# Neutrino-Nucleus Interaction Simulations: *Relevance, Status and Impact on Oscillation Studies*

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# Outline

- What are we hoping to learn?
- Neutrino oscillations
- Key questions for accelerator-based neutrino programme
  - Leptonic CP violation
  - Sterile neutrinos
- Model-dependencies in oscillation searches
- Neutrino Monte Carlo generators
- Illustration of issues
  - QE puzzle
  - $\pi$ puzzle
  - Shallow and Deep Inelastic scattering
- Summary

# Neutrinos: What are we hoping to learn?

The study of neutrino masses and mixings is a **window to new physics**.

Several key questions:

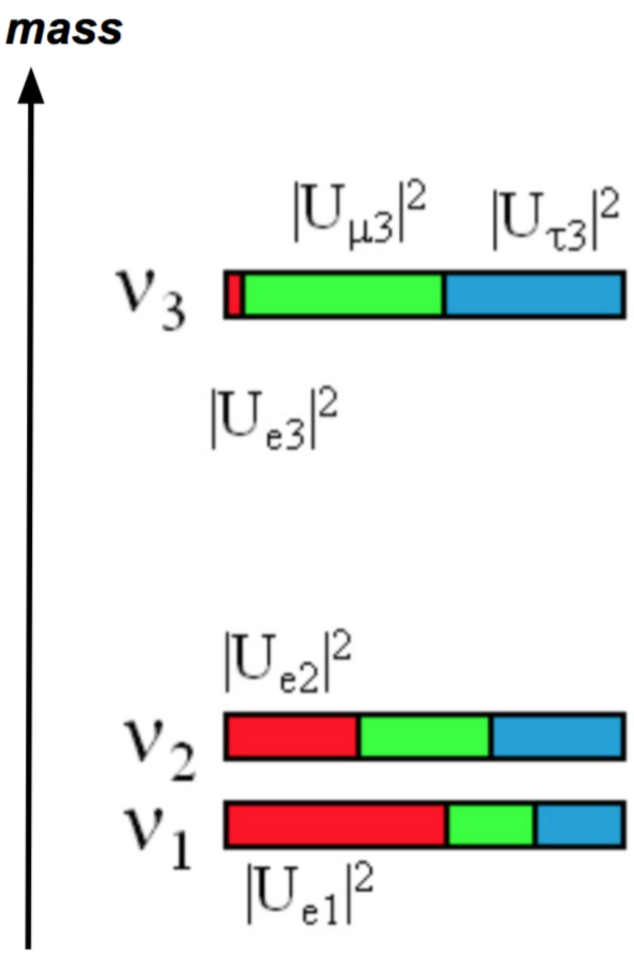
- **What is the neutrino mass generation mechanism?**
  - Could the neutrino be a Majorana particle?
  - Why are the masses so small?
- **What do neutrinos tell us about flavour?**
  - Nearly (exactly?) maximal mixing observed: '$\mu$' and '$\tau$' flavour interchangeable!
- **What is the connection between quarks and leptons?**
  - Why the corresponding mixing matrices are so different?
- **What are the implications for the universe we live in?**
  - Baryon asymmetry of the universe: Leptogenesis requires CPV + Majorana mass
  - Dark matter: Sterile neutrino is a candidate.

# Neutrino oscillations

Neutrino oscillation a **sensitive tool for new physics searches**.

Each flavour eigenstate is a **superposition of mass eigenstates**.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

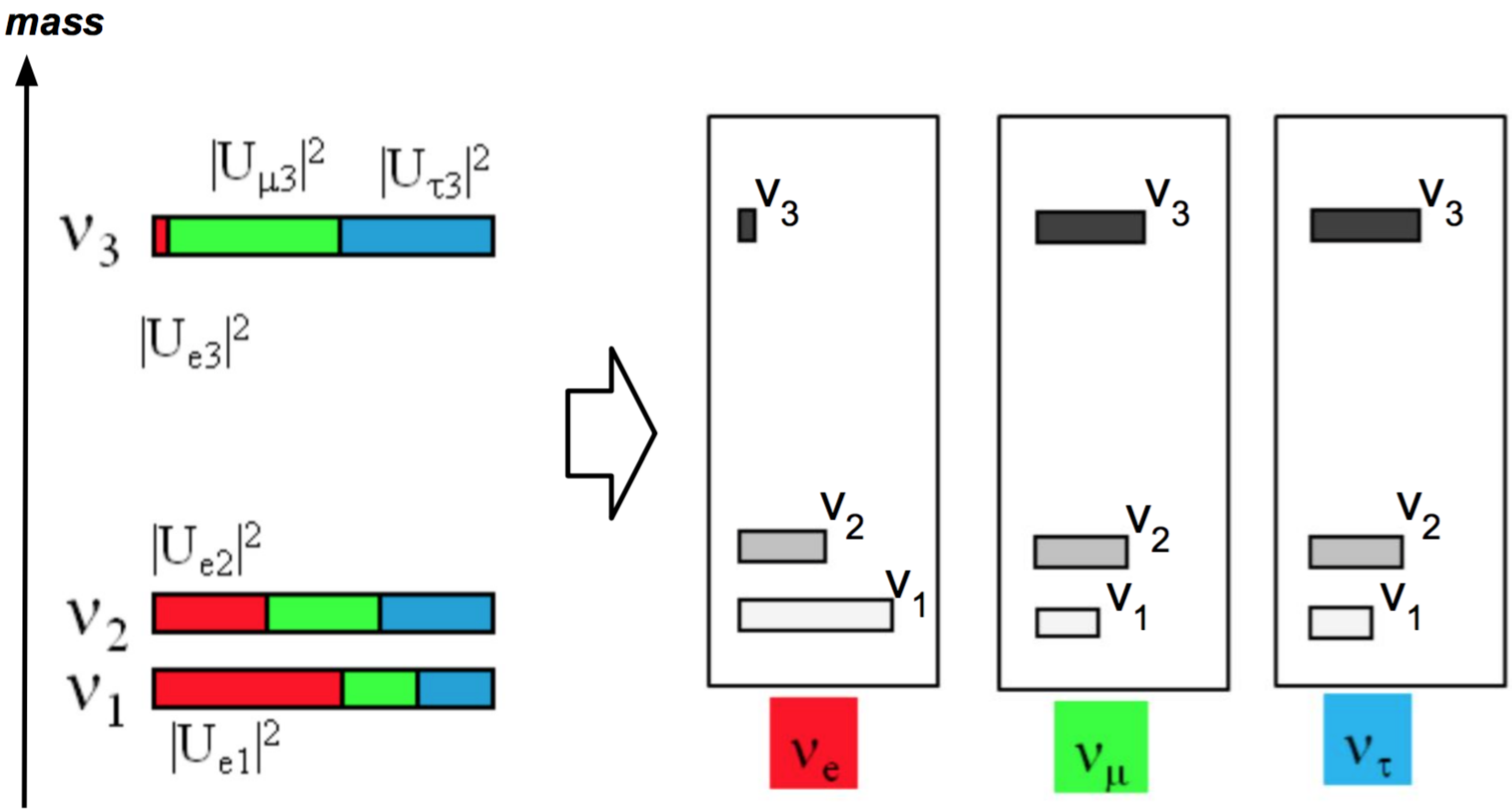



For antineutrinos:

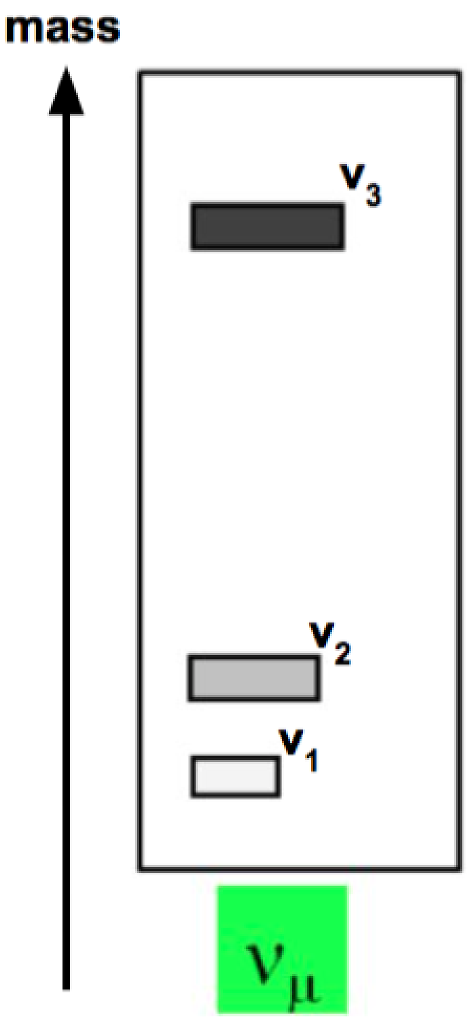
$$U_{PMNS} \rightarrow U^{\star}_{PMNS}$$

**PMNS**: **P**ontecorvo-**M**aki-**N**akagawa-**S**akata

# Neutrino oscillations

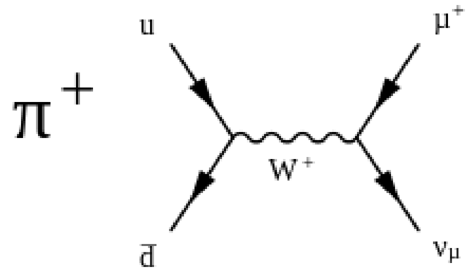


# Neutrino oscillations




A muon-neutrino, **at the very moment it gets created**, is described by the following state:

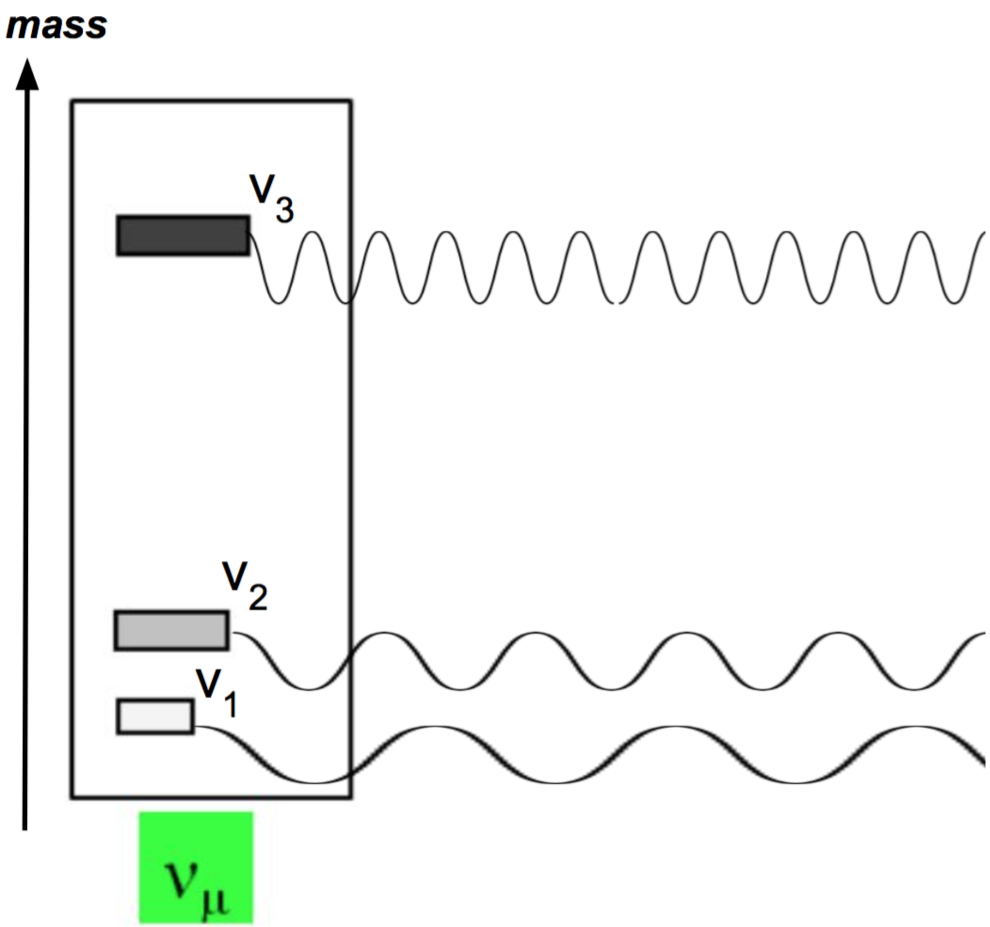
$$|\nu_\mu > \approx 0.4 \cdot |\nu_1 > + 0.6 \cdot |\nu_2 > +0.7 \cdot |\nu_3 >$$




So, at that time, a muon-neutrino is:

- $100 * (0.4)^2 \approx 15\% \ \nu_1$
- $100 * (0.6)^2 \approx 35\% \ \nu_2$
- $100 * (0.7)^2 \approx 50\% \ \nu_3$

# Neutrino oscillations




The propagation of each mass eigenstate i (i=1,2,3) is described by a plane wave:

$$|\nu_i(L)> = e^{-i\mathbf{m_i^2}L/2E} \cdot |\nu_i(0)>$$

Immediately after its creation, **the superposition** that makes up a flavour eigenstate **gets altered**.

The neutrino now has a **finite probability to be observed as a different flavour state**.

# What do we measure in neutrino oscillation experiments?

Probability for $\nu_\alpha \to \nu_\beta$ $(\alpha, \beta : e, \mu, \tau)$ flavour oscillation:

$$\begin{aligned} P_{\alpha\beta} = \delta_{\alpha\beta} \quad & - \quad 4\sum_{i>j} Re[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}] sin^2(\frac{1}{4}\frac{L}{E}\Delta m^2_{ij}) \\ & + \quad 2\sum_{i>j} Im[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}] sin(\frac{1}{2}\frac{L}{E}\Delta m^2_{ij}) \end{aligned}$$

Sensitivity to oscillations by tuning L/E (baseline to energy ratio)

For a purely phenomenological description of neutrino oscillations, assuming 3 active neutrinos, we need:

- Any 2 squared mass splittings (e.g. $\Delta m^2_{21}$,$\Delta m^2_{32}$)
- 3 mixing angles ($\theta_{12}$, $\theta_{13}$, $\theta_{23}$)
- 1 CP invariance violating phase ($\delta_{CP}$)

# What do we measure in neutrino oscillation experiments?

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$


| Parameter | best-fit ($\pm 1\sigma$) | $3\sigma$ |
|---|---|---|
| $\Delta m^2_{21}$ [$10^{-5}$ eV $^2$] | $7.54^{+0.26}_{-0.22}$ | $6.99 - 8.18$ |
| $\lvert\Delta m^2\rvert$ [$10^{-3}$ eV $^2$] | $2.43 \pm 0.06$ $(2.38 \pm 0.06)$ | $2.23 - 2.61$ $(2.19 - 2.56)$ |
| $\sin^2\theta_{12}$ | $0.308 \pm 0.017$ | $0.259 - 0.359$ |
| $\sin^2\theta_{23}$, $\Delta m^2 > 0$ | $0.437^{+0.033}_{-0.023}$ | $0.374 - 0.628$ |
| $\sin^2\theta_{23}$, $\Delta m^2 < 0$ | $0.455^{+0.039}_{-0.031}$, | $0.380 - 0.641$ |
| $\sin^2\theta_{13}$, $\Delta m^2 > 0$ | $0.0234^{+0.0020}_{-0.0019}$ | $0.0176 - 0.0295$ |
| $\sin^2\theta_{13}$, $\Delta m^2 < 0$ | $0.0240^{+0.0019}_{-0.0022}$ | $0.0178 - 0.0298$ |

$$U_{PMNS} \approx \begin{pmatrix} 0.80 & 0.55 & 0.15 \\ 0.40 & 0.60 & 0.70 \\ 0.40 & 0.60 & 0.70 \end{pmatrix}$$

# Key question: Leptonic CP violation?

The CP-violating phase in PMNS is largely unconstrained.

The magnitude of the CP effect is given by the **Jarlskog Invariant**:

$$J_{CP}^{PMNS} = \frac{1}{8}\, sin2\theta_{12}\, sin2\theta_{13}\, sin2\theta_{23}\, cos\theta_{13}\, sin\delta_{CP}$$

Given the current best fit values, and assuming the normal hierarchy:

$$J_{CP}^{PMNS} = 0.035\, sin\delta_{CP}$$

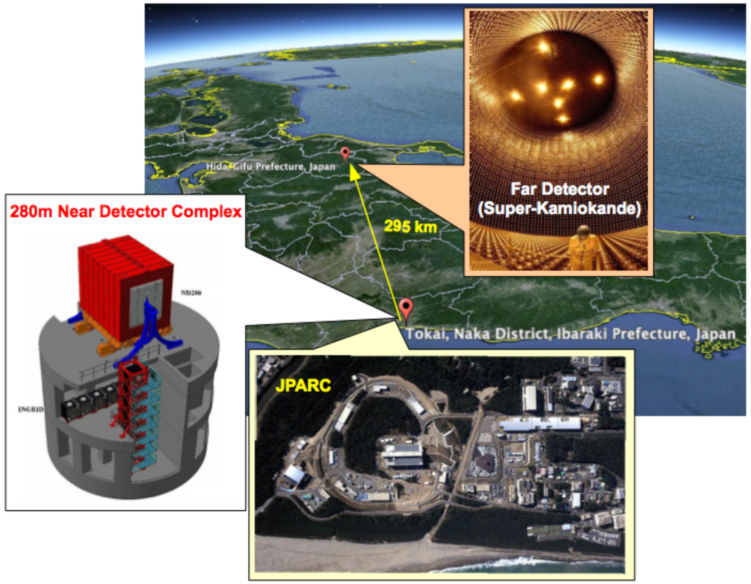
In contrast, in the quark sector, despite the large value of the CP phase:

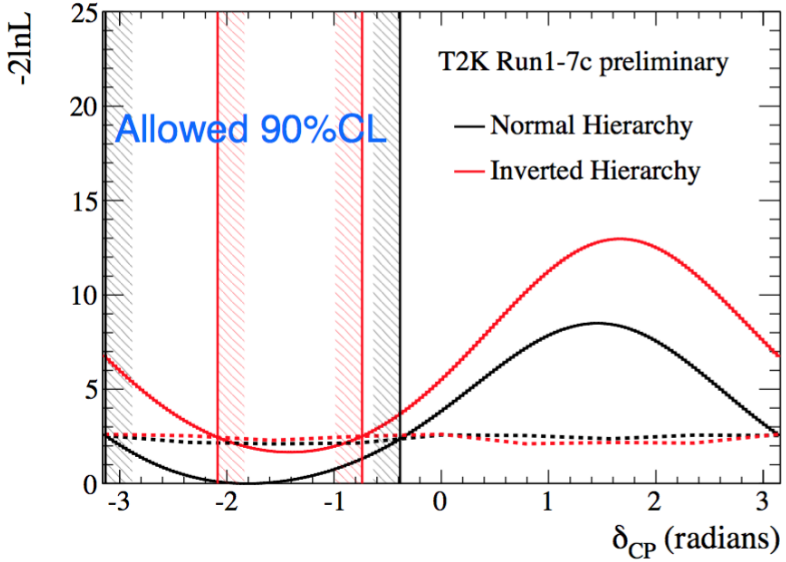
$$J_{CP}^{CKM} \approx (3 \pm 1) \times 10^{-5}$$

$J_{CP}^{PMNS}$ is **potentially large!**

Measurement of leptonic CPV could have a tremendous impact on our understanding of the origin of the **Baryon Asymmetry of the Universe**.

# Hints for leptonic CP violation?




[Phys.Rev.Lett. 118 (2017) no.15, 151801]

- $7.57\times10^{20}$ $\nu$ mode + $7.53\times10^{20}$ $\bar{\nu}$ mode (20% of approved exposure)
- Observed 135 (66) 1-ring $\mu$-like and 32 (4) 1-ring e-like events in $\nu$ ($\bar{\nu}$) mode
- 5% - 6% systematic uncertainty in the expected Far detector event rate
- **"Conserved CP' hypothesis excluded at 90% C.L.**
  - Best-fit: $\delta_{CP}$ = -1.885, NH
  - $\delta_{CP} = 0$ is excluded at $2\sigma$ C.L., while $\delta_{CP} = \pi$ is excluded at 90% C.L.
  - Allowed 90% C.L. regions: [-3.13,0.39] (NH), [-2.09,-0.74] (IH)

Similar results from NOvA - See Phys.Rev.Lett. 118 (2017) no.23, 231801

# Key question: Sterile neutrinos?

The 3-active-neutrino paradigm successful in describing most data:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino mixing framework could be $n \times n$ (with some constraints):
- sum of neutrino masses O(1 eV)
- small mixing between 3 active and additional sterile $\nu$'s (O(10%))

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \cdots \\ \cdots \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots & \cdots & U_{en} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots & \cdots & U_{\mu n} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \cdots & \cdots & U_{\tau n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ U_{s1} & U_{s2} & U_{s3} & \cdots & \cdots & U_{sn} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \cdots \\ \cdots \\ \nu_n \end{pmatrix}$$

# Hints for sterile neutrinos?

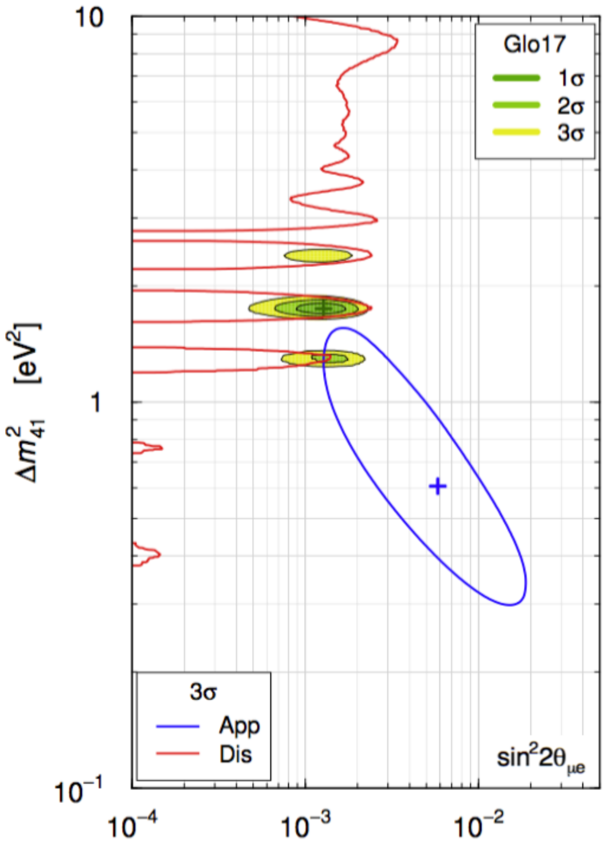
- **LSND anomaly**
  $\sim$50 MeV $\bar{\nu}_e$ appearance ($\sim 3.8\sigma$)
- **MiniBooNE anomaly**
  $\sim$1 GeV $\nu_e$ and $\bar{\nu}_e$ appearance ($\sim 3.8\sigma$)
- **Reactor anomaly**
  Few-MeV $\bar{\nu}_e$ disappearance ($\sim 3.0\sigma$)
- **Gallium anomaly**
  Sub-MeV $\nu_e$ disappearance ($\sim 2.7\sigma$)

Can be interpreted as large-$\Delta m^2$ oscillation, requiring the addition of new sterile neutrino(s).

- Severe tensions with null $\nu_\mu \to \nu_\mu$ results.
- Definite null result would settle a long-standing open question.
- Confirmation would be a major discovery.
- Implications for CPV searches.

Resuts of a global (3+1) $\nu_\mu \to \nu_e$ analysis

including recent MINOS, IceCuBE, NEOS results:




[S.Gariazzo et al., arXiv:1703.00860v3]

# Future accelerator-based oscillation programme

Current accelerator-based oscillation experiments statistics limited.

- T2K, NOvA

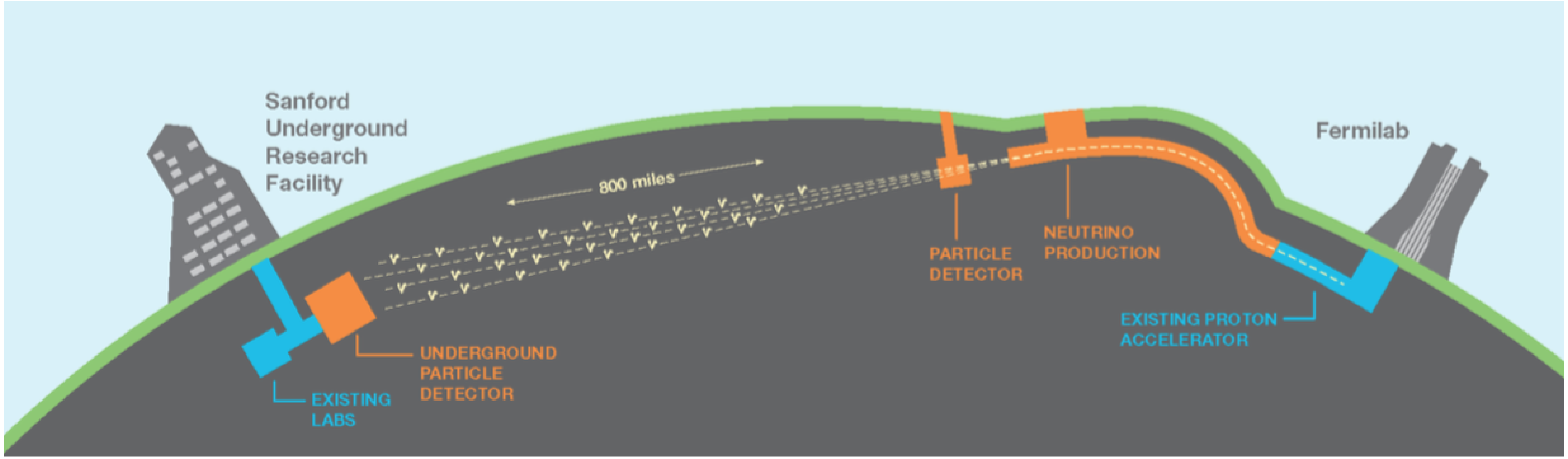
Future accelerator program being built to address key science questions:

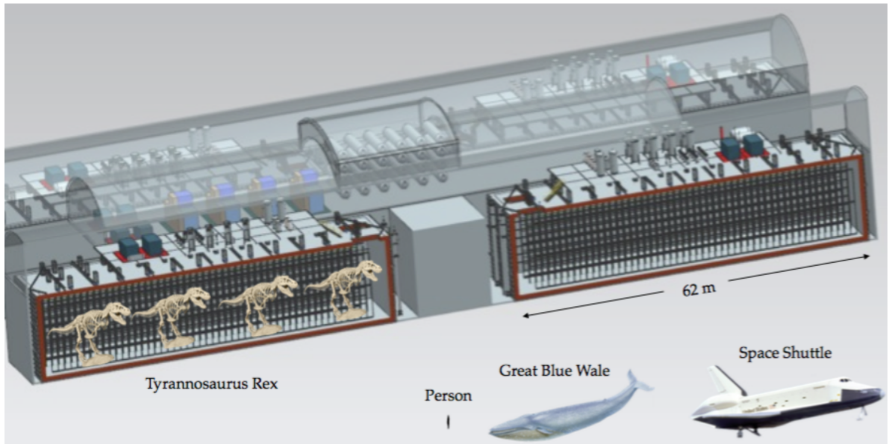
- **Long-baseline** (DUNE @ Fermilab, HyperK @ Japan)
  - O($1B) scale investment!
- Short-baseline (SBN @ Fermilab)

Science goals at risk!

A generational advance in neutrino interaction studies is required!

# Flagship LBL accelerator-based programme (DUNE)



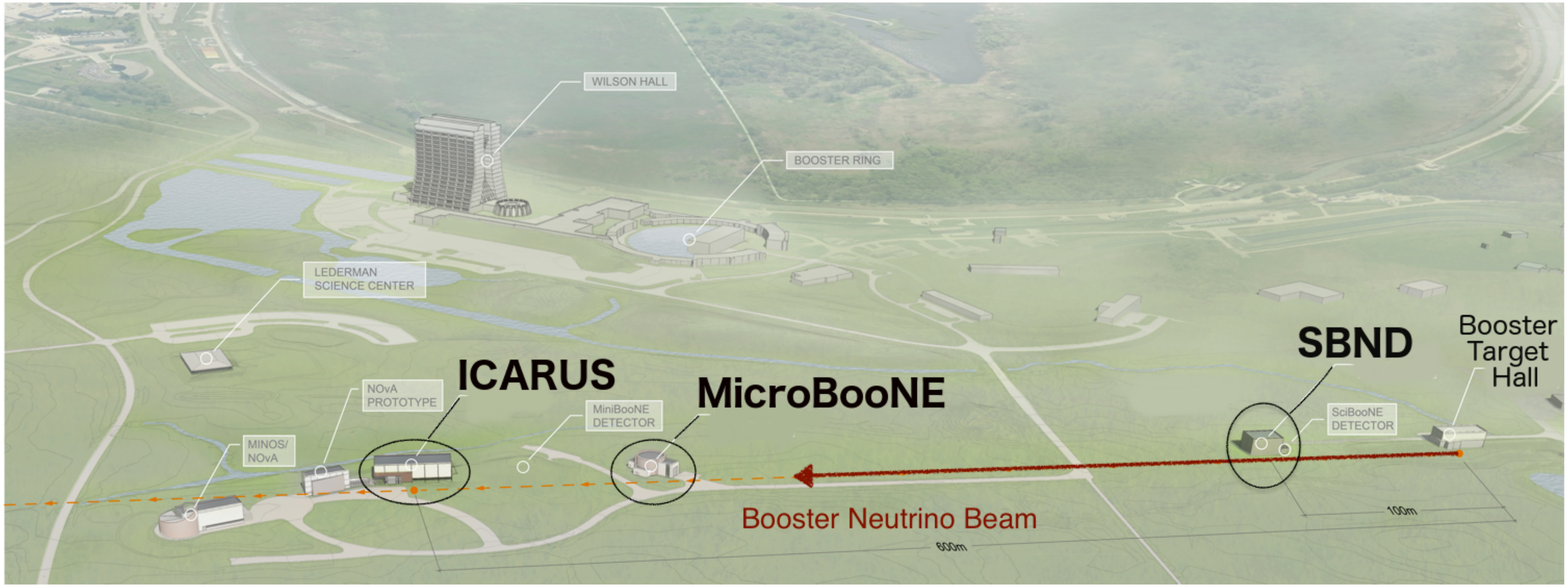




- New **wide-band** $\nu_\mu/\bar{\nu}_\mu$ beam at FNAL pointing towards SURF (**1300 km** away)
  - 1.2 MW protons from PIP-II by 2026.
  - Upgradeable to **2.4 MW by 2030**!
- **40-kt fiducial mass LAr TPC** located deep underground at SURF **4850-ft** level
  - first 10-kt module deployed in 2024!
- **High-resolution/fine-grained near detector**

Also, Hyper-Kamiokande in Japan - a complementary programme

# Flagship SBL accelerator-based programme (SBN)

A Three LArTPC Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam [arXiv:1503.01520]




| Detector | Baseline (m) | Active LAr mass (tonnes) |
|---|---|---|
| SBND | 110 | 112 |
| MicroBooNE | 470 | 87 |
| ICARUS | 600 | 476 |

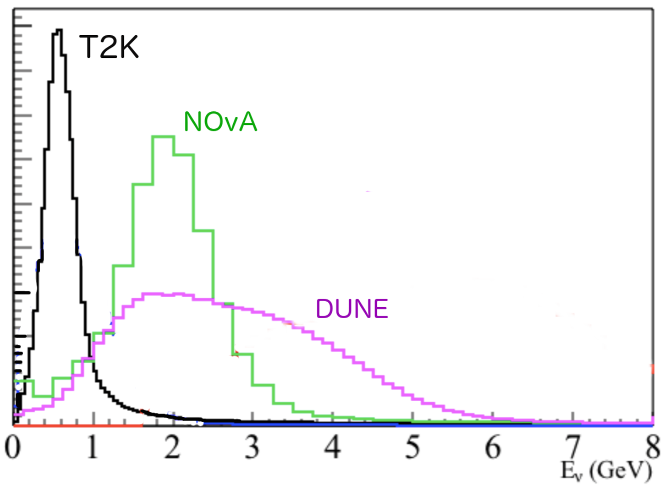
Same neutrino beam, nuclear target, detector technology: Reducing effect of systematic uncertainties.

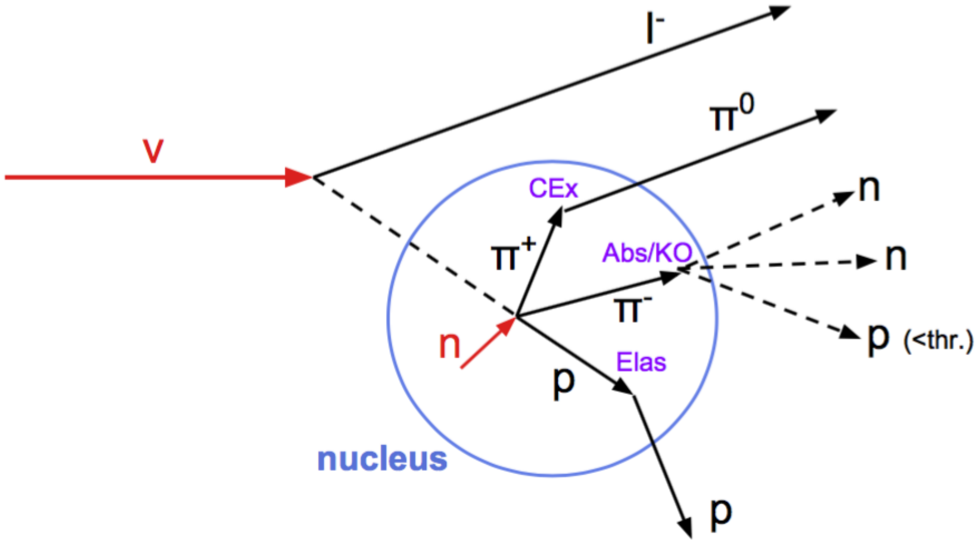
# What matters for oscillation searches?

Oscillation probabilities (for given oscillation parameters and baseline) are **functions of the <u>true</u> neutrino energy alone**!

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} Re[U_{\beta i} U^{*}_{\alpha i} U^{*}_{\beta j} U_{\alpha j}] sin^2(\frac{1}{4}\frac{L}{E}\Delta m^2_{ij}) + 2\sum_{i>j} Im[U_{\beta i} U^{*}_{\alpha i} U^{*}_{\beta j} U_{\alpha j}] sin(\frac{1}{2}\frac{L}{E}\Delta m^2_{ij})$$

The $\nu$ energy is <u>not known</u> on an event-by-event basis (broad distribution).
The $\nu$ energy has to be deduced from the observed final state!



# What matters for oscillation searches?

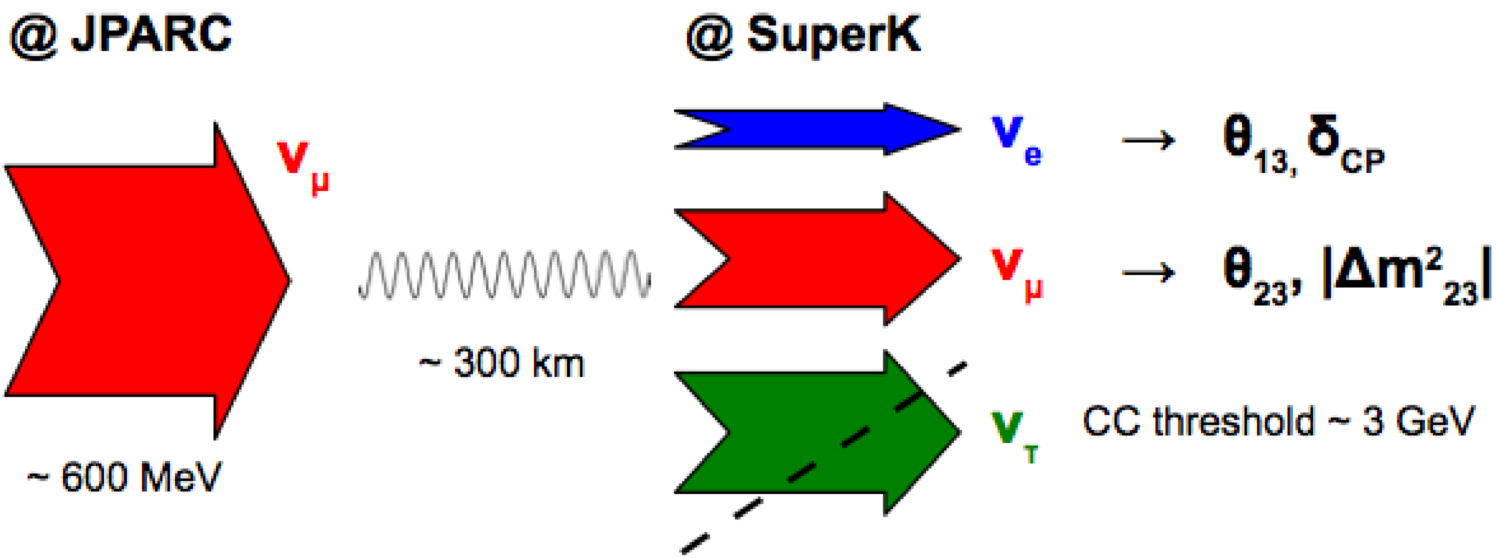
Essentially, observed oscillation probabilities are **ratios of neutrino fluxes**.

Fluxes are **estimated from the observed event rate**

- correcting for misID'ed events / backgrounds,
- unfolding detector efficiency effects, and
- unfolding nuclear effects / cross-sections.

Detector response and event ID a complex function of the final state - Efficiency calculation requires a reliable simulation.

We're particularly sensitive to unaccounted for differences between $\nu$ - $\bar{\nu}$ and $\nu_e$ - $\nu_\mu$.



# How we found ourselves in the few-GeV energy range?

## Accelerator-based LBL oscillation experiments:

Maximize oscillation sensitivity at "atmospheric" squared mass splitting:

$$1.267 \frac{|\Delta m^2_{32}|(eV^2/c^4) \cdot L(km)}{E_\nu(GeV)} = \frac{\pi}{2} \xrightarrow{|\Delta m^2_{32}| \approx 2.4 \times 10^{-3} eV^2/c^4} E_\nu(GeV) = 0.002 \cdot L(km)$$

## Accelerator-based SBL oscillation experiments:

Maximize oscillation sensitivity at O(1 $eV^2/c^4$) squared mass splitting:

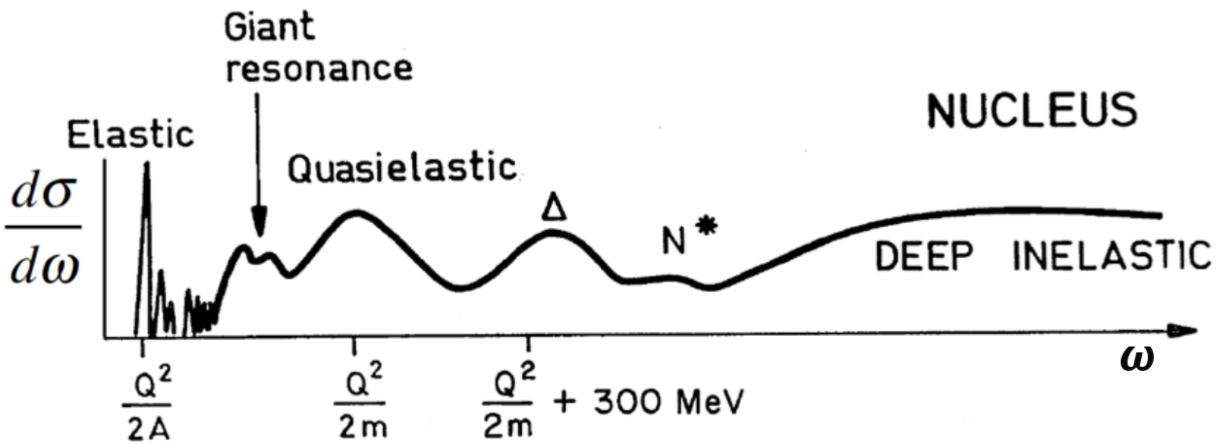
$$1.267 \frac{|\Delta m^2_{41}|(eV^2/c^4) \cdot L(km)}{E_\nu(GeV)} = \frac{\pi}{2} \xrightarrow{|\Delta m^2_{41}| \approx 1 eV^2/c^4} E_\nu(GeV) \approx L(km)$$

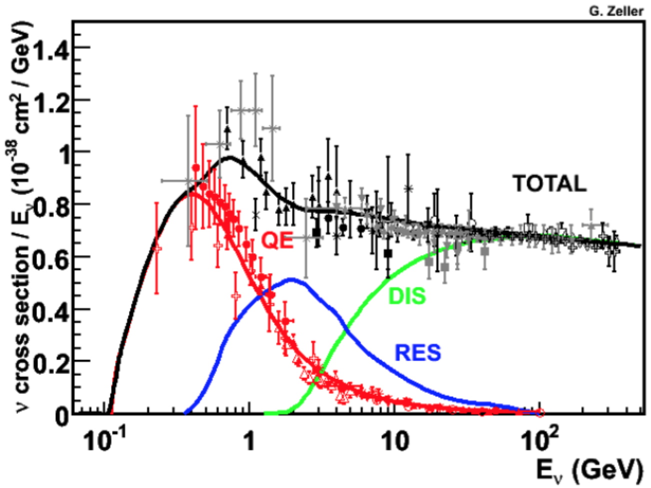
| Experiment | L (km) | E (GeV) |
|---|---|---|
| T2K/HK (LBL) | 292 | 0.6 |
| NOvA (LBL) | 810 | 1.6 |
| DUNE (LBL) | 1300 | 2.6 |
| ICARUS (SBL) | 0.6 | 0.6 |

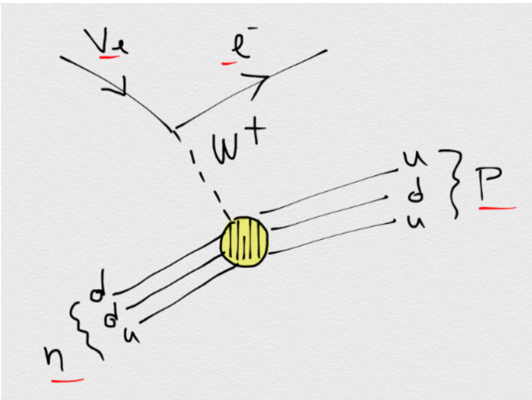
Need to understand neutrino-nucleus interactions at the few-GeV energy range!

# Scattering mechanisms at the few-GeV energy range

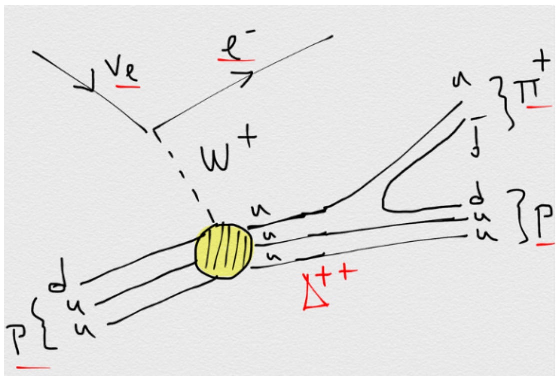
Broad energy range: Several scattering mechanisms are important.
Crossing the boundary between the non-perturbative and perturbative regimes.



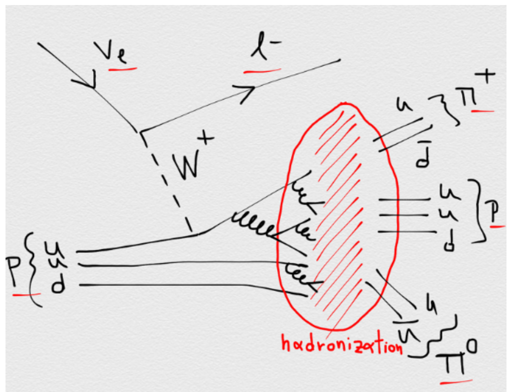



QE



Resonances

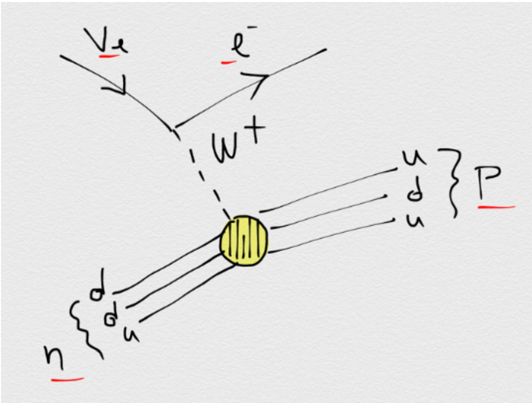



DIS

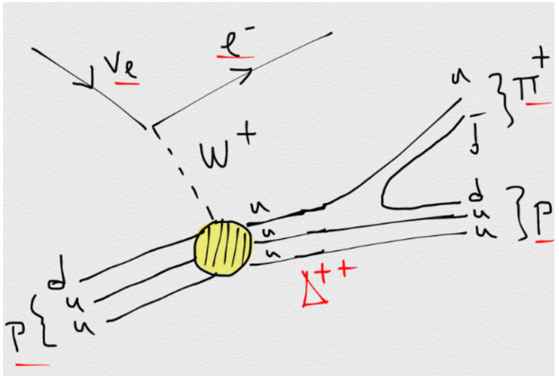
# Particle Physics meets Nuclear Physics

Simulating neutrino-nucleus interactions in a kinematical regime where
a) the impulse approximation is poor, and
b) intranuclear hadron rescattering effects are substantial.

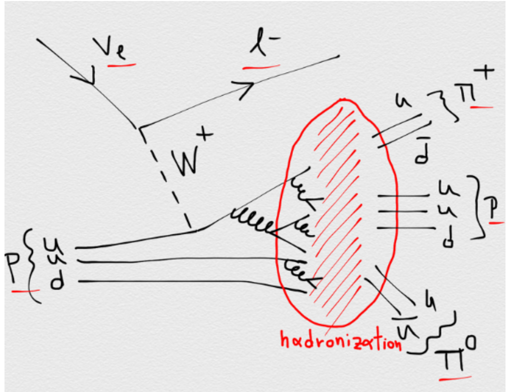
[analogy by Dave Schmitz, NuFact2013]




**QE ($\sim 0\pi$)**




**Resonances ($\sim 1\pi$)**




**DIS**

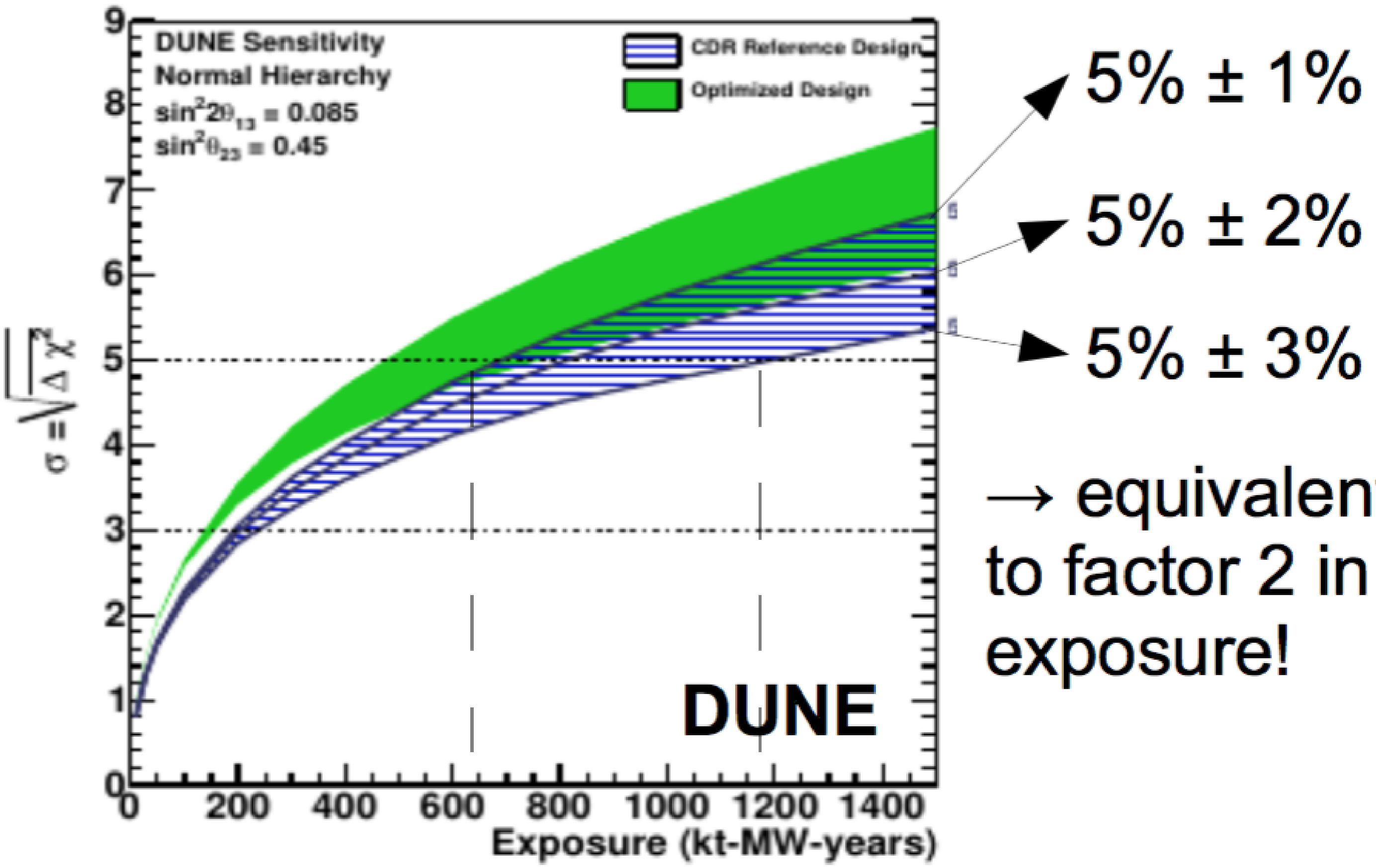
But also worry about many other processes (not mentioned in this talk):

- Coherent and diffractive production of mesons
- $\Delta S = 1$ interactions
- $\Delta C = 1$ interactions
- $\nu + e^-$, ...
- ... ...

# Systematic error requirements

It is aimed that this new generation of LBL neutrino oscillation experiments (DUNE, HyperK) will be taking first beam data at 2026!!

Control of systematic uncertainties to O(1% level) is required.




→ equivalent to factor 2 in exposure!

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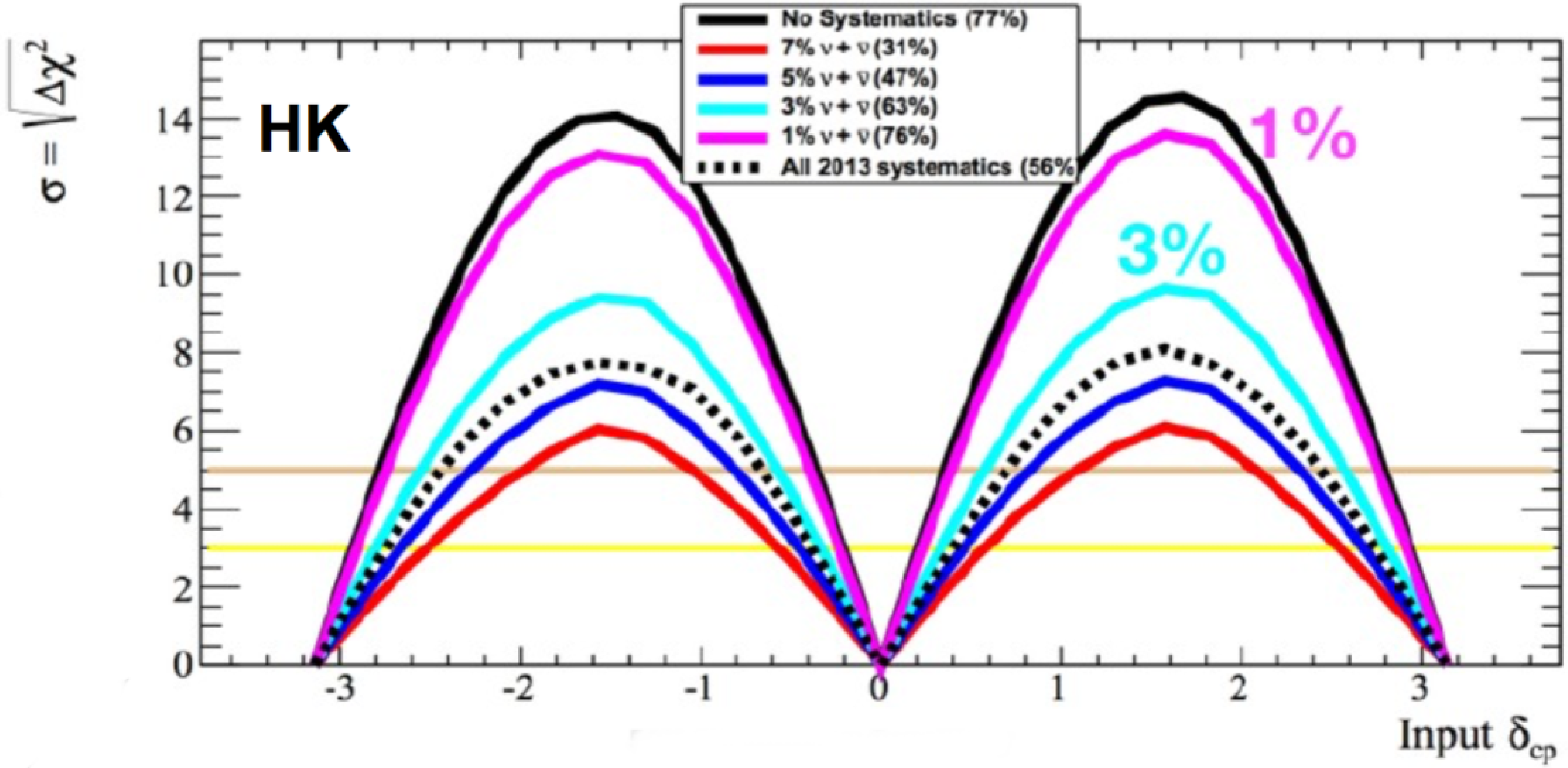
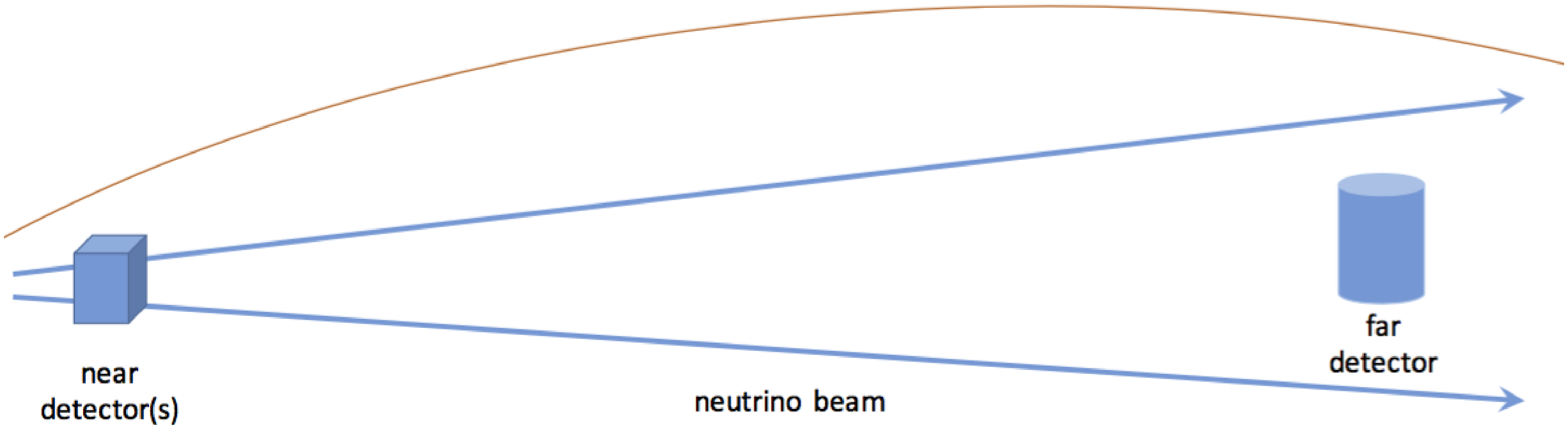


# Extrapolation from Near to Far Detector

To mitigate the effect of (flux and interaction) uncertainties, we perform experiments with detectors at multiple baselines (Near and Far)




Near to Far extrapolation:

- Provides data-driven estimate of unoscillated event rate at the Far detector.
- Influenced by uncertainties in the knowledge of flux and cross-sections.

# Extrapolation from Near to Far Detector

The mantra of an LBL experiment is that reliance on models is limited by using 2 "functionally identical" detectors (Near and Far).

Very schematically, the event rate at the Far and Near detector is given by:

$$N_{\nu_\mu;Far}(E_\nu) \propto \epsilon_{\nu_\mu;Far}(E_\nu) \times \Phi_{\nu_\mu;Far}(E_\nu) \times \sigma_{\nu_\mu}(E_\nu, A) \times P_{\nu_\mu \to \nu_\mu}(E_\nu)$$

$$N_{\nu_\mu;Near}(E_\nu) \propto \epsilon_{\nu_\mu;Near}(E_\nu) \times \Phi_{\nu_\mu;Near}(E_\nu) \times \sigma_{\nu_\mu}(E_\nu, A)$$

Therefore, for functionally identical detectors ($\epsilon_{\nu_\mu;Far}(E_\nu) \approx \epsilon_{\nu_\mu;Near}(E_\nu)$) with a nuclear target of the same atomic mass A:

$$N_{\nu_\mu;Far}(E_\nu) \propto N_{\nu_\mu;Near}(E_\nu) \times \frac{\Phi_{Far}(E_\nu)}{\Phi_{Near}(E_\nu)} \times P_{\nu_\mu \to \nu_\mu}(E_\nu)$$

Cancelled detector efficiency and cross-section errors. Flux information enters in a ratio, so only the uncorrelated Far/Near uncertainty plays a role.

# Reliance on models

In practise, the situation is **substantially more complicated**:

- There is no such thing as "functionally identical" detectors
  - Near detector closer to source and at shallower depth
    - Different beam-related backgrounds
    - Different flux (line source vs point source, oscillations!)
  - High rate in the Near hall can necessitate different technology
    - Uncorrelated detector systematics between Near and Far detectors
    - Different acceptance from the (usually $4\pi$) Far detector
    - Different nuclear targets
- The true neutrino energy is not known on an event-by-event basis
  - The true neutrino energy comes from a broad distribution
  - The mapping between the true and reconstructed energy is driven by detailed event characteristics (ID and momentum of all f/s particles)
  - Complex detector response/acceptance for each f/s.

It is **impossible to avoid reliance on models.**

- But models not predictive enough

# Reliance on models: $\nu_e$ and $\bar{\nu}_e$ cross-sections

- Large observed value of $\theta_{13}$ a **mixed blessing**
- **Large $\nu_e$ and $\bar{\nu}_e$ appearance rate**

$$P(\nu_\mu \to \nu_e) \simeq \boxed{\sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}}$$

Phys. Rev. D64 (2001) 053003

Leading term

CP violating
$$-\alpha \sin\delta_{CP} \times \sin^2 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

"+" for antineutrino

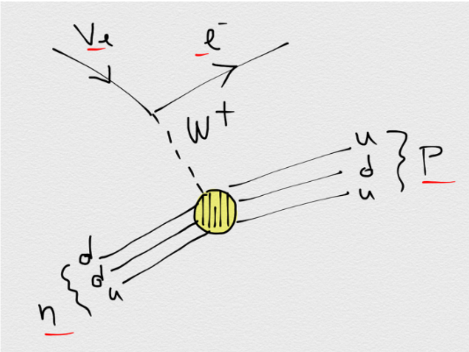
CP conserving
$$\alpha \cos\delta_{CP} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \times \cos\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$+O(\alpha^2) \qquad x = \frac{2\sqrt{(2)}G_F N_e E}{\Delta m^2_{31}} \qquad \alpha = |\frac{\Delta m^2_{21}}{\Delta m^2_{31}}| \sim \frac{1}{30} \qquad \Delta = \frac{\Delta m^2_{31} L}{4E}$$

- **But small CP asymmetry!**

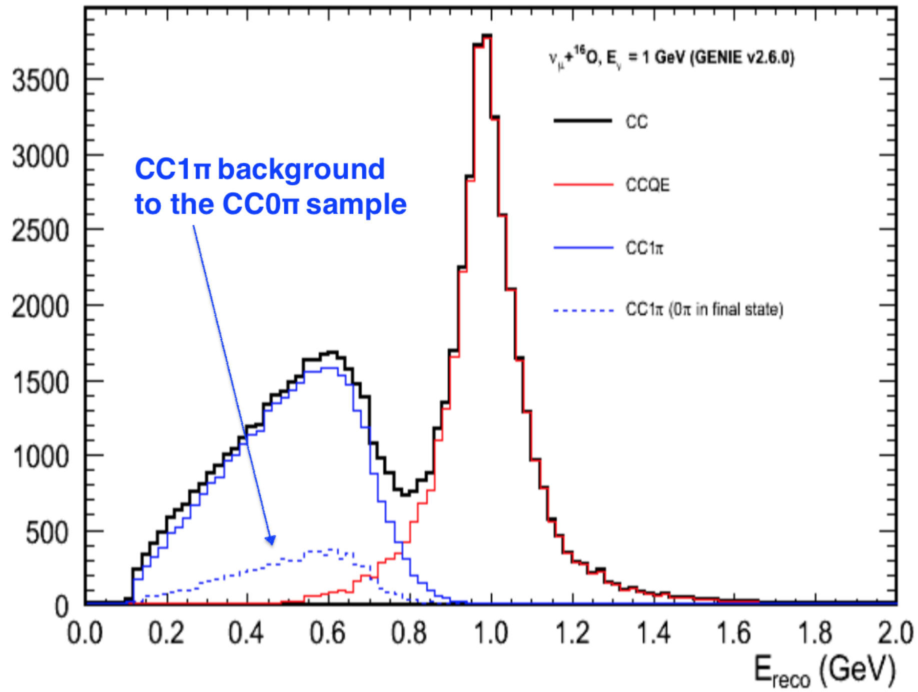
$$A_{CP} \propto \frac{sin2\theta_{12}}{sin\theta_{13}} sin\delta_{CP}$$

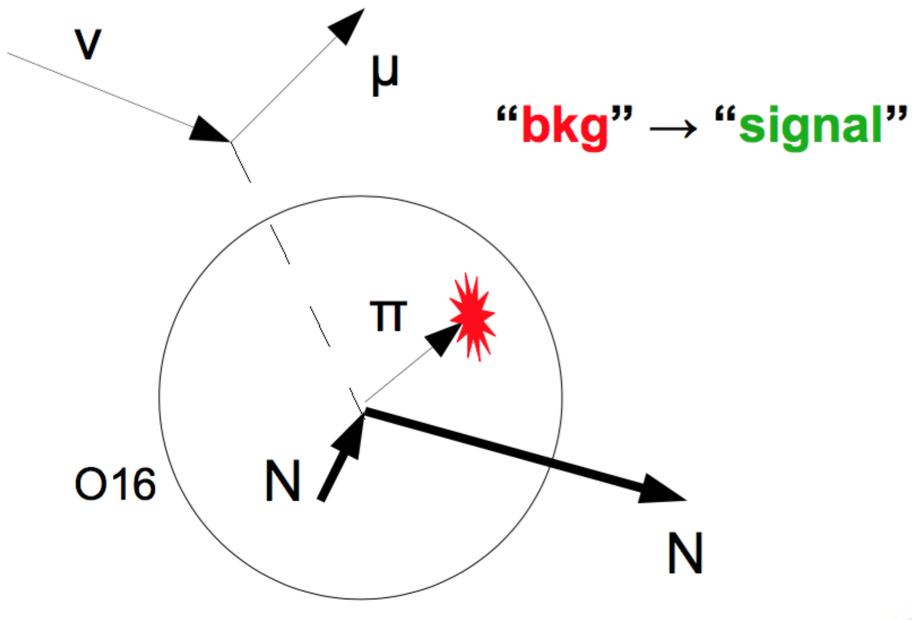
- **"Signal" systematics important**
  - Oscillation "signal" absent from NDs
  - Intrinsic $\nu_e$ contamination low and at different energy range

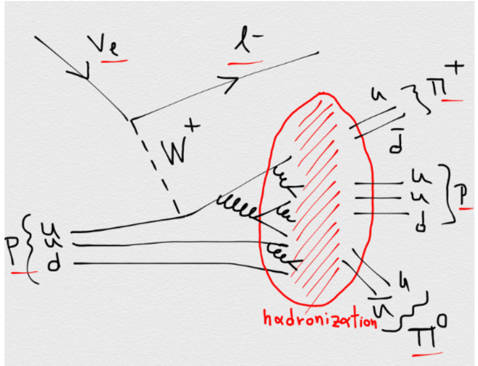



Reconstruction based on **2-body kinematics** for QE-enhanced samples

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

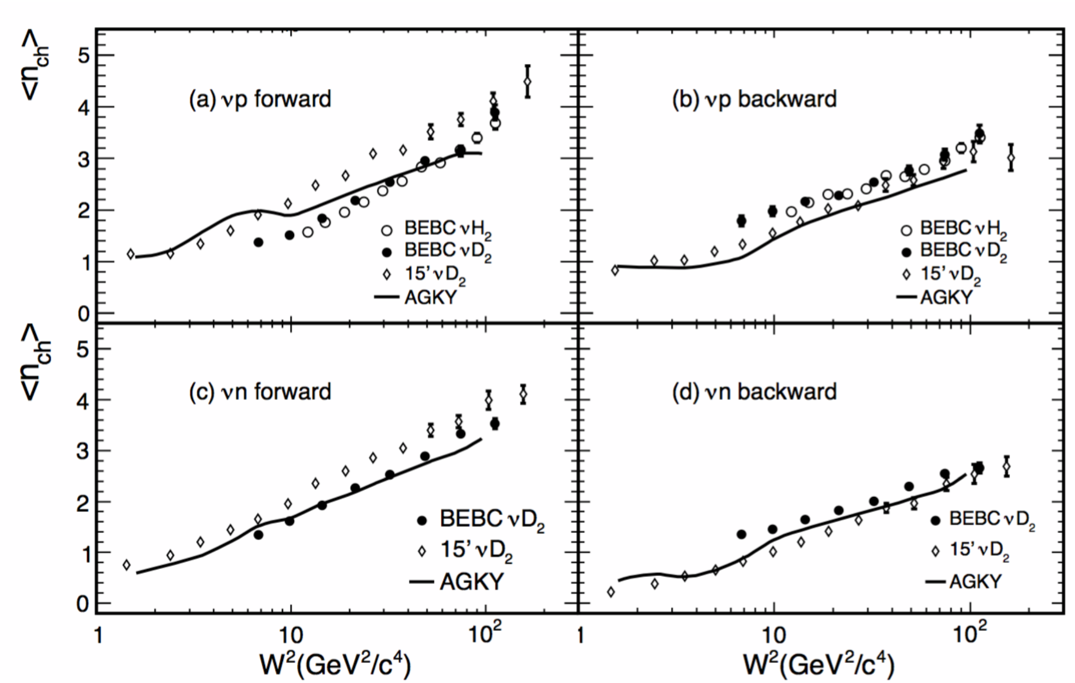


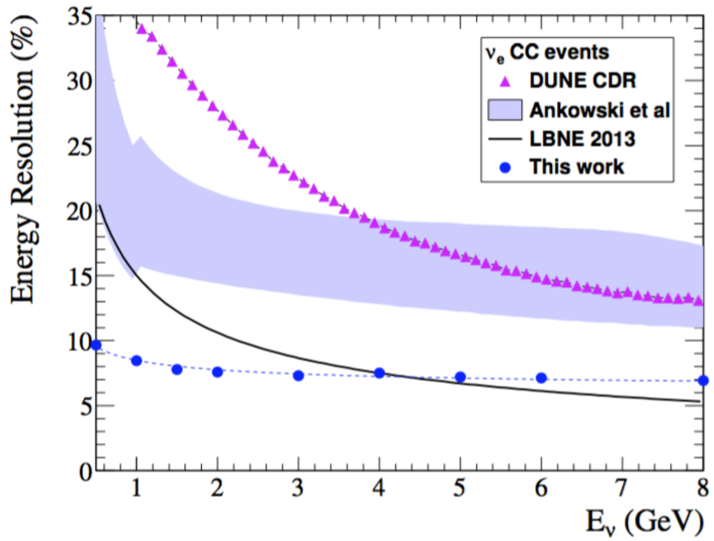



**Calorimetric** approach to energy reconstruction:

$$E_\nu = {\color{red}E_{leptonic}} + {\color{green}E_{hadronic}}$$



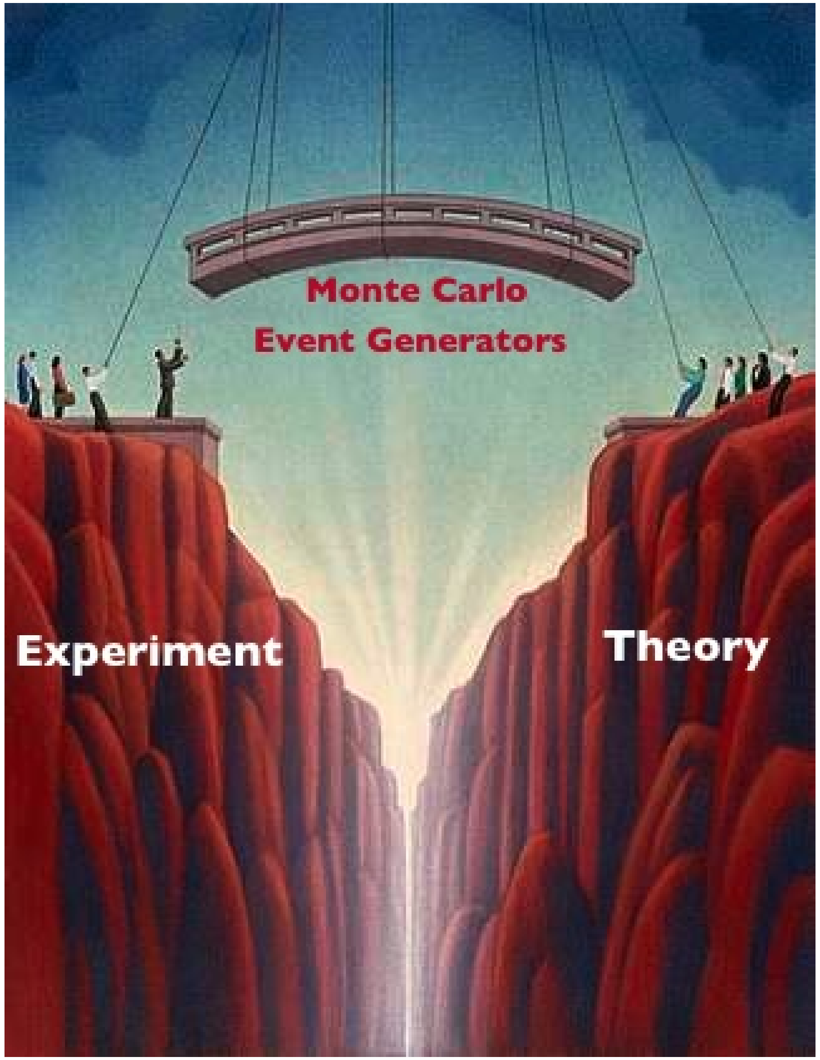

[Eur.Phys.J.C63:1-10,2009]




[arXiv:1607.00293]

# Neutrino MC Generators: A Theory/Experiment Interface

Model dependence encapsulated in comprehensive Neutrino MC Generators




Neutrino MC Generators **connect the true and observed event topologies and kinematics**.

Every observable a convolution of flux, interaction physics and detector effects.

Neutrino MC Generators allow experimentalists to access, improve, validate, assess the uncertainty of and tune the *physics* models that drive the result of that convolution.

# Neutrino MC Generators: Versatile tools

- Front-ends for fast neutrino event generation / 4-vector level studies.
- Back-ends in experimental Monte Carlo simulation chains.
- Libraries of calculated neutrino cross-sections.
- Event re-weighting engines, used for evaluating systematic errors and propagating them in physics analyses.
- Data-bases of experimental neutrino, electron and hadron scattering data used for model tuning and systematic error evaluation.
- Toolkits for model tuning, data/MC comparisons, ...
- Non-neutrino event generators
  - Electron-Nucleus and Hadron-Nucleus generators to extract model constraints from complementary non-neutrino scattering data.
  - Nucleon Decay generators.

# Neutrino MC Generators: Versatile tools

MC Generators are used from the time an experiment gets proposed

- prediction of event rates and feasibility studies
- physics-driven requirements for the experiment design
- ...

till the final publication

- evaluation and propagation of systematic uncertainties
- evaluation of acceptances and backgrounds
- ...

# Neutrino MC Generators

Only few such neutrino MCs exist, actively developed, and in wide use:

**GENIE** (http://www.genie-mc.org) - developed mostly by experimental groups

- Activelly developed by a large group of authors.
- Universal and most commonly-used generator used by nearly all experiments (GENIE predictions a "standard candle" for comparing experiments).
- Large constellation of models (a platform for model validation and tuning).
- Large collection of tools to support analysis activities
- Written in C++ using modern OO design architectures.
- Strict validation / deployment procedures to ensure end product.
- Community engagement through the GENIE Incubator.
- Comparisons/Tuning closed source. Generator open source but no forking!.

**NEUT** - developed mostly by experimental groups

- A legacy fortran-77 generator inherited from Super-Kamiokande.
- Developed by Yoshinari Hayato and collaborators.
- Used primarily by Super-Kamiokande / T2K.
- "Open source" (if you manage to get hold of it).

# Neutrino MC Generators

Only few such neutrino MCs exist, actively developed, and in wide use:

**NuWro** (https://github.com/NuWro) - developed mostly by theorists

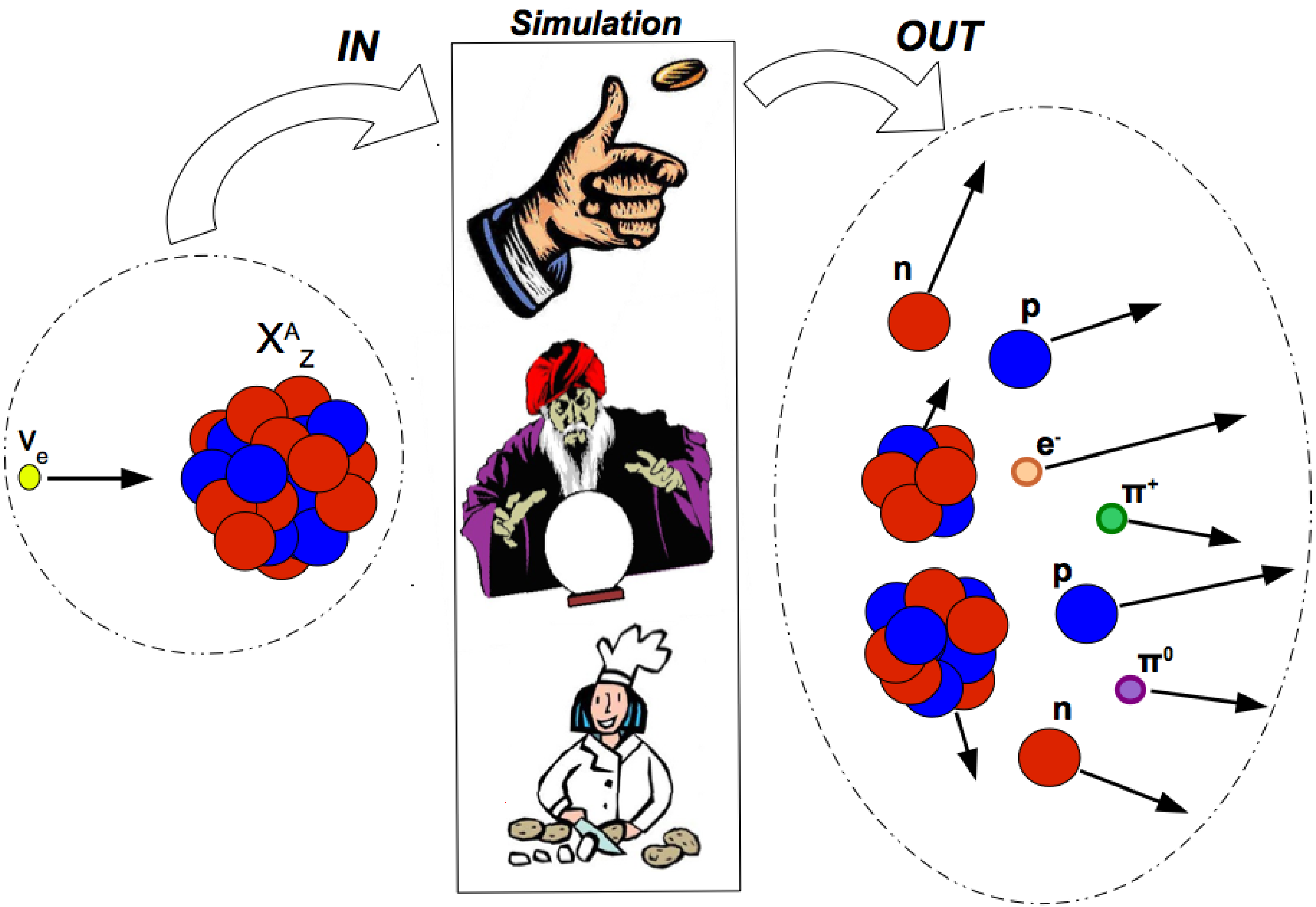
- Developed by Jan Sobczyk and collaborators at Wroclaw (and now Ghent).
- Written in C++ / Open source.
- Very quick deployment of new models (but at own risk) - Primarily a tool for R&D efforts of the Wroclaw group.
- Plays an important role! Used by several experiments for cross-checks, but usually not embedded in the full MC chain.

**GiBUU** (https://gibuu.hepforge.org) - developed mostly by theorists

- Developed by Ulrich Mosel and collaborators at Giessen.
- Written in Fortran-2003 / Open source.
- A unified theory and transport framework (Boltzmann-Uehling-Uhlenbeck)
- U.Mosel: "GiBUU is nature" (it probably is!)
- U.Mosel: "It doesn't matter if the theory describes the data, as long as the theory is correct" (conflicts with view of us, experimentalists, who tend to want to describe the data, even with an incorrect theory or no theory (empirical corrections)).

# What do we want to simulate?

To boost the event rate, experiments use nuclear targets. Dozens of different isotopes present in our detectors, but typically the bulk of detector fiducial mass is made of C12, O16, Ar40, Fe56.
**A Neutrino MC Generator needs to simulate, on an event-by-event basis, the types and 4-momenta of *all* final state particles produced in interactions of neutrinos with nuclei.**



# What do we want to simulate?

In addition, Monte Carlo generators are required to simulate events

- in the full kinematical phase space accessible to experiments, and
- for all combinations of $\nu/\bar{\nu}$, flavour (e,$\mu$,$\tau$), CC/NC and A (from H to Pb!).

However, some of the best theoretical descriptions

- provide part of the answer (e.g. allow simulation of leptonic part but not of hadronic part),
- have built-in kinematical limits,
- have poor coverage (typically only $\nu$ CC for selected nuclei)

This leaves generators with substantial freedom, even if the same theoretical models are used as inputs.

Different approaches for combining theoretical inputs and data to build comprehensive descriptions of empirical data.

# Basic models used in MC generators

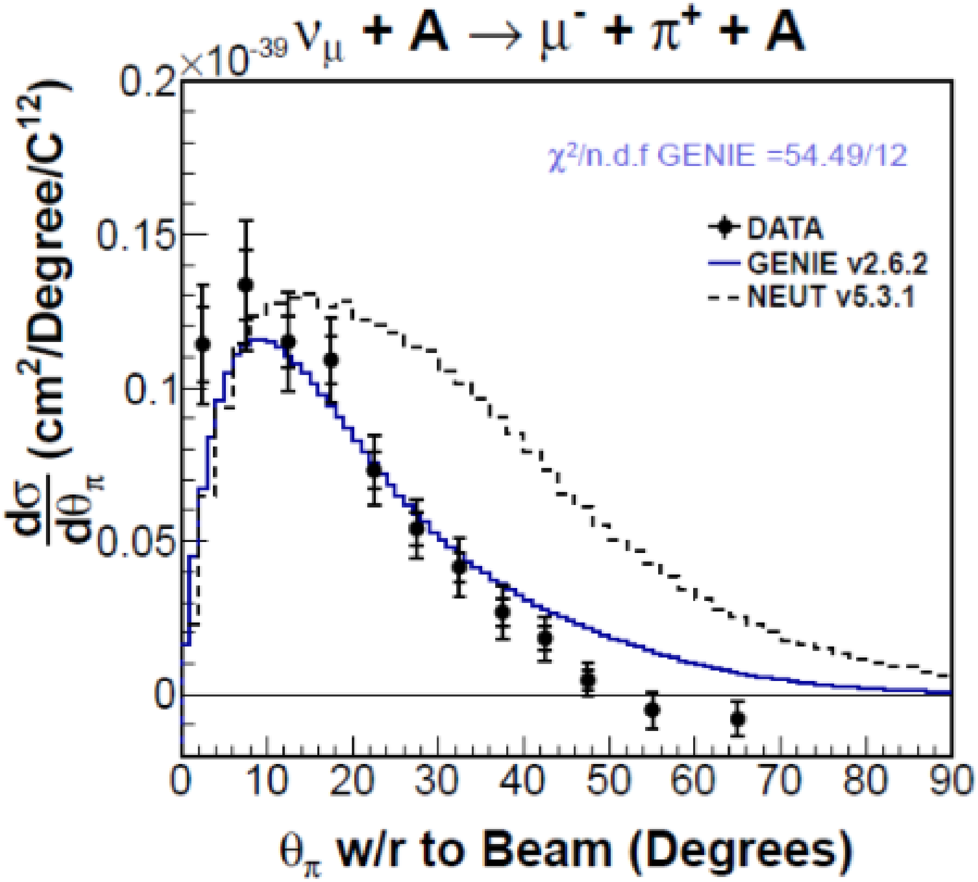
Largely same physics, but non-trivial differences!

| Model/generator | GENIE | NuWro | NEUT |
|---|---|---|---|
| QE | Lwlyn-Smith<br>Nieves, Eff MA | Lwlyn-Smith<br>RPA | Lwlyn-Smith<br>Eff RPA |
| Nuclear model | RFG, LFG, Effective spectral function | RFG, LFG, spectral function | RFG, LFG, spectral function |
| MEC | Valencia<br>Empirical | Valencia<br>Marteau | Valencia |
| Delta model | Rein-Sehgal (updated) | Home-grown | Rein-Sehgal (update) |
| Coherent | Rein-Sehgal(corrected)<br>Berger-Sehgal | Rein-Sehgal<br>Berger-Sehgal | Rein-Sehgal<br>Berger-Sehgal |
| FSI | Schematic<br>Cascade (med corr) | Cascade(med corr) | Cascade(med corr) |

S.Dytman, NuINT17

# A trivial but striking example

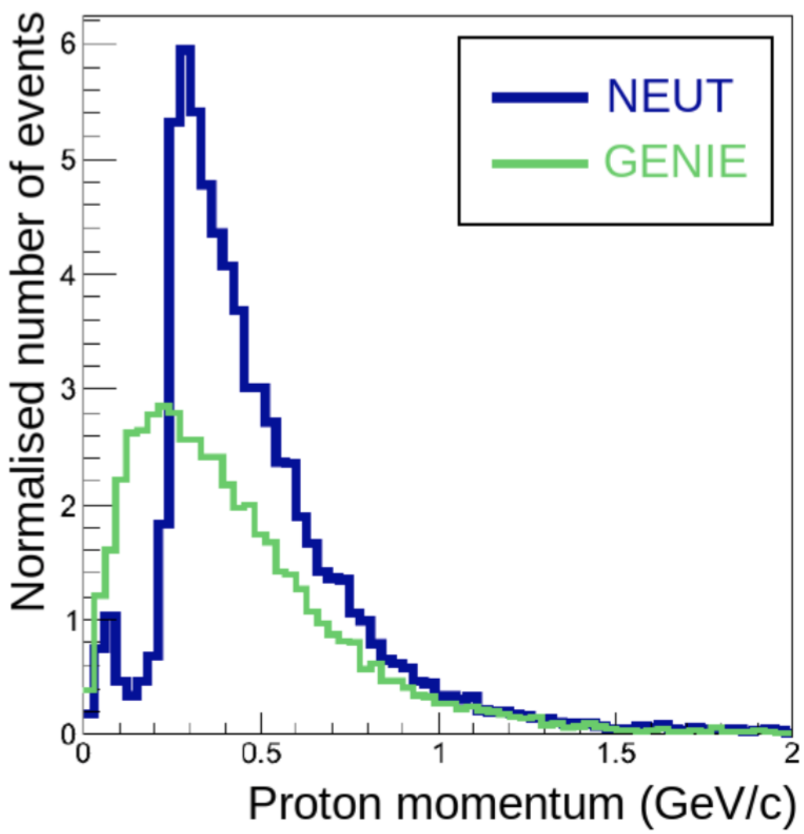
Same theoretical model implementation for coherent meson production in GENIE and NEUT, compared with MINERvA data.




- Similar inputs in all generators, but several non-trivial differences.
- Substantial effort to understand sources of differences.
- Can be indicative of uncertainties which can be hard to quantify.

# A striking example

Similar theoretical models for nucleon binding and momentum districution, Pauli-blocking, and multi-nucleon knockout...




[Dan Scully]

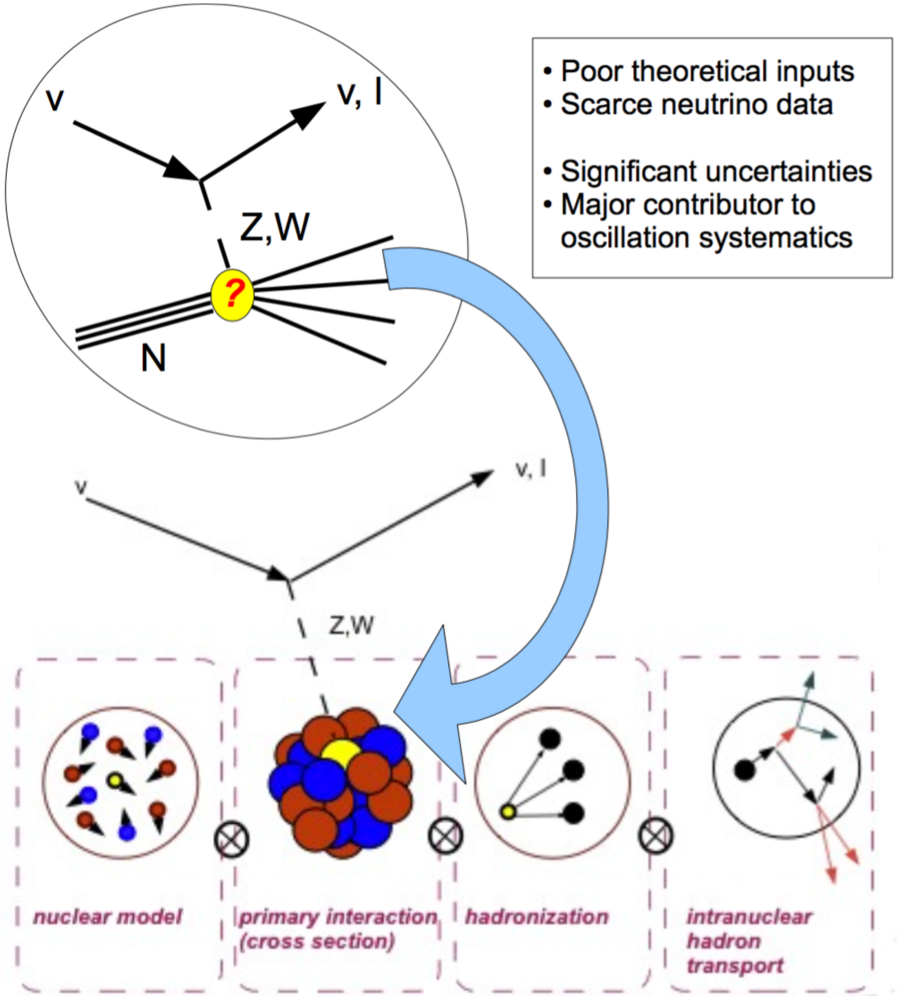
- Similar inputs in all generators, but several non-trivial differences.
- Substantial effort to understand sources of differences.
- Can be indicative of uncertainties which can be hard to quantify.

# The art of developing Neutrino Monte Carlos

- Using the best theory models, each one in the region where it is valid.
- Determining how to best extrapolate and merge models outside of their stated validity range.
- Developing empirical models to bridge the gaps and cover the full required phase space.
- Address double-counting issues.
- Validating / tuning using a variety of complementary data.
- Maintaining CPU-efficiency, as experiments require high-statistics samples.
- Fully evaluating all sources of model uncertainty (to do physics, knowledge of the error on the model is as necessary as the model itself)

# Neutrino MC Generator factorization

Cross-section calculation at the **neutrino - nucleon level** a starting point.




The nucleon is not a simple object!

Process dynamics described by the invariant amplitude $|M|^2 = L_{\mu\nu} W^{\mu\nu}$ where:

$$W_{\mu\nu} = W_1 \delta_{\mu\nu} + W_2 p_\mu p_\nu + W_3 \epsilon_{\mu\nu\alpha\beta} p^\alpha p^\beta +$$

$$+ W_4 q_\mu q_\nu + W_5 (p_\mu q_\nu + p_\nu q_\mu) + W_6 (p_\mu q_\nu - p_\nu q_\mu)$$

Issue: Knowledge of $W_1$, $W_2$, ... in a kinematical regime that bridges the non-perturbative and perturbative pictures of the nucleon.

Neutrino-nucleus simulations by adding effects:

- the initial nuclear state dynamics
- hadronization
- intranuclear hadron transport

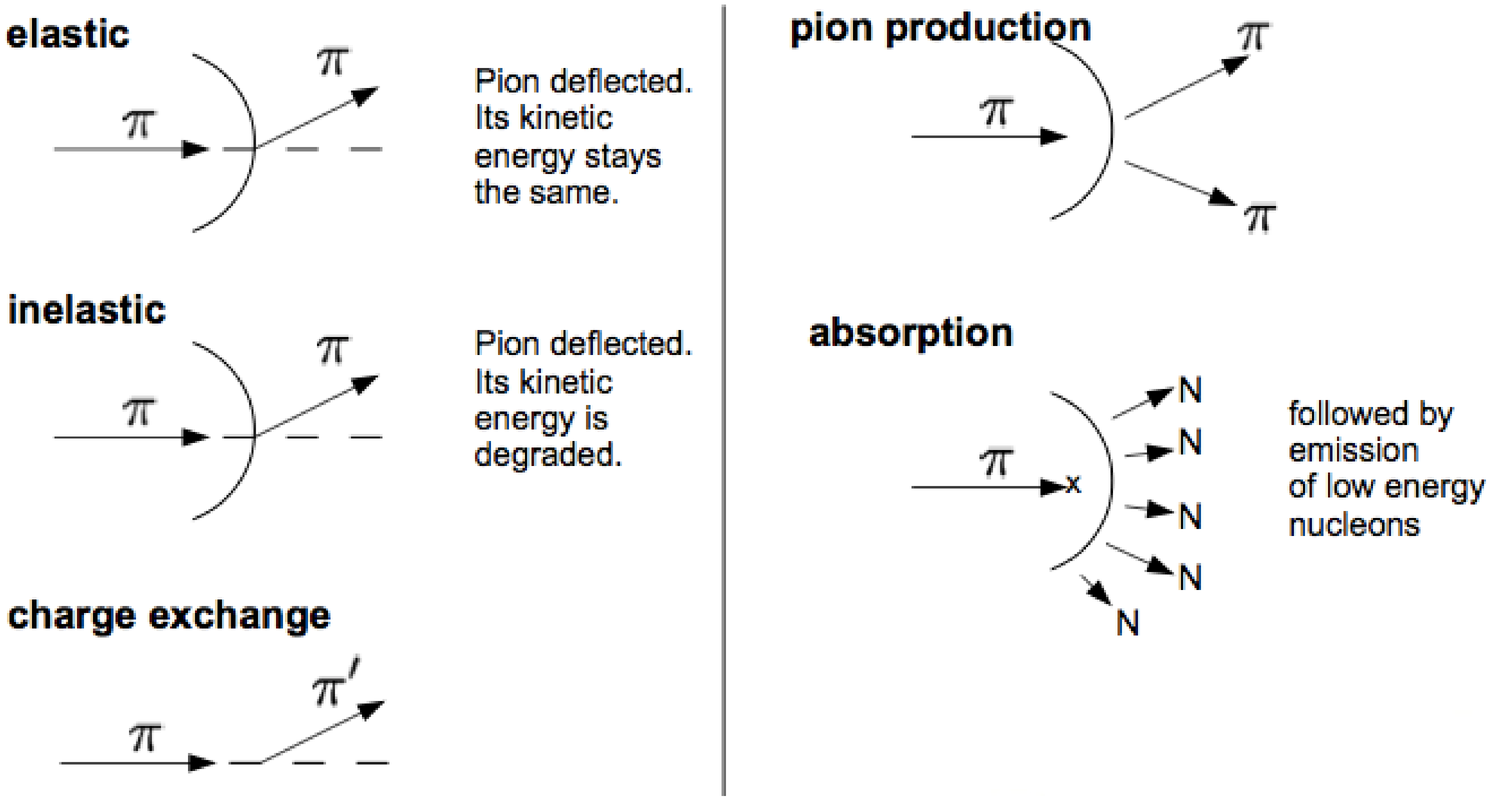
# Our canvas is a nucleus

# Our canvas is a nucleus

- Event simulated within a nucleus
  - Typical target materials: $C^{12}$, $O^{16}$, $Ar^{40}$, $Fe^{56}$, ...
- The nuclear environment can have a dramatic effect
  - Initial state dynamics
  - Effect on form factors / structure functions
  - Final state re-interactions
- Lack of good data on hydrogen/deuterium targets
  - Existing experimental observables can not easily disentangle nuclear mismodelling from mismodelling of thefree-nucleon cross-section.

# Final state re-interactions

**At ∼1 GeV, 2/3 of all primary hadrons re-interact in the nucleus.**
A number of scattering mechanisms are possible.




Home-grown and/or external cascade models to simulate re-interactions.
Single most important source of difference between generators.

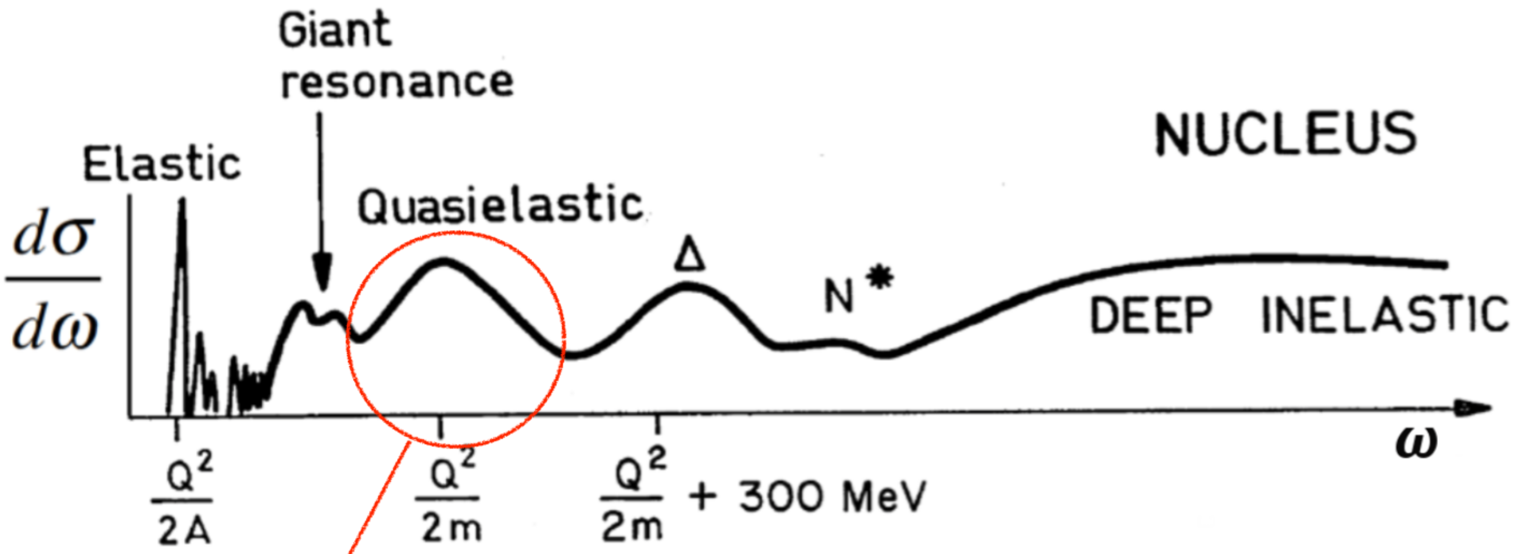
# Final state re-interactions

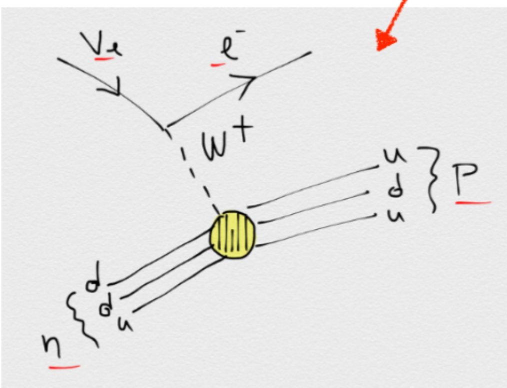
Intranuclear rescattering degrades the hadron energy, smears their angular distributions and mixes the event topologies.

| Final-State | Primary Hadronic System | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $0\pi X$ | $1\pi^0 X$ | $1\pi^+ X$ | $1\pi^- X$ | $2\pi^0 X$ | $2\pi^+ X$ | $2\pi^- X$ | $\pi^0\pi^+ X$ | $\pi^0\pi^- X$ | $\pi^+\pi^- X$ |
| $0\pi X$ | **293446** | 12710 | 22033 | 3038 | 113 | 51 | 5 | 350 | 57 | 193 |
| $1\pi^0 X$ | 1744 | **44643** | 3836 | 491 | 1002 | 25 | 1 | 1622 | 307 | 59 |
| $1\pi^+ X$ | 2590 | 1065 | **82459** | 23 | 14 | 660 | 0 | 1746 | 5 | 997 |
| $1\pi^- X$ | 298 | 1127 | 1 | **12090** | 16 | 0 | 46 | 34 | 318 | 1001 |
| $2\pi^0 X$ | 0 | 0 | 0 | 0 | **2761** | 2 | 0 | 260 | 40 | 7 |
| $2\pi^+ X$ | 57 | 5 | 411 | 0 | 1 | **1999** | 0 | 136 | 0 | 12 |
| $2\pi^- X$ | 0 | 0 | 0 | 1 | 0 | 0 | **134** | 0 | 31 | 0 |
| $\pi^0\pi^+ X$ | 412 | 869 | 1128 | 232 | 109 | 106 | 0 | **9837** | 15 | 183 |
| $\pi^0\pi^- X$ | 0 | 0 | 1 | 0 | 73 | 0 | 8 | 5 | **1808** | 154 |
| $\pi^+\pi^- X$ | 799 | 7 | 10 | 65 | 0 | 0 | 0 | 139 | 20 | **5643** |

$\nu_\mu + O^{16}$, T2K spectrum

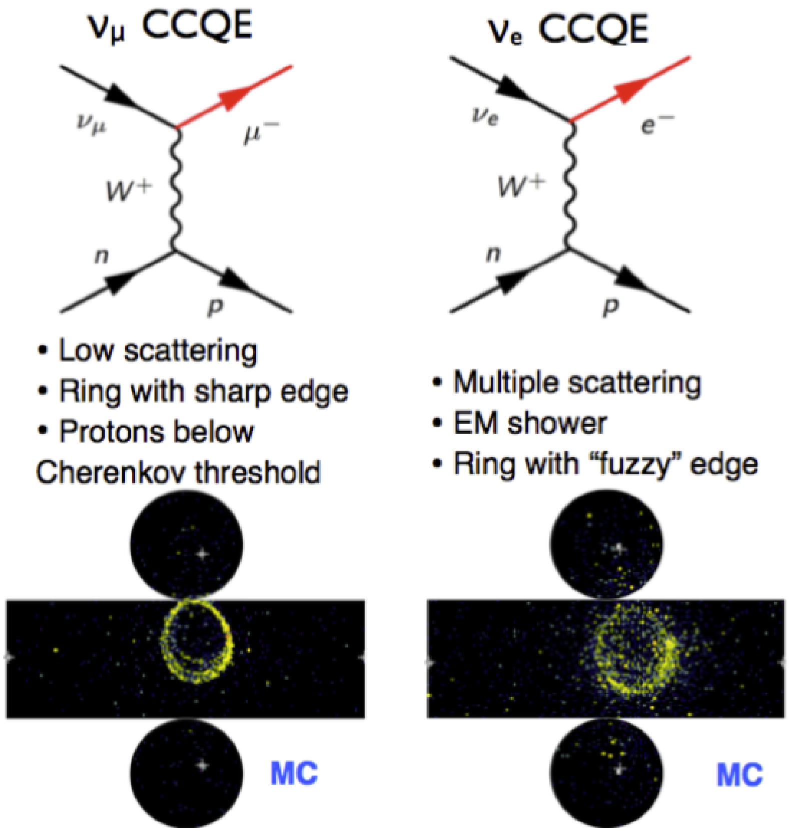
# Quasi-Elastic (QE) scattering



# CCQE interactions

QE: A **golden channel** for oscillation searches, especially at T2K & HyperK (poor imaging of hadronic showers $\rightarrow$ low-energy NBB to suppress non-QE)




2-body kinematics allow $E_\nu$ reconstruction from lepton momentum/angle alone:

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

# Example: Composition of T2K FD analysis samples

$\nu$-mode, 1-ring $\mu$-like candidates

| | $\nu_\mu$ | $\nu_e$ | $\bar{\nu_\mu}$ | $\bar{\nu_e}$ | Osc. $\nu_e$ | Osc. $\bar{\nu_e}$ | Total |
|---|---|---|---|---|---|---|---|
| CCQE | 71.194 | 0.037 | 4.620 | 0.002 | 0.190 | 0.002 | 76.045 |
| CC1pi | 18.214 | 0.019 | 1.686 | 0.001 | 0.061 | 0.001 | 19.981 |
| CCcoherent | 0.351 | 0.000 | 0.086 | 0.000 | 0.001 | 0.000 | 0.438 |
| MEC | 20.442 | 0.011 | 0.910 | 0.000 | 0.045 | 0.000 | 21.408 |
| CCother | 8.340 | 0.009 | 0.533 | 0.001 | 0.002 | 0.000 | 8.885 |
| NC1pi0 | 0.580 | 0.018 | 0.019 | 0.001 | N/A | N/A | 0.617 |
| NC1piPM | 4.253 | 0.096 | 0.153 | 0.009 | N/A | N/A | 4.511 |
| NCcoherent | 0.017 | 0.000 | 0.002 | 0.000 | N/A | N/A | 0.019 |
| NCother | 3.229 | 0.130 | 0.178 | 0.013 | N/A | N/A | 3.550 |
| NC1gamma | 0.004 | 0.000 | 0.000 | 0.000 | N/A | N/A | 0.004 |
| Total | 126.624 | 0.321 | 8.185 | 0.027 | 0.299 | 0.003 | 135.459 |

- 56% CC QE
- 16% CC 2p-2h (*)
- 15% CC 1$\pi$

$\nu$-mode, 1-ring e-like candidates

| | $\nu_\mu$ | $\nu_e$ | $\bar{\nu_\mu}$ | $\bar{\nu_e}$ | Osc. $\nu_e$ | Osc. $\bar{\nu_e}$ | Total |
|---|---|---|---|---|---|---|---|
| CCQE | 0.056 | 2.129 | 0.001 | 0.088 | 15.875 | 0.099 | 18.249 |
| CC1pi | 0.016 | 0.348 | 0.000 | 0.027 | 1.688 | 0.017 | 2.096 |
| CCcoherent | 0.000 | 0.002 | 0.000 | 0.002 | 0.015 | 0.002 | 0.021 |
| 2p-2h | 0.008 | 0.710 | 0.000 | 0.022 | 3.901 | 0.019 | 4.659 |
| CCother | 0.001 | 0.045 | 0.000 | 0.003 | 0.029 | 0.001 | 0.080 |
| NC1pi0 | 0.524 | 0.012 | 0.017 | 0.001 | N/A | N/A | 0.553 |
| NC1piPM | 0.099 | 0.002 | 0.003 | 0.000 | N/A | N/A | 0.105 |
| NCcoherent | 0.174 | 0.004 | 0.018 | 0.001 | N/A | N/A | 0.197 |
| NCother | 0.126 | 0.005 | 0.008 | 0.001 | N/A | N/A | 0.139 |
| NC1gamma | 0.464 | 0.007 | 0.021 | 0.001 | N/A | N/A | 0.494 |
| Total | 1.469 | 3.264 | 0.069 | 0.145 | 21.508 | 0.138 | 26.594 |

- 69% CC QE
- 18% CC 2p-2h (*)
- 8% CC 1$\pi$

# CCQE cross-section

Lorentz symmetry allows us to write the differential CCQE cross-section as:

$$\frac{d\sigma}{dQ^2} = \frac{G_F^2 |V_{ud}|^2 M^2}{8\pi E_\nu^2} \Big( A(Q^2) \mp B(Q^2) \cdot \frac{s-u}{M^2} + C(Q^2) \cdot (\frac{s-u}{M^2})^2 \Big)$$

$A(Q^2)$, $B(Q^2)$ and $C(Q^2)$ functions of the

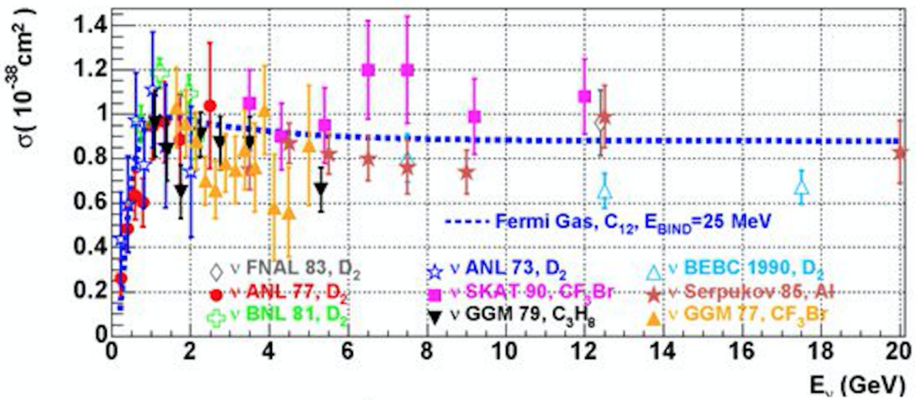
- $F_v^1$, $F_v^2$ vector form factors
    - determined from electron scattering via CVC
- $F_A$ axial vector form factor
    - dipole form is usually assumed

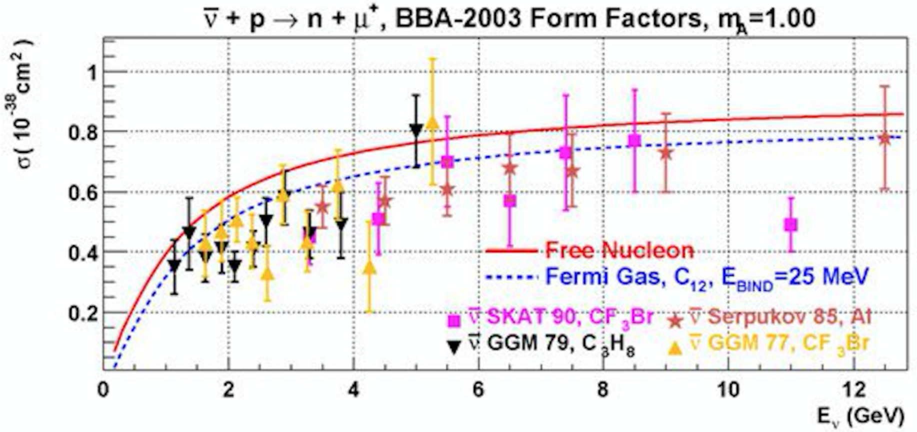
$$F_A(Q^2) = g_A (1 + \frac{Q^2}{M_A^2})^{-2}$$

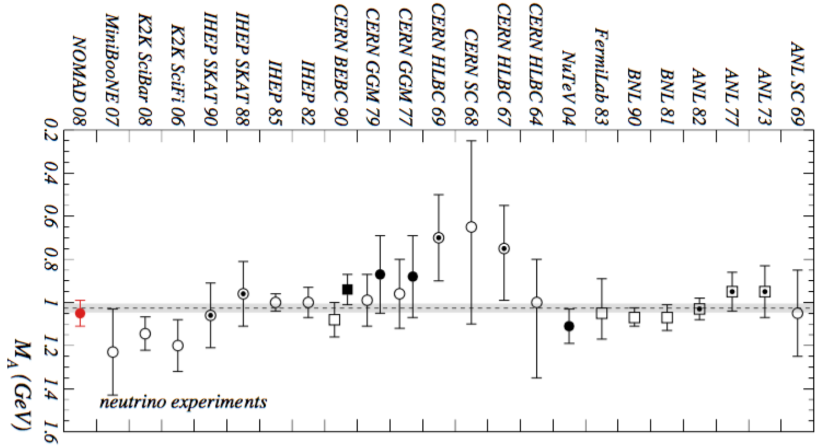
# CCQE cross-section

**On single nucleons**, the QE process is **theoretically understood and well constrained** by experimental information from

- electron scattering, neutron $\beta$ decay, and
- $\nu$ experiments on Hydrogen/Deuterium.



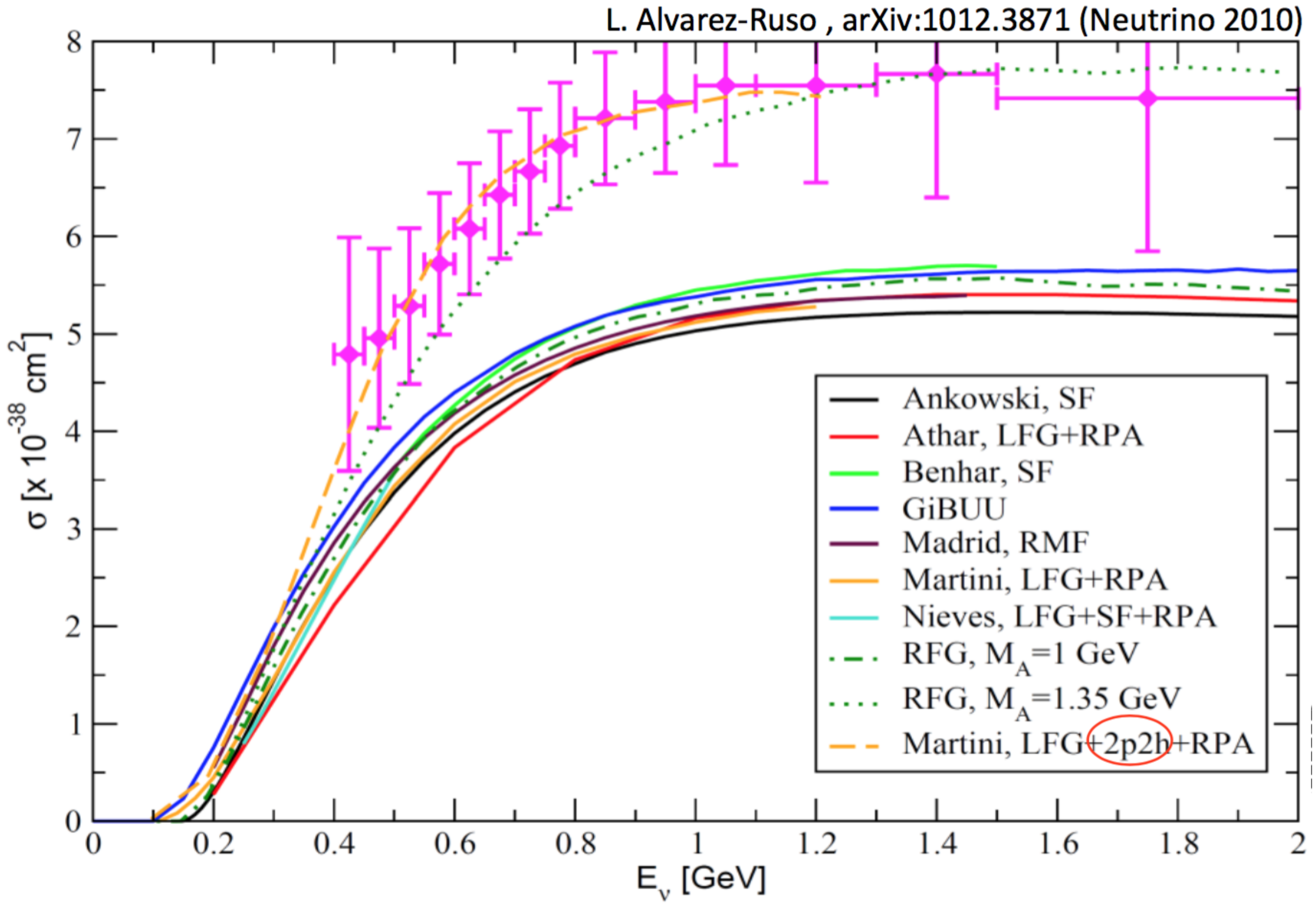




[Eur.Phys.J. C63 (2009) 355-381]

# The QE puzzle

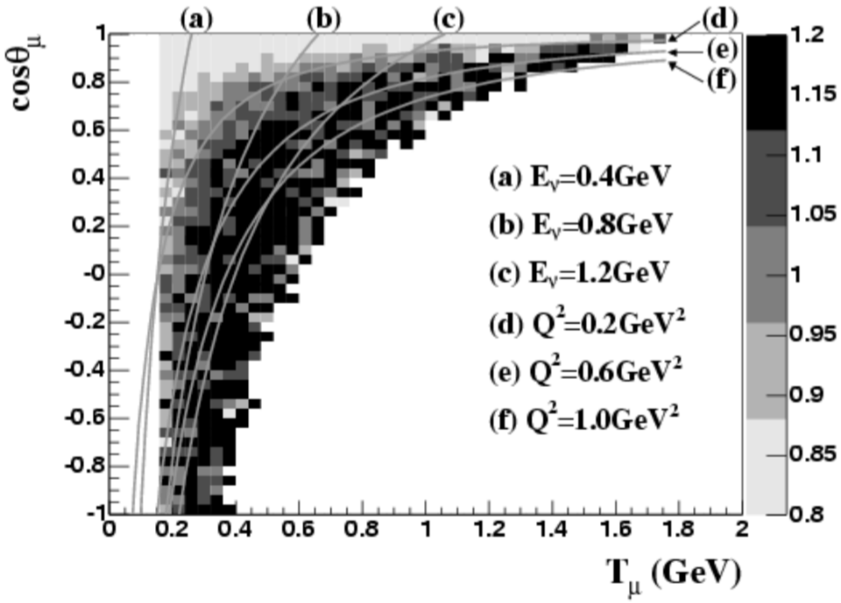
**Unable to describe nuclear QE-like data** with models based on interactions on single nucleons (The QE puzzle).

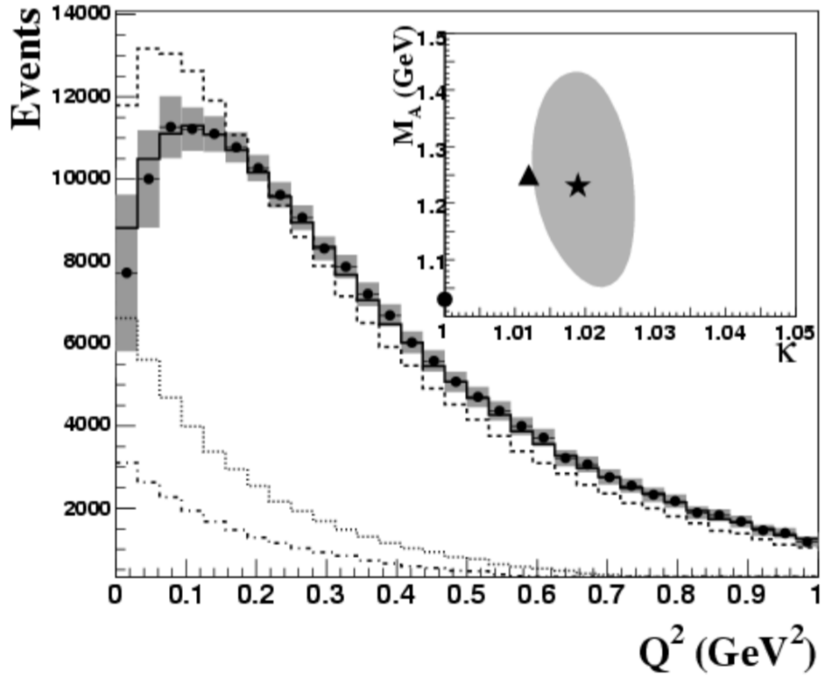


# The QE puzzle: The $M_A = 1.3$ GeV saga

Hints that discrepancy was related to cross-section modelling.
Start tweaking axial form factors and Pauli blocking.

$$F_A(Q^2) = g_A(1 + \frac{Q^2}{M_A^2})^{-2}$$




[T.Katori, PhD thesis]

# The QE puzzle: The $M_A = 1.3$ GeV saga

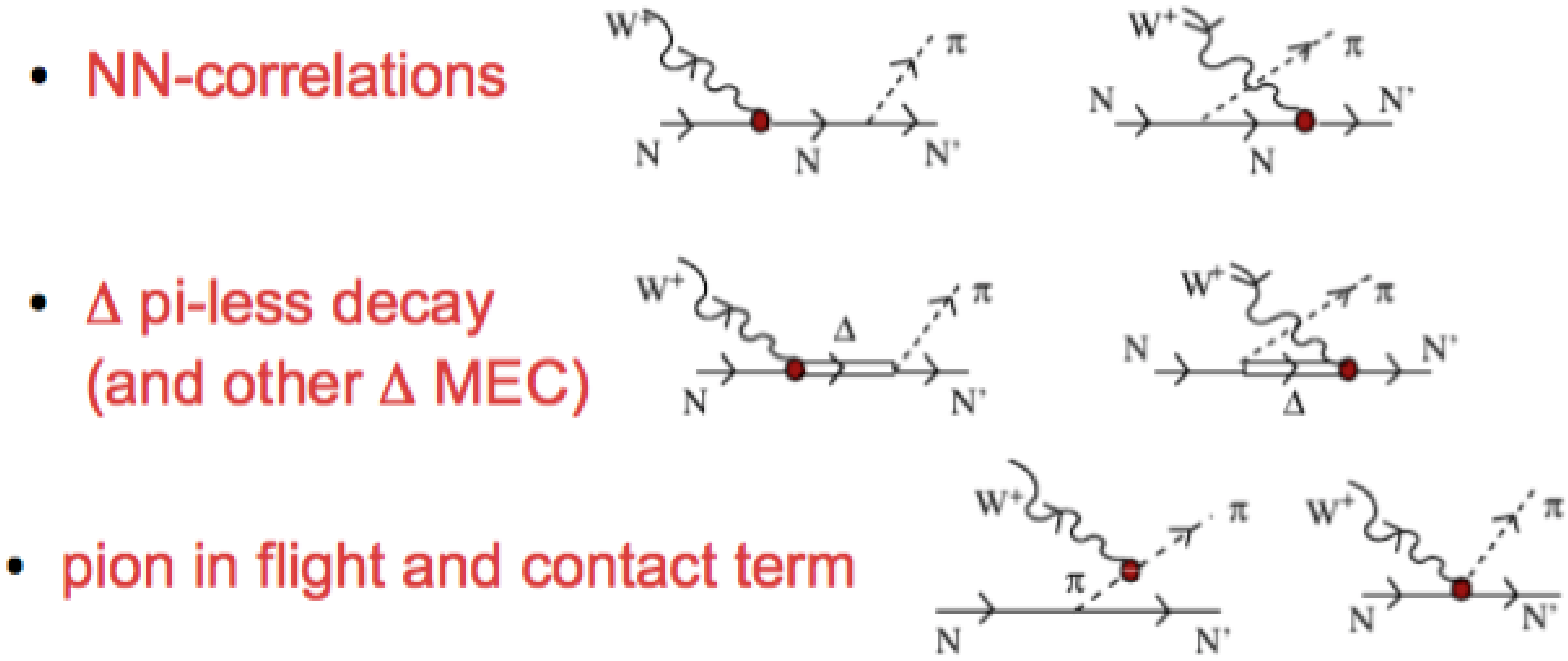

The issue of $M_A$ was discussed as fervently the gender of the angels by medieval theologists...

- $M_A$ an effective parameter?
- Accounting for mismodelled nuclear dynamics?
- Attempts to include more sophisticated initial state dynamics resulted in even larger $M_A$ [Nucl.Phys.Proc.Sup. 229-232 (2012) 174-178]
- A new paradigm?

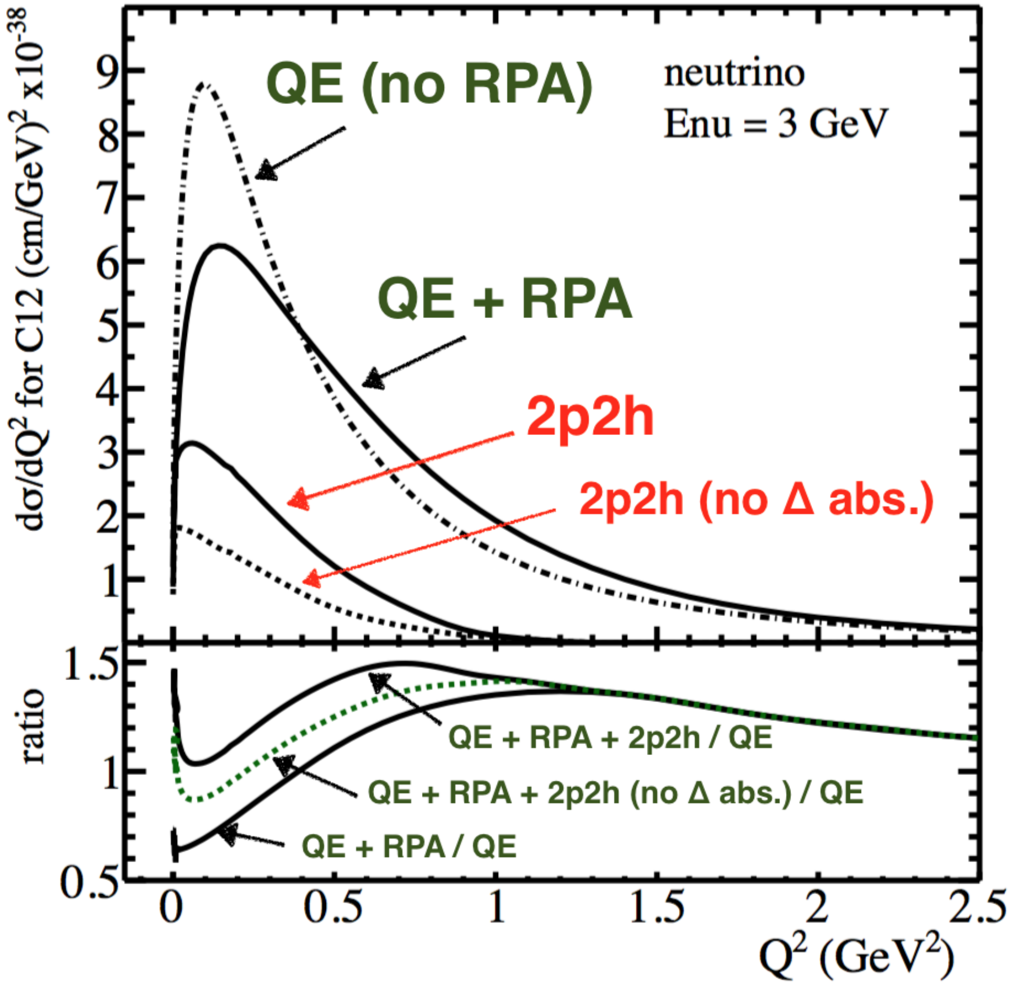
# The QE puzzle: Importance of 2p2h and RPA

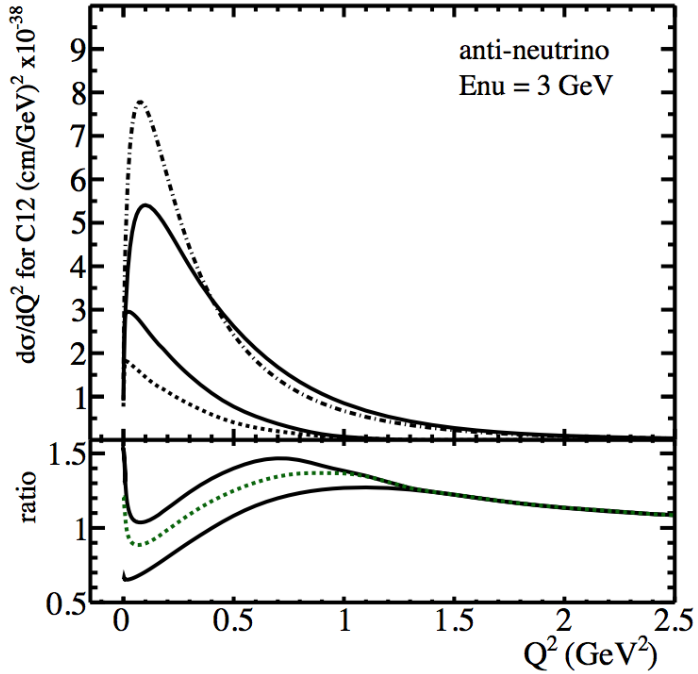
The observed dicrepancy revealed the importance of two-nucleon interactions and long-range correlations (weak screening effect approximated using RPA).

This was further stressed by ab-initio calculations of nuclear response functions.



# The QE puzzle: Importance of 2p2h and RPA

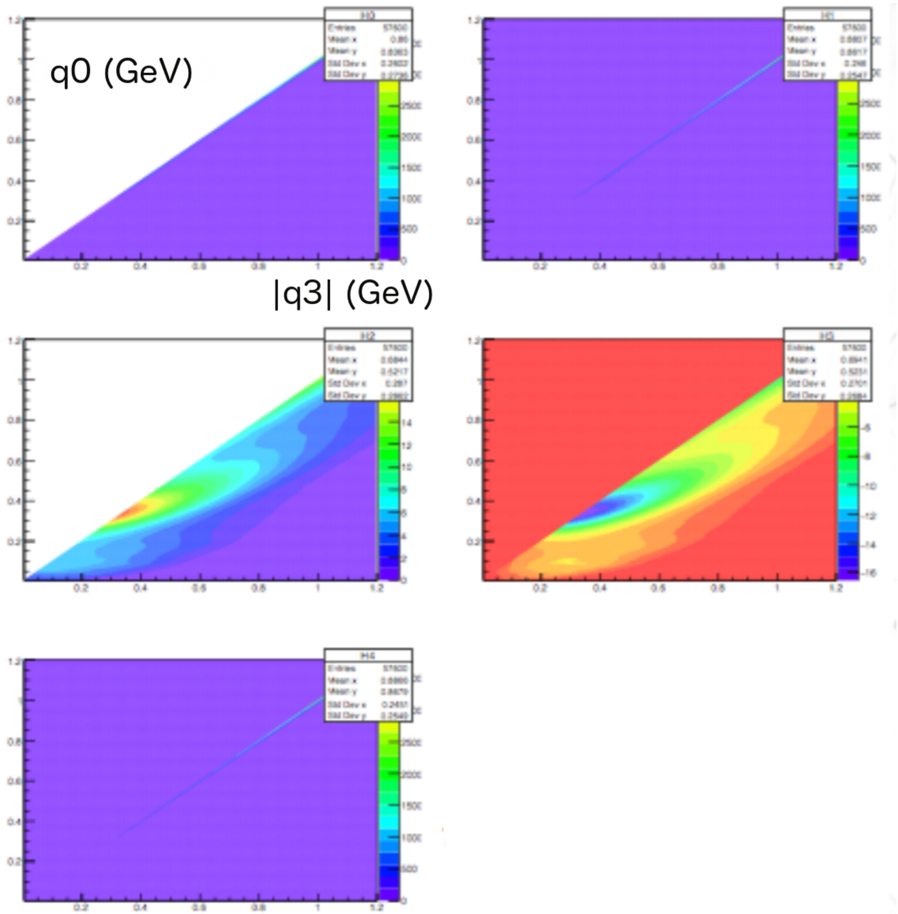



[Phys.Rev. D88 (2013) no.11, 113007]

# 2p2h and RPA: MC implementations

- Complex and slow codes prepared by nuclear theory groups
- How to best integrate in MC codes?



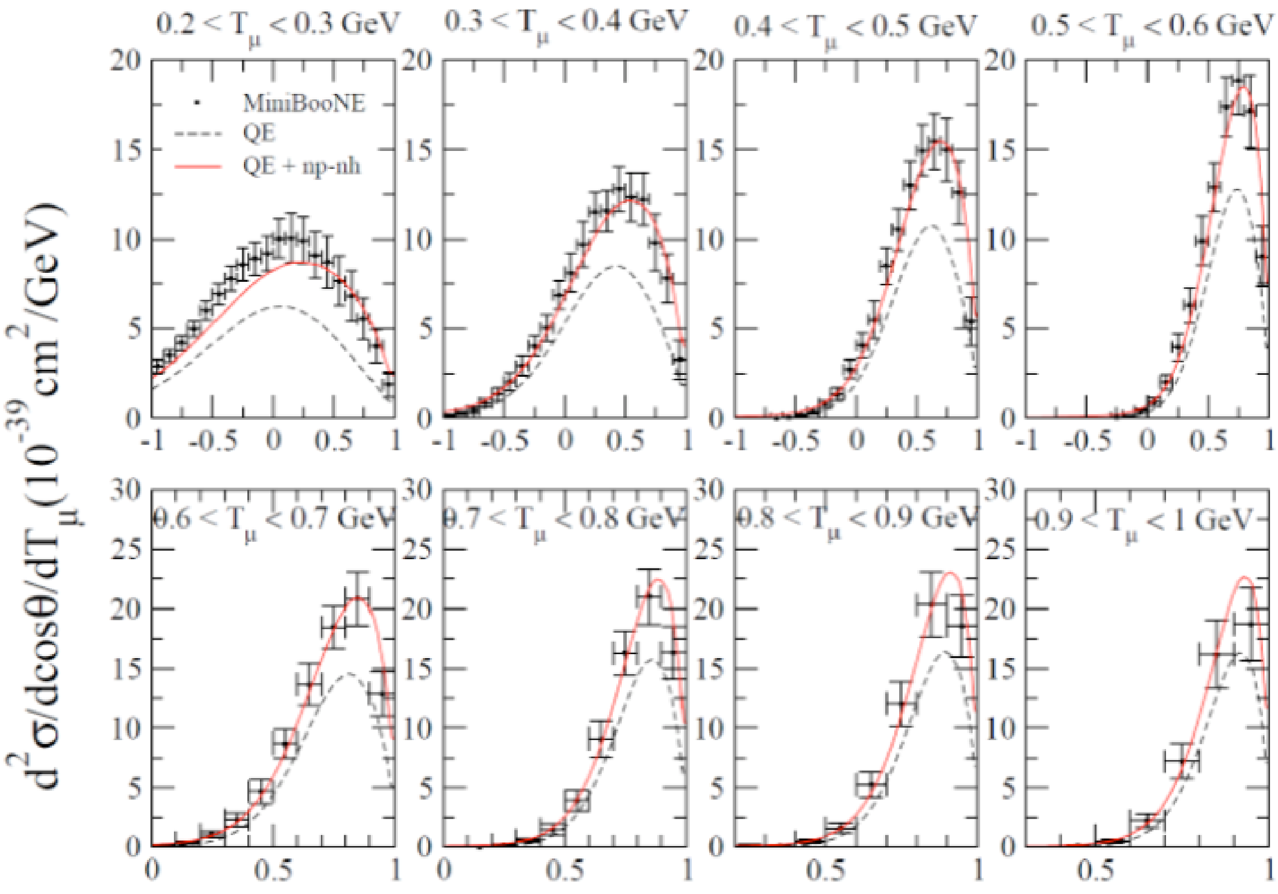

[F.Sanchez, R.Gran]

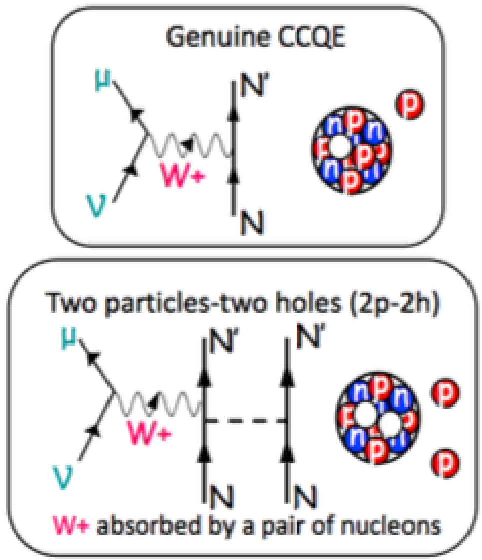
$$\frac{d^2\sigma}{d\Omega dE'} = \frac{|\vec{k}'|}{|\vec{k}|}\frac{G^2}{4\pi^2}L_{\mu\sigma}W^{\mu\sigma}$$

- Community opted for very basicbut realistic solution of tabulating calculations of the nuclear theory groups (hadronic tensor as functio of $q_0$, —$\vec{q}_3$—)
- Only inclusive cross-section
- Simple model for generating the hadronic system

# The QE puzzle: Improved data/MC agreement

The observed dicrepancy revealed the importance of two-nucleon interactions.
This was further stressed by ab-initio calculations of nuclear response functions.



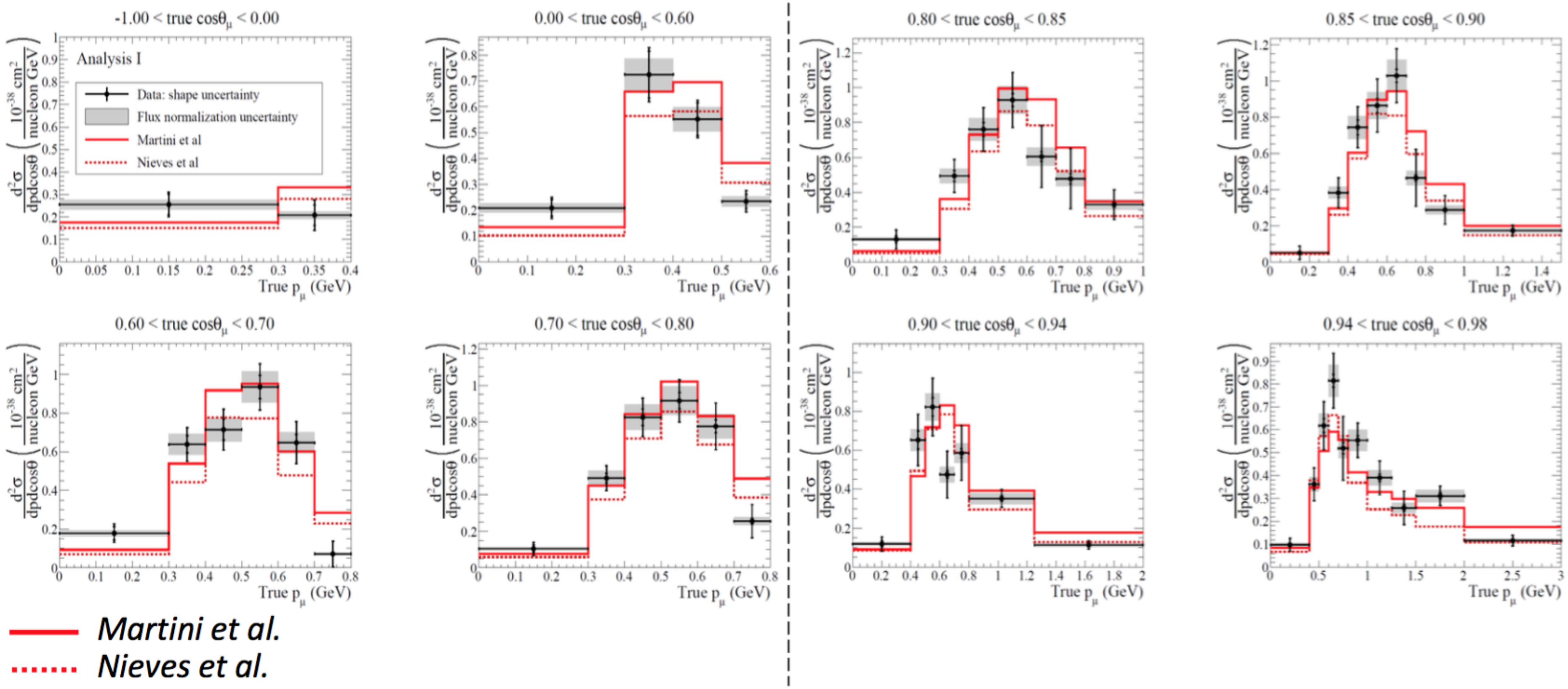

Meson exchange between two bound nucleons

(e.g through virtual Δ or contact term).

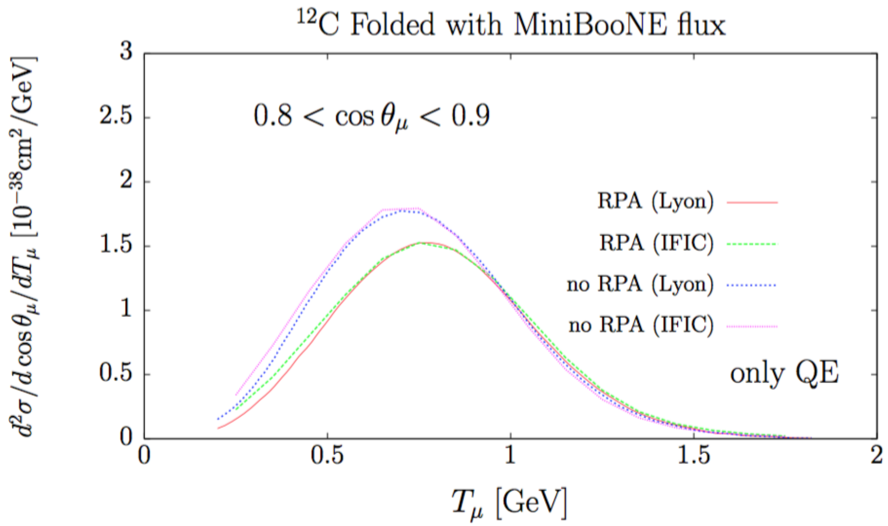
[Martini et al. PRC 84 055502 (2011)]; MiniBooNE data shown

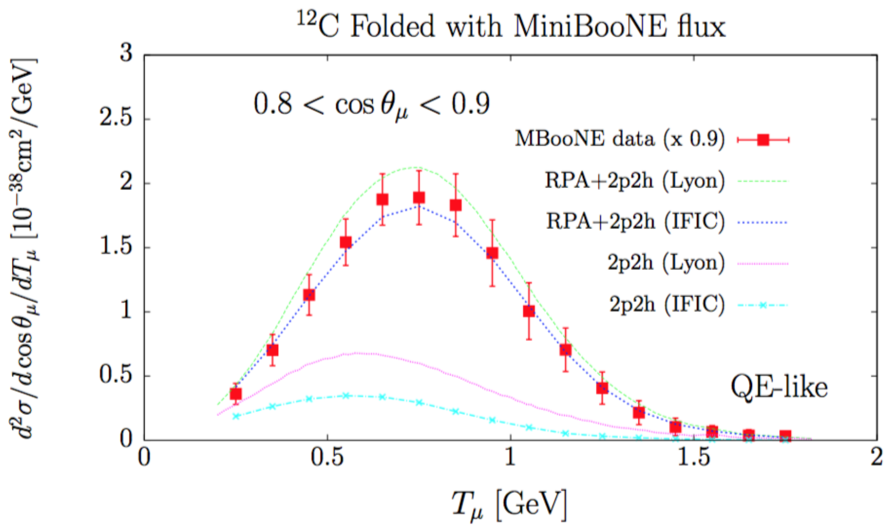
Recent CC0$\pi$ measurements from T2K in agreement with theoretical models including 2p2h.

*T2K collaboration: Abe et al. Phys. Rev. D 93 11012 (2016)*



# The QE puzzle: Two-nucleon interactions




[Nucl.Part.Phys.Proc. 273-275 (2016)]

Several new models: Common physics but some important differences!

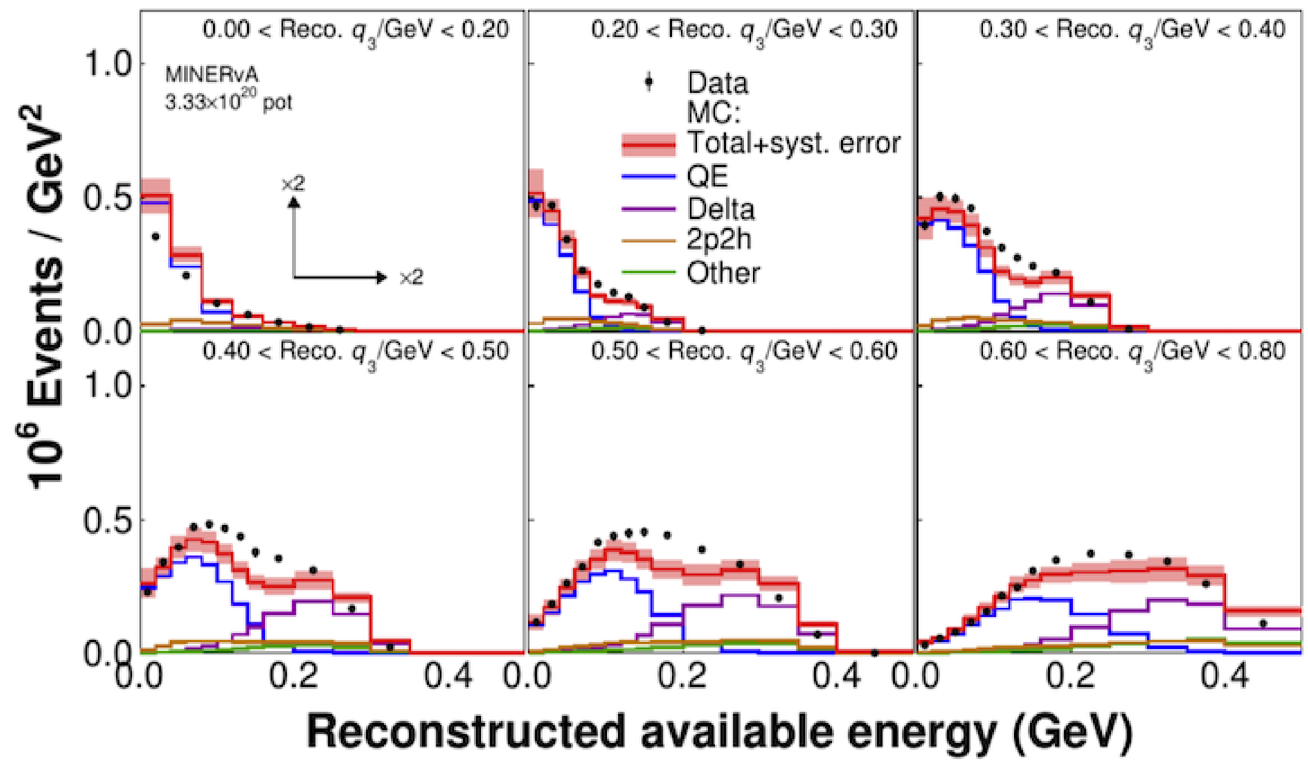
*Martini et al.* *Nieves et al.* *Amaro et al.* *Lovato et al.* *Bodek et al.*

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

[M.Martini, FUNFACT JLab workshop]

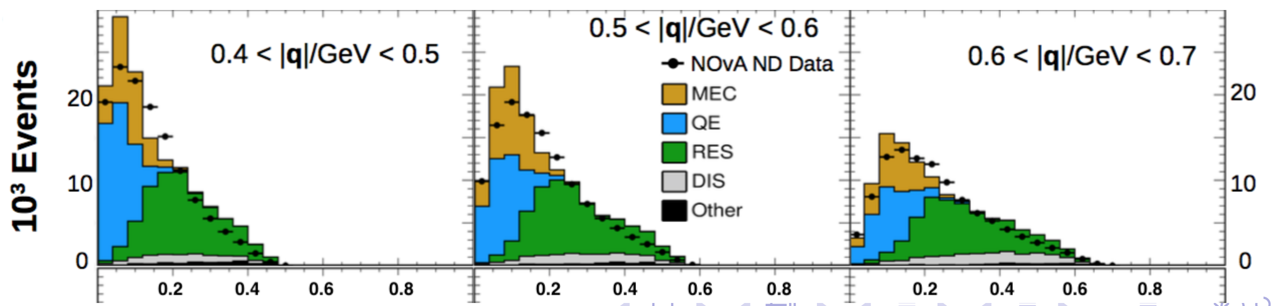
# The QE puzzle: Towards a resolution

[Phys.Rev. D94 (2016) no.11, 112007]



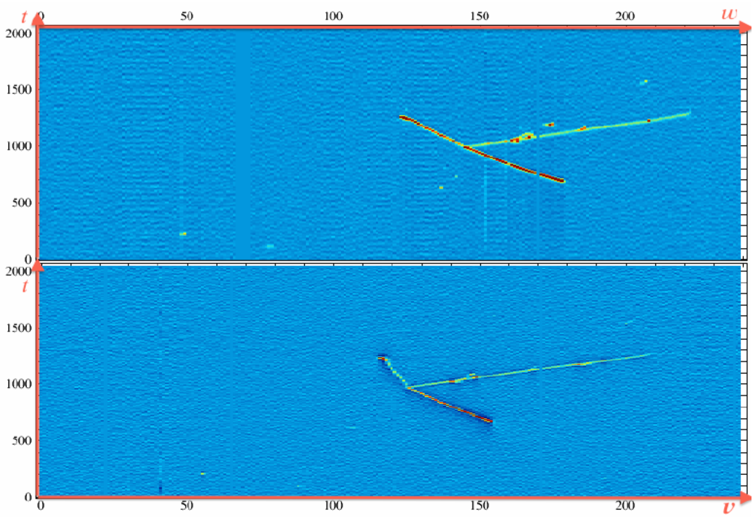

MINERvA **Inclusive $\nu_\mu$ CC data in $(q_0, |\vec{q_3}|)$:**. Exploiting the different kinematical dependency of each component to disentangle 2p2h.

Similar approach by NOvA.
[Phys.Rev. D93 (2016) no.7, 071101]



# The QE puzzle: Towards a resolution

- Characteristic events with 2 back-to-back f/s nucleons seen in ArgoNEUT.
  - low statistics, but very low proton KE threshold (20 MeV)
- Future CC0$\pi$ data from LArTPCs (SBND) further subdivided based on nucleon observables crucial for disentangling FSI and 2p2h effects.



[Phys.Rev. D90 (2014) 1, 012008]

$\nu_\mu$ CC, BNB/FHC, $6.6\times10^{20}$ POT, 112 tonnes active mass

| | GENIE Model Configurations | |
|---|---|---|
| **Hadronic Final State** | **G17_01b** | **G17_02a** |
| Inclusive | 5,389,168 | 5,329,241 |
| 0 $\pi$ | 3,814,198 | 3,744,108 |
| 0 $\pi$ + 0p | 27,269 | 34,696 |
| 0 $\pi$ + 1p (> 20 MeV) | 1,629,252 | 2,235,338 |
| 0 $\pi$ + 2p (> 20 MeV) | 1,150,368 | 637,535 |
| 0 $\pi$ + 3p (> 20 MeV) | 413,956 | 229,239 |
| 0 $\pi$ + >3p (> 20 MeV) | 396,212 | 263,727 |

SBND expected CC 0$\pi$ statistics

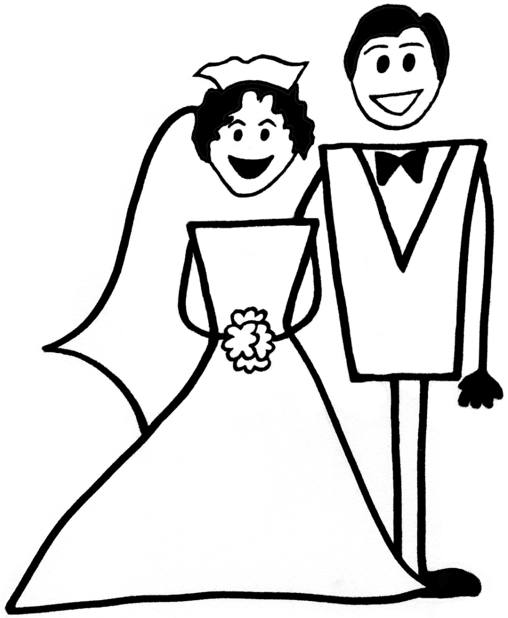
# QE: Particle Physics meets Nuclear Physics

First encounter was a bit rough...

[analogy by Dave Schmitz, NuFact2013]

# QE: Particle Physics meets Nuclear Physics

But a (happy ?) marriage at the end!



In the last decade, moved well beyond effective models ($M_A$ saga) and towards an improved understanding of microscopic physics.

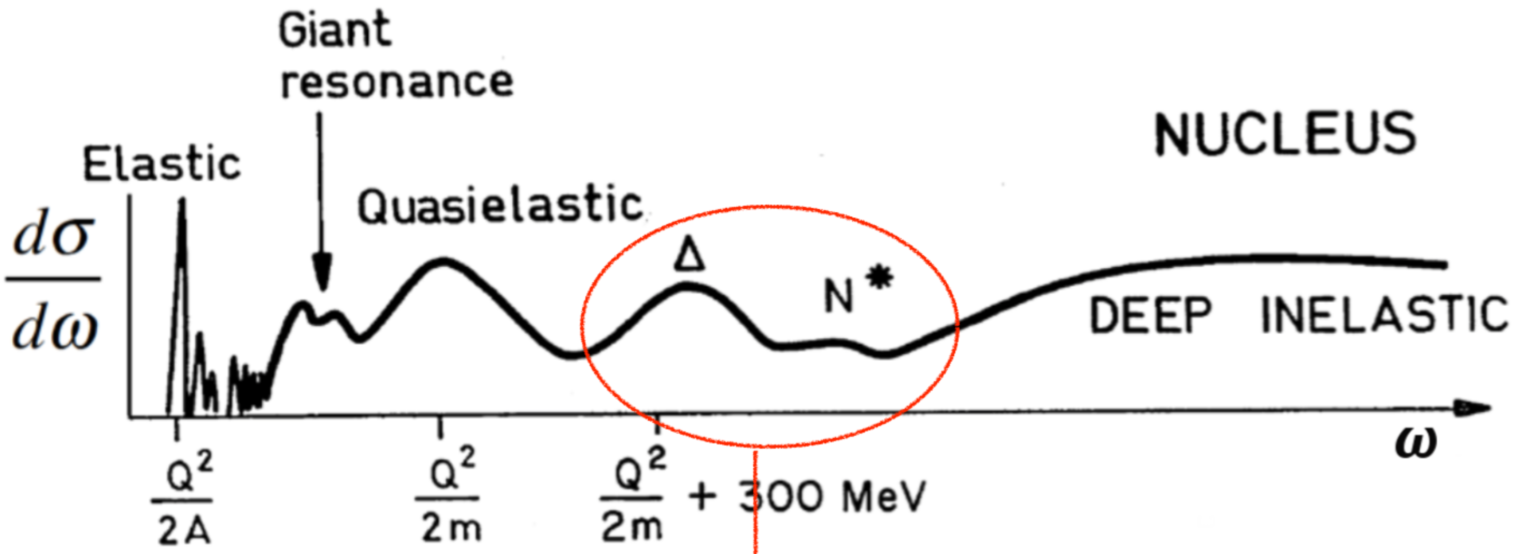
- Long range correlations.
- Two nucleon interactions.

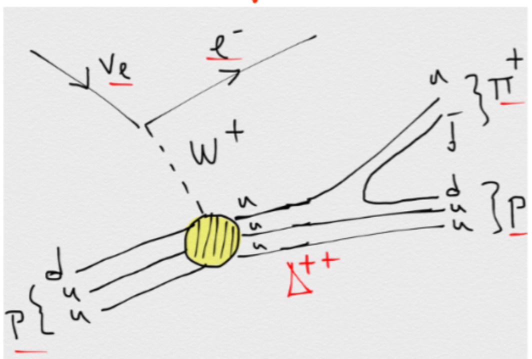
Some improved MC implementations by tabulating outputs of advanced nuclear physics calculations.

- Easy solution, but leaves a lot to be desired.
- Should aim towards more direct code interfaces.

- Near future LArTPC measurements / new hadronic observables crucial for model testing / validation and for improving the microphysics.
- Close to resolving the QE puzzle and having adequate descriptions of neutrino-nucleus scattering around the QE peak.

# Resonance neutrino-production

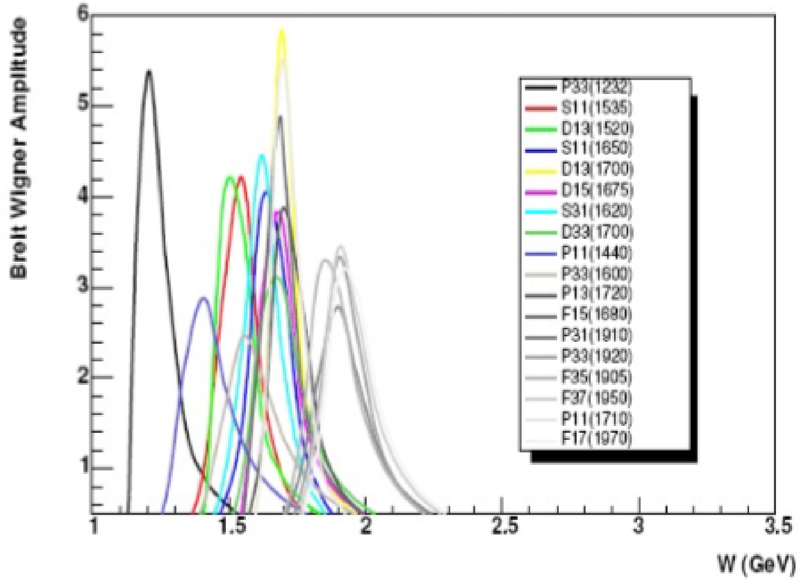


# Resonance neutrino-production

Several resonances from inelastic threshold up to W $\approx$ 2 GeV

| *Resonance Mass (MeV)* | *L(2I,2J)* | *PDG status* | *Breit − Wigner Width (MeV)* | *FKR n* | *BR $N^* \to N\pi$* |
|---|---|---|---|---|---|
| $\Delta(1232)$ | $P_{33}$ | **** | 120 | 0 | 100% |
| N(1535) | $S_{11}$ | **** | 150 | 2 | 45% |
| N(1520) | $D_{13}$ | **** | 120 | 1 | 55% |
| N(1650) | $S_{11}$ | **** | 150 | 1 | 73% |
| N(1700) | $D_{13}$ | *** | 100 | 1 | 10% |
| N(1675) | $D_{15}$ | **** | 150 | 1 | 45% |
| $\Delta(1700)$ | $D_{33}$ | **** | 300 | 1 | 15% |
| N(1440) | $P_{11}$ | **** | 350 | 1 | 65% |
| $\Delta(1600)$ | $P_{33}$ | *** | 350 | 2 | 18% |
| N(1720) | $P_{13}$ | **** | 150 | 2 | 15% |
| N(1680) | $P_{15}$ | **** | 130 | 1 | 65% |
| $\Delta(1910)$ | $P_{31}$ | **** | 250 | 2 | 23% |
| $\Delta(1920)$ | $P_{33}$ | *** | 200 | 2 | 13% |
| $\Delta(1905)$ | $F_{35}$ | **** | 350 | 2 | 10% |
| $\Delta(1950)$ | F37 | **** | 300 | 2 | 10% |
| N(1710) | $P_{11}$ | *** | 100 | 2 | 38% |

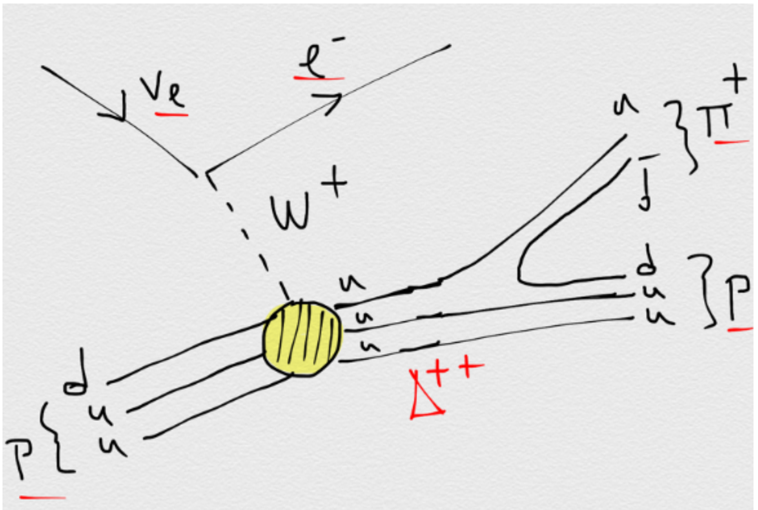


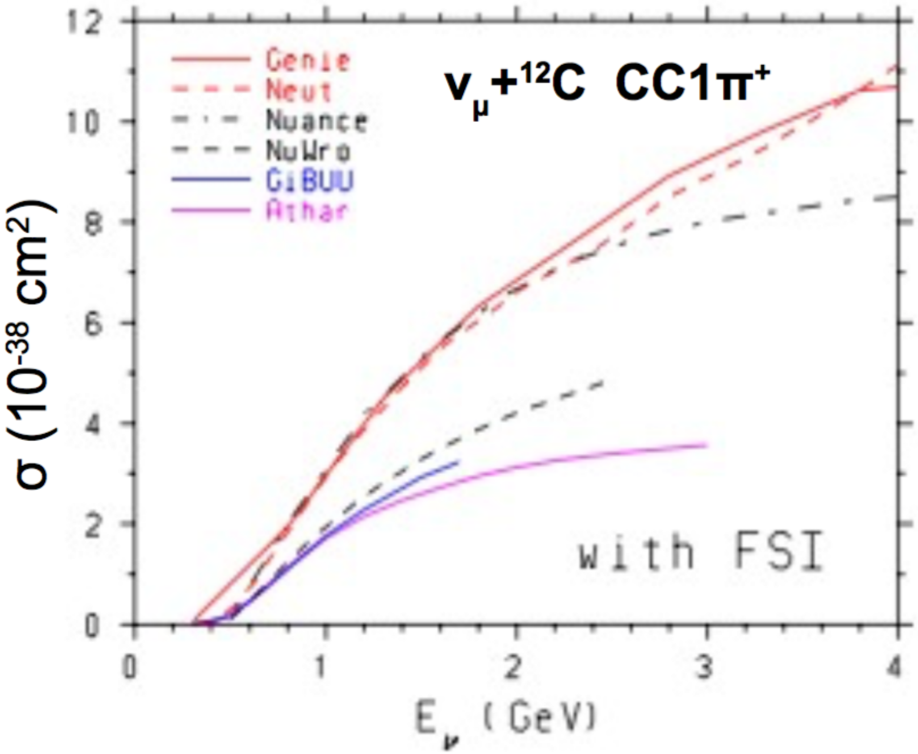

Resonance production is the dominant contribution to single-pion channels.

# Single-$\pi$ production

Important process for oscillation physics (both as a signal and background).

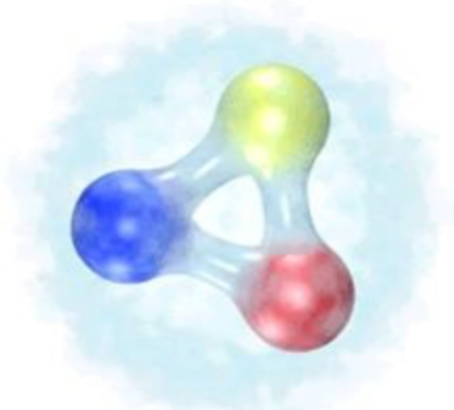
- In DUNE, resonance events contribute ~30% to the CC inclusive rate.
- In T2K(/HK), CC 1-pion events where the pion is absorbed in the nucleus (or not detected) can be classified as single-ring (QE-enhanced) signal events
- NC1$\pi^0$ an important background for $\nu_e/\bar{\nu}_e$ appearance



# Resonance neutrino-production modeling

The most widely used model for resonance neutrinoproduction
(*D.Rein, L.M Sehgal*, **Ann.Phys.133, 79 (1981)**)
uses the FKR dynamical model
(*R.P.Feynman, M.Kislinger, F.Ravndall*, **Phys.Rev.D 3, 2706 (1971)**)
to describe excited states of a 3 quark bound system.



**kinematical factors**

$$\frac{d^2\sigma}{dW\,dq^2} \propto u^2\sigma_L(q^2,W) + v^2\sigma_R(q^2,W) + 2uv\sigma_S(q^2,W)$$

**Helicity Cross Sections *(L,R,S)***
*They depend on the details of the FKR model*

**Axial & Vector**
**transition form factors:**
*assuming dipole form $Q^2$ dependence*

$$G^{V,A}(Q^2) = \left(1+\frac{Q^2}{4M^2}\right)^{1/2-n}\left(1+\frac{Q^2}{M_{V,A}^2}\right)^{-2}$$

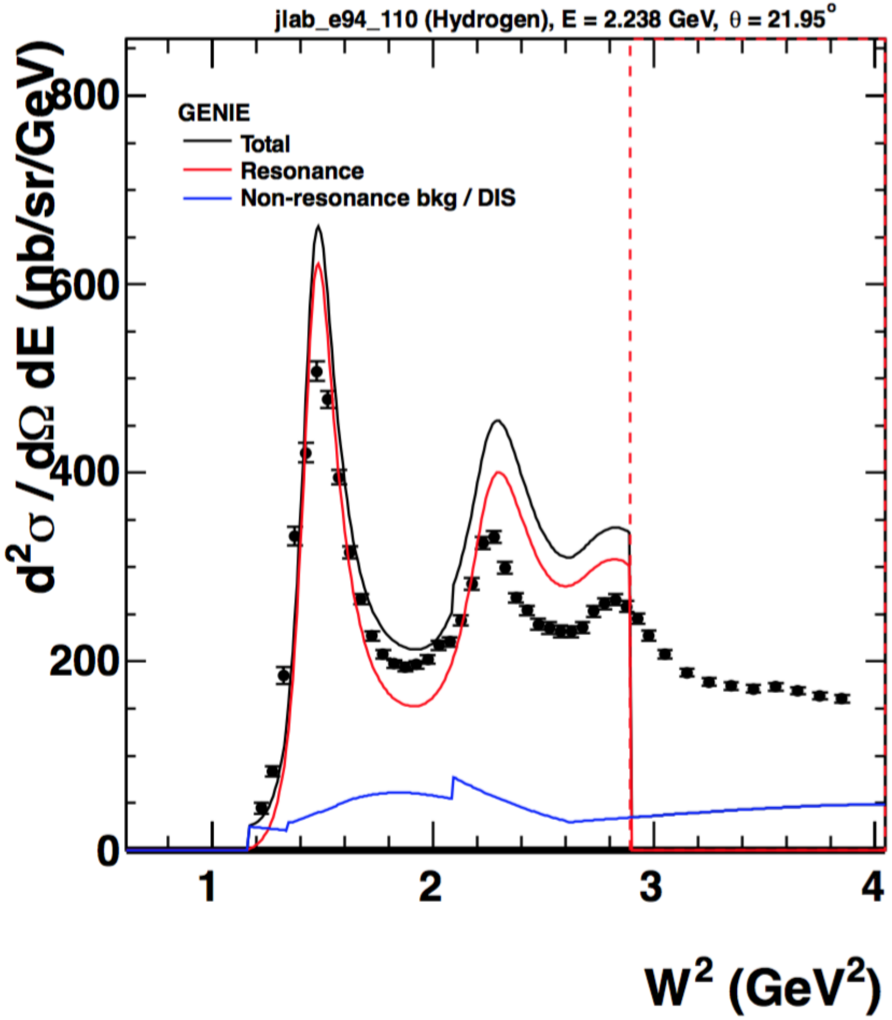
$M_V$=0.84 GeV/c^2, $M_A$

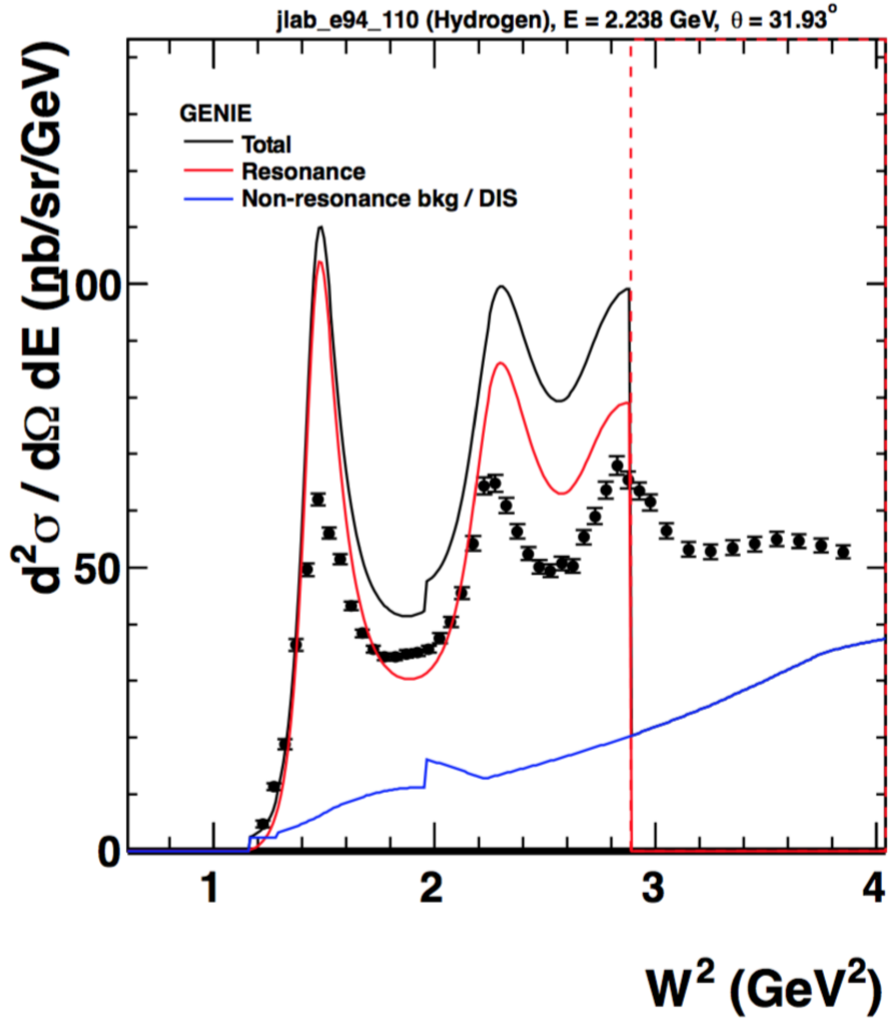
# Resonance neutrino-production modeling

- Model generally hated by theorists, but implemented in all MCs
- A workshorse - Covers a crucial area of our phase space
- Several incremental improvements over the years (update resonance data, include lepton mass terms in calculation, updated form factors)
- Several inmplementation difference (adding resonance coherently or not, angular distributions for angular decays)
- Intimately tied with approaches for simulating non-resonance backgrounds and transitioning from the resonance to DIS regions.

# Resonance neutrino-production modeling

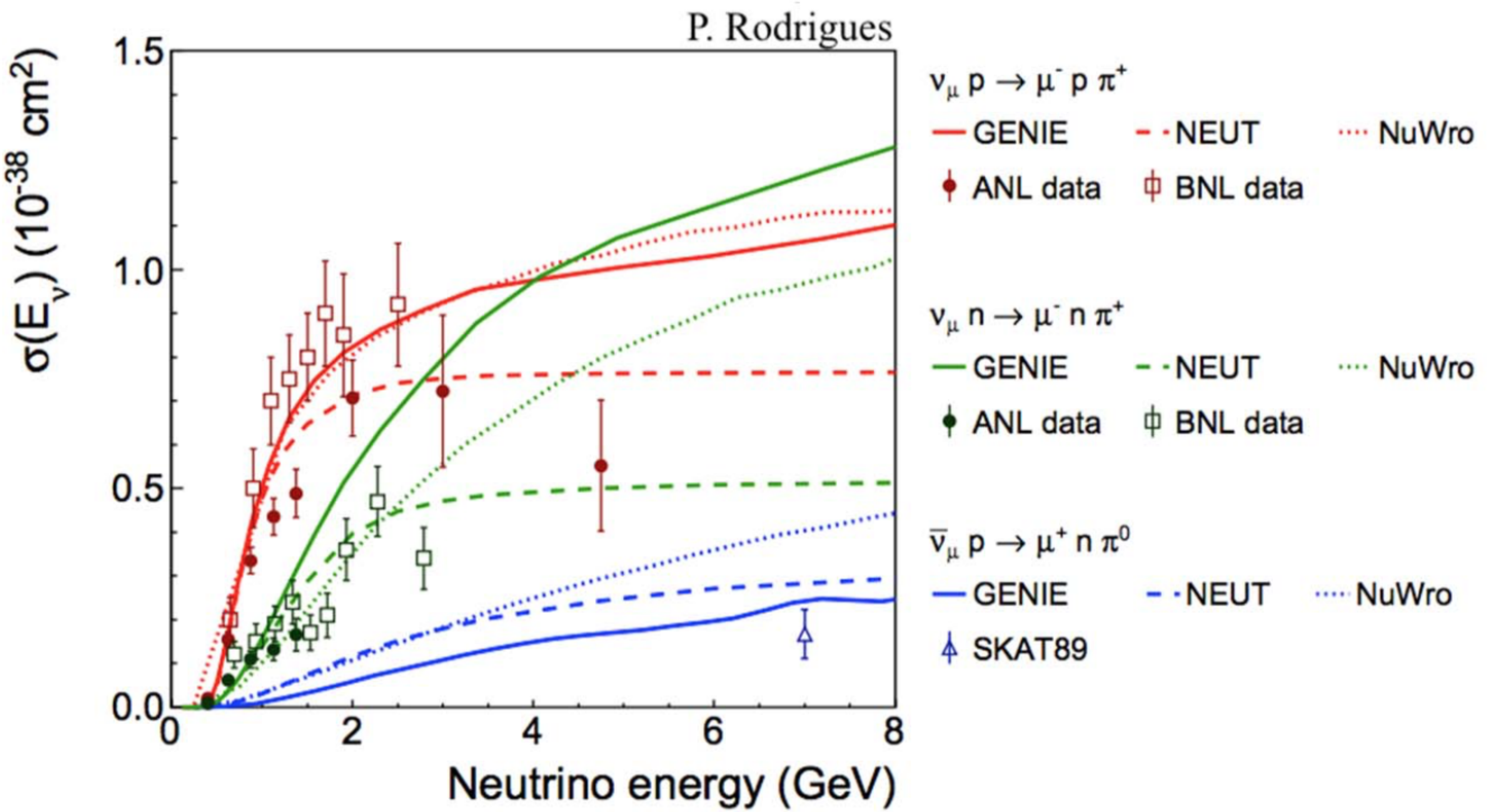
Relatively poor agreement with electron scattering data.



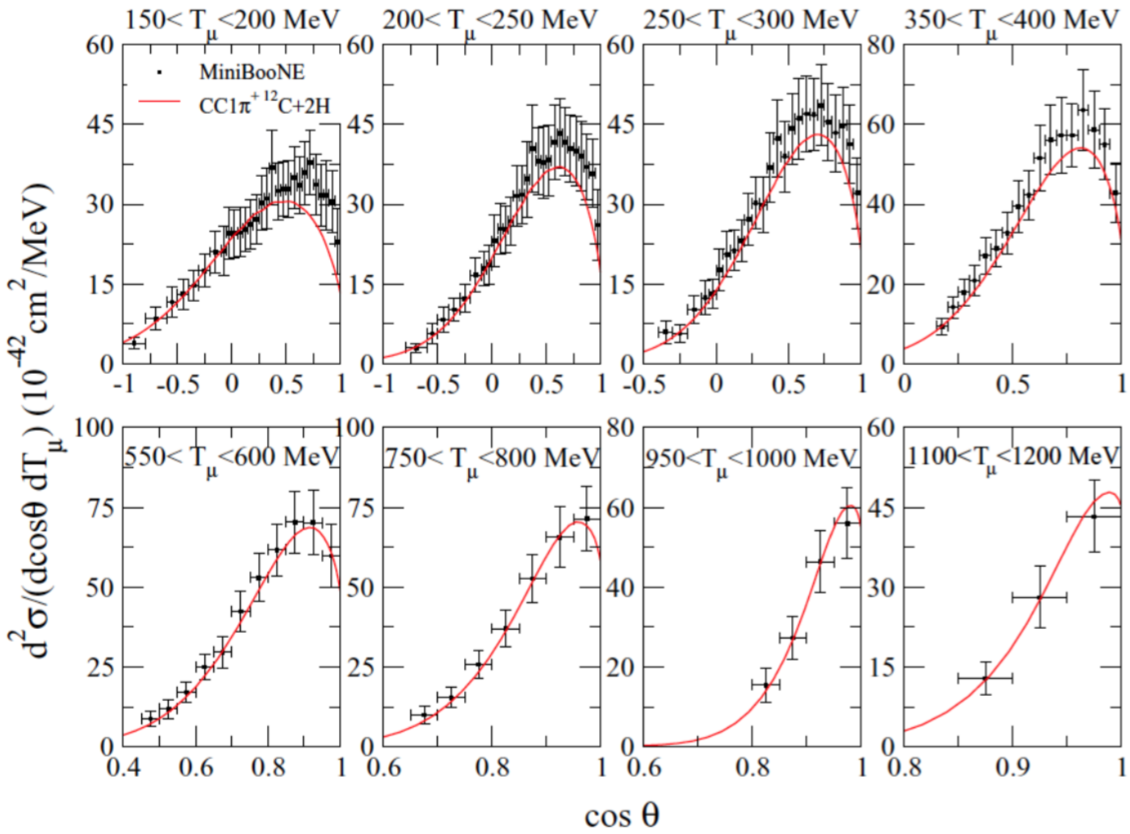



# Single-$\pi$ production: ANL/BNL difference

- Model differences due to discrepancy between historical data (ANL, BNL).
- BNL extracted higher cross-section than ANL at low energies.
- Recent re-analysis by Wilkinson et al. favours ANL.



First recent (flux integrated double-differential) $CC1\pi^{\pm}$ (predominantly $CC1\pi^{+}$) measurement was performed by MiniBooNE [Phys.Rev.D83, 052007 (2011)]



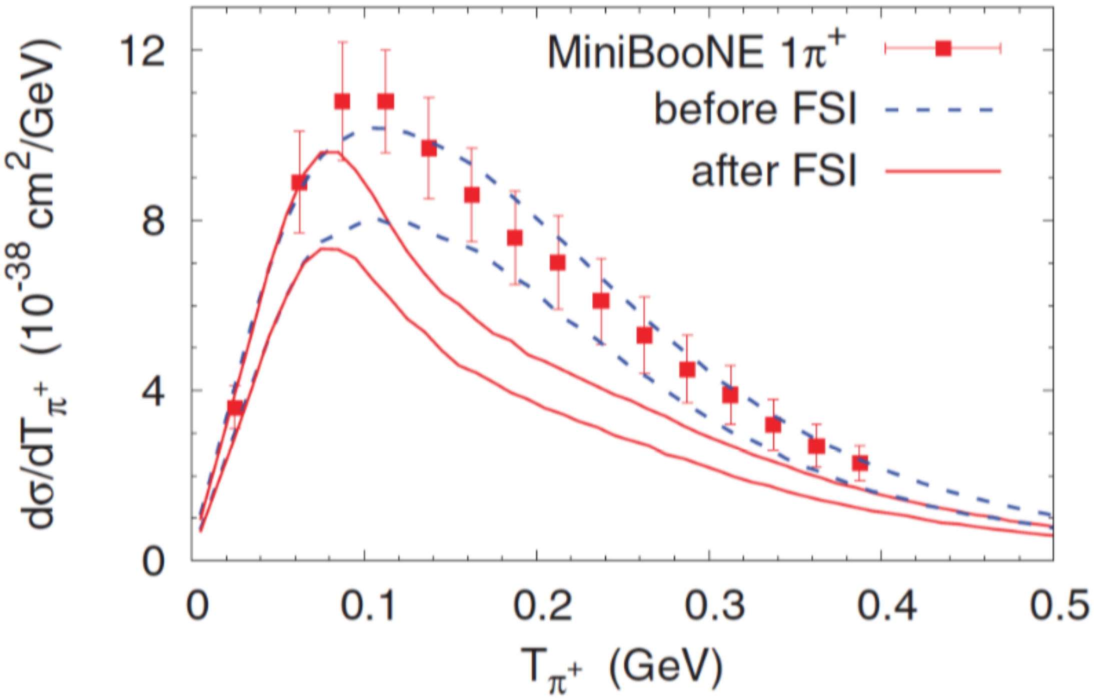

[Phys.Rev.C90,025501(2014)]

Differential cross-section in muon kinematics (muon kinetic energy $T_\mu$ and muon scattering angle $\theta_\mu$).

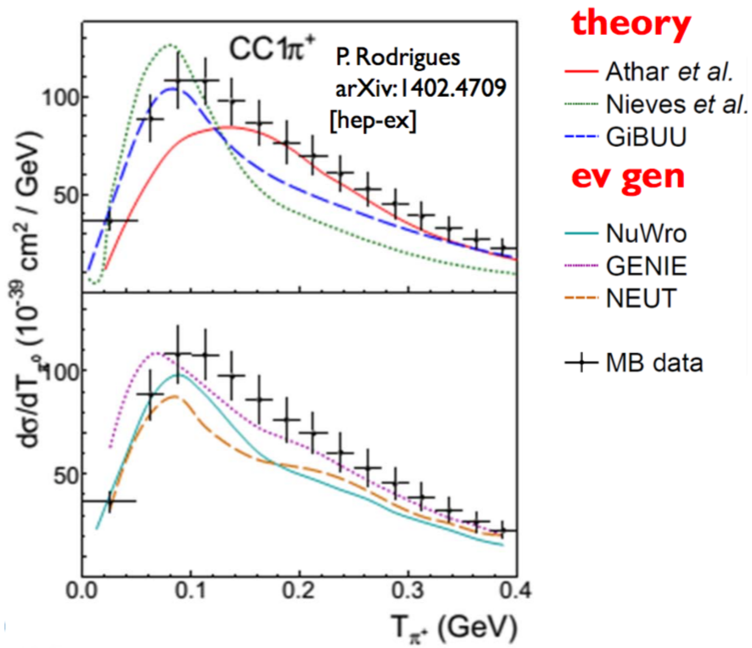
Reasonable agreement is obtained with several models.

# The single-$\pi$ puzzle

But MiniBooNE data in terms of pion kinematics very hard to understand within any model. In particular, the shape of MiniBooNE $T_\pi$ distribution seems to prefer the absence of FSI effects!

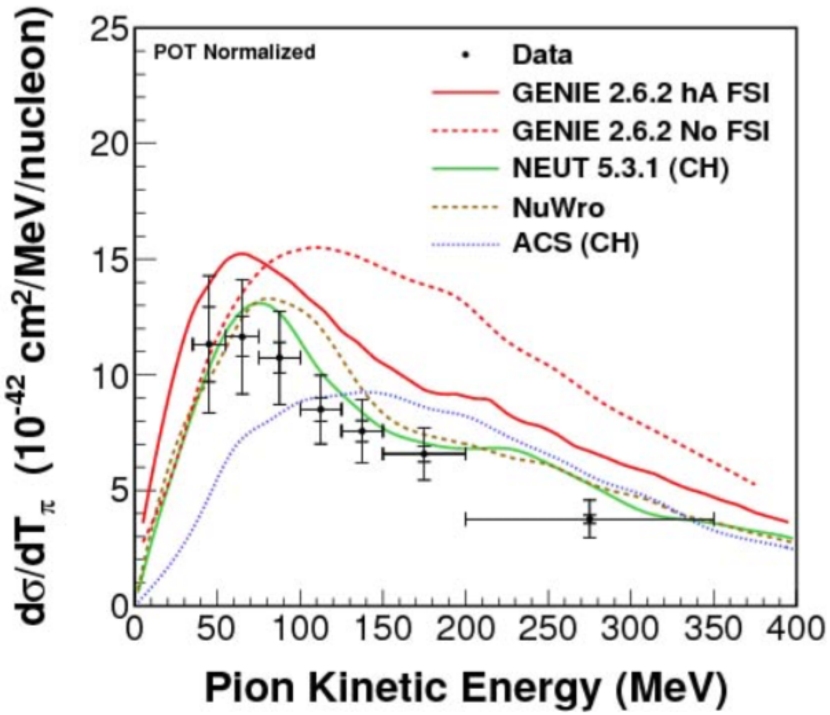



[Phys.Rev.C87, 014602 (2013)]



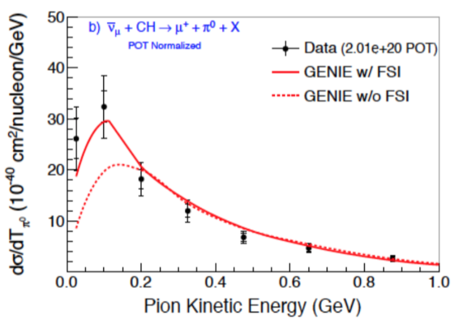

[arXiv:1402.4709 [hep-ex]]

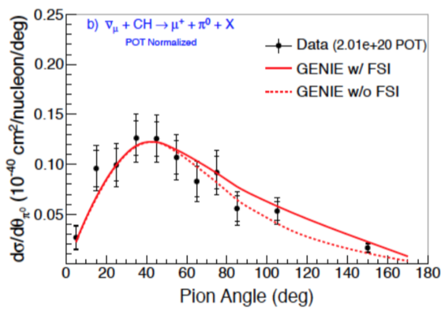
New neutrino CC1$\pi^+$ and anti-neutrino CC1$\pi^0$ measurements by MINERvA in CH, at higher energy than MiniBooNE.



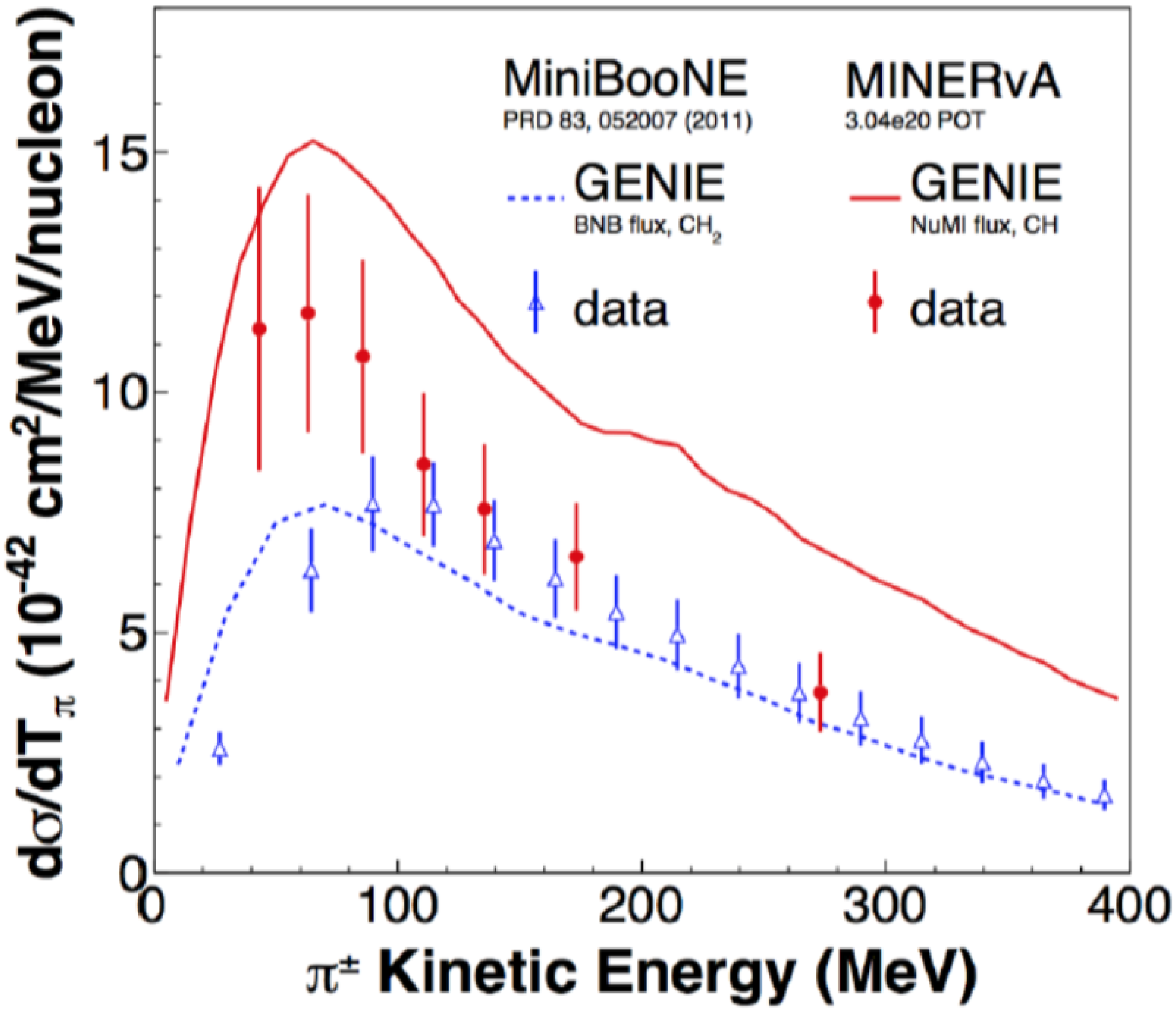

[Phys.Rev.D92, 092008 (2015)]

- Generator shape close to data
- As with MiniBooNE data, FSI stronly affects the prediction.
- Models with no FSI give wrong shape



# The single-$\pi$ puzzle




[Phys.Rev.D92, 092008 (2015)]

- Difficult to resolve the differences between MiniBooNE and MINERvA within our usual models.
- This tension between MiniBooNE and MINERvA data is not understood.

# 1$\pi$: Particle Physics meets Nuclear Physics

Again, first encounter was a bit rough...

[analogy by Dave Schmitz, NuFact2013]

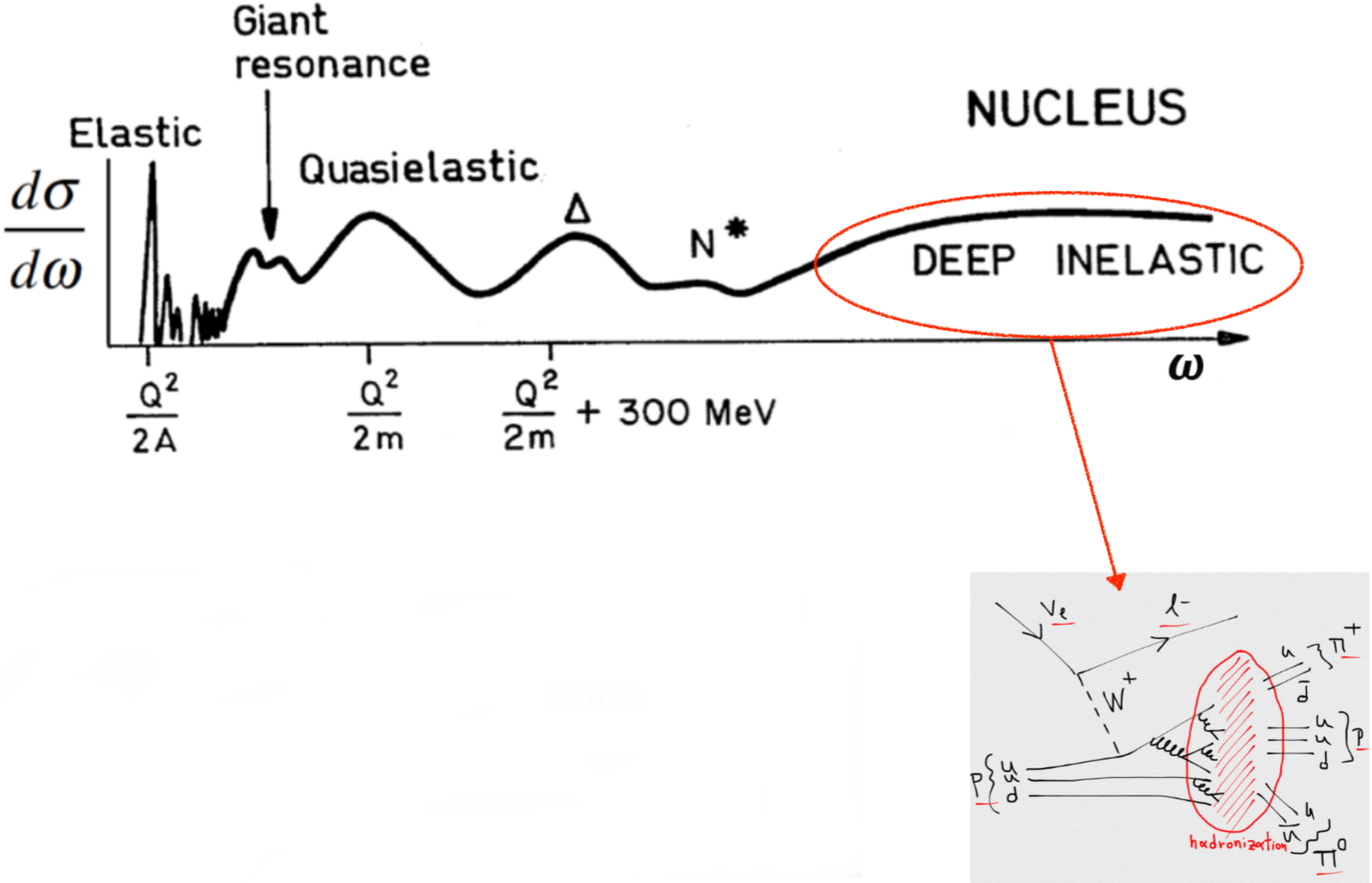
# $1\pi$: Particle Physics meets Nuclear Physics

But in this case not a happy marriage yet!

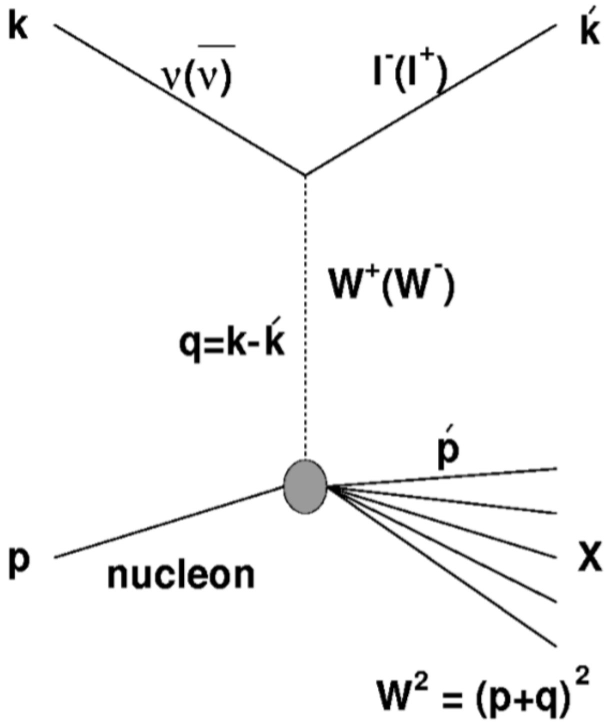
A quantitative understanding of single-pion production is still pending. Same microscopic physics used for CCQE modelling, should also affect $\Delta$ production (e.g. long-range correlations, two-body currents)?

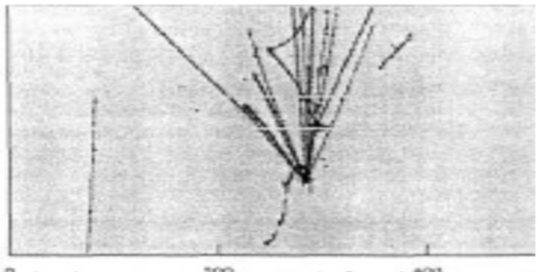
Not close to resolving the single-$\pi$ puzzle, but with new LArTPC data and theoretical frameworks used for CCQE this could well happen within the next decade!

# Shallow and Deep Inelastic Scattering



# Shallow and Deep Inelastic Scattering



*LAr images, courtesy A.Curríoni*

Differential cross section in terms of 5 structure functions:

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M_N E}{\pi(1+Q^2/M_W^2)^2} \sum_{i=1}^{5} A_i\,(x,y,E)\,F_i\,(x,Q^2)$$

where:

$$A_1 = y\left(xy + \frac{m_\mu^2}{2M_N E}\right),$$

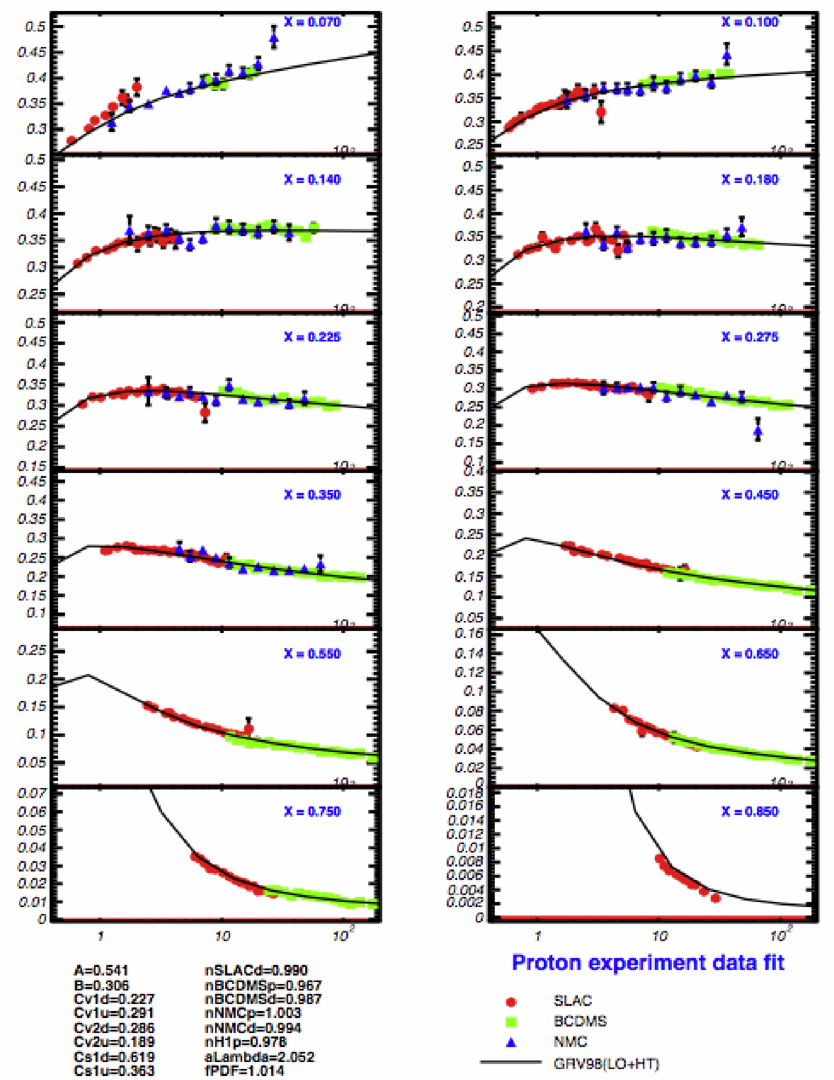
$$A_2 = 1 - \left(1 + \frac{M_N x}{2E}\right) y - \frac{m_\mu^2}{4E^2},$$

$$A_3 = \pm y\left[x\left(1 - \frac{y}{2}\right) - \frac{m_\mu^2}{4M_N E}\right],$$

$$A_4 = \frac{m_\mu^2}{2M_N E}\left(y + \frac{m_\mu^2}{2M_N E x}\right),$$

$$A_5 = -\frac{m_\mu^2}{M_N E}.$$

# Effective LO models for Monte Carlos




[AIP Conf.Proc. 792 (2005) 257-260]

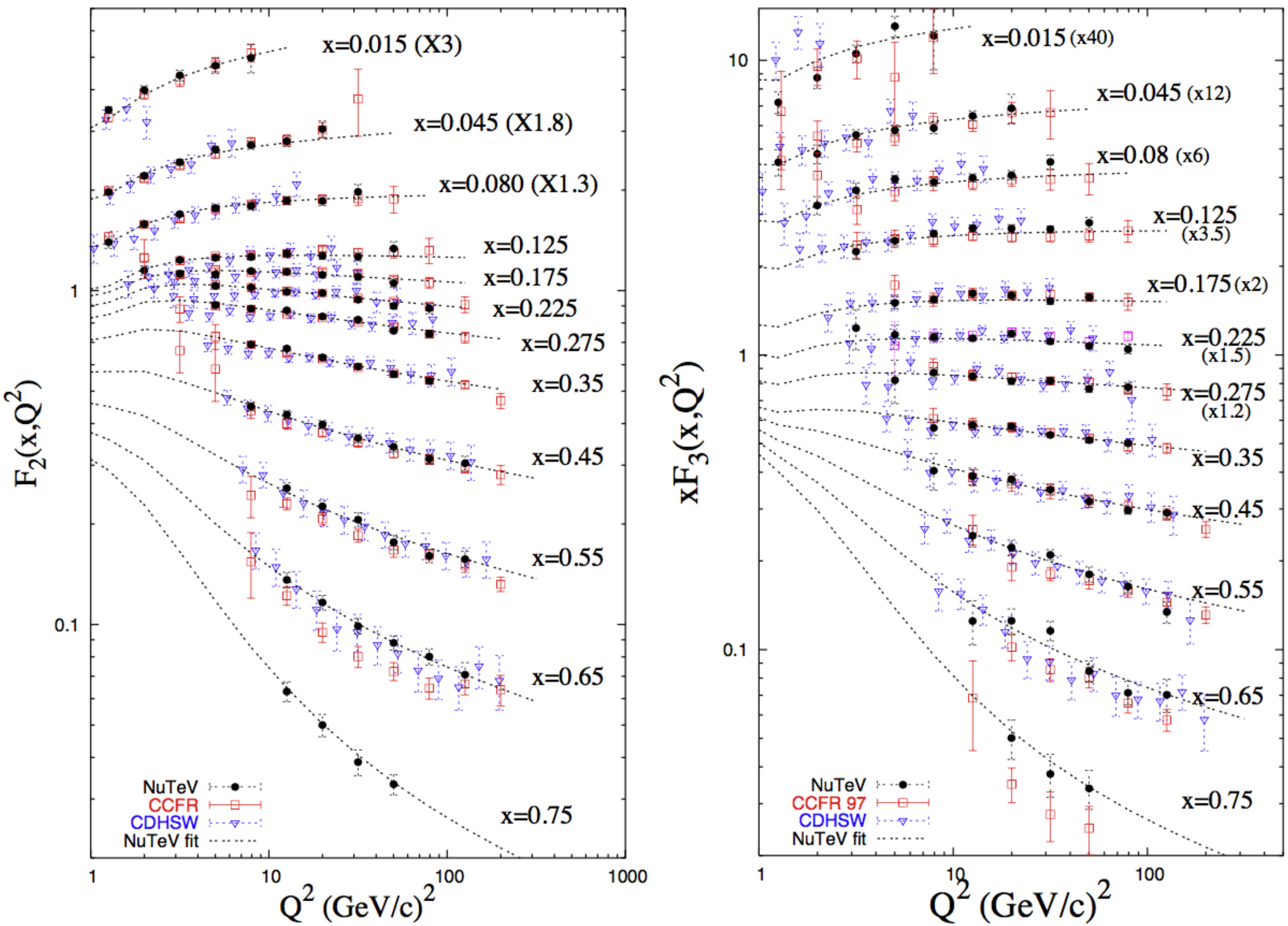
- LO PDFs (GRV98LO)
- New scaling variable

$$\xi_w = \frac{2x(Q^2 + M_f^2 + B)}{Q^2(1 + sqrt1 + (2Mx)^2/Q^2) + 2Ax}$$

  absorbs target mass, higher-twist and higher order corrections

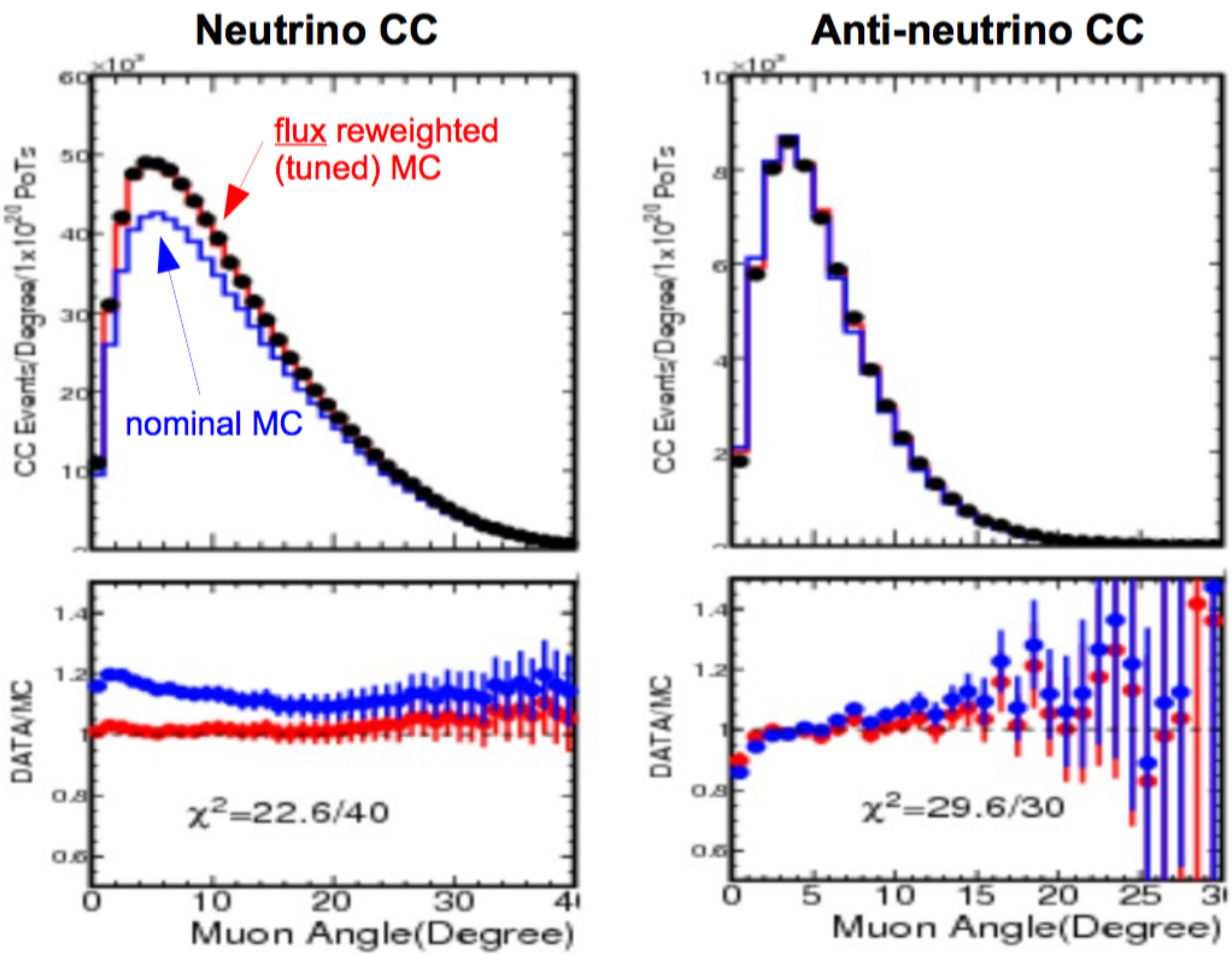
- Scaling factors for valence and sea PDFs
- Fit to charged lepton F2 data (SLAC / BCDMS / NMC / HERA) and photo-production data on hydrogen and deuterium.

# Structure functions



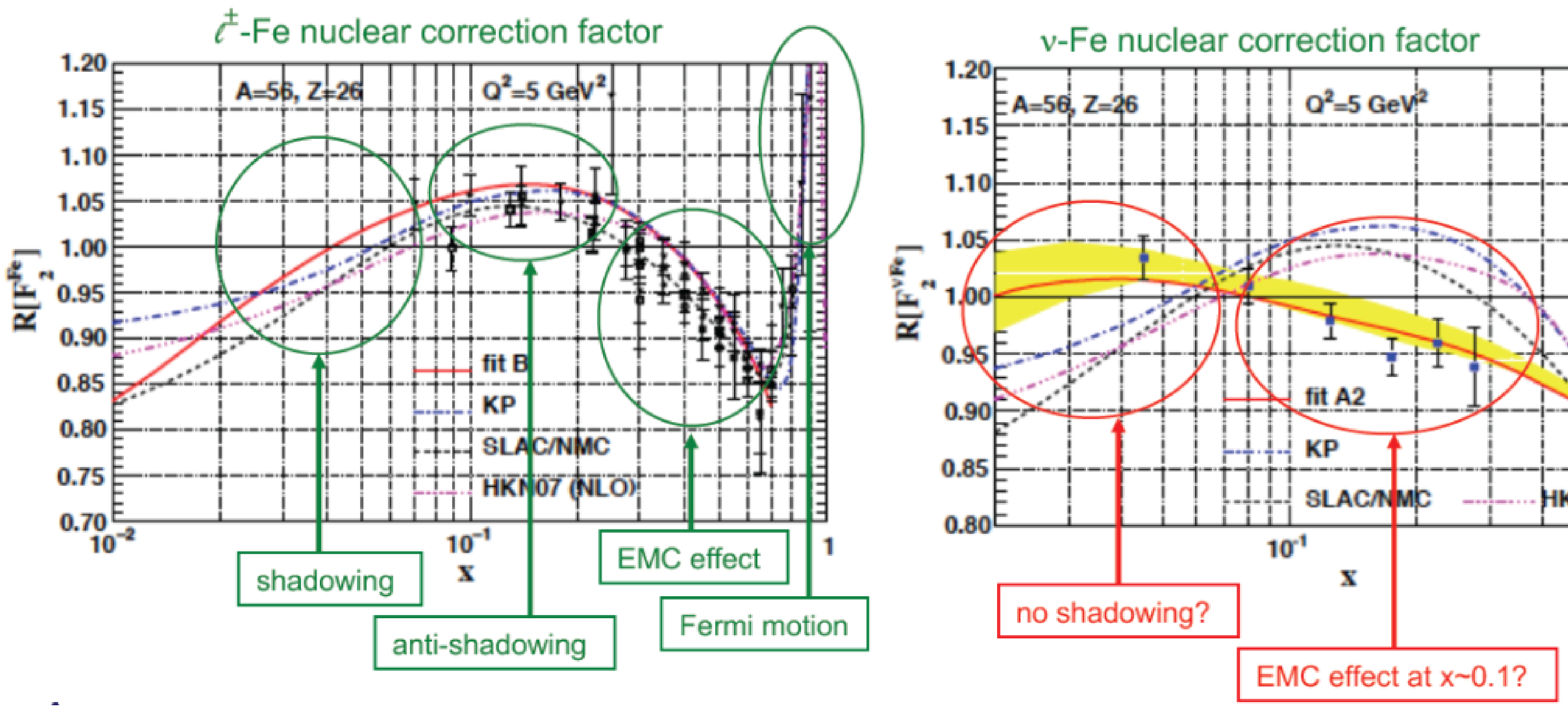

[arXiv:0507040[hep-ex]]

Muon angle distribution: Sensitive to x, $Q^2$ distributions. Excellent agreement.



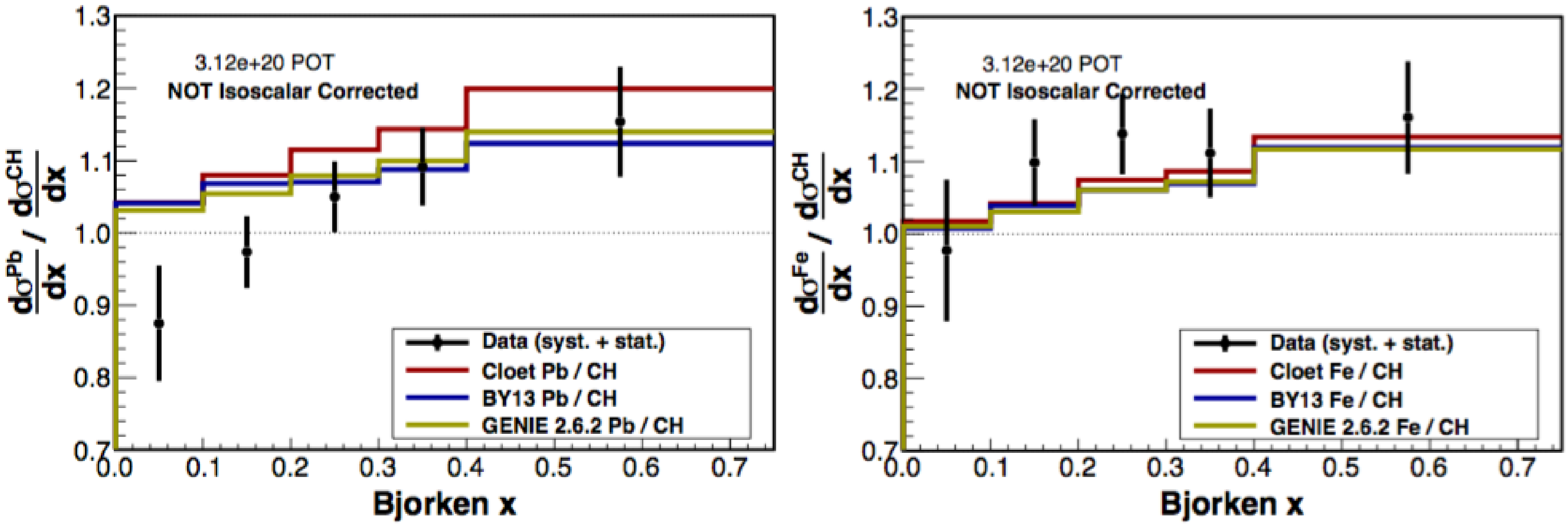

[Bhattacharya, FERMILAB-THESIS-2009-11]

# Shallow and Deep Inelastic Scattering




[U.Mosel, NuINT17 summary; arXiv:1208.6541[hep-ph]]

# Shallow and Deep Inelastic Scattering




[PRD93, 071101 (2016)]

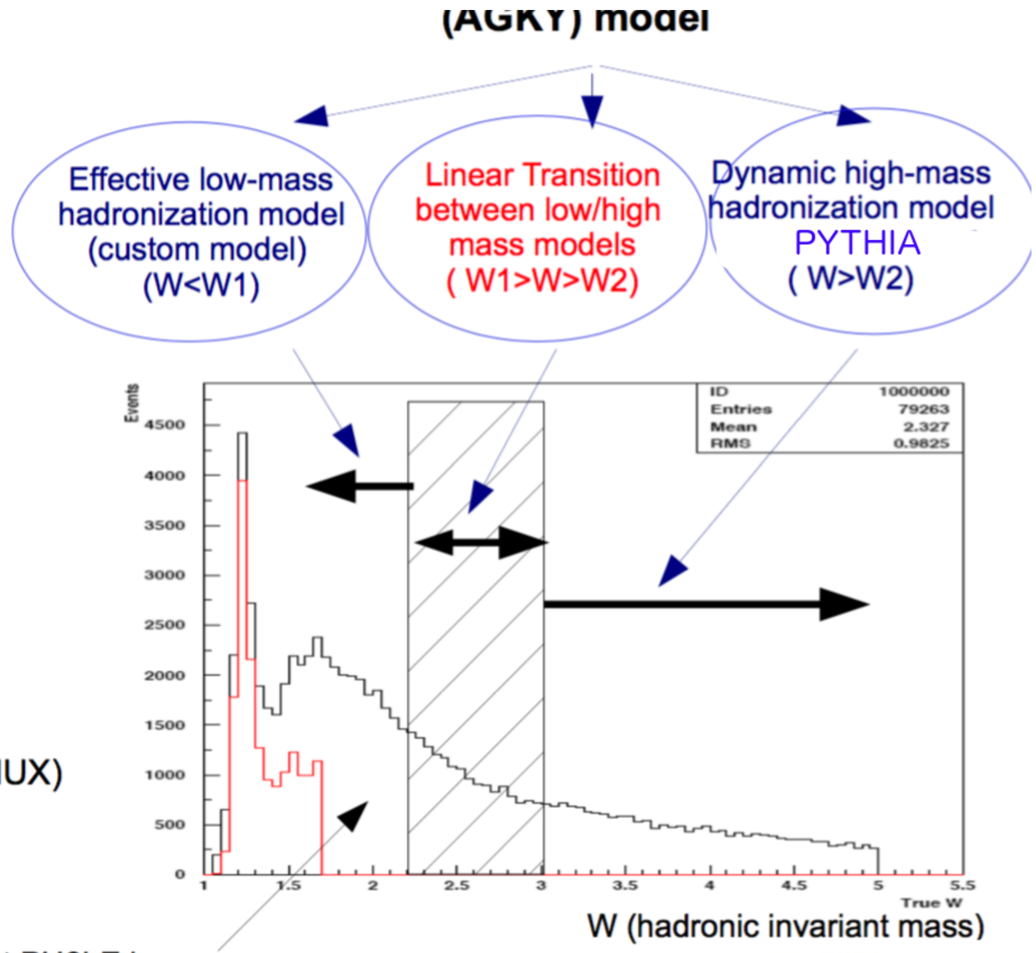
# Deep Inelastic Scattering / low-W Hadronization

## At low hadronic invariant masses:

- severe kinematical constraints – limit dynamics
- effective model using KNO scaling and data-driven modelling of average multiplicities, forward/backward asymmetries, pT-dep. Etc...

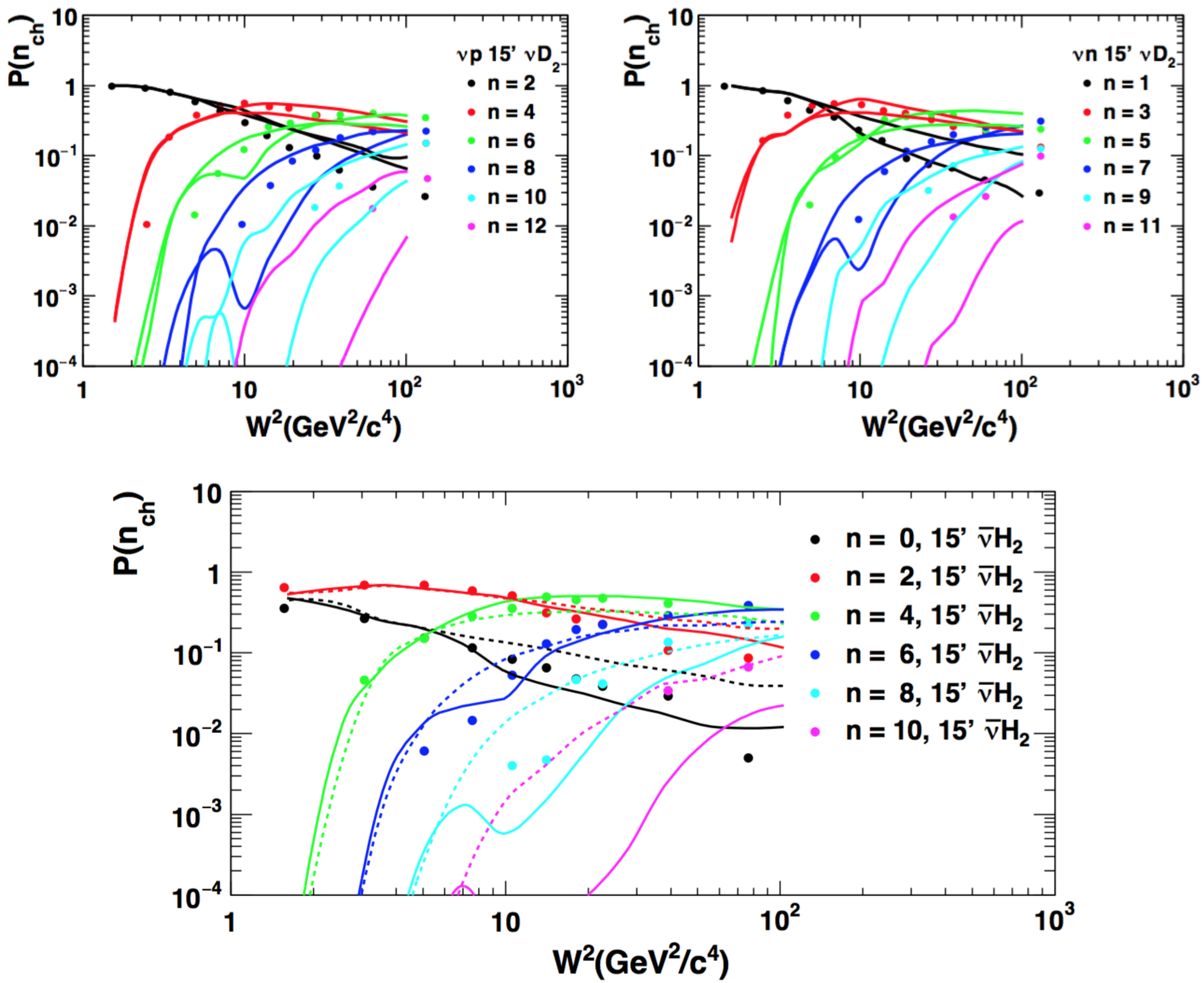
## At high hadronic invariant masses:

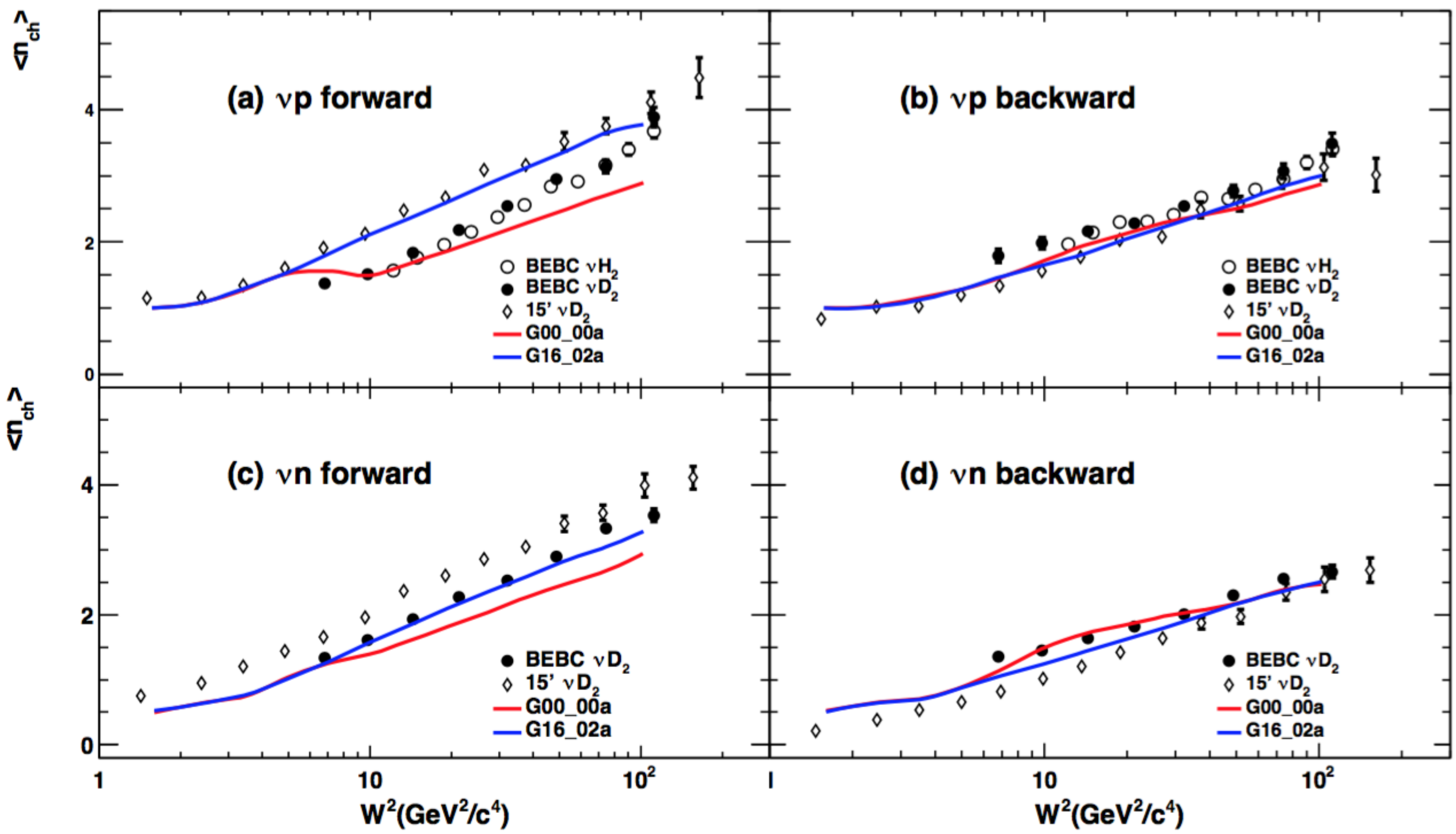
- rich dynamics
- using PYTHIA model
- tuned energy cutoff, pT, ssbar suppression (as in NUX)




Minos kinematical coverage at PH2LE beam

# Deep Inelastic Scattering / low-W Hadronization





(a) νp forward
(b) νp backward
(c) νn forward
(d) νn backward
BEBC νH2
BEBC νD2
15' νD2
G00_00a
G16_02a
<n_ch>
W²(GeV²/c⁴)

# Shallow and Deep Inelastic Scattering

- $0\pi$ and $1\pi$ studies revealed puzzles.
- No real effort beyond $\Delta$ ($1\pi$)
- No high-energy neutrino measurements in near future
- Several new puzzles lurking!
- A problem for DUNE (30% of event rate)

# Summary

- A detailed understanding of neutrino-nucleus interactions at the GeV energy range is still missing! **Several puzzles**!
- 2-detector experiments have been successful in mitigating the effects.
- We're approaching a precision where this paradigm starts to crack!
- A detailed understanding of neutrino interaction physics is required!

Steady progress is happening:

- Several recent measurements (+ many new ones expected at SBN)
- Theory is improving
- Substantial effort to improve MC generators and produce global tunes
- Improvements of LBL analyses methods to further mitigate effects

# Summary

But progress is not happening fast enough!

- World effort in neutrino Monte Carlos: A few FTE
    - ($<$ 10, possibly much less?)
- Joint nuclear theory / experimental neutrino physics projects do not fit easily in the portfolio of agencies that fund specific domains of research (nuclear OR particle).

Science goals of future accelerator program at risk

GENIE a universal neutrino Monte Carlo generator and a welcoming environment

- New expansion to underpin new model devel and global fit effort
- Join us and make a difference!

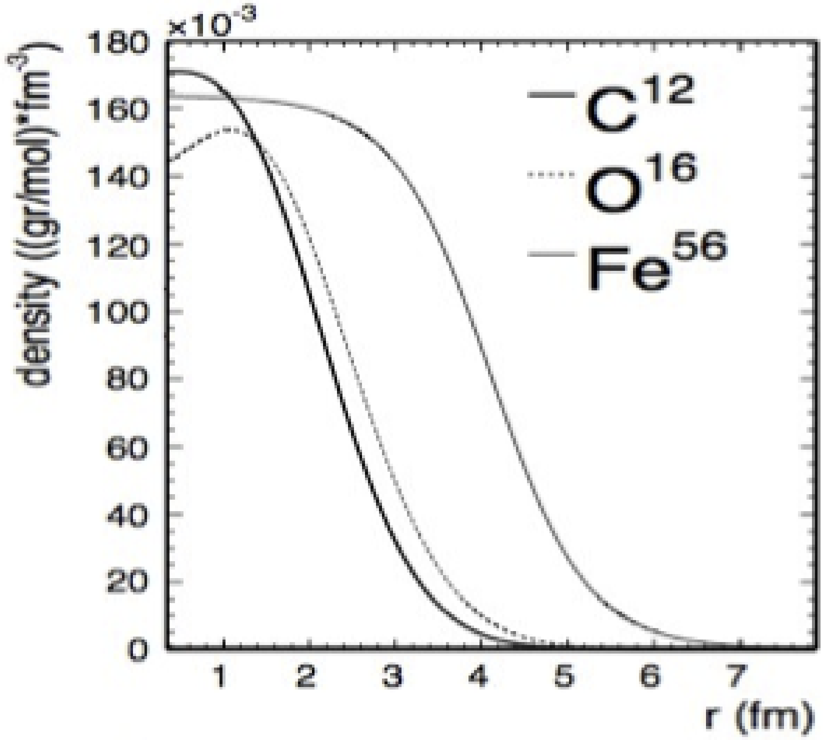
# Complementary slides

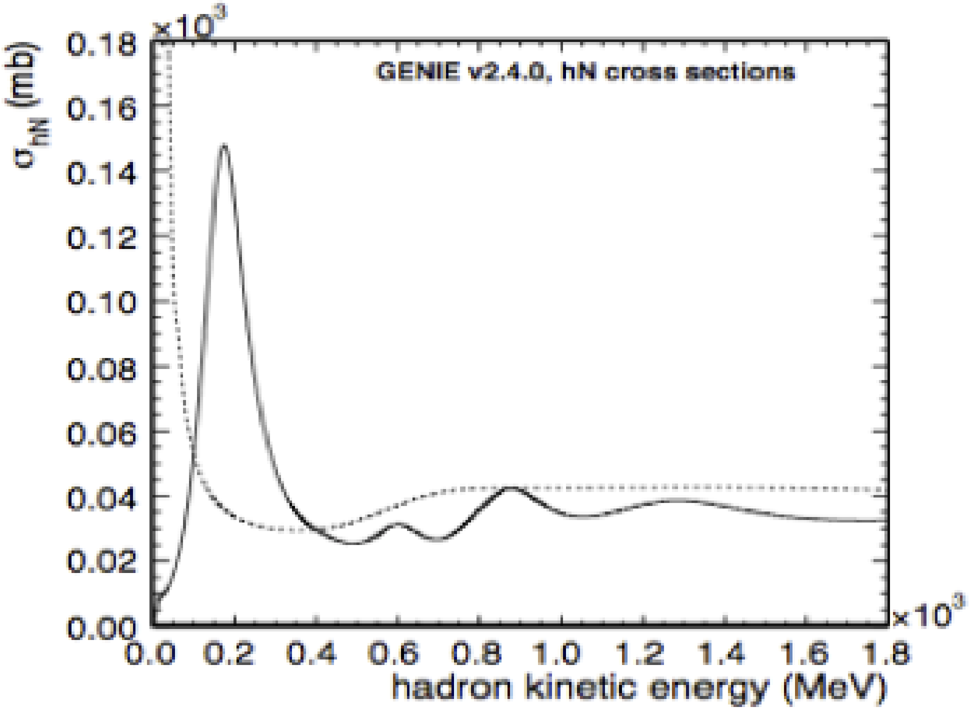
# Final state re-interactions

**At ∼1 GeV, 2/3 of all primary hadrons re-interact in the nucleus.**

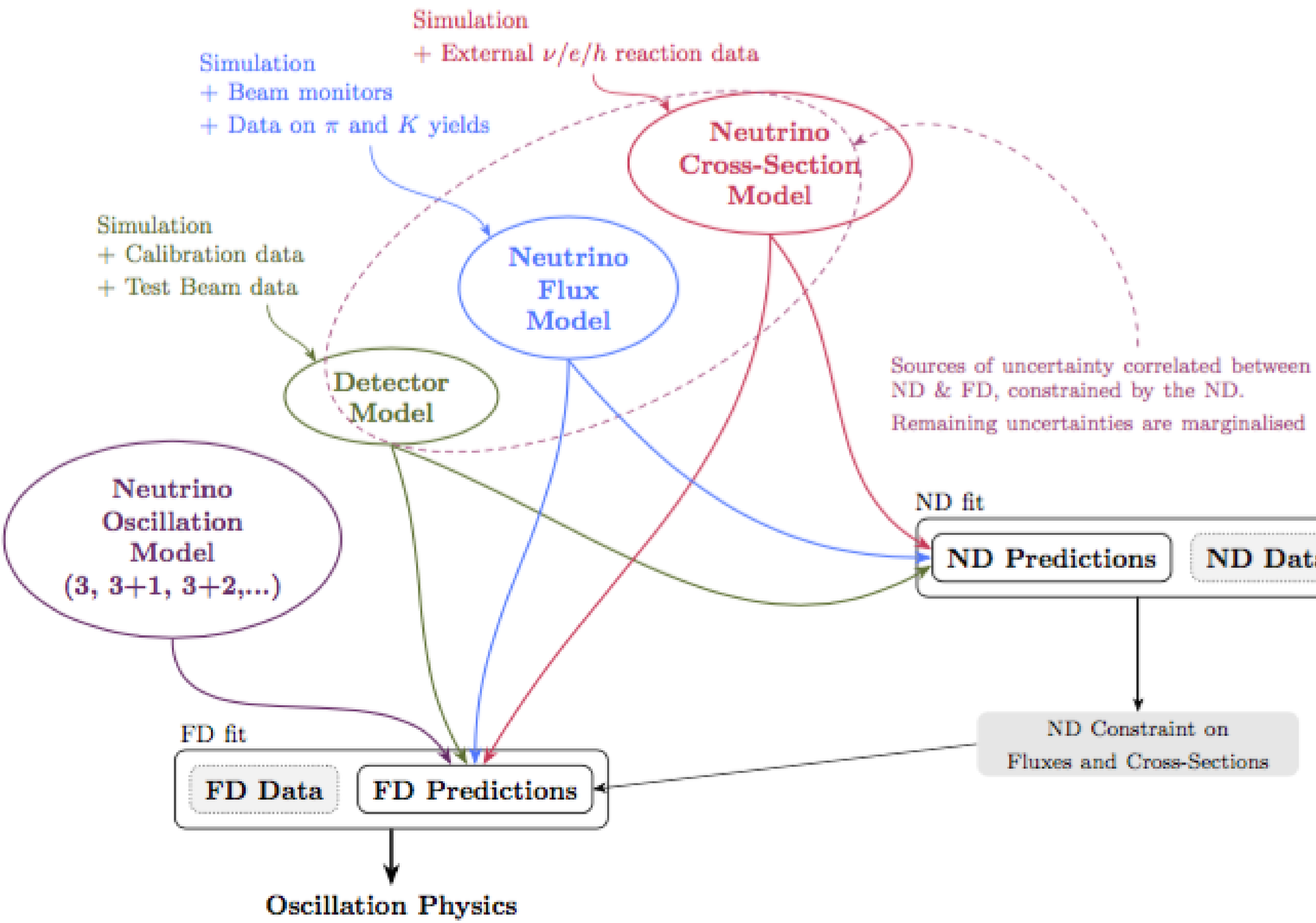
$$P^h_{rescat} = 1 - \int dre^{-r/\lambda^h(\vec{r},E_h)}$$

$$\lambda^h(\vec{r}, E_h) = 1/(\rho_{nucl}(r) \cdot \sigma^{hN}(E_h))$$



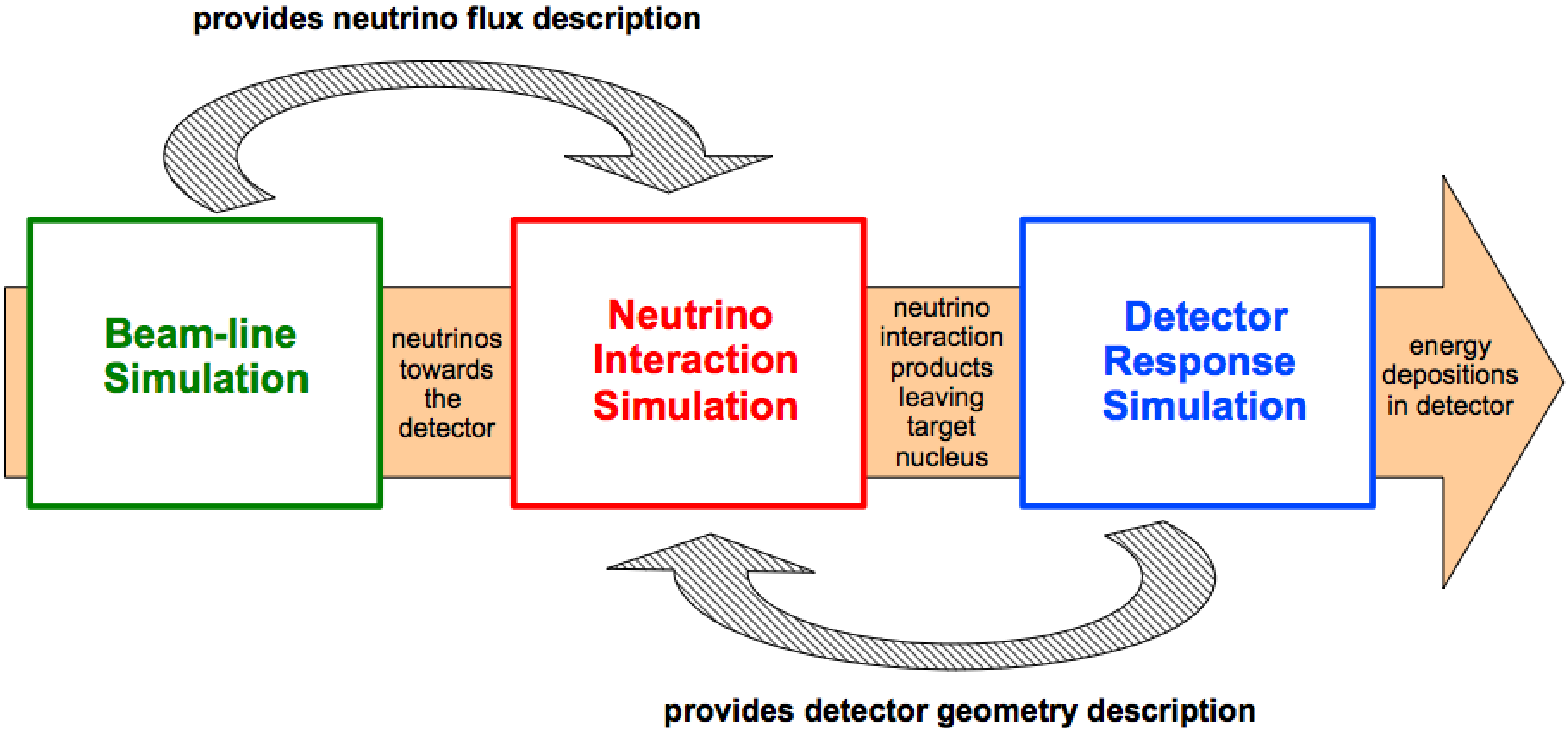



# Oscillation analysis method



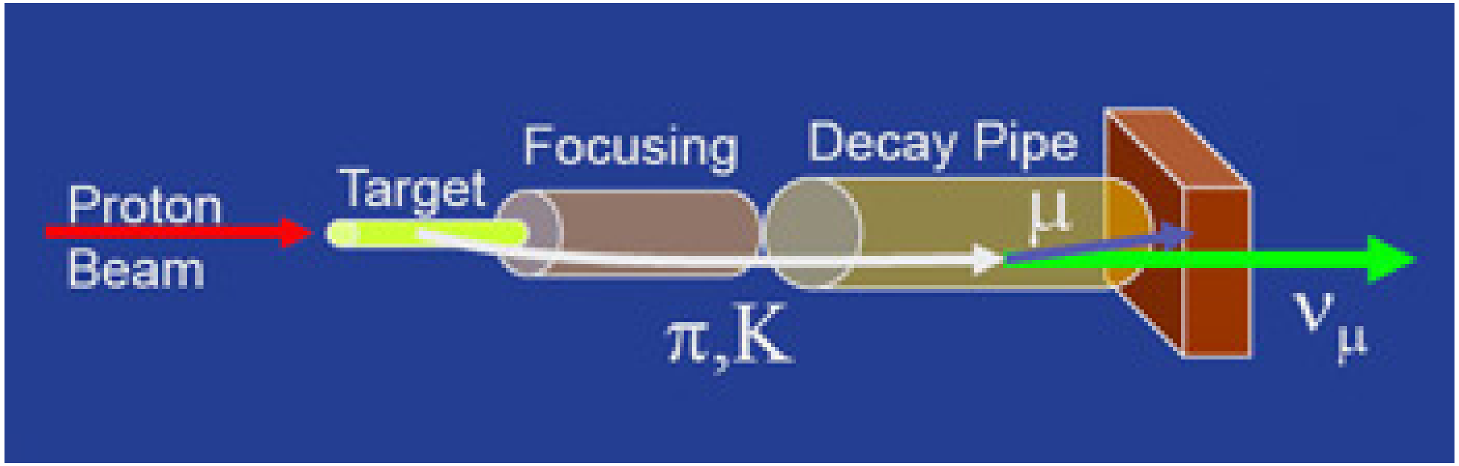
# Generating a neutrino interaction event: A detailed walkthrough

# A typical accelerator neutrino experiment simulation chain



# Simulation chain upstream the Neutrino Generator

Experiments run detailed FLUKA/Geant simulations of their neutrino beamlines. These simulations start from the primary proton beam interactions in the target and track all daughter particles simulating their subsequent interactions and decays. The beam-line simulations typically produce "neutrino flux rays" that are fed into the neutrino generator.




Where do our $\nu$'s come from?

$\pi^+ \to \nu_\mu + \mu^+$
$\pi^- \to \bar{\nu}_\mu + \mu^-$
$\mu^+ \to \bar{\nu}_\mu + \nu_e + e^+$
$\mu^- \to \bar{\nu}_e + \nu_\mu + e^-$
$K^+ \to \nu_\mu + \mu^+$
$K^+ \to \nu_e + \pi^0 + e^+$
$K^+ \to \nu_\mu + \pi^0 + \mu^+$
$K^- \to \bar{\nu}_\mu + \mu^-$
$K^- \to \bar{\nu}_e + \pi^0 + e^-$
$K^- \to \bar{\nu}_\mu + \pi^0 + \mu^-$
$K_L^0 \to \bar{\nu}_\mu + \pi^+ + \mu^-$
$K_L^0 \to \nu_\mu + \pi^- + \mu^+$
$K_L^0 \to \bar{\nu}_e + \pi^+ + e^-$
$K_L^0 \to \nu_e + \pi^- + e^+$

# Generator tasks

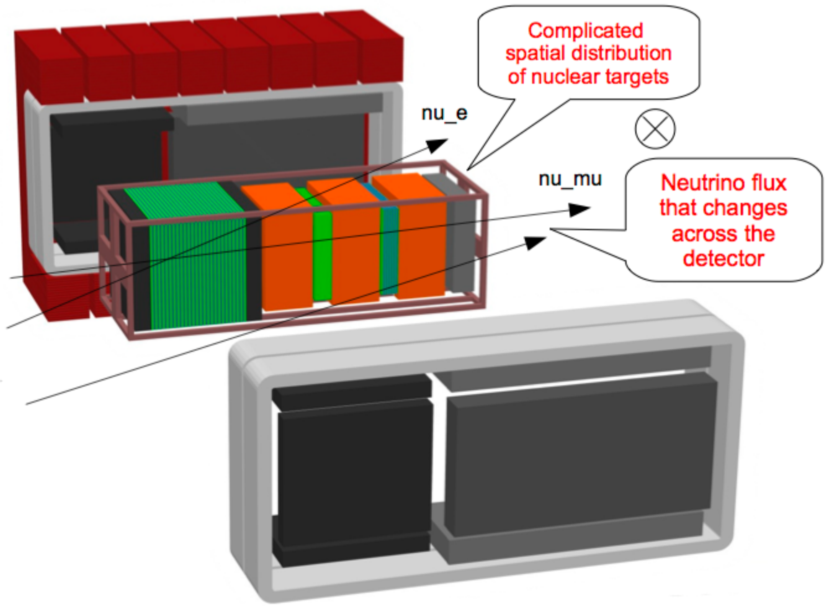
The beam-line simulations typically produce "neutrino flux rays" that are fed into the neutrino generator.

The neutrino generator task is then to:

- Propagate the neutrino rays towards the detectors.
- Establish whether the neutrino interacts and where exactly.
- Select an interaction type for the given neutrino and target.
- Generate all final state particles for the selected interaction.

# Does the flux neutrino interact?

An easy question in principle. In practise, this is one of the most complex and CPU-intensive calculations generators do.




- Detectors not uniform, with a complex distribution of nuclear targets
- Neutrino fluxes also not uniform for detector locations close to the neutrino target, changing across the detector
- For CPU efficiency, experiments need to be able to consider events in specific volumes only, sometimes not related with any actual geometry volume. Need to be able to mask out arbitrarily defined parts of the geometry.
- Experiments also want to consider interactions in large external volumes (eg surrounding rock) to estimate beam-related backgrounds.
- Avoid oddities from recycling flux rays.
- Keep track of the absolute sample normalization in terms of protons on target.

# Does the flux neutrino interact?

The fundamental problem here is to compute a complex multi-dimensional integral

$$N_{ev} \propto \int dE_\nu dcos\theta_\nu d\phi_\nu dxdydt \sum_{f(lavor)} \frac{d^6\Phi_f(E_\nu, cos\theta_\nu, \phi_\nu, x, y, t)}{dE_\nu dcos\theta_\nu d\phi_\nu dxdydt} \int_0^\infty ds \sum_{i(sotope)} \frac{\rho(\vec{r}) w_i(\vec{r}) \sigma^{tot}_{f;i}(E_\nu)}{A_i(\vec{r})}$$

for which an analytical answer is not possible.

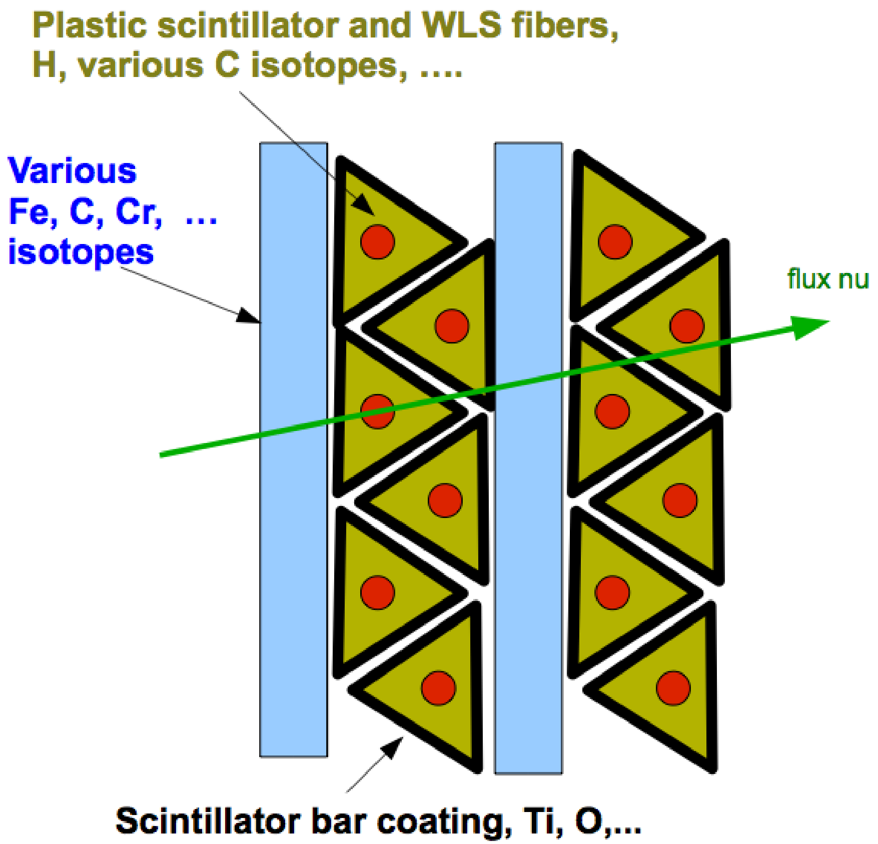
---

- $E_\nu$: neutrino energy
- $cos\theta_\nu$: flux neutrino zenith angle
- $\phi_\nu$: flux neutrino azimuthal angle
- $dxdy$: unit area in some surface upstream of any volume where we consider interactions
- $t$: time
- $ds$: infinitesimal step along the neutrino direction
- $\vec{r} = \vec{r}(s, cos\theta_\nu, \phi_\nu, x, y)$: position along the neutrino ray in the detector coordinate system
- $\frac{d^6\Phi_f}{dE_\nu dcos\theta_\nu d\phi_\nu dxdydt}$: differential number of neutrinos of flavour f
- $\rho(\vec{r})$: detector density at position $\vec{r}$ (typically a mixture)
- $w_i(\vec{r})$: weight fraction for isotope i, in the mixture at position $\vec{r}$
- $A_i(\vec{r})$: mass number for isotope i, in the mixture at position $\vec{r}$
- $\sigma^{tot}_{f;i}(E_\nu)$: total cross-section for interactions of neutrinos of flavour f with isotope i, at energy $E_\nu$.

# Does the flux neutrino interact?

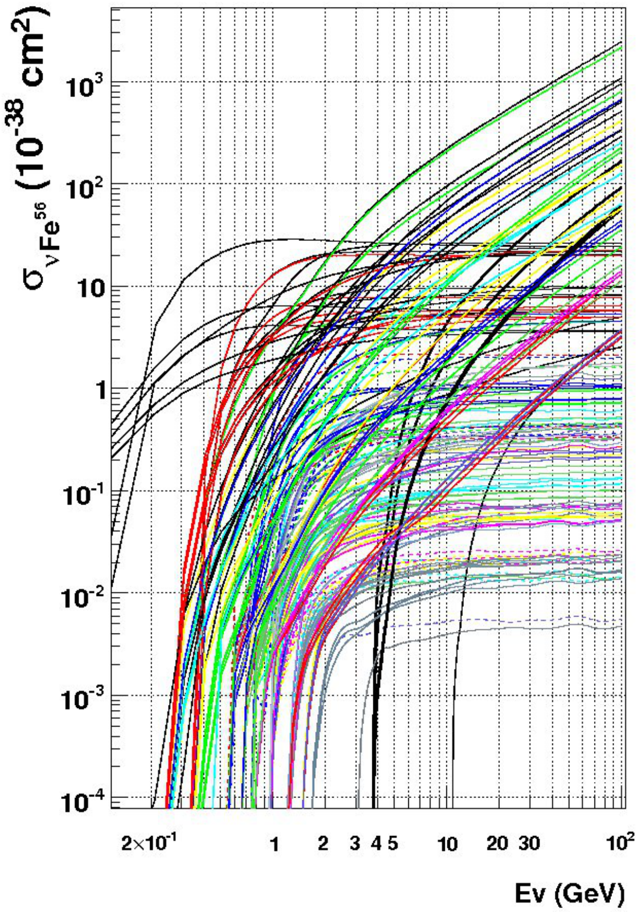
The integration involves:

- Pull random flux rays from the neutrino beam-line simulation and "throw" towards the detector.
- Follow the ray, stepping through the geometry and, in the absence of external fiducial cuts, getting all segments described by the entry and exit points of the flux ray in every single volume it passes through.
- For each segment, which is purely within a volume, figure out the corresponding mixture information (density, isotopic composition, weight fraction for each isotope) and calculate the density-weighted path length for each isotope seen along the trajectory.



# Does the flux neutrino interact?

$\nu_\mu$, $\bar{\nu_\mu}$ + *Fe*, all processes




- The generator needs to calculate the total cross-section, at the given energy, for the given neutrino flavour and target isotope.
- The generator then needs to look at all the physics processes enabled, and sum-up their cross-section.
- Calculation of each cross-section requires numerical integration of the corresponding differential cross-section model.
  - $\sim 10^2$ isotopes in typical detector geometries
  - $\sim 10^2$ interaction modes per given initial state (neutrino+isotope)
  - $\sim 10^4$ differential cross-section evaluations per numerical integration
  - $\sim 10^8$ **differential cross-section evaluations to decide whether a neutrino interacts**
- All generators, in one way or another, pre-compute the numerical integrals for a series of neutrino energies and then intrepolate.

# Does the flux neutrino interact?

The interaction probability for each isotope is calculated using the **integrated density-weighted path length**, along the neutrino trajectory, and the **total interaction cross-section**, at the given energy, as:

$$P \propto \frac{\rho \cdot L \cdot \sigma^{tot}}{A}$$

As it is well known, these interaction probabilities are exceedingly small.

But the absolute number does not matter that much for the generator.

One needs to find the maximum possible interaction probability $P_{max}$ for the current MC run (obtained with a neutrino that has the highest allowed energy and which travels along the trajectory that sees the most detector mass).

$P_{max}$ can then be used to scale all interaction probabilities and improve CPU efficiency (there is an associated weight, but all events have that same weight so, effectively, the sample is still unweighted - effectively one just redefines the sample normalization)

# Does the flux neutrino interact?

However there is **fundamental source of inefficiency**:

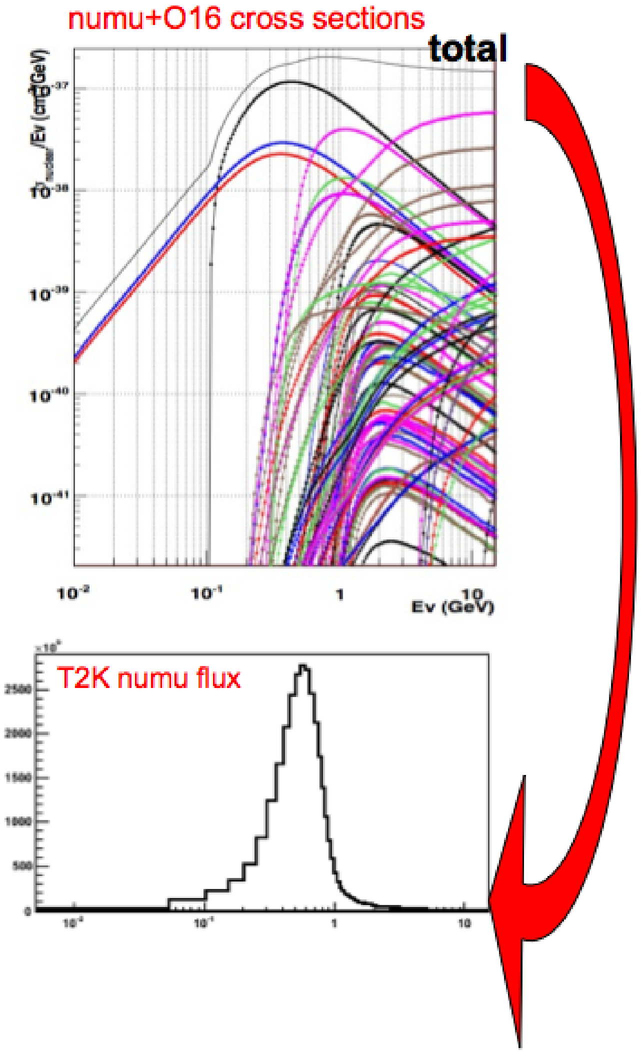
$P_{max}$ is obtained for an event at the tail of the energy spectrum (∼100 Gev) for a flux that typically peaks around ∼ 1 GeV.

Since the cross-section increases 100-fold between 1 and 100 GeV, the maximum interaction probability will be more than 100 times larger than the values most likely obtained with typical neutrinos. This means that, even after re-normalizing the interaction probabilities, hundreds of flux $\nu$'s need to be to be thrown before one interacts.

Several optimizations are typically implemented to make that work efficiently.

A very efficient work-around would have been to generate weighted events, but it is difficult to combine multiple weighted events into a single simulated beam spill (multiple events are seen in the detector during each beam spill).

Remember all above next time you wonder why the simulation speed dropped as soon as you included a flux and geometry description

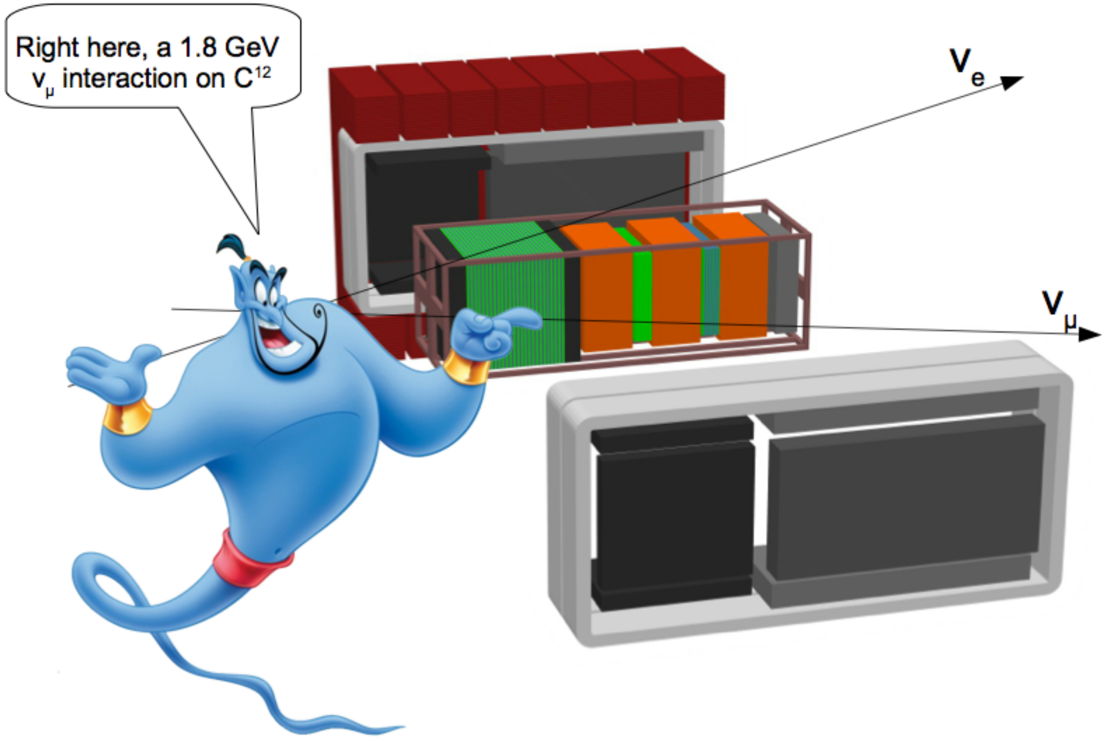


# Does the flux neutrino interact?

Eventually the generator decides that the neutrino interacted with isotope i.

It also generates a vertex position along the neutrino trajectory, by generating a random density-weighted path length between 0 and the maximum one computed for the given trajectory and isotope.
The generator steps through the geometry once again following the neutrino trajectory so as to make sure that the vertex is placed in the appropriate position, in a volume that does contain isotope i.

**Then, the next generator task is to select an actual interaction type and generate the final state particles.**

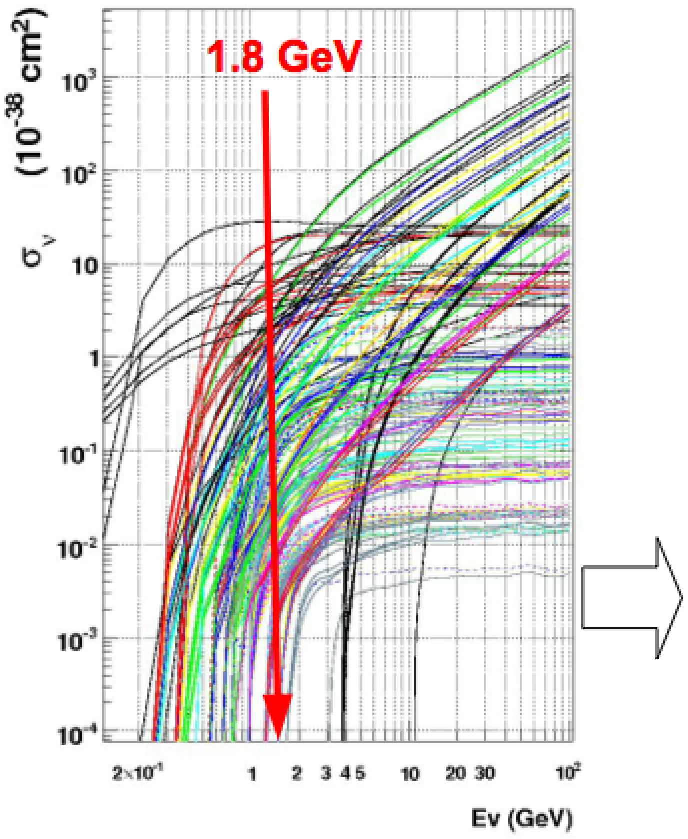


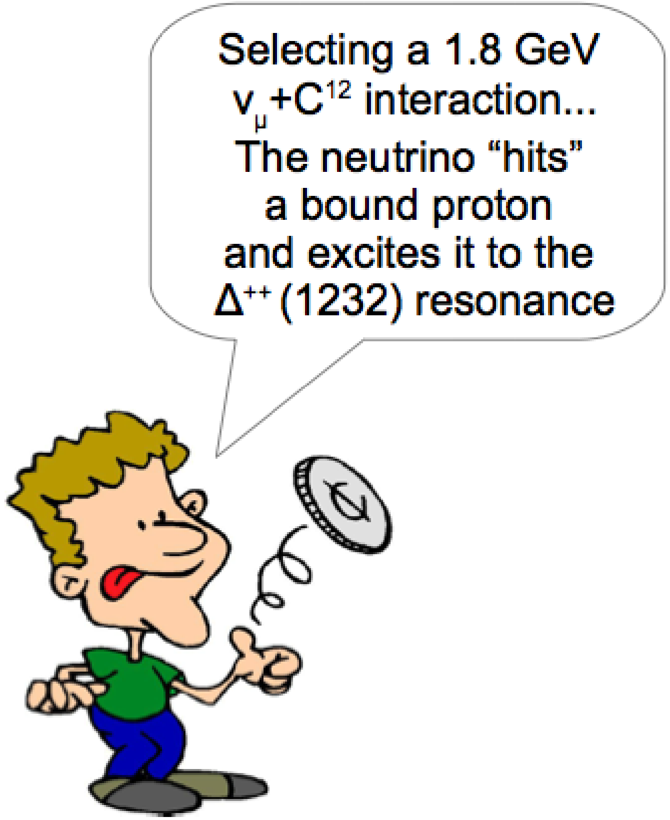
# Generating event kinematics

```
|------------------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                              |
|------------------------------------------------------------------------------------------------------------------------|
| Idx |          Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |       m  |
|------------------------------------------------------------------------------------------------------------------------|
|   0 |         nu_mu |   0 |         14 |  -1 |  -1 |           |   0.000 |   0.000 |   1.800 |   1.800 |   0.000 |
|   1 |           C12 |   0 | 1000060120 |  -1 |  -1 |           |   0.000 |   0.000 |   0.000 |  11.179 |  11.179 |
```

# Generating event kinematics

```
|-----------------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                              |
|-----------------------------------------------------------------------------------------------------------------------|
| Idx |          Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |       m |
|-----------------------------------------------------------------------------------------------------------------------|
|   0 |         nu_mu |   0 |         14 |  -1 |  -1 |           |   0.000 |   0.000 |   1.800 |   1.800 |   0.000 |
|   1 |           C12 |   0 | 1000060120 |  -1 |  -1 |           |   0.000 |   0.000 |   0.000 |  11.179 |  11.179 |
```

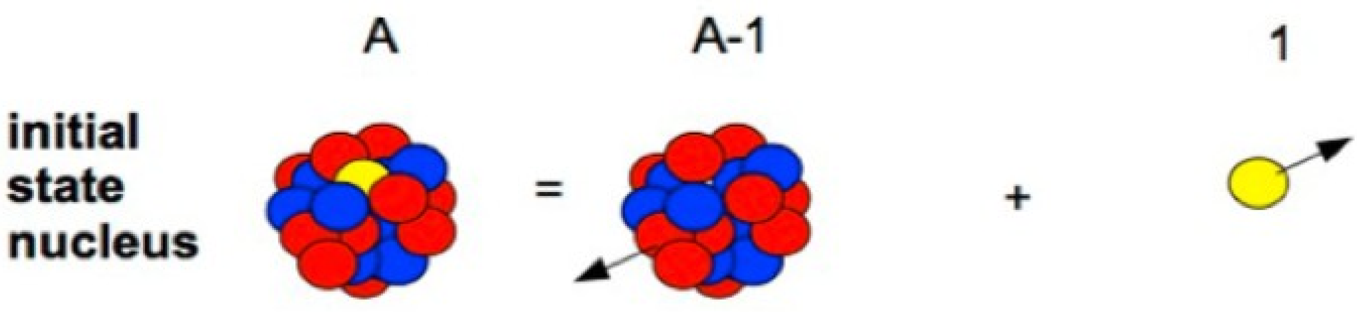


# Generating event kinematics

GENIE GHEP Event Record [print level: 3]

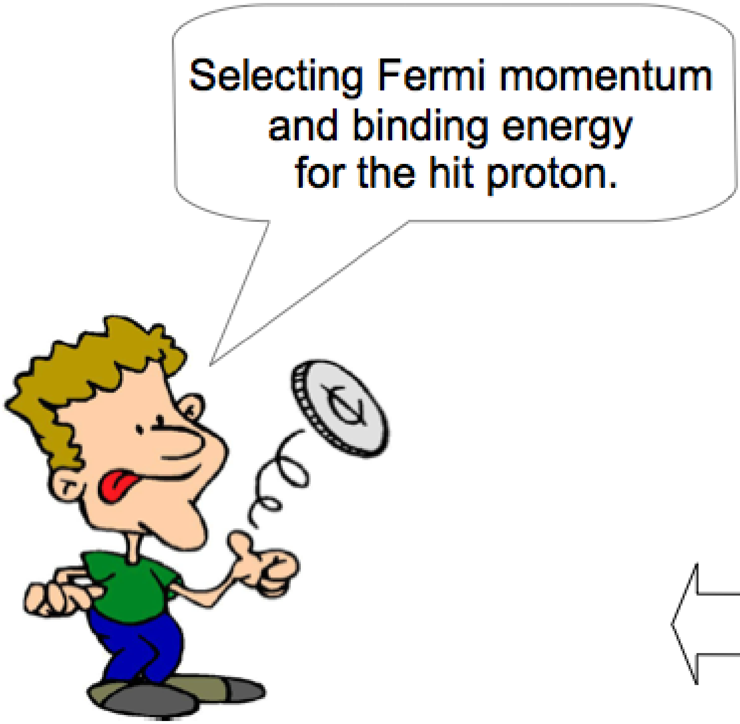
| Idx | Name | Ist | PDG | Mother | | Daughter | | Px | Py | Pz | E | m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | nu_mu | 0 | 14 | -1 | -1 | | | 0.000 | 0.000 | 1.800 | 1.800 | 0.000 |
| 1 | C12 | 0 | 1000060120 | -1 | -1 | 2 | 3 | 0.000 | 0.000 | 0.000 | 11.179 | 11.179 |
| 2 | proton | 11 | 2212 | 1 | -1 | | | | | | | |
| 3 | B11 | 2 | 1000050110 | 1 | -1 | | | | | | | |



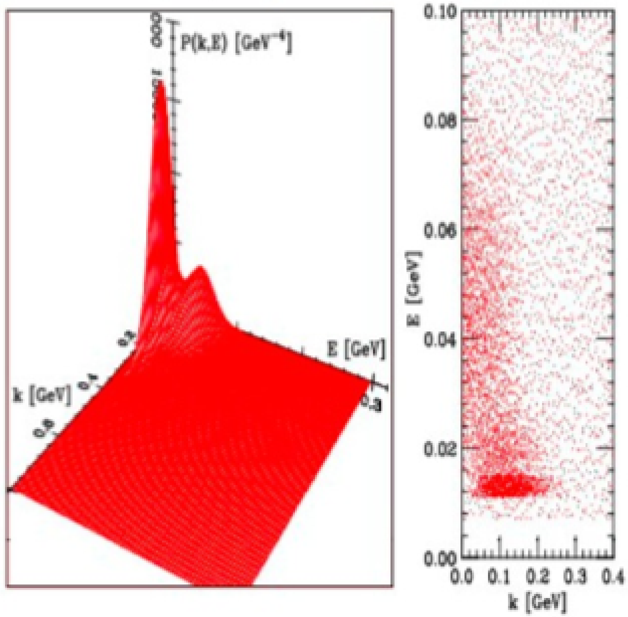
# Generating event kinematics

GENIE GHEP Event Record [print level: 3]

| Idx | Name | Ist | PDG | Mother | | Daughter | | Px | Py | Pz | E | m | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | nu_mu | 0 | 14 | -1 | -1 | | | 0.000 | 0.000 | 1.800 | 1.800 | 0.000 | |
| 1 | C12 | 0 | 1000060120 | -1 | -1 | 2 | 3 | 0.000 | 0.000 | 0.000 | 11.179 | 11.179 | |
| 2 | proton | 11 | 2212 | 1 | -1 | | | -0.050 | -0.055 | 0.135 | 0.923 | **0.938 | M = 0.910 |
| 3 | B11 | 2 | 1000050110 | 1 | -1 | | | 0.050 | 0.055 | -0.135 | 10.256 | 10.255 | |



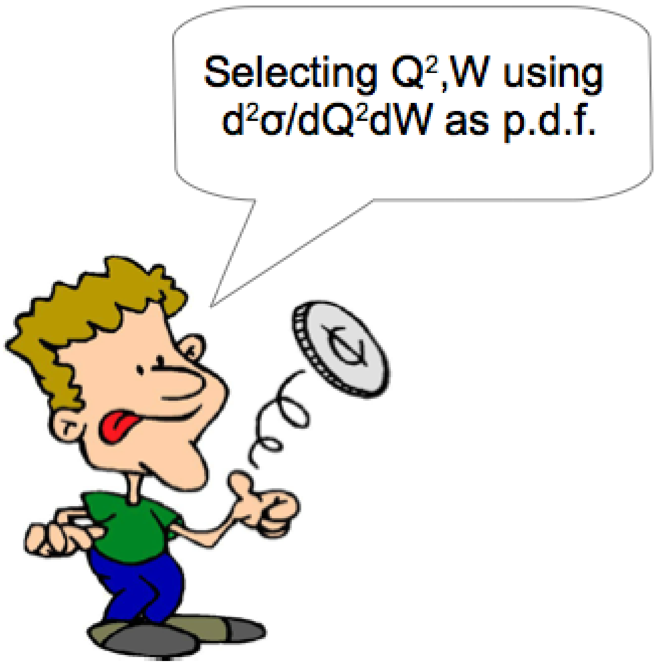

O.Benhar et,al., Phys.Rev.D72:053005,2005.

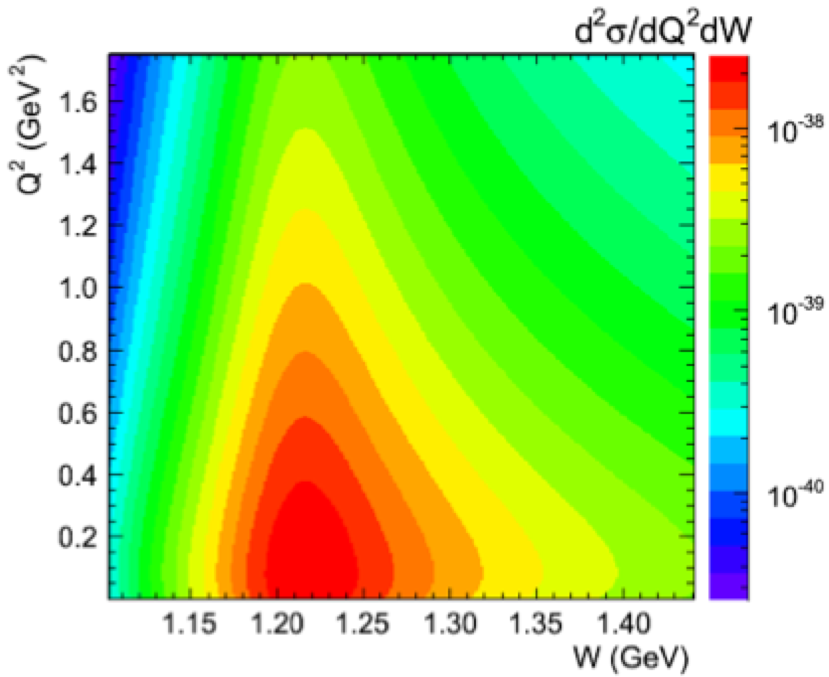


# Generating event kinematics

GENIE GHEP Event Record [print level: 3]

| Idx | Name | Ist | PDG | Mother | | Daughter | | Px | Py | Pz | E | m | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | nu_mu | 0 | 14 | -1 | -1 | 4 | 4 | 0.000 | 0.000 | 1.800 | 1.800 | 0.000 | |
| 1 | C12 | 0 | 1000060120 | -1 | -1 | 2 | 3 | 0.000 | 0.000 | 0.000 | 11.179 | 11.179 | |
| 2 | proton | 11 | 2212 | 1 | -1 | 5 | 5 | -0.050 | -0.055 | 0.135 | 0.923 | **0.938 | M = 0.910 |
| 3 | B11 | 2 | 1000050110 | 1 | -1 | | | 0.050 | 0.055 | -0.135 | 10.256 | 10.255 | |
| 4 | mu- | 1 | 13 | 0 | -1 | -1 | -1 | 0.151 | 0.140 | 0.987 | 1.014 | 0.106 | P = (-0.149,-0.138,-0.979) |
| 5 | Delta++ | 3 | 2224 | 2 | -1 | 6 | 7 | -0.201 | -0.195 | 0.947 | 1.709 | **1.231 | M = 1.394 |

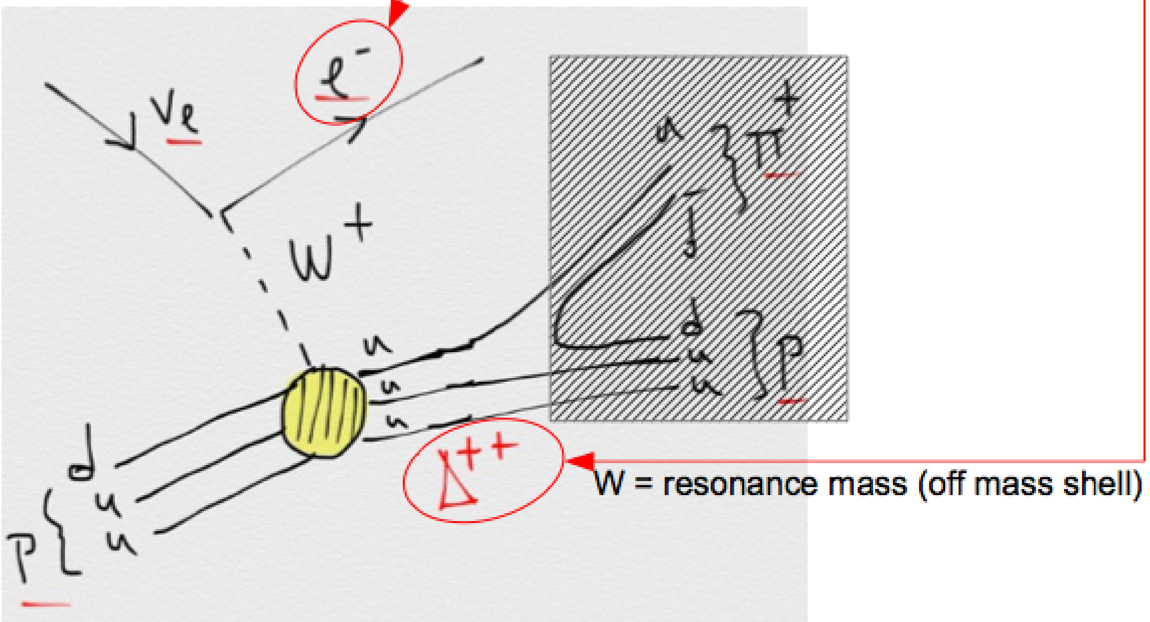


# Generating event kinematics

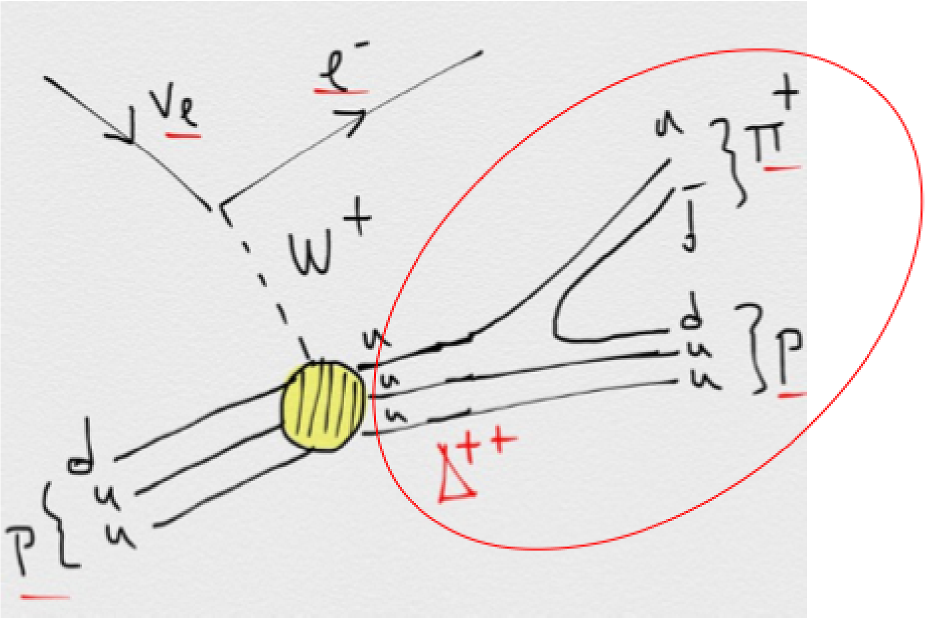
GENIE GHEP Event Record [print level: 3]

| Idx | Name | Ist | PDG | Mother | | Daughter | | Px | Py | Pz | E | m | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | nu_mu | 0 | 14 | -1 | -1 | 4 | 4 | 0.000 | 0.000 | 1.800 | 1.800 | 0.000 | |
| 1 | C12 | 0 | 1000060120 | -1 | -1 | 2 | 3 | 0.000 | 0.000 | 0.000 | 11.179 | 11.179 | |
| 2 | proton | 11 | 2212 | 1 | -1 | 5 | 5 | -0.050 | -0.055 | 0.135 | 0.923 | **0.938 | M = 0.910 |
| 3 | B11 | 2 | 1000050110 | 1 | -1 | | | 0.050 | 0.055 | -0.135 | 10.256 | 10.255 | |
| 4 | mu- | 1 | 13 | 0 | -1 | -1 | -1 | 0.151 | 0.140 | 0.987 | 1.014 | 0.106 | P = (-0.149,-0.138,-0.979) |
| 5 | Delta++ | 3 | 2224 | 2 | -1 | 6 | 7 | -0.201 | -0.195 | 0.947 | 1.709 | **1.231 | M = 1.394 |



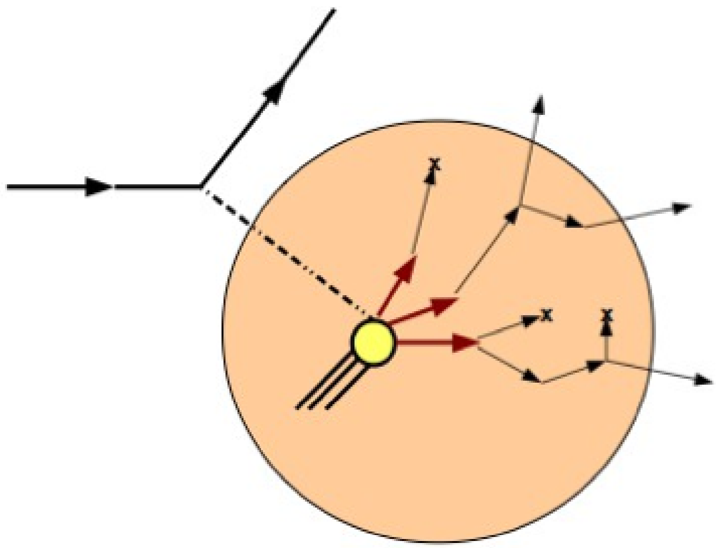
# Generating event kinematics

```
|------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                      |
|------------------------------------------------------------------------------------------------|
| Idx |      Name | Ist |        PDG |   Mother  | Daughter  |     Px |     Py |     Pz |      E |      m |
|------------------------------------------------------------------------------------------------|
|   0 |     nu_mu |   0 |         14 |  -1 |  -1 |   4 |   4 |  0.000 |  0.000 |  1.800 |  1.800 |  0.000 |
|   1 |       C12 |   0 | 1000060120 |  -1 |  -1 |   2 |   3 |  0.000 |  0.000 |  0.000 | 11.179 | 11.179 |
|   2 |    proton |  11 |       2212 |   1 |  -1 |   5 |   5 | -0.050 | -0.055 |  0.135 |  0.923 | **0.938 | M = 0.910
|   3 |       B11 |   2 | 1000050110 |   1 |  -1 |           |  0.050 |  0.055 | -0.135 | 10.256 | 10.255 |
|   4 |       mu- |   1 |         13 |   0 |  -1 |  -1 |  -1 |  0.151 |  0.140 |  0.987 |  1.014 |  0.106 | P = (-0.149,-0.138,-0.979)
|   5 |   Delta++ |   3 |       2224 |   2 |  -1 |   6 |   7 | -0.201 | -0.195 |  0.947 |  1.709 | **1.231 | M = 1.394
|   6 |    proton |  14 |       2212 |   5 |  -1 |           | -0.059 | -0.010 |  0.269 |  0.978 |  0.938 |
|   7 |       pi+ |  14 |        211 |   5 |  -1 |           | -0.142 | -0.184 |  0.679 |  0.731 |  0.140 |
```



# Generating event kinematics

```
|------------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                        |
|------------------------------------------------------------------------------------------------------------------|
| Idx |        Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |       m |
|------------------------------------------------------------------------------------------------------------------|
|   0 |       nu_mu |   0 |         14 |  -1 |  -1 |   4 |   4 |   0.000 |   0.000 |   1.800 |   1.800 |   0.000 |
|   1 |         C12 |   0 | 1000060120 |  -1 |  -1 |   2 |   3 |   0.000 |   0.000 |   0.000 |  11.179 |  11.179 |
|   2 |      proton |  11 |       2212 |   1 |  -1 |   5 |   5 |  -0.050 |  -0.055 |   0.135 |   0.923 | **0.938 | M = 0.910
|   3 |         B11 |   2 | 1000050110 |   1 |  -1 |           |   0.050 |   0.055 |  -0.135 |  10.256 |  10.255 |
|   4 |         mu- |   1 |         13 |   0 |  -1 |  -1 |  -1 |   0.151 |   0.140 |   0.987 |   1.014 |   0.106 | P = (-0.149,-0.138,-0.979)
|   5 |     Delta++ |   3 |       2224 |   2 |  -1 |   6 |   7 |  -0.201 |  -0.195 |   0.947 |   1.709 | **1.231 | M = 1.394
|   6 |      proton |  14 |       2212 |   5 |  -1 |   8 |   9 |  -0.059 |  -0.010 |   0.269 |   0.978 |   0.938 | FSI = 4
|   7 |         pi+ |  14 |        211 |   5 |  -1 |  10 |  11 |  -0.142 |  -0.184 |   0.679 |   0.731 |   0.140 | FSI = 4
|   8 |      proton |   1 |       2212 |   6 |  -1 |  -1 |  -1 |   0.030 |   0.054 |   0.150 |   0.952 |   0.938 |
|   9 |      proton |   1 |       2212 |   6 |  -1 |  -1 |  -1 |   0.095 |  -0.023 |   0.173 |   0.959 |   0.938 |
|  10 |         pi+ |   1 |        211 |   7 |  -1 |  -1 |  -1 |  -0.411 |  -0.142 |   0.325 |   0.561 |   0.140 |
|  11 |     neutron |   1 |       2112 |   7 |  -1 |  -1 |  -1 |   0.363 |   0.022 |   0.428 |   1.095 |   0.940 |
```

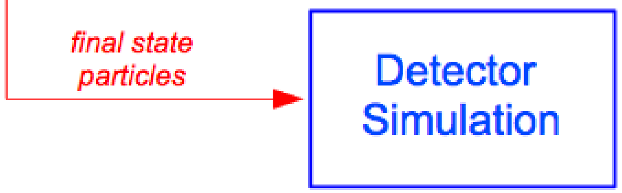


# Generating event kinematics

```
|------------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                        |
|------------------------------------------------------------------------------------------------------------------|
| Idx |          Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |       m  |
|------------------------------------------------------------------------------------------------------------------|
|   0 |         nu_mu |   0 |         14 |  -1 |  -1 |   4 |   4 |   0.000 |   0.000 |   1.800 |   1.800 |   0.000  |
|   1 |           C12 |   0 | 1000060120 |  -1 |  -1 |   2 |   3 |   0.000 |   0.000 |   0.000 |  11.179 |  11.179  |
|   2 |        proton |  11 |       2212 |   1 |  -1 |   5 |   5 |  -0.050 |  -0.055 |   0.135 |   0.923 | **0.938  | M = 0.910
|   3 |           B11 |   2 | 1000050110 |   1 |  -1 |  12 |  12 |   0.050 |   0.055 |  -0.135 |  10.256 |  10.255  |
|   4 |           mu- |   1 |         13 |   0 |  -1 |  -1 |  -1 |   0.151 |   0.140 |   0.987 |   1.014 |   0.106  | P = (-0.149,-0.138,-0.979)
|   5 |       Delta++ |   3 |       2224 |   2 |  -1 |   6 |   7 |  -0.201 |  -0.195 |   0.947 |   1.709 | **1.231  | M = 1.394
|   6 |        proton |  14 |       2212 |   5 |  -1 |   8 |   9 |  -0.059 |  -0.010 |   0.269 |   0.978 |   0.938  | FSI = 4
|   7 |           pi+ |  14 |        211 |   5 |  -1 |  10 |  11 |  -0.142 |  -0.184 |   0.679 |   0.731 |   0.140  | FSI = 4
|   8 |        proton |   1 |       2212 |   6 |  -1 |  -1 |  -1 |   0.030 |   0.054 |   0.150 |   0.952 |   0.938  |
|   9 |        proton |   1 |       2212 |   6 |  -1 |  -1 |  -1 |   0.095 |  -0.023 |   0.173 |   0.959 |   0.938  |
|  10 |           pi+ |   1 |        211 |   7 |  -1 |  -1 |  -1 |  -0.411 |  -0.142 |   0.325 |   0.561 |   0.140  |
|  11 |       neutron |   1 |       2112 |   7 |  -1 |  -1 |  -1 |   0.363 |   0.022 |   0.428 |   1.095 |   0.940  |
|  12 |      HadrBlob |  15 | 2000000002 |   3 |  -1 |  -1 |  -1 |  -0.228 |  -0.050 |  -0.264 |   8.398 | **0.000  | M = 8.391
|------------------------------------------------------------------------------------------------------------------|
|       Fin-Init:                                                |  -0.000 |   0.000 |  -0.000 |   0.000 |          |
|------------------------------------------------------------------------------------------------------------------|
|       Vertex:         nu_mu @ (x =      0.00000 m, y =      0.00000 m, z =      0.00000 m, t =             0 s) |
|------------------------------------------------------------------------------------------------------------------|
| Err flag [bits:15->0] : 0000000000000000     |  1st set:                                                  none |
| Err mask [bits:15->0] : 1111111111111111     |  Is unphysical:    NO |   Accepted:   YES                      |
|------------------------------------------------------------------------------------------------------------------|
| sig(Ev) =       4.3934e-38 cm^2  | d2sig(W,Q2;E)/dWdQ2 =      5.5985e-38 cm^2/GeV^3 | Weight =                  1 |
|------------------------------------------------------------------------------------------------------------------|
```

# Simulation chain downstream the Neutrino Generator

```
|---------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                     |
|---------------------------------------------------------------------------------------------------------------|
| Idx |          Name | Ist |        PDG |   Mother  | Daughter  |     Px |     Py |     Pz |      E |       m |
|---------------------------------------------------------------------------------------------------------------|
|   0 |         nu_mu |   0 |         14 | -1 |  -1 |  4 |  4 |  0.000 |  0.000 |  1.800 |  1.800 |   0.000 |
|   1 |           C12 |   0 | 1000060120 | -1 |  -1 |  2 |  3 |  0.000 |  0.000 |  0.000 | 11.179 |  11.179 |
|   2 |        proton |  11 |       2212 |  1 |  -1 |  5 |  5 | -0.050 | -0.055 |  0.135 |  0.923 | **0.938 | M = 0.910
|   3 |           B11 |   2 | 1000050110 |  1 |  -1 | 12 | 12 |  0.050 |  0.055 | -0.135 | 10.256 |  10.255 |
|   4 |           mu- |   1 |         13 |  0 |  -1 | -1 | -1 |  0.151 |  0.140 |  0.987 |  1.014 |   0.106 | P = (-0.149,-0.138,-0.979)
|   5 |       Delta++ |   3 |       2224 |  2 |  -1 |  6 |  7 | -0.201 | -0.195 |  0.947 |  1.709 | **1.231 | M = 1.394
|   6 |        proton |  14 |       2212 |  5 |  -1 |  8 |  9 | -0.059 | -0.010 |  0.269 |  0.978 |   0.938 | FSI = 4
|   7 |           pi+ |  14 |        211 |  5 |  -1 | 10 | 11 | -0.142 | -0.184 |  0.679 |  0.731 |   0.140 | FSI = 4
|   8 |        proton |   1 |       2212 |  6 |  -1 | -1 | -1 |  0.030 |  0.054 |  0.150 |  0.952 |   0.938 |
|   9 |        proton |   1 |       2212 |  6 |  -1 | -1 | -1 |  0.095 | -0.023 |  0.173 |  0.959 |   0.938 |
|  10 |           pi+ |   1 |        211 |  7 |  -1 | -1 | -1 | -0.411 | -0.142 |  0.325 |  0.561 |   0.140 |
|  11 |       neutron |   1 |       2112 |  7 |  -1 | -1 | -1 |  0.363 |  0.022 |  0.428 |  1.095 |   0.940 |
|  12 |      HadrBlob |  15 | 2000000002 |  3 |  -1 | -1 | -1 | -0.228 | -0.050 | -0.264 |  8.398 | **0.000 | M = 8.391
|---------------------------------------------------------------------------------------------------------------|
|       Fin-Init:                                            | -0.000 |  0.000 | -0.000 |  0.000 |             |
|---------------------------------------------------------------------------------------------------------------|
|       Vertex:         nu_mu @ (x =     0.00000 m, y =     0.00000 m, z =     0.00000 m, t =            0 s) |
|---------------------------------------------------------------------------------------------------------------|
| Err flag [bits:15->0] : 0000000000000000     |  1st set:                                              none |
| Err mask [bits:15->0] : 1111111111111111     |  Is unphysical:    NO |   Accepted:   YES                  |
|---------------------------------------------------------------------------------------------------------------|
| sig(Ev) =        4.3934e-38 cm^2  | d2sig(W,Q2;E)/dWdQ2 =      5.5985e-38 cm^2/GeV^3 | Weight =             1 |
|---------------------------------------------------------------------------------------------------------------|
```



# Neutrino Generators' definition of final state particles

**Whatever leaves the nucleus and could, in principle, be detected.**

- Much of what could be detected, will not be detected in practise.
- But the generator, by default, makes no assumption about the capabilities of your detector technology and the sophistication of your analysis methods.

For example, $\Lambda_c^+$ and $D_s$ have $c\tau_0$ which is much much larger than the nuclear radius. If $C^{12}$ was as big as the Earth, those particles would decay a light years away. From the generator point of view, these are 'final state particles'. Similarly, most detectors will not track a $\tau$ lepton, but some did. The $\tau$ lepton is also a 'final state particle' which is not decayed be default.

Many detector technologies and analyses will not pick them some of the produced particles and one is really interested in their decay products.

Make sure who understand which particles get produced by the neutrino generator and define who has the responsibility to decay the unstable ones. Both the neutrino generator and the detector simulation would decay these particles, if asked. A common mistake though is that neither is asked to.