The latest results from T2K

To δ_{CP} and Beyond

Stephen Dolan

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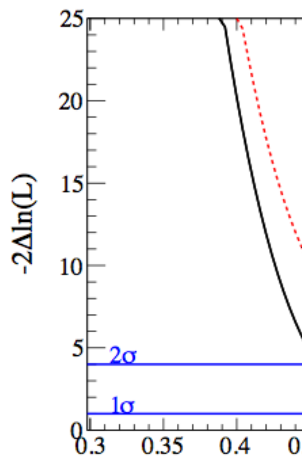
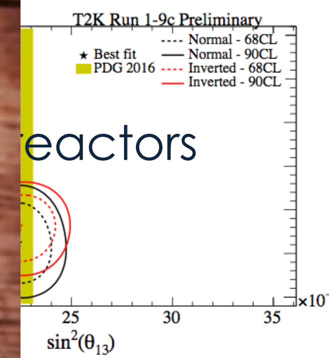
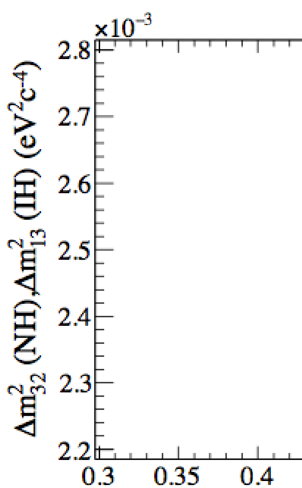
Physique des 2 Infinis et des Origines

Since I have your attention ...

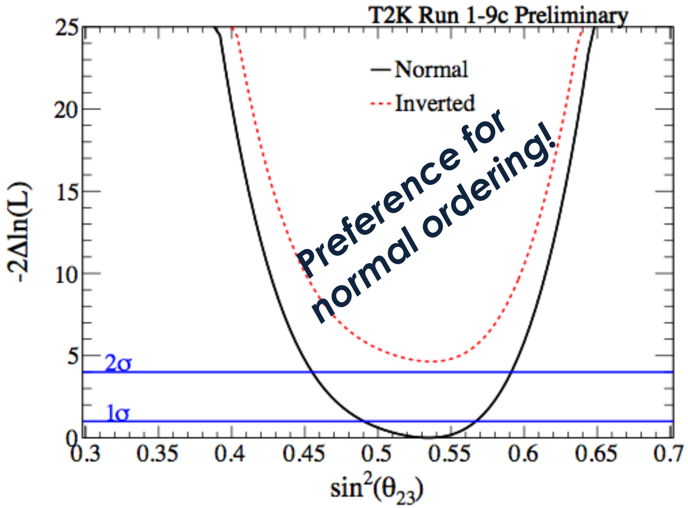


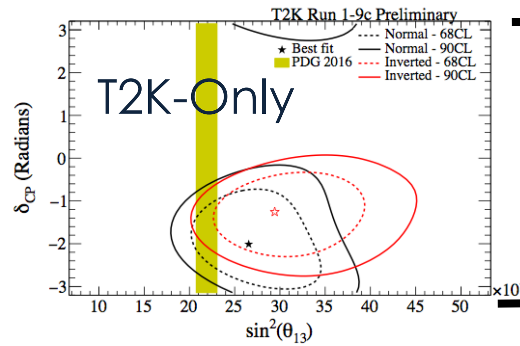


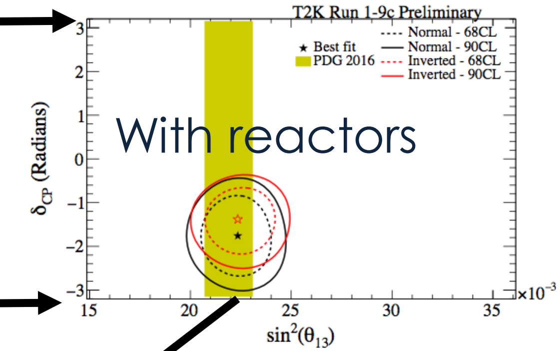


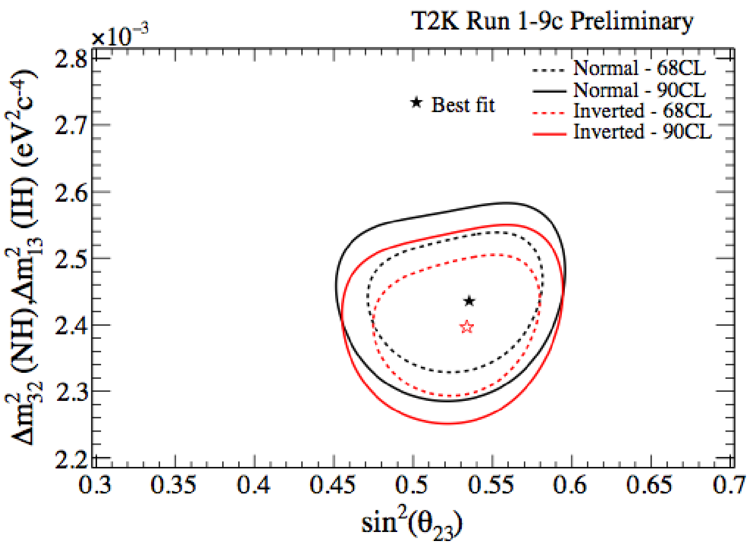
hin reach!

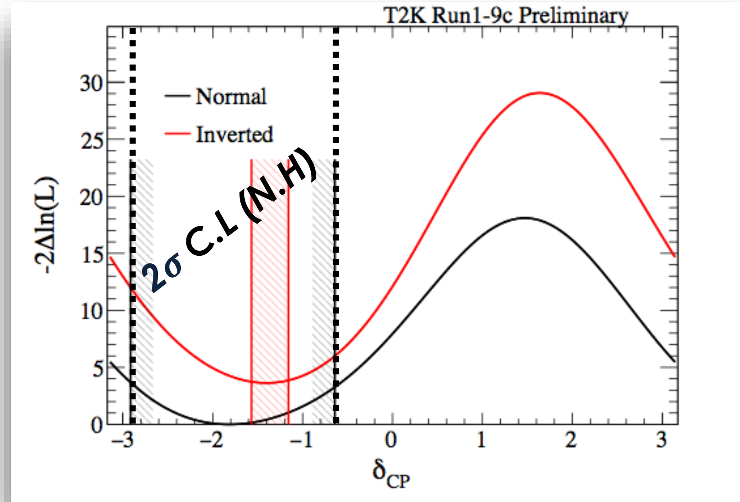
… here's the latest T2K results!











CPV in the neutrino sector is within reach!

But how did we get here!?

- Neutrino oscillations and the T2K experiment
- **The latest results/analyses from T2K**

And where are we going?

- Neutrino oscillations and the T2K experiment
- **The latest results/analyses from T2K**
- Limiting factor: neutrino nucleus cross sections
- *The latest cross section results*
- The future of T2K

Neutrino Oscillations

flavor | atmospheric | accelerator/reactor | solar | mass

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

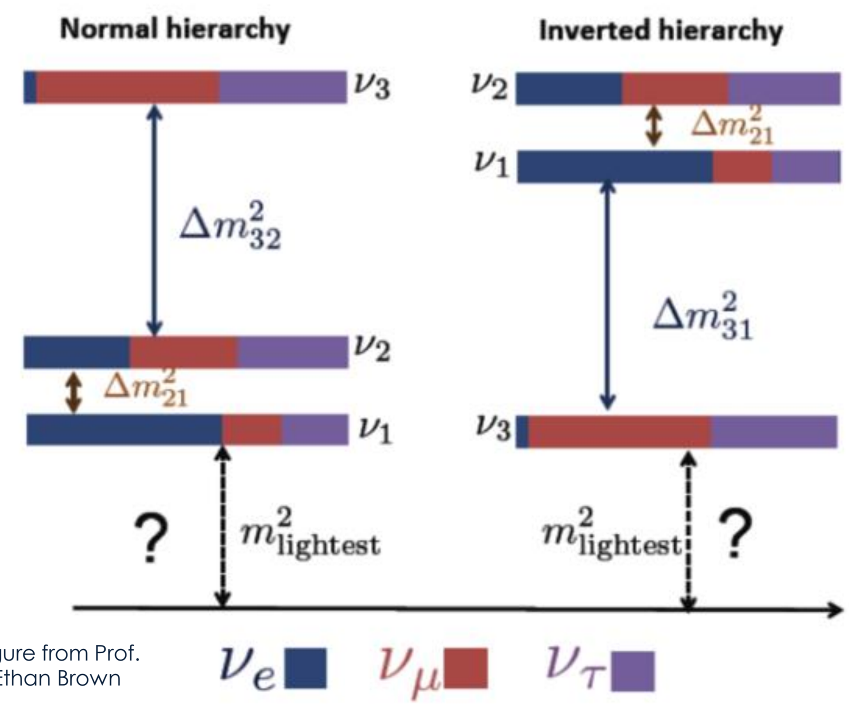


Figure from Prof. Ethan Brown

- What is the value of δ_{CP}??
- What is the mass hierarchy?
- Precision measurements of the mixing parameters

- Is PMNS all there is?
- What about the absolute neutrino mass scale?
- Why is it so small?
- Dirac or Majorana?

The T2K Collaboration (2018)

~500 members, 67 Institutes, 12 countries

Canada
TRIUMF
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
LLR E. Poly.
LPNHE Paris

Germany
Aachen U.

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Institute Tech
Tokyo Metropolitan U.
U. Tokyo
Tokyo U of Science
Yokohama National U.

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroclaw U.

Russia
INR

Spain
IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid

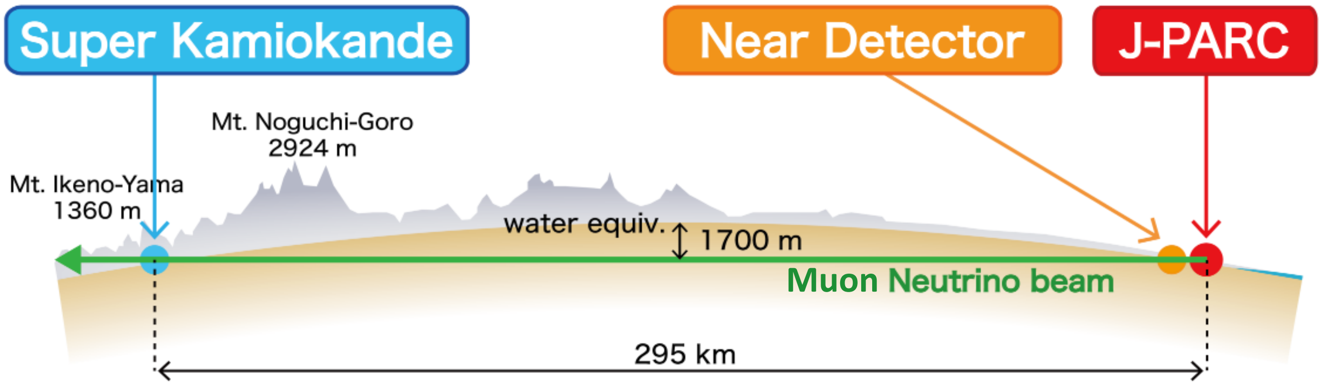
Switzerland
ETH Zurich
U. Bern
U. Geneva

United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
Royal Holloway U.L.
STFC/Daresbury
STFC/RAL
U. Glasgow
U. Liverpool
U. Sheffield
U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana State U.
Michigan S.U.
SLAC
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

Vietnam
IFIRSE
IOP, VAST

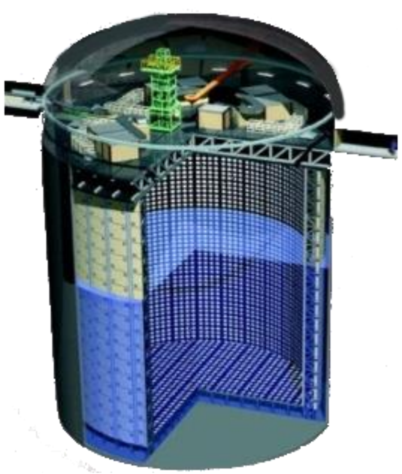
The T2K Experiment



Use off-axis beam to give a narrow neutrino energy spread

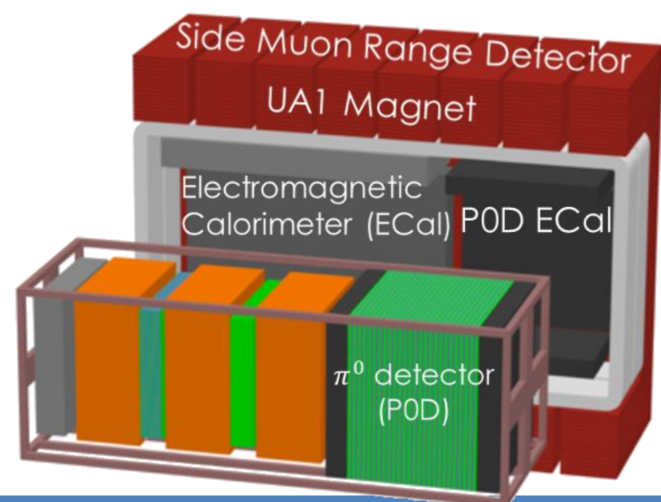
Far Detector (Off-Axis)

Super-Kamiokande

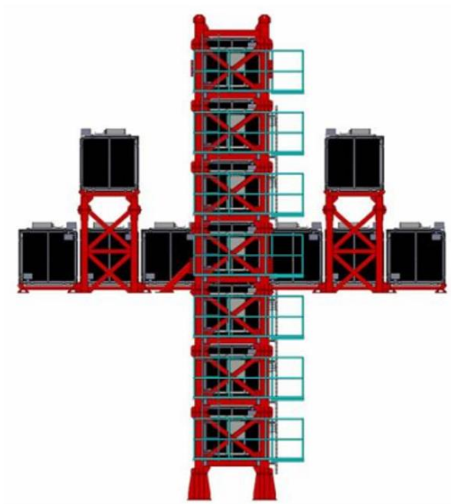


Near Detectors

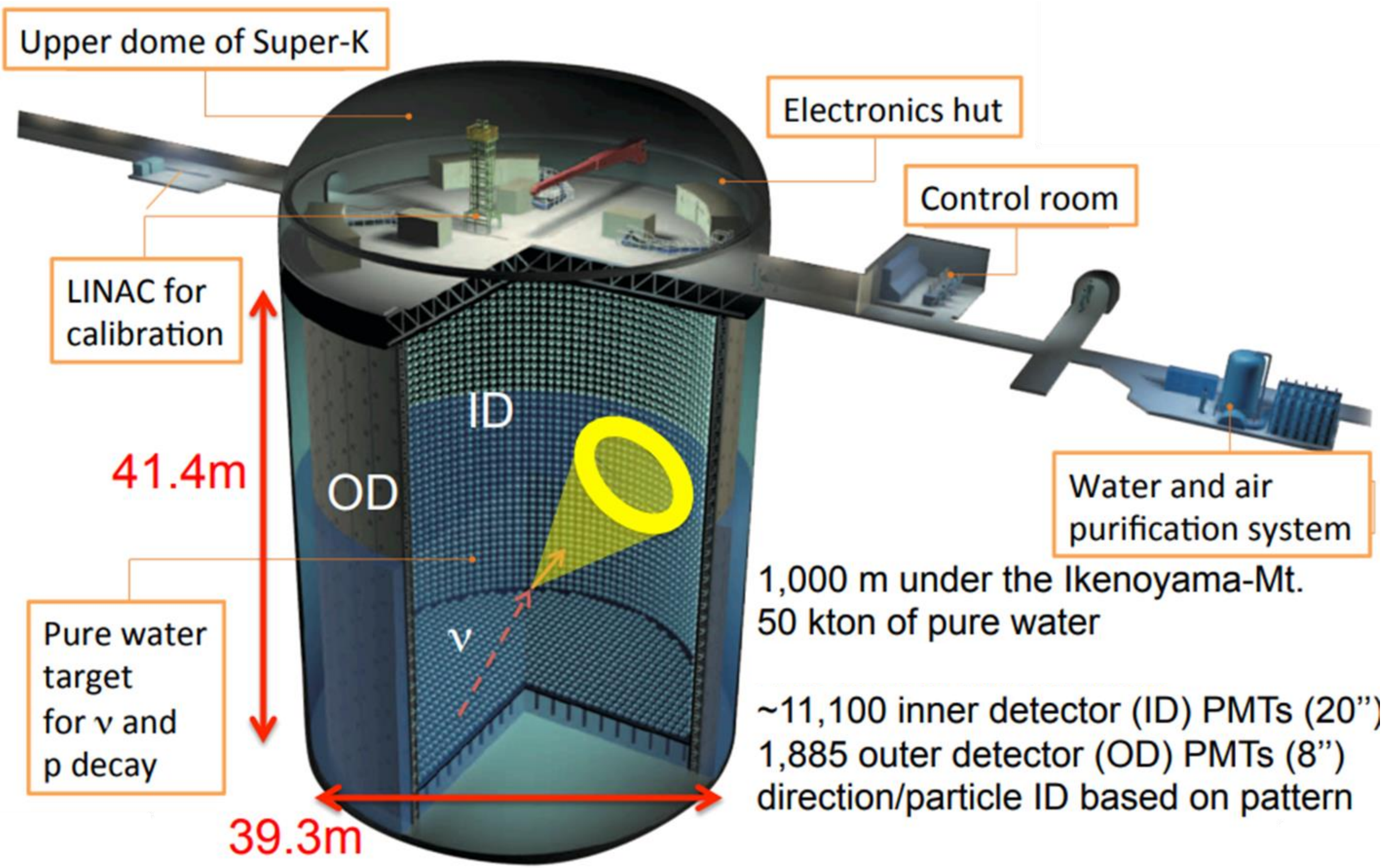
Off-Axis: ND280



On-Axis: INGRID



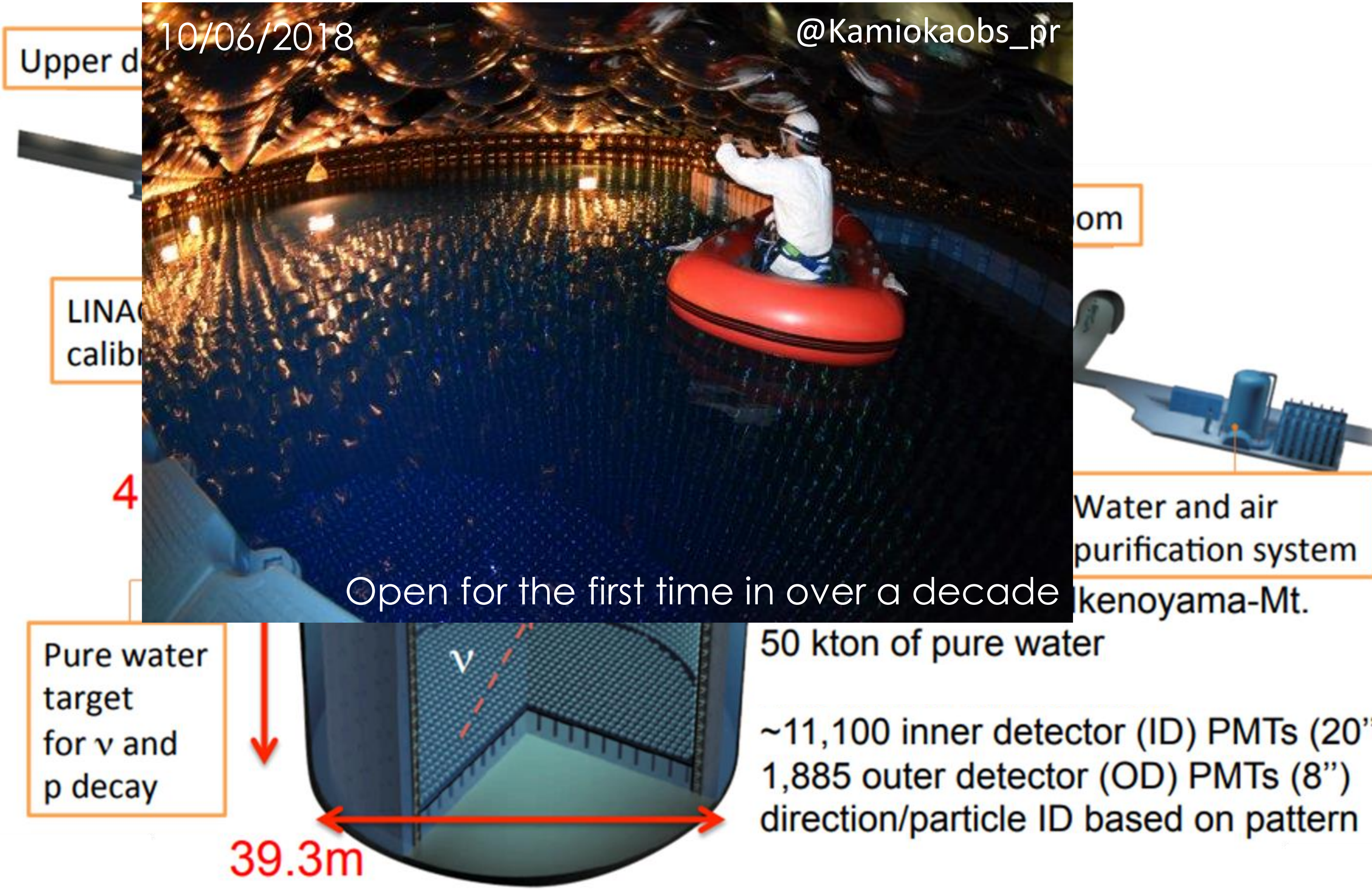
The Super-Kamiokande detector



1,000 m under the Ikenoyama-Mt.
50 kton of pure water

~11,100 inner detector (ID) PMTs (20'')
1,885 outer detector (OD) PMTs (8'')
direction/particle ID based on pattern

The Super-Kamiokande detector

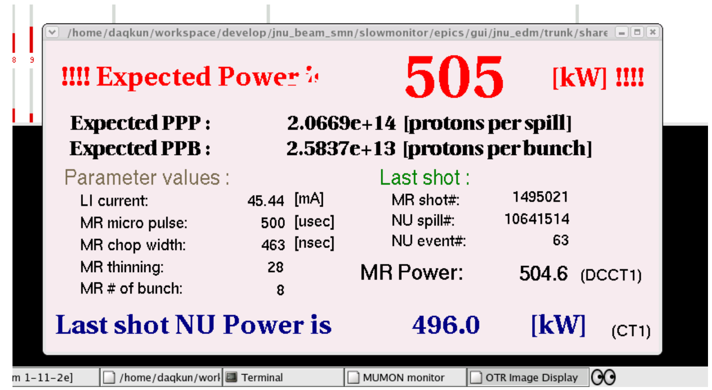


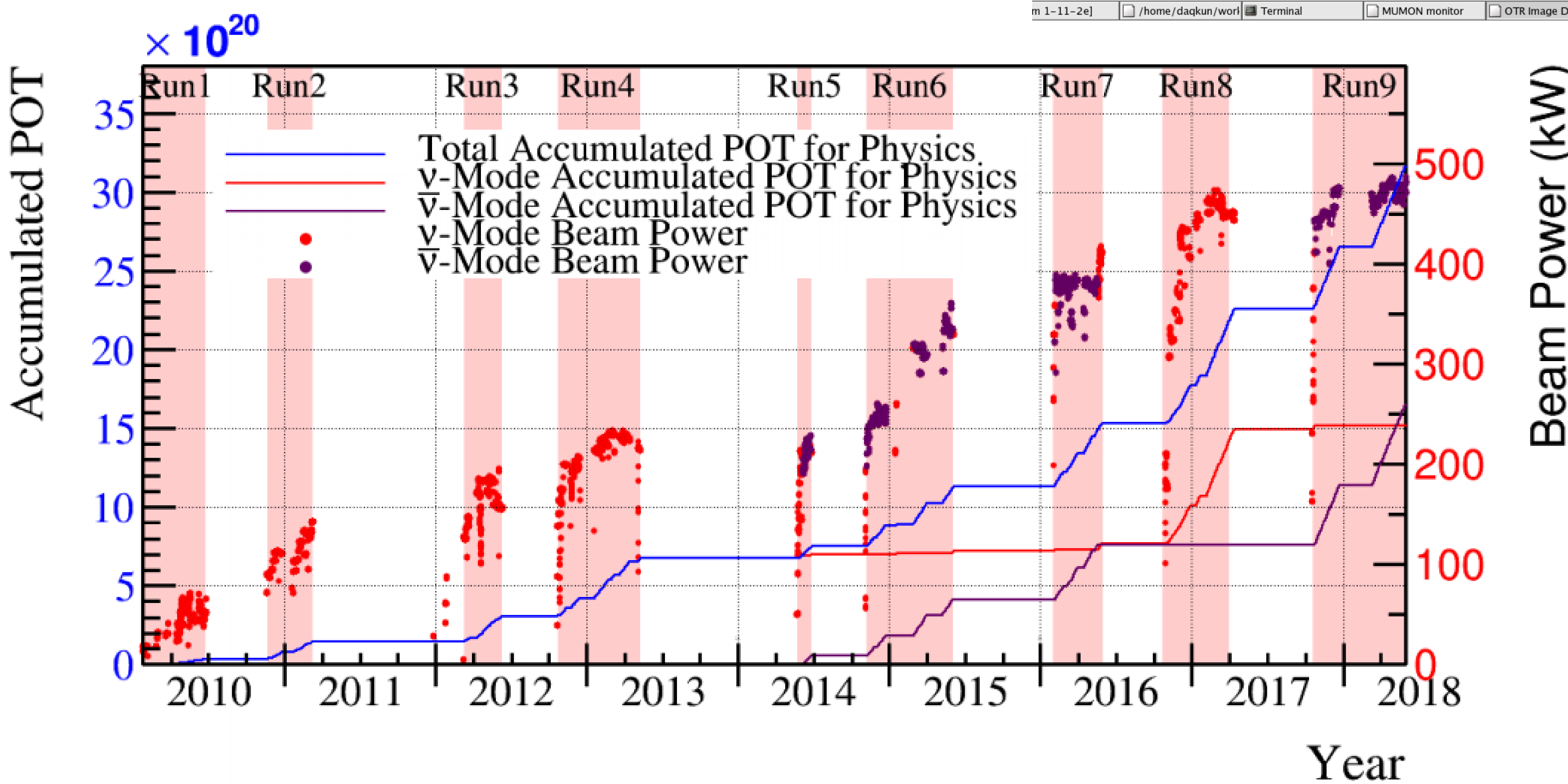
Ikenoyama-Mt.
50 kton of pure water

~11,100 inner detector (ID) PMTs (20”)
1,885 outer detector (OD) PMTs (8”)
direction/particle ID based on pattern

Data collection

- T2K has been gathering data at an accelerating rate
- **More than doubled $\overline{\nu}$ data in 2017/18**
- **500 kW beam power!**

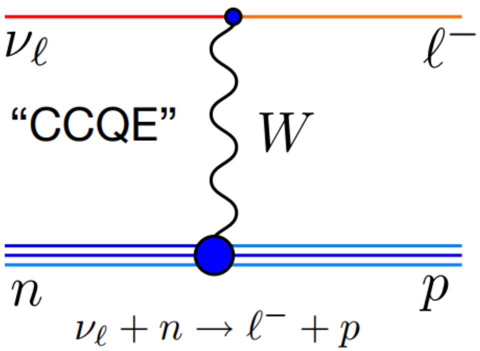




Now the part I already spoiled

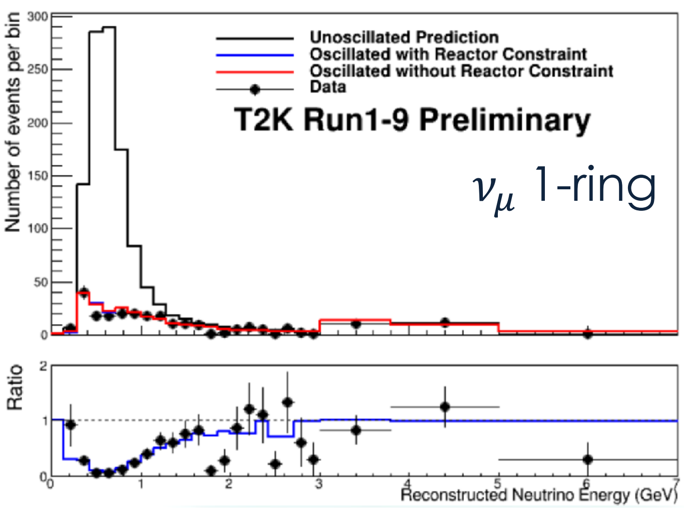
- Neutrino oscillations and the T2K experiment
- **The latest results from T2K**
- Limiting factor: neutrino nucleus cross sections
- *The latest cross section results*
- The future of T2K

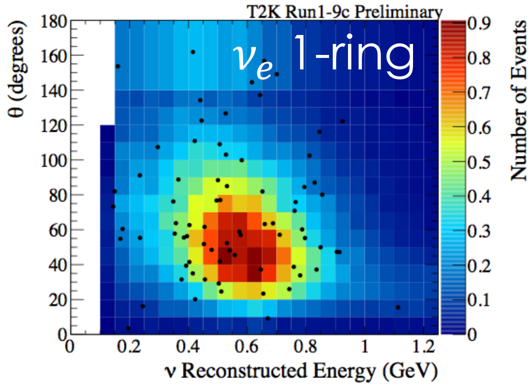
T2K-SK samples



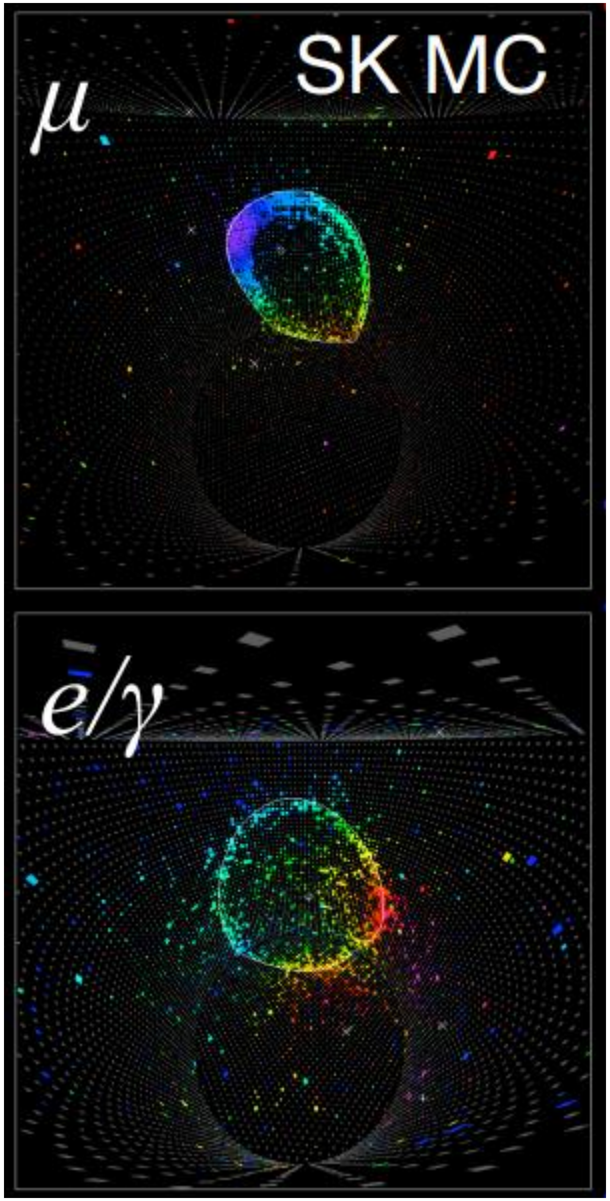
- Select CCQE-like $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_e$ events (1-ring)
- Reconstruct neutrino energy assuming CCQE

$$E_\nu^{\rm rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_l^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l + p_l\cos\theta_l)}$$





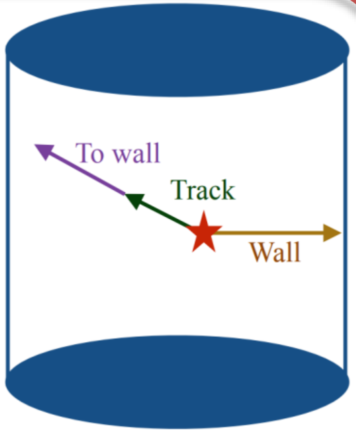
Each point is a real ν_e event



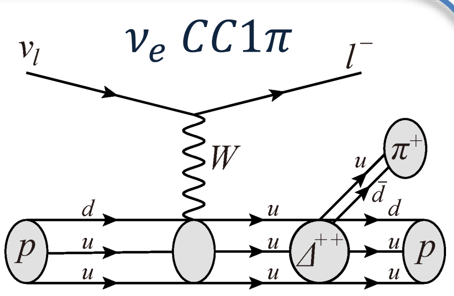
- Not shown: anti-neutrino samples

NEW: better reco. and 1π sample

- *Old analysis:* Define SK fiducial volume using only the distance from vertex to nearest wall ("wall")
- ***New analysis***: Define SK fiducial volume using both "wall" and distance to wall along track trajectory ("To wall")
- **Result:** 15-20% statistics increase and less NC backgrounds



- *Old analysis:* Use only the aforementioned CCQE-like ν_e samples
- ***New analysis***: Add ν_e sample with a final state π^+ by identifying electron from the decay chain: $\nu_e + N \rightarrow e^- + \pi^+ + X$, $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- **Result:** ~17% statistics increase neutrino mode ν_e



Overall: 30% increase in statistics for neutrino mode electron samples and 20% increase in antineutrino mode

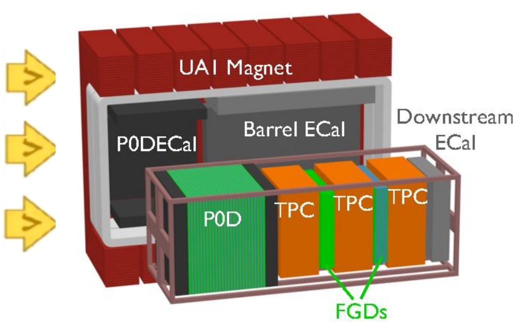
Nuisance constraints

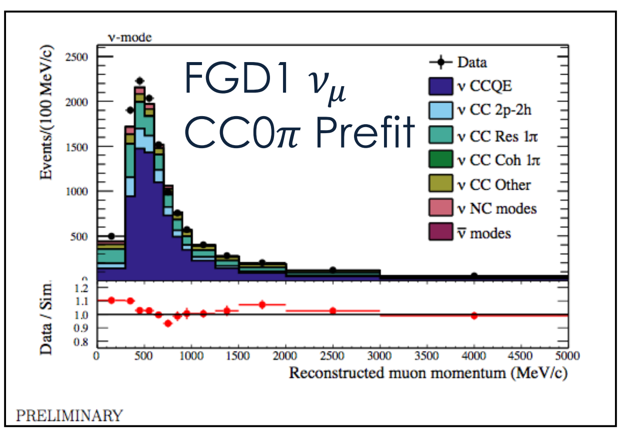
- We don't measure the oscillated flux directly

$$N_{pred}(E_\nu^{reco}) = \Phi(E_\nu^{true})\,\sigma(E_\nu^{true})\,P(\alpha\rightarrow\beta, E_\nu^{true})\,\epsilon(E_\nu^{true})\,S(E_\nu^{true}, E_\nu^{reco})$$

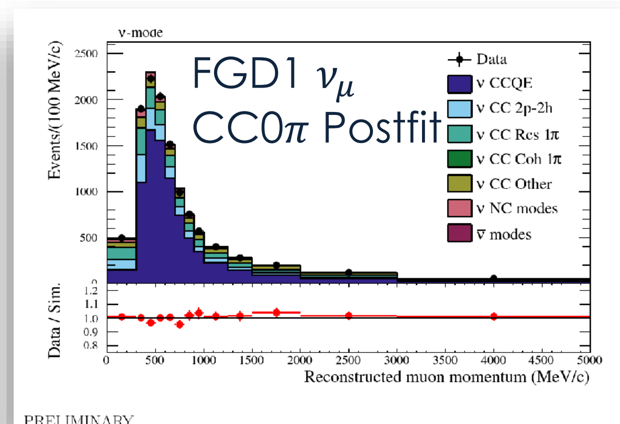
$N_{pred}(E_\nu^{reco})$	=	Expected number of events	$P(\alpha\rightarrow\beta, E_\nu^{true})$	=	Oscillation probability
$\Phi(E_\nu^{true})$	=	Neutrino flux	$\epsilon(E_\nu^{true})$	=	Selection efficiency
$\sigma(E_\nu^{true})$	=	Interaction cross sections	$S(E_\nu^{true}, E_\nu^{reco})$	=	Smearing matrix

- We use external data and our ND280 near detector to constrain the nuisances (using theory-driven parameterisations)

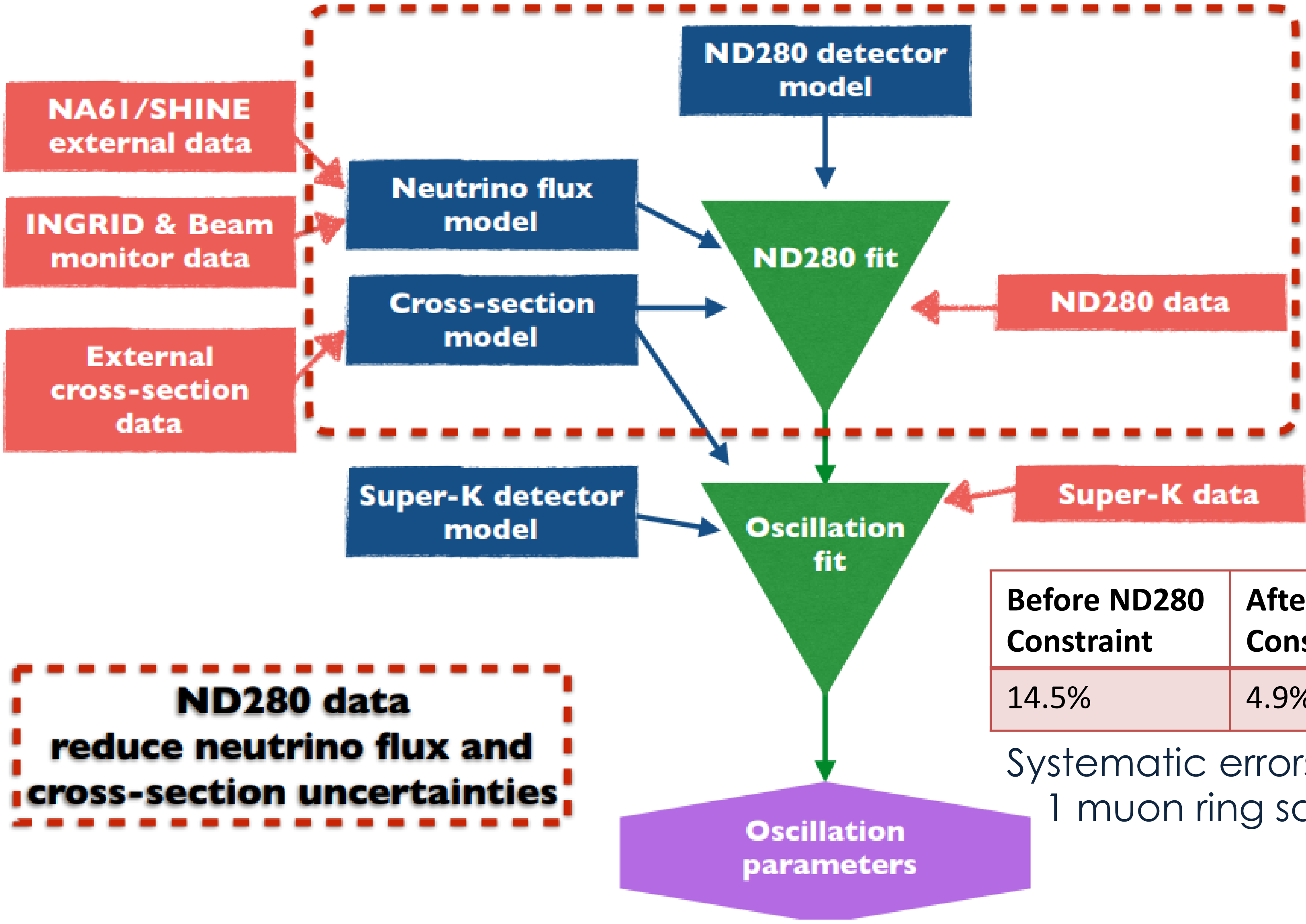




Fit to data



Neutrino oscillation analysis



Before ND280 Constraint	After ND280 Constraint
14.5%	4.9%

Systematic errors on the 1 muon ring sample

SK observed and expected

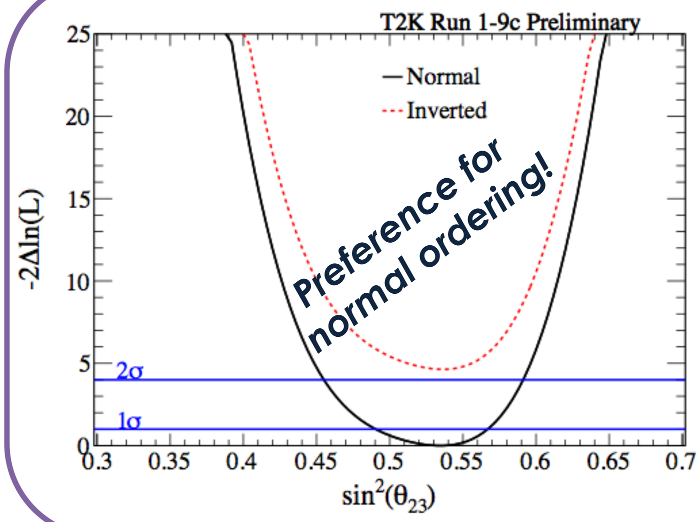
- Observed and predicted rates for each SK sample after oscillation analysis

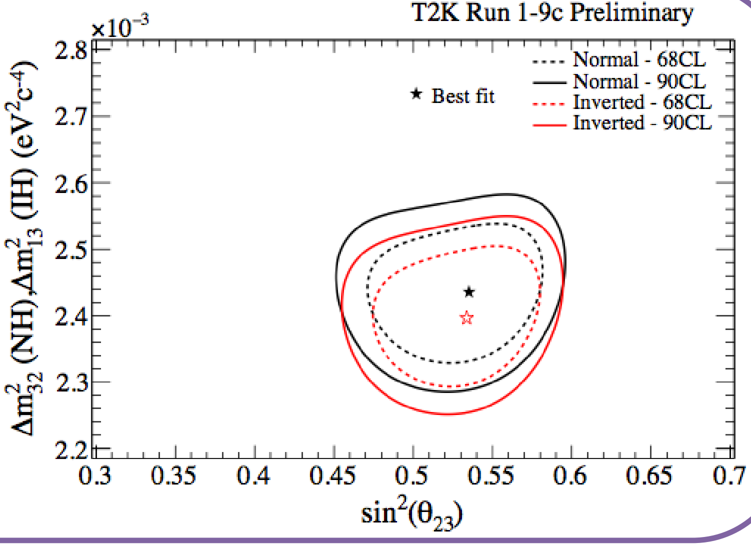
SAMPLE	PREDICTED				OBSERVED
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$	
FHC 1Rμ	268.5	268.2	268.5	268.9	243
RHC 1Rμ	95.5	95.3	95.5	95.8	102
FHC 1Re 0 decay-e	73.8	61.6	50.0	62.2	75
FHC 1Re 1 decay-e	6.9	6.0	4.9	5.8	15
RHC 1Re 0 decay-e	11.8	13.4	14.9	13.2	9

- Event rates are in line with expectations from 3-flavour neutrino oscillations
- Larger variation in the decay electron sample
  - P-value for such a fluctuation in 1 of 5 samples is ~5%

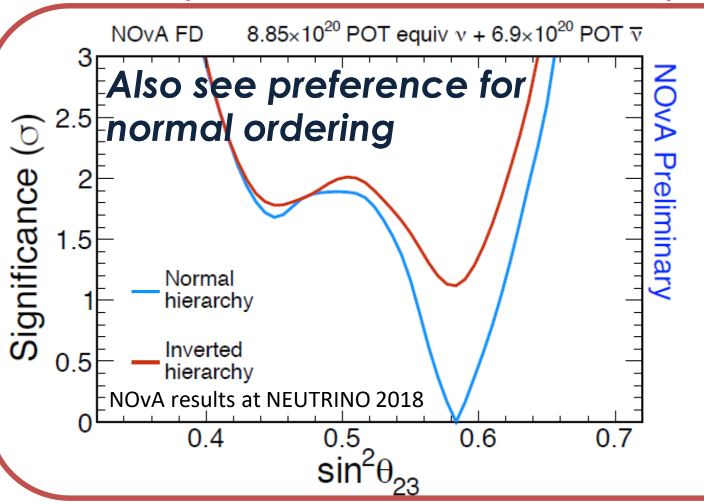
Atmospheric sector results

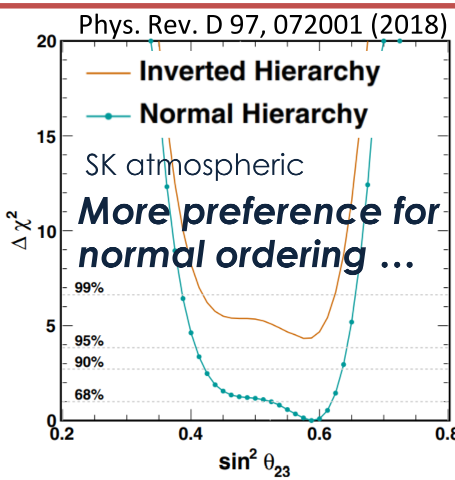
T2K+Reactors

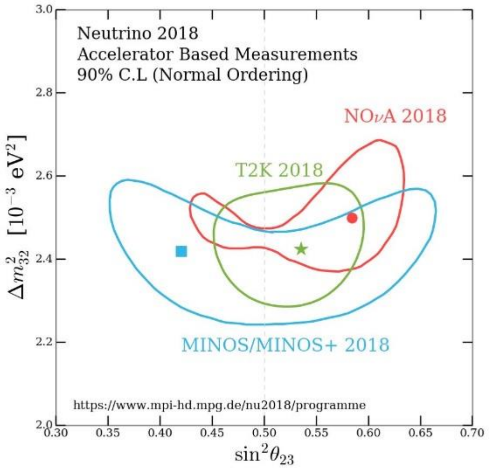




Comparison with other experiments

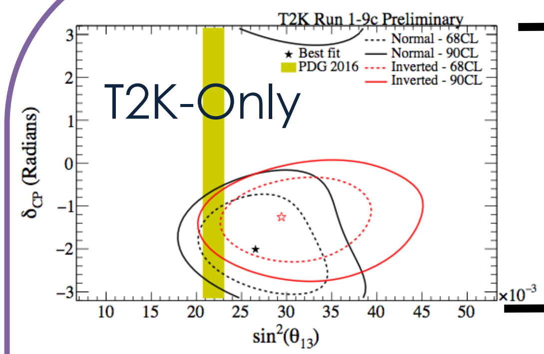


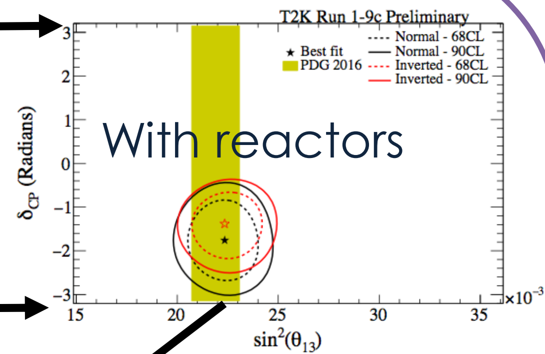


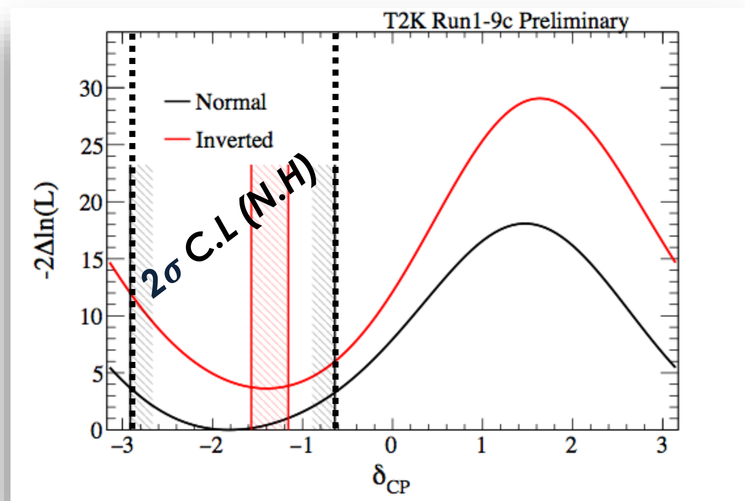


CP-violating phase results

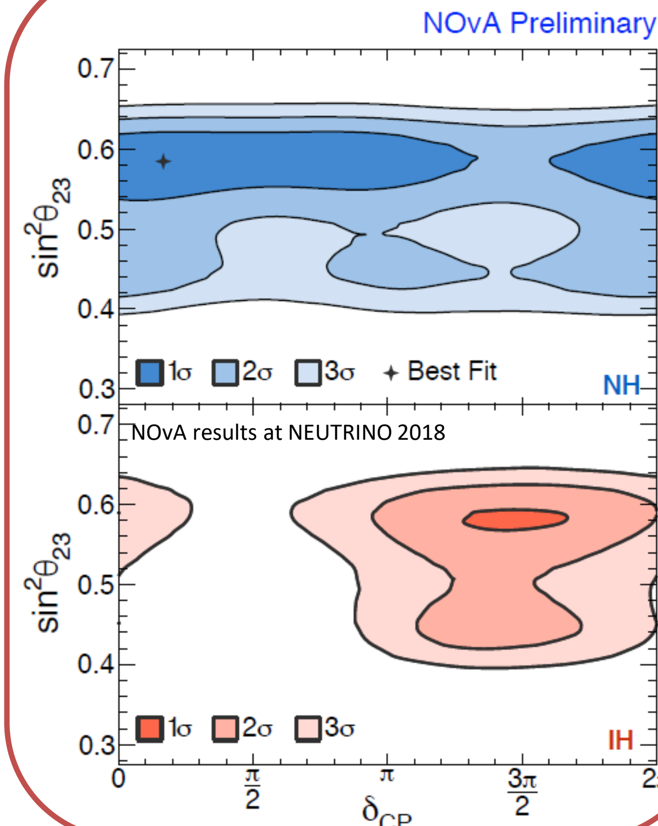
T2K+Reactors







Comparison with NOvA



T2K and NOvA are working together for a joint analysis by 2021

CPV in the neutrino sector is within reach!

How can we do better?

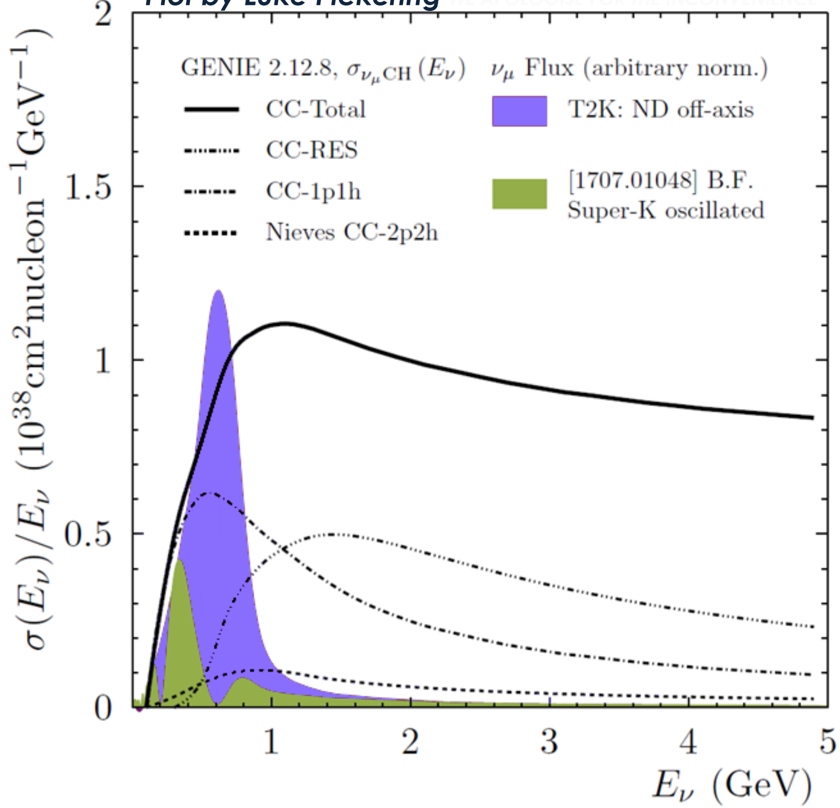
Taken form Simon Bienstock's 11/17 GDR talk

Source of Uncertainties			SK event sample: $\Delta N_{SK}/N_{SK}$ (1σ error)				
			ν-beam			$\bar{\nu}$-beam	
			1-ring μ-like	1-ring e-like	CC-1π^+ e-like	1-ring μ-like	1-ring e-like
SK: Detector + Final State Int. + 2ndary int.			4.2%	3.5%	14.0%	11.1%	4.0%
Beam + Near detectors	Neutrino Beam flux		3.6%	3.7%	3.6%	3.8%	3.8%
	ν-interaction cross-section	*MEC (corr)*	*3.5%*	*3.9%*	*0.5%*	*3.0%*	*3.0%*
		MEC bar (corr)	*0.2%*	*0.1%*	*0.0%*	*1.8%*	*2.3%*
		NC 1γ (uncorr)	*0.0%*	*1.5%*	*0.4%*	*0.0%*	*3.0%*
		$\sigma(\nu_e) / \sigma(\nu_\mu)$	*0.0%*	*2.6%*	*2.4%*	*0.0%*	*1.5%*
		(Cross-section: sub total)	4.0%	5.1%	4.8%	4.2%	5.5%
	(Flux + Cross-section Sub total)		2.9%	4.2%	5.0%	3.5%	4.7%
Oscillation parameters: $\sin^2\theta_{13}$, $\sin^2\theta_{12}$, Δm^2_{21}			0.0%	4.2%	3.8%	0.0%	4.0%
Total			5.1%	6.8%	15.3%	11.7%	7.4%

- Large component of the uncertainty stems from "**MEC**" and Final State Interactions (**FSI**).
- These are related to our naivety of **neutrino nucleus interactions.**

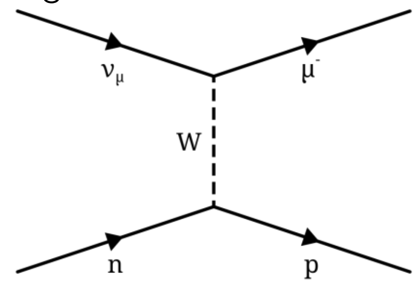
Neutrino Interactions at T2K

Plot by Luke Pickering



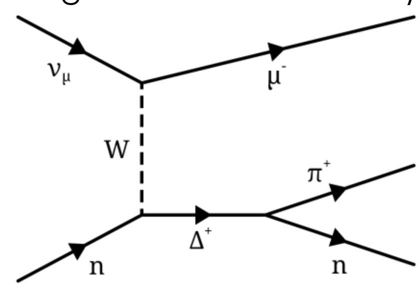
CCQE (1p1h)

(Charged-Current Quasi-Elastic)



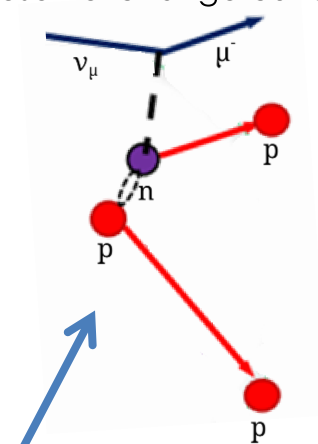
CCRES

(Charged-Current Resonant)

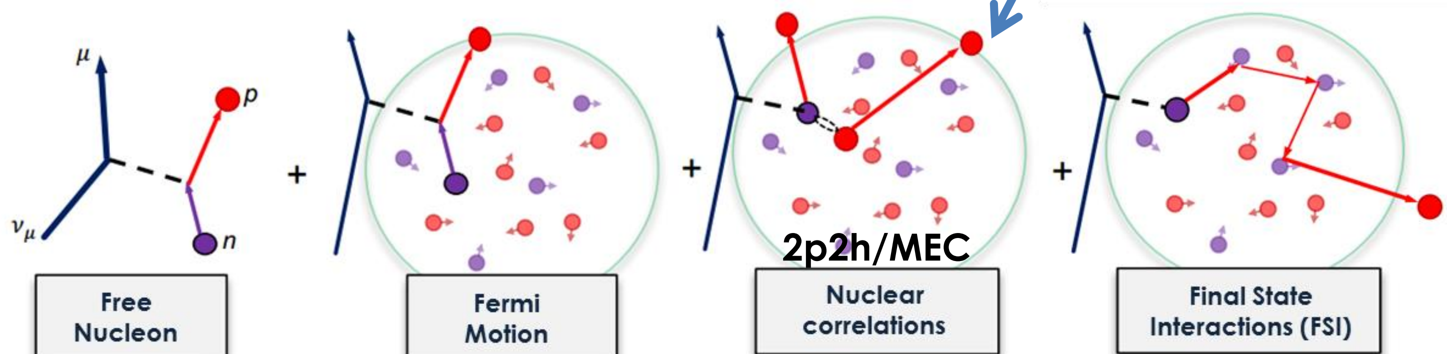


2p2h (MEC)

(2 particle – 2 hole / meson exchange current)



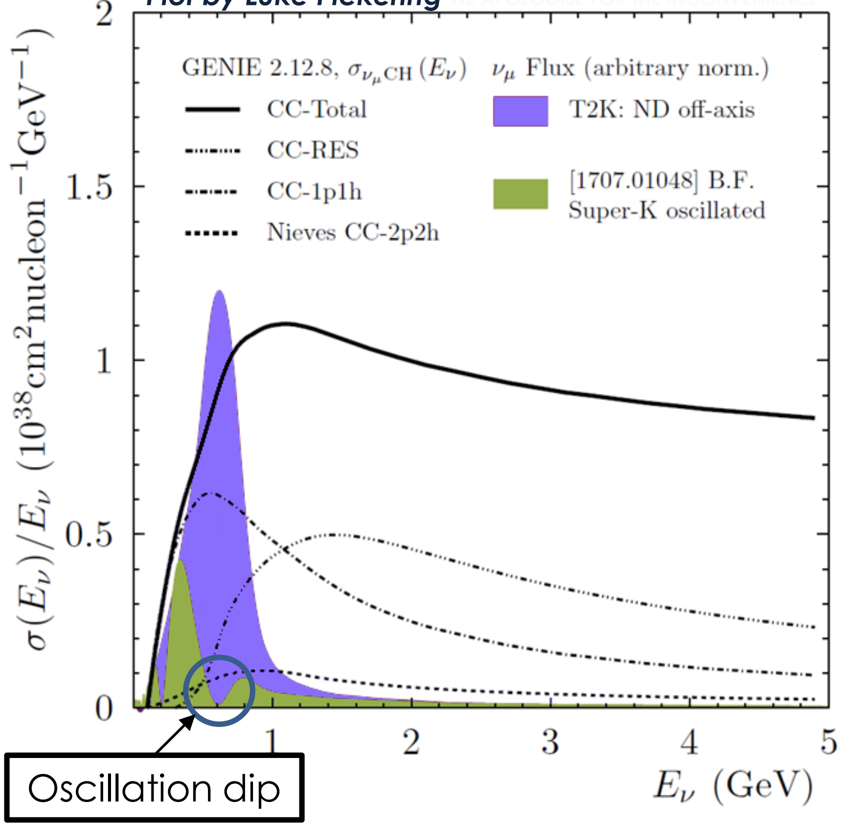
Nuclear Effects

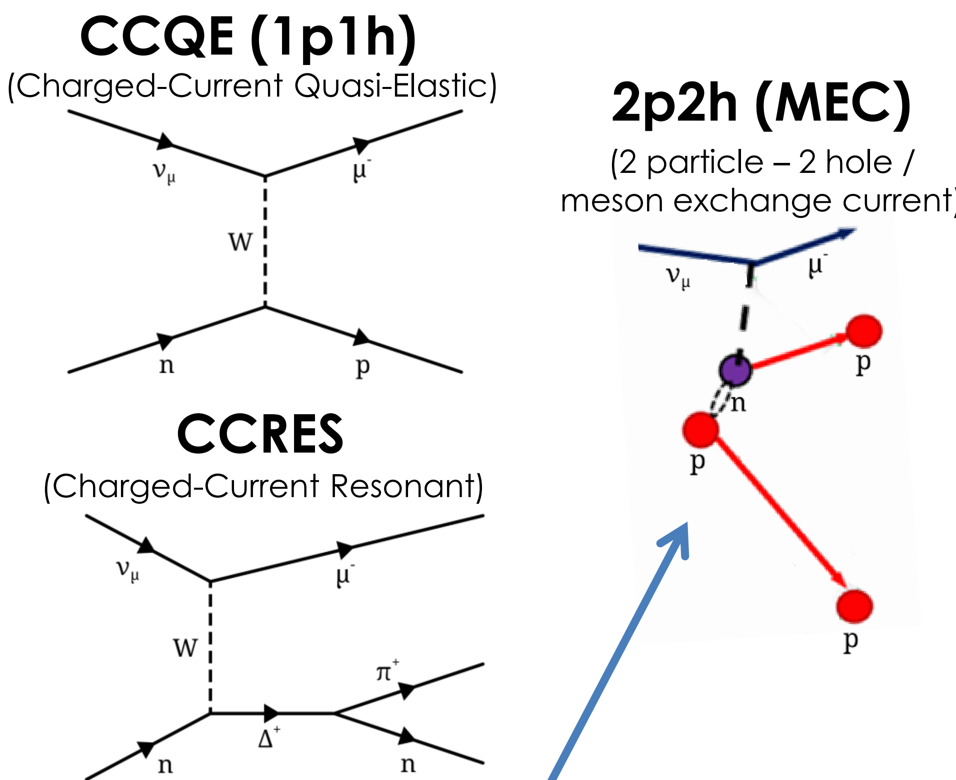


Diagrams by Patrick Stowell

Neutrino Interactions at T2K

Plot by Luke Pickering





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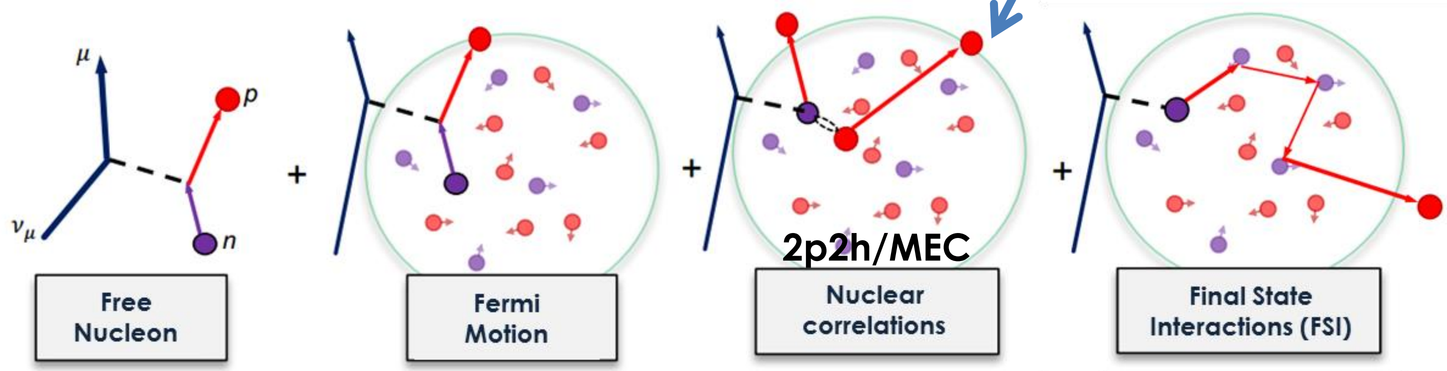

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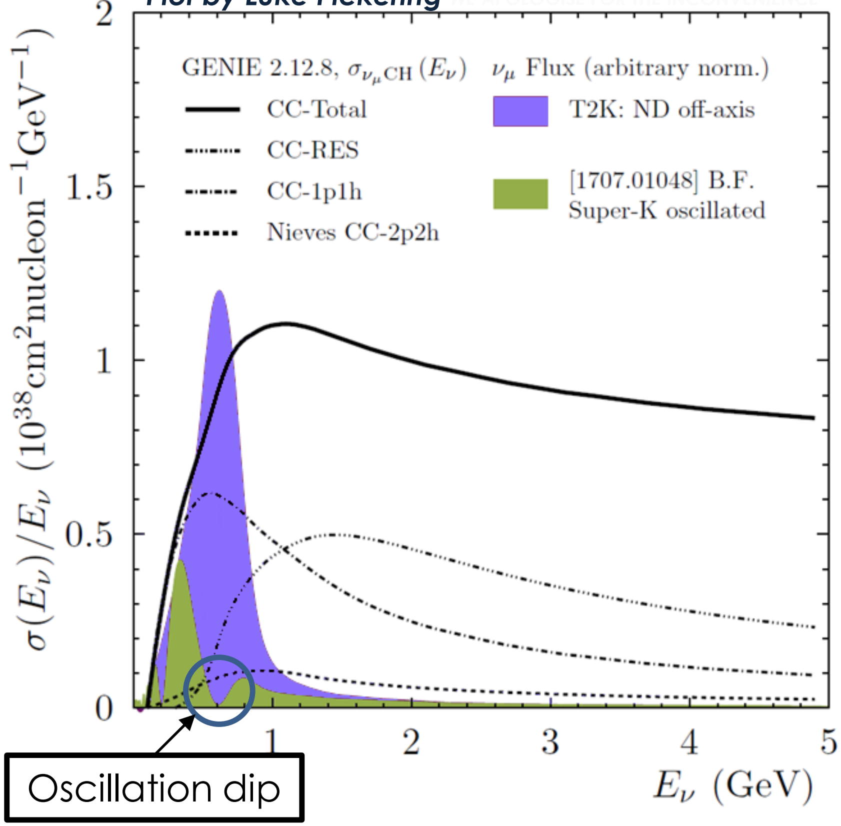
Plot by Luke Pickering



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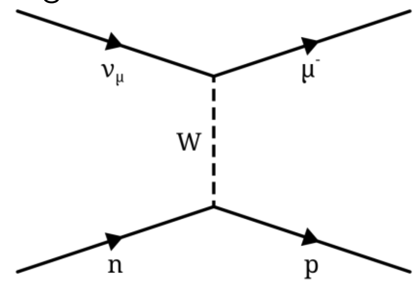
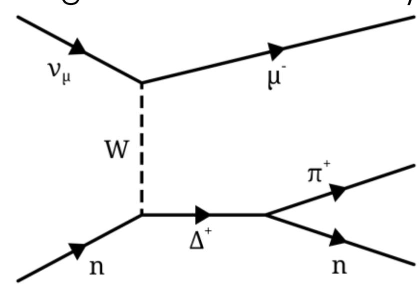
(Charged-Current Quasi-Elastic)



CCRES

(Charged-Current Resonant)



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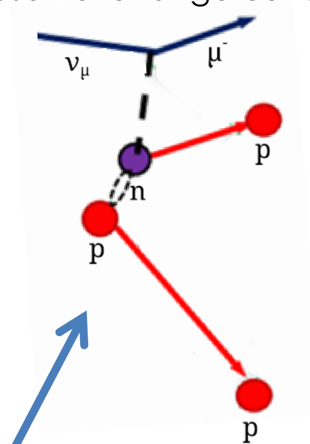
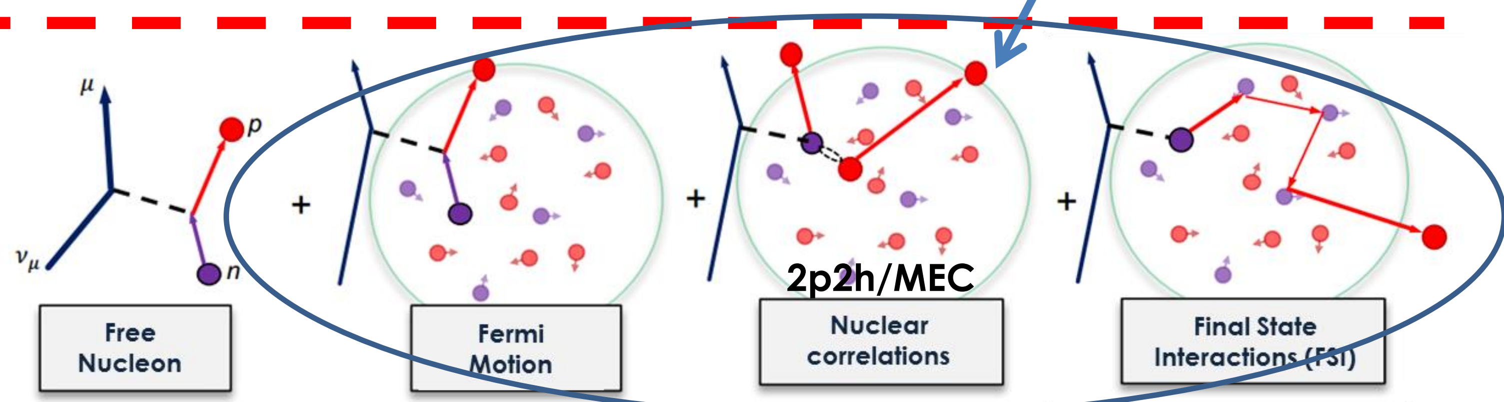
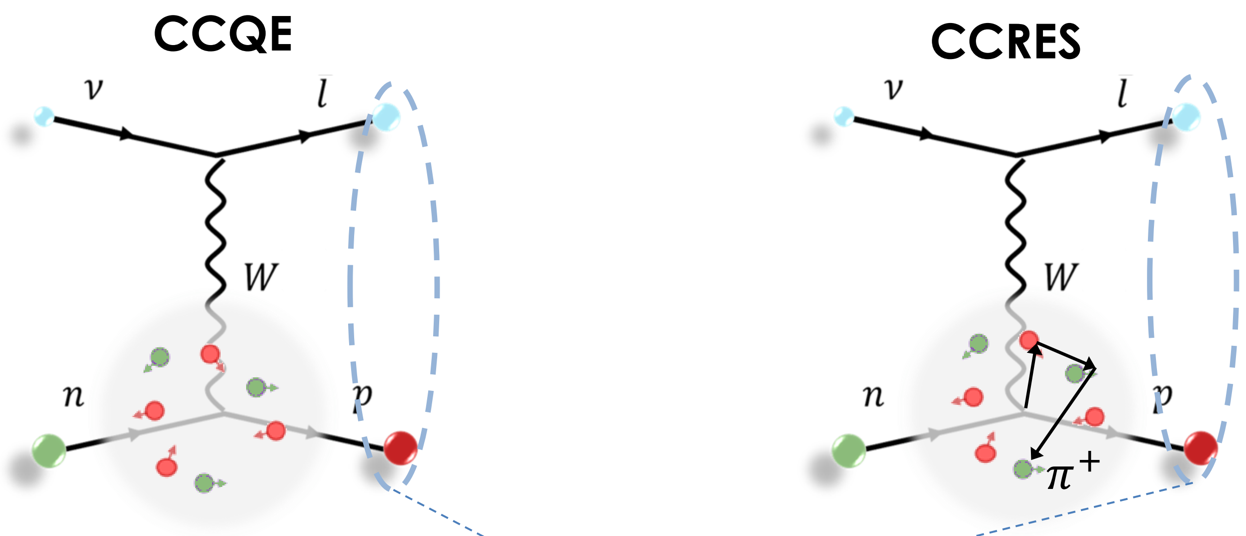


Nuclear Effects



Diagrams by Patrick Stowell

Nuclear effects at SK

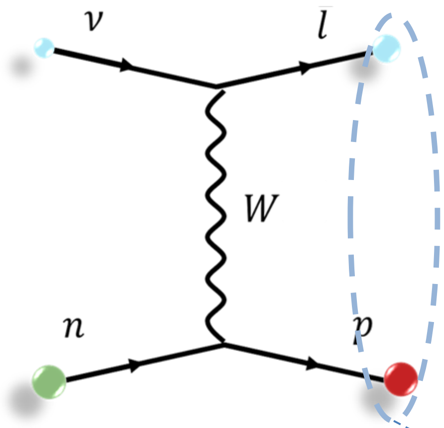


Final state interactions (FSI) can cause different interaction modes to have the same final state

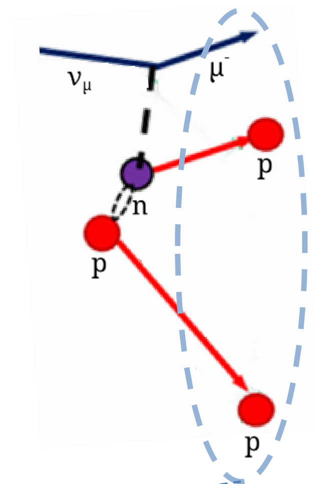
- Due to **FSI** SK's CCQE-like selection can contain CCRES events
- We have a very limited understanding of how many → large systematic

Nuclear effects at SK

CCQE (no FSI)



2p2h (MEC)



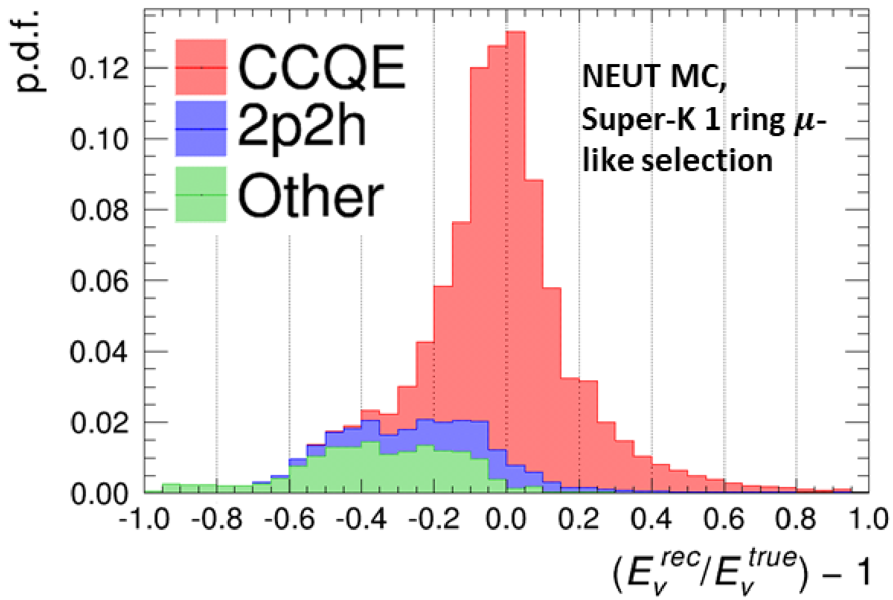
SK can't (yet) see nucleons, it can't distinguish CCQE from 2p2h (even if neglect the impact of FSI)

- SK's CCQE-like selection **can contain 2p2h events**
- We have a very limited understanding of how many → large systematic

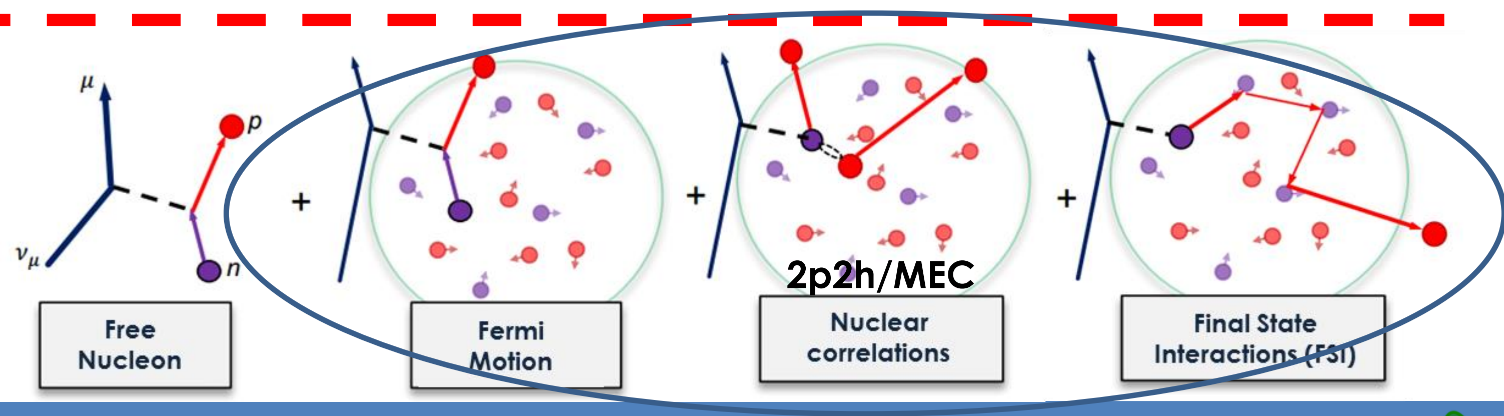
Neutrino energy reconstruction

- Find E_ν^{reco} in oscillation analyses using observed μ at SK assuming **stationary target** and **CCQE scattering**

- Nuclear effects cause SK's selections to contain more than just CCQE events
- **These will not have a well reconstructed neutrino energy**
- But we need the neutrino energy to do oscillation analyses!
- We don't understand nuclear effects: large systematics are applied.

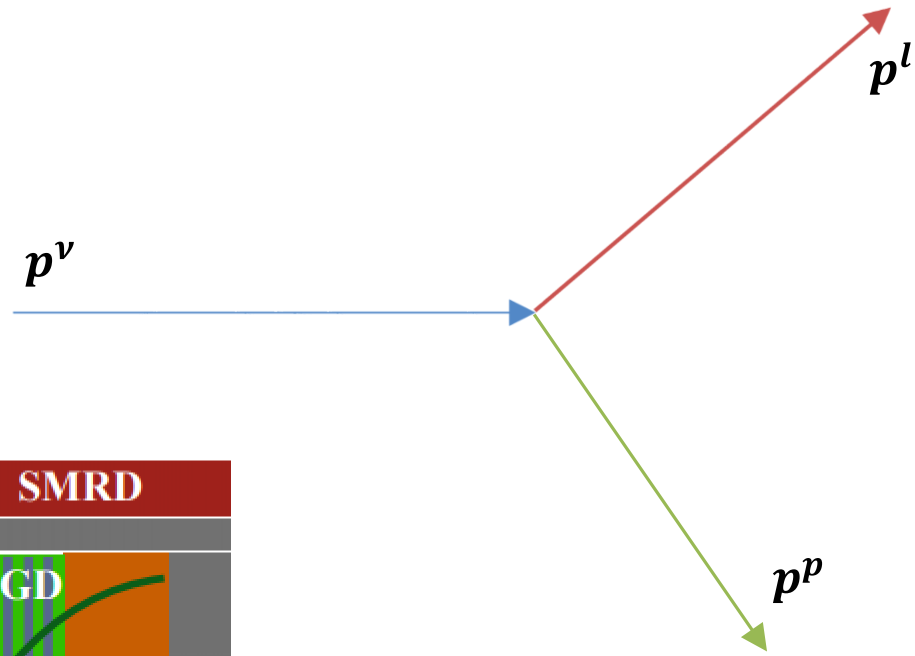


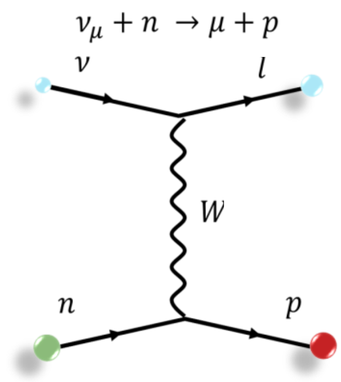
Nuclear Effects



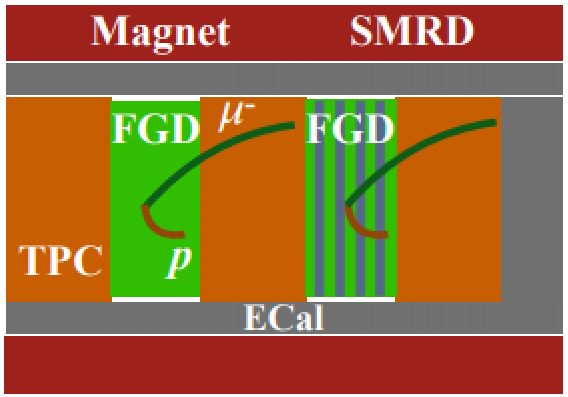
Diagrams by Patrick Stowell

Single Transverse Variables



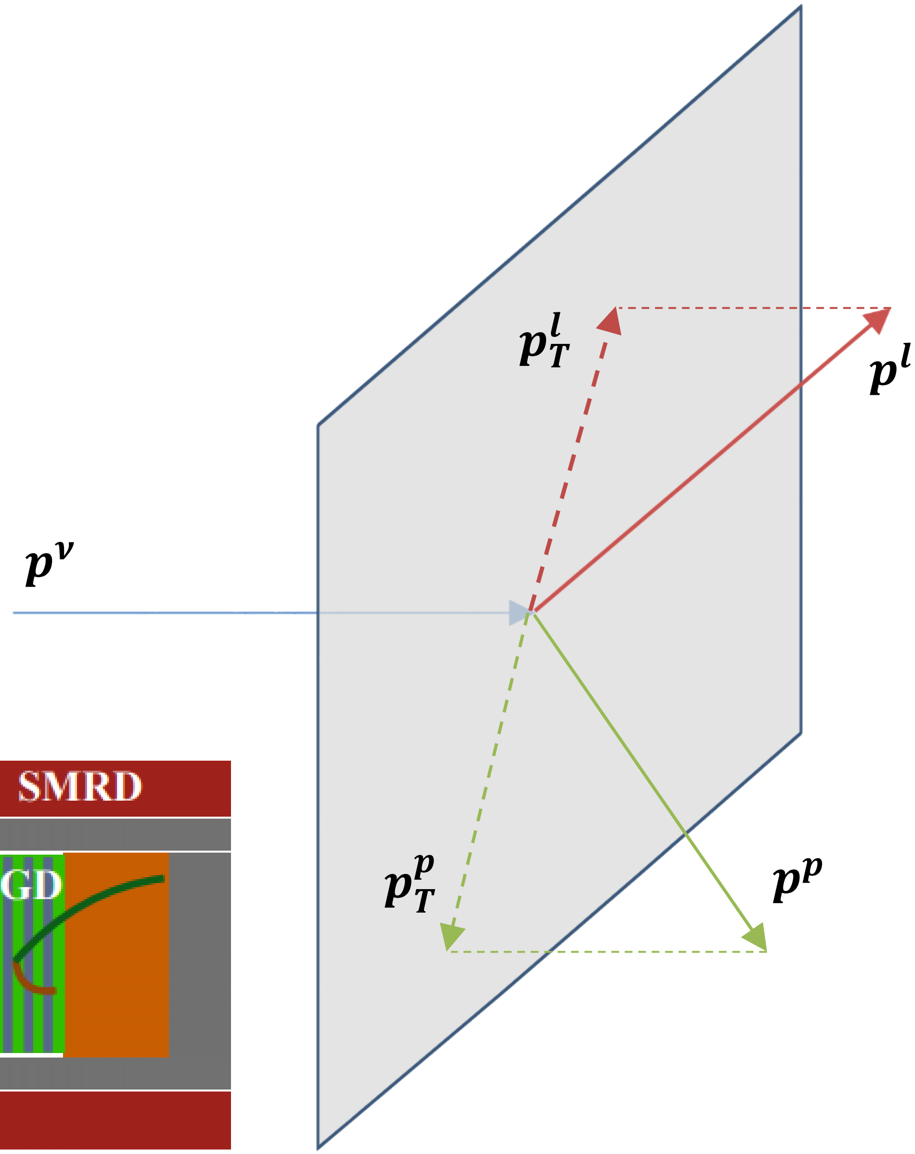


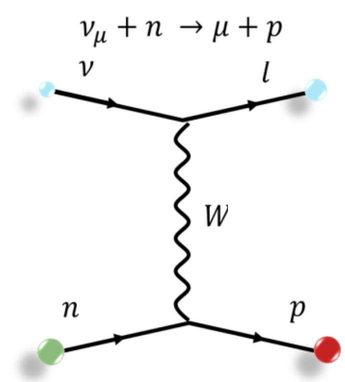
No nuclear Effects



Can measure protons at ND280

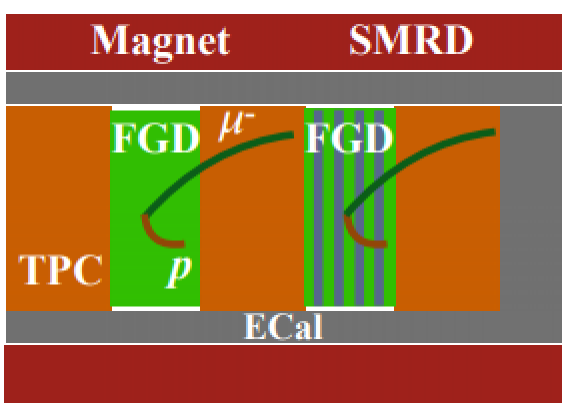
Single Transverse Variables





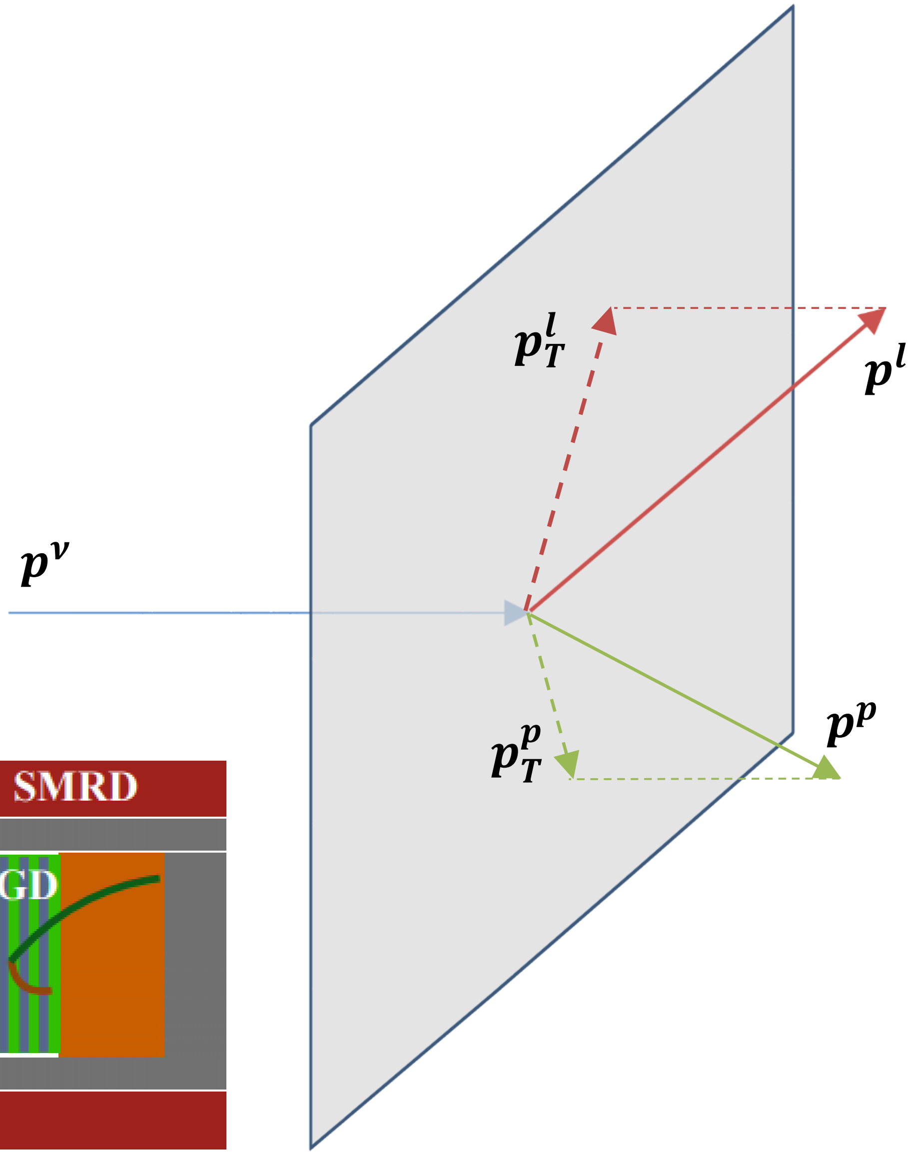
No nuclear Effects

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

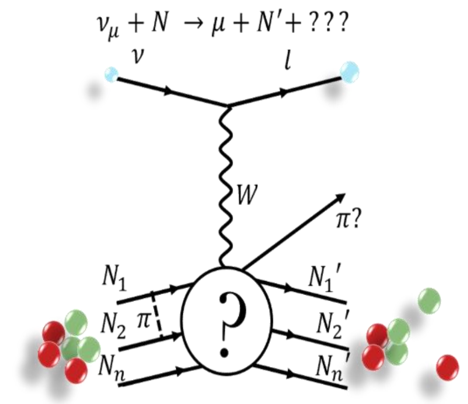


Can measure protons at ND280

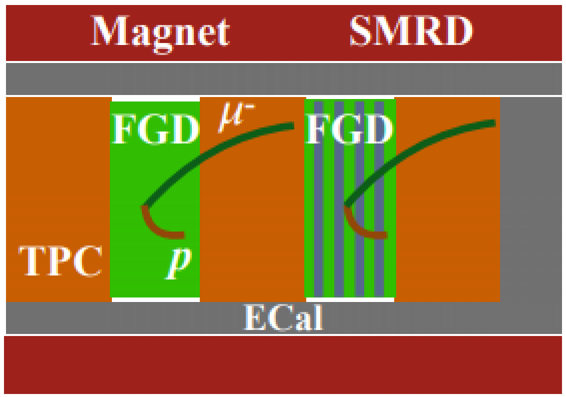
Single Transverse Variables



$p_T^l \neq -p_T^p$



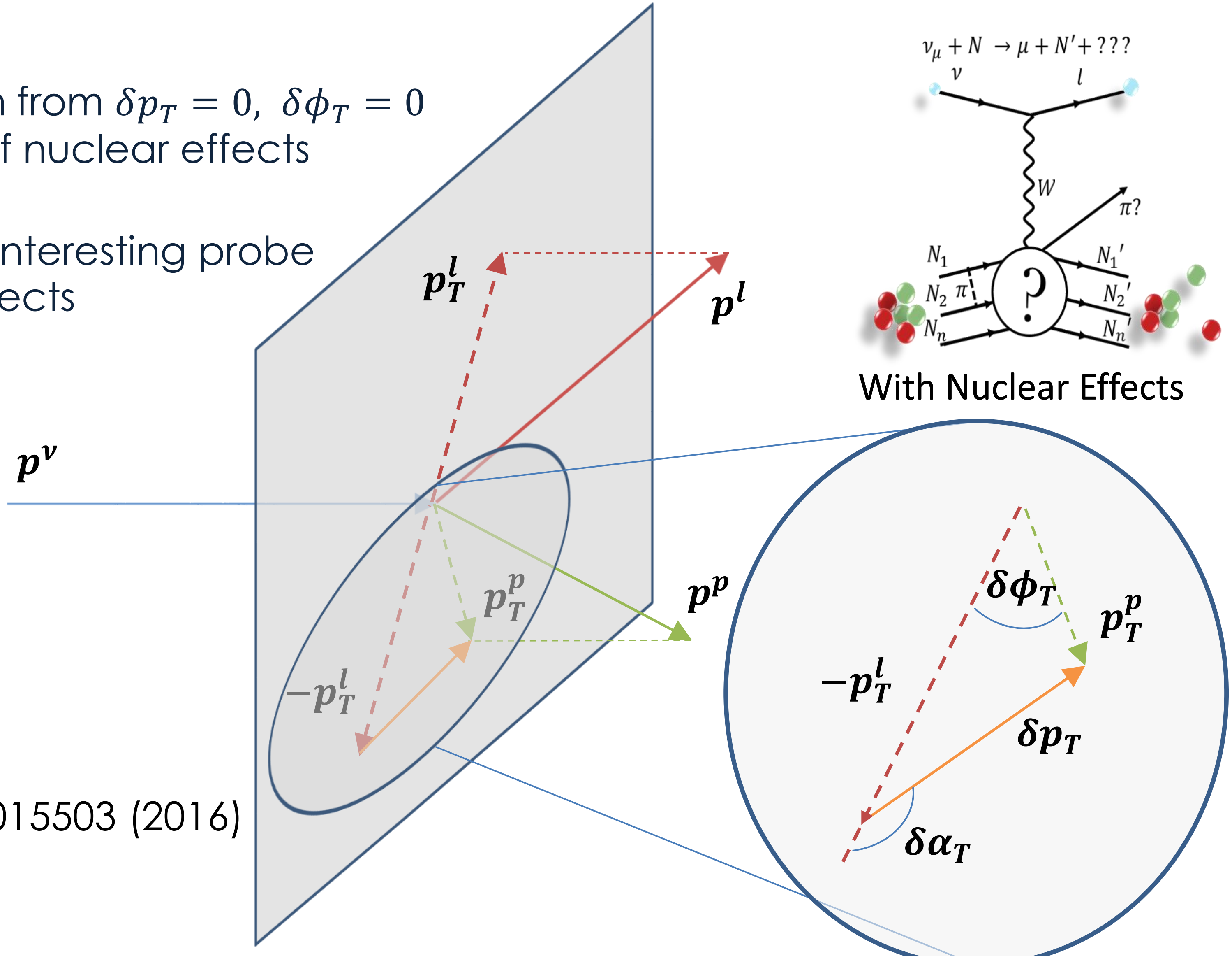
With Nuclear Effects



Can measure protons at ND280

Single Transverse Variables

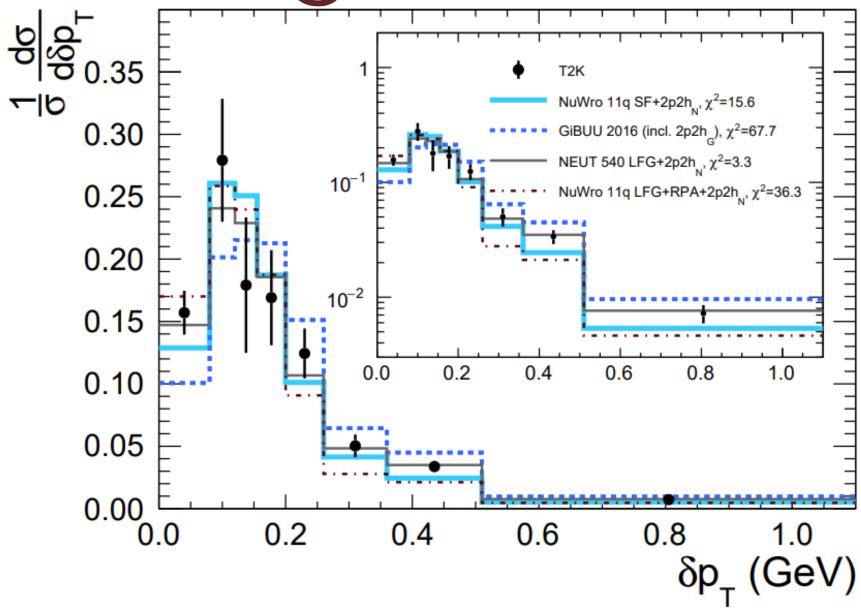
- Any deviation from $\delta p_T = 0,\ \delta\phi_T = 0$ is indicative of nuclear effects
- STVs offer an interesting probe of nuclear effects

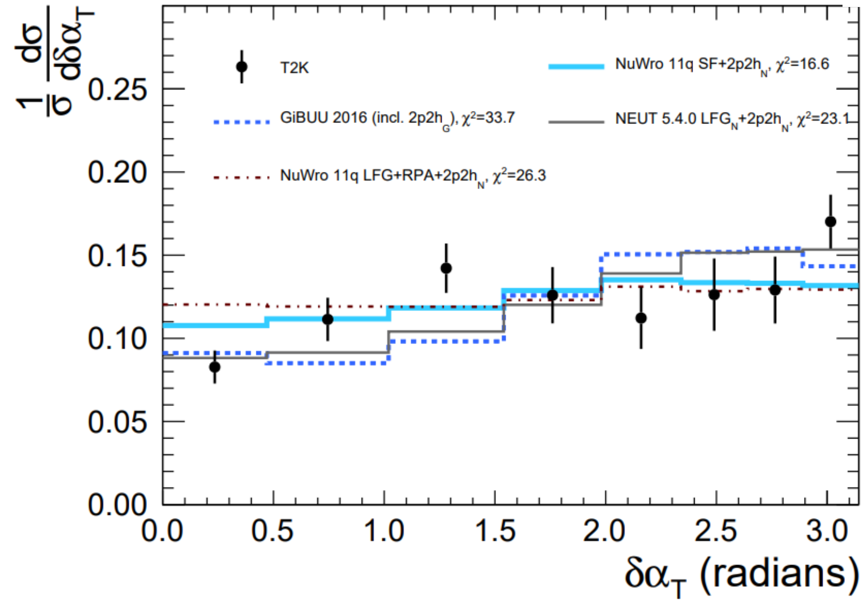


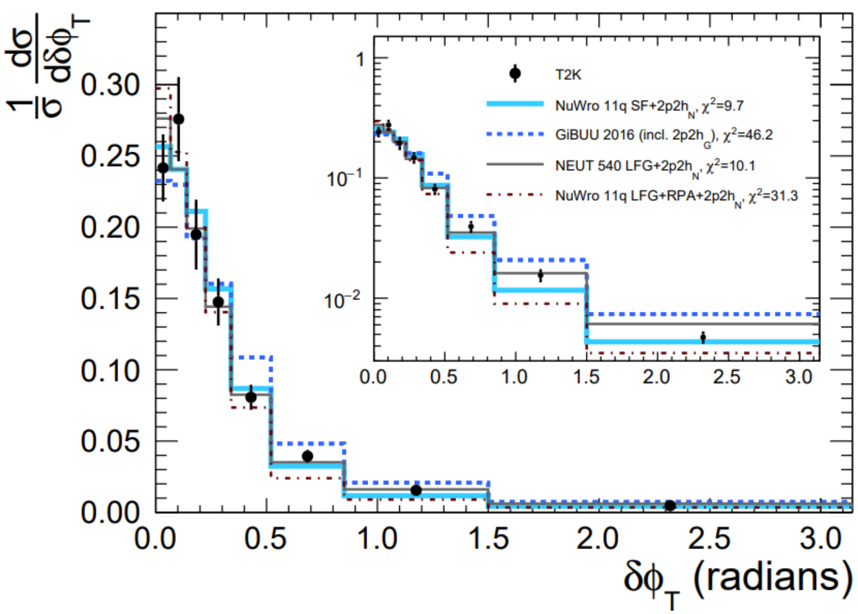
Phys. Rev. C **94**, 015503 (2016)

Probing nuclear effects

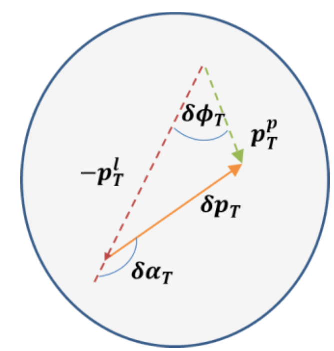
arxiv: 1802.05078





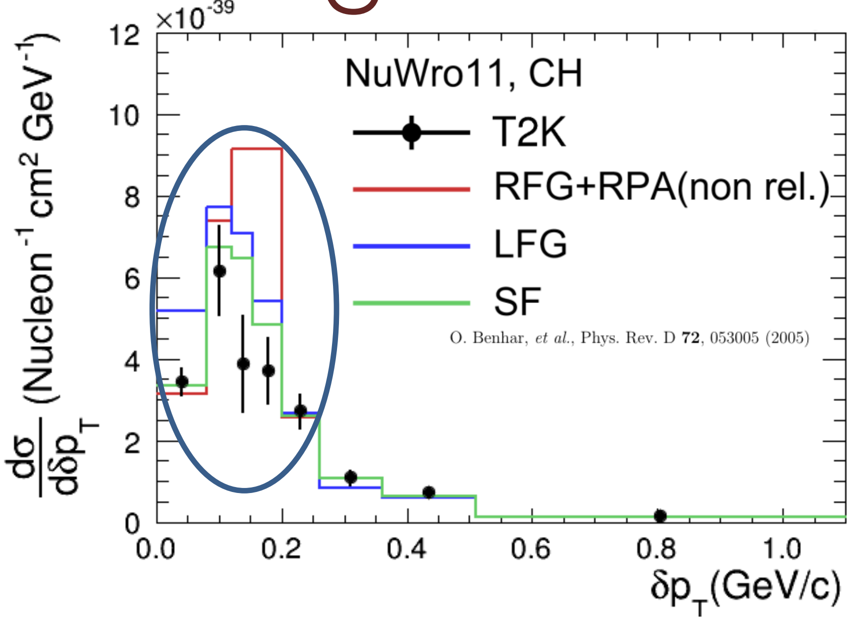


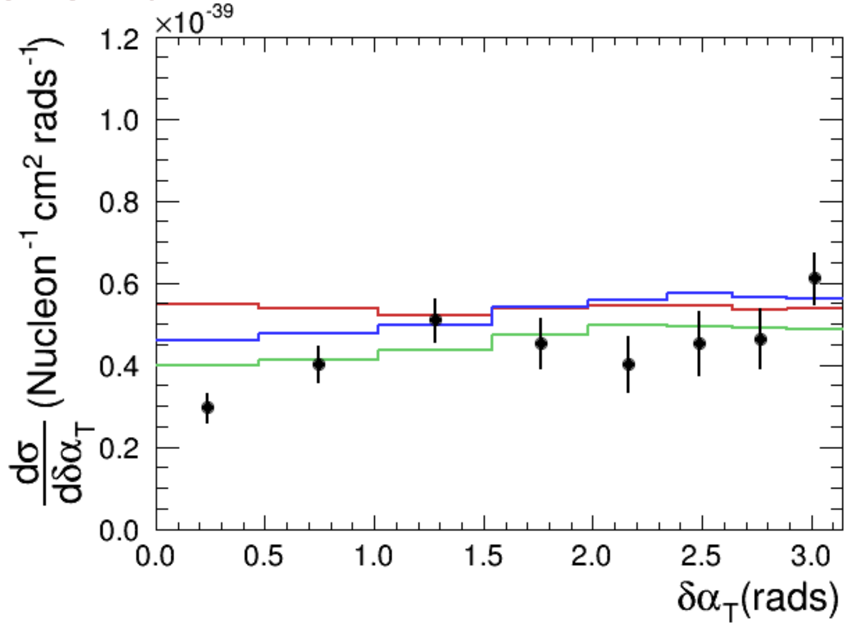
- Measure fiducial cross section of CCQE-like interactions using ND280
- Compare to state-of-the-art simulation predictions

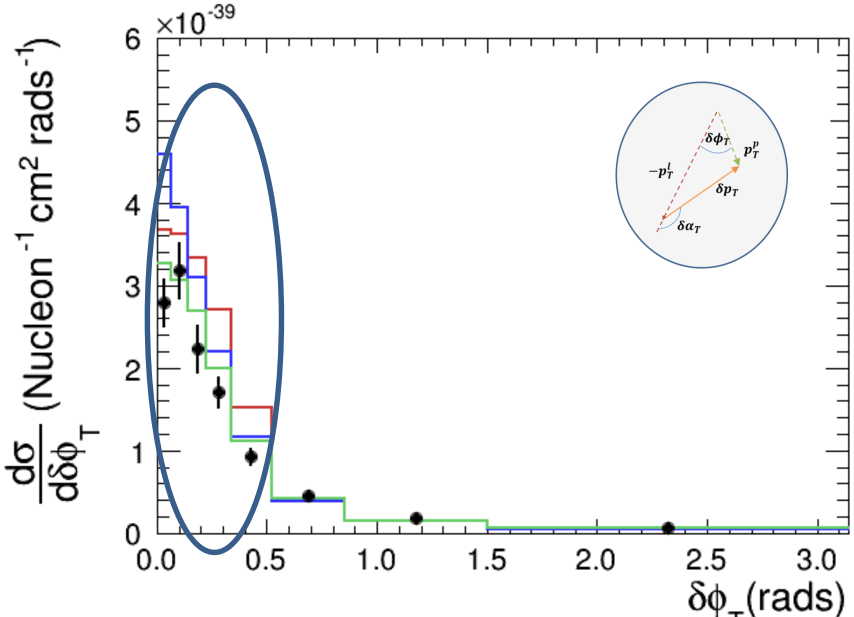


Probing nuclear effects

arxiv: 1802.05078



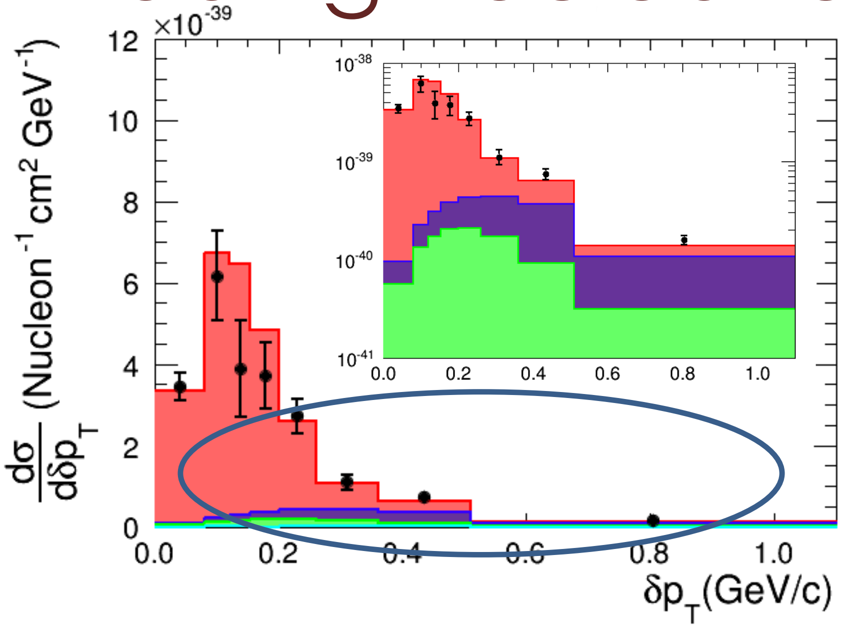


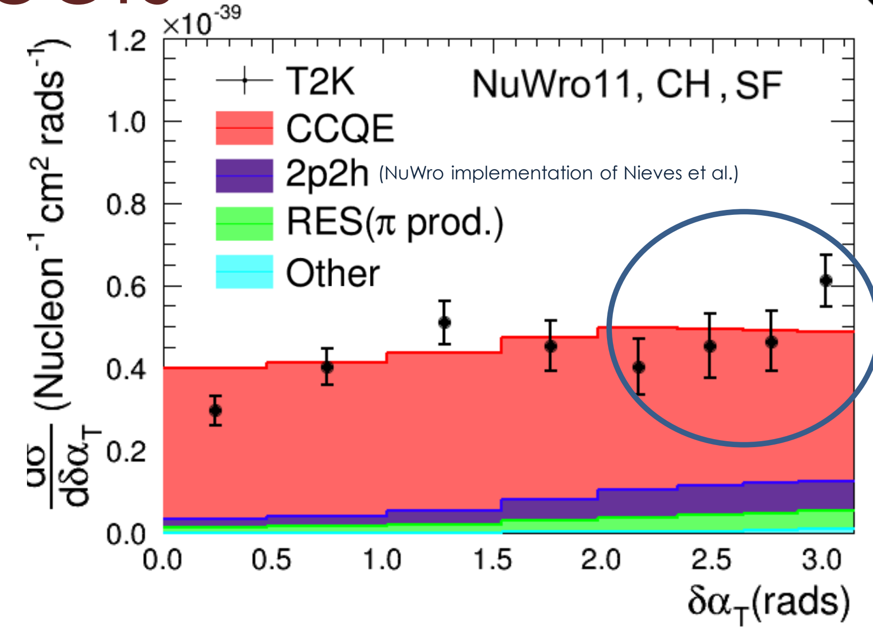


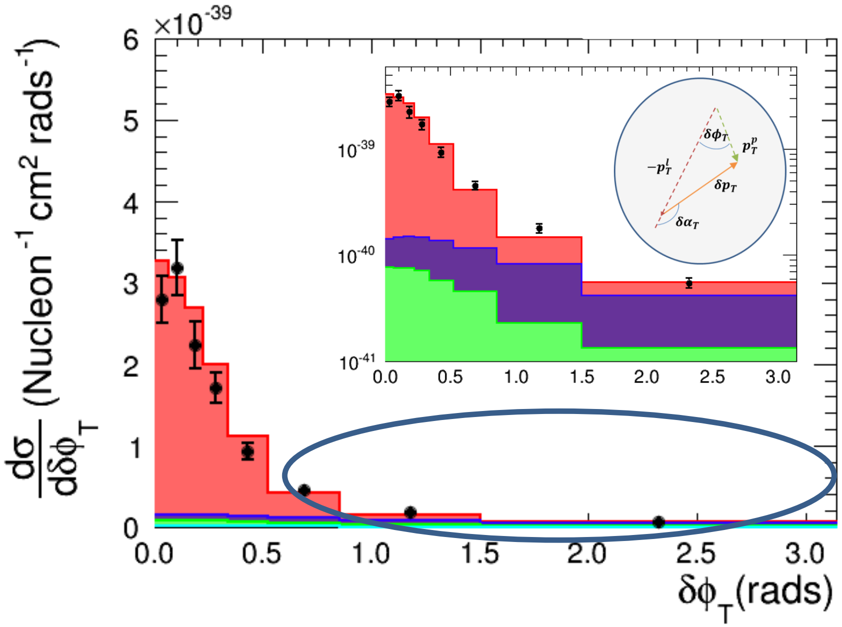
- The peak position and early bins in δp_T and $\delta\phi_T$ tell us about **Fermi Motion**.

Probing nuclear effects

arxiv: 1802.05078



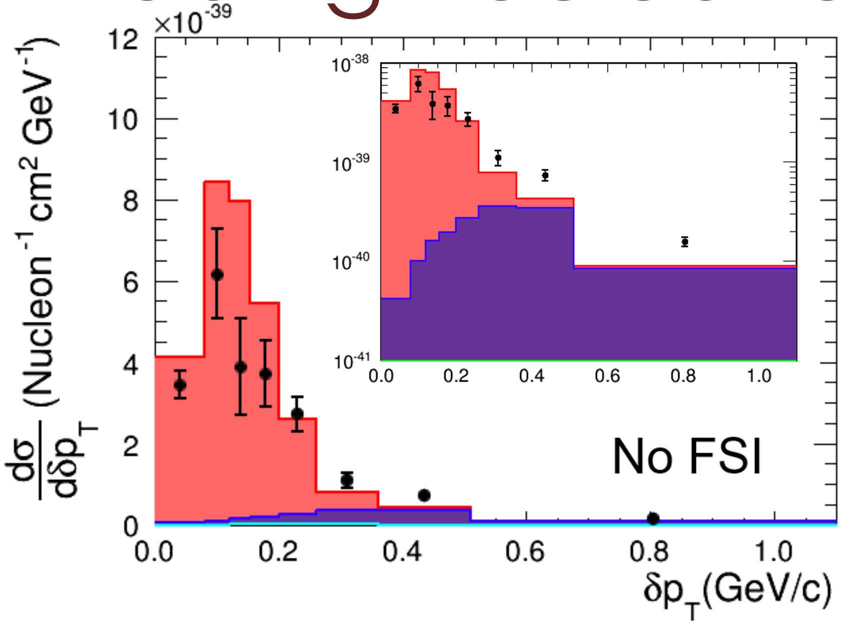


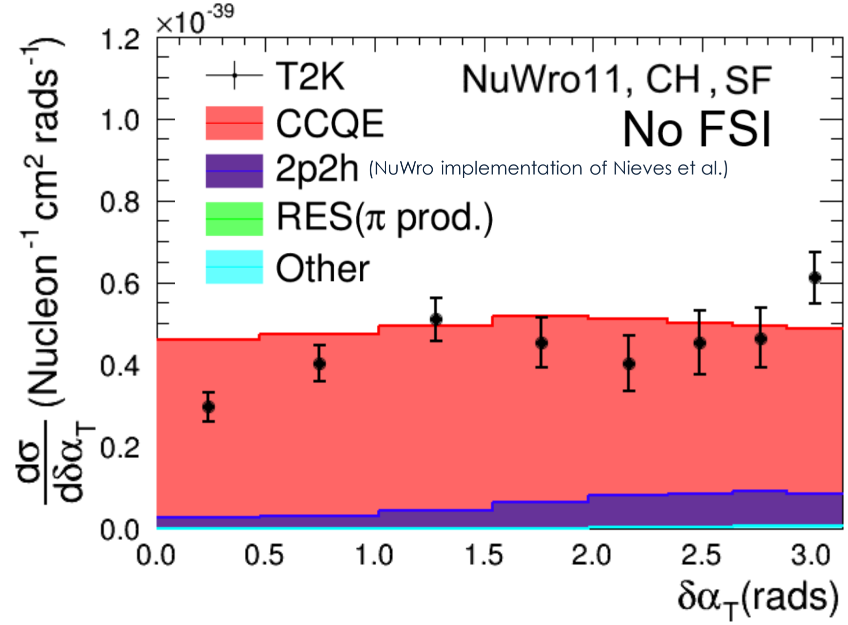


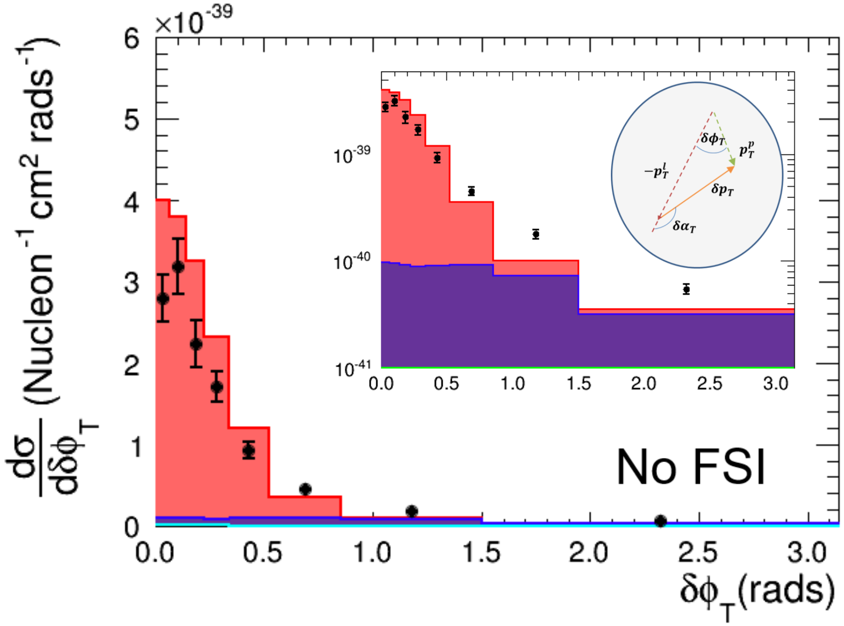
- The peak position and early bins in δp_T and $\delta\phi_T$ tell us about **Fermi Motion**.
- The tails in δp_T and $\delta\phi_T$ and the extent of the rise at large $\delta\alpha_T$ partially isolate the effects of Fermi Motion from **2p2h**.

Probing nuclear effects

arxiv: 1802.05078





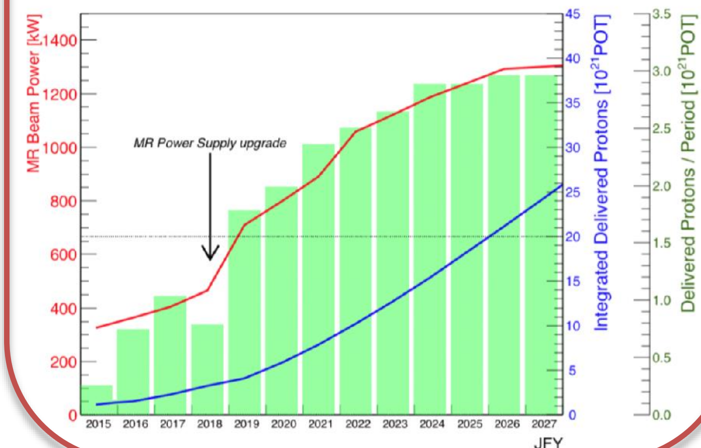


- The peak position and early bins in δp_T and $\delta\phi_T$ tell us about **Fermi Motion**.
- The tails in δp_T and $\delta\phi_T$ and the extent of the rise at large $\delta\alpha_T$ partially isolate the effects of Fermi Motion from **2p2h**.
- Weaker **FSI** causes a relative deficit of events in the tails, but an increased normalisation.

The Future of T2K

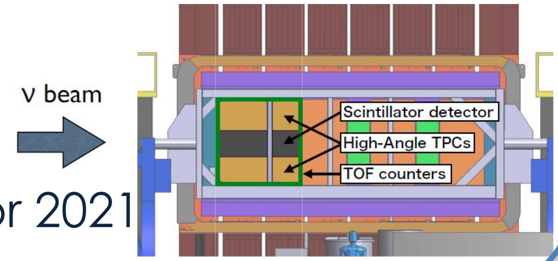
T2K phase 2

- Proposal to collect ~7.5 times more data than shown in this talk by ~2026
- Achieved with beam upgrade
- Stage-1 status by KEK
- Up to 3σ CPV sensitivity with no improvements to systematics



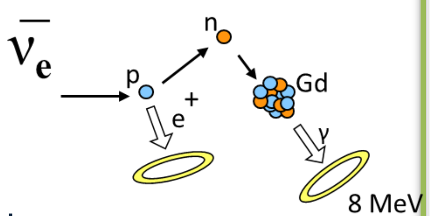
ND280 Upgrade

- Add advanced scintillator detector a two high angle TPCs to ND280
- Will allow improved flux and interaction constraints
- Hope to reduce systematics to 4%
- Aim to be ready for 2021



SK-Gd project

- Add Gd to SK water to greatly enhance neutron detection
- Neutron multiplicity can act as a powerful CCnonQE discriminator
- Can also identify $\bar{\nu}$ in ν beam
- SK tank is being repaired to be ready for Gd-loading now



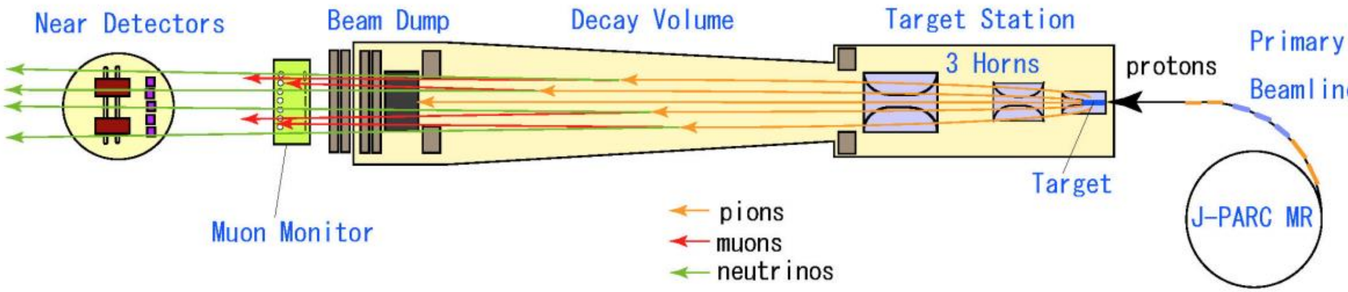
Conclusions

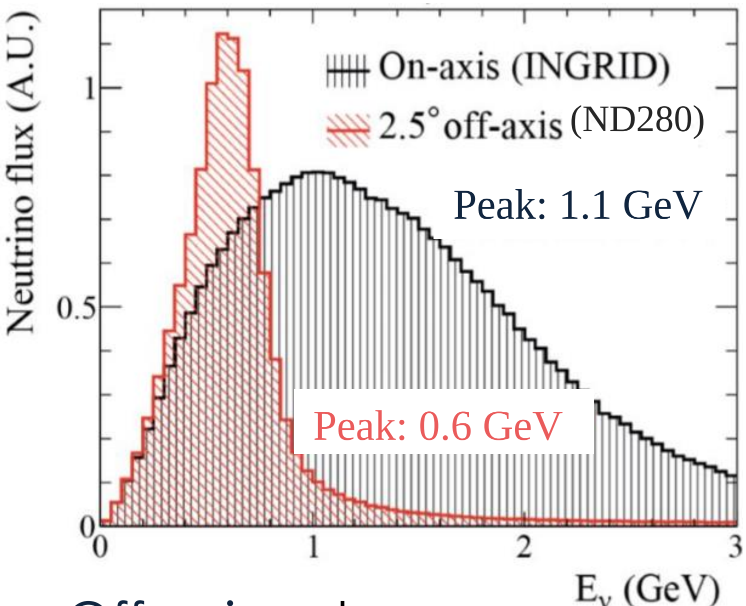
- T2K (and other experiments) show a preference for the normal neutrino mass hierarchy
- CP-conserving values of δ_{CP} lie outside 2σ region
- New cross section measurements are constraining some of the dominant systematics
- Upgrades of the beam, near and far detectors are progressing well
- Can expect another oscillation analysis update in late summer 2018

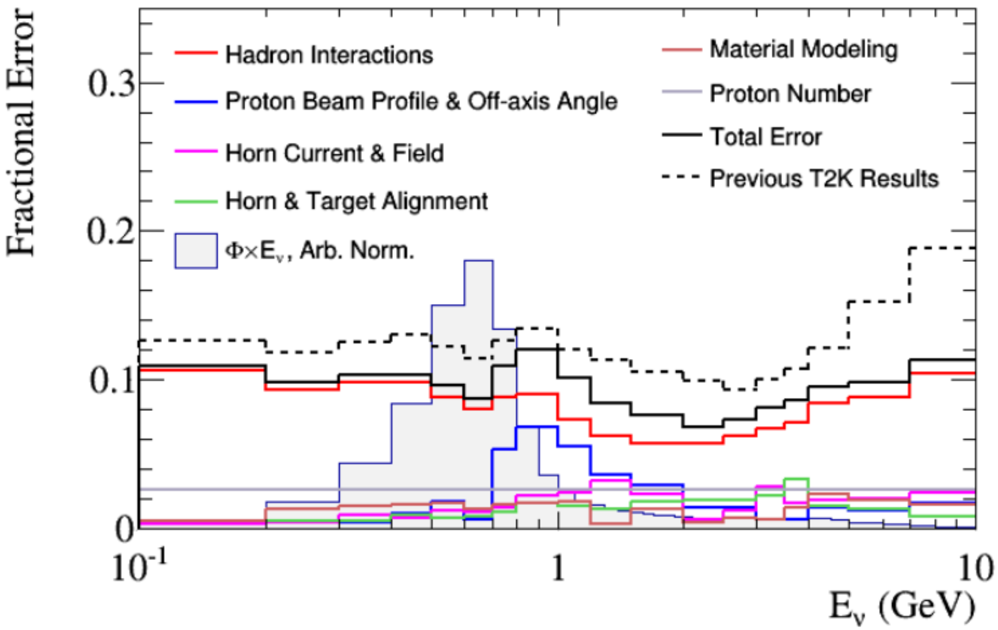
Thank you for listening

BACKUPS

The Beam



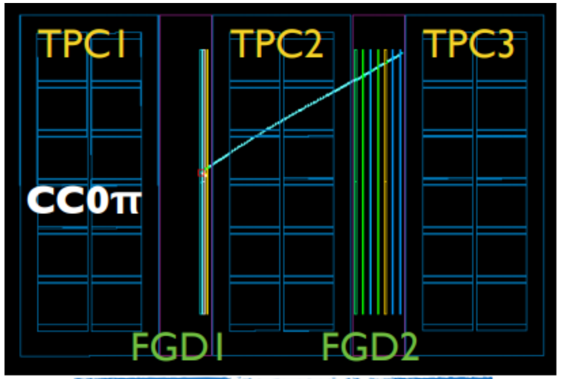




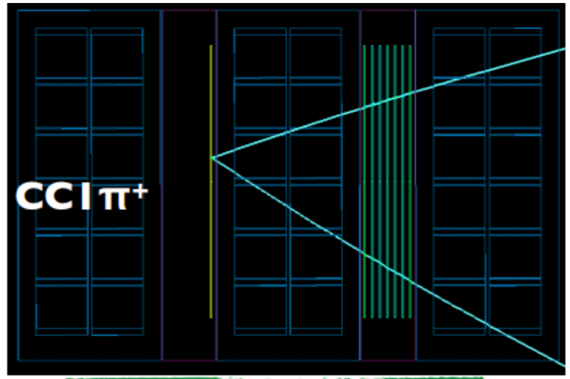
- Off-axis ν_μ beam
  - Tightly-peaked at 600 MeV 2.5° off-axis towards SK
  - Low contamination from non-ν_μ components
  - Flux estimation aided by hadron production measurements from NA61/SHINE at CERN

Phys. Rev. D 87, 012001

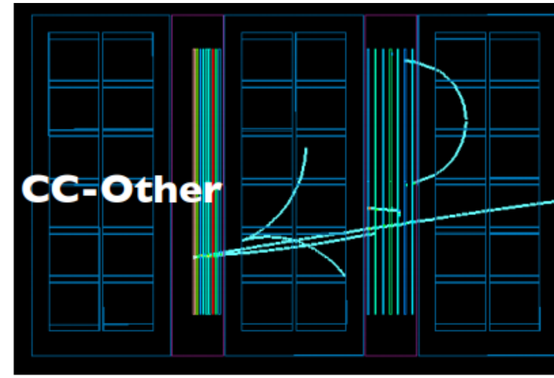
ND280 samples for oscillation analysis



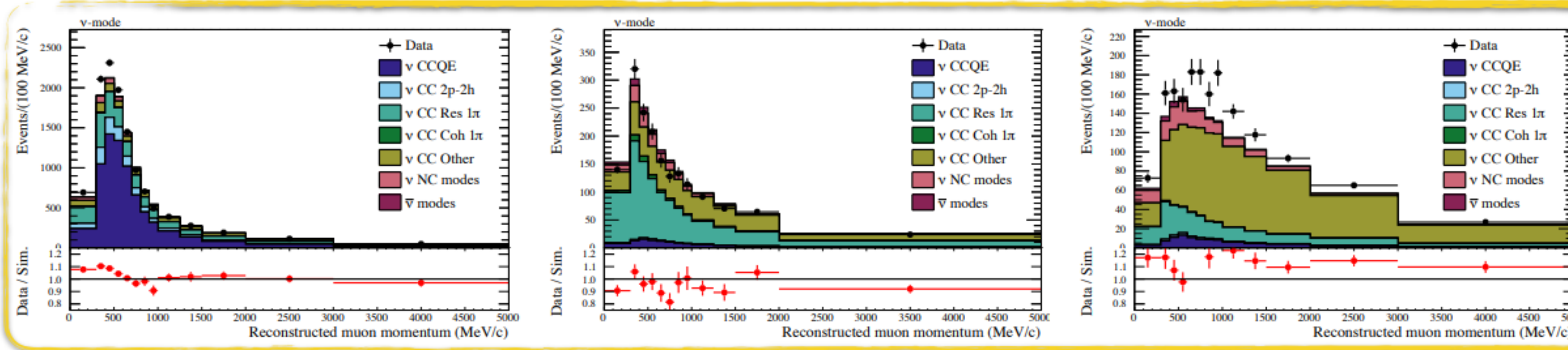
CC interaction with NO π in final state



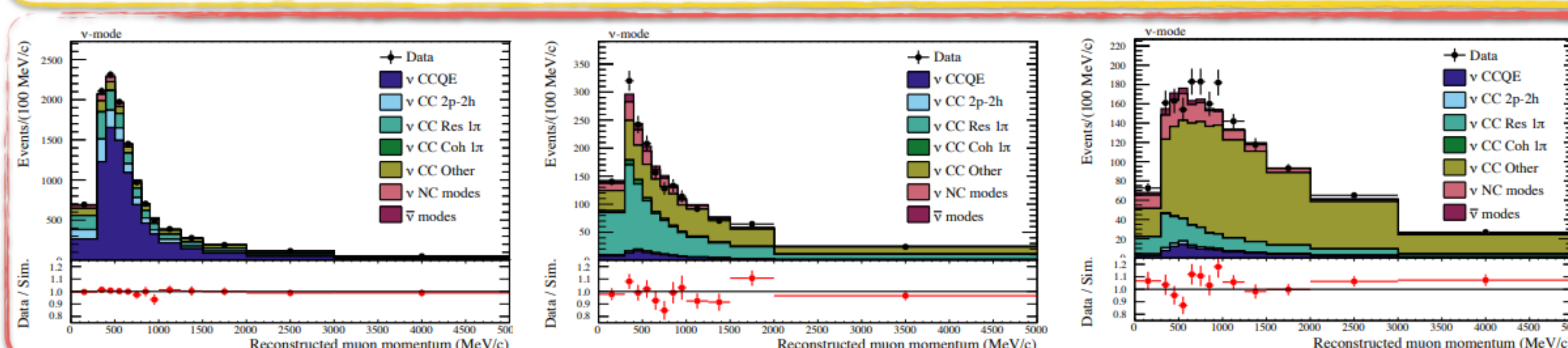
CC interaction with ONE π⁺ in final state



Other CC interactions

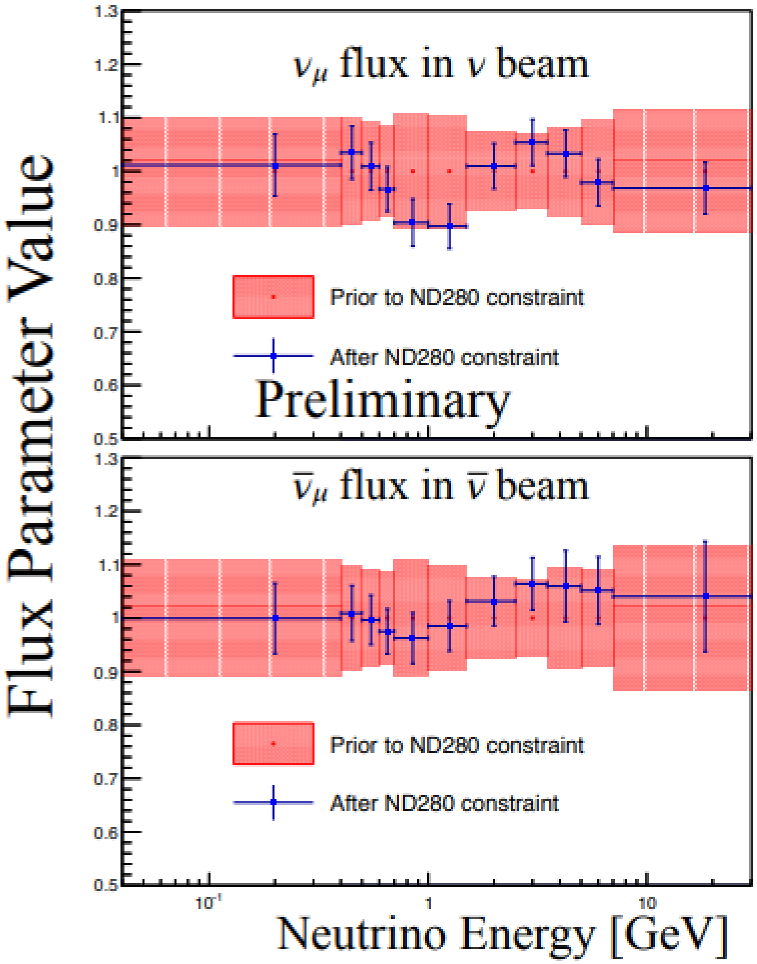


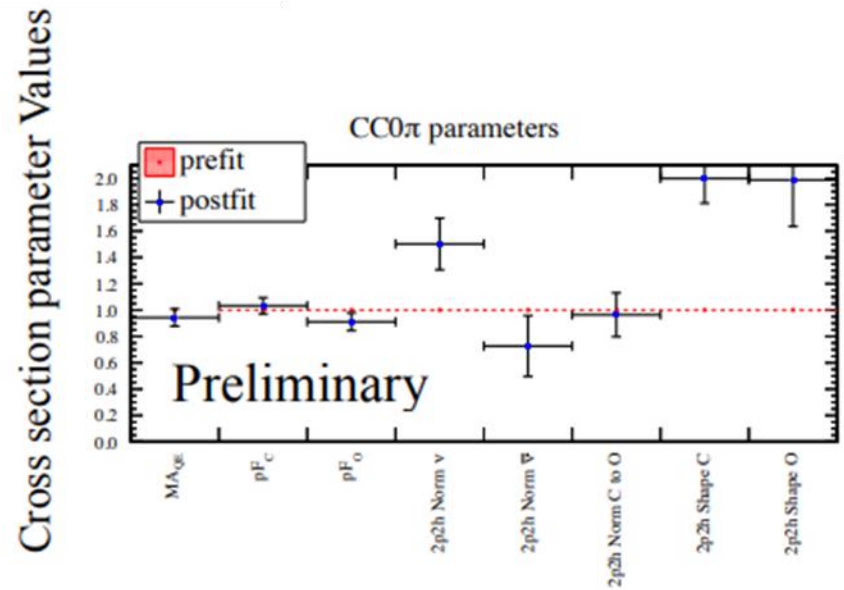
pre-ND280 fit



post-ND280 fit

Postfit Nuisances



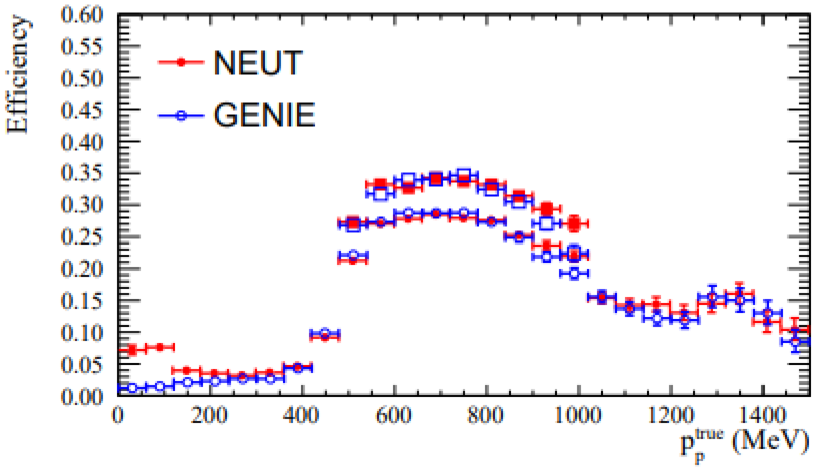


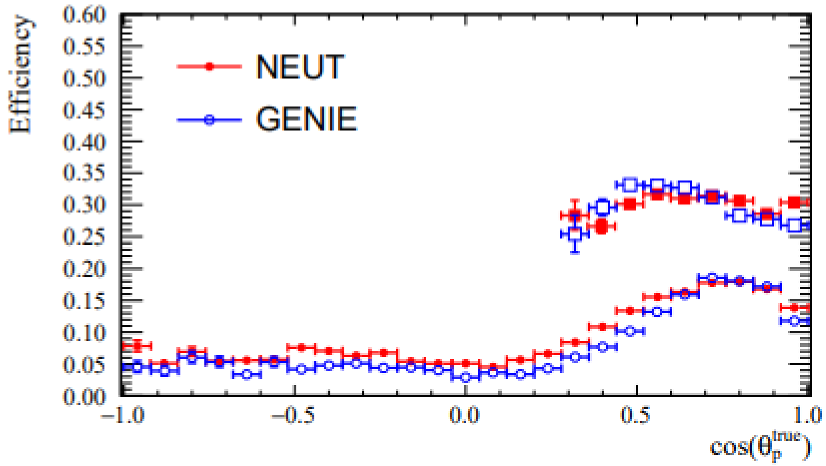
CC0π+Np in STV

- Measure fiducial flux-integrated CC0$\pi + Np$ cross section **in bins of STV**
- Restrict cross section to ND280 acceptance
  - *Essential to mitigate model-dependence of acceptance correction*

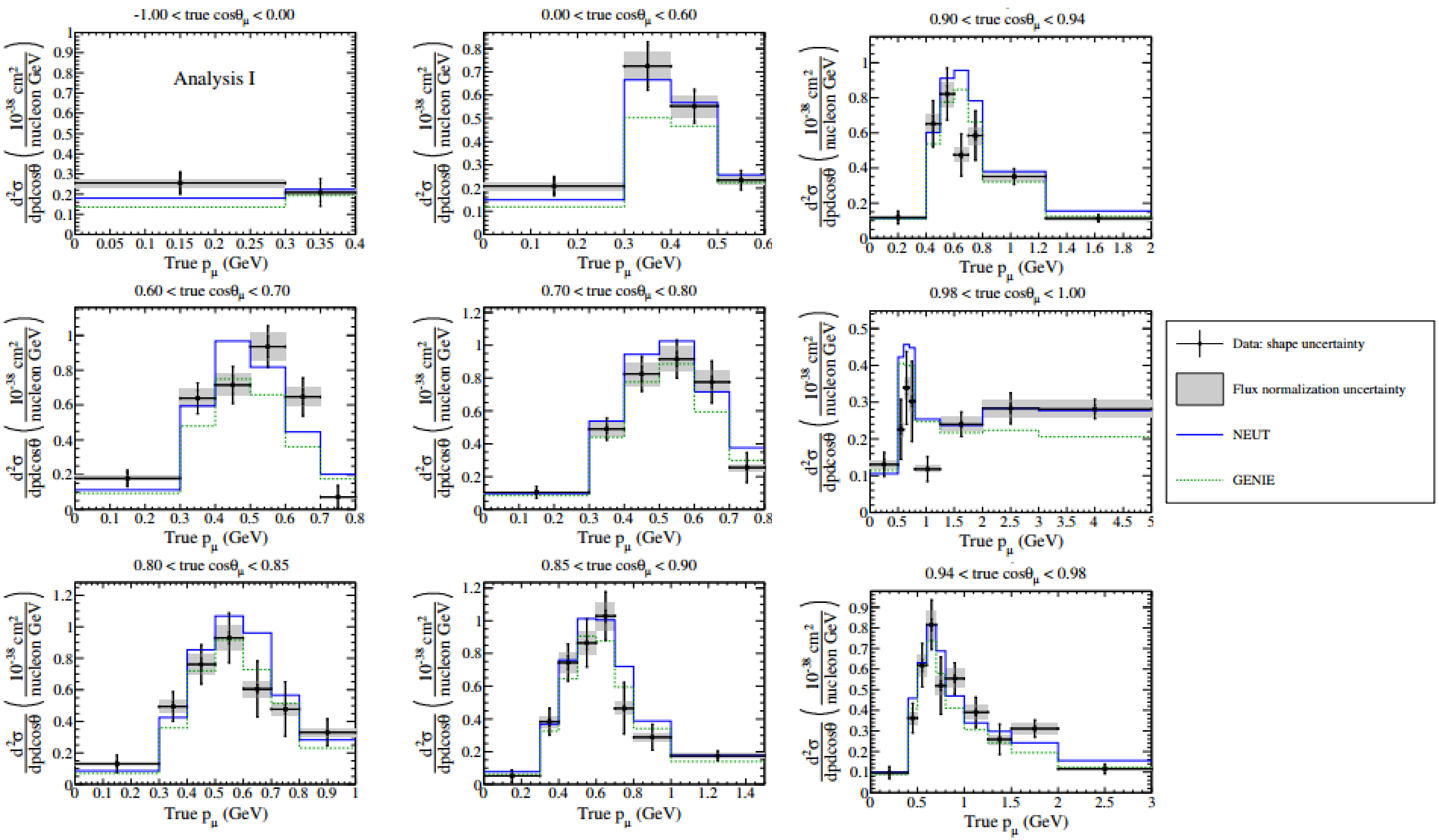
$$p_\mu > 250\ MeV/c$$
$$\cos(\theta_\mu) > -0.6$$
$$450\ MeV/c < p_\mu < 1\ GeV/c$$
$$\cos(\theta_p) > 0.4$$

- Extract cross section using a binned likelihood fit with a **data driven** regularisation





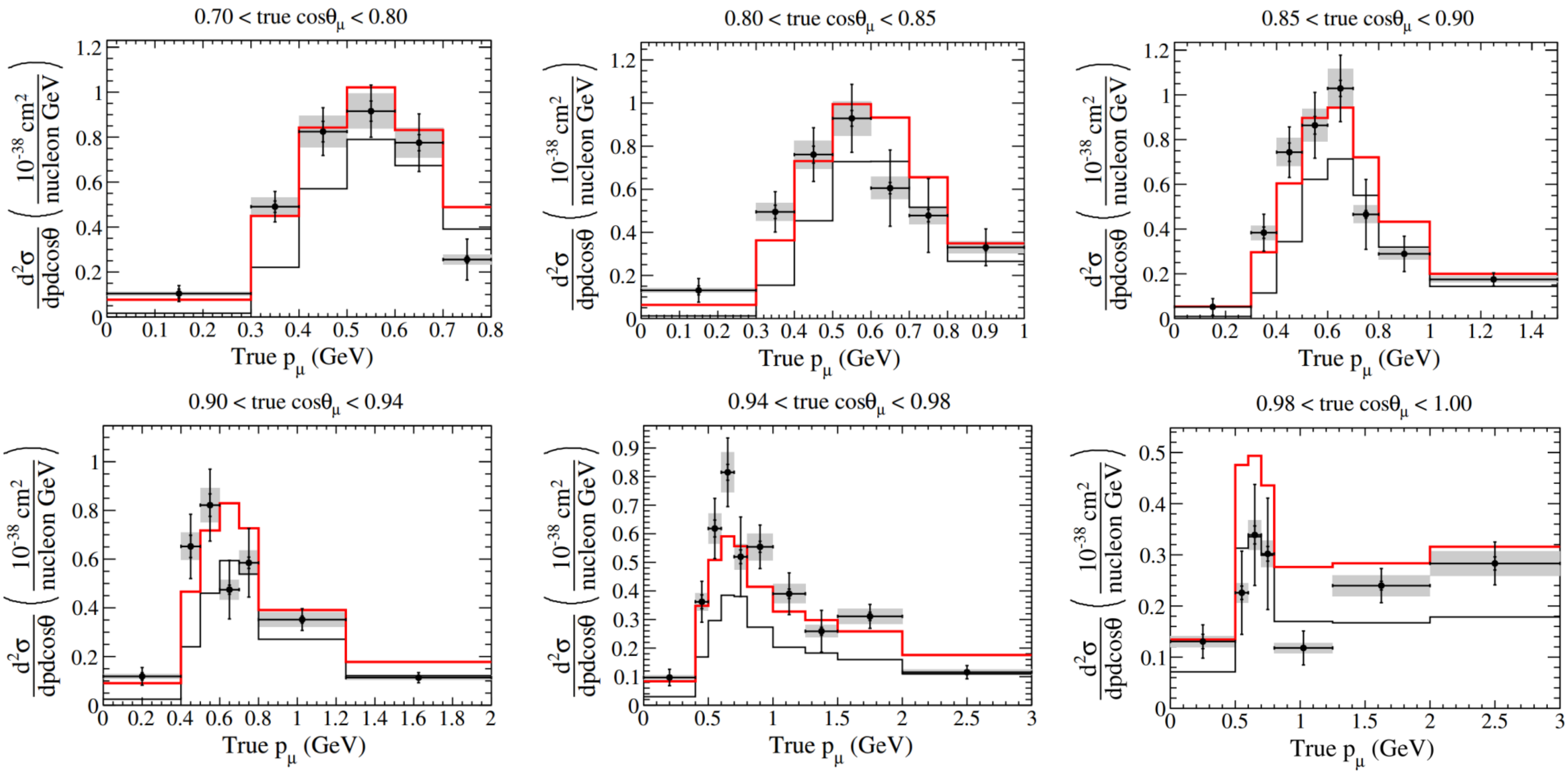
ND280 Off-Axis CC0π Result



Detector: ND280 – FGD1 **Target:** Carbon **Signal:** CC0π **Status:** Phys. Rev. D **93**, 112012

ND280 Off-Axis CC0π Result

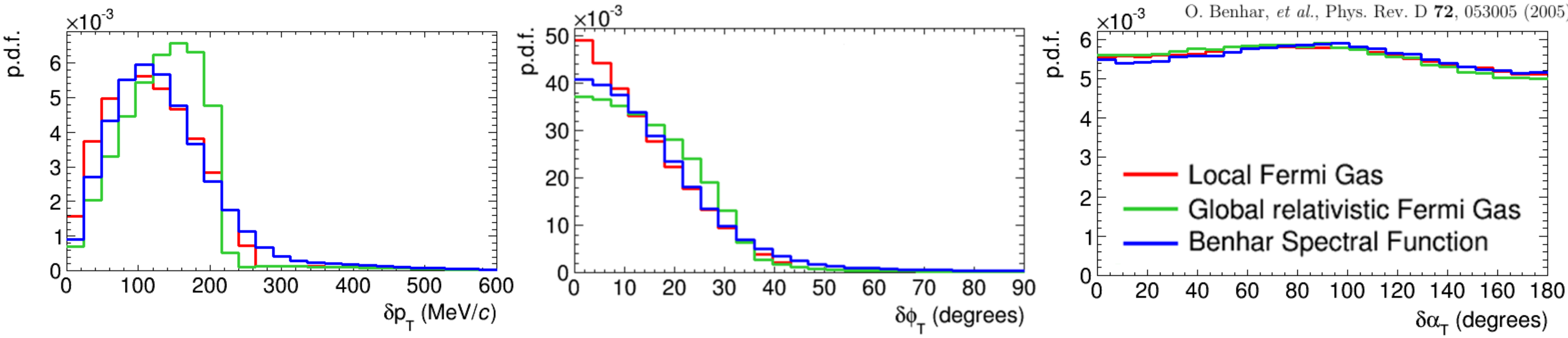
- Results compared to Martini *et al.* model **with(red)**/**without(black)** 2p2h
- Data prefer a 2p2h contribution



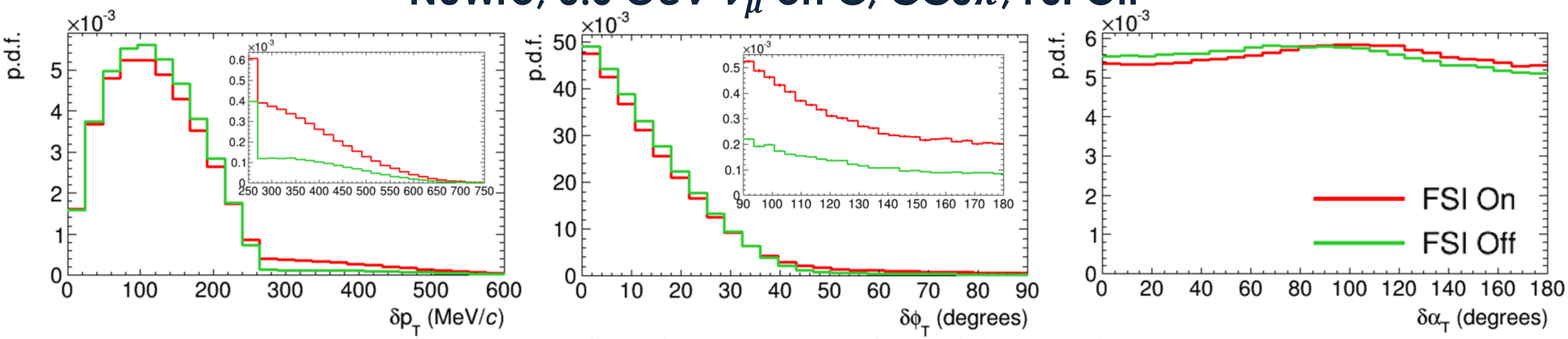
Detector: ND280 – FGD1	**Target:** Carbon	**Signal:** CC0π	**Status:** Phys. Rev. D **93**, 112012

CC0π in STV - Fermi Motion and FSI

- Moving from CCQE→CC0Pi+Np, STV still a probe of nuclear effects



NuWro, 0.6 GeV ν_μ on C, CC0π, FSI Off



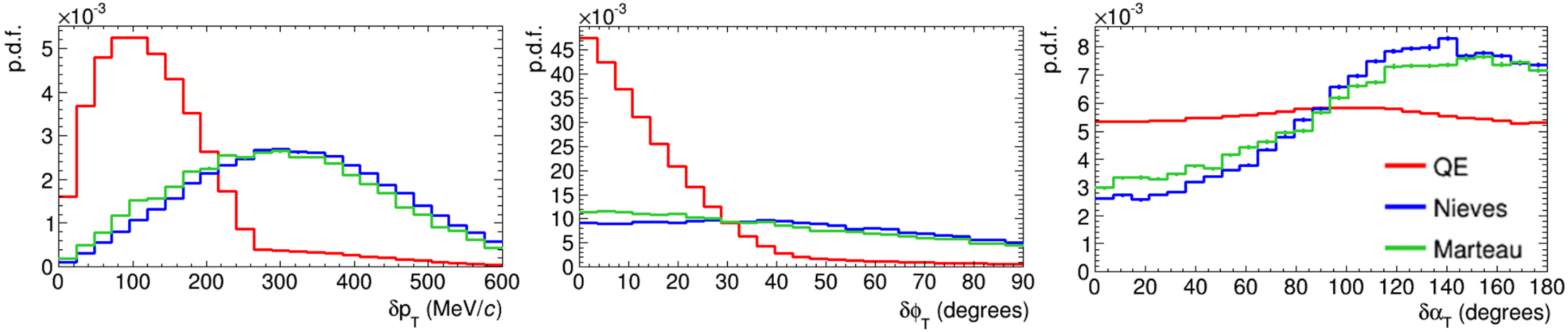
NuWro, 0.6 GeV ν_μ on C, CC0π, LFG

Quasi-real CC0Pi selection, keep events within rough ND280 acceptance :

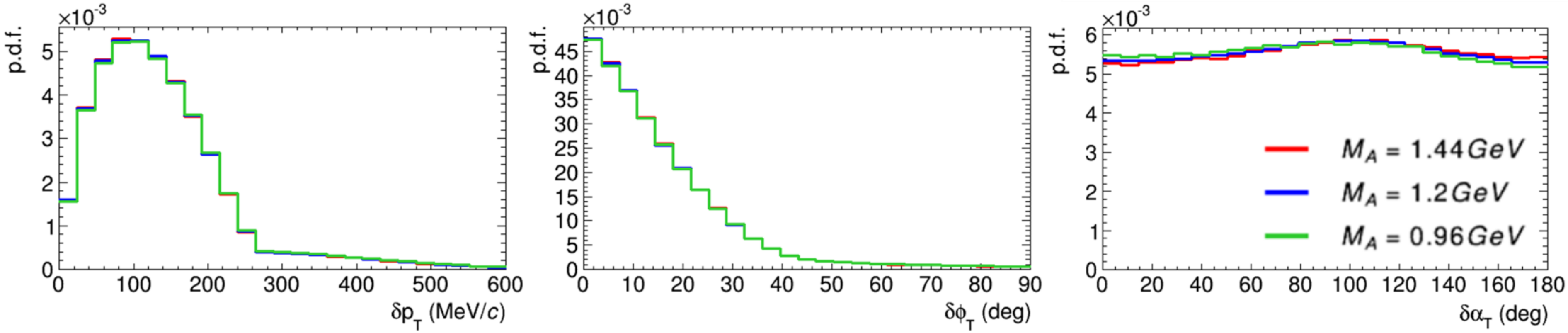
No Pions, 1 Muon, >0 Protons. $p_\mu > 250\ MeV, p_p > 450\ MeV, \cos(\theta_\mu) > -0.6, \cos(\theta_p) > 0.4$

CC0π in STV - 2p2h and M_A

M. Martini, M. Ericson, G. Chanfray, and J. Marteau, Phys. Rev. C **80**, 065501 (2009) J. Nieves, I. R. Simo, and M. J. V. Vacas, Phys. Rev. C **83**, 045501 (2011)



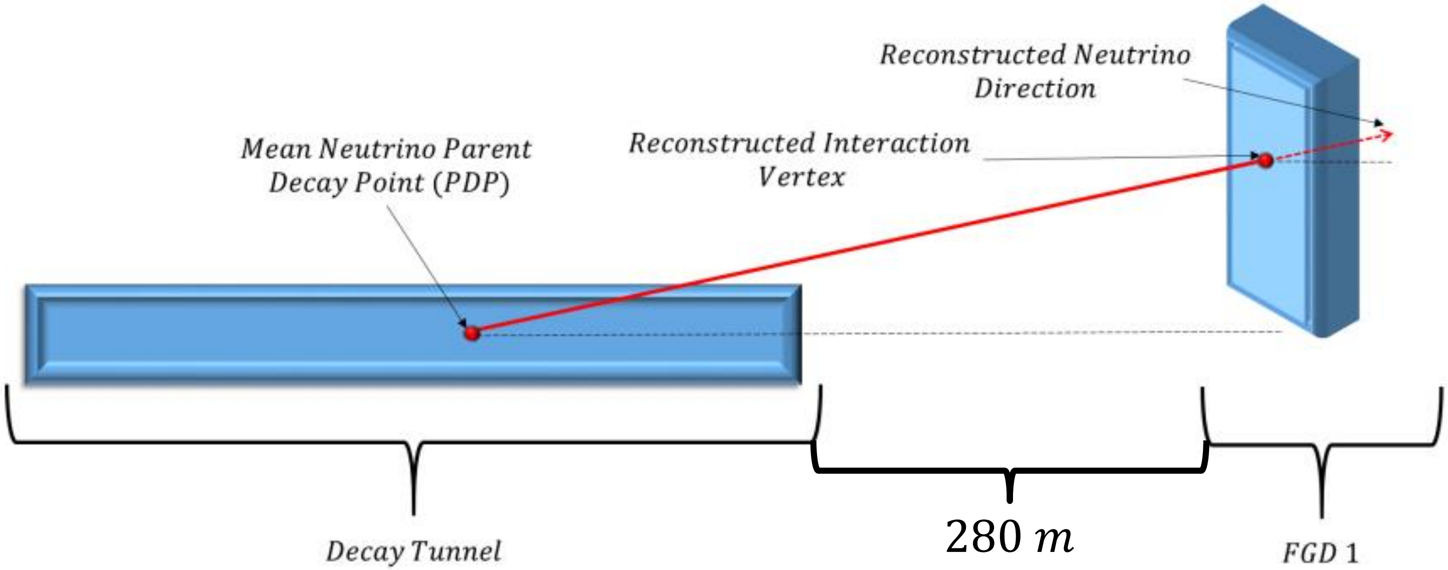
NuWro, 0.6 GeV ν_μ on C, CC0π, FSI On, LFG

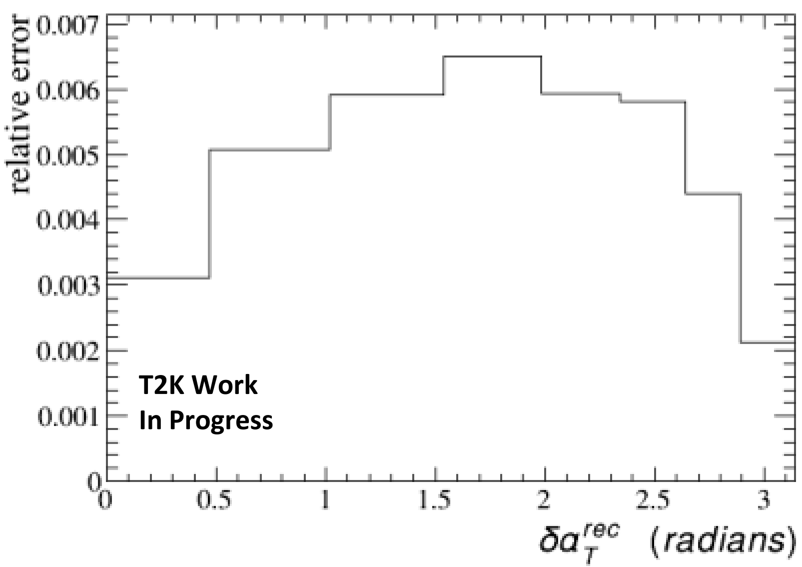


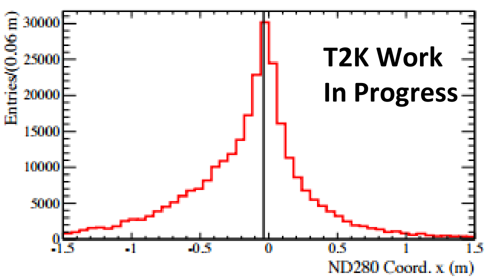
NuWro, 0.6 GeV ν_μ on C, CC0π, FSI On, LFG

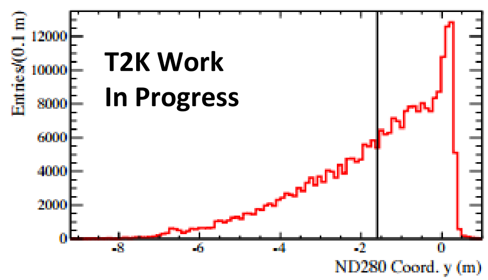
- STV shape invariant with M_A
  - No ambiguity over M_A or nuclear effect contributions (MiniBooNE M_A puzzle)

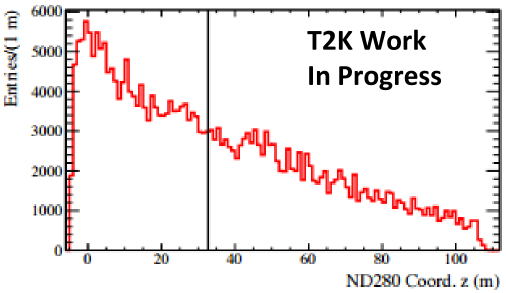
Reconstructing the Neutrino Direction





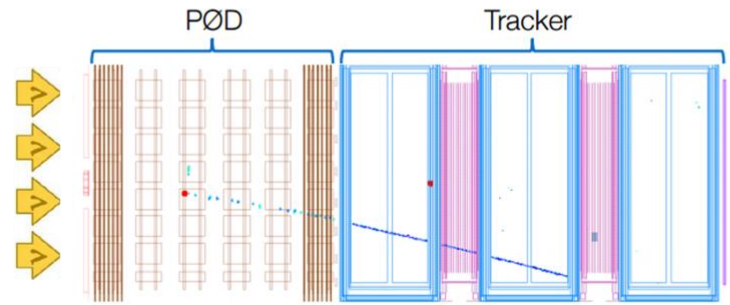


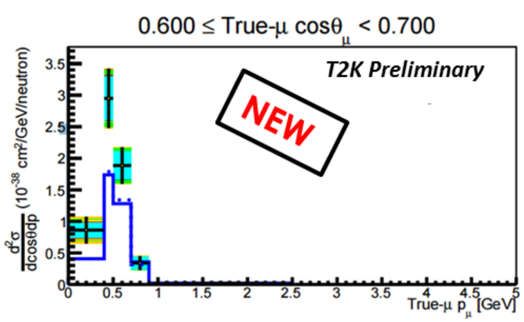


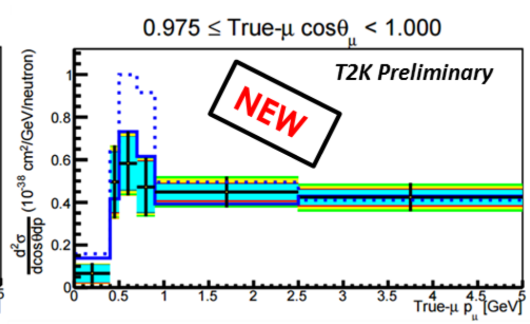


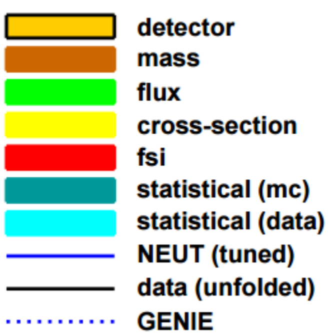
CC0π water cross section

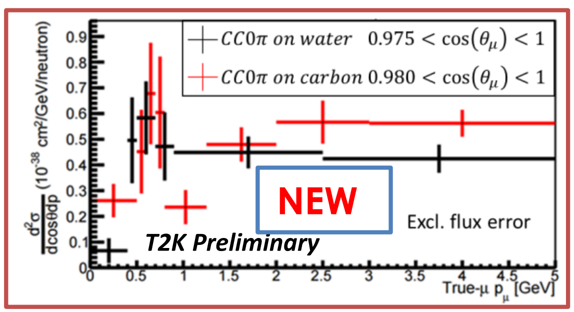
- Isolate CC0π events starting in the PØD, but use TPC for tracking
- Separate data taking periods into when PØD water target is full/empty
  - Subtract to get water cross section











- Construct **CC0π** flux integrated double-differential cross section in $p_\mu, \cos(\theta_\mu)$
  - Compare MC predictions
- Compare to FGD1 CC0π on Carbon result
- Similar studies underway using FGD2 water layers to extract Oxygen:Carbon cross section ratio

ND280 (off axis)

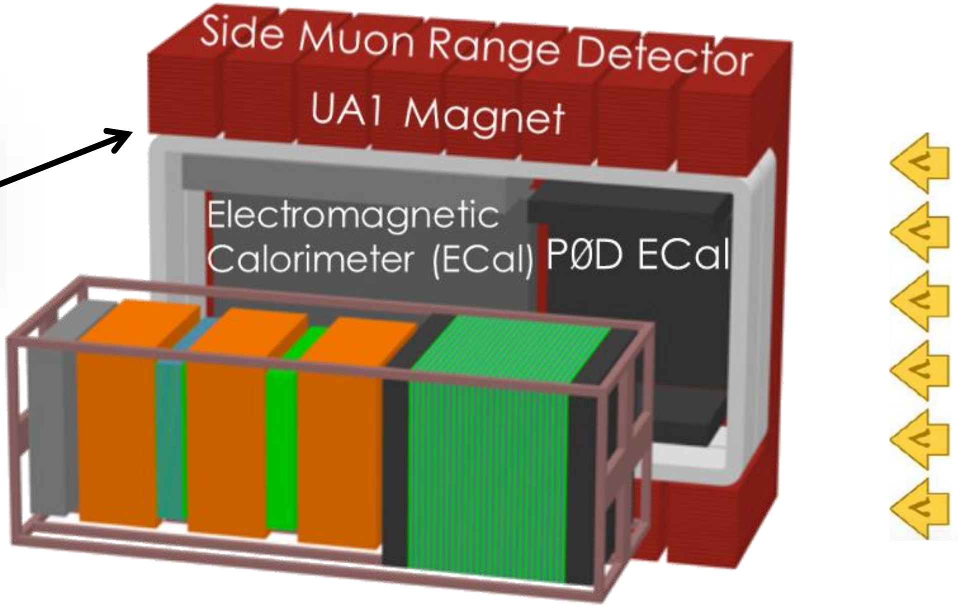
On Axis ~ 1.1 GeV

Peak E_ν

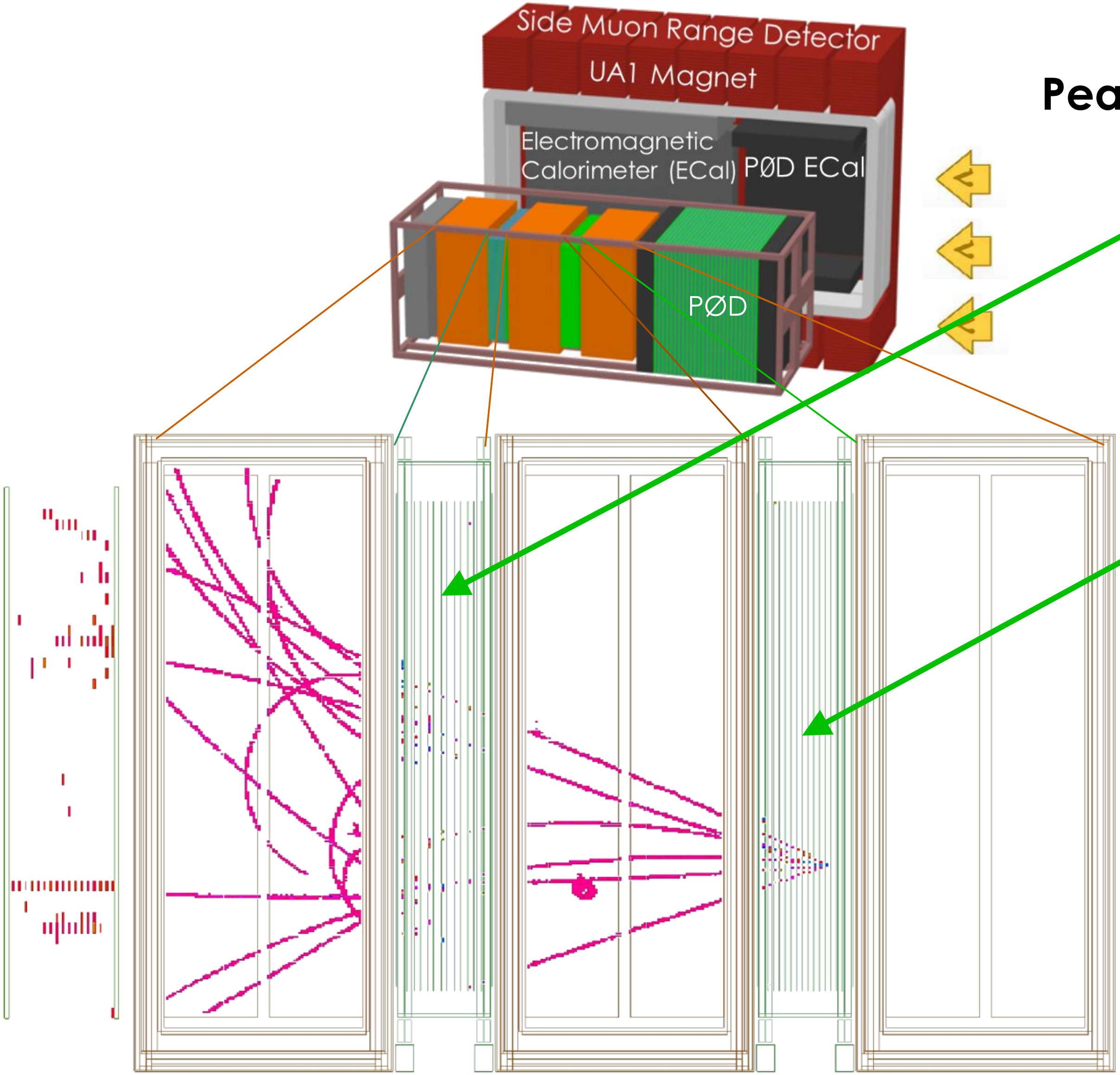
Off Axis ~ 0.6 GeV

Former UA1 Magnet:

- Provides 0.2 T field



ND280 (off axis)



On Axis ~ 1.1 GeV

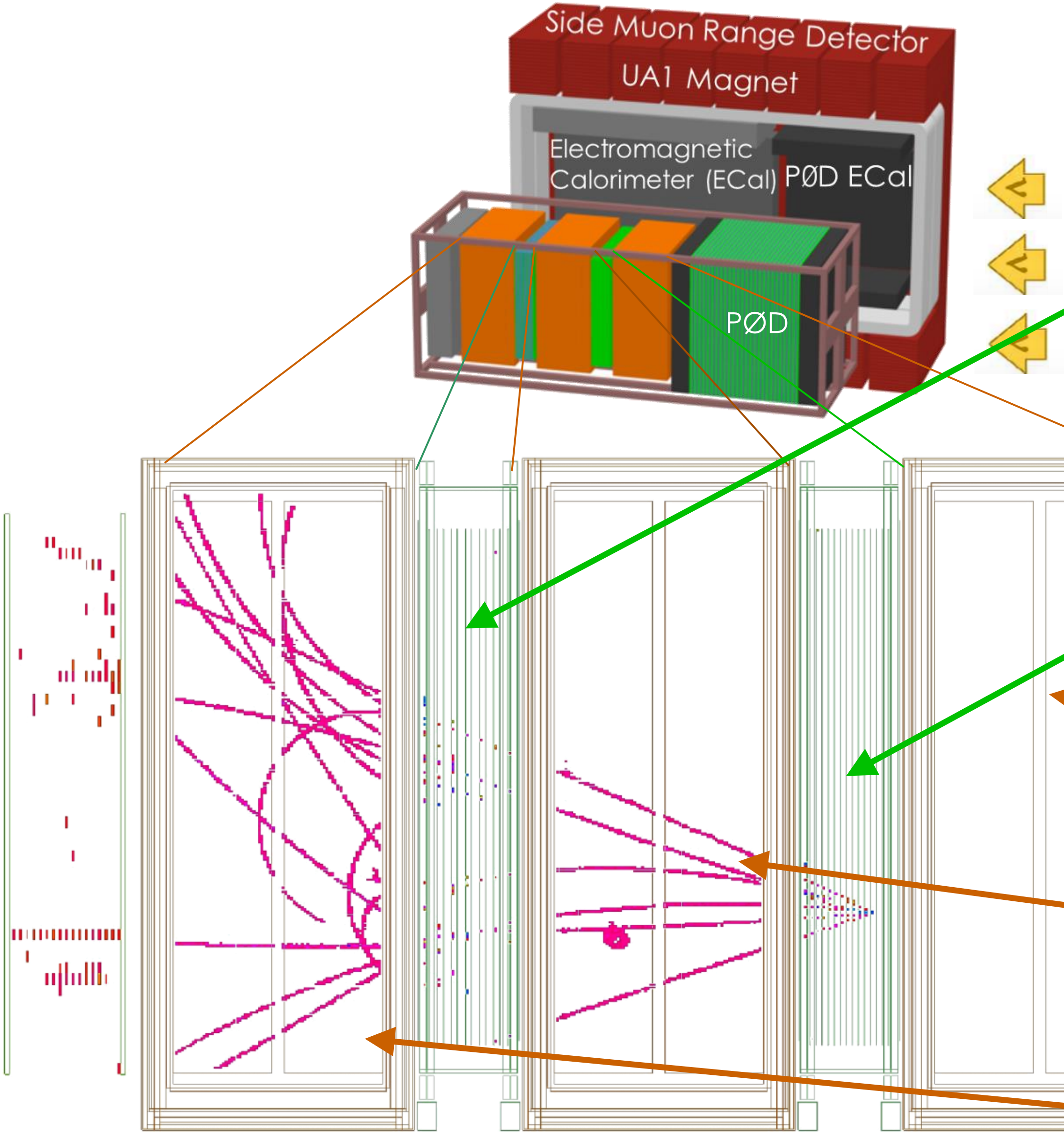
Peak E_ν

Off Axis ~ 0.6 GeV

Fine-Grained Detectors (FGD 1 & 2):

- CH scintillator tracker
- Target for ν
- FGD2 contains water

ND280 (off axis)



On Axis ~ 1.1 GeV

Peak E_ν

Off Axis ~ 0.6 GeV

Fine-Grained Detectors (FGD 1 & 2):

- CH scintillator tracker
- Target for ν
- FGD2 contains water

Time Projection Chambers (TPC):

- Excellent tracking
- High-res charged-particle momenta
- Accurate particle ID