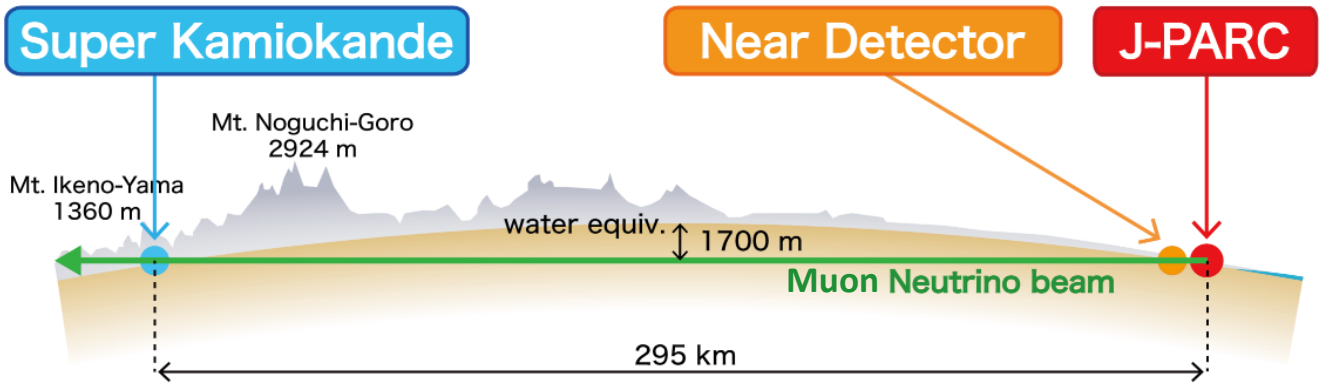
Neutrino-Nucleus Interactions at T2K

Deconstructing Frankenstein's Models

Stephen Dolan
For The T2K Collaboration

stephen.joseph.dolan@cern.ch

The T2K Experiment



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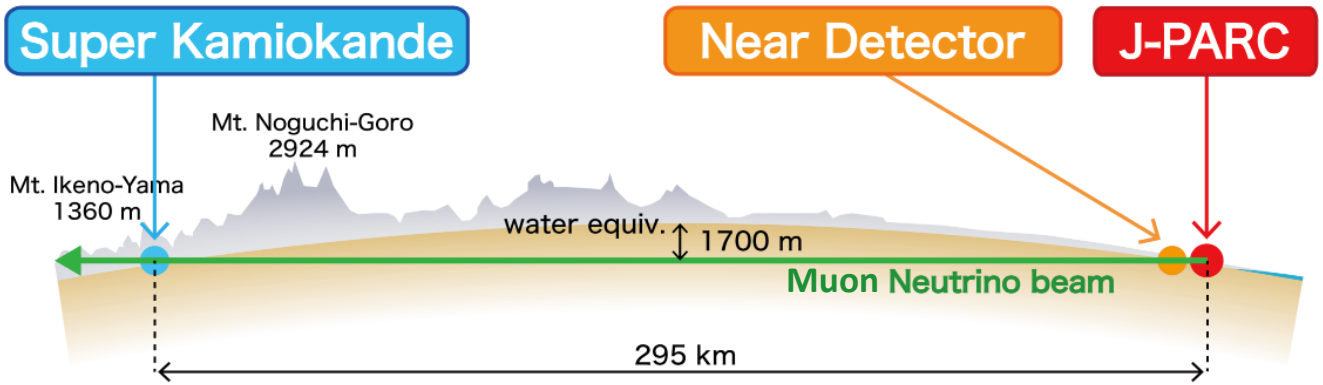

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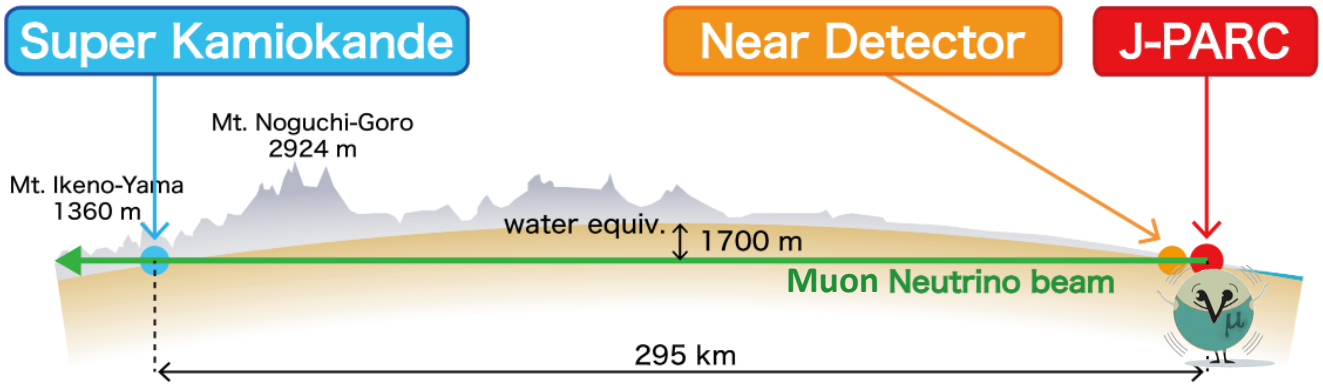

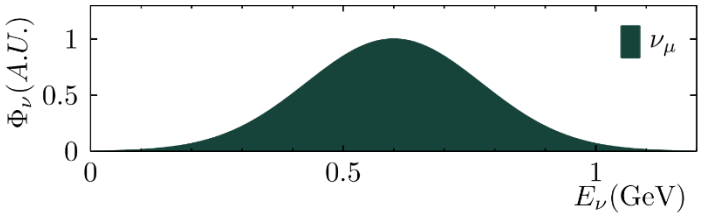

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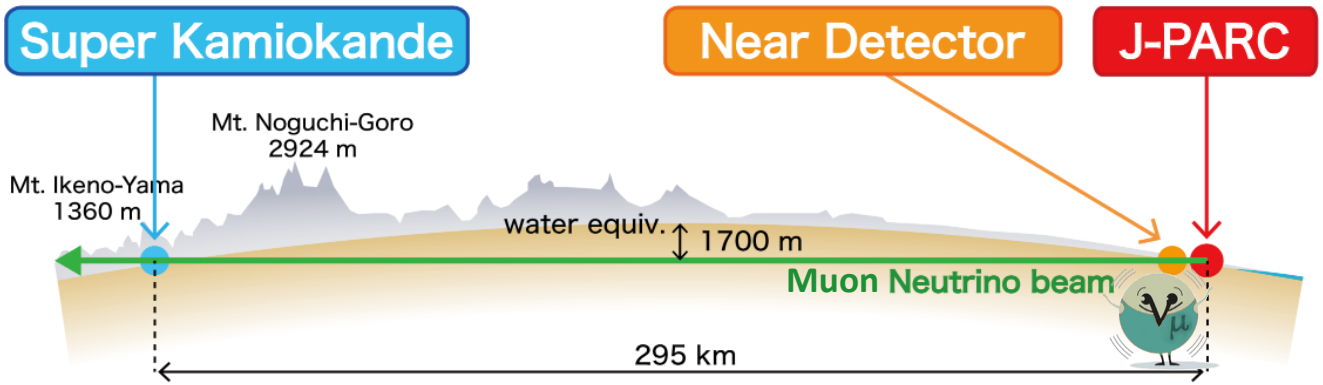
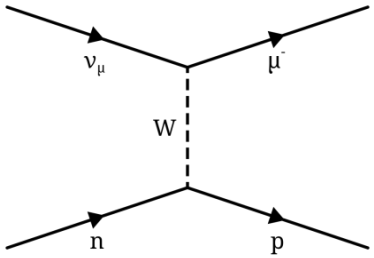
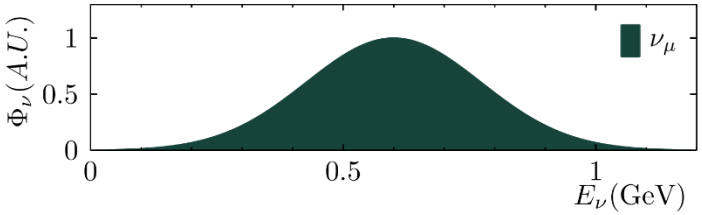






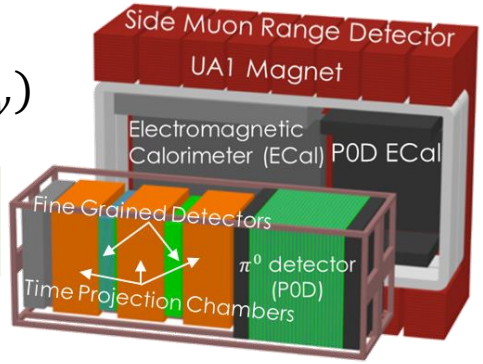
$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Interaction cross section

Neutrino flux

Detector effects

Near Detector
ND280



(Mostly Hydrocarbon Scintillator)

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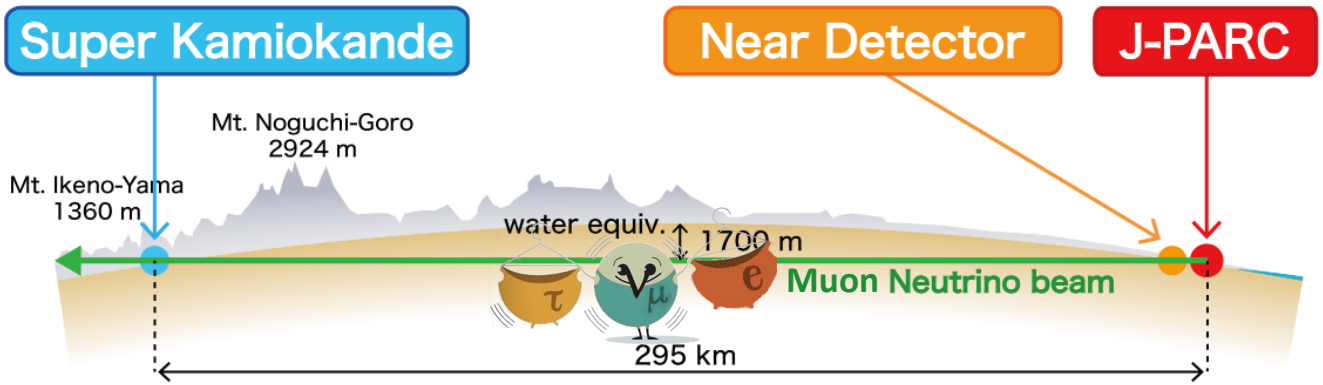
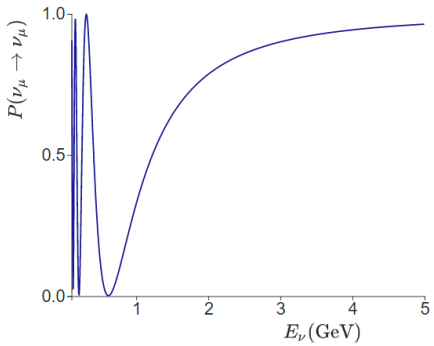
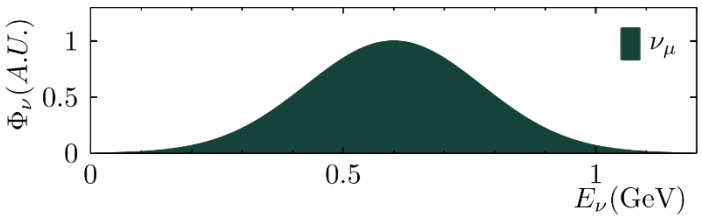
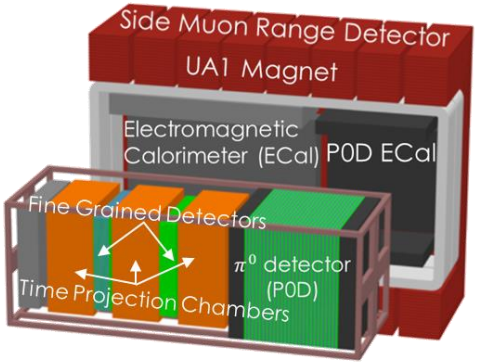






Near Detector
ND280



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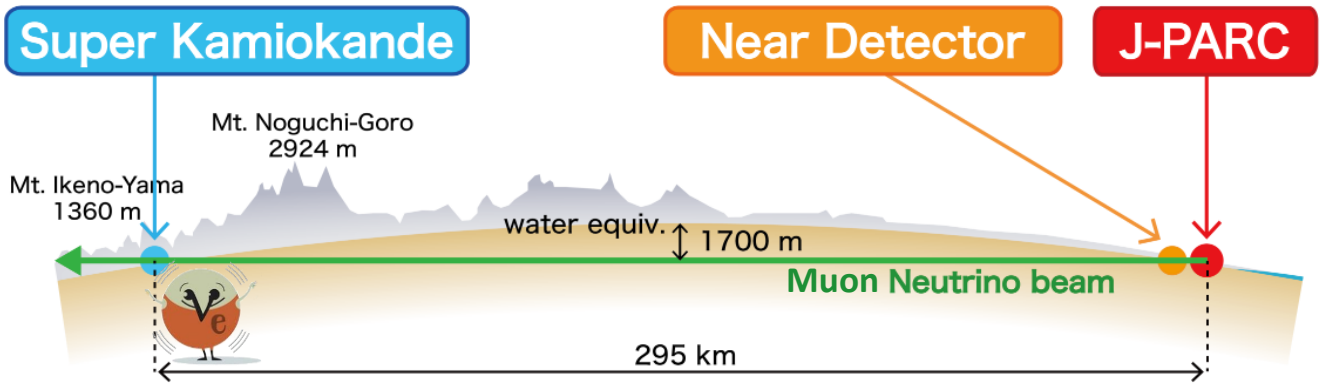

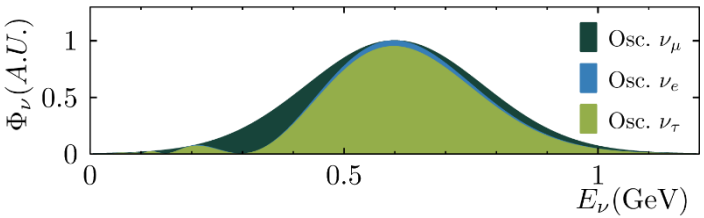

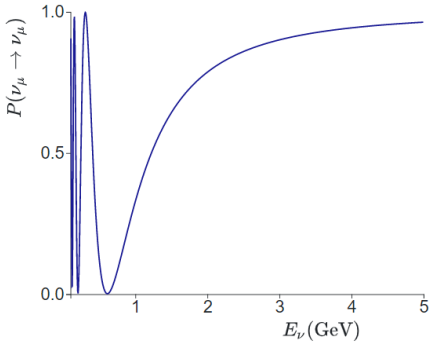

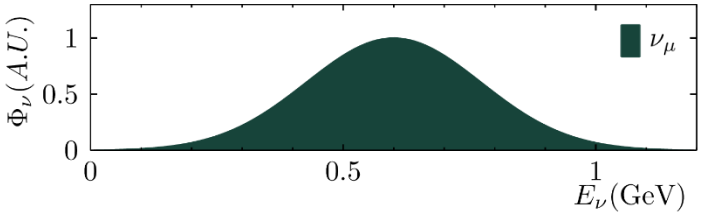

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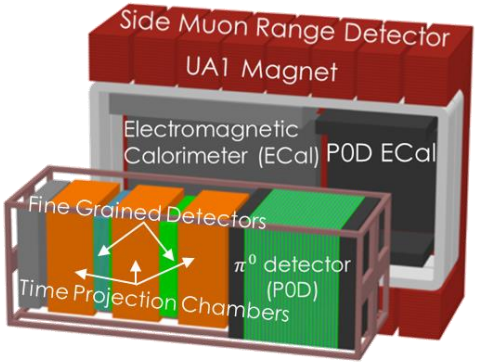
ND280



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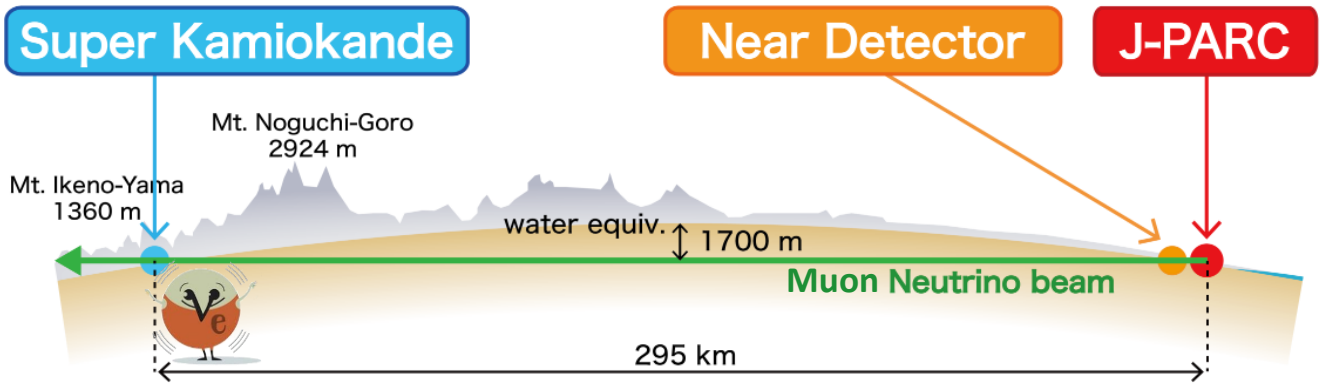
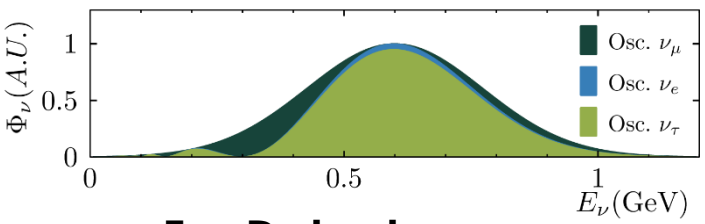
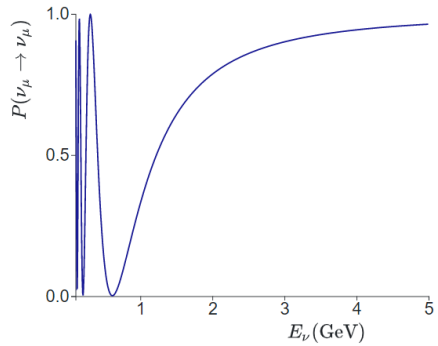
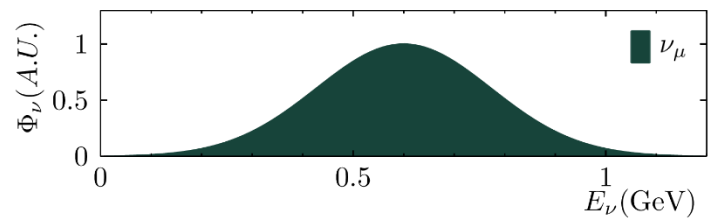




Far Detector
Super-Kamiokande





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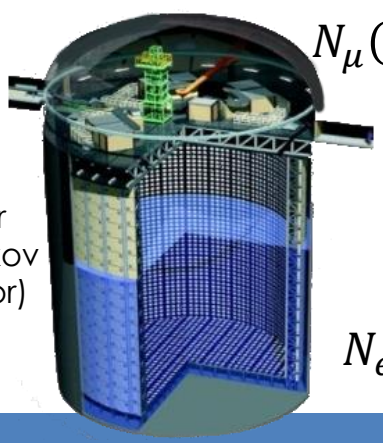

(Water Cherenkov Detector)

Oscillation probability

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

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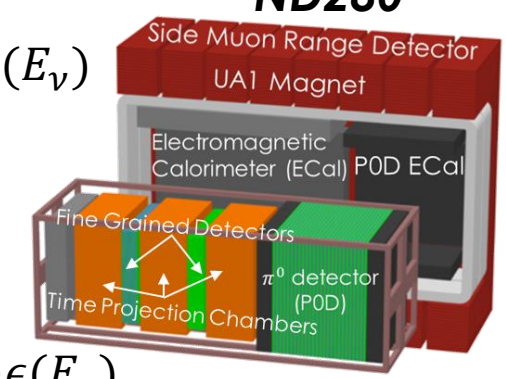

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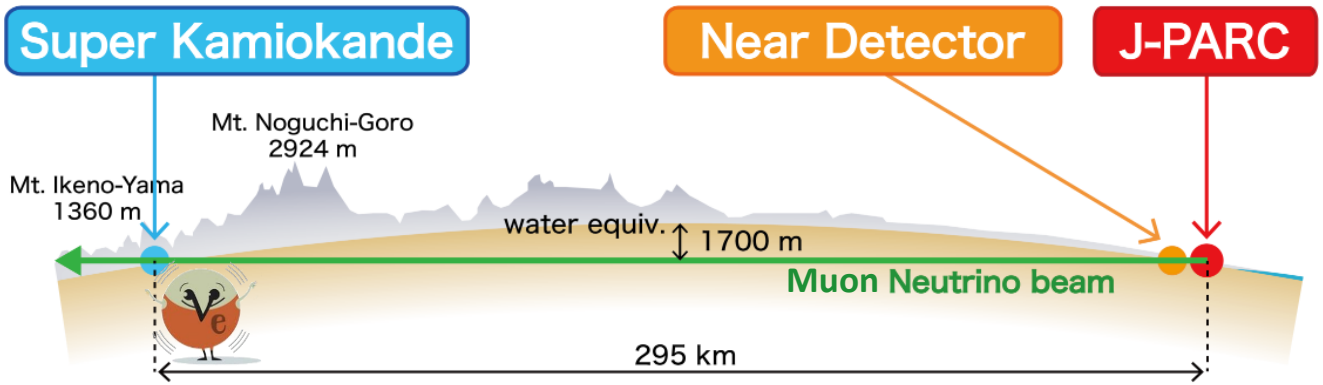

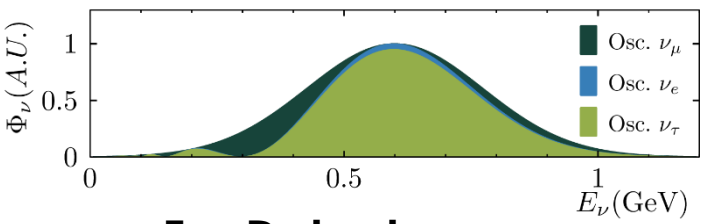

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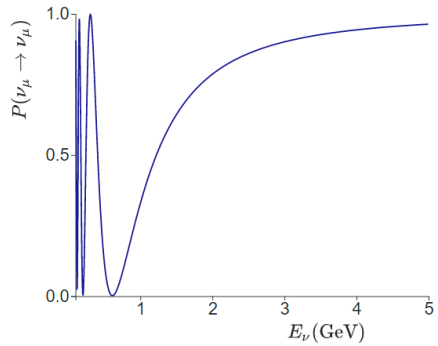

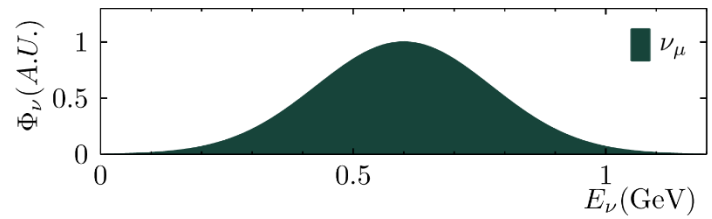

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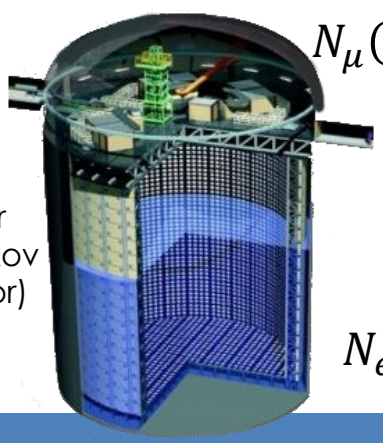

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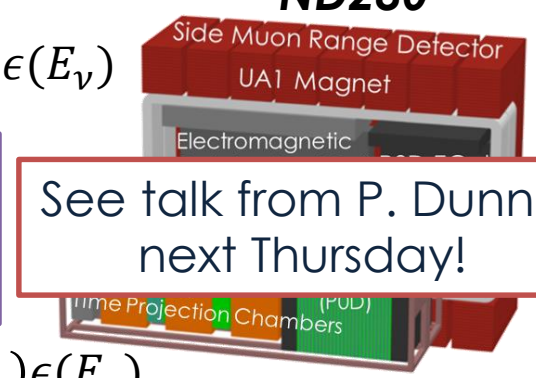

See talk from P. Dunne next Thursday!

(Mostly Hydrocarbon Scintillator)

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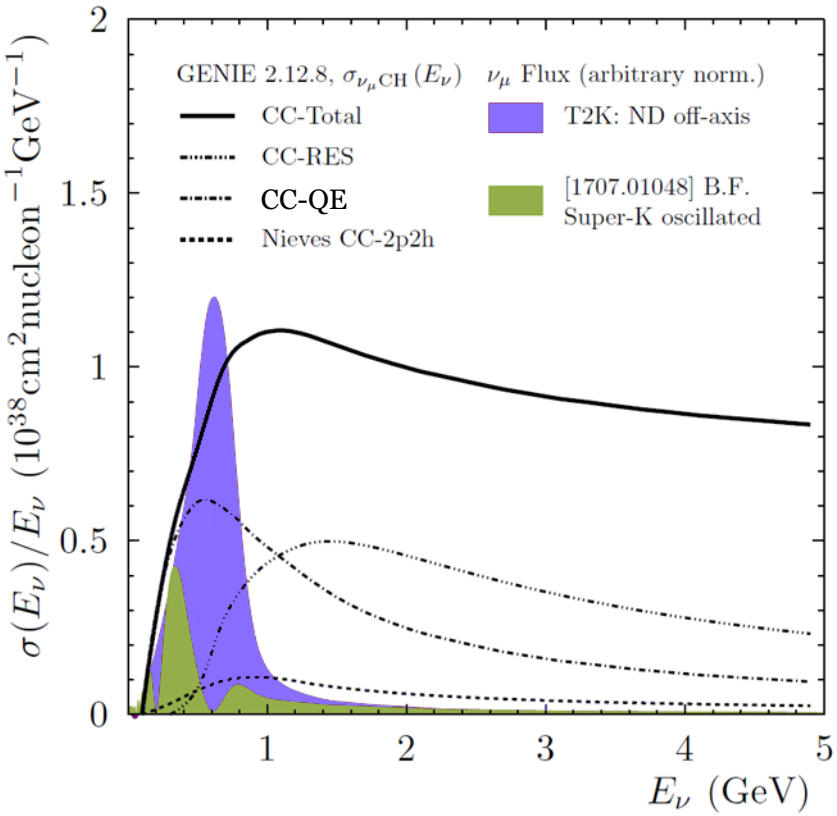

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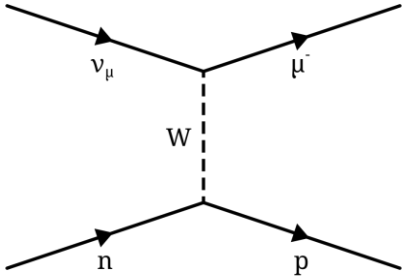
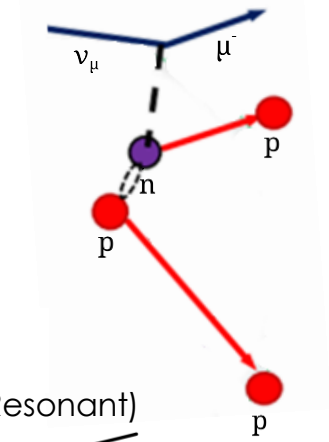
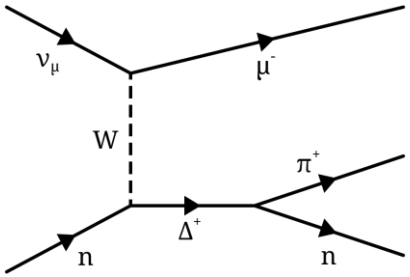
CCQE (1p1h)
(Charged-Current Quasi-Elastic)



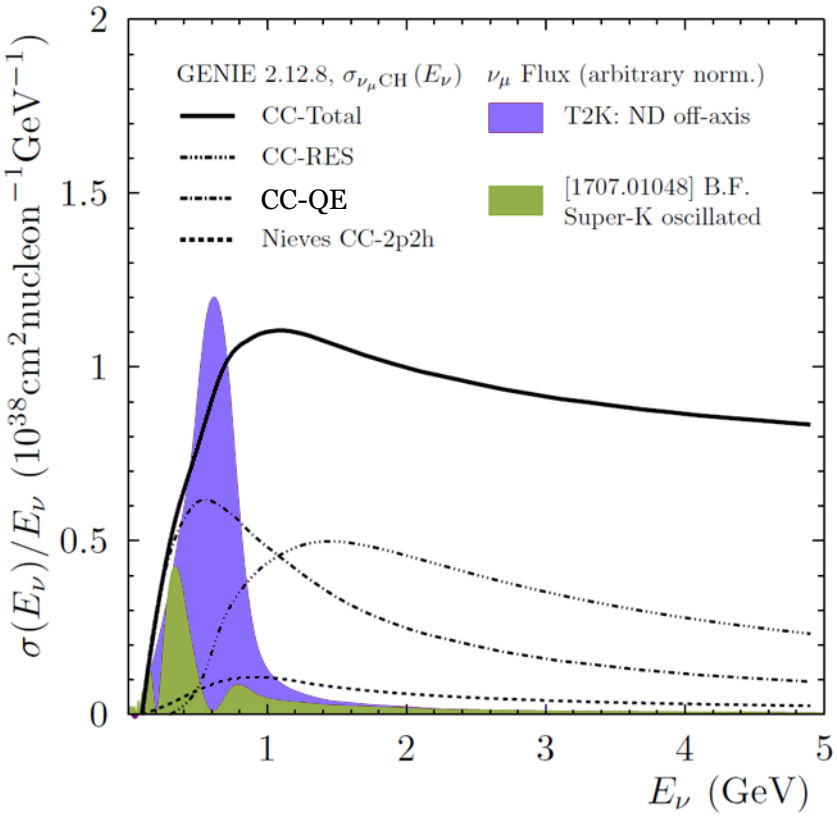
2p2h
(2 particle, 2 hole)



CCRES
(Charged-Current Resonant)



Neutrino Interactions at T2K



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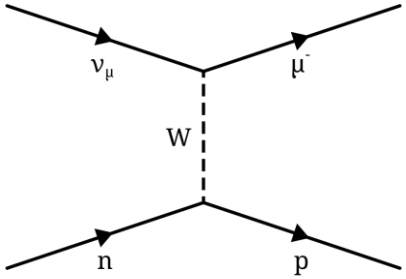
CCQE (1p1h)
(Charged-Current Quasi-Elastic)



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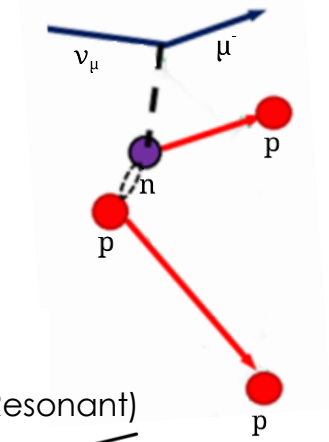

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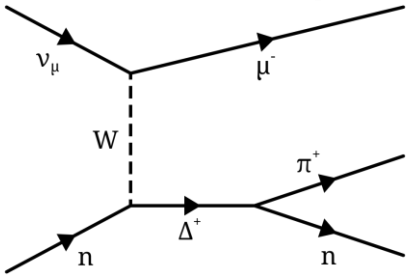
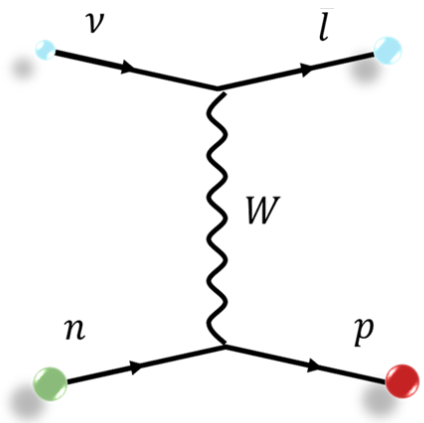
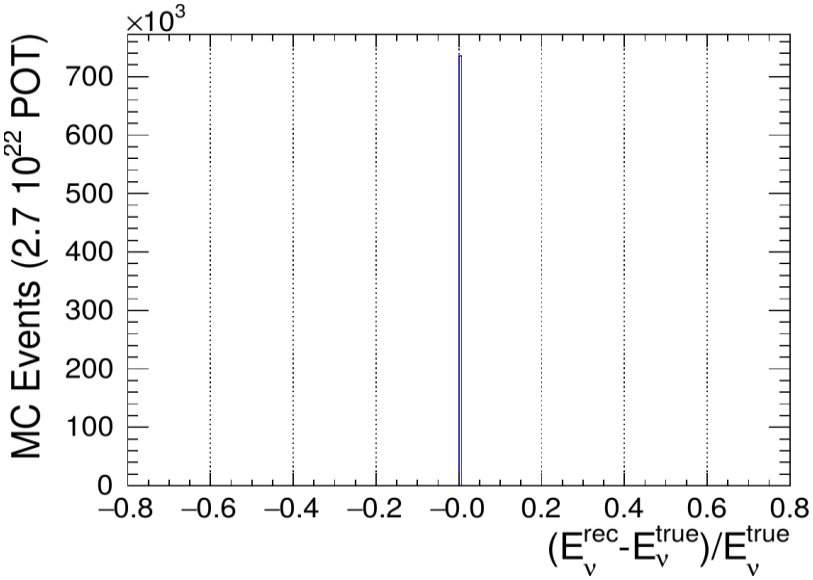


- Build a proxy for neutrino energy from muon kinematics in **CC mesonless** (CC0π) events

Nuclear effects and E_ν

CCQE (1p1h)

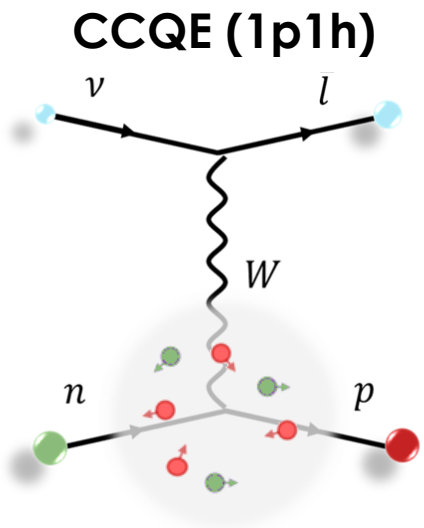


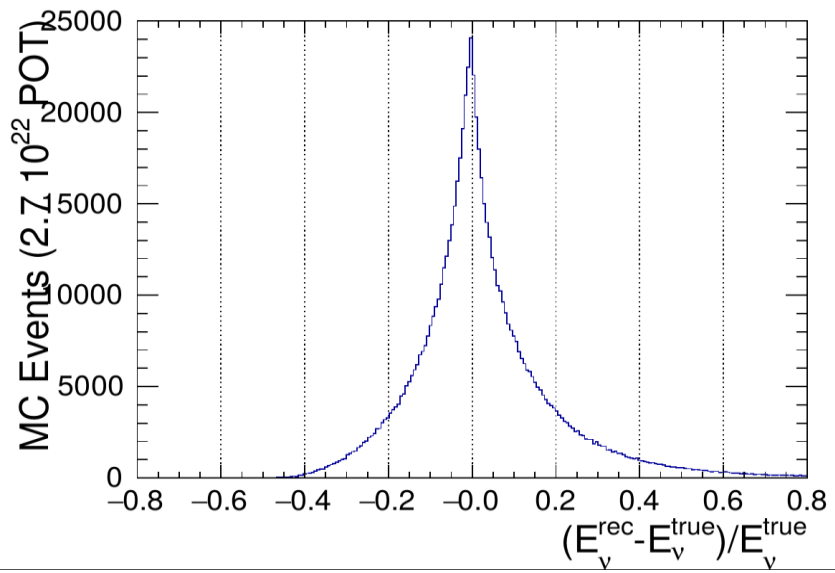


$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

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

Nuclear effects and E_ν





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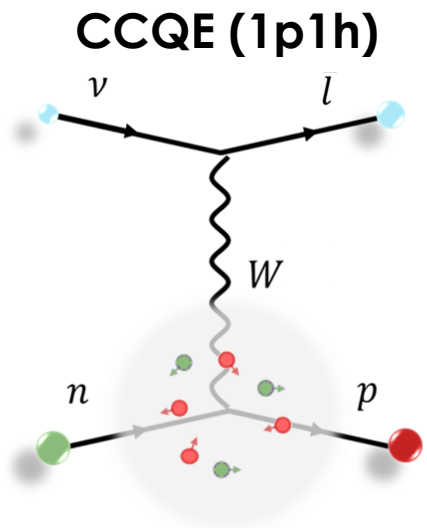
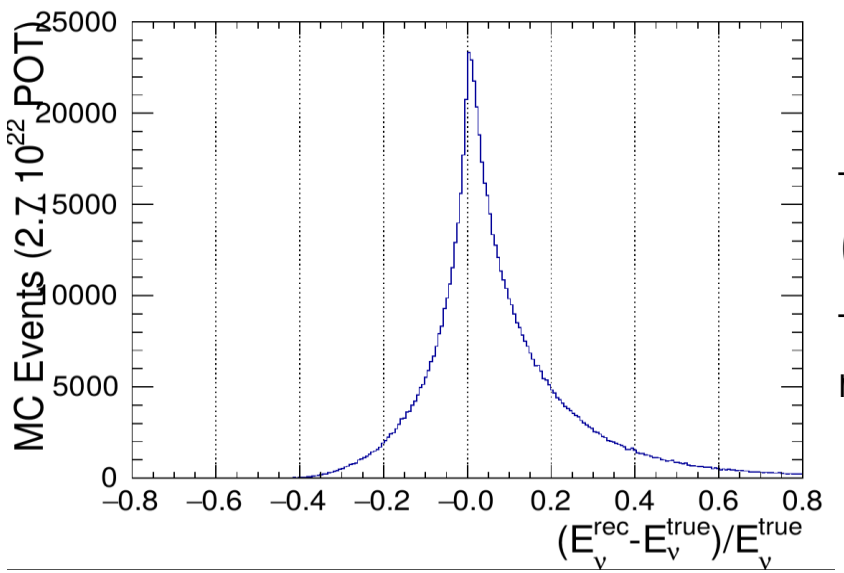
The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

Nuclear effects and E_ν





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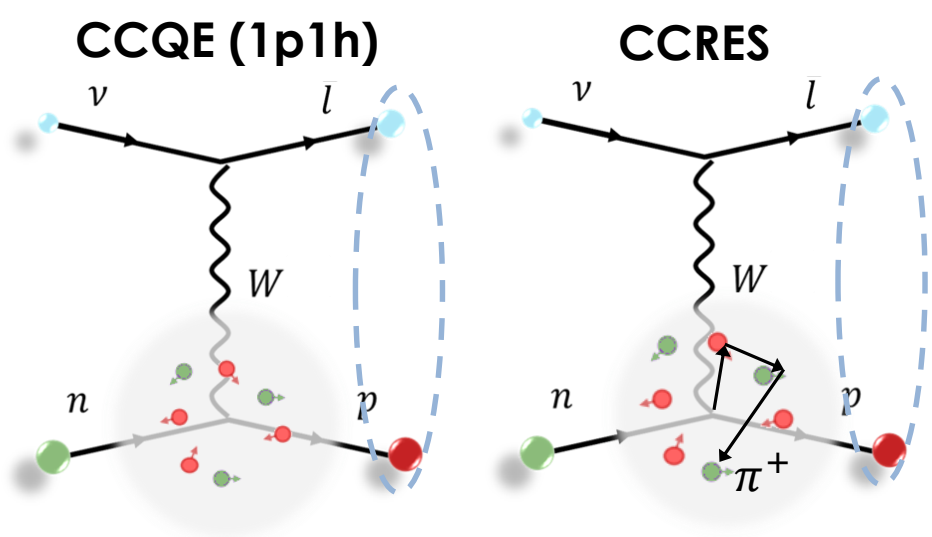
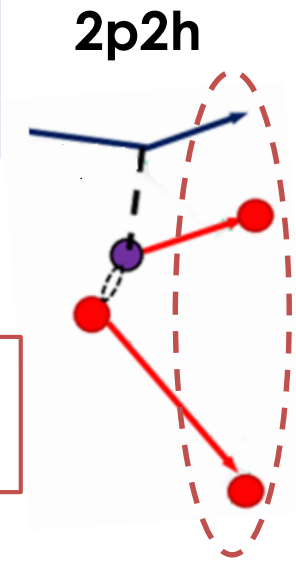
The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a **bias**

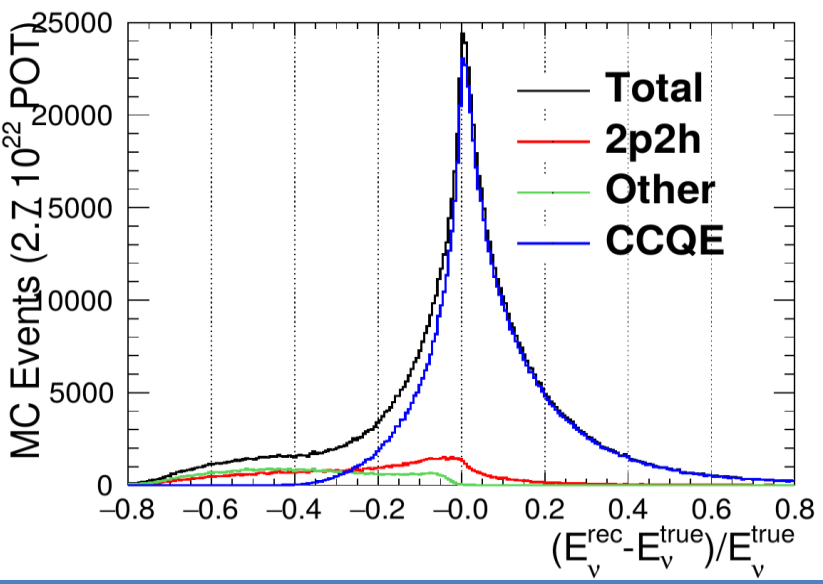
Nuclear effects and E_ν



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

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





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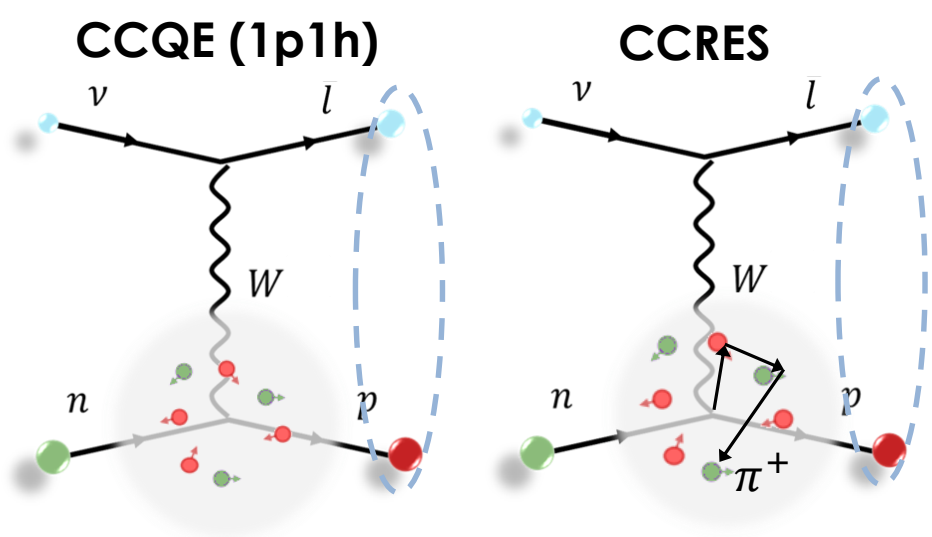
The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

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



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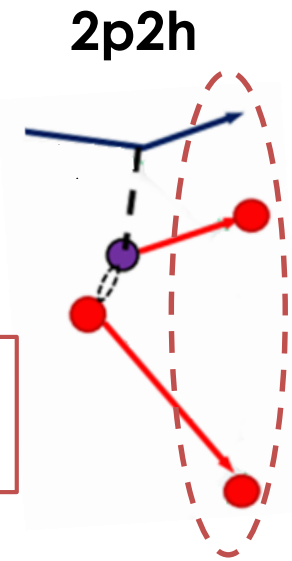
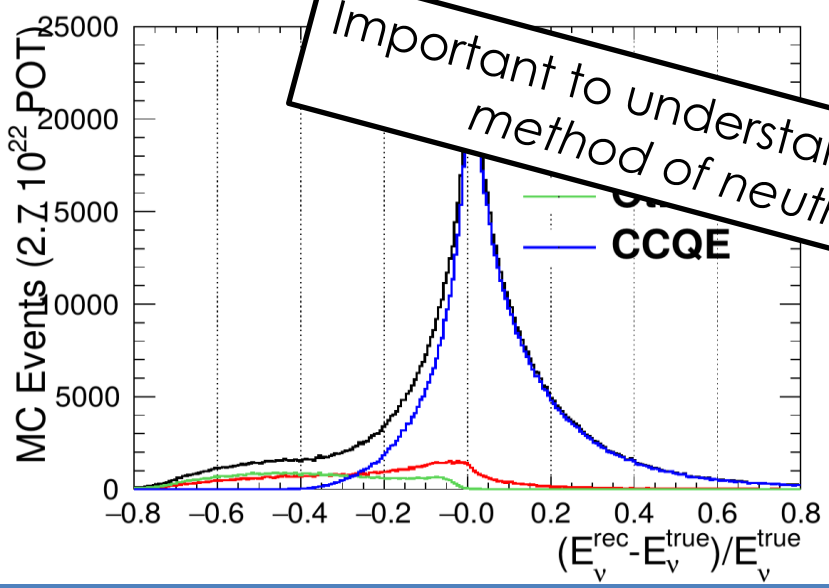
Interactions off a bound state of two nucleons can result in **2p2h** final states





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

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

the nucleons inside the nucleus

smearing on E_ν

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

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

Five things we need to know

(a non exhaustive list)

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   - *So we know how often we mis-reconstruct* E_ν

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   - *So we know how to use our ND constraints on ν_μ in ν_e app. analyses*

KEEP CALM
AND
MEASURE dσ/dx

The ND280 Near Detector

ND280

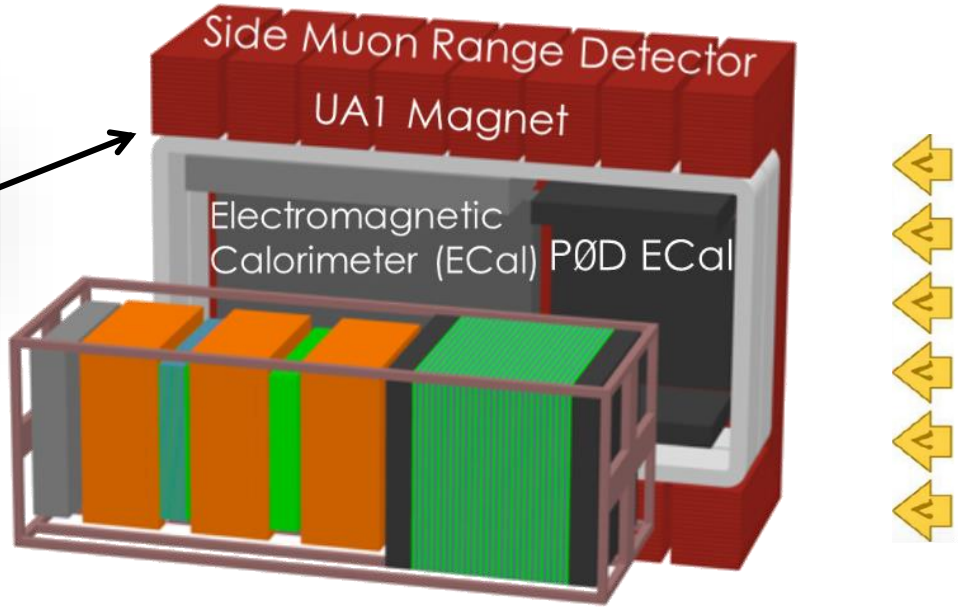
On Axis ~ 1.1 GeV

Peak E_ν

Off Axis ~ 0.6 GeV

Former UA1 Magnet:

- Provides 0.2 T field



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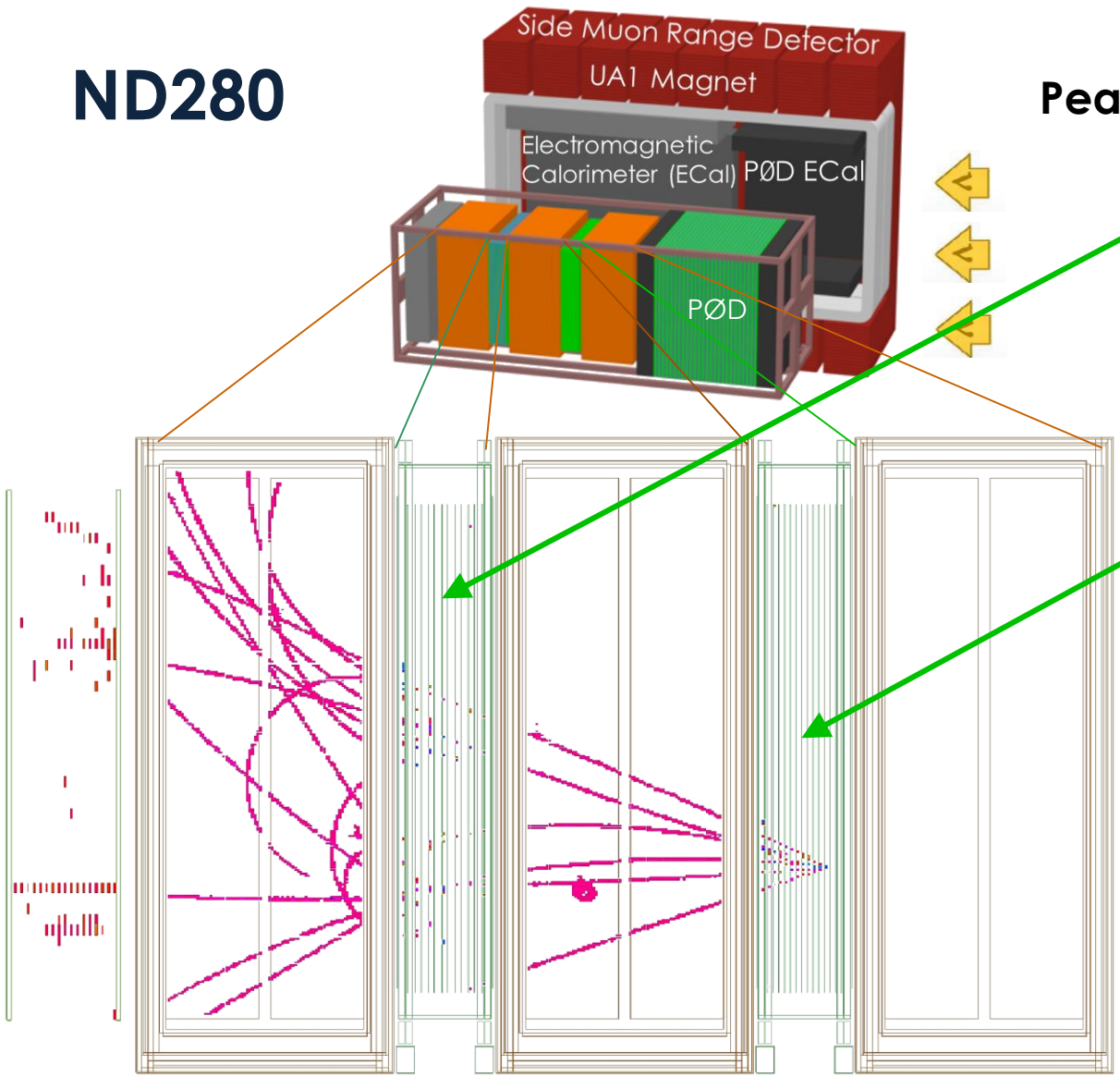

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Fine-Grained Detectors (FGD 1 & 2):

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

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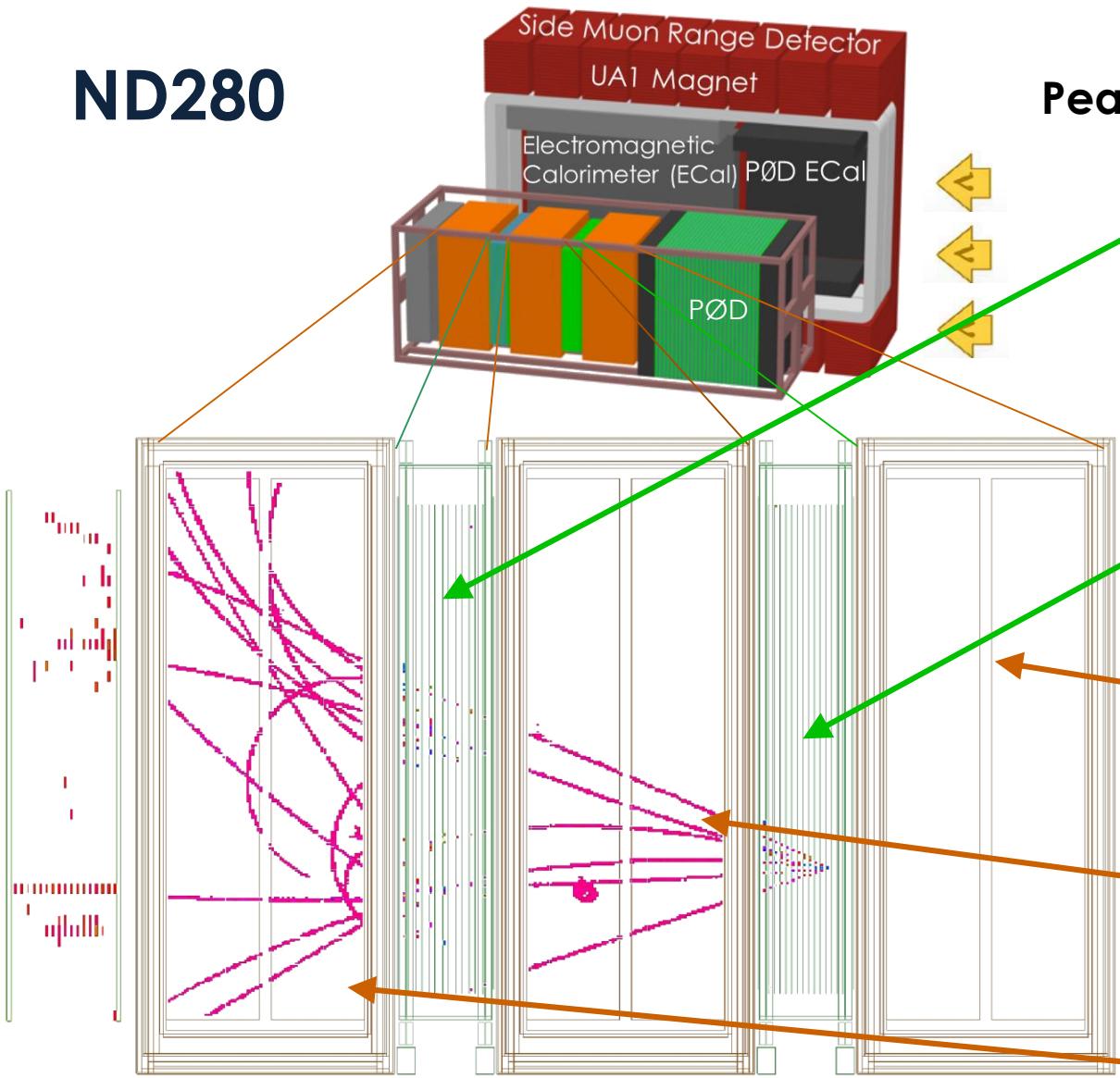

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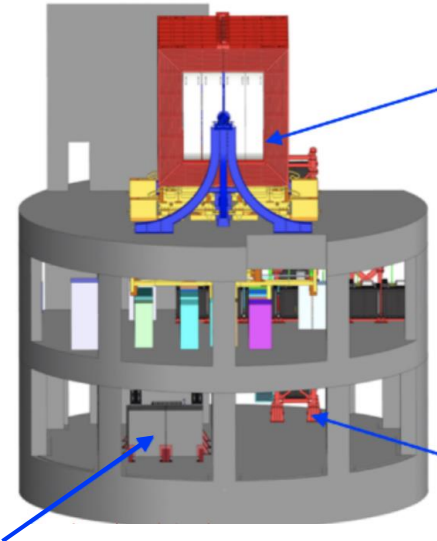
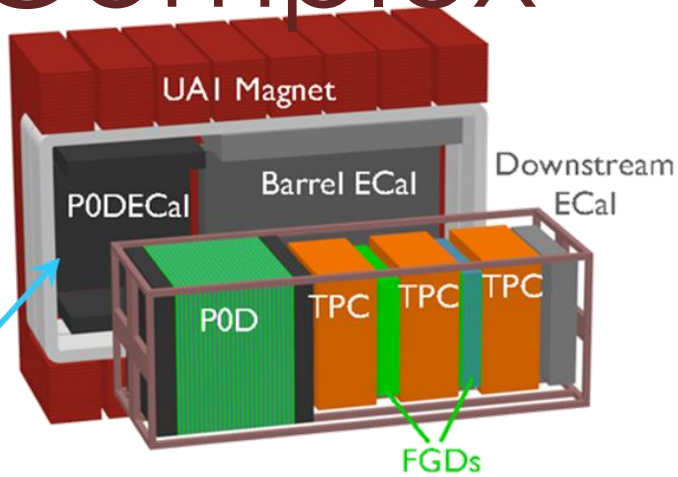
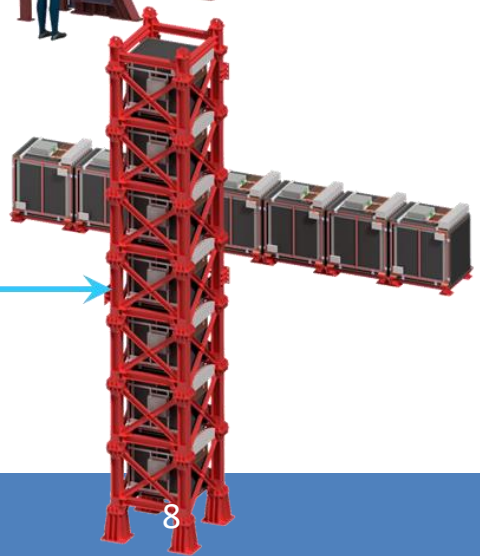
Time Projection Chambers (TPC):

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

The Near Detector Complex







ND280
$E_\nu^{peak} \sim 0.6\ GeV$

WAGASCI + BabyMIND
$E_\nu^{peak} \sim 0.9\ GeV$

INGRID
$E_\nu^{peak} \sim 1.1\ GeV$

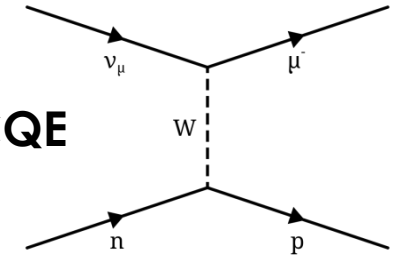
$2.5°$

$1.5°$

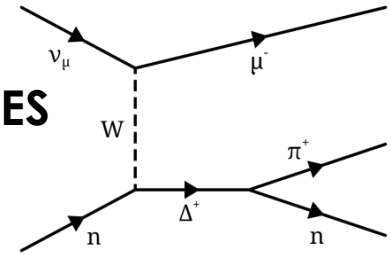
What can we measure?

Interaction Modes

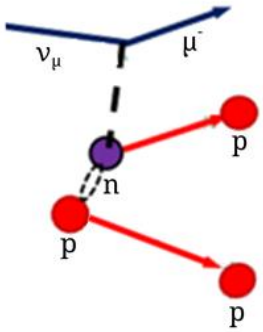
CCQE



CCRES



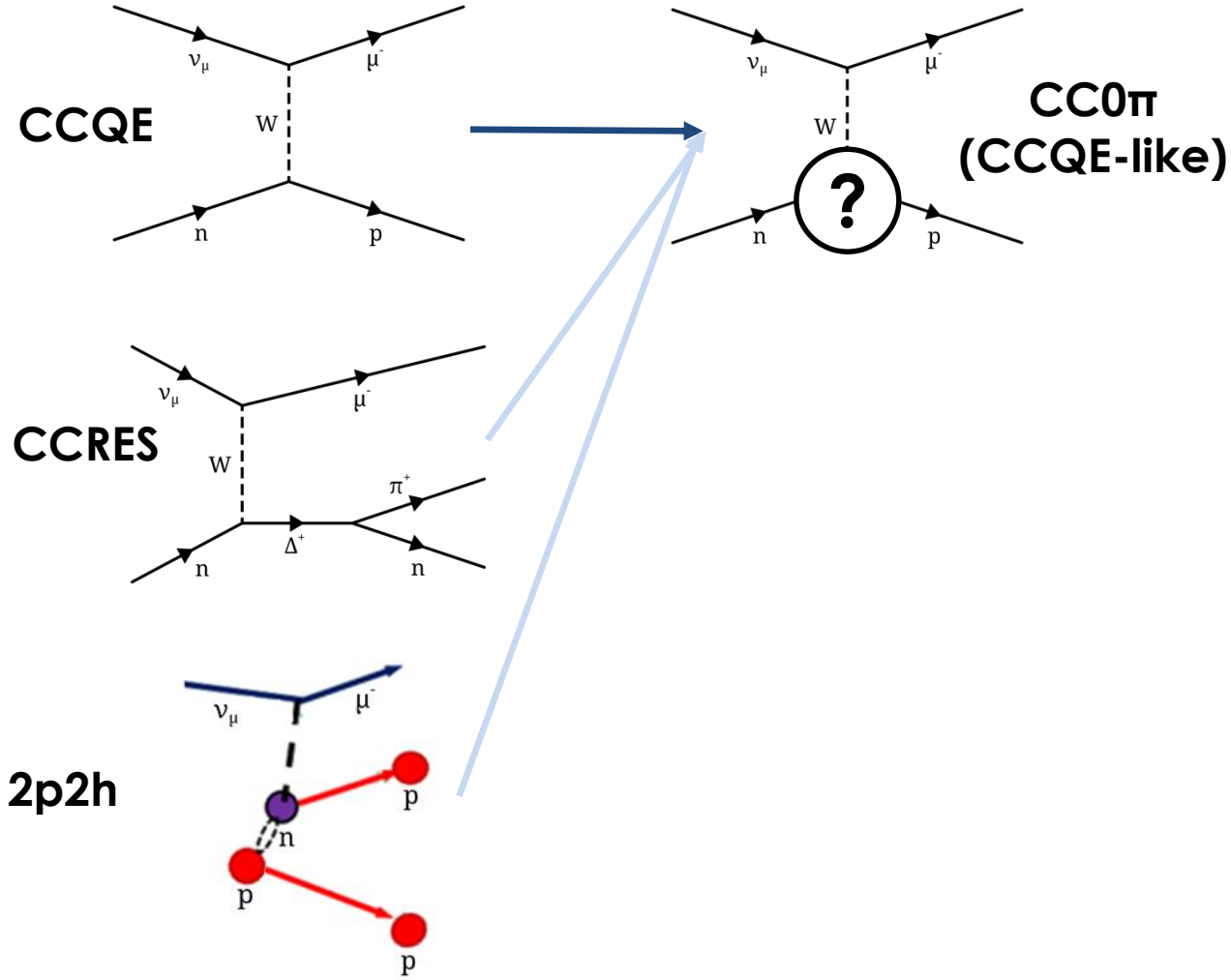
2p2h



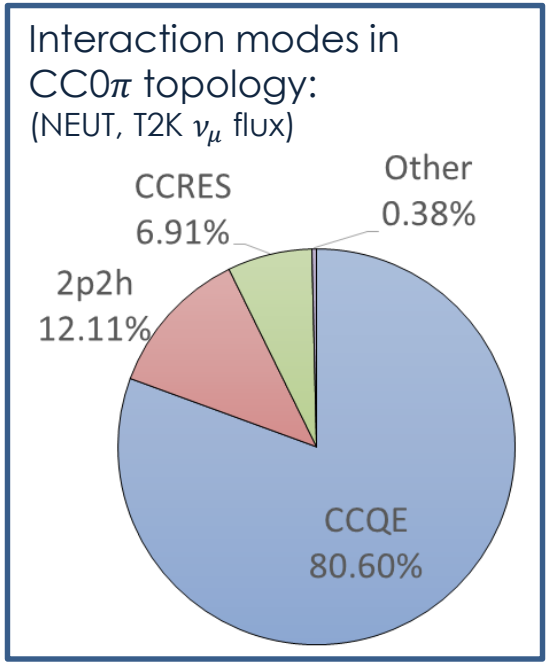
What can we measure?

Interaction Modes

Interaction Topologies



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



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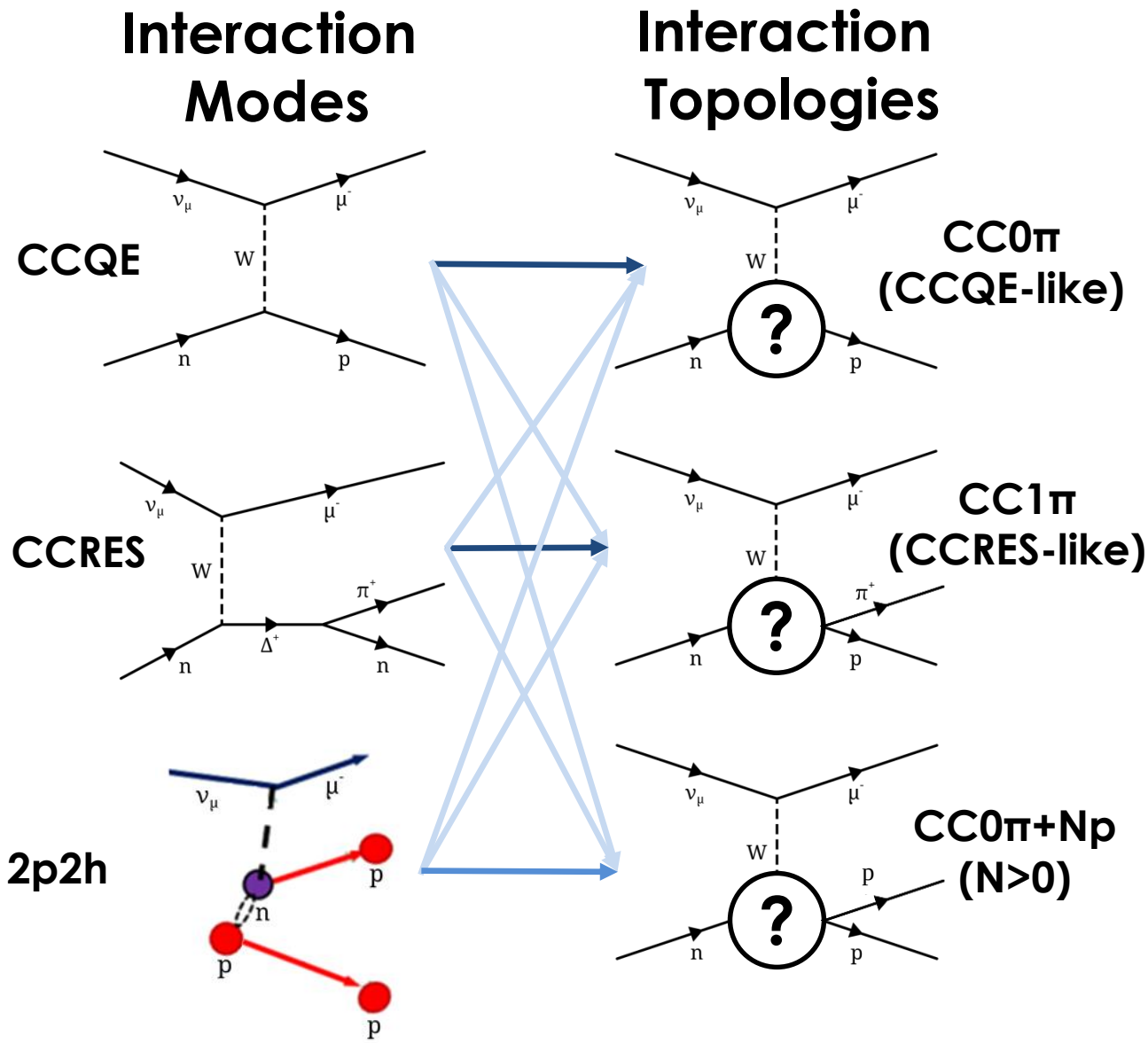

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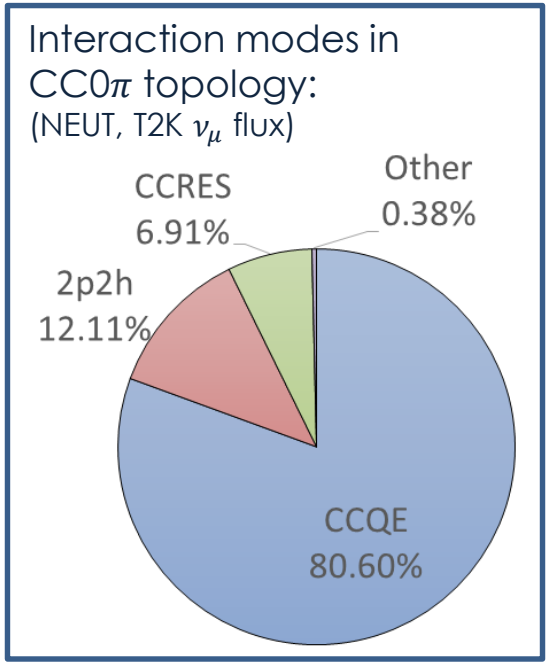

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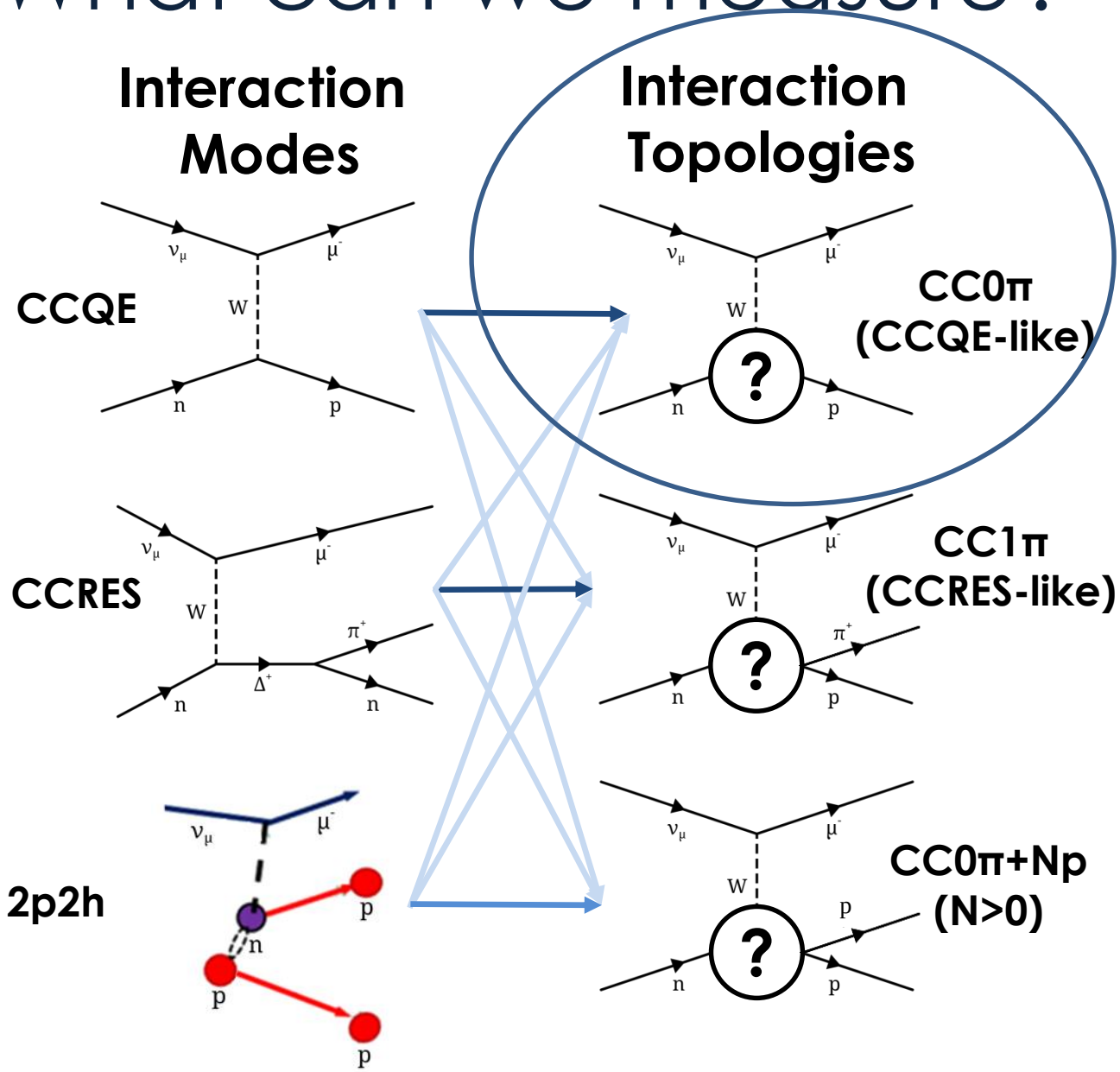

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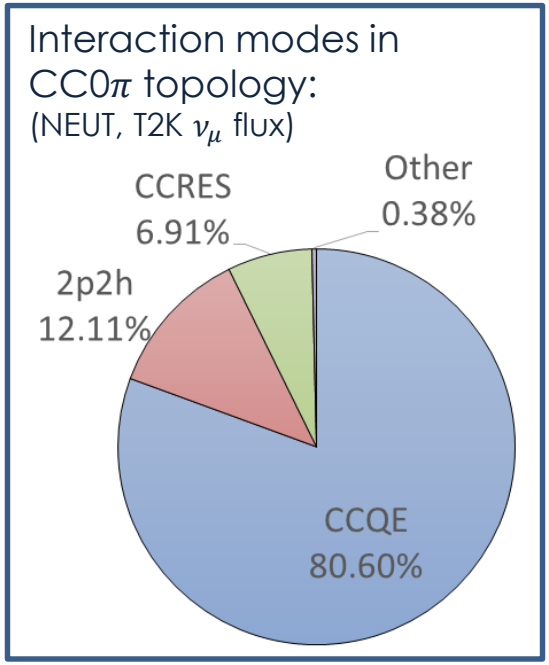

Frankenmodels

Theory Inputs

- ✓ Neutrino scattering predictions carefully constructed from nuclear theory.
- ✓ Precisely validated with electron scattering data
- X Usually have limited scope of application. E.g.:
  - Limited predictive power for hadron kinematics
  - Only valid for one process (e.g. only CCQE)
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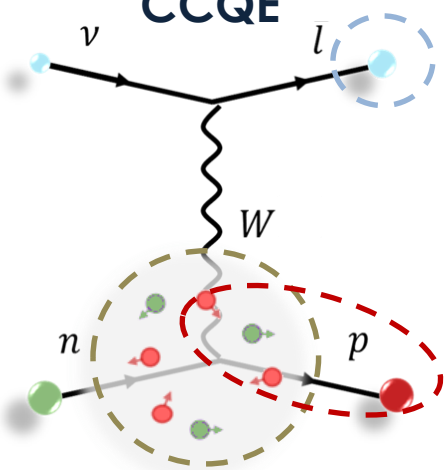
Event generators

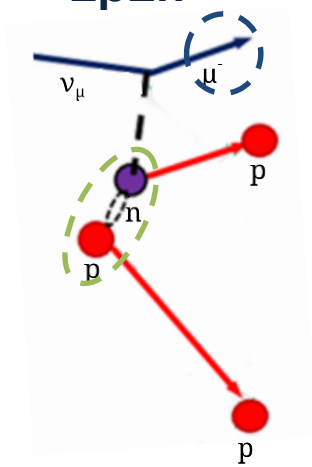
- Inputs to our oscillation measurements
- Stitch together available models however we can
- Fill in the gaps with semi-classical approaches

CCQE



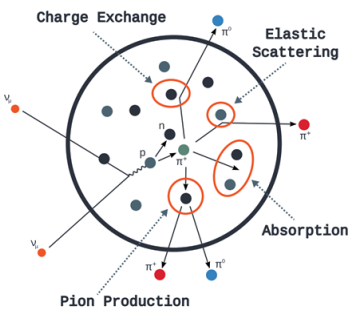
+

2p2h



+ … +

Final State Interactions



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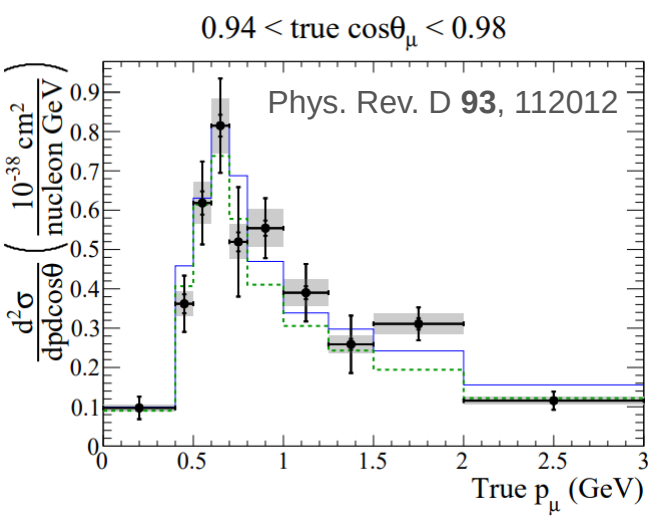

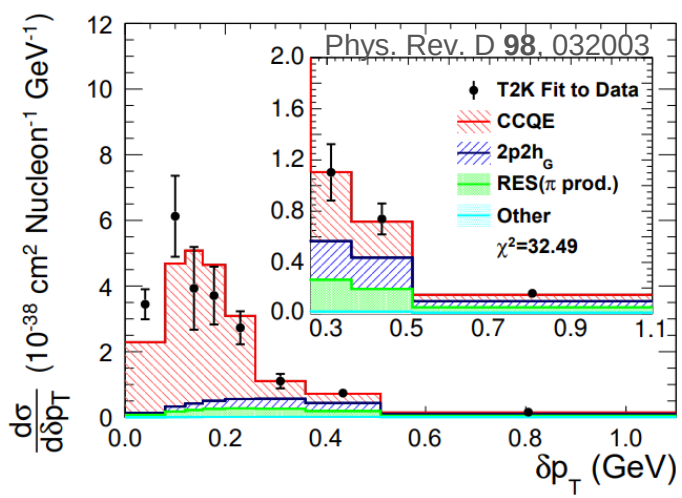

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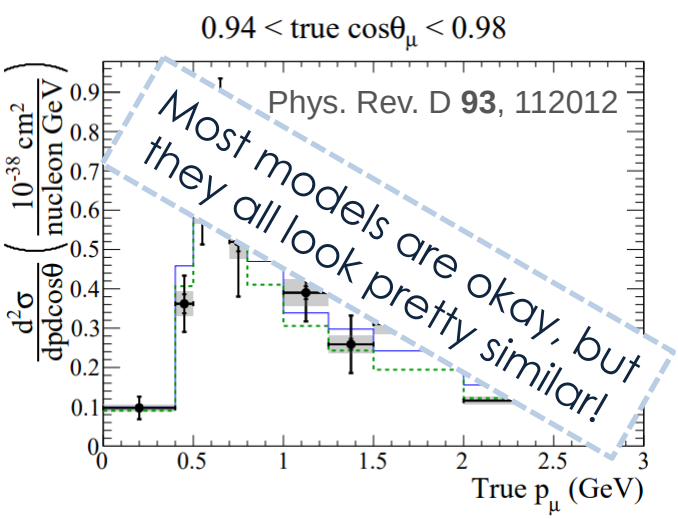

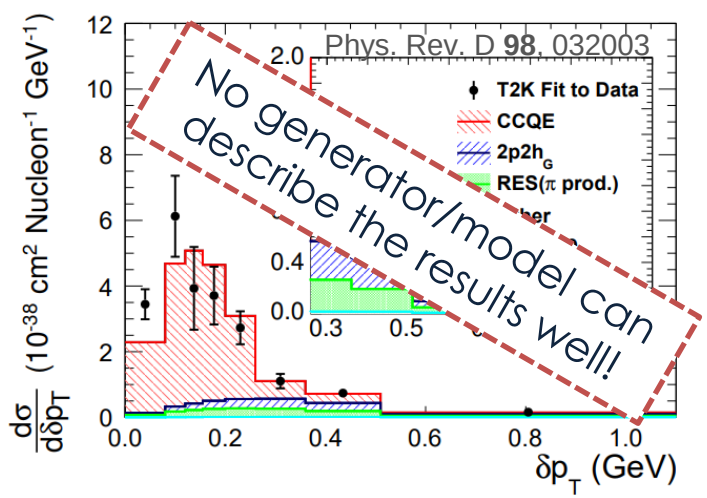

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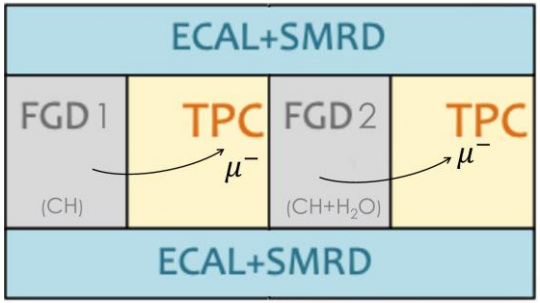
Test extrapolation from ND to FD

Sensitive to nuclear effects via C/O ratio



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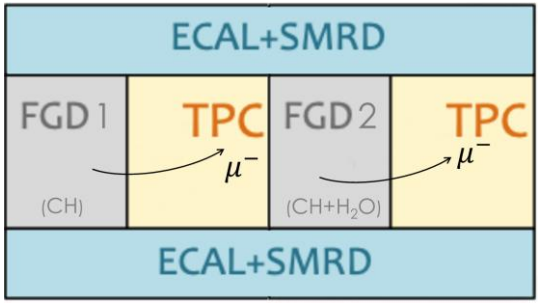

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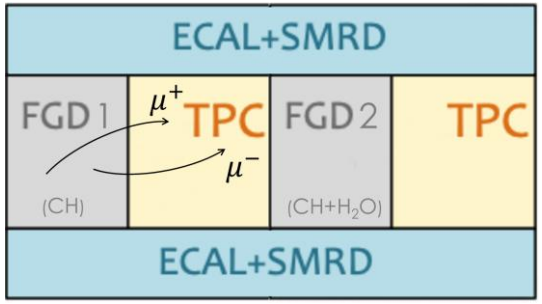
Characterise $\nu_\mu/\bar{\nu}_\mu$, critical for δ_{CP} sensitivity

Sensitive to nuclear effects via $\nu_\mu/\bar{\nu}_\mu$ asymmetry



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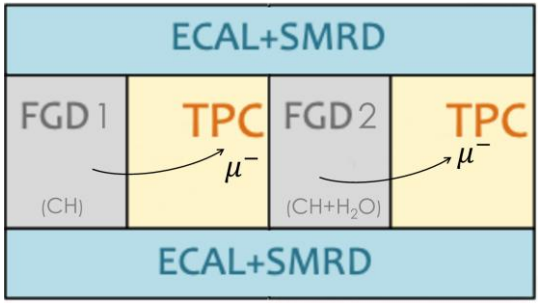

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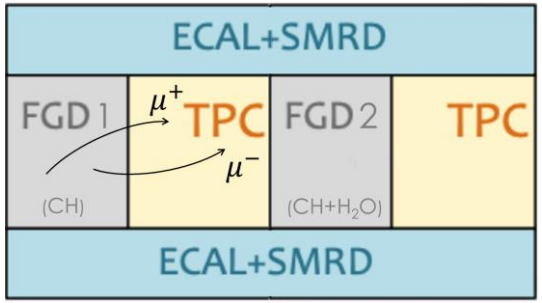
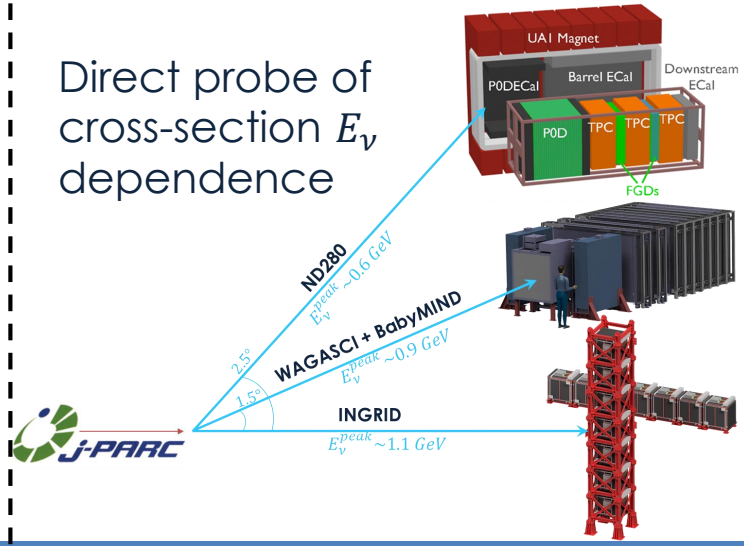


On+Off axis

Direct probe of cross-section E_ν dependence



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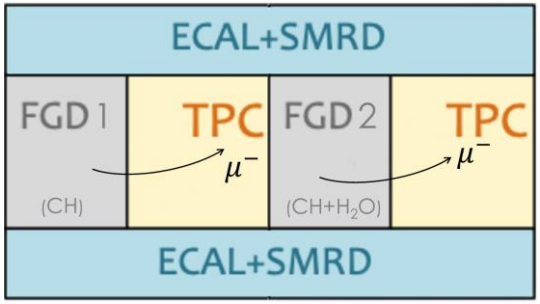

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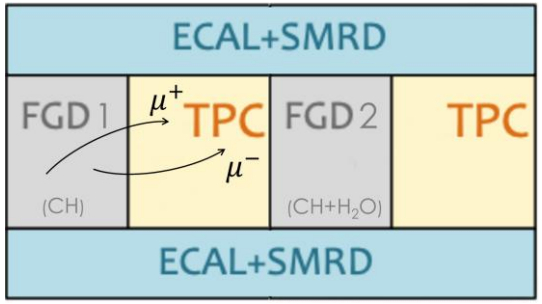

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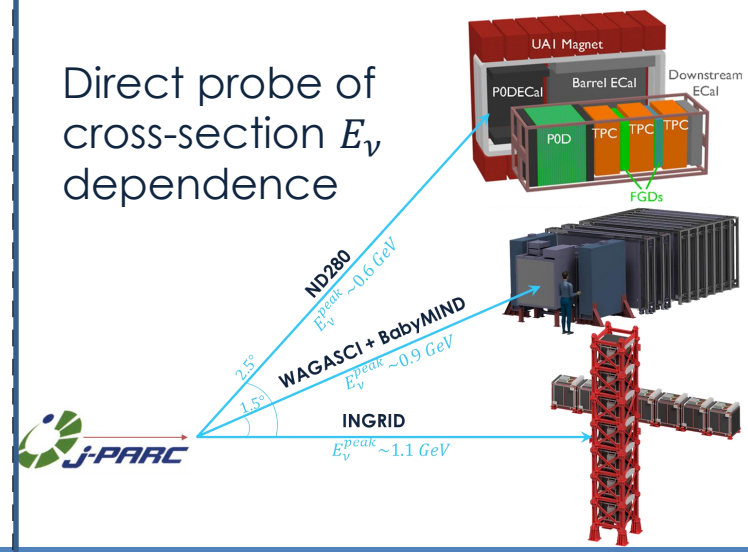

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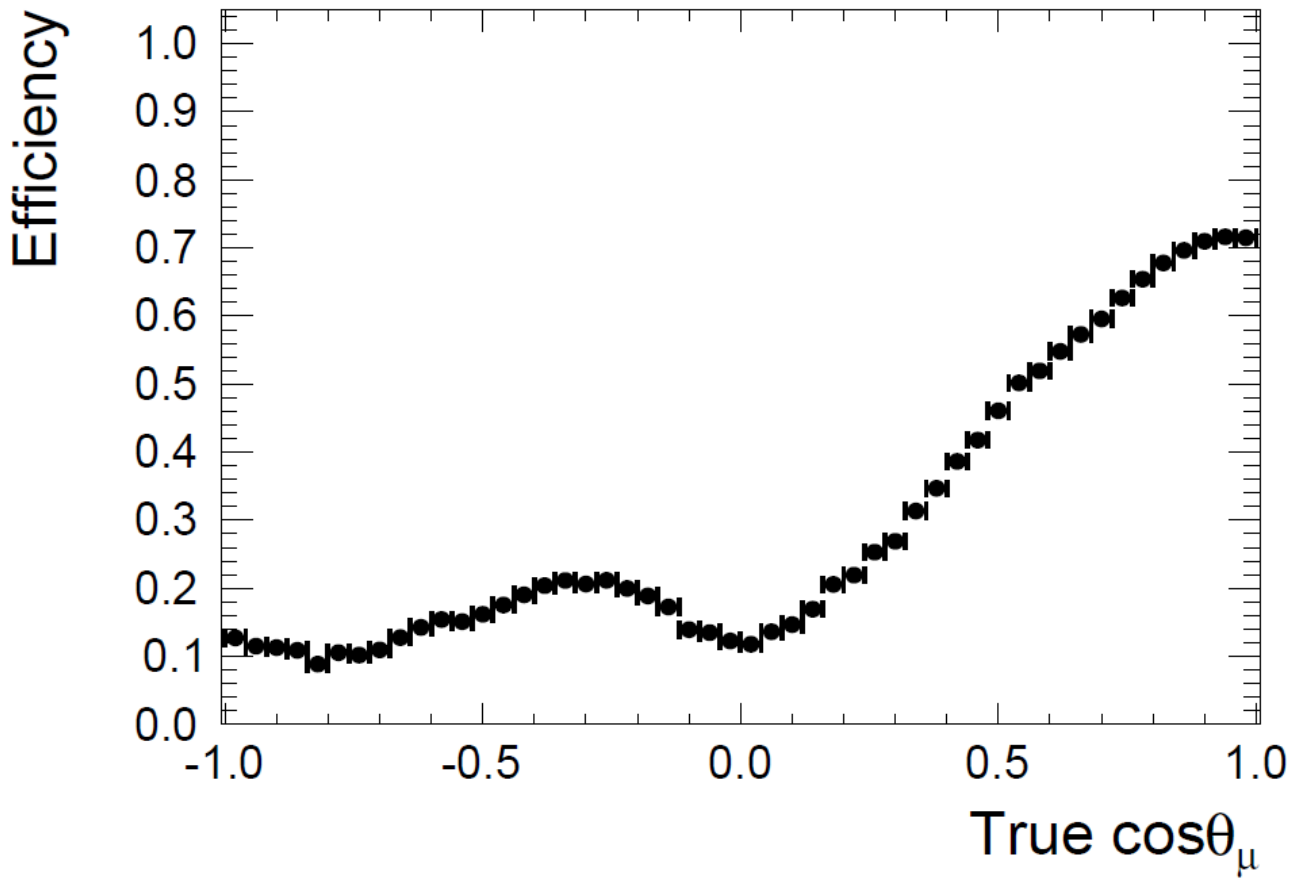
- Remaining background constrained with dedicated control samples



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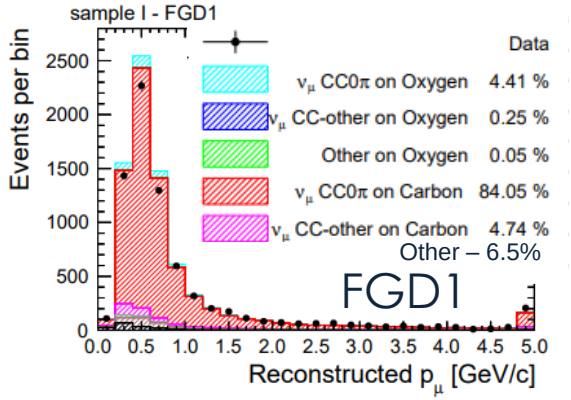
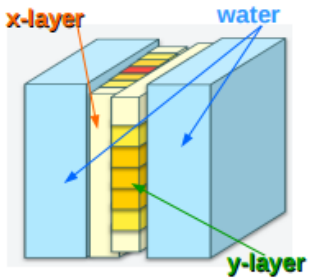
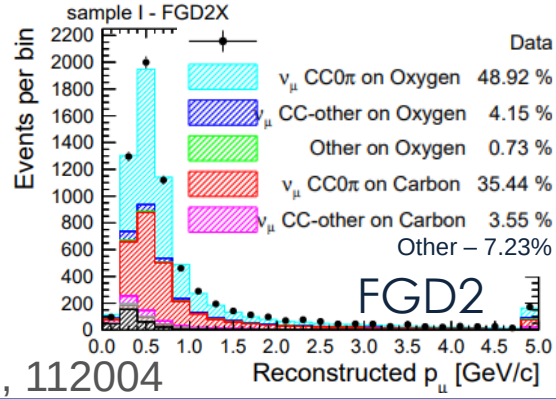
Carbon + Oxygen

- Split selection by which FGD is used
- Use vertex position to identify interactions on FGD2 water layers







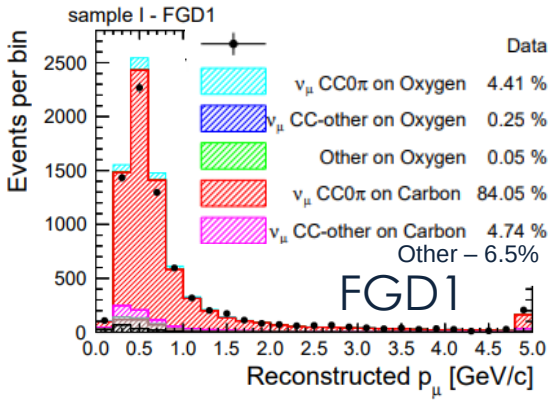
Phys. Rev. D **101**, 112004

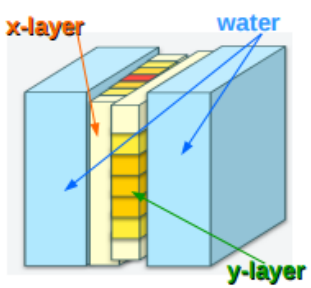
CC0π Selections

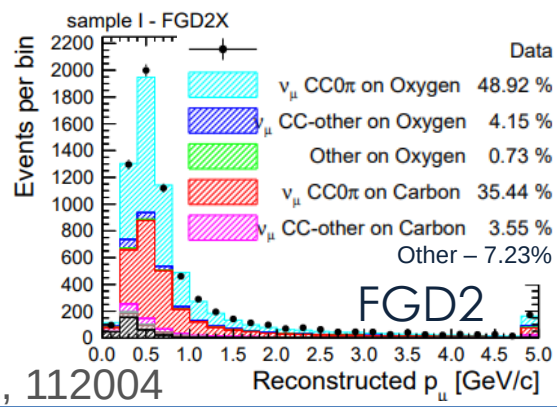
- Select events with at least one identified μ, any number of protons and nothing else. Achieve ~70-90% CC0π purity, ~45% efficiency.
- Remaining background constrained with dedicated control samples

Carbon + Oxygen

- Split selection by which FGD is used
- Use vertex position to identify interactions on FGD2 water layers



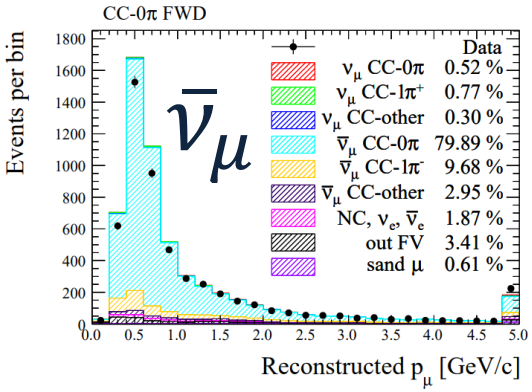


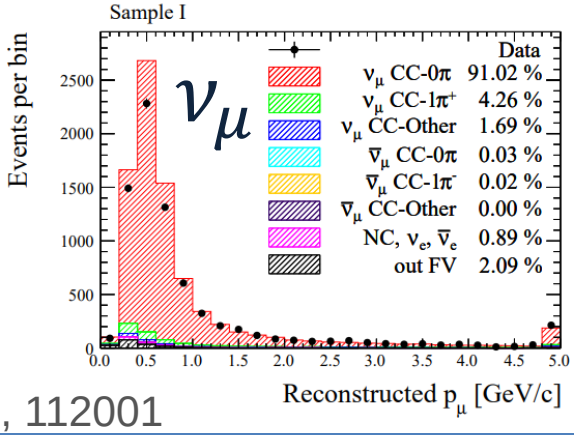


Phys. Rev. D **101**, 112004

Neutrino + Antineutrino

- Apply selection in FGD1 when running, split by if using a ν_μ or $\bar{\nu}_\mu$ focussed beam





Phys. Rev. D **101**, 112001

Cross section extraction

Bin width

$$\frac{d^2\sigma_{CC0\pi}}{dp_\mu d\cos(\theta_\mu)}\Big|_i = \frac{N_{signal,i}}{\epsilon_i \, \Phi \, N_{tgts}} \frac{1}{\left(\Delta p_\mu \Delta \cos(\theta_\mu)\right)_i}$$

Incoming ν_μ flux

Number of targets (nucleons)

Cross section extraction

Number of signal events, background subtracted and corrected for detector smearing

Bin width

$$\frac{d^2\sigma_{CC0\pi}}{dp_\mu d\cos(\theta_\mu)}\Big|_i = \frac{N_{signal,i}}{\epsilon_i \, \Phi \, N_{tgts}} \frac{1}{\left(\Delta p_\mu \Delta \cos(\theta_\mu)\right)_i}$$

Incoming ν_μ flux

Number of targets (nucleons)

- Parameters controlling $N_{signal,i}$, as well as the flux, background and detector response are simultaneously fit to signal and control region data: ***background model directly constrained by data.***
- Cross-section results with no explicit regularisation are provided: ***minimal input model bias from unfolding.***

Cross section extraction

Detector efficiency

Number of signal events, background subtracted and corrected for detector smearing

Bin width

$$\frac{d^2\sigma_{CC0\pi}}{dp_\mu d\cos(\theta_\mu)}\Big|_i = \frac{N_{signal,i}}{\epsilon_i \, \Phi \, N_{tgts}} \frac{1}{\left(\Delta p_\mu \Delta \cos(\theta_\mu)\right)_i}$$

Incoming ν_μ flux

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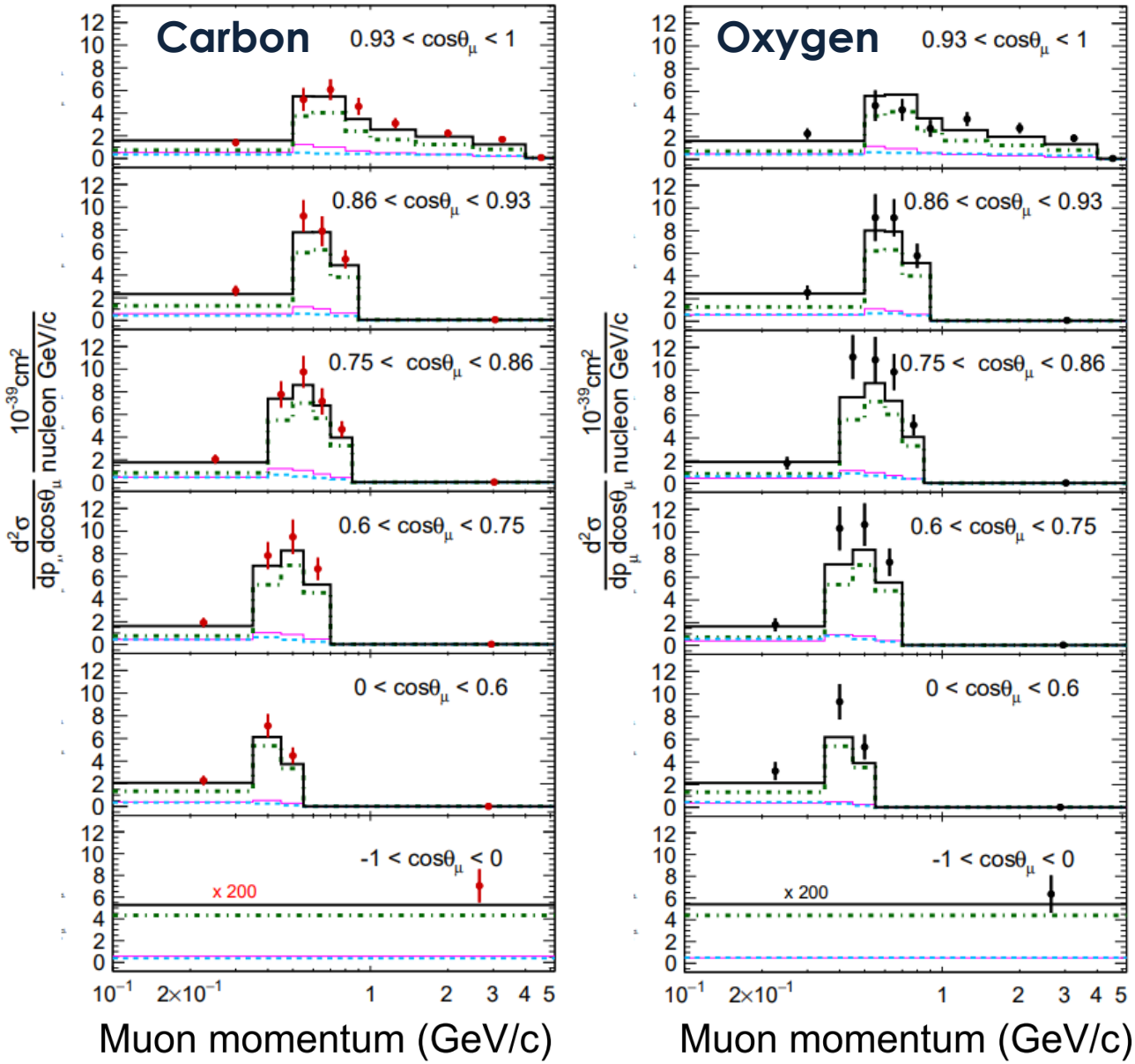
- Cross-section results with no explicit regularisation are provided: ***minimal input model bias from unfolding.***
- Efficiency correction always made in all relevant model dependent observables that can affect detector response: ***minimise model bias here too.***

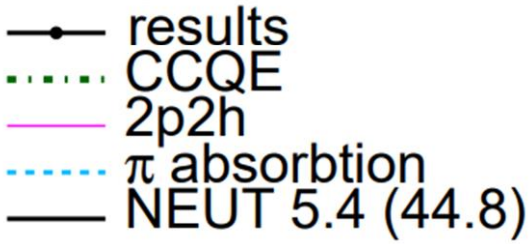
Results (Carbon + Oxygen)

Phys. Rev. D **101**, 112004



- Simultaneous measurement (correlations between C+O provided)
- CCQE dominated across the entire phase space
- Notable other contributions from 2p2h and π abs. FSI

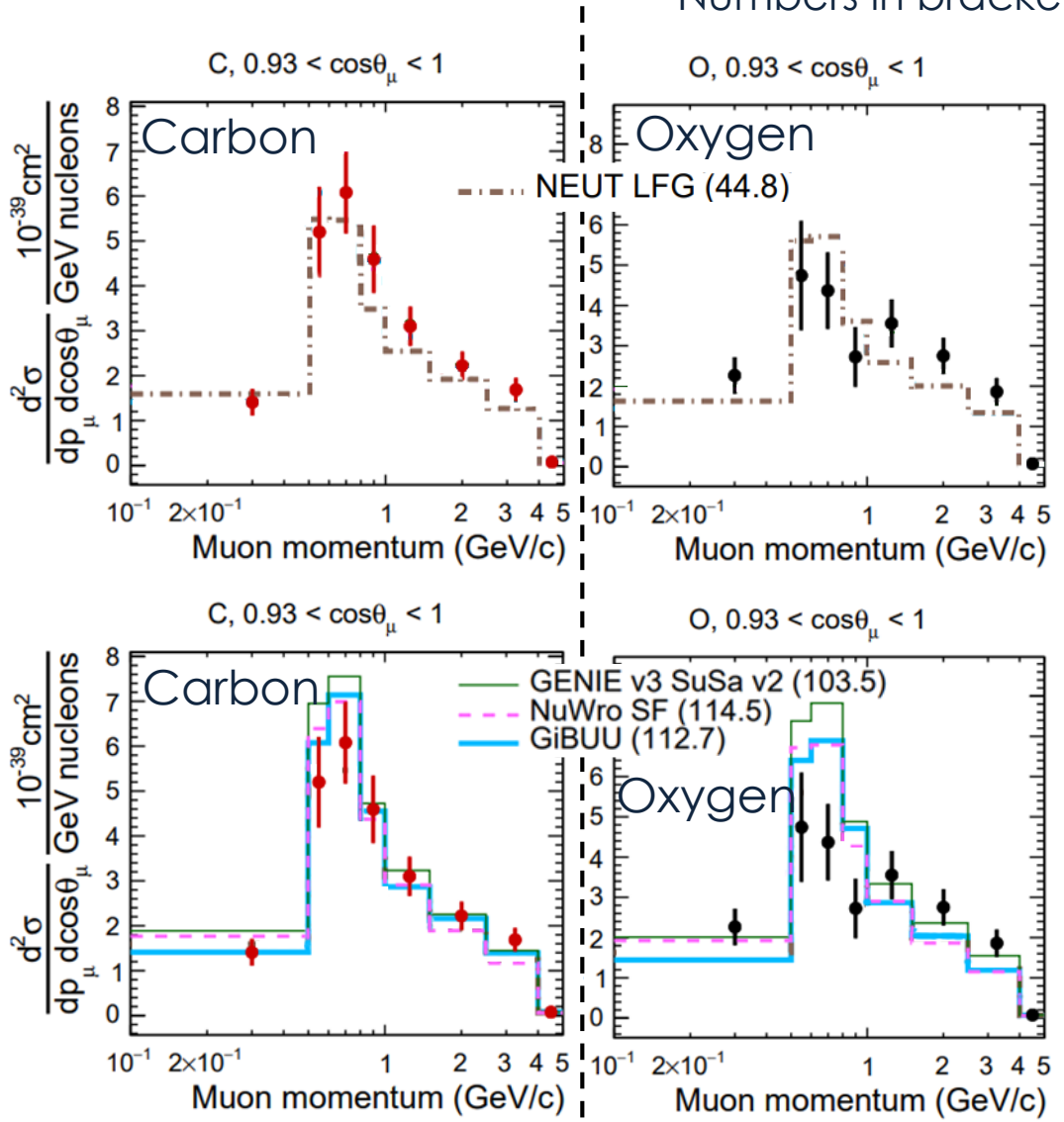
Phys. Rev. D **101**, 112004



Results (Carbon + Oxygen)

Phys. Rev. D **101**, 112004

Numbers in brackets show the χ^2 including all 58 C+O bins



- Interesting nuclear model separation. Mostly from the most forward bin (low momentum + energy transfer for CCQE) and from C vs O differences.
- The result favours more "simple" CCQE Fermi gas nuclear models (LFG) over more sophisticated models (SuSAv2, SF, GiBUU)
- This is largely due to the substantial "RPA" low energy transfer suppression that the Fermi gas models employ

G. Megias, Poster 102 Session 3

Results (Carbon + Oxygen)

Phys. Rev. D **101**, 112004

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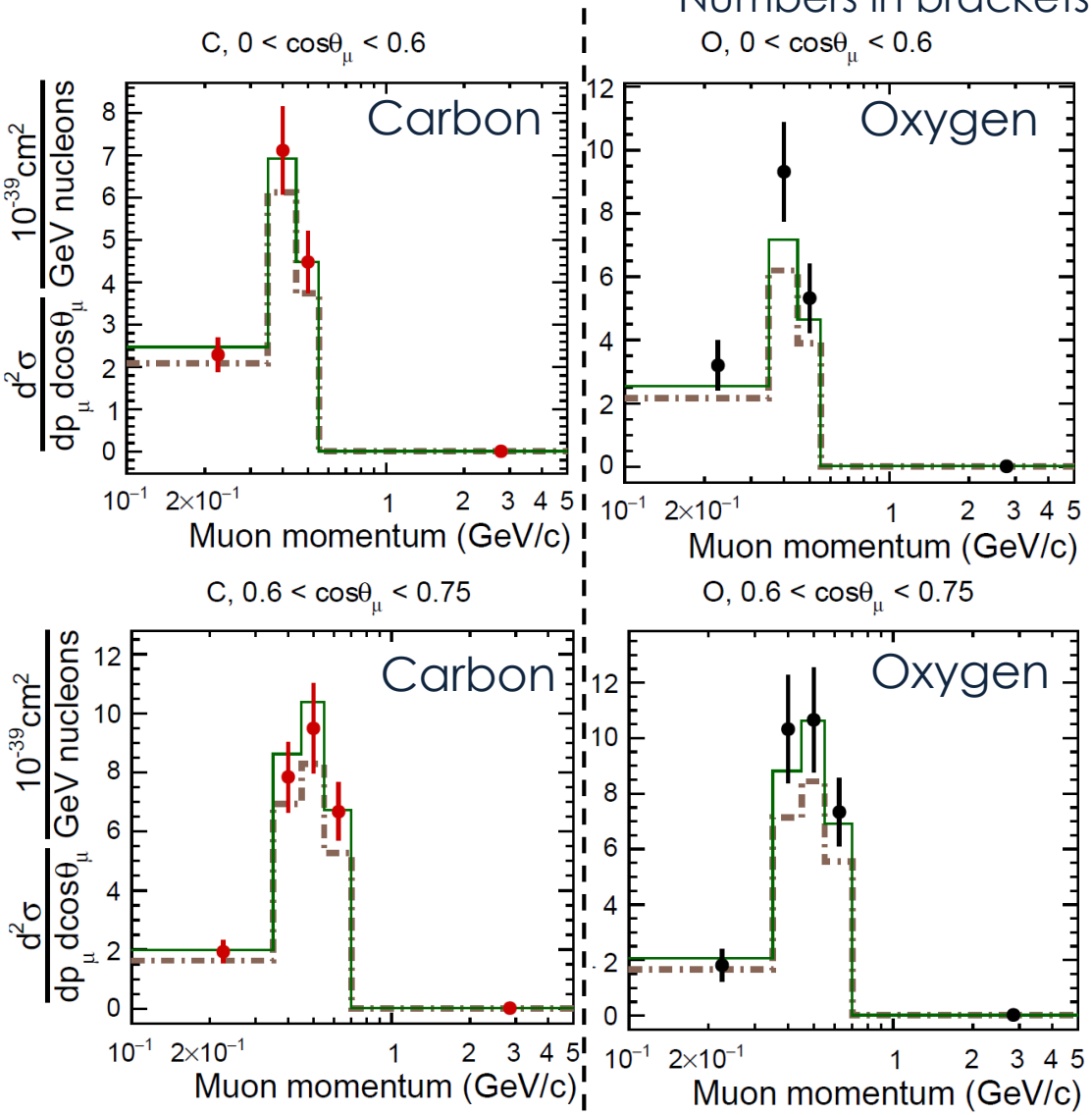


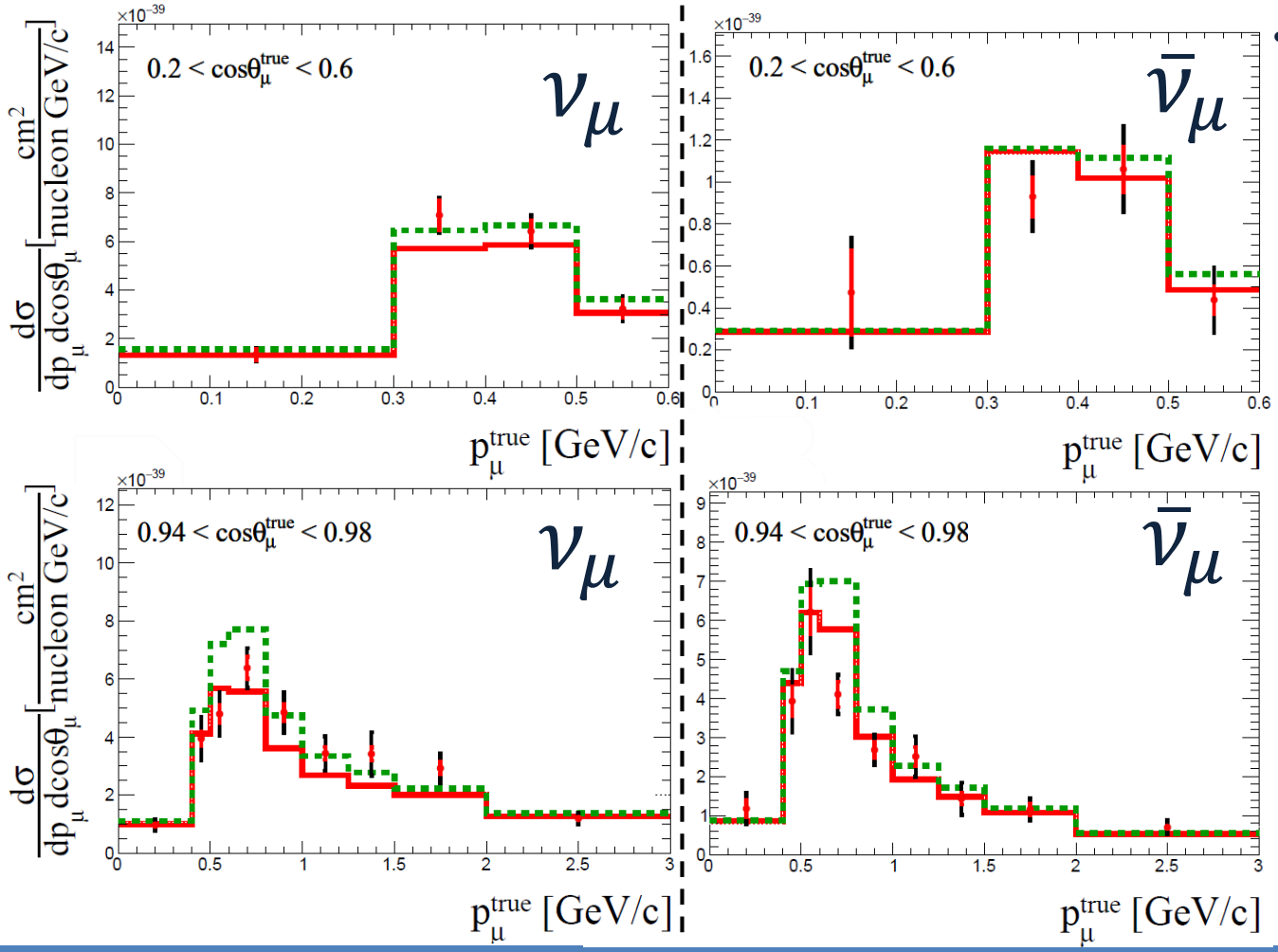
GENIE v3 SuSa v2 (103.5)
NEUT LFG (44.8)

- At higher scattering angle the CCQE LFG models *underestimate* the data
- The CCQE in these bins are more affected by *nucleon-level form factors* rather than *nuclear effects*
- But these cannot explain the Carbon/Oxygen difference
- Need to enhance the nonQE (2p2h, π abs)?

Results (Neutrino + Antineutrino)

Phys. Rev. D **101**, 112001

- Broadly similar conclusions to C/O analysis
  - Need a reduction of the cross section at forward angles
  - Need an enhancement over simple Fermi gas models at higher angles



- But this time **no model describes the whole result very well**

Generator/model	χ^2_{total} (116 dof)
GENIE LFG w/ 2p2h	333.1
NEUT LFG w/ 2p2h	366.7
NEUT LFG w/o 2p2h	236.7
NUWRO LFG w/ 2p2h	408.9
NUWRO SF w/ 2p2h	650.0
GIBUU	488.2
Martini *et al.*	368.6
SUSAV2	565.9

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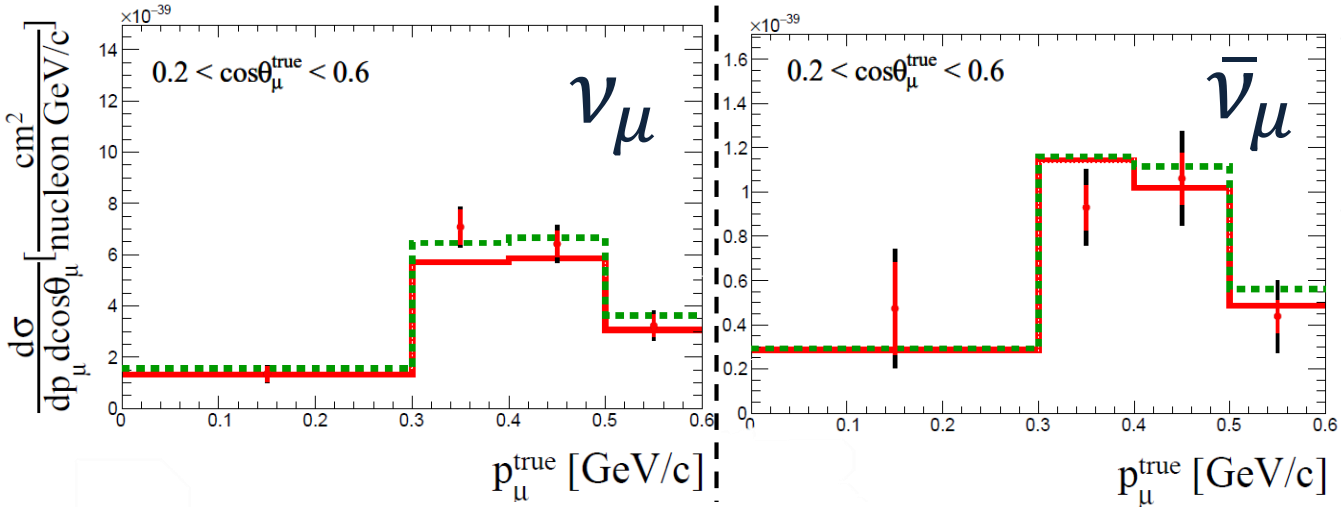
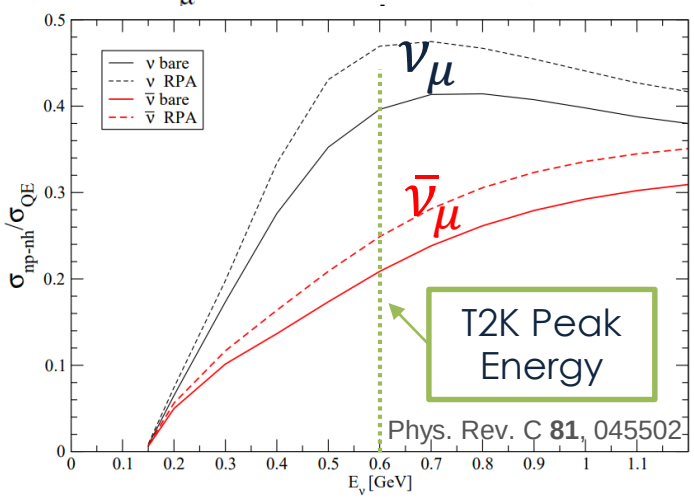


- But this time **no model describes the whole result very well**
- Expect (relatively) less 2p2h contribution for $\bar{\nu}$



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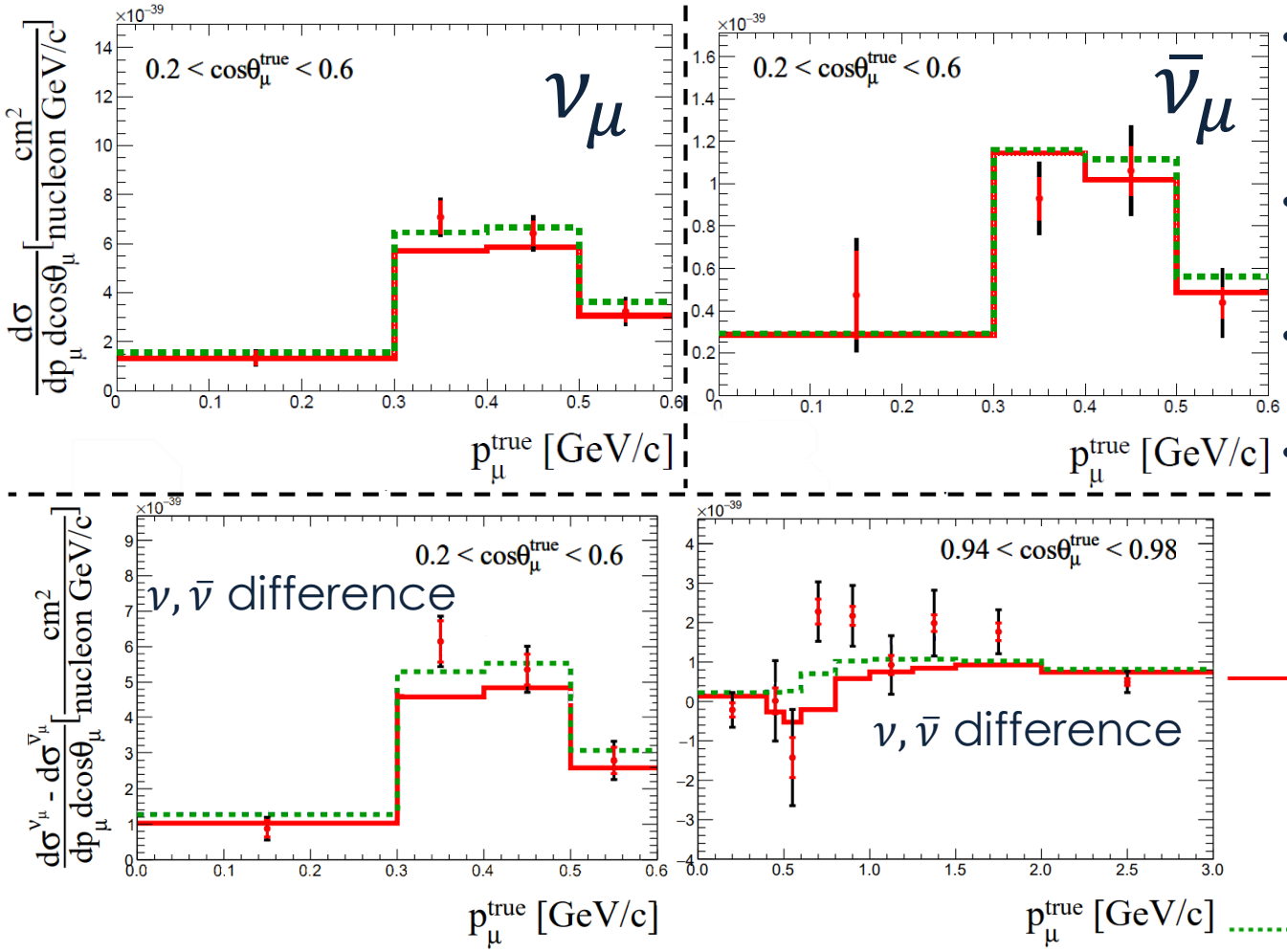

- But this time **no model describes the whole result very well**
- Expect (relatively) less 2p2h contribution for $\bar{\nu}$
- $\nu, \bar{\nu}$ differences offer some extra 2p2h sensitivity
- No model can describe this across all bins

Generator/model	χ^2_{total} (116 dof)	χ^2_{diff} (58 dof)
GENIE LFG w/ 2p2h	333.1	76.2
NEUT LFG w/ 2p2h	366.7	79.5
NEUT LFG w/o 2p2h	236.7	87.6
NUWRO LFG w/ 2p2h	408.9	87.0
NUWRO SF w/ 2p2h	650.0	97.6
GIBUU	488.2	120.1
Martini *et al.*	368.6	119.6
SUSAV2	565.9	119.2

Five things we need to know

(a non exhaustive list)

1. Relative CC0π contribution of CCQE and other processes
   - *So we know how often we mis-reconstruct E_ν*
2. Initial state nucleon momentum and energy
   - *So we know how wide (and biased) our CCQE E_ν reconstruction is*
3. Neutrino energy dependence of cross sections and their differences on Carbon and Oxygen
   - *So we know how to extrapolate from our ND to our FD*
4. Differences in $\nu/\bar{\nu}$ cross sections
   - *So we know when $\nu/\bar{\nu}$ differences imply CP-violation*
5. Differences in ν_e/ν_μ cross sections
   - *So we know how to use our ND constraints on ν_μ in ν_e app. analyses*

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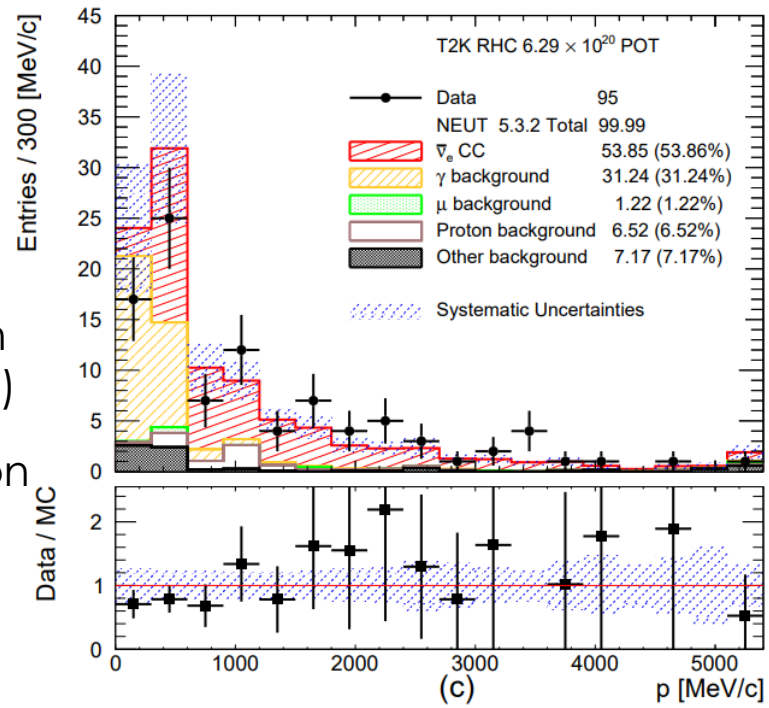
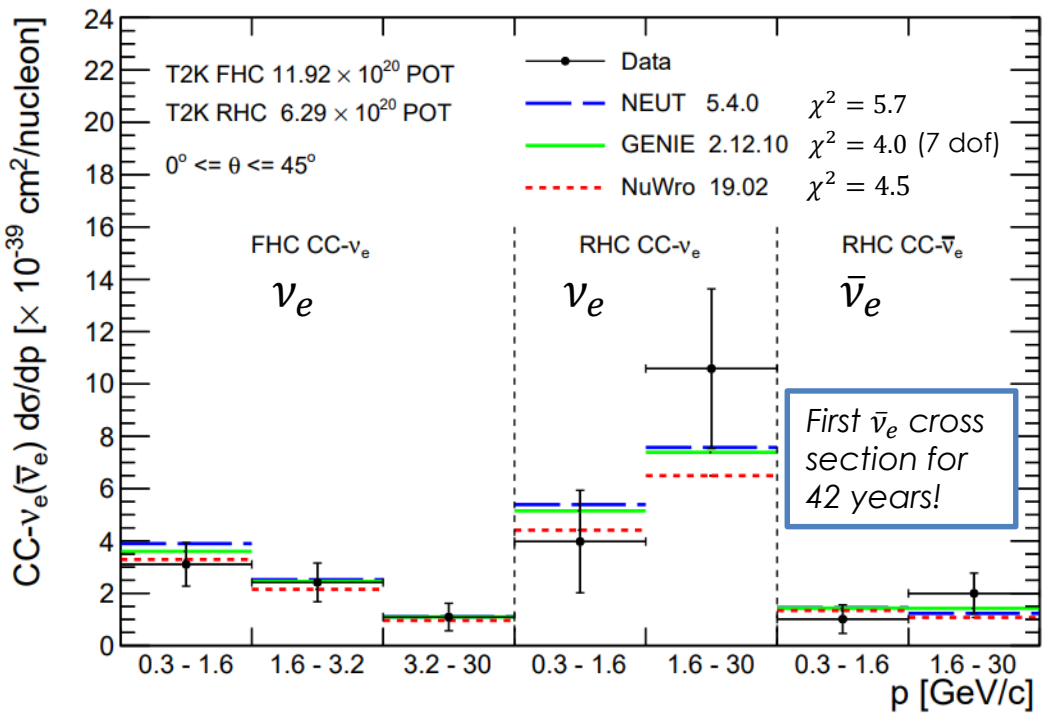
Electron neutrino measurement

arXiv:2002.11986

Selection

- Identify interactions of intrinsic $\overset{(-)}{\nu}_e$ contribution to flux (ν_e is ~1% of the ν_μ) when running to produce predominantly ν_μ (FHC) and $\bar{\nu}_\mu$ (RHC)
- Major background at low reconstructed electron momentum from photons (largely from π^0 decay)
- This is constrained with a dedicated control region





Cross section Measurement

- Detector acceptance limits measurement to: $p_e > 300$ MeV/c, $\theta_e < 45°$
- Large statistical uncertainties
- Good agreement with event generators

Future analyses

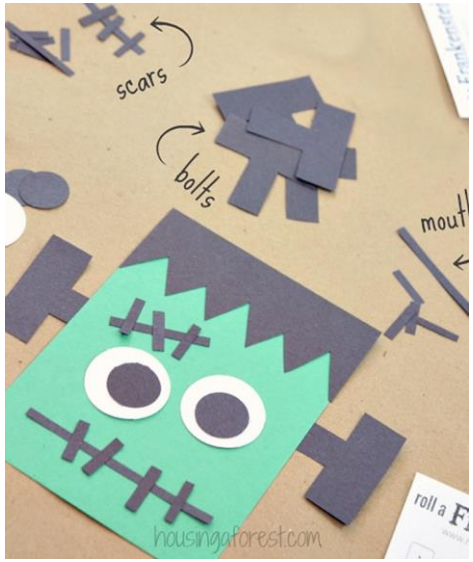
G. Zarnecki, Poster 180 Session 1

New measurements of hadron kinematics
- Transverse imbalance, calorimetry, π kinematics …

Theory Inputs
- ✓ Neutrino scattering predictions carefully constructed from nuclear theory.
- ✓ Precisely validated with electron scattering data
- X Usually have limited scope of application. E.g.:
  - Limited predictive power for hadron kinematics
  - Only valid for one process (e.g. only CCQE)
  - Not valid for very low or high energy transfer

Event generators
- Inputs to our oscillation measurements
- Stitch together available models however we can
- Fill in the gaps with semi-classical approaches

More Joint Measurements
- On/off axis, $C/O/\nu/\bar{\nu}$, …
- Repeat for CC1π, 0π/1π



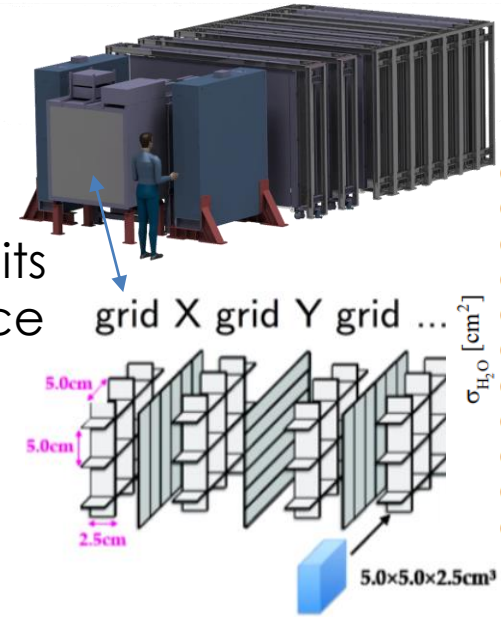
- Continue deconstructing our Frankenmodels with new cross-section measurements

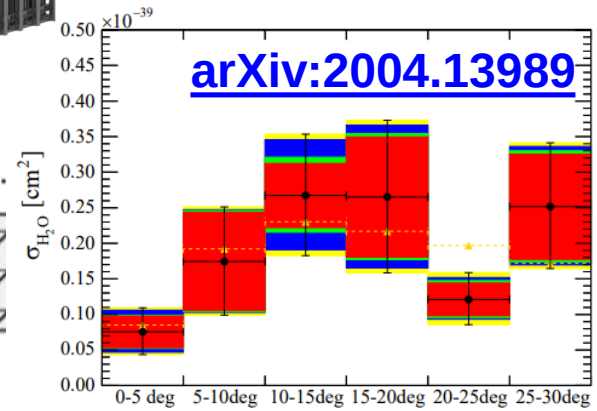
S. Jenkins, Poster 346 Session 4

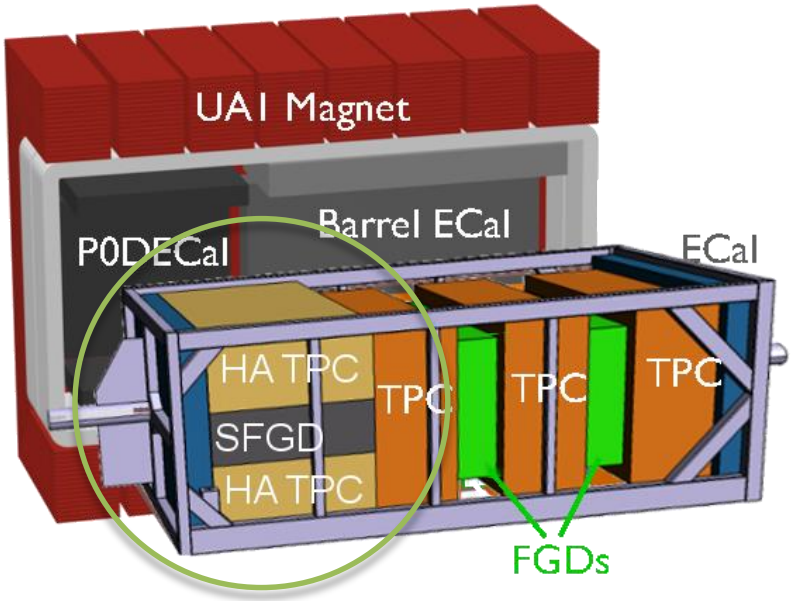
New Detectors

WAGASCI+BabyMIND

- Scintillator "Grid" structure permits excellent high angle acceptance and high relative water mass
- Just released a first analysis!
- $\nu_\mu + \bar{\nu}_\mu$ 1 track on C+O

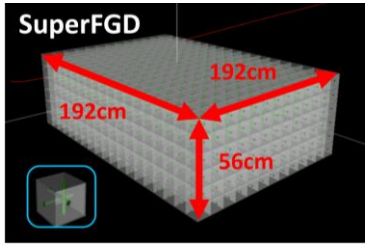






ND280 Upgrade

- Super FGD and two high angle TPCs and surrounding Time-of-Flight counters placed upstream at ND280
- High acceptance low threshold tracking
- Planned installation in 2022



Total # of cubes: 2,064,384
Total # of MPPC ch: 58,368
Total target mass:
2.2 (FGDs) +2.1 (SuperFGD) = 4.3 tons

TDR: CERN-SPSC-2019-001 (SPSC-TDR-006) arXiv:1901.03750

Summary

- To avoid future oscillation analyses becoming **pre-maturely limited by systematic uncertainties**, *it is essential to better understand neutrino-nucleus interactions*

- T2K is 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.**

- T2K's measurements will continue to benefit from increasing statistics in addition to using new and upgraded detectors .

- Taking steps towards *understanding neutrino interactions to the level that will be required for next-generation oscillation physics.*

For more on T2K at NEUTRINO 2020 …

Talk

The Latest Neutrino Oscillation Results from T2K, P. Dunne
(02/07, 9:45 am CET)

Posters

Towards a $\bar{\nu}_\mu CC1\pi^-$ cross-section measurement, **G. Zarnecki**
(Poster 180, Session 1)

T2K's MaCh3 Oscillation Analysis, **K. Wood**
(Poster 208, Session 2)

Development of a multi-ring sample at the T2K far detector, **T. Towstego**
(Poster 250, Session 2)

The relevance of neutrino-nucleus interaction models in T2K, **G. Megias** *et. al*
(Poster 102, Session 3)

Towards a MW-class high power proton beam at J-PARC, **S. Cao**
(Poster 186, Session 3)

Reconstructing pions in an extended phase, **S. Jenkins, X. Lu**
(Poster 346, Session 4)

Measuring the CP-Violating Phase with a new parametrisation , **X. Zhao**
(Poster 272, Session 4)

ν_μ and $\bar{\nu}_\mu$ disappearance analysis from T2K, **S. Zsoldos**
(Poster 325, Session 4)

Backups

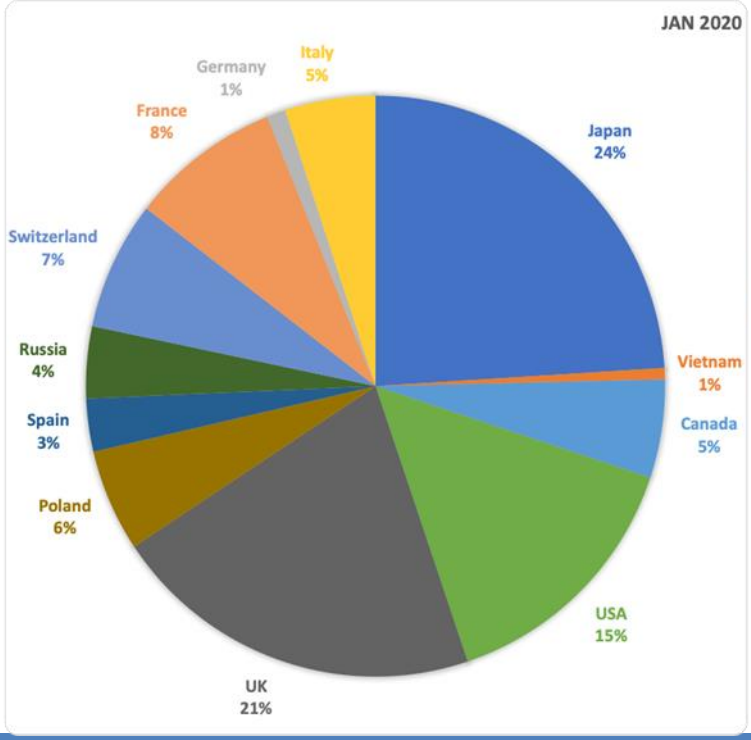
The T2K Collaboration

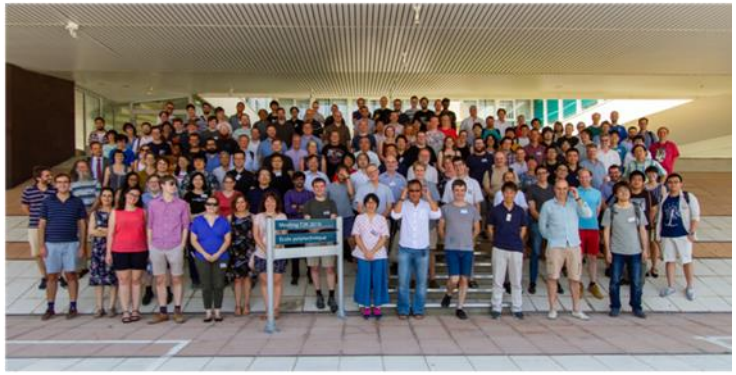
~500 members, 69 Institutes, 12 countries

Asia	117
Japan	114
Vietnam	3

Americas	96
Canada	26
USA	70

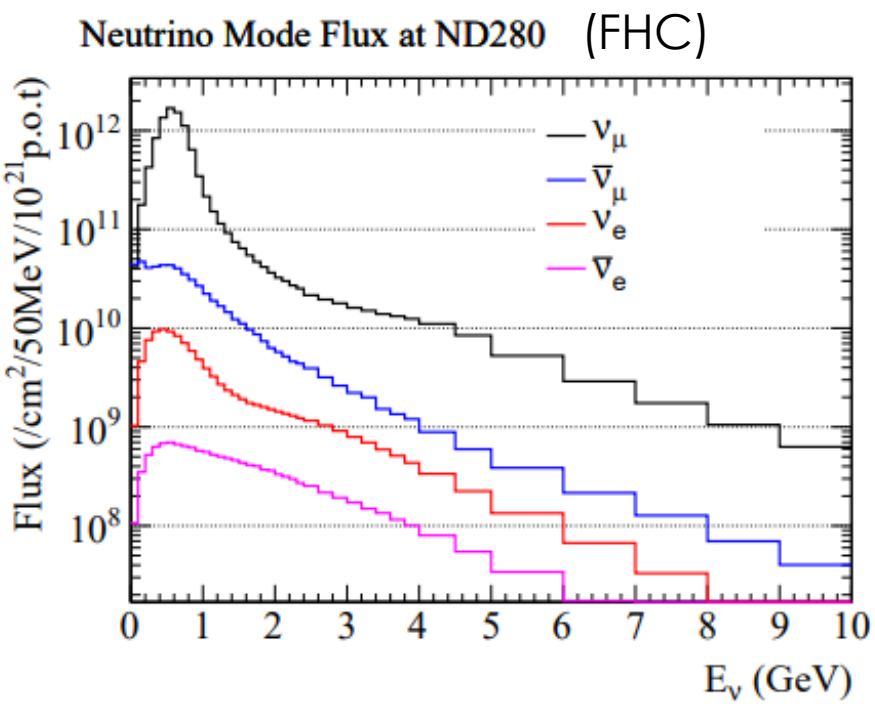
Europe	262
France	40
Germany	5
Italy	24
Poland	27
Russia	19
Spain	14
Switzerland	34
UK	99

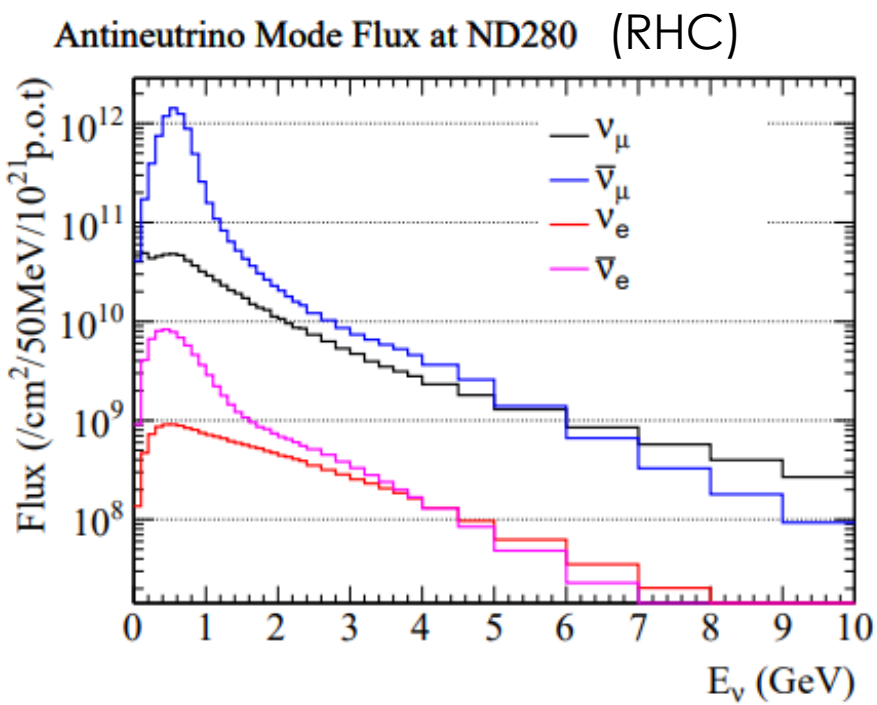




The T2K Neutrino Flux

Phys. Rev. D **87**, 012001





ν oscillations need ν cross sections

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

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

- Need to know $\Phi \times \sigma$ in order to interpret N_{obs} as $P(\alpha \rightarrow \beta)$

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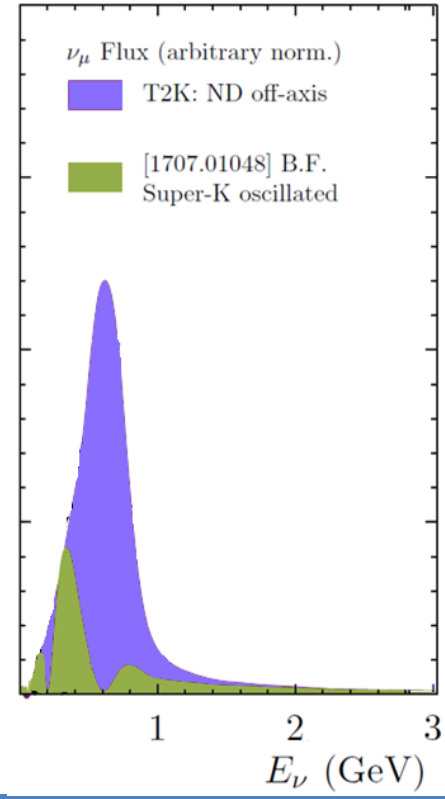
- Need to know $\Phi \times \sigma$ in order to interpret N_{obs} as $P(\alpha \rightarrow \beta)$
- Near / far ratios don't fully cancel this:
  - Dramatic change in E_ν distribution
  - ν_μ at ND vs ν_e at FD (for appearance)
  - Different ND/FD design, acceptance



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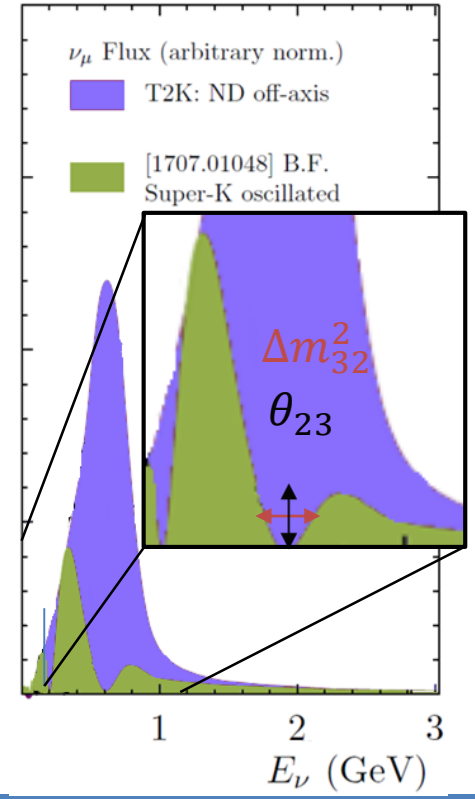
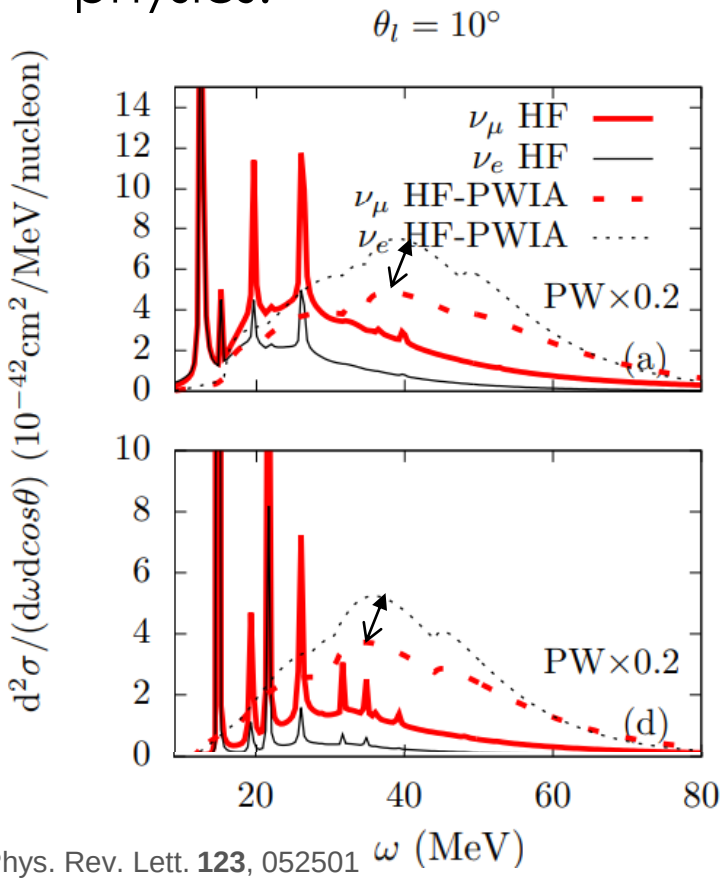
  - Different ND/FD design, acceptance
- Not just counting experiments: Require a model to relate E_ν^{reco} to E_ν^{true}



Electron vs muon neutrino cross sections

- Difference between $\sigma(\nu_e)$ and $\sigma(\nu_\mu)$ critical for oscillation analyses
  - Measure ν_μ at ND but need to know about ν_e to measure δ_{CP}

- The size of these differences also stems from subtleties in the nuclear physics.



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

- If the outgoing nucleon is not affected by the nuclear potential: $\sigma(\nu_e) > \sigma(\nu_\mu)$

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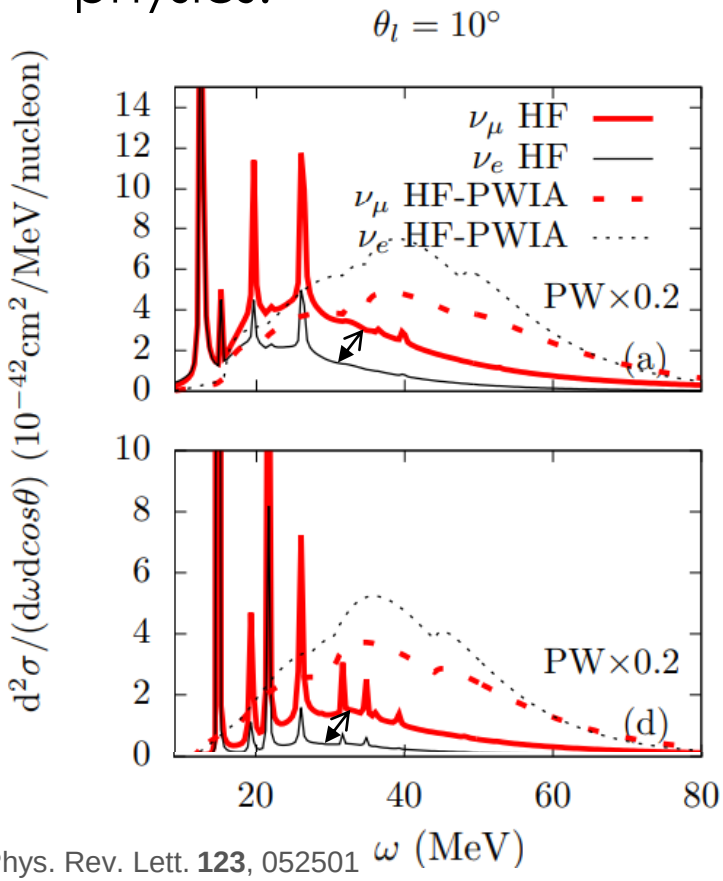


Phys. Rev. Lett. **123**, 052501

- If the outgoing nucleon is not affected by the nuclear potential: $\sigma(\nu_e) > \sigma(\nu_\mu)$

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

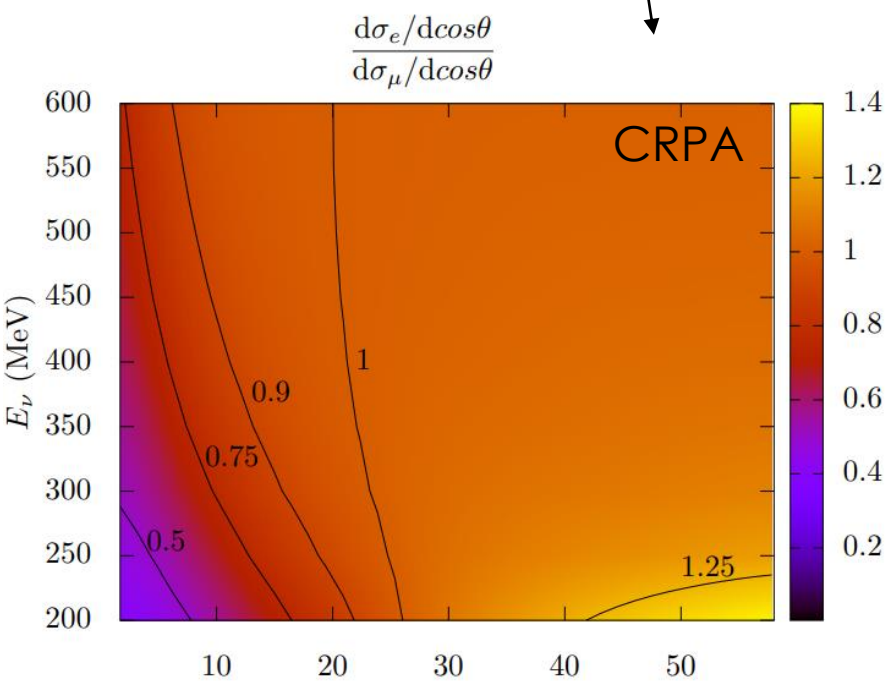
Electron vs muon neutrino cross sections

- Different models can predict quite different cross section ratios!
- Critical for the future

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

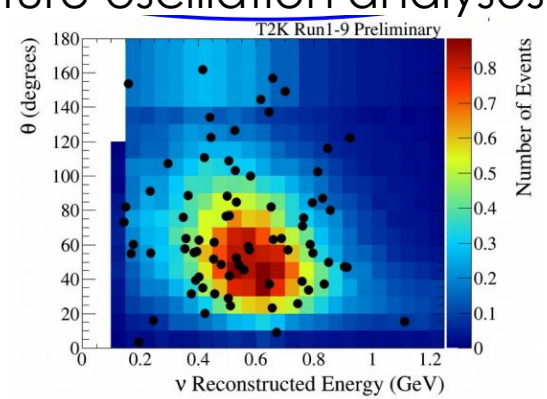
	$E_\nu = 200\ MeV$		$E_\nu = 600\ MeV$	
Model	5°	60°	5°	60°
RFG (w/PB)	0.64	1.61	0.97	1.03
SF (full)	1.41	1.92	1.04	1.03
CRPA	~0.5	~1.4	~0.9	~1.0

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



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

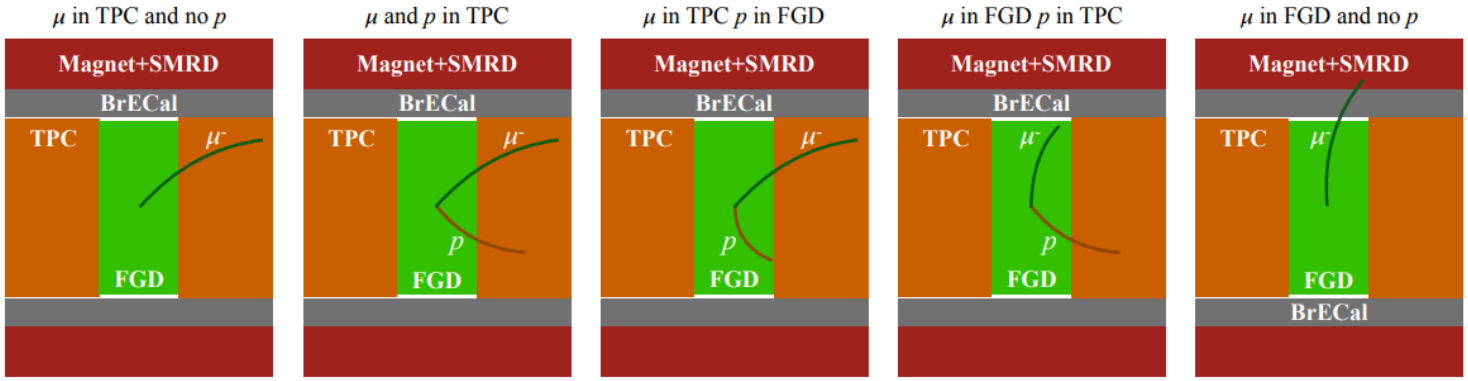
These differences are predicted in regions that are relevant to future oscillation analyses



CC0π Selection Samples

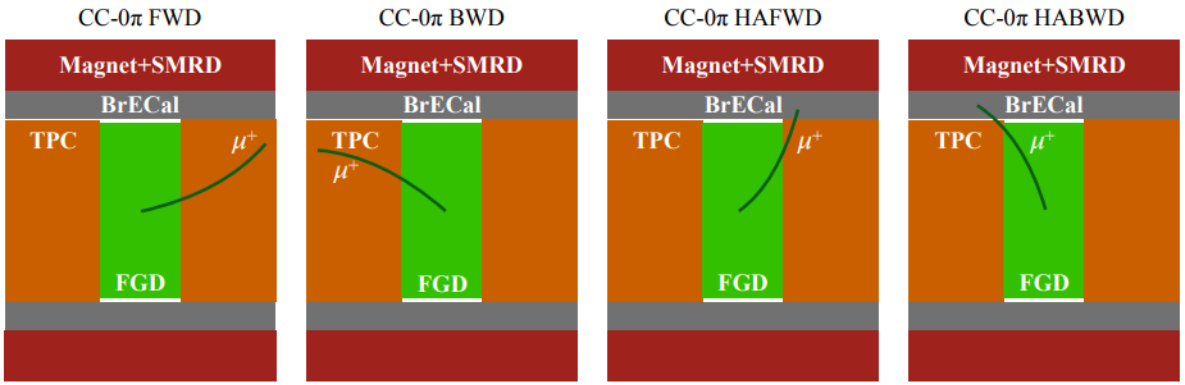
ν_μ

(~12,500 events in FGD 1)

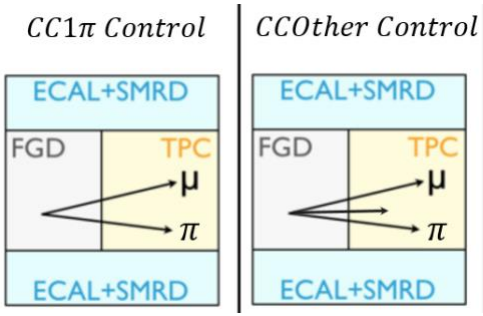


$\bar{\nu}_\mu$

(~5000 events in FGD 1)

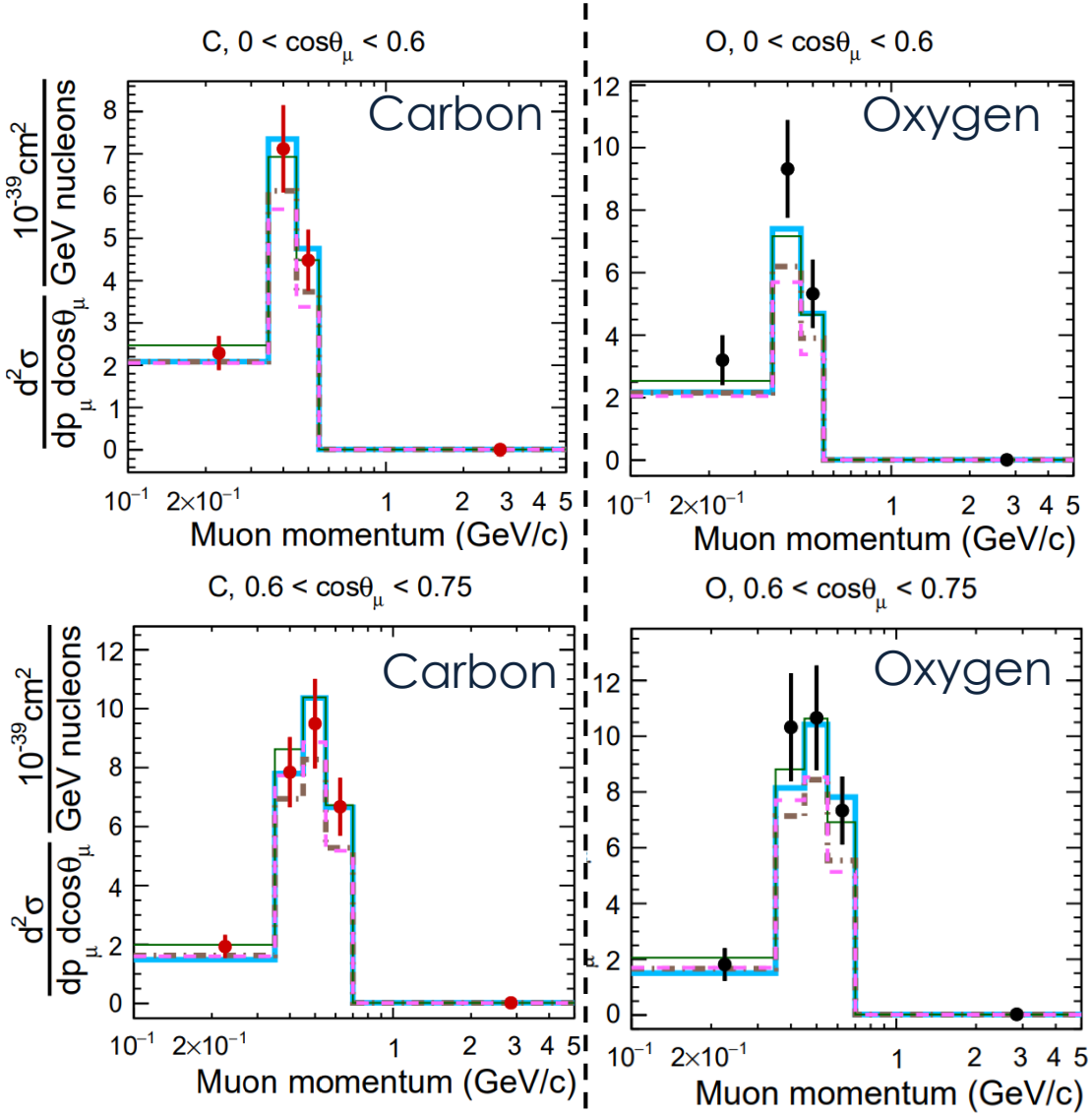


Control Samples



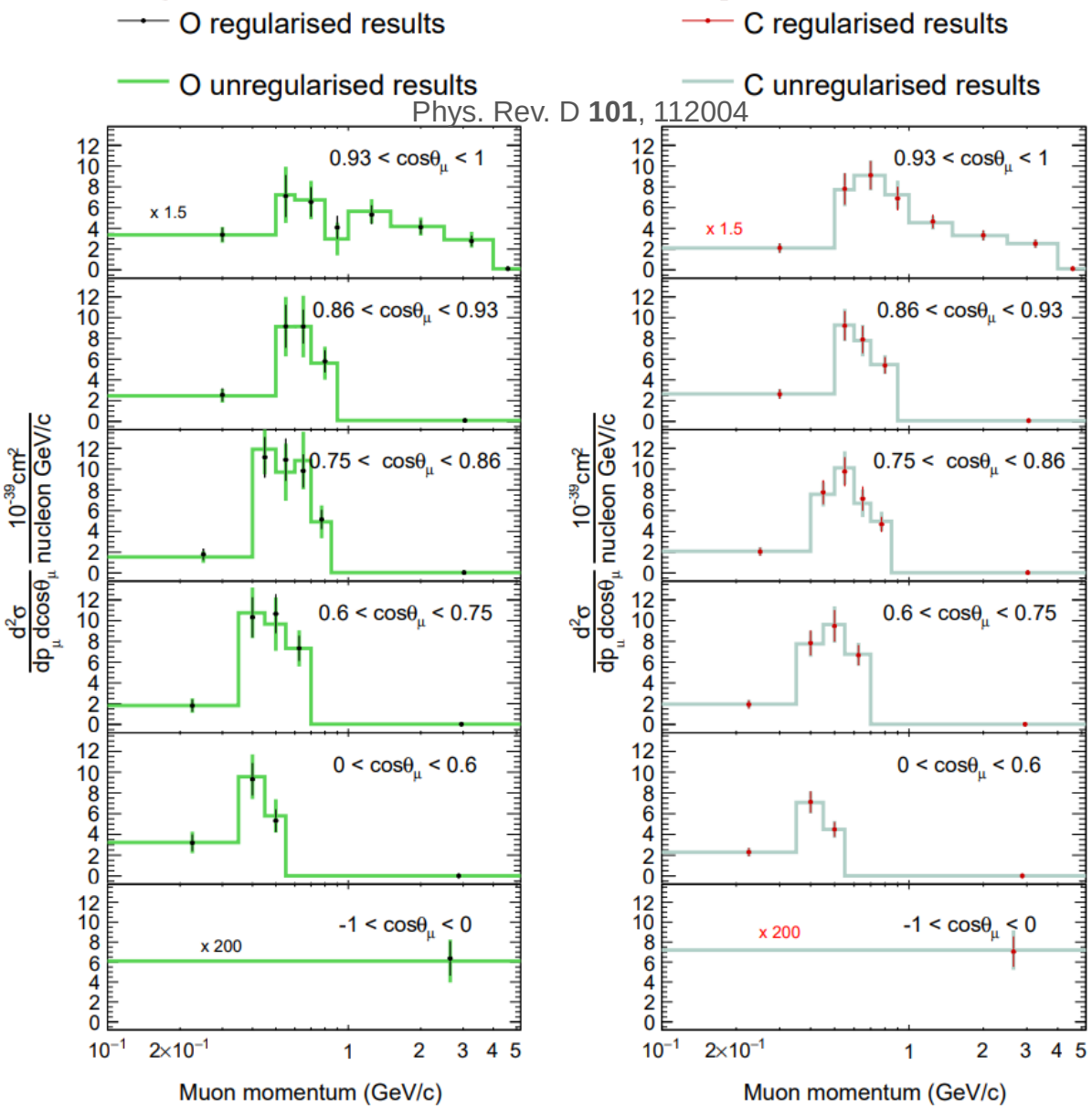
Separated for ν_μ and $\bar{\nu}_\mu$ selections

Results (Carbon + Oxygen)



- At higher scattering angle (larger momentum transfer for CCQE) the CCQE LFG models *underestimate* the data
- The CCQE in these bins are more affected by *nucleon-level form factors* rather than *nuclear effects*
- But these cannot explain the Carbon/Oxygen difference
- Need to enhance the nonQE (2p2h, π abs)?

Regularisation (Carbon + Oxygen)



Regularisation (Carbon + Oxygen)

Phys. Rev. D **101**, 112004

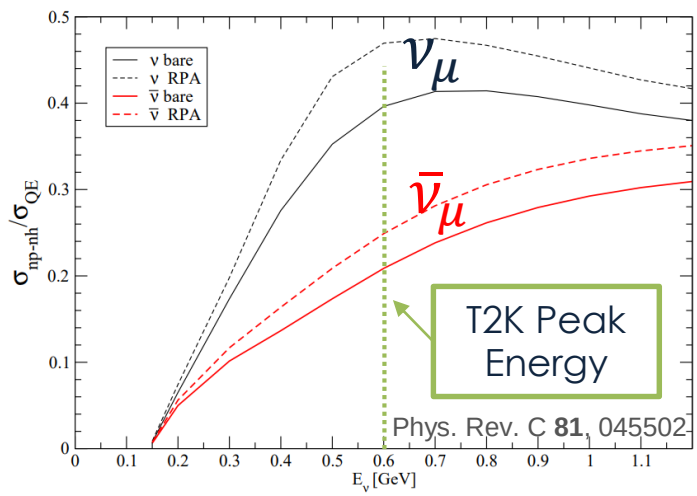
Generator	result	Total χ^2 (shape only) (ndof = 58)	χ^2 w/o last $\cos\theta_\mu$ bin (ndof = 50)	only O χ^2 (ndof = 29)	only C χ^2 (ndof = 29)	O/C ratio χ^2 (ndof = 29)
NEUT 5.4.1 LFG	reg.	44.8 (58.6)	17.9 (21.1)	26.0 (34.5)	15.2 (20.1)	30.8
	unreg.	44.4 (62.3)	17.3 (22.5)	26.4 (39.1)	14.0 (19.4)	30.6
NEUT 5.4.0 SF	reg.	111.0 (156.8)	45.3 (69.0)	50.0 (77.6)	40.1 (58.3)	31.7
	unreg.	116.8 (166.7)	45.1 (70.1)	53.7 (86.5)	38.6 (56.2)	32.2
NuWro 18.2 LFG	reg.	64.7 (83.7)	21.0 (30.5)	31.9 (45.0)	23.5 (31.5)	33.1
	unreg.	66.8 (88.7)	21.1 (32.1)	32.9 (49.9)	22.6 (30.6)	33.5
NuWro 18.2 SF	reg.	114.5 (180.1)	50.2 (80.9)	50.1 (86.1)	44.8 (70.3)	34.2
	unreg.	119.2 (189.0)	48.7 (80.9)	52.7 (94.8)	42.6 (67.4)	33.9
Genie 3 LFG hN	reg.	48.9 (58.5)	22.3 (24.6)	24.9 (32.1)	18.4 (22.3)	33.5
	unreg.	46.6 (60.0)	20.1 (23.8)	24.7 (35.6)	16.3 (20.4)	34.0
Genie 3 LFG hA	reg.	55.4 (62.0)	22.9 (25.5)	27.8 (34.3)	19.8 (22.3)	32.3
	unreg.	52.9 (62.0)	21.0 (24.5)	27.7 (37.0)	17.7 (20.4)	32.6
Genie 3 SuSAv2	reg.	103.5 (105.4)	39.0 (44.7)	50.6 (57.3)	35.8 (36.8)	29.8
	unreg.	110.3 (111.3)	40.3 (45.6)	55.4 (62.8)	35.1 (35.5)	30.1
RMF (1p1h)	reg.	90.6 (97.5)	48.2 (60.5)	31.4 (37.8)	43.9 (51.3)	31.3
+ SuSAv2 (2p2h)	unreg.	95.8 (102.2)	49.3 (60.7)	34.0 (42.1)	41.9 (48.1)	30.7
GiBUU	reg.	112.7 (117.0)	47.2 (50.6)	46.8 (58.0)	46.6 (46.1)	39.3
	unreg.	107.5 (112.2)	41.7 (46.8)	43.5 (56.0)	41.0 (41.2)	37.0

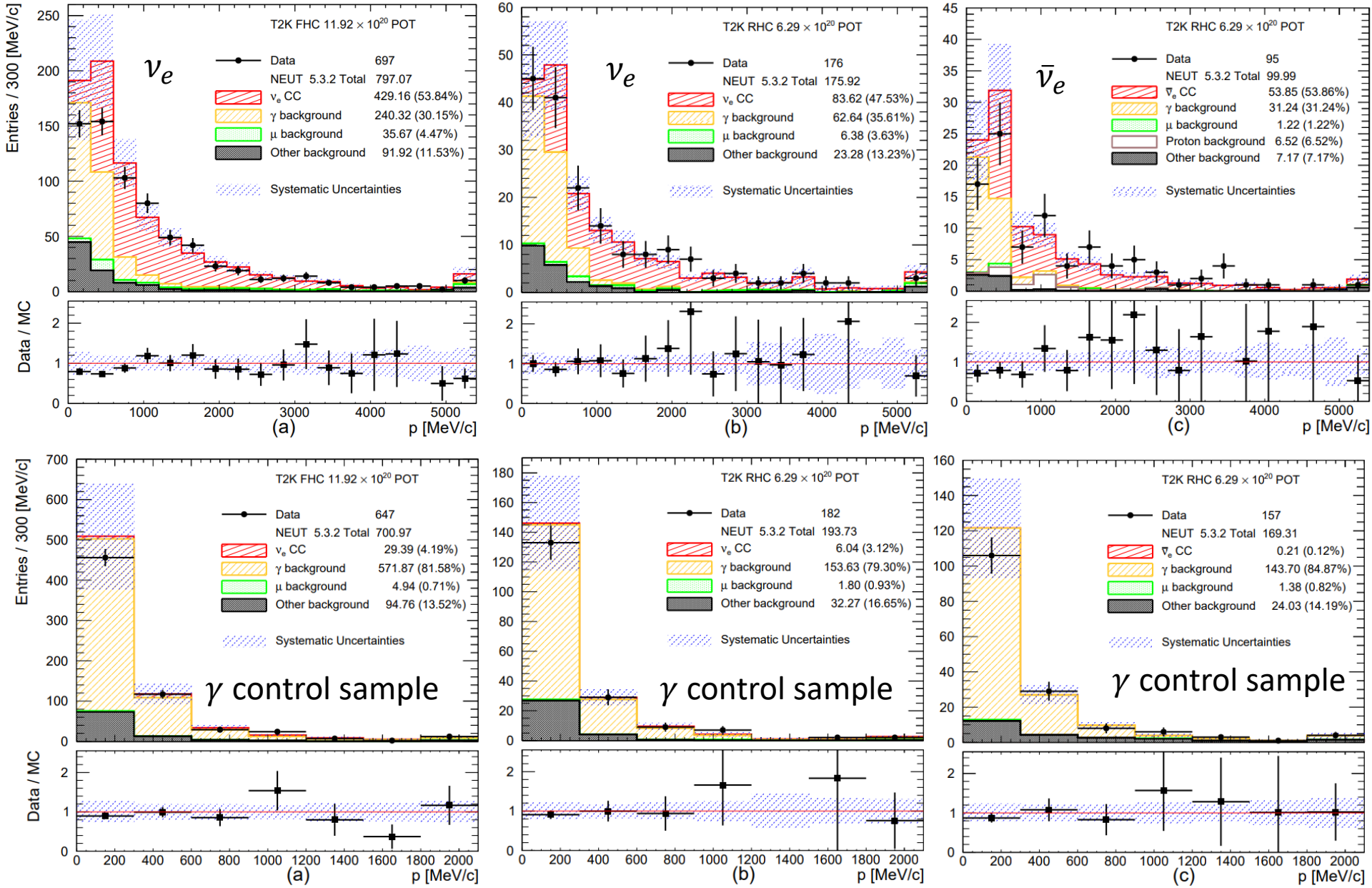
Neutrino-Antineutrino 2p2h Sensitivity

(Anti)neutrino and interactions differ by the sign of the V-A interference term. The relative weight of the different nuclear responses and the relative role of the multi-nucleon ejection are different

$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \frac{G_F^2\cos^2\theta_c}{2\,\pi^2}k'\epsilon'\cos^2\frac{\theta}{2}\left[\frac{(q^2-\omega^2)^2}{q^4}G_E^2\,R_\tau + \frac{\omega^2}{q^2}G_A^2\,R_{\sigma\tau(L)} + \right.$$
$$\left. + \;2\left(\tan^2\frac{\theta}{2}+\frac{q^2-\omega^2}{2q^2}\right)\left(G_M^2\frac{\omega^2}{q^2}+G_A^2\right)R_{\sigma\tau(T)} \pm 2\,\frac{\epsilon+\epsilon'}{M_N}\tan^2\frac{\theta}{2}\,G_A\,G_M\,R_{\sigma\tau(T)}\right]$$

Neutrino-antineutrino cross section differences can shed light on the multi-nucleon ejection



Electron neutrino measurement

arXiv:2002.11986