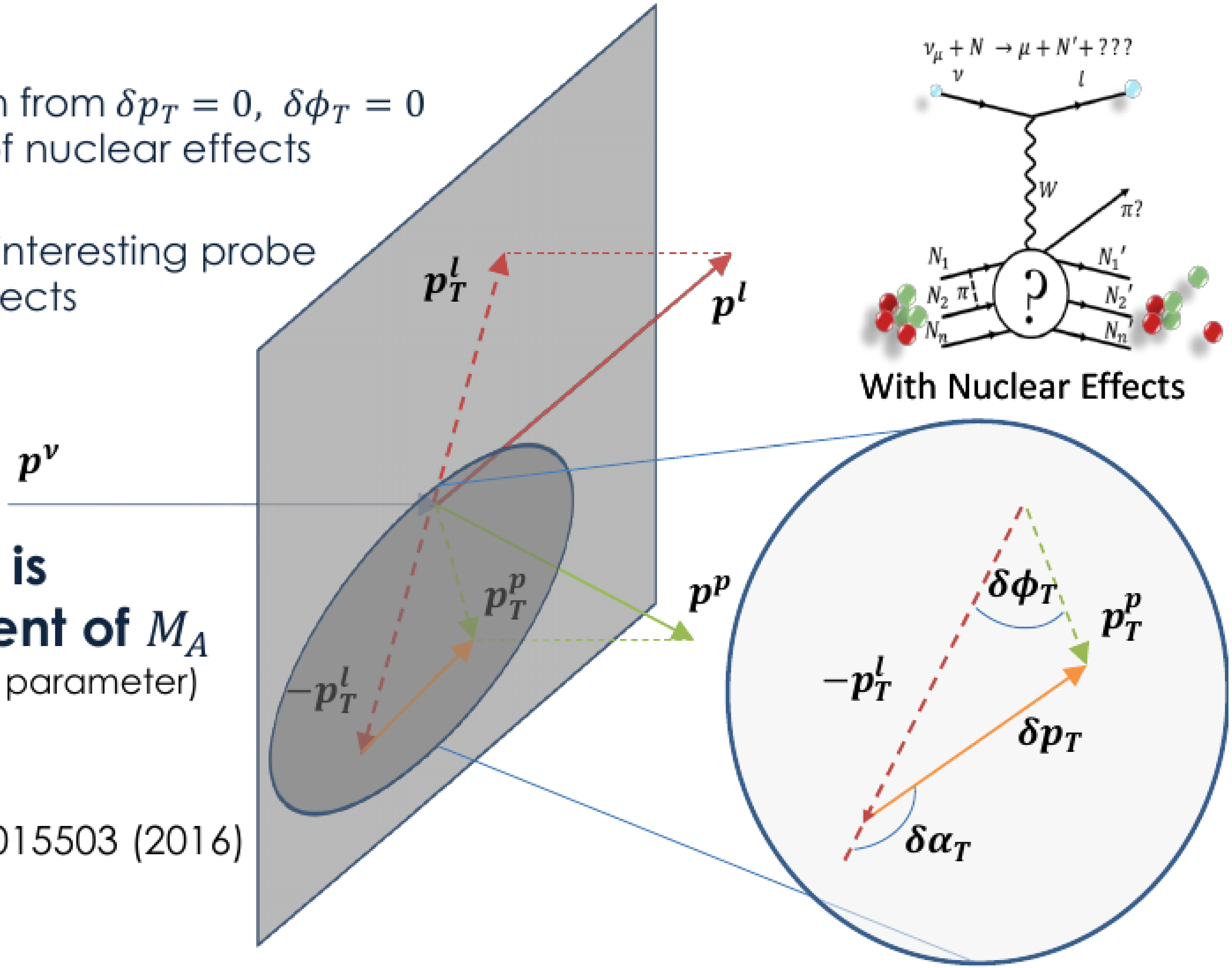




Potential for neutrino interaction model rejection

Single Transverse Variables

- Any deviation from $\delta p_T = 0,\ \delta\phi_T = 0$ is indicative of nuclear effects
- STVs offer an interesting probe of nuclear effects
- **STV shape is independent of M_A** (primary CCQE parameter)

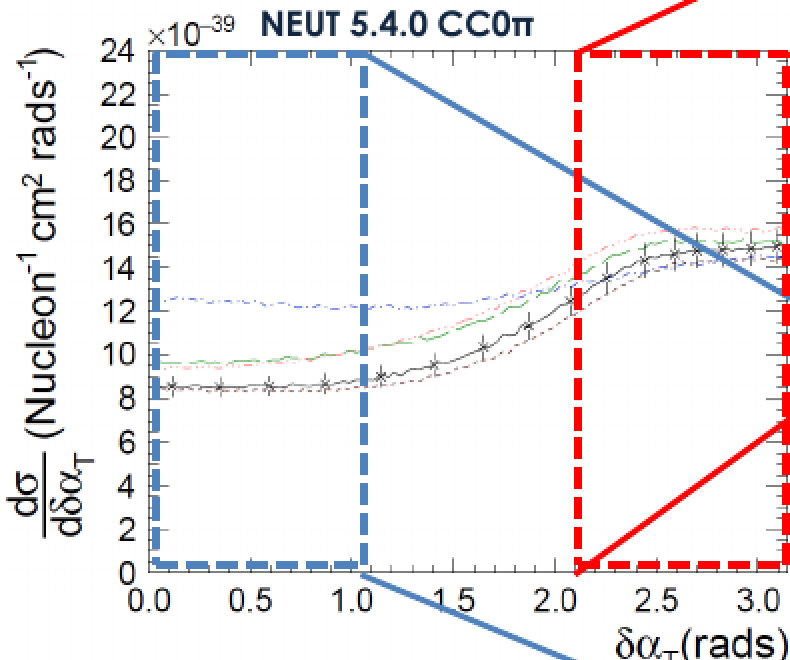


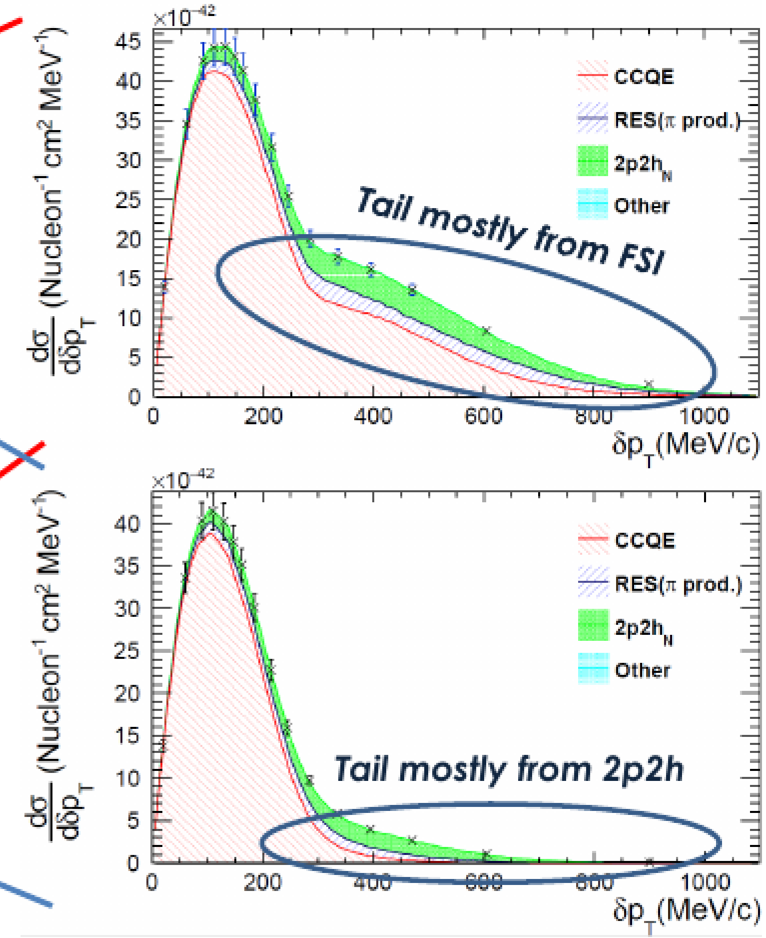
Phys. Rev. C **94**, 015503 (2016)

S. Dolan

Multi-differential STV

Analysis from L. Munteanu



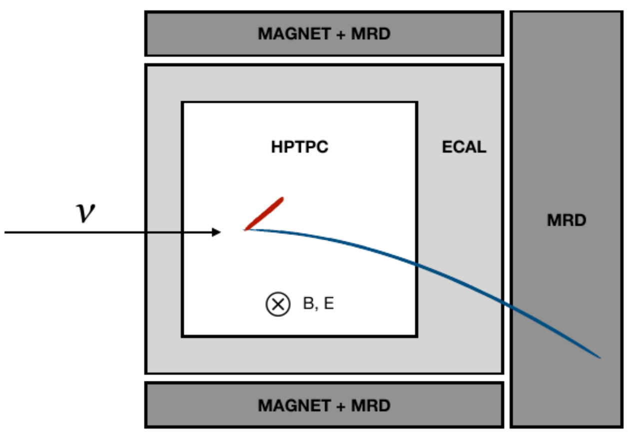


Measuring δp_T in bins of $\delta\alpha_T$ using the SuperFGD may allow excellent separation of 2p2h and FSI

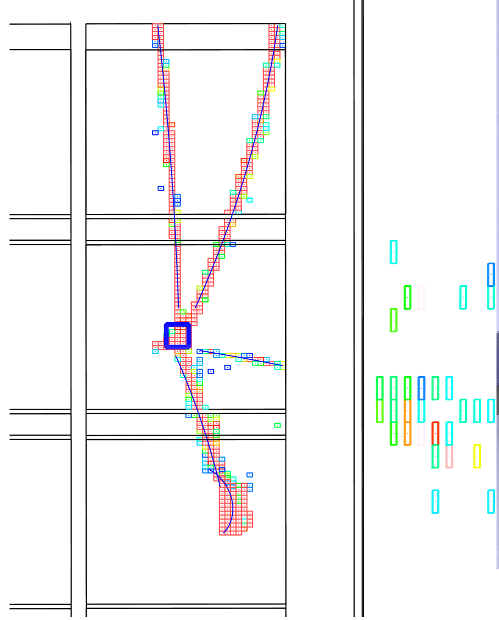
Figure 4: δp_T distributions broken down by interaction modes in different regions of $\delta\alpha_T$. Figures 4c & 4d show the sample which has no FSI processes, whereas figures 4a & 4b show a realistic LFG model.

High Pressure TPC

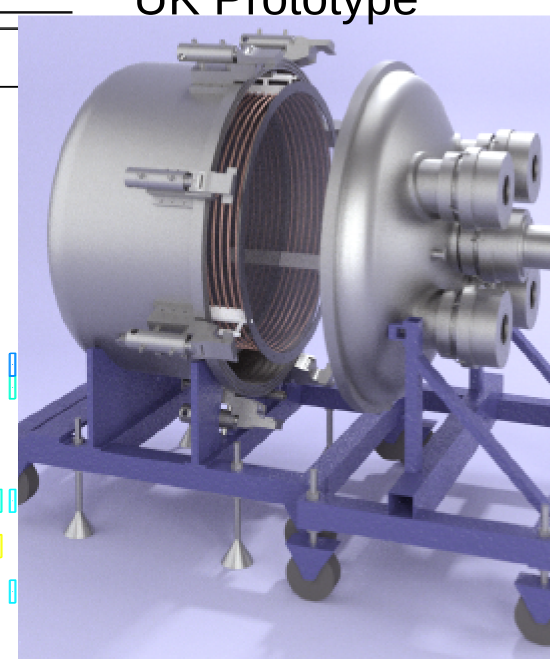
- A high pressure TPC is an attractive option for a near detector
- First considered within the LAGUNA-LBNO study, now for DUNE and Hyper-Kamiokande
- Low mass but unique proton threshold below 100 MeV/c !



T2K interaction on TPC gas



UK Prototype

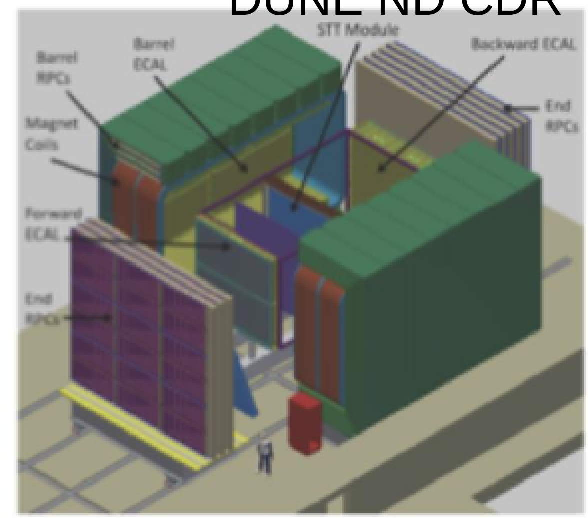


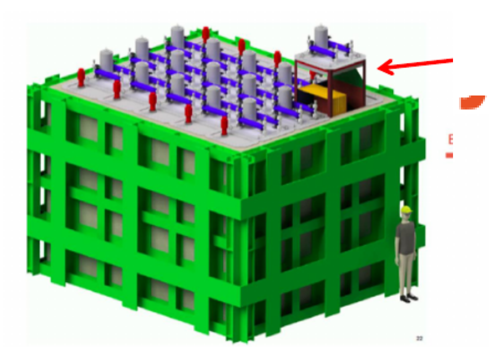
FNAL Prototype

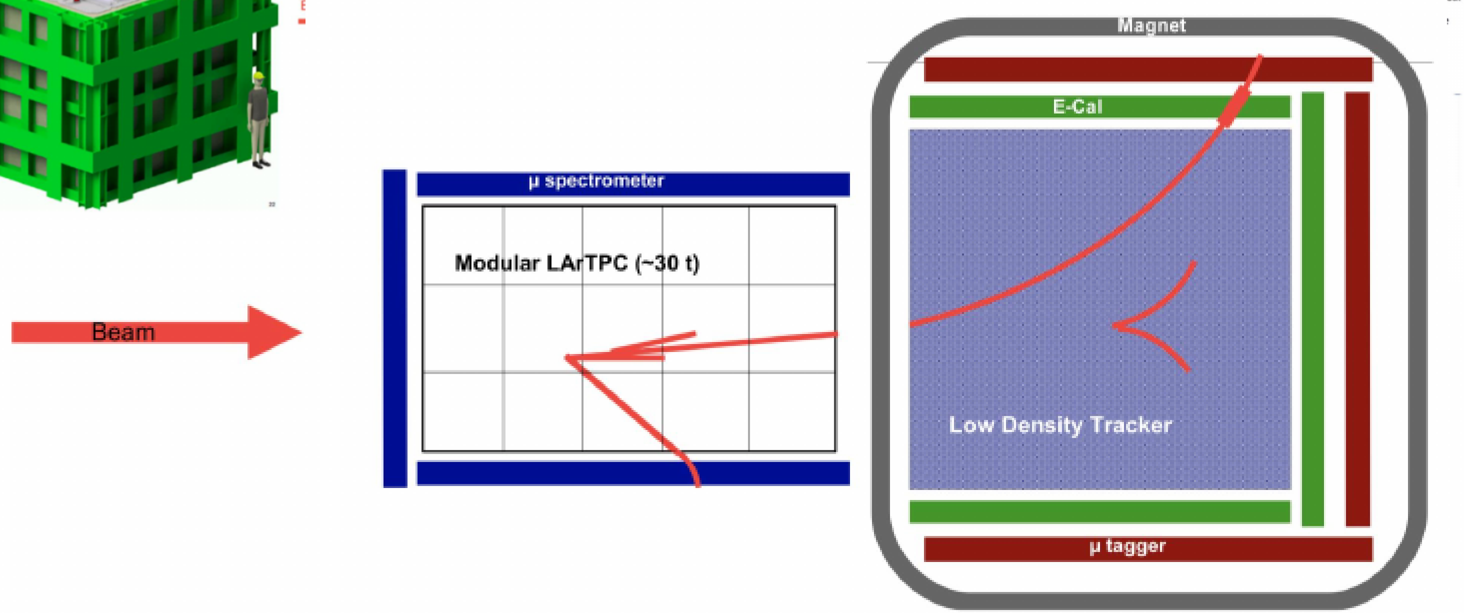
DUNE Near Detector Concept

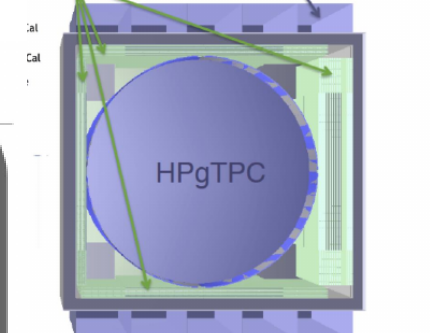
An evolving concept from the 2015 CDR, now considering a hybrid detector that might include:
- a small Liquid Argon TPC (ArgonCube)
- a 3DST (on the line of T2K SuperFGD)
- a large volume magnet
- a low density tracker (possibly a HPTPC or straw tubes)

DUNE ND CDR







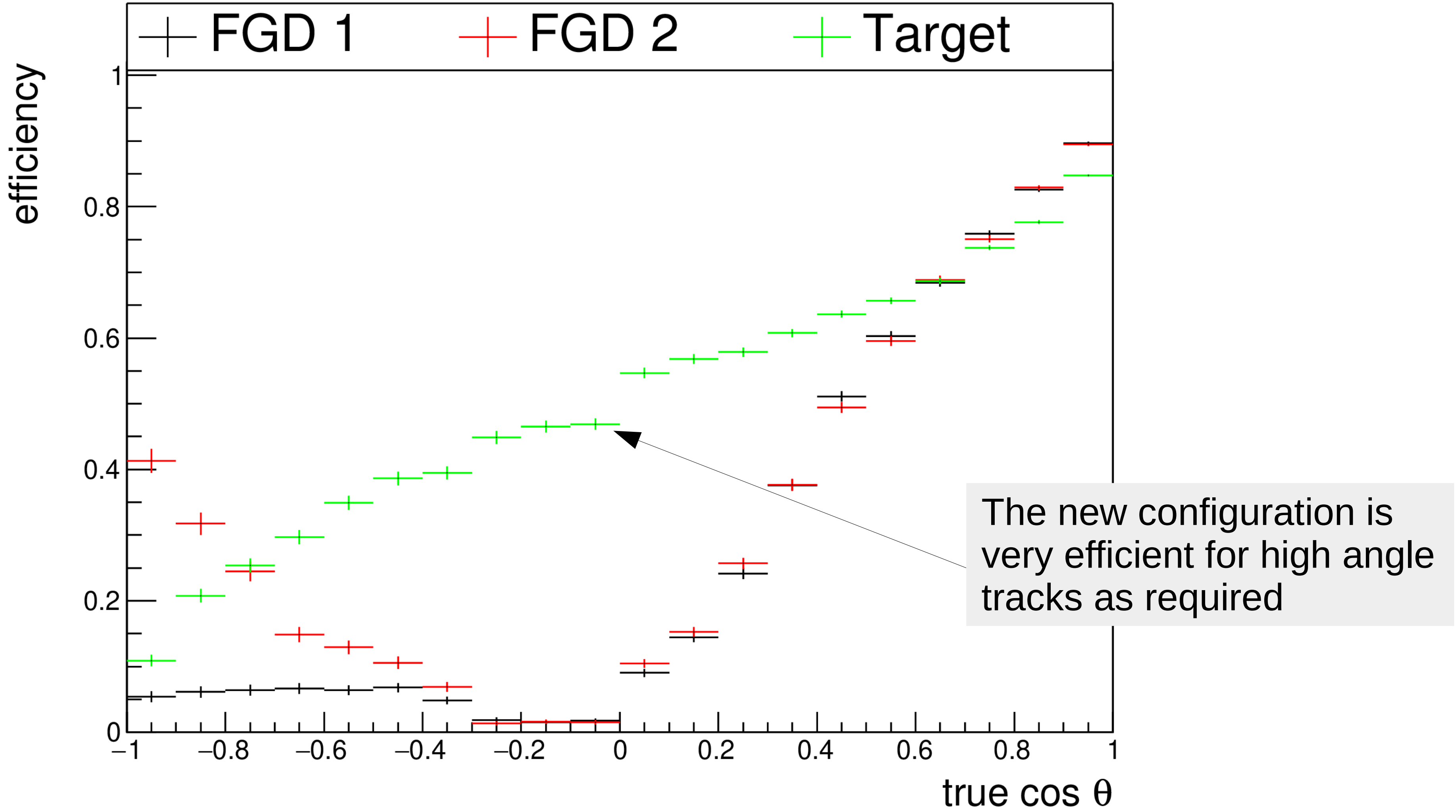


Conclusions

- High precision measurements of neutrino oscillation using long-baseline experiments face several challenges
- Cutting edge near detectors are a mandatory components of these projects
- They enable new measurements to disentangle neutrino cross-sections from other effects
- Strong natural synergy between future projects

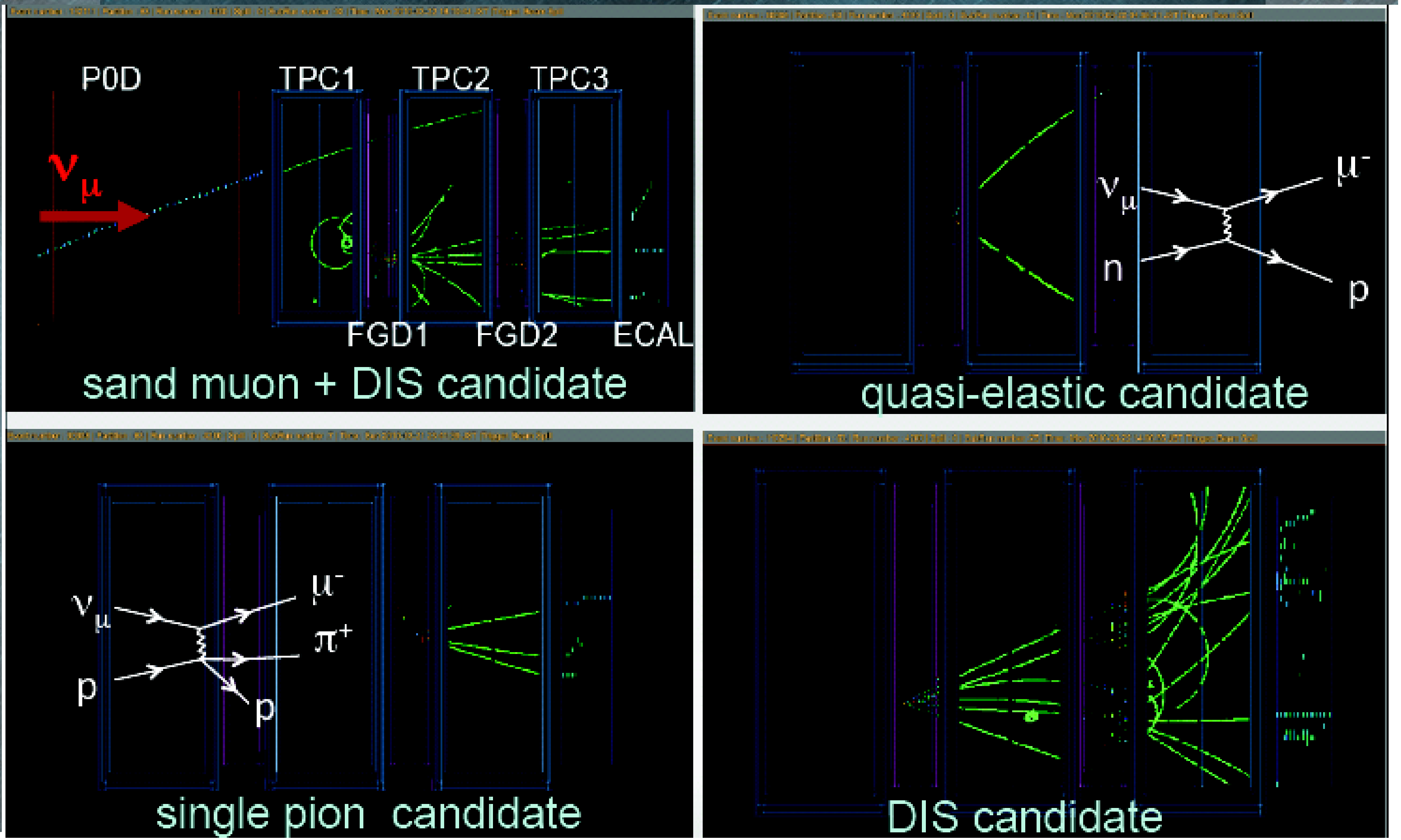
Backup

Muon tracking efficiency



Studies with full GEANT4 simulation

Neutrino interactions in ND280



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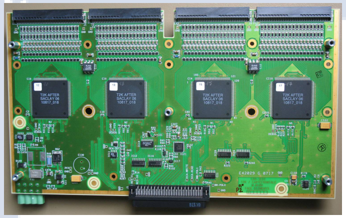
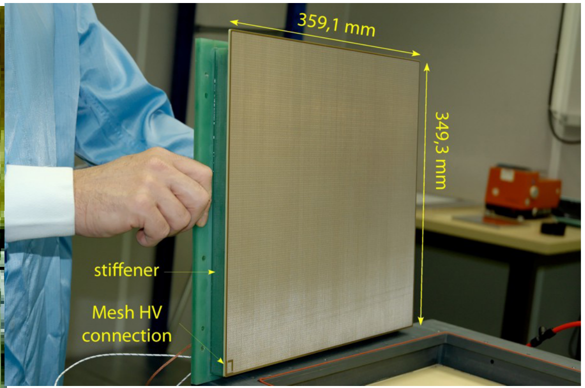
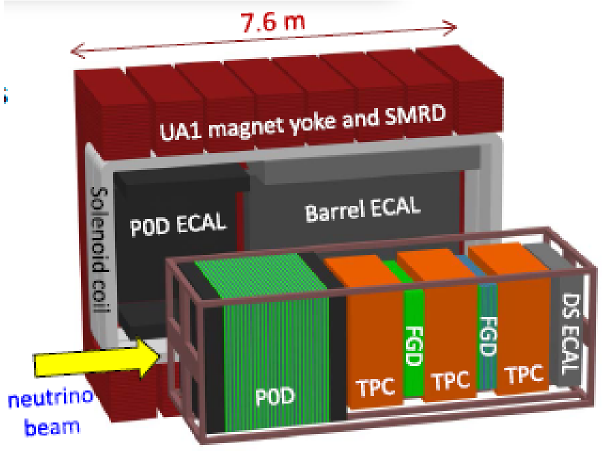
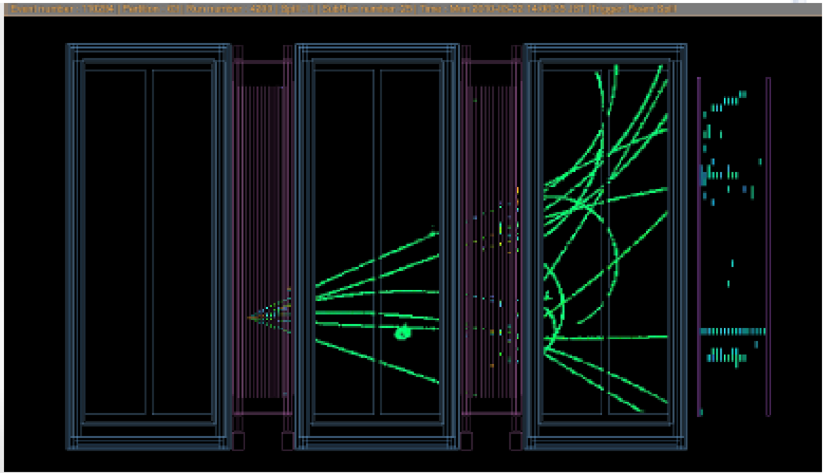


The T2K near detector TPC



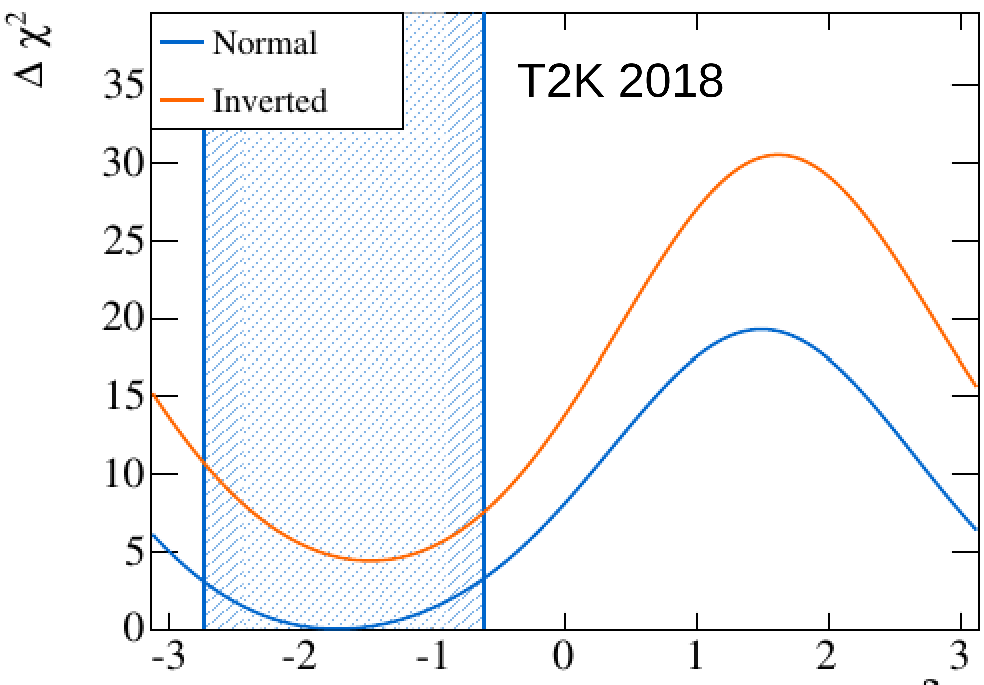


- Three large TPC for the T2K near detector
- The first large TPC using MPGD
- ~9 m**2 equipped with bulk Micromegas detectors
- Playing a key role in the study of the neutrino flux and interactions (charge, momentum and dE/dx PID)
- Space resolution : 0.6 mm
- Momentum res. 9% at 1 GeV
- dE/dx: 7.8 % (MIP)

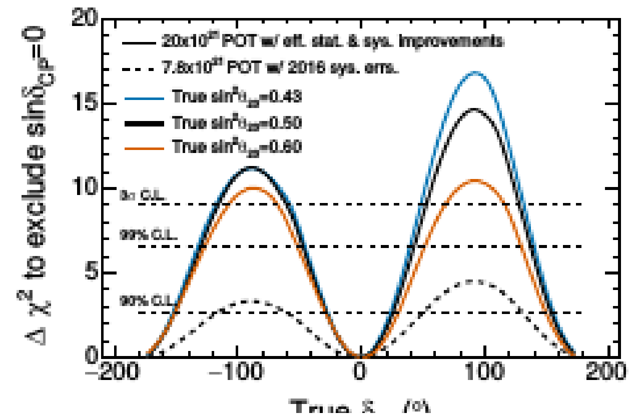


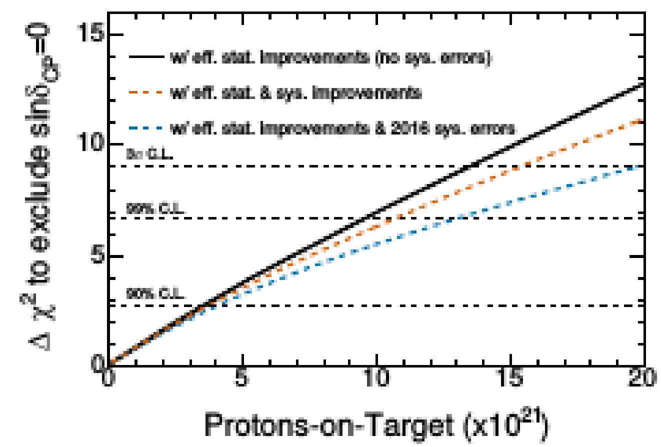
72 Micromegas and 120k channels functioning flawlessly since 2009 (dead channels 144/124272)

T2K: CP sensitivity



	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	Data
FHC 1Rμ	268.45	268.16	268.42	268.80	243
FHC 1Re	73.82	61.64	50.09	63.45	75
RHC 1Rμ	95.49	95.27	95.49	95.73	102
RHC 1Re	11.76	13.42	14.91	13.10	9
FHC 1R ν_e CC1π^+	6.928	6.00	4.86	5.89	15





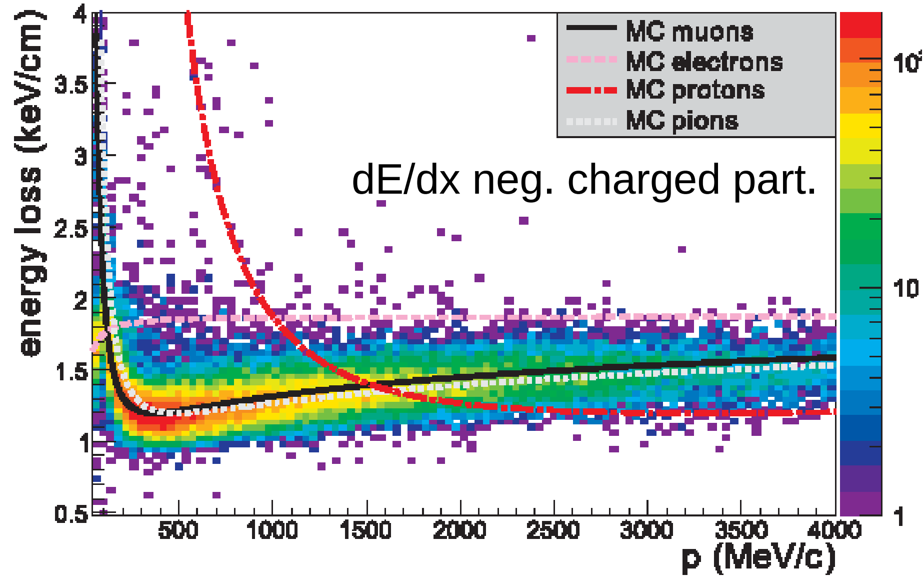
T2K-II: continue to take data until 2026 with Main Ring upgrade and other improvements

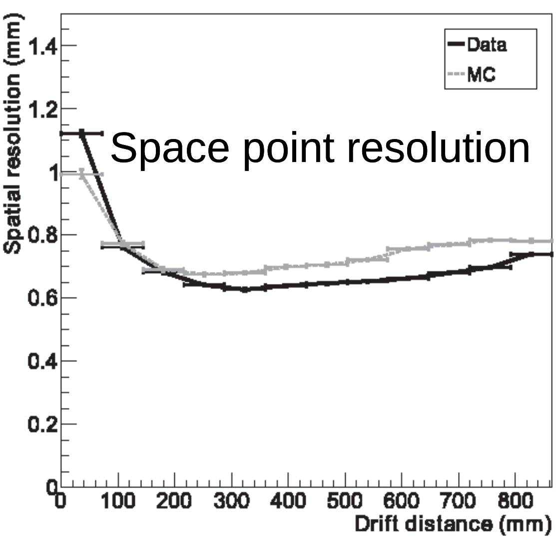
POT: 3 10^{21} (2018) → 20 10^{21}(2026). Possibility to reach 3 sigma for 40% of the CP phase space

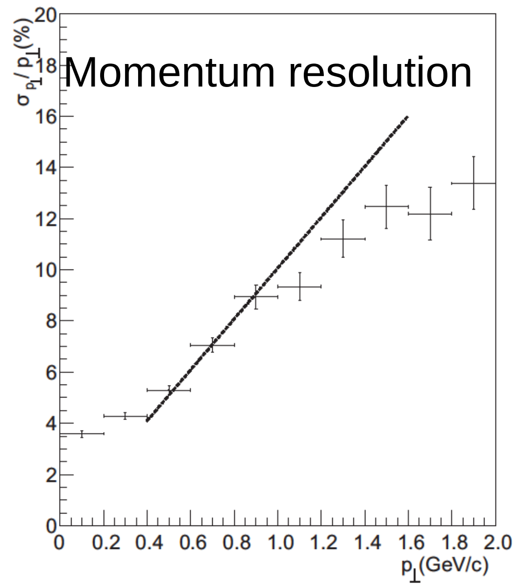
N(nue): 75 (2018) → ~468 (2026)

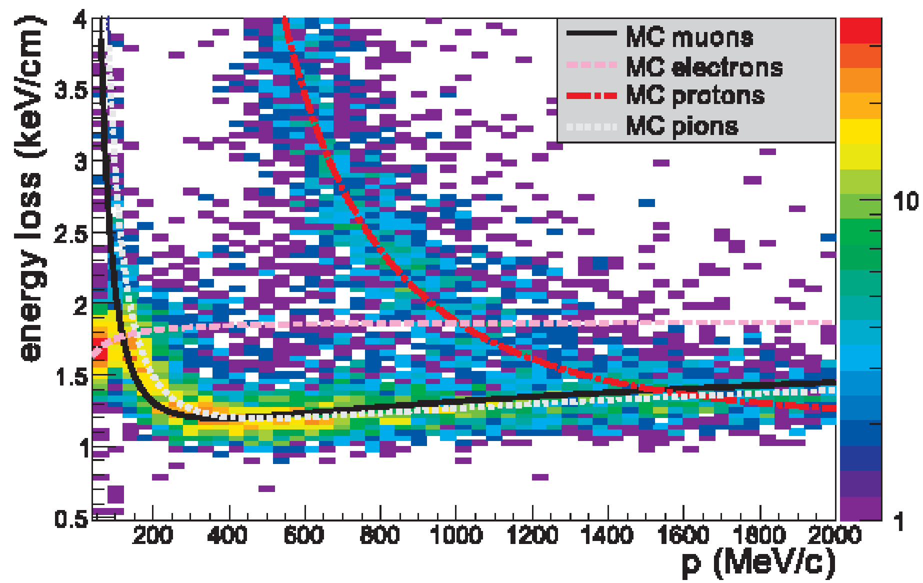
TPC performances

- Three large TPC for the T2K near detector
- The first large TPC using MPGD
- ~9 m**2 equipped with bulk Micromegas detect
- Playing a key role in the study of the neutrino fl interactions (charge, momentum and dE/dx PID
- Space resolution : 0.6 mm
- Momentum res. 9% at 1 GeV
- dE/dx: 7.8 % (MIP)









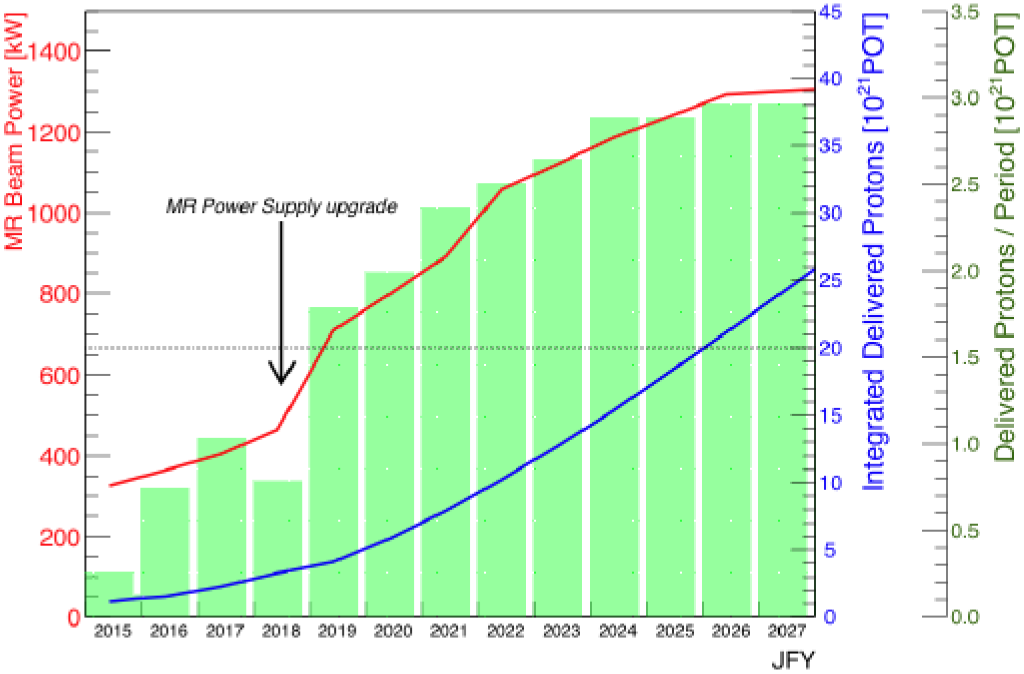
dE/dx pos. charged part.

arxiv:1607.08004

T2K phase2 target statistics and systematics

J-PARC MR expected performance
and T2K-2 POT accumulation scenario

- Target Beam power 1.3 MW
- 20E21 POT by 2025~2026
- Increase effective statistics by up to 50%
  - horn current, SK fiducial volume, new event samples
- Reduce systematic error ~6% → ~4%



Expected number of events (1:1 ν: $\bar{\nu}$ running case)

ν_e sample : 468 evts ± 20% change depending on δ_{CP}

$\bar{\nu}_e$ sample : 134 evts ± 13% change depending on δ_{CP}

ND280 within B1