Neutrino Cross Section and Interaction Rate Measurements involving Charged Current ν_e and Neutral Current π^0 with the T2K Near Detector

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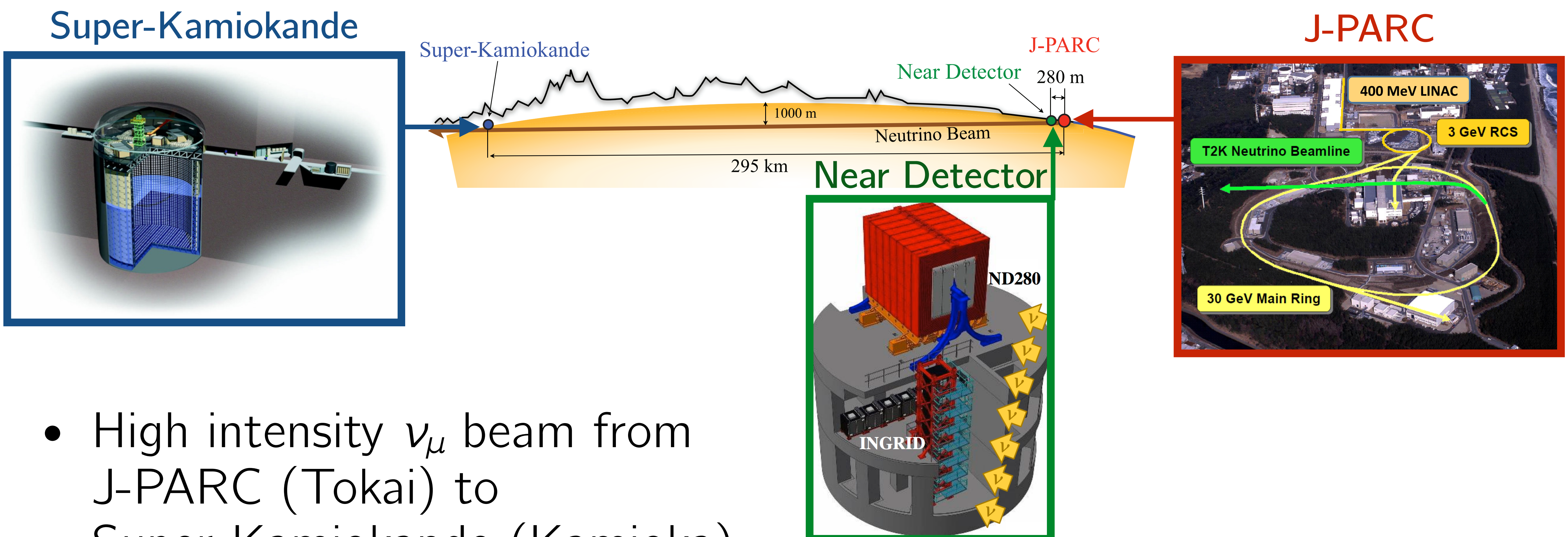
on behalf of T2K Collaboration

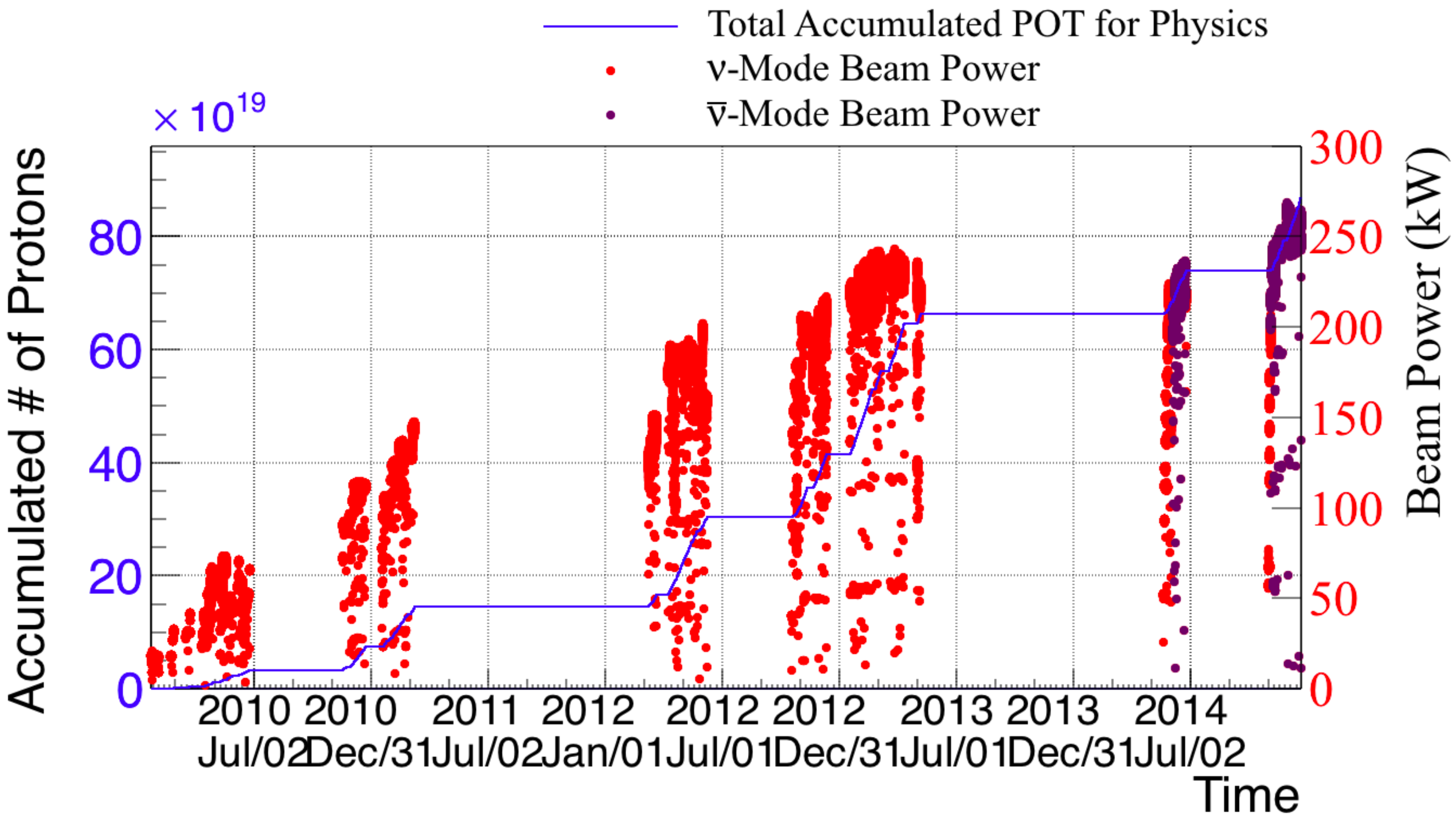
February 21, 2015
Lake Louise Winter Institute 2015

T2K Experiment



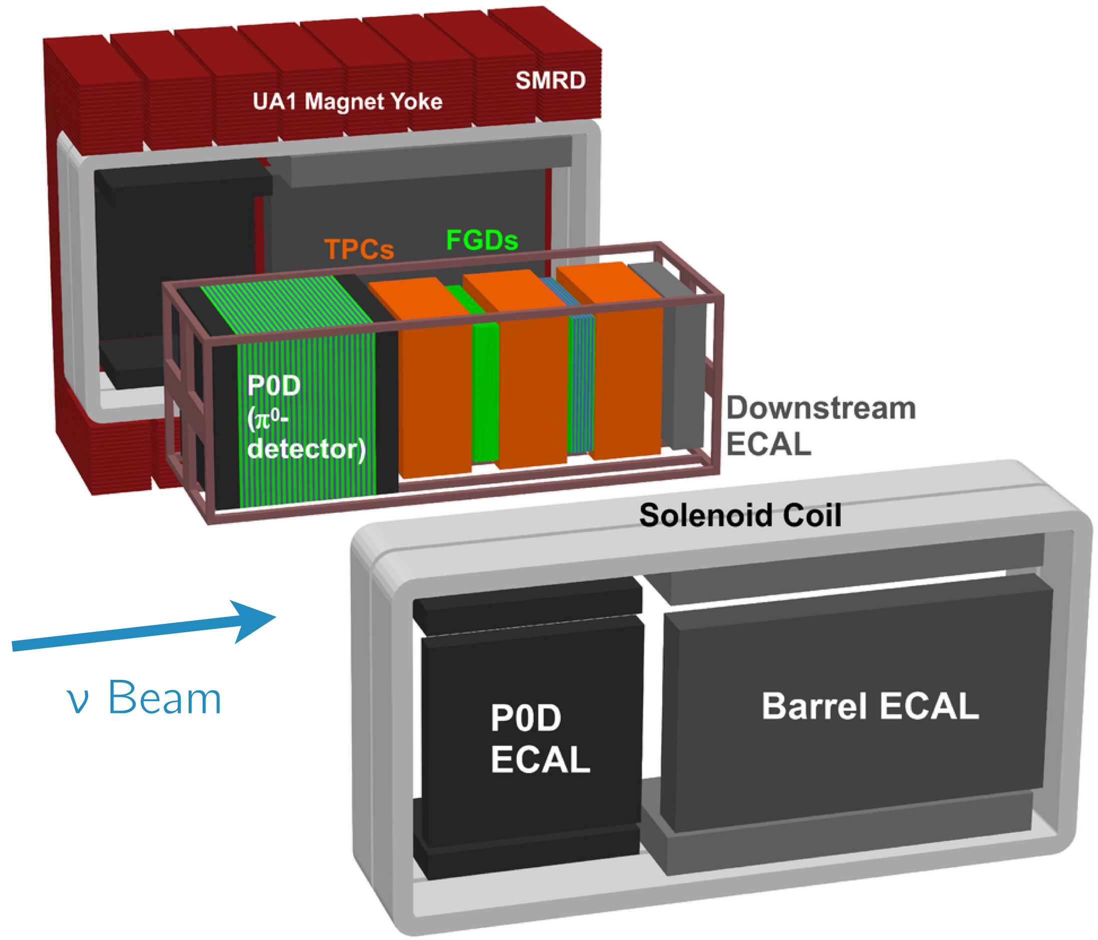
- High intensity ν_μ beam from J-PARC (Tokai) to Super-Kamiokande (Kamioka)
- Neutrinos measured by near detectors (INGRID, ND280) and a far detector (Super-K)
- Precise measurement of ν_e appearance and ν_μ disappearance
- Currently running in anti-neutrino mode

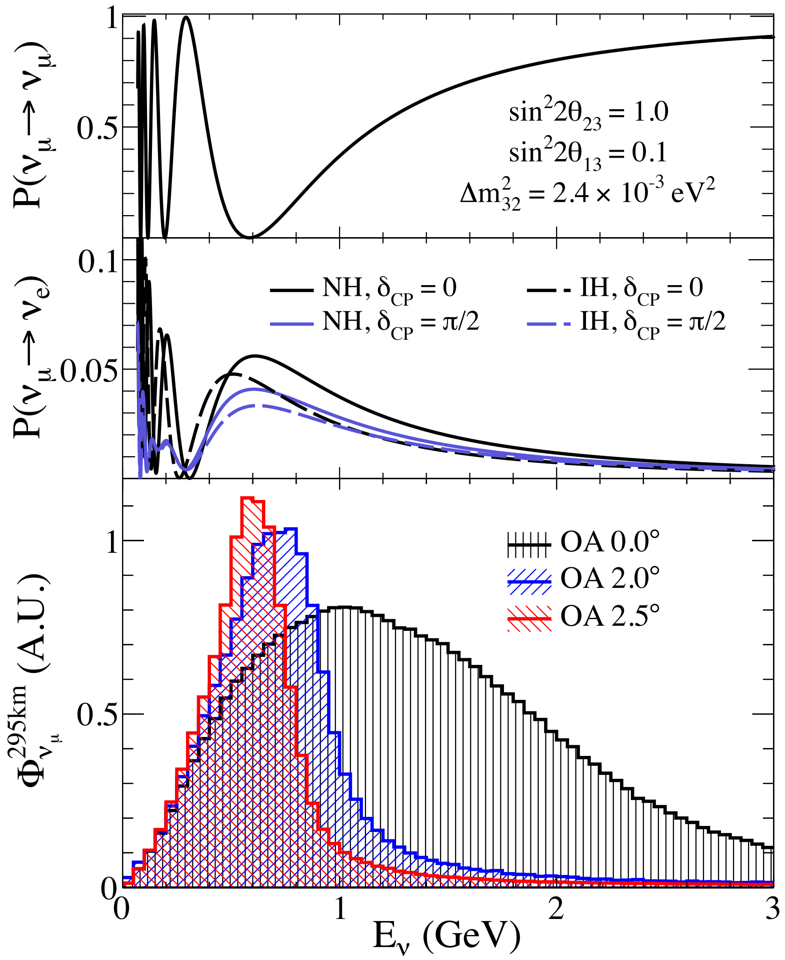
T2K Data



- Maximum stable beam power recorded ~275kW recently
- Beam delivery
  - 8.7×10^{20} protons on target so far (~10% of approved P.O.T)
    - 6.9×10^{20} protons on target in ν-mode
    - 1.8×10^{20} protons on target in $\bar{\nu}$-mode

ND280 Off-axis Detector





- Located at 2.5 degrees off-axis
- Off-axis gives 'narrow band' beam peak at 1st oscillation maximum, E~600MeV
  - Higher statistics of oscillated neutrinos
  - Reduced contamination from non-oscillated high energy neutrinos

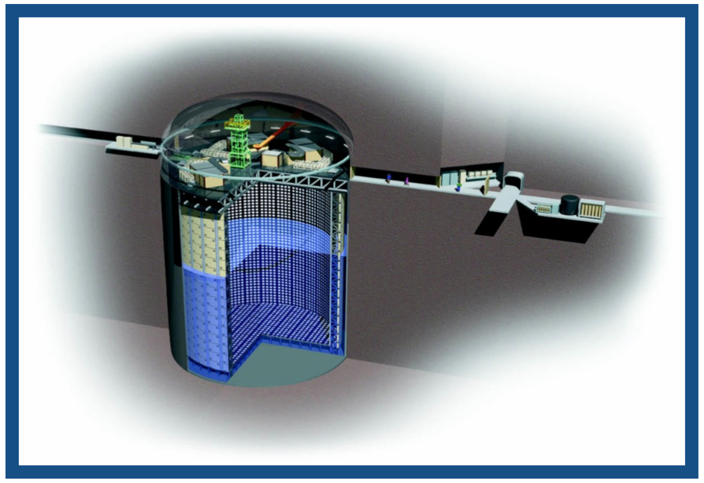
Motivation for $CC\nu_e$ & $NC\pi^0$ analyses in ND280

- The largest systematic uncertainty in T2K oscillation analysis comes from neutrino cross section error
- δ_{cp} is searched through ν_e appearance channel
  - Better cross section measurements on C & H_2O are needed
  - Measurements only on C in ND280 were used in 2013 T2K oscillation analysis

<The uncertainty on the predicted number of ν_e/ν_μ events>

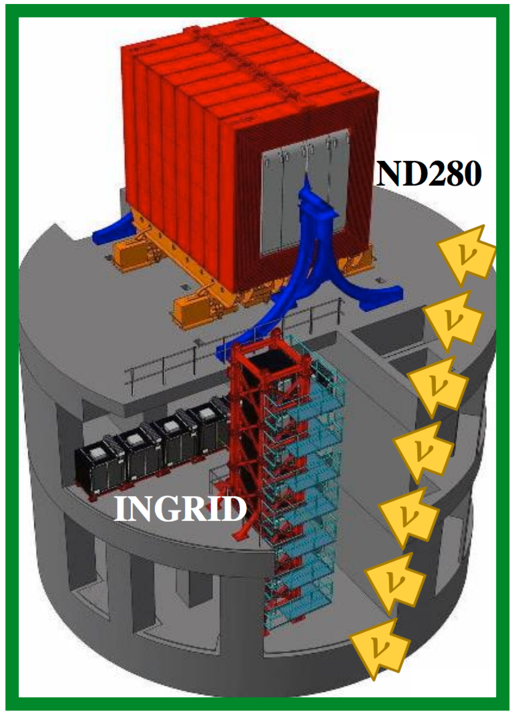
Error source [%]	ν_μ sample	ν_e sample
Beam flux and near detector	2.74	3.15
(w/o ND280 constraint)	(21.75)	(26.04)
Uncorrelated ν interaction	5.00	4.69
Far detector	4.03	2.72
FSI+SI+PN	2.98	2.44
Total	7.65	6.75

Super-Kamiokande



H_2O Target

Near Detector



C, H_2O Target

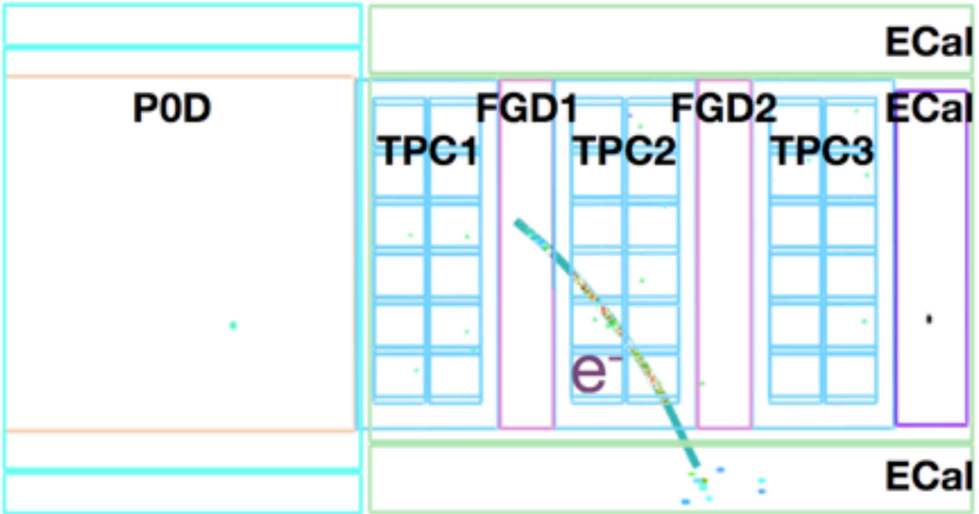
Inclusive ν_e Charged Current Cross Section on Carbon

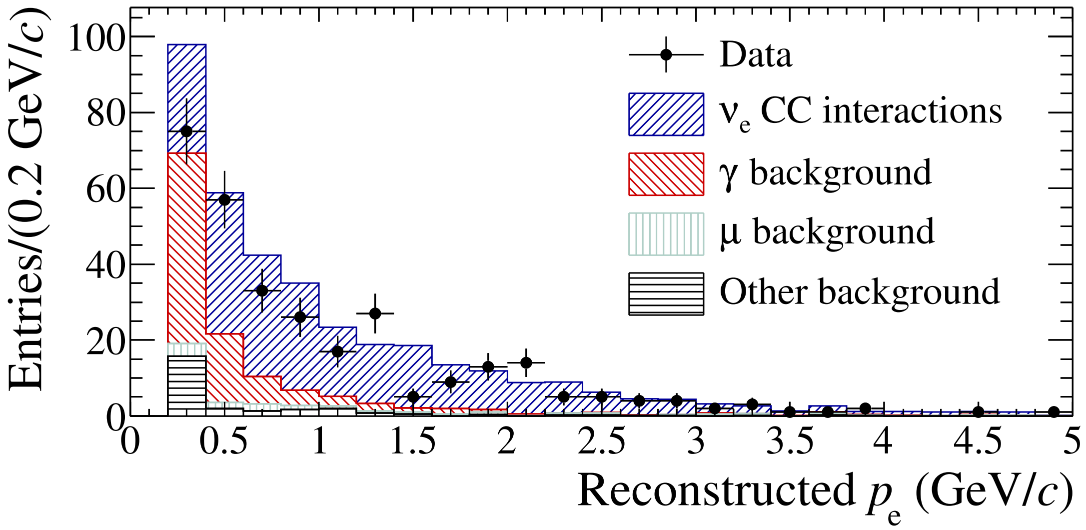
Inclusive ν_e Charged Current Cross Section on Carbon

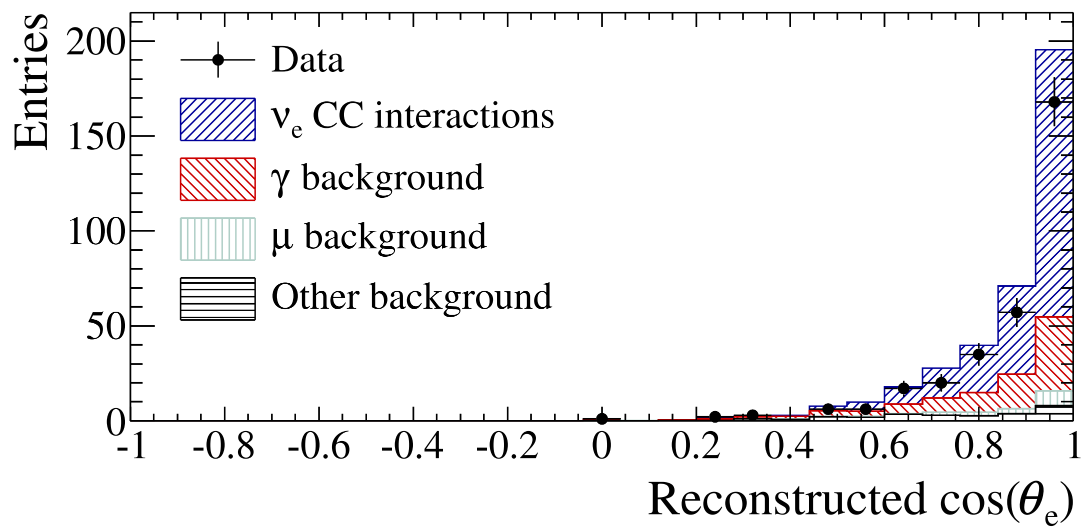
- Select e^- track starting in FGD

- Use TPC & ECal PID to reject muons

- Main background comes from photon conversions
  - Constrain gamma background (from π^0) with e^+e^- sample



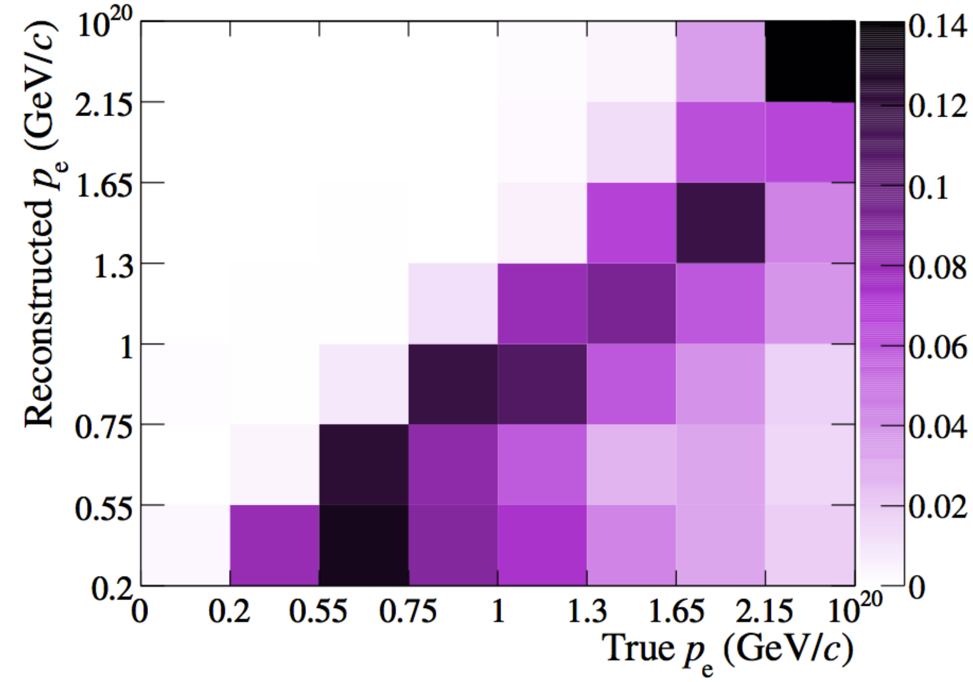


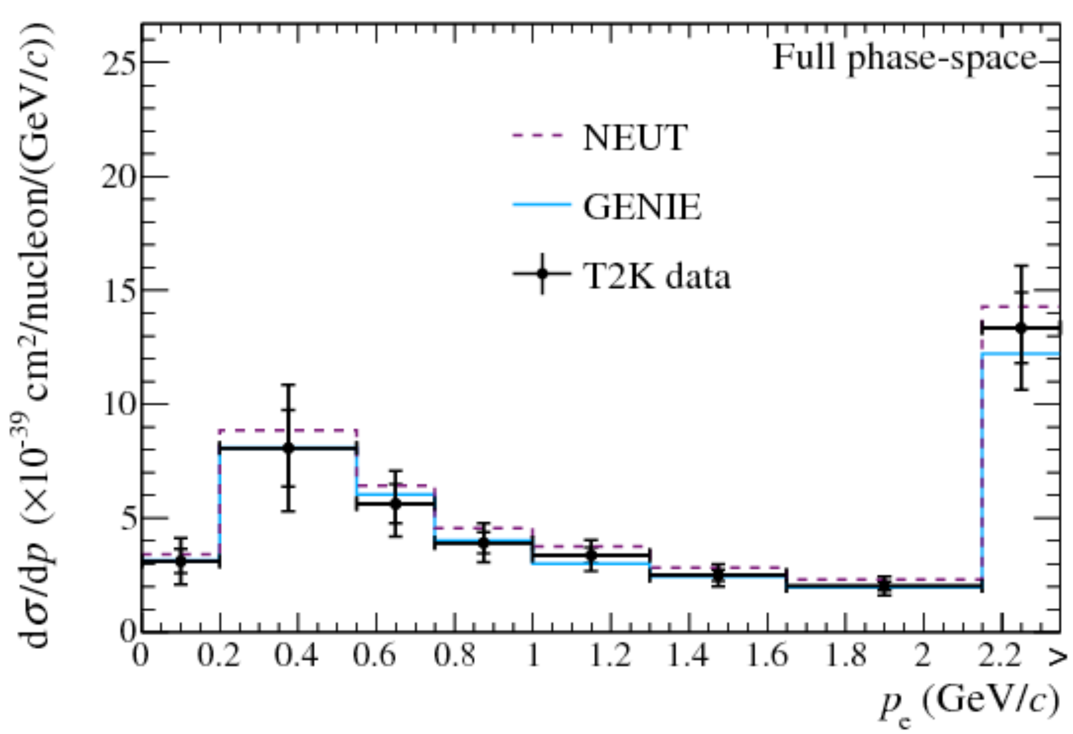


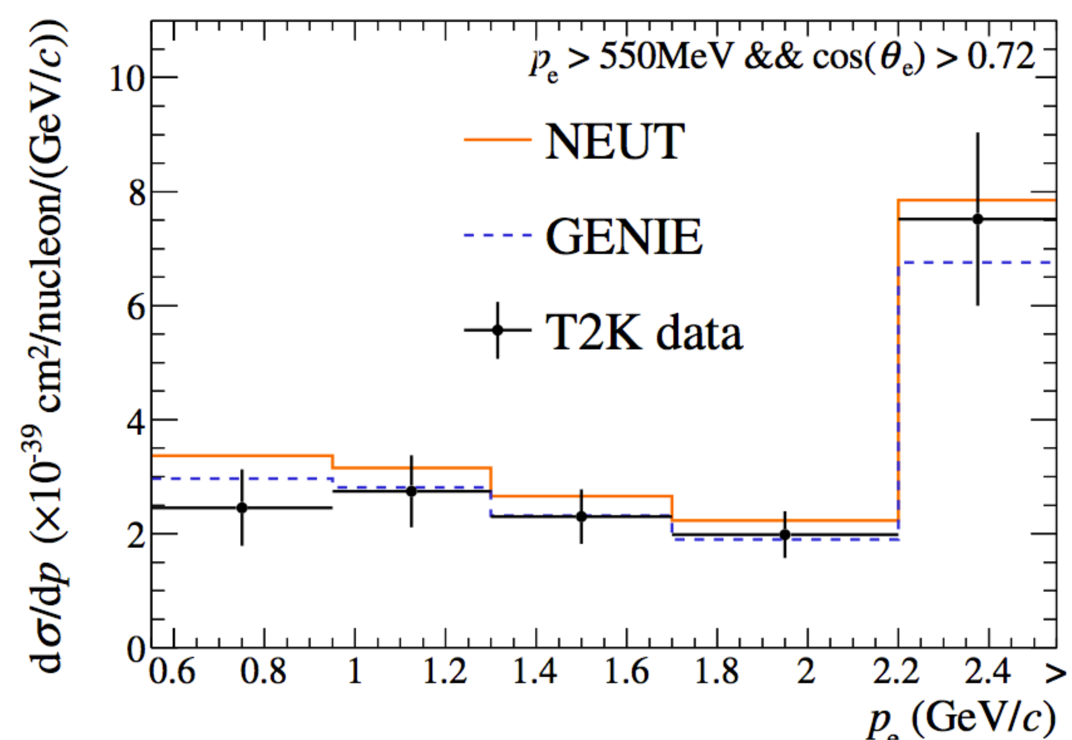
K.Abe *et al.*, Phys. Rev. Lett 113, 241803 (2014)

Inclusive ν_e Charged Current Cross Section on Carbon

- Use Bayesian unfolding
  - Large smearing in momentum due to Bremsstrahlung
- Results with both full phase space and restricted phase space are presented
  - Reduces model dependence







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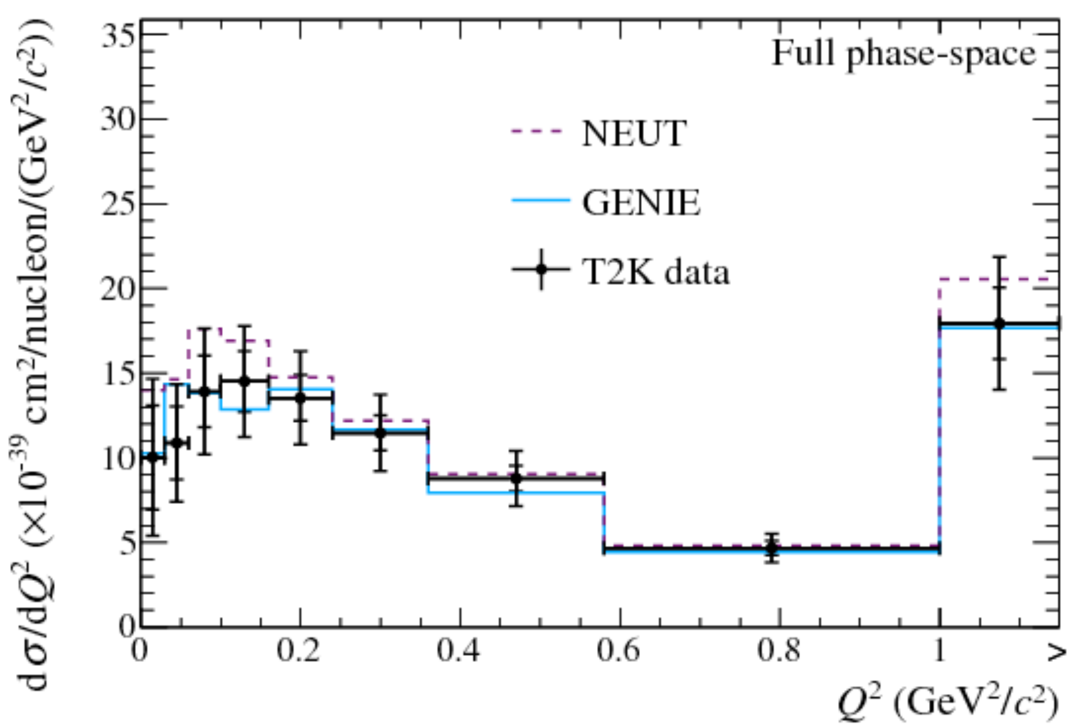
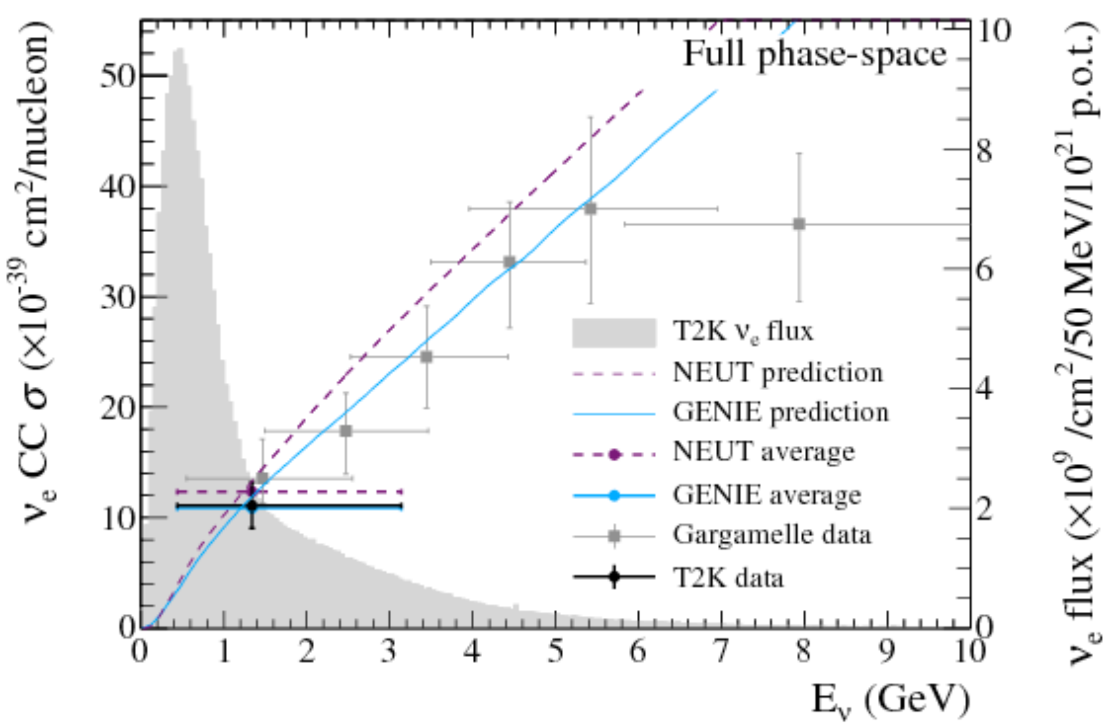
Inclusive ν_e Charged Current Cross Section on Carbon





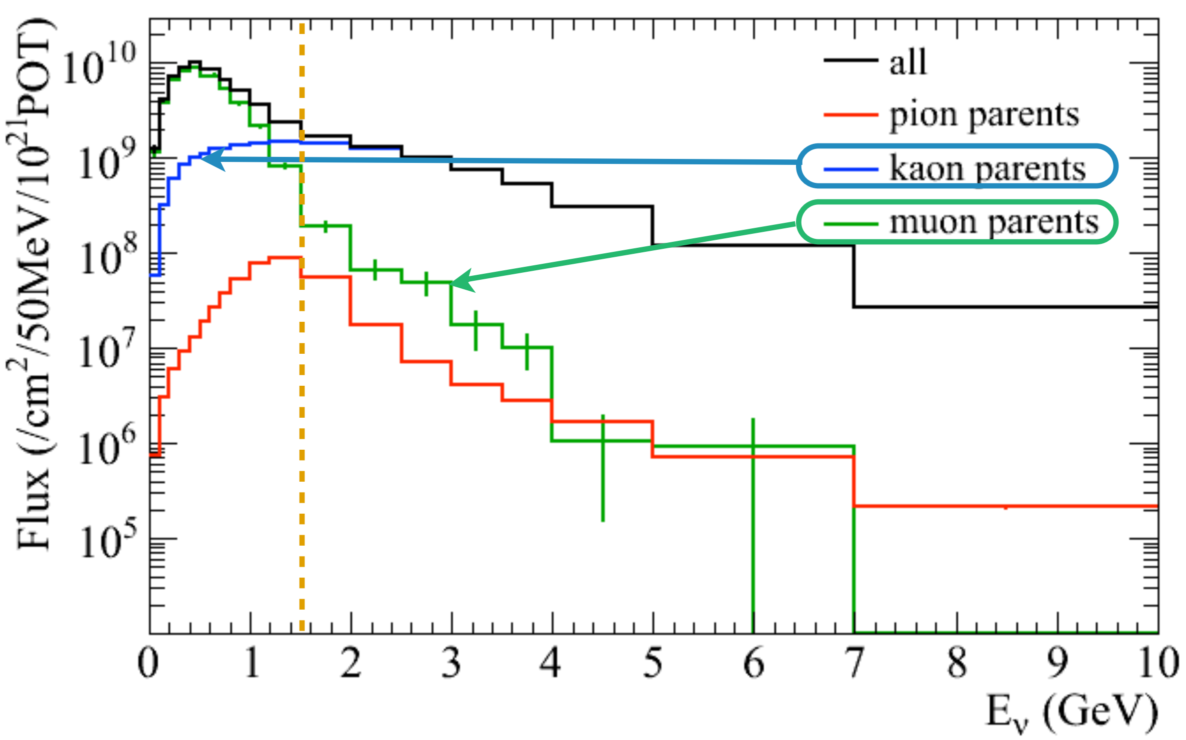
K.Abe *et al.*, Phys. Rev. Lett 113, 241803 (2014)

- Largest uncertainties are:
  - Flux (13.6%)
  - Statistics (8.6%)
  - Detector (8.4%)
- Total flux averaged cross-section:
  - $\langle\sigma\rangle_\varphi$ = 1.11 ± 0.09 (stat) ± 0.18 (syst) x 10^{-38} cm^2/nucleon
- First measurement of inclusive ν_e cross section at the GeV scale
  - Only Gargamelle experiment measured the total ν_e CC inclusive cross-section (1978)
  - Possible because of excellent detector with magnetic field
  - Published in Phys. Rev. Lett 113, 241803 (2014)

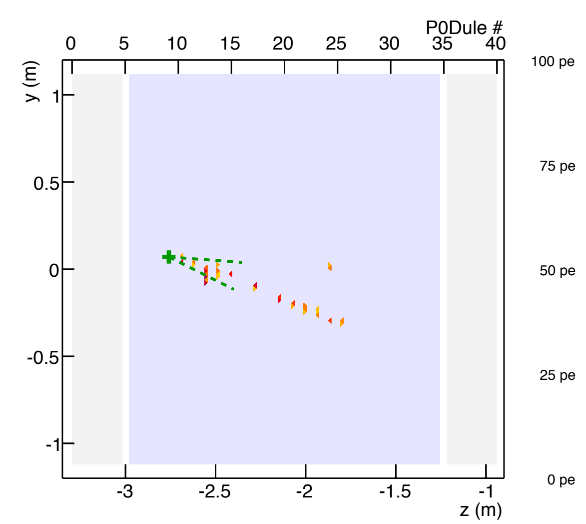
Charged Current ν_e Interaction Rate on Water

Charged Current ν_e Interaction Rate on Water

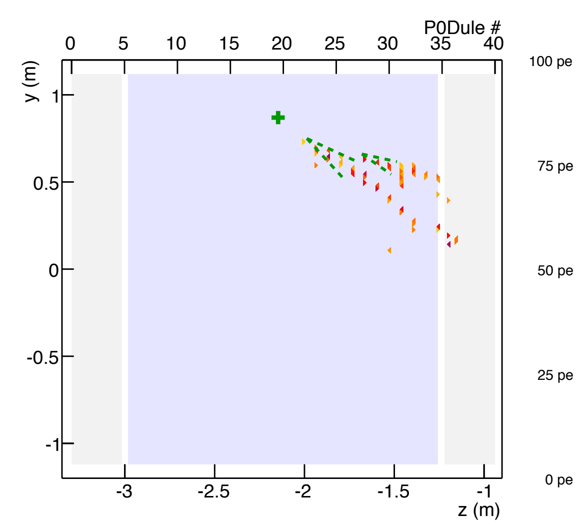
- With water-in and water-out configurations, P0D is capable of on-water measurement
- The *largest* background to the ν_e appearance at Super-K is the intrinsic ν_e beam contamination
  - $E_\nu > 1.5$GeV is the region where the ν_e contamination is predominantly from K decay
- Use width based P0D PID to remove muon and neutral pion backgrounds



Total ν_e Flux at ND280 by Parent Type

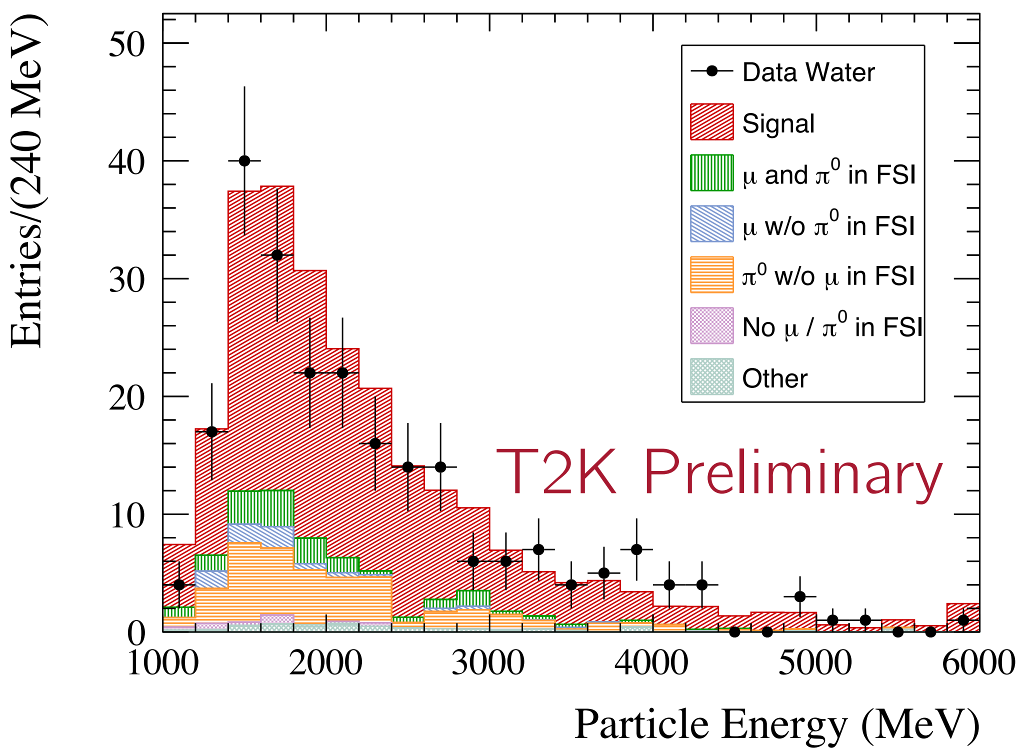


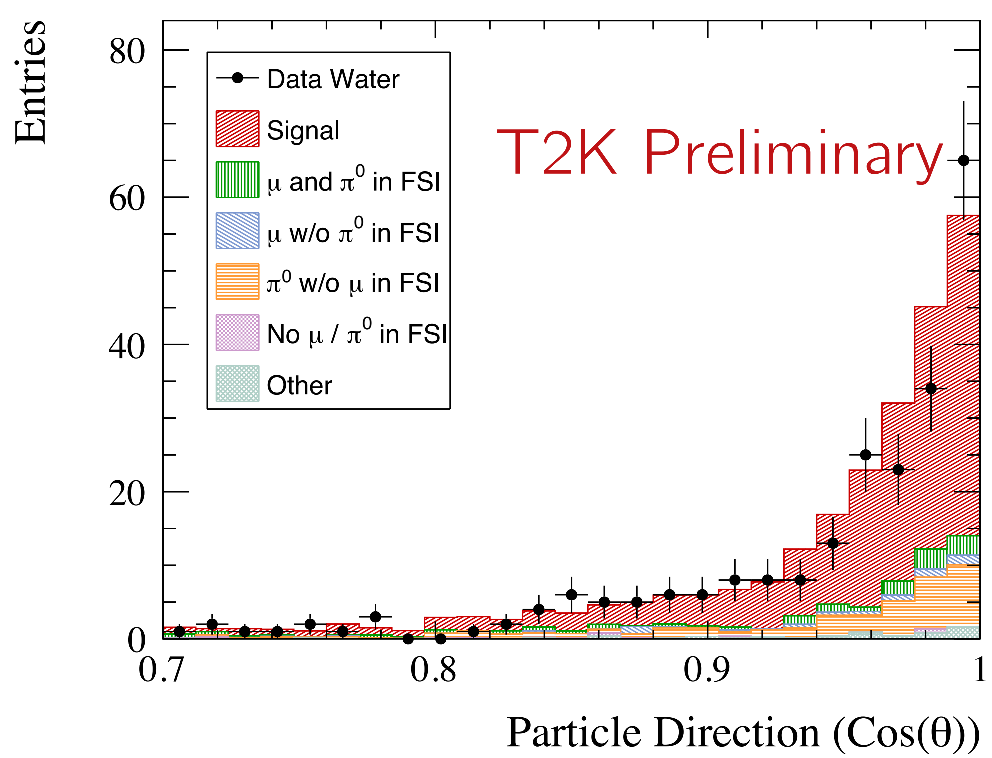
EM Shower Event (Signal)



NC Pi0 Event (Background)

Charged Current ν_e Interaction Rate on Water



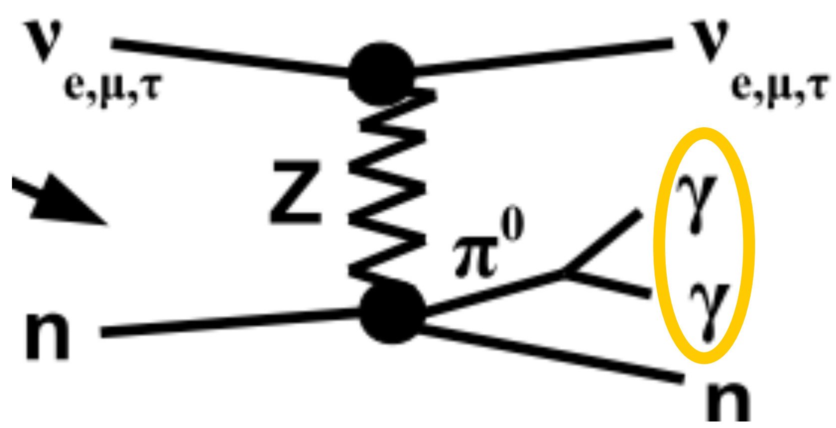


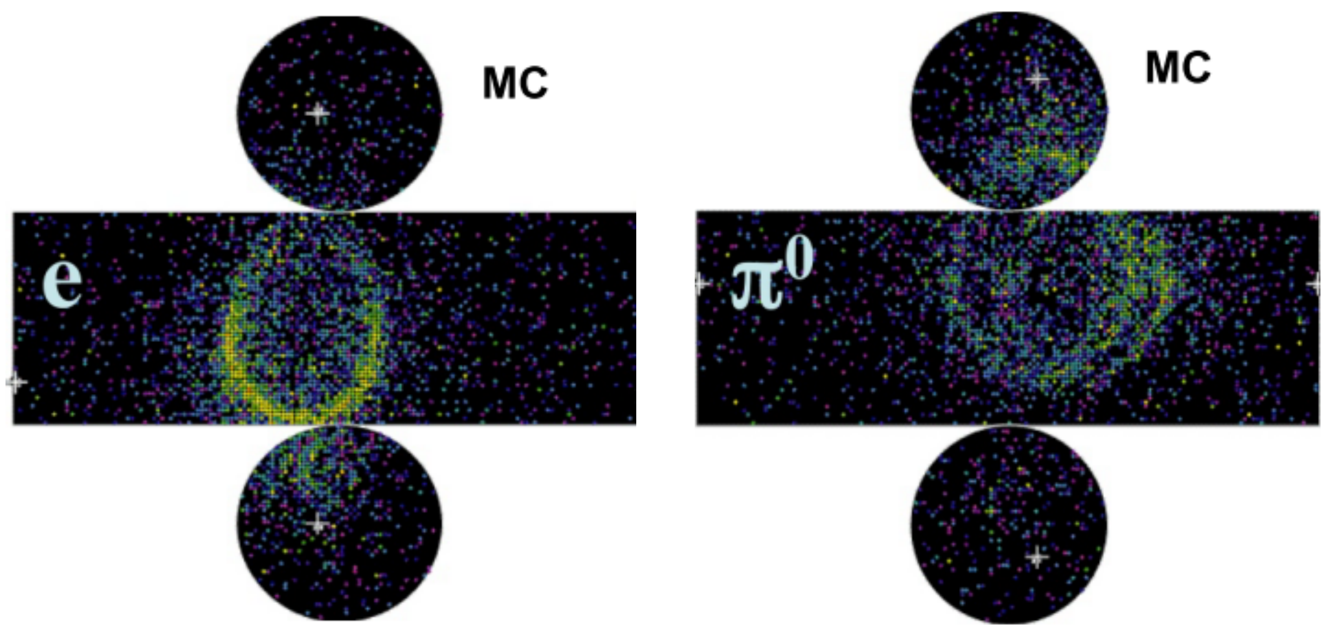
- Data/MC ratio of on-water is measured to be:
  - $R_{\text{on-water}}$ $= 0.87 \pm 0.33\ (\text{stat.}) \pm 0.21\ (\text{syst.})$
- Largest uncertainties are:
  - Statistics (0.33)
  - Detector - Energy Scale (0.10)
  - Reconstruction - Track PID (0.09)
- First rate measurement of CCν_e interaction on water
- A paper will soon be submitted to Phys. Rev. D.

Neutral Current π^0 Production Rate on Water

Neutral Current π^0 Production Rate on Water

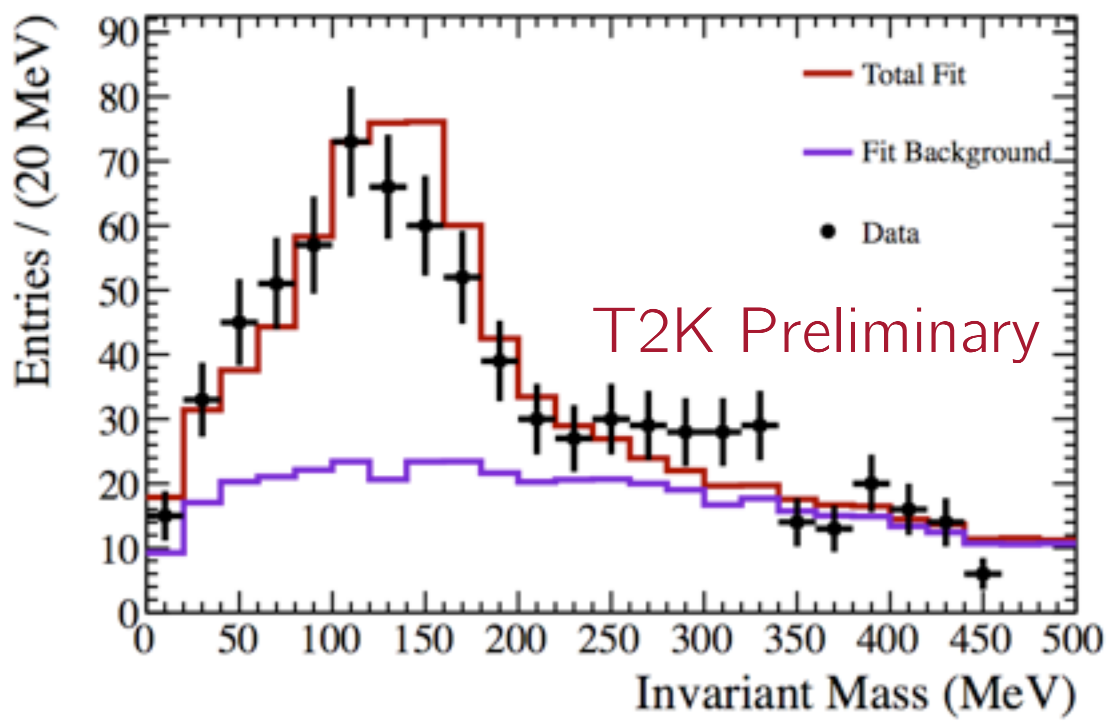
- NC1π^0 constitutes the *second largest* background to the data at Super-K
- Select two reconstructed EM-like objects that are assumed to be the resulting photons of a π^0 decay
- Shower separation cut introduced to get the cleanest reconstruction result



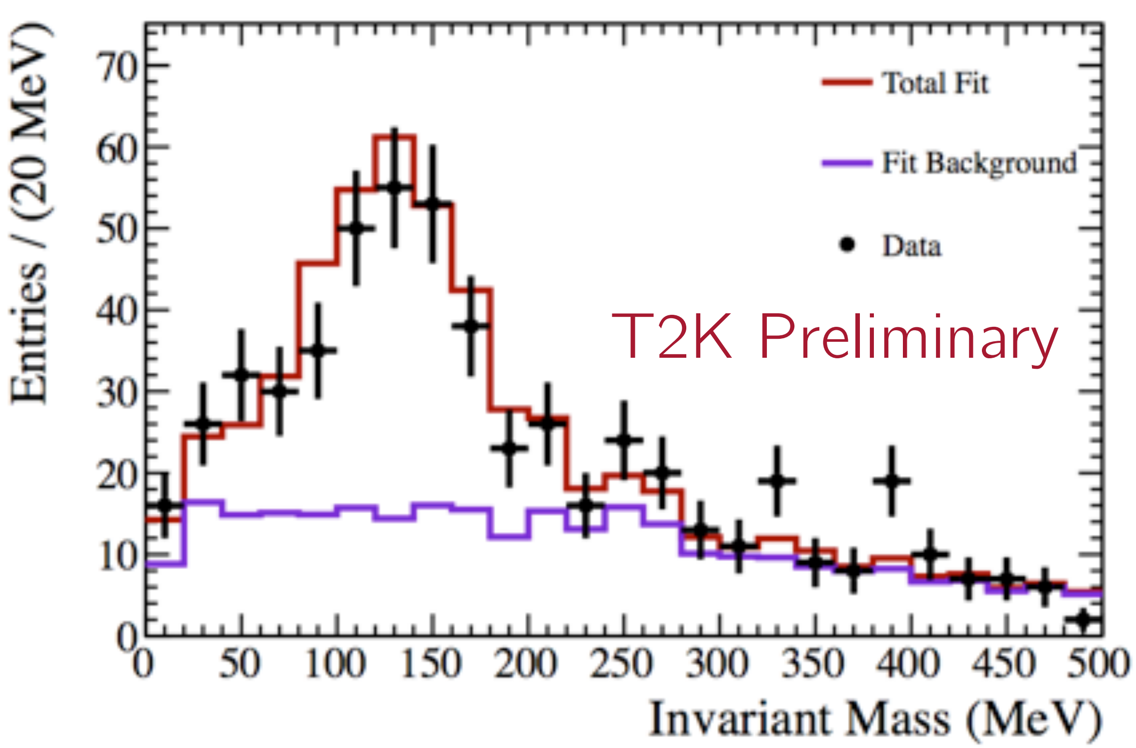


Neutral Current π^0 Production Rate on Water

Water-in



Water-out



- Data/MC ratio of on-water is measured to be:
  - $R_{\text{on-water}} = 0.677 \pm 0.261$ (stat.) $\pm$ 0.462 (syst.)
- Largest uncertainties are
  - Statistics (~26%)
  - Reconstruction - Shower Separation (~11%)
  - Detector - Energy scale (~6%)
- First rate measurement of NCπ^0 production on water
- A paper will soon be submitted to Phys. Rev. Lett.

Summary

- Detailed understanding of the neutrino interactions is required for the future ν_e appearance precision measurements

- T2K Off-axis near detector allowed many exciting measurements recently

  - Inclusive ν_e Charged Current cross section on carbon

    - $\langle\sigma\rangle_\varphi$ = 1.11 ± 0.09 (stat) ± 0.18 (syst) x 10^{-38} cm^2/nucleon

  - Charged current ν_e interaction rate measurement on water

    - $R_{\text{on-water}}$ = 0.87 ± 0.33 (stat.) ± 0.21 (syst.)

  - Neutral current π^0 production rate measurement on water

    - $R_{\text{on-water}}$ = 0.677 ± 0.261 (stat.) ± 0.462 (syst.)

  - More measurements are coming soon!

  - Near future: Anti-neutrino analysis on-going

- More T2K talks are up next, on T2K oscillation analysis (T. Kikawa) and CCν_μ analyses in ND280 (S. Short)


Thank you

Backup

T2K Setup

Even more details on Detectors & Setup[1]

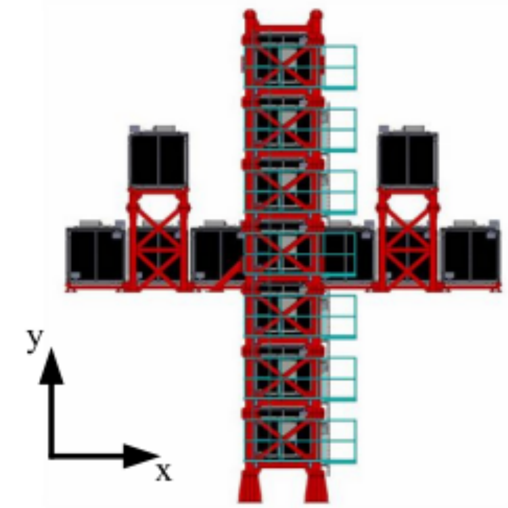


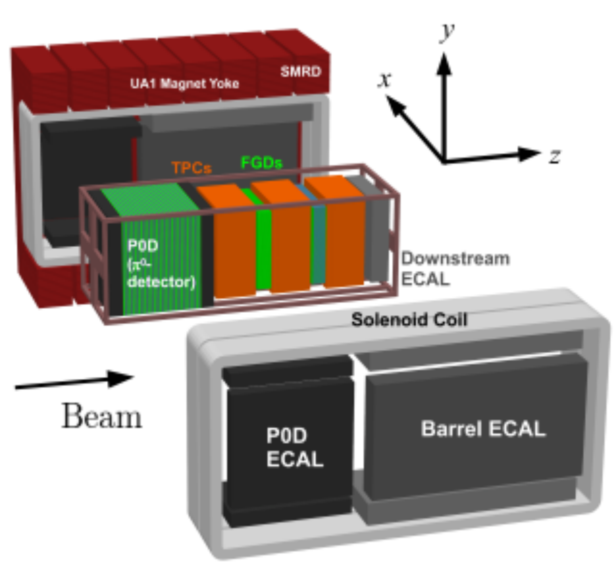
Figure 11: INGRID on-axis detector

1. **J-PARC** » 30 GeV proton to ν beam line
   » Focusing π^+ with Magnetic Horns

2. **INGRID** » Measures ν beam profile and rate
   » Monitors directly the ν beam direction and intensity by means of ν

   interaction in iron
   » Surrounded by veto scintillator planes to reject interaction o
   utside each 16 module

3. **ND280 Off-Axis Detector**: » Measures the flux, E spectrum, ν_e contamination, a
   ›s for various ν cross sections
   » Requirements: **a**. Must provide info to determine
   ν_μ at SK
   b. Must measure ν_e content of the beam
   c. Must measure ν_μ interaction
   → predict backgrounds to ν_e appearance
   ‹ (NC1π)



T2K Setup

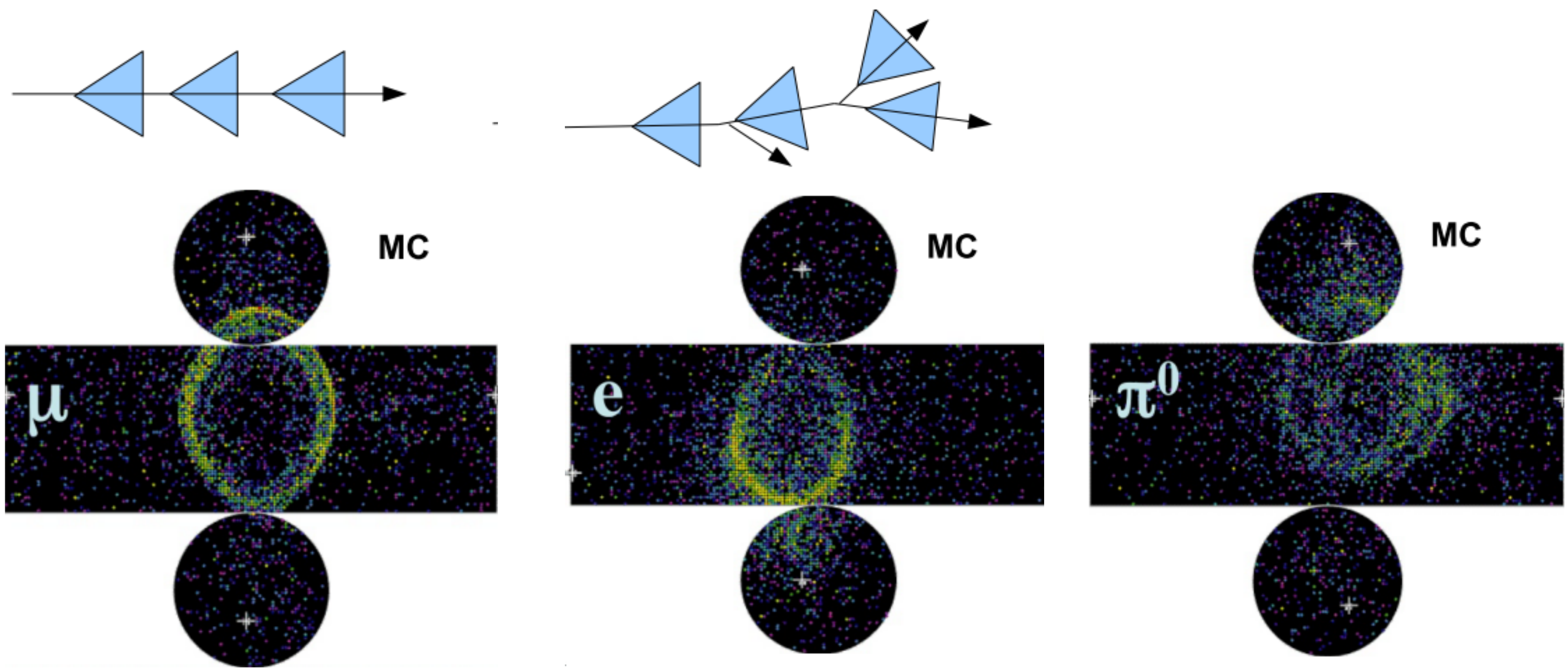
4. Super-Kamiokande: Water Cherenkov detector

»50 kton water, ~11,000 PMT for Inner detector and ~2,000 for Outer det ector

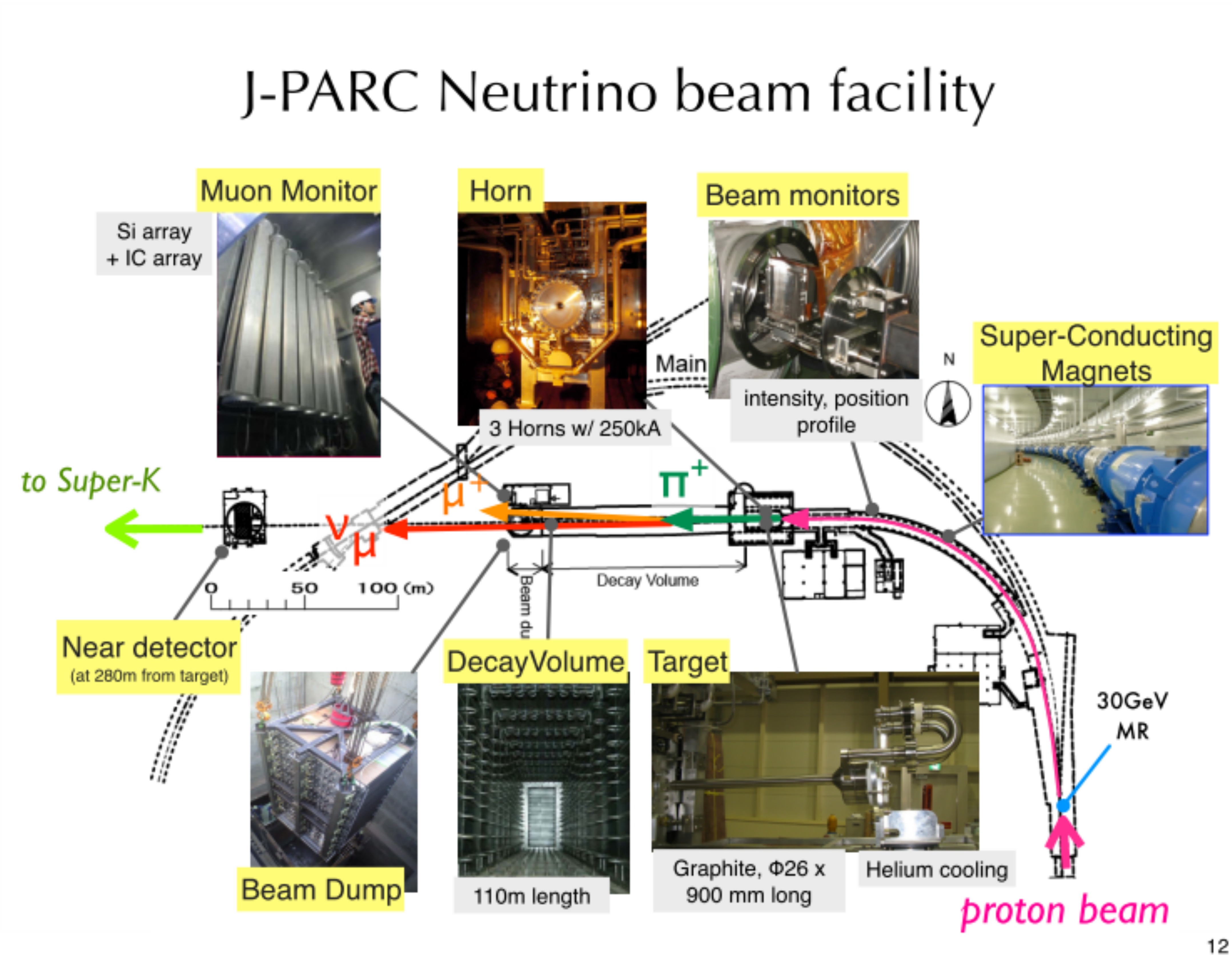
» Inner detector: 40% photo-cathode coverage

» Outer detector: Active veto of cosmic ray μ and other backgrounds

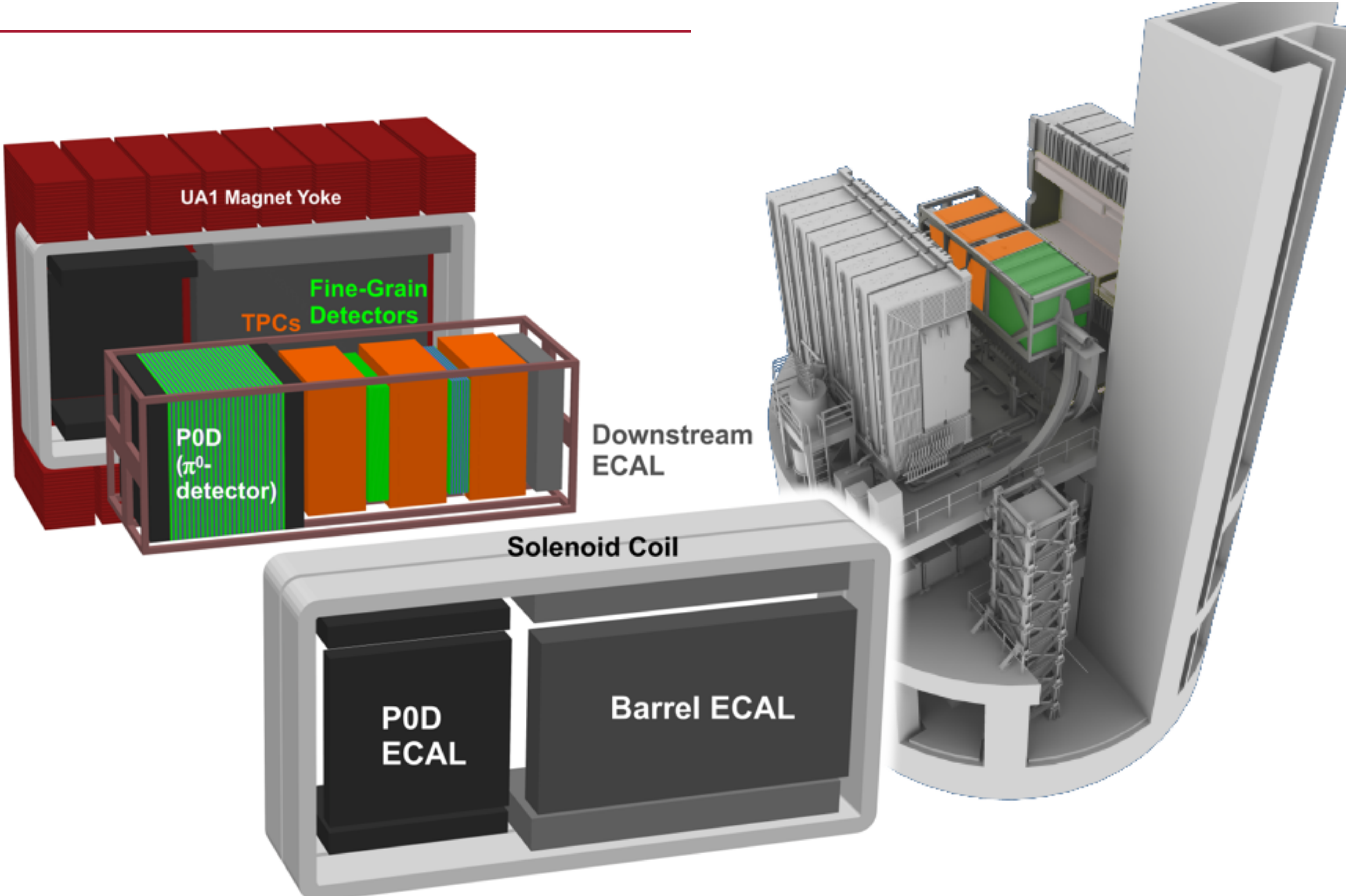
» Ring detection



J-PARC


J-PARC Neutrino beam facility
Muon Monitor
Si array
+ IC array
Horn
3 Horns w/ 250kA
Beam monitors
Main
intensity, position
profile
N
Super-Conducting
Magnets
to Super-K
ν
μ
μ+
π+
0
50
100 (m)
Decay Volume
Near detector
(at 280m from target)
DecayVolume
110m length
Target
Graphite, Φ26 x
900 mm long
Helium cooling
Beam Dump
30GeV
MR
proton beam
12

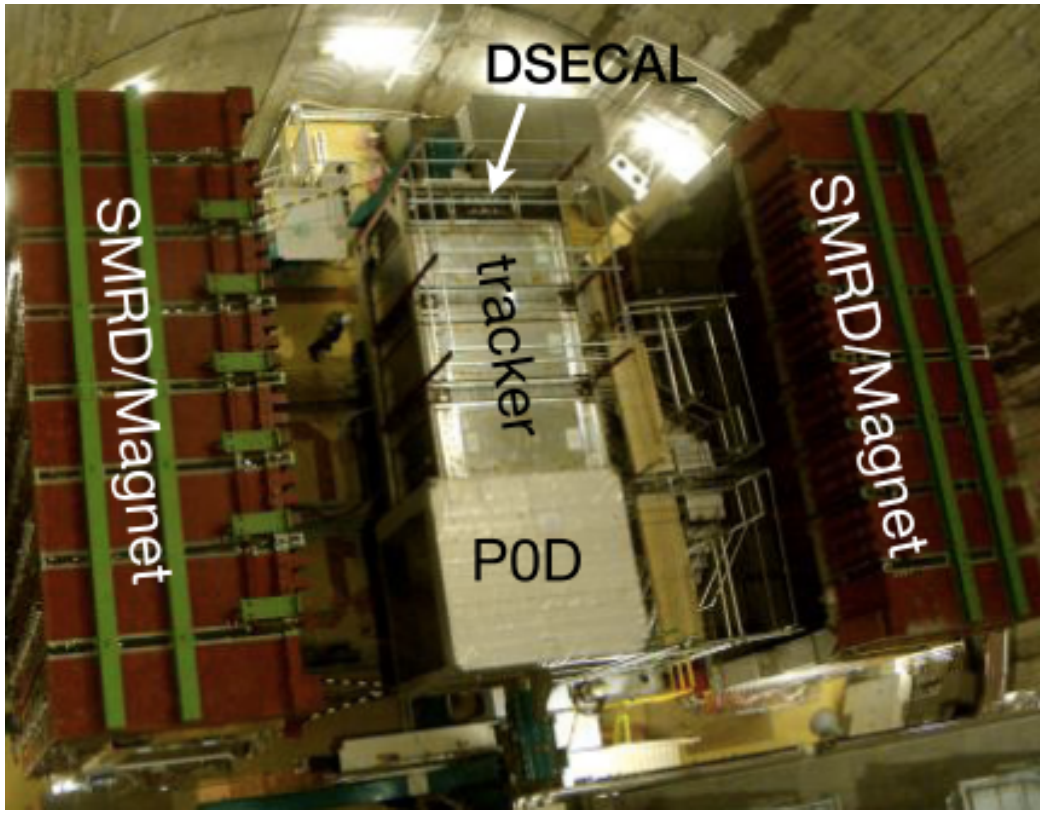
ND280 Off-axis detector Elements



ND280 Off-axis Detector

» **ND280 is composed of:**

I. PØD » Measures neutral current process
(ν_x+N→ ν_x+N+π^0+X) on H_2O target
(Primary goal)



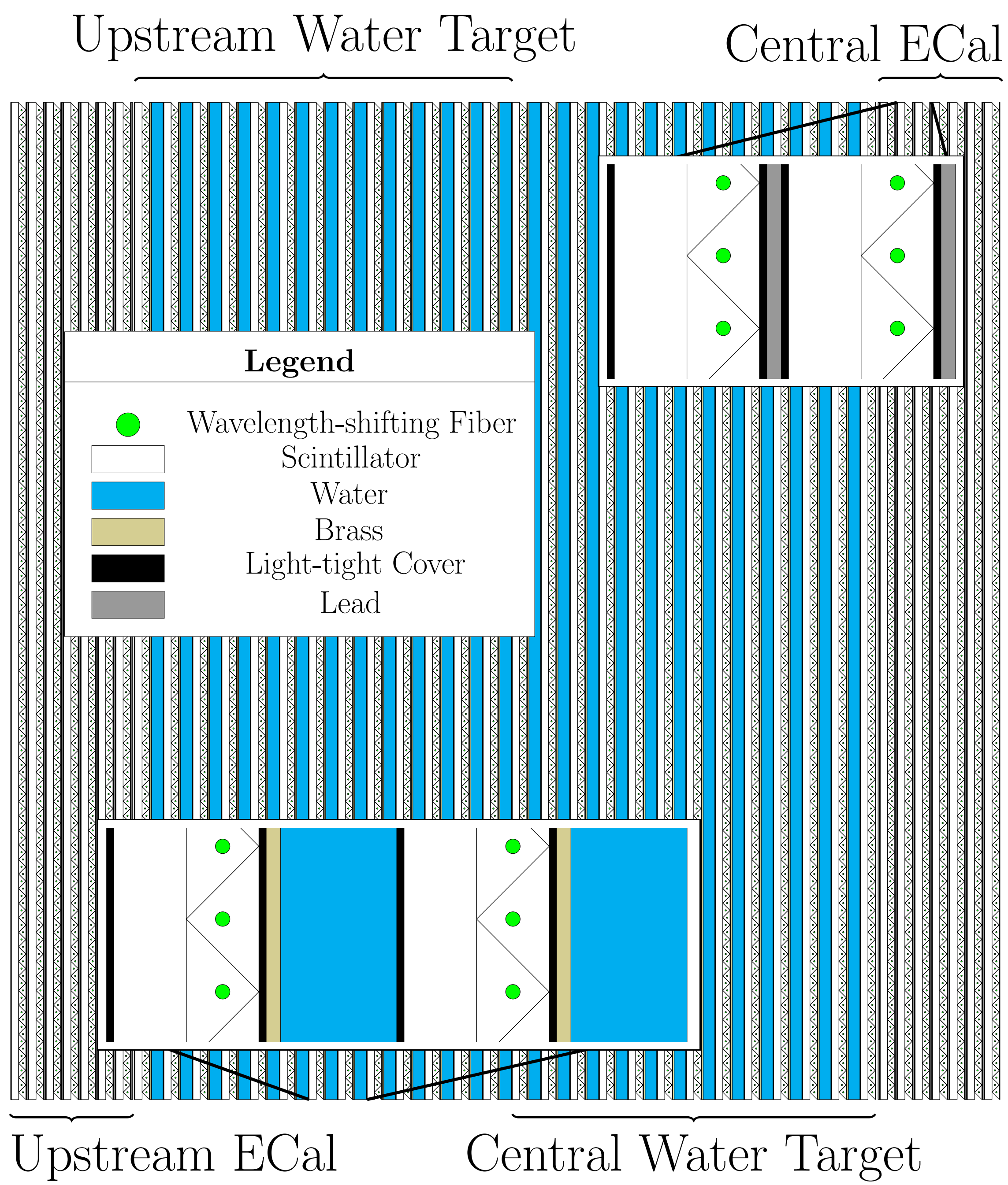
II. TPC » Precise kinematic reconstruction
of tracks with 0.2 T magnetic field
» Particle ID

III. FGD » Provide target mass for ν interaction
» Tracking of charged particle
coming from interaction vertex

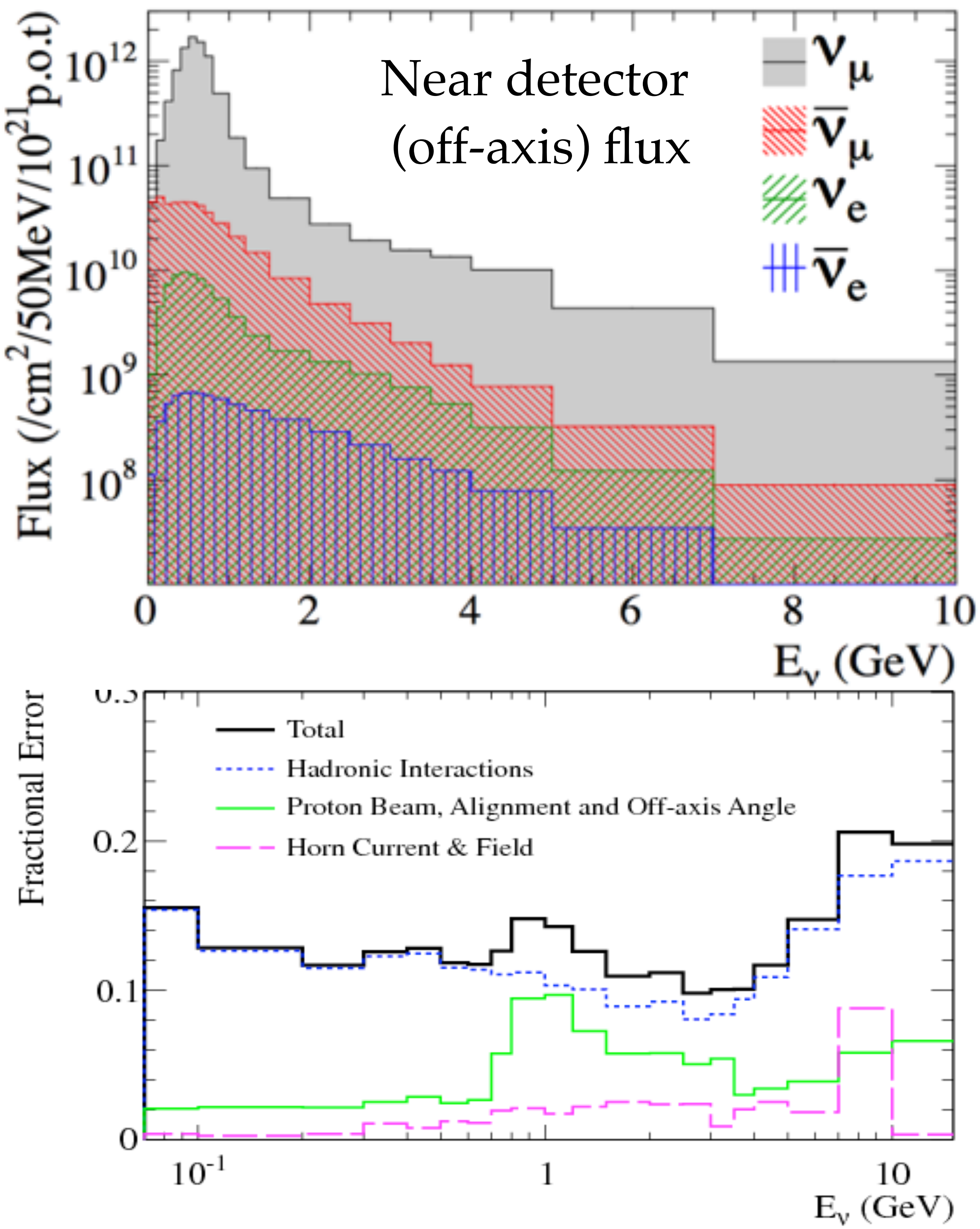
IV. Ecal » Pb/scintillator tracking calorimeter for γ reconstruction and e/μ/π identifi cation

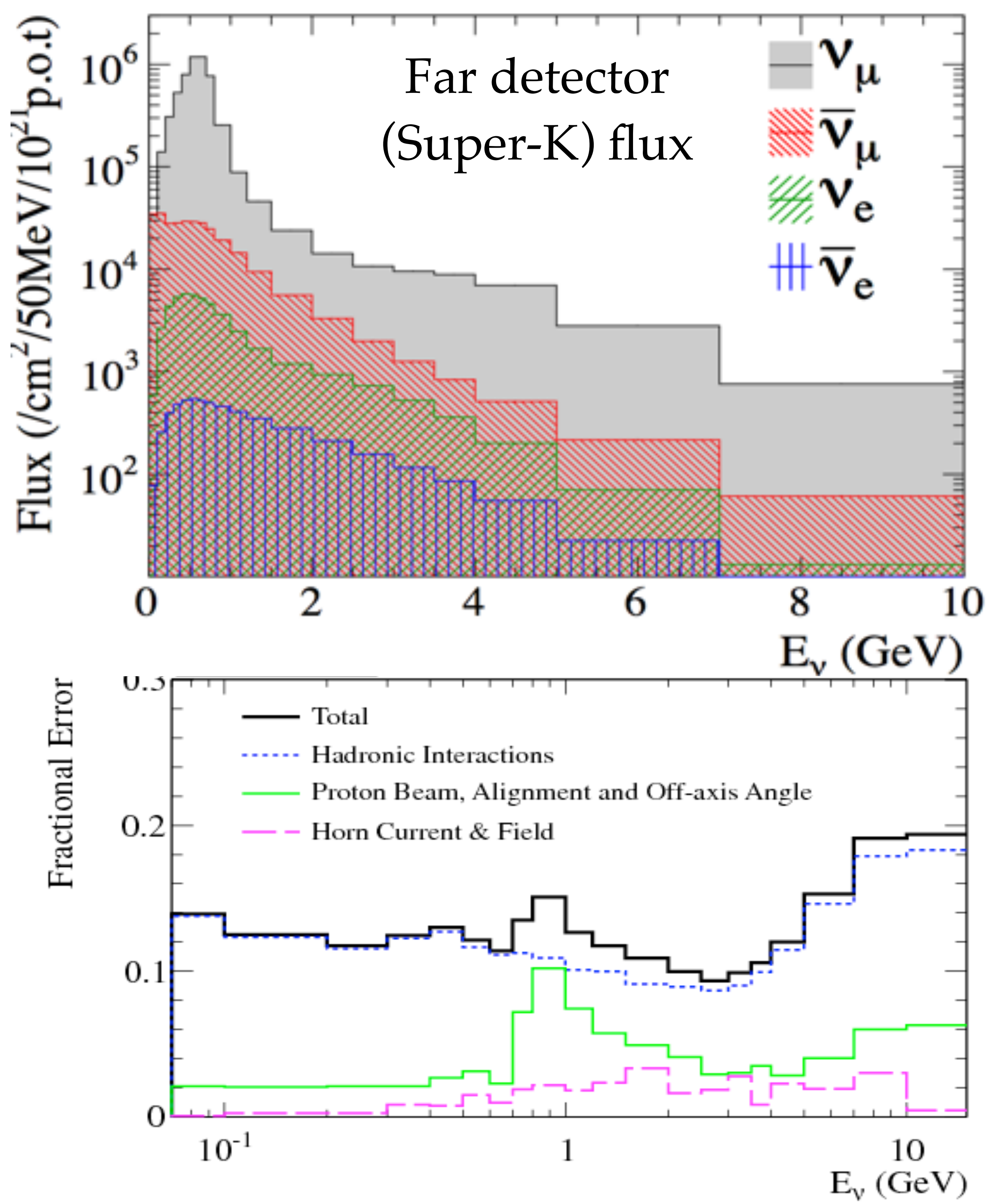
V. SMRD » Records μ escaping with scintillator planes

P0D Detector



Flux and Uncertainties

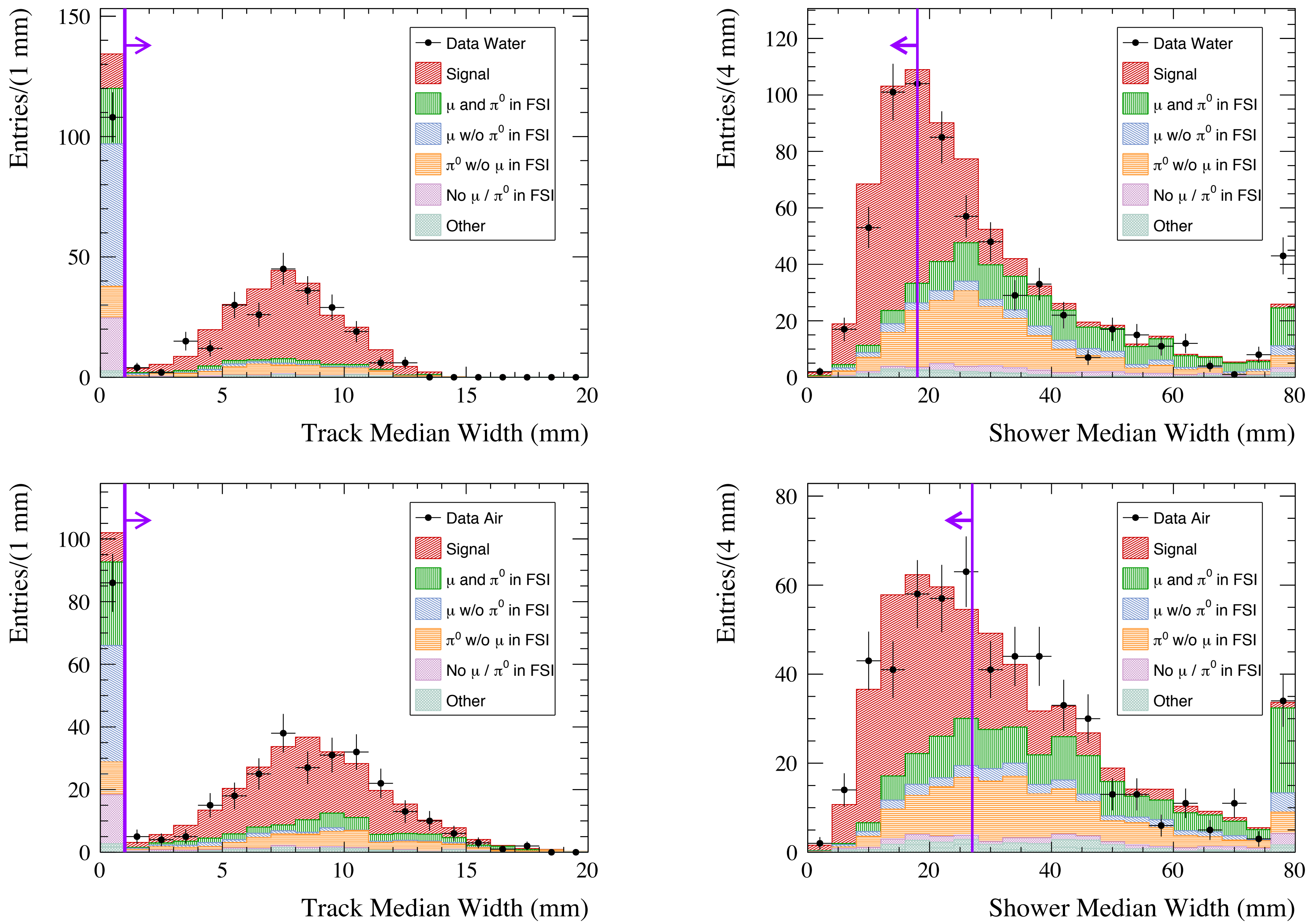




Inclusive ν_e Charged Current Cross Section on Carbon: Systematics

Q^2 (GeV^2/c^4)	Data stat.	MC stat.	Detector	Flux + x-sec	OOFV	Total
0.00–0.03	22.4	7.9	16.6	21.7	0.3	36.2
0.03–0.06	16.2	6.6	12.9	16.7	0.9	27.4
0.06–0.10	13.2	5.2	10.8	15.6	0.9	23.7
0.10–0.16	11.4	4.6	9.2	14.5	0.9	21.1
0.16–0.24	9.7	4.4	7.8	14.5	0.7	19.6
0.24–0.36	9.0	3.8	7.8	14.2	0.6	18.9
0.36–0.58	8.8	3.3	7.8	13.7	0.5	18.4
0.58–1.00	9.5	3.4	7.4	13.4	0.4	18.3
>1.00	12.4	4.0	9.2	15.6	0.8	22.3
Total	8.6	2.6	8.4	13.6	0.5	18.4

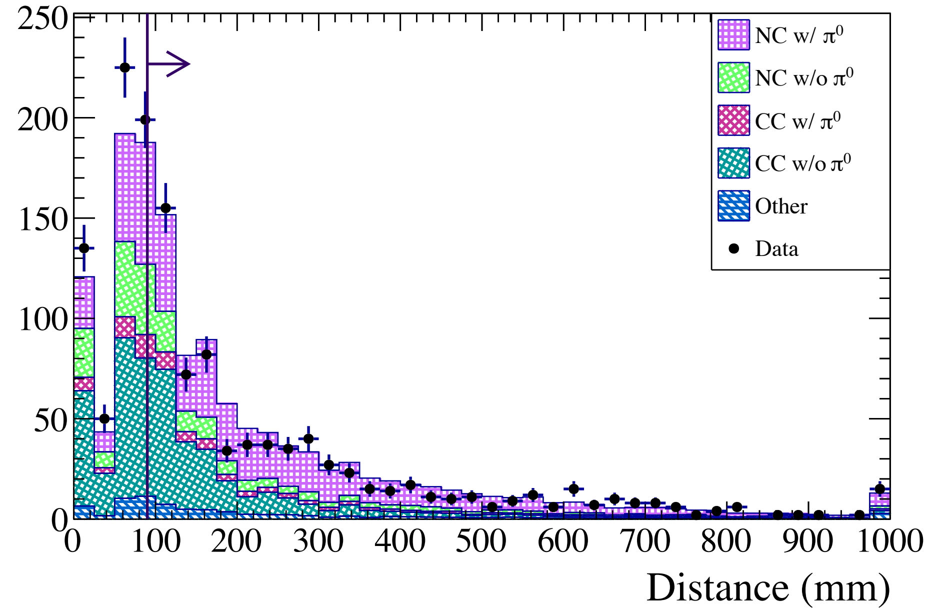
Charged Current ν_e Interaction Rate on Water: Width PID



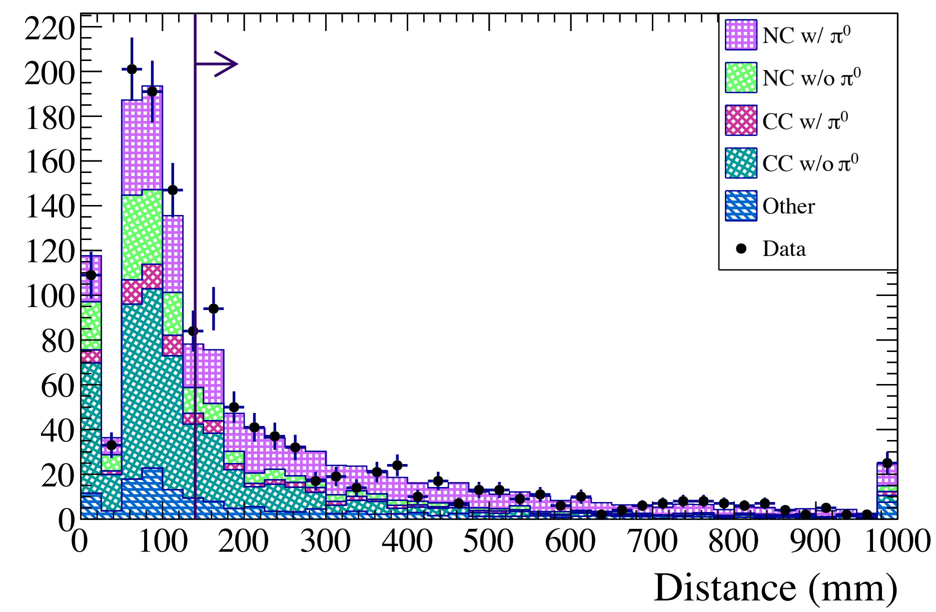
Charged Current ν_e Interaction Rate on Water: Systematics

Systematic Uncertainty for CCν_e Data/MC Ratio	R_{water}	R_{air}	$R_{\text{on-water}}$
MC Statistics	0.03	0.04	0.12
Bias Analysis Method	0.00	0.00	0.02
PØD Mass	0.01	0.01	0.01
PØD Fiducial Volume	< 0.01	< 0.01	< 0.01
PØD Alignment	< 0.01	< 0.01	< 0.01
Energy Scale	0.05	0.05	0.10
Hit Matching	< 0.01	< 0.01	< 0.01
Track PID	0.05	0.05	0.09
Energy Resolution	< 0.01	< 0.01	0.01
Angular Resolution	< 0.01	< 0.01	0.01
Track Median Width	< 0.01	< 0.01	< 0.01
Shower Median Width	0.04	0.04	0.08
Shower Charge Fraction	0.01	0.04	0.04
Flux and Cross Sections Pre-Fit	0.22	0.26	0.17
Flux and Cross Sections Post-Fit	0.07	0.09	0.06
Total with Pre-Fit	0.24	0.28	0.27
Total with Post-Fit	0.11	0.13	0.21

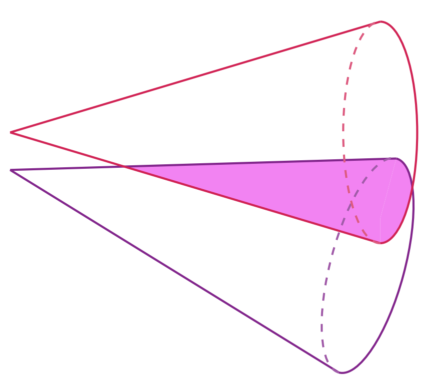
Neutral Current π^0 Production Rate On Water: Shower Separation



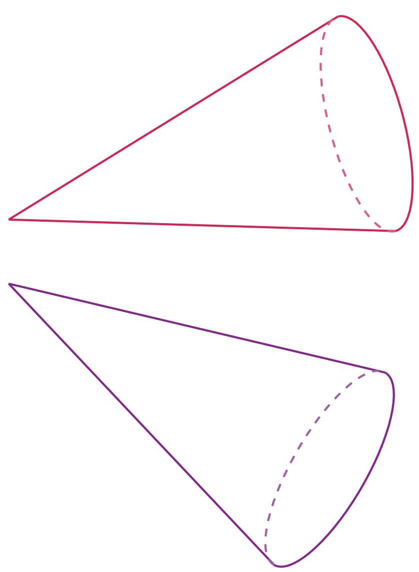
(a) Water-in configuration.



(b) Water-out configuration



(a) Sample X-Z projection



(b) Sample Y-Z projection

Neutral Current π^0 Production Rate On Water: Systematics

Parameter	Uncertainty	
	Water	Air
Geometry Differences	2.8%	2.8%
PE Peak Discrepancy	0.6%	0.4%
Energy Scale	4.4%	0.6%
Detector Variations	$< 0.1\%$	$< 0.1\%$
PØD Response	1.8%	1.8%
Mass Uncertainty	0.5%	0.9%
Alignment	$< 0.1\%$	$< 0.1\%$
Fiducial Volume Scaling	1.5%	2.0%
Fiducial Volume Shift	1.1%	1.7%
Flux and Event Generator	2.9% (1.5%)	3.7% (1.9%)
Track PID Efficiency	5.4%	5.1%
Shower Separation	10.9%	13.5%
PID Weight	8.1%	3.4%
Charge In Shower	7.8%	3.0%
g Factor (statistical)	3.8%	4.2%
Total Systematic	18.2%(18.0%)	16.7%(16.4%)
g Factor (systematic)	16.4%	23.2%