The needs of the accelerator-based neutrino program

Snowmass theory white paper workshop

Credit: James Montgomery Flagg

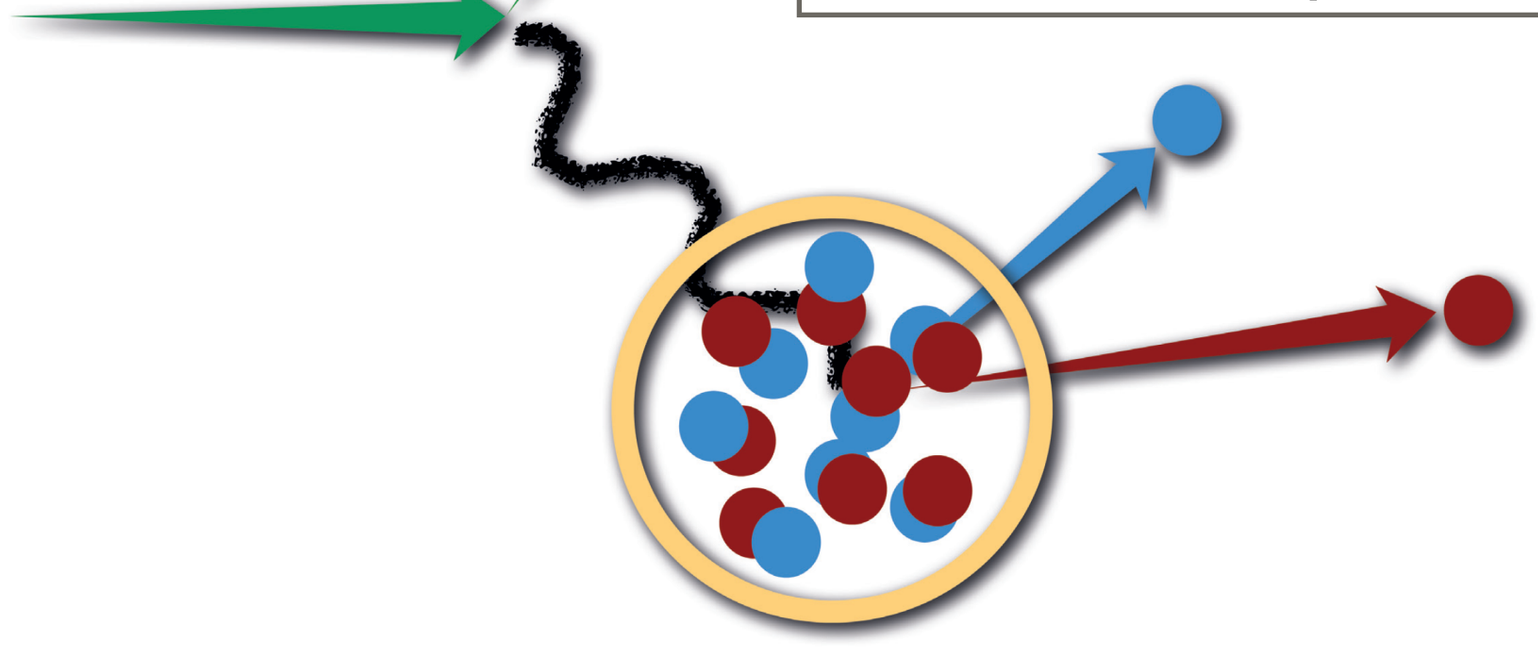
Kendall Mahn
Michigan State University

Aug 25th 2021

Outline

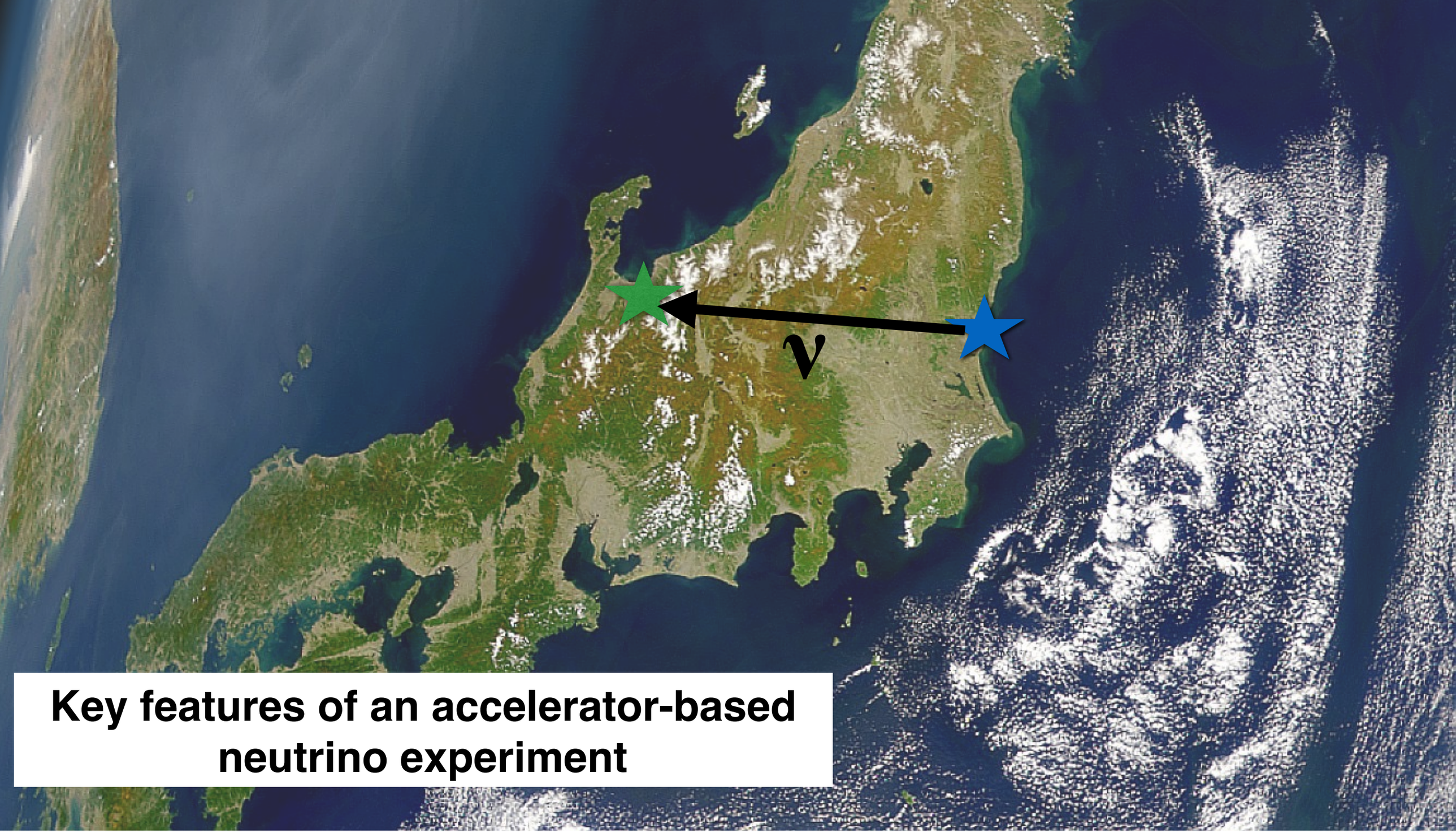
What physics is planned for the current and future accelerator-based neutrino program?

Why is neutrino-nucleus theory important to those expt's?



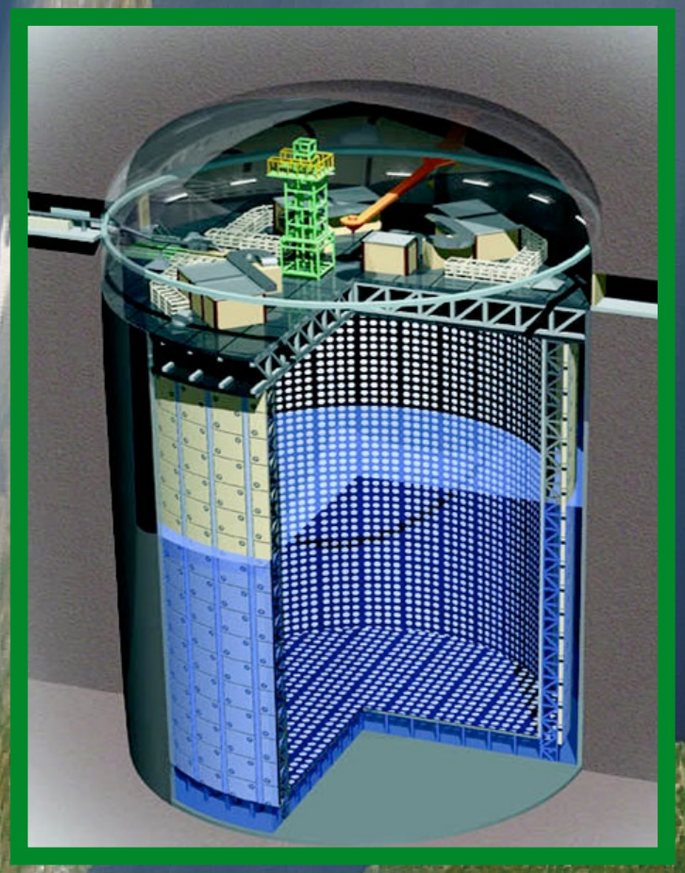
What needs to be studied and understood?

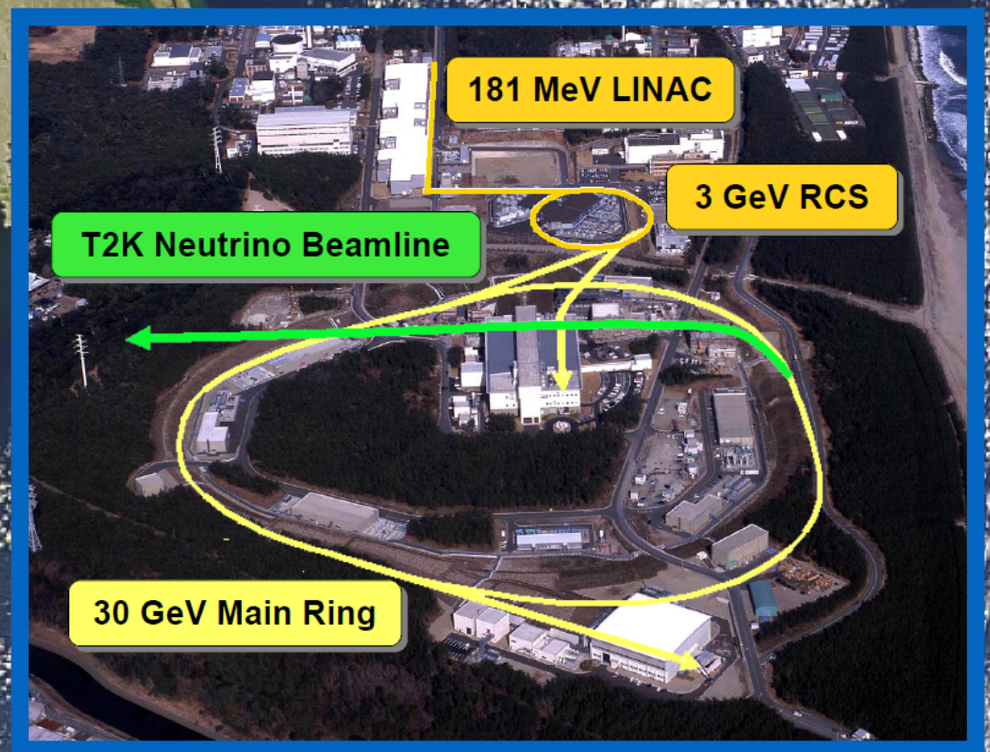
What is the plan for the white paper?



Key features of an accelerator-based neutrino experiment

- Example is Tokai-to-Kamioka (T2K) experiment





Key features of an accelerator-based neutrino experiment

- **Accelerator** produces an intense (anti)neutrino source
- Massive **(far) detector** (Super-Kamiokande), additional detectors **near** production

Current:

Atmospheric: Super-Kamiokande

Accelerator: T2K, NOvA, Short-Baseline Neutrino Program (SBN)

US-funded program is broad.

Neutrino oscillation, exotica (e.g. sterile neutrino, dark matter searches), proton decay

Future:

Accelerator/Atmospheric: Deep Underground Neutrino Experiment

Signal (or background) processes are 0.1-20 GeV charged current (CC) or neutral current (NC) neutrino or antineutrino interactions for **atmospheric and accelerator based programs**

Neutrino oscillation open questions

Oscillation depends on:

- Amplitude determined by mixing angles: θ_{12}, θ_{23}, θ_{13}

  Is $\sin^2(\theta_{23})=0.5$? (maximal mixing?)

- Frequency determined by mass splittings: $|\Delta m^2_{32/31}|$,Δm^2_{21}

  What is the ordering of the masses ($\Delta m^2_{32/31} > 0$?)

- CP violating phase (CPV)

  Is there CPV in neutrinos?

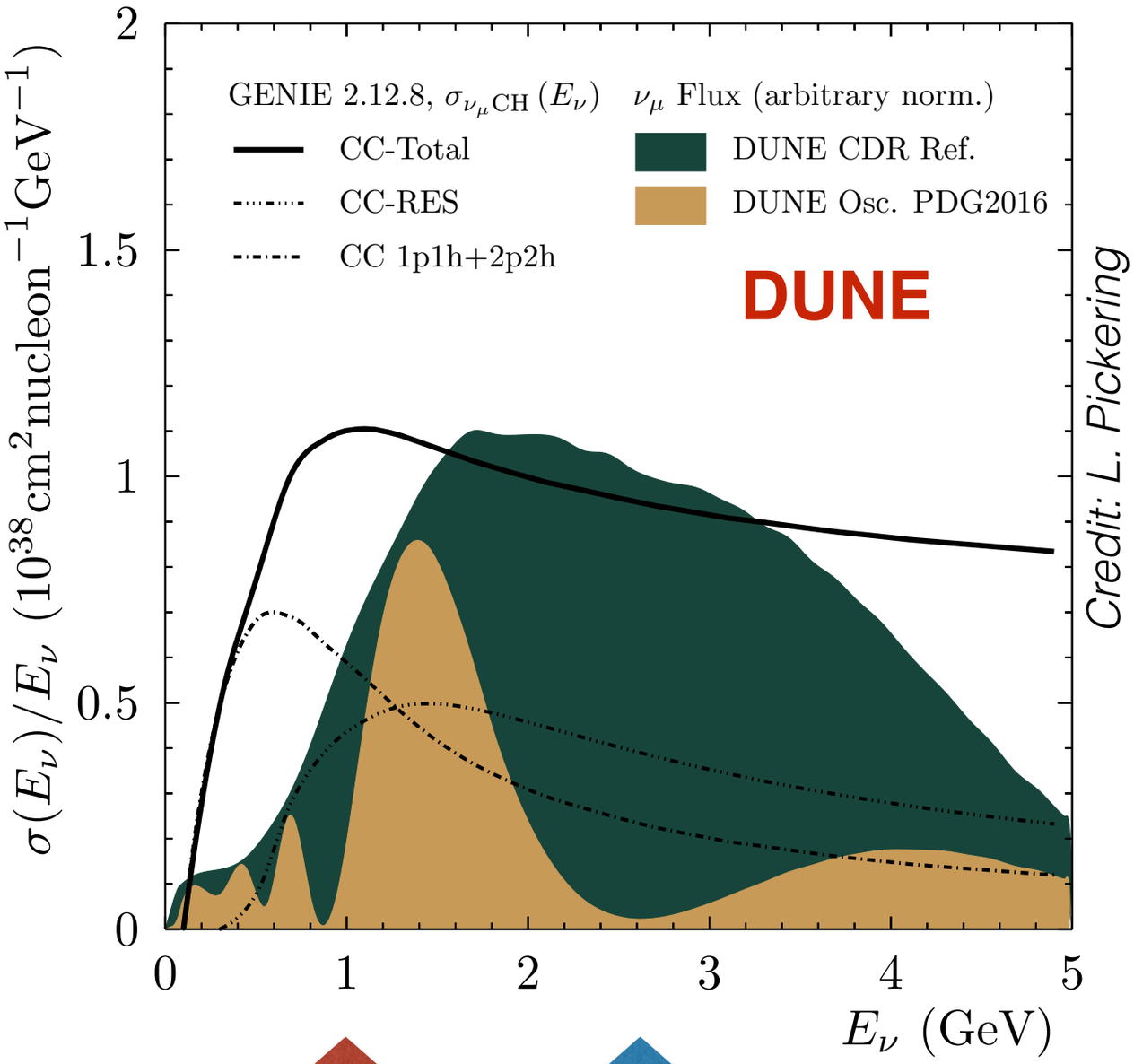
Valuable detail in energy spectra

Oscillation depends on:

- Amplitude determined by mixing angles: θ_{12}, θ_{23}, θ_{13}
- Frequency determined by mass splittings: $|\Delta m^2_{32/31}|$, Δm^2_{21}
- CP violating phase (CPV)

Largely independent of δ_{CP} effects

ν_μ and $\bar{\nu}_\mu$ disappearance channel



Second osc. max

First osc. max @ L=1300km

Valuable detail in energy spectra

Oscillation depends on:

- Amplitude determined by mixing angles: θ_{12}, θ_{23}, θ_{13}
- Frequency determined by mass splittings: $|\Delta m^2_{32/31}|$,Δm^2_{21}
- CP violating phase (CPV)

ν_e and $\bar{\nu}_e$ appearance channel

For $\delta_{CP} = -\pi/2$, suppress $\bar{\nu}_e$ appearance, enhance ν_e appearance

Increasing θ_{23} enhances both ν_e and $\bar{\nu}_e$ appearance

Normal mass ordering to inverted suppresses ν_e appearance, enhances $\bar{\nu}_e$ appearance

T2K	PREDICTED			
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$
ν_e appearance	73.8	61.6	50.0	62.2
$\bar{\nu}_e$ appearance	11.8	13.4	14.9	13.2

Oscillation analysis strategy

$\Delta m^2_{32/31}$, θ_{13}, θ_{23}, δ_{CP}, mass hierarchy

ν_e event rate

$\bar{\nu}_e$ event rate

ν_μ event rate

$\bar{\nu}_\mu$ event rate

$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma^i_\beta(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

- Fit **event rate** to determine oscillation parameters for muon, electron neutrino and antineutrino subsamples

Oscillation analysis depends on interaction model

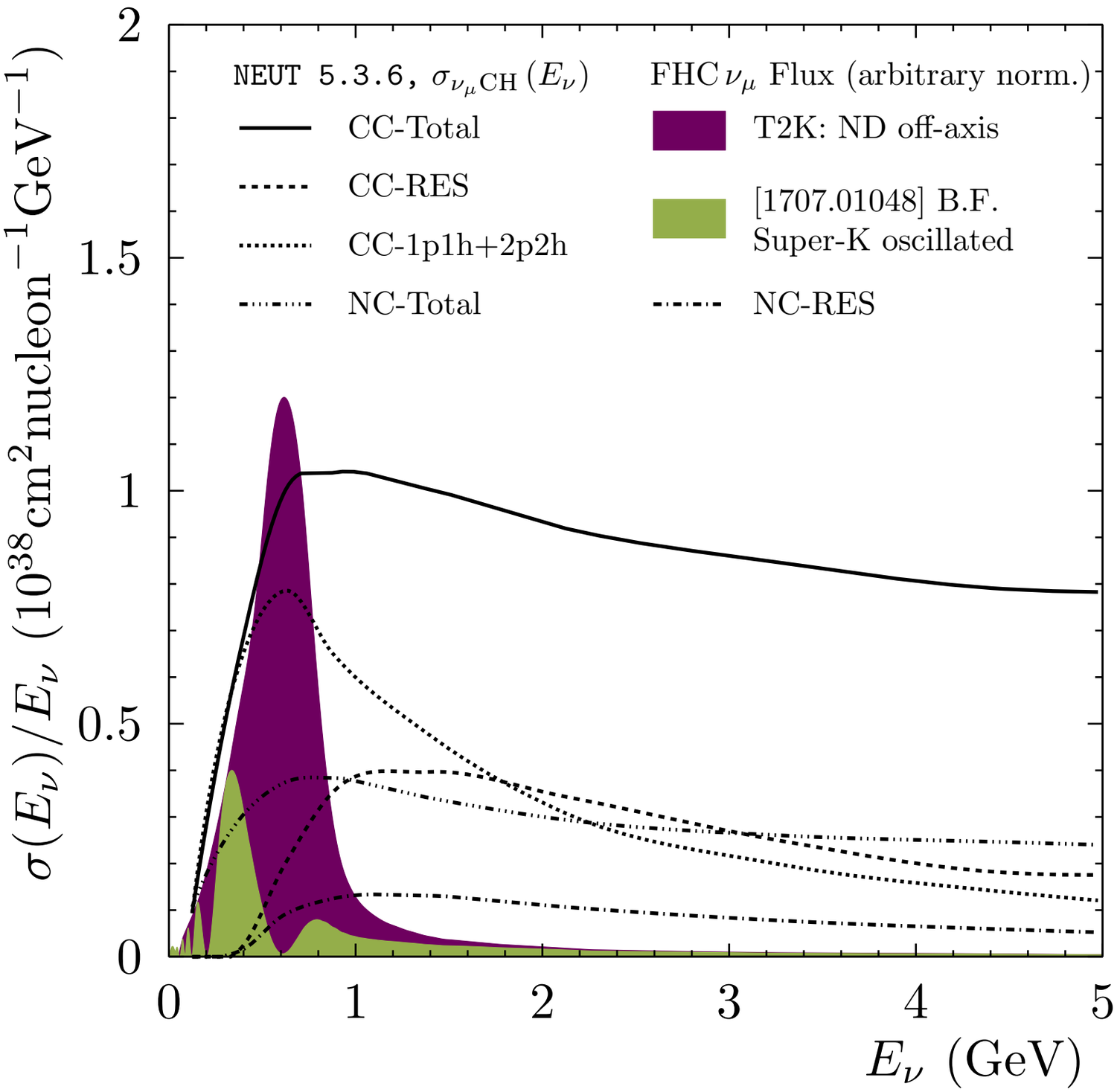
Cross section (true kinematics)

Efficiency (true kinematics)

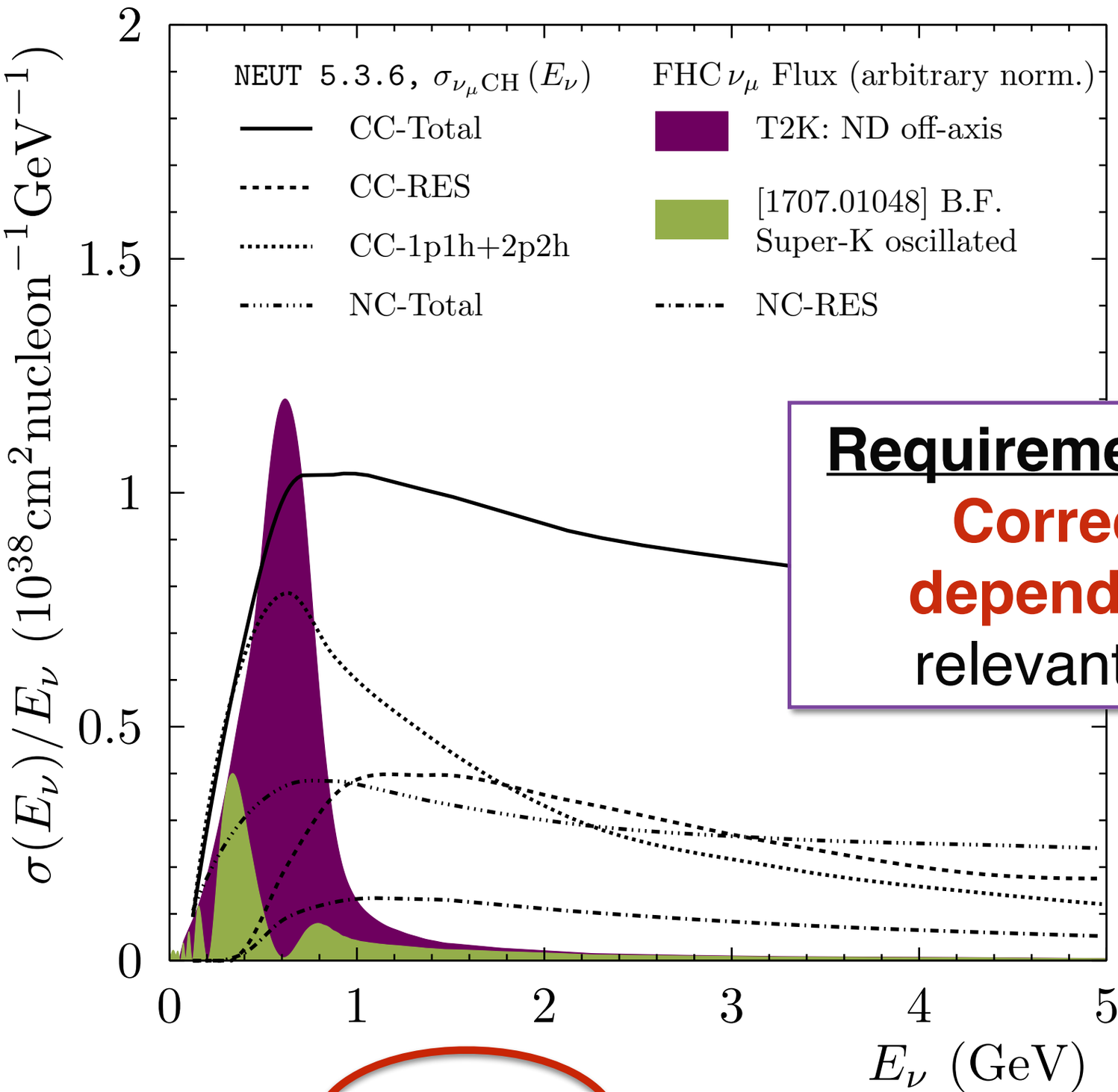
Relationship between true and reconstructed kinematics)

$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

Can’t isolate single processes: “wide beams”



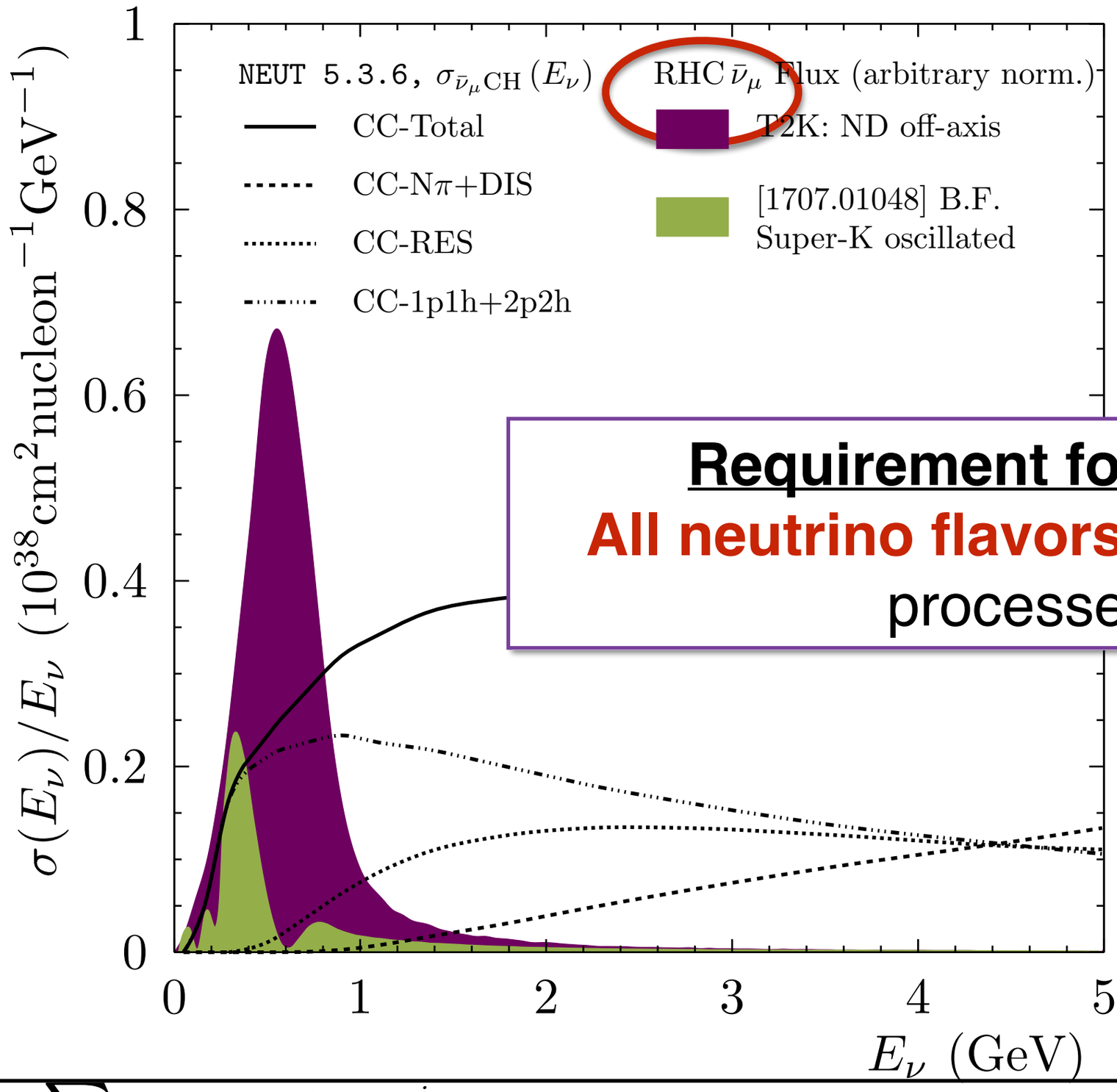
Incident energy is not known. Spread of beam is larger than nuclear effects.



Requirement for model:

Correct energy dependance for all relevant processes

$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

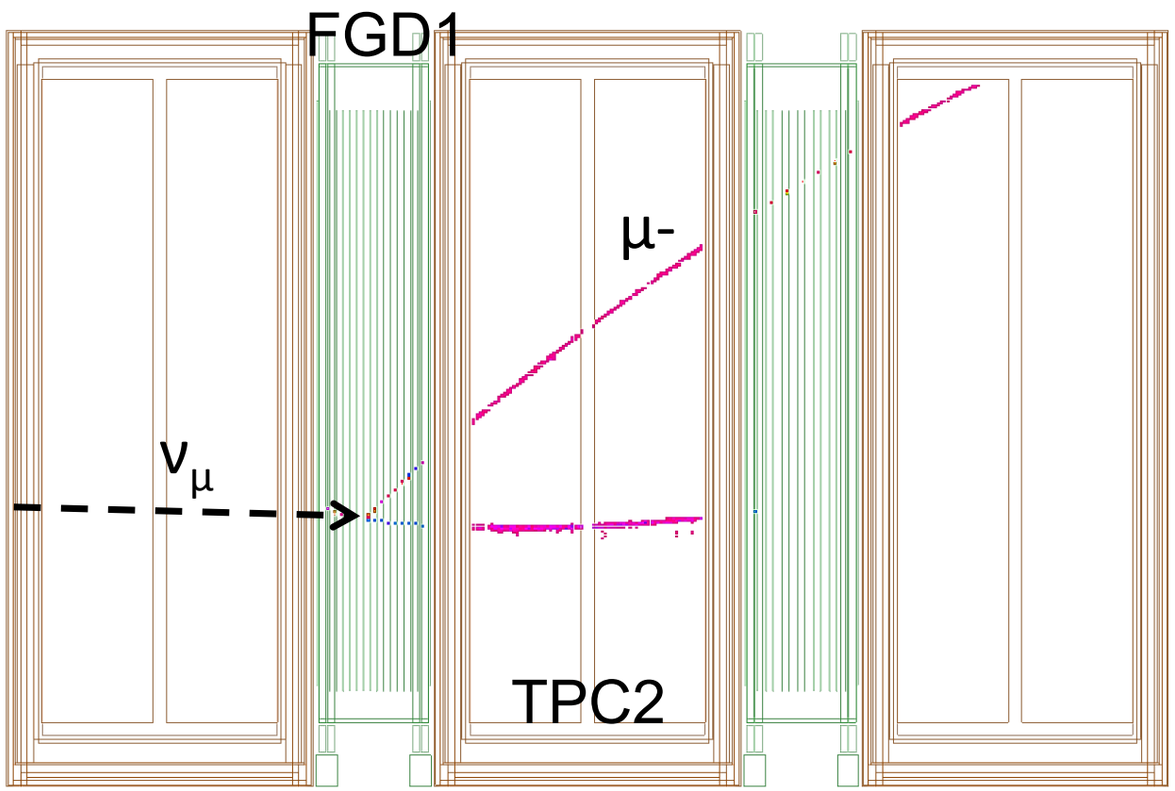


Requirement for model:

All neutrino flavors! for relevant processes

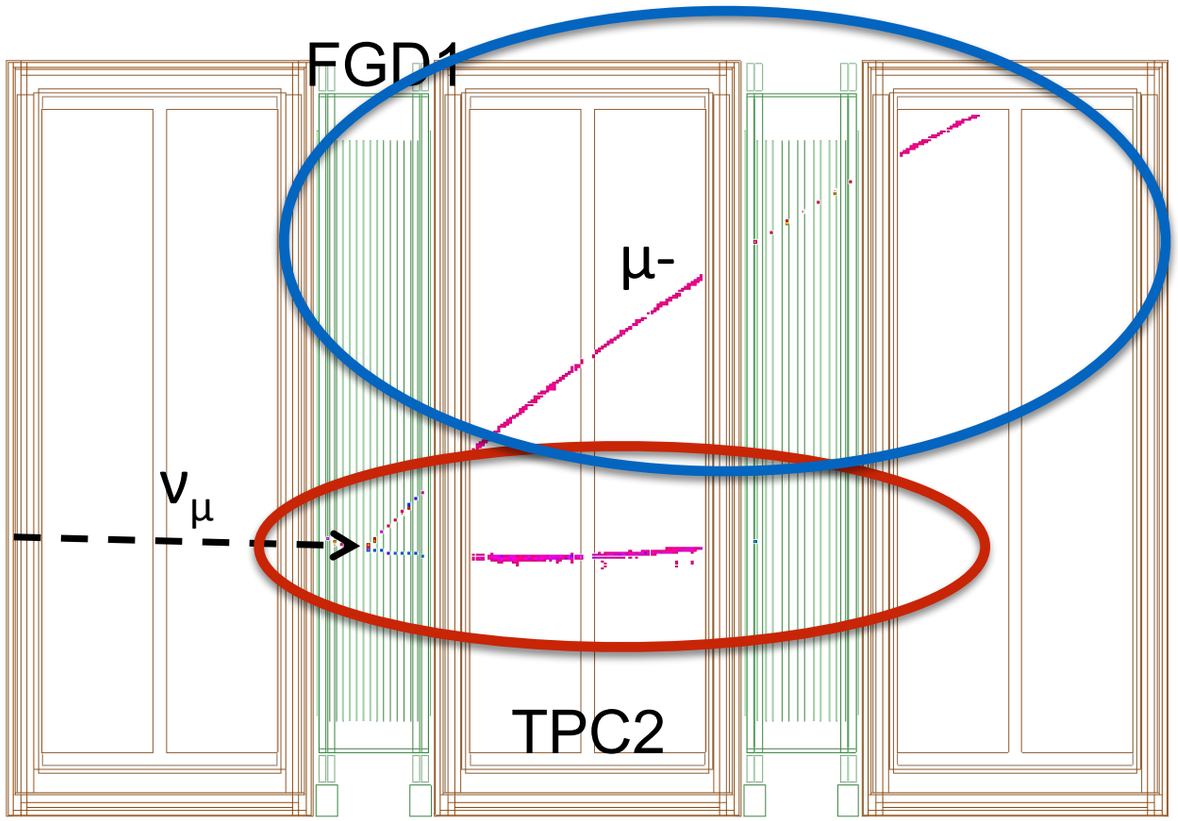
$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

Need: hadronic state description



- T2K event display
- CC0π “topology”: 1 muon, no pion
- Includes CCQE, 2p2h, CC1π (pion absorbed in nucleus)

Needs: semi to exclusive final states



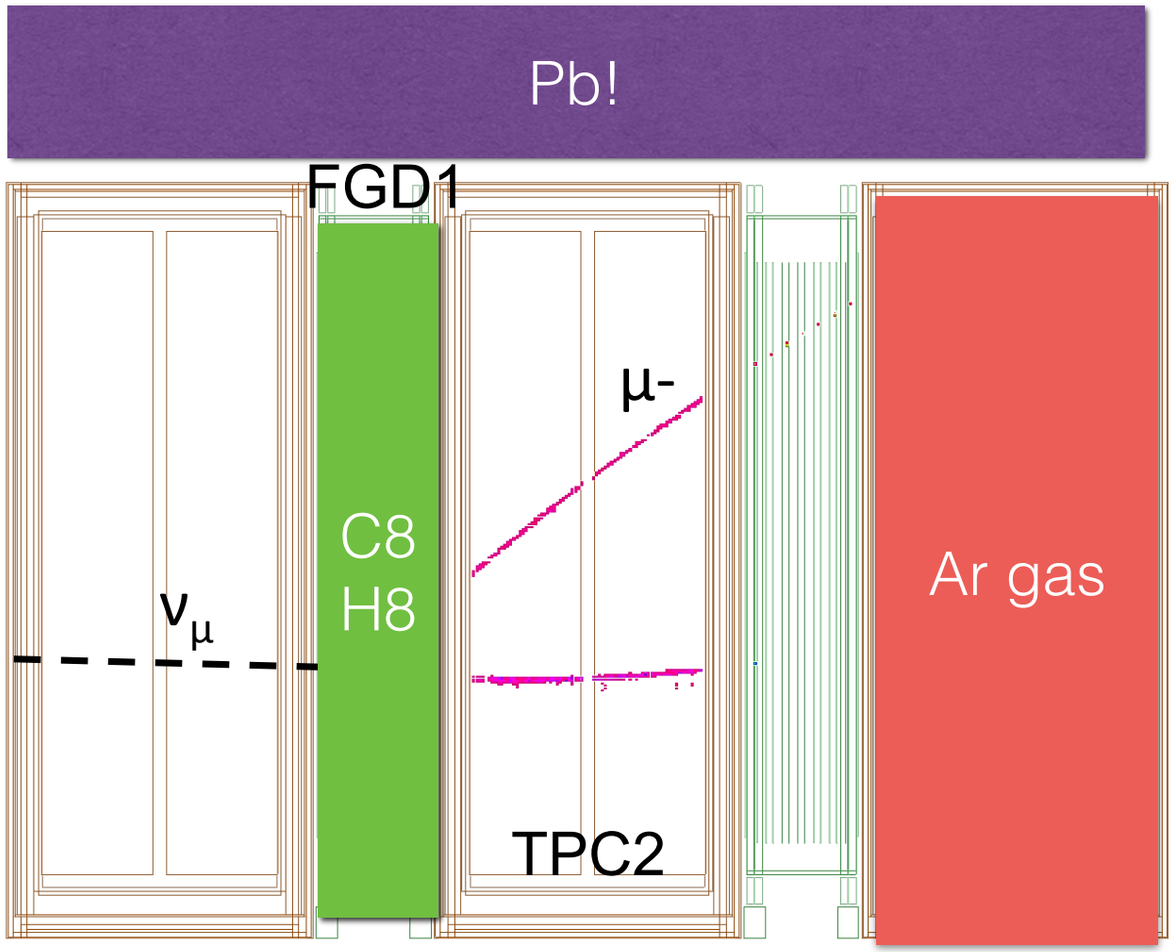
- T2K event display
- CC0π “topology”: 1 muon, no pion
- Includes CCQE, 2p2h, CC1π (pion absorbed in nucleus)

Requirement for model:

- All visible particles for efficiency (background) and energy estimates

$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

Needs: target material



Target materials:

- T2K: H2O
- NOvA: CH+Cl
- SBN, DUNE: Ar

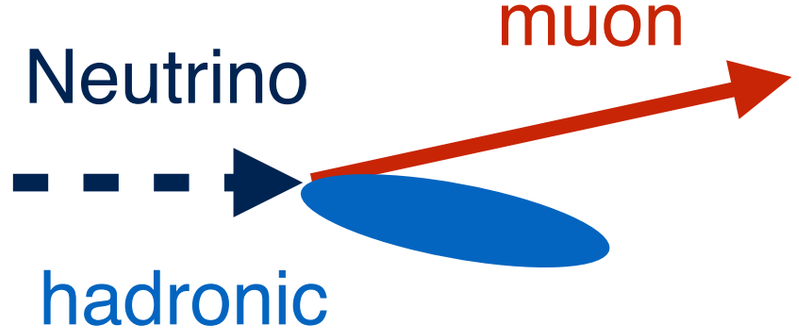
<u>Requirement for model:</u>

- Most nuclear targets, esp C, O, Ar

Needs: Energy estimation

- Oscillation depends on energy
  - Estimate from hadronic and/or leptonic information

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)} \qquad E_\nu = E_\mu + \sum E_{hadronic} + \overline{E}_b$$



T2K
Super-Kamiokande

SBN
DUNE

NOvA

Needs: Energy estimation

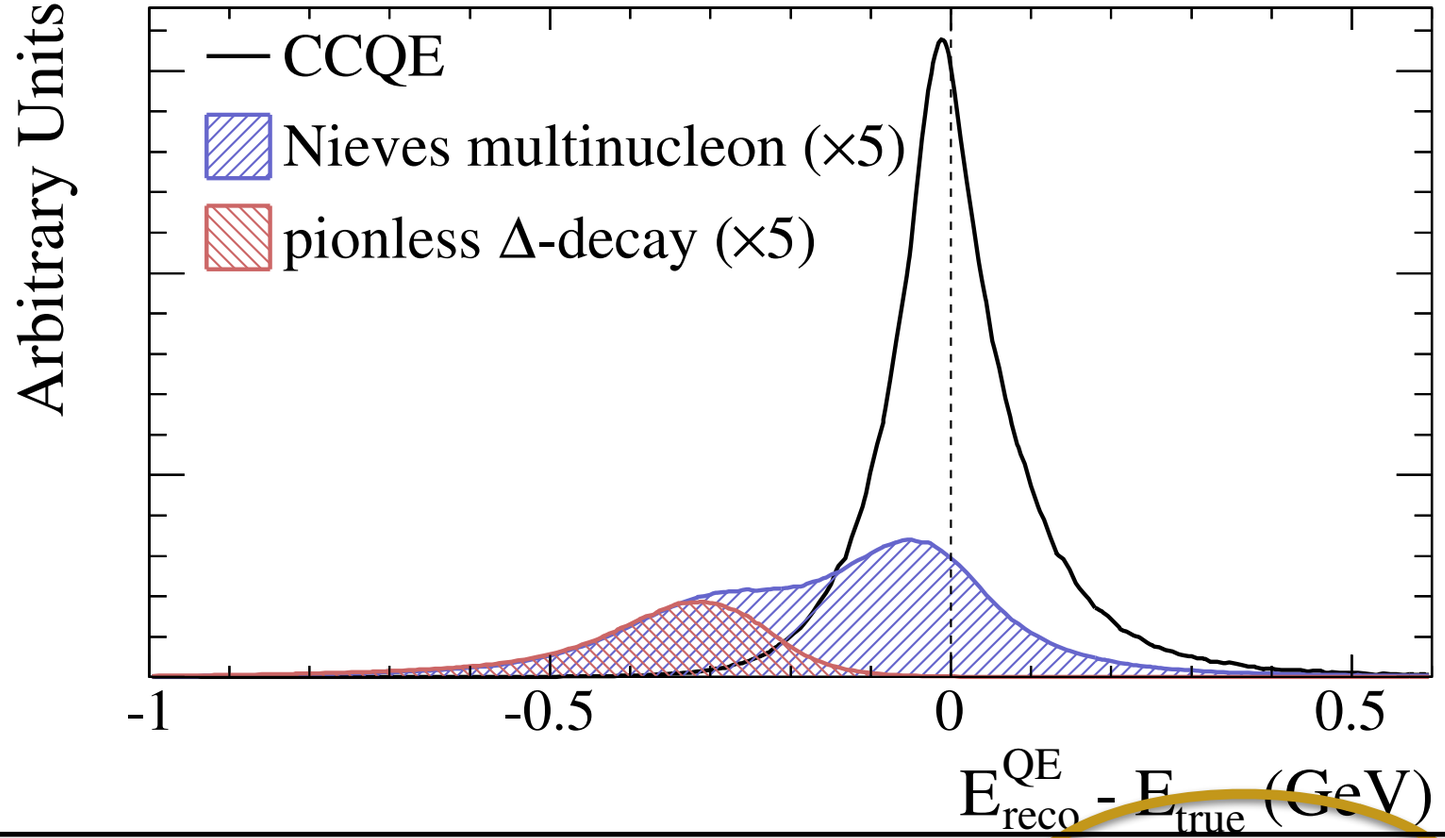
- Nuclear effects bias true and estimated neutrino energy

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$

T2K, PRL 112, 181801 (2014)

Requirement for model:

- Correct mix of processes per topology
- true - reconstructed kinematic relationship



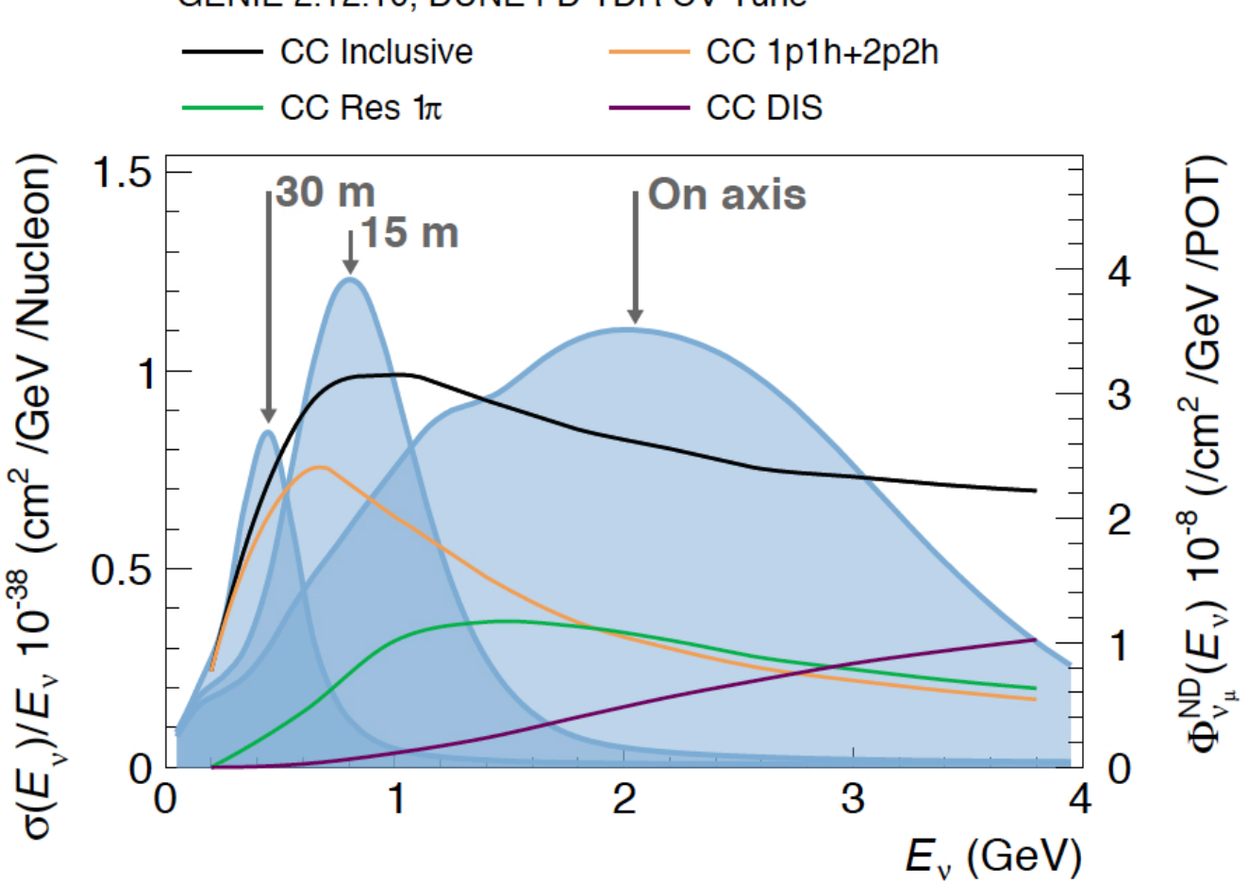
$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

Experimental solutions

$$N_{FD}^{\alpha\to\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

$$N_{ND}^{\alpha} E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\alpha^i(E_{true}) \times \epsilon_\alpha(E_{true}) \times R_i(E_{true}; E_{reco})$$

- Near detector information provide stability monitoring, improved event rate prediction and reduces shared systematic uncertainty from flux, interaction model
- Example ND sample: nu-e scattering (low rate, but well known cross section, direct constraint of flux)
- Example: PRISM, ND rates will be sampled at a range of energies



DUNE ND CDR, arXiv 2103.13910

Experimental solutions

$$N_{FD}^{\alpha\rightarrow\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

$$N_{ND}^{\alpha} E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\alpha^i(E_{true}) \times \epsilon_\alpha(E_{true}) \times R_i(E_{true}; E_{reco})$$

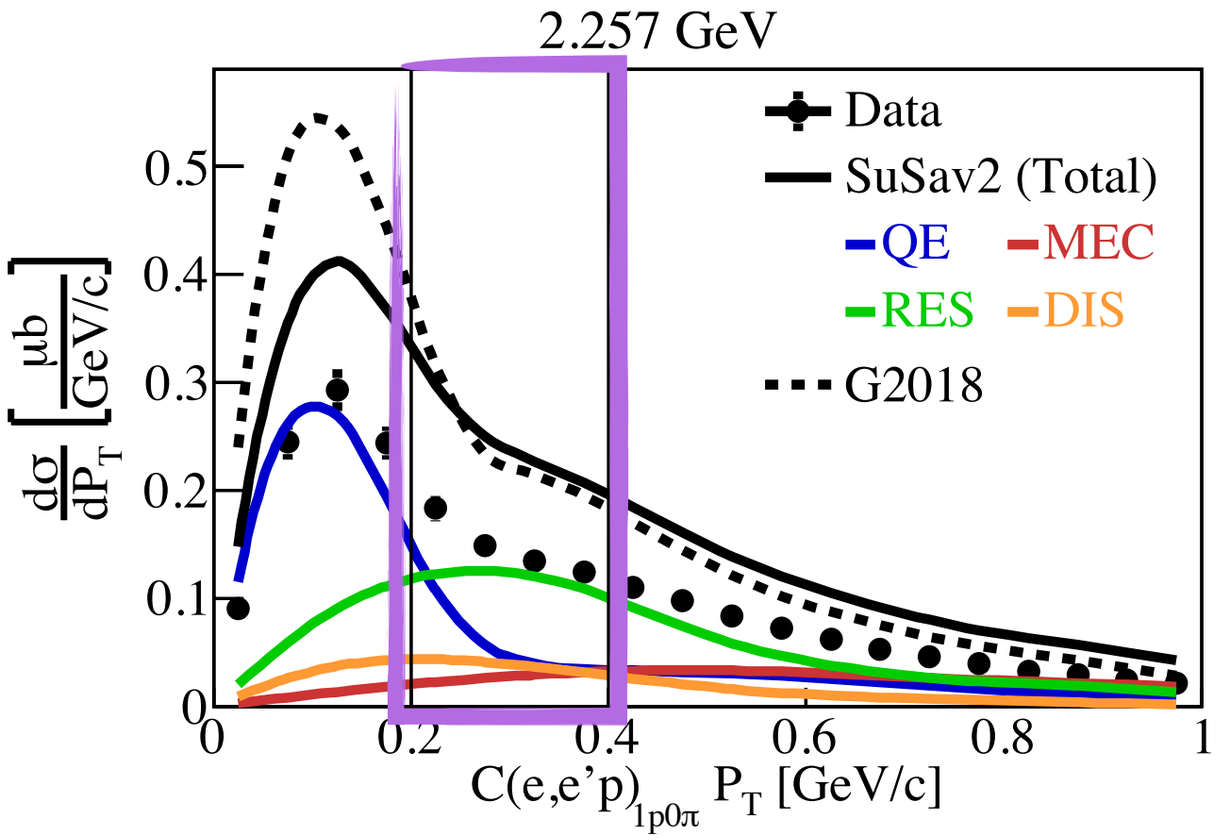
- Near detector information provide stability monitoring, improved event rate prediction and reduces shared systematic uncertainty from flux, interaction model

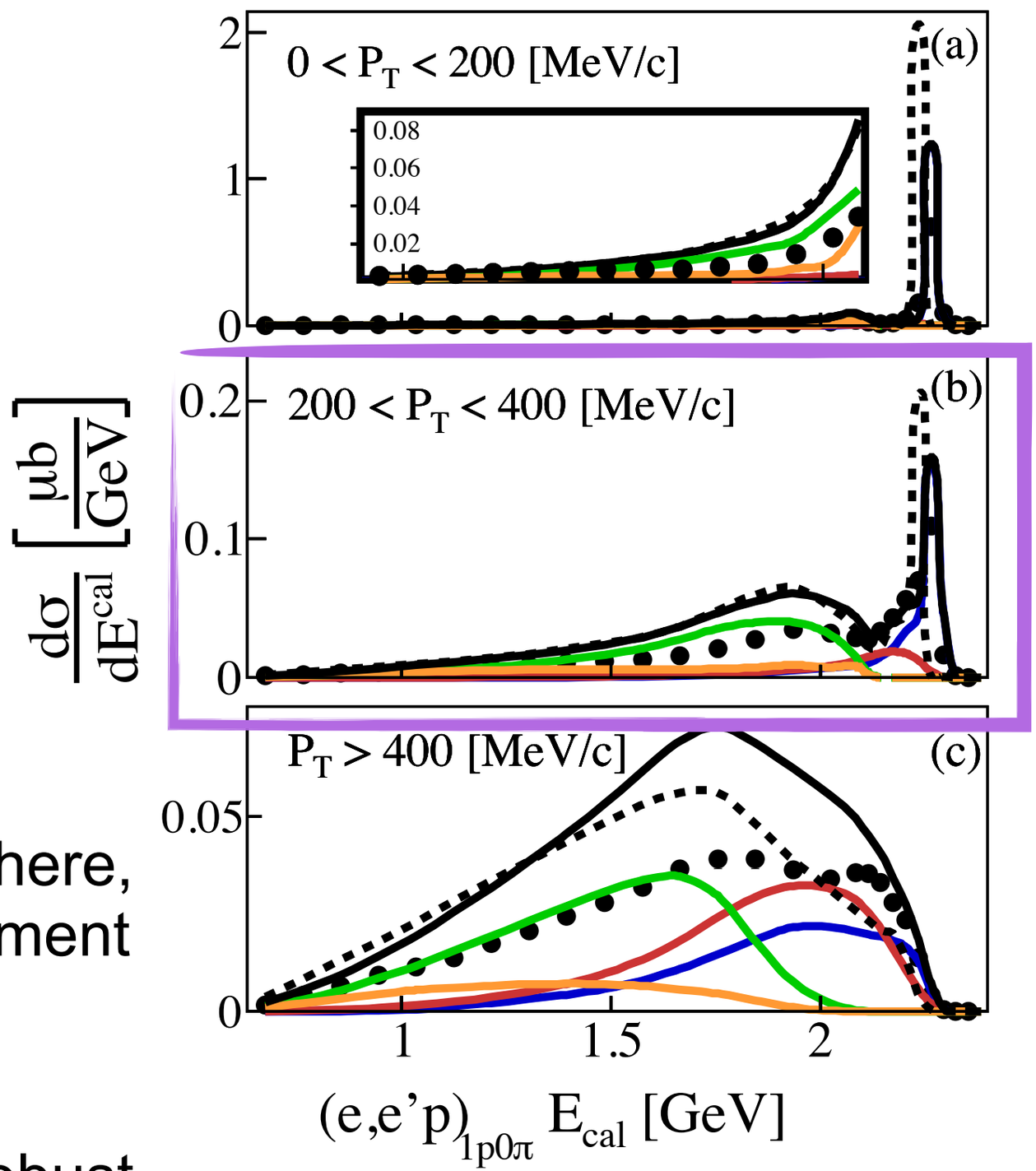
- External experiments are also important:
  - Example: electron scattering experiments - *white paper planned*
  - Example: neutrino scattering off H/D - *options in supplemental slides*
  - Example: pion, proton scattering, transparency measurements - *related to electron programs*
  - Example: neutrino scattering measurements on heavier targets (e.g. MINERvA) - *new proposal in supplemental slides - FASERnu*

Electron scattering programs are growing

- E12-14-012 experiment @JLAB
  - inclusive: *PRC 100, 054606 (2019)*
  - exclusive Ar(e,e'p): *PRC 103 (2021) 3, 034604*
- e4nu @JLAB
  - New electron scattering implementation in GENIE - *PRD D 103, 113003*
  - Updated analysis of CLAS6 data - *upcoming Nature paper*
  - Upcoming run at CLAS in end of 2021 - *see supplemental slide*
- Upcoming: LDMX @SLAC - *see next talk, supplemental slide*
- Possible option: MAMI @Mainz
  - inclusive run on Argon Jet target scheduled for 2021

Electron scattering programs show work is needed

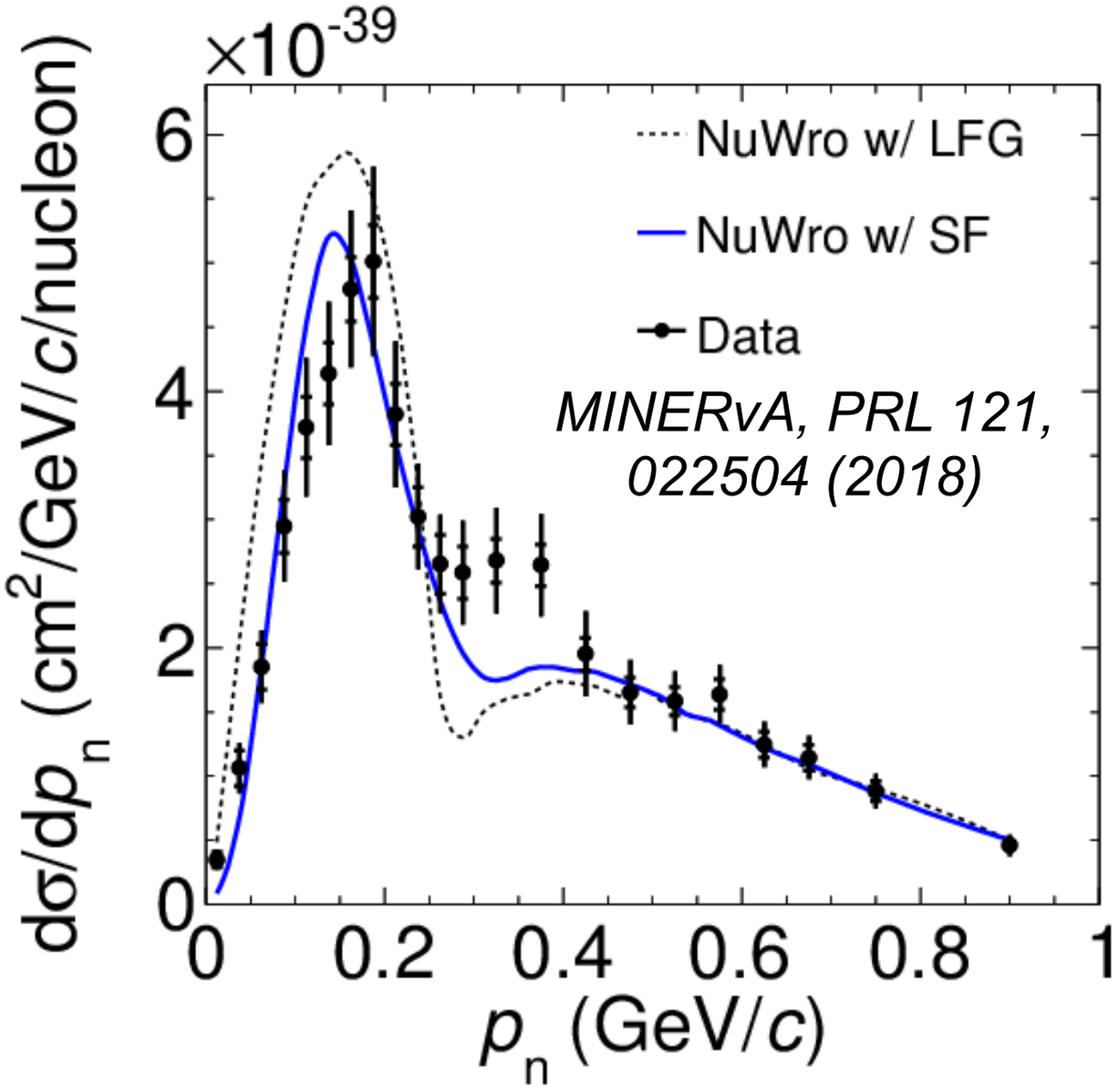




- **e4nu**
  - Use the same energy estimator (here, calorimetric) as a neutrino experiment (with comparable acceptance).
  - Feeddown at 2.2 GeV is not well represented; theory needed for robust application to neutrinos

Persistent challenges: *we need theory*

- **Robust implementation**
  - Simulations are using inclusive calculations (quasielastic plus 2p2h plus pion production) with a fragmentation model, plus an FSI cascade or transport.
  - Example: Disagreements in semi-inclusive data



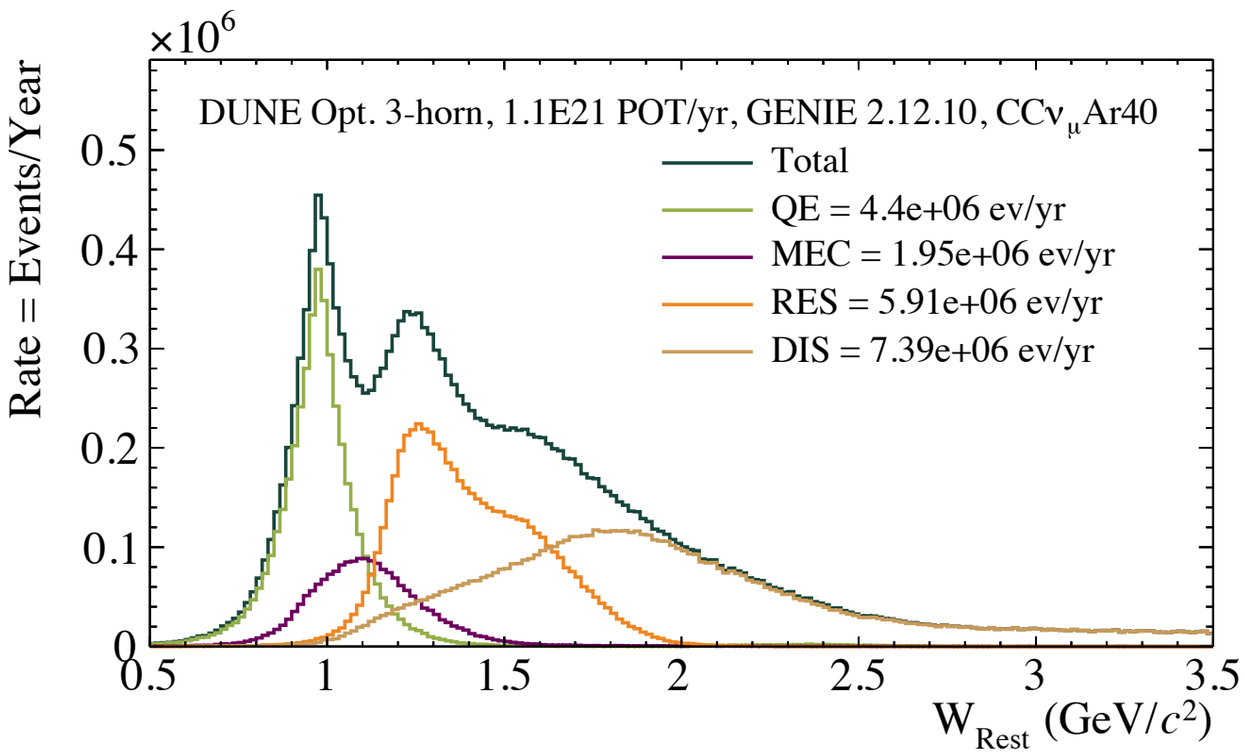
  - OK, so this model doesn't agree… well none of them do!
  - We need **real semi-inclusive** theory for the hadronic state (NOvA, SBN DUNE… and T2K's neutron tagging…)
  - We need to question simplifications/approximations/ extrapolations
  - *See discussion later today for generator connection*

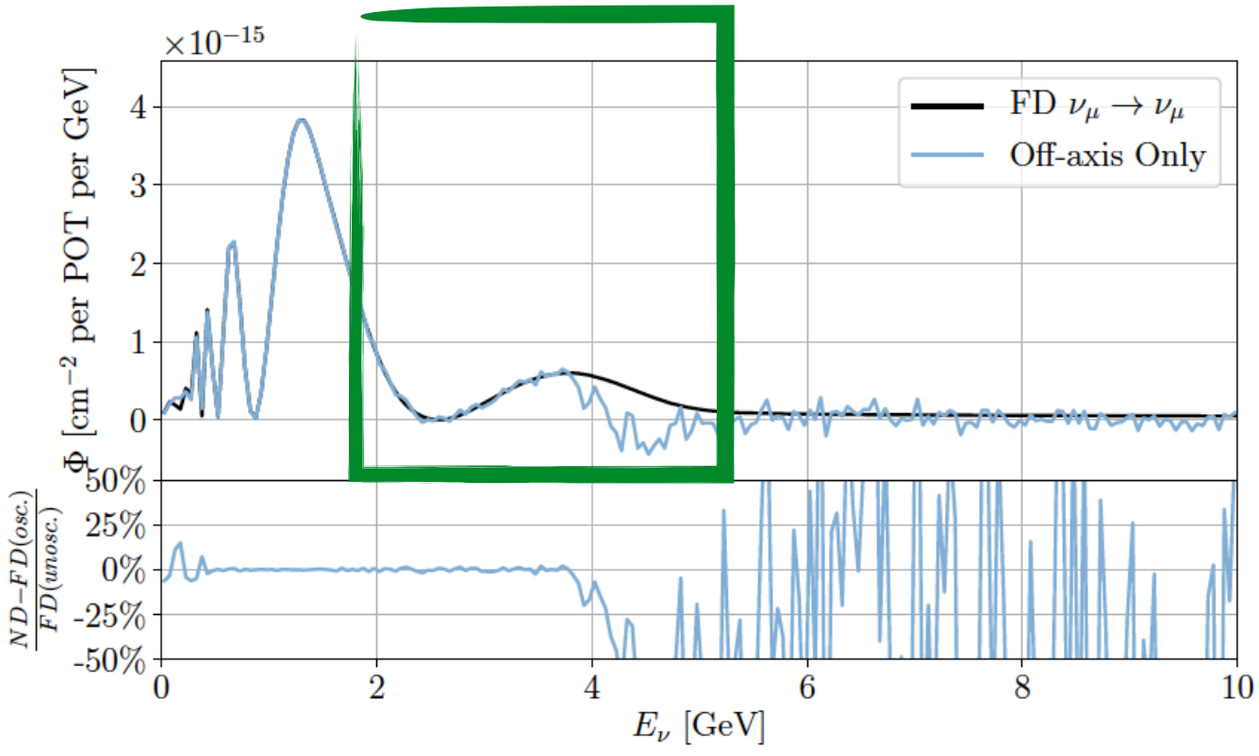
Persistent challenges: *we need theory*

- Robust implementation
- **Processes with small rates at near detectors**
  - Limited near detector information
  - NC single photon production, NC diffractive production
  - Electron (anti)neutrinos cross sections
  - Related: Radiative corrections to exclusive processes on nuclei

Persistent challenges: *we need theory*

- Robust implementation
- Processes with small rates at near detectors
- **Transition region** // Shallow Inelastic // Deep Inelastic Scattering
  - Little/no single nucleon data to start from
  - How do we handle double counting? Extrapolations/approximations?





DUNE ND CDR, arXiv 2103.13910

Persistent challenges: *we need theory*

- Robust implementation
- Processes with small rates at near detectors
- Transition region // Shallow Inelastic // Deep Inelastic Scattering
- **Continued work on QE/multinucleon/resonant processes**

  - 5+ year effort to implement new QE, 2p2h models has produced a much easier interface for theory groups within generators and has been remarkably successful at predicting the lepton.
  - Expand into resonance! semi-inclusive! Heavier targets!

Key feature: close collaboration between theory and experimental groups

Persistent challenges: *we need theory*

- Robust implementation
- Processes with small rates at near detectors
- Transition region // Shallow Inelastic // Deep Inelastic Scattering
- Continued work on QE/multinucleon/resonant processes
- **Uncertainty estimation and treatment**
  - Are there other processes missing?
  - Is our propagation of an uncertainty correct (within a model?) What alternate choices may be considered which are valid/reasonable?
  - Models may be limited in regions of validity (e.g. 2p2h status). We must push past incomplete models with some sensible uncertainty.
  - Crucial help in electron scattering data interpretation for neutrino experiments.

Key feature: confront and discuss issues together

Plan for the white paper

Short section highlighting importance to address:

- Robust implementation; continued work on QE/multinucleon/ resonant processes
- Processes with small rates at near detectors
- Transition region // Shallow Inelastic // Deep Inelastic Scattering
- Uncertainty estimation and treatment
- Experimental data used by theory (electron scattering, nu H/D, etc)

Plan for the white paper

Short section highlighting importance to address:

- Robust implementation; continued work on QE/multinucleon/ resonant processes
- Processes with small rates at near detectors
- Transition region // Shallow Inelastic // Deep Inelastic Scattering
- Uncertainty estimation and treatment
- Experimental data used by theory (electron scattering, nu H/D, etc)

Need of this experimentalist: feedback, comments, concerns please!

Discussion today

What are the specific theory needs for oscillation experiments? (0.6-1-20 GeV) energy range, generator discussion will be held separately)

- Quasi-elastic
- Resonance production
- SIS and DIS
- Processes which affect nue but not numu
- Rare processes (e.g. NC single photon production)
- Uncertainty estimation and treatment on all of the above
- **Are there any other categories to be added here?**

Are there dedicated experimental measurements or data needed to refine theory? If so, what? What barriers exist? What has been successfully used so far?

- Electron scattering
- neutrino scattering on H/D
- Hadronic measurements (e.g. pion scattering, proton transparency)
- **Any more measurements?**

What kind of collaboration is desired from theorists to aid in interfacing to the experimental effort effectively?

Supplement on new programs

Future Plans -Approved run for CLAS12

Acceptance down to 5° $Q^2 > 0.04$ GeV^2

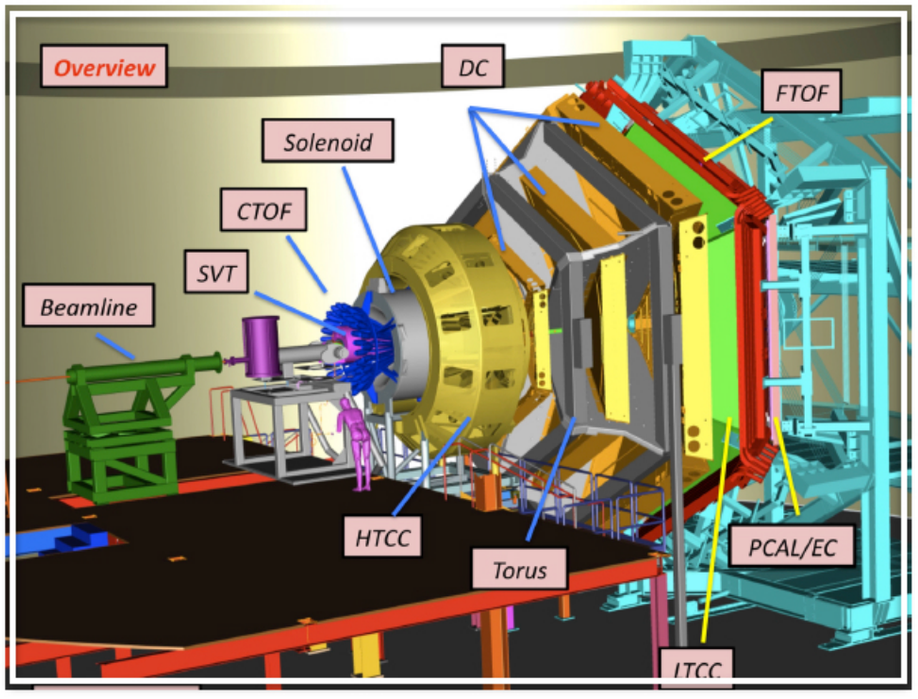
x10 luminosity [10^{35} cm^{-2}s^{-1}]

Keep low thresholds

Targets: ^{2}D, ^{4}He, ^{12}C, ^{16}O, **^{40}Ar**, ^{120}Sn

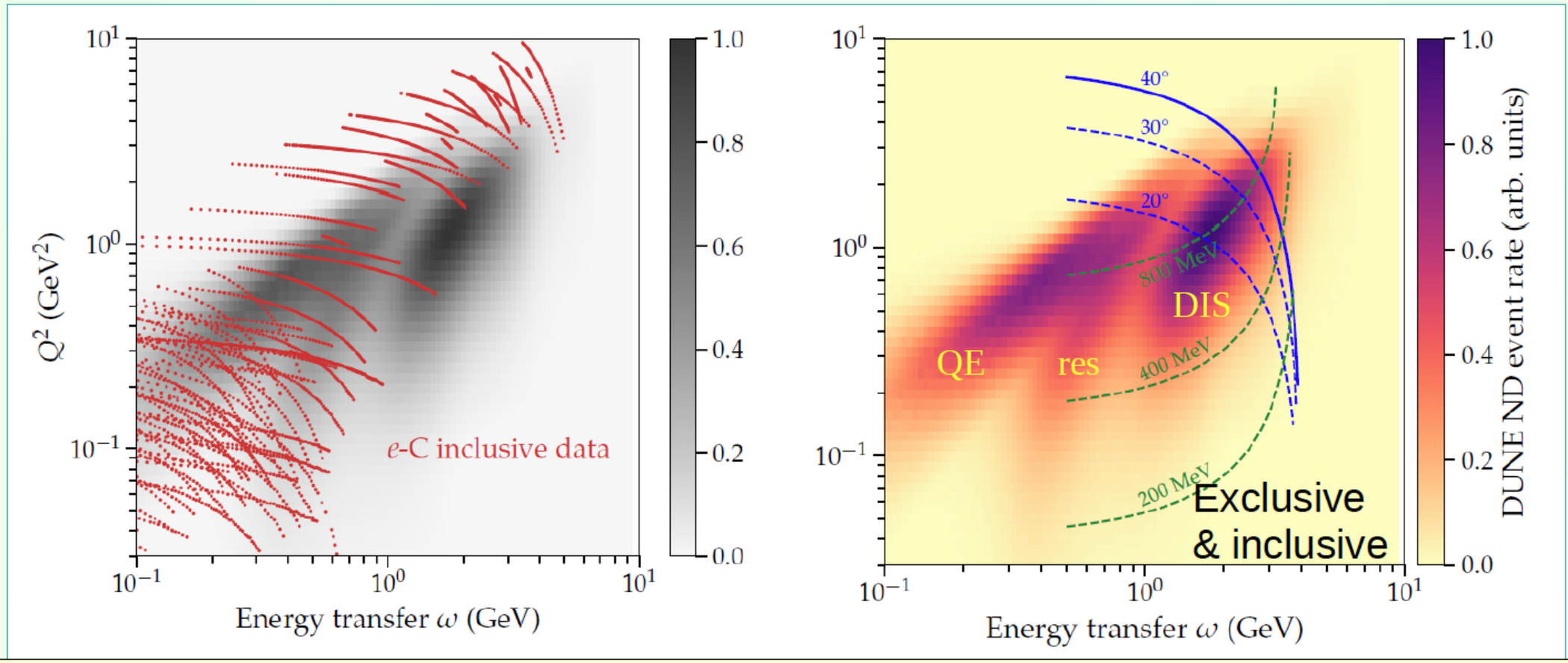
1 - 7 GeV (relevant for DUNE)

Running planned for 2021



e4ν + [come join us! :]

Light Dark Matter eXperiment (LDMX)



A.M.A., A. Friedland, S. W. Li, O. Moreno, P. Schuster, N. Toro & N. Tran, PRD 101, 053004 (2020)

- opportunity to measure inclusive and exclusive cross sections in addition to the DM search, *not explored before*
- huge statistics (10^{14} eot in 6 months)
- proton, pion, and neutron spectra could be measured

Possible nu H/D measurements - *T. Junk*

1) **measure neutrino-H interactions using hydrocarbons in SAND with carbon target subtraction and transverse imbalance kinematics** - It's low-cost, and it's already one of the designs considered for SAND. The eventual precision is not yet known, and there would not be measurements on D

2) **Put a H/D-rich gas in ND-GAr** We'd have to build ND-GAr, and the gas would have to be a mixture with other elements (pure H2/D2 is not permitted by safety requirements). And we may sacrifice GAr running for the H2/D2-rich gas running.

3) **Build another hall upstream of the LBNF near detector hall and put a bubble chamber and auxiliary calorimeters and muon detectors.** Expensive, but gives us the most physics

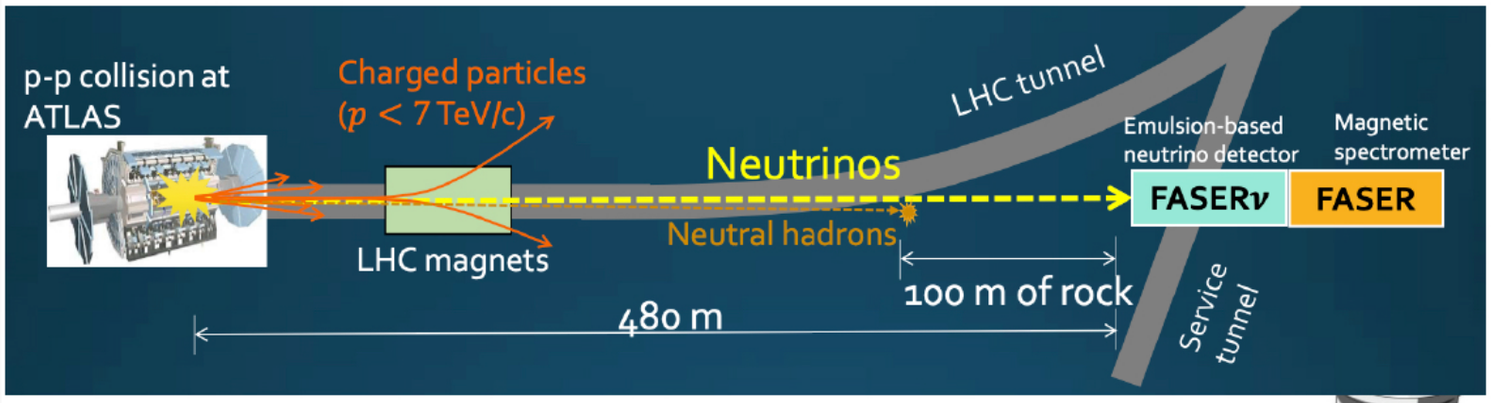
4) **Build a new hall on the surface at the near site** -- not in the LOI, but it would be cheaper than going underground. The off-axis beam flux will be much smaller than the on-axis flux, and it may not tell us about the beam we want, but it may be able to get us some physics measurements of interest.

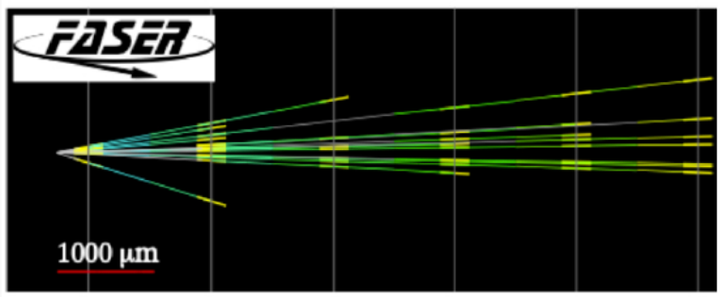
5) **Build a polarized H2/D2 target.** Existing polarized targets for electron and proton scattering are all much smaller than is needed for a neutrino experiment. But the measurements are exciting and as yet untouched.

LOI: https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF6_NF3-TF11_TF5_LauraFields_RichardHill_TomJunk-165.pdf

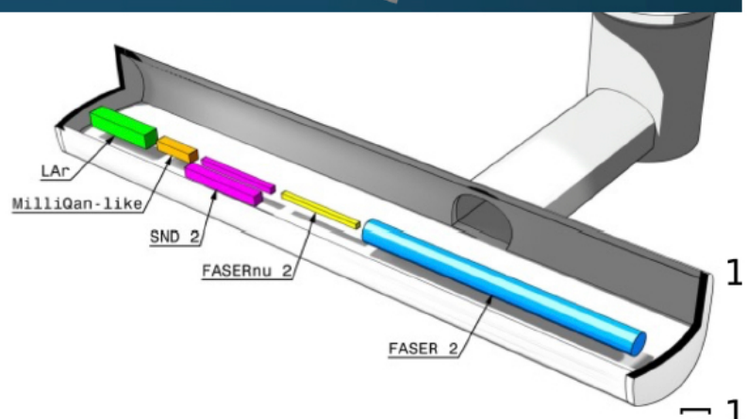
Neutrino scattering at the forward physics facility - *V. Pandey*

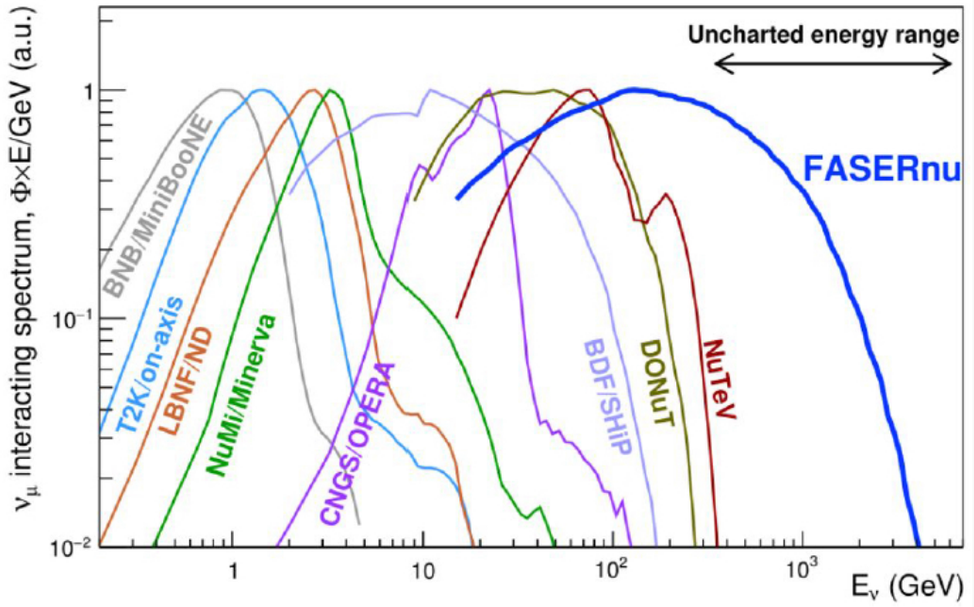
- LHC produces an intense and strongly collimated beam of highly energetic neutrinos of **all three flavors** in the far-forward direction. A **Forward Physics Facility (FPF)** is created to house a suite of experiments for the High Luminosity-LHC (HL-LHC) era.

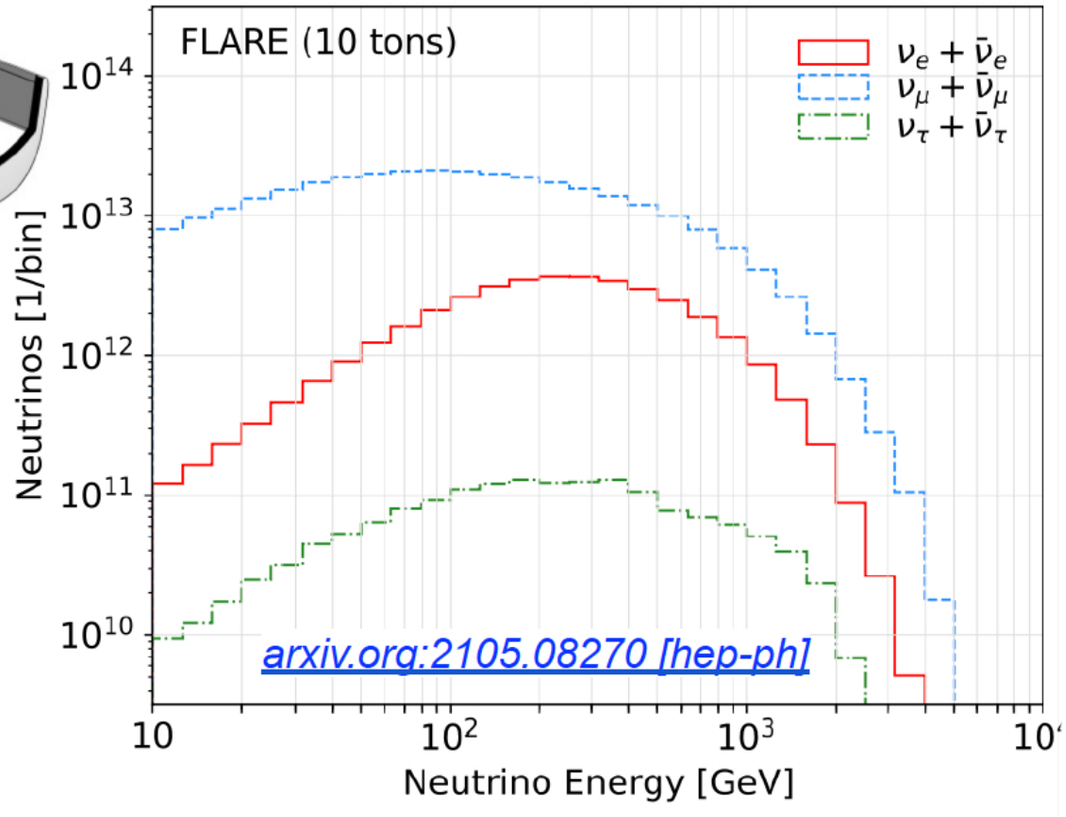




First neutrino interaction candidate
arXiv:2105.06197 [hep-ex]







Estimated neutrino flux at a proposed 10 ton LAr detector (FLArE) at the FPF

- The FPF facility has a rich **neutrino physics, BSM physics, and QCD physics** program.

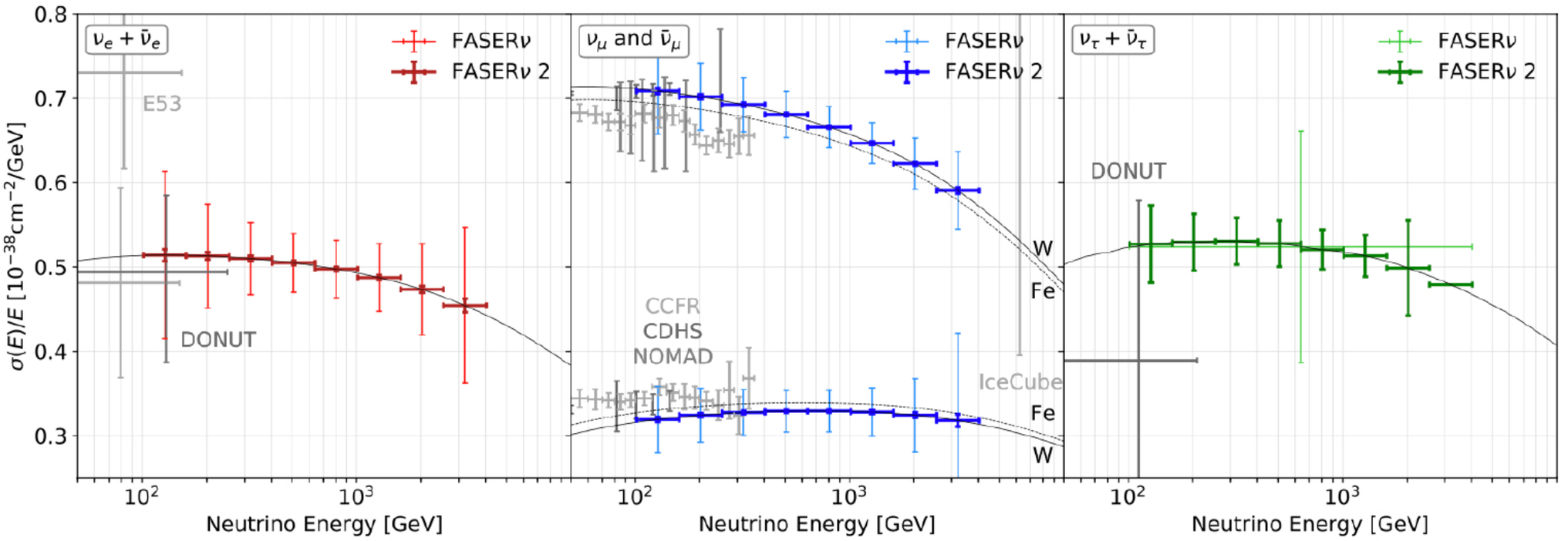
- The facility already has a couple of experiments approved: FASERν (tungsten target), SND (tungsten target). More proposals (including a LArTPC) are in the pipeline.

- Expected Run Planned: LHC Run 3 (2022 - 2024), HL-LHC (2027 - 2036)

  - *For more info, please check recent FPF workshops:*
    https://indico.cern.ch/event/955956/
    https://indico.cern.ch/event/1022352/

Neutrino scattering at the forward physics facility - *V. Pandey*

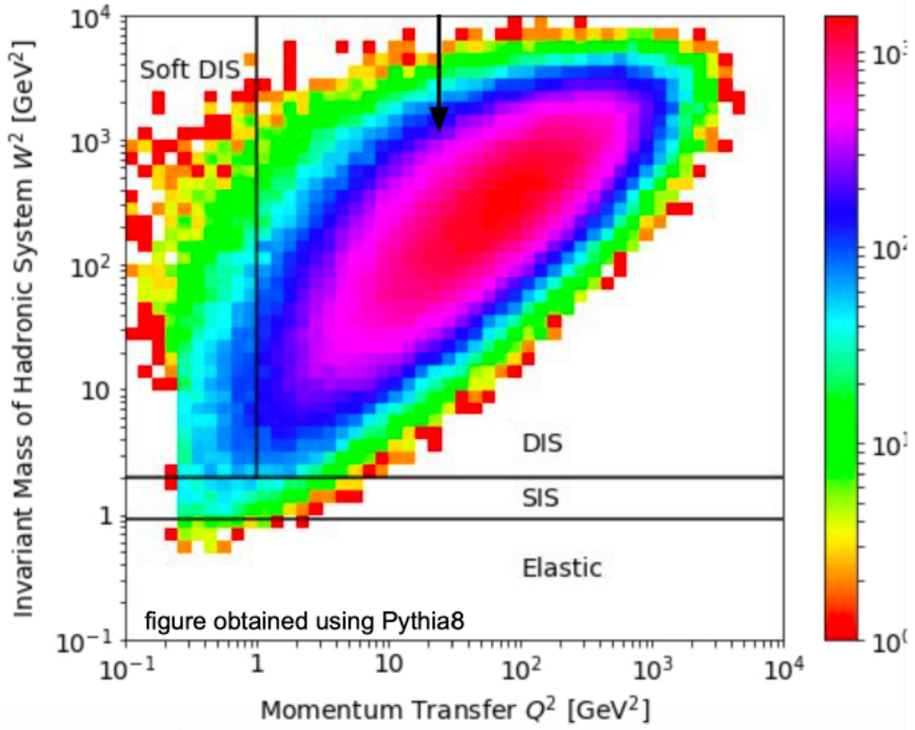
- The facility will measure high statistics CC and NC neutrino-nucleon/nucleus cross sections on a **variety of nuclear targets**. Cross section measurements cover **uncharted energy region between the accelerator and IceCube neutrino energies.** The phase space also complements accelerator neutrinos.
  - **DIS cross section:** Large statistics at completely unexplored energy region.



- **SIS/DIS cross section:** Phase space covers 1000s of expected events in the SIS/DIS transition region.
- **QE/RES cross section:** Significant expected events in the QE & RES region.

>10^3 expected quasi-elastic and resonant events (estimated with GENIE)

at FLArE	CCQE				CCRES				NCEL	NCRES
	ν_e	ν_μ	$\bar{\nu}_e$	$\bar{\nu}_\mu$	ν_e	ν_μ	$\bar{\nu}_e$	$\bar{\nu}_\mu$	all	all
Event Rate	58	590	47	366	167	1673	184	1219	175	1206

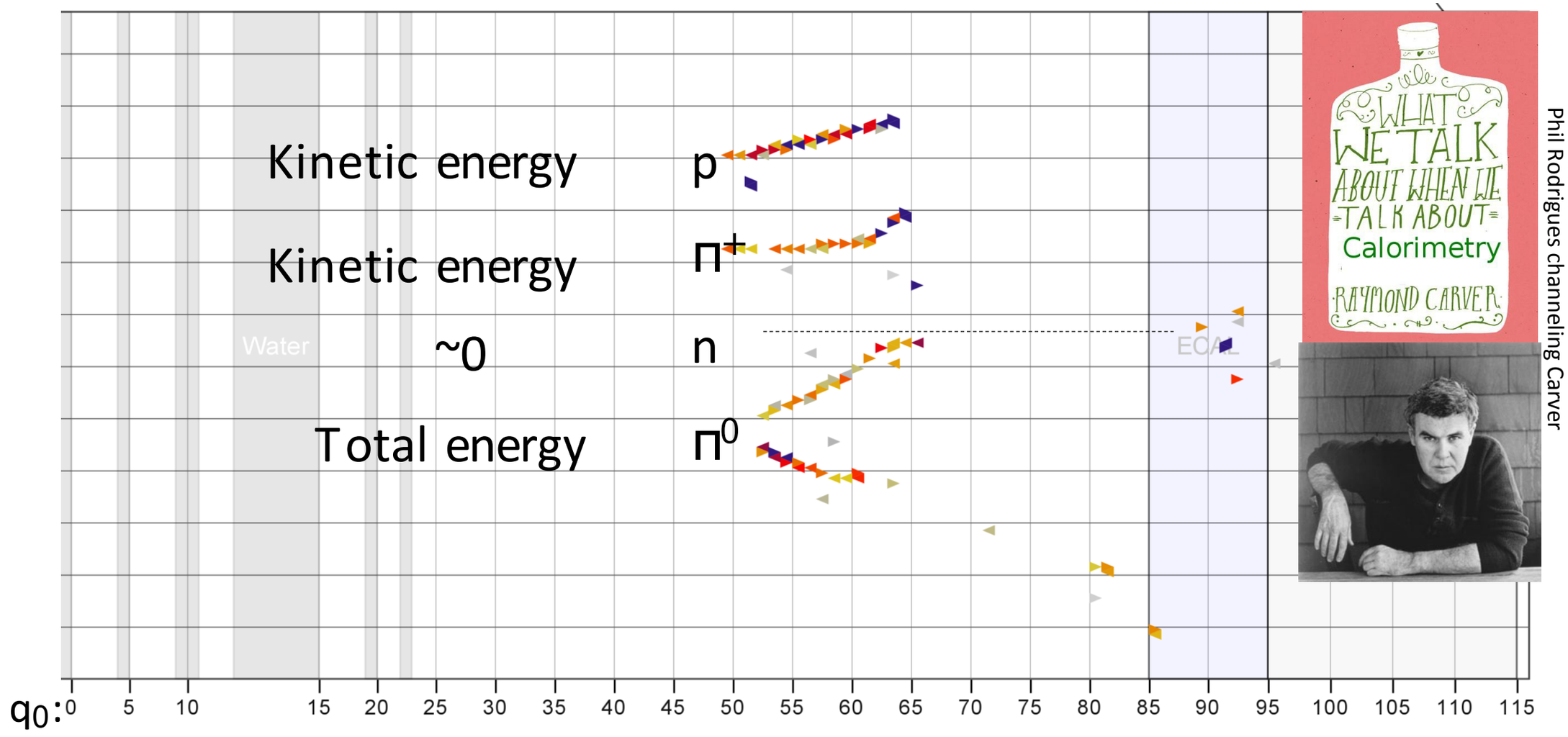


- **Test of lepton universality:** Intense beam of neutrinos of all three flavors allows unique opportunity to test lepton universality in neutrino scattering.

Backup slides

What we mean when we say “visible energy”

Courtesy: Kevin McFarland, Phil Rodrigues



$$E_{avail} \equiv (\text{Proton and } \pi^{\pm} \text{ KE}) + (\text{Total E of other particles except neutrons})$$

Calorimetric detectors energy estimation depends on particle type -> exclusive

T2K as an example circa 2018

Error source	1-ring μ-like		1-ring e-like			
	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode CC1π	$\nu_e/\bar{\nu}_e$

- **Four flavors, five samples:** predominantly neutrino beam or predominantly antineutrino. ν_μ with no pion, ν_e with pion and without pion
- **Primarily CCQE, 2p2h, resonant pion production processes**
- But, NC pion production backgrounds for both ν_e and ν_μ; photons mimic nue, pion may mimic ν_μ

T2K as an example circa 2018

Error source	1-ring μ-like		1-ring e-like			
	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode CC1π	$\nu_e/\bar{\nu}_e$
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87

- **Total uncertainty is about 5% - 18%, sample dependent**
  - Near detector reduces uncertainty by about a factor of ~2, recall wide flux, different acceptance, and ν_μ -> ν_e inferences

$$N_{FD}^{\alpha\to\beta}(\mathbf{p}_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(\mathbf{p}_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(\mathbf{p}_{true}) \times R_i(\mathbf{p}_{true};\mathbf{p}_{reco})$$

$$N_{ND}^{\alpha}(\mathbf{p}_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\alpha^i(\mathbf{p}_{true}) \times \epsilon_\alpha(\mathbf{p}_{true}) \times R_i(\mathbf{p}_{true};\mathbf{p}_{reco})$$

T2K as an example circa 2018

Error source	1-ring μ-like		1-ring e-like			
	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode CC1π	$\nu_e/\bar{\nu}_e$
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\nu_\mu)$	0	0	2.63	1.46	2.62	3.03
NC1γ	0	0	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87

- **Detector and final state interactions (pion reinteraction model)**

  Includes some cross section uncertainties, but this also lumps purely detector effects (e.g. secondary interactions) as both are tuned to external pion scattering data)

T2K as an example circa 2018

Error source	1-ring μ-like		1-ring e-like			
	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode CC1π	$\nu_e/\bar{\nu}_e$
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\nu_\mu)$	0	0	2.63	1.46	2.62	3.03
NC1γ	0	0	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87

- **Detector and final state interactions (pion reinteraction model)**
- **Near detector constraint** (limited by acceptance, different energy dependance)
  - Convolves input priors in a nontrivial way

T2K as an example circa 2018

Error source	1-ring μ-like		1-ring e-like			
	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode CC1π	$\nu_e/\bar{\nu}_e$
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\nu_\mu)$	0	0	2.63	1.46	2.62	3.03
NC1γ	0	0	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87

- **Detector and final state interactions (pion reinteraction model)**
- **Near detector constraint (limited by acceptance, different energy dependance)**
- **Uncertainties which shift the relationship between true and reconstructed energy**
  - Nucleon removal energy; Large uncertainty before upcoming e,e'p constraint
  - Other uncertainties ALSO shift the true-reco response — 2p2h (in ND) and FSI (top line)

T2K as an example circa 2018

Error source	1-ring μ-like		1-ring e-like			
	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode CC1π	$\nu_e/\bar{\nu}_e$
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\nu_\mu)$	0	0	2.63	1.46	2.62	3.03
NC1γ	0	0	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87

- Detector and final state interactions (pion reinteraction model)
- Near detector constraint (limited by acceptance, different energy dependance)
- Uncertainties which shift the relationship between true and reconstructed energy
- Differences between ν_μ and ν_e cross section
  - See Kevin's talk, theoretically driven uncertainty, difficult to probe experimentally

T2K as an example circa 2018

Error source	1-ring μ-like		1-ring e-like			
	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode CC1π	$\nu_e/\bar{\nu}_e$
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\nu_\mu)$	0	0	2.63	1.46	2.62	3.03
NC1γ	0	0	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87

- **Detector and final state interactions (pion reinteraction model)**
- **Near detector constraint (limited by acceptance, different energy dependance)**
- **Uncertainties which shift the relationship between true and reconstructed energy**
- **Differences between ν_μ and ν_e cross section**
- **Single photon production -** difficult to measure at ND, small rate, large uncertainty

What the community is worried about

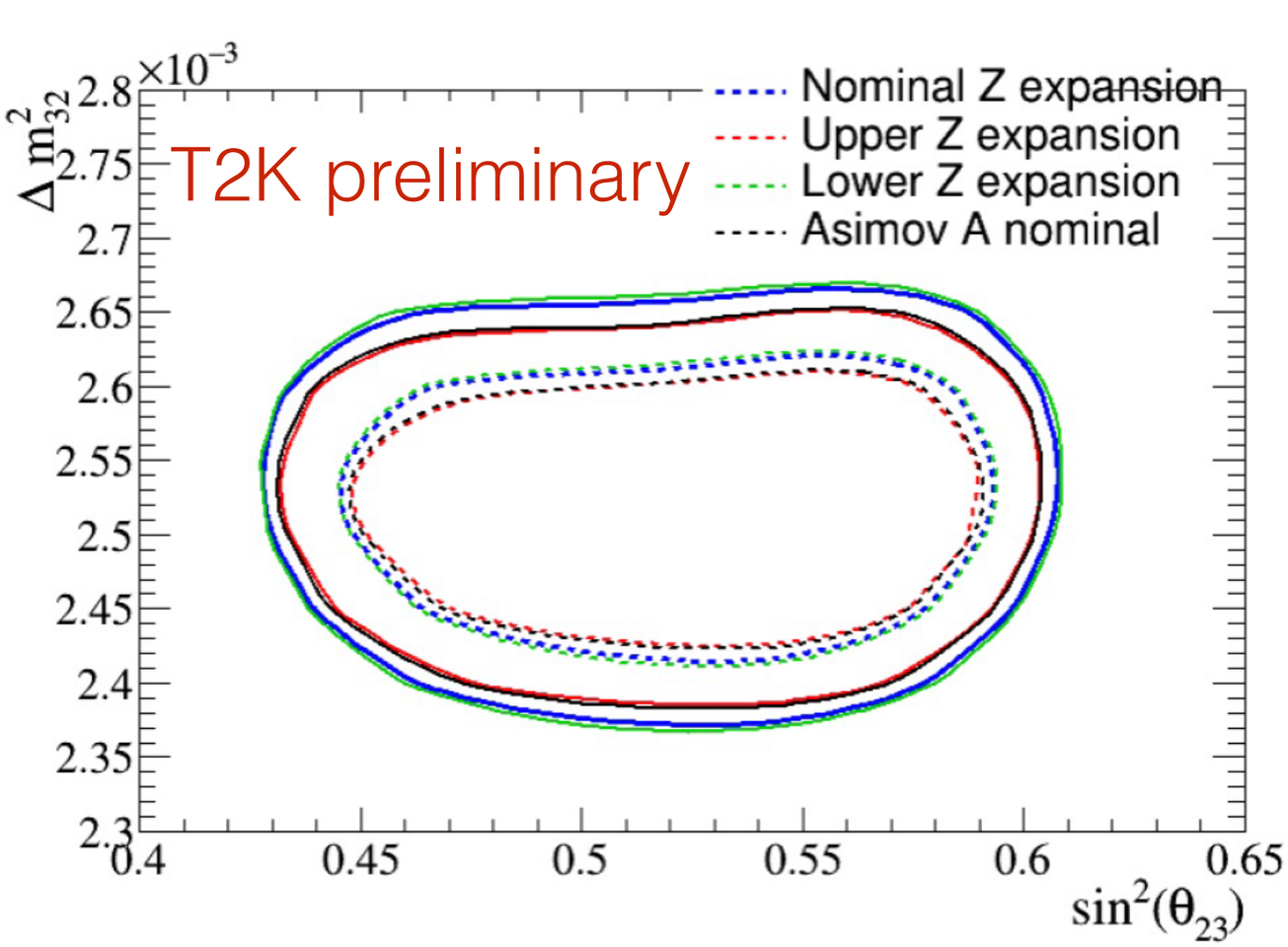
From Nu-Print workshop: https://indico.fnal.gov/event/15849/timetable/#20180312

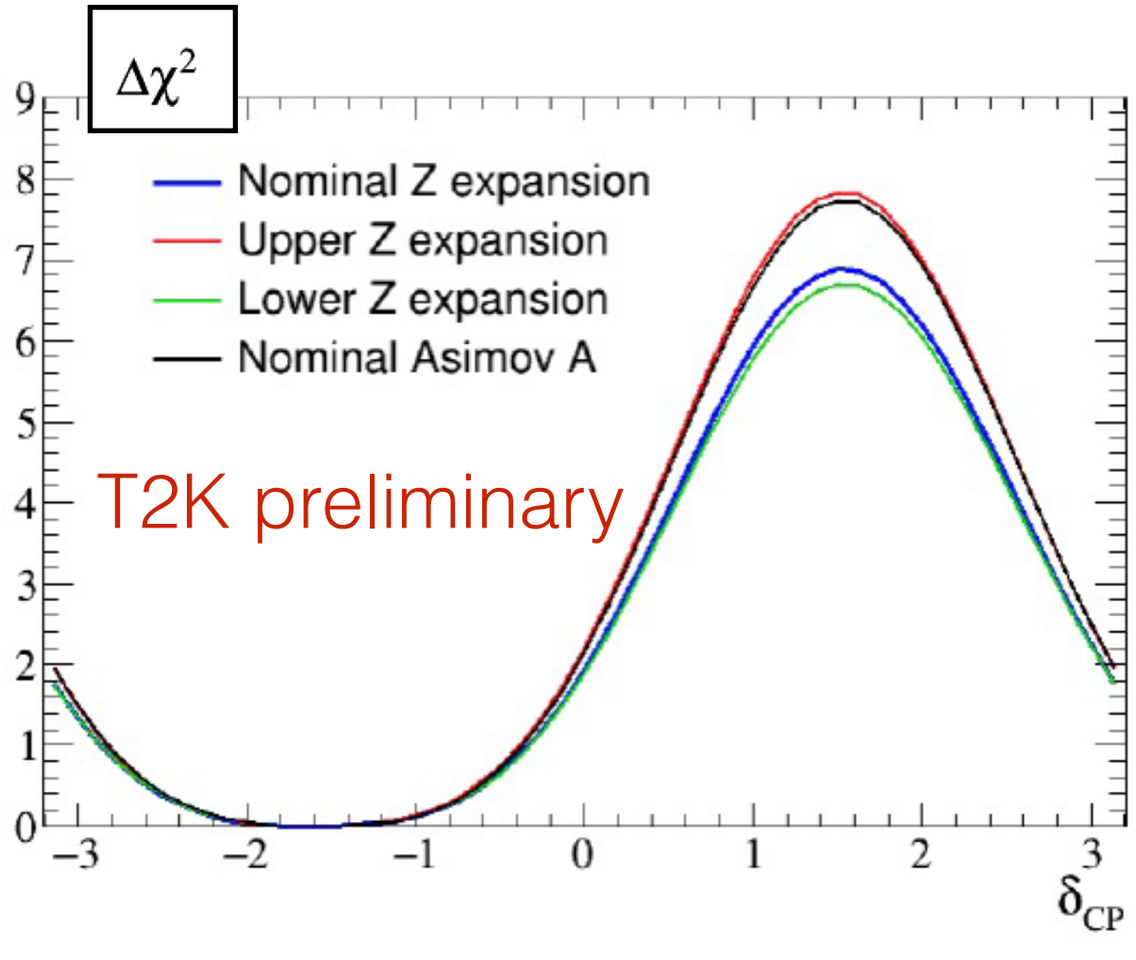
- What are the uncertainties needed for the 2p2h?
  - Large uncertainties on leptonic side (across q0-q3?). Differences between nu and nubar in overall strength.
  - What should be the hadronic final state association? And how much energy into (which) outgoing particles?
- Insufficiency of current resonance model to describe pion kinematics, low Q2 discrepancies.
  - Is 2p2h-like processes in resonance production?
  - Need NC for significant backgrounds (or exotic signals)
- Transition region! Incomplete experimental and theoretical footing
- Need heavier targets (Ar!) model efforts
- Nue/numu uncertainties
- *Kendall adds: NC diffractive processes not explicitly assessed*

Studies on impact of alternate form factor

- Use as alternate models: “Z expansion”, 3 component fit and perform T2K analysis with current dipole model (6 fits)

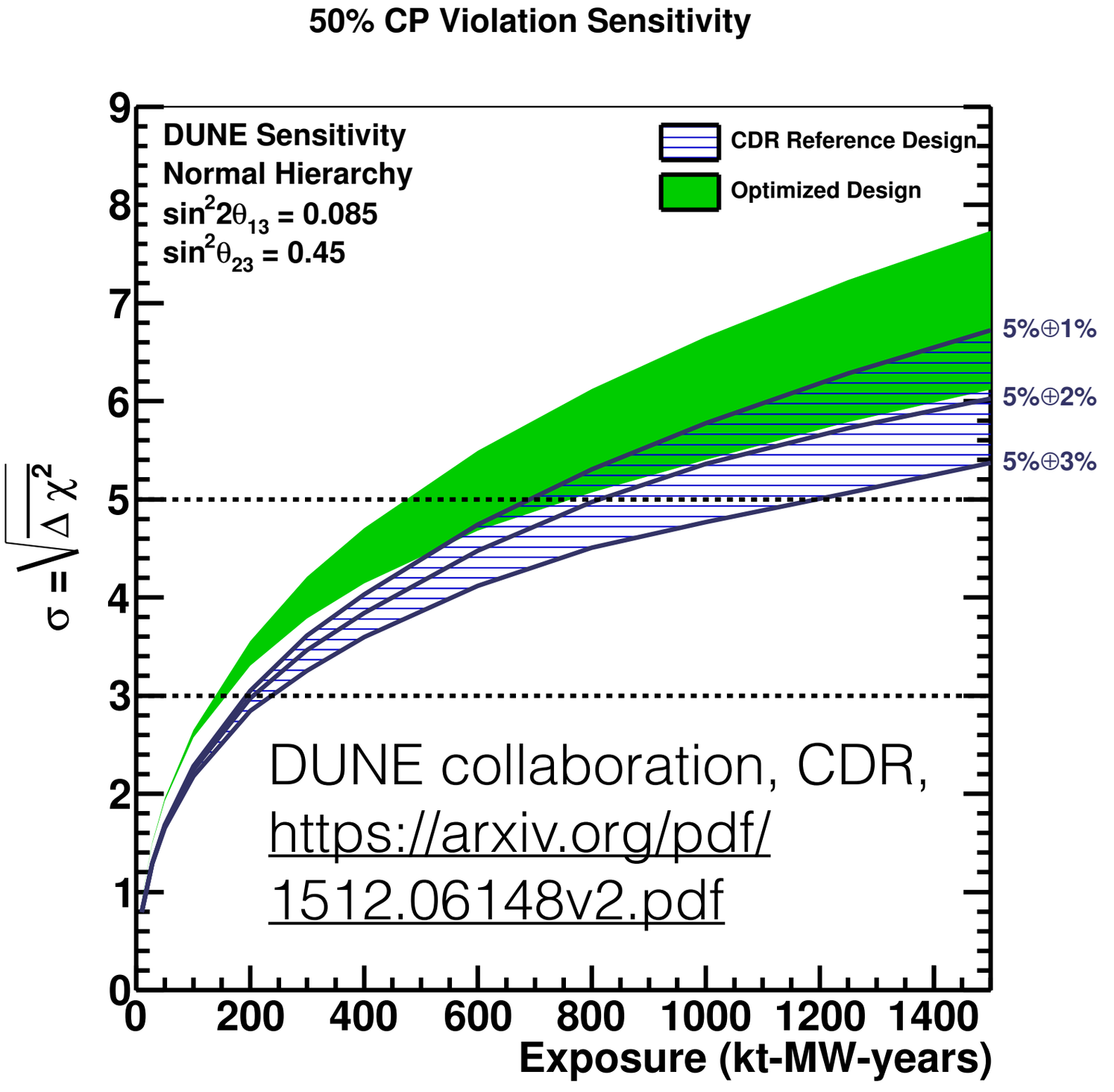
- For T2K 2018 analysis, the (Q^2) nuclear model parameters compensate for mis-modeling (no bias)





Will discuss next steps of this in a minute…

How well do we need to know v-A?

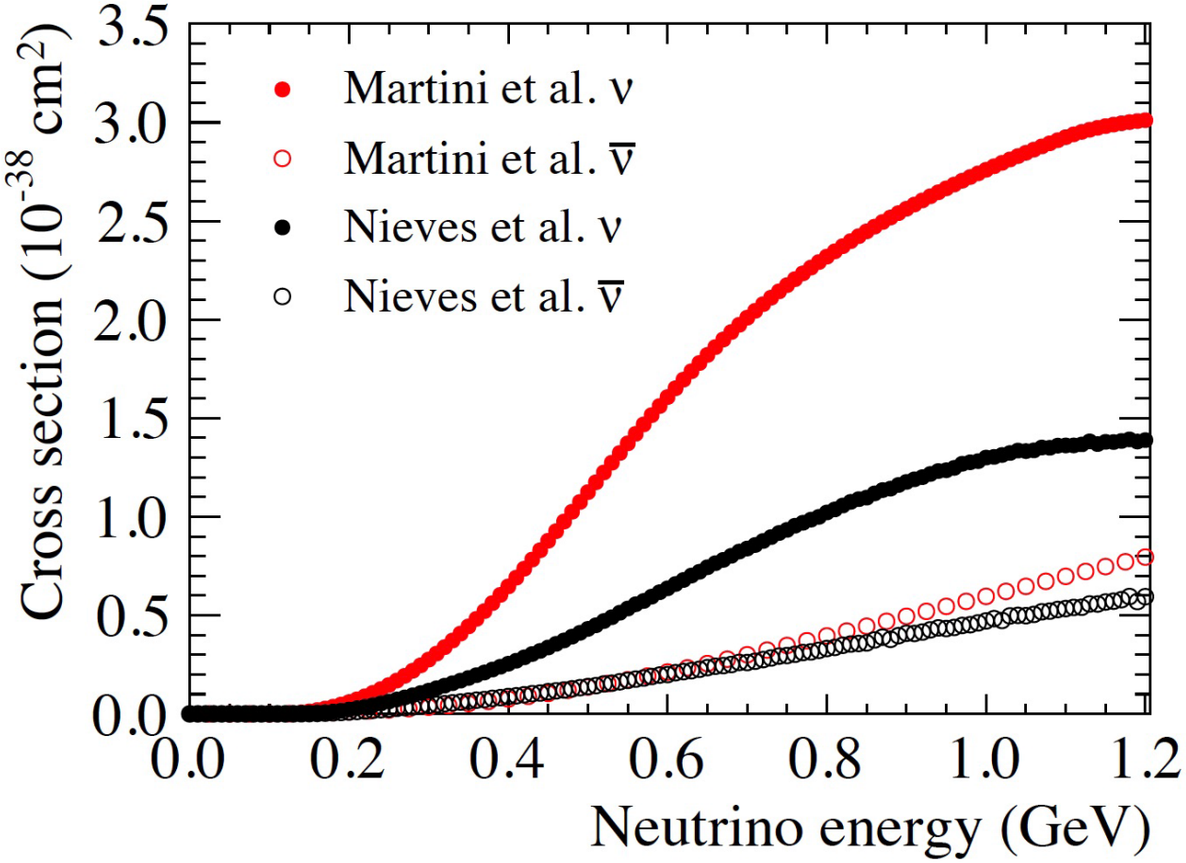


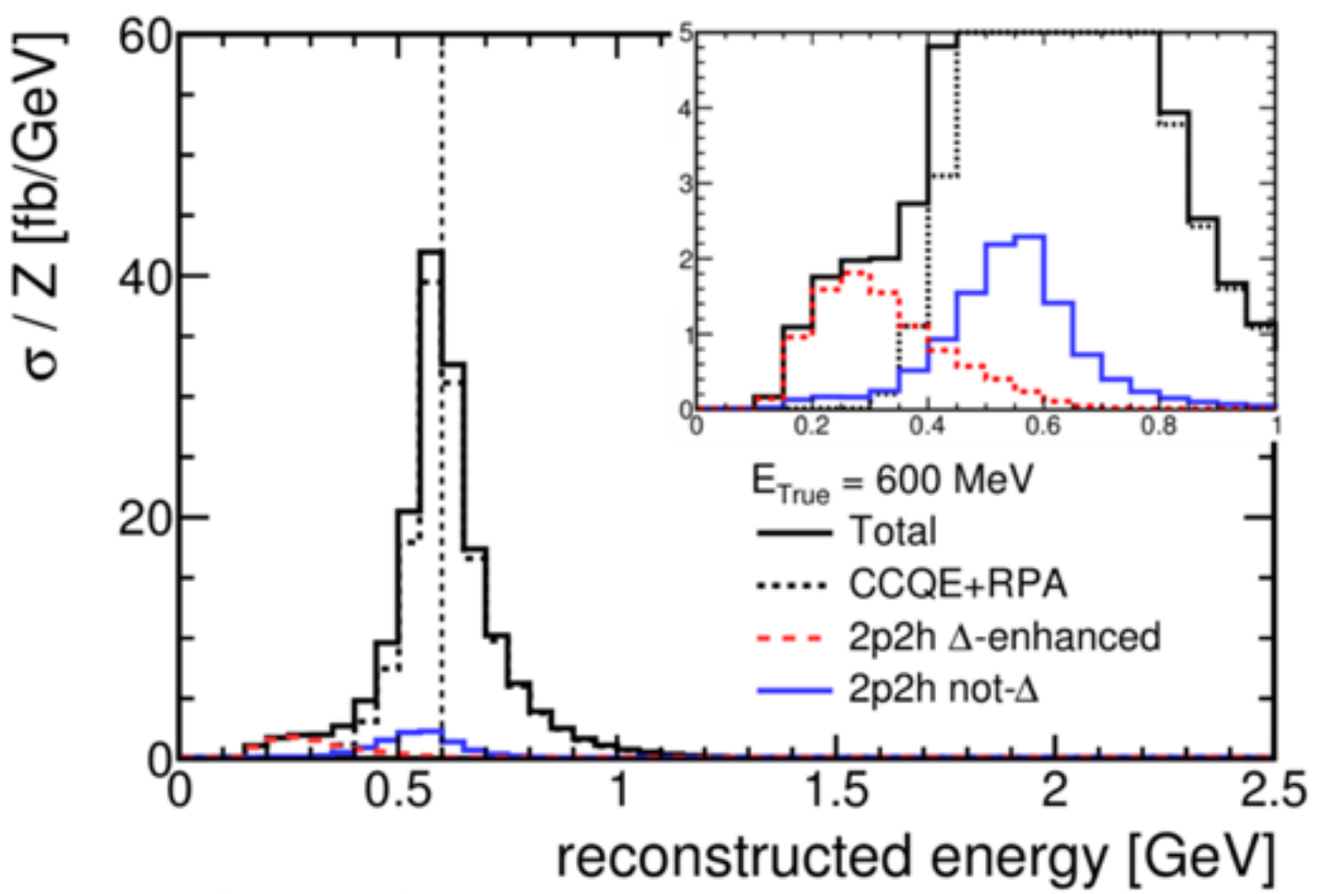
- Examples shown for T2K are for current statistical uncertainty
- Problems only grow with reduced statistical uncertainty

(Nuclear model) questions about QE+2p2h

- Multiple processes “stack” in observables; need uncertainties on all aspects

- What is the energy dependance of 2p2h? Between models? And neutrino scattering measurements?





PRD 96, 092006 (2017)

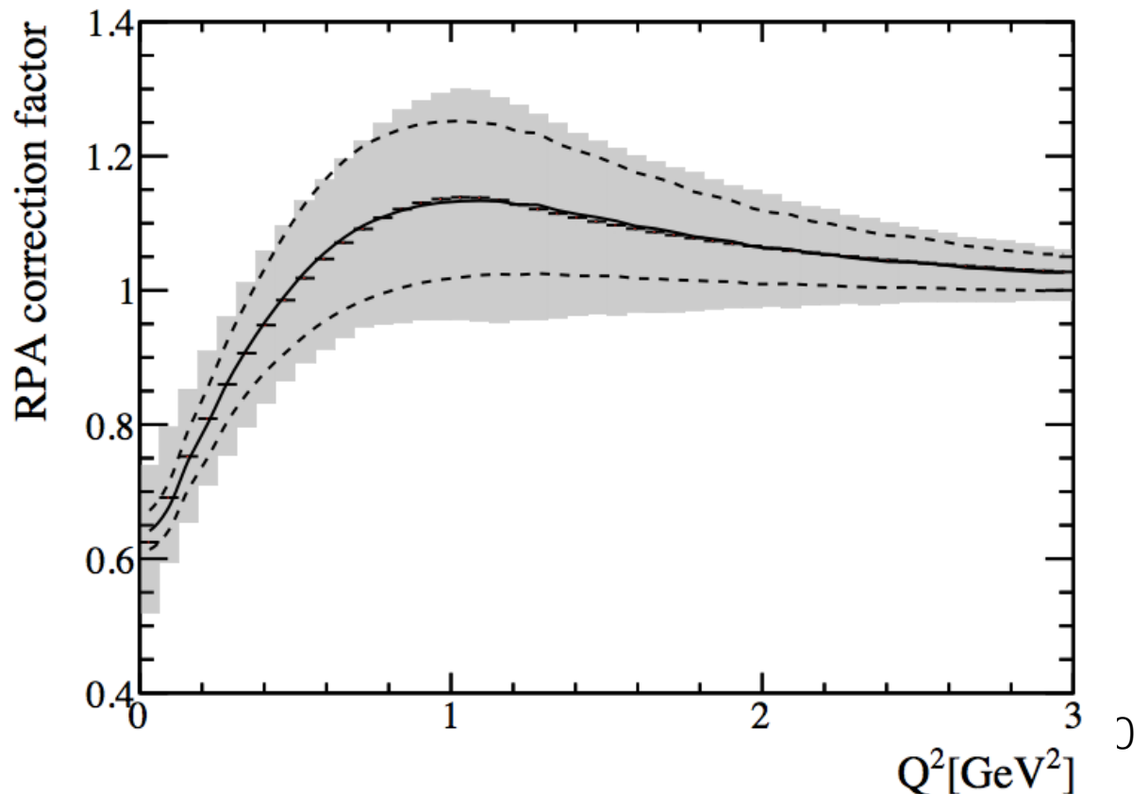
(Nuclear model) questions about QE+2p2h

- Multiple processes “stack” in observables; need uncertainties on all aspects

- What is the energy dependance of 2p2h? Between models? And neutrino scattering measurements?

- What does the cross section do at high Q^2?

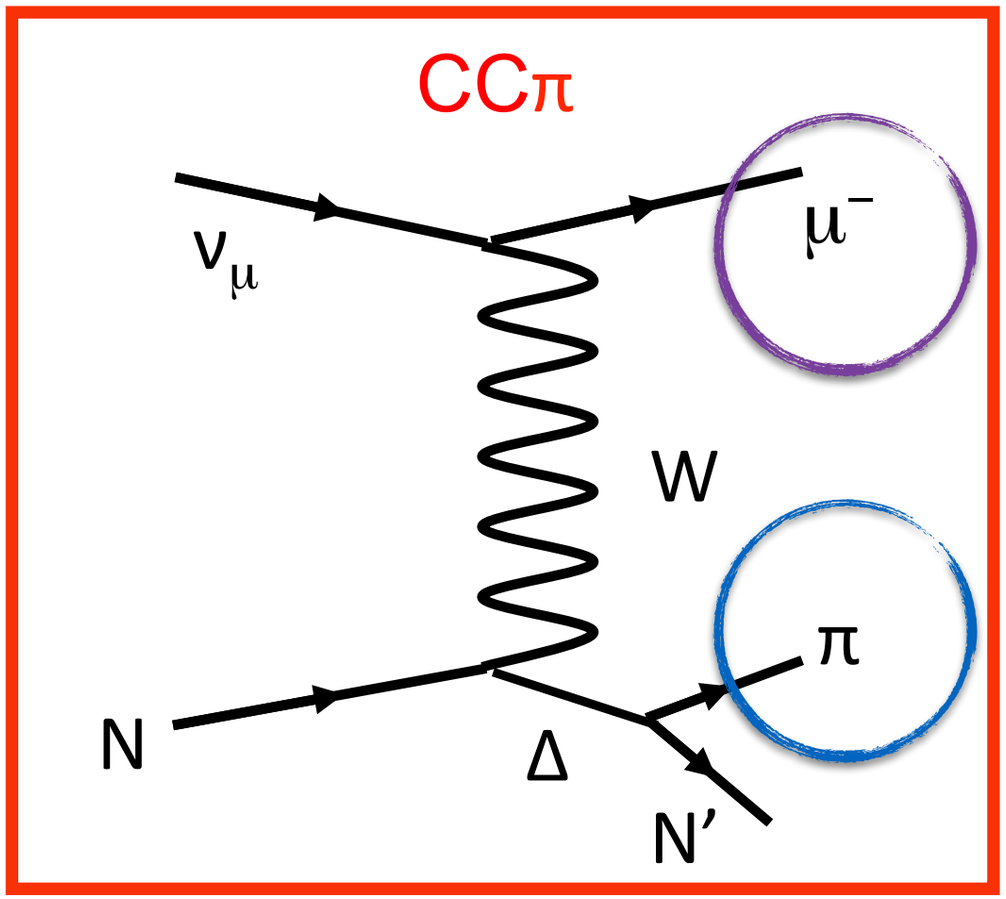
  - Nuclear model and (single nucleon) axial form factor dipole or not?



What is the role of single nucleon form factors in oscillation experiments?

- Important background (and signal) process for oscillation (non-standard) physics

- **Challenge to model!**
  - non-resonant backgrounds?
  - pion re-interaction (final state interaction) model?
  - **Busted single nucleon model?**



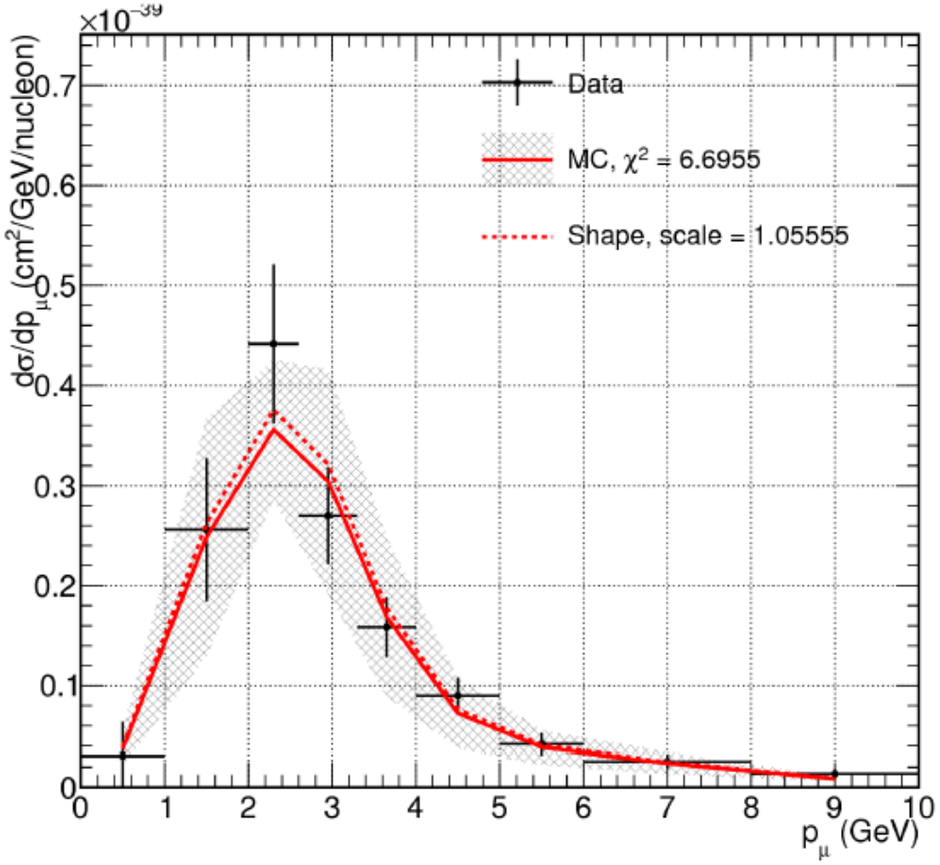
- Example from NUISANCE software framework thanks to C. Wilkinson - *Dec 2016 seminar:* http://npc.fnal.gov/neutrino-seminar-series/2016-2017-season/

Single Pion Production Puzzles

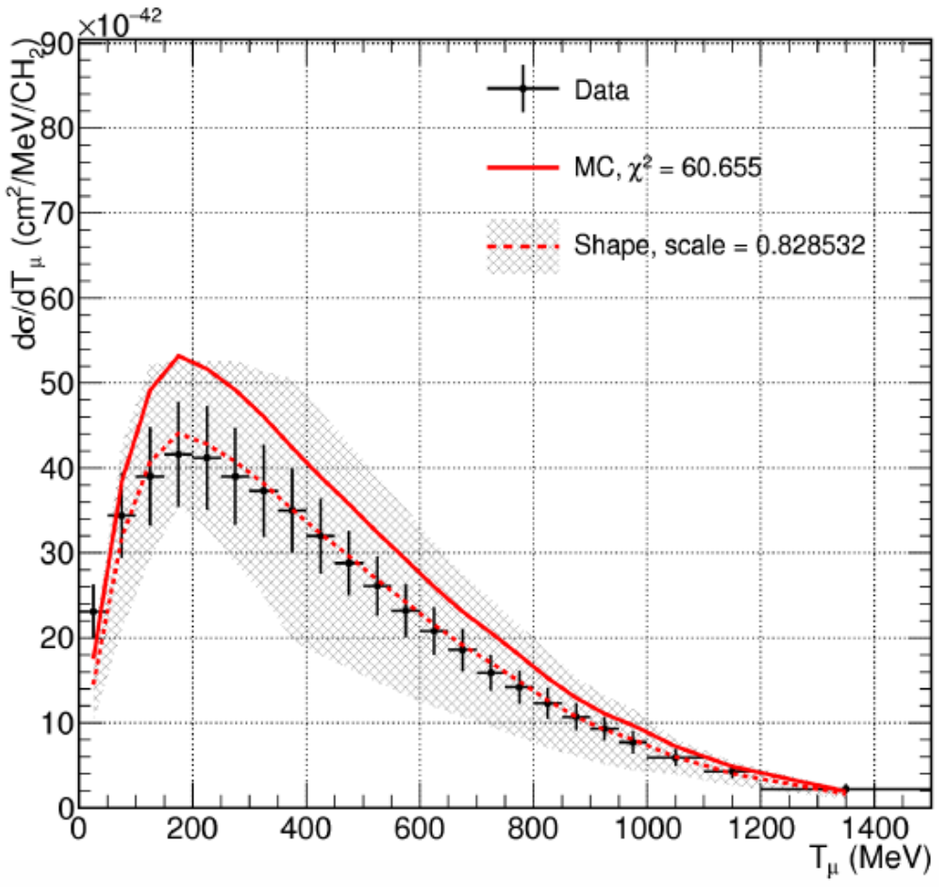
- **Reasonable agreement in outgoing muon spectrum**

- Terrible agreement in outgoing pion spectrum

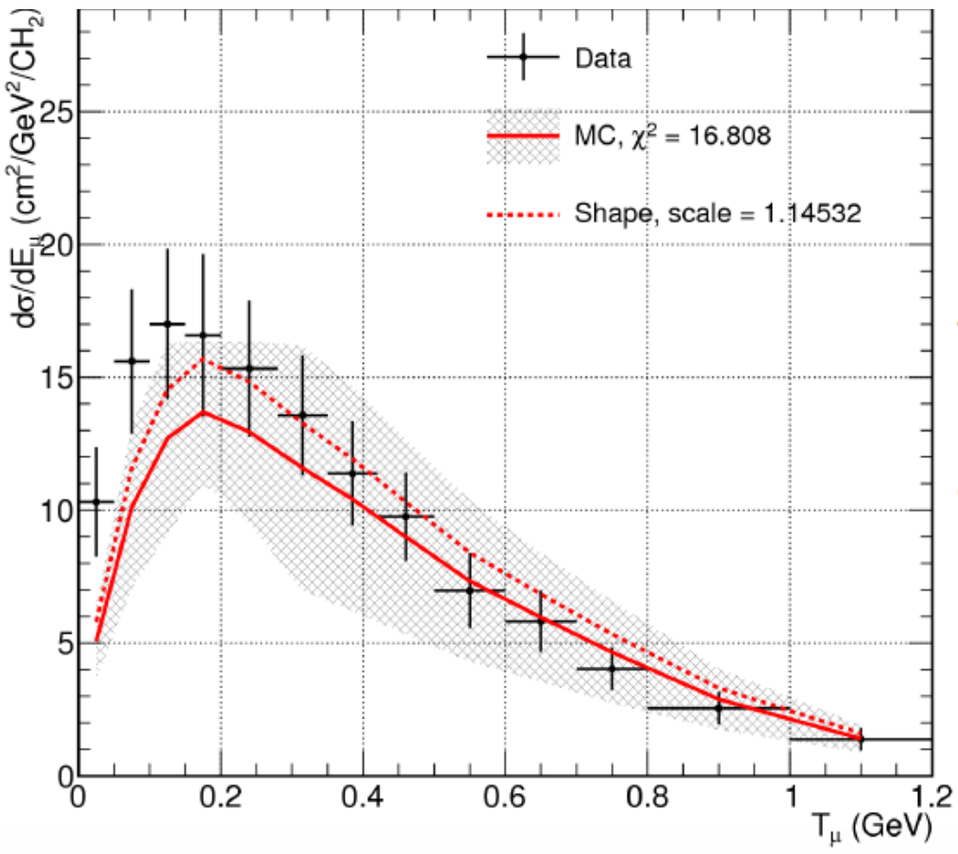
- Model development essential



MIN $\bar{\nu}_\mu$-CH CC1π^0
PRD 94 (2016) 052005



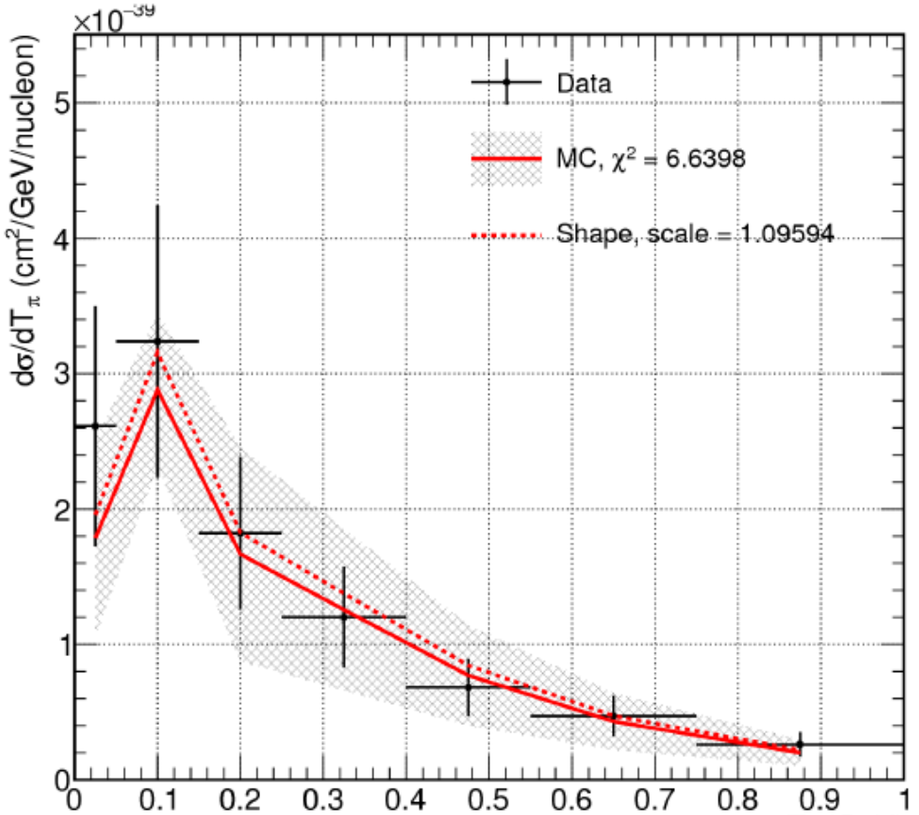
MB ν_μ-CH_2 CC1π^+
PRD 83 (2011) 052007



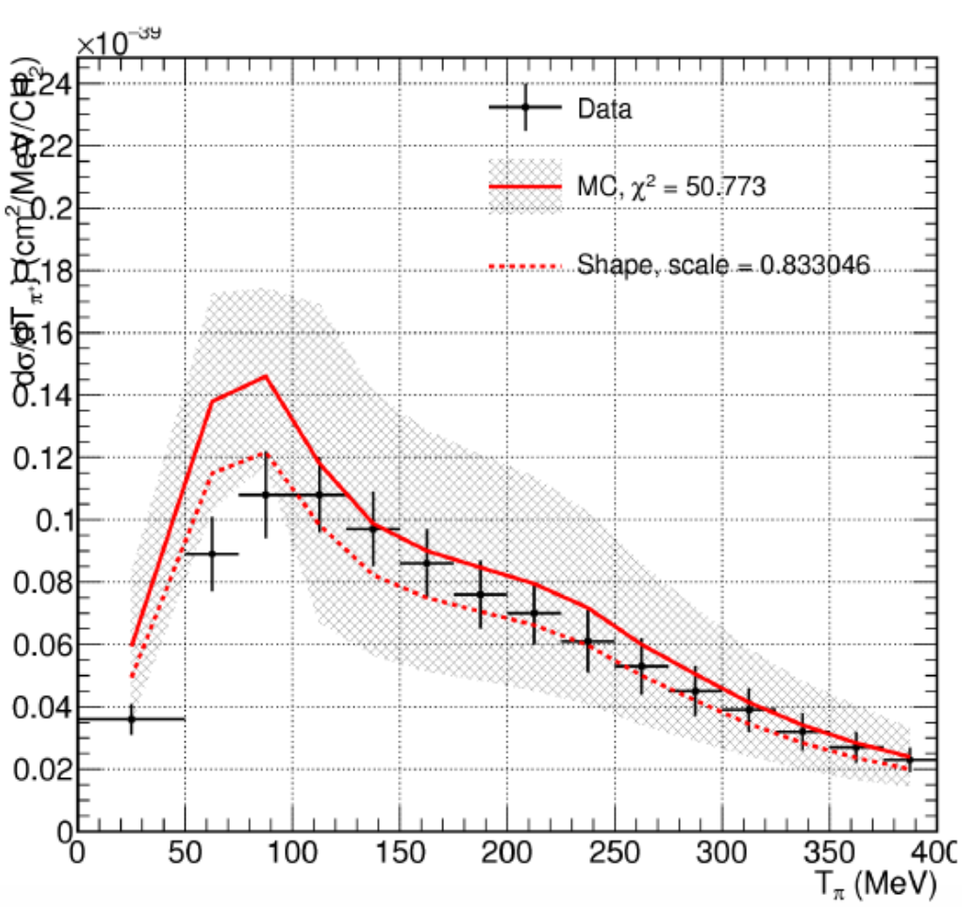
MB ν_μ-CH_2 CC1π^0
PRD 83 (2011) 052009

Single Pion Production Puzzles

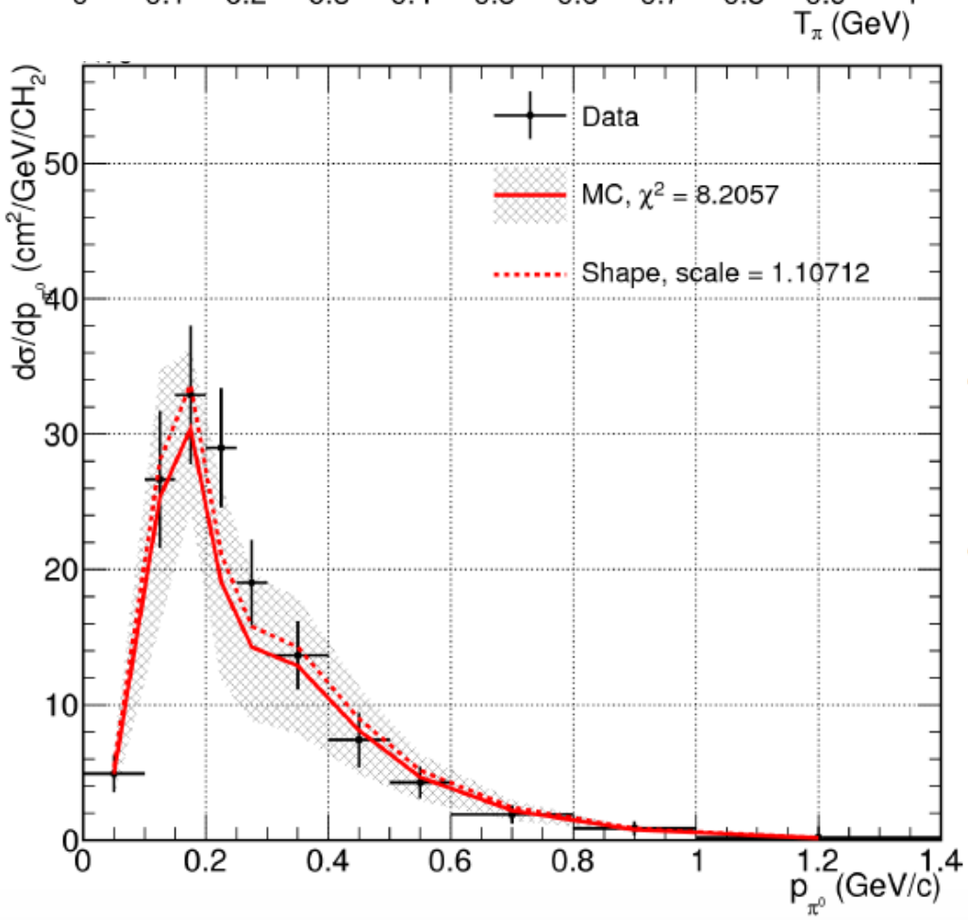
- Reasonable agreement in outgoing muon spectrum
- **Terrible agreement in outgoing pion spectrum**
- Model development essential



MIN $\bar{\nu}_\mu$-CH CC1π^0
PRD 94 (2016) 052005



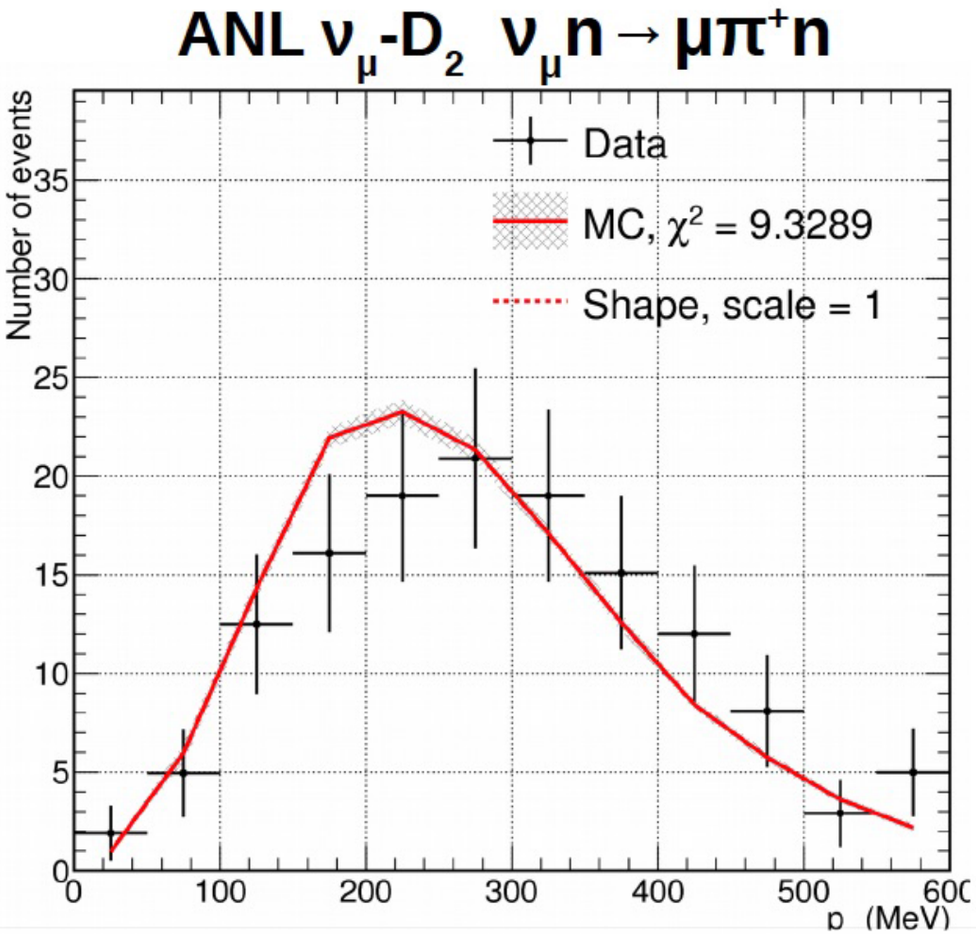
MB ν_μ-CH$_2$ CC1π^+
PRD 83 (2011) 052007

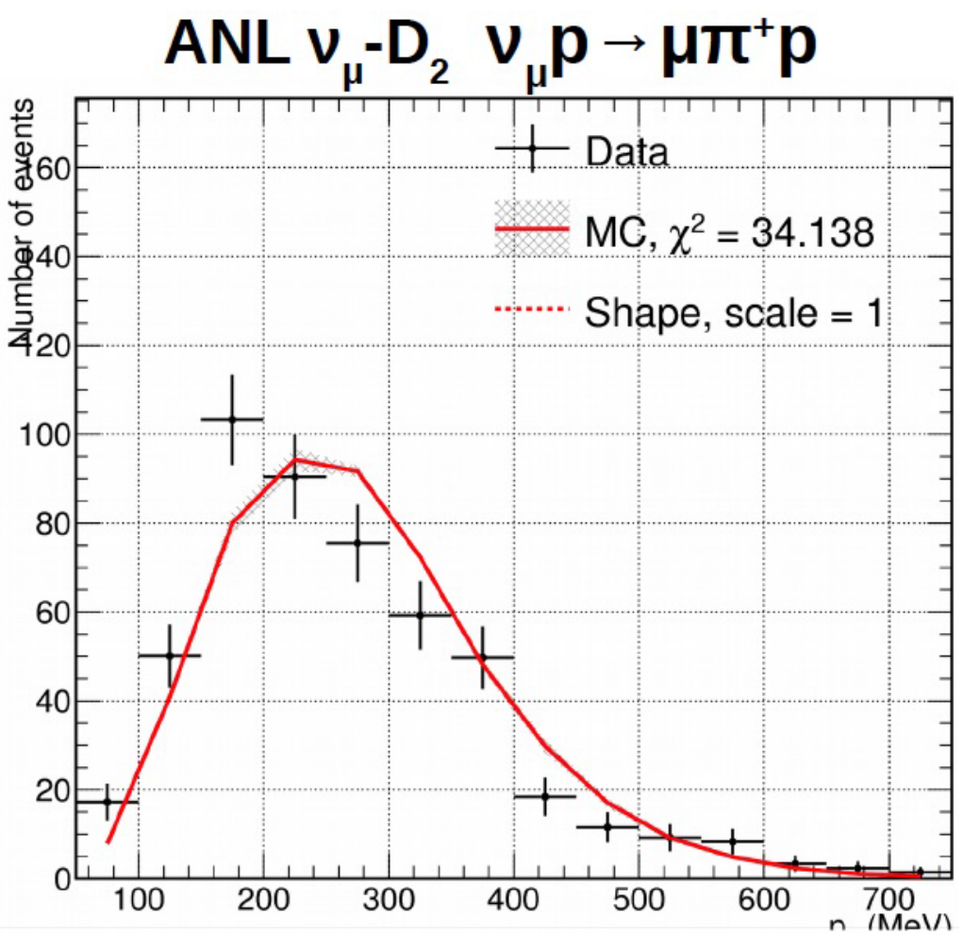


MB ν_μ-CH$_2$ CC1π^0
PRD 83 (2011) 052009

Single Pion Production Puzzles

- Very little flexibility in the interaction model to change the pion kinematics.
- Agreement with ANL data not amazing. More work required before moving onto FSI uncertainties/ nuclear effects.





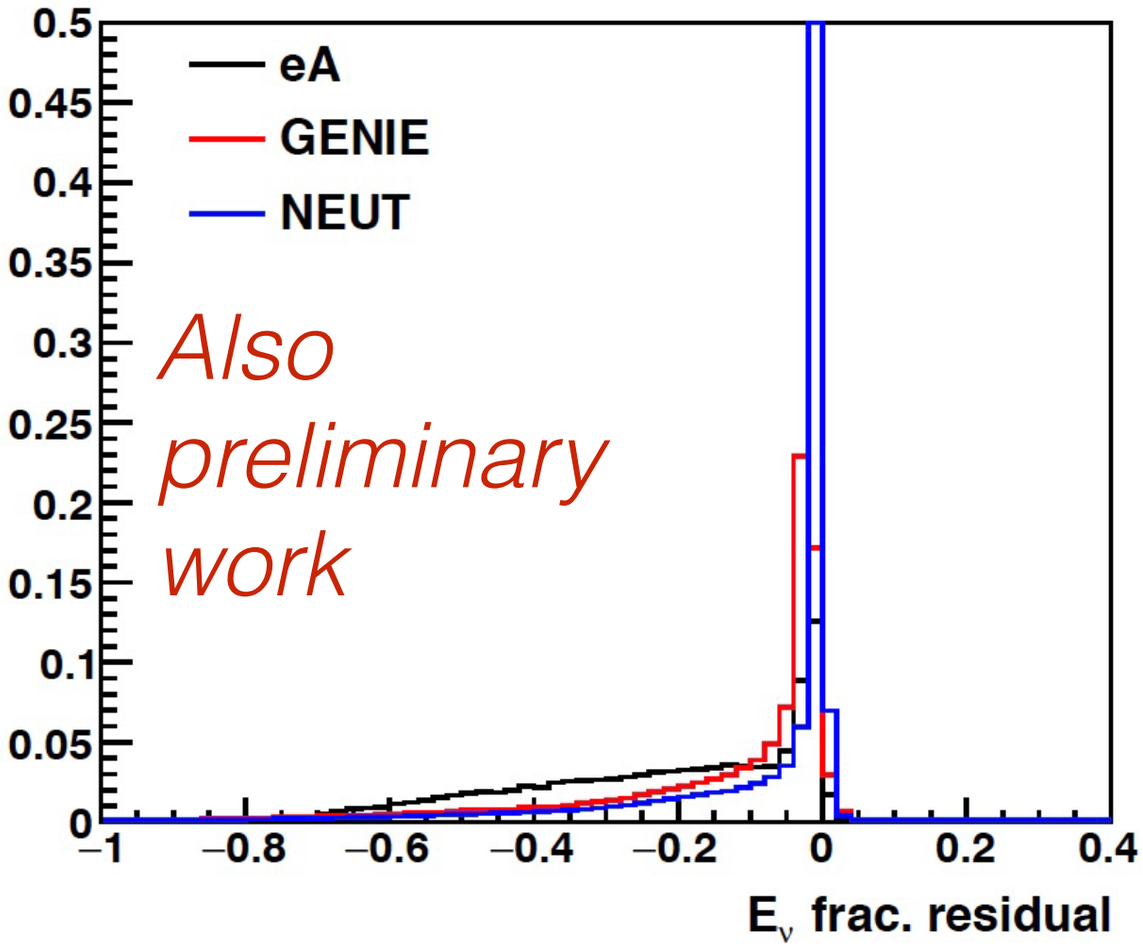
PRD 25 (1982) 1161

What should be the model uncertainty?

Especially: pion kinematics?

Electron scattering connection

How bad are our approximations?



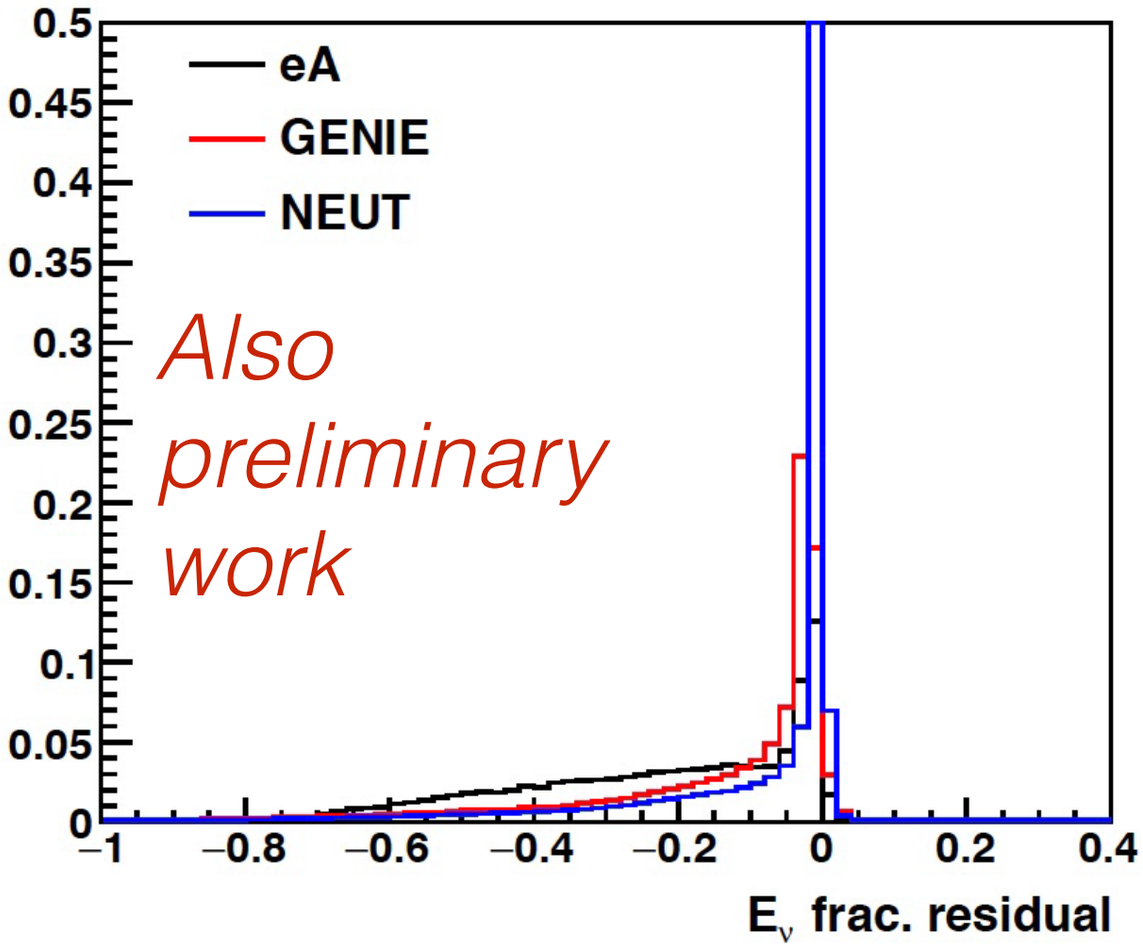
See Adi's talk - collaboration of Or Hen, Larry Weinstein, Afroditi Papadopoulou ,Mariana Khachatryan, Luke Pickering, Adrian Silva, Axel

- Comparison of (2.2 GeV, fixed energy) electron scattering data (corrected for Mott xsec) against neutrino simulations; acceptance corrections included. CC0pi signal.

- Electron scattering data (broad acceptance) tests particle multiplicity and kinematics through energy estimator

Electron scattering connection

How bad are our approximations?



Interface success? -core projection of response function assumed in osc analysis

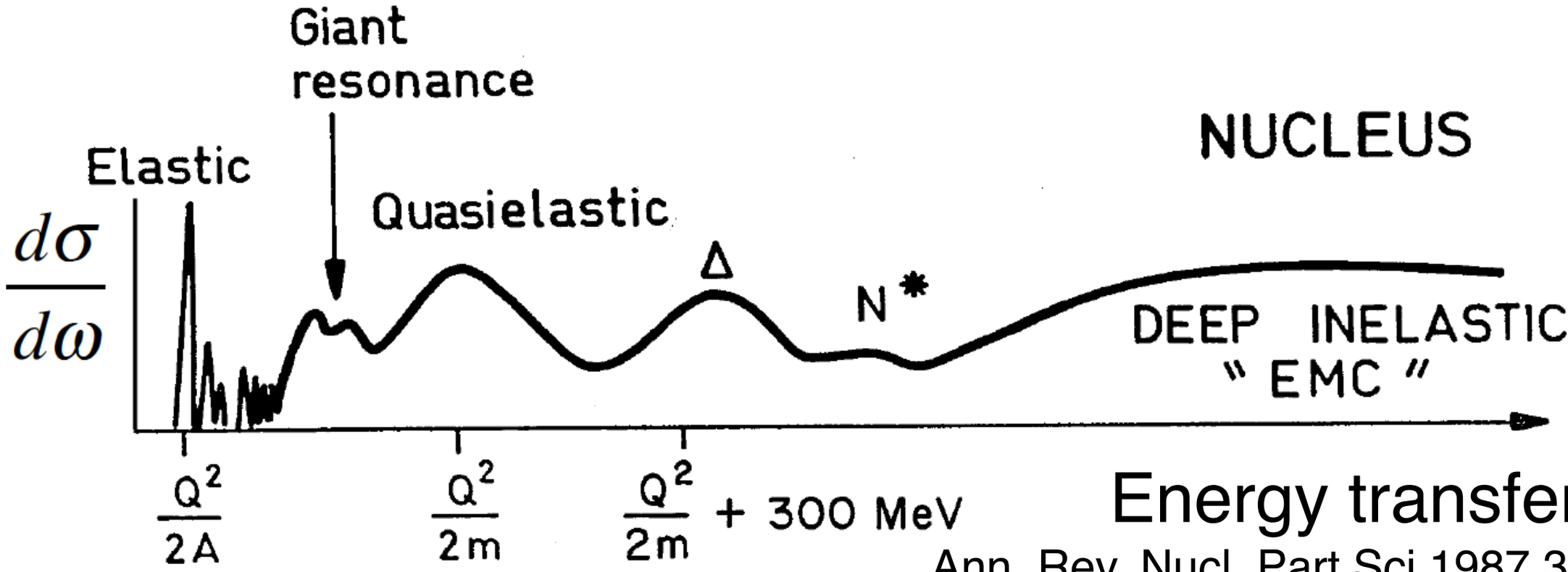
- Comparison of (2.2 GeV fixed energy) electron scattering data

$$N_{FD}^{\alpha\to\beta}(\mathbf{p}_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(\mathbf{p}_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(\mathbf{p}_{true}) \times R_i(\mathbf{p}_{true};\mathbf{p}_{reco})$$

corrections included. CCQE signal.

- Electron scattering data (broad acceptance) tests particle multiplicity and kinematics through energy estimator

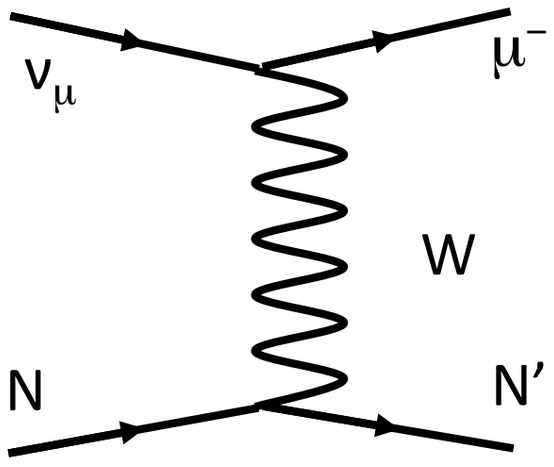
Processes in Neutrino Scattering



Ann. Rev. Nucl. Part.Sci.1987.37: 133-7

- Charged Current Quasi Elastic (CCQE) and multinucleon processes (2p2h)

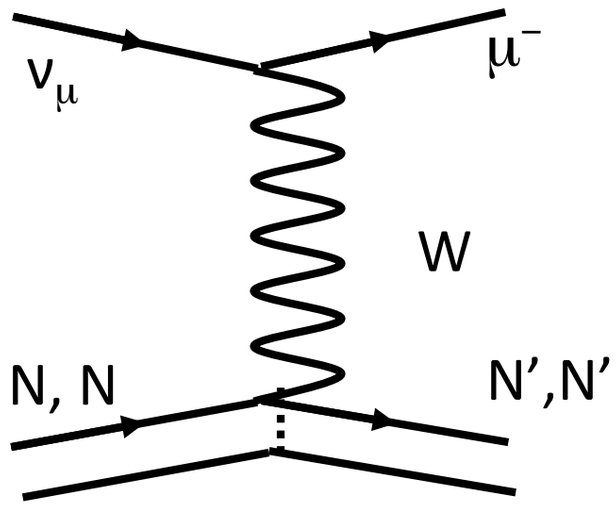
CCQE



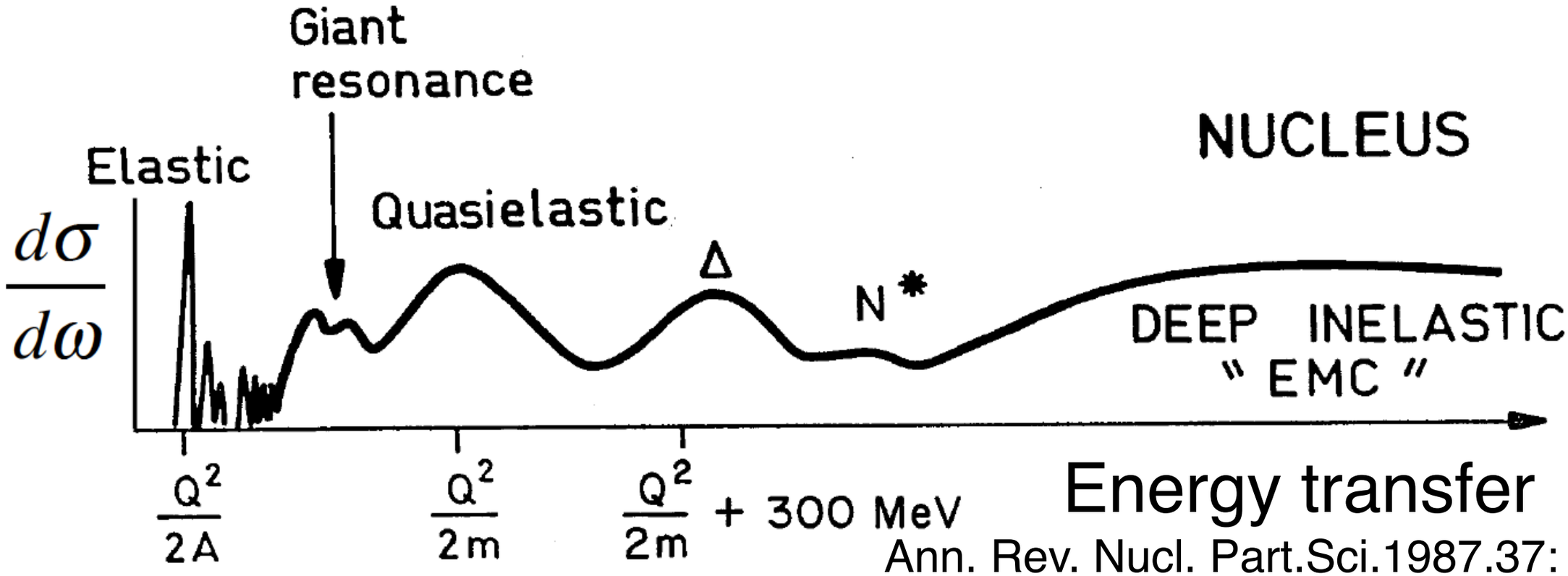
Observable

- neutrino (anti)
- muon or electron (+)
- proton (neutron)

2p2h



Processes in Neutrino Scattering

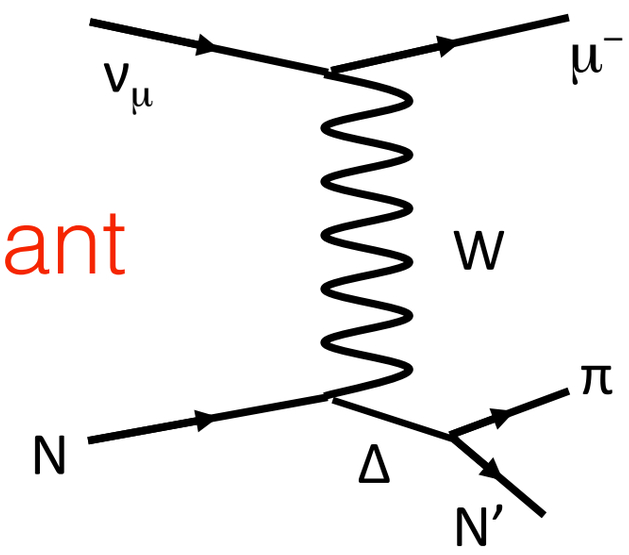


Ann. Rev. Nucl. Part.Sci.1987.37: 133-76

- Production of pions, CC1$\pi^{+/0/-}$ and NC1$\pi^{+/0/-}$

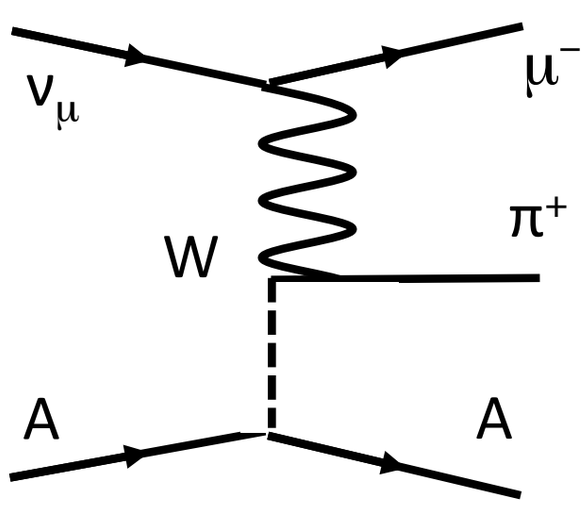
CCπ

resonant



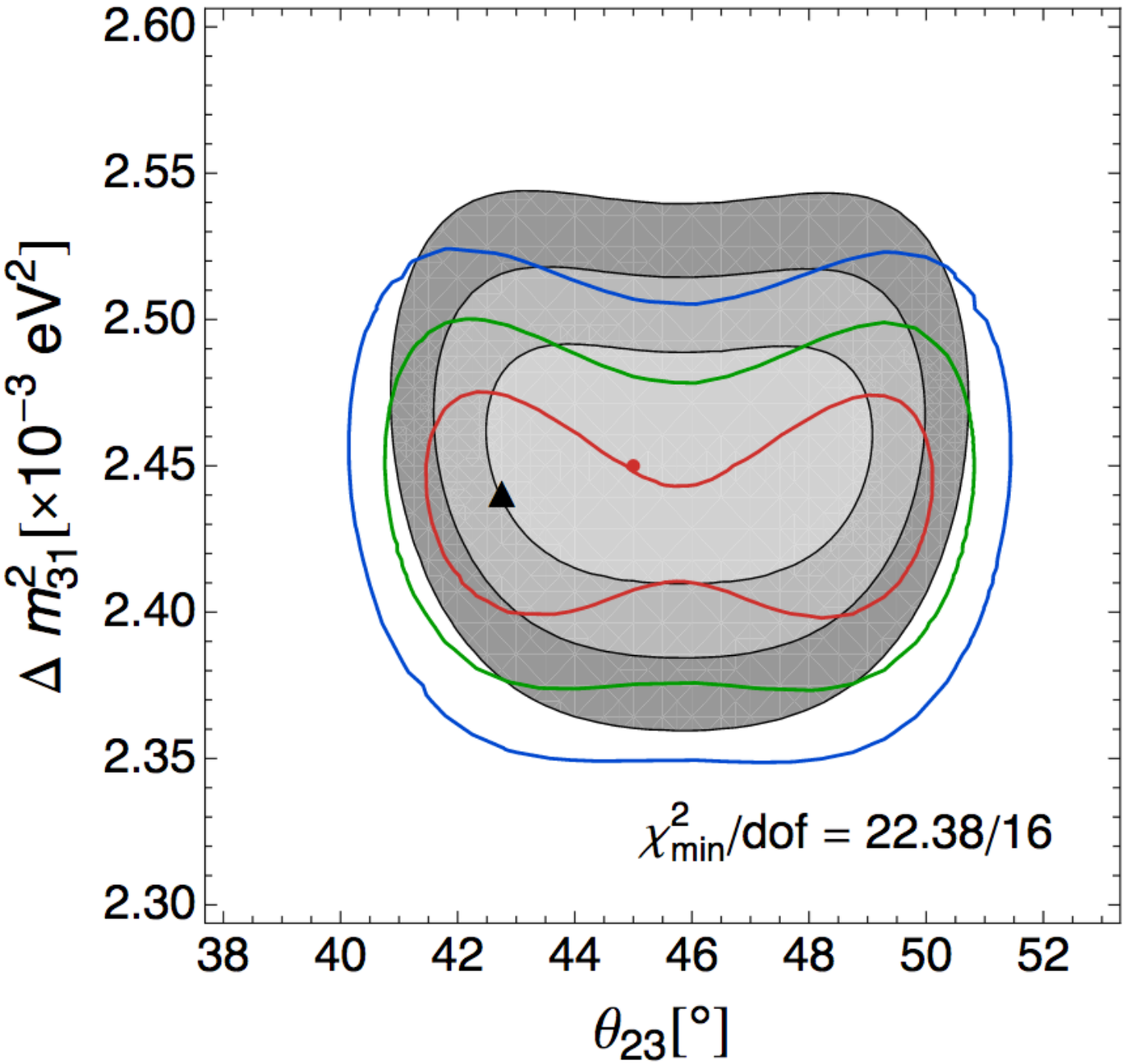
CCπ

coherent



Effect of v-A on oscillation physics

- **Model choice determines:**
- Size of effect on oscillation physics
- Parameterization of the v-A uncertainties



P. Coloma, P. Huber, C-M. Jen, C. Mariani, PRD 89, 073015 (2014)

Effect of v-A on oscillation physics

Specific study within DUNE

**add ref

- **Model choice determines:**
- Size of effect on oscillation physics
- Parameterization of the v-A uncertainties
- Which oscillation parameter(s) are affected
- Which method (QE or calormetric) is used

Generic example: P. Coloma, P. Huber, C-M. Jen, C. Mariani, PRD 89, 073015 (2014)