T2K

The Charged-Current Cross Section on Water at the T2K Near Detector

Enrico Scantamburlo
University of Geneva

on behalf of the T2K Collaboration

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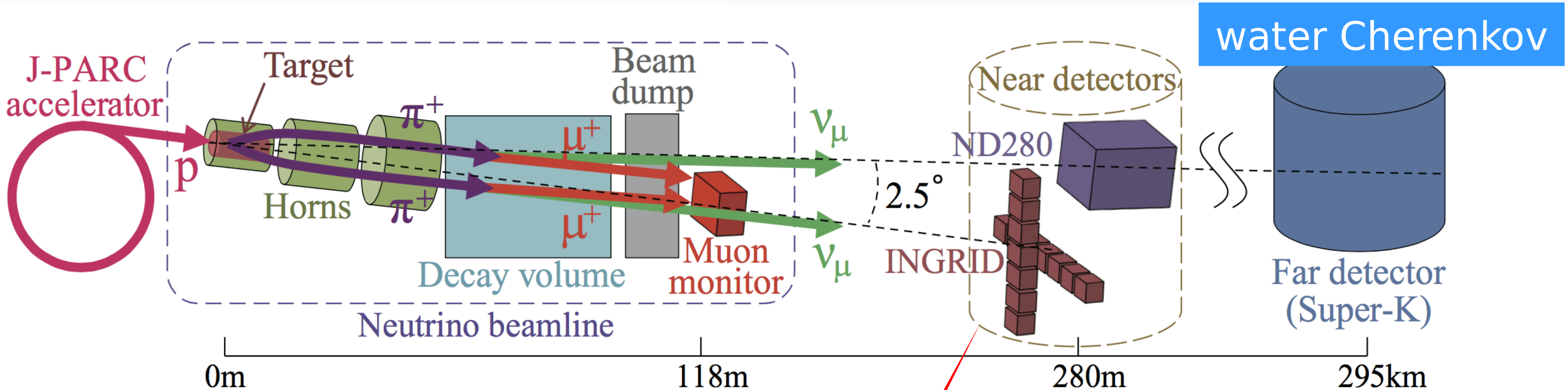
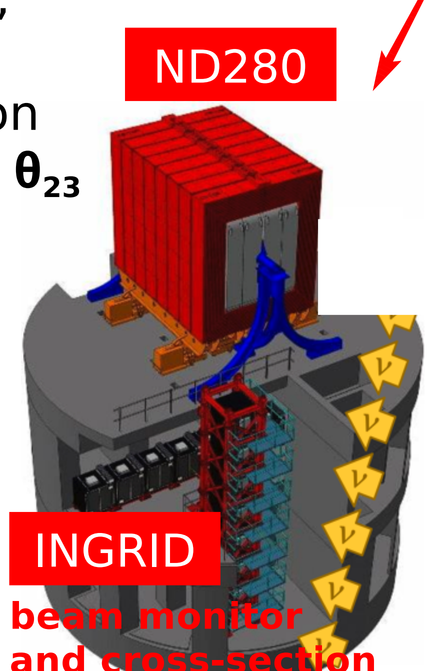
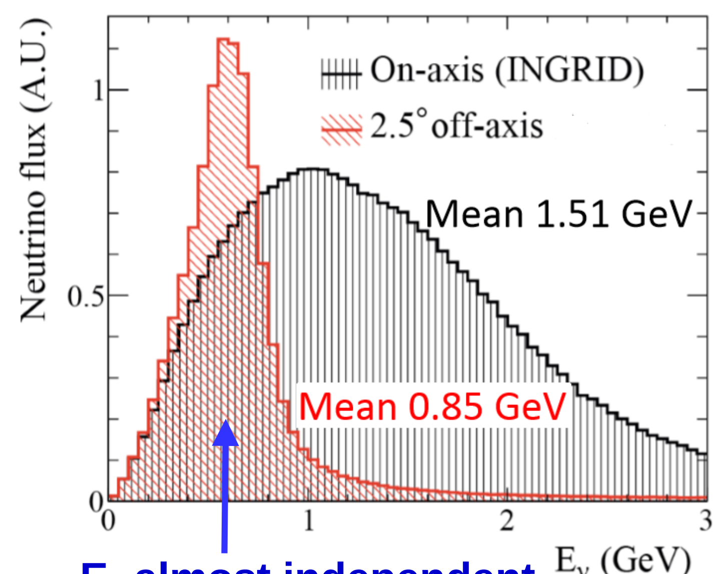
The Tokai-2-Kamioka ν experiment: T2K



- First **off-axis ν** experiment, first demonstration of **appearance** (first indication of non-zero $\boldsymbol{\theta_{13}}$), world best $\boldsymbol{\theta_{23}}$
- High intensity, muon neutrino **beam** (or anti-ν), narrow band, peaked at oscillation maximum
- **NA61** at CERN measures the hadron production on a T2K replica target

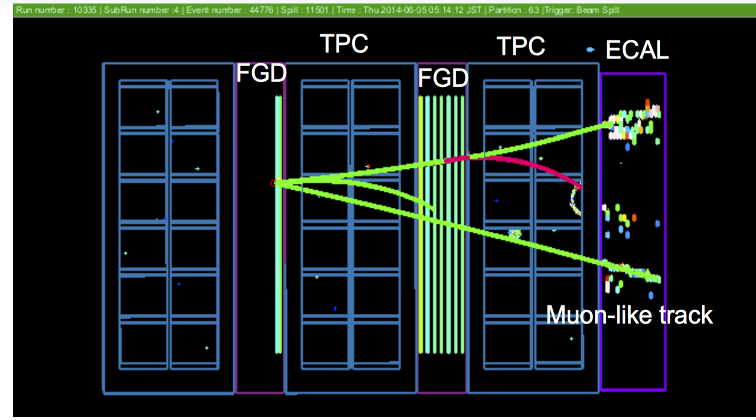




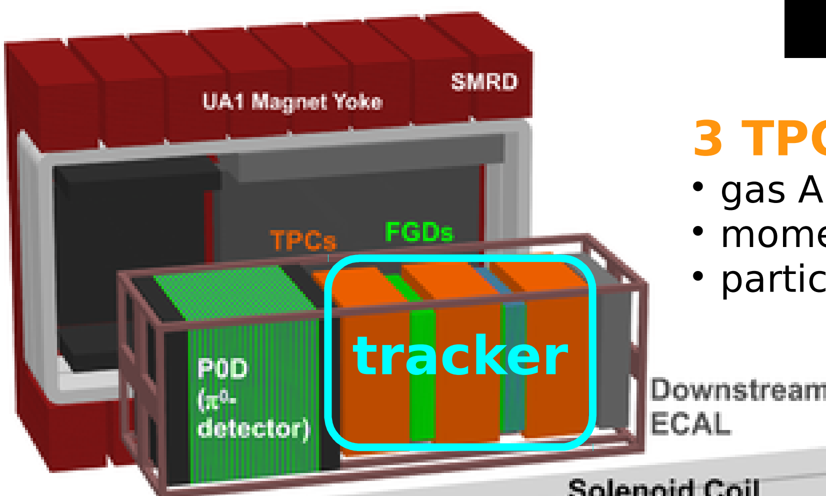
E_ν almost independent of parent π energy

The off-axis Near Detector: ND280

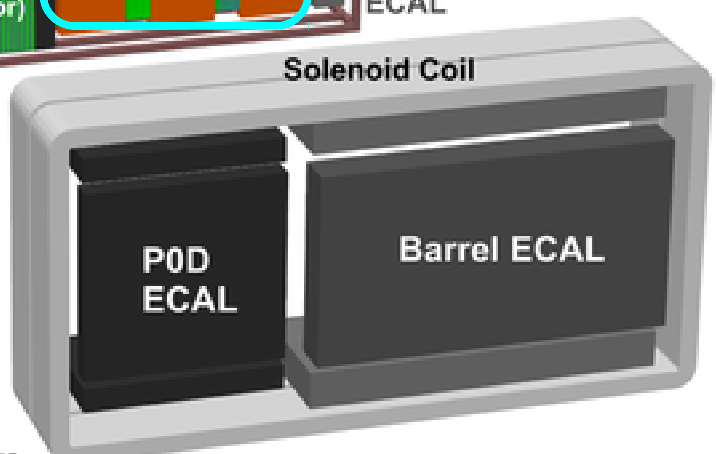
- Unoscillated ν_μ and ν_e measurements: constrain flux, cross section and background for oscillation
- Cross-section measurements on CH (active) and H_2O (same target of Super-Kamiokande)
- 50k ν_μ events in $6 \cdot 10^{20}$ protons on target (POT) accumulated in neutrino beam mode



SMRD (Side Muon Range Detector)
- tag cosmic μ and side-exiting μ



ν beam



3 TPCs (Time Projection Chambers)
- gas Ar 95%
- momentum measurement in 0.18 T
- particle ID (dE/dx measurement)

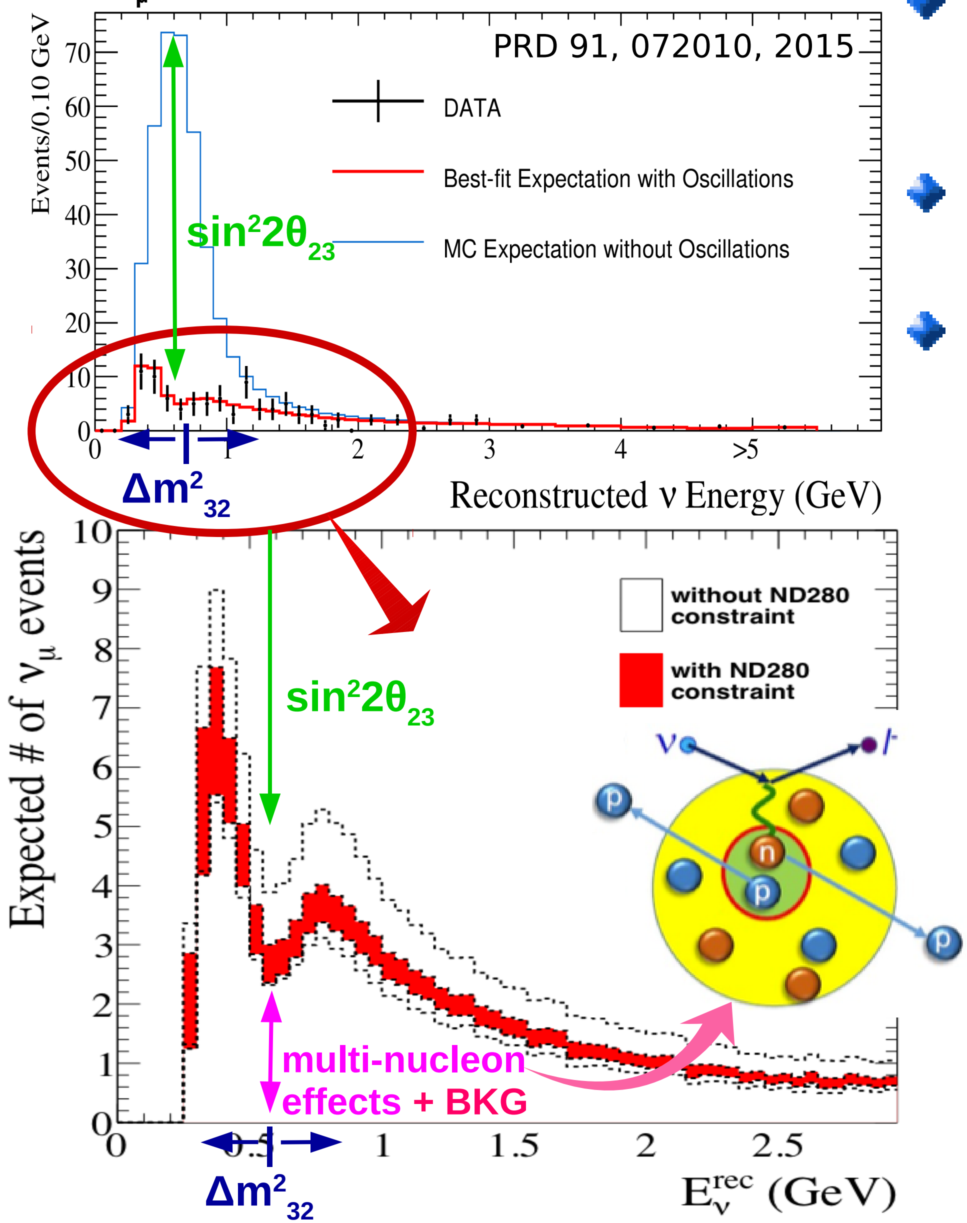
2 FGDs (Fine-Grained Detectors)
- active CH target mass
- FGD2 interleaved with H_2O
- recoil protons detection

P0D (π^0 Detector)
- scintillator target which can be filled with water
- π^0 tagging

ECAL (Electromagnetic calorimeters)
- detect γ rays and tag π^0

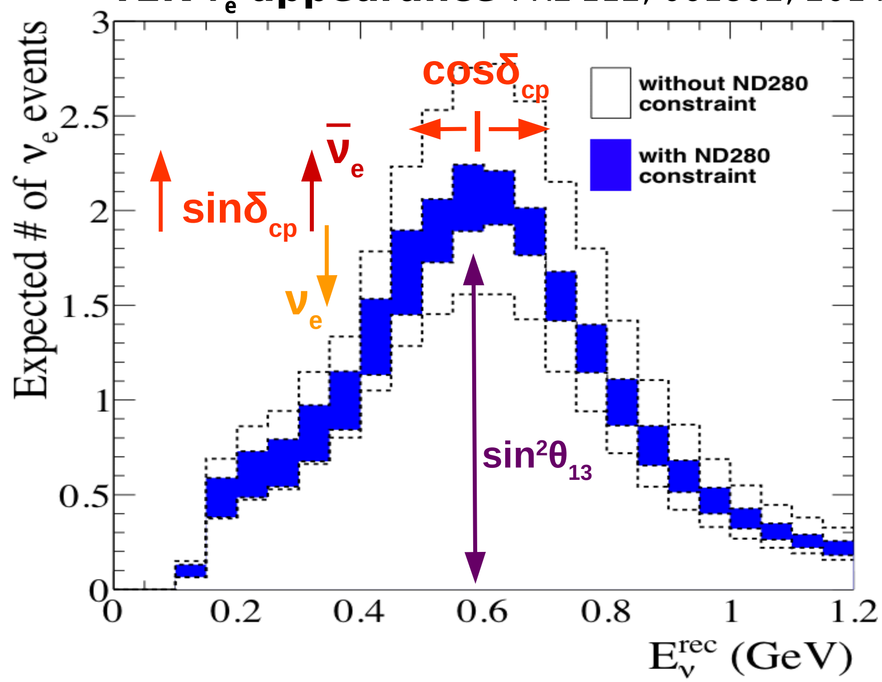
ND280 constraints for oscillation analyses

T2K ν_μ disappearance PRL 111, 211803, 2013



- In the previous talk G. Christodoulou showed the importance of ND280 constraints for **ν** oscillation analyses
- Need smaller uncertainties to measure precisely θ_{23}, θ_{13} and δ_{CP}
- Systematics limited by the neutrino interaction model

T2K ν_e appearance PRL 112, 061802, 2014



ND280 constraints for oscillation analyses

- Flux and interaction models constrained to **3% level except** for uncertainties related to **different target material** of near vs far detector (CH vs H_2O)
- ND280 greatly improves predictions of event rates at Super-K using its **fully active CH target**, now is important to **improve the constraints on water**, using FGD2, the water target

T2K oscillation systematic (fractional) errors		2014 analysis: ν_μ sample 2014	2014 analysis: ν_e sample 2014	2015 analysis: ν_μ sample 2015	2015 analysis: ν_e sample 2015
ν flux		16%	11%	7.1%	8%
ν flux and cross section	without ND280 constraint	21.7%	26.0%	9.2%	9.4%
	WITH ND280 constraint	2.7%	3.2%	3.4%	3.0%
independent cross sections (different nuclear targets)		**5.0%**	**4.7%**	***10%**	***9.8%**
Final State Interaction / Secondary Interaction at Super-K		3.0%	2.5%	2.1%	2.2%
Super-K detector		4.0%	2.7%	3.8%	3.0%
Total	without ND280 constraints	23.5%	26.8%	14.4%	13.5%
	WITH ND280 constraints	**7.7%**	**6.8%**	***11.6%**	***11.0%**

*** included effects of multi-nucleon bound states**

Cross-section measurements at ND280

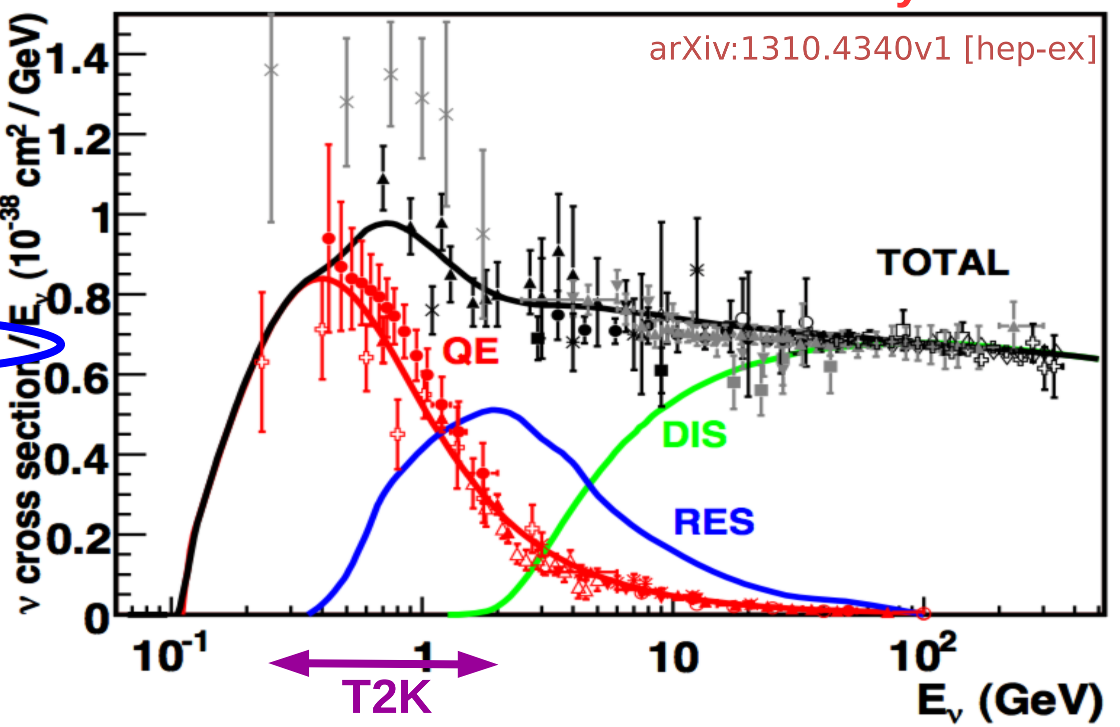
- T2K is producing world-class measurements for a variety of neutrino interaction channels at few-GeV energies:

How to constrain separately flux and cross-section?
→ Hard to deal with neutrino interaction theory

- **Cross section analyses at ND280**:
  - Inclusive ν_μ Charged-Current (CC) Cross Section on carbon (Phys. Rev. D 87, 092003, 2013)
  - Inclusive ν_e CC Cross Section on carbon (Phys. Rev. Lett. 113, 241803, 2014)
  - ν_μ CC Quasi-Elastic Cross Section on carbon (Phys. Rev. D 92, 112003, 2015)
  - ν_μ CC Coherent on carbon (preliminary)
  - ν_μ CC 0π on carbon (preliminary)
  - ν_μ CC $1\pi^+$ on carbon (preliminary)
  - ν_μ CC $1\pi^+$ on water (preliminary)
  - many other work in progress
  - Inclusive ν_μ CC $\sigma^{water}/\sigma^{scint}$

Scaling from C to O is not trivial

more measurements really needed



Charged-Current (CC)

$1\pi^+$

cross section

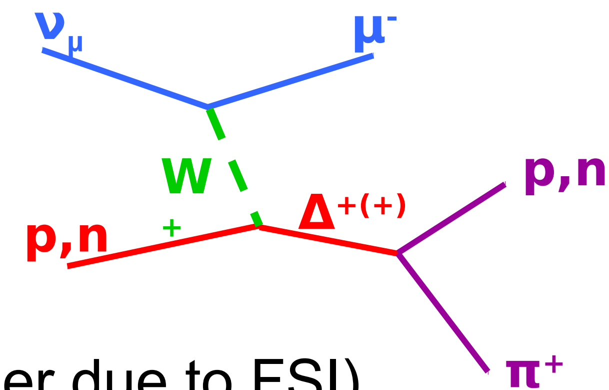
in water FGD2

t2k preliminary

CC $1\pi^+$ on water FGD2

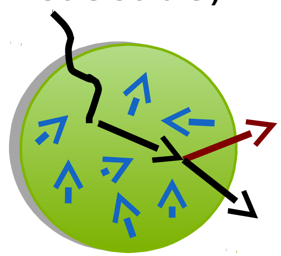
- **Signal**: Charged-Current (CC) interaction with 1 π^+, in water

$$\nu_\mu + N \rightarrow \mu^- + \pi^+ + N'$$

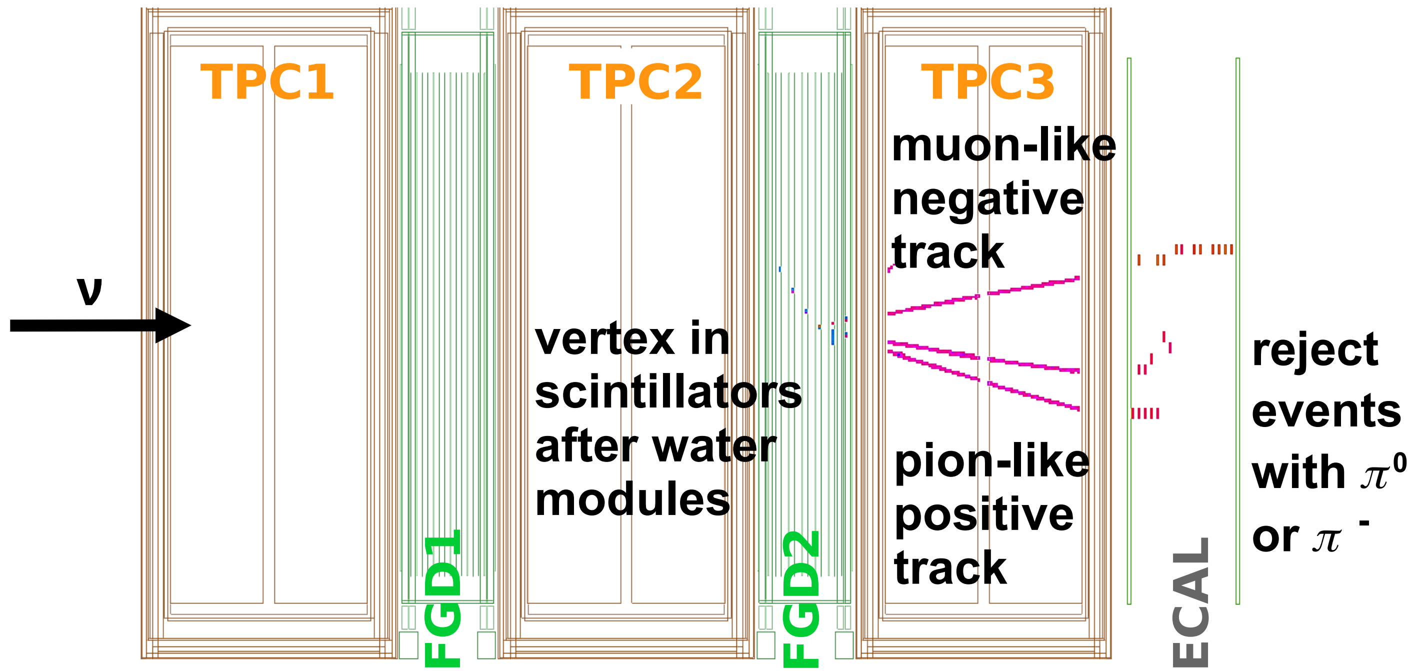


- Main contribution from **Δ resonance** (and other due to FSI)

Final State Interaction (intranuclear cascade)



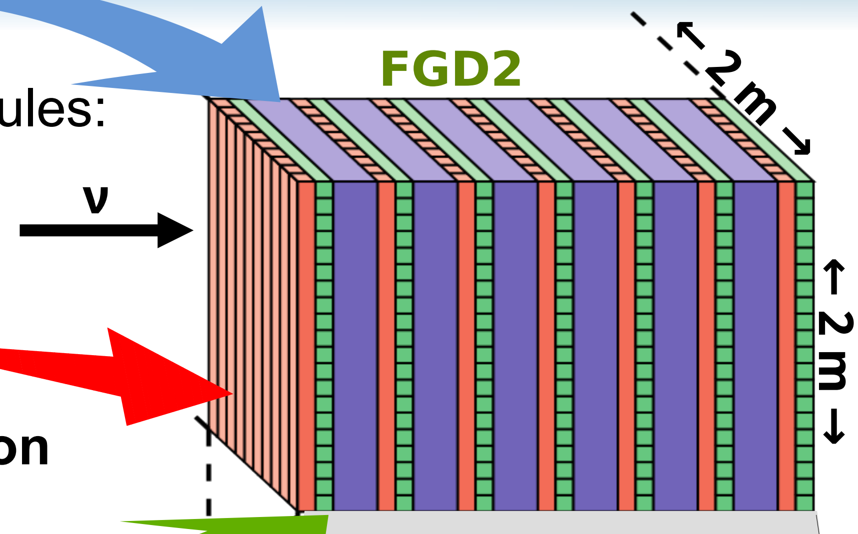
- **Event selection**:

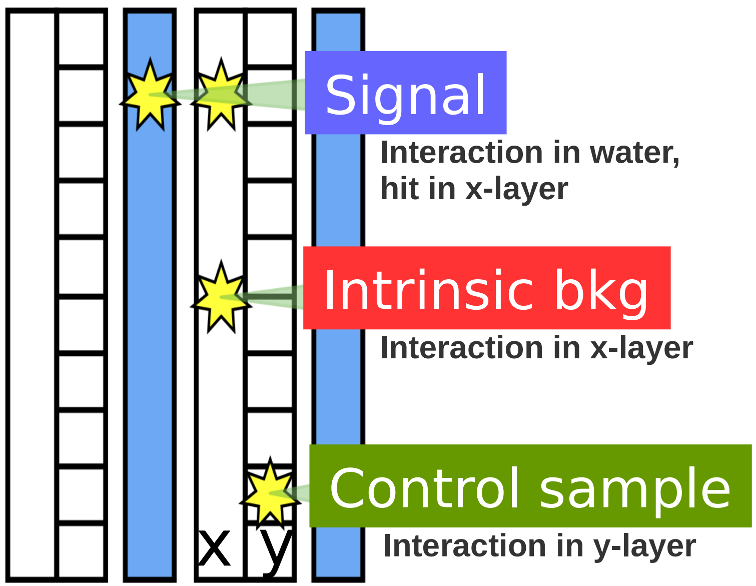


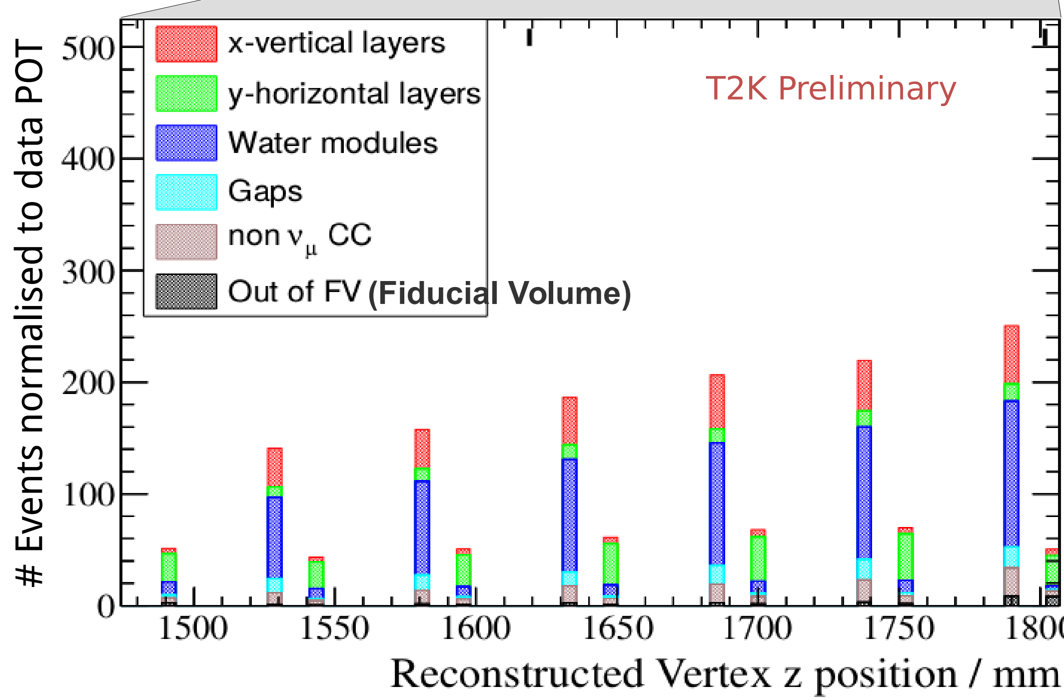
Event selection in water FGD2

- 6 water modules interleaved by XY modules:

  2 layers of scintillating bars (Ø 1x1 cm^2), 192 bars each
  - X-layers (vertical bars), carbon and **water** events
  - Y-layers (horizontal bars), mainly **carbon** events





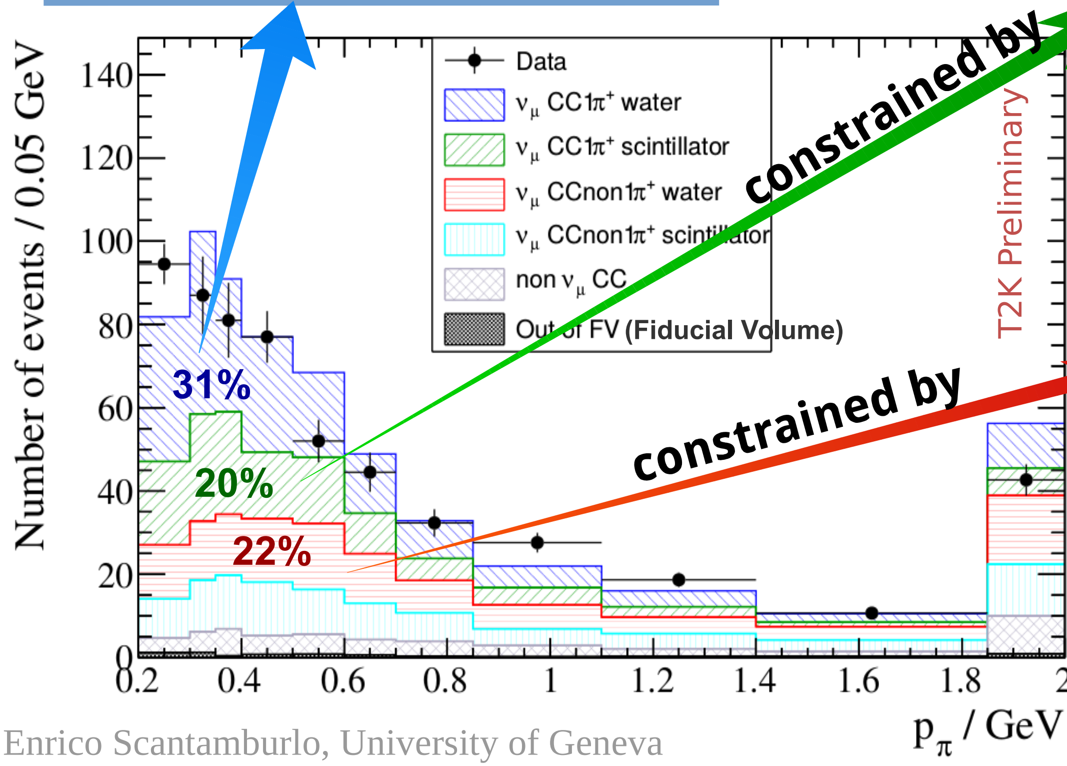


CC 1π⁺ signal and background

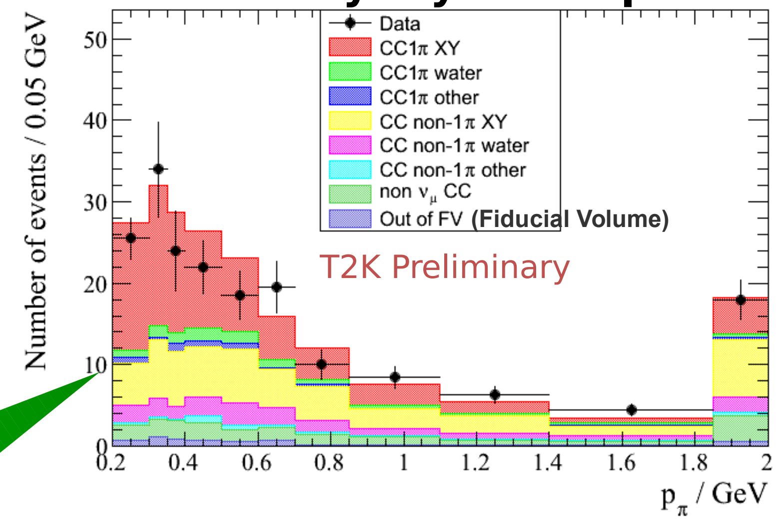
- Dominant **background**:
  - CC $1\pi^+$ in scintillator
  - CC non-$1\pi^+$: 0π, $N\pi$, $1\pi^+$+Nmesons (dominated by DIS)

→ **Two control samples** to constrain the background (MC agrees with data)

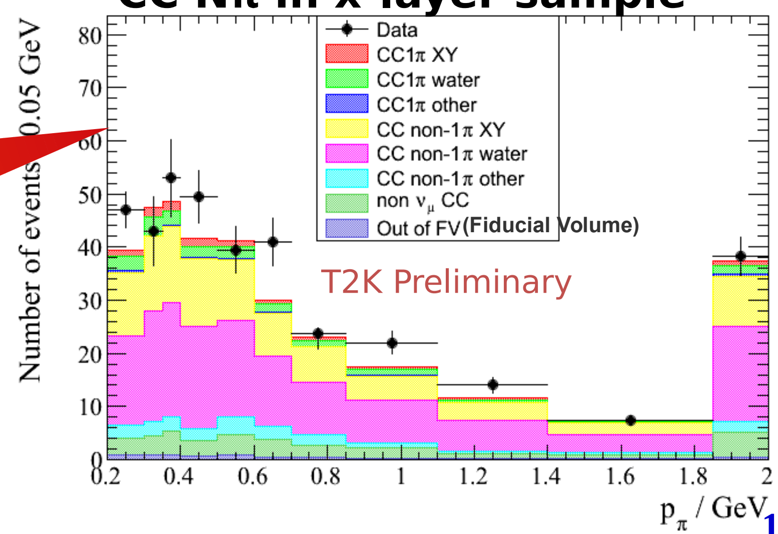
signal: CC 1π⁺ in water



Control sample 1:
CC 1π⁺ in y-layer sample



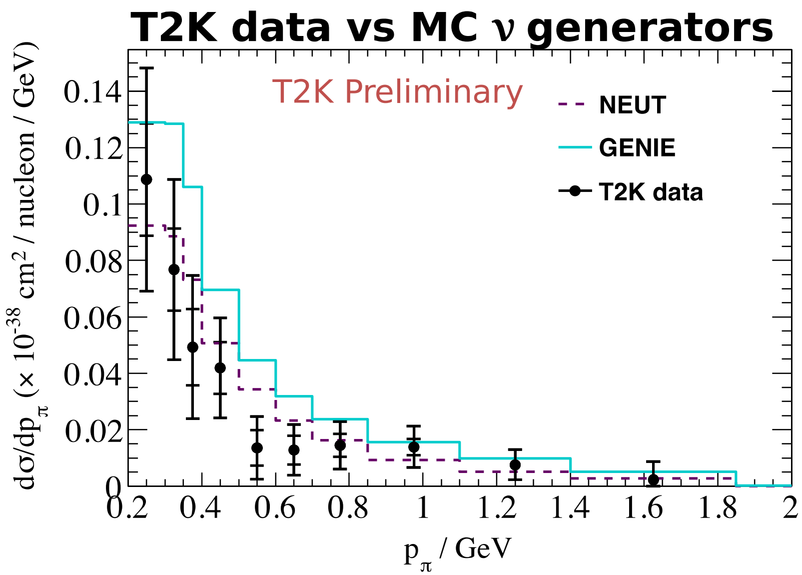
Control sample 2:
CC Nπ in x-layer sample

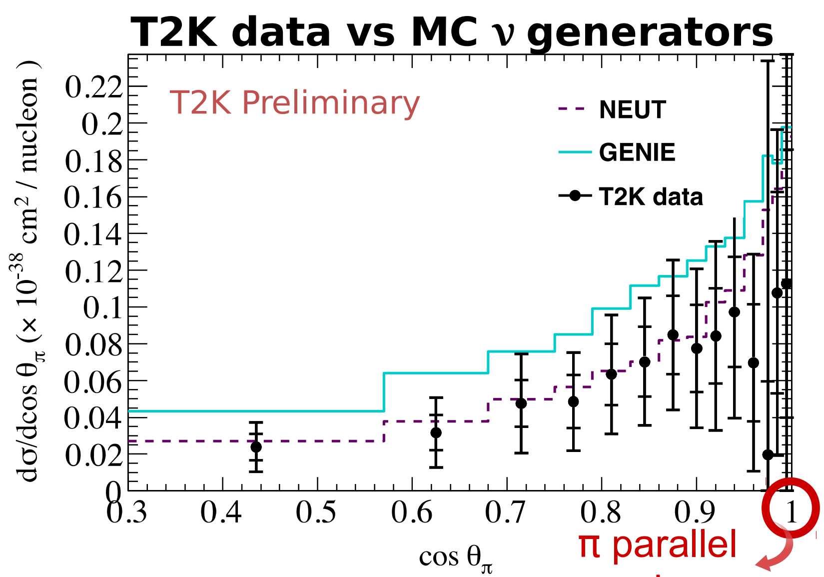


CC 1π^+ results

- **Flux-integrated differential cross section** with the Bayesian unfolding method of D'Agostini (arXiv:1010.0632 [physics.data-an])
  - in muon kinematics
  - in pion kinematics
  - in muon-pion angle
  - in reconstructed neutrino energy

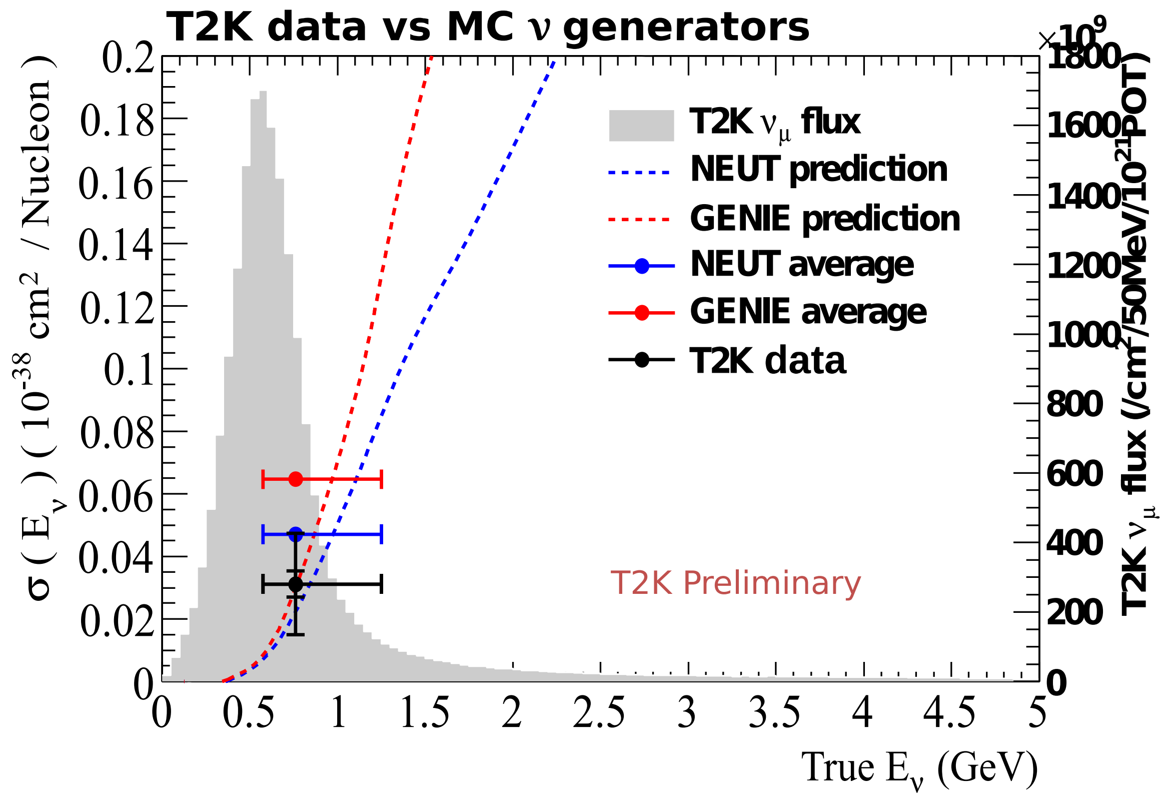
- **Suppression** at low pion momentum and low pion angle (forward direction)





CC 1π^+ results

- We can condense our measurement into one flux averaged point: also the **total cross section** is lower than the prediction for both GENIE and NEUT (MC neutrino generators)
- Both generators use the Rein-Sehgal Model, but with different tuning



(Aslo MINERνA observes that GENIE overestimates this channel)

Inclusive

Charged-Current

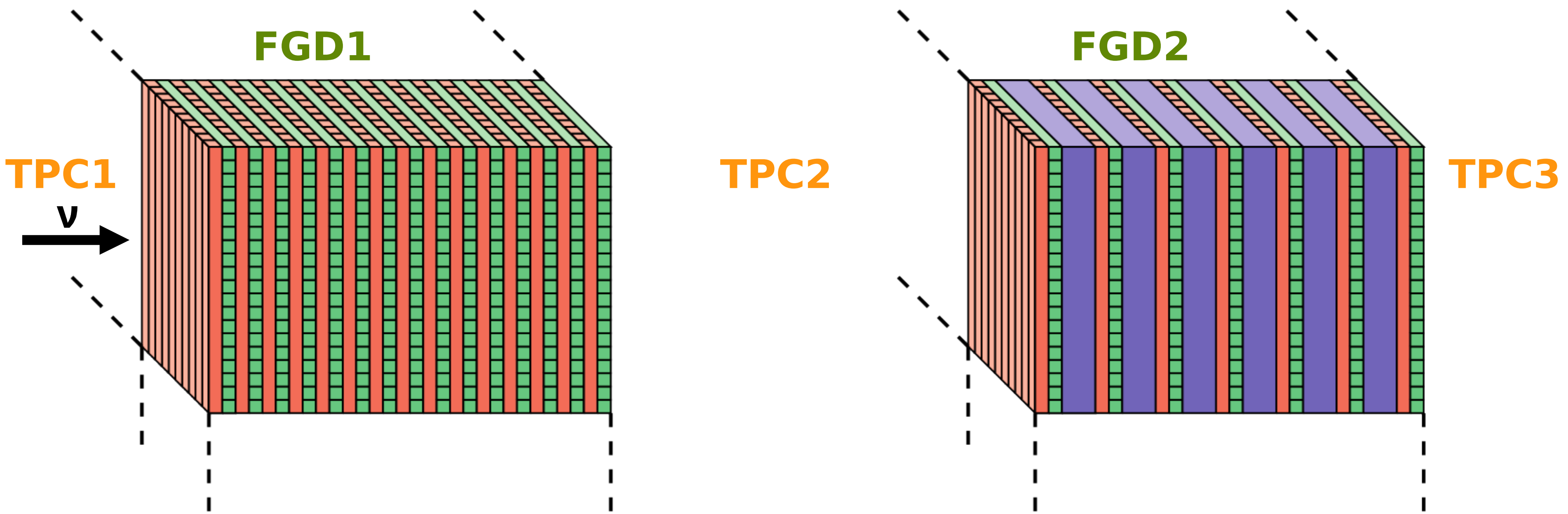
$$\frac{\sigma^{water}}{\sigma^{scint}} \text{ and } \frac{d^2\sigma^{water}}{dp_\mu \, d\cos\theta_\mu} \Big/ \frac{d^2\sigma^{scint}}{dp_\mu \, d\cos\theta_\mu}$$

in FGD1+FGD2

work in progress

Water measurements by subtraction

- Use both **FGD1** (fully active CH) and **FGD2** (interleaved with water modules): very **similar design** meant to do **subtraction analyses**



- FGD2 = ~ 400 Kg of water + 53% of FGD1 (in the fiducial volume)
  (errors on masses are 0.6 %, as built)

  → **The cross section on water can be achieved by subtraction**

Inclusive CC $\sigma^{water}/\sigma^{scint}$ in FGD1+FGD2

$$\frac{\sigma^{water}}{\sigma^{scint}} \sim \frac{\sigma^{FGD2} - a \cdot \sigma^{FGD1}}{\sigma^{FGD1}}$$

→ **flux** normalization **cancels**

→ **detector syst. cancels**

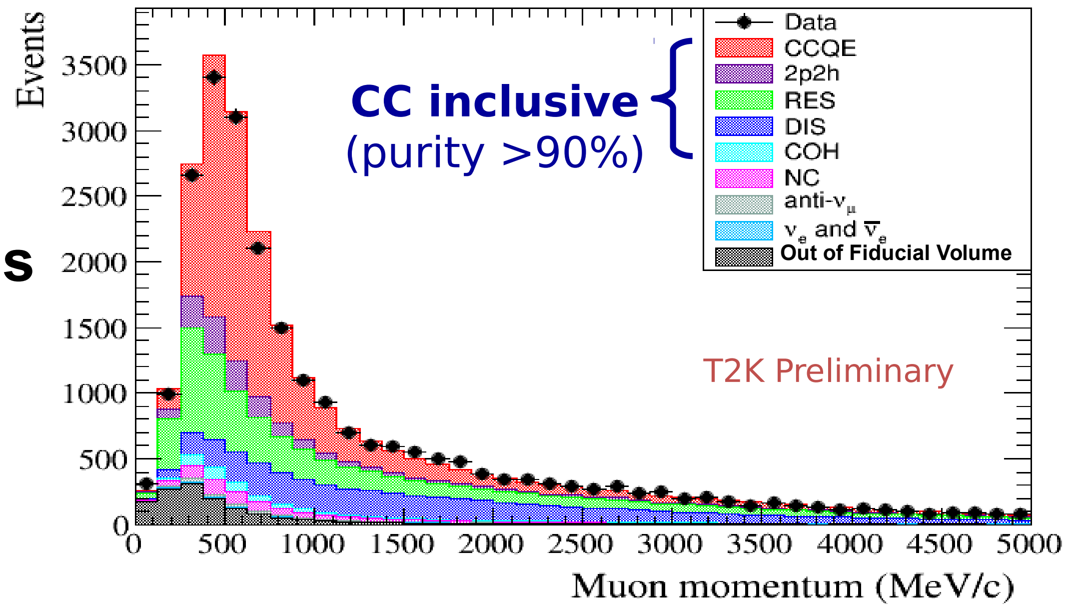
- **Inclusive** CC sample

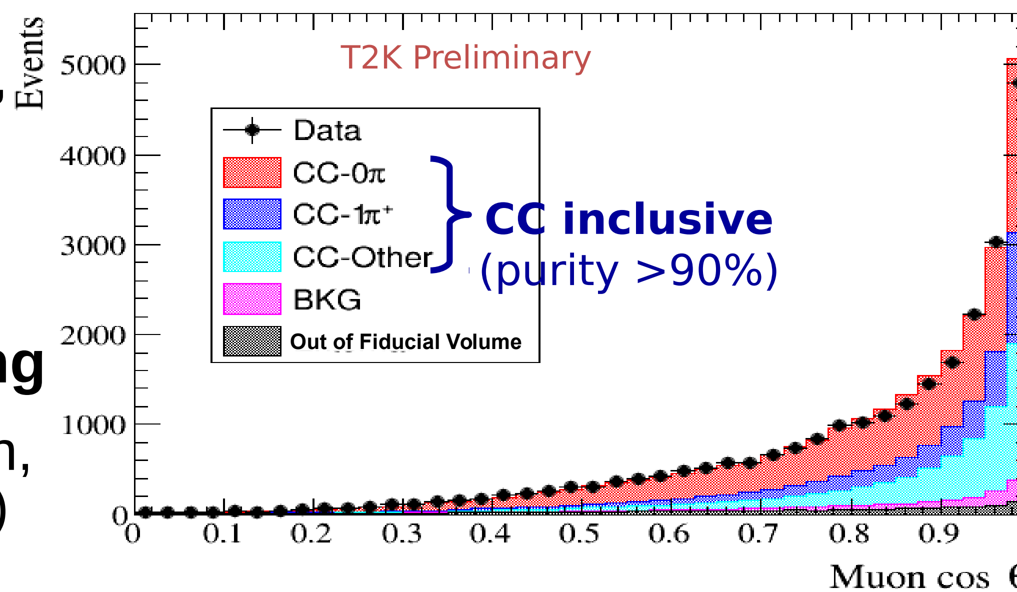
→ high **statistics**

→ high **purity** (strong signal, only the muon matters)

aim for very small uncertainties and fine binning

(stat. 2.3% for total cross section, even smaller systematic errors)





Summary

- ND280 is **essential** to reduces the systematic uncertainties in the predicted event rate at Super-Kamiokande

- First exclusive **CC**$1\pi^+$ cross-section measurement **in water** indicates suppression in pion kinematics

- σ^{water} can be achieved by subtraction of cross sections from almost identical sub-detectors

- $\boldsymbol{\sigma^{water} / \sigma^{scint}}$ will have very small uncertainties (< 3%)

- Plenty more work to be done on neutrino cross sections!
(If we are lucky, CPV may be around the corner...)

Thanks

500 people, 59 institute, 11 countries