Neutrino interactions for neutrino oscillations

and why ν oscillations need ν cross sections!

Stephen Dolan

stephen.joseph.dolan@cern.ch

The precision era of ν oscillations

Latest results

- **Indication of CP violation!**
- Currently largely limited by statistics … but not for long!

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Current systematic uncertainties

Source (T2K)	$N(\nu_e)$
Binding Energy	7.1%
Total Syst.	**8.8%**

Nature **580**, 339-344

Source (NOvA)	$N(\nu_e)$
$\sigma_{\nu N}$ and FSI	7.7%
Total Syst.	**9.2%**

Phys. Rev. D **98**, 032012

- Current results use ~100 $\nu_e + \bar{\nu}_e$, expect **1000-2000** for DUNE/HK
- ~2-3% stat. precision on CP asymmetry

The precision era of ν oscillations

Latest results

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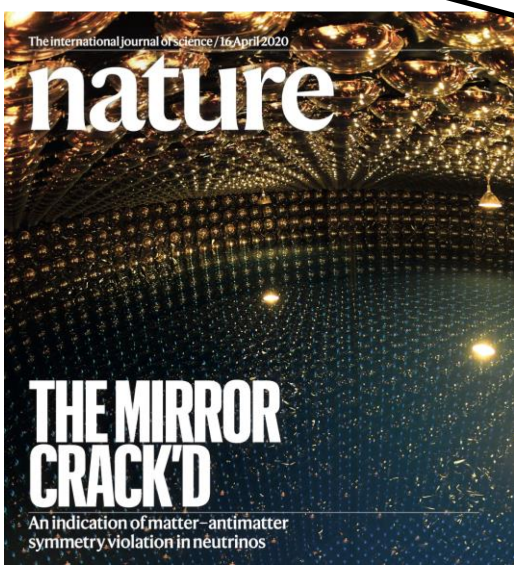
Neutrino interaction uncertainties must be reduced for DUNE/Hyper-K to succeed



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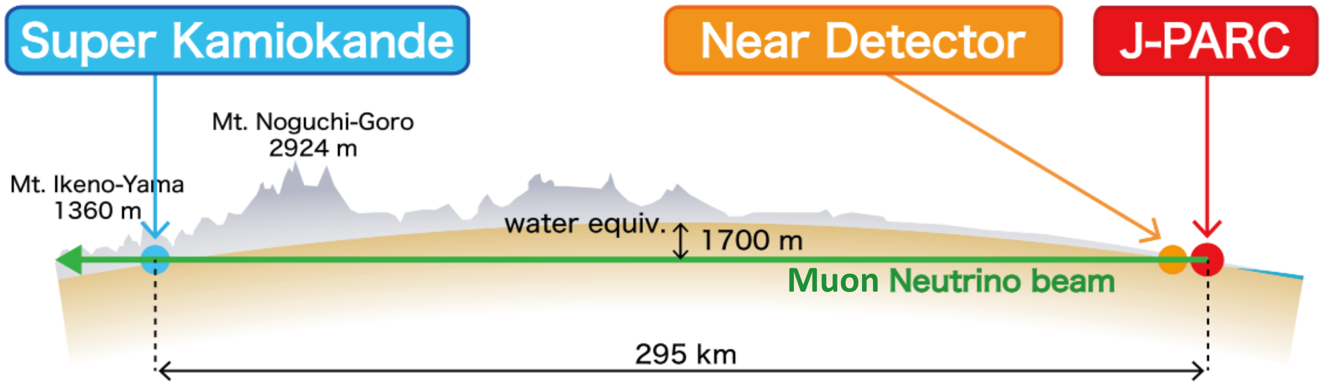
Overview

- Neutrino oscillation experiments
- Neutrino-nucleus interactions: the cause of our largest systematic uncertainties
- Neutrino cross-section measurements: how do our current models describe the data?

Neutrino oscillation experiments



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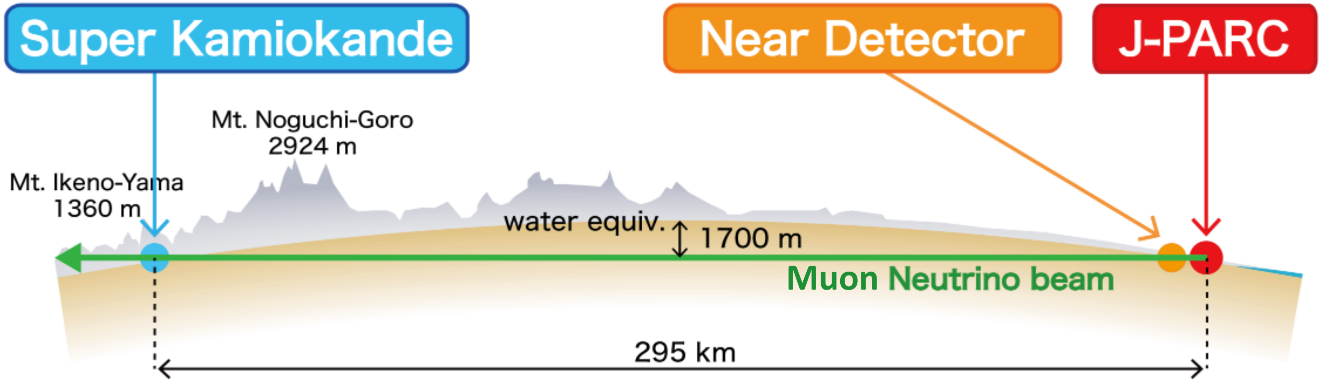
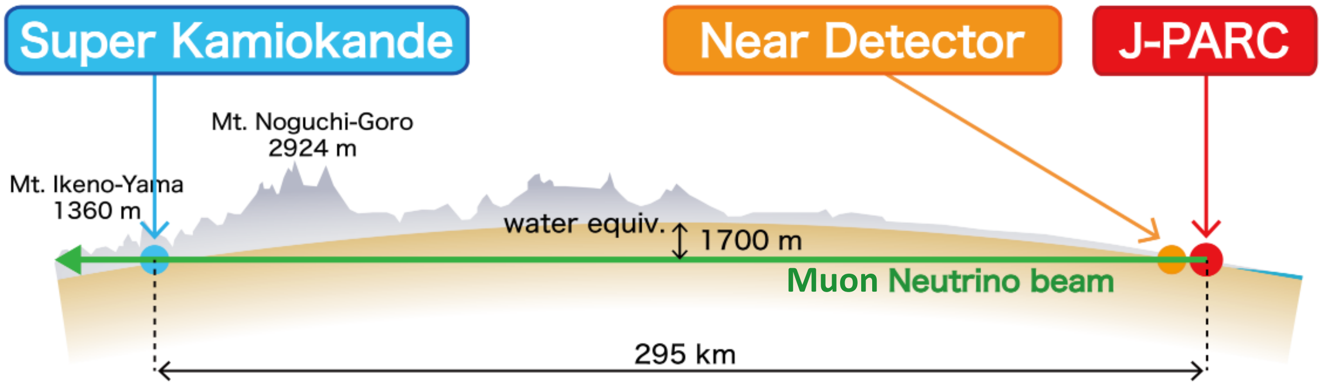


T2K

Neutrino oscillation experiments



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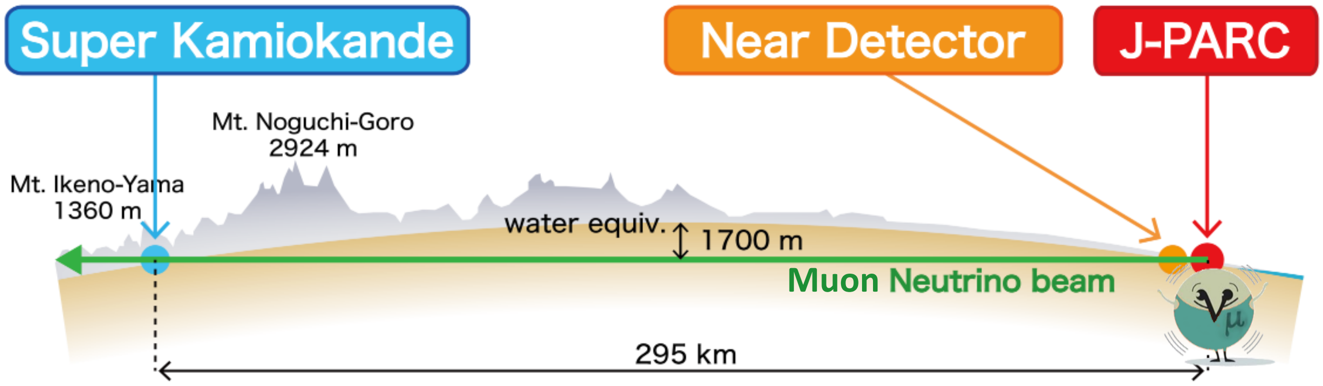

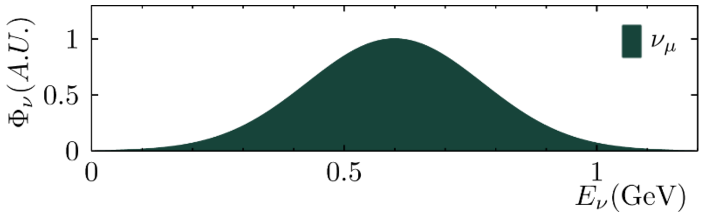

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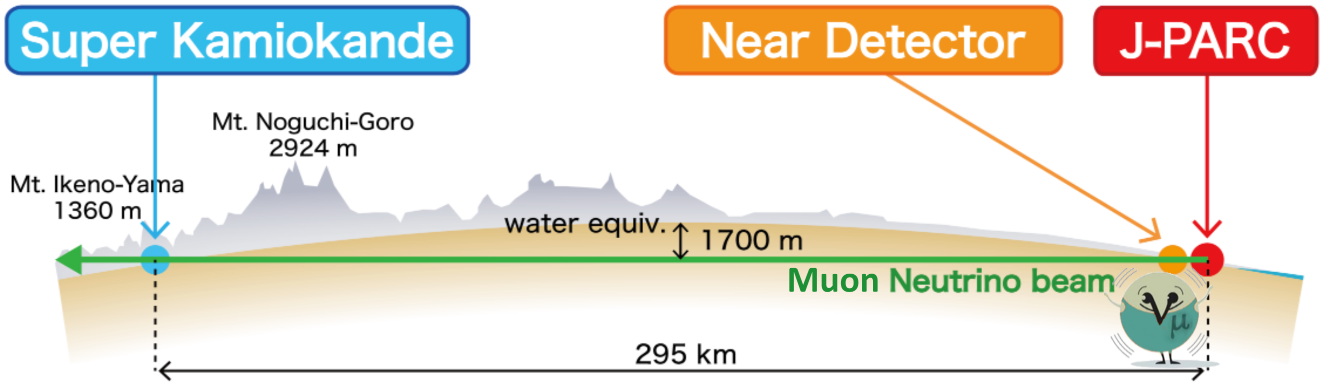
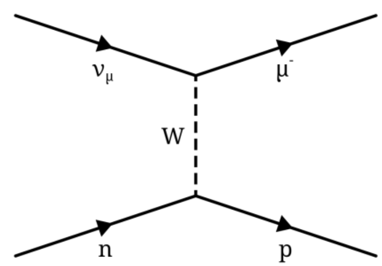
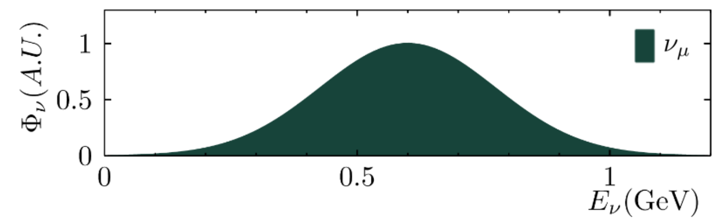






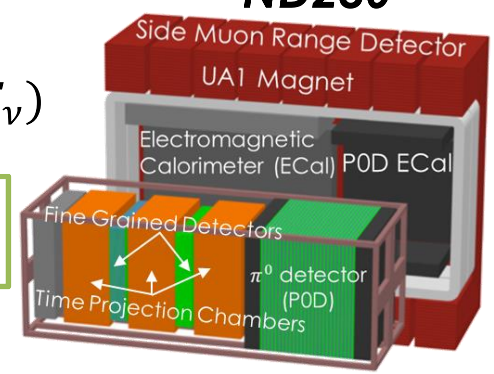
$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Interaction cross section

Neutrino flux

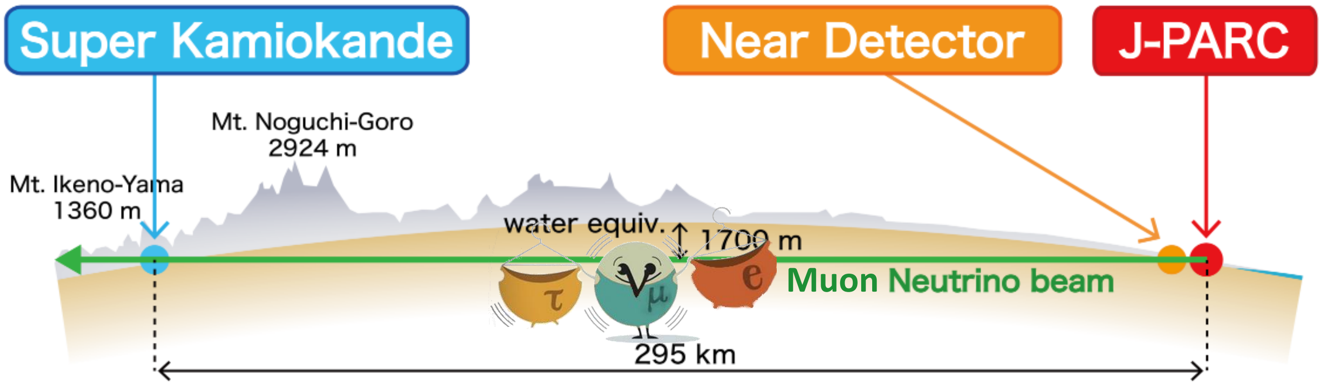
Detector effects

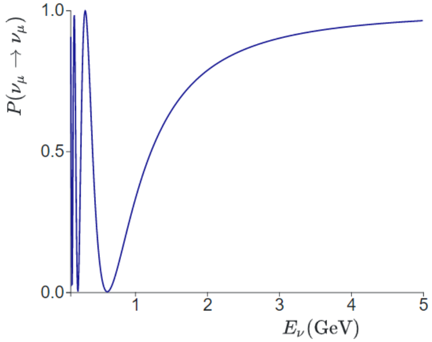
Near Detector
ND280

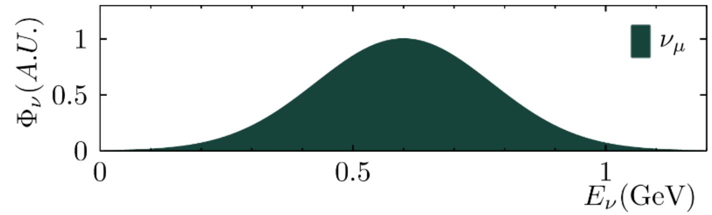


(Mostly Hydrocarbon Scintillator)

Neutrino oscillation experiments







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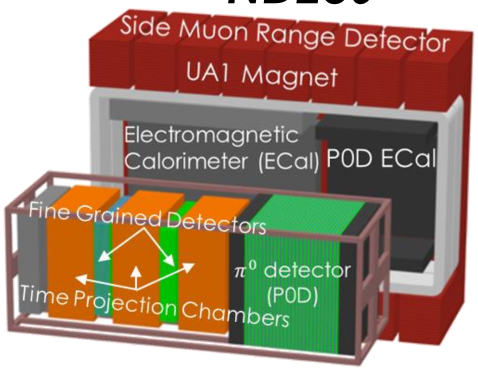

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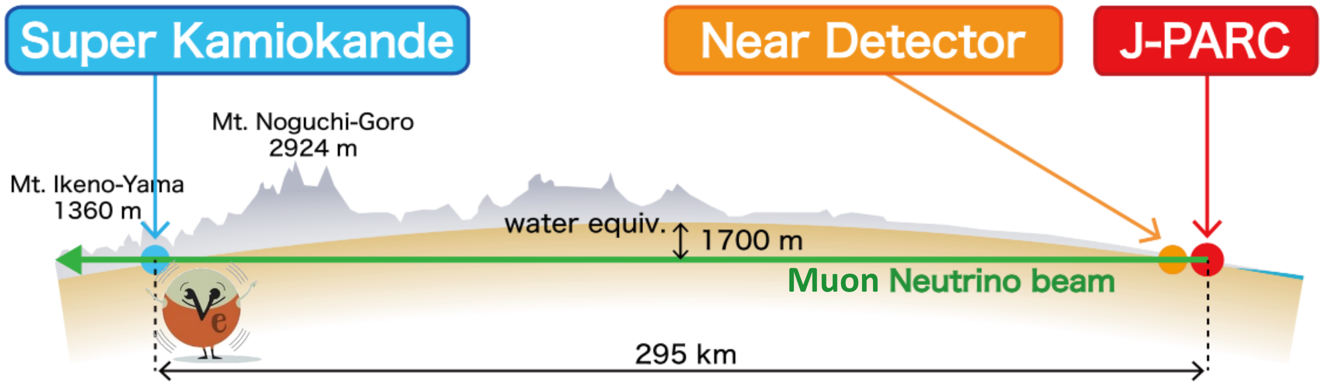
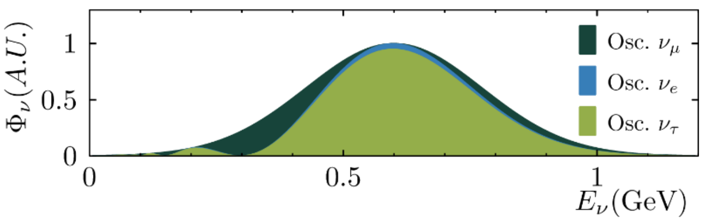
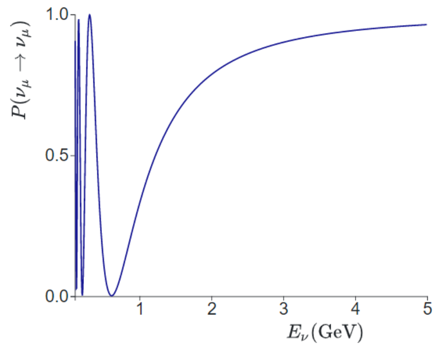
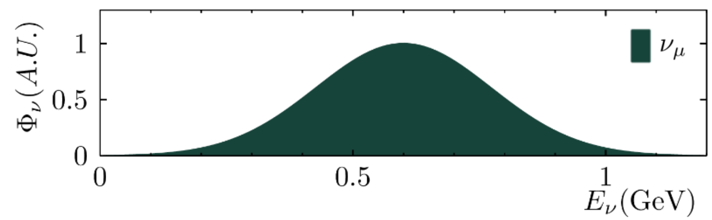
Neutrino oscillation experiments









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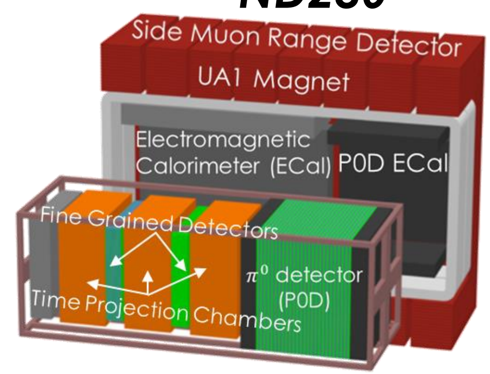
ND280



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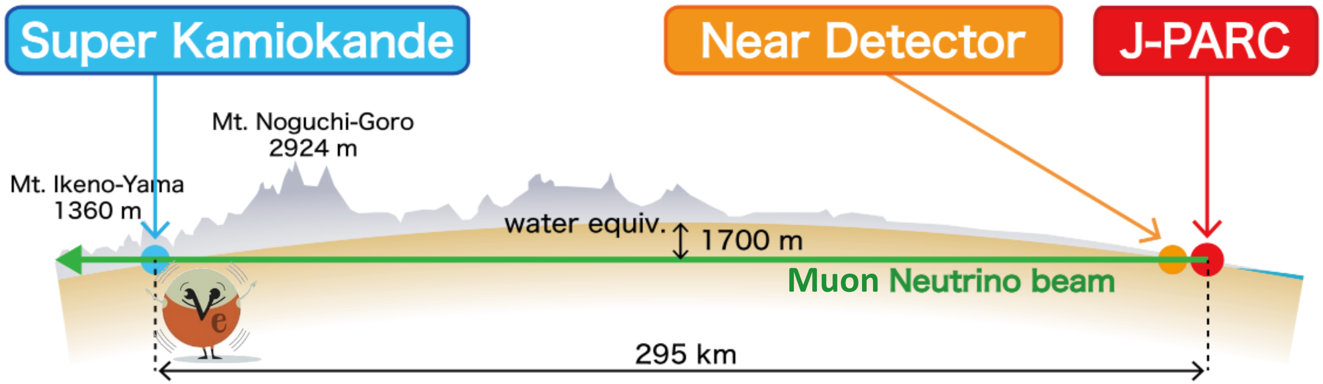
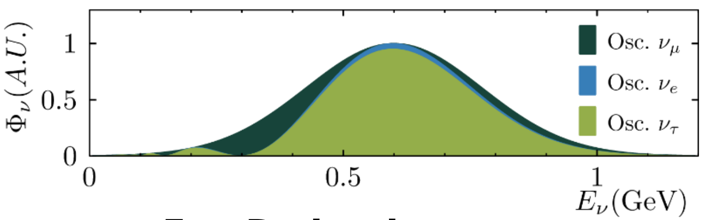
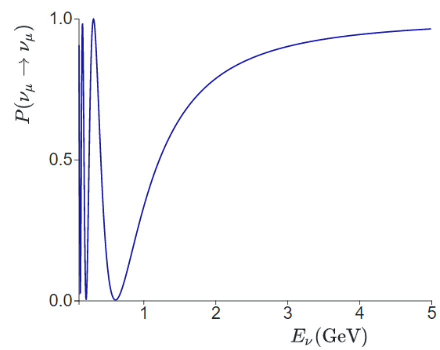
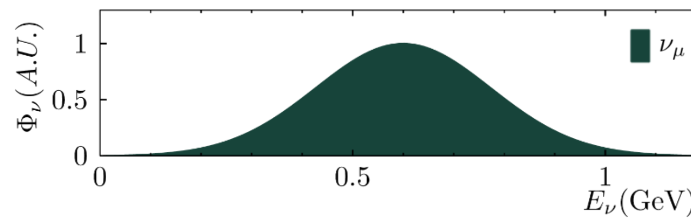
Neutrino oscillation experiments

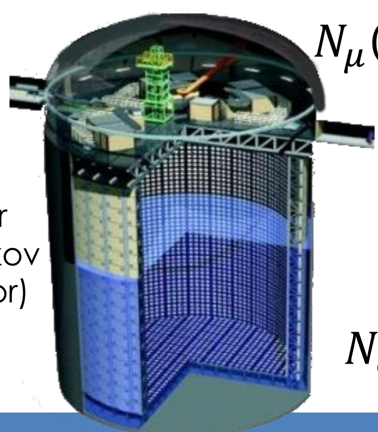








Far Detector
Super-Kamiokande



(Water Cherenkov Detector)

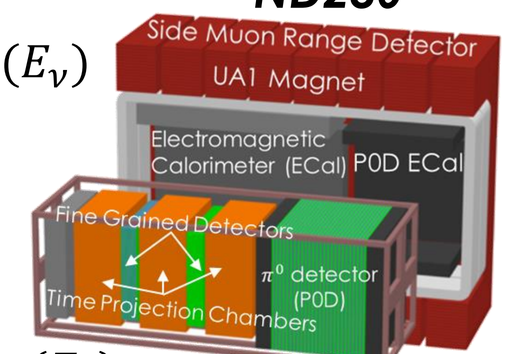
$$N_\mu(E_\nu) = P(\nu_\mu \to \nu_\mu)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Oscillation probability

PMNS Mixing
δ_{CP} θ_{13}
Δm^2_{32} θ_{23}

$$N_e(E_\nu) = P(\nu_\mu \to \nu_e)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Near Detector
ND280



(Mostly Hydrocarbon Scintillator)

ν oscillations need ν cross sections

$$N_\ell(E_\nu) = P\left(\nu_\mu \to \nu_\ell\right)(E_\nu)\, \sigma(E_\nu)\, \Phi_\nu(E_\nu)\, \epsilon(E_\nu)$$

$N_\ell(\mathrm{E}_\nu)$ = Event rate
$P(\nu_{\ell'} \to \nu_\ell)(E_\nu)$ = Oscillation probability
$\Phi_\nu(\mathrm{E}_\nu)$ = Neutrino flux
$\epsilon(E_\nu)$ = Detector efficiency
$\sigma_\ell(E_\nu)$ = Interaction cross section

- Need to know $\Phi \times \sigma$ in order to interpret N_ℓ as $P\left(\nu_\mu \to \nu_\ell\right)$

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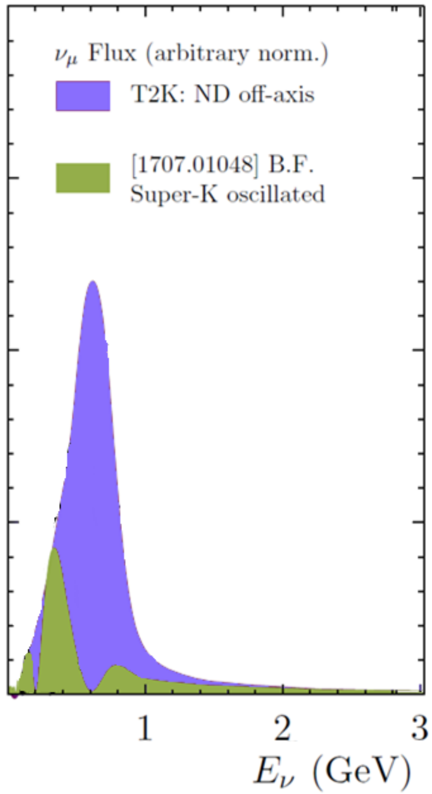
  - Dramatic change in E_ν distribution
  - ν_μ at ND vs ν_e at FD (for appearance)
  - Different ND/FD design, acceptance



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- Near / far ratios don't fully cancel this:
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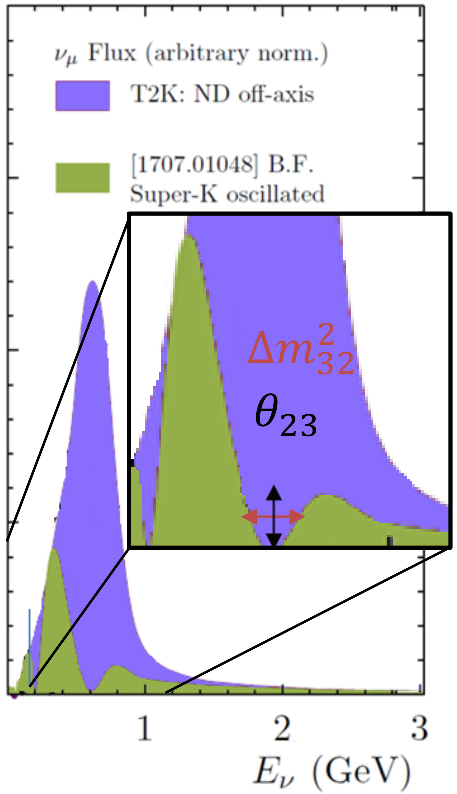
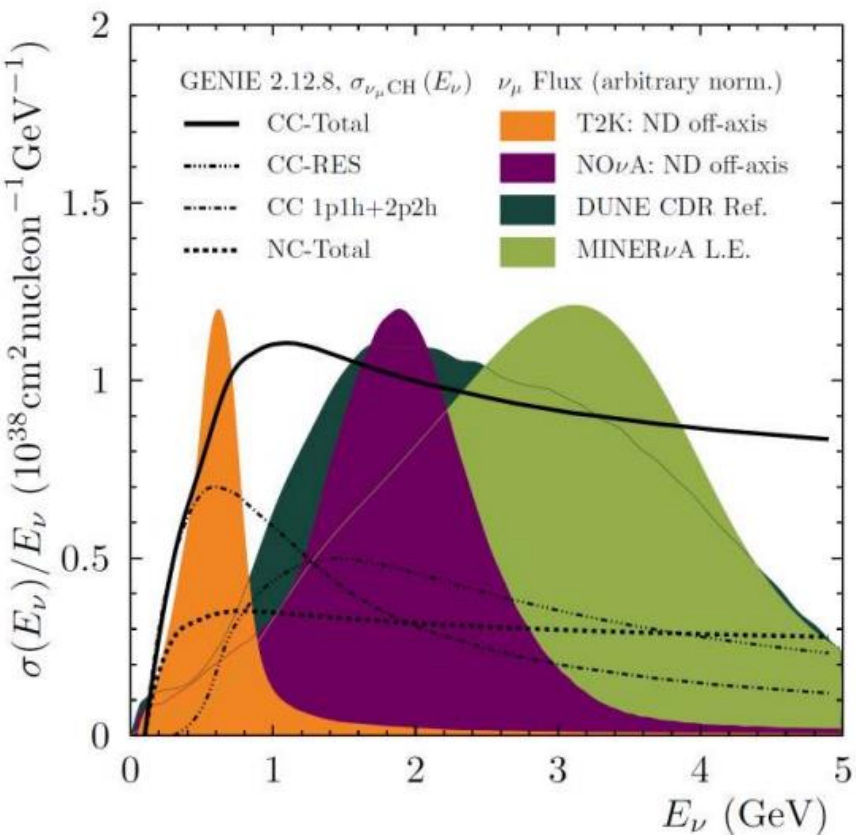
  - Different ND/FD design, acceptance
- Not just counting experiments: Require a model to relate E_ν^{reco} to E_ν^{true}

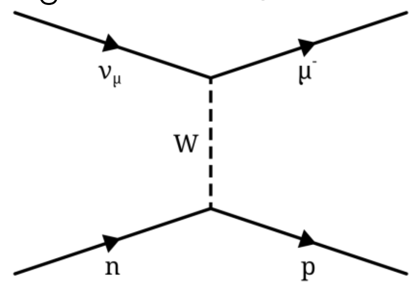


Neutrino interactions

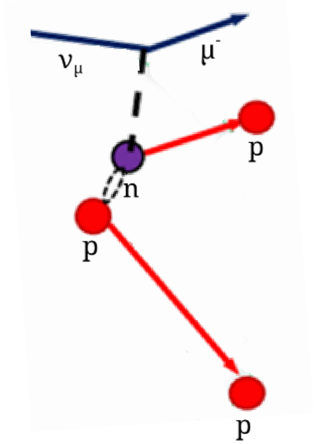


Key challenge: estimating E_ν

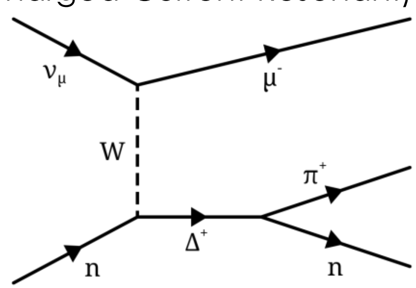
CCQE (1p1h)
(Charged-Current Quasi-Elastic)



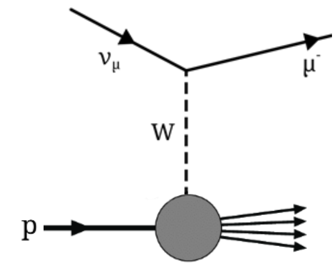
CC 2p2h
(2 particle, 2 hole)



CCRES
(Charged-Current Resonant)

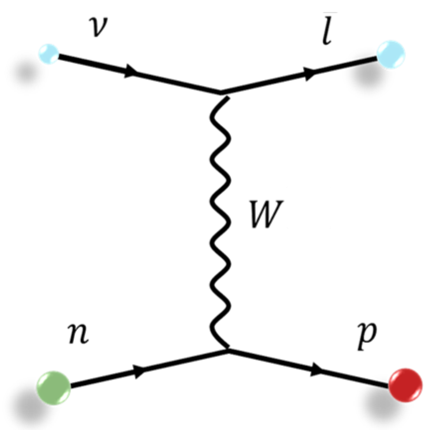


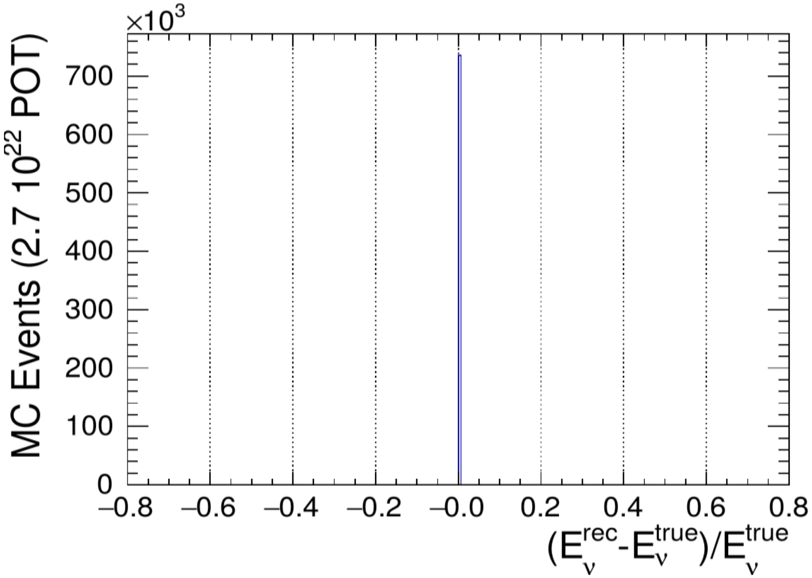
CCDIS
(Deep Inelastic Scattering)



Nuclear effects and E_ν (T2K/HK)

CCQE (1p1h)

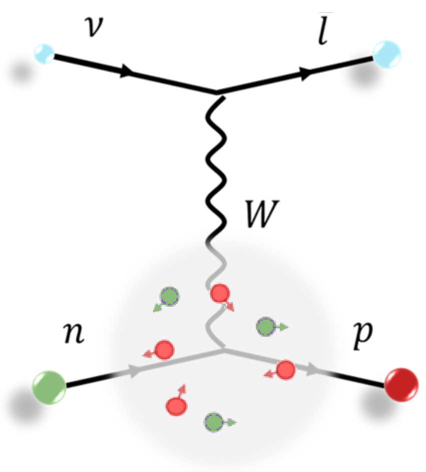


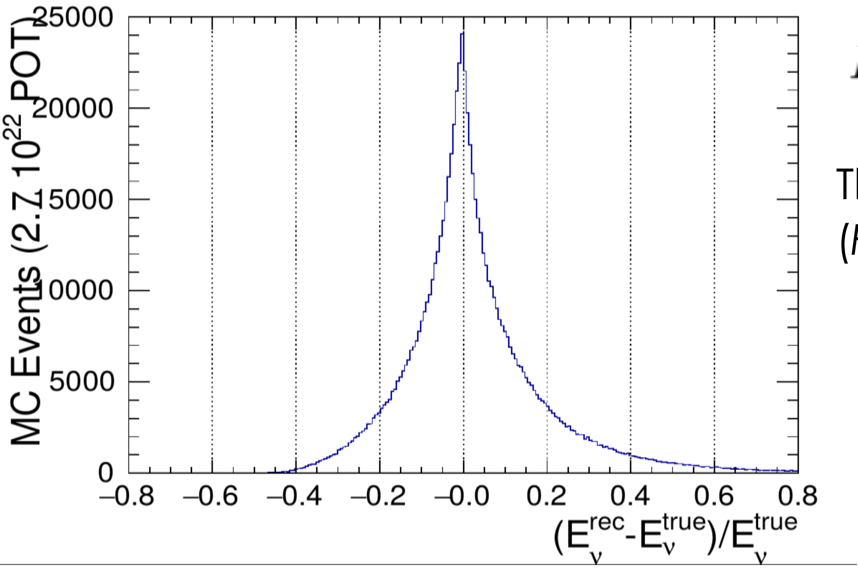


$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

Proxy for E_ν from lepton kinematics is perfect only for **CCQE elastic scattering** off a **stationary nucleon**

Nuclear effects and E_ν (T2K/HK)





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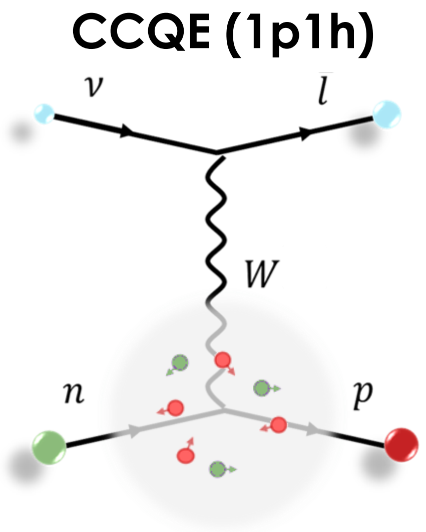
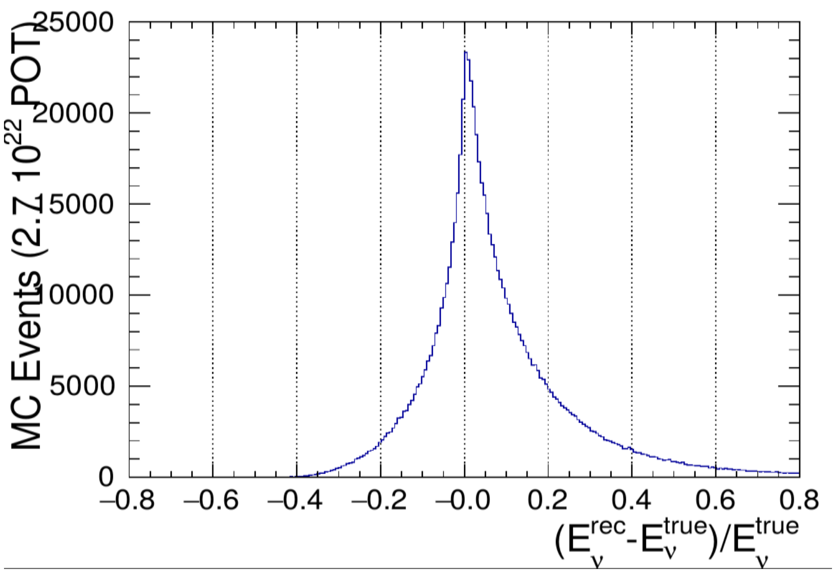
The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

Nuclear effects and E_ν (T2K/HK)





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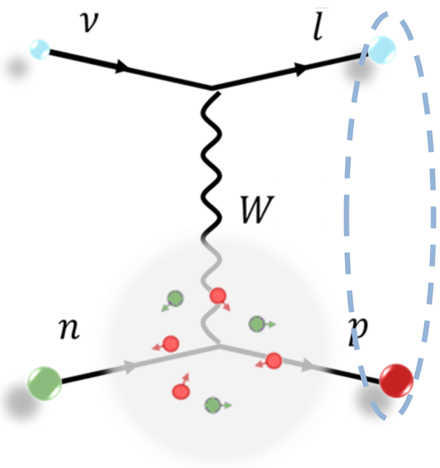
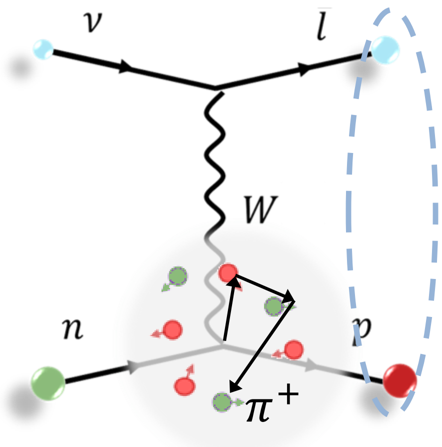
The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a **bias**

Nuclear effects and E_ν (T2K/HK)

CCQE (1p1h)

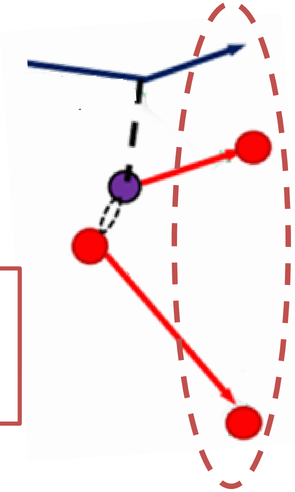


CCRES

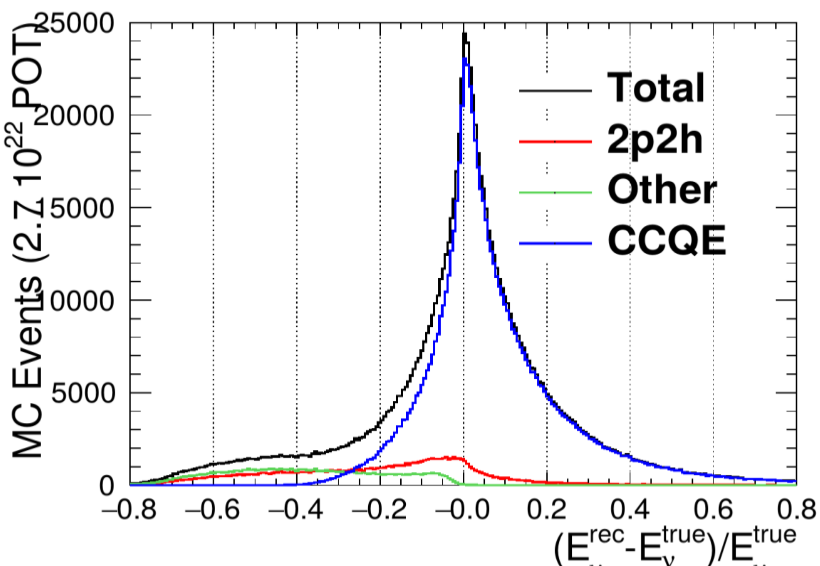


Final state interactions (FSI) can cause different interaction modes to have the same final state

2p2h



Interactions off a bound state of two nucleons can result in **2p2h** final states



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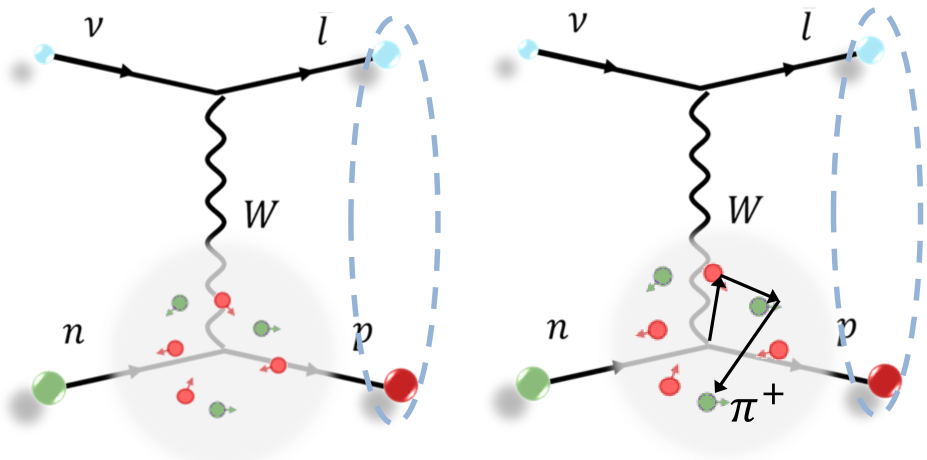
The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a **bias**

Not a good proxy for non-CCQE events: 2p2h and CC1π with pion abs. FSI

Nuclear effects and E_ν (T2K/HK)



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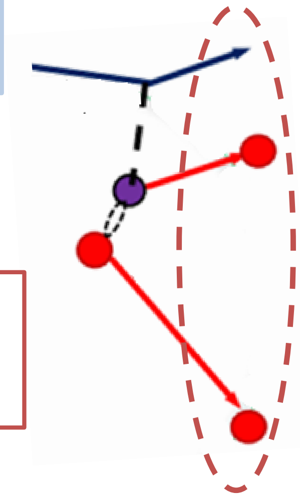
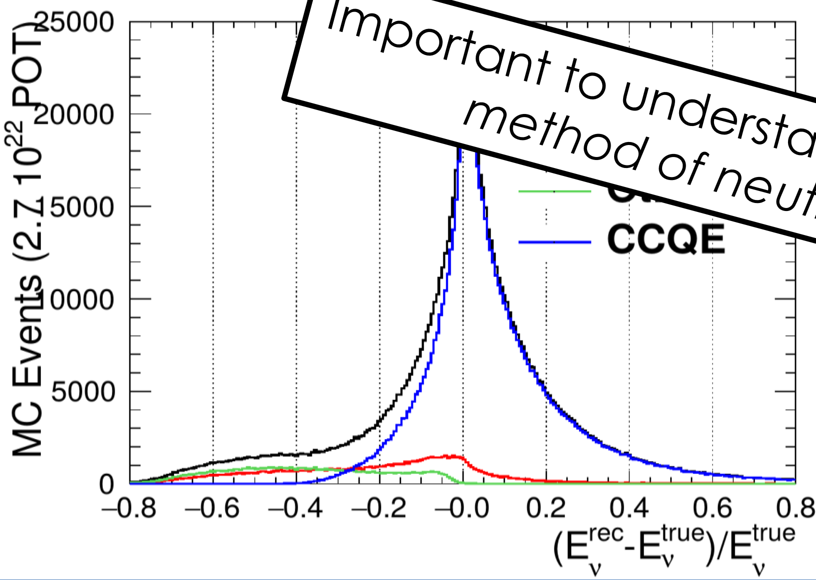


Interactions off a bound state of two nucleons can result in **2p2h** final states

Important to understand these "**nuclear effects**" for any method of neutrino energy reconstruction



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... f the nucleons inside the nucleus ... **smearing** on E_ν

The energy loss ... act the struck nucleon from its shell) intro... **ias**

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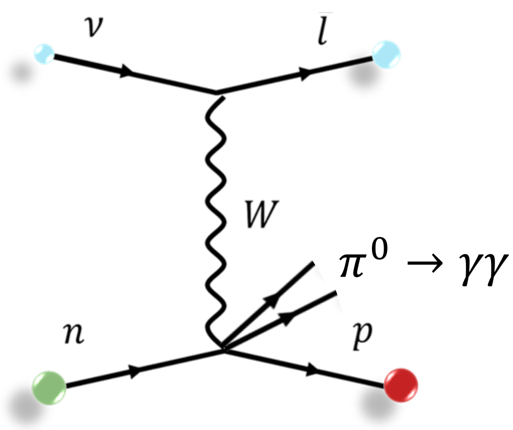
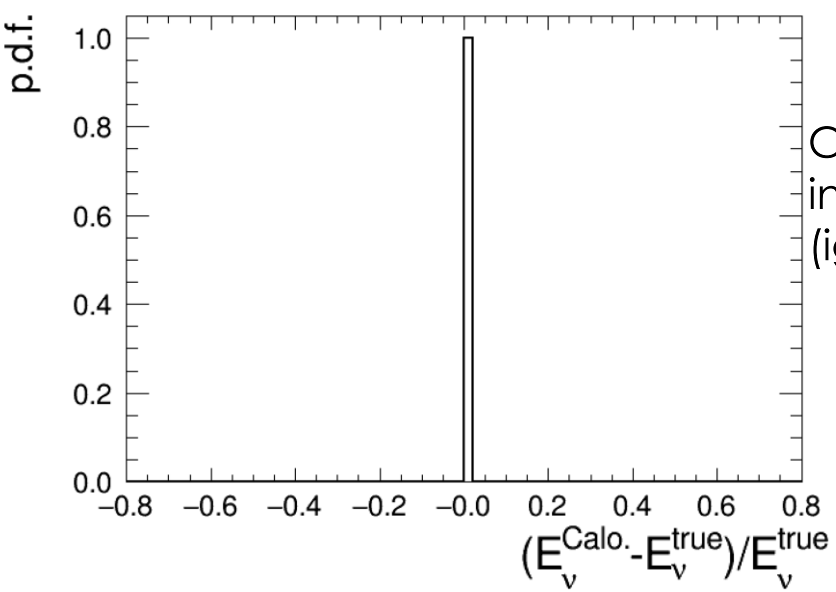
Nuclear effects and E_ν (SBN/DUNE/NOvA)



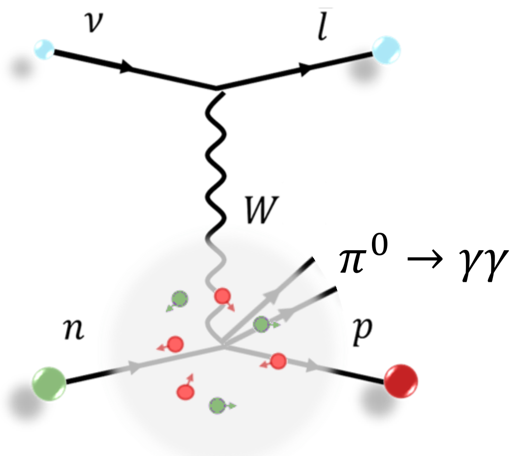


$$E_\nu^{calo} = E_\ell + E_{had.} = E_\ell + \Sigma T_p + \Sigma T_{\pi^\pm} + \Sigma E_\gamma$$

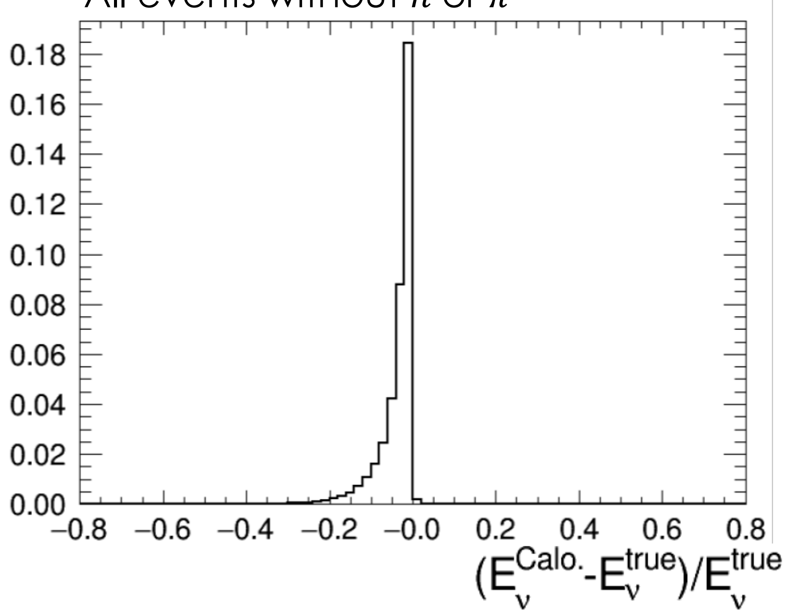
Calculation from calorimetry is perfect only for interactions **without neutrons and charged pions** (ignore heavier mesons here) off a **stationary nucleon**

Usefulness is not restricted to QE-like interactions (no final state pions)

Nuclear effects and E_ν (SBN/DUNE/NOvA)



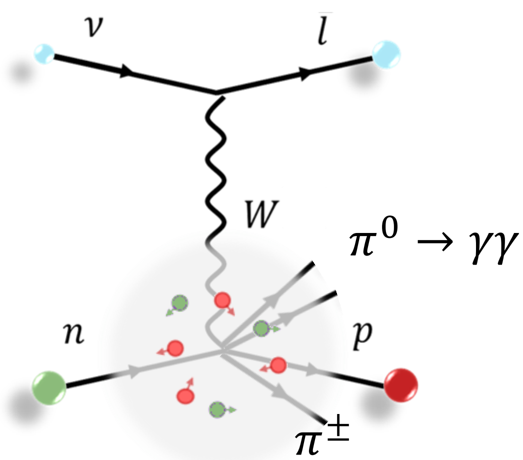
All events without n or $\pi^\pm$



$$E_\nu^{calo} = E_\ell + E_{had.} = E_\ell + \Sigma T_p + \Sigma T_{\pi^\pm} + \Sigma E_\gamma$$

Impact of initial state effects (Fermi motion and removal energy) smaller than in QE approach

Nuclear effects and E_ν (SBN/DUNE/NOvA)



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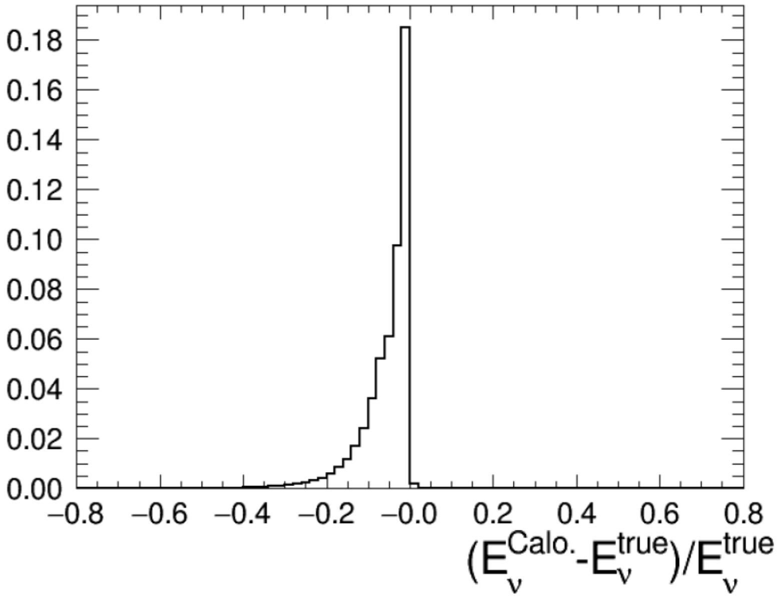

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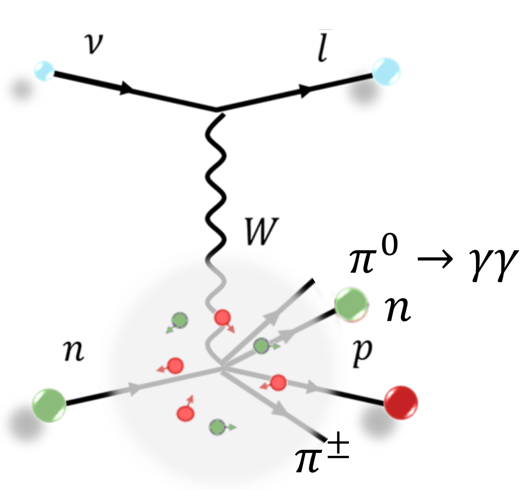
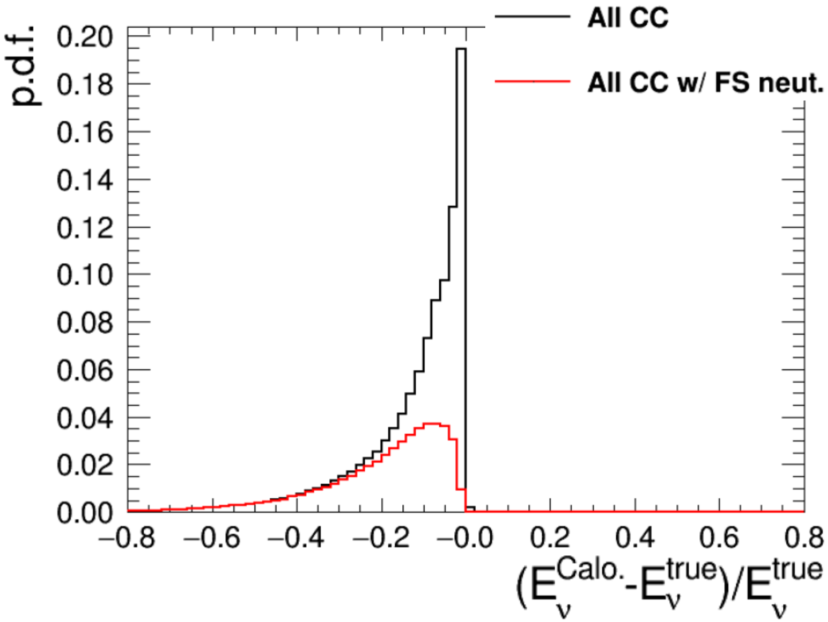
Impact of initial state effects (Fermi motion and removal energy) smaller than in QE approach

Charged pion masses also play a fairly small role

Nuclear effects and E_ν (SBN/DUNE/NOvA)





$$E_\nu^{calo} = E_\ell + E_{had.} = E_\ell + \Sigma T_p + \Sigma T_{\pi^\pm} + \Sigma E_\gamma$$

Impact of initial state effects (Fermi motion and removal energy) smaller than in QE approach

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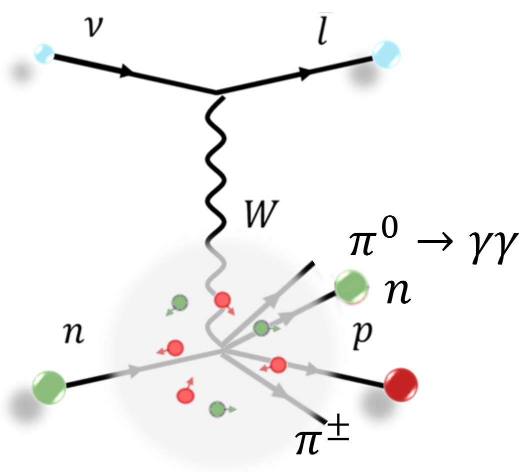
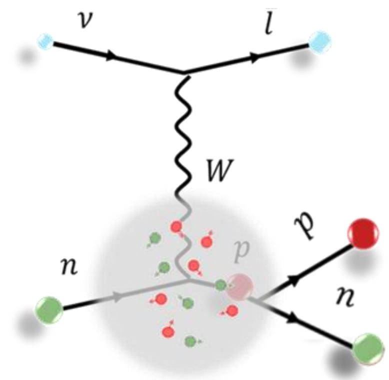
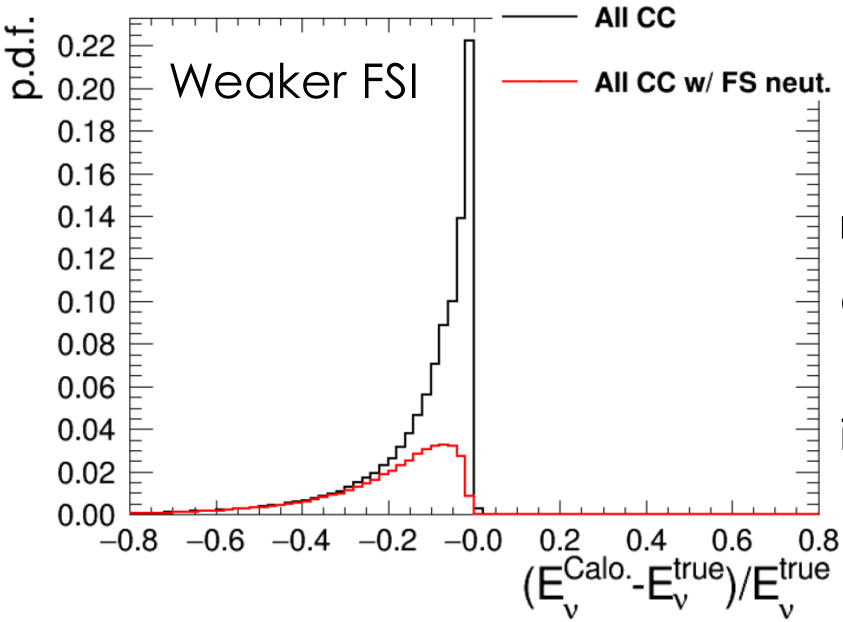


Final State Interactions (FSI)





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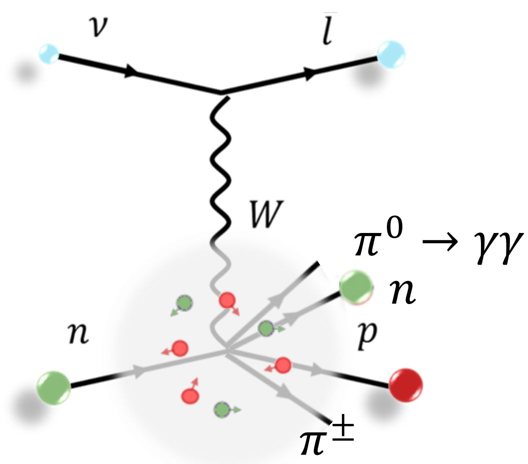
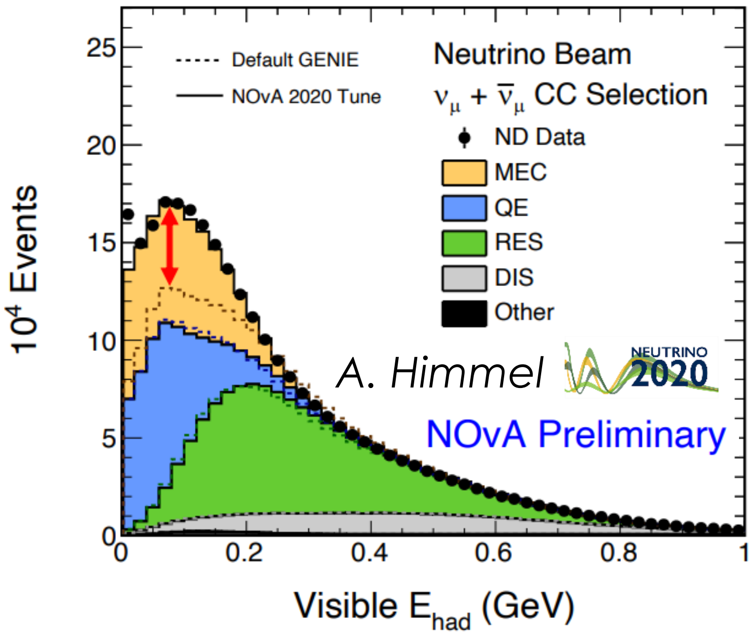
Nuclear effects and E_ν (SBN/DUNE/NOvA)





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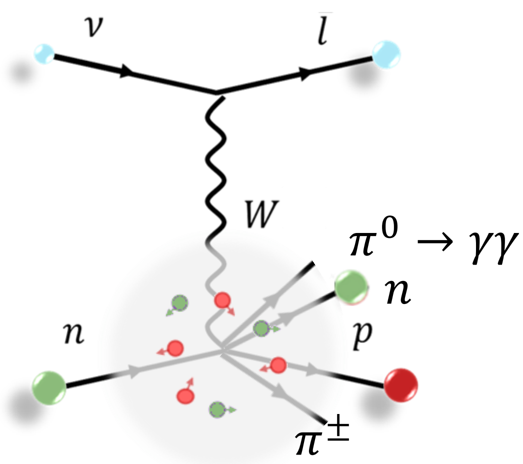

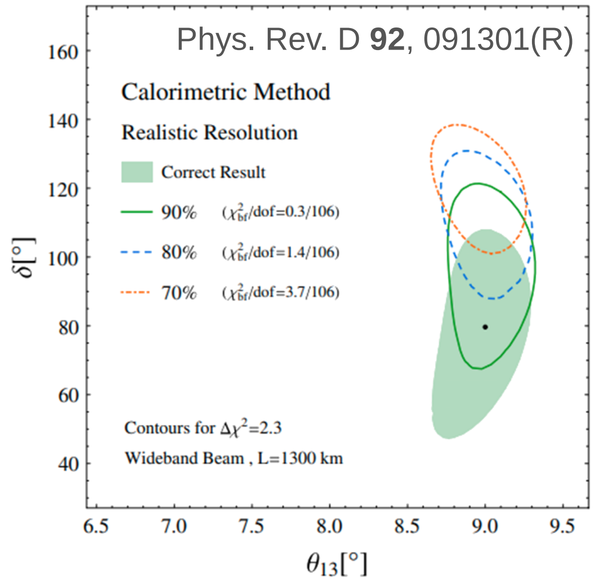

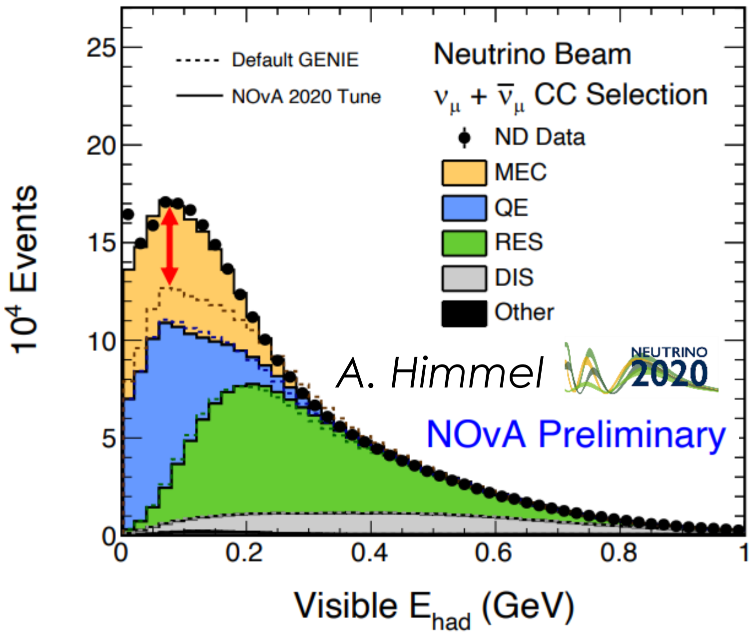

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What we need to know (a non exhaustive list!)

T2K/HK

("kinematic" E_ν proxy)

Critical

- Nuclear ground state: **Fermi motion** and "**binding energy**"
- **2p2h** and **pion absorption FSI** contributions to 0π final states

Important

- Impact of **nucleon FSI** on $\sigma(\nu_e)/\sigma(\nu_\mu)$ (see backups for details)
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SBN/DUNE/NOvA

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  - **FSI**
  - **2p2h**
  - DIS hadronisation

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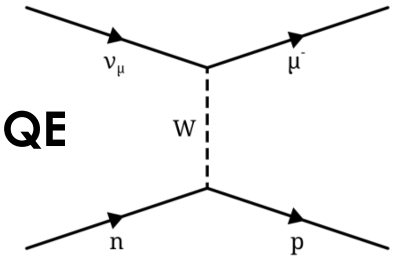
Neutrino interaction modelling is crucial all upcoming experiments, but different experiments have different priorities: **complimentary approaches**!


KEEP CALM
AND
MEASURE dσ/dx

What can we measure?

Interaction Modes

CCQE



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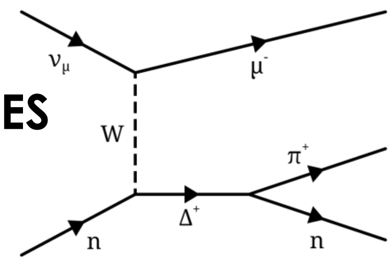
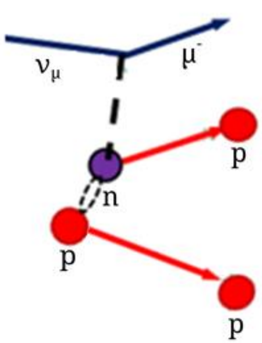
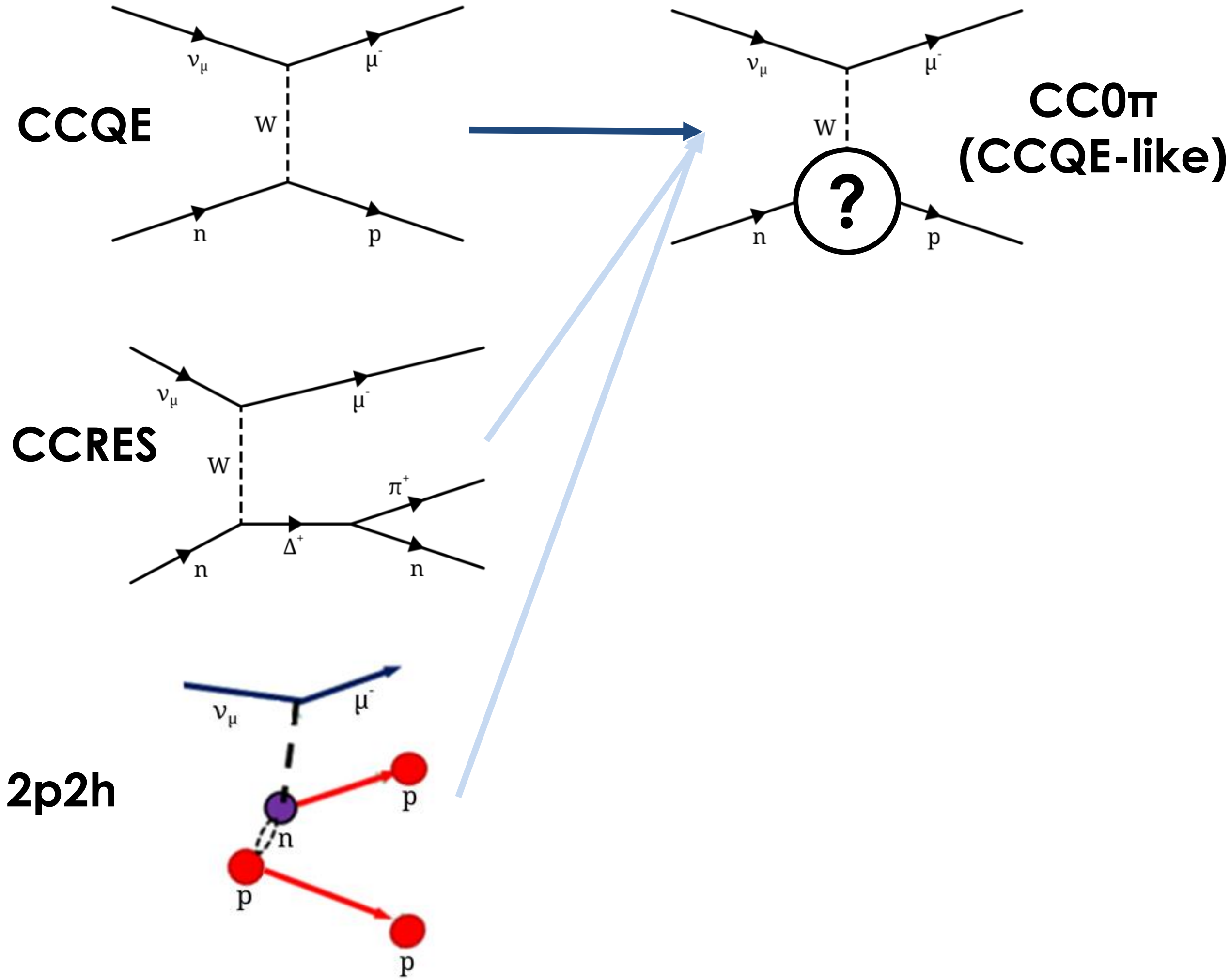


2p2h



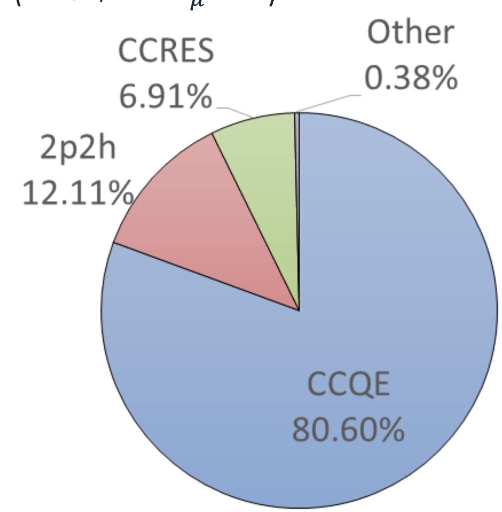
What can we measure?

Interaction Modes | **Interaction Topologies**



- We measure what our detector actually sees
- But this contains all sorts of physics …

Interaction modes in CC0π topology:
(NEUT, T2K ν_μ flux)



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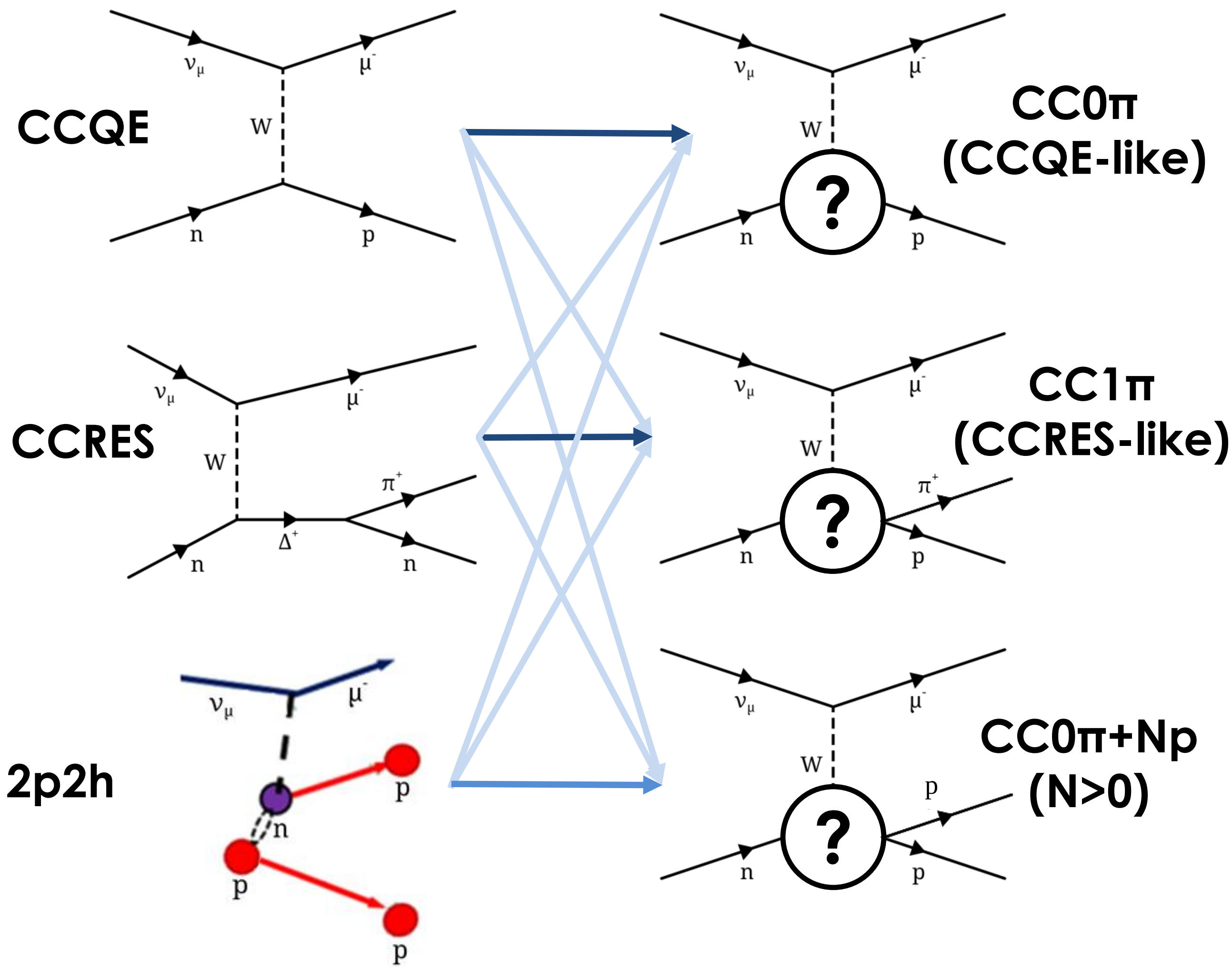

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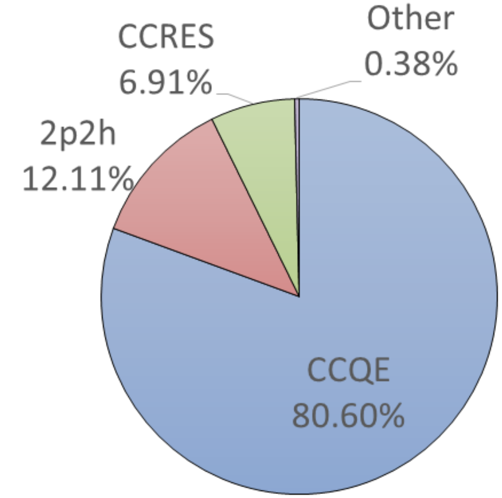
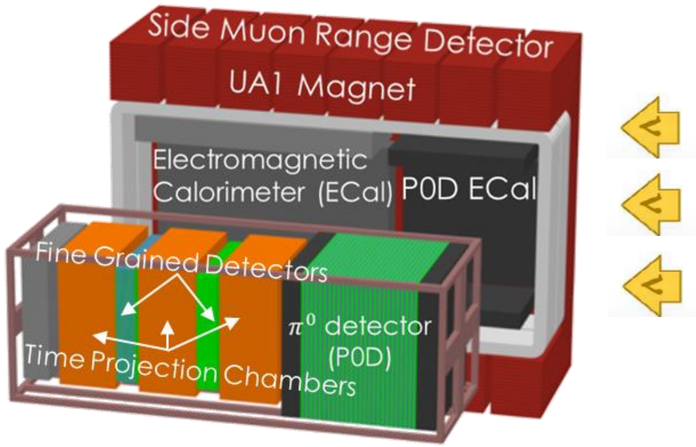


ND280 and MINERvA

ND280 (Near detector for T2K)



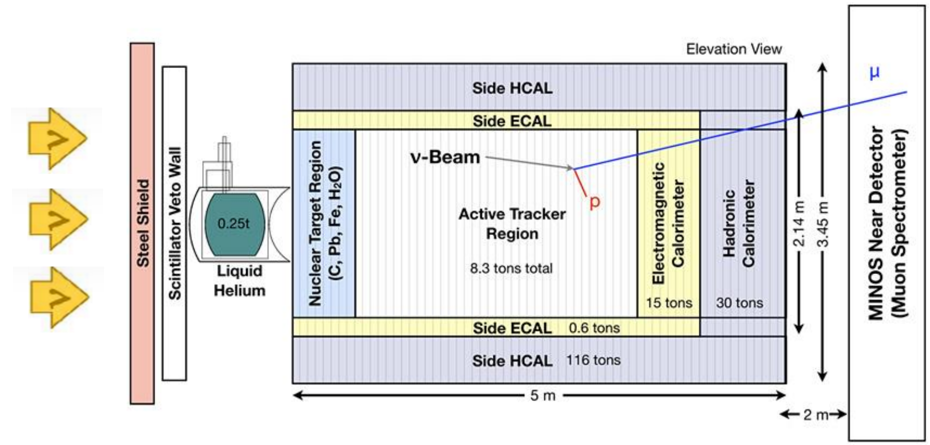
Primary targets: CH, H_2O

On Axis ~ 1.1 GeV

Peak E_ν

Off Axis ~ 0.6 GeV

MINERvA



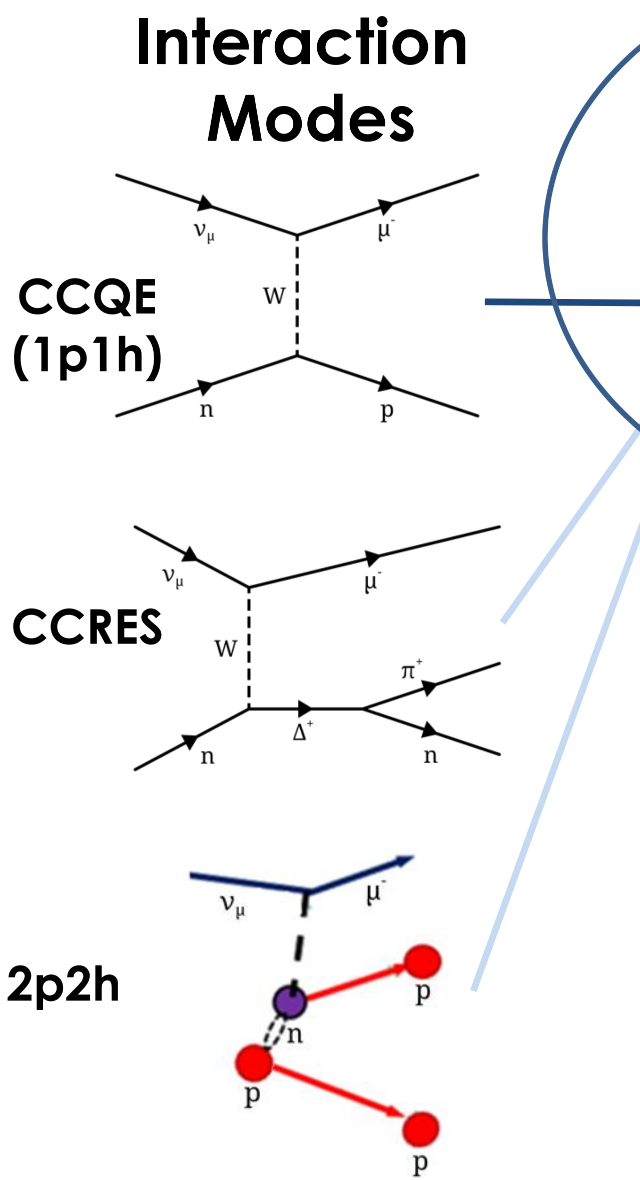
Primary targets: CH, Pb, Fe

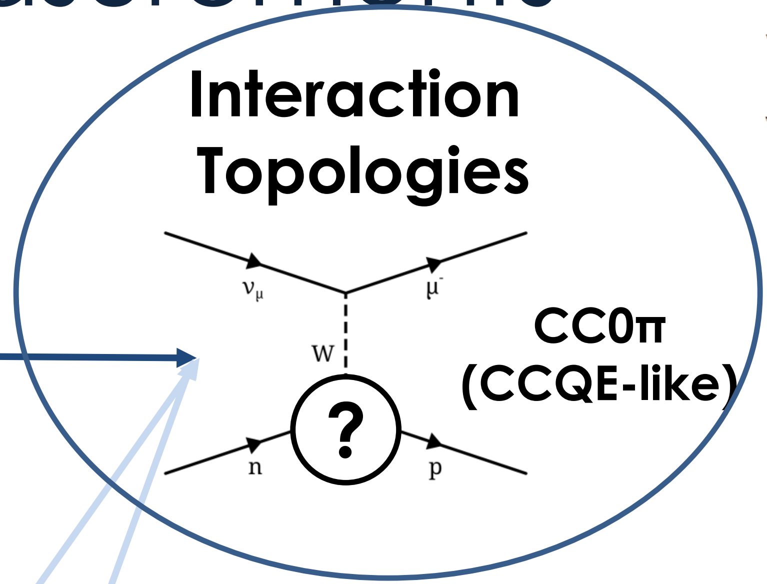
ME~ 5.8 GeV

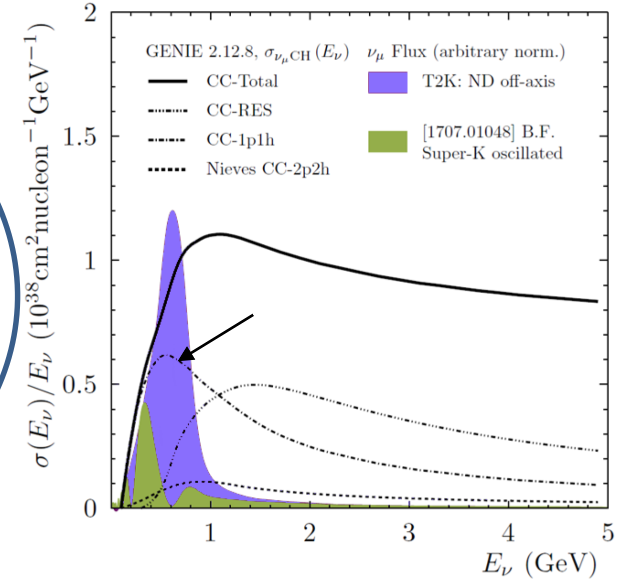
Peak E_ν

LE ~ 3.2 GeV

CC0π measurements



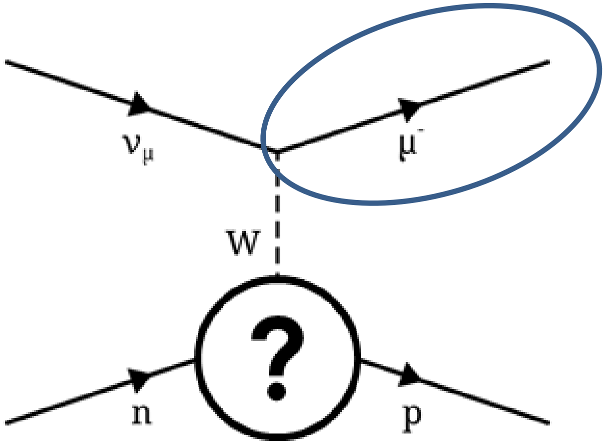




- The thing we know “best”
- Dominant community focus for ~10 years
- Signal process for T2K/HK

Which observables?

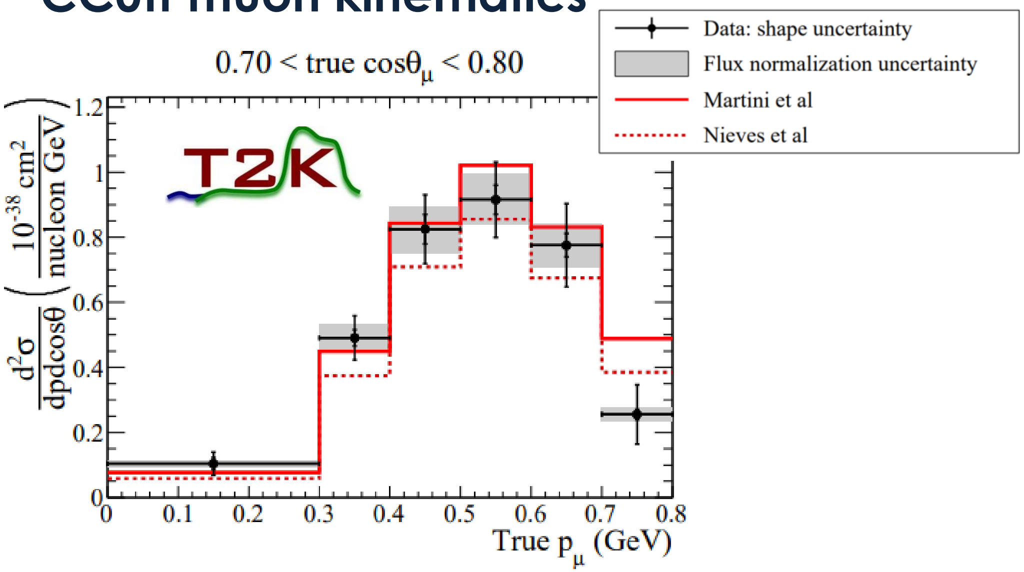
Just the muon?

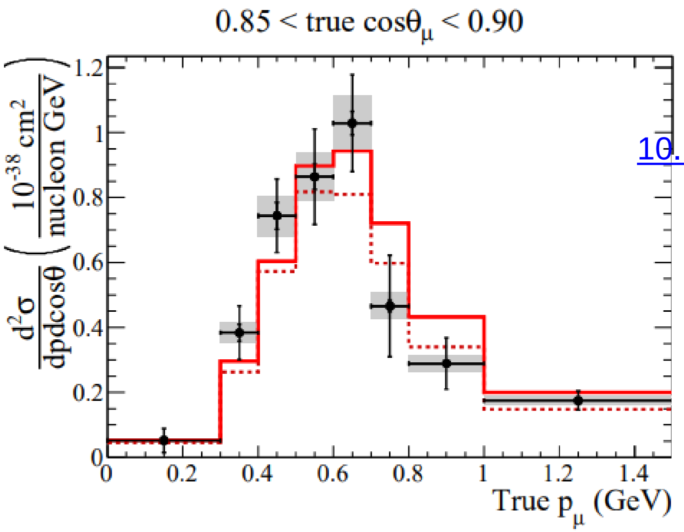


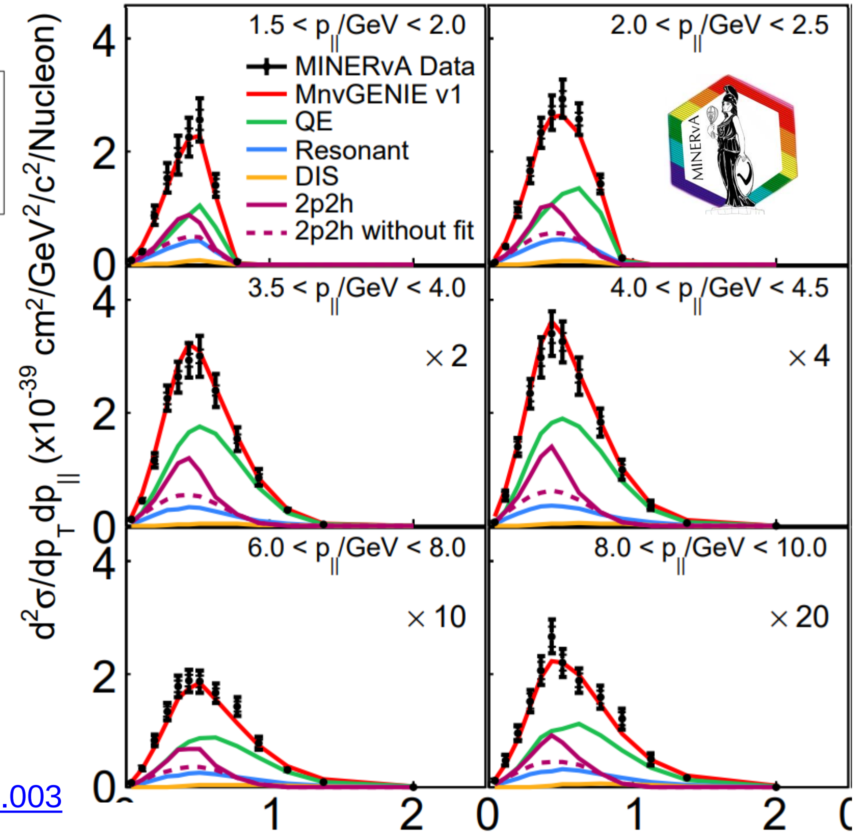
Our current models vs data

Phys. Rev. D **99**, 012004

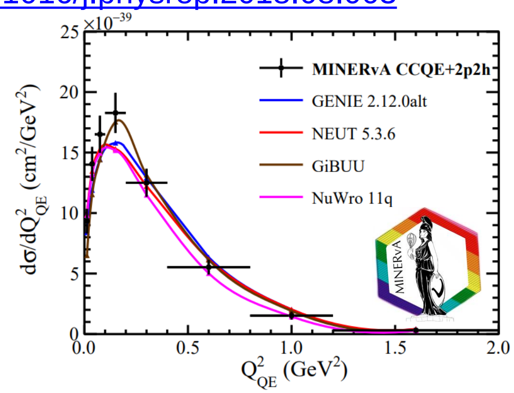
CC0π muon kinematics







10.1016/j.physrep.2018.08.003



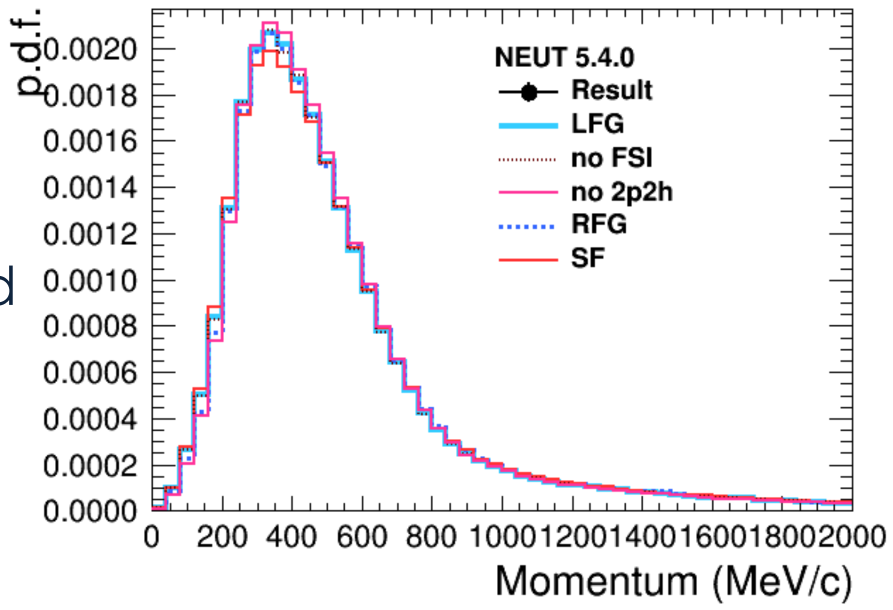
Agreement is generally reasonable. Some significant problems at high or very forward angles

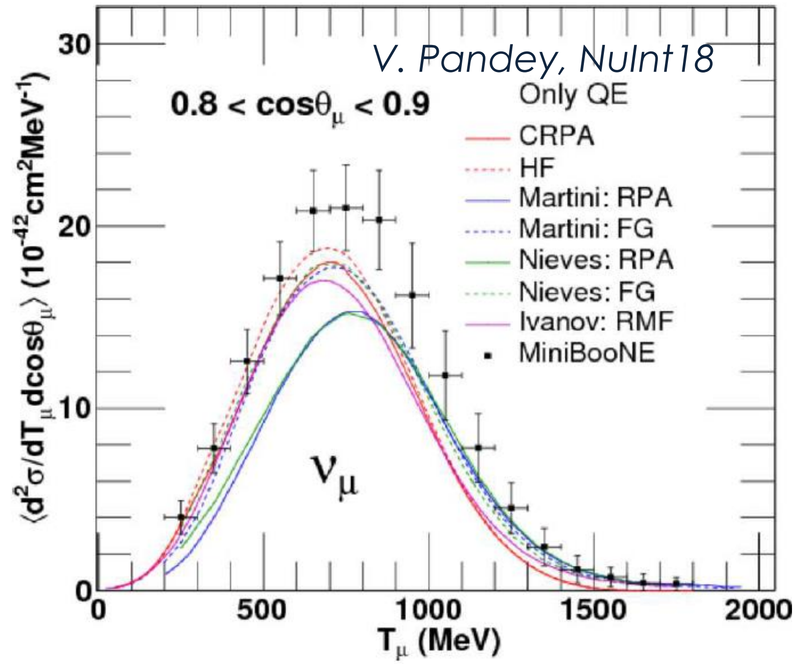
What to measure?

Muon kinematics?

✓ Muon kinematics can be predicted directly from most theories

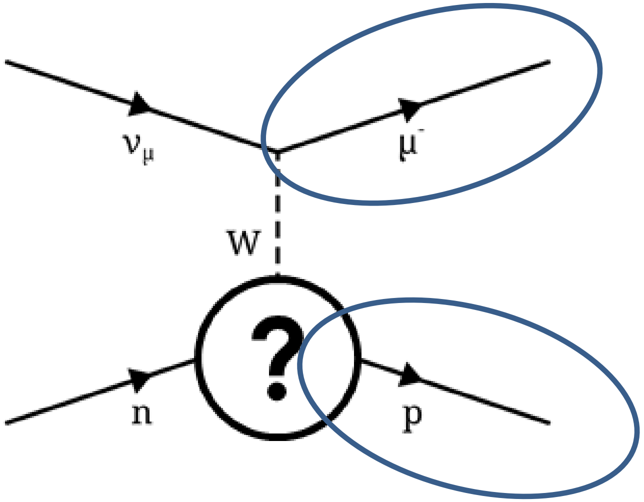
X But very different theories can predict very similar things in muon kinematics





Which observables?

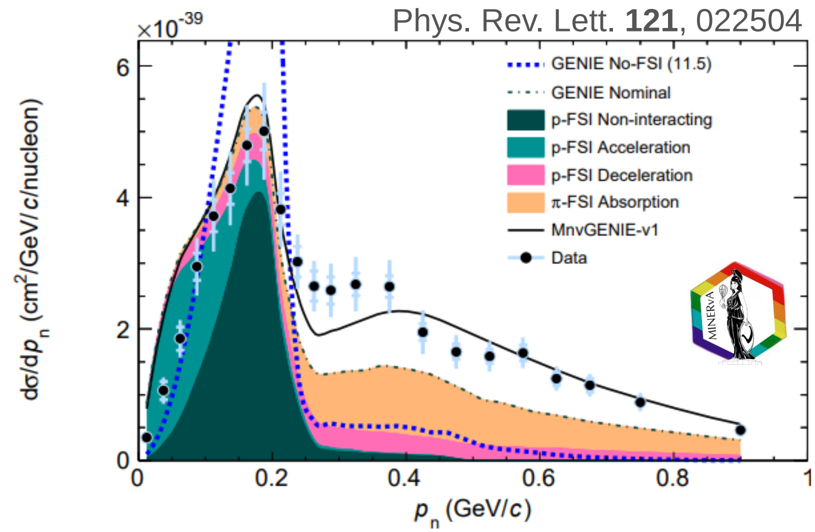
Lepton and proton?

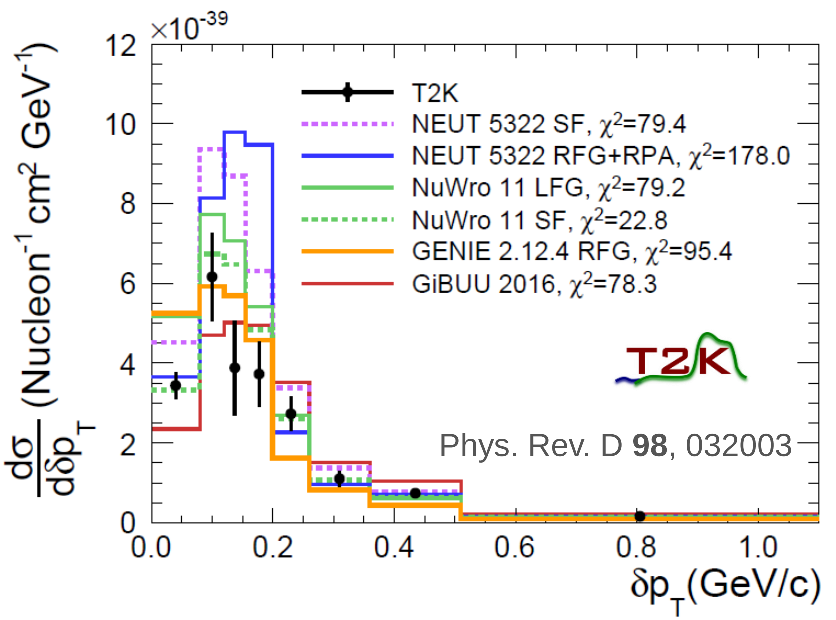


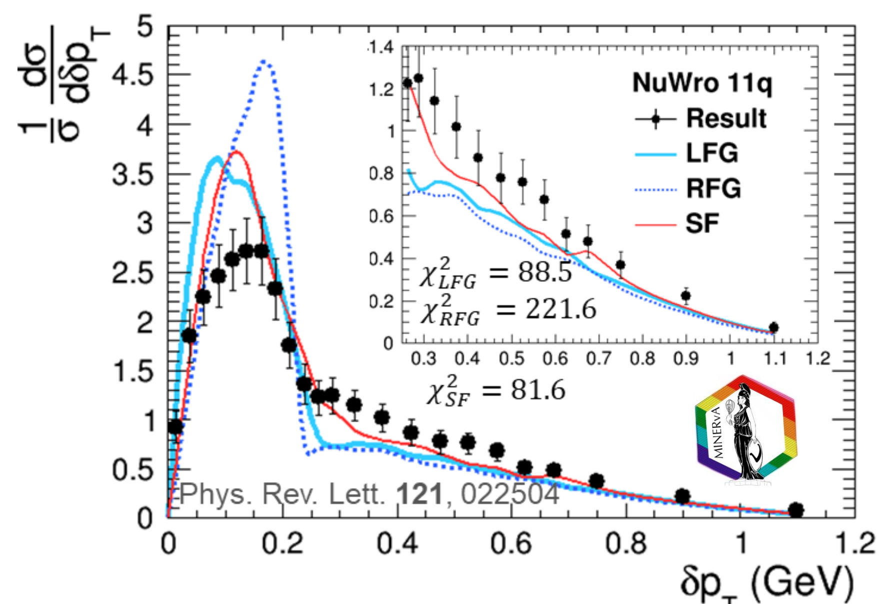
Correlations between the muon and proton kinematics allow us to disentangle nuclear effects from neutrino energy

Our current generators vs data

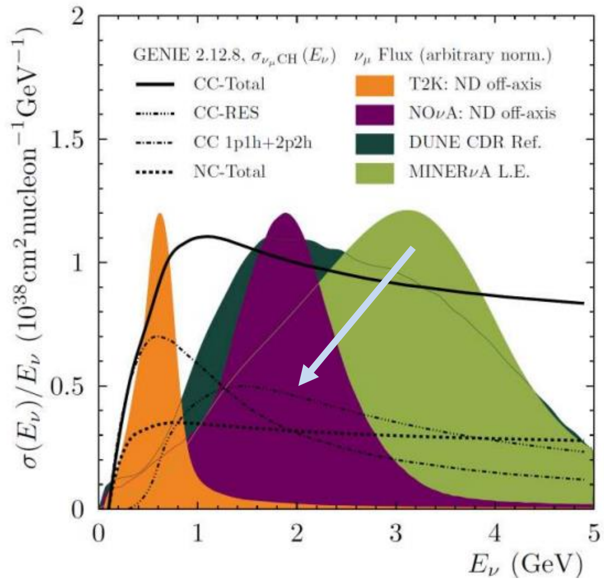
- Measure the missing transverse momentum: δp_T (details in backups)
- Sensitive to the nuclear effects most important for T2K/HK
- No model that can be compared to the data can fully describe it





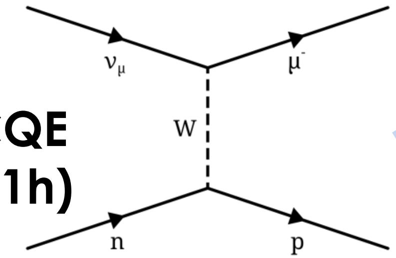


What can we measure



Interaction Modes

CCQE (1p1h)



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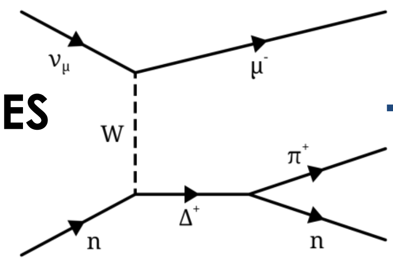
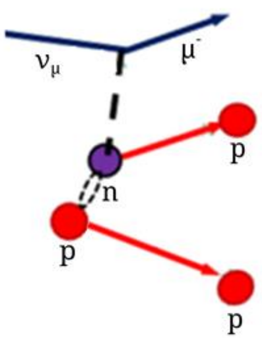
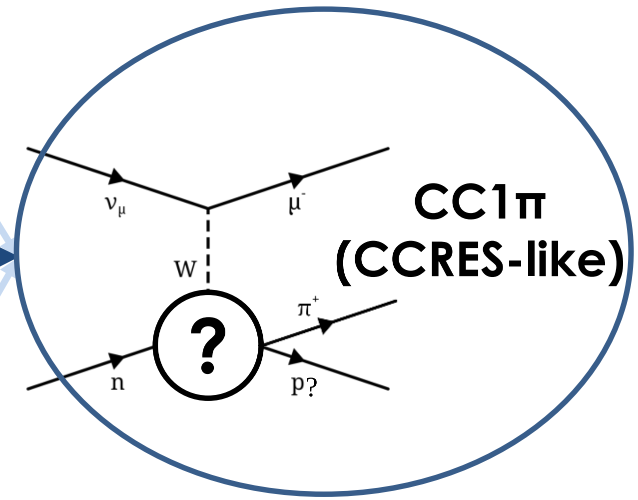


2p2h



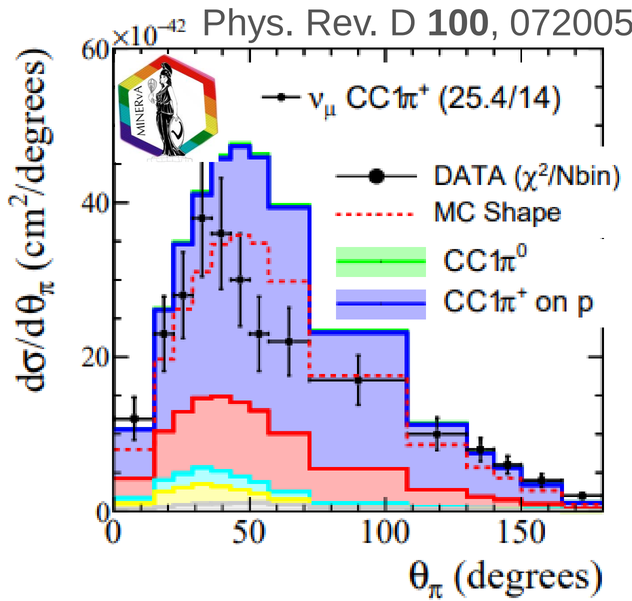
Interaction Topologies

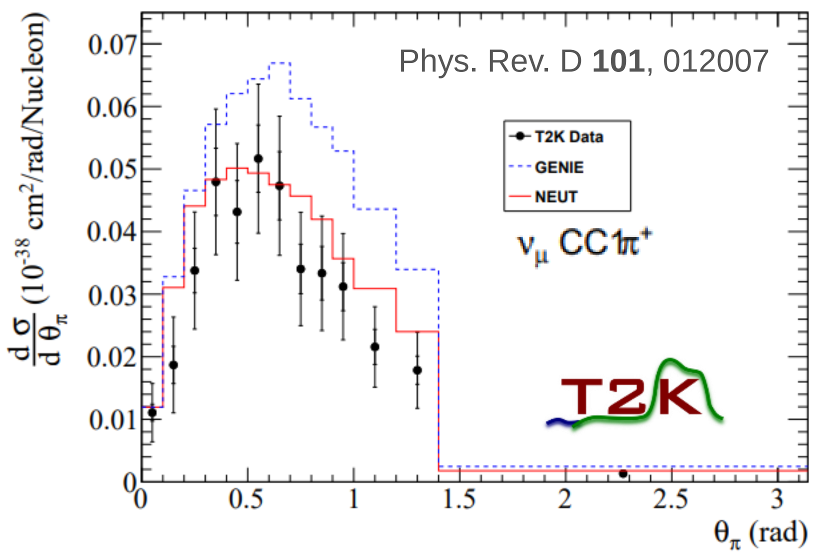


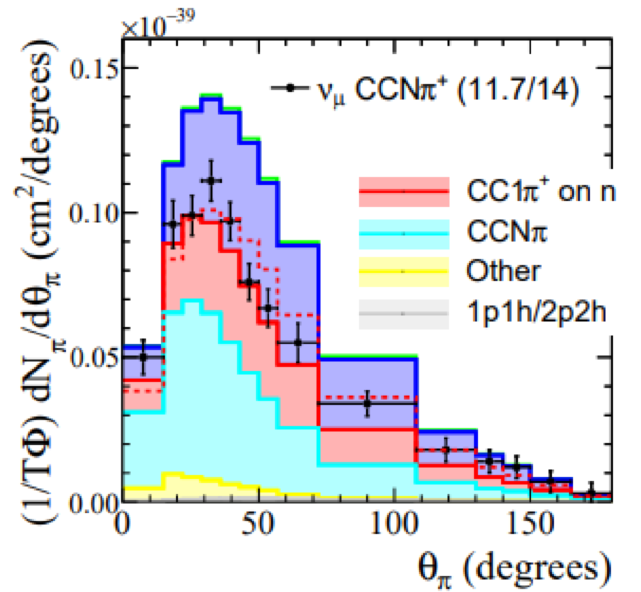
- Key contributor to all experiments

Our current generators vs data

- Models generally able to predict lepton kinematics reasonably well
- But pion kinematics are poorly described across experiments







Let's Recap

- ✓ T2K, MINERvA and others have made a wide range of innovative cross-section measurements aimed to target the physics most pertinent to future oscillation analyses

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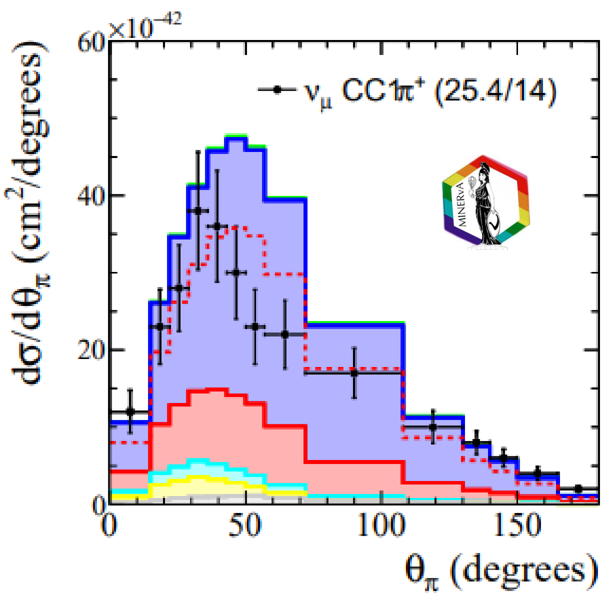
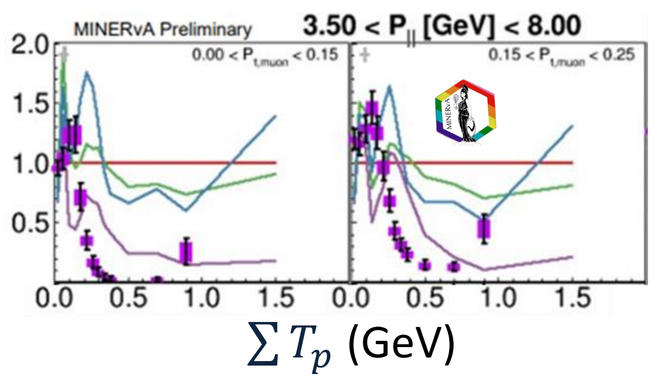
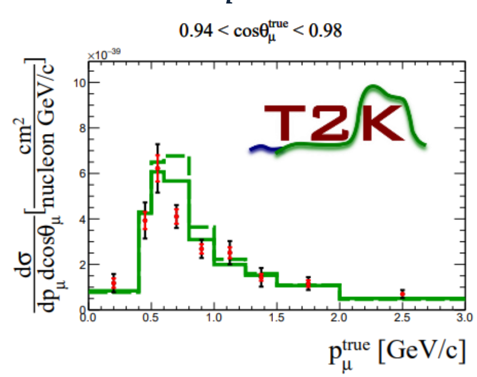
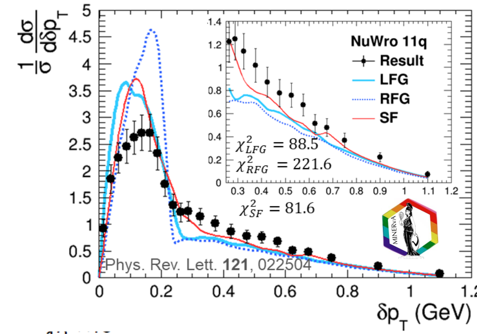
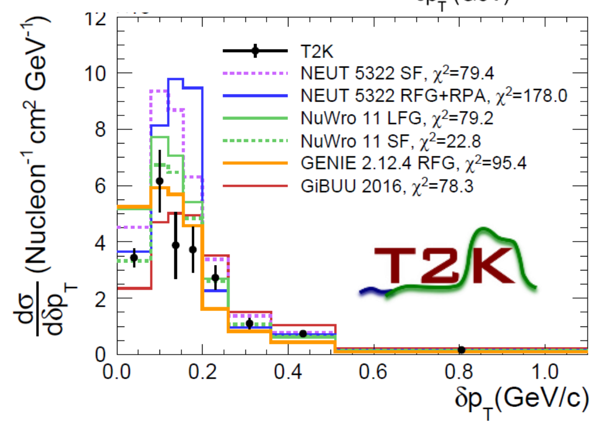
X Our current simulations are unable to really describe more than the lepton kinematics …







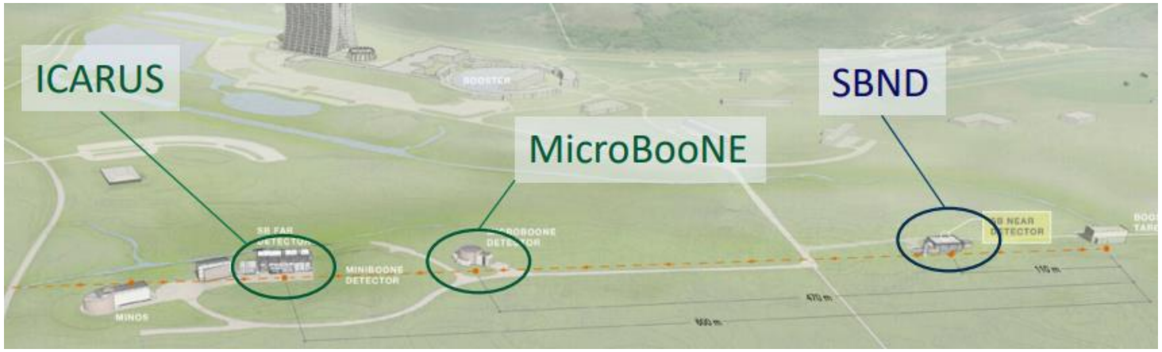





DON'T
PANIC

New experiments, new data

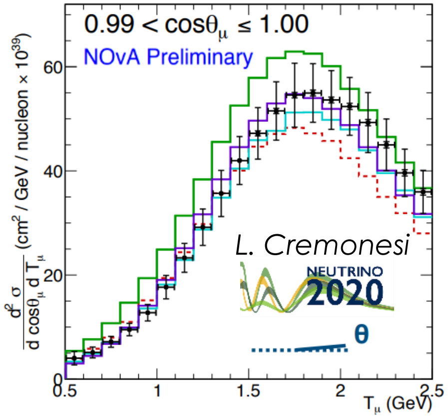
Short Baseline Program: Fermilab liquid Argon detectors in "Booster" beam (~0.8 GeV)



- **MicroBooNE** (already producing interesting results)
- **ICARUS** (first beam has just arrived)
- **SBND** (enormous event rates, neutrino data coming soon)

NOvA ND Cross Sections

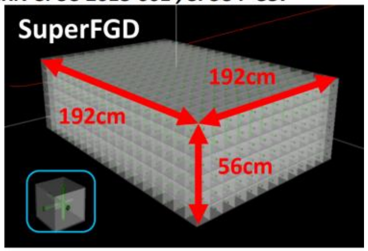
- High data rate, flux is peaked in an interesting region
- Many exciting results to come!



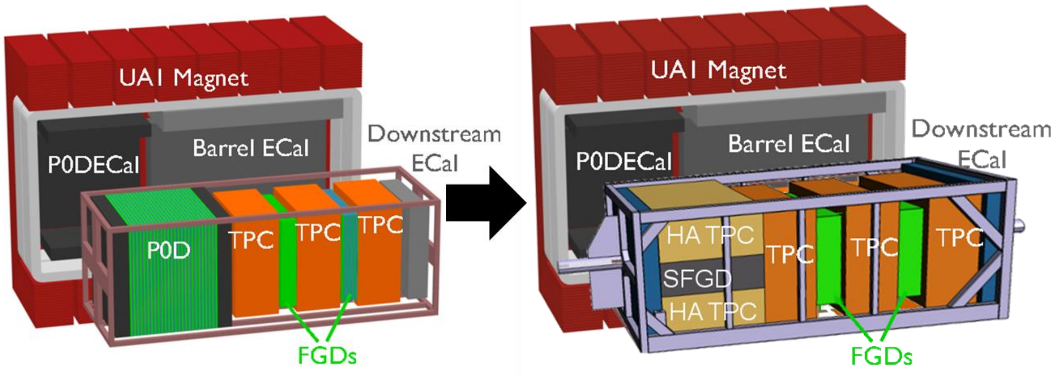
ND280 Upgrade

T2K

CERN-SPSC-2018-001 ; SPSC-P-357



- New "SuperFGD": made of 3 readout plane 1cm³ cubes
- Surrounding new TPCs



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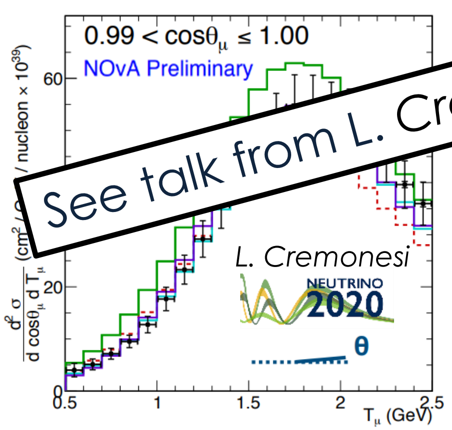

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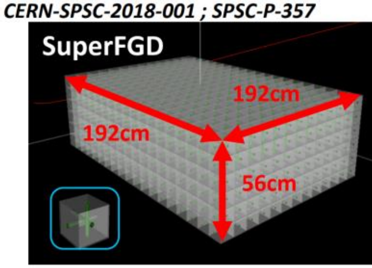

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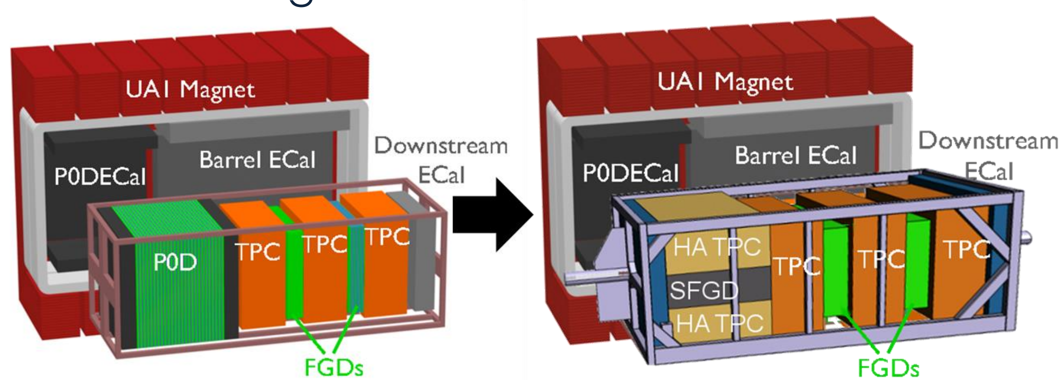
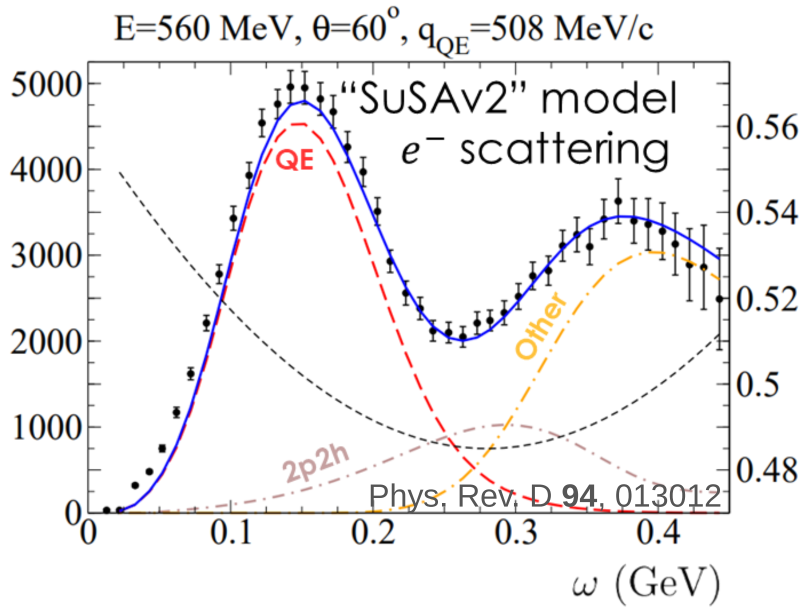
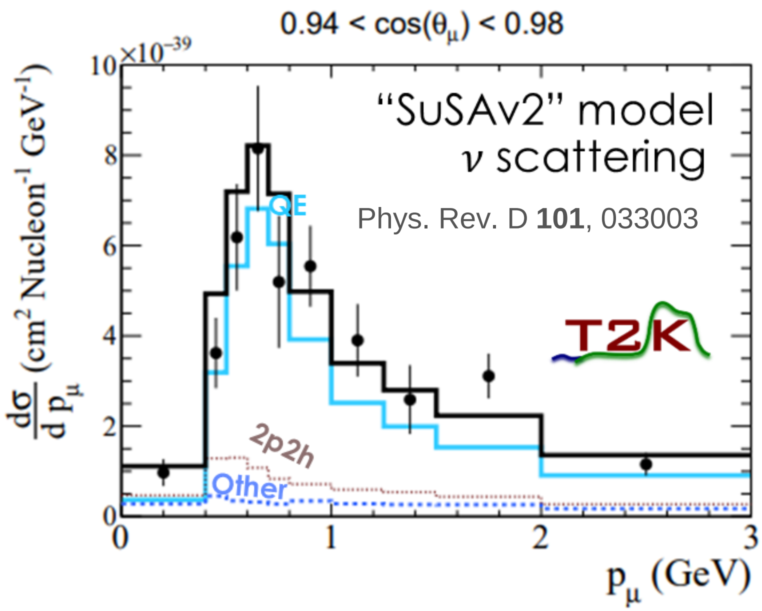


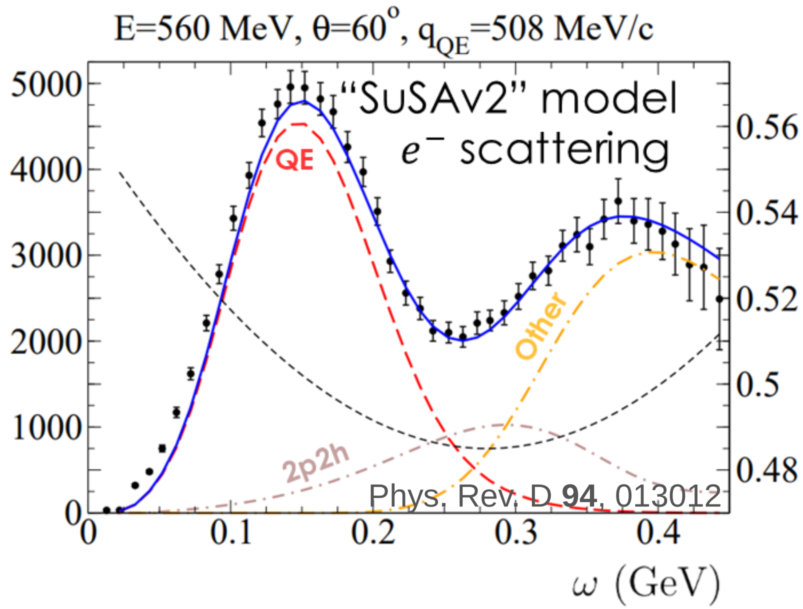
New models, new constraints

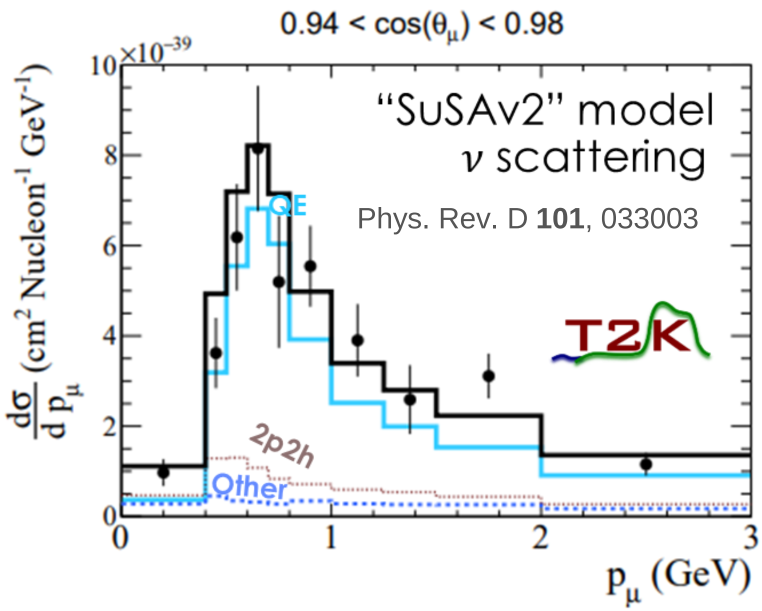




- New models, successful in describing electron scattering data, are now being implemented in neutrino interaction simulations
- Such models that describe e^- and ν interactions in the same framework can be directly constrained by precision e^- data
- New theoretical efforts are allowing models to be much more predictive

New models, new constraints





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  - **See talk from K. Niewczas for examples with π production**

- Such models that describe e^- and ν interactions in the same framework can be directly constrained by precision e^- data
  - **See talks from A. Ashkenazi and A. Ankowski**

- New theoretical efforts are allowing models to be much more predictive
  - **See talks from J. Sobczyk and A. Lovato**

Summary

- To avoid future oscillation analyses becoming **pre-maturely limited by systematic uncertainties**, *it is essential to better understand neutrino-nucleus interactions*
- The key physics can only be effectively understood by **measuring lepton and hadron information**
- Experiments are making a variety of neutrino interaction measurements targeting the sources of these uncertainties
- Comparisons of measurements to event generators show they still need a lot of work. **Theoretical input will be essential.**
- **Future measurements of** neutrino interactions and **continued collaboration with the nuclear theory community** are critical

Backups

A way out?

Input from and collaboration between experimentalists and theorists is fundamental to overcoming these challenges

- Experiments have outstripped the over simplified models in generators.

NuInt 18 Experimental summary talk – K. McFarland

With every topic we find that the challenges can be met only with the active support and collaboration among specialists in strong interactions and electroweak physics that include theorists and experimentalists from both the nuclear and high energy physics communities.

NuSTEC White Paper (Prog.Part.Nucl.Phys. 100 (2018) 1-68)

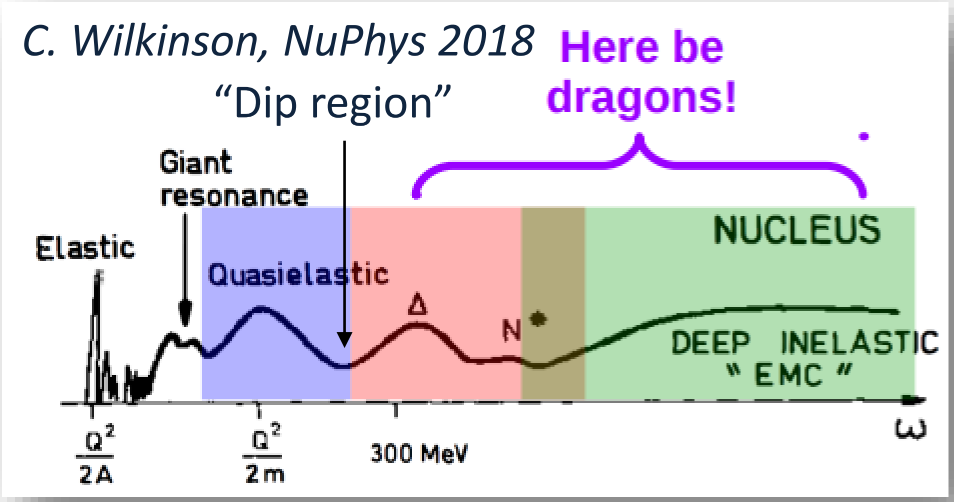
- Apart from rigorous work, inspiration (and whining abilities ☺) (especially young) theorists need institutional support!

NuInt 18 Theoretical summary talk – V. Pandey

NEUTRINO 2018 cross-section talk - U. Mosel

- Precision era of neutrino physics requires more sophisticated generators and a dedicated joint effort in nuclear theory and generator development
- This joint effort has to be funded as integral part of experiments

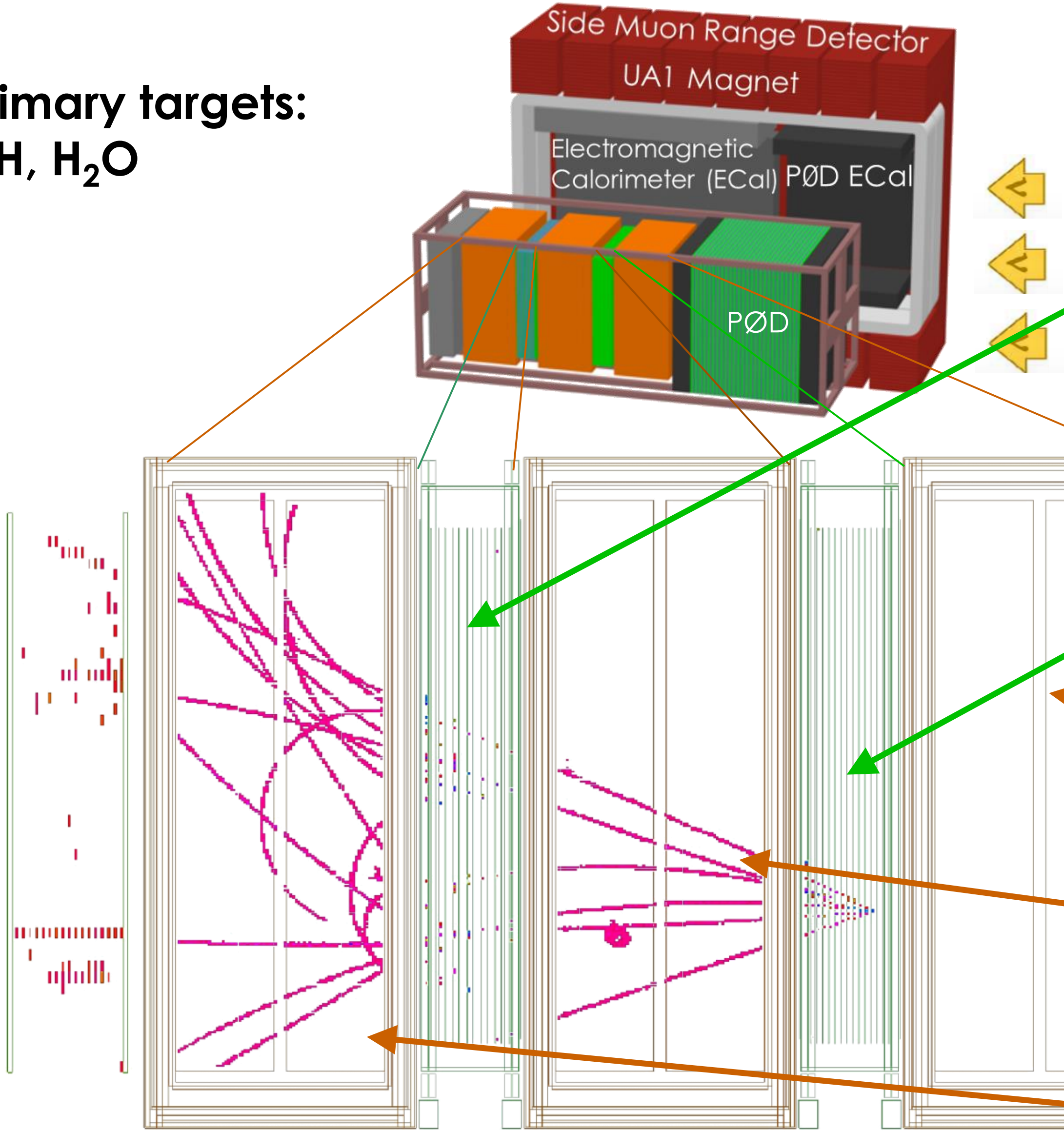
Pion production



- Pion productions spans many different theory models
  - Coherent, Resonant, Deep Inelastic Scattering
- High multiplicity = hard to characterise experimentally
- Region beyond at higher energy transfer is very challenging (dragons!)

ND280 (T2K Near Detector)

Primary targets:
CH, H_2O



Peak E_ν
On Axis ~ 1.1 GeV
Off Axis ~ 0.6 GeV

Fine-Grained Detectors (FGD 1 & 2):

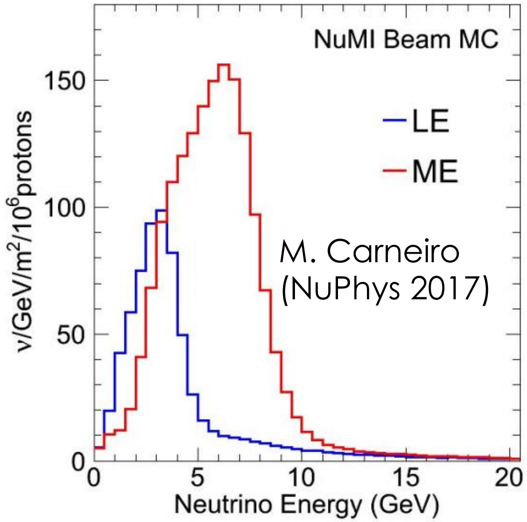
- CH scintillator tracker
- Target for ν
- FGD2 contains water

Time Projection Chambers (TPC):

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

MINERvA

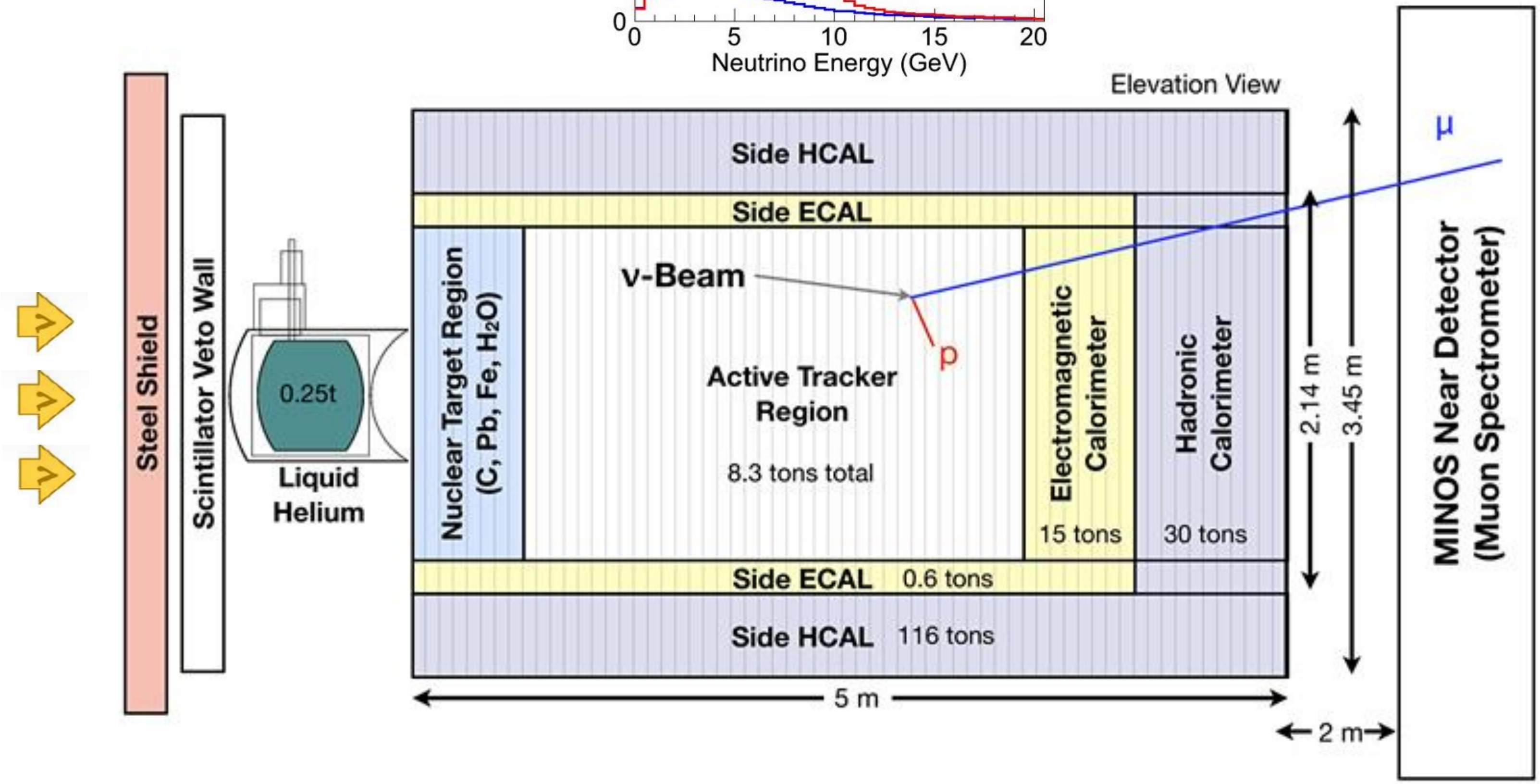
Primary targets:
CH, Pb, Fe



Peak E_ν

ME~ 5.8 GeV

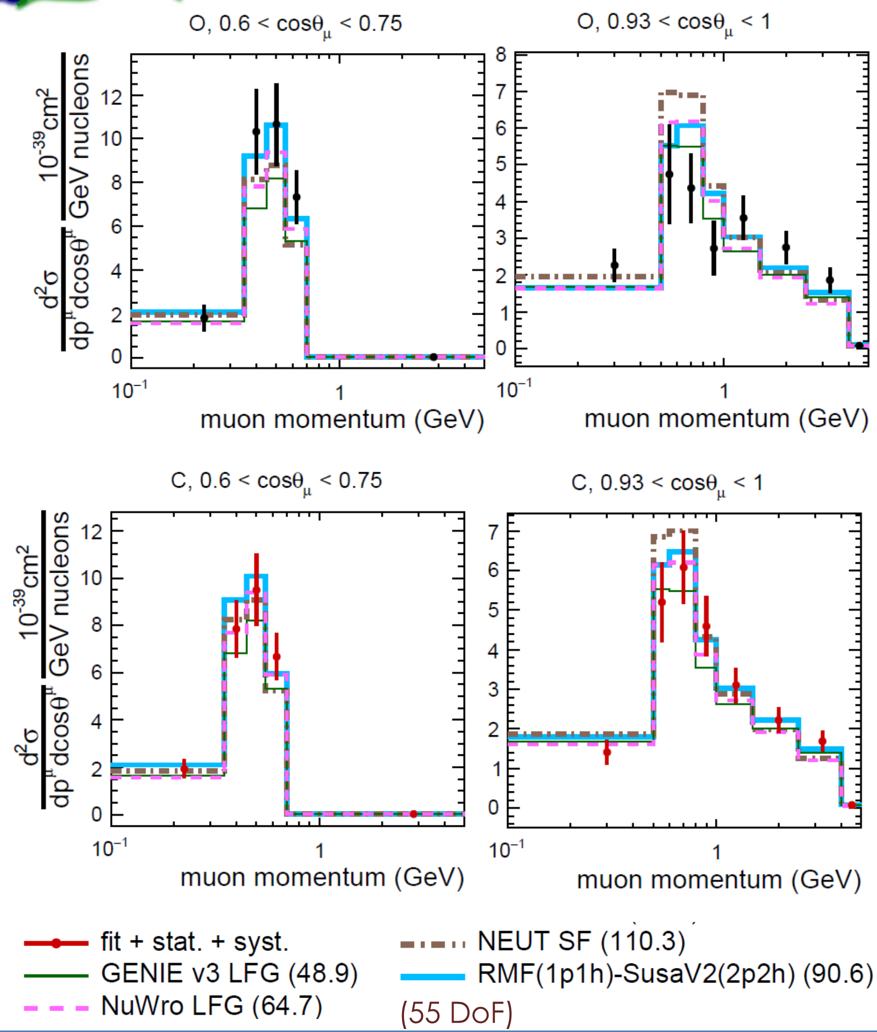
LE ~ 3.2 GeV



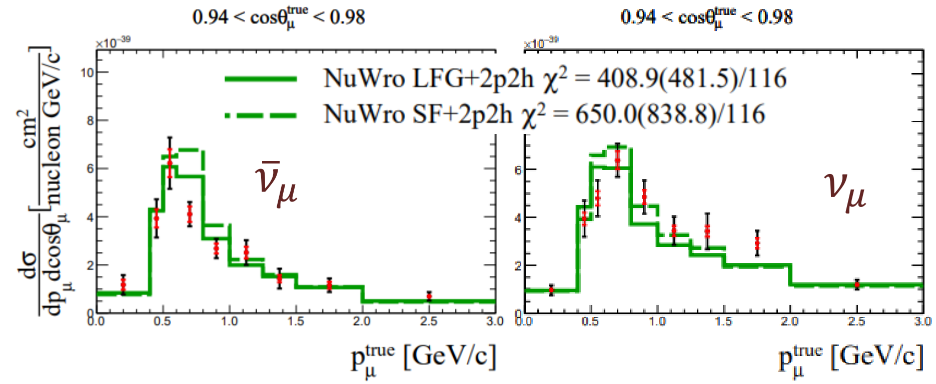
"Joint" measurements

Joint ν_μ / $\bar{\nu}_\mu$

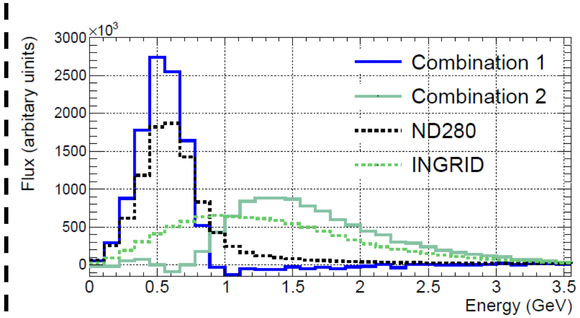
Joint Carbon / Oxygen



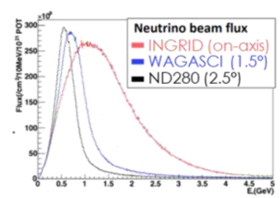
(55 DoF)

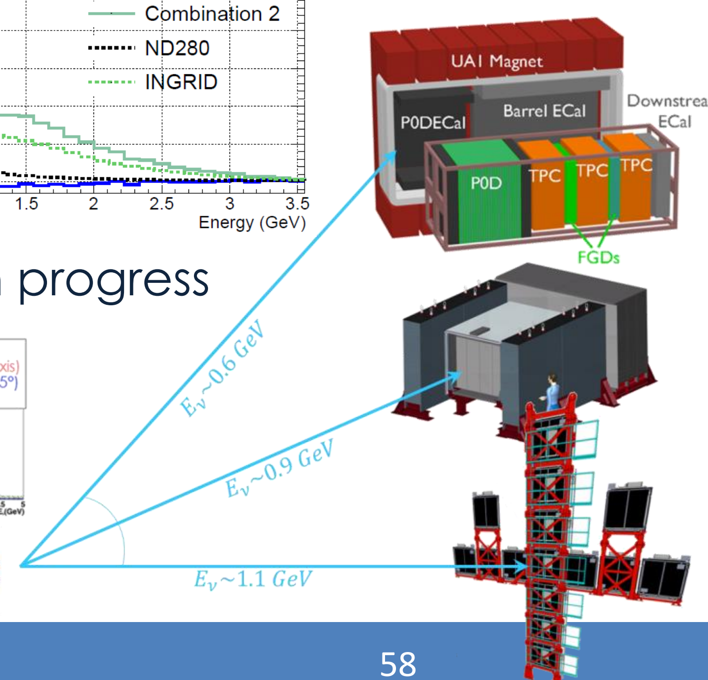


Joint off-axis angles



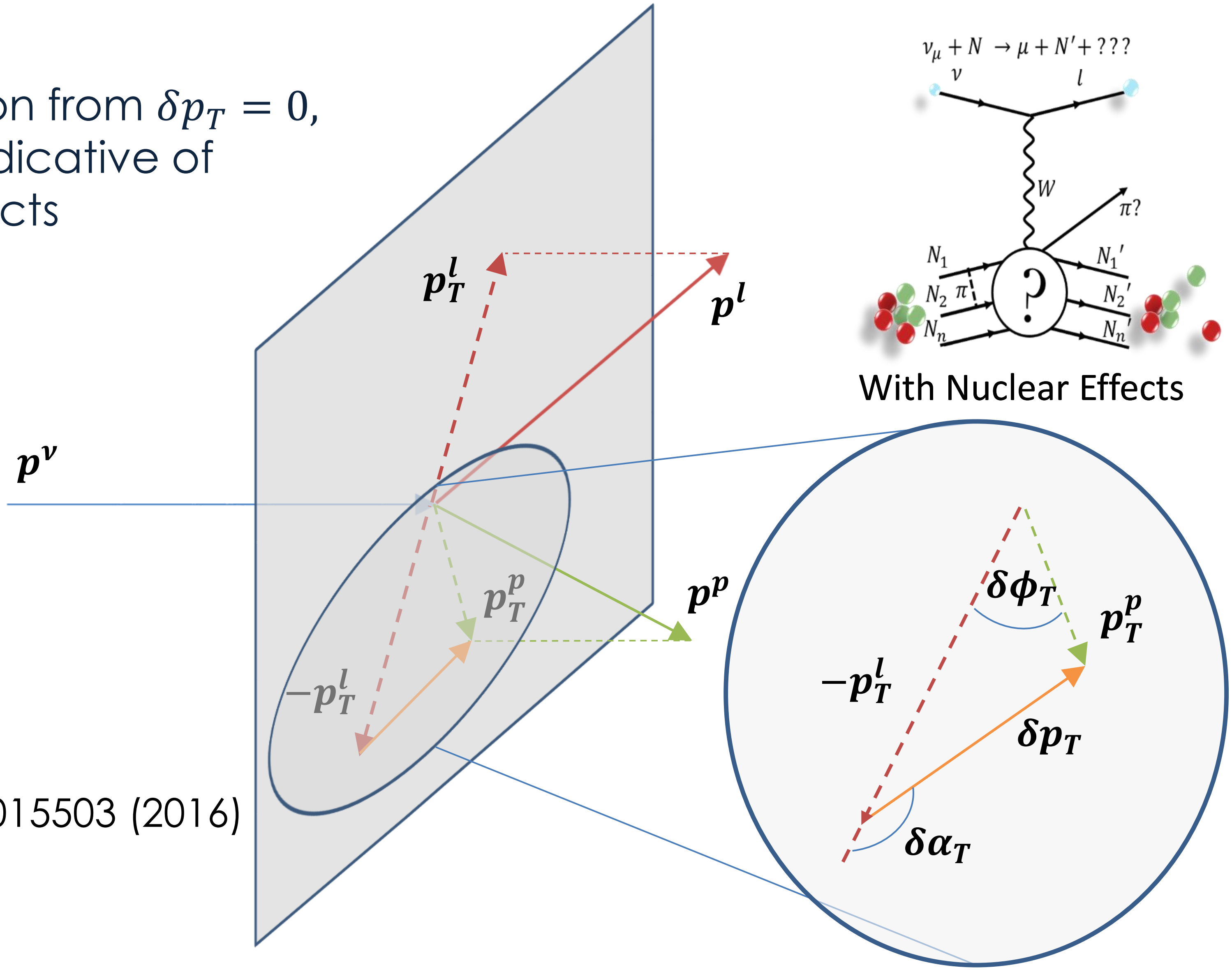
Work in progress





Single Transverse Variables

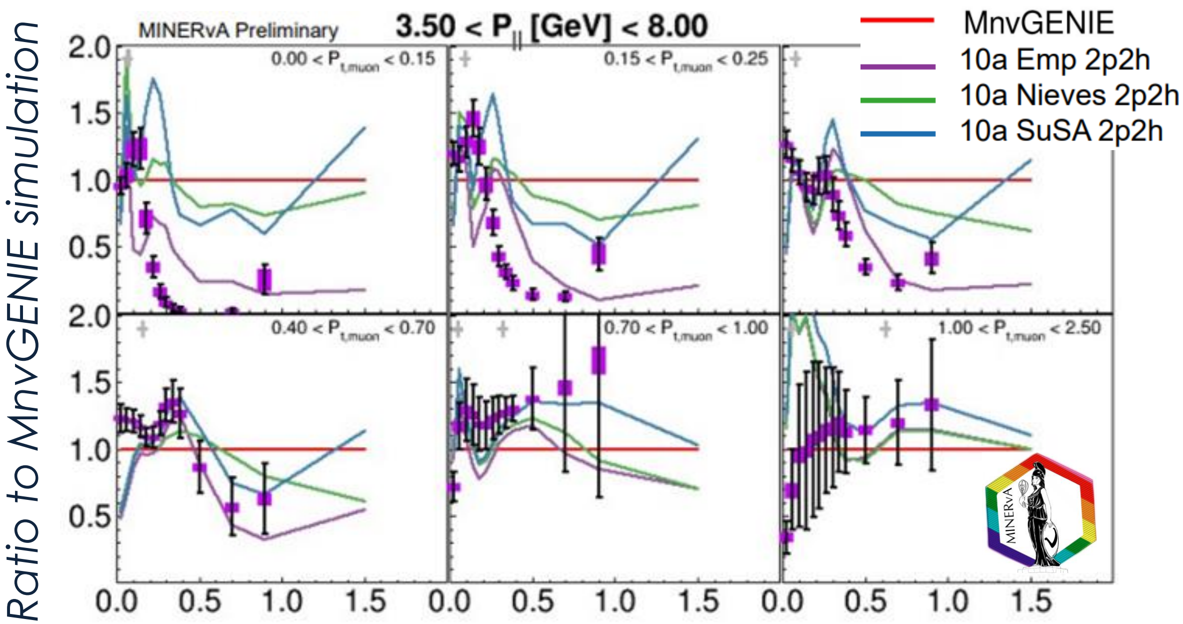
- Any deviation from $\delta p_T = 0$, $\delta\phi_T = 0$ is indicative of nuclear effects



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

Calorimetric measurements

- Sum energy deposited in the detector not associated with lepton
  - Reject pions: excess energy is the sum of proton kinetic energies
- Measure $\sum T_p$ as a function of lepton kinematics
- Very sensitive to effects most important DUNE/NOvA/SBN



$\sum T_p$ (GeV)

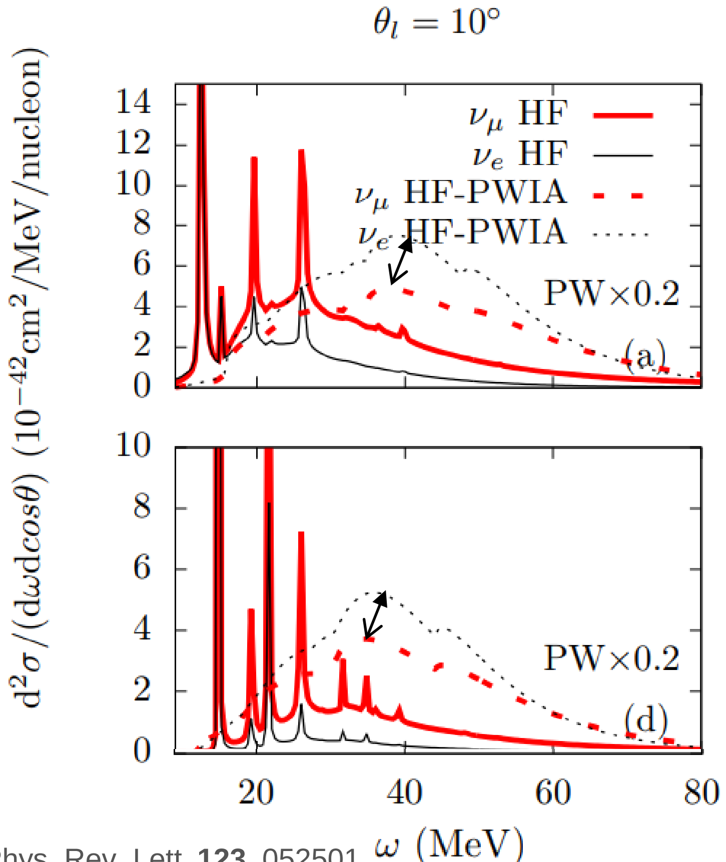
Best model agreement with data: $\chi^2 = 5062/238$

D. Ruterbories, JETP Fermilab seminar

Nuclear effects and $\sigma(\nu_e)/\sigma(\nu_\mu)$

- Ratio of ν_e to ν_μ critical for future oscillation analyses
  - Measure ν_μ at ND but need to know about ν_e to measure δ_{CP}

- This is also subject to subtleties in the nuclear physics…



Phys. Rev. Lett. **123**, 052501

- If the outgoing nucleon exits the nucleus as a “plane wave” (no FSI): $\sigma(\nu_e) > \sigma(\nu_\mu)$

Nuclear effects and $\sigma(\nu_e)/\sigma(\nu_\mu)$

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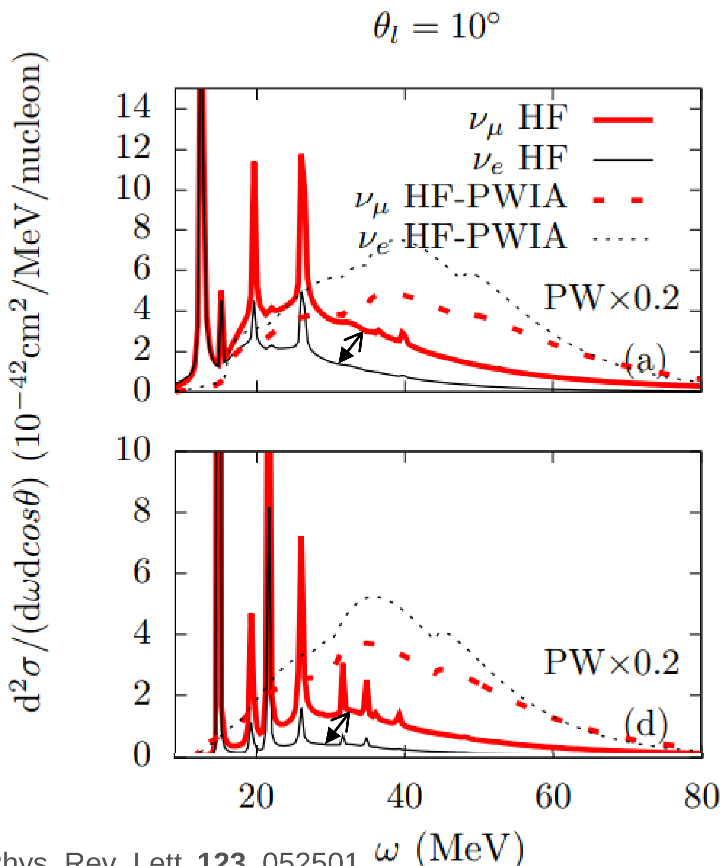


Phys. Rev. Lett. **123**, 052501

- If the outgoing nucleon exits the nucleus as a "plane wave" (no FSI): $\sigma(\nu_e) > \sigma(\nu_\mu)$

- If the outgoing nucleon is distorted by the nuclear potential (FSI): $\sigma(\nu_e) < \sigma(\nu_\mu)$

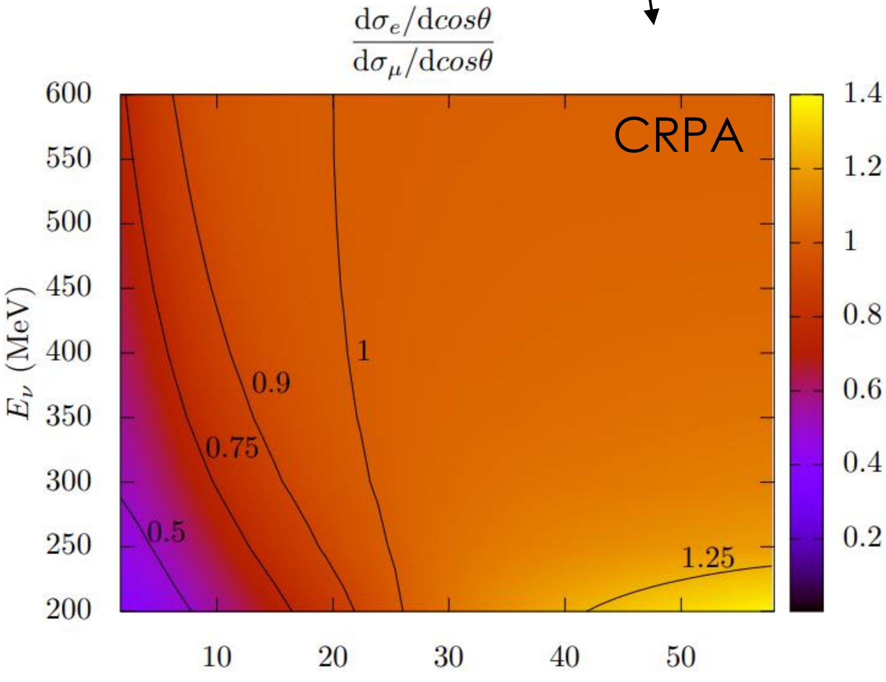
Nuclear effects and $\sigma(\nu_e)/\sigma(\nu_\mu)$

- Different models can predict quite different cross section ratios!
- Important for T2K/HK!

$\frac{d\sigma_e/d\cos\theta}{d\sigma_\mu/d\cos\theta}$

	$E_\nu = 200\ MeV$		$E_\nu = 600\ MeV$	
Model	5°	60°	5°	60°
RFG (w/PB)	0.64	1.61	0.97	1.03
SF (full)	1.41	1.92	1.04	1.03
CRPA	~0.5	~1.4	~0.9	~1.0

Tabulated from Phys. Rev. C **96**, 035501 and the left figure



Phys. Rev. Lett. **123**, 052501

These differences are predicted in regions that are relevant to T2K/HK oscillation analyses