T2K neutrino-nucleus cross-section results

M. Buizza Avanzini on behalf of the T2K collaboration

xsec

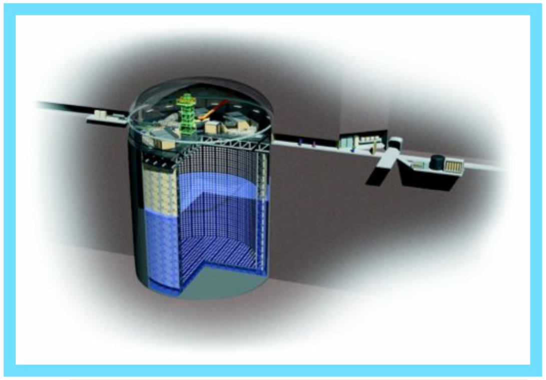
NOW 2018

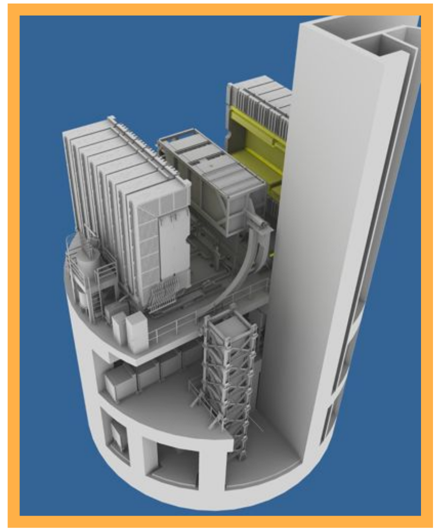
Rosa Marina, Ostuni, Sep. 12th 2018

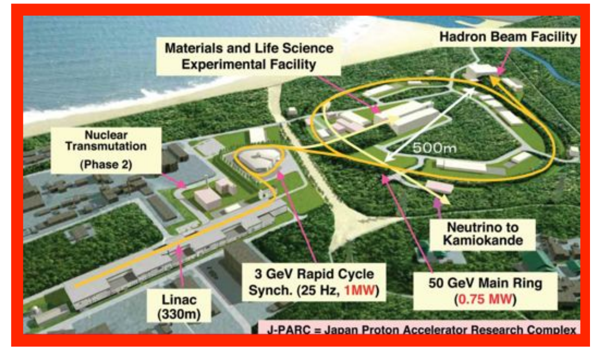
T2K experiment

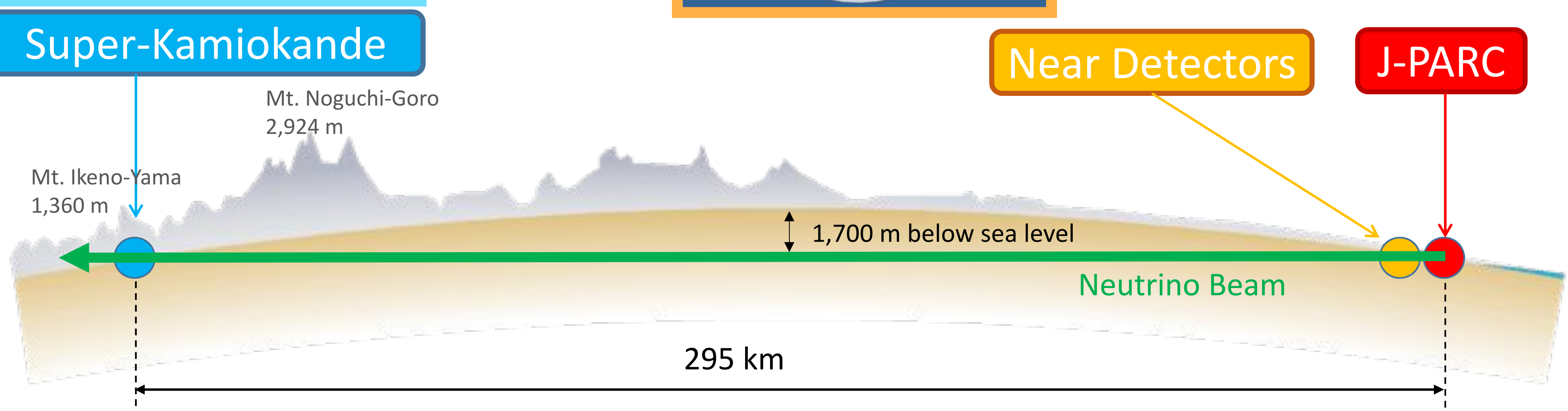
See E. Zimmerman talk… the first of the conference!

Long-baseline accelerator neutrino oscillation experiment… off-axis!









Far detector: oscillation analyses

Near detectors:

- Constrain flux and cross-section model before oscillation
- Cross-section measurements in unoscillated beam

Why cross section uncertainty is a problem?

Oscillation experiments require to know $\Phi(E_\nu)$, $\sigma(E_\nu,x)$ & $D(x)$…
simplified version:

$$\frac{N^{far}_{events}(\vec{x})}{N^{near}_{events}(\vec{x})} = \frac{\sigma(E_\nu,\vec{x}) \otimes \Phi(E_\nu) \otimes D^{far}(\vec{x}) \otimes P_{osc}(E_\nu)}{\sigma(E_\nu,\vec{x}) \otimes \Phi(E_\nu) \otimes D^{near}(\vec{x})}$$

Why cross section uncertainty is a problem?

Oscillation experiments require to know $\Phi(E_\nu)$, $\sigma(E_\nu, x)$ & $D(x)$…
simplified version:

$$\frac{N_{events}^{far}(\vec{x})}{N_{events}^{near}(\vec{x})} = \frac{\sigma(E_\nu,\vec{x}) \otimes \Phi(E_\nu) \otimes D^{far}(\vec{x}) \otimes P_{osc}(E_\nu)}{\sigma(E_\nu,\vec{x}) \otimes \Phi(E_\nu) \otimes D^{near}(\vec{x})}$$

ν beam is not monochromatic

Why cross section uncertainty is a problem?

Oscillation experiments require to know $\Phi(E_\nu)$, $\sigma(E_\nu,\vec{x})$ & $D(\vec{x})$…
simplified version:

Cross-sections relate E_ν and observables; do not cancel in the ratio

$$\frac{N^{far}_{events}(\vec{x})}{N^{near}_{events}(\vec{x})} = \frac{\sigma(E_\nu,\vec{x}) \otimes \Phi(E_\nu) \otimes D^{far}(\vec{x}) \otimes P_{osc}(E_\nu)}{\sigma(E_\nu,\vec{x}) \otimes \Phi(E_\nu) \otimes D^{near}(\vec{x})}$$

ν beam is not monochromatic

Why cross section uncertainty is a problem?

Oscillation experiments require to know $\Phi(E_\nu)$, $\sigma(E_\nu, \bar{x})$ & $D(\bar{x})$…
simplified version:

Cross-sections relate E_ν and observables; do not cancel in the ratio

$$\frac{N^{far}_{events}(\vec{x})}{N^{near}_{events}(\vec{x})} = \frac{\sigma(E_\nu,\vec{x}) \otimes \Phi(E_\nu) \otimes D^{far}(\vec{x}) \otimes P_{osc}(E_\nu)}{\sigma(E_\nu,\vec{x}) \otimes \Phi(E_\nu) \otimes D^{near}(\vec{x})}$$

ν beam is not monochromatic

Detector effects (efficiency, acceptance, target, resolution)

Why cross section uncertainty is a problem?

Oscillation experiments require to know $\Phi(E_\nu)$, $\sigma(E_\nu, \bar{x})$ & $D(\bar{x})$…
simplified version:

Cross-sections relate E_ν and observables; do not cancel in the ratio

Oscillation probability depends on true E_ν

$$\frac{N^{far}_{events}(\vec{x})}{N^{near}_{events}(\vec{x})} = \frac{\sigma(E_\nu,\vec{x}) \otimes \Phi(E_\nu) \otimes D^{far}(\vec{x}) \otimes P_{osc}(E_\nu)}{\sigma(E_\nu,\vec{x}) \otimes \Phi(E_\nu) \otimes D^{near}(\vec{x})}$$

ν beam is not monochromatic

Detector effects (efficiency, acceptance, target, resolution)

Why cross section uncertainty is a problem?

Oscillation experiments require to know $\Phi(E_\nu)$, $\sigma(E_\nu, \bar{x})$ & $D(\bar{x})$...
simplified version:

Cross-sections relate E_ν and observables; do not cancel in the ratio

Oscillation probability depends on true E_ν

$$\frac{N^{far}_{events}(\vec{x})}{N^{near}_{events}(\vec{x})} = \frac{\sigma(E_\nu, \vec{x}) \otimes \Phi(E_\nu) \otimes D^{far}(\vec{x}) \otimes P_{osc}(E_\nu)}{\sigma(E_\nu, \vec{x}) \otimes \Phi(E_\nu) \otimes D^{near}(\vec{x})}$$

ν beam is not monochromatic

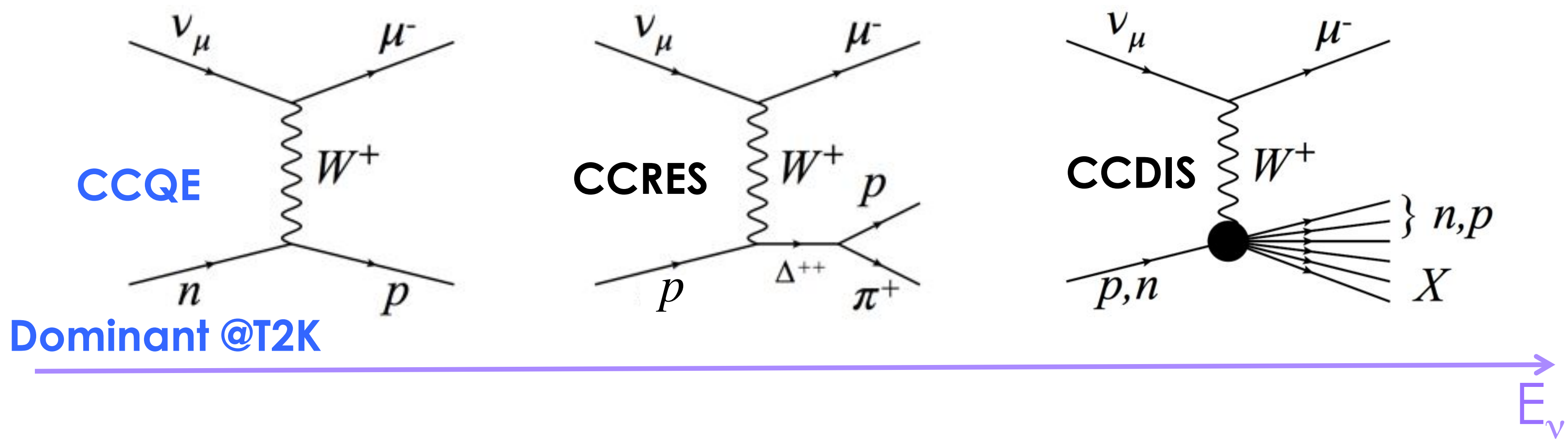
Detector effects (efficiency, acceptance, target, resolution)

Near/far ratios don't fully cancel systematics:

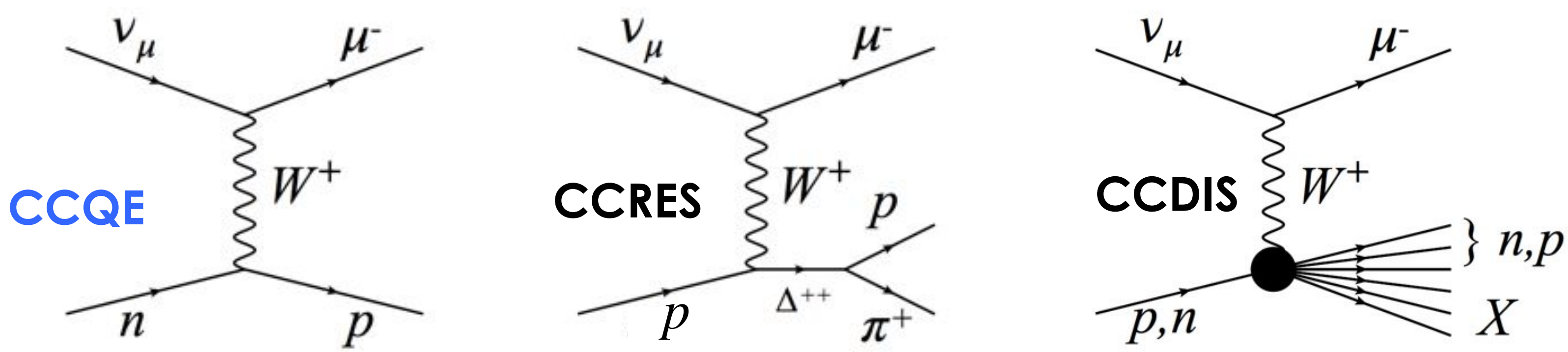
- $\Phi(E_\nu)$ change due to geometry and oscillation
- Acceptance, efficiency and targets different in the 2 detectors
- ND is ν_μ dominated, but used to infer (via model) ν_e

Uncertainties on cross section is the main source of systematics for T2K.
For future Long baseline experiments: require few % cross-section systematics!

Neutrino Interactions
(and nuclear effects)



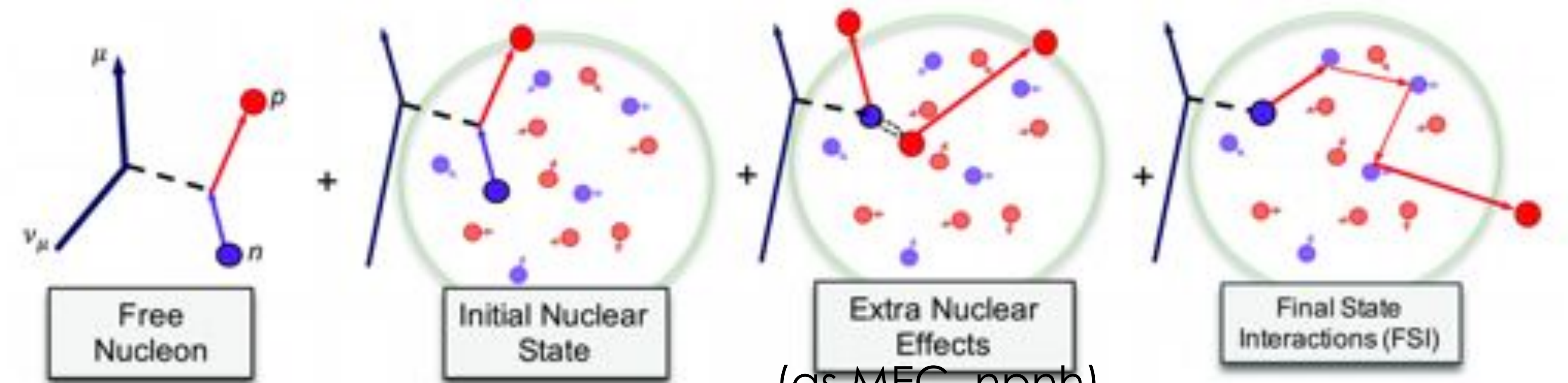
Neutrino Interactions (and nuclear effects)



Dominant @T2K

E_ν

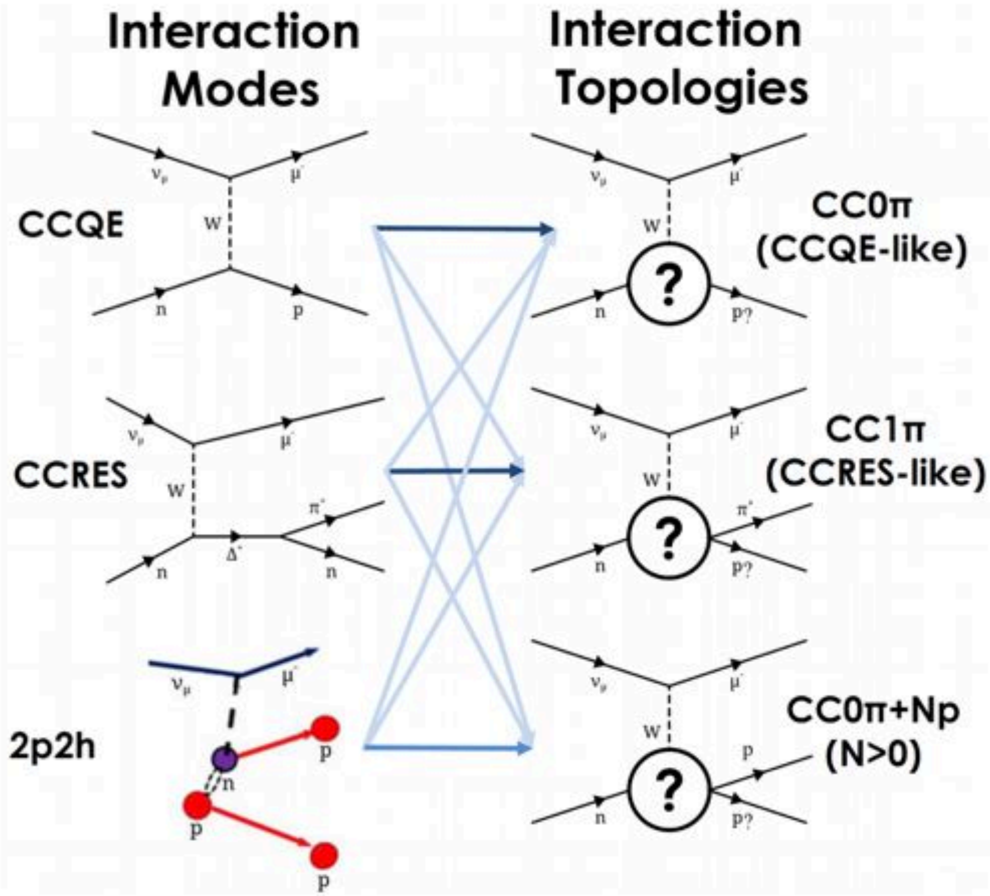
But Nucleons bound in the nucleus ⇒ Nuclear effect!



(as MEC, npnh)

How to select a genuine CCQE interaction?? No way…

T2K strategy: topology catalogue



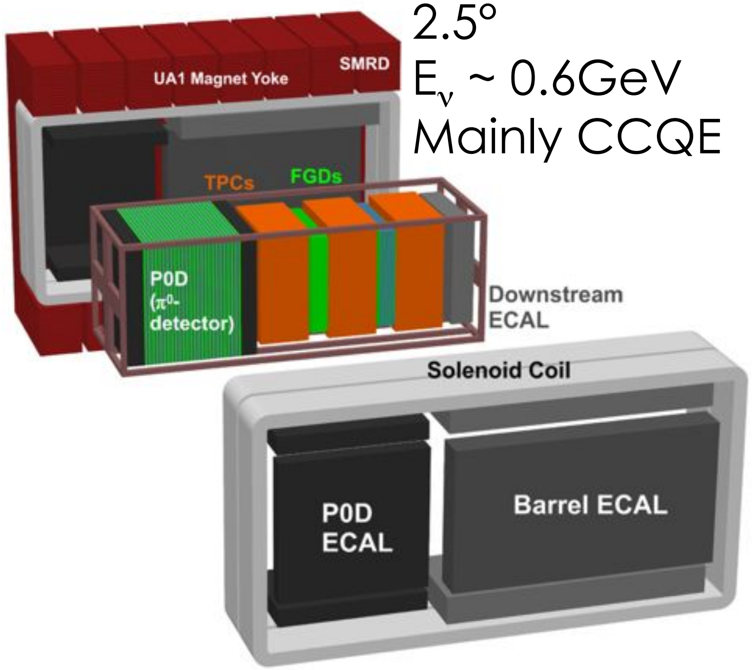
Nuclear and **detector effects** obfuscate true interaction mode
Signal definition based on **final state topology**, to avoid model dependence trying to extract a CCQE component

NEUT 5.3.2

Int/topo	CC0π	CC1π
CCQE	82%	0.3%
CCRES	6%	77.1%
CCDIS	0.2%	7%
2p2h	11.8%	0.04%

Comparing different generators: NEUT, GENIE, NuWro, GIBUU

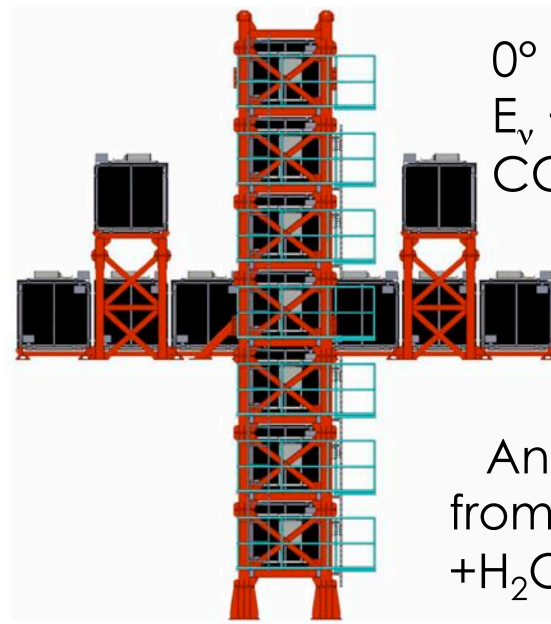
T2K strategy: multi target, multi flux



2.5°
E_ν ~ 0.6GeV
Mainly CCQE

ND280 off-axis detector located 280 m from the target:

- π^0 detector (P0D); targets: CH+H_2O+Pb
- 3 Time Projection Chambers (TPC); target: Ar
- 2 Fine-grained detectors (FGD); targets: CH +H_2O
- Electromagnetic calorimeters (ECal)
- UA1 refurbished Magnet instrumented with side muon range detector (SMRD)



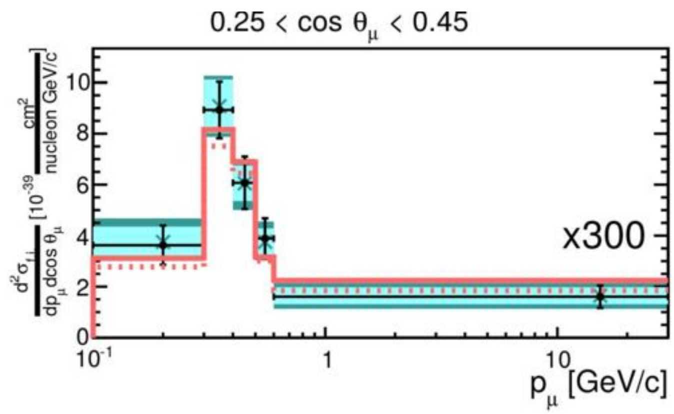
0°
E_ν ~ 1GeV
CCRES important!

INGRID on-axis detector:
- Monitor the beam direction
- 14 modules arranged as a cross and other 2 outside the main cross; targets: CH+Fe
- Extra modules
- Proton Module (CH)
- Water module (H_2O)

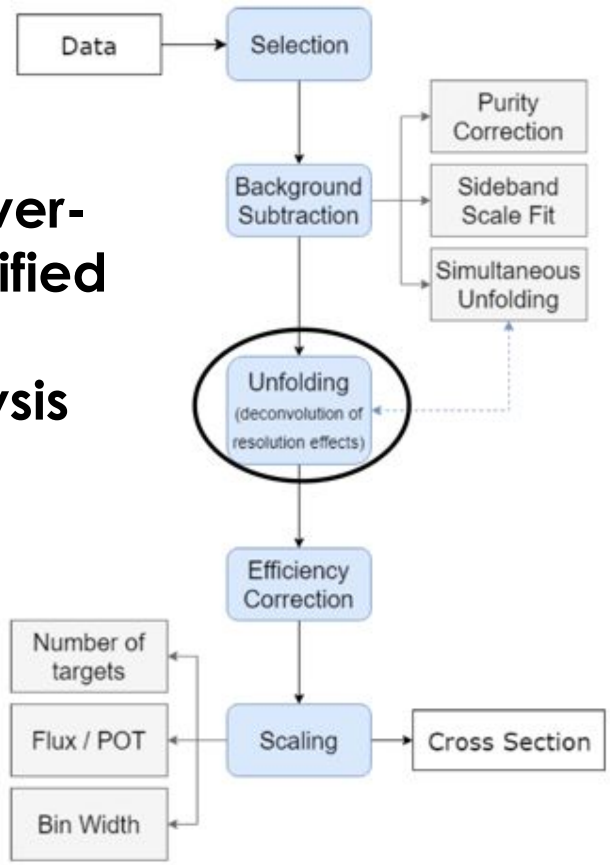
And soon data from Wagasci (CH +H_2O), 1.6° off axis

T2K strategy: observables & techniques

Observables chosen in order to avoid model dependence: mainly muon kinematics (p_μ and $\cos\theta_\mu$) but also new (xsec) model independent variables for hadrons. Usually double differential and flux integrated xsec measured



An over-simplified xsec analysis



- **Techniques**: blind analysis. D'Agostini or binned likelihood fit for unfolding. Data-driven regularization. No bias from prior checked on lots of pseudo data sets. After lot of checks and reviews: unblind

- Also started « forward folding » techniques (not yet shown here)

T2K measurements

1. **CC-inclusive**
   - on CH off axis
   - on CH, Fe, H_2O on axis

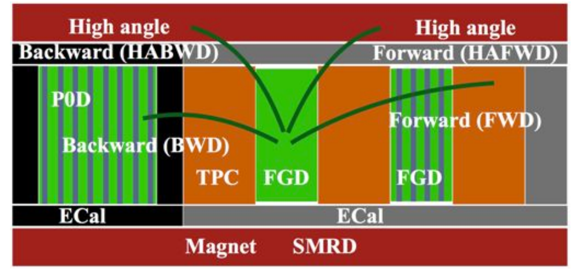
2. **CC0π**
   - ν_μ on CH off-axis
   - $\nu_\mu$on H_2O off axis
   - ν_μ+p on CH off-axis
   - Anti-ν_μ on H_2O off axis (NEW!)

3. **CC1π on CH and H_2O**

4. **NC1π^0**

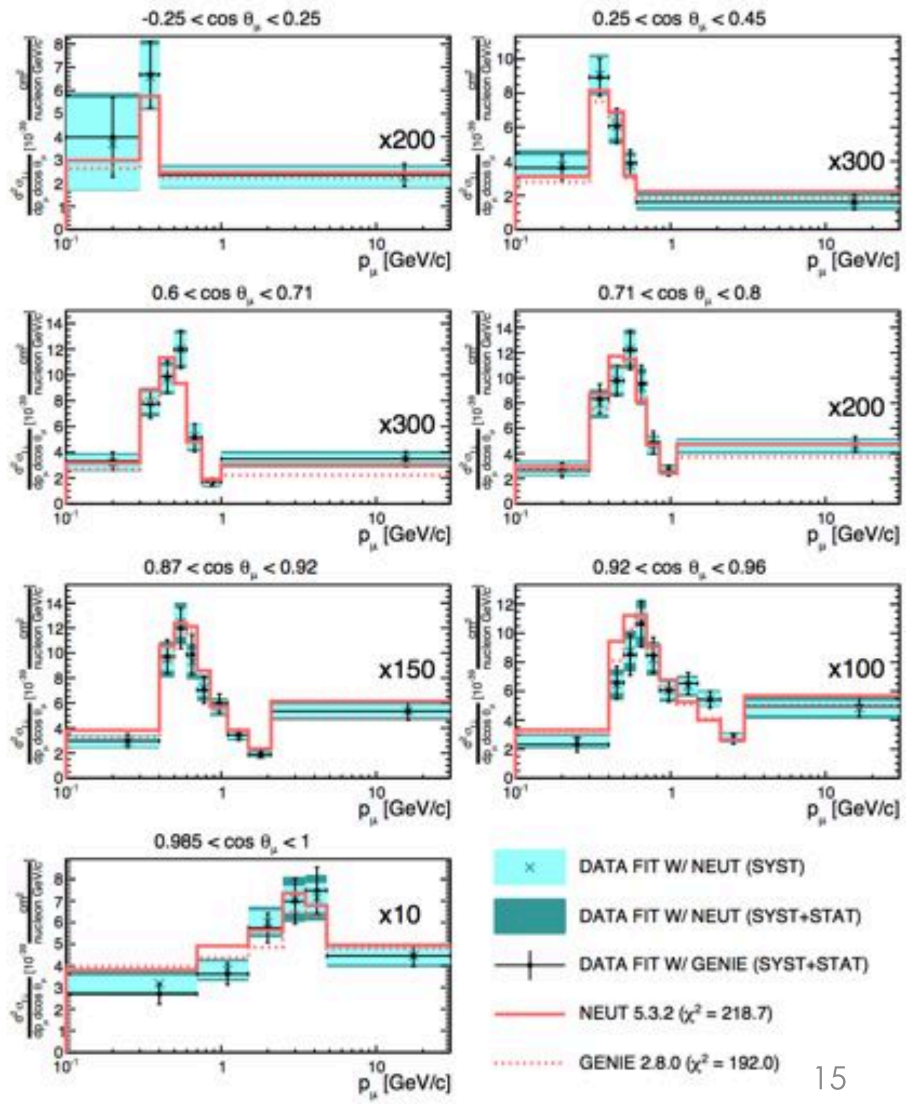
5. **ν_e selection**

CC Inclusive on CH



Muon kinematics double differential cross section.

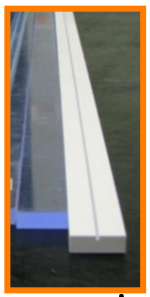
- Off-axis (FGD1)
- Dominated by CCQE due to low energy beam
- 4π selection
- Maximum likelihood fit
- Flux integrated cross section to avoid neutrino energy dependence
- Data fit with NEUT and GENIE as prior to check we do not have model dependence
- Background constrained with two sidebands
- 5.7×10^{20} POT



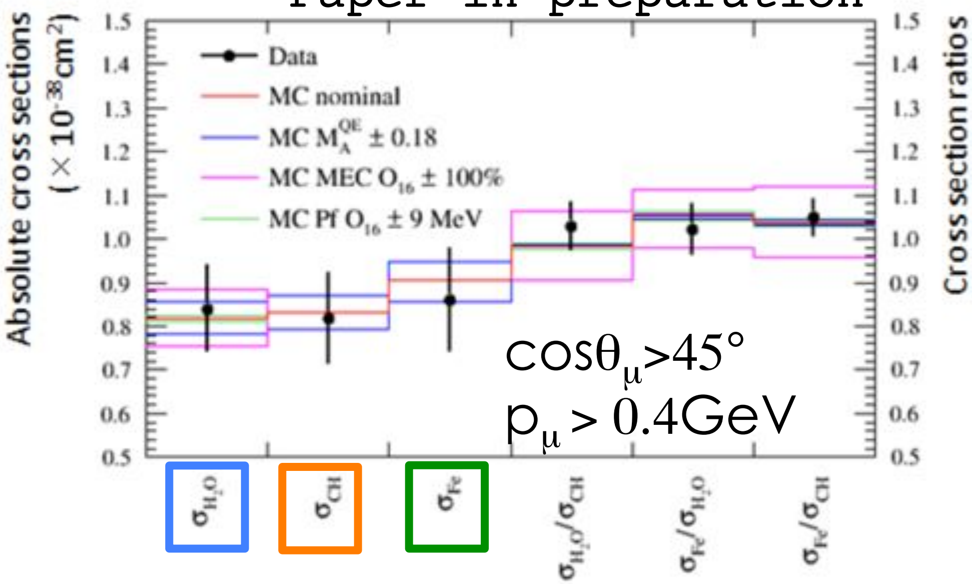
PRD 98, 012004 (2018)

CC Inclusive A scaling

Combination measurements to constrain physics models: Look at different targets to probe A-scaling models: how the cross section scale with the size of the nucleus
On axis: H_2O, CH and Fe targets



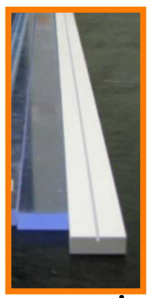
Paper in preparation



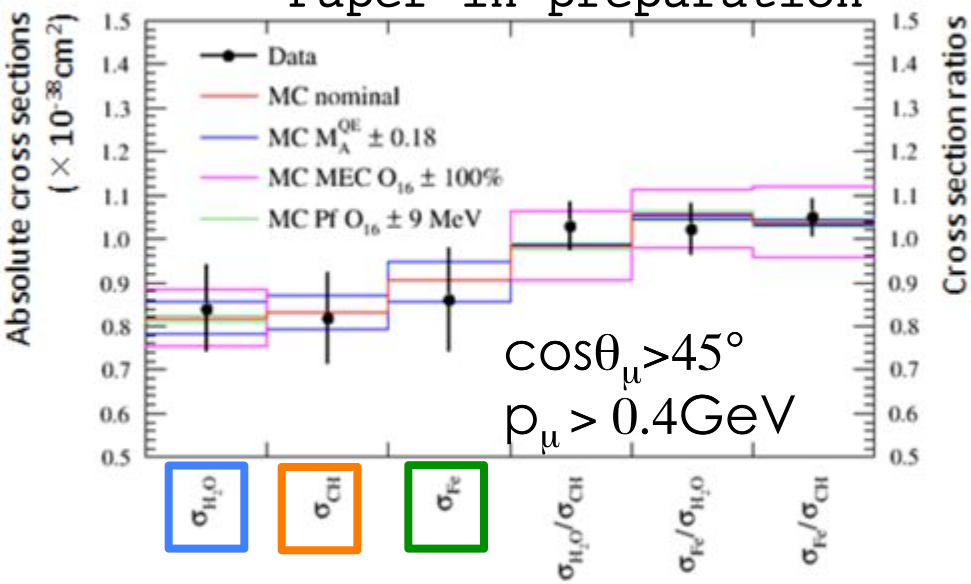
CC Inclusive A scaling

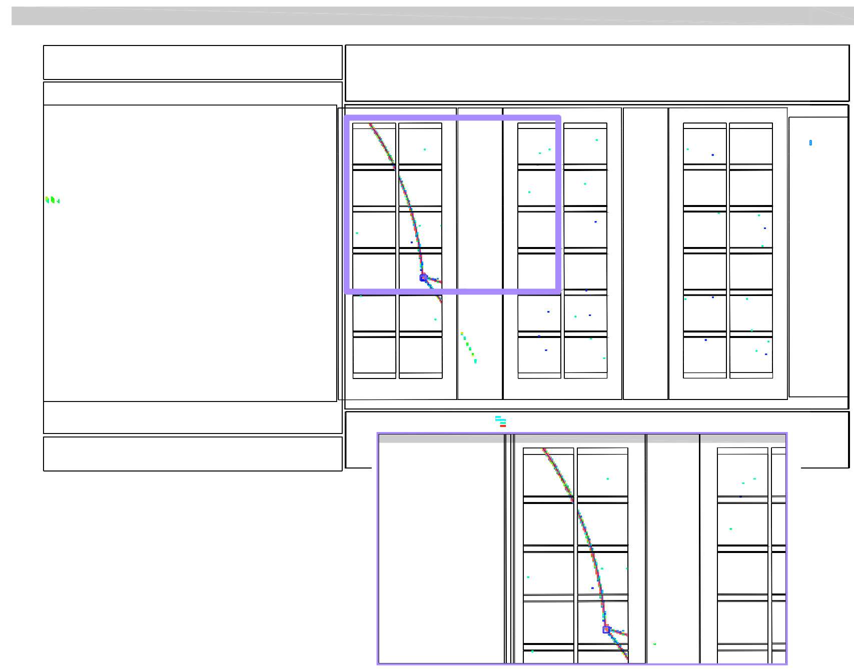
Combination measurements to constrain physics models: Look at different targets to probe A-scaling models: how the cross section scale with the size of the nucleus

On axis: H_2O, CH and Fe targets



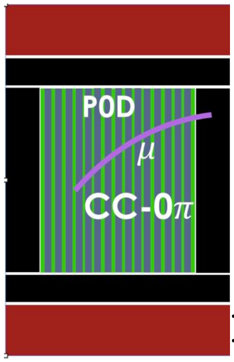
Paper in preparation



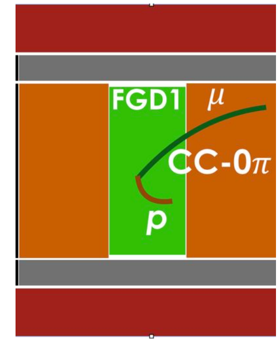


Promising event reconstruction in gas TPC… soon cross section measurement on Ar???

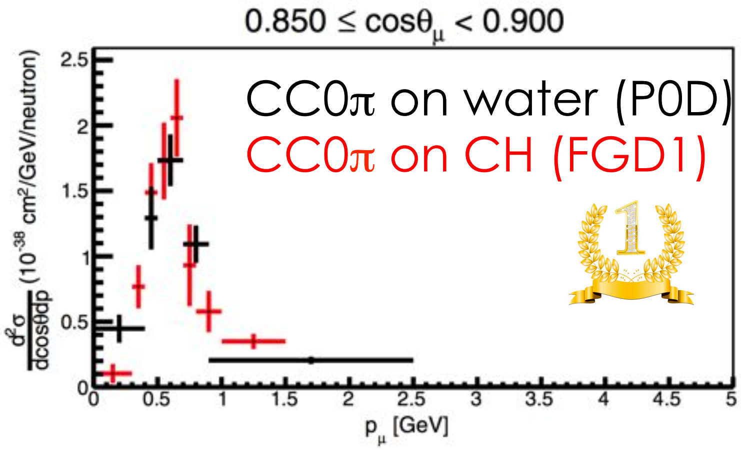
Important for future LBL experiments



CC0π on CH and H_2O

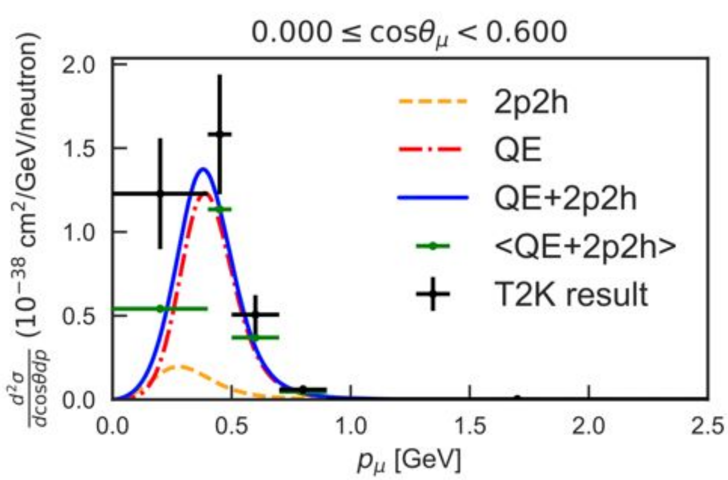


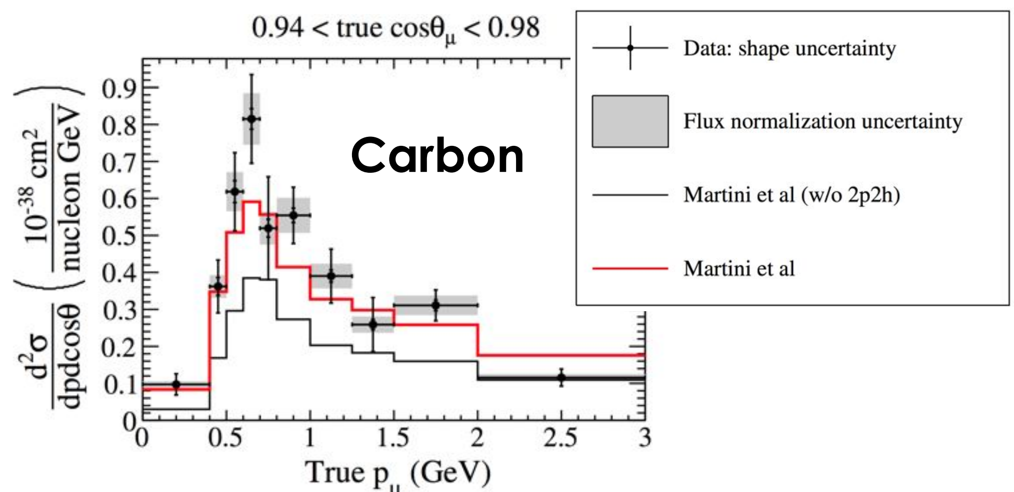
PRD 97, 012001 (2018)



- Off axis.
- CC0π ~ 80% CCQE + 12% 2p2h
- Two independent measurements: FGD1 (2016) and P0D (2018)
- Comparison with various models
- Low momentum, high angle region under-predicted
- 2p2h required
- Try to look at the protons to learn more!

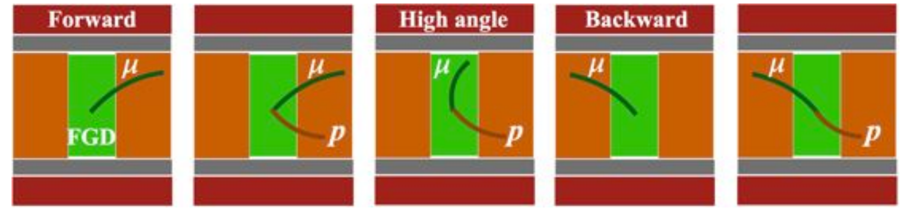
Water: comparison with Susav2



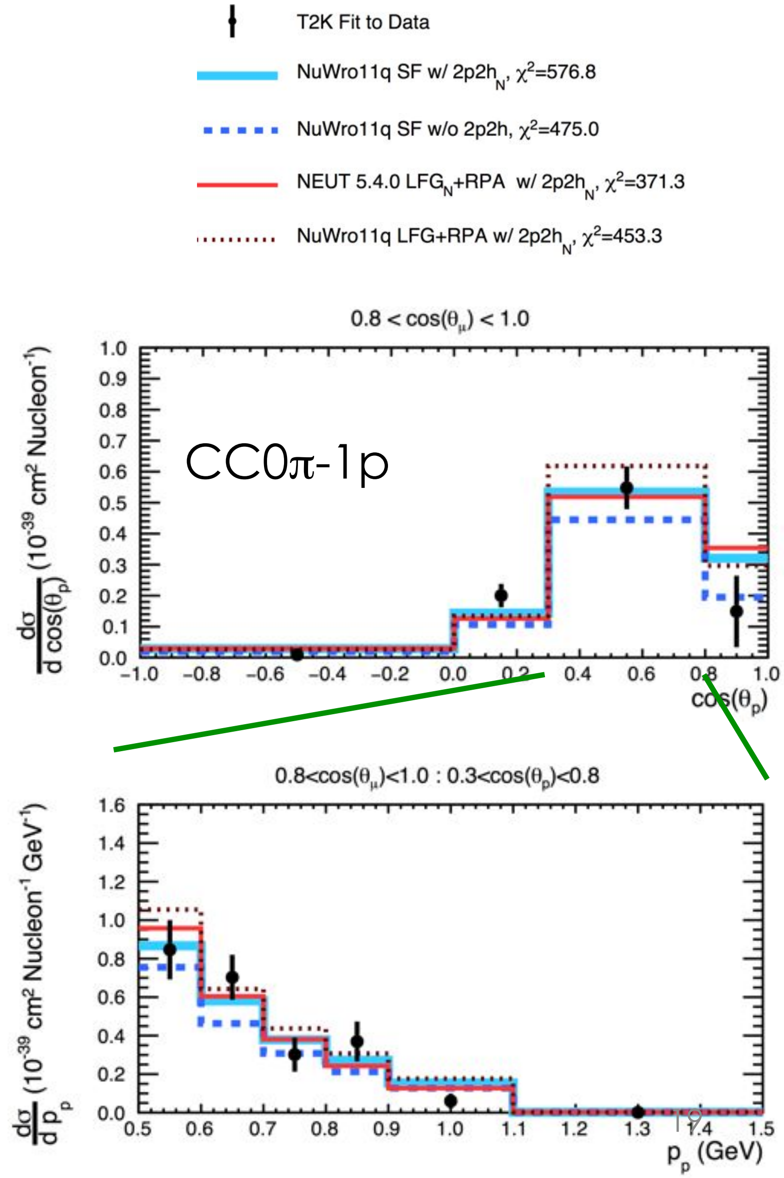


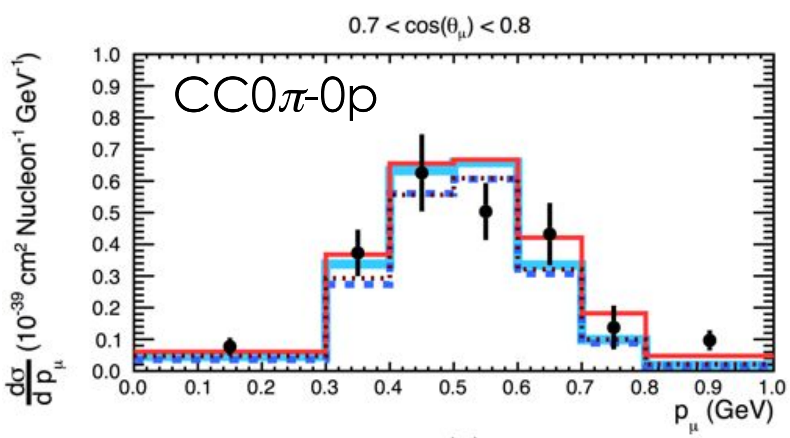
PRD 93, 112012 (2016)

CC0π+p on CH



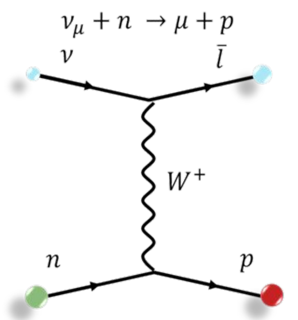
- Off axis
- Cross section extracted as function of the muon momentum and angle for CC0π-0p
- Cross section extracted as function of the muon and proton angle and muon momentum for CC0π-1p with momentum greater than 500 MeV/c
- No model describing correctly the whole considered phase space





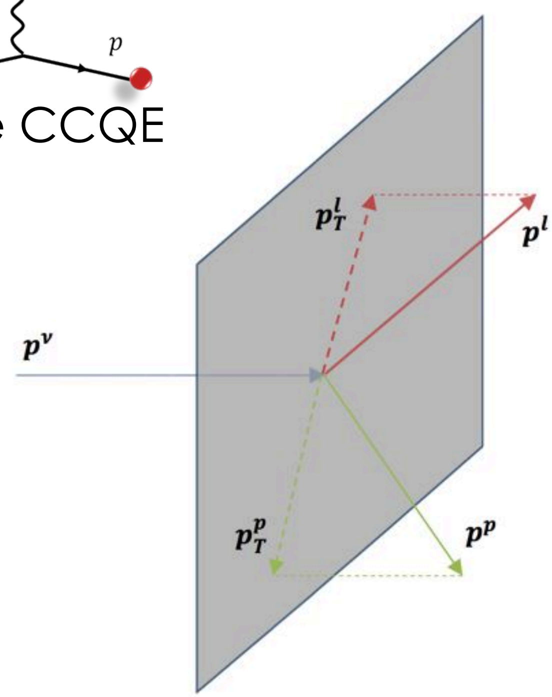
PRD 98, 032003 (2018)

Single Transverse Variables (STV)



Pure CCQE

Looking at new observables as suggested in `Phys. Rev. C 94, 015503 (2016)`

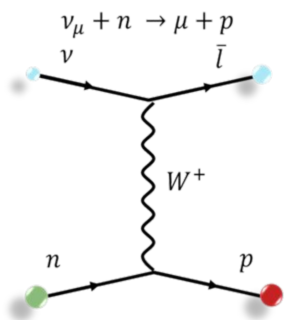


$$p_T^l = -p_T^p$$

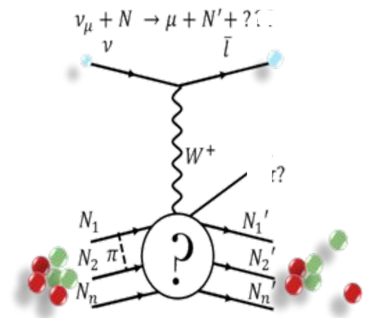
Search for momentum imbalance (lepton-hadron) in the transverse plane. Approaching 2p2h and Final State Interaction with hadron variables.

Single Transverse Variables (STV)

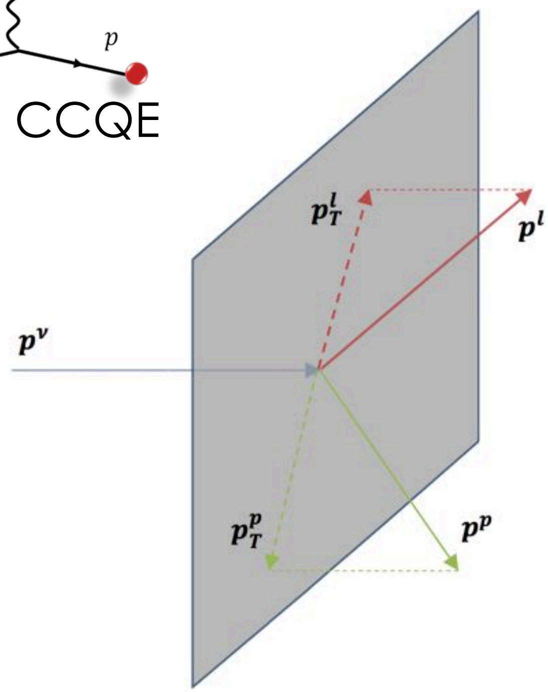
Looking at new observables as suggested in `Phys. Rev. C 94, 015503 (2016)`



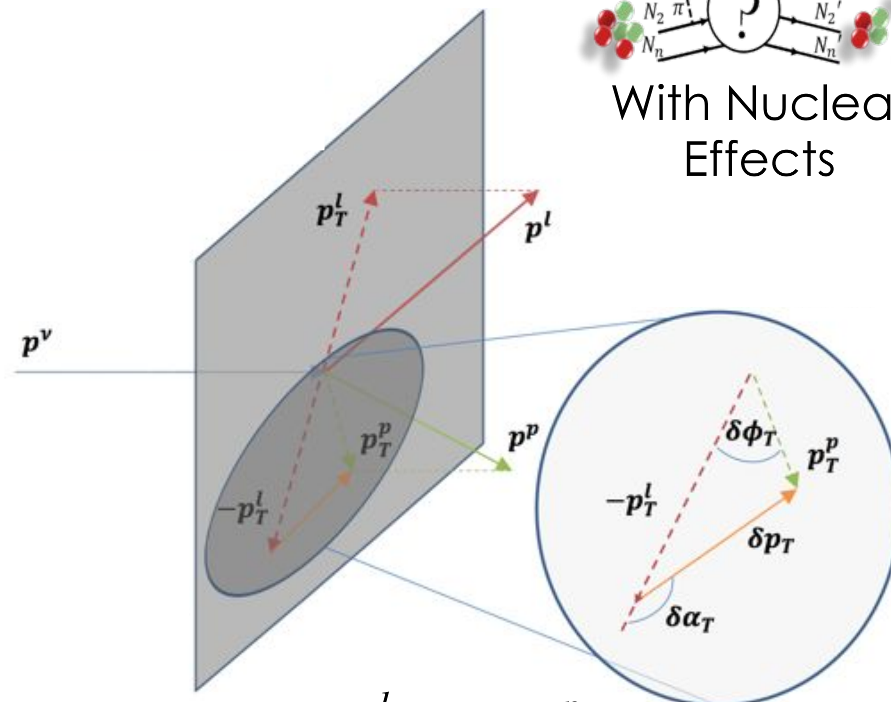
Pure CCQE



With Nuclear Effects



$$p_T^l = -p_T^p$$



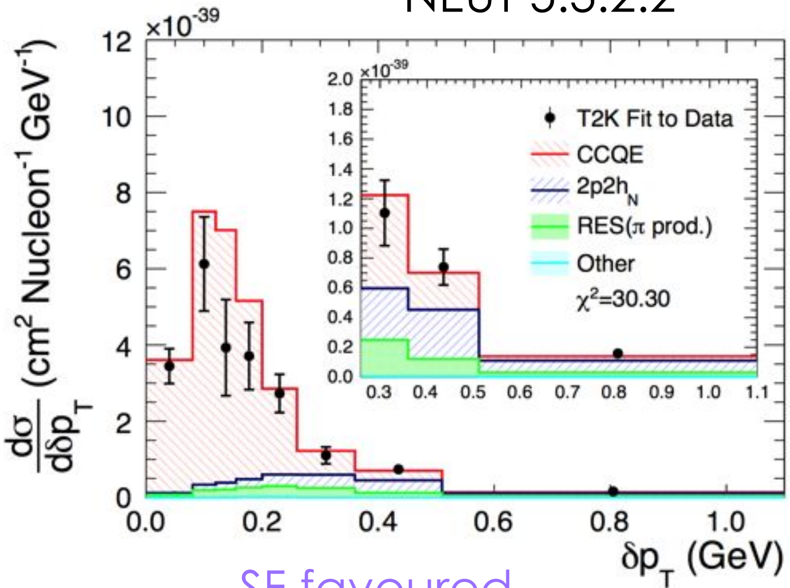
$$p_T^l \neq -p_T^p$$

Search for momentum imbalance (lepton-hadron) in the transverse plane.
Approaching 2p2h and Final State Interaction with hadron variables.

CC0π+p on CH with STV

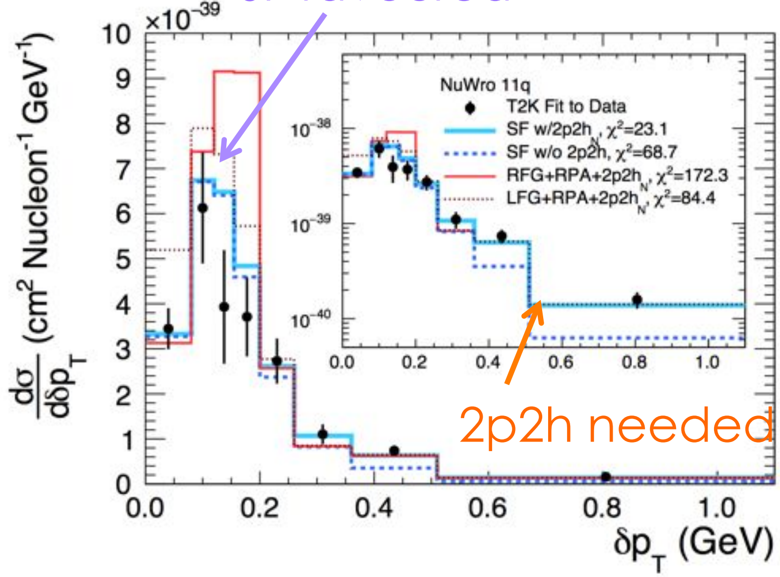
NEUT 5.3.2.2

PRD 98, 032003 (2018)

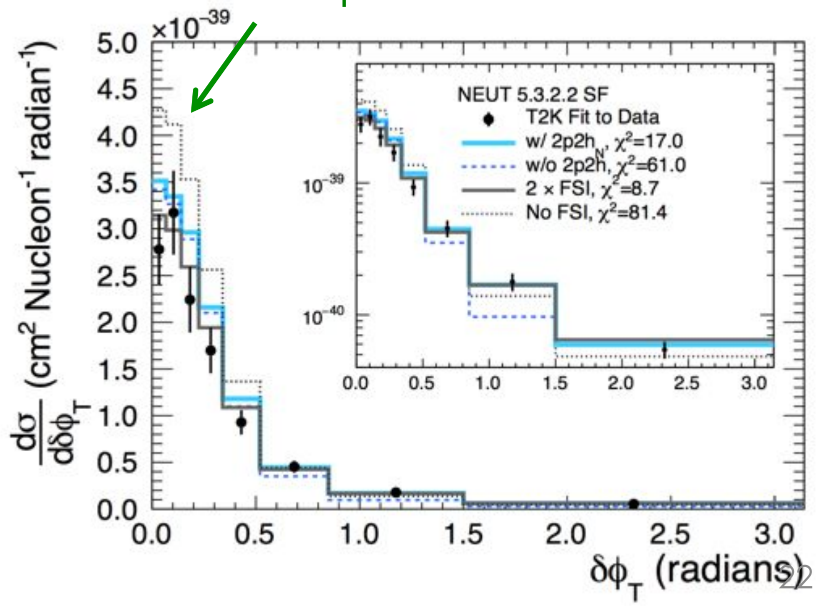


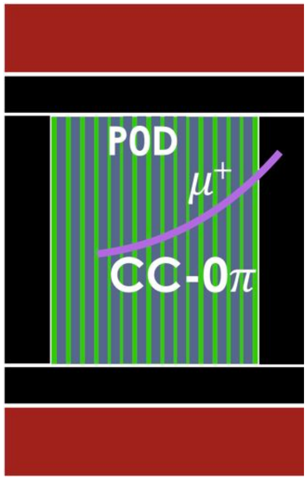
- Low δp_t, below Fermi momentum: mainly CCQE
- δp_t probe for initial state nucleon
- Preference for spectral function
- Not clear winner yet

SF favoured



More FSI required

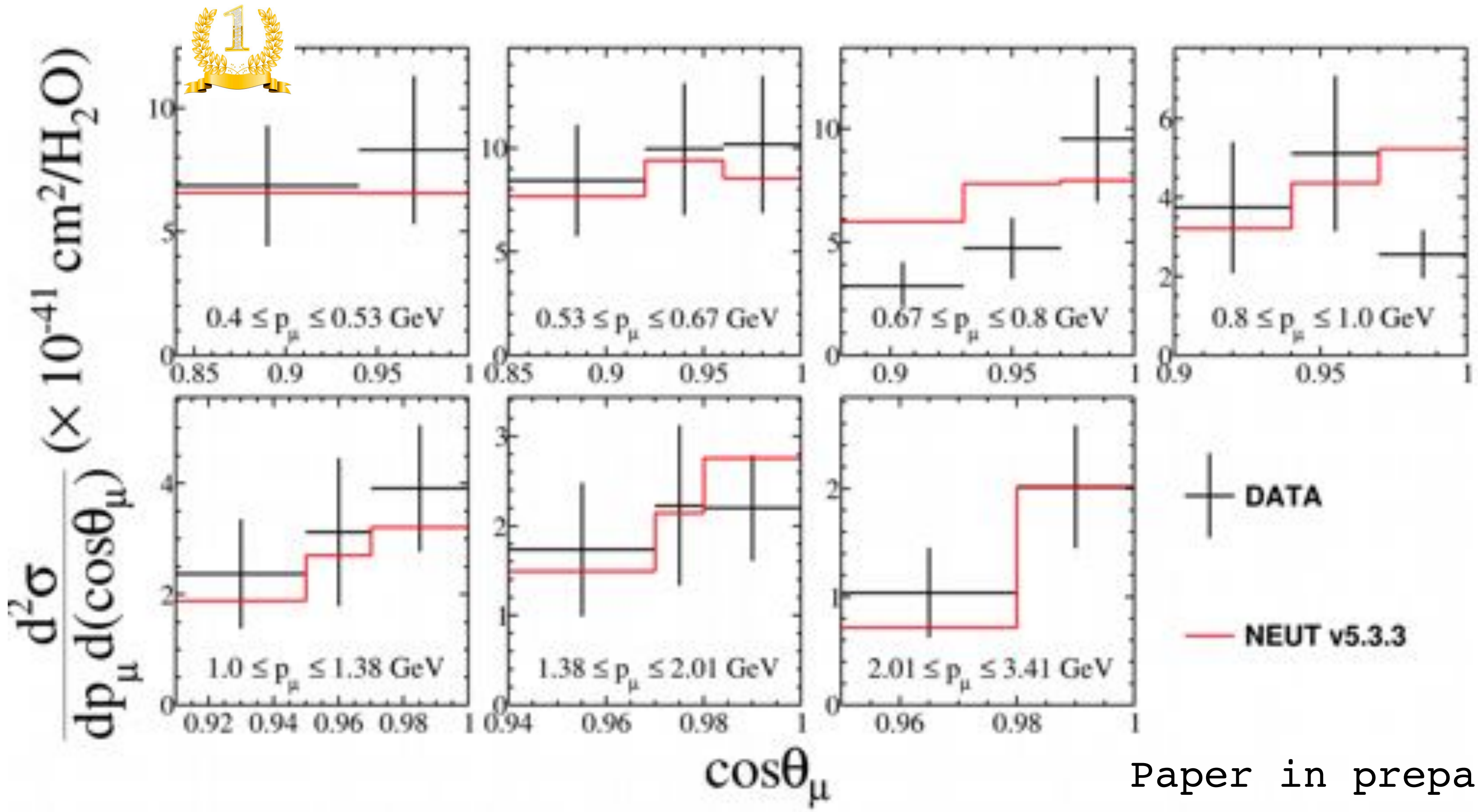




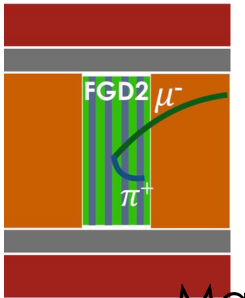
CC0π anti-ν_μ on H_2O

NEW!

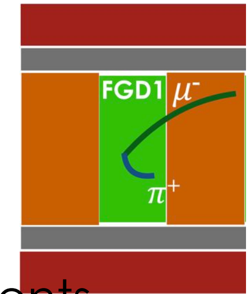
- Off axis
- P0D data with and without water bags filled.
- **Joint fit:** Fit simultaneously water-in and water-out samples: water out samples act as control regions for non-water events



Paper in preparation



$CC1\pi^+$ on CH and H_2O

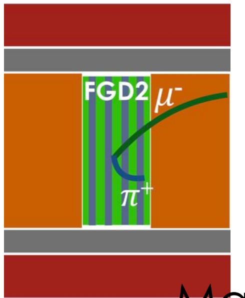


Look at muon and pion kinematics

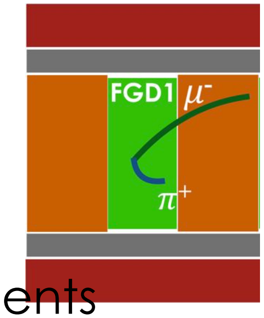
Main background for T2K, but signal for other oscillation experiments

Already public results: off axis on H_2O (FGD2) and CH (FGD1)

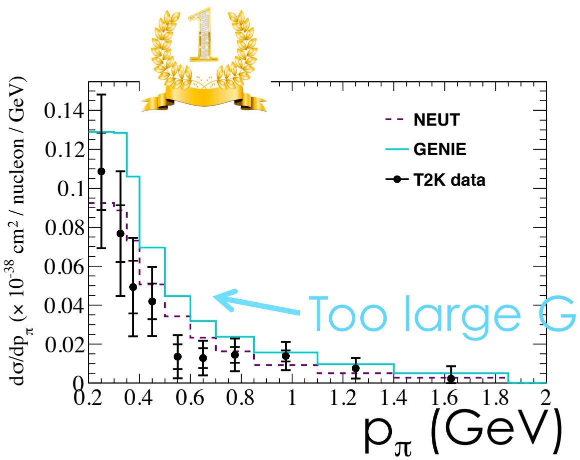
Many other analyses on-going: ν_μ on axis on CH and H_2O, anti-ν_μ and ν_μ off-axis on CH and H_2O



$CC1\pi^+$ on CH and H_2O



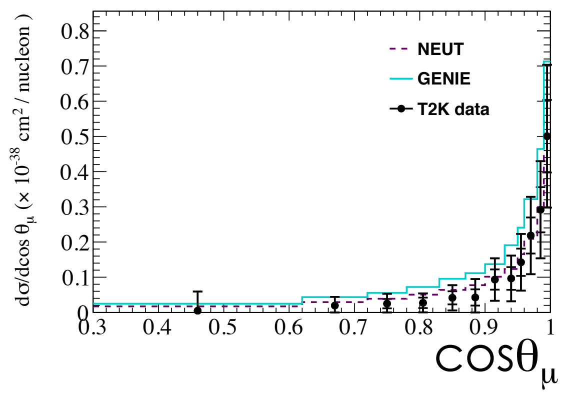
Look at muon and pion kinematics
Main background for T2K, but signal for other oscillation experiments
Already public results: **off axis on H_2O (FGD2)** and CH (FGD1)
Many other analyses on-going: ν_μ on axis on CH and H_2O, anti-ν_μ and ν_μ off-axis on CH and H_2O

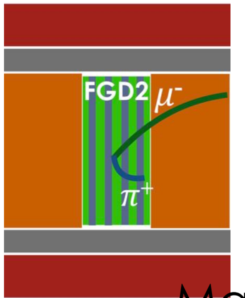


Too large GENIE xsec

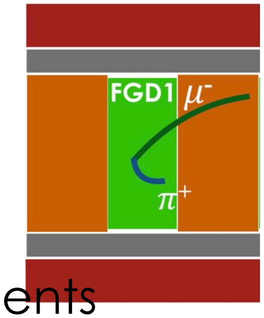
PRD 95 (2017) 012010

$\cos\theta_\mu, \theta_\pi > 0.3$
p_μ, $p_\pi > 0.2$ GeV





CC1π^+ on CH and H_2O

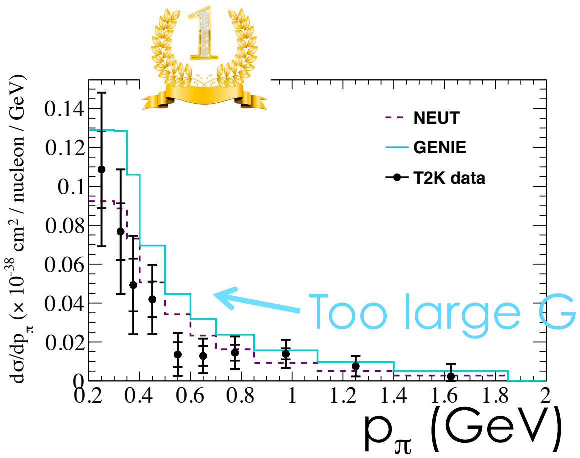


Look at muon and pion kinematics

Main background for T2K, but signal for other oscillation experiments

Already public results: **off axis** on **H2O (FGD2)** and **CH (FGD1)**

Many other analyses on-going: ν_μ on axis on CH and H_2O, anti-ν_μ and ν_μ off-axis on CH and H_2O

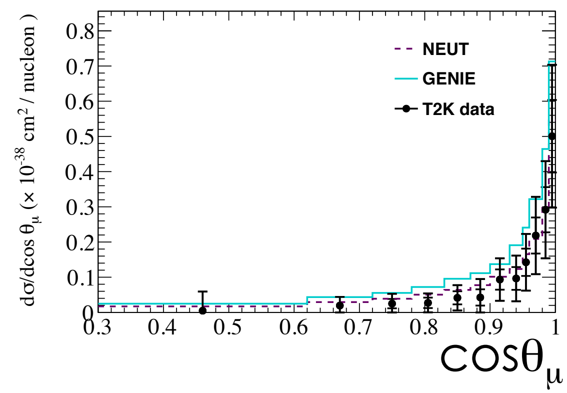


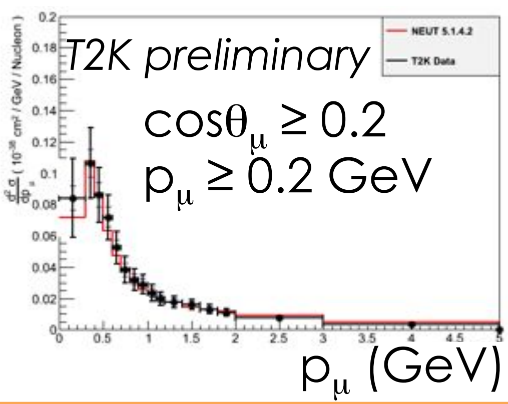
Too large GENIE xsec

PRD 95 (2017) 012010

$\cos\theta_\mu, \theta_\pi > 0.3$

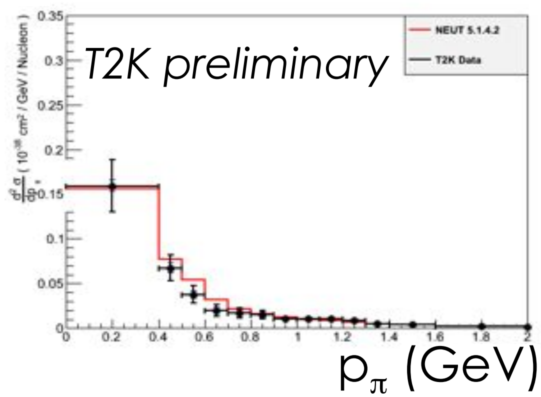
p_μ, $p_p > 0.2$ GeV





$\cos\theta_\mu \geq 0.2$

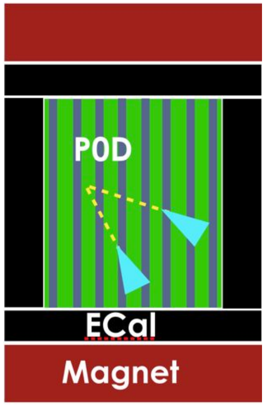
$p_\mu \geq 0.2$ GeV

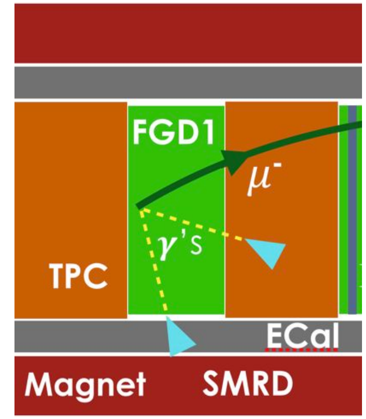


Paper in preparation: differential and double-differential cross section in large number of variables, included planar angle and hadron invariant mass

ν_μ CC1π^+ in P0D almost public, larger statistics and acceptance, first attempt to forward folding

NC1π^0 and CC1π^0

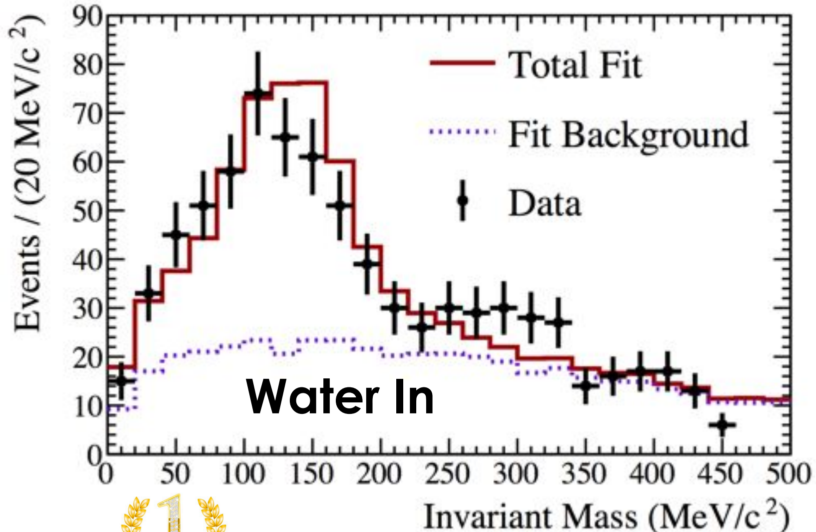




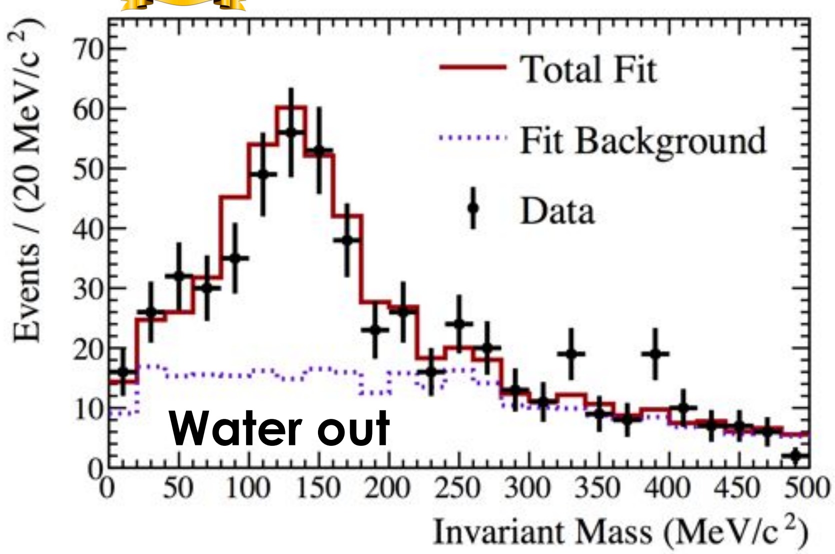
π^0, decaying in 2 γ' s, important background for appearence measurements at SK.

NC1π^0 rate measured in the P0D with subtraction method.

Consistent with prediction but still large uncertainties.



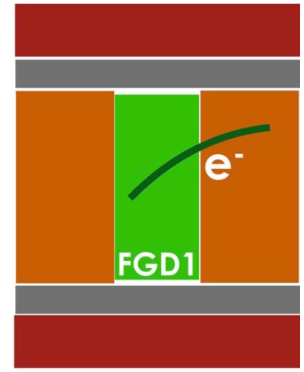
PRD 97 032002 (2018)



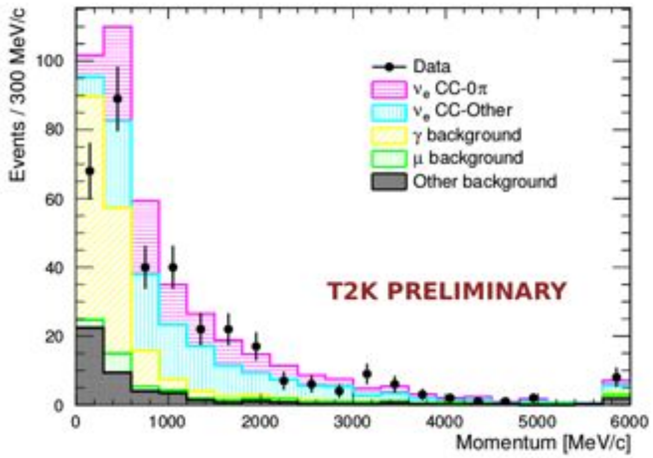
Ongoing xsec measurements of NC1π^0 in the P0D CC1π^0 analysis in FGD1

Data / Pred (water) = 0.68 ± 0.26(stat) ± 0.44(sys) ± 0.12(flux)

Electron neutrinos



ν_e in ν mode

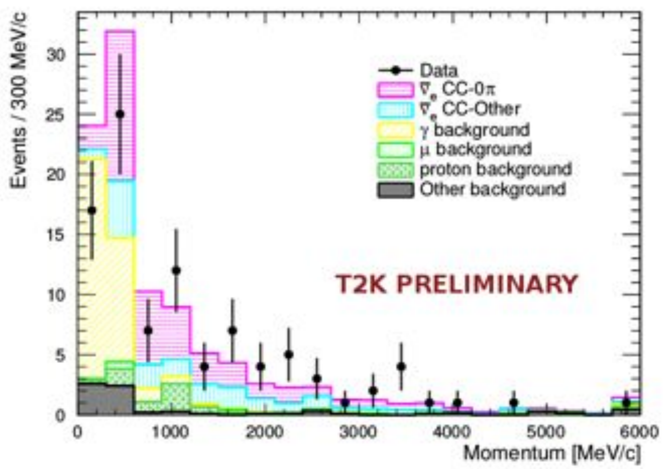


In the appearence channel (ν_μ -> ν_e), the intrinsic ν_e component in the ν_μ beam is the main **background**.

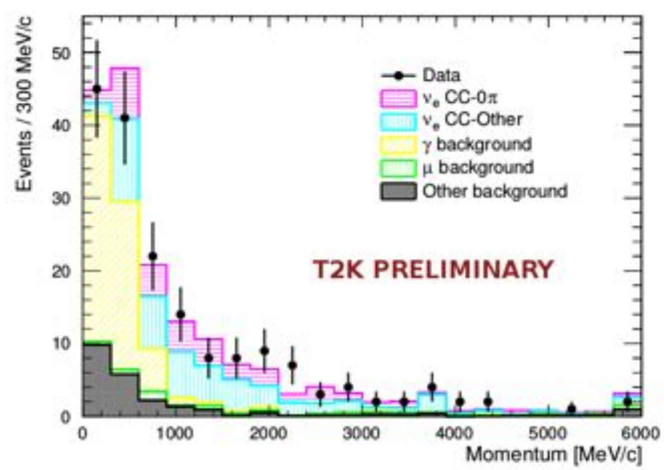
Very few measuerements existing

ν_e: very challenging selection because of low statistic and π^0 background

Anti-ν_e in anti-ν mode



ν_e in anti-ν mode



Cross section analysis coming soon, stay tuned!

Still working hard

Ongoing analyses (ready soon):

- CCinclusive:
  - Anti-ν_μ
  - On Ar
- CC0π:
  - ν+antiν joint fit on C off axis
  - C+O off axis
  - C+Pb off axis
  - C on/off axis
  - +CC1π^+ on axis and off axis
  - Vertex activity for CC0π-1p
- CC1π
  - ν_μ H_2O off axis
  - ν_μ on axis on C and H_2O
- NC1π^0 and CC1π^0 on H_2O and CH off axis
- NC1γ

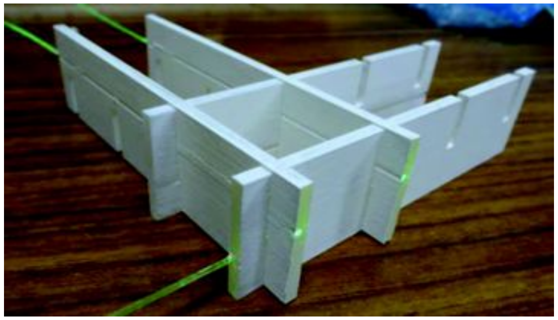
Plus many others at earlier stage

Almost 20 advanced analyses!

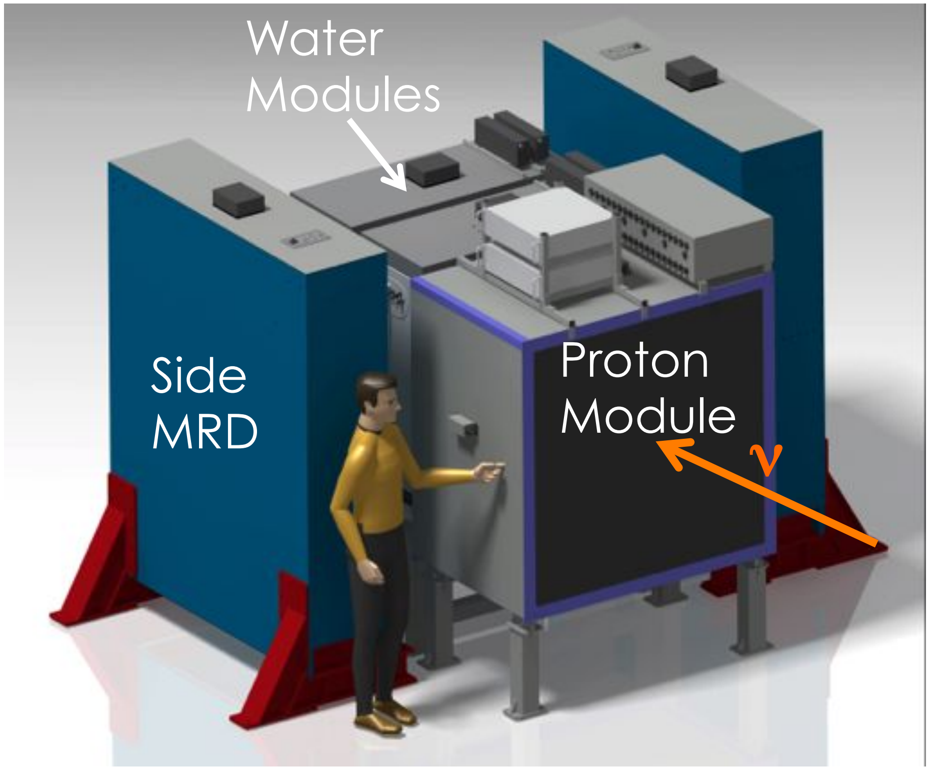
+ other 20 at earlier stage!

Future… almost present

WAGASCI: first near detector upgrade.
Now part of T2K



Segmented cubic CH/H_2O (WAGASCI) and SMRD
+Baby MIND, 1.6° off axis

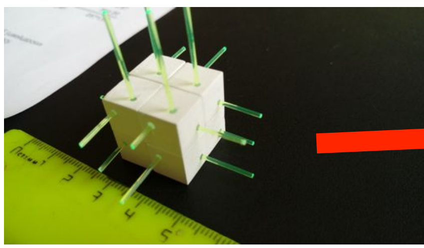


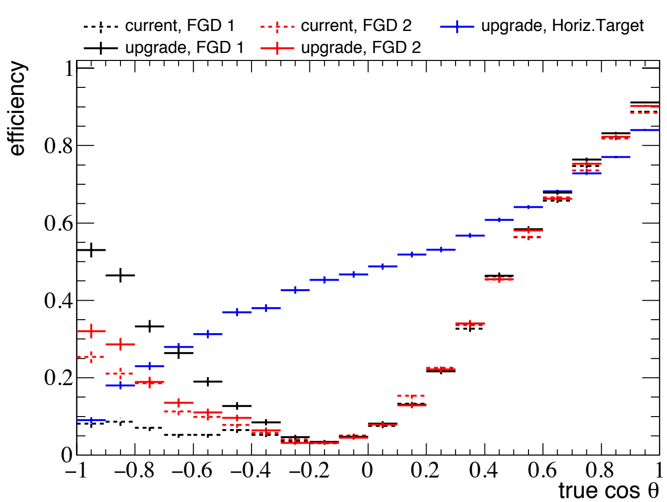
Baby MIND (JINTS 12 C07028)
installation @ JPARC

Future: ND280 Upgrade by 2021

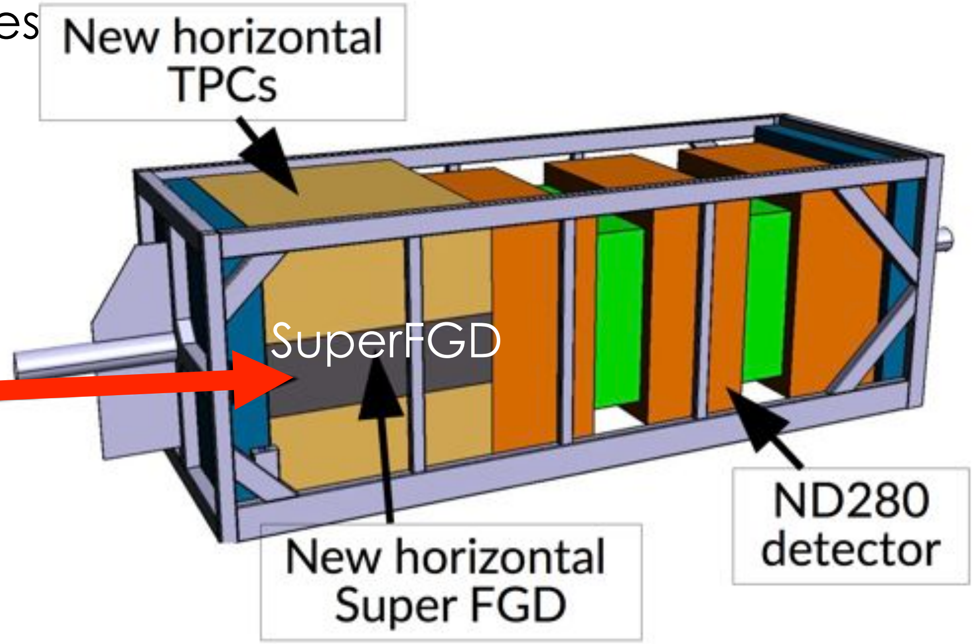
P0D replaced with a totally active target
SuperFGD: segmented 1cm^3 cubes
FGD Sandwiched by 2 TPCs

2 millions of 1cm^3 cubes.
Optical fibers in 3 directions





JINST 13 P02006, CERN-SPSC-P357



Improve:
- vertex reconstruction
- Acceptance 4π
- Low momentum protons
- Vertex activity
- Neutrons?

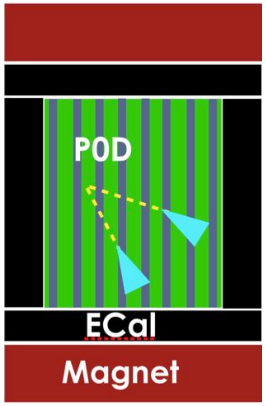
14 publications

Conclusions

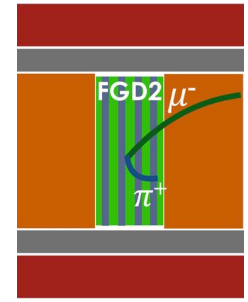
~20 ongoing analyses!

- Neutrino interaction uncertainties are critical for present and mostly future oscillation experiments
- Lot of efforts in T2K devoted to produce results with different targets, fluxes and as much as possible model independent
- Not clear picture yet… a part that we should increase our knowledge and understanding of these interactions soon!
- Still working hard to increase acceptance, statistics and to look at rare events with new variables
- T2K upgrades will produce even better results… stay tuned!

~20 planned analyses!



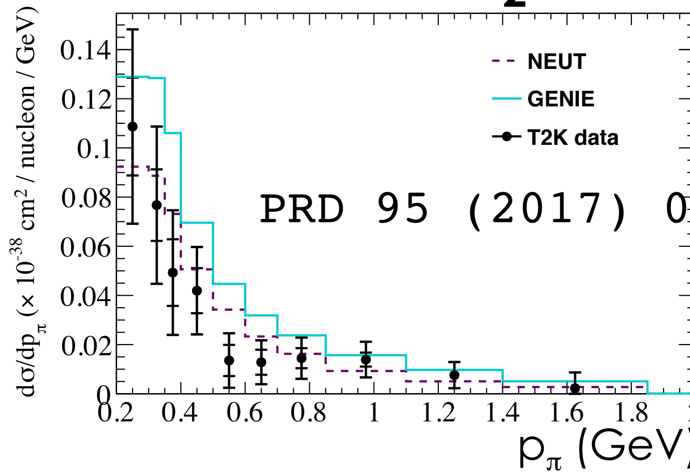
No time for everything!



See backup slides!

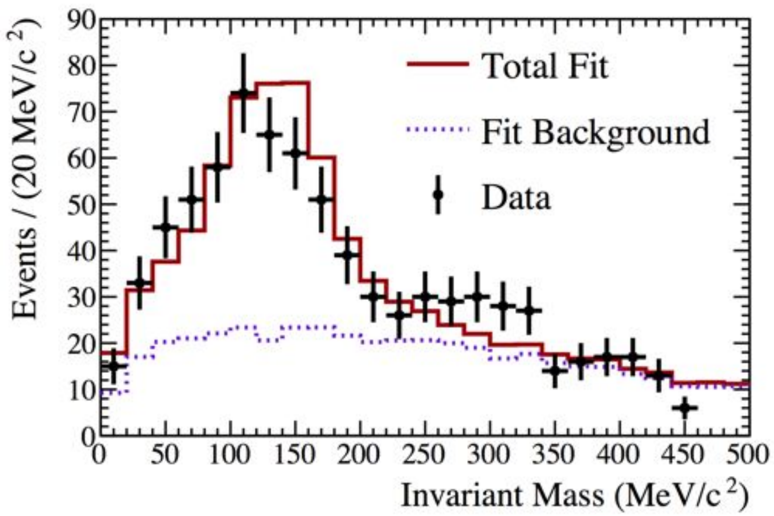
- NC1π^0 rate off axis on water
- CC1π^+: off axis on water and carbon

CC1π on H_2O



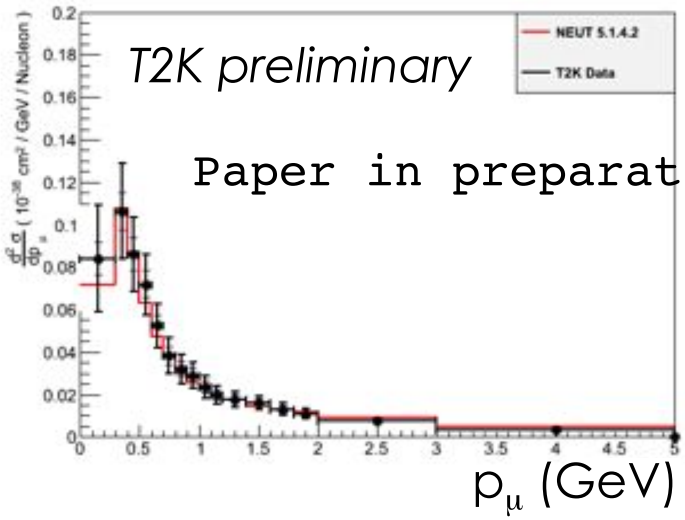
PRD 95 (2017) 012010

NC1π^0 rate in the P0D

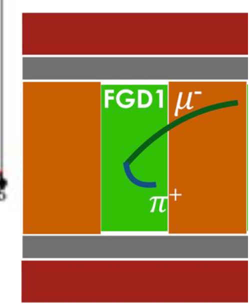


PRD 97 032002 (2018)

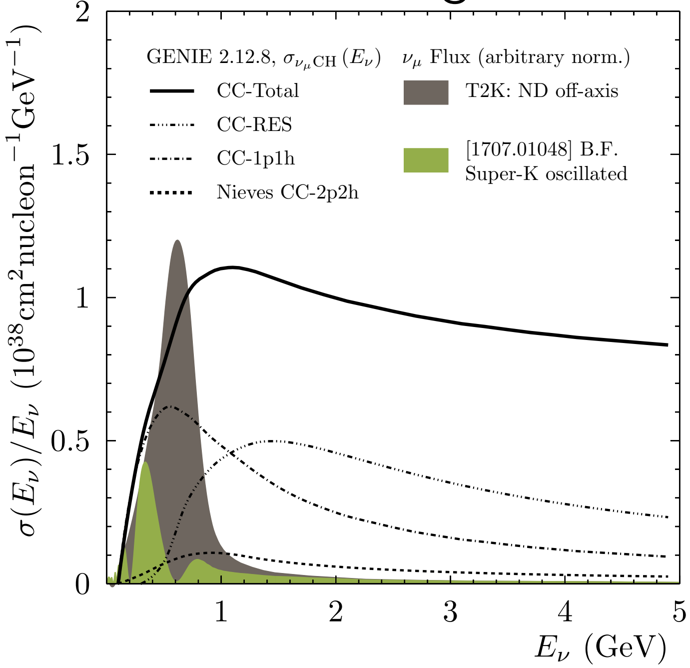
CC1π on CH



Paper in preparation



From Luke Pickering



Why cross section uncertainty is a problem?

T2K has off axis approach to select the neutrino energy: narrow beam centered around 0.6 GeV
Mainly CCQE (CC-1p1h) at this energy
Precise measurements of xsec crucial for T2K

???

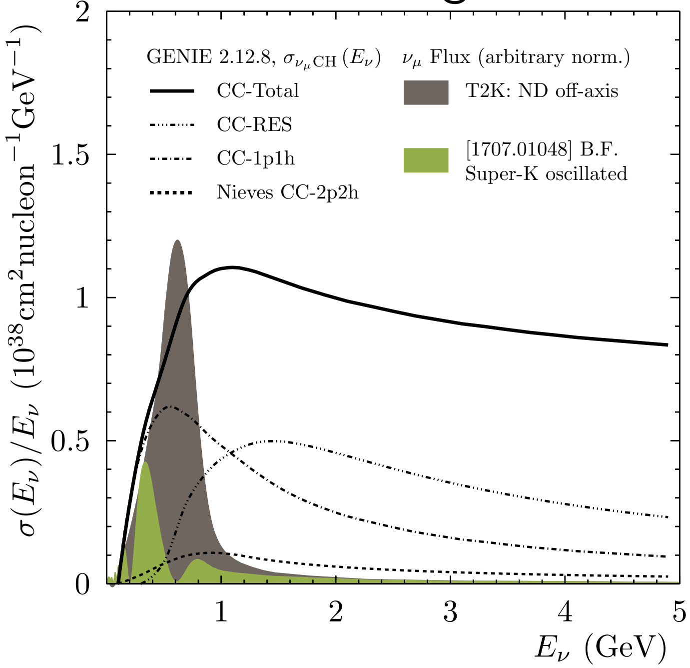
TABLE I. Systematic uncertainty on far detector event yields.

Source [%]	ν_μ	ν_e	$\nu_e\pi^+$	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ND280-unconstrained cross section	2.4	7.8	4.1	1.7	4.8
Flux & ND280-constrained cross sec.	3.3	3.2	4.1	2.7	2.9
SK detector systematics	2.4	2.9	13.3	2.0	3.8
Hadronic re-interactions	2.2	3.0	11.5	2.0	2.3
Total	5.1	8.8	18.4	4.3	7.1

arXiv:1807.07891

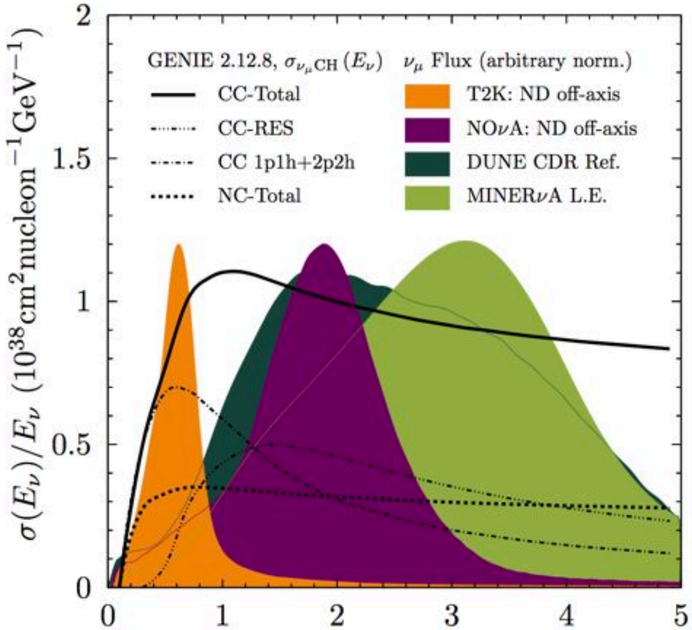
Why cross section uncertainty is a problem?

From Luke Pickering



T2K has off axis approach to select the neutrino energy: narrow beam centered around 0.6 GeV.
Mainly CCQE (CC-1p1h) at this energy
Precise measurements of xsec crucial for T2K

???



arXiv:1803.08848

But also for other present and future oscillation experiments: a region full of reaction thresholds and sparse data.

	NEUT 5.3.2	GENIE 2.8.0
CCQE	SF (Benhar et al., 2000) BBA05 (Bradford et al., 2005) $M_A^{QE} = 1.21$ GeV/c^2 p_F [^{12}C] = 217 MeV/c E_B [^{12}C] = 25 MeV	RFG (Bodek et al., 1981) BBA05 (Bradford et al., 2005) $M_A^{QE} = 0.99$ GeV/c^2 p_F [^{12}C] = 221 MeV/c E_B [^{12}C] = 25 MeV
2p2h	Nieves et al., 2011	-
CCRES	$W<2$ GeV Rein-Sehgal, 1981 FF (Graczyk et al., 2008)	$W<1.7$ GeV Rein-Sehgal, 1981 FF (Kuzmin et al., 2016)
CCDIS	$W>1.3$ GeV (w/o single π) GRV98 PDF (Glück et al. 1998) BY corr. at low Q2 (Bodek et al. 2003)	$W>1.7$ GeV (for $W<1.7$ GeV is tuned) GRV98 PDF (Glück et al. 1998) BY corr. at low Q2 (Bodek et al. 2005)
Hadronization	$W < 2$ GeV KNO scaling (Koba et al. 1972) $W > 2$ GeV PYTHIA/JETSET	$W < 2.3$ GeV AGKY (Koba et al. 1972) 2.3 GeV $< W <$ 3 GeV AGKY (Koba et al. 1972) + PYTHIA/JETSET $W > 3$ GeV PYTHIA/JETSET
FSI	Intra-nuclear cascade	Intra-nuclear cascade (INTRANUKE hA)

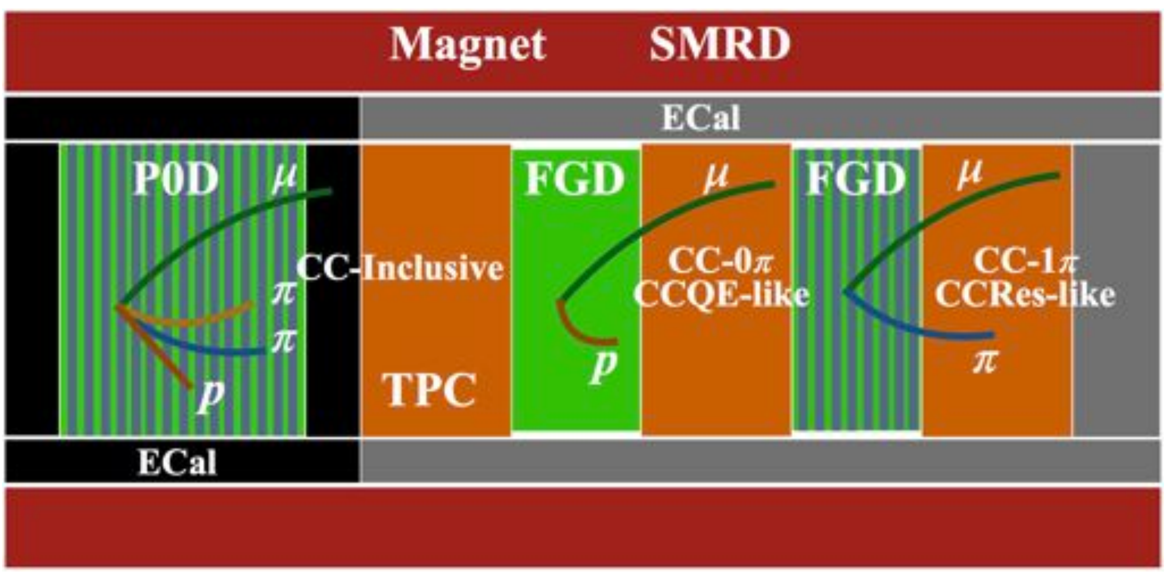

Magnet
SMRD
ECal
P0D
μ
π
π
p
CC-Inclusive
TPC
FGD
μ
p
CC-0π
CCQE-like
FGD
μ
π
CC-1π
CCRes-like
ECal

Table 20: Uncertainty on the number of event in each SK sample broken by error source before the BANFF fit. The new E_b fake data spline parameter is included in the non-constrained by ND280 cross-section parameters.

	1-Ring μ		1-Ring e		
Error source	FHC	RHC	FHC	RHC	FHC CC1π
Beam	7.6%	6.6%	8.4%	7.4%	8.4%
Cross-section (all)	12.5%	10.3%	13.8%	11.2%	9.1%
Beam + Cross-section (all)	14.4%	12.2%	15.7%	13.2%	12.5%
Total	14.7%	12.6%	16.0%	13.9%	19.9%

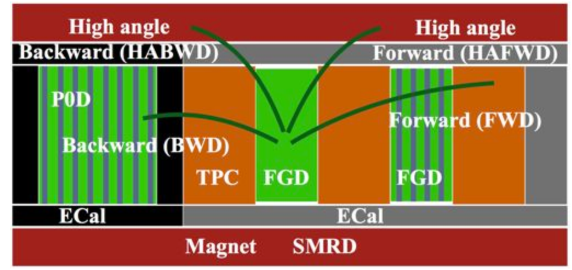
OA2018, TN321

Table 21: Uncertainty on the number of event in each SK sample broken by error source after the BANFF fit.

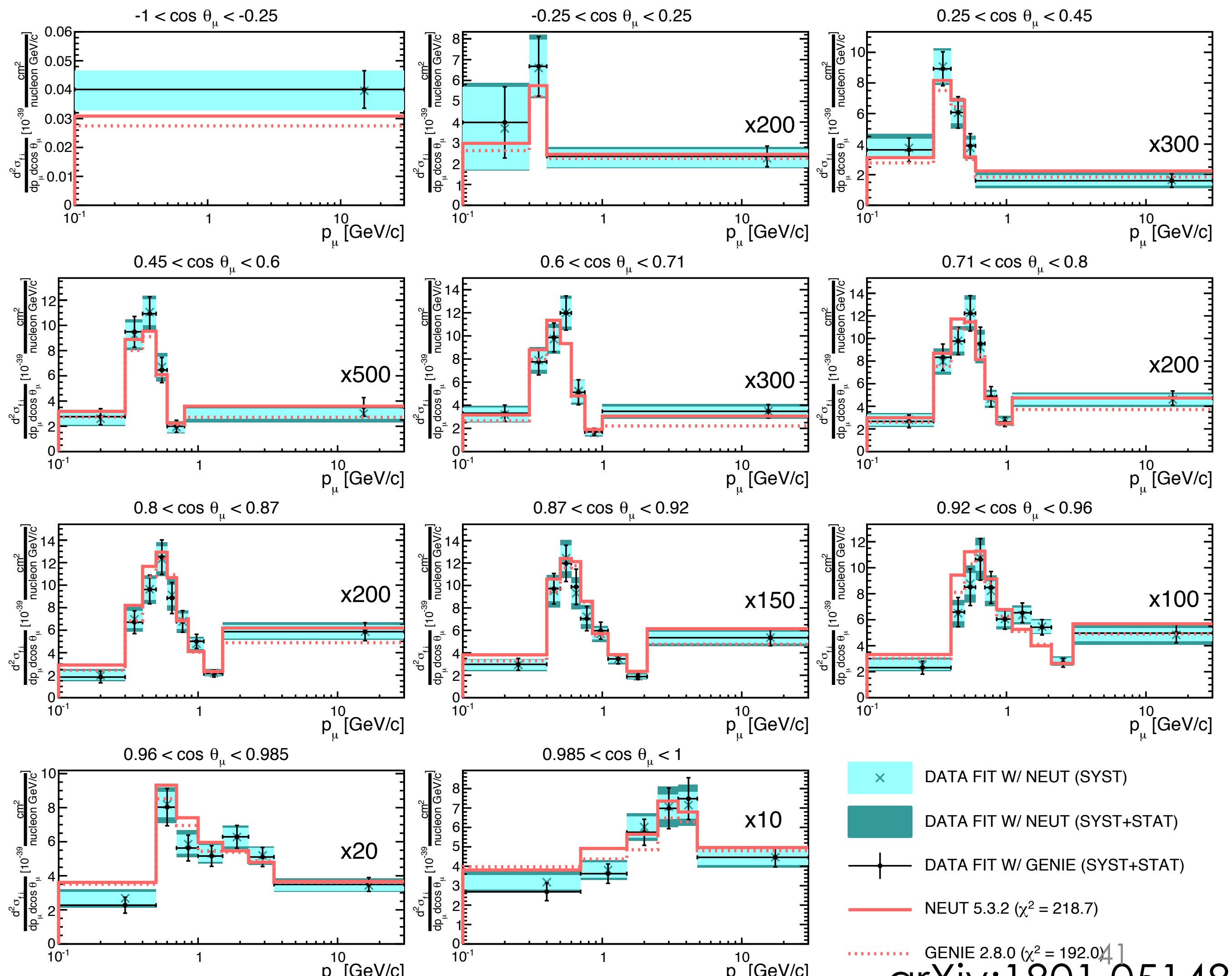
	1-Ring μ		1-Ring e		
Error source	FHC	RHC	FHC	RHC	FHC CC1π
Beam	3.9%	3.8%	4.1%	3.9%	4.1%
Cross-section (constr. by ND280)	4.7%	4.0%	4.7%	4.1%	4.1%
Cross-section (all)	5.6%	4.3%	8.6%	6.3%	5.7%
Beam + Cross-section (constr. by ND280)	2.9%	2.7%	3.0%	2.9%	3.8%
Beam + Cross-section (all)	4.2%	3.1%	7.8%	5.5%	5.4%
New E_b fake data parameter	3.3%	1.3%	7.3%	4.2%	2.9%
SK+FSI+SI	3.3%	2.9%	4.1%	4.4%	16.8%
Total	5.3%	4.2%	8.7%	7.1%	17.7%

CC Inclusive on CH

Muon kinematics double differential cross section.



- Off-axis
- Dominated by CCQE due to low energy beam
- 4p selection
- Maximum likelihood fit
- Flux integrated cross section to avoid neutrino energy dependence
- Data fit with NEUT and GENIE: equal results = no bias from prior!
- Background constrained with two sidebands
- 5.7×10^{20} POT



arXiv:1801.05148

CC inclusive in ingrid

Table 6.4: Elemental composition of the scintillators in the fiducial volume region

Element	H	C	N	O	Ti	Si
	7.4%	88.7%	0.4%	2.8%	1.1%	0.2%

Table 6.5: The elemental composition of the water in the fiducial region

Element	H_2O	H	C	N	O
Mass fraction	99.95%	0%	0.03%	0.02%	0%

$$\sigma_{CC}^{H_2O} = (0.840^{+0.010}_{-0.010}(\text{stat.})^{+0.10}_{-0.081}(\text{syst.})) \times 10^{-38}\text{cm}^2/\text{nucleon}$$

$$\sigma_{CC}^{CH} = (0.817^{+0.007}_{-0.007}(\text{stat.})^{+0.11}_{-0.082}(\text{syst.})) \times 10^{-38}\text{cm}^2/\text{nucleon}$$

$$\sigma_{CC}^{Fe} = (0.859^{+0.003}_{-0.003}(\text{stat.})^{+0.12}_{-0.10}(\text{syst.})) \times 10^{-38}\text{cm}^2/\text{nucleon}$$

$$\frac{\sigma_{CC}^{H_2O}}{\sigma_{CC}^{CH}} = 1.028^{+0.016}_{-0.016}(\text{stat.})^{+0.05}_{-0.05}$$

$$\frac{\sigma_{CC}^{Fe}}{\sigma_{CC}^{H_2O}} = 1.023^{+0.012}_{-0.012}(\text{stat.})^{+0.05}_{-0.057}$$

$$\frac{\sigma_{CC}^{Fe}}{\sigma_{CC}^{CH}} = 1.049^{+0.010}_{-0.010}(\text{stat.})^{+0.043}_{-0.043}(\text{syst.})$$

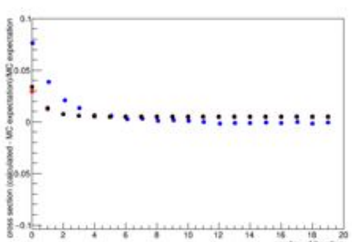


Figure 6.8: Relation between the number of iterations and calculated cross section. Black is σ_{H2O}, red is σ_{CH} and blue is σ_{Fe}.

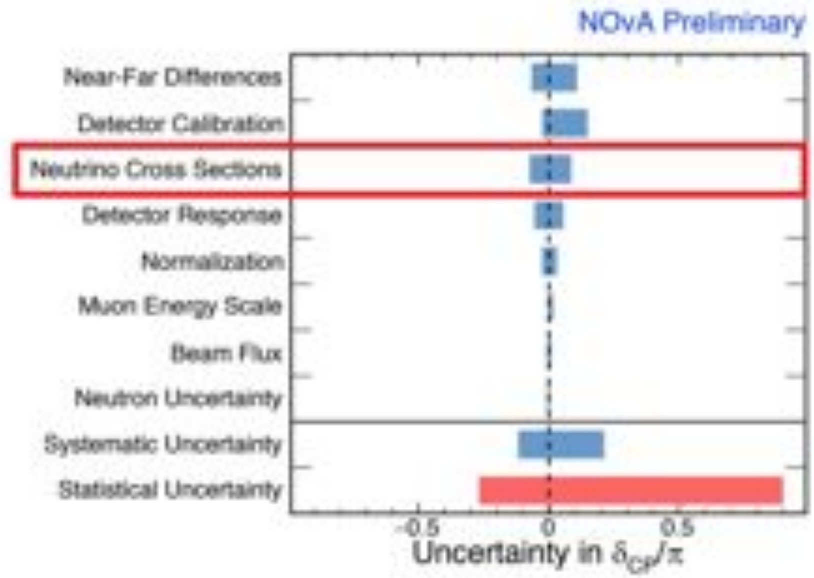
T2K and NOVA systematics

Neutrino cross sections in OA

- Large systematics at T2K and NOvA long-baseline oscillation experiments

Source [%]	ν_μ	ν_e	$\nu_e\pi^+$	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ND280-unconstrained cross section	2.4	7.8	4.1	1.7	4.8
Flux & ND280-constrained cross sec.	3.3	3.2	4.1	2.7	2.9
SK detector systematics	2.4	2.9	13.3	2.0	3.8
Hadronic re-interactions	2.2	3.0	11.5	2.0	2.3
Total	5.1	8.8	18.4	4.3	7.1

T2K August 2018, https://arxiv.org/pdf/1807.07891.pdf



NOvA Wine and Cheese, A. Himmel, June 15, 2018

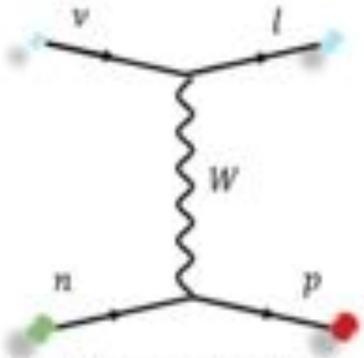
- NOvA's extensive detector calibration makes neutrino interactions dominant systematic for atmospheric parameters in future

C. Wret, NuFact 2018

Inferred Proton Kinematics

WARWICK
THE UNIVERSITY OF WARWICK

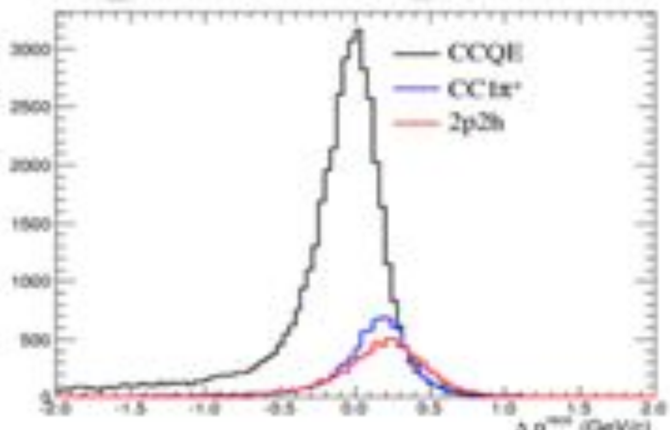
Assuming a 2 body interaction the proton kinematics can be determined from the measured lepton kinematics



$$E_\nu = \frac{m_p^2 - m_\mu^2 + 2E_\mu(m_n - E_b) - (m_n - E_b)^2}{2[(m_n - E_b) - E_\mu + p_\mu cos\theta_\mu]},$$

$$E_p^{inferred} = E_\nu - E_\mu + m_p,$$

$$\overrightarrow{p}_p^{inferred} = (-p_\mu^x, -p_\mu^y, -p_\mu^z + E_\nu),$$



$$\Delta p_p = |\overrightarrow{p}_p^{measured}| - |\overrightarrow{p}_p^{inferred}|,$$

$$\Delta\theta_p = \theta_p^{measured} - \theta_p^{inferred},$$

$$|\Delta \mathbf{p}| = |\overrightarrow{p}_p^{measured} - \overrightarrow{p}_p^{inferred}|.$$

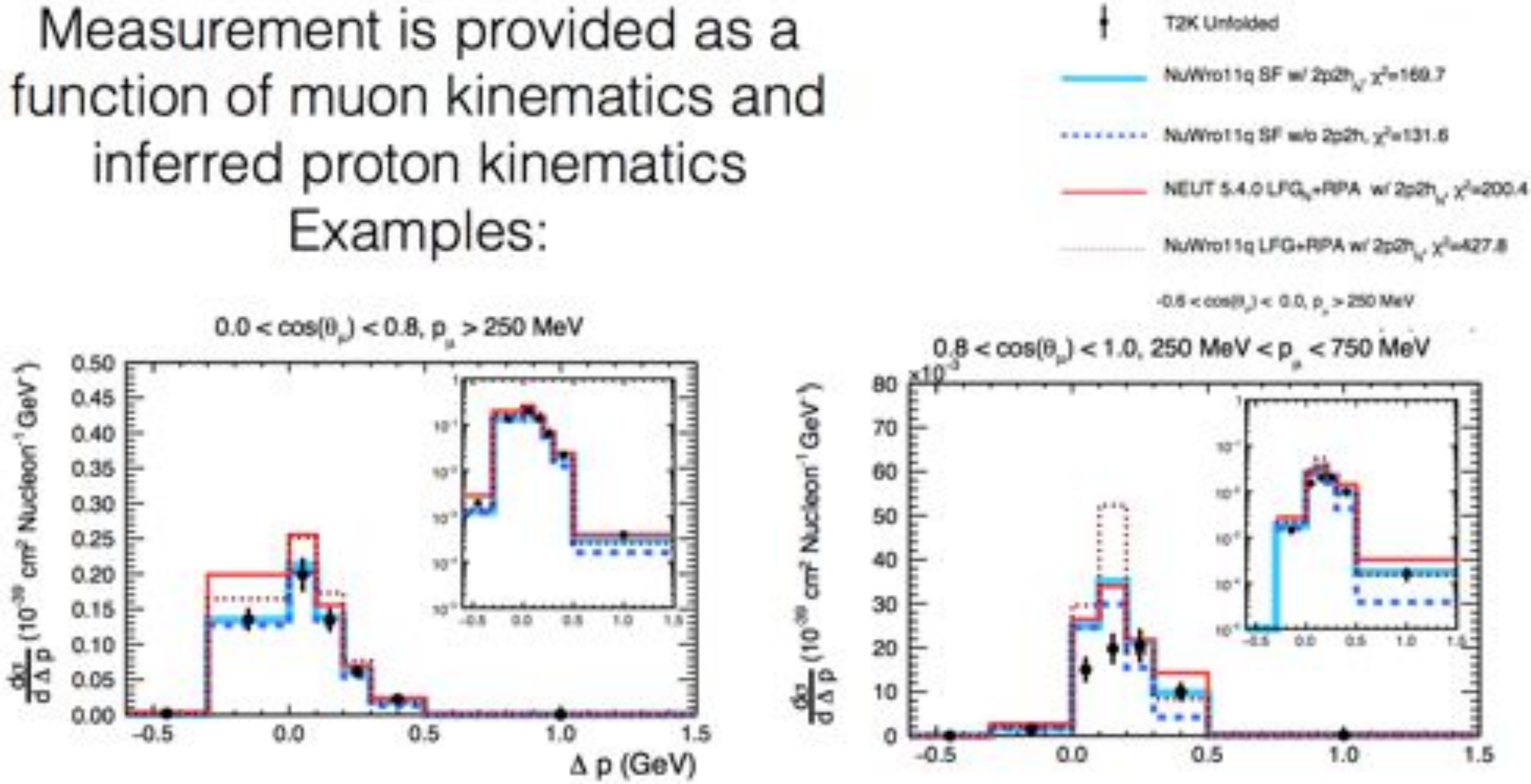
Differences between inferred and measured proton kinematics manifest due to nuclear effects

Steve Hadley, ICHEP 2018

Inferred Proton Kinematics

WARWICK

Measurement is provided as a function of muon kinematics and inferred proton kinematics
Examples:



No model tested perfectly describes the data everywhere (as indicated by large χ^2)

8

Steve Hadley, ICHEP 2018

In FHC, the anti-νe component is tiny, however in RHC the neutrino energy tail has almost identical populations of ν e and anti-ν e. Thus, for the anti-neutrino oscillations the knowledge of both ν e and anti-ν e beam composition is important, as they both are irreducible backgrounds at far detector.

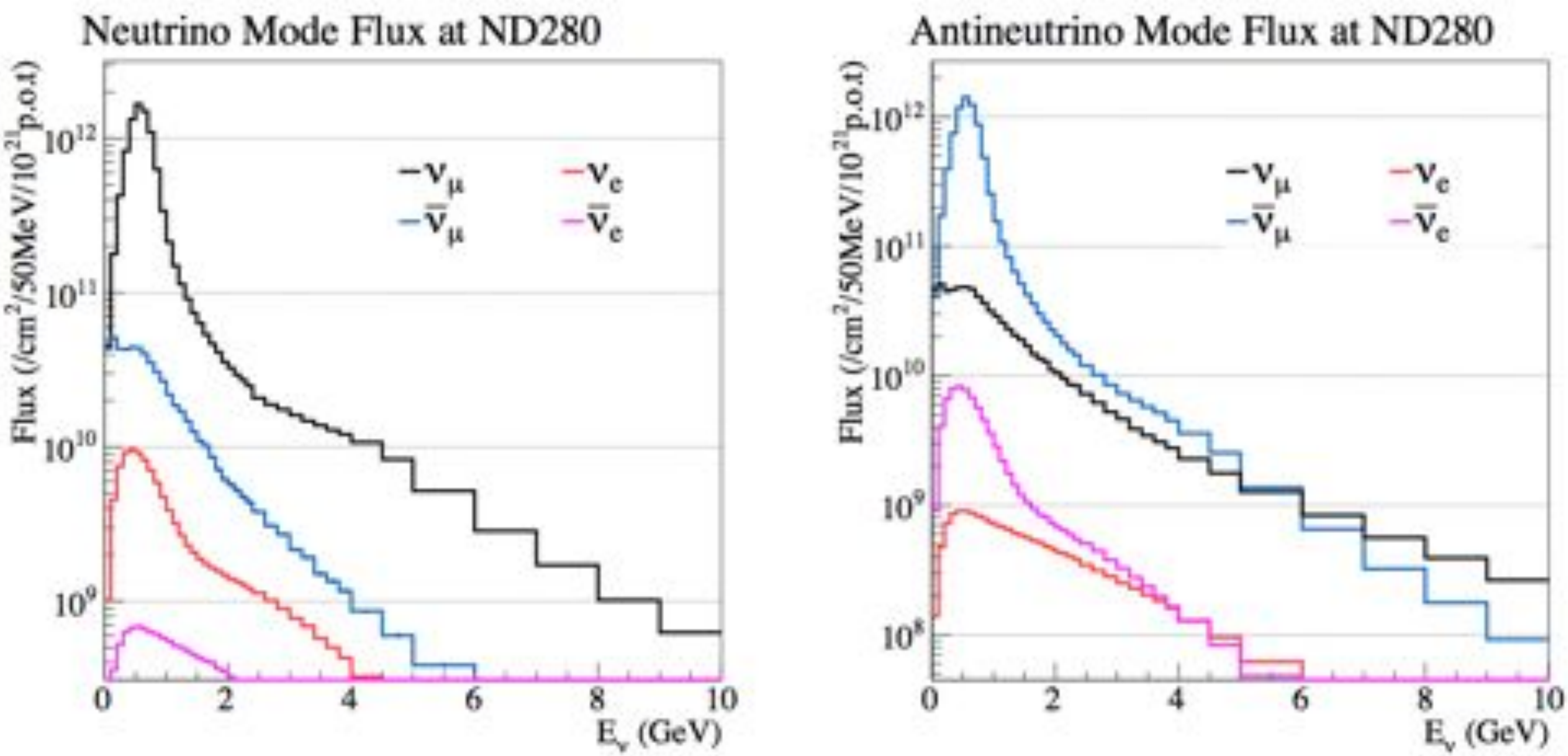


Figure 1: The neutrino flux in FHC (left) and RHC (right). From [1].

[1] T2K Technical Note 217

Nue and antinue flux

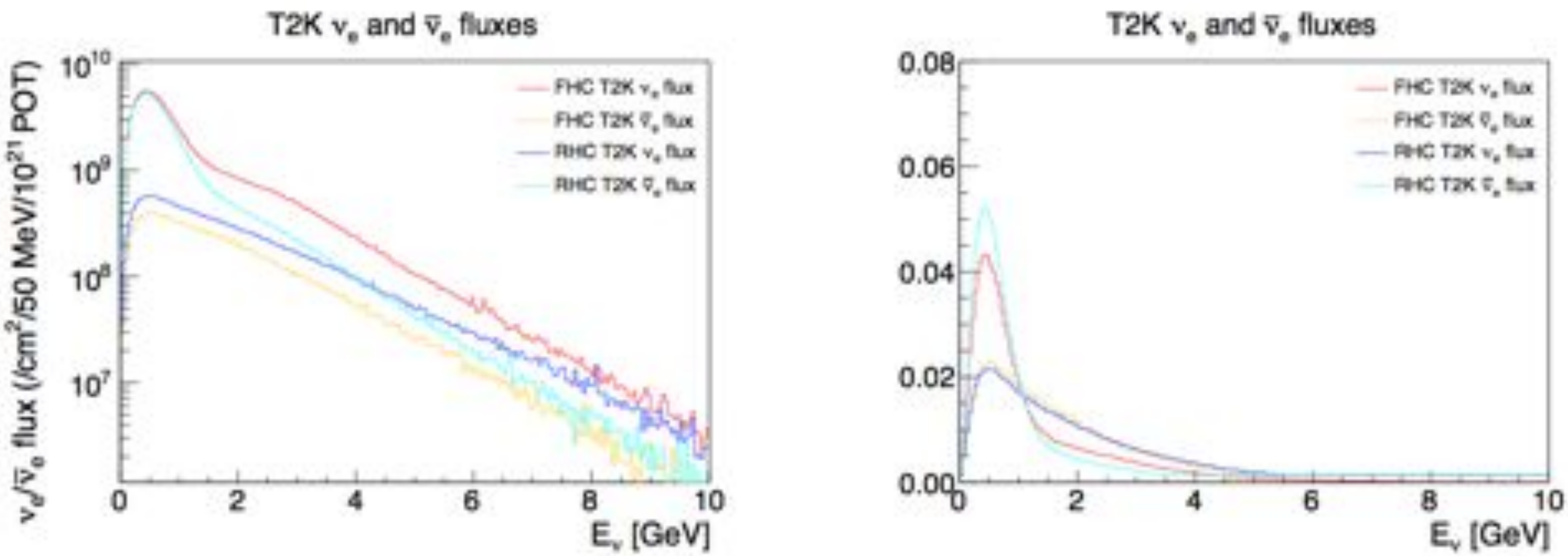
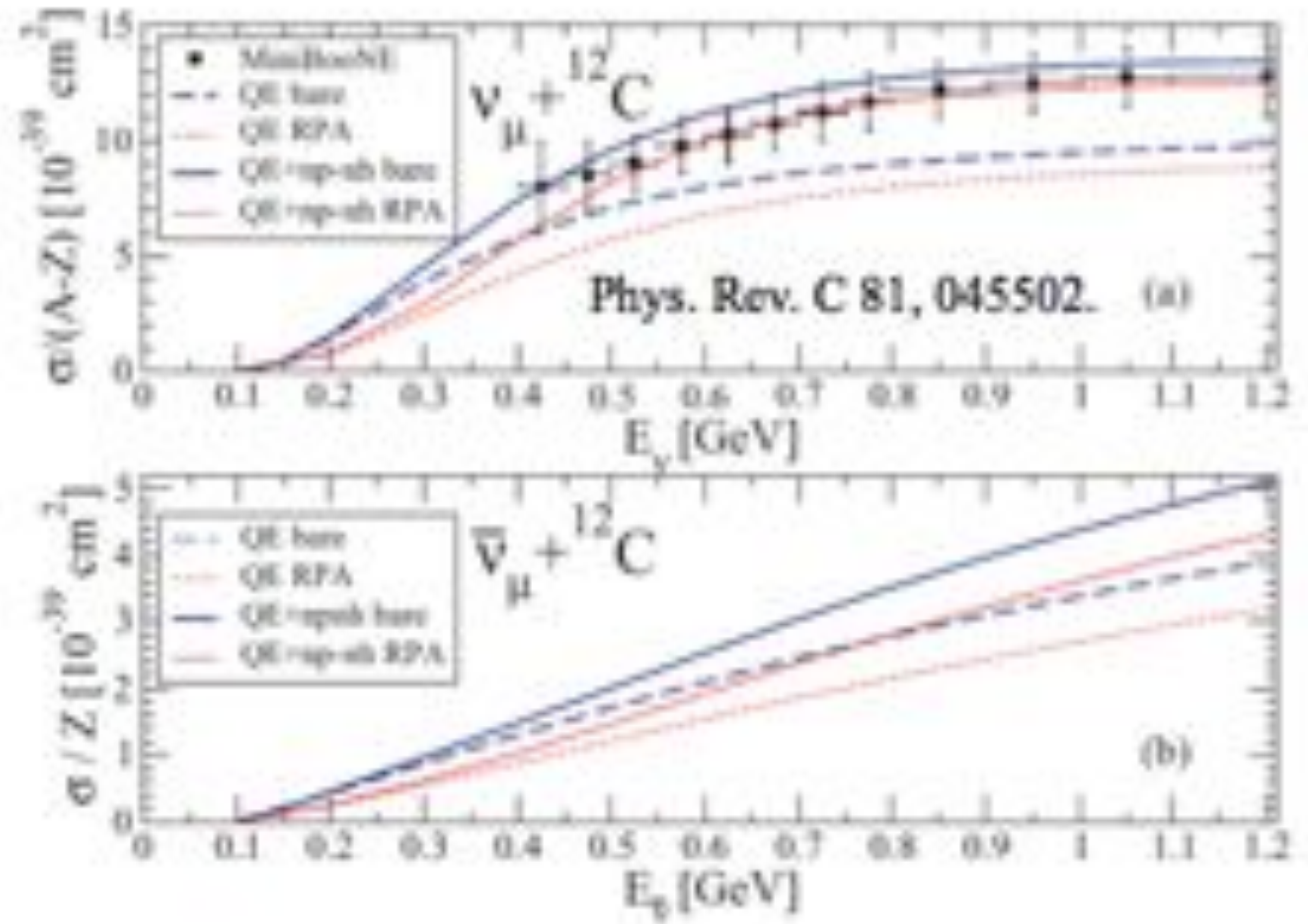
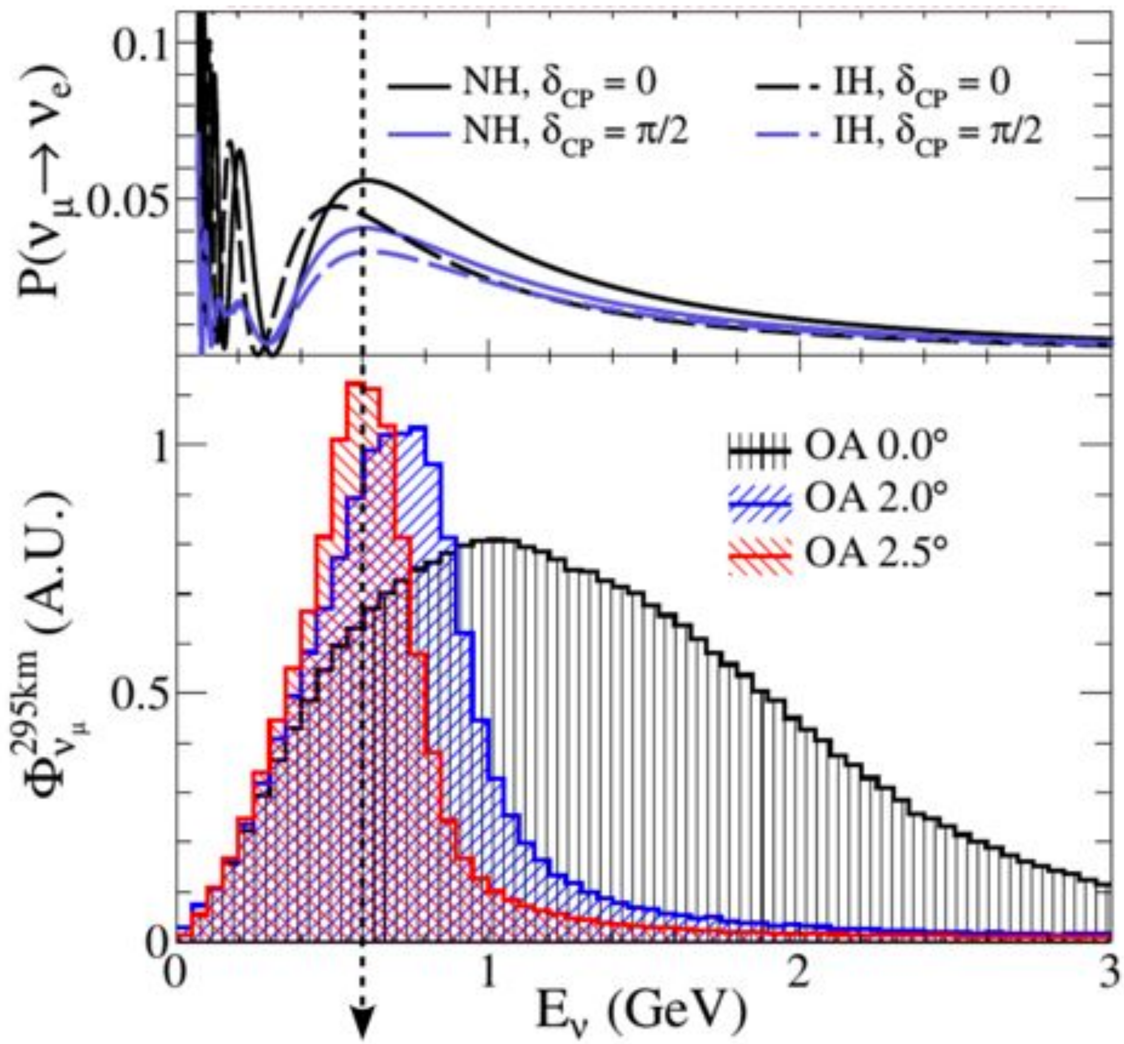


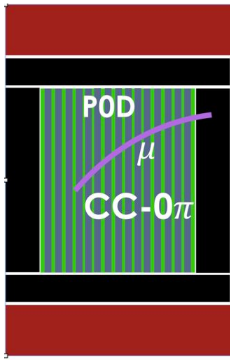
Figure 2: The ν_e and $\bar{\nu}_e$ neutrino fluxes in FHC and RHC. All fluxes in right plot are normalised to unity.

ν_μ and anti-ν_μ as 2p2h probe

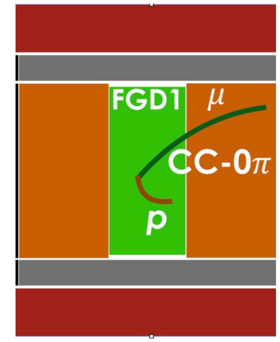


Off and on axis fluxes



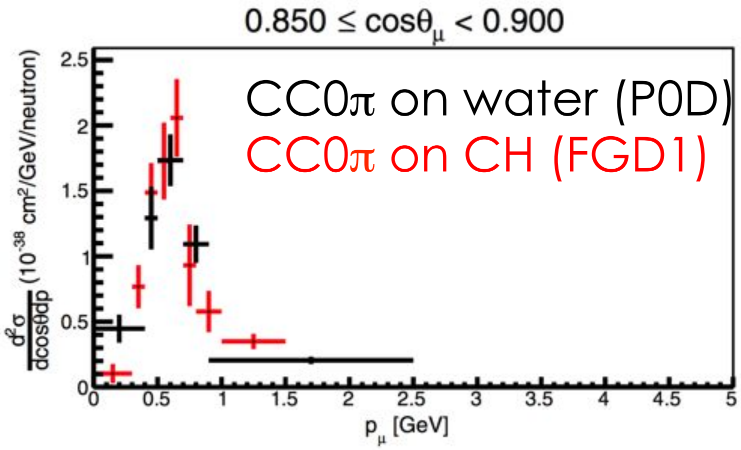


CC0π on CH and H_2O

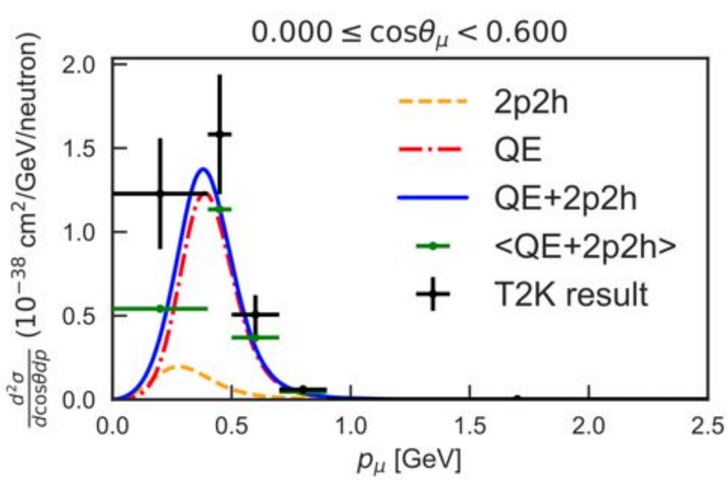


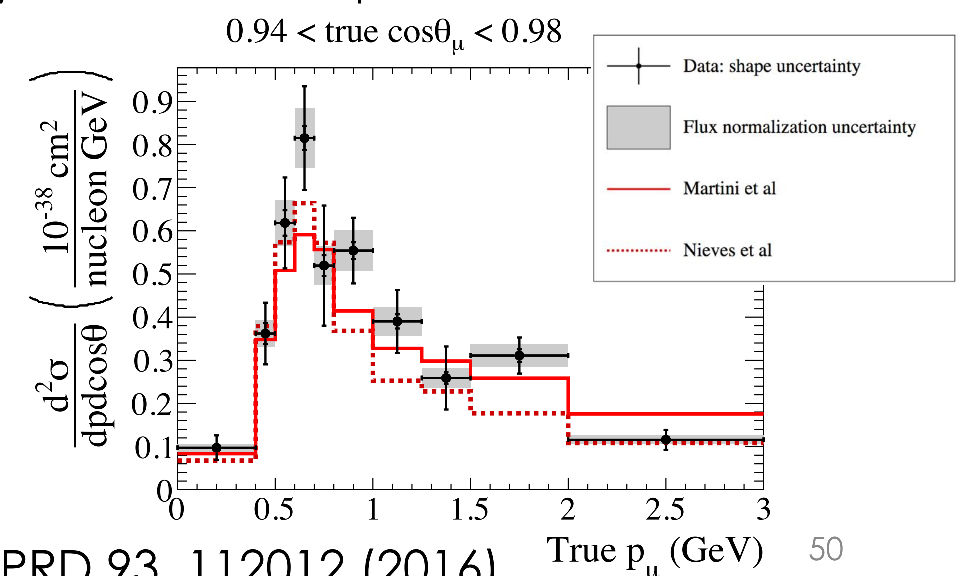
- Off axis.
- CC0π ~ 80% CCQE + 12% 2p2h
- Two independent measurements: FGD1 (2016) and P0D (2018)
- Comparison with various models
- Low momentum, high angle region under-predicted
- 2p2h required
- Try to look at the protons to learn more!

PRD 97, 012001 (2018)



Water: comparison with Susav2





PRD 93, 112012 (2016)