Neutrino oscillation physics and cross sections

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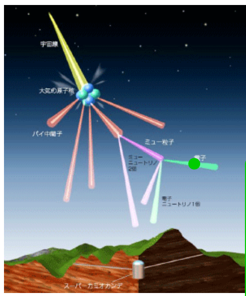
Oscillation status ~2015

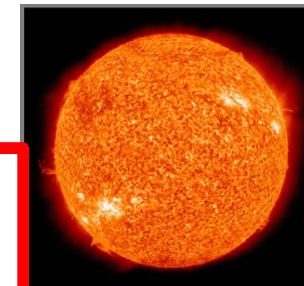
Atmospheric



Accelerator

Reactor

Solar



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

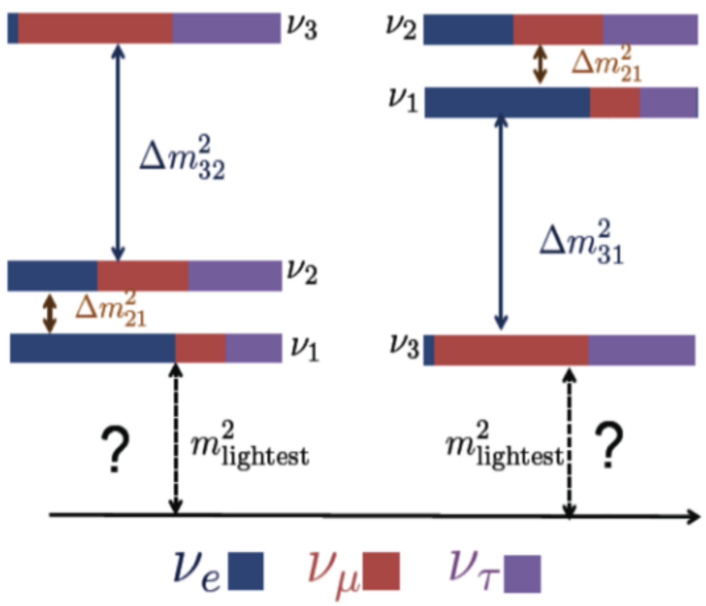
Parameter	$\lvert\Delta m^2\rvert$	θ_{23}	δ	θ_{13}	Δm^2_{21}	θ_{12}
Uncertainty PDG 2016	1.7%	9%	20%	5%	2.4%	5.8%

Two length scales

$\lvert\Delta m^2\rvert$ ~2 x 10^{-3}

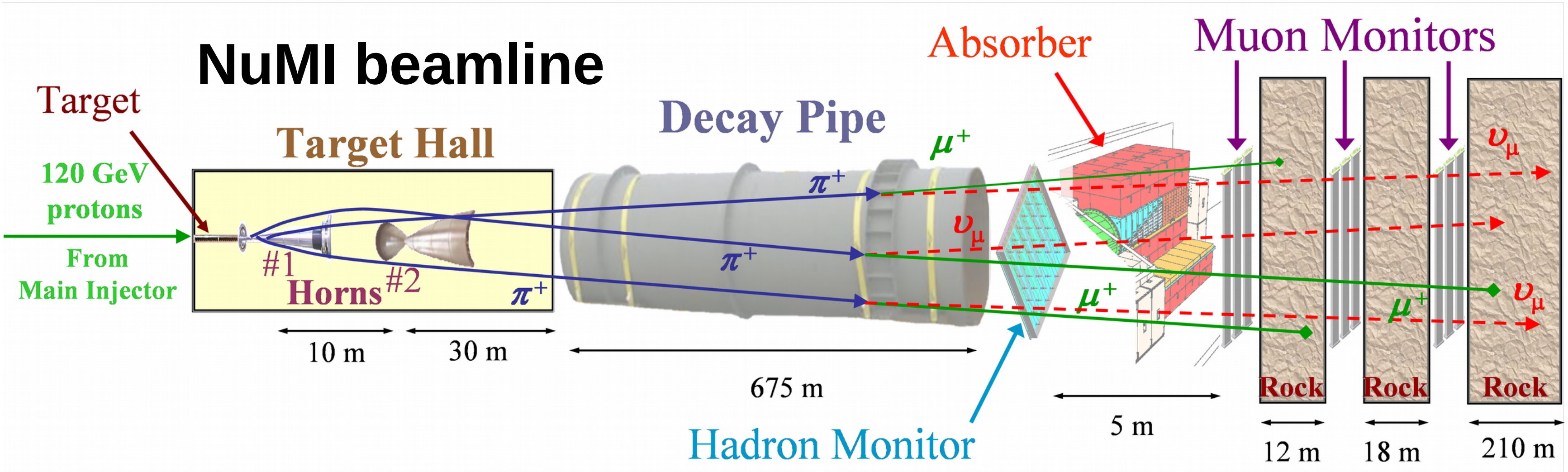
Δm^2_{21} ~7 x 10^{-5}

Open questions



- What is the mass ordering?
- Leptonic CP violation? $\delta_{CP} \neq 0$?
- Is $\theta_{23} = 45^\circ$? If not, is $\theta_{23} < 45^\circ$ or $> 45^\circ$?
- Is neutrino mixing fully described by a 3x3 matrix?

Accelerator neutrino beams

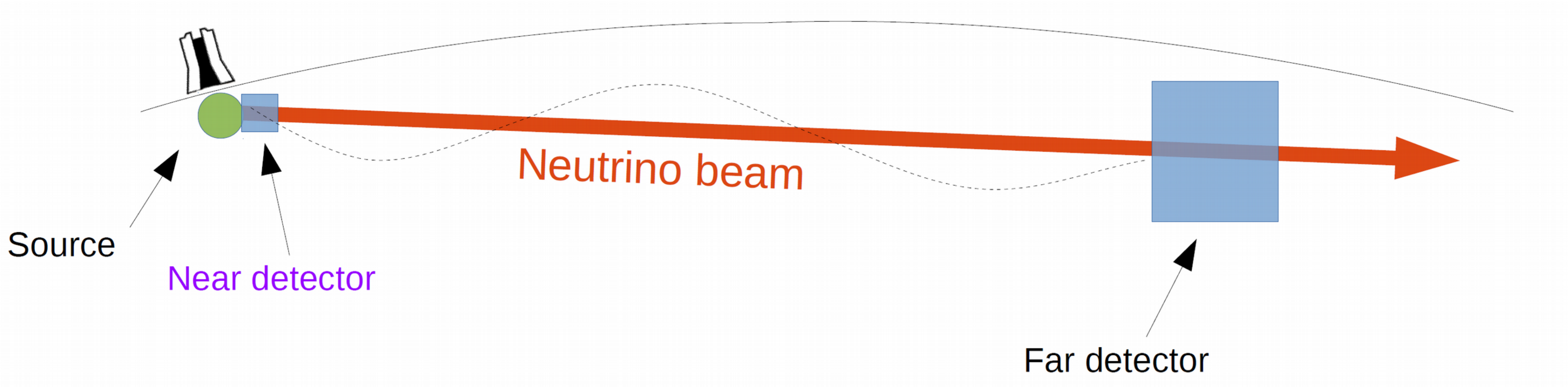


Advantages:

- Narrow and tunable energy range
- Narrow beam spill windows
- Relatively pure ν_μ or $\bar{\nu}_\mu$ beams
- Can be turned on and off

Able to probe all outstanding questions

Basic layout

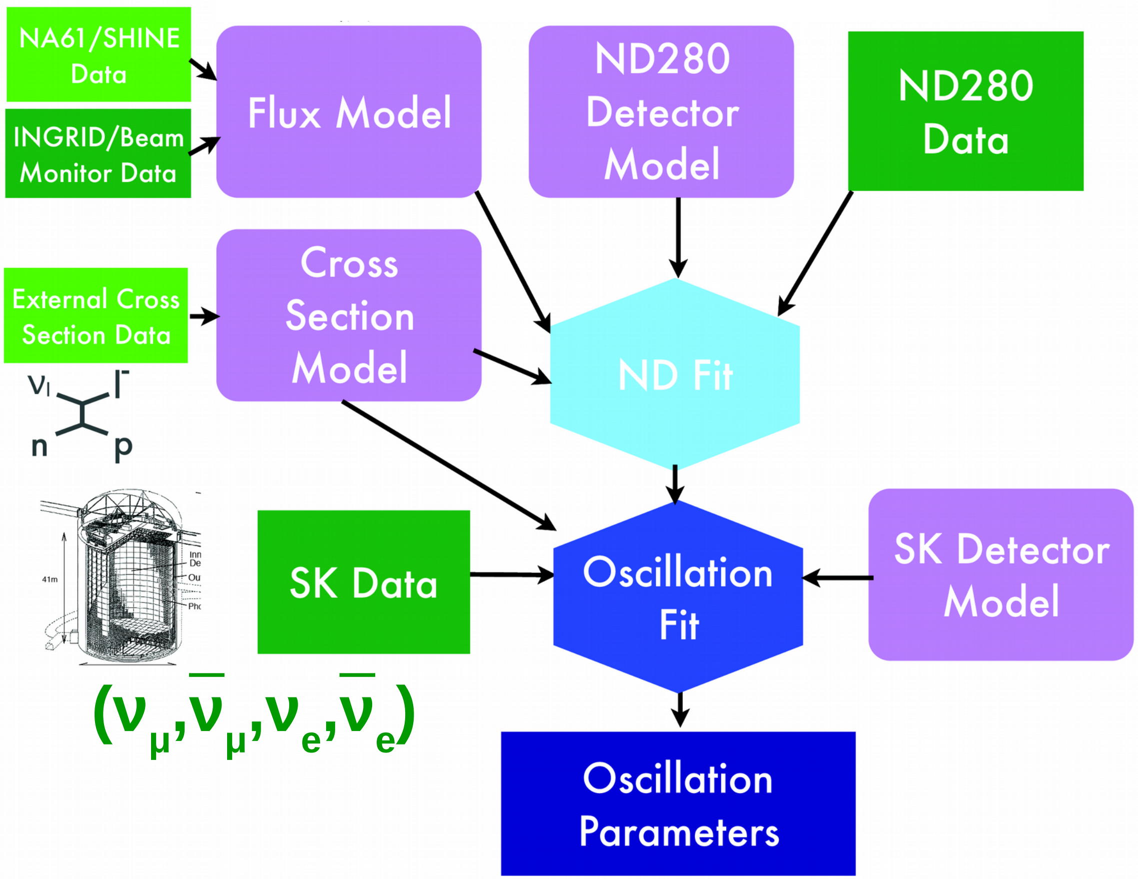


- Δm^2_{32} sets P_{max}~500 L/E_ν (km/GeV)
- Trade-off between L and E:
  - $R \sim 1/L^2$
  - $R \sim E_\nu$
- $0.1 \leq E_\nu \leq 10$ GeV
- Accelerator/mine location often limits L

Analysis technique (T2K example)

$$R(\vec{\mathbf{x}}) = \underbrace{\overbrace{\Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times P(\nu_A \to \nu_B)}_{\text{Far}}$$

Event rate
Neutrino flux
Cross section
Detector smearing
Oscillation probability



$(\Delta m^2_{32}, \theta_{23}, \theta_{13}, \delta_{CP})$

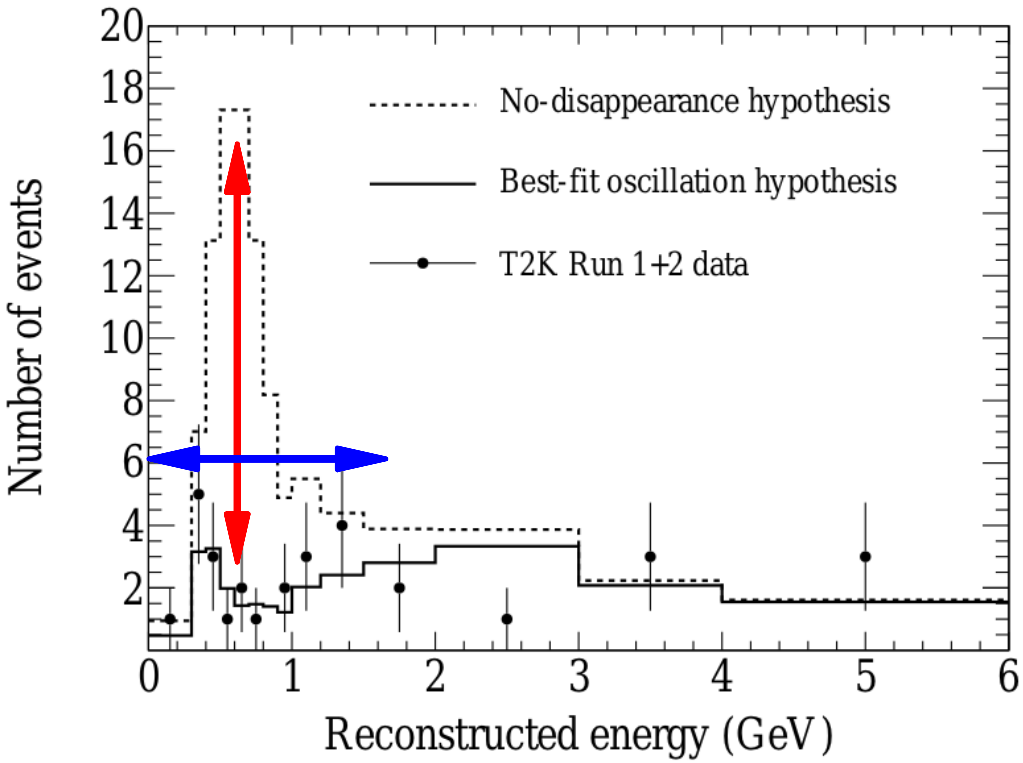
Muon (anti)neutrino disappearance

Same probability for ν_μ and $\bar{\nu}_\mu$

Weak dependence on θ_{23} > 45° or < 45°

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) = 1 - \left(\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23}\right)\sin^2\Phi_{32} + \ldots$$

$$\Phi_{ji} = \frac{1.27\Delta m^2_{ji} L}{E_\nu}$$



Oscillation controlled by an **amplitude**, and a **phase**

Electron (anti)neutrino appearance

Dependence on $\pm\Delta m^2_{31}$

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Phi_{31}$$

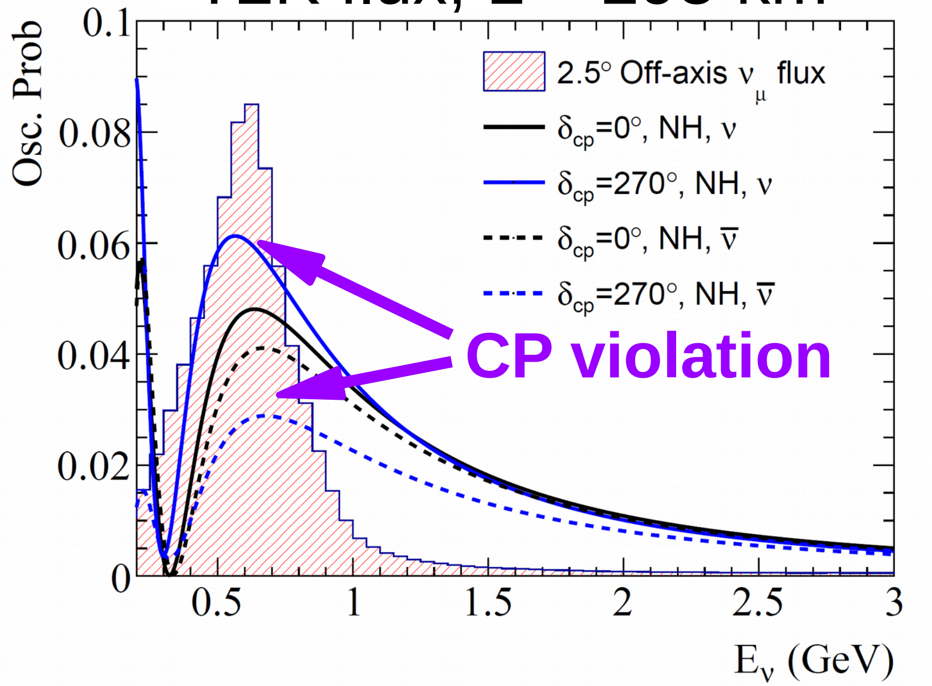
Sign change for ν_e and $\bar{\nu}_e$

$$- \boxed{\sin\delta_{\mathrm{CP}}}\,\frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin^2 2\theta_{13}\sin\Phi_{21}\boxed{\sin\Phi_{31}}$$

$$+ \ldots$$

$$\Phi_{ji} = \frac{1.27\Delta m^2_{ji} L}{E_\nu}$$

T2K flux, L = 295 km



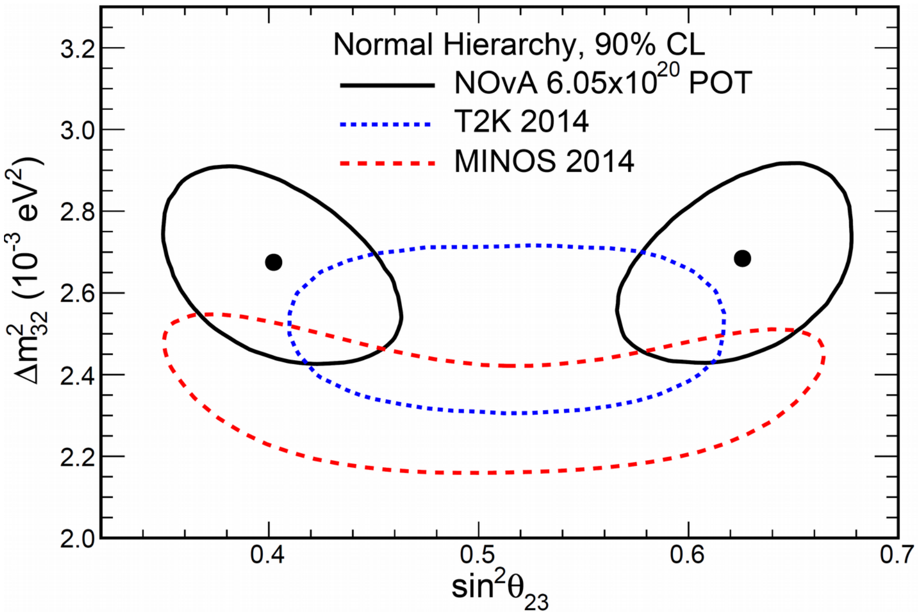
Complex relationship between parameters. Require high statistics and excellent E_ν resolution!

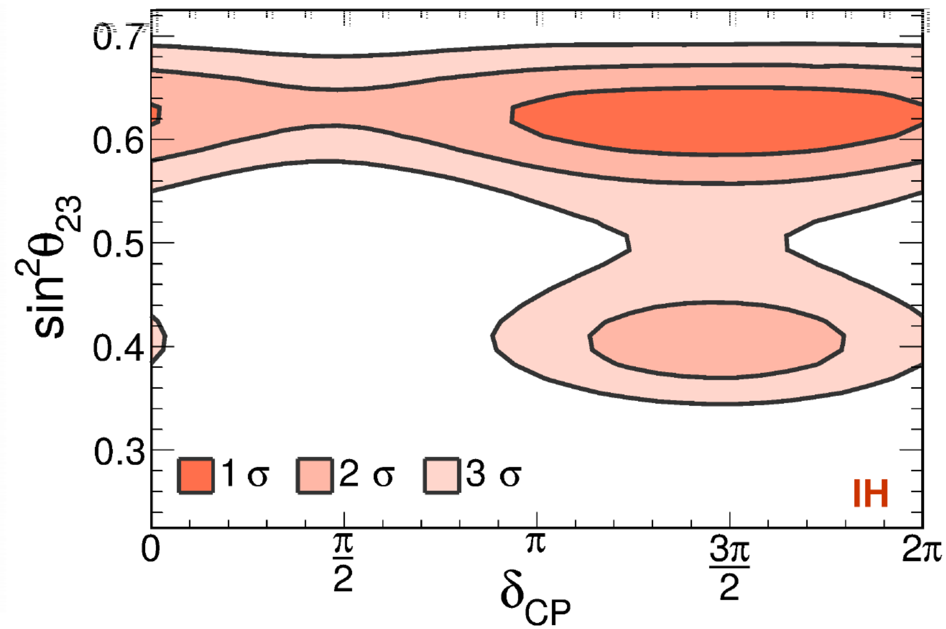
$$\frac{\delta E_\nu}{E_\nu} \lesssim 5\%$$

Accelerator neutrino experiments

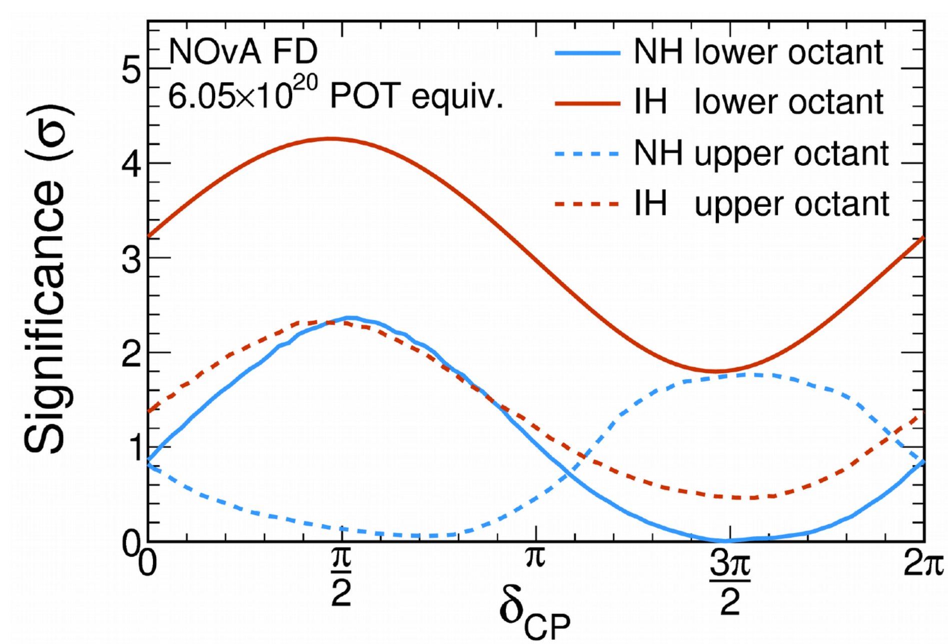
	Name	L (km)	Peak E_ν (GeV)	Year (projected)	FD mass	
Past	K2K	250	1	1999-2004	50 kT	
	MINOS	735	3	2005-2012	5.4 kT	
	OPERA	732	17	2008-2012	1.35 kT	
Present	T2K	295	0.6	2010-(2026)	50 kT	L/E at osc. max.
	NOvA	810	2	2013-(2024)	14 kT	
Future	DUNE	1300	3	(2026-2036)	30 kT	Bigger
	Hyper-K	295	0.6	(2026-2036)	260 kT	

Latest NOvA results

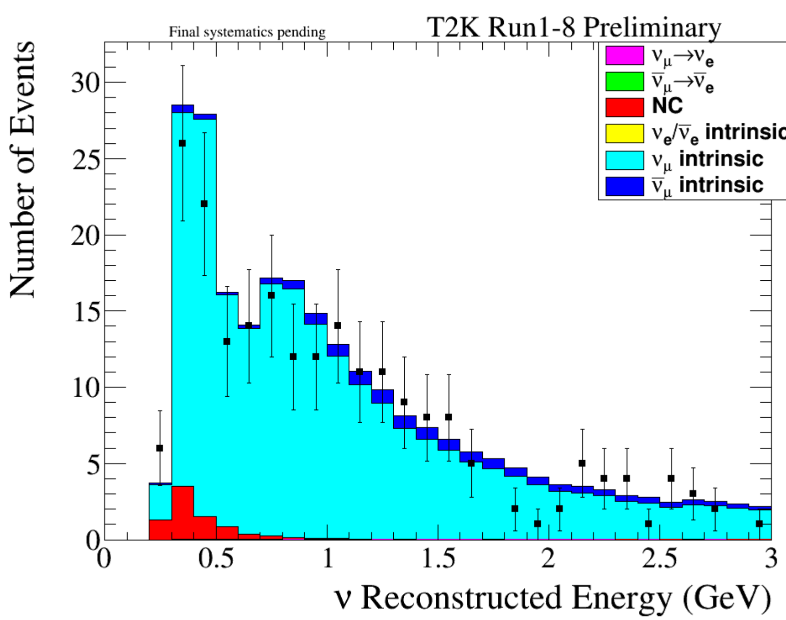


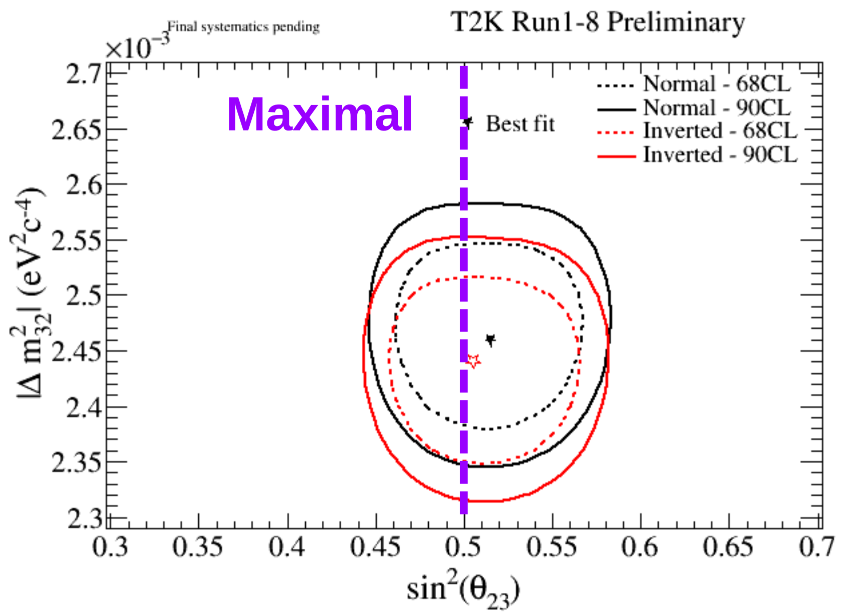


- ~20% of design exposure
- 2.6σ hint that $\theta_{23} \neq 45°$
- Degeneracy between θ_{23} octant, hierarchy and δ_{CP}

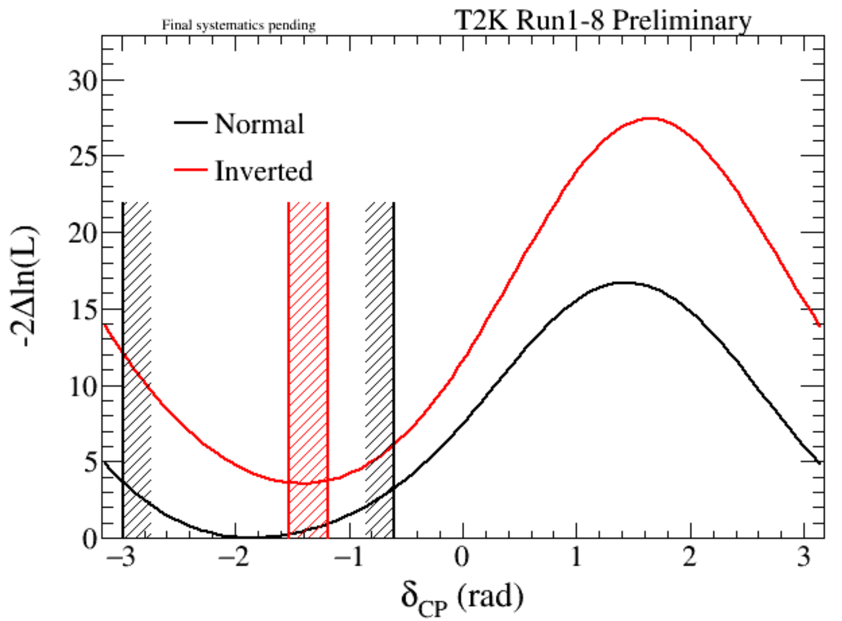


Latest T2K results

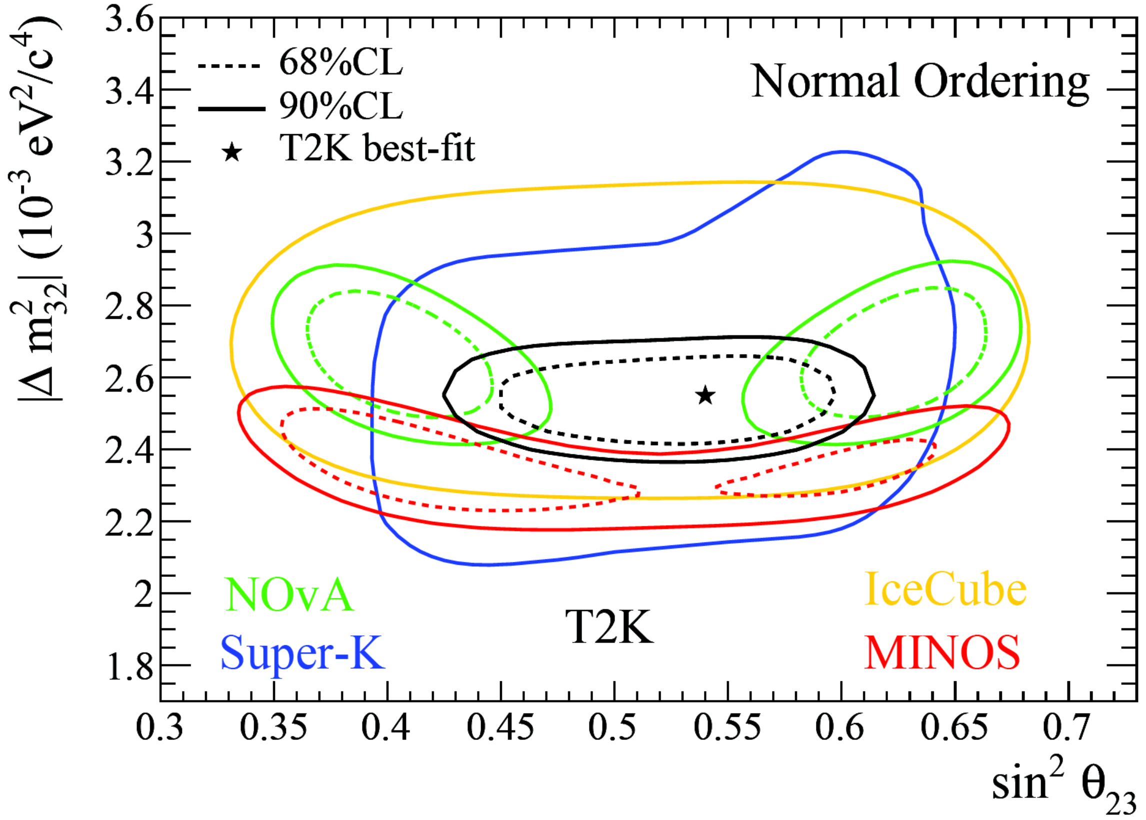




- ~20% of design exposure
- Consistent with maximal mixing
- 2σ exclusion of CP conserving values, $\delta_{CP} = 0,\pi$



Oscillation status



- Entering precision era, a lot more data to come.
- However, the two running experiments do not agree
- Why? New physics? Inadequate systematics?

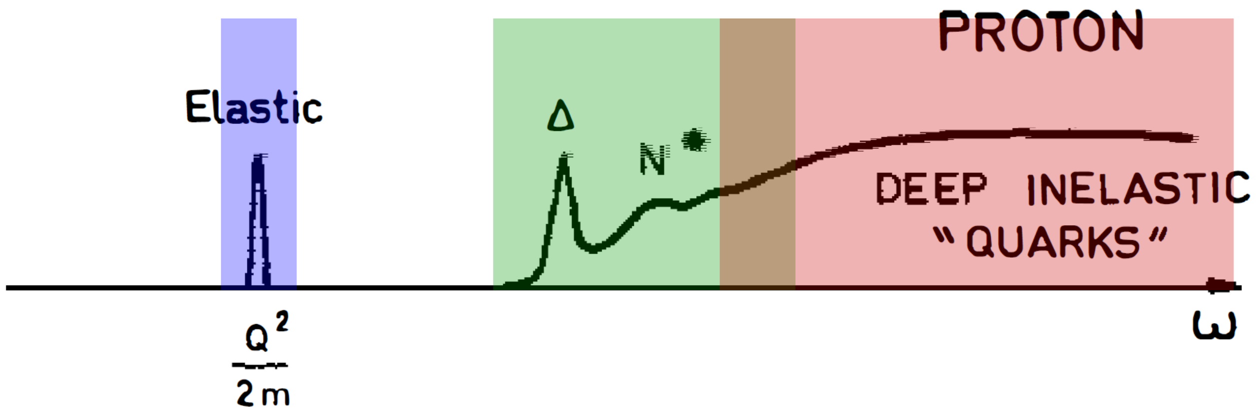
What do we really measure?

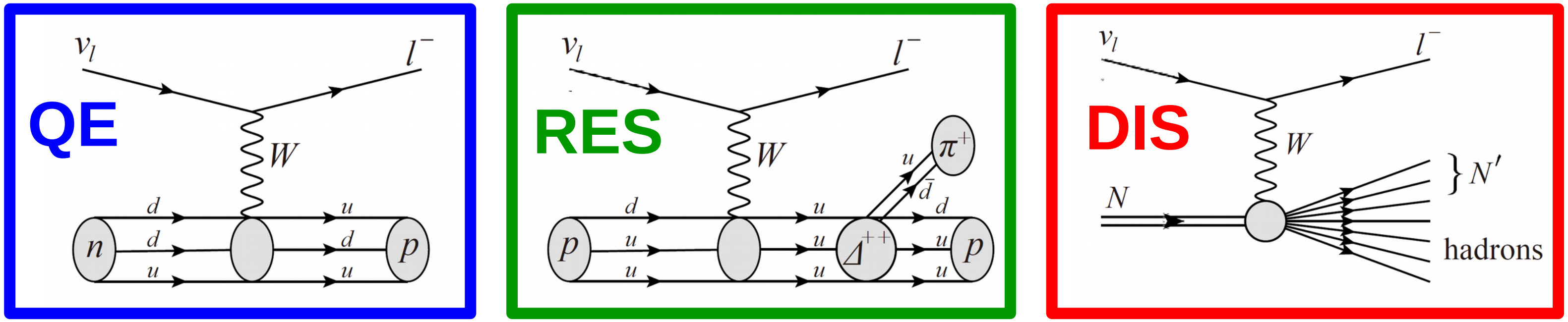
$$R(\vec{\mathbf{x}}) = \overbrace{\Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}})}^{\text{Near}} \times P(\nu_A \to \nu_B)$$

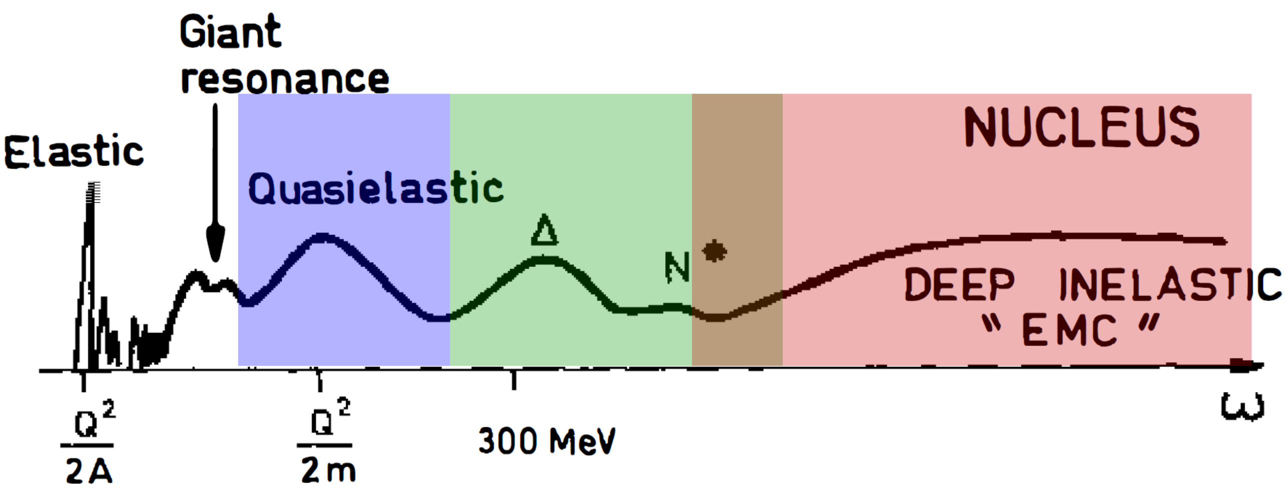
$$\underbrace{\Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}}) \times P(\nu_A \to \nu_B)}_{\text{Far}}$$

- Event rate; Neutrino flux; Cross section; Detector smearing; Oscillation probability.
- Cannot measure *interaction* variables, e.g. ω, Q^2, W^2, E_ν
- Measure outgoing particle kinematics, rely on model to infer E_ν
- So let's look at that model…

Cross section basics

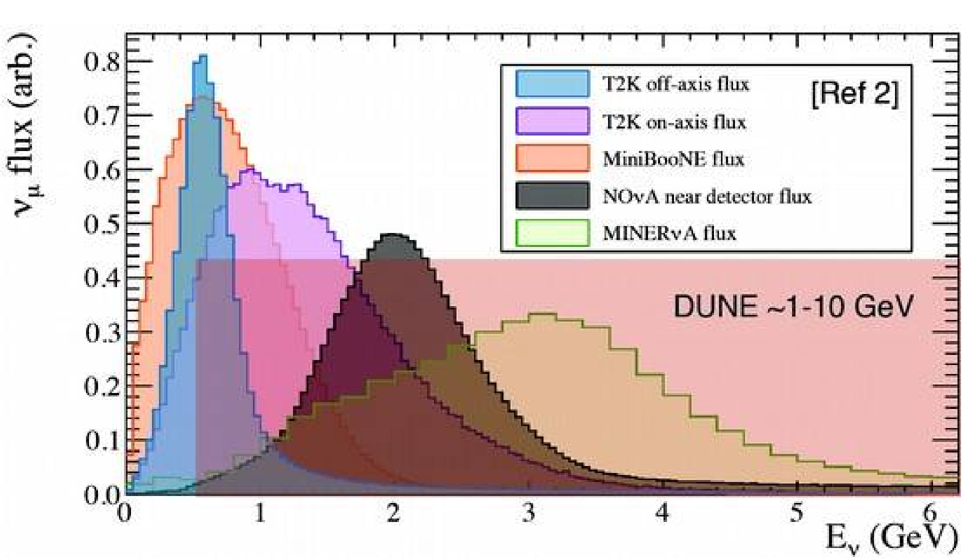


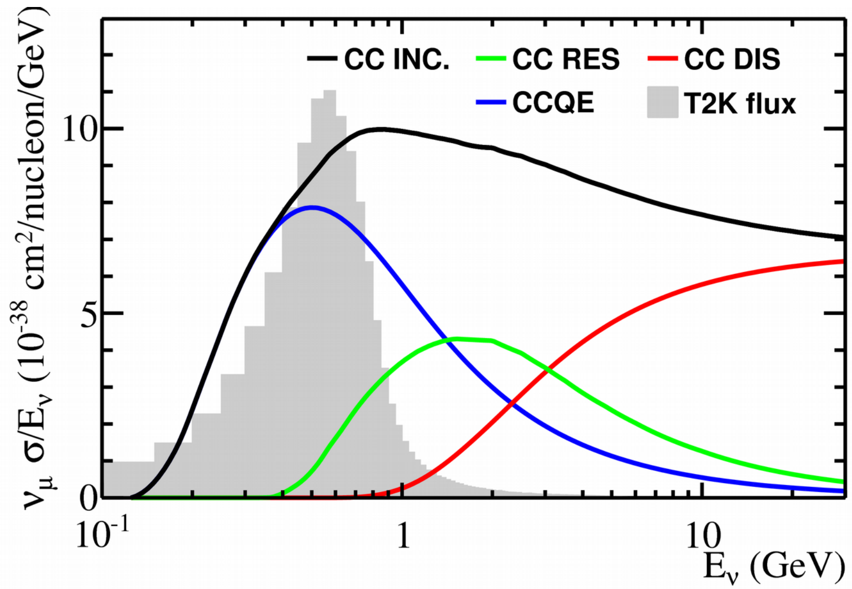




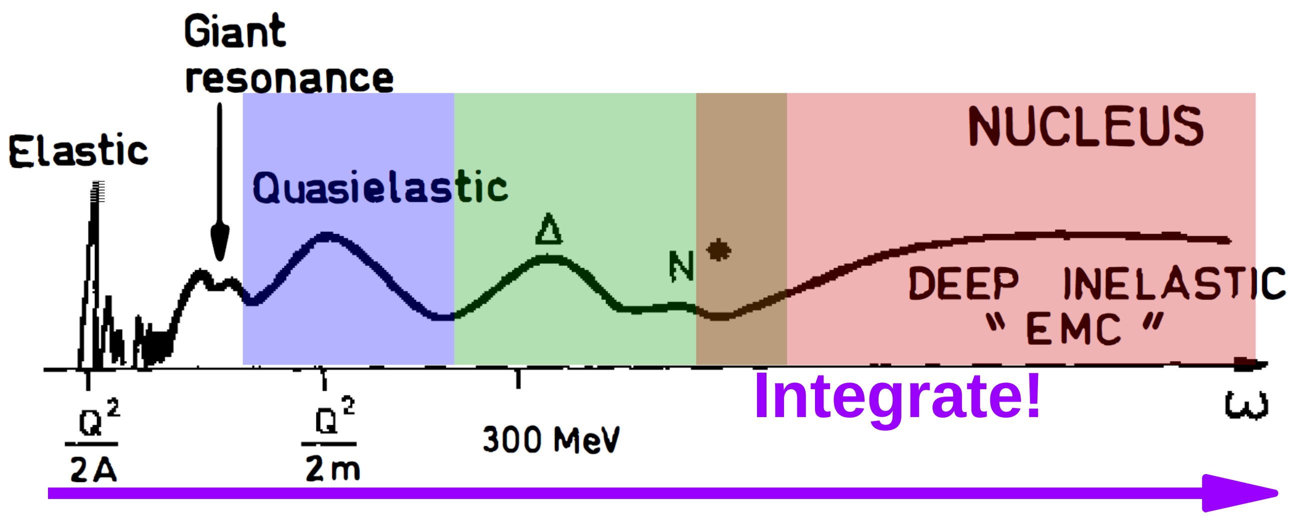
Complex nuclear response at low energy transfer, ω

Cross section basics

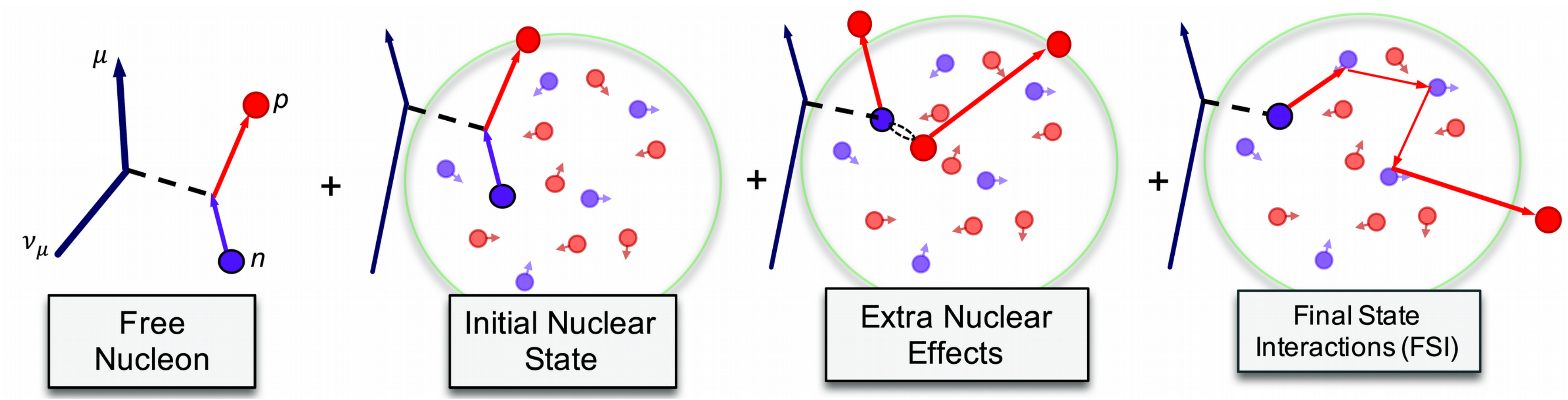




Broad neutrino fluxes, have to integrate over the entire response. **No consistent theoretical description**



The plot thickens

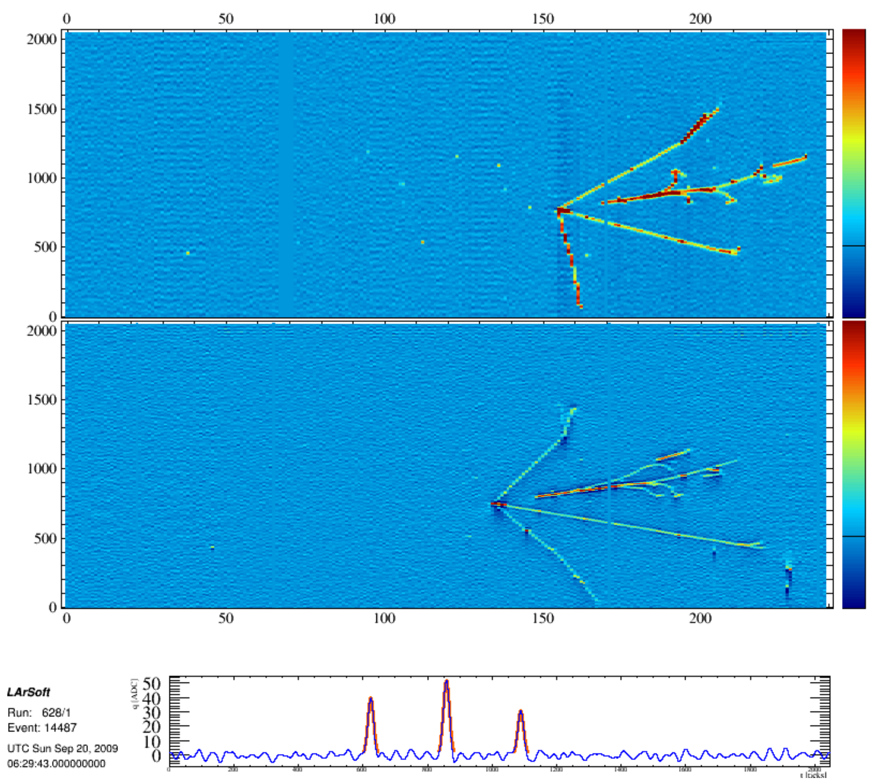


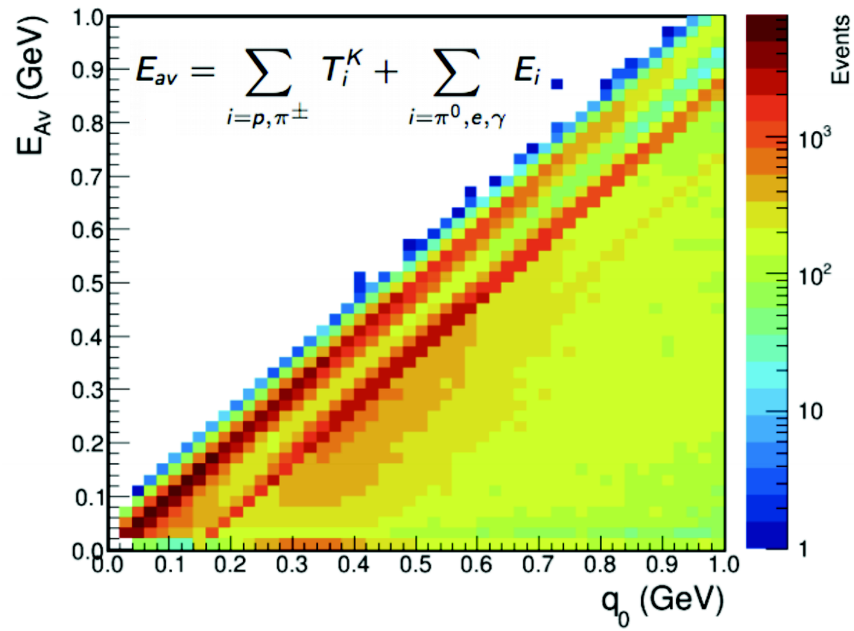
$$R(\vec{\mathbf{x}}) = \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}}) \times P(\nu_A \to \nu_B)$$

Neutrino energy reconstruction (1)

- Use **leptonic** and **hadronic** information:

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



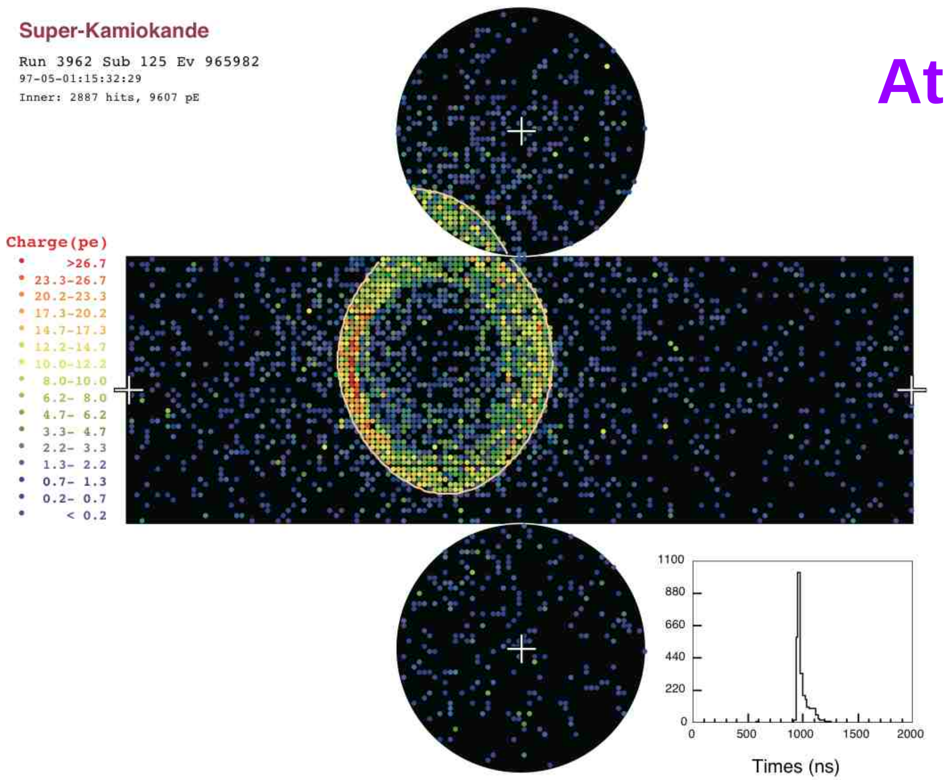


- Miss neutral particles
- Without track by track PID, miss particle masses
- Smearing from initial nuclear state

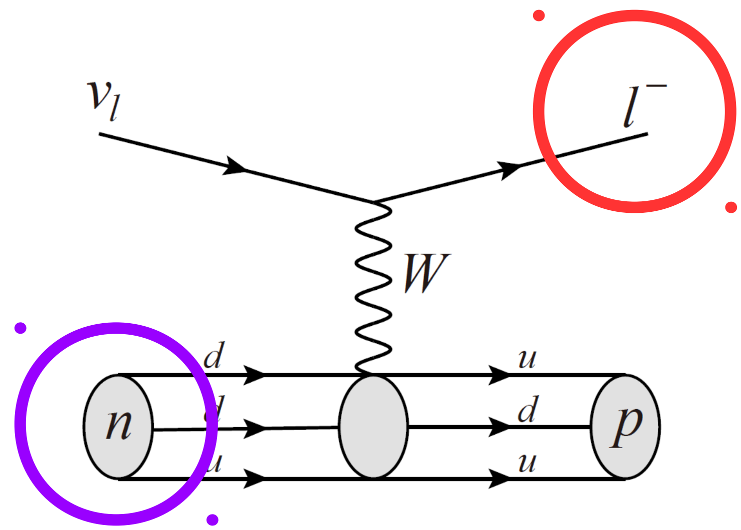
Neutrino energy reconstruction (2)

- Use **leptonic** variables only:

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

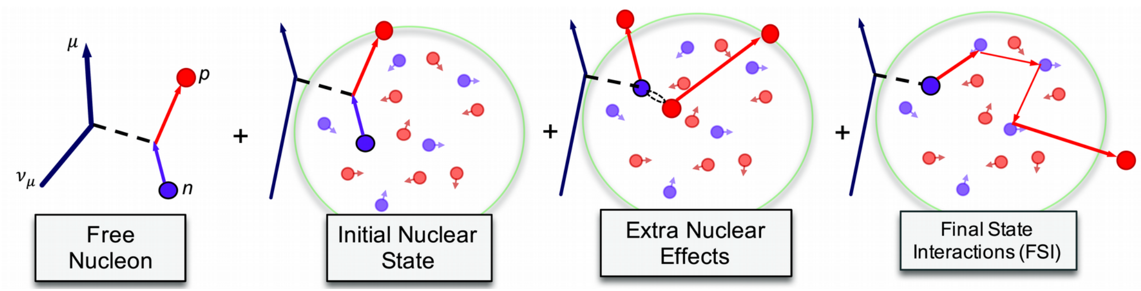


At rest?



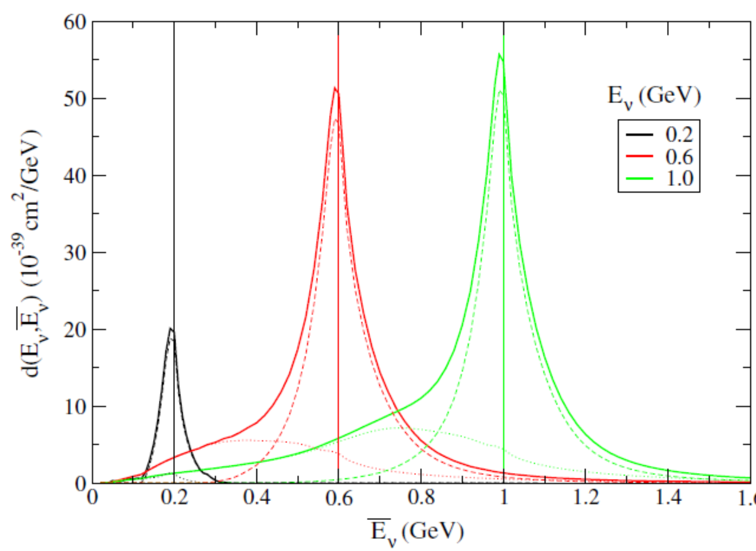
- CCQE (two-body) assumption requires low E_ν beam!
- Smearing due to nuclear effects
- All processes with 1μ and 0π **in the final state** contribute

Neutrino energy reconstruction (2)



= CC0π

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

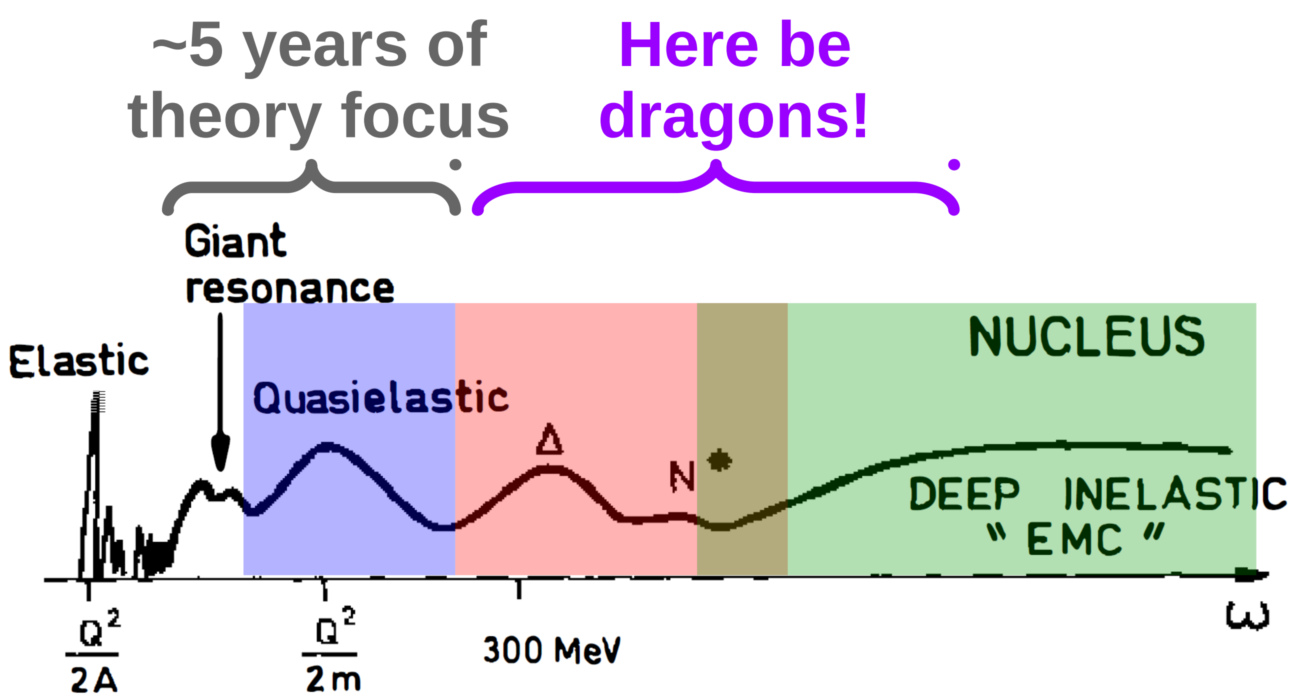


- Intranuclear motion introduces smearing (dashed lines)
- Interactions with multiple nucleons (2p2h) introduces bias (solid lines)
- Processes which produce pions contribute through FSI
- *Reasonable agreement with data*

CC0π = 1p1h + 2p2h + 1π(+abs) + ...

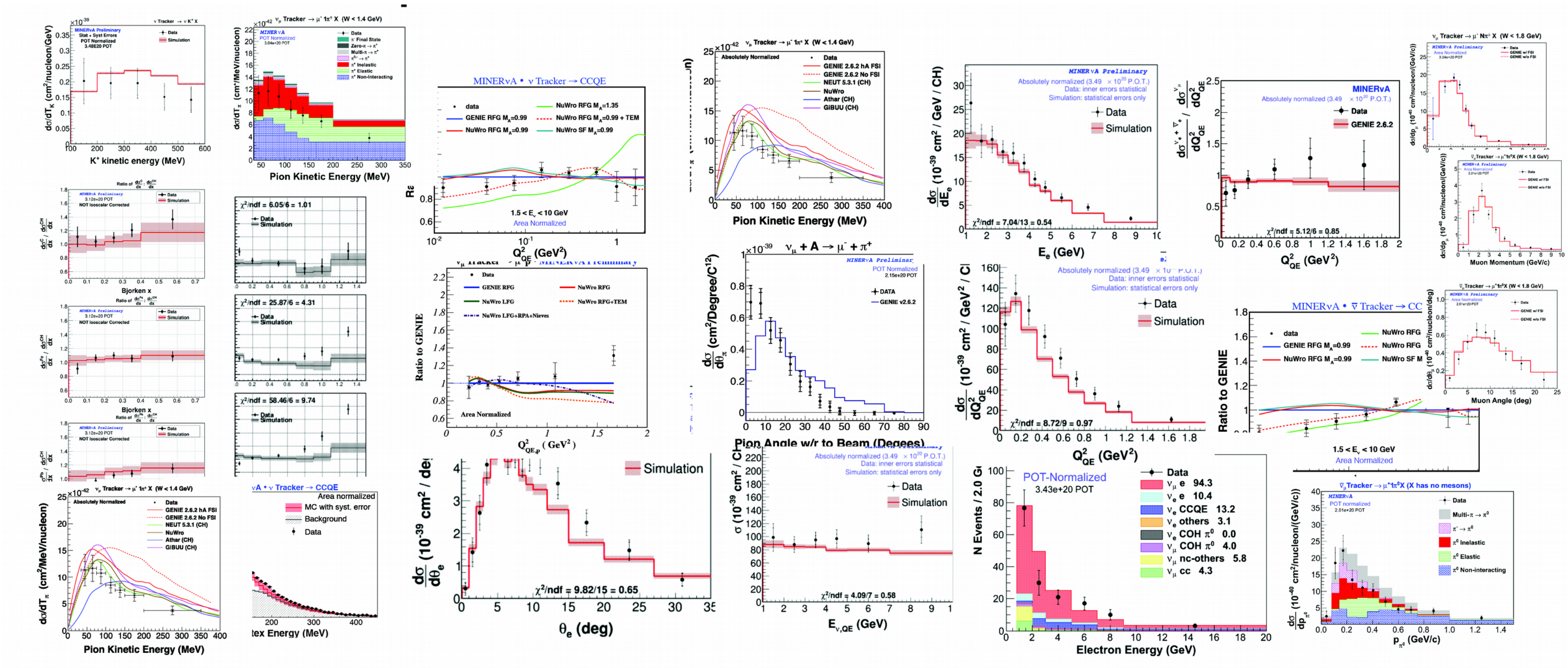
Cross section outlook

- CC0π model improved over ~5 years. Still not perfect
- CC0π *should* be the easiest channel to model… similar issues for higher-ω processes, but no models
- Lack of theoretical development in the area is rapidly becoming the limiting factor for oscillation experiments...



Cross section data

A wealth of data has been produced in recent years. Data from 1/~10 active experiments shown.

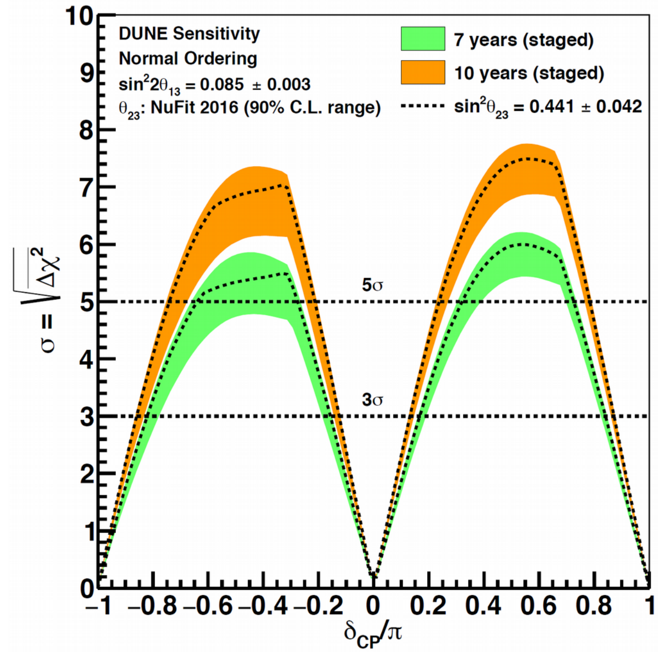


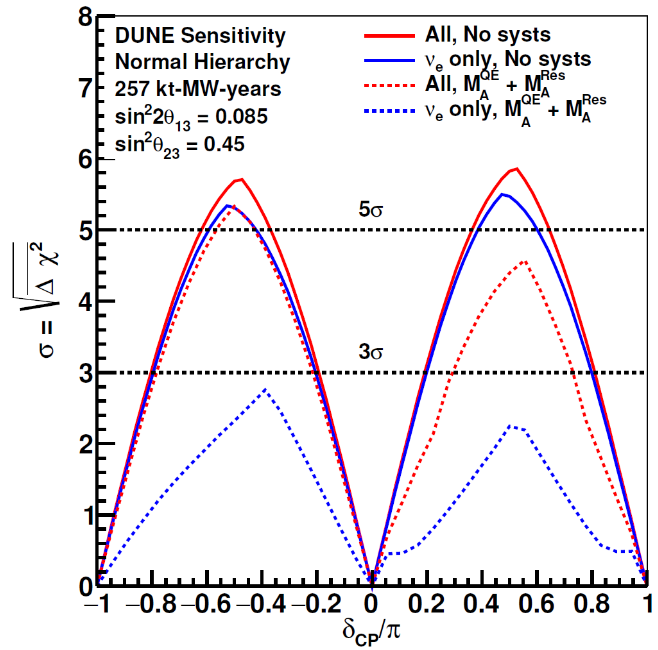
Unfortunately, attempts to tune models to available data fail, the models are not sufficient...

Future experiments

- Two big projects on the horizon: DUNE and Hyper-K
- Aim to resolve open questions and measure all relevant OA parameters
- Stringent systematic budgets:
  - ~2% cross section uncertainties
  - E_ν resolution of ~100 (~50) MeV for DUNE (HK)
- Need significant improvement on current situation

Example: *degradation in DUNE sensitivity using current uncertainties*



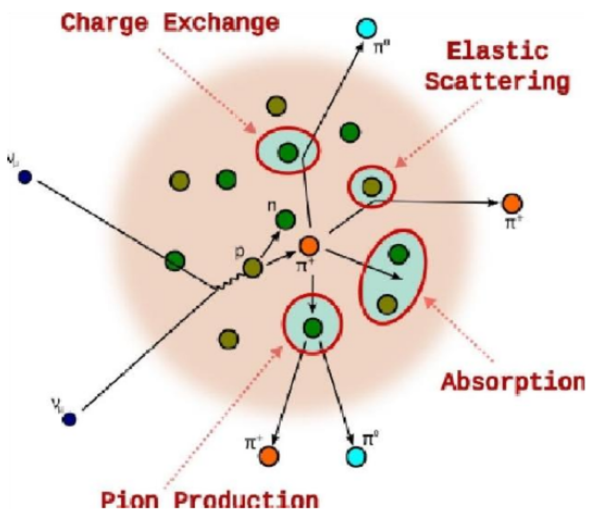


Conclusions

- Entering precision era of neutrino oscillation physics
- Exciting accelerator neutrino results, more to come!
- Cross section model is limiting factor for current and future experiments
- Difficult problem, no clear path to reduce cross section uncertainties to the required level

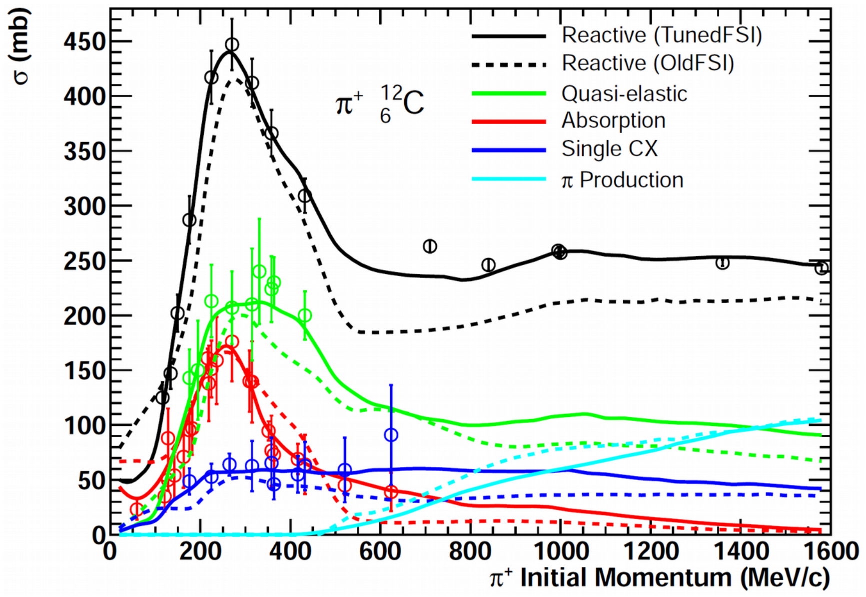
Backup

Final State Interactions

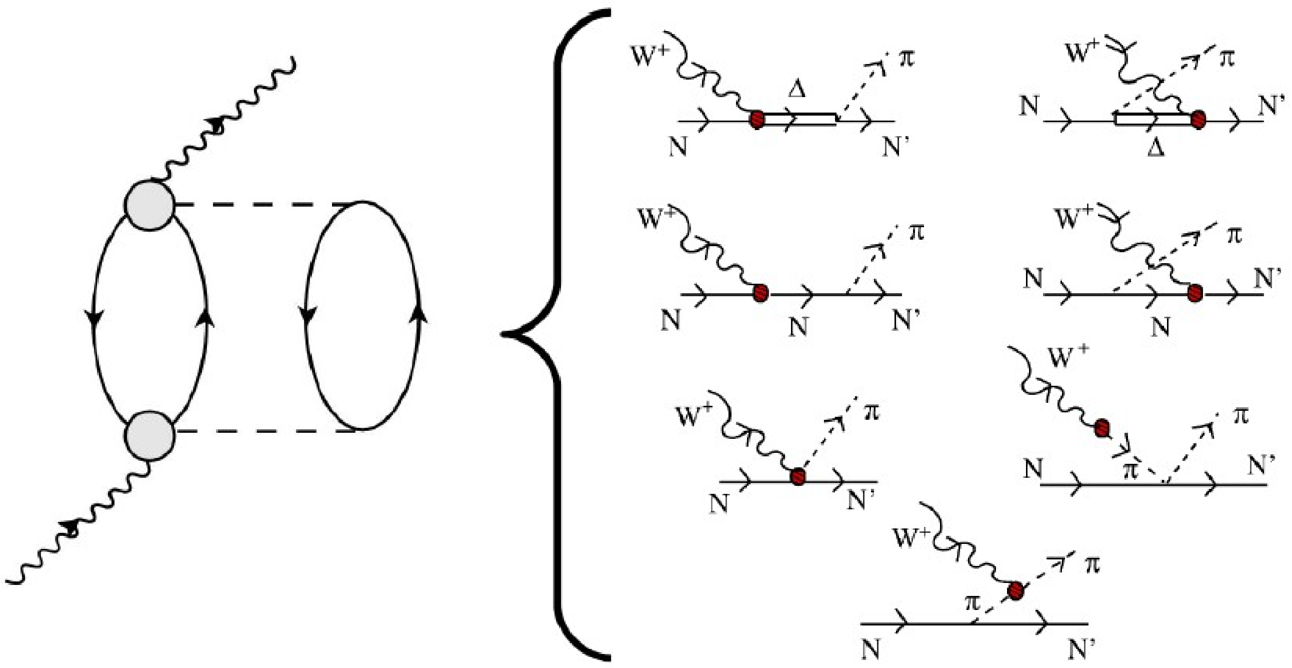


- Pions or nucleons can re-interact with the nuclear medium, or each other before leaving the nucleus.
- Significantly distorts the outgoing kinematics or particle content of observable final state

- Theory driven, with some constraints from π-A or N-A data
- But, always require a model to relate the data to ***intra-nuclear*** scattering



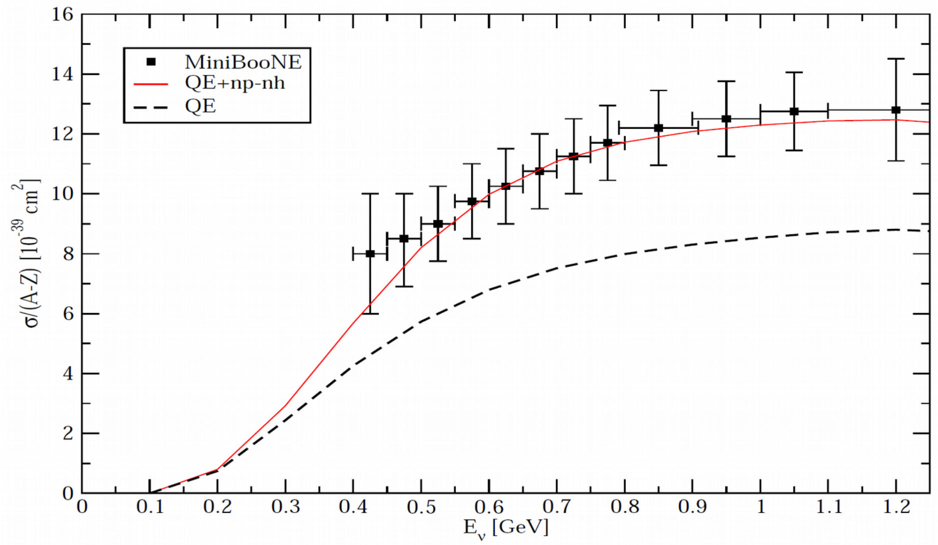
2p2h



- Second order contributions to the cross section, where the probe interacts with two or more bound nucleons.
  - ~30% effect on total cross section
  - Now implemented in neutrino generators (although not perfect!).

CC0π models

- New theoretical models describe CC0π process
- Significantly improve agreement with ν-A data (many experiments)
- Supported by e-A data.



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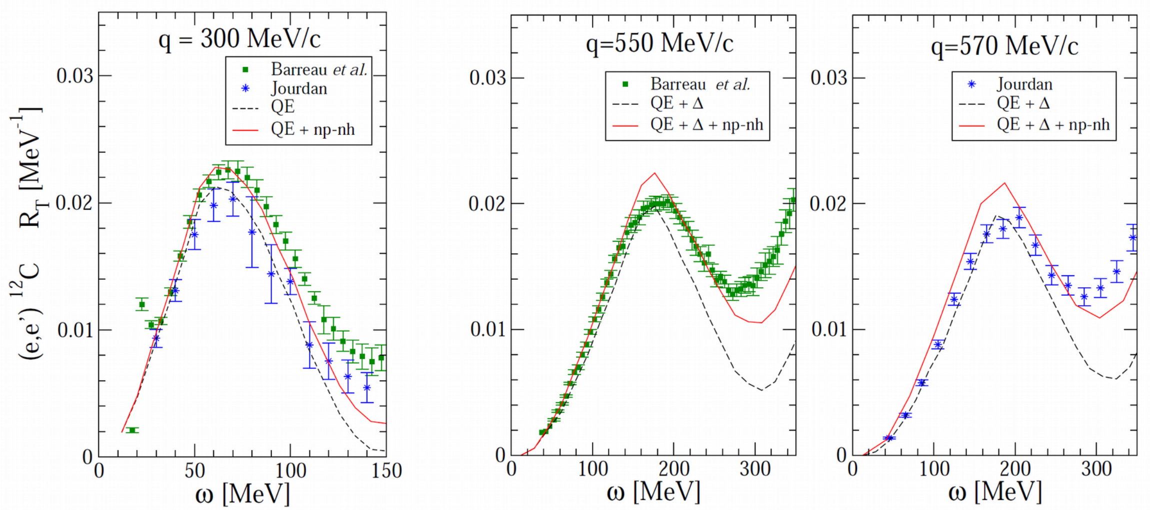

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ν-A cross sections

- Only ***topological* cross sections** are independent of a model:

$$\widetilde{\sigma}_k(\vec{\mathbf{x}}) = \sum_i \int_{E_{min}}^{E_{max}} \sigma_i(E_\nu, \vec{\mathbf{x}}) \times \mathrm{FSI}(\vec{\mathbf{x}}) dE_\nu$$

E.g. **CC0π** = 1p1h + 2p2h + CC1π(+abs) + ...

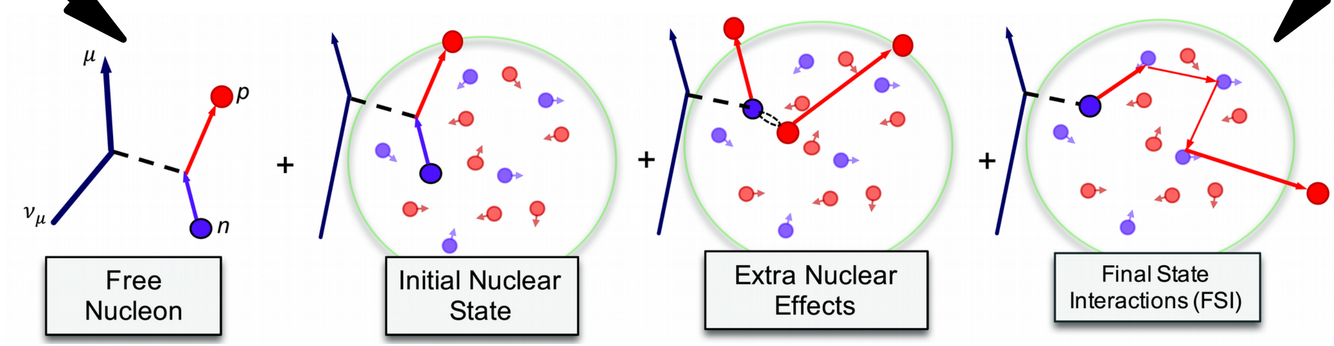
- Need to integrate out all degrees of freedom other than ***x***. **FSI** makes this integral difficult/impossible analytically
  - Direct theory comparisons to data are difficult
  - Require Monte Carlo generator to do integrals numerically

External cross section model constraints

ν-D_2 bubble chamber
(1970s-1980s)

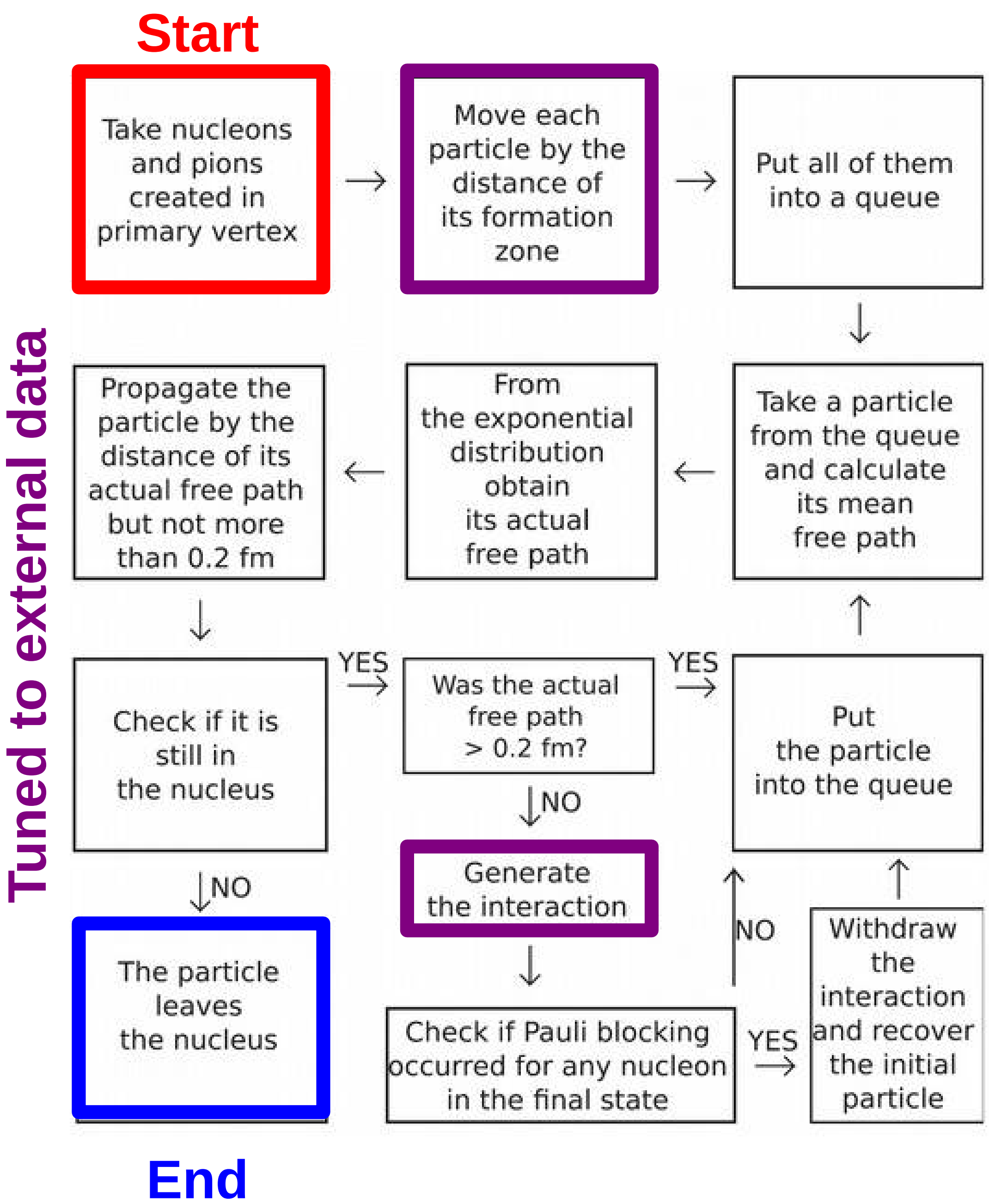
e-A scattering
(1970s-present)

Pion/nucleon



Neutrino heavy
target experiments

Cascade model



Neglect interactions between outgoing particles, propagate each individually (except for GiBUU).

Formation zones are motivated by data (high E, high Q^2). Interaction cross sections suppressed after production.

- NuWro: all modes
- GENIE & NEUT: DIS only
- Others: no formation zone

Re-interactions depend on local density of the nucleus.