Probing neutrino cross-section models with T2K near-detector data

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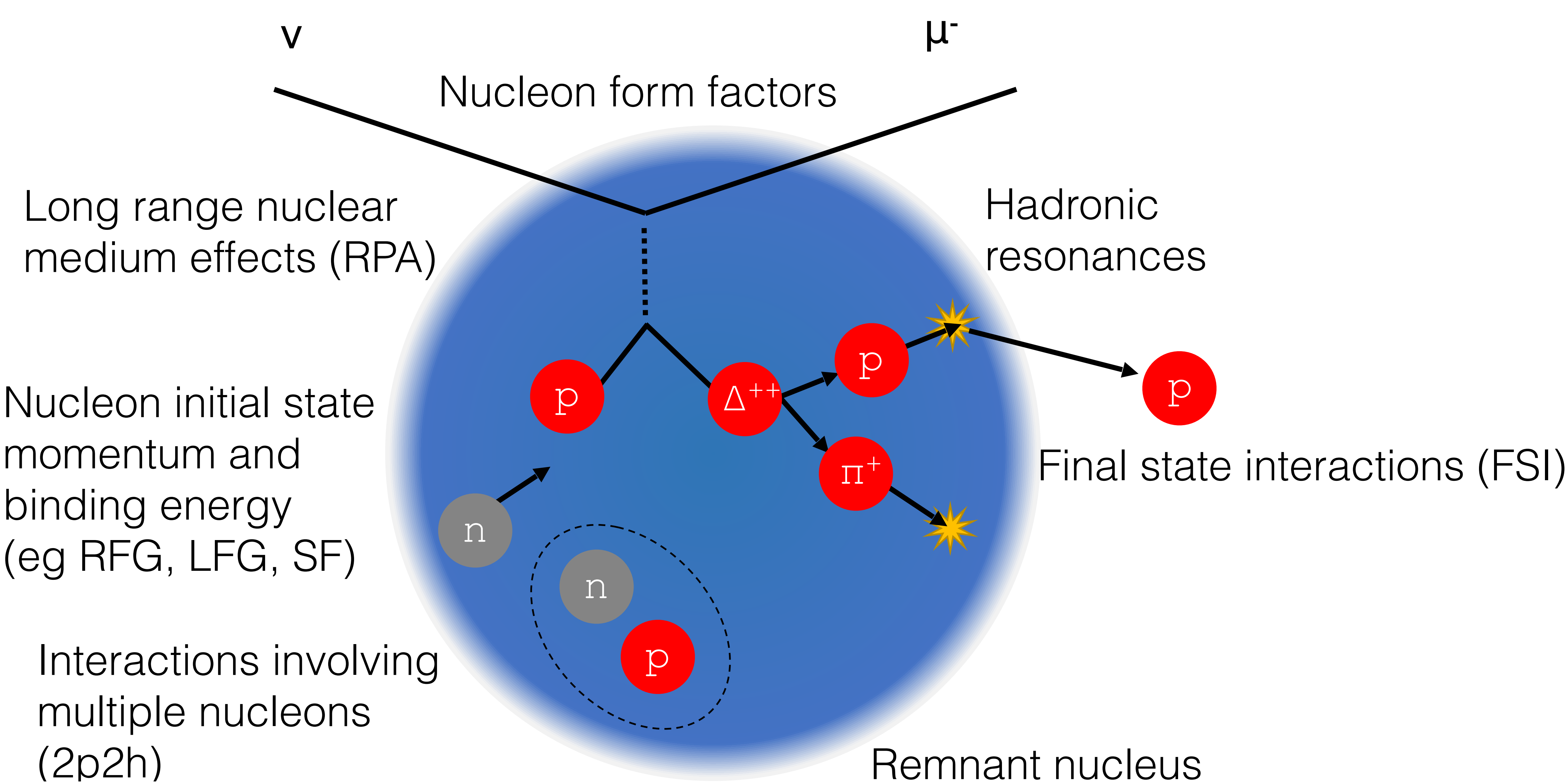
David Hadley on behalf of the T2K experiment

ICHEP 2018, Seoul

Neutrino-nucleus Interactions

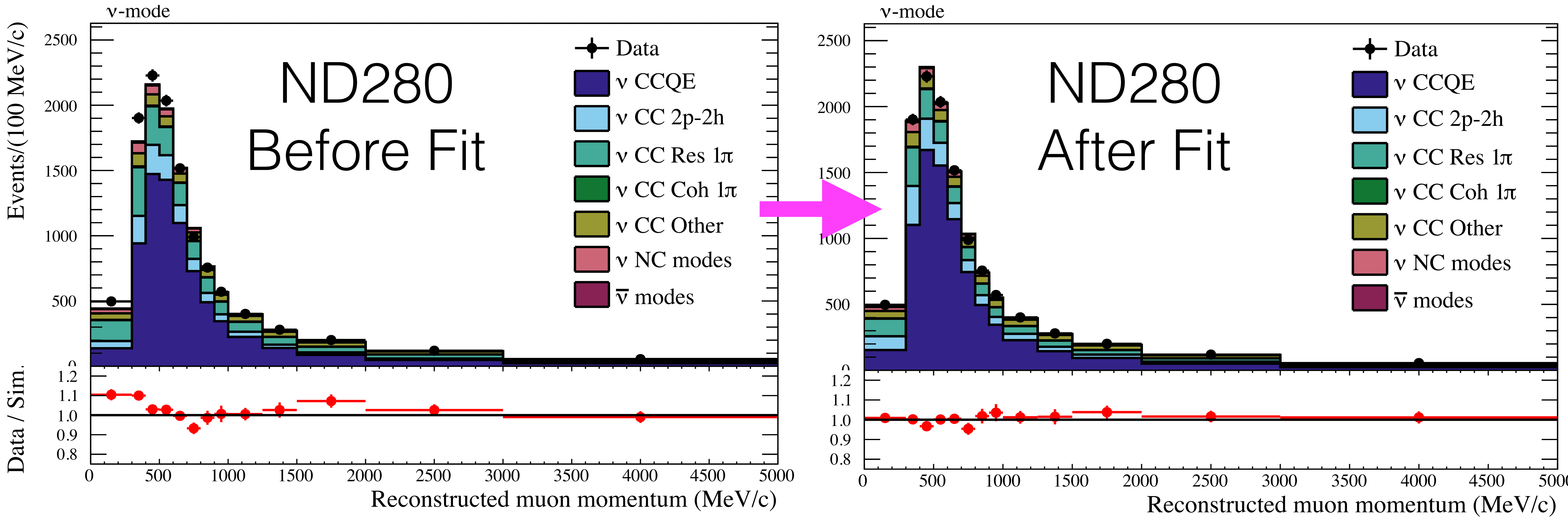
The nuclear environment is complex!



T2K Oscillation Measurement

Parameterise flux and interaction model

Fit these parameters to measurements in the near detector

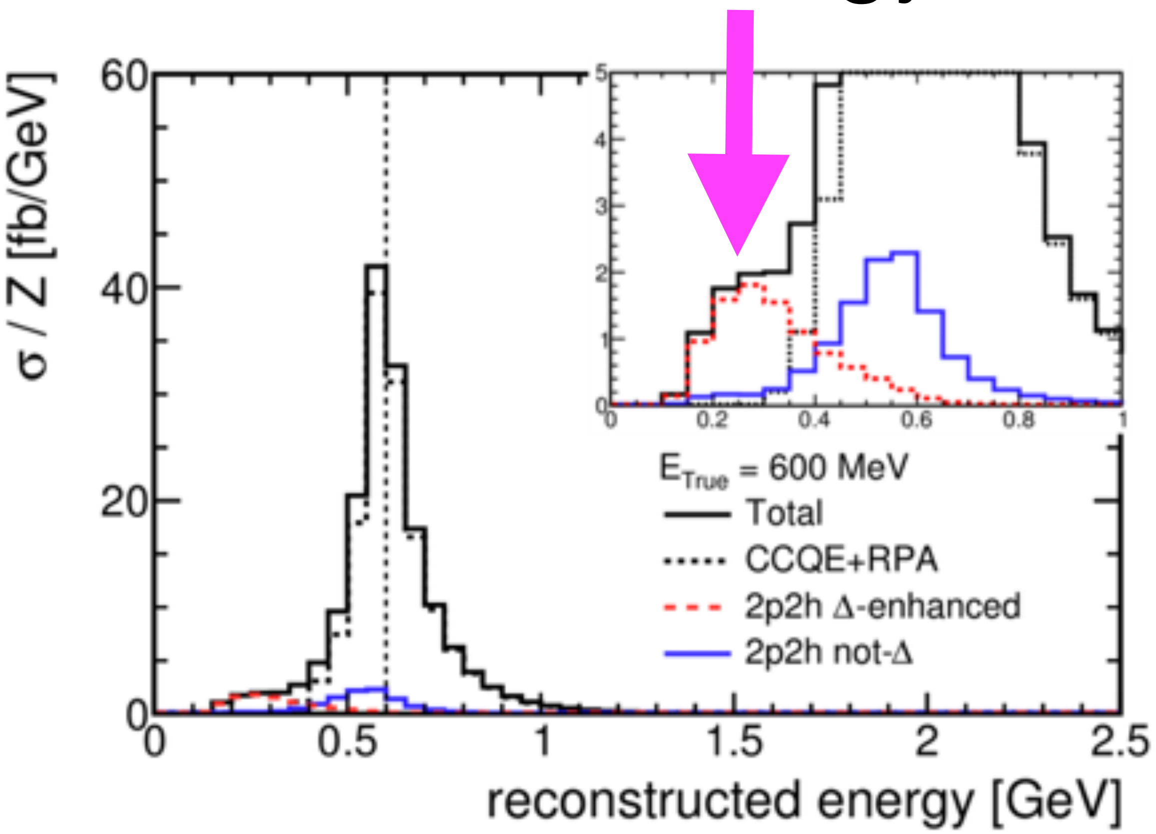


Updated model propagated to far detector to extract oscillation parameters

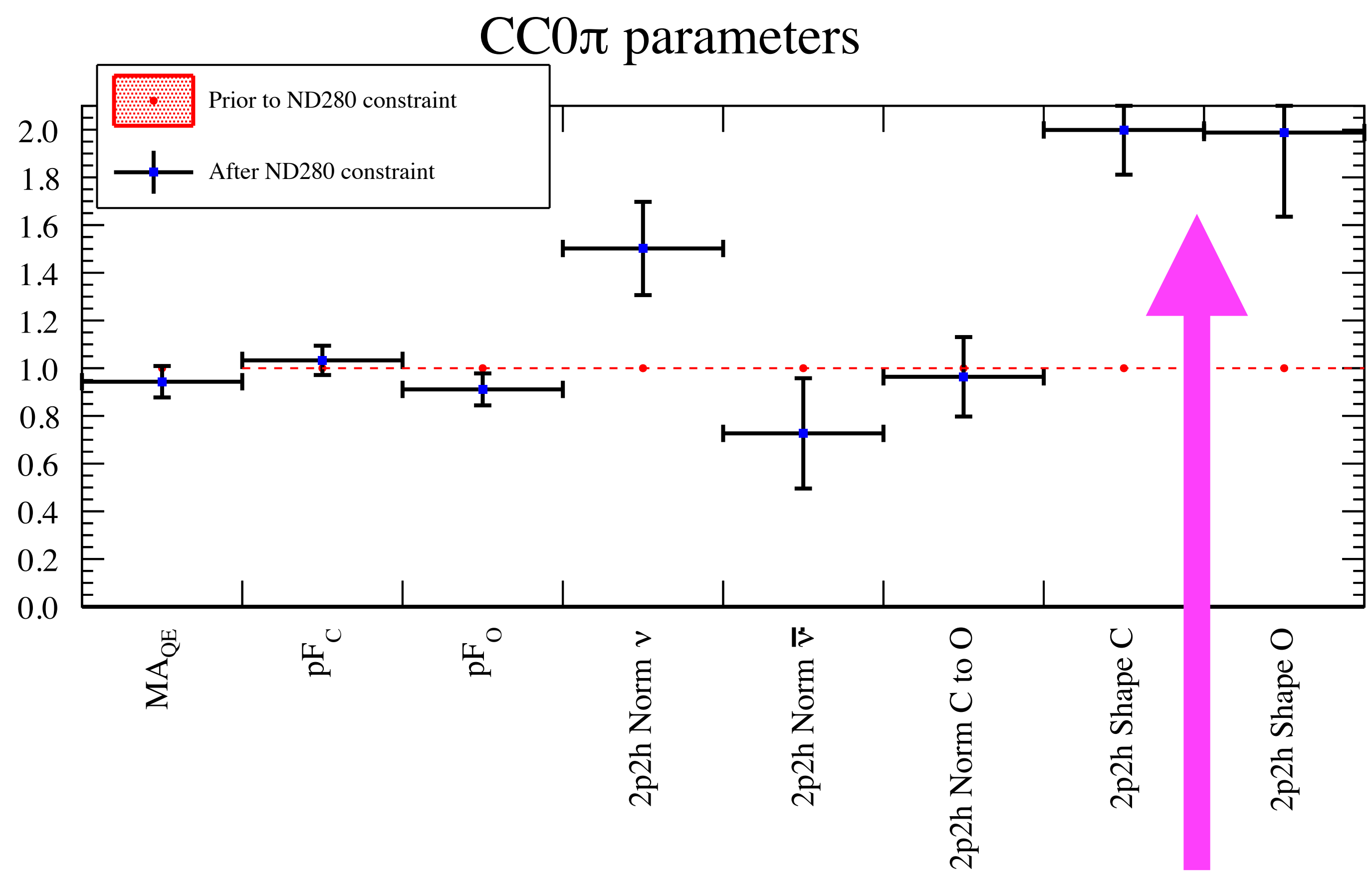
ND280 constraint reduces error from 13%→3% for the parameters that it constrains

Tuning the Model

Some event types may have large biases in neutrino energy reconstruction



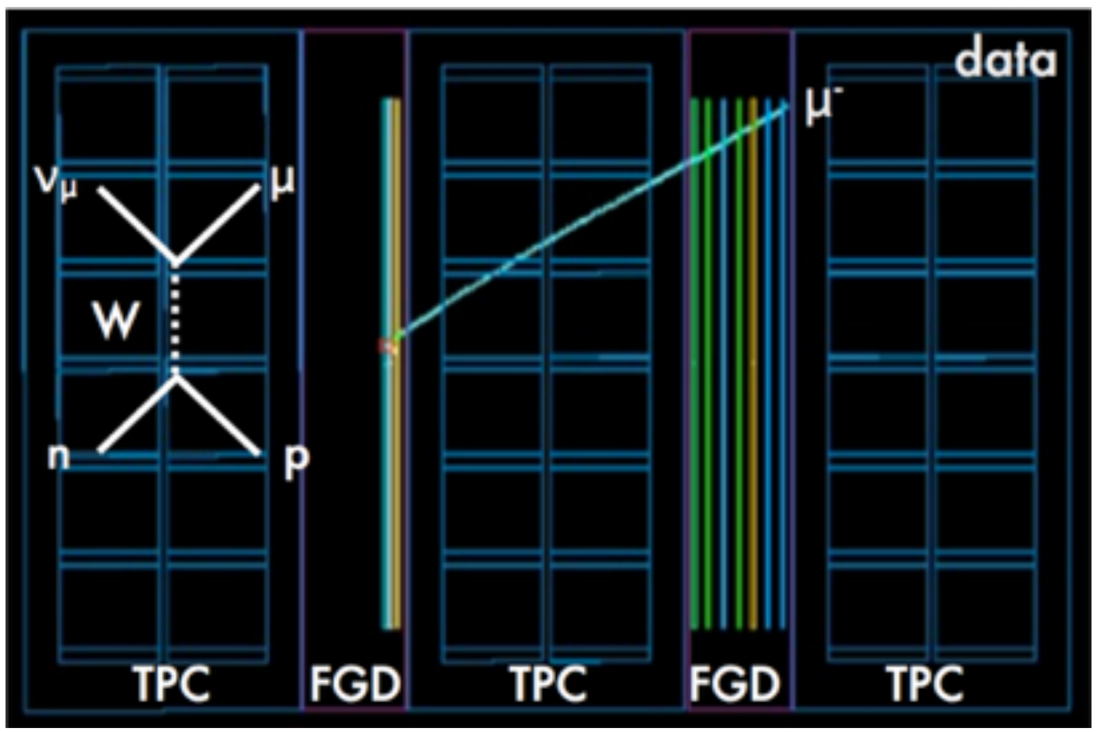
It is important to model these accurately and to measure these processes in our near detectors

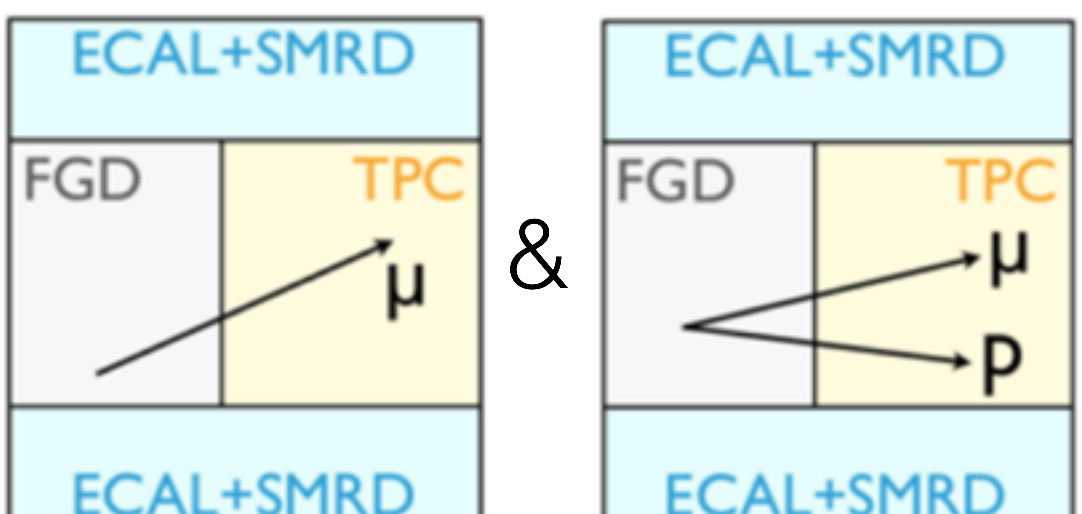


Large deviations from the nominal for some parameters Indicates deficiencies in the prior interaction model

CC 1μ + 0π + Np

Charged current interactions with no pions (“CCQE-like”) is the main signal in the oscillation analysis at T2K





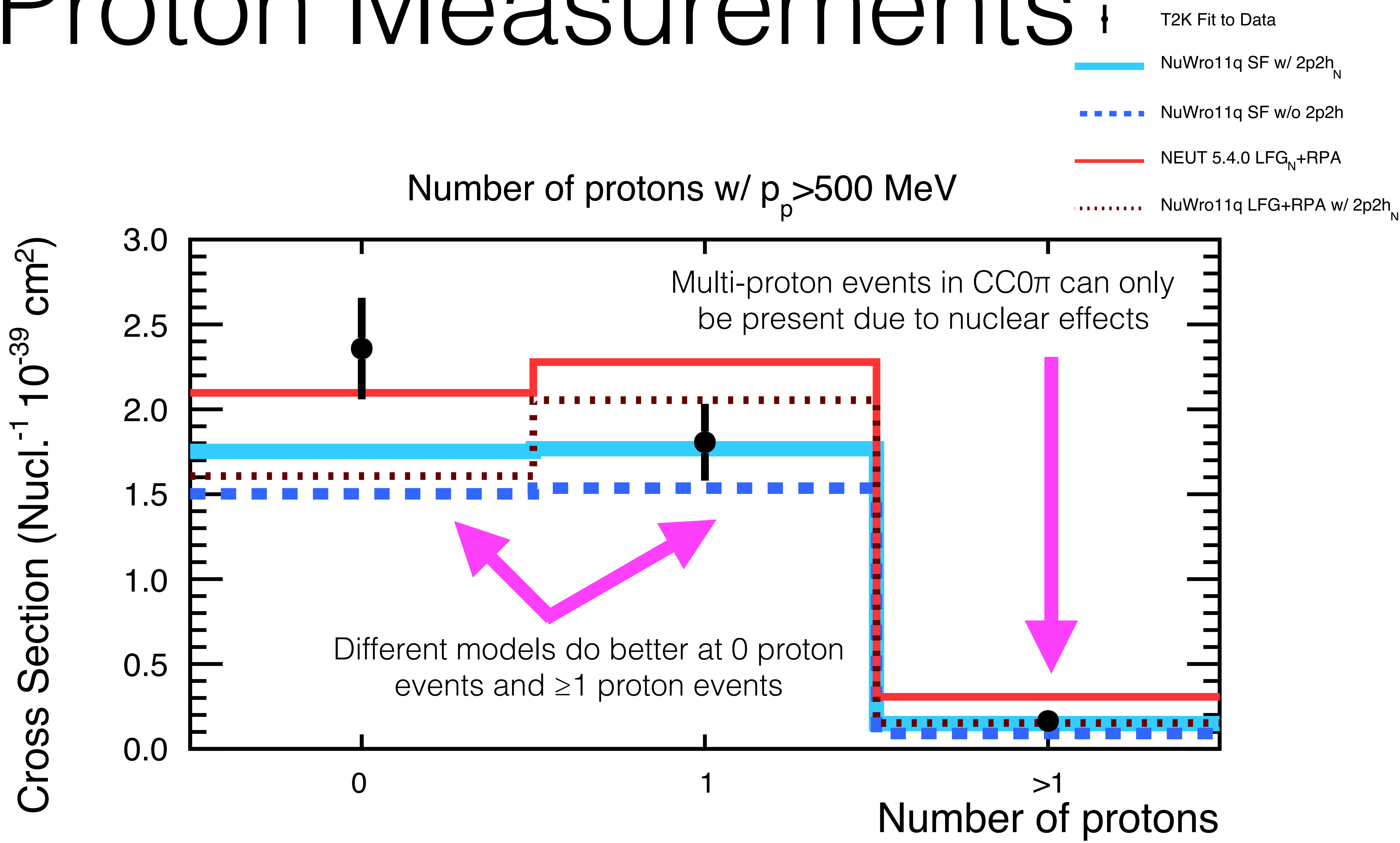
Previous measurements based only on measured lepton kinematics

New data includes observed proton data

Innovative new observables

See: arXiv:1802.05078 [hep-ex] (submitted to PRD)

Proton Measurements

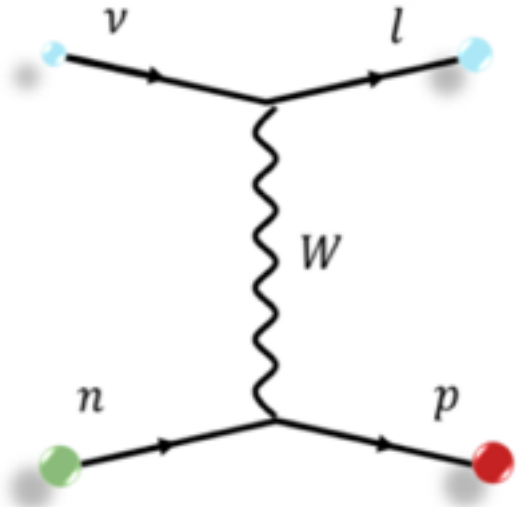


Proton measurements are provided as a function of μ and p kinematics

arXiv:1802.05078 [hep-ex]

Inferred Proton Kinematics

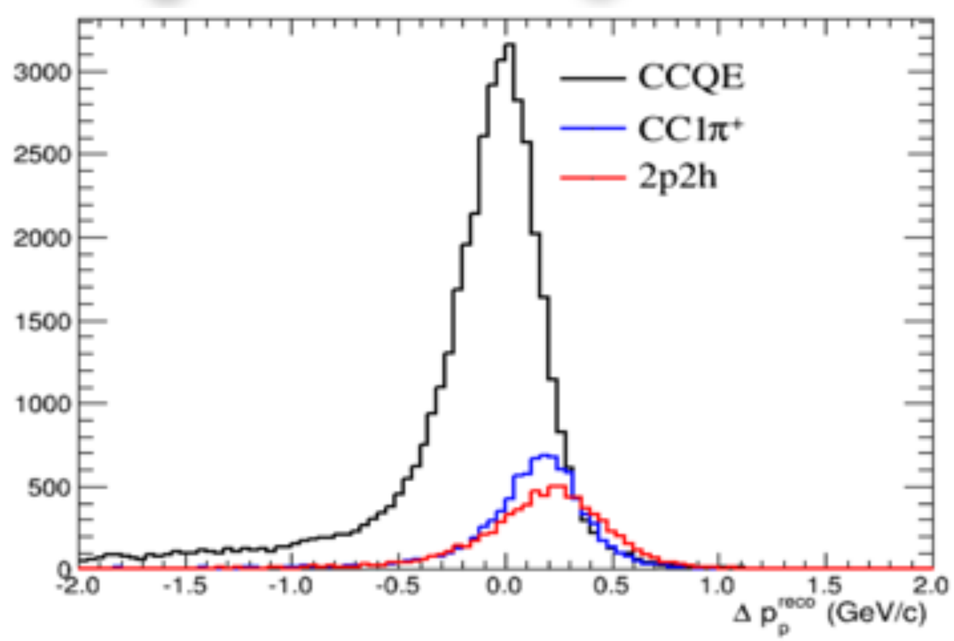
Assuming a 2 body interaction the proton kinematics can be determined from the measured lepton kinematics



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

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

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



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

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

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

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

Inferred Proton Kinematics

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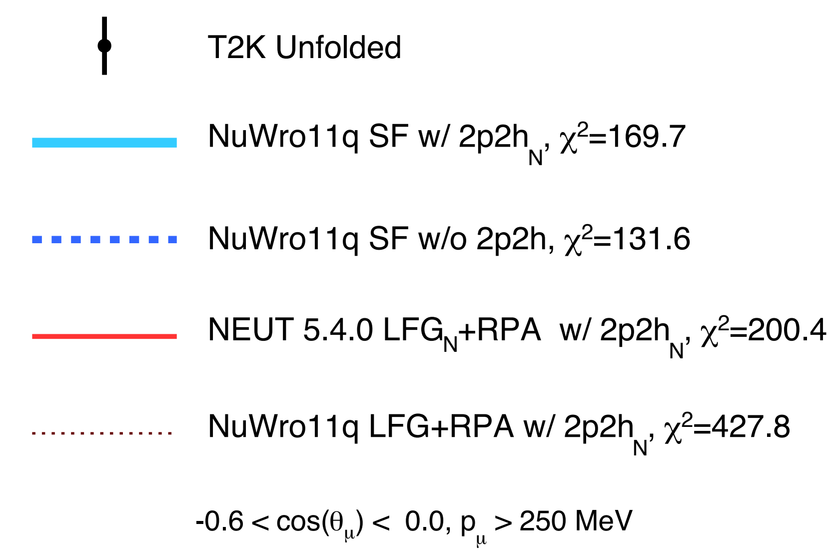
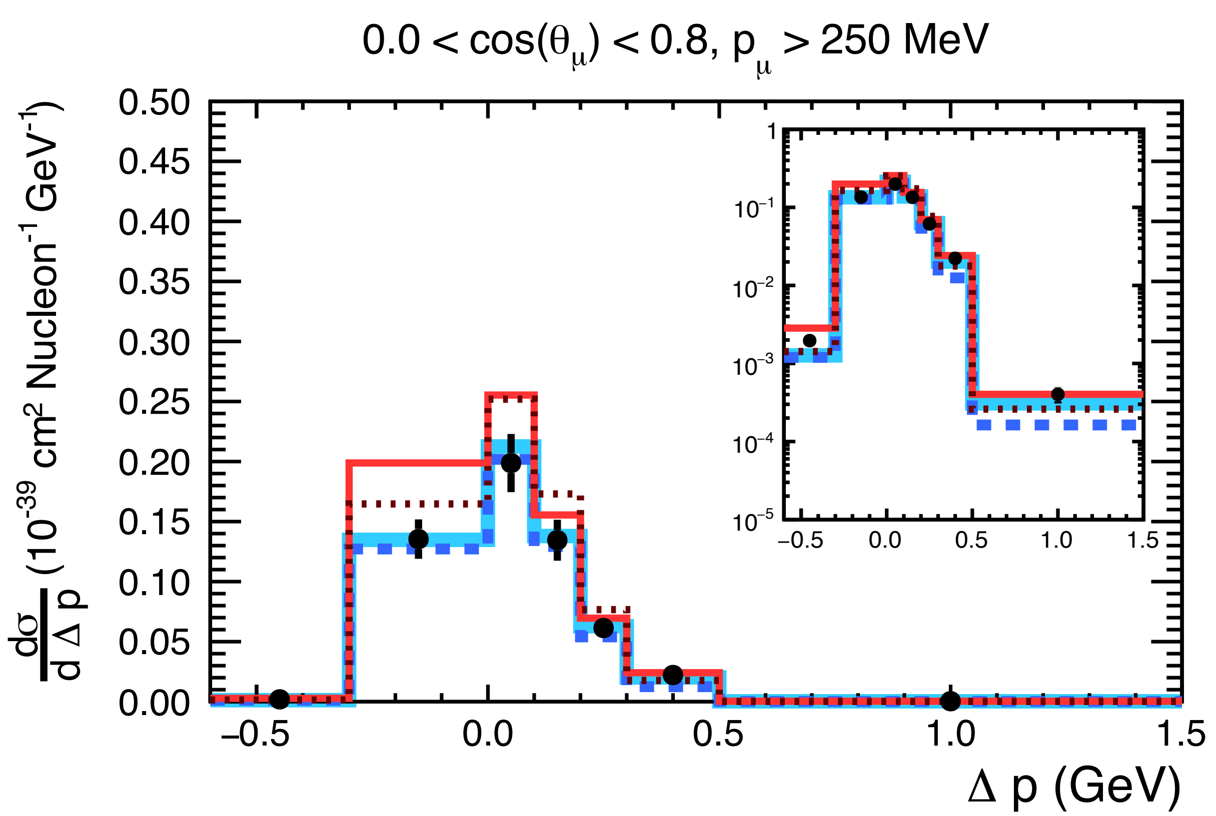
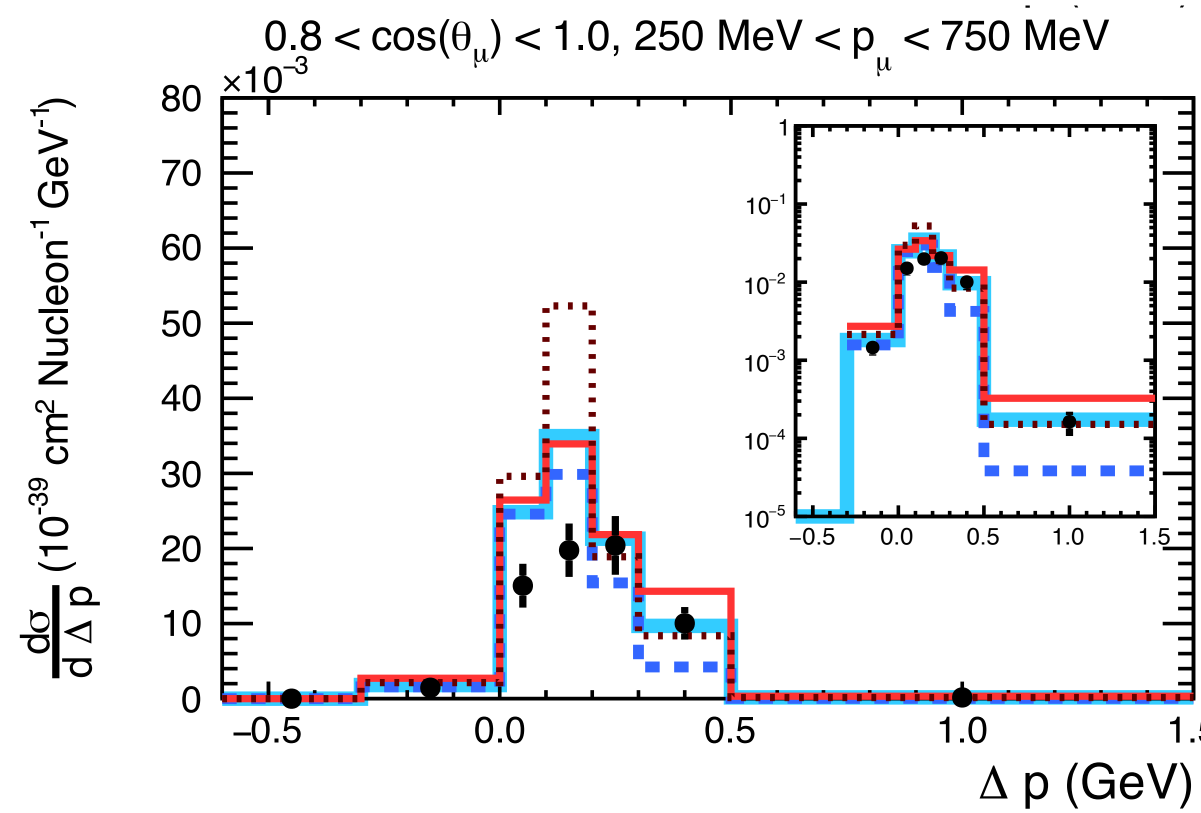
Measurement is provided as a function of muon kinematics and inferred proton kinematics
Examples:





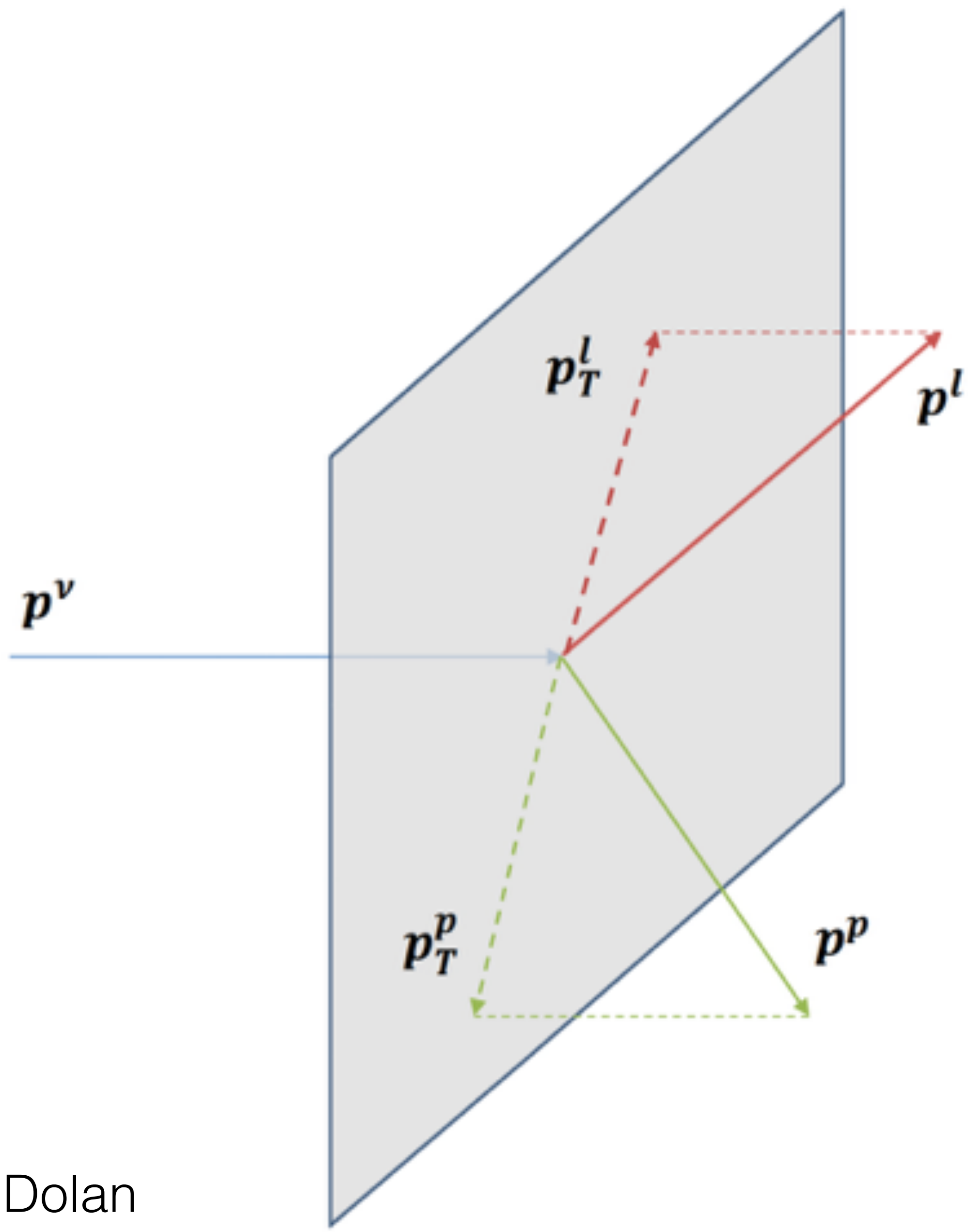


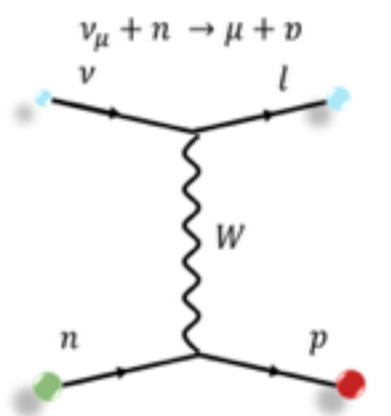
No model tested perfectly describes the data everywhere (as indicated by large χ^2)

arXiv:1802.05078 [hep-ex]

Kinematics in the Transverse Plane

Project kinematics to the plane transverse to incident neutrino direction





No nuclear Effects

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

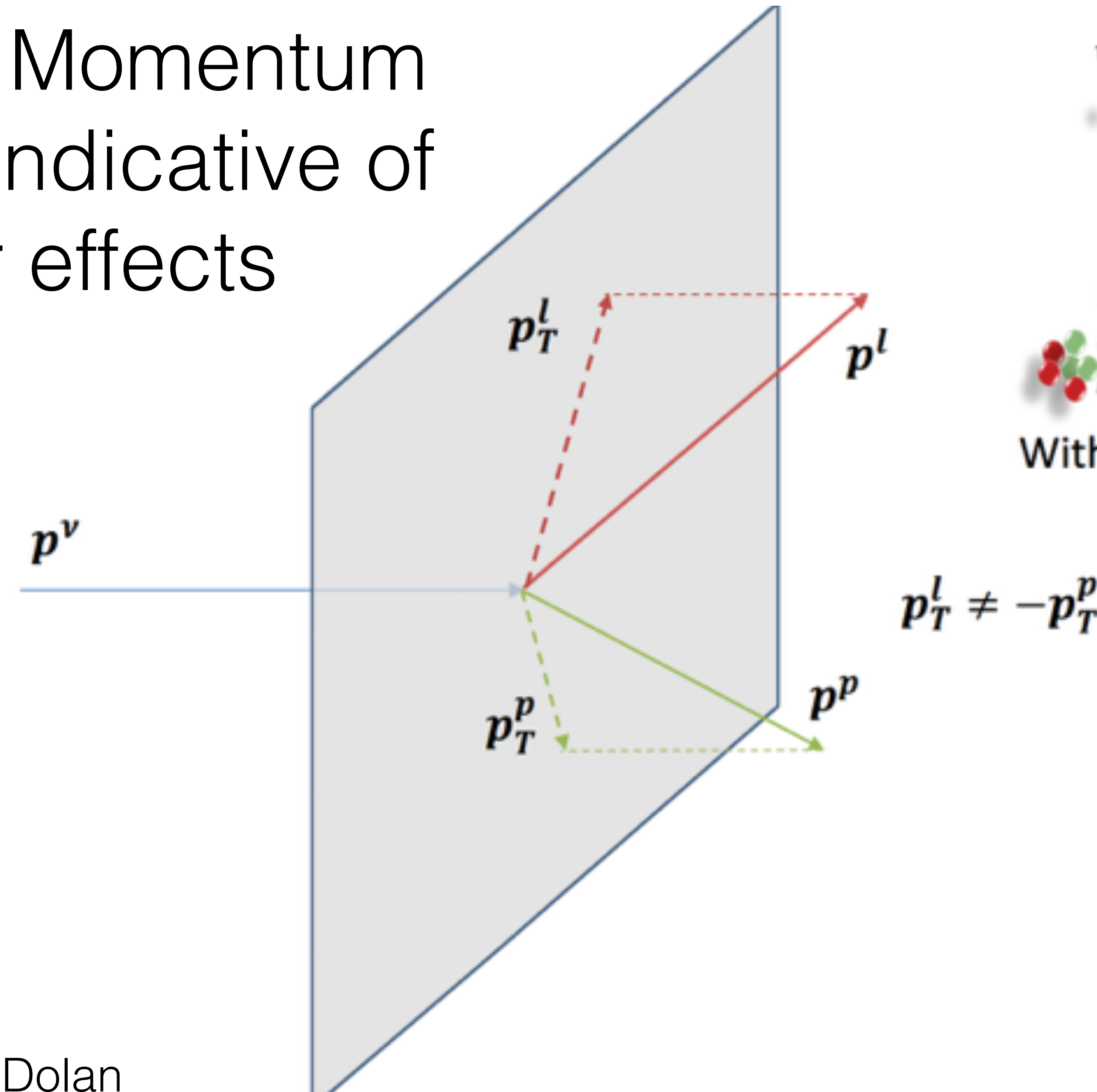
Diagrams courtesy S Dolan

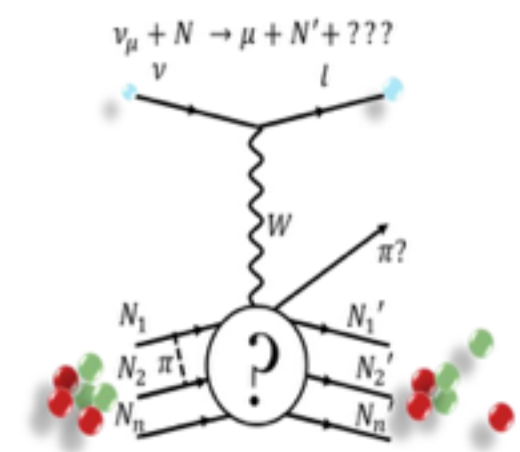
X.-G. Lu et al, Phys. Rev. C 94, 015503 (2016)

Kinematics in the Transverse Plane

Project kinematics to the plane transverse to incident neutrino direction

Transverse Momentum imbalance indicative of nuclear effects





With Nuclear Effects

Diagrams courtesy S Dolan

 X.-G. Lu et al, Phys. Rev. C 94, 015503 (2016)

Kinematics in the Transverse Plane

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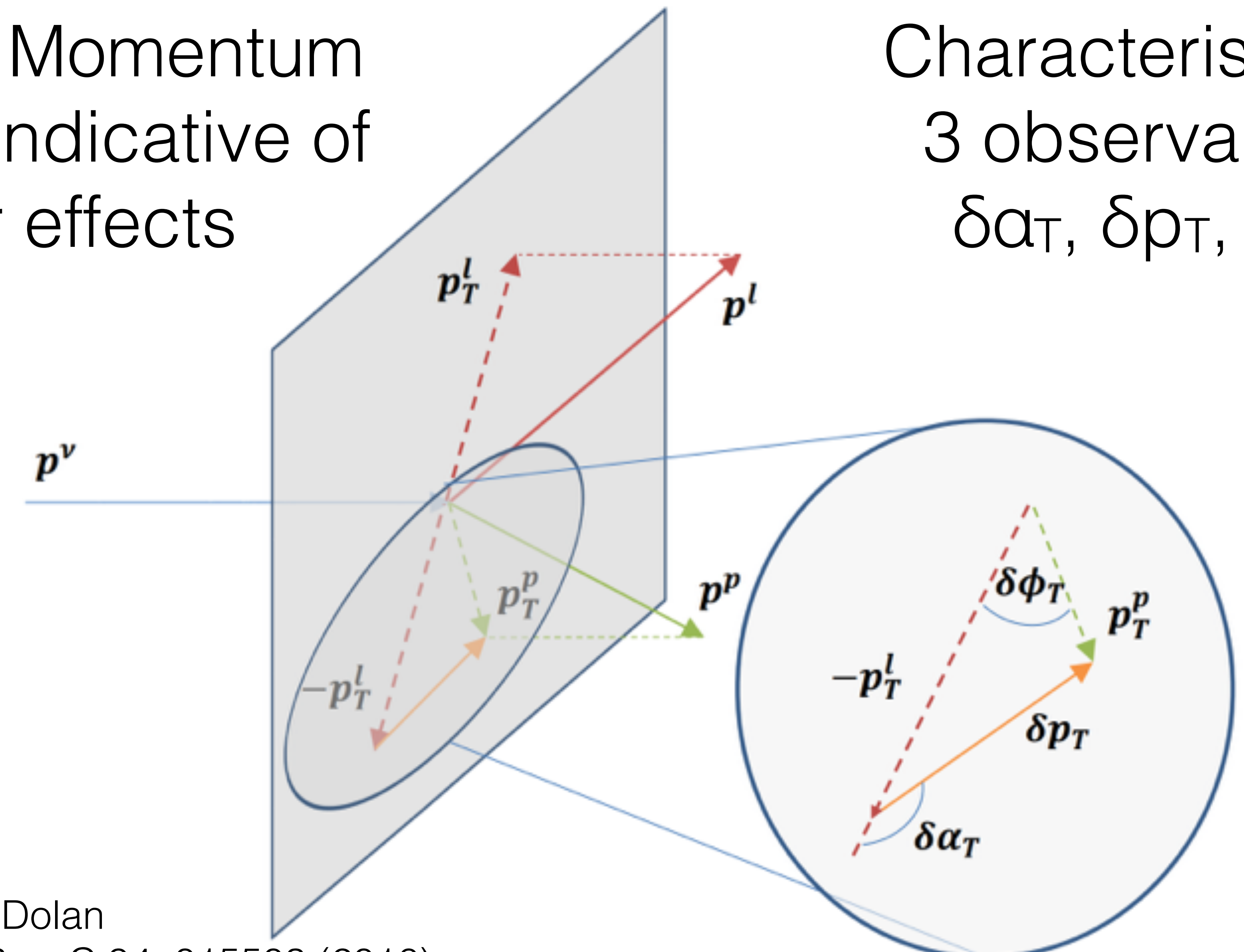
Project kinematics to the plane transverse to incident neutrino direction

Transverse Momentum imbalance indicative of nuclear effects

Characterised by 3 observables: $\delta\alpha_T$, δp_T, $\delta\phi_T$

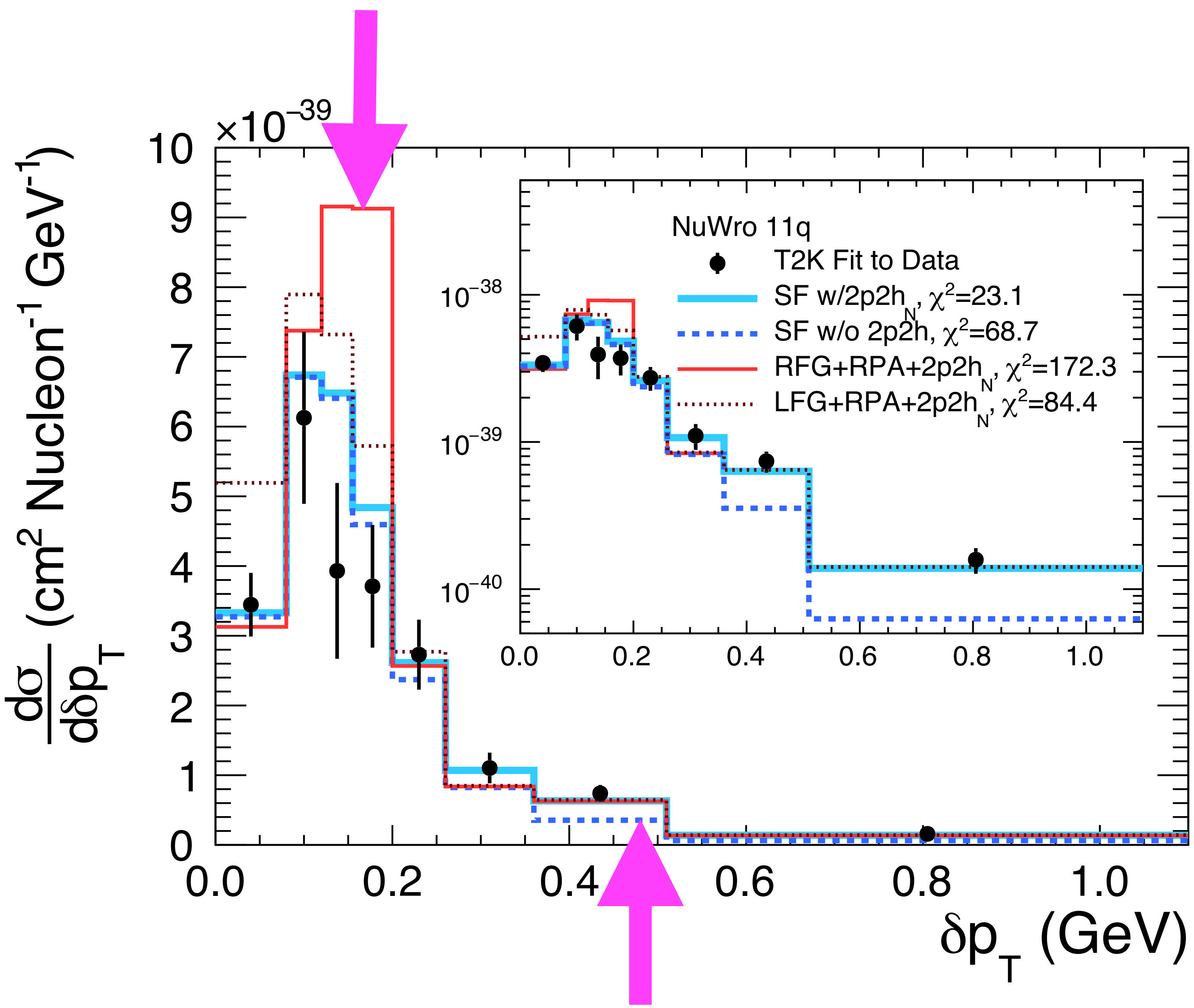


Diagrams courtesy S Dolan

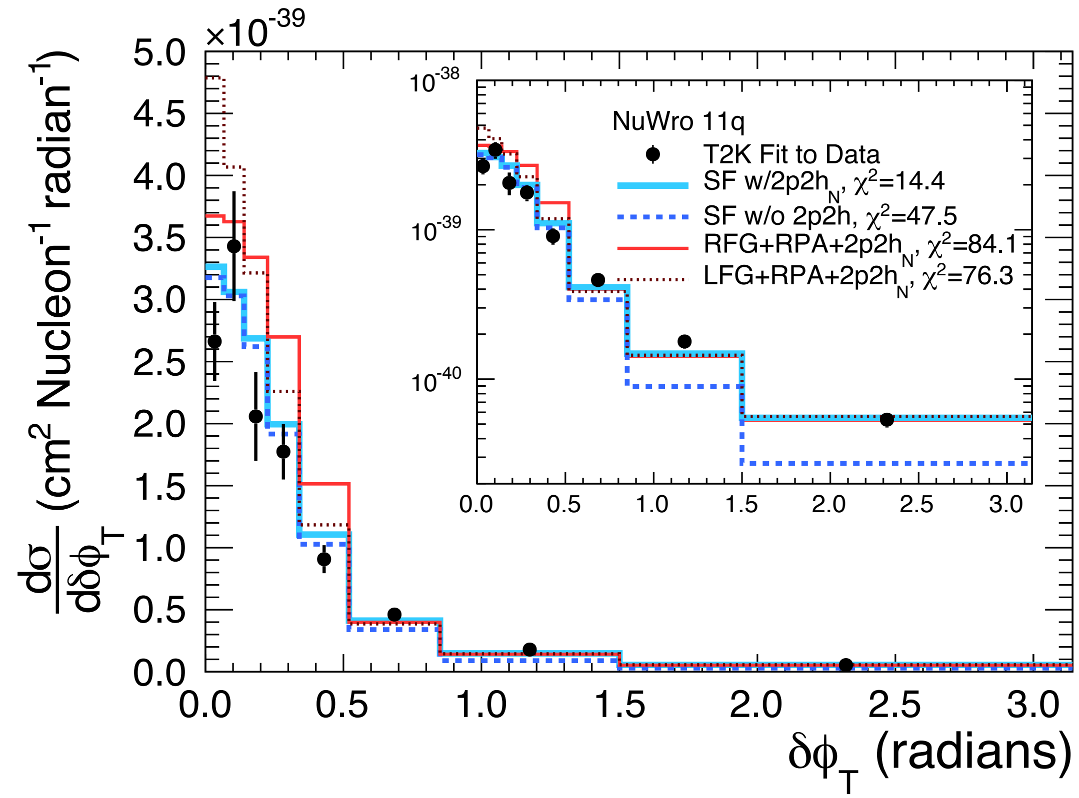
X.-G. Lu et al, Phys. Rev. C 94, 015503 (2016)

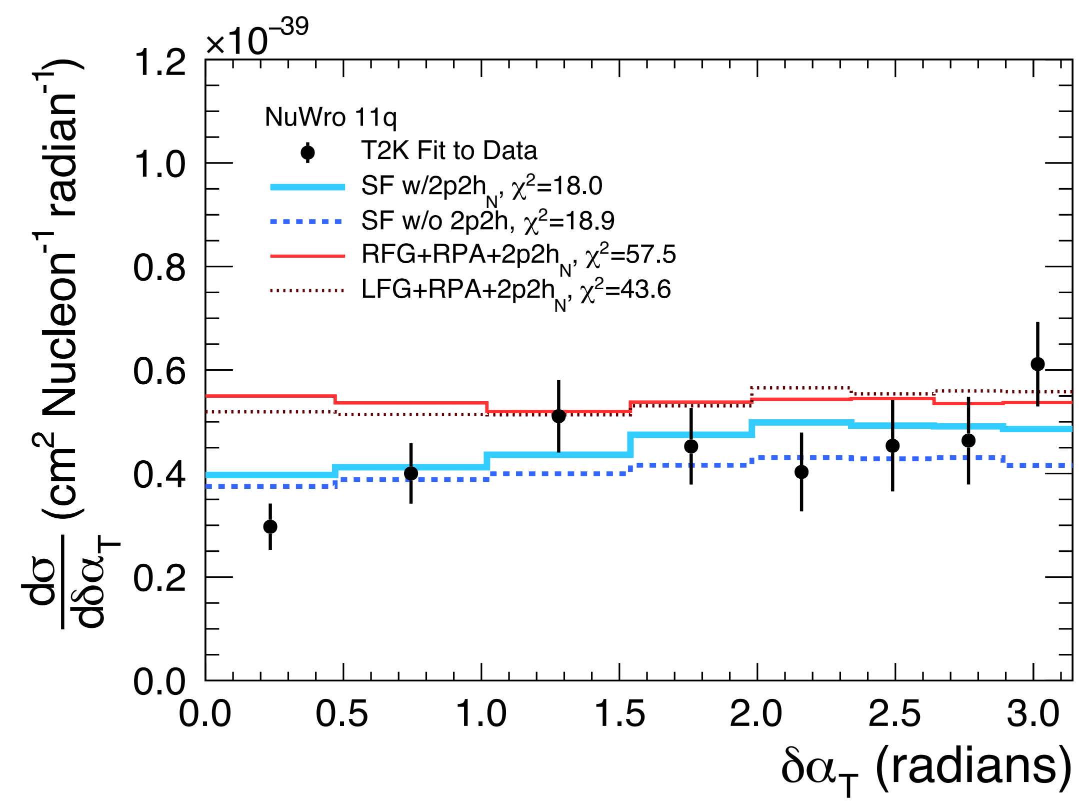
Kinematics in the Transverse Plane

Fermi gas model fails to describe transverse observables



2 particle-2 hole interactions needed to describe high δp_T tail





arXiv:1802.05078 [hep-ex]

Conclusion

A rich dataset of μ + p observables is now available

Multiple new variables sensitive to nuclear effects (individual particle kinematics, inferred kinematics, transverse kinematics)

No model tested simultaneously describes the full dataset but these data gives hints on possible causes of discrepancies

The widely used RFG nuclear model is disfavoured by these data
With the models tested, spectral function + multi-nucleon interactions are needed to reproduce features of the transverse kinematics variables

I only had time to show some cherry-picked highlights
See arXiv:1802.05078 [hep-ex] for the full picture

Backup

GENIE 2.12.4 default with empirical MEC comparisons to Transverse Variables

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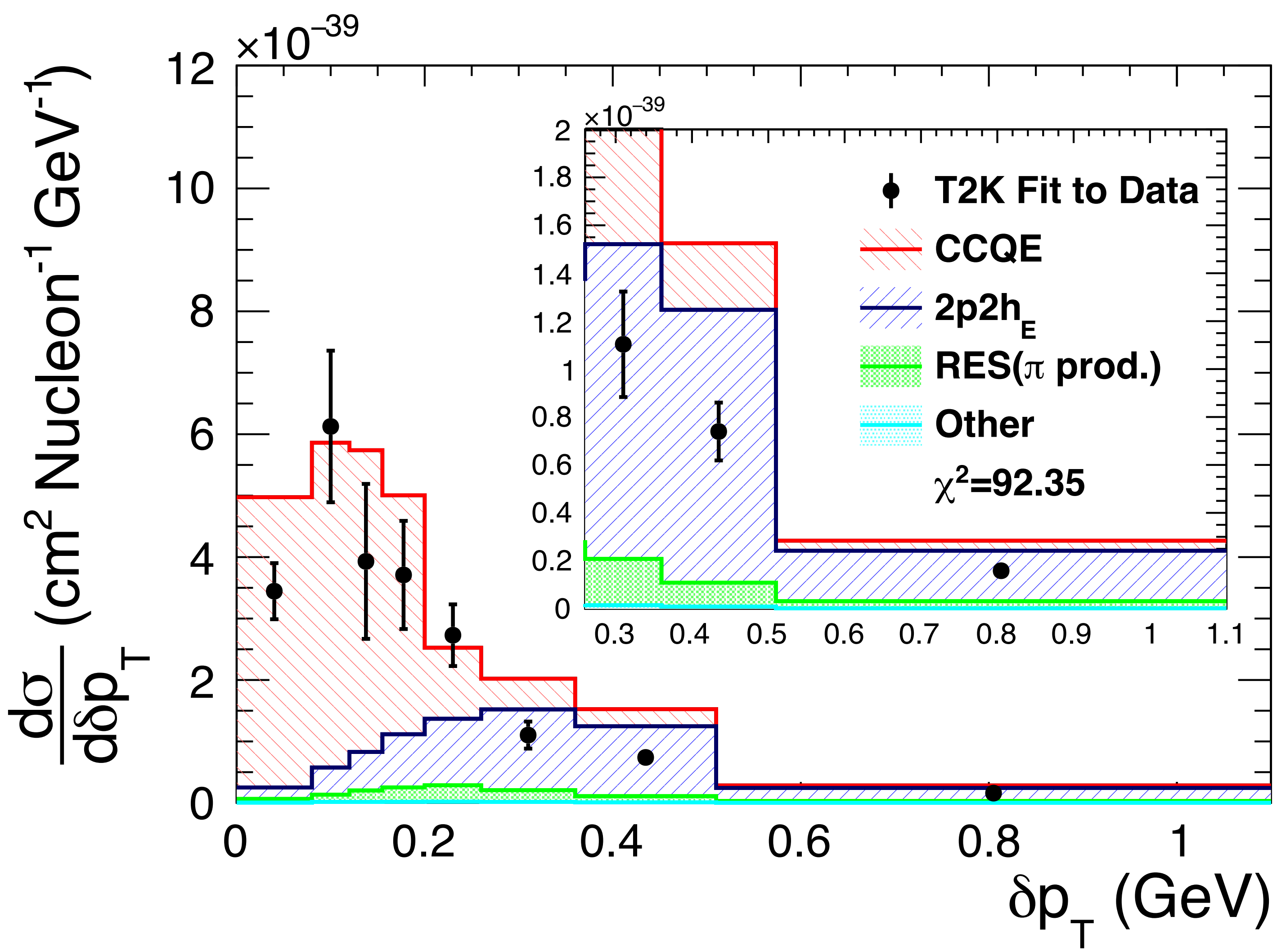

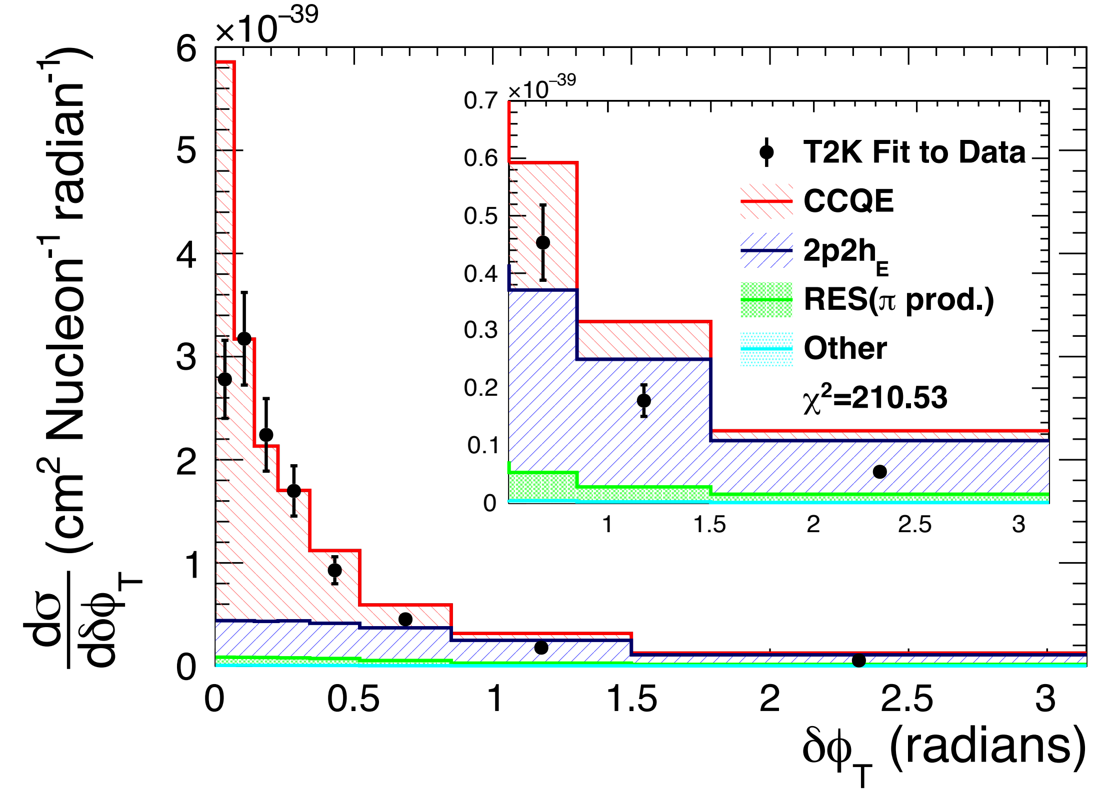

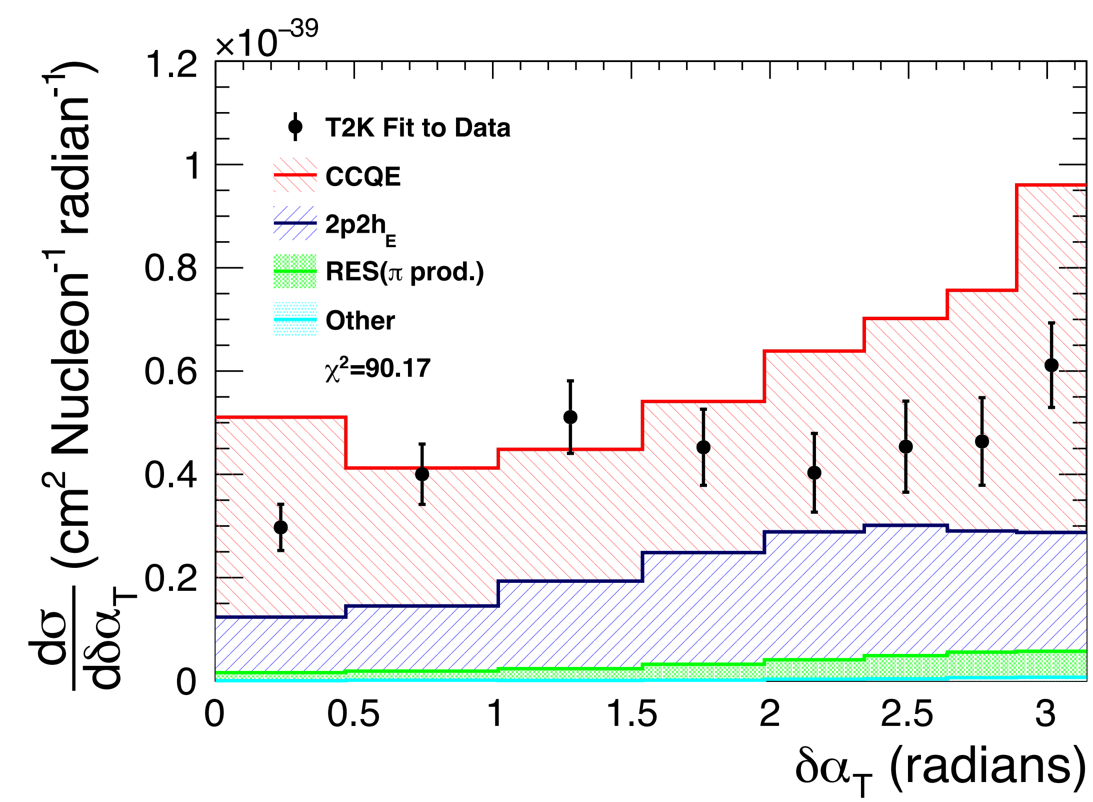

GIBUU 2016 comparisons to Transverse Variables

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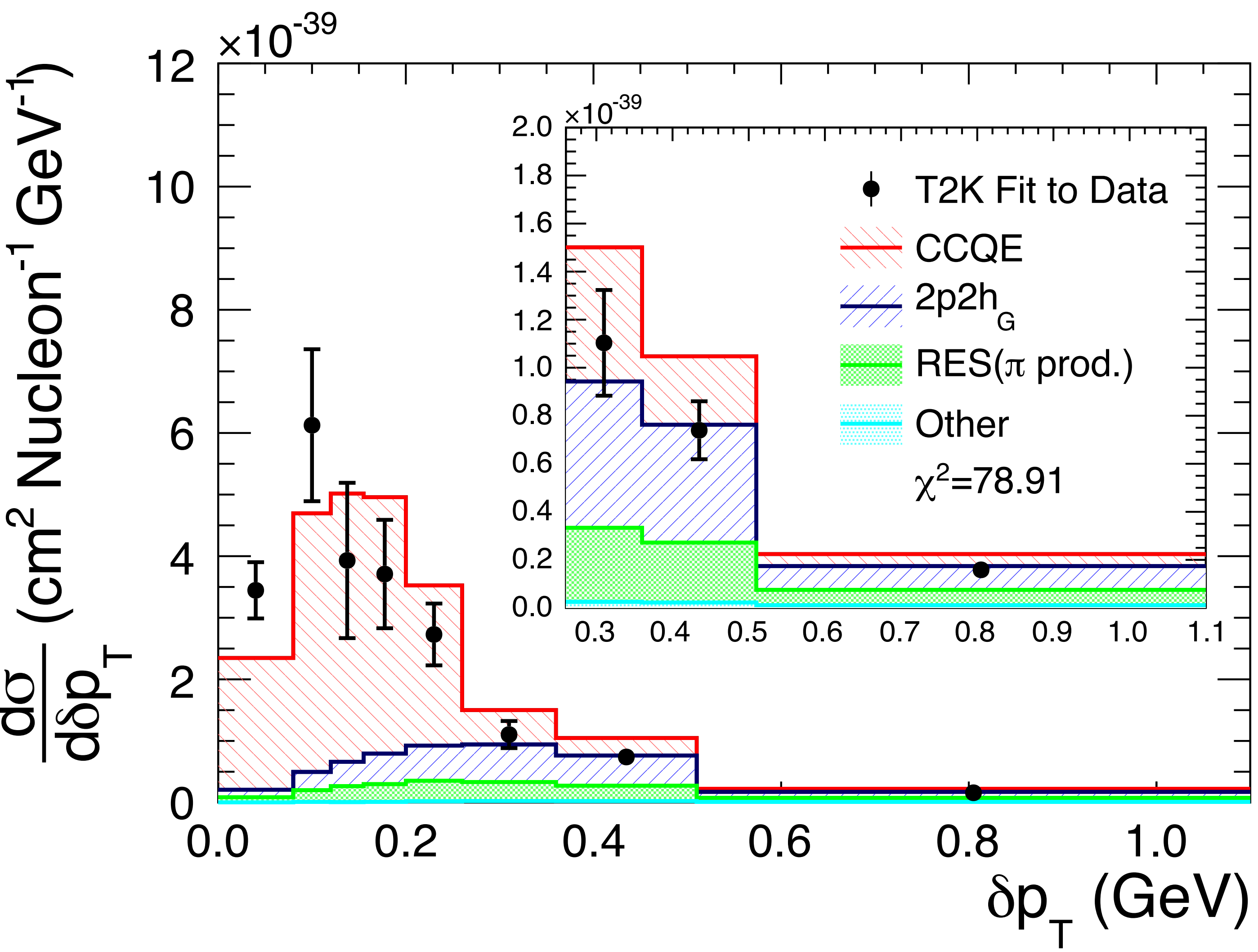

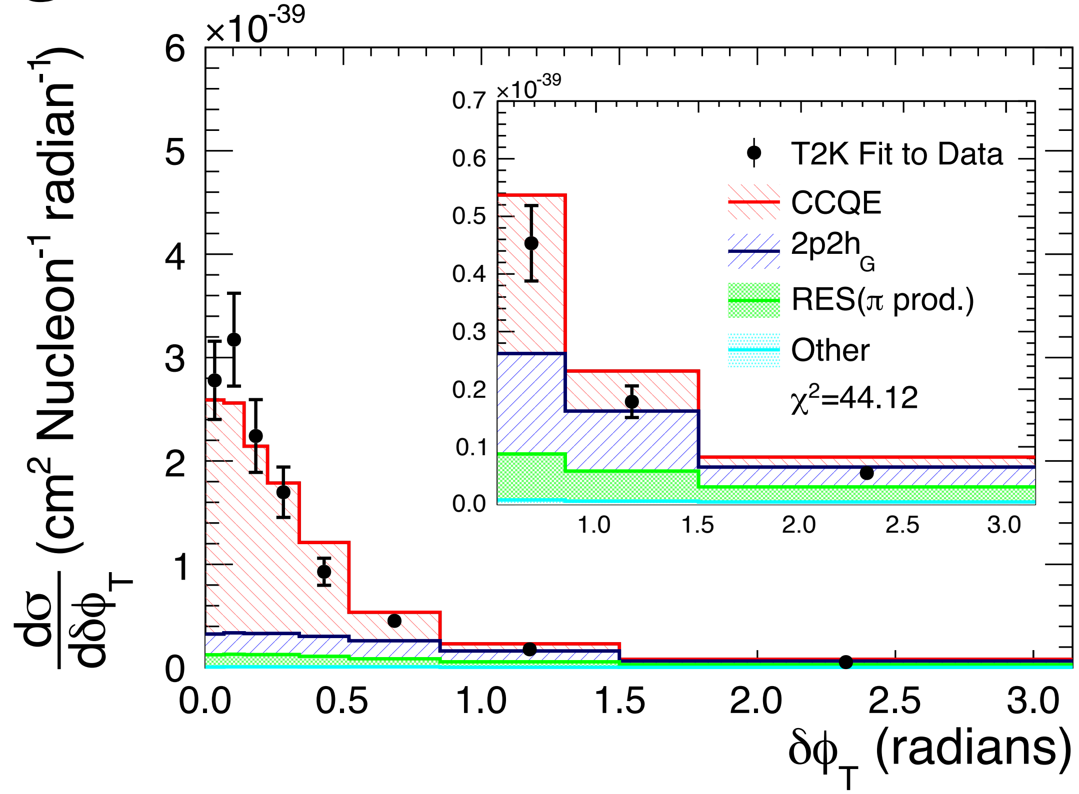

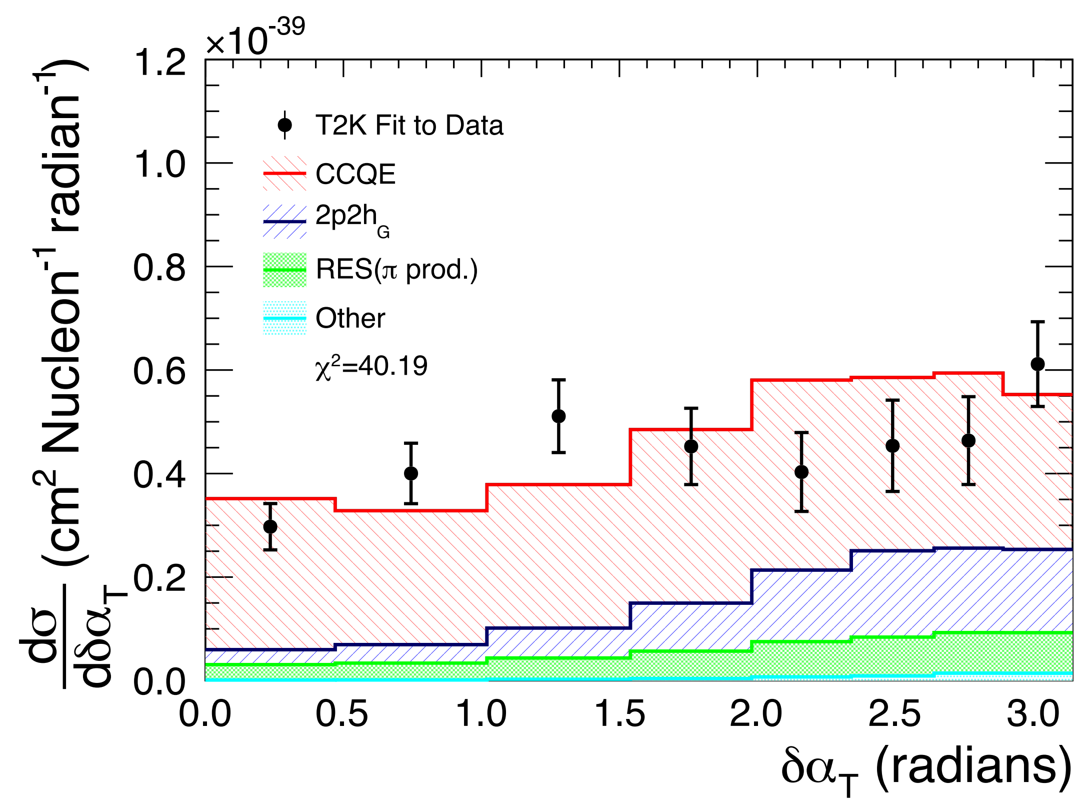

T2K Oscillation Measurement

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$$R_{near}(\vec{x}_{reco}) = \int \Phi(E_\nu)\, \sigma(E_\nu, \vec{x}_{true})\, \varepsilon_{near}(\vec{x}_{true}, \vec{x}_{reco})\, dE_\nu\, d\vec{x}_{true}$$

$$R_{far}(\vec{x}_{reco}) = \int \Phi(E_\nu)\, \sigma(E_\nu, \vec{x}_{true})\, \varepsilon_{far}(\vec{x}_{true}, \vec{x}_{reco})\, P(E_\nu, \vec{\theta})\, dE_\nu\, d\vec{x}_{true}$$

Measured

Parameters of interest

Neutrino Flux

Neutrino nucleus interaction model

Large a priori uncertainties

Detector efficiency and resolution

Oscillation Probability

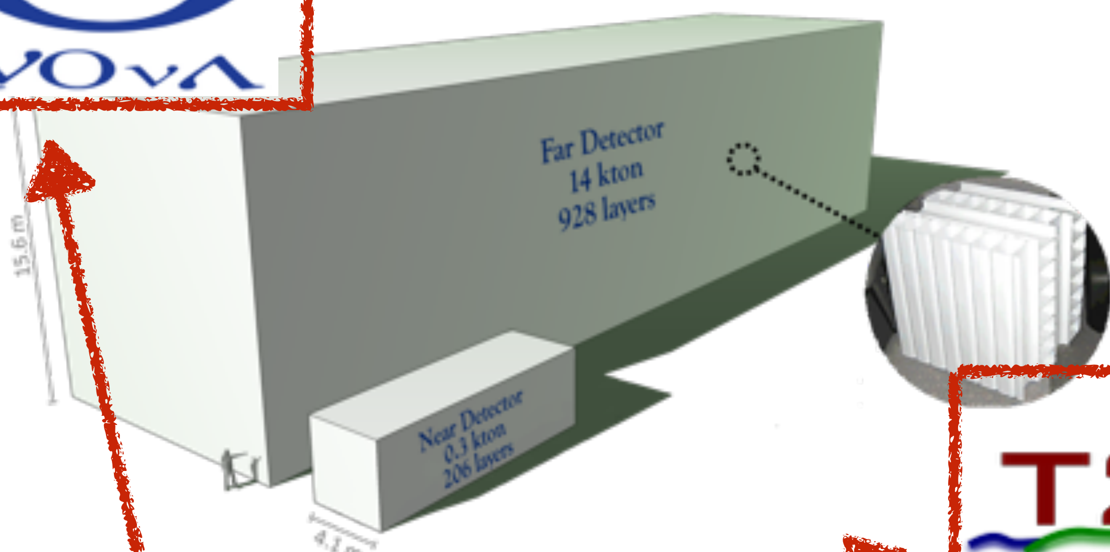
Use measurements at near detector to constrain $(\Phi \times \sigma)$

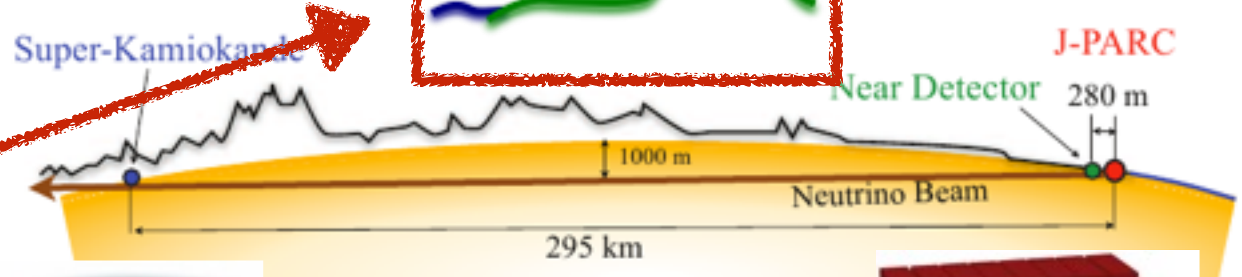
Depend on interaction model for:

$\vec{x}_{true}$ to E_ν

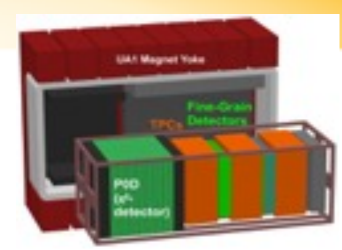
Extrapolate from near to far energy distribution

Accelerator based Neutrino Oscillation Experiments

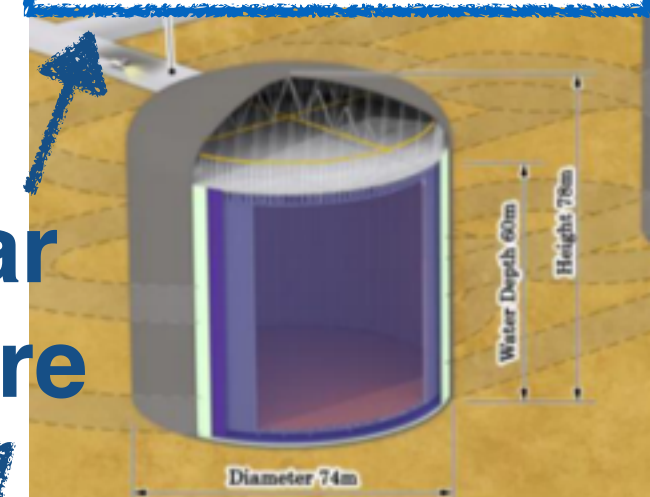


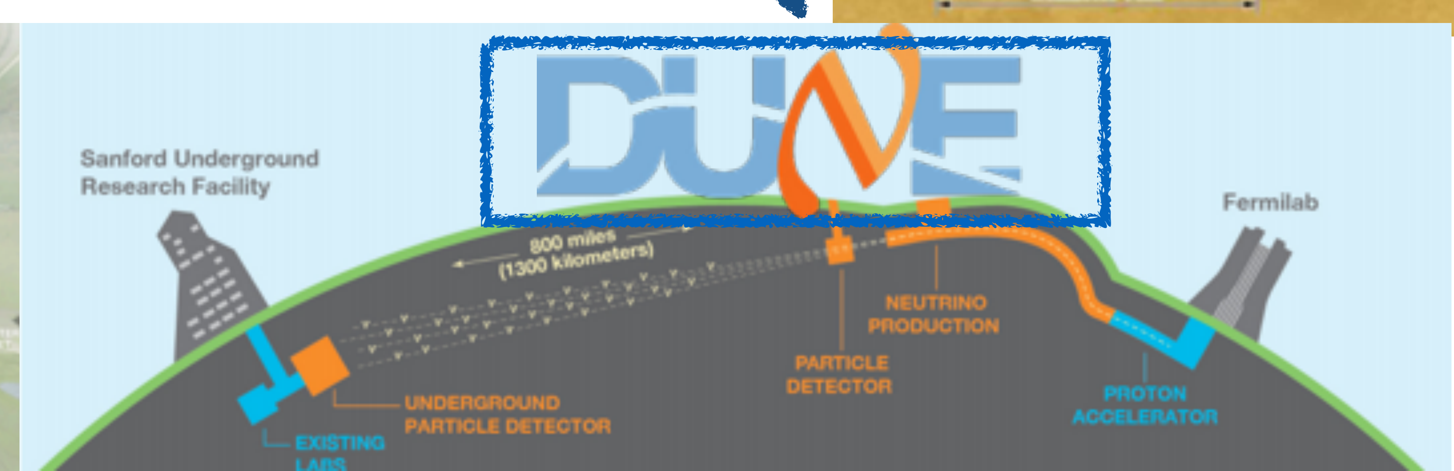


Currently running long baseline experiments



Near future





What is measured?

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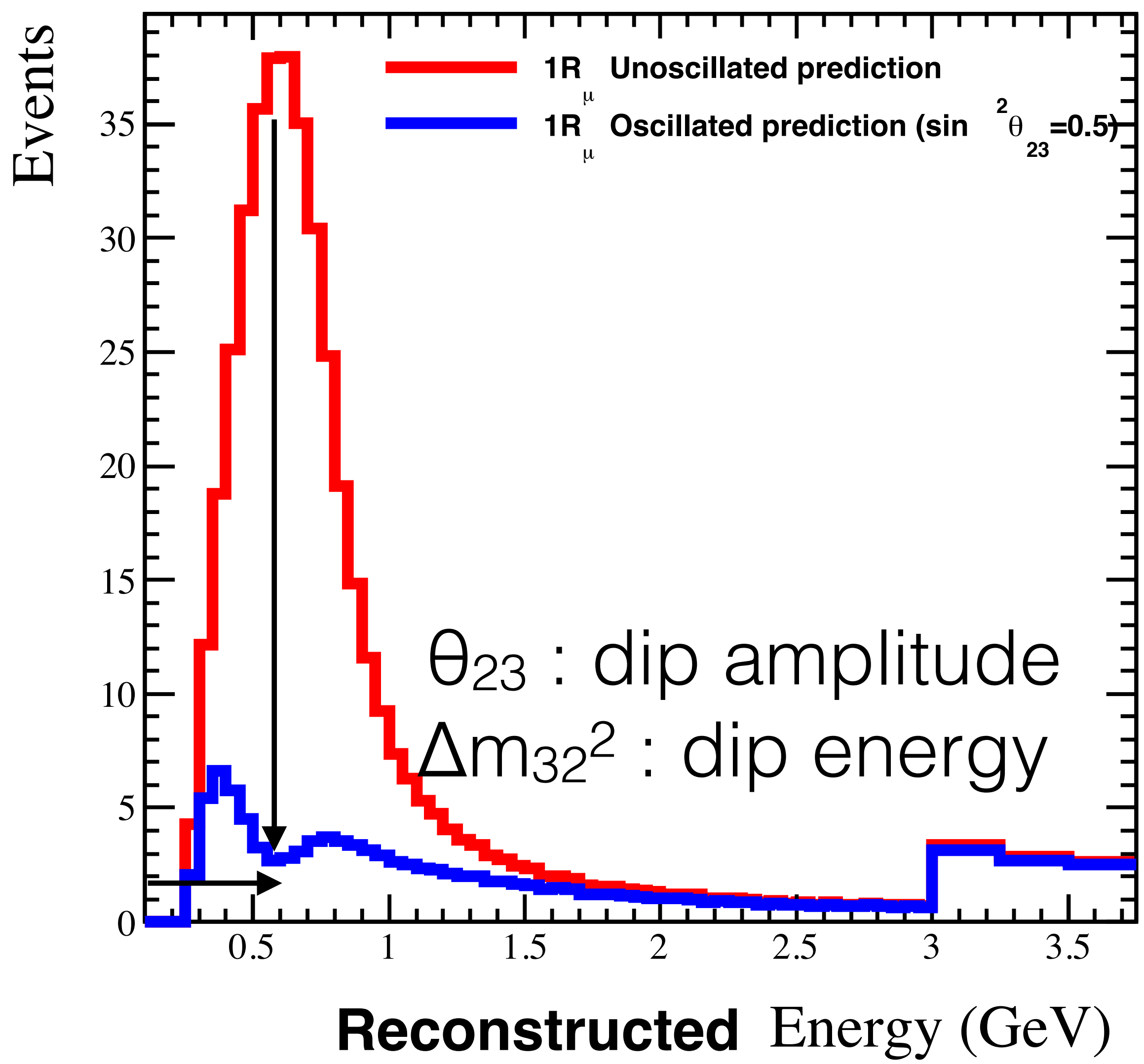
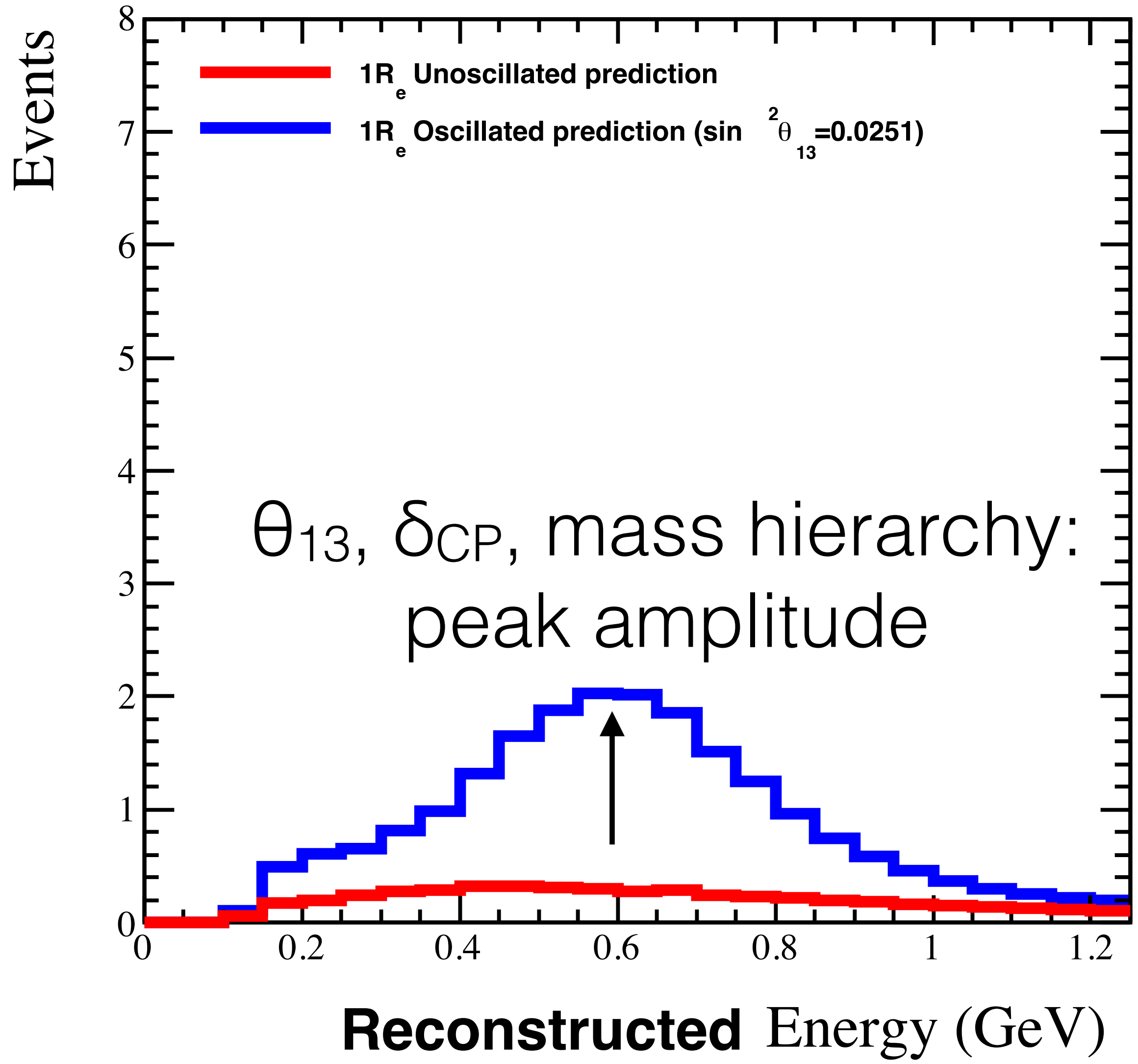
ν_μ disappearance



ν_e appearance

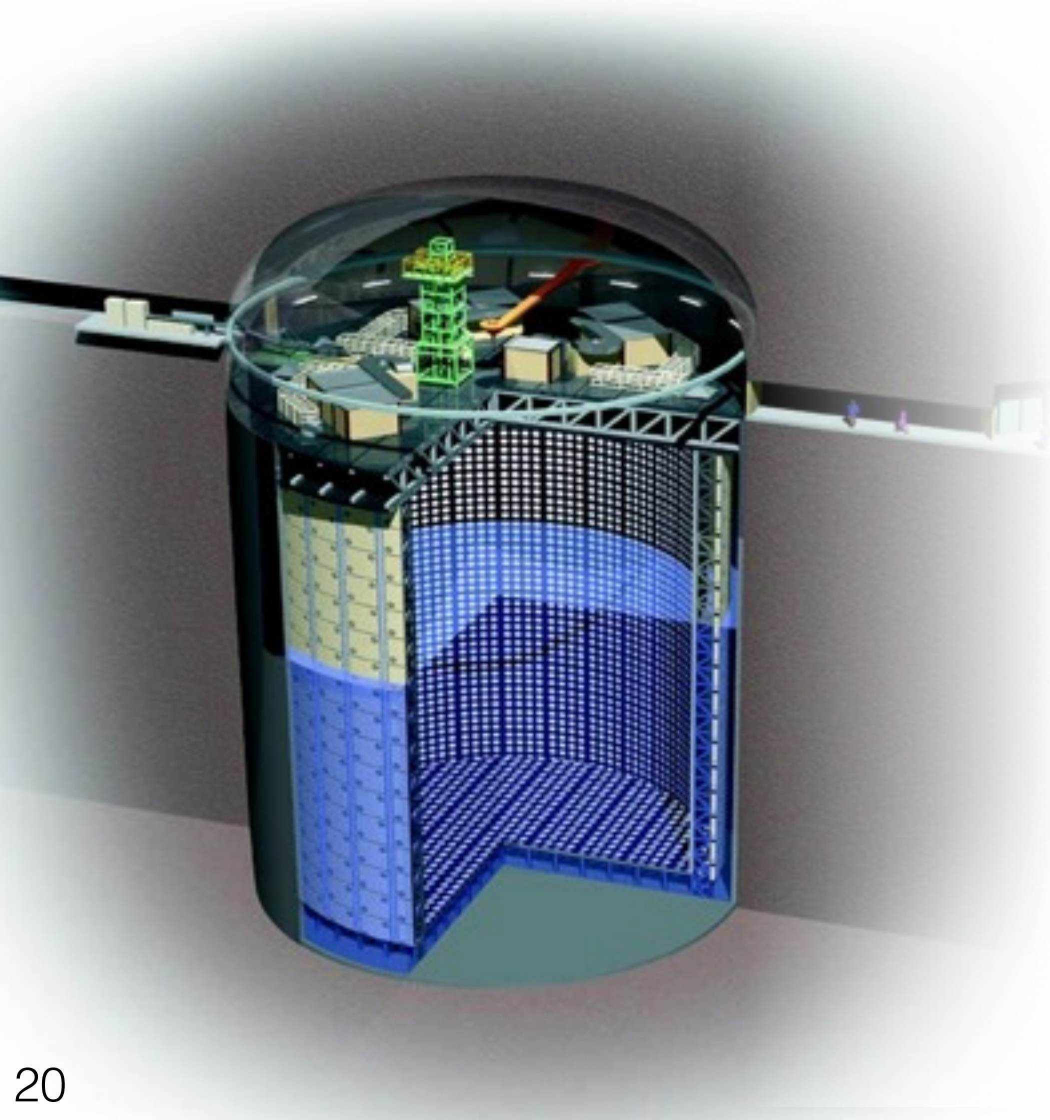


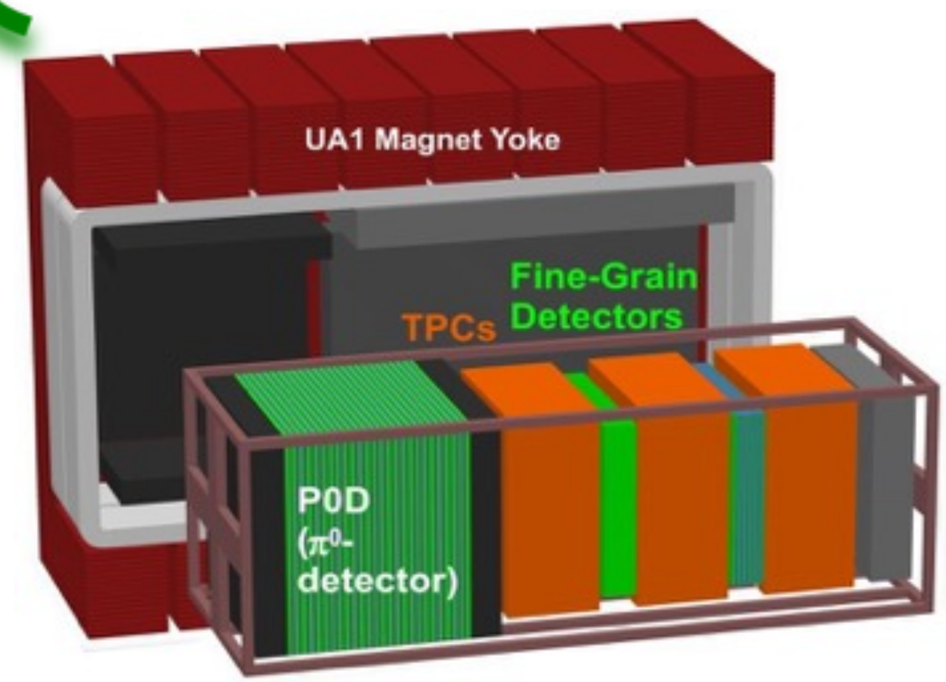
Measurement precision limited by:

- Statistics
- Neutrino energy reconstruction
- Knowledge of unoscillated spectrum and background contamination

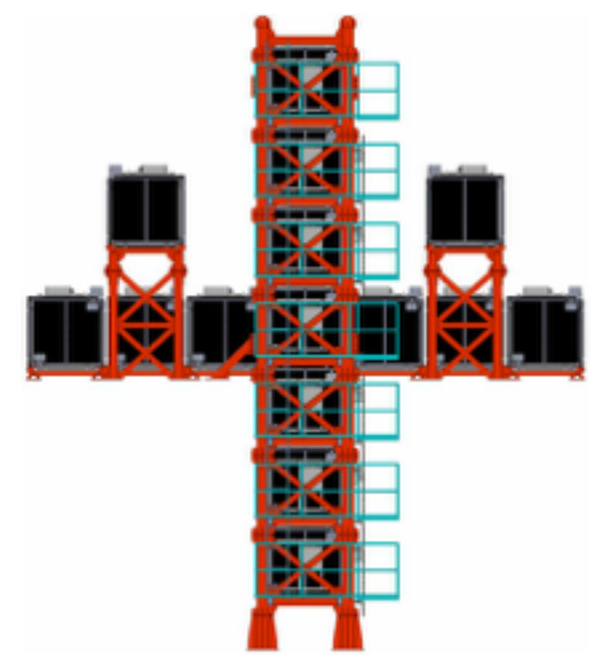
T2K

Far Detector
(Super-K)

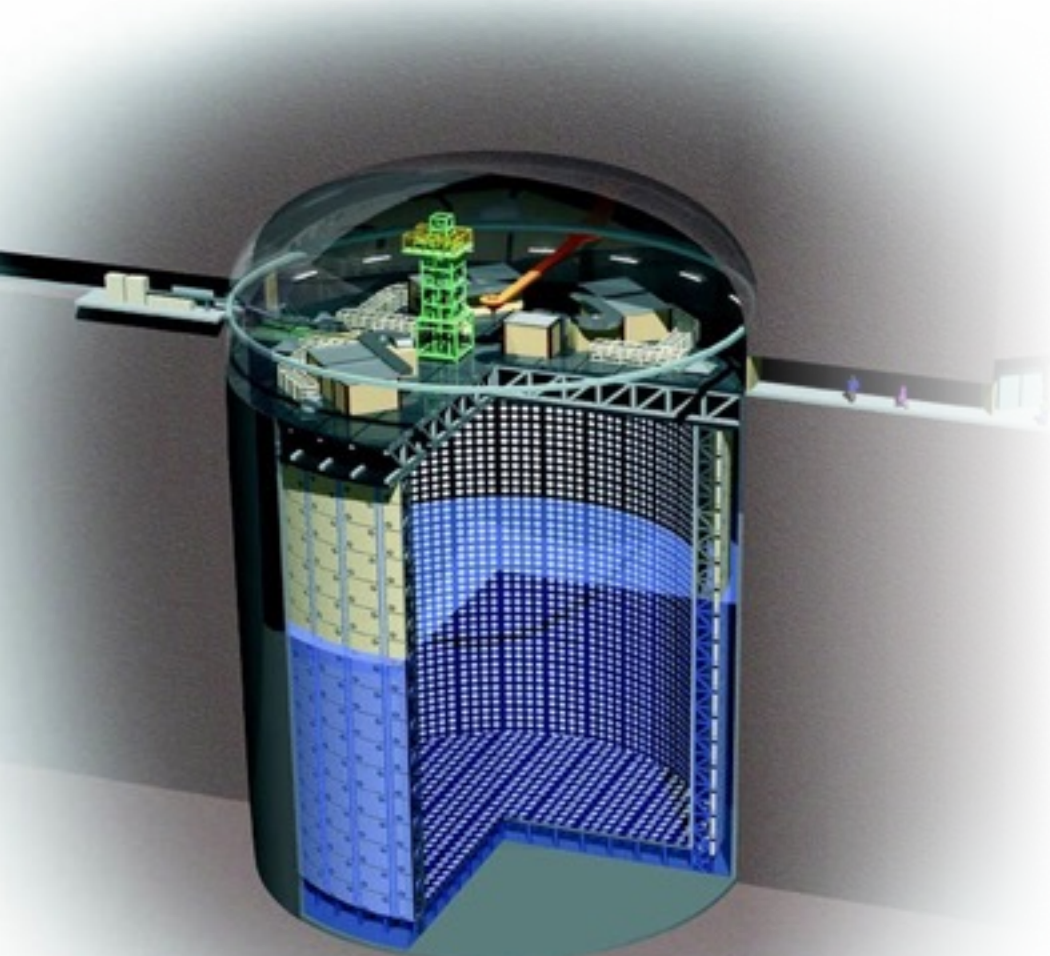


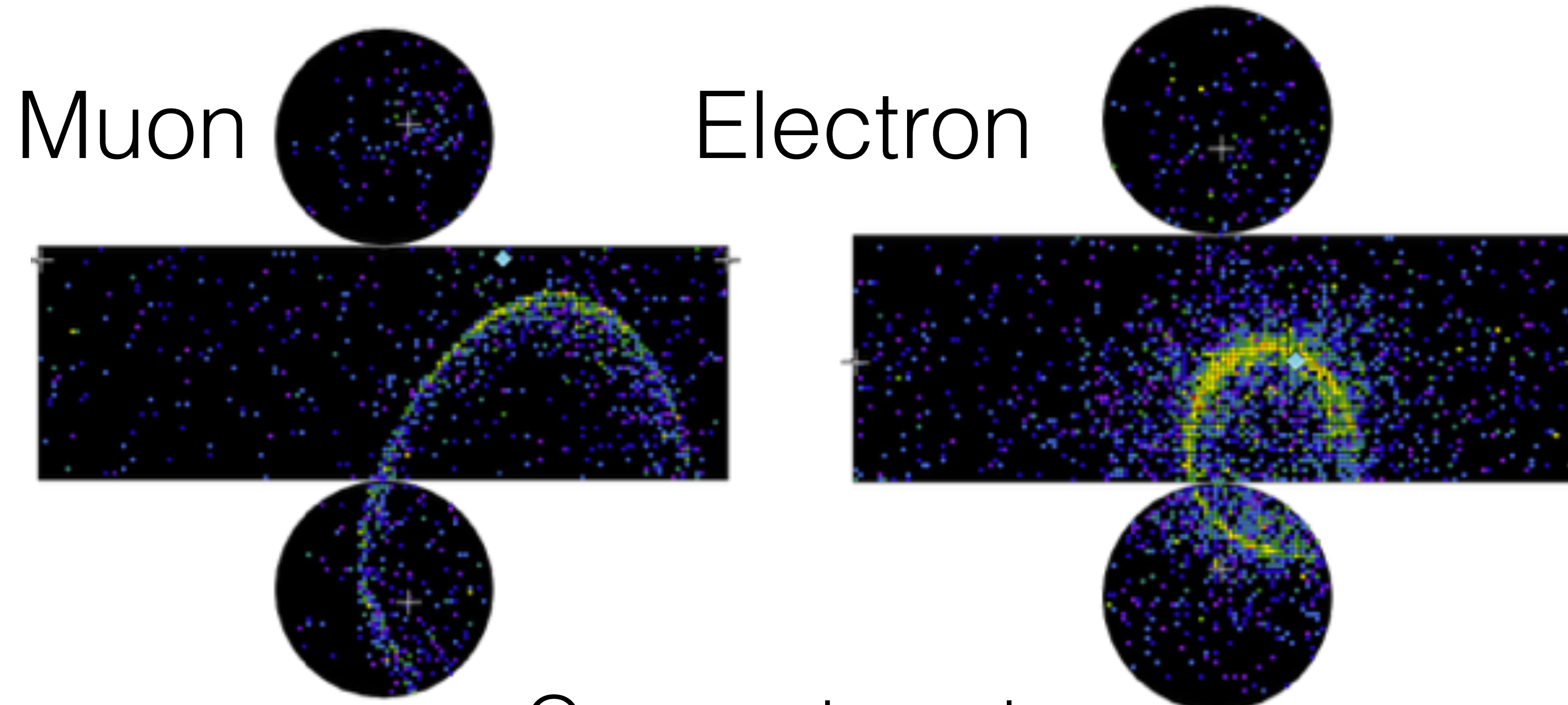


Near Detectors
(ND280+INGRID)



Water Cherenkov Far Detector
>22.5 kt fiducial mass





Oxygen target
4π acceptance

Energy reconstruction from lepton kinematics

Blind to particles below Cherenkov threshold
for protons < 1.1 GeV/c.
(neutron counting possible with SK-Gd)

T2K

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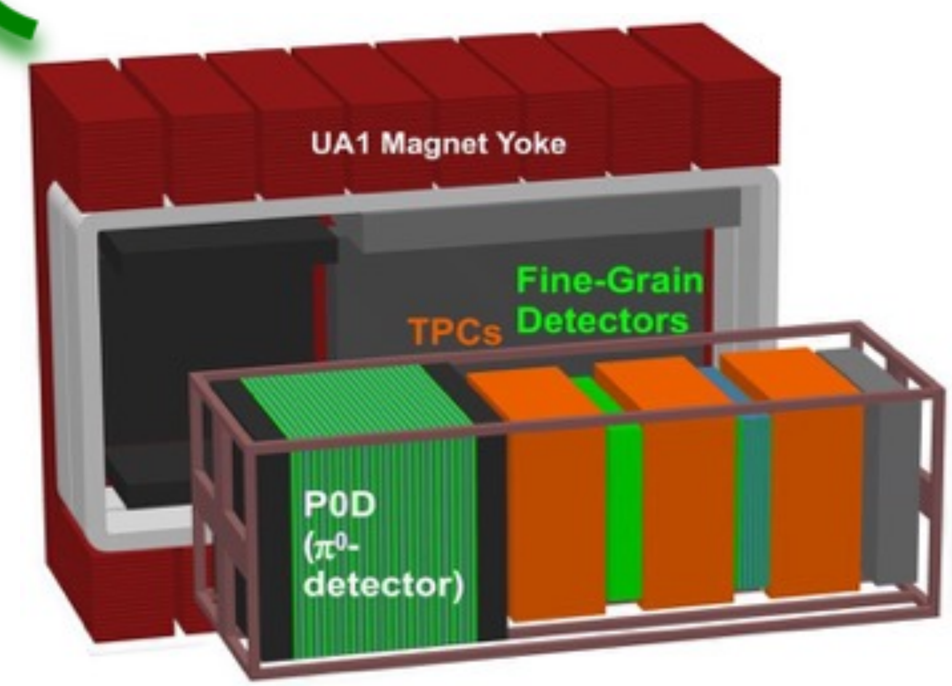
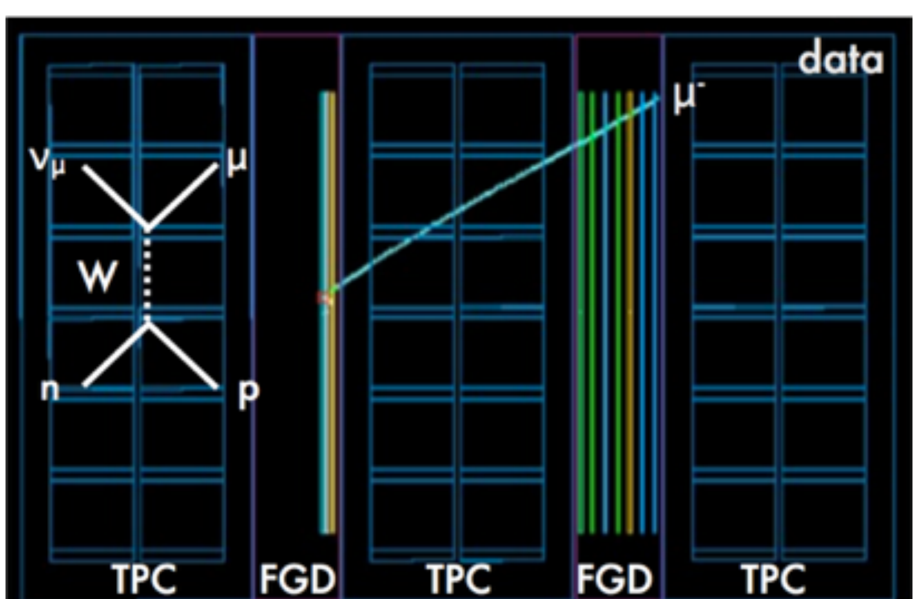
Carbon and Oxygen target materials

Acceptance differs from far detector

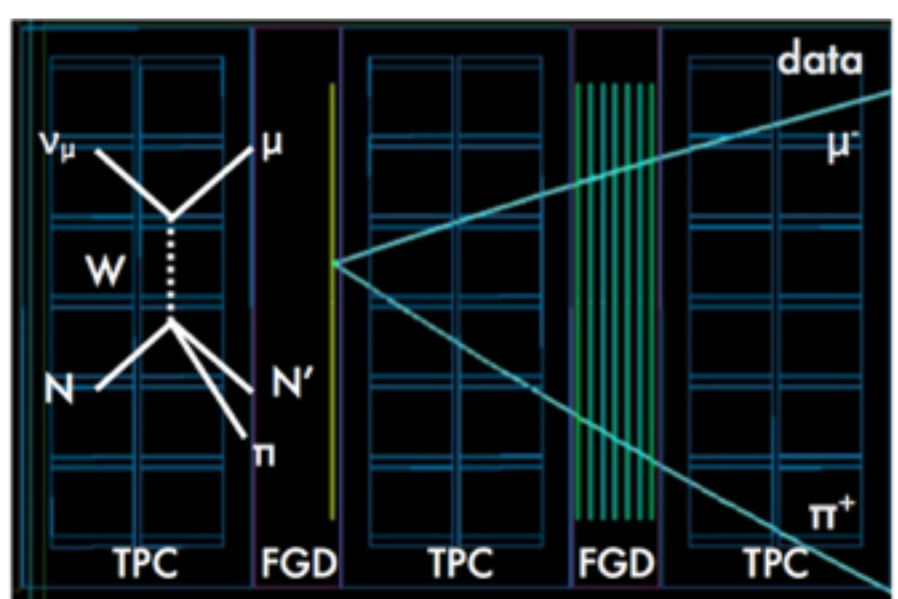
Magnetic field for sign selection



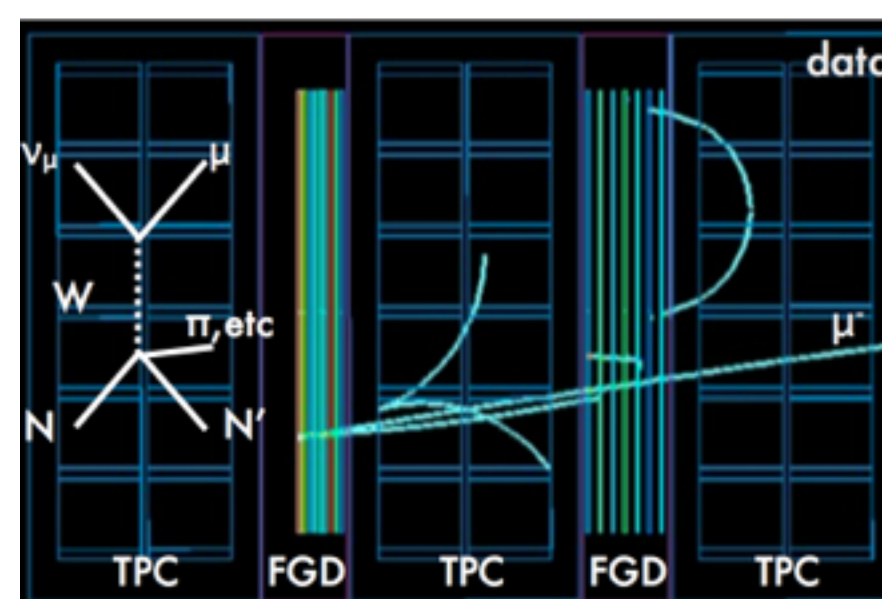
Near Detector (ND280)



CC $1\mu + 0\pi + X$



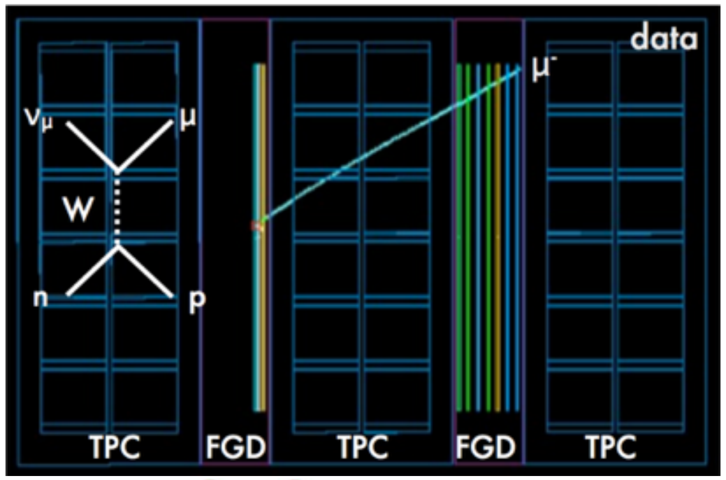
CC $1\mu + 1\pi^+ + X$

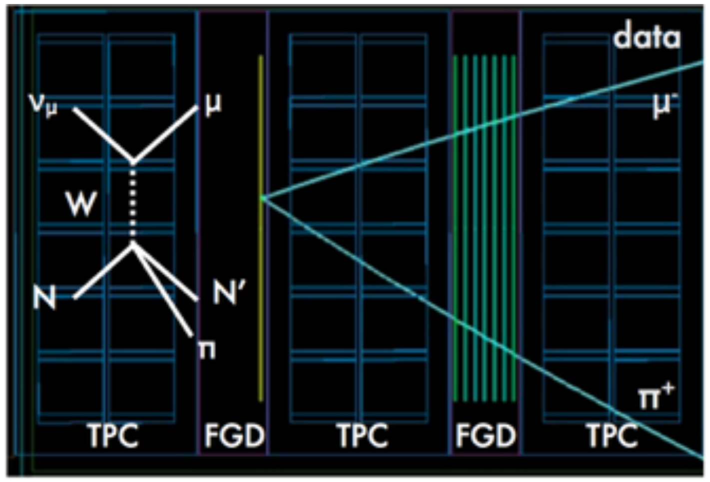


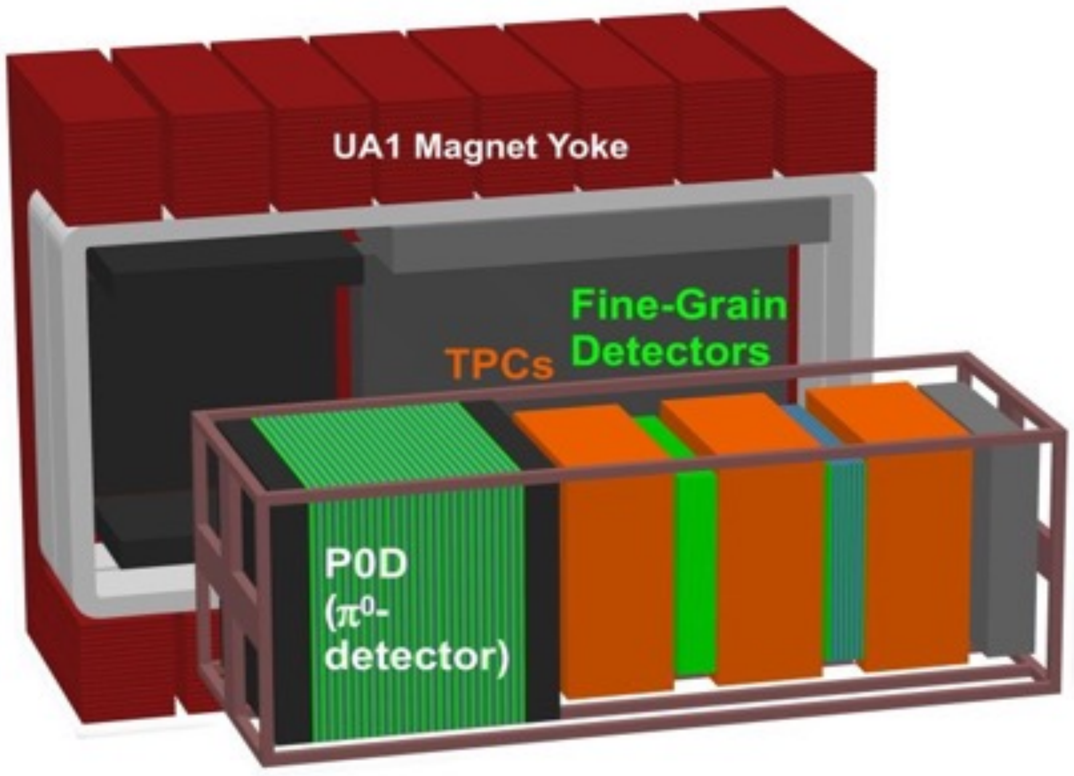
CC other

T2K Near Detectors

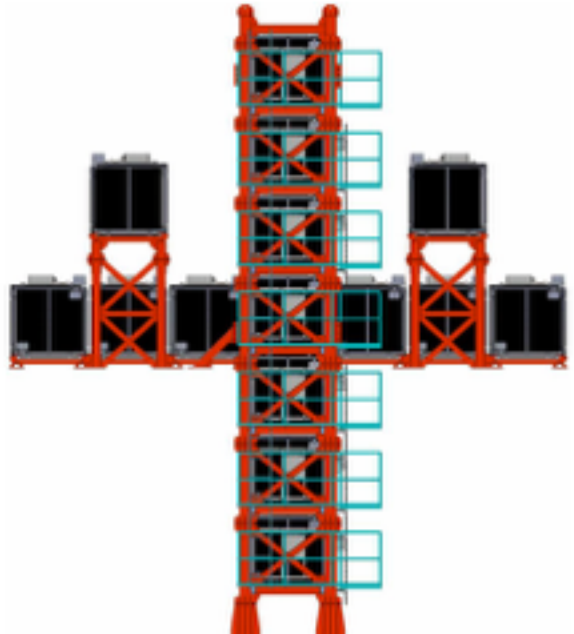
Off-axis in line to SK, narrow band flux
Carbon and Oxygen target materials
Magnetic field for sign selection





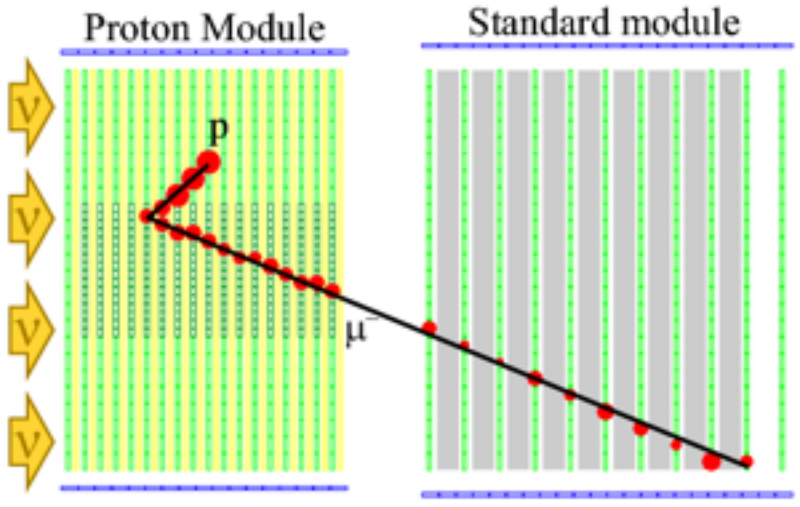


ND280 off-axis detector



INGRID on-axis detector

High statistics
Monitor neutrino beam stability and direction



T2K Cross-Section Model

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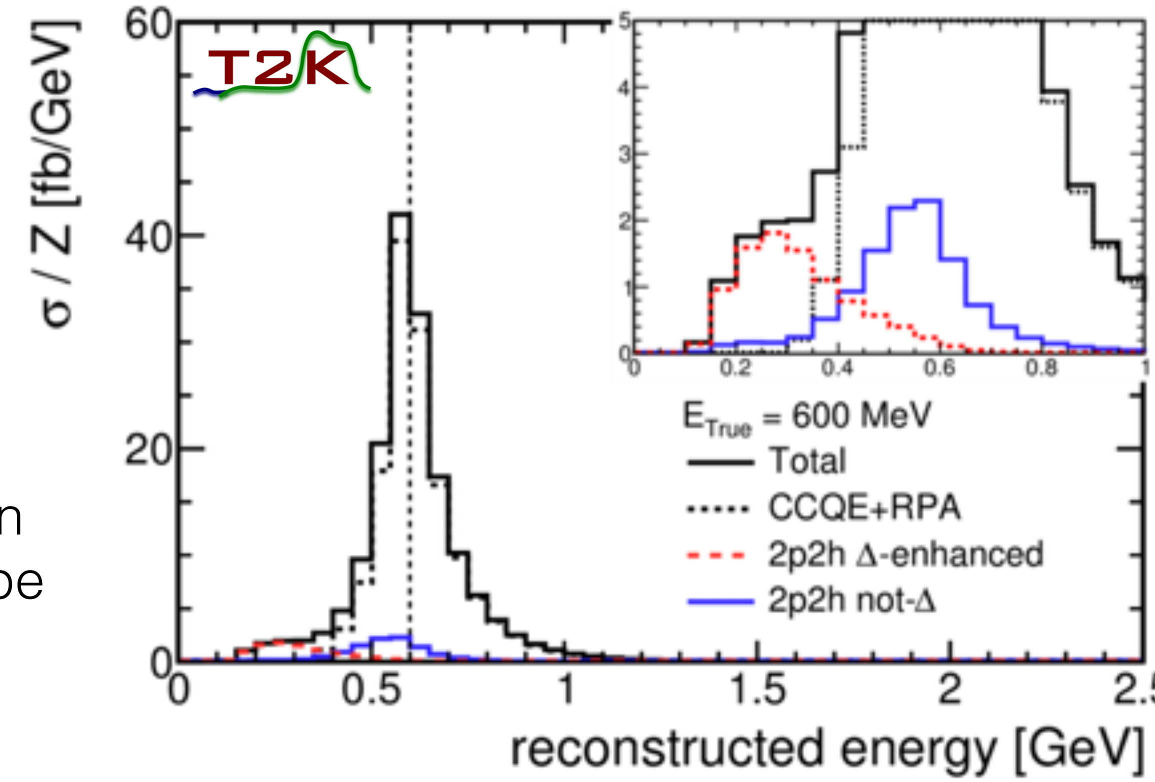
Implemented in NEUT MC generator

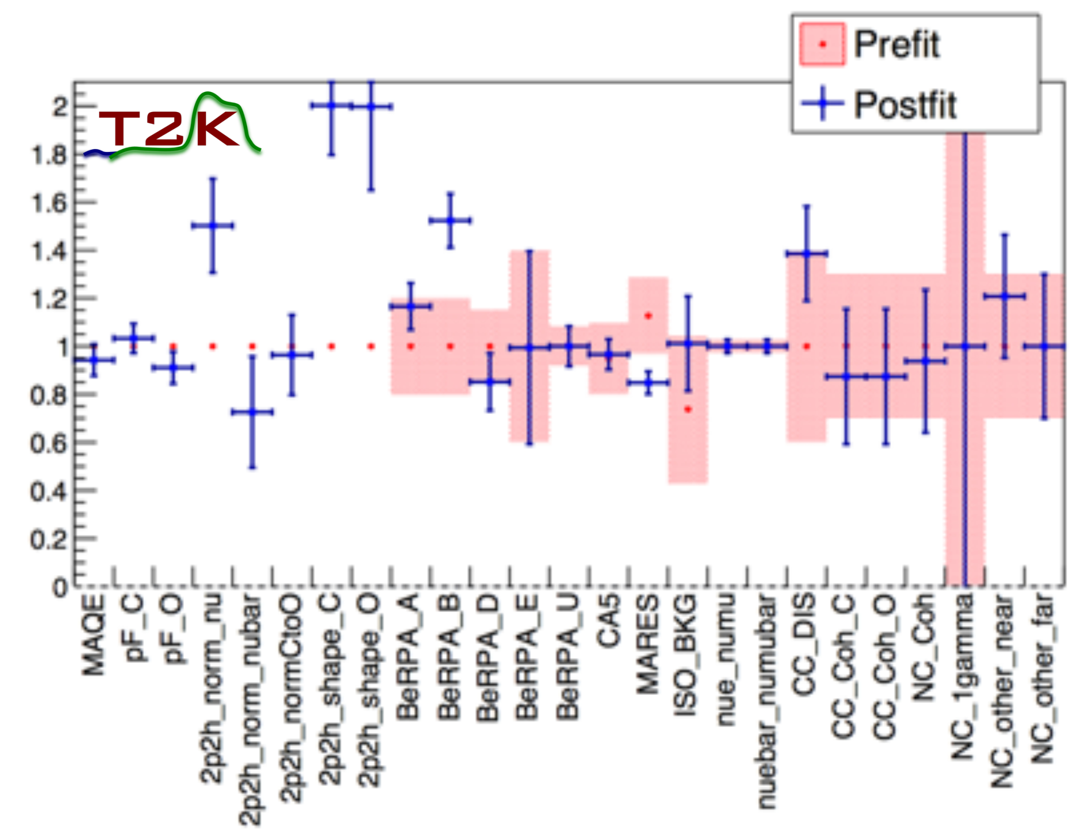
Quasi-elastic scattering most important process at T2K energies

- Valencia 2p-2h model Phys. Rev. C83 (2011) 045501
- Long-range effects with Random Phase Approximation
- Parameters introduced to vary normalisation and shape
- Relativistic Fermi Gas (RFG) nuclear model
- Uncertainties from RFG ↔ Local Fermi Gas
- Final state interactions with cascade model

No priors on most CCQE parameters
Constraint from near detector

Impact of alternative models not implemented in oscillation analysis evaluated with fake data studies





Statistics

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Experiment	$\nu_e + \bar{\nu}_e$	$1/\sqrt{N}$	Ref.
T2K (current)	74 + 7	12% + 40%	2.2×10^{21} POT
NOvA (current)	33	17%	FERMILAB-PUB-17-065-ND
NOvA (projected)	110 + 50	10% + 14%	arXiv:1409.7469 [hep-ex]
T2K-I (projected)	150 + 50	8% + 14%	7.8×10^{21} POT, arXiv:1409.7469 [hep-ex]
T2K-II	470 + 130	5% + 9%	20×10^{21} POT, arXiv1607.08004 [hep-ex]
Hyper-K	2900 + 2700	2% + 2%	10 yrs 2-tank staged KEK Preprint 2016-21
DUNE	1200 + 350	3% + 5%	3.5+3.5 yrs x 40kt @ 1.07 MW arXiv:1512.06148 [physics.ins-det]

Current appearance measurements stats dominate

$O(10^3)$ ν_e at future experiments → demands ~2% systematics

$O(10^4)$ ν_μ → need systematics as good as we can get!