Uses of electron scattering data in neutrino oscillation experiments

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U.S. Department of Energy

Current:

Atmospheric: Super-Kamiokande, IceCube

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

Current program is broad.

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

Future:

Accelerator/Atmospheric: Hyper-Kamiokande, 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**

Processes in Neutrino Scattering

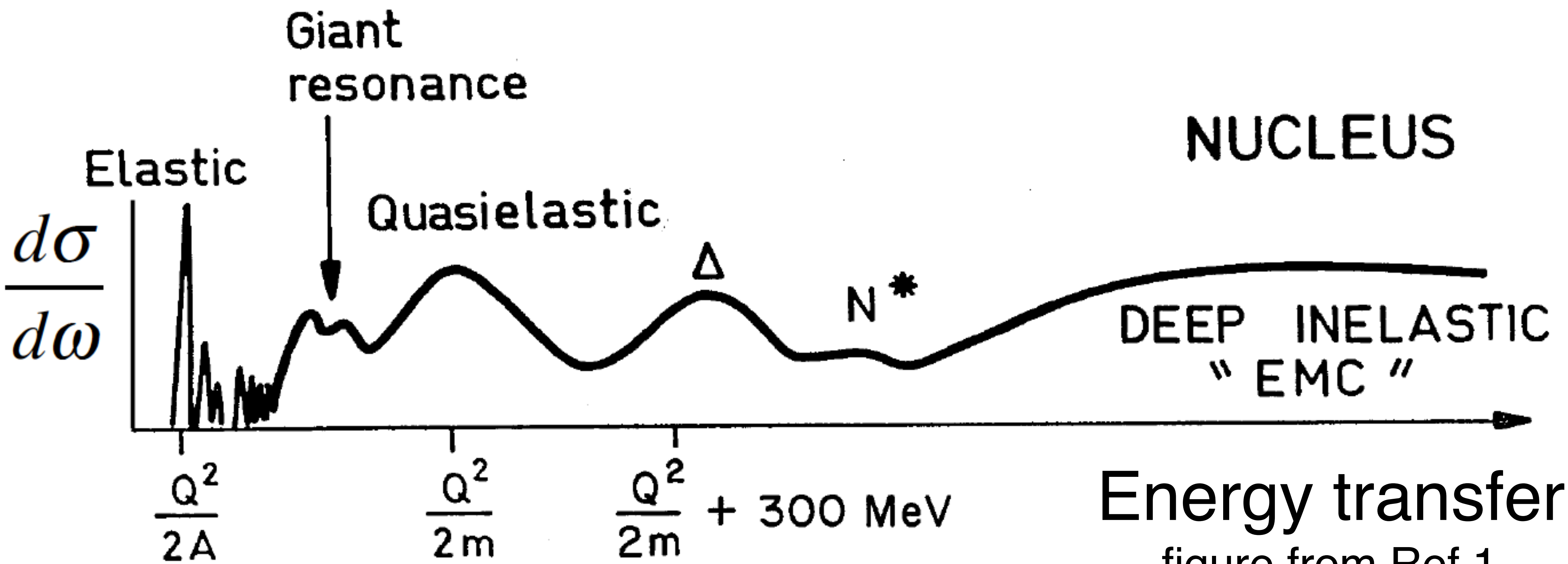
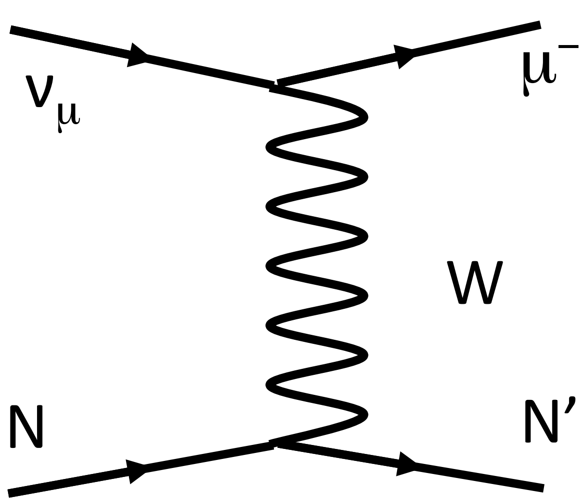


figure from Ref 1

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

CCQE

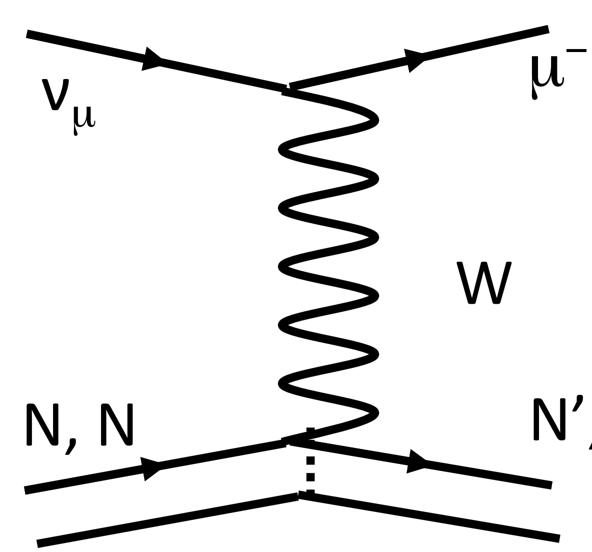


Observable

neutrino (anti)

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

2p2h



Processes in Neutrino Scattering

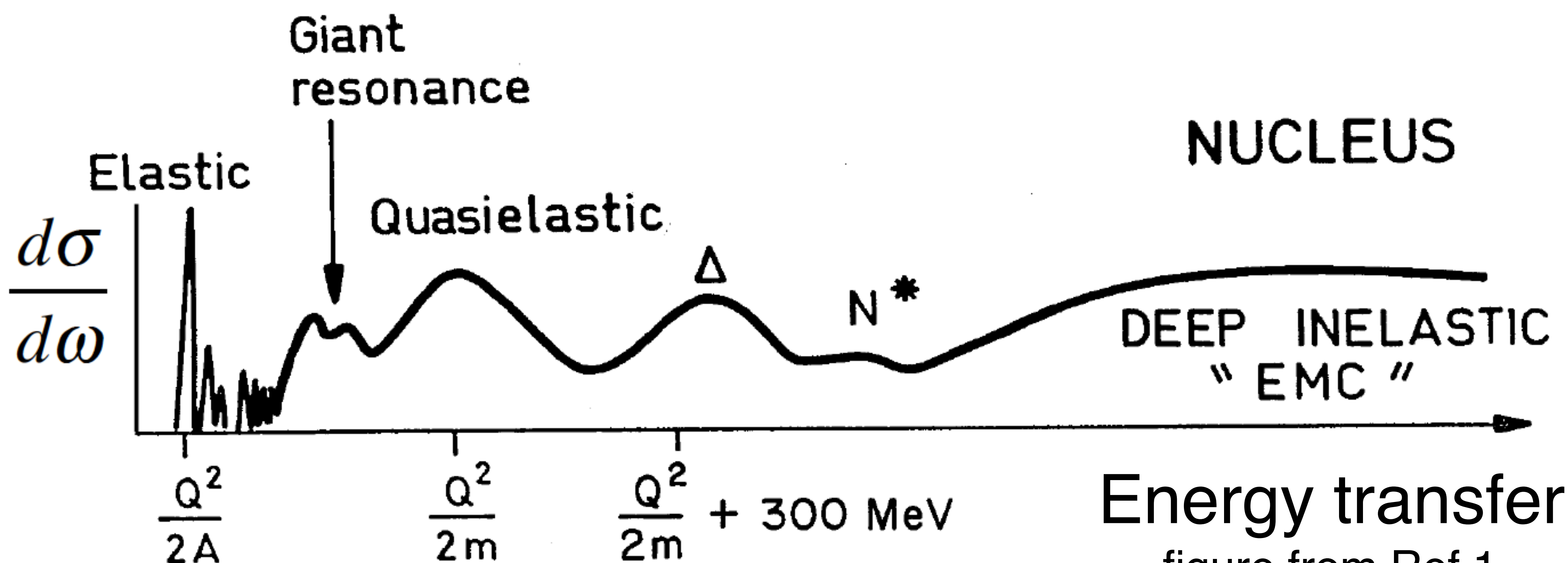
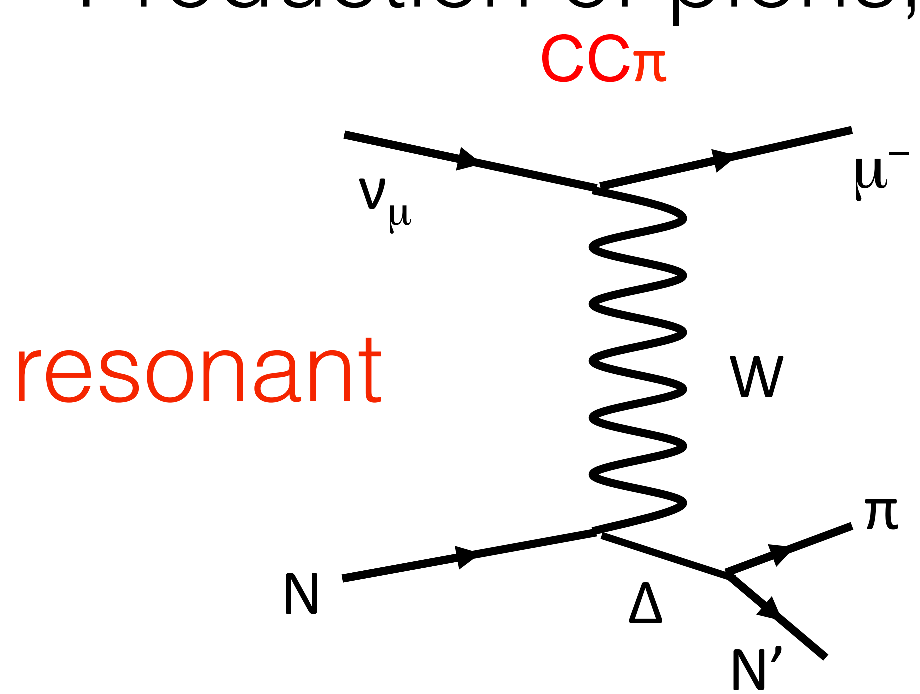
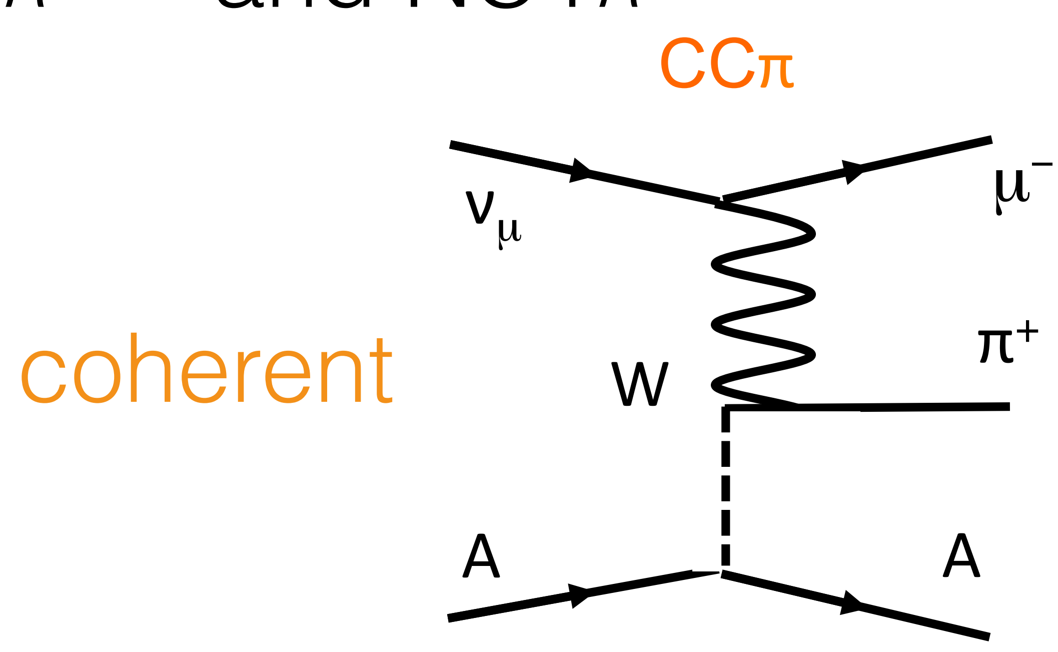


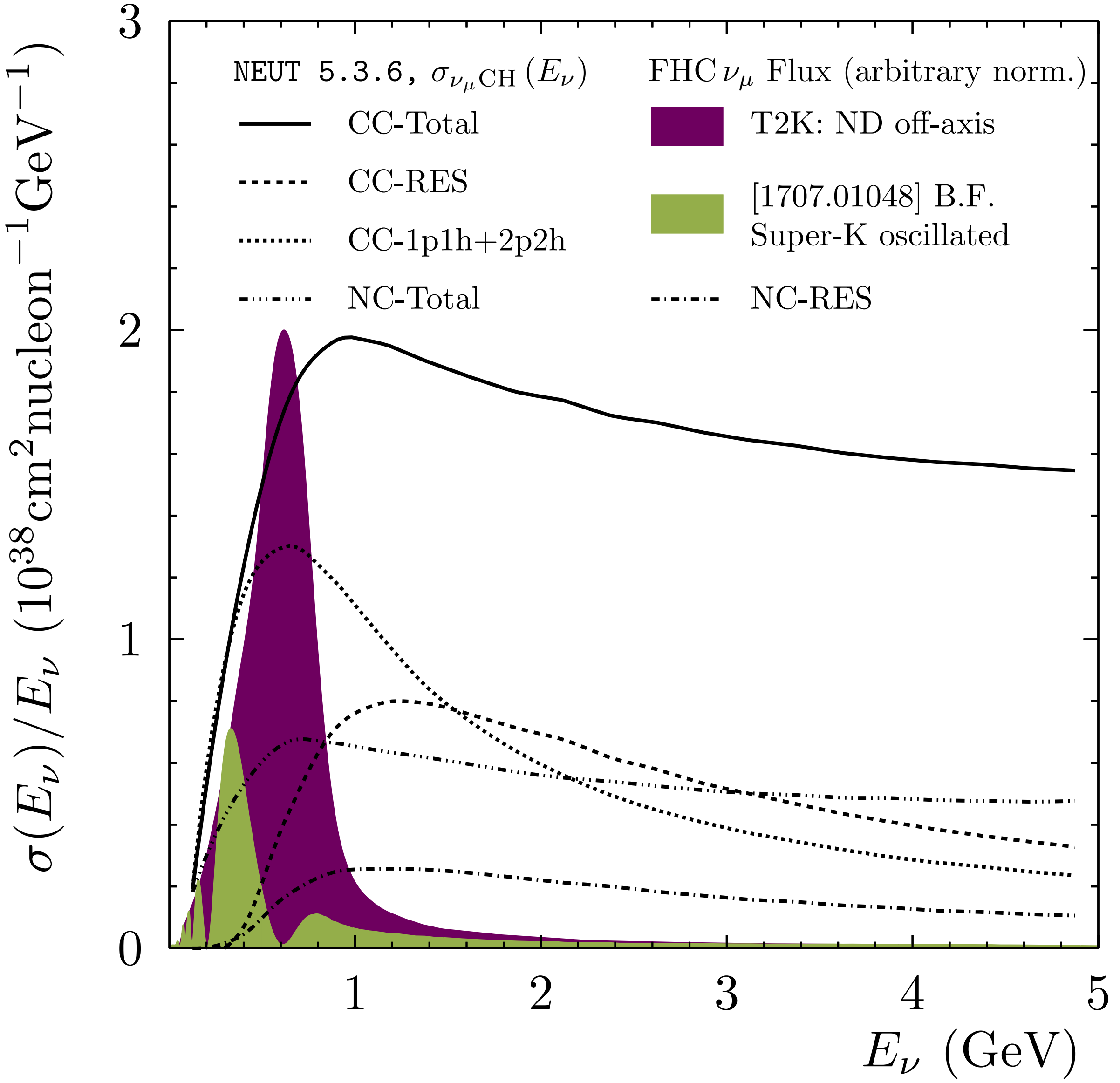
figure from Ref 1

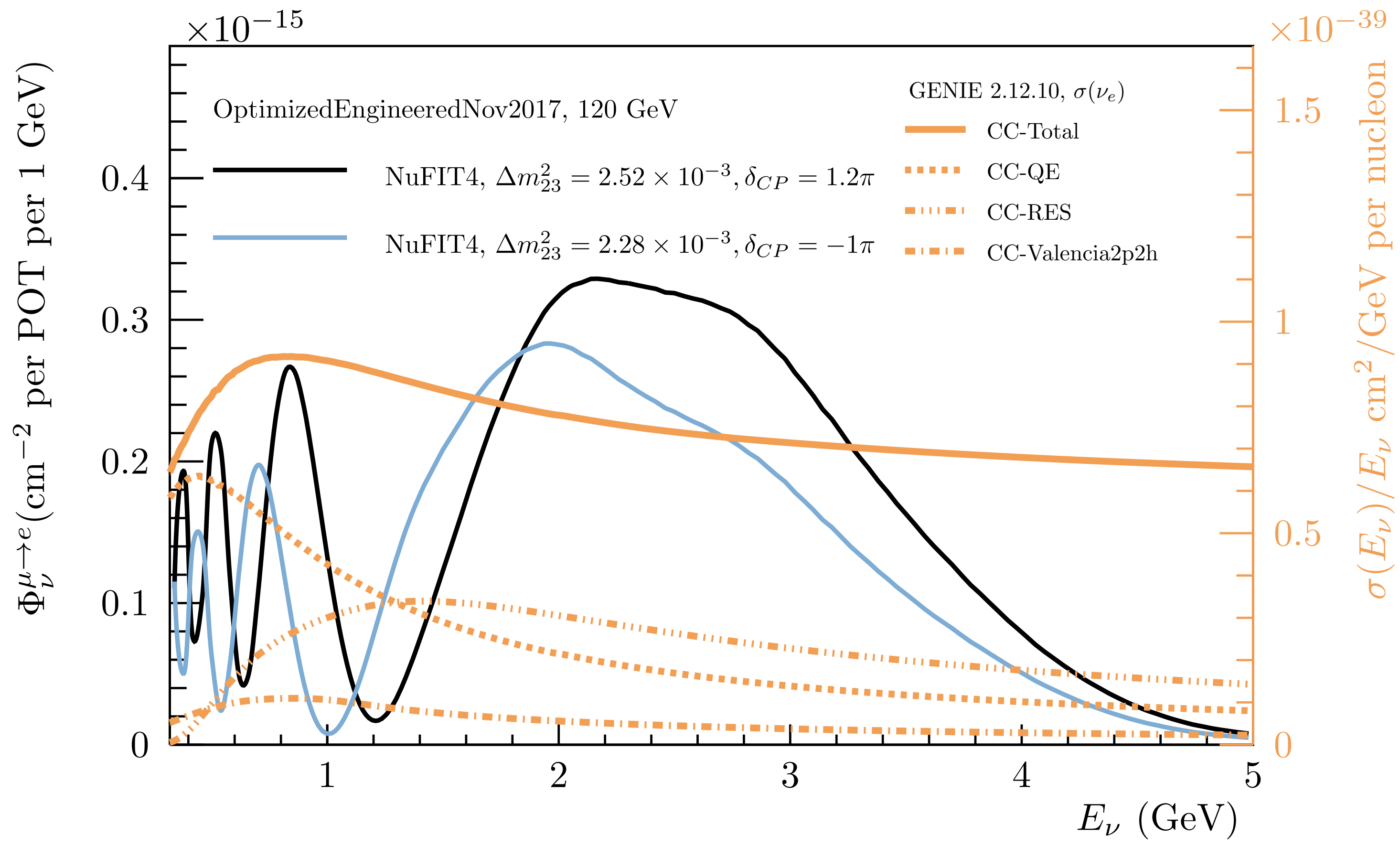
- Production of pions, CC1$\pi^{+/0/-}$ and NC1$\pi^{+/0/-}$





Neutrino oscillation analyses rely on neutrino cross section models





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

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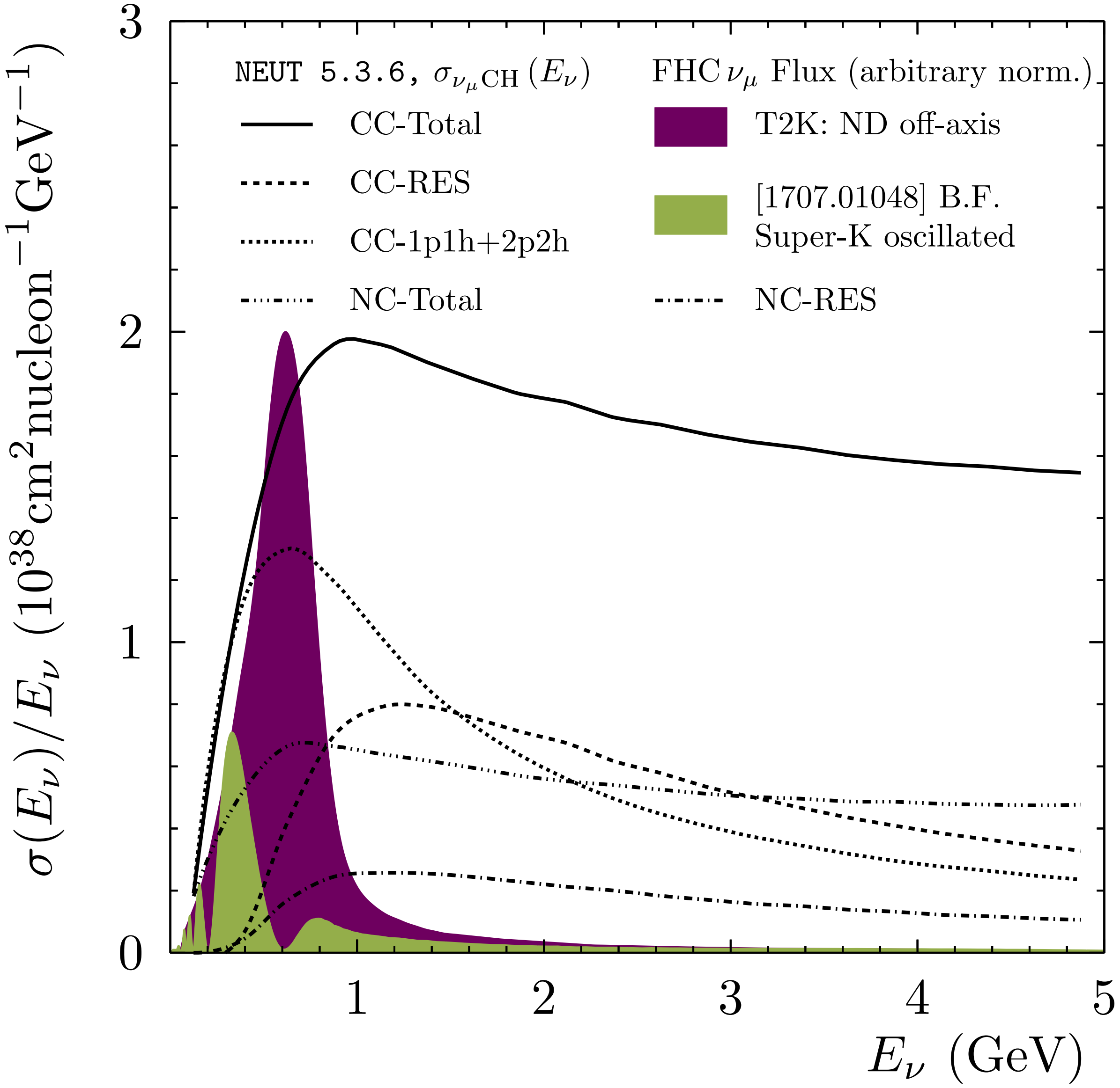

A model is needed to predict event rates in oscillation experiments

All relevant processes (and flavors)

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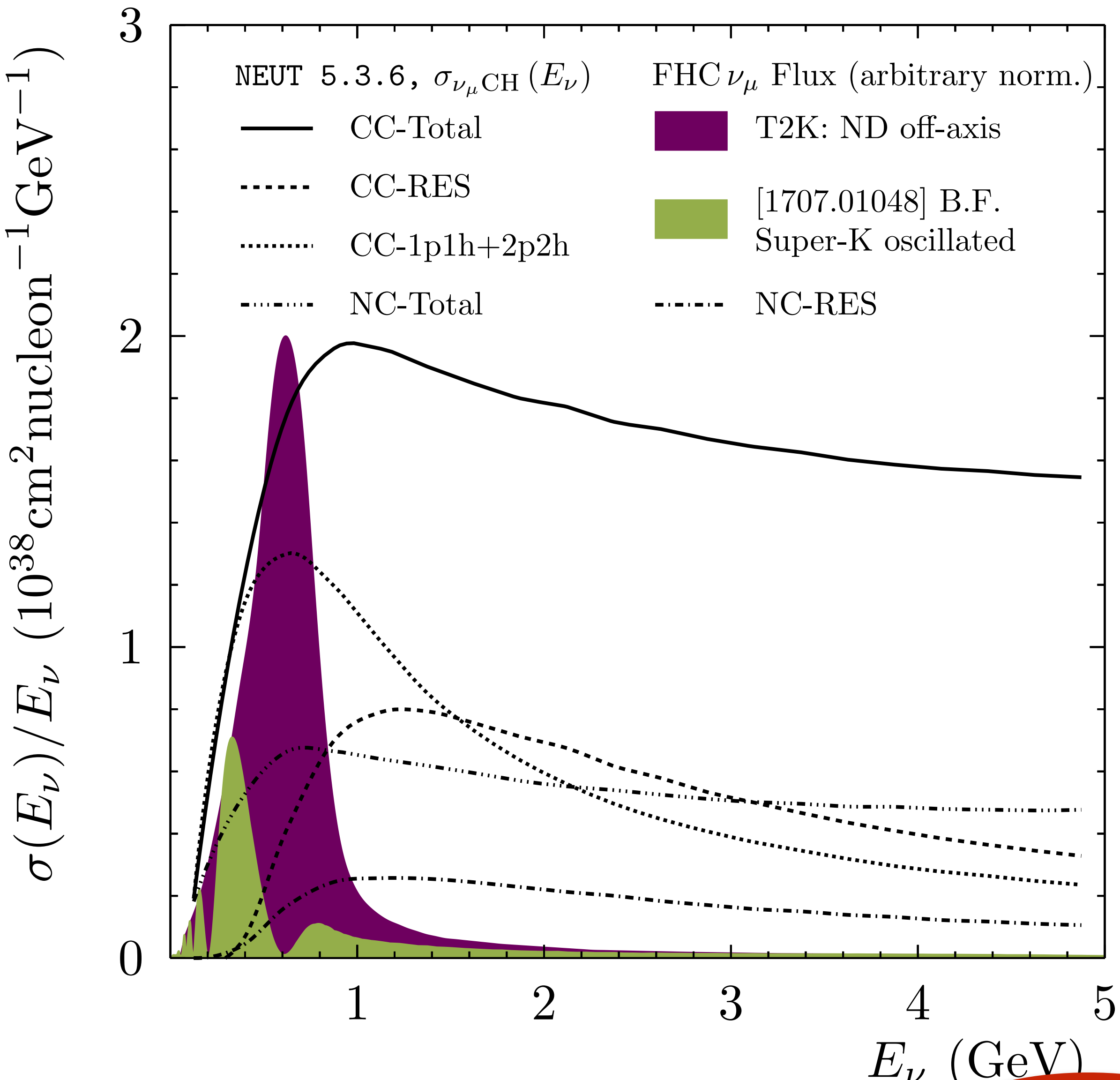

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All relevant processes (and flavors)

Relationship between true and reconstructed kinematics)

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Cross section (true kinematics)

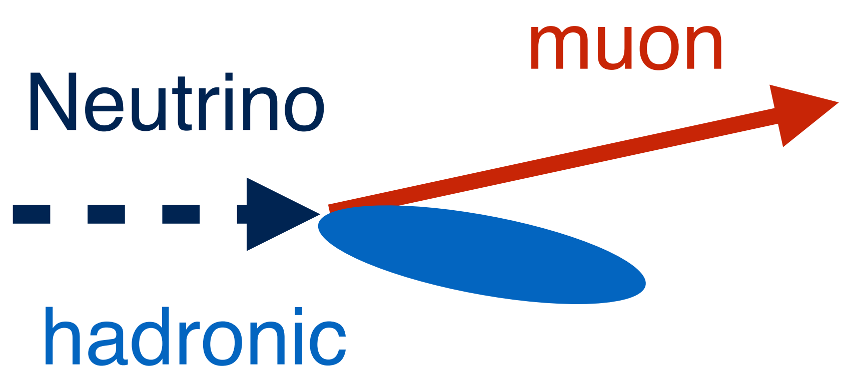
Efficiency (true kinematics)

Needs: Energy estimation

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

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

$$E_\nu = E_\mu + \sum E_{hadronic}$$



T2K
Super-Kamiokande

SBN
DUNE

NOvA

Needs: Energy estimation

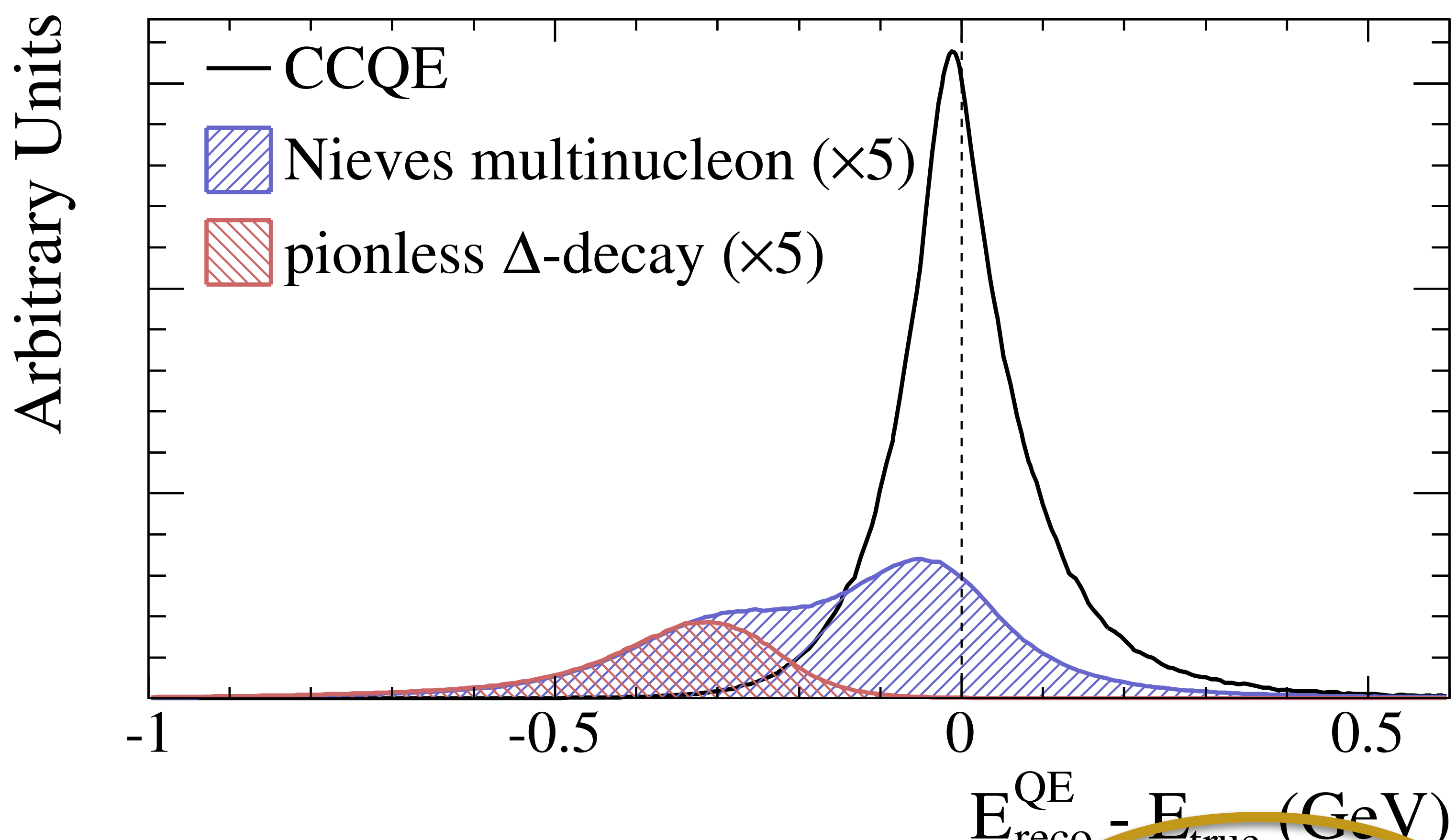
- Nuclear effects bias true and estimated neutrino energy

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

T2K, PRL 112, 181801 (2014)

Requirement for model:

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



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

Example: model tuning on T2K

For more details, see NuInt2018 and NuFact2018 meetings which have talks from NOvA, T2K, GENIE, NuWro and NUISANCE efforts

Example: model tuning on T2K

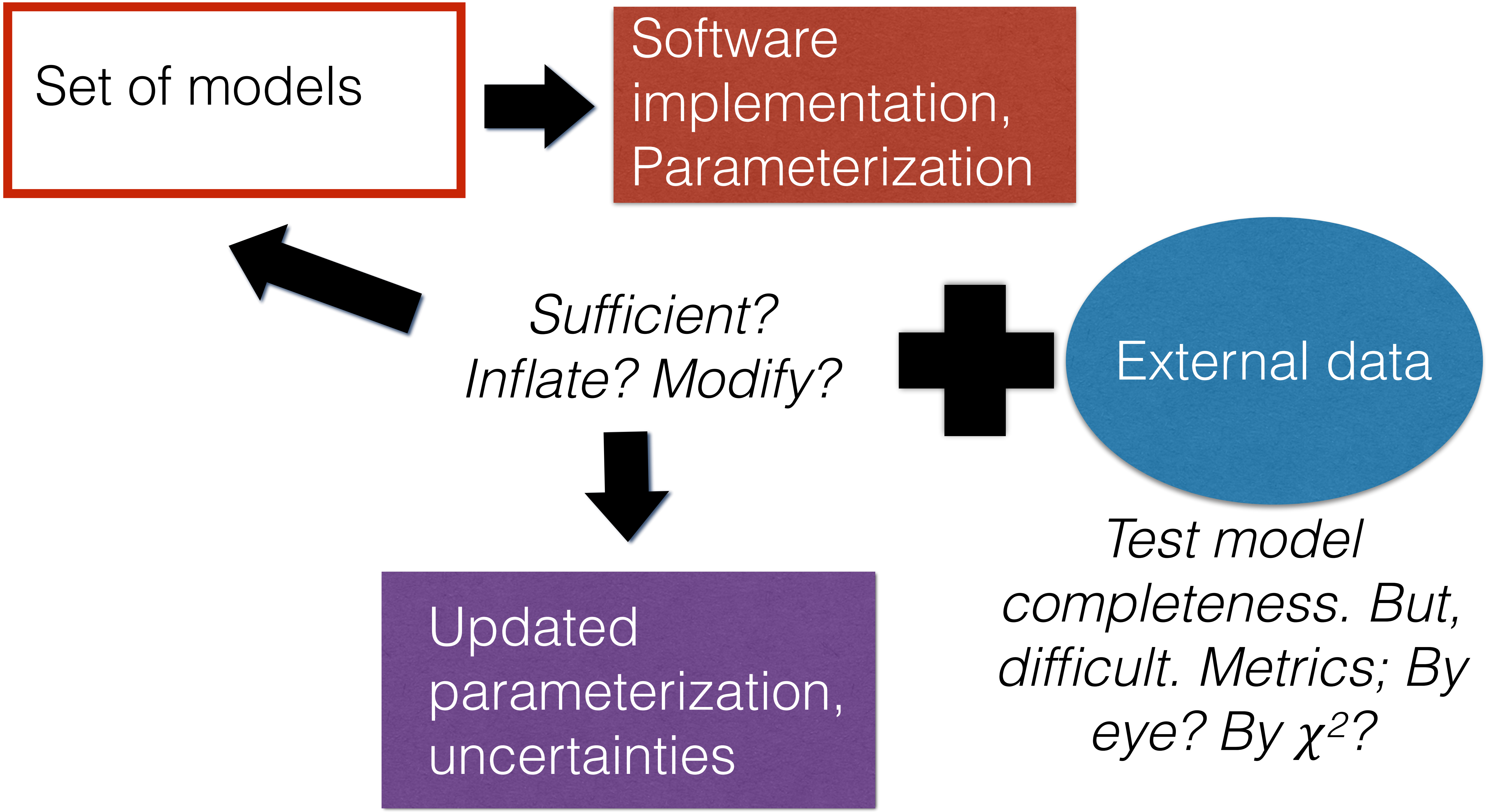
Set of models → Software implementation, Parameterization

May include validation against various data sets, including electron scattering

Not complete list of theory groups who try to do this: GiBUU, Benhar et. al, SuSA

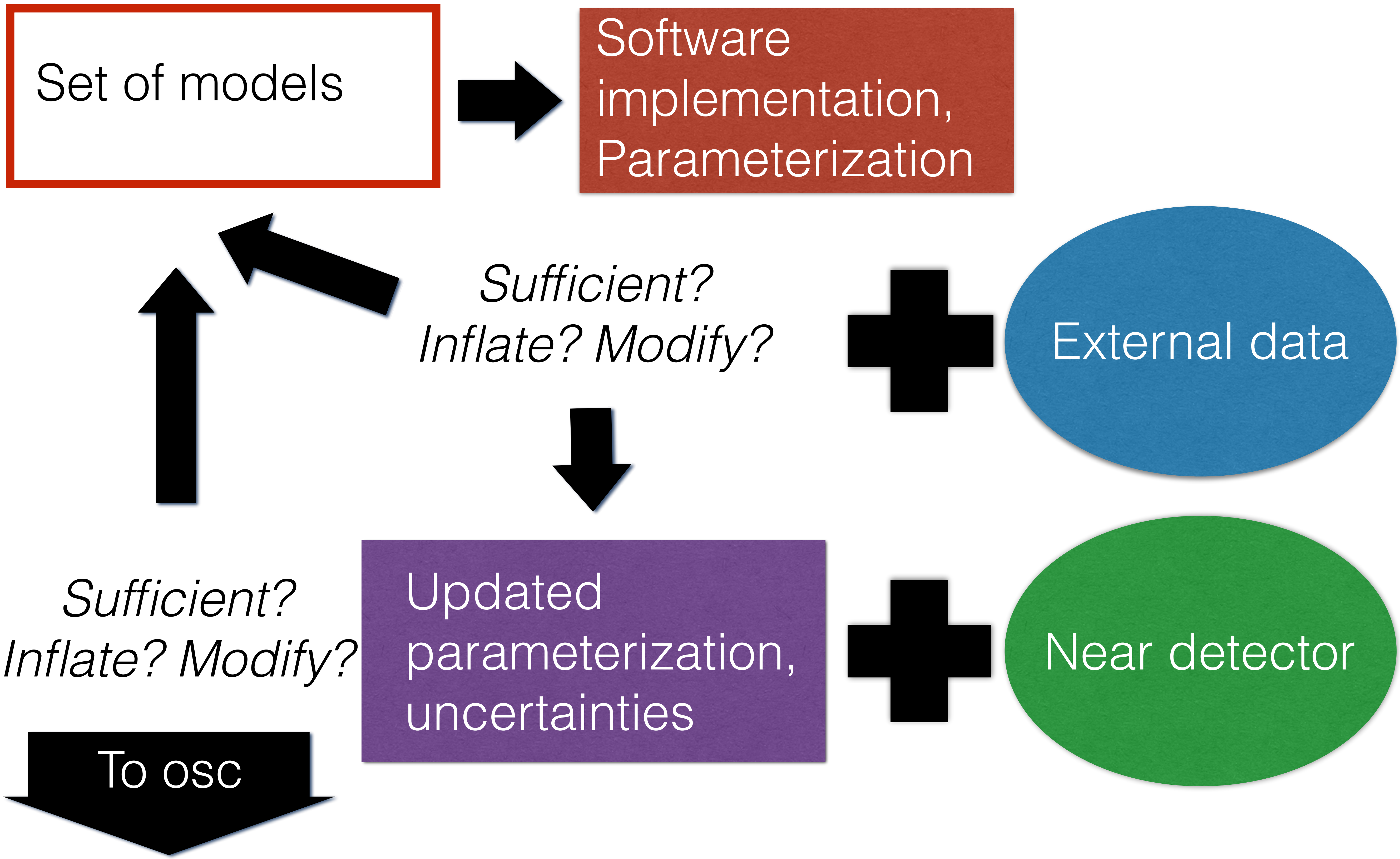
This makes approximations or simplifications (e.g. factorization? right degrees of freedom?)

Example: model tuning on T2K



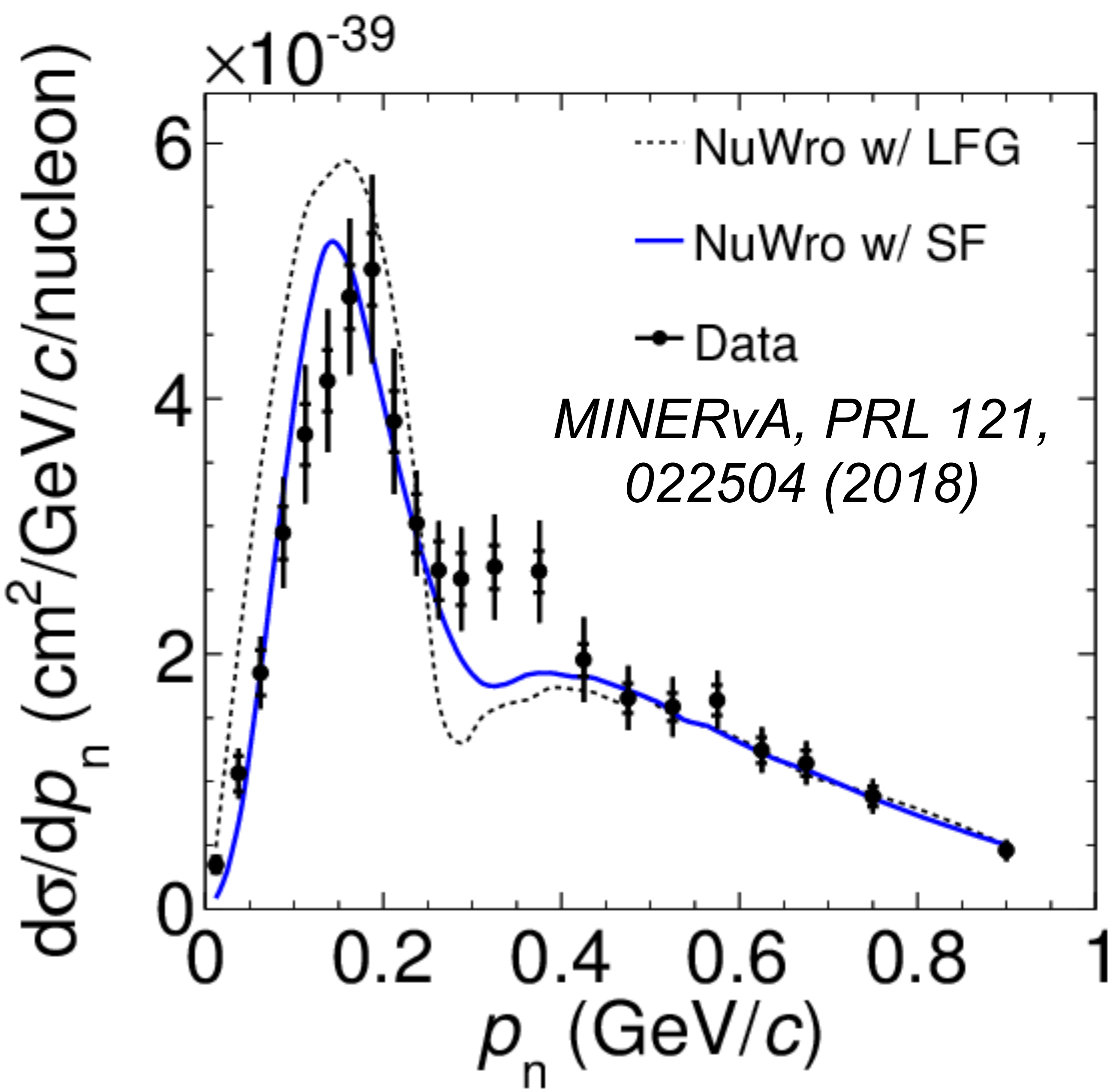
T2K not yet used eA data directly

Example: model tuning on T2K



Example: existing disagreement

- 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

Efforts to apply electron scattering

Possibly incomplete list of effort, in addition to theory groups:

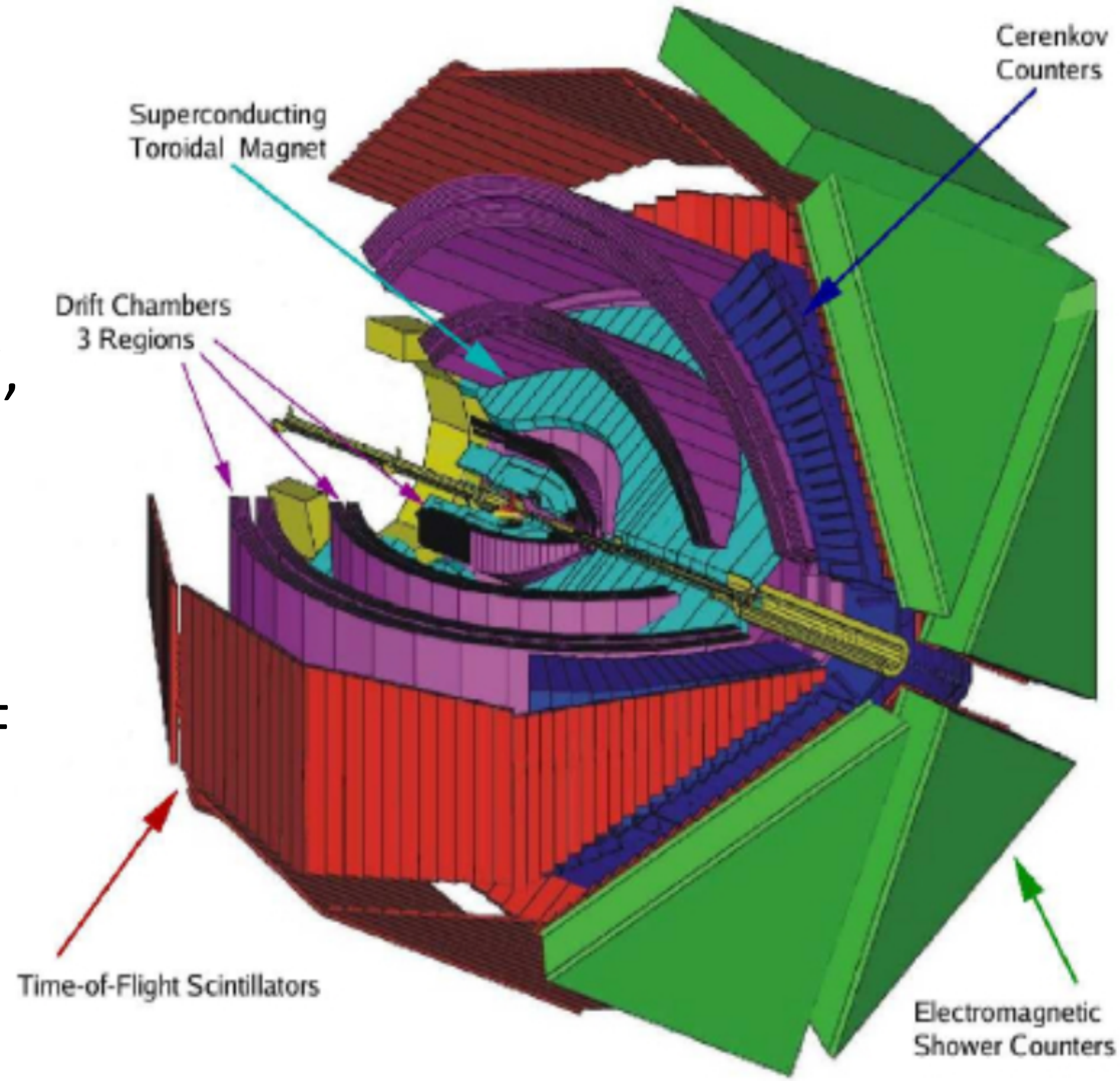
Experiments at JLab: JUPITER (E04-001), e-Ar experiment (E12-14-012), Data Mining with CLAS

Software packages ("generators"): GiBUU, NuWro, GENIE

Other external groups: example: Bodek, Cai: https://arxiv.org/abs/1801.07975

Example: Data Mining with CLAS

- 1 - 5 GeV electron beam,
- (almost) 4π acceptance,
- Charged particles (8^o-143^o): Toroidal field + tracking, TOF, Cerenkov, and EM Calorimeter,
- Neutral particles: EM Calorimeter (8^o-75^o) and TOF (8^o-143^o).
- Low detection threshold (~300MeV/c),
- <u>OPEN TRIGGER !</u>

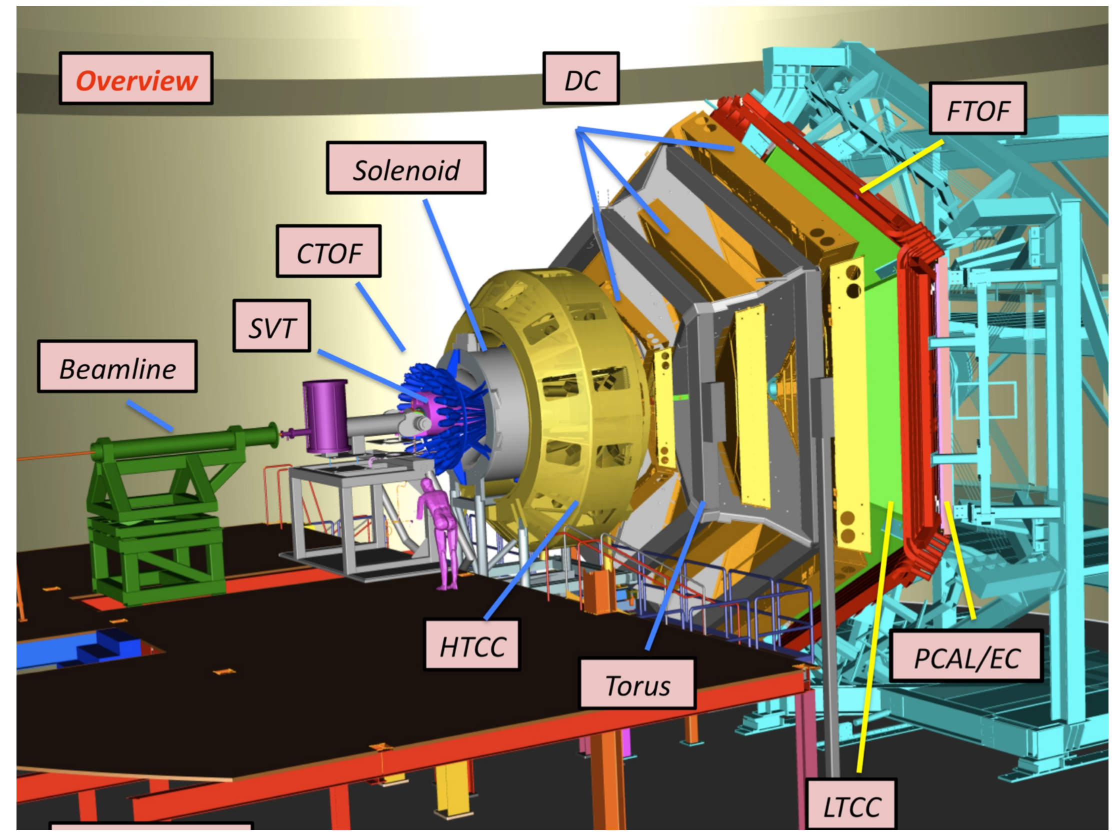


Example: E4Nu electron scattering effort

Target	Beam Energy, GeV (# Triggers x $10^{allot!}$)		
	1.161	2.261	4.461
^{3}He	141	217	186
^{4}He	-	333	445
^{12}C	62	238	310
^{56}Fe	-	23	30
CH_2	10	35	21
Empty Cell	19	69	33

+ CLAS EG2 Experiment: 5 GeV on d, ^{12}C, ^{27}Al, ^{56}Fe, ^{208}Pb

Approved proposal with CLAS12
C12-17-006

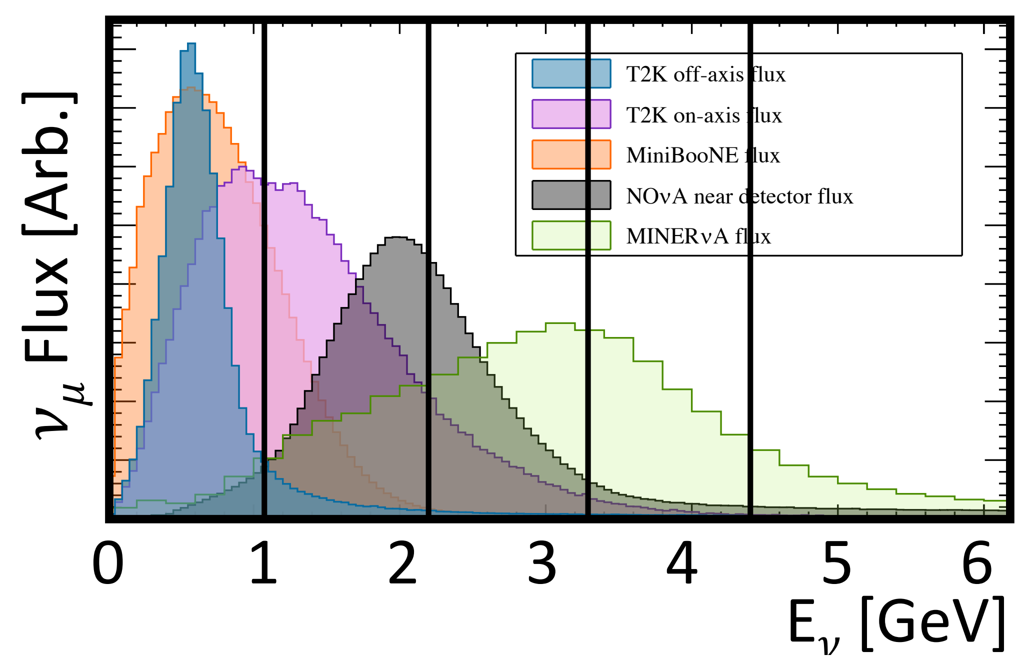


Targets:
^{4}He, ^{12}C, ^{16}O, ^{40}Ar, ^{208}Pb

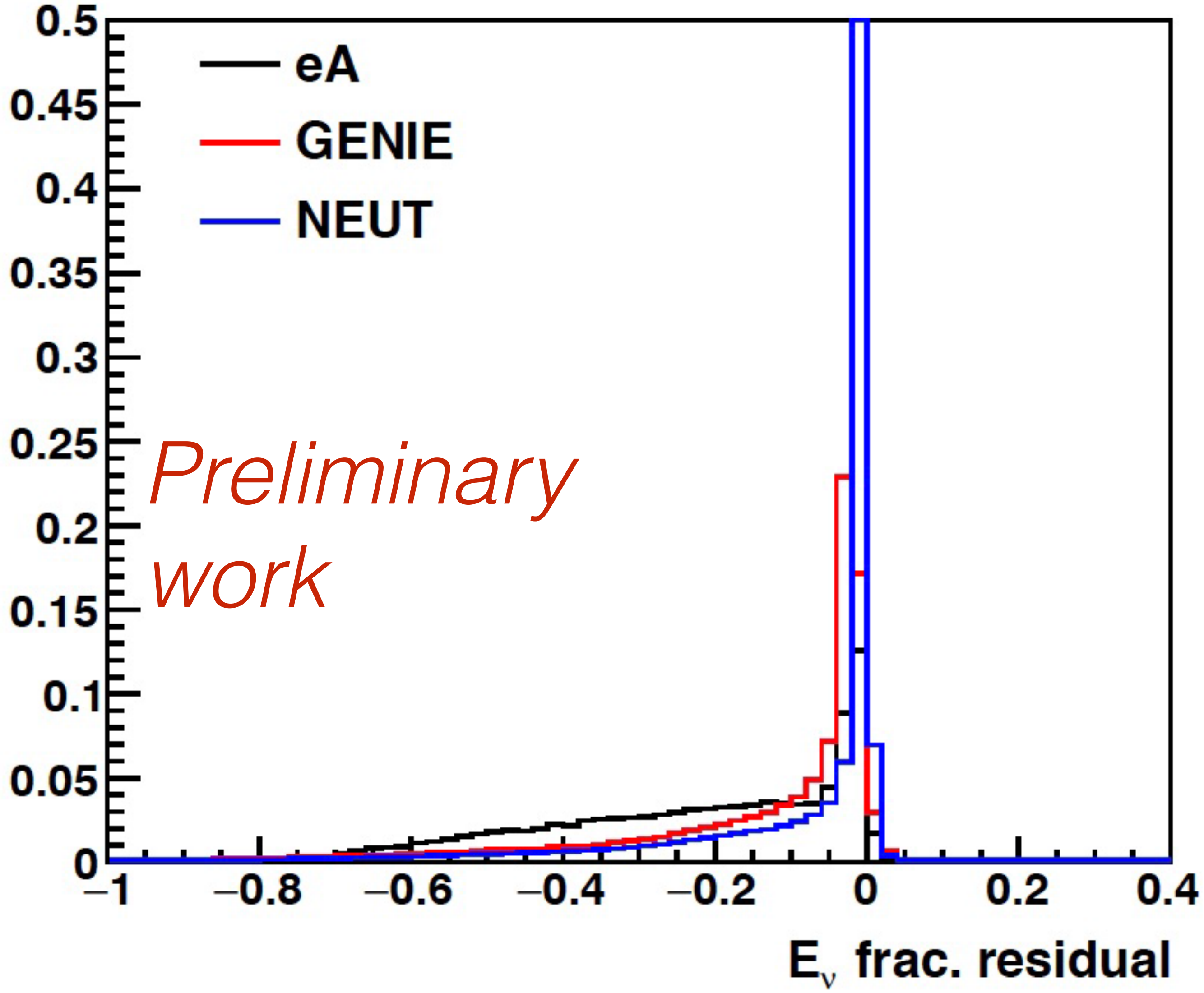
Beam Energies:
1.1, 2.2, (3.3), 4.4, 6.6 GeV

CLAS12 Spectrometer:
- Luminosity: x10 higher than CLAS6 !
- Charged Particles: 5° – 120°
- Neutrons: 5° – 120° + 160° – 170°
- Threshold: ~300 MeV/c

=> High stat. semi-inclusive and exclusive data sets on multiple



Energy estimator (E4Nu)



- Comparison of (2.2 GeV, fixed energy) electron scattering data (corrected for Mott xsec)
- acceptance corrections included.
- CC0π signal.

- **Update will include eA data to eA GENIE (and GiBUU), then nuA NEUT, GENIE comparisons**
  - Factor of ~two in feeddown tail is potentially a big issue

Electron scattering data challenges

- **What is different for QE?** Mott cross section; radiative corrections; Coulomb corrections on the outgoing lepton; struck nucleon (p vs. n) and axial component

This still takes a very talented graduate student + postdoc months with generator people to code up

Electron scattering data challenges

- **What is different for QE?** Mott cross section; radiative corrections; Coulomb corrections on the outgoing lepton; struck nucleon (p vs. n) and axial component

- **What about 2p2h? Resonant?** not as easy as just ‘turning on or off’ axial part.

    - Example: rate of production for the Delta elastic scattering (protons to neutrons) may be different.

    - Need to check exclusive channels to understand applicability.

- Statements from a few theory groups that measurements of exclusive processes may be important for resonance model development (e.g: e,pi,   e,p,pi)

Rampant speculation on impact

- Generally, uncertainties on the vector part of the cross section are not an issue in oscillation analyses
- What is a problem is if energy dependent effects are misattributed
- Example with resonance model:
  - Retuning resonance model may make dramatic changes to vector part.
  - But, model builders tune to neutrino bubble chamber data. The axial part compensates and rates may not change at neutrino scattering experiments.
  - But^2, as we move to precision experiments, shifting vector uncertainty to axial will affect neutrino vs. antineutrino rates (and perhaps dCP)

~~Summary~~ Personal view

- It is very important to make sure that neutrino experiments use models properly validated with electron scattering data

    - Validation of semi->fully exclusive approximate simulations

- It does not seem as easy as I hoped to apply what we learn directly to neutrino experiments. But that’s never stopped us before!

    - Need careful investment (simpler interface for theory? other tools? a wall of documentation?) to propagate and test impact

Thank you to the organizers for the invitation!

Speaker supported by:

Department of Energy

Michigan State University

Backup slides