SYSTEMATIC UNCERTAINTIES

THE NEUTRINO EXPERIMENT EXPERIENCE

Professor Costas Andreopoulos

UNIVERSITY OF LIVERPOOL

Science & Technology Facilities Council
Particle Physics Department

Outline

Systematics for neutrino experiments is an impossible topic to cover in any detail in 30'!

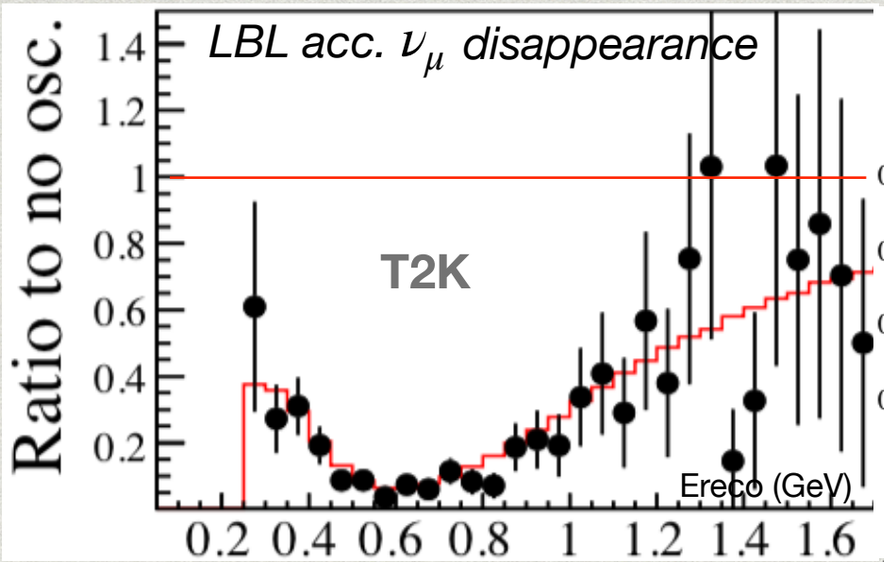
Given constraints and the presence of a broad audience (statisticians, collider physicists) I aim to give a broad picture and, as much as possible, avoid detailed technical discussion.

Focussing on systematics for accelerator-based neutrino oscillation experiments.

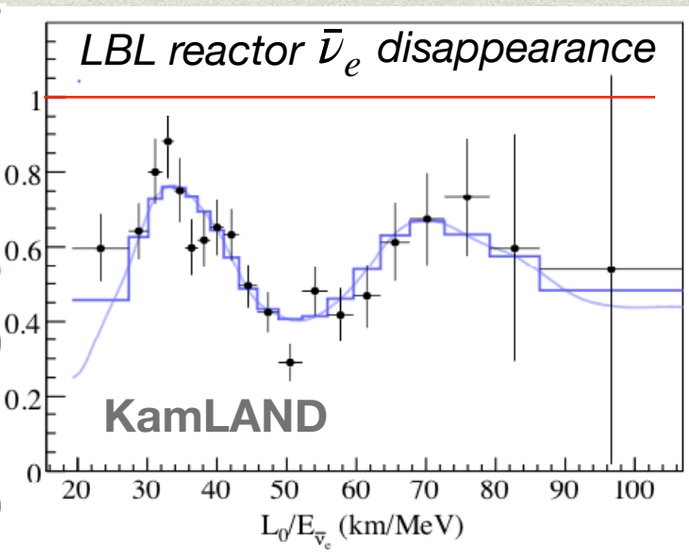
- What we measure
- What we infer from our measurements
- Types of uncertainties
- Oscillation analysis paradigms / mitigation of uncertainties
- Comparison of analysis paradigms and limitations
- Systematic error reduction achieved
- Requirements of future experiments
- Thoughts

What we measure

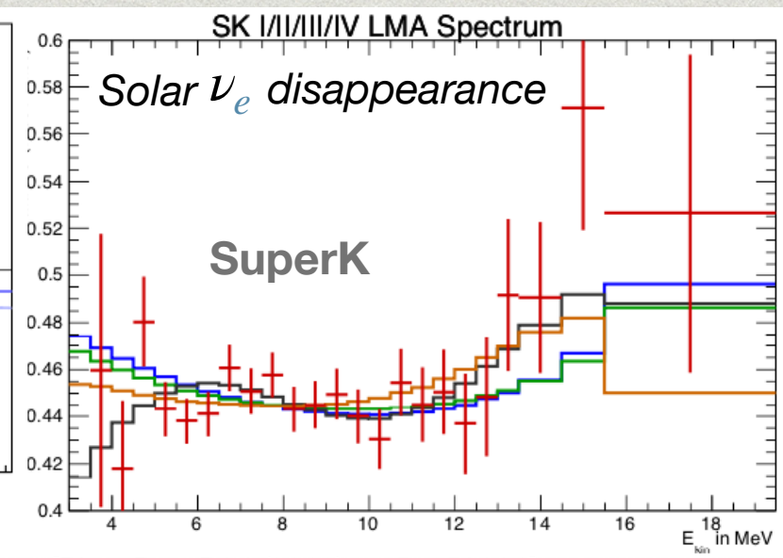
How (anti)neutrinos are **disappearing** and/or **appearing** as function of their energy and distance of travel (baseline)



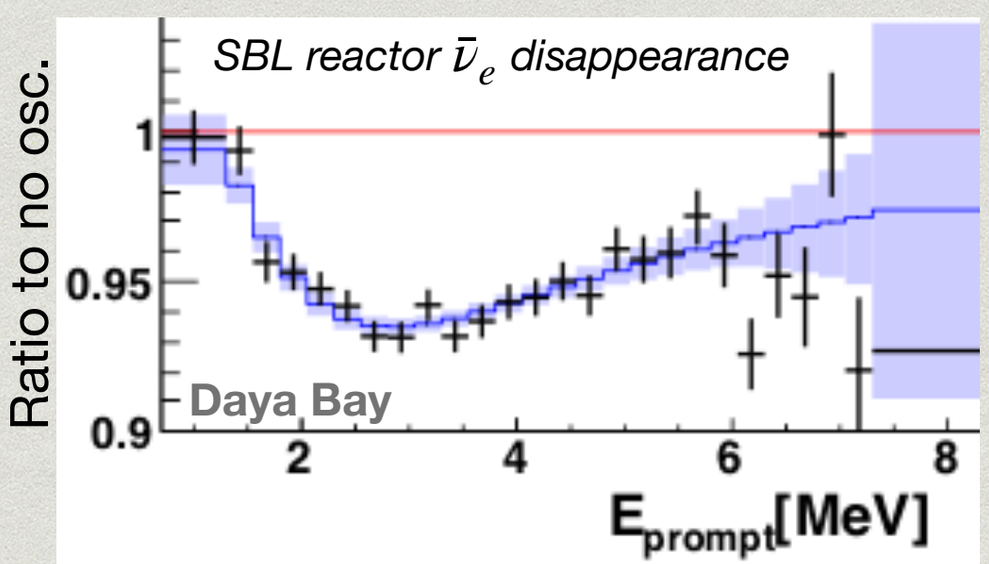
[Phys.Rev.Lett. 121 (2018) no.17, 171802]



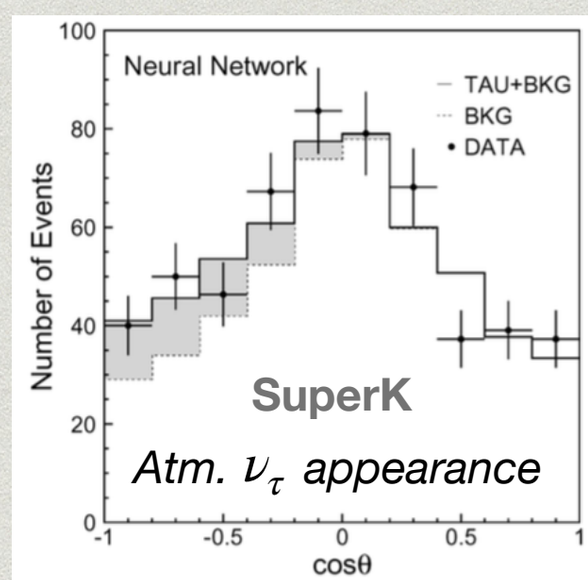
[Phys.Rev.Lett. 100 (2008) 221803]



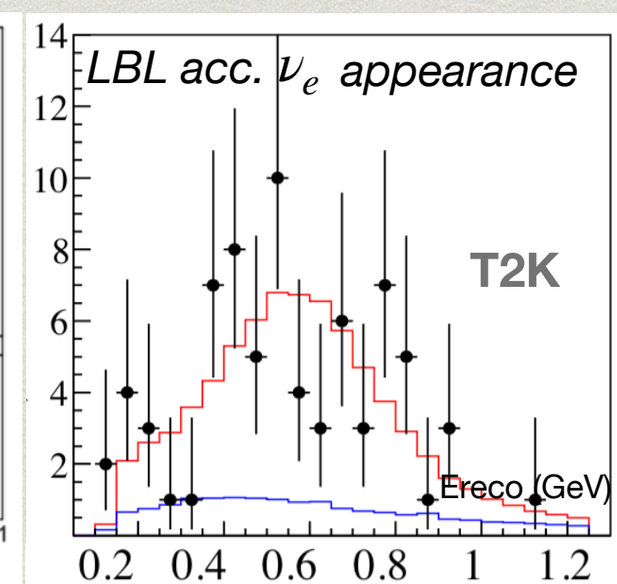
[Phys.Rev. D94 (2016) no.5, 052001]



[Phys.Rev.Lett. 121 (2018) no.24, 241805]



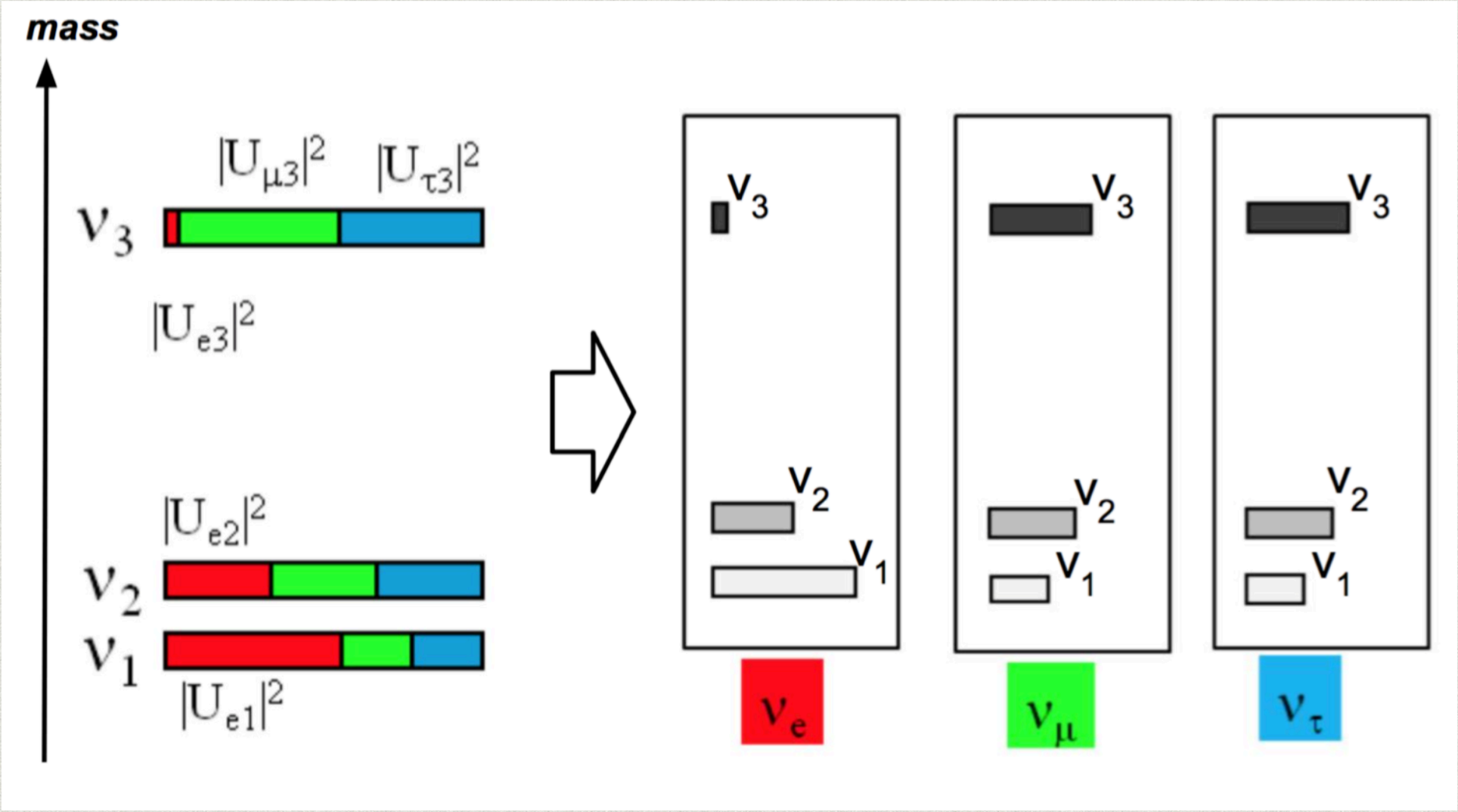
[Nucl.Phys.Proc.Suppl. 218 (2011) 309-313]



[Phys.Rev.Lett. 121 (2018) no.17, 171802]

What we infer from measurements

We infer properties of **neutrino mixing**



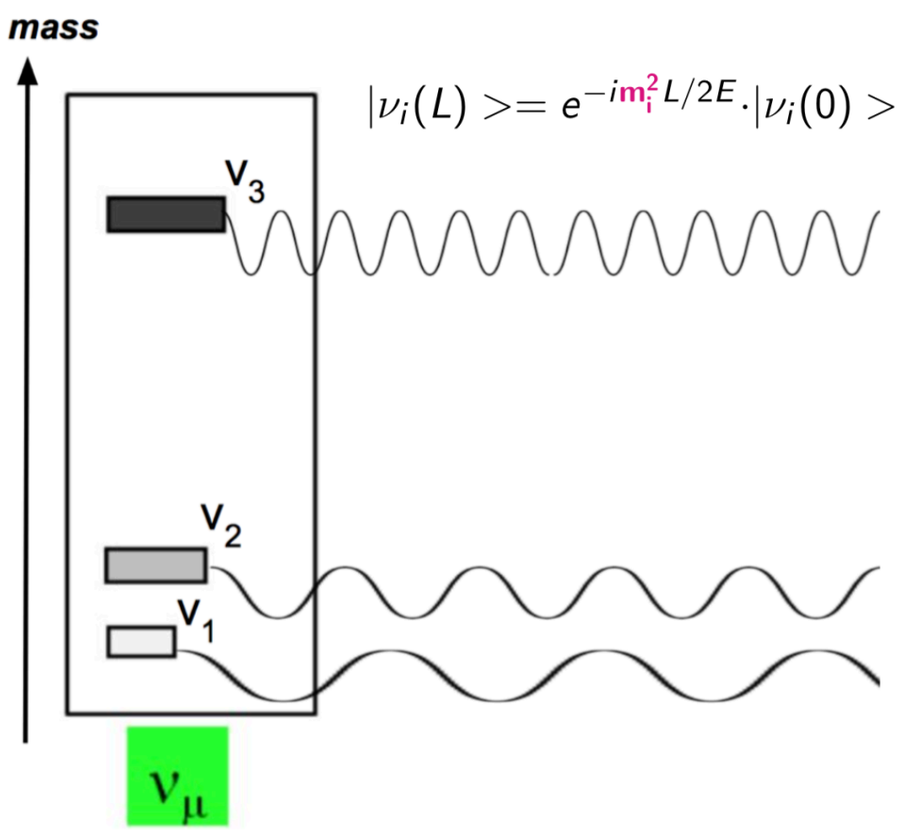
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Known flavour states are superpositions (mixtures) of mass eigenstates

Mixture is described by U_{PMNS} (U_{PMNS}* for antineutrinos)

What we infer from measurements

Each mass eigenstate evolves at own "pace"



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

Probability for flavour oscillation (ν_α -> ν_β):

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

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

- Any 2 squared mass splittings (e.g. Δm^2_{21},Δm^2_{32})
- 3 mixing angles (θ_{12}, θ_{13}, θ_{23})
- 1 CP invariance violating phase (δ_{CP})

Above picture can be expanded with more (sterile) neutrinos or other new physics effects

<u>Motivation</u>: Neutrino mixing is a **sensitive probe of new physics**

Main systematics

- Can not dead reckon the expected number of neutrino events to better than **~30%**.
- Yet, we do oscillation measurements at **a few-% level**.
- Experiments able to easily mitigate some of the largest overall normalisation uncertainties

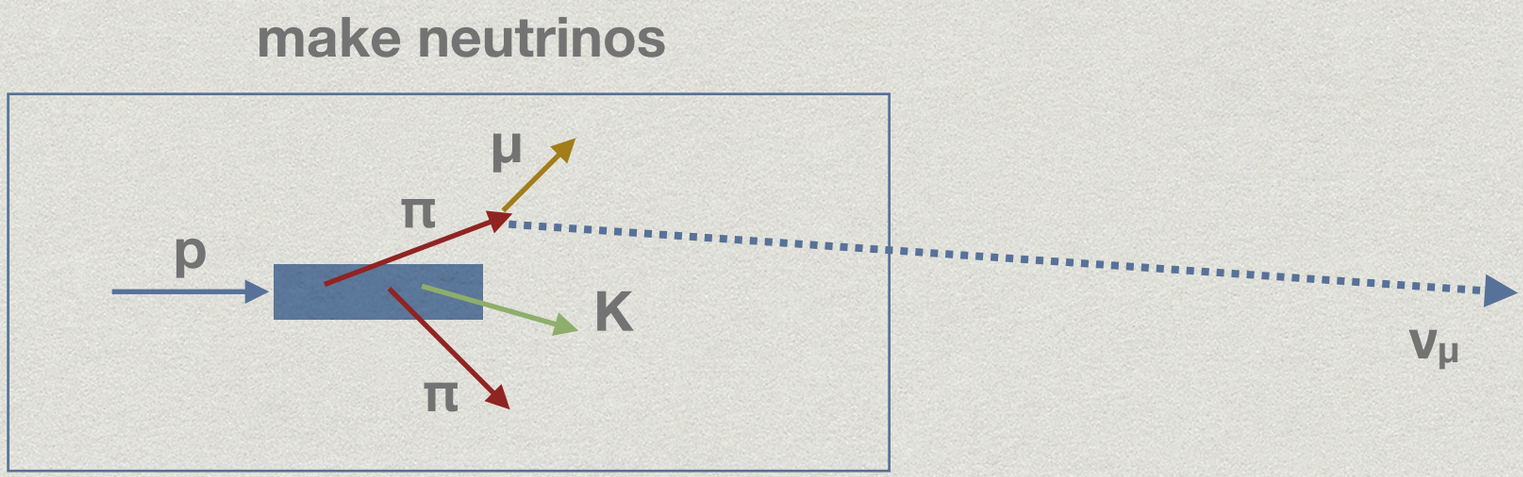
Considering that

- We measure oscillations between neutrino flavours
- We are interested in differences between neutrino and antineutrino appearance (CPV)
- Oscillations have a characteristic neutrino energy pattern

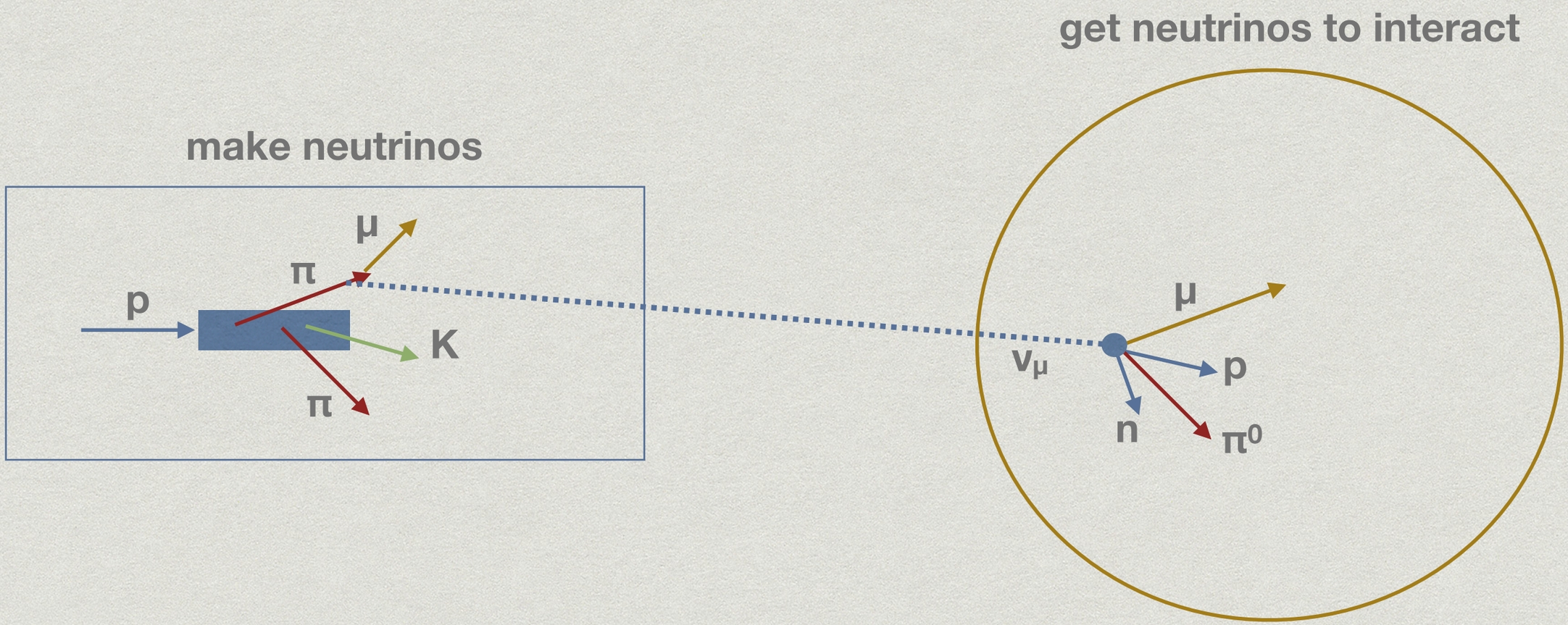
We are particularly sensitive to

- Not modelled **differences between electron and muon (anti)neutrinos**
- Not modelled **differences between neutrinos and antineutrinos**
- Not modelled **influences on neutrino energy reconstruction**

Three main ingredients

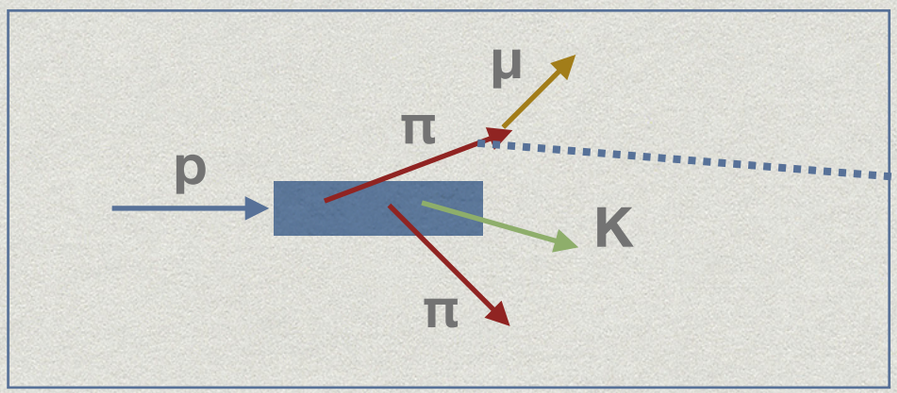


Three main ingredients

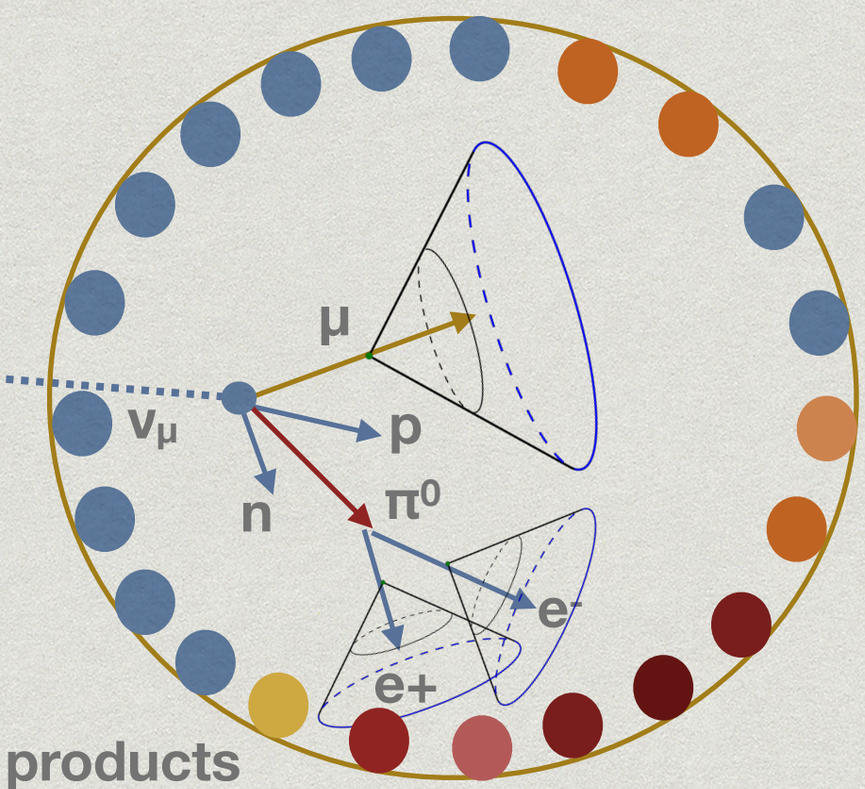


Three main ingredients

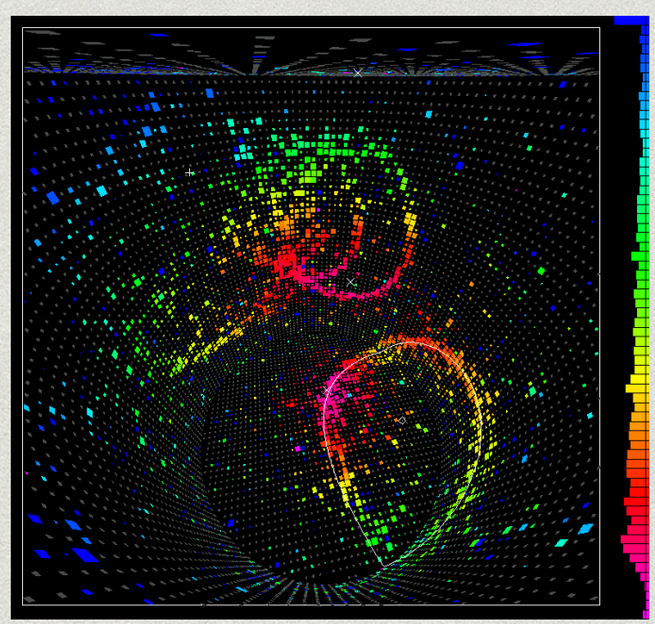
make neutrinos

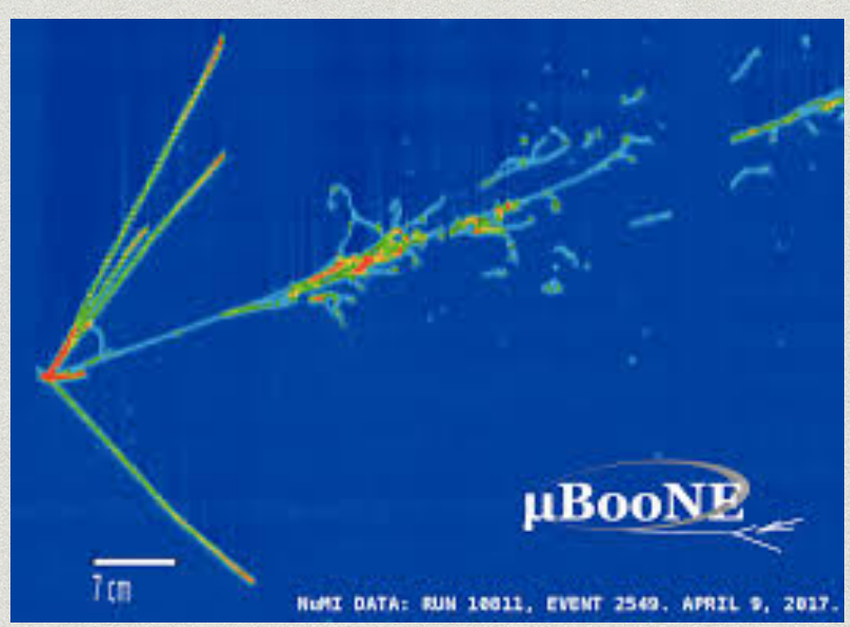


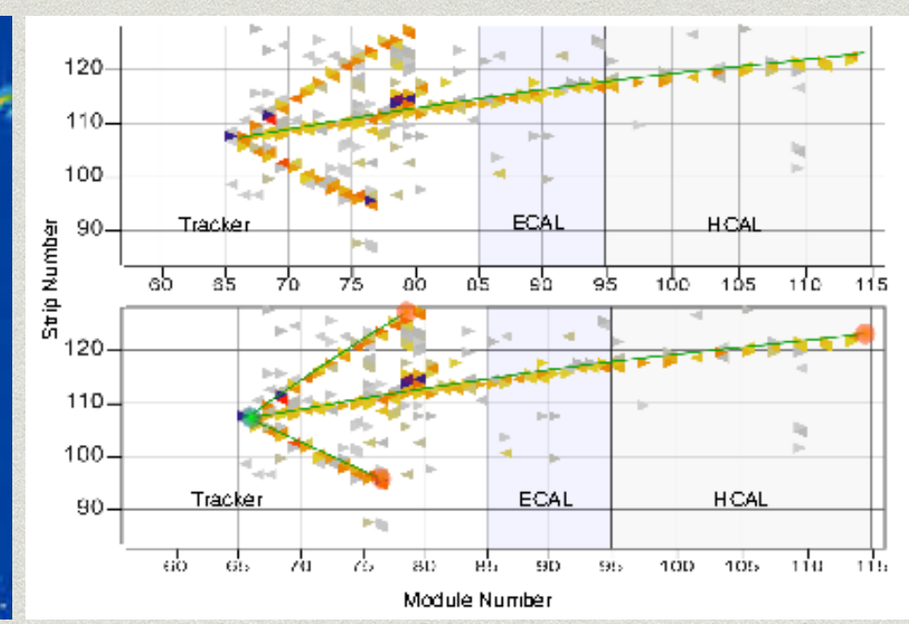
get neutrinos to interact



measure detector response to neutrino interaction products







Systematics

Arising from uncertainties in our understanding of

- the **neutrino source**,
- **neutrino interactions**,
- and the **detector response**

Systematics

Arising from uncertainties in our understanding of

- the **neutrino source**,

- **neutrino interactions**,

- and the **detector response**

You don’t mix

the good, the bad and the ugly

There is bloodshed

Yet, mixing the good, the bad and the ugly
is what we have to do to compare with measurements of **event rates**

Measuring **event rates**

An event rate is a complex convolution of:

neutrino fluxes, **oscillation probabilities**, **interaction cross-sections**, and **detector effects**

Expected number of events, of some type, identified as coming from neutrino flavour ν_f

Reconstructed (observed) neutrino energy E_r

Sum over initial flavours ν_i

Integral over entire range of true neutrino energies E_t

Flux of neutrino flavour ν_i at a particular true energy bin

Probability for $\nu_i \rightarrow \nu_f$ flavour oscillation

Oscillation parameters to be determined

Efficiency for detecting neutrino flavour ν_f

$$N^{exp}_{\nu_f}(E_r) \propto \sum_{\nu_i} \int dE_t \frac{d\Phi_{\nu_i}(E_t)}{dE_t} P^{\nu_i \rightarrow \nu_f}_{osc}(E_t; \vec{\alpha}) \epsilon_{\nu_f}(E_t) \sum_A w_A \sum_i \int dK^n_t \frac{d^n \sigma^i_{\nu_f A}(E_t, K^n_t)}{dK^n_t} R_i(E_r; E_t, K^n_t)$$

Sum over target nuclei

Weight fraction each nucleus

Sum over exclusive final states

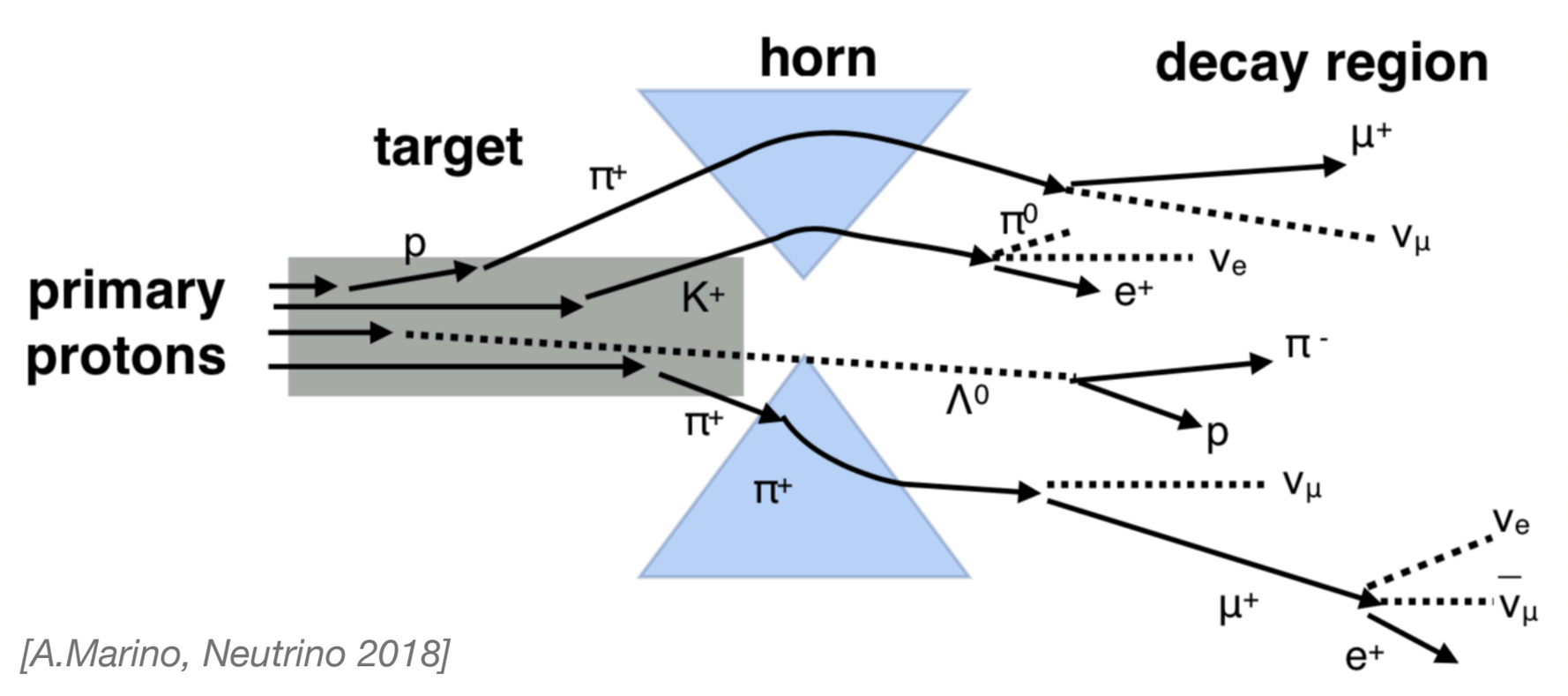
Integral over kinematical phase space

Differential cross-section for exclusive final state

"True to reconstructed energy" transfer function

Neutrino flux simulation and uncertainties

Flux is estimated by simulating interactions of primary protons, and following interaction products (simulating further re-interactions and decays) till they fall below an energy threshold.



[A.Marino, Neutrino 2018]

Where do our ν's come from?

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

Two main types of uncertainty:

- **Hadro-production:** Uncertainties in hadron production models driving the kinematic distributions of hadrons emanating from hadronic interactions in the beam-line.
- **Focusing:** Uncertainties in proton beam intensity, horn/target material, geometry, alignment, magnetic field calculation etc.

Substantial uncertainties - spread of predictions at the ~20% level!

Constraining flux uncertainties

External hadro-production measurements

- **Thin target** measurements (few % of interaction length λ)
- **Thick target** measurements
- or, even, **replica target** measurements

BNB	8.9 GeV/c
K2K	12.9 GeV/c
J-PARC	31 GeV/c
NuMI	120 GeV/c
CNGS	400 GeV/c

< 25 GeV/c

Reaction	Experiment	Particles Measured	Reference
8.9 GeV/c p + thin Be	HARP	π^+	Eur. Phys J C **52** (2007) 29
6.4, 12.3, and 17.5 GeV/c p + thin Be	BNL E910	$\pi^\pm$	Phys 0152
12.9 GeV/c p + thin Al	HARP	π^+	Nuc (200
12 GeV/c p and $\pi^\pm$ + C	HARP	$\pi^\pm$	Astr
19.2 GeV/c p on p,Be, Al, Cu, Pb	Allaby et al	p,pbar, $\pi^\pm$, $K^\pm$	Tech 197
24 GeV/c p on Be, Al, Cu, Pb	Eichten et al (CERN-Rome)	p,pbar, $\pi^\pm$, $K^\pm$	Nuc (197

120 - 160 GeV/c

Reaction	Experiment	Particles Measured	Reference
58, 84, 120 GeV/c p + various thin targets	E907/MIPP	n	
120 GeV/c p + NuMI low energy target	E907/MIPP	$\pi^\pm$	
158 GeV/c p +C	NA49	$\pi^\pm$	
158 GeV/c p +C	NA49	p, pbar, n, d, t	

400 - 450 GeV/c

Reaction	Experiment	Particles Measured	Reference
400 GeV/c p + 10-50 cm Be target	NA20	$\pi^\pm$, $K^\pm$,p,pbar	CERN Tech. Rept. 80-70 (1980)
450 GeV/c p + 10 cm Be target	NA56/SPY	K/π ratio	Phys. Lett. B**420** (1998) 225
450 GeV/c p + 10 cm Be target	NA56/SPY	$\pi^\pm$	Phys. Lett. B**425** (1998) 208
450 GeV/c p + Be target	NA56/SPY	$\pi^\pm$, $K^\pm$,p,pbar	Eur. Jour. Phys. C**10** (1999) 605

SHINE thin target

Reaction	Particles Measured	
31 GeV/c p + C	$\pi^\pm$	[1] Phys. Rev. C**84** (2011) 034604
31 GeV/c p + C	K^+	[2] Phys. Rev. C**85** (2012) 035210
31 GeV/c p + C	K^0_s, Λ	[3] Phys.Rev. C**89** (2014) 025205
31 GeV/c p + C	$\pi^\pm$, $K^\pm$,K^0_s, Λ,p	[4] Eur.Phys.J. C**76** (2016) 84

SHINE replica target

Reaction	M	
31 GeV/c p + T2K replica target	π^+	Eur.Phys.J. C76 (2016) no.11, 617
31 GeV/c p + T2K replica target	$\pi^\pm$	Preliminary release: https://edms.cern.ch/document/1828979/1
31 GeV/c p + T2K replica target	$\pi^\pm$,$K^\pm$,p	Paper in preparation

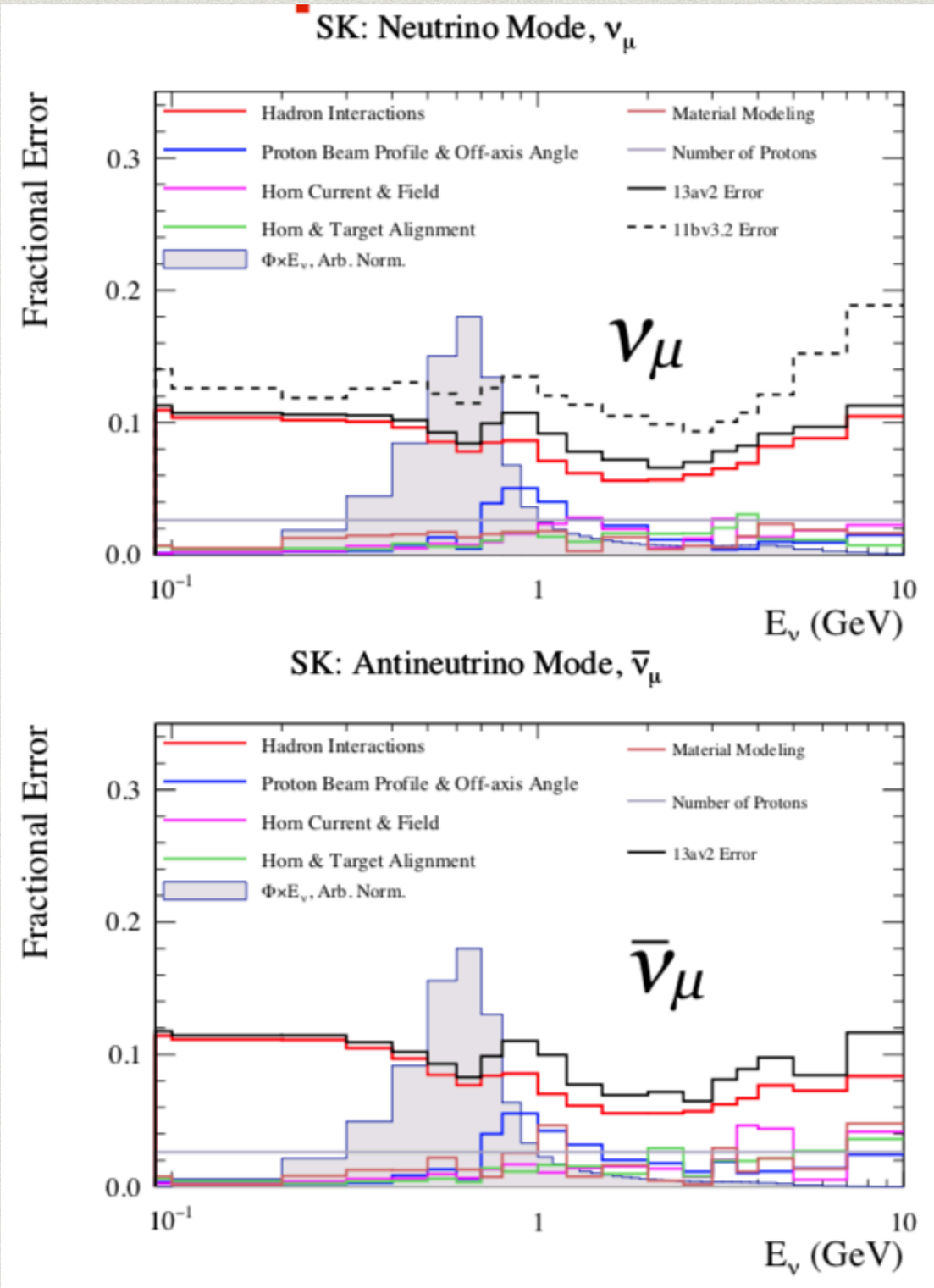
[Compilation of measurements by A.Marino, Neutrino 2018]

Constraining flux uncertainties

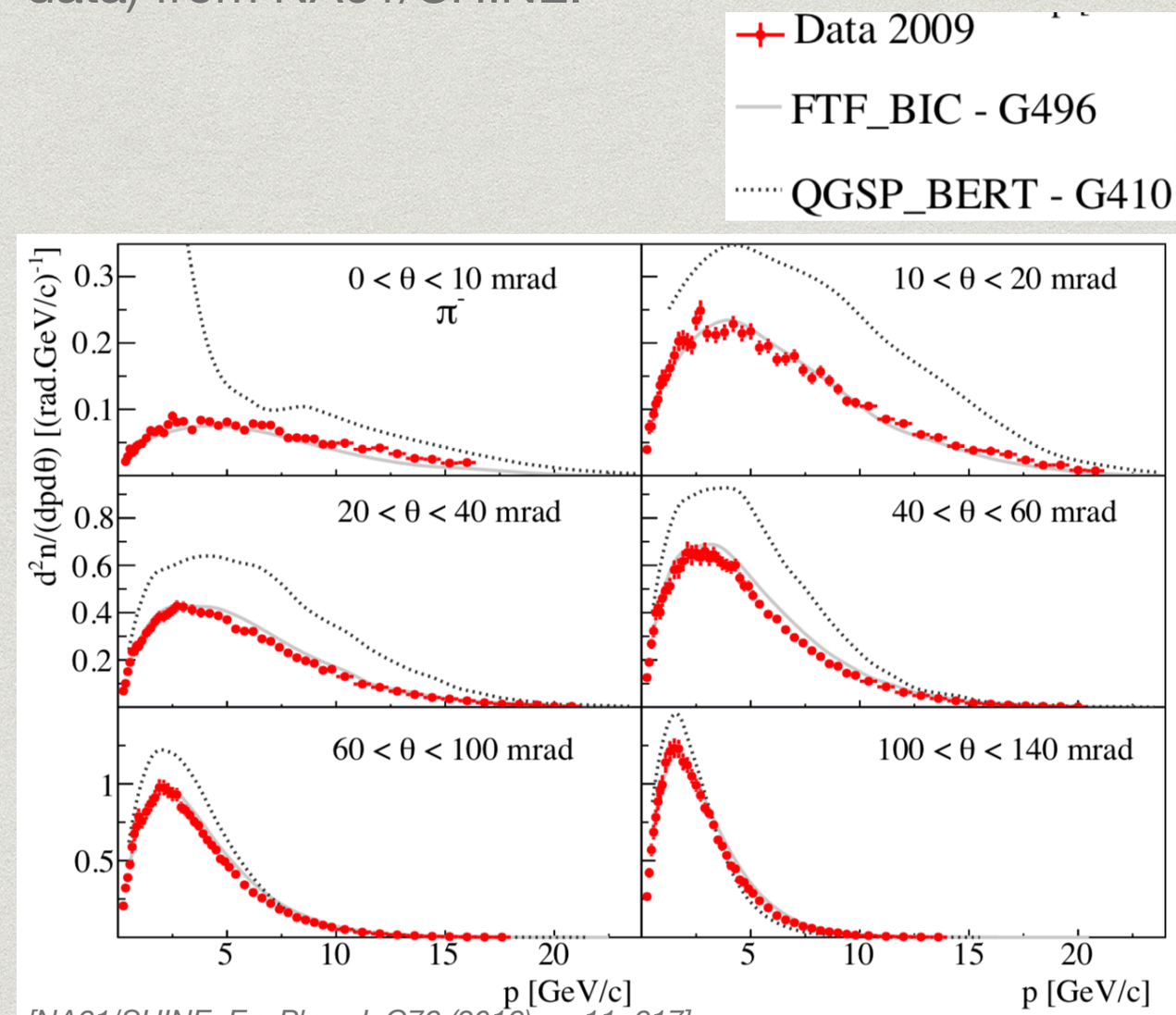
In situ measurements

- Hadro-production (in future, proposed LBNF Spectrometer and ENUBET projects)
- Hadron and muon monitors
- Primary proton beam instrumentation

Estimated flux uncertainties - Example from T2K



Tuned to hadron production spectra (thin target data) from NA61/SHINE.

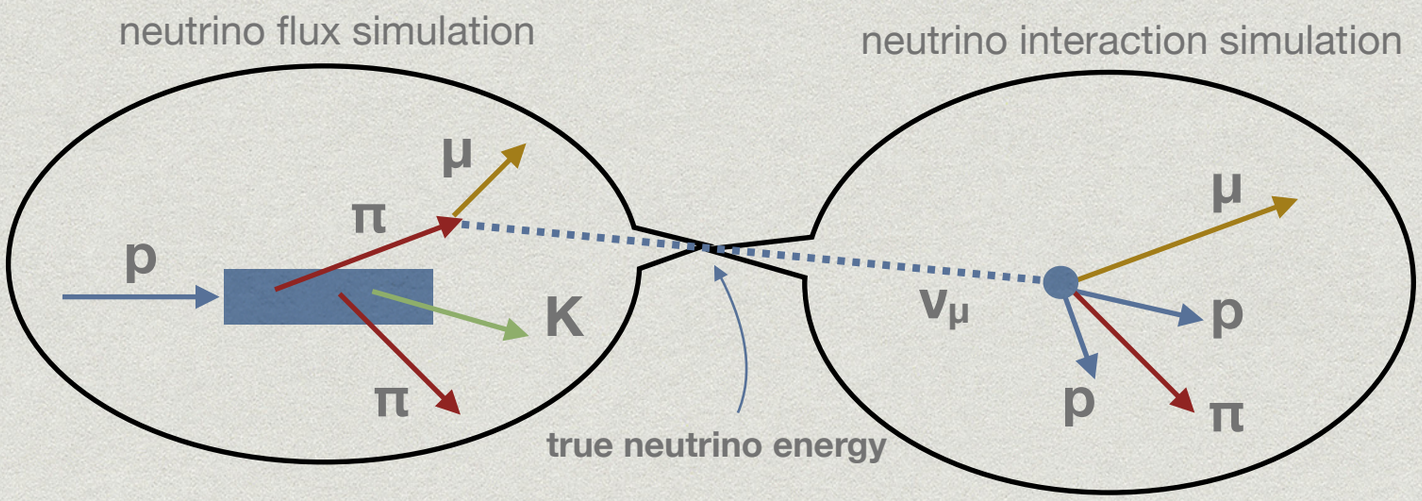


[NA61/SHINE, Eur.Phys.J. C76 (2016) no.11, 617]

Uncertainty reduced from ~20+% to ~8%

Expect to reduce to ~5% with replica target data

Treatment of flux uncertainties

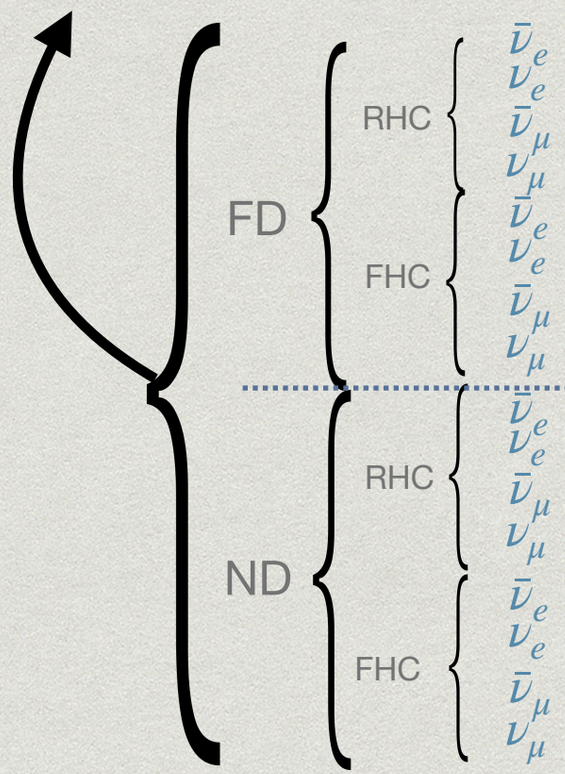


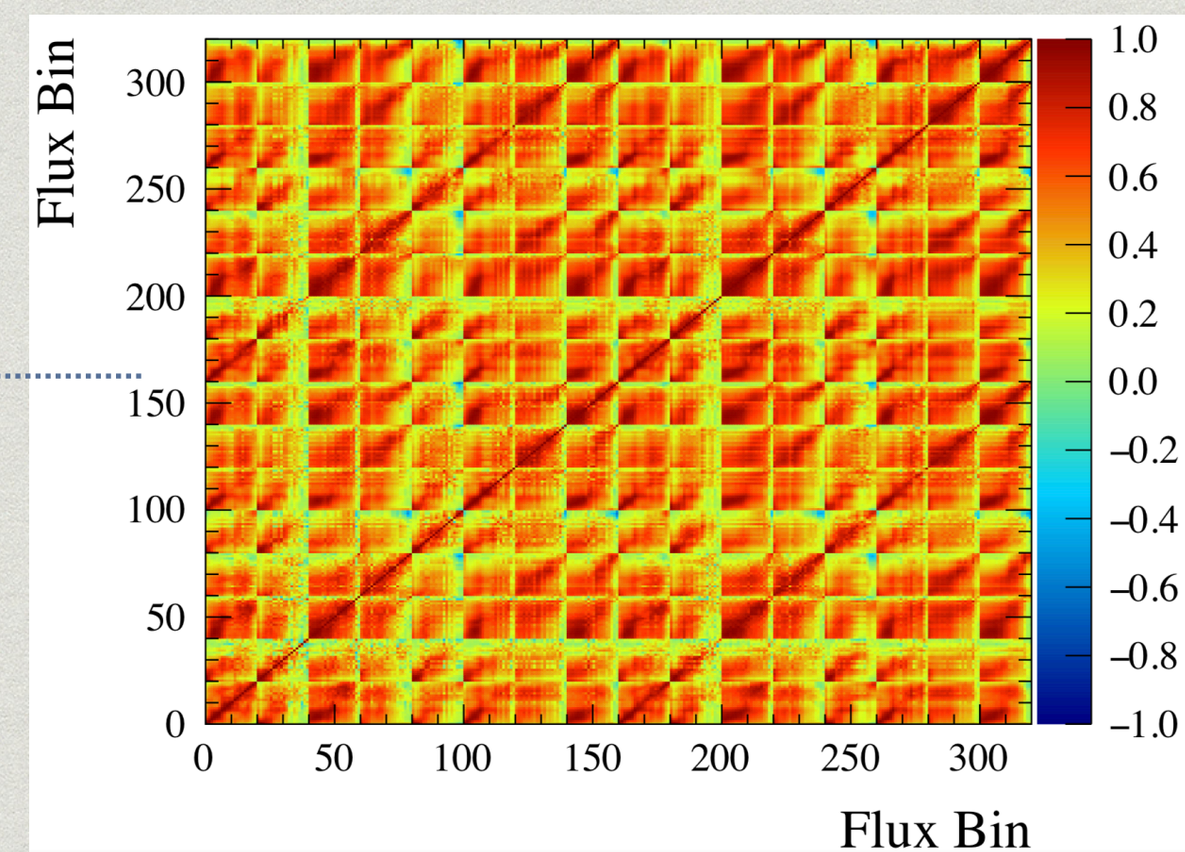
The **true neutrino energy** is the only kinematic variable that connects neutrino flux simulations and downstream event simulations.

$$N^{exp}_{\nu_f}(E_r) \propto \sum_{\nu_i} \int dE_t \frac{d\Phi_{\nu_i}(E_t)}{dE_t} P^{\nu_i \to \nu_f}_{osc}(E_t; \vec{\alpha}) \epsilon_{\nu_f}(E_t) \sum_A w_A \sum_i \int dK^n_t \frac{d^n \sigma^i_{\nu_f A}(E_t, K^n_t)}{dK^n_t} R_i(E_r; E_t, K^n_t)$$

Typically, neutrino experiments build **flux covariance matrices in energy bins** (spanning different locations, beam configurations and neutrino species).

Other weighting schemes also in use, accessing the parent information for a neutrino on an (MC) event-to-event basis





Neutrino flux systematics

Substantial uncertainties - spread of predictions at the ~20% level!

- Sufficiently **predictive models**
  - Well-motivated empirical parameterisation of hadron-production yields
  - Basic particle transport MC
- Programme of **measurements** (other than neutrino rates) **to constrain uncertainties**
  - Rigorous external hadro-production measurements
  - In-situ hadro-production measurements (in future)
  - Hadron and muon monitoring
  - Primary beam line monitoring and alignment
- **Further in-situ constraints using neutrino data**
  - Simple/unambiguous but comprehensive way of incorporating nuisance parameters

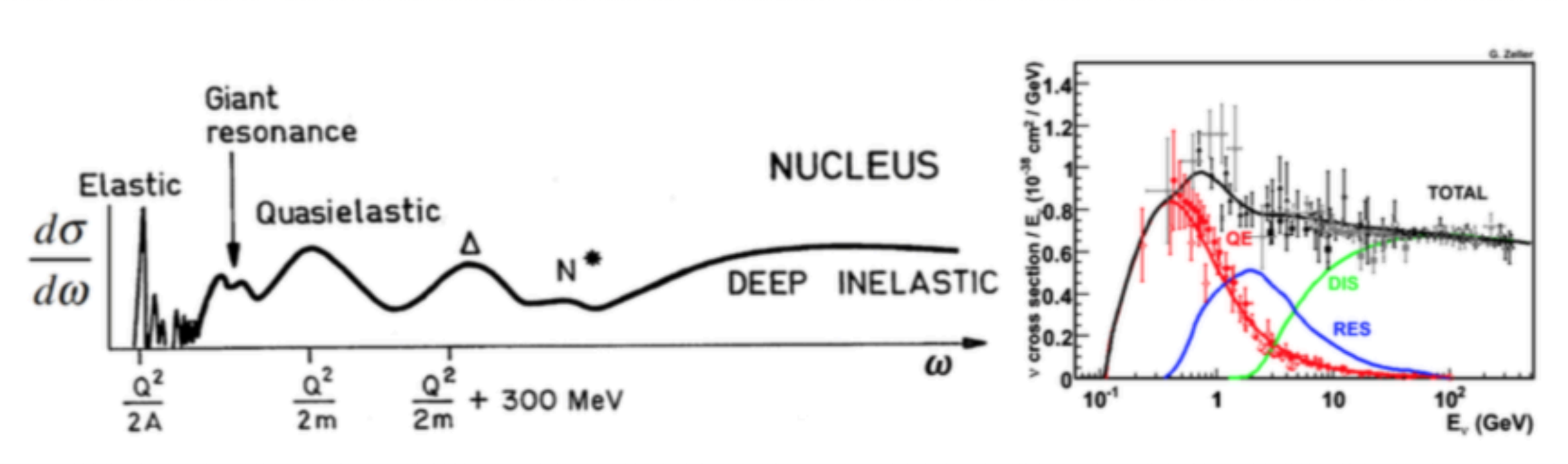
Neutrino interaction simulations and uncertainties

In accelerator-based experiments, neutrinos span a **very broad energy range**:

- Several scattering mechanisms are important.
- Crossing the **boundary between the non-perturbative and perturbative regimes**.

Simulating neutrino-**nucleus** interactions in a kinematical regime where

- the **impulse approximation is poor**, and
- **intranuclear hadron re-scattering effects are substantial**.

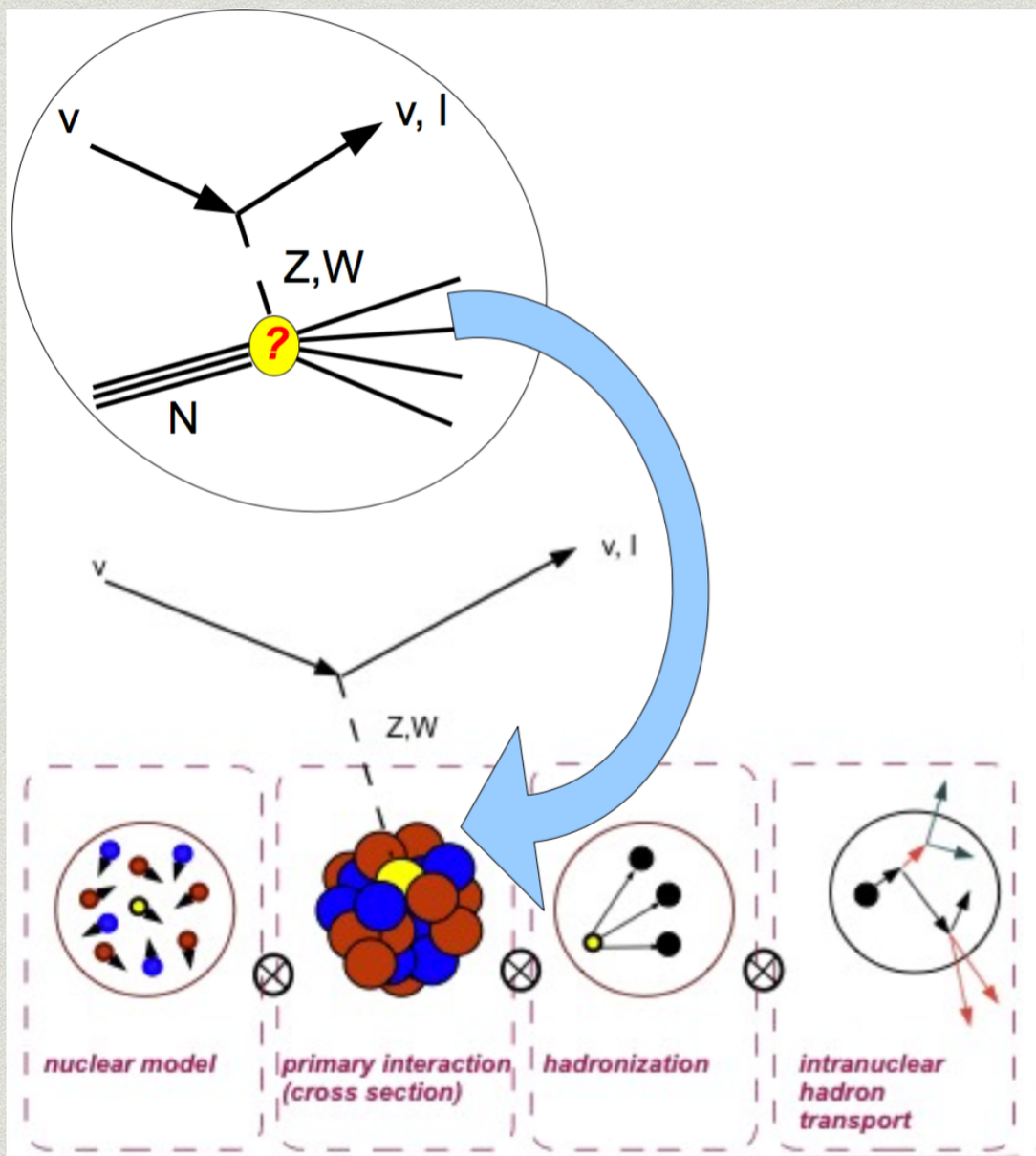


Neutrino interaction simulations and uncertainties

Poor theory coverage: Specific processes only, limited nuclei, limited phase space.

Simulation by mixture of theoretical and empirical models.

Forced factorisation and **difficult to enforce consistency**.



Building comprehensive simulations:

- 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 validity range.
- Merge models and address double counting.
- Developing empirical models to bridge the gaps and cover the full required phase space.
- Make up stuff in absence of both theory and data.

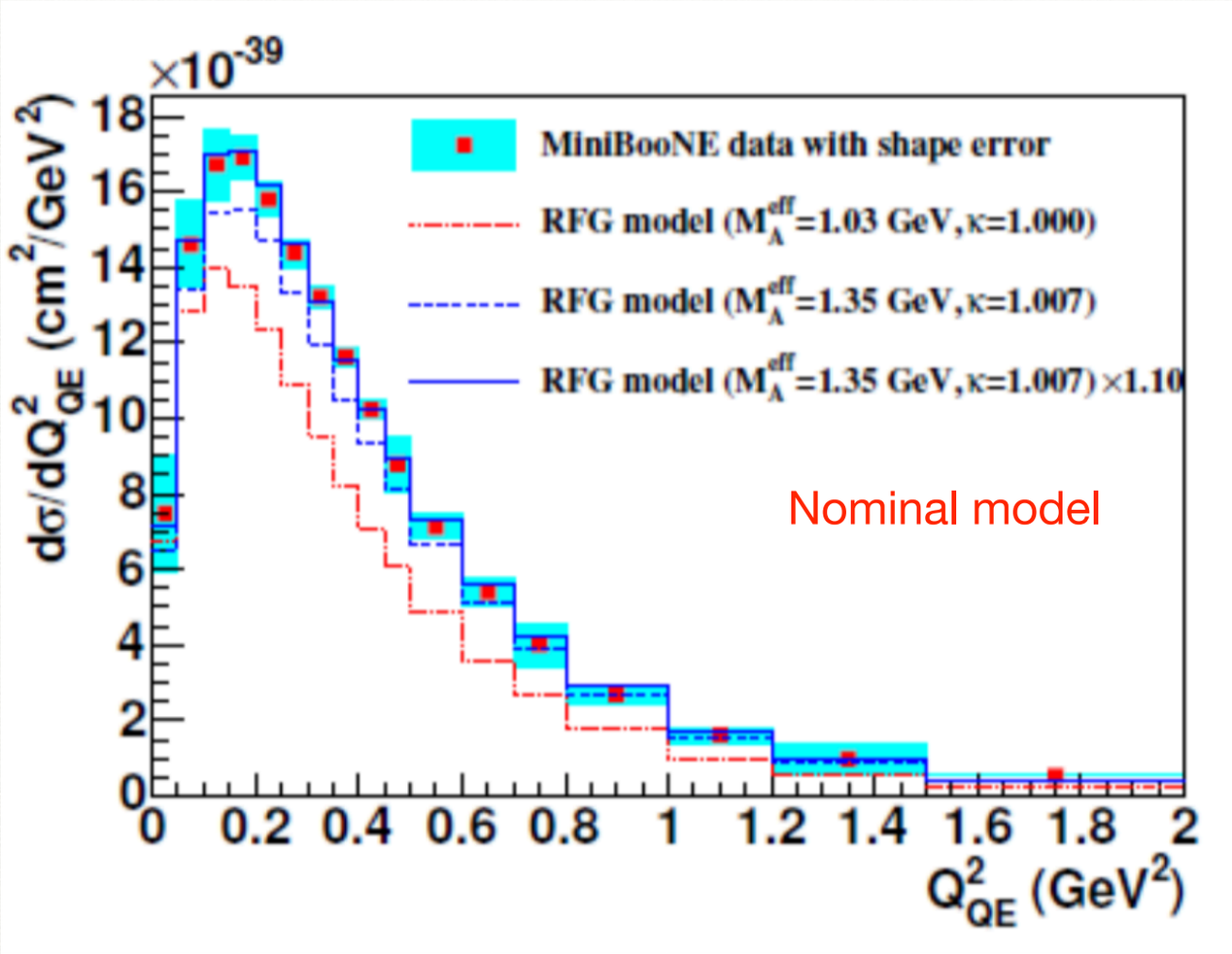
Highly **non-trivial uncertainties at each stage**

Experiments confronting data/MC discrepancies

Experiments need a model that describes their data

However, often, **data/MC agreements are handled in a non-satisfactory way**

- Overemphasising own data - breaking consistency with other neutrino data
- Largely ignoring complementary constraints from charged-lepton and hadron scattering



A typical (and conveniently old and non-controversial) example comes from the MiniBooNE experiment:

Tweaking axial form factor parameter

- Axial mass 1.03 -> 1.35 GeV
- Not consistent with bubble chamber results

Tweaking Pauli blocking

- Not consistent with textbook physics

Good description of own data.

But wrong physics!

Consistency and agreement across multiple datasets

Experiments, typically, have **narrower focus** and **lack some of the necessary expertise** (and tools).

Recently, Neutrino MC groups (closer contact with underlying models) have stepped up their game!

Development of tools and **comprehensive model characterisation using <u>complementary</u> data**

- (Anti)neutrino-nucleon/nucleus scattering
- Electron-nucleon/nucleus scattering
- Hadron-nucleus scattering

Development of global analyses within MC groups, informs model development

- Reusing some of the tools developed for LHC

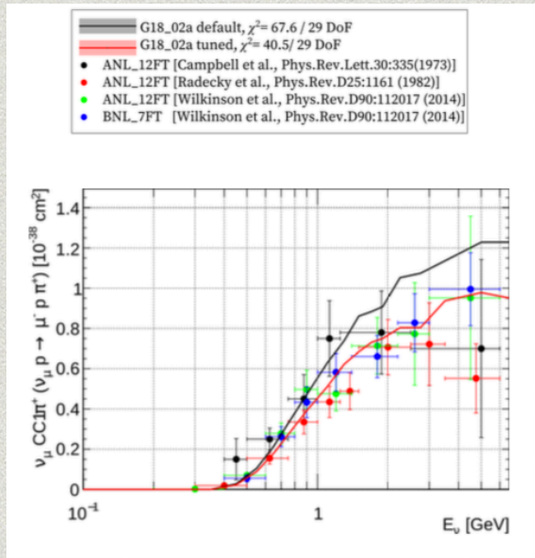
Expanded to **bring experts from the nuclear and electron scattering** communities (eg CLAS)

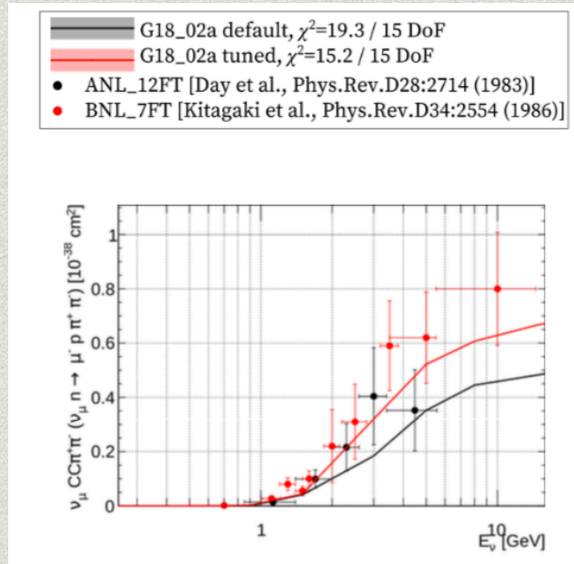
On our way to deliver **less-fine tuned, more predictive simulations**

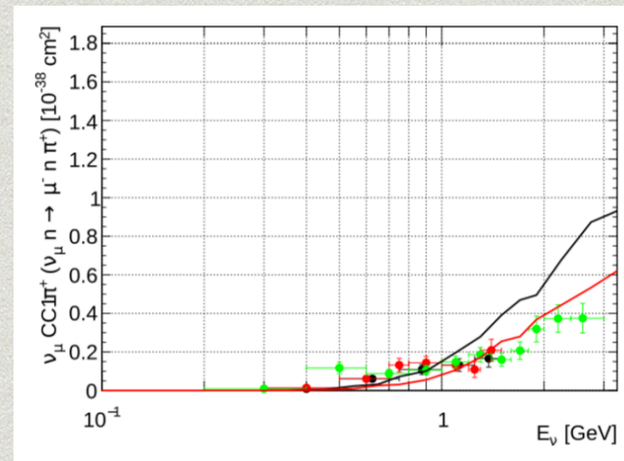
Currently, neutrino MC (and other fit) groups struggle to understand **tensions in data**

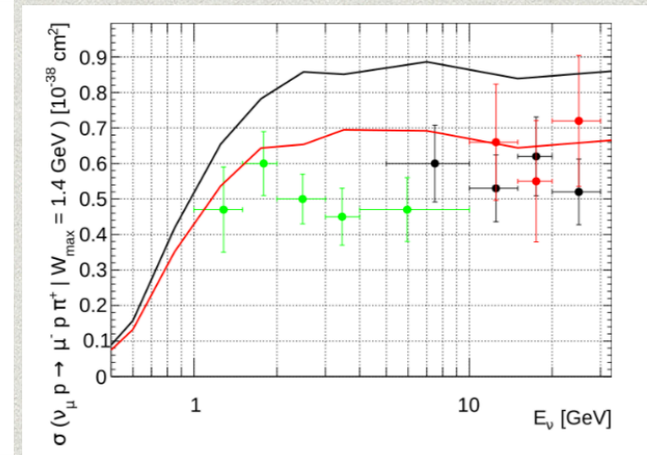
Tensions in neutrino interaction data

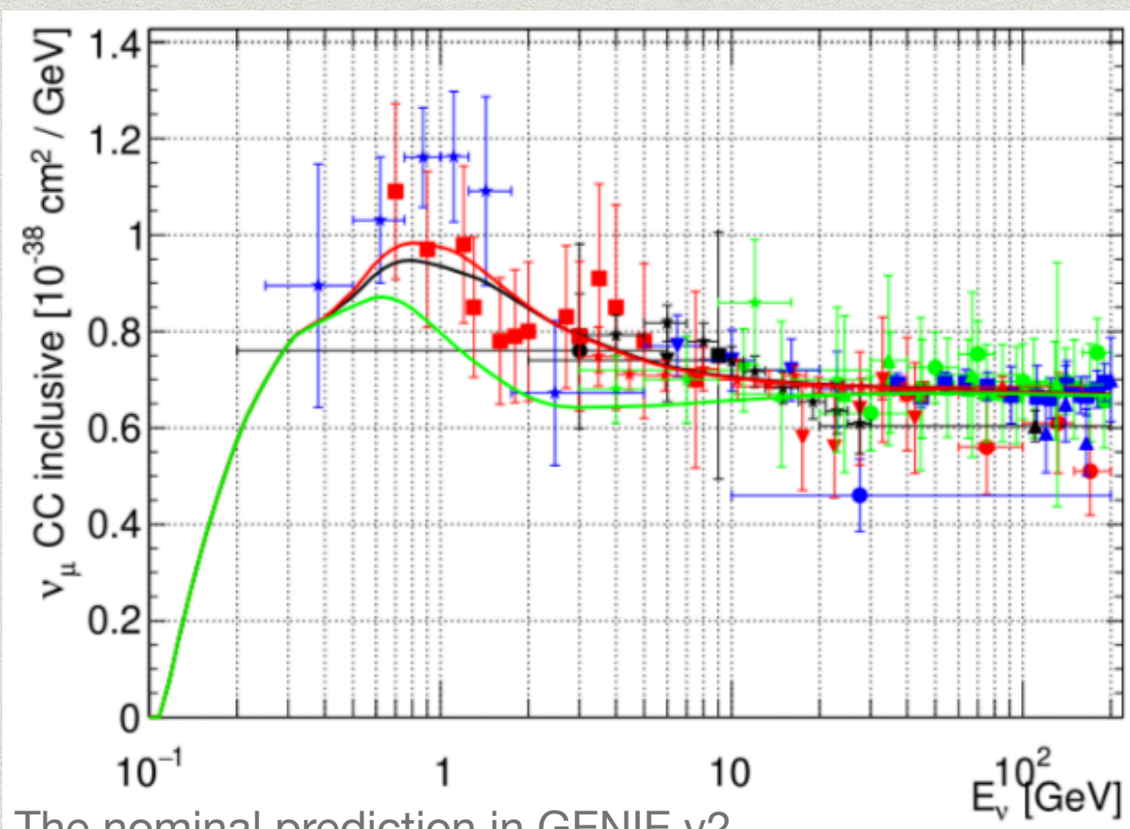
Example: **Tensions between historic exclusive and inclusive data**







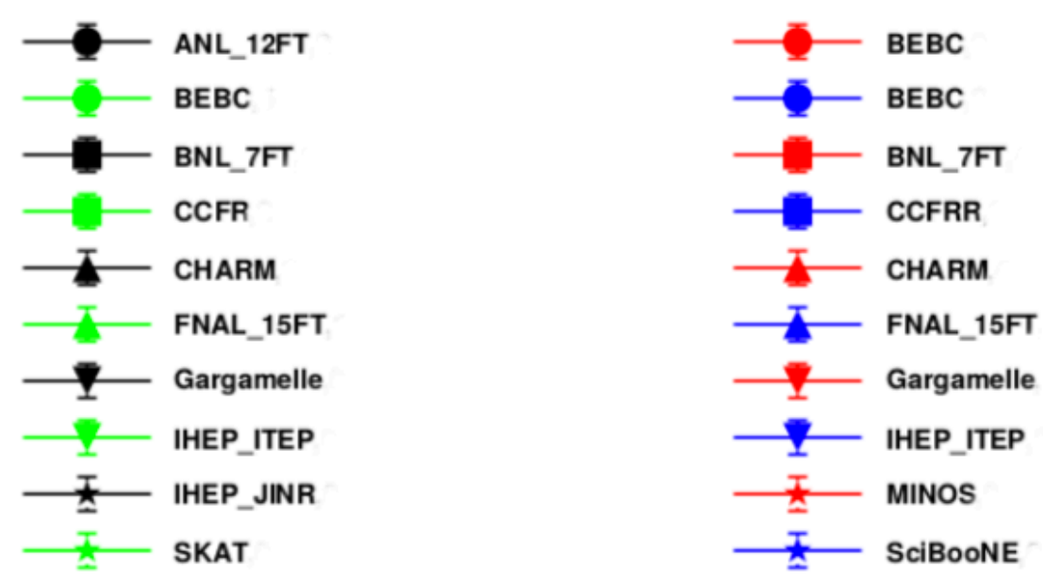




The nominal prediction in GENIE v2

Neutrino CC inclusive cross-section

[Free isoscalar target]



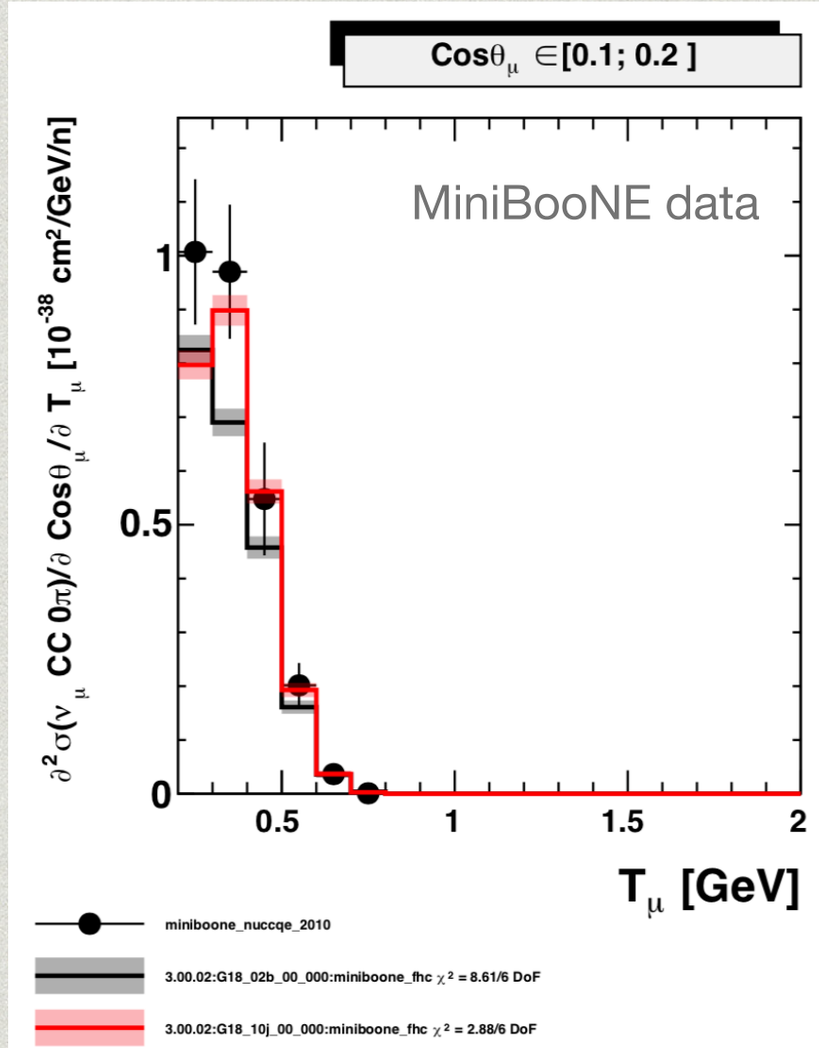
Prediction informed by a new tune against **inclusive data only** (GENIE v3, G18_01a configuration)

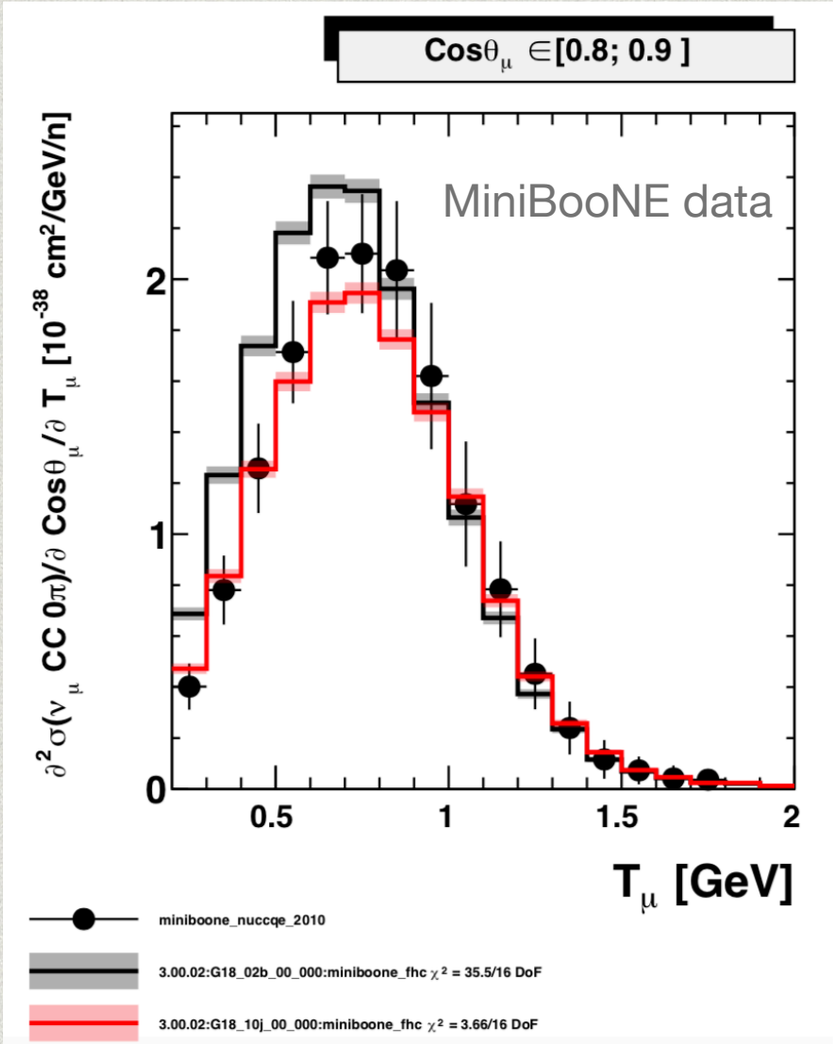
Prediction informed by a new tune against **exclusive data only** (GENIE v3, G18_01a configuration)

Tensions in neutrino interaction data

Example: **Tensions between data from modern experiments**

- **G18_02b:** An improved empirical model in GENIE3.
- **G18_10j:** A more theory-based model configuration in GENIE3.





GENIE tune	χ^2/ndf
G18_02b_00_000	330 / 137
G18_10j_00_000	63.7 / 137

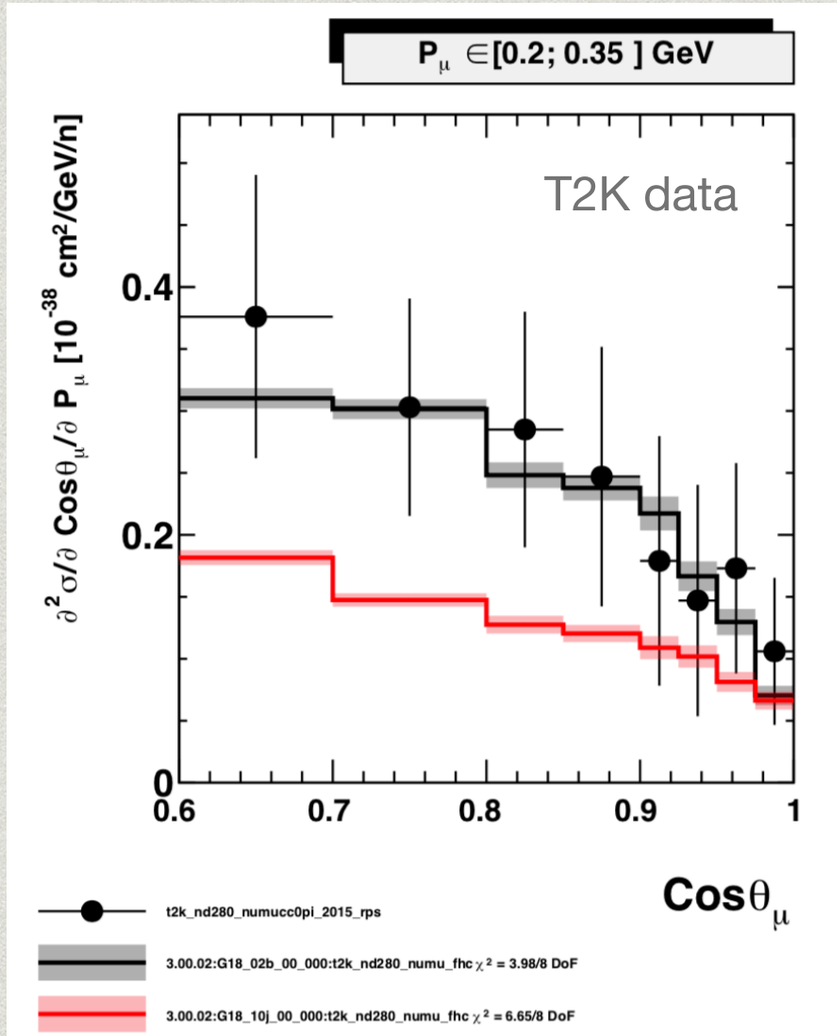
MiniBooNE data

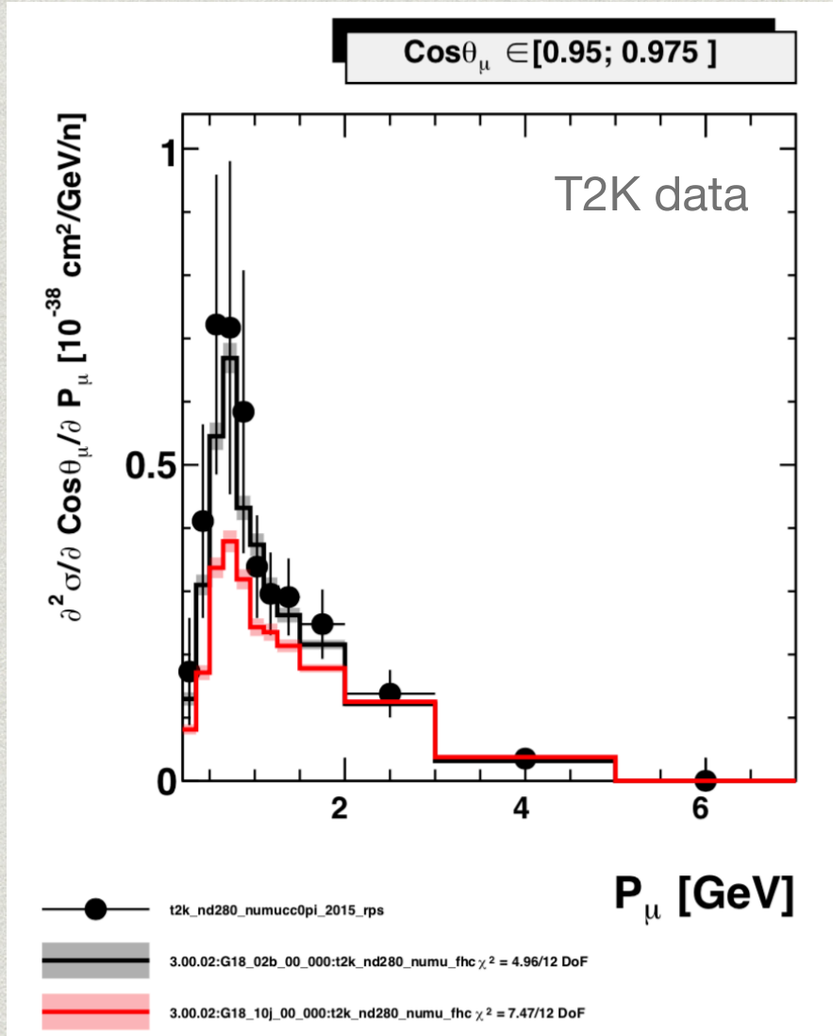
prefers G18_10j

Tensions in neutrino interaction data

Example: **Tensions between data from modern experiments**

- **G18_02b:** An improved empirical model in GENIE3.
- **G18_10j:** A more theory-based model configuration in GENIE3.





GENIE tune	χ^2/ndf
G18_02b_00_000	73.9 / 80
G18_10j_00_000	80.4 / 80

T2K data

prefers G18_02b

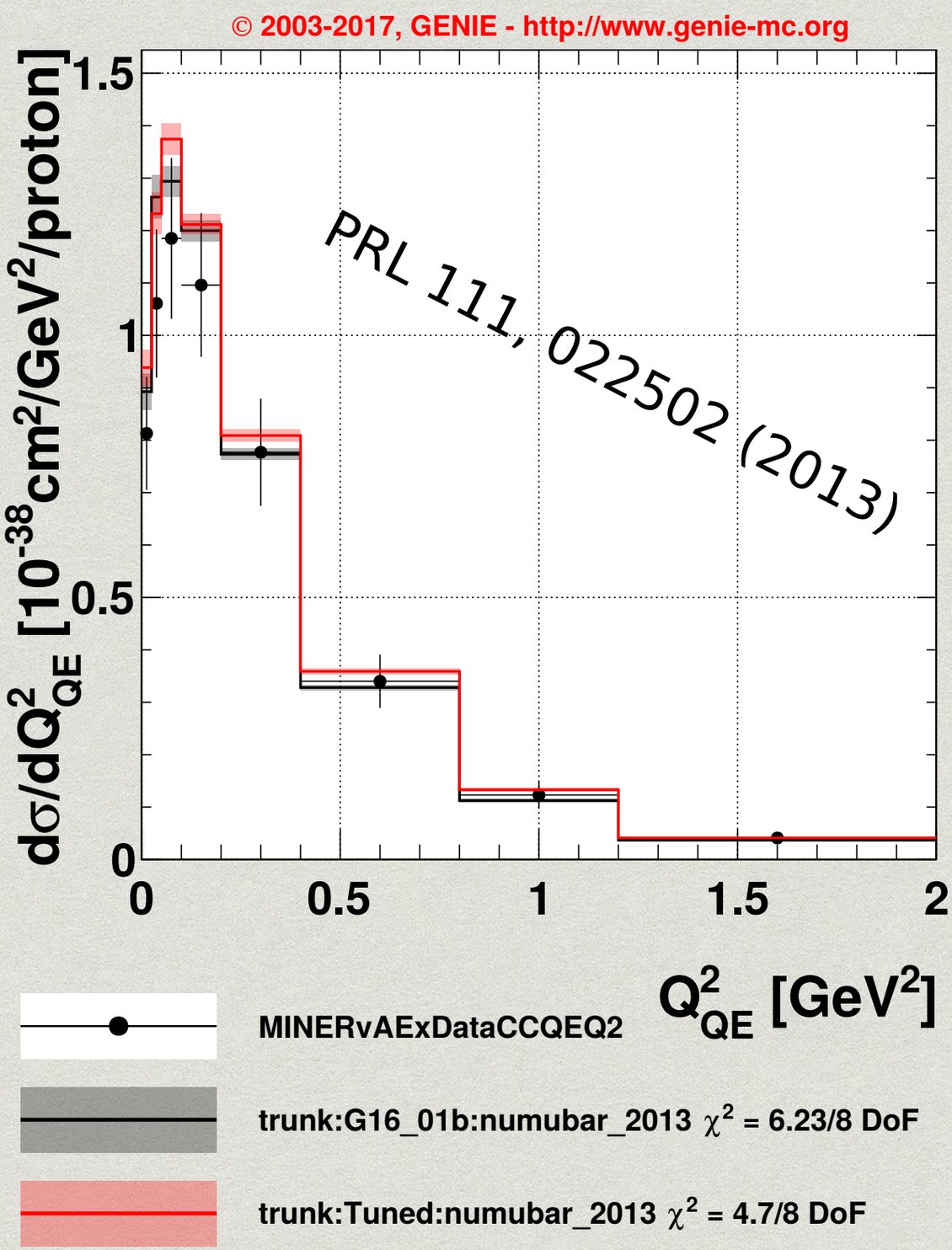
Tensions in neutrino interaction data

Currently taking a **conservative view** trying to provide errors that account for the tensions and differences between datasets.

Exploring what tension may imply for our models.

Plans (at least in GENIE) to provide several **partial tunes** for **consistent sets of measurements** only.

Eyeball comparisons and incomplete data



In neutrino conferences we get to view a lot of comparisons and draw conclusions by eye!

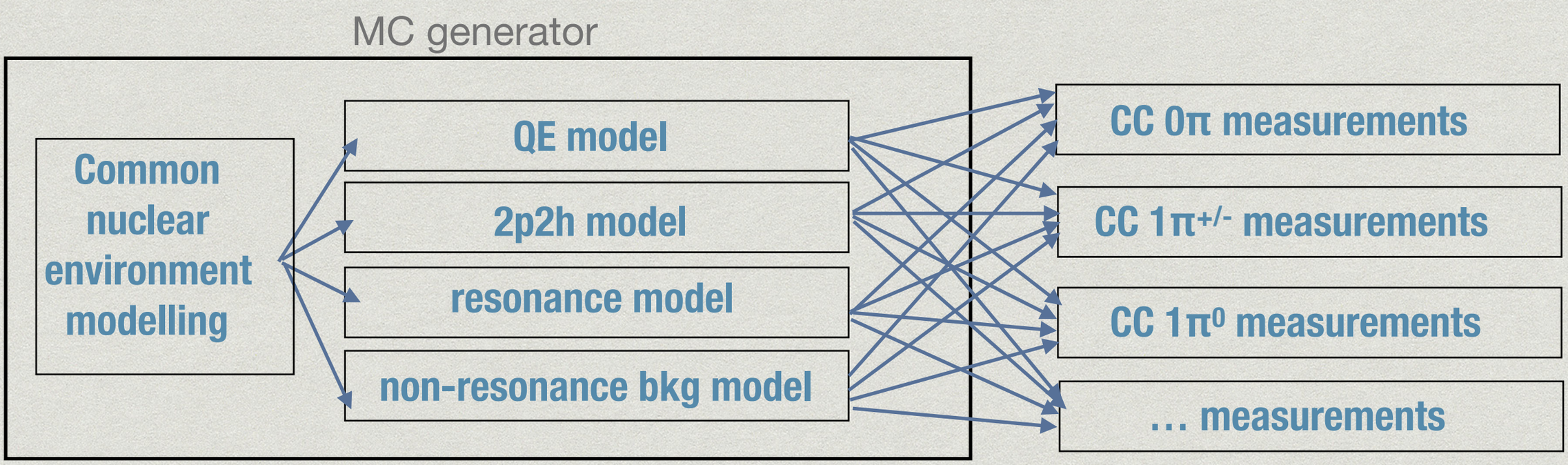
Correlations can alter the conclusion.

Correlations are important! (What a surprise!)

Crucial correlations missing even from (recent) measurements of dedicated cross-section measurement experiments.

Incomplete data

Crucial correlations missing even from (recent) measurements of dedicated cross-section experiments.



Everything couples to everything - **Need correlations across observables for <u>different</u> exclusive channels** to underpin comprehensive model characterisation and global fits.

Incomplete data -> **Diminished scientific legacy of experiments**

Aim to improve usability of data and analyses in near future experiments (**SBND**) -> improving neutrino-Argon interaction modelling for **DUNE**.

Interesting ideas and technology developed in the collider community (RECAST) aided by container technology - **The future for preserving analyses and tune MCs using folded data?**

The unopened can of worms

- Problems in 0π and 1π modelling and tensions between measurements
  - But we have barely scratched the surface
- Low-Q2, high-x DIS, hadronization modelling and in-medium effects to hadronization an unopened can of worms.
  - Important for DUNE!
  - New sources of uncertainty to consider
- No time at this talk; See recent **NuSTEC topical DIS workshop at GSSI** (Oct 2018)

Neutrino interaction systematics

- Challenging and intellectually-intensive simulations
  - **Mix of theory, empirical models, extrapolations, guesses**
    - **Consistency?**
  - Generally, **simulations not sufficiently predictive** though progress takes place
  - **Difficult to parameterise many sources of uncertainty**

- **Data**, even recent, **can not underpin detailed characterisation and tuning**
  - Absolute cross-section measurements not more accurate than knowledge of flux
  - Incomplete neutrino data
    - Eg, measurements of many complementary channels **but no inter-channel correlations**
  - Tensions between neutrino data
  - Under-utilised non-neutrino data

- **Strong adherence to an insufficient paradigm for propagating systematics**
  - Reweighting (as long as it is provided by GENIE)
  - But many key uncertainties (hadronic simulations) are not reweightable - tend to ignore

Detector systematics (*)

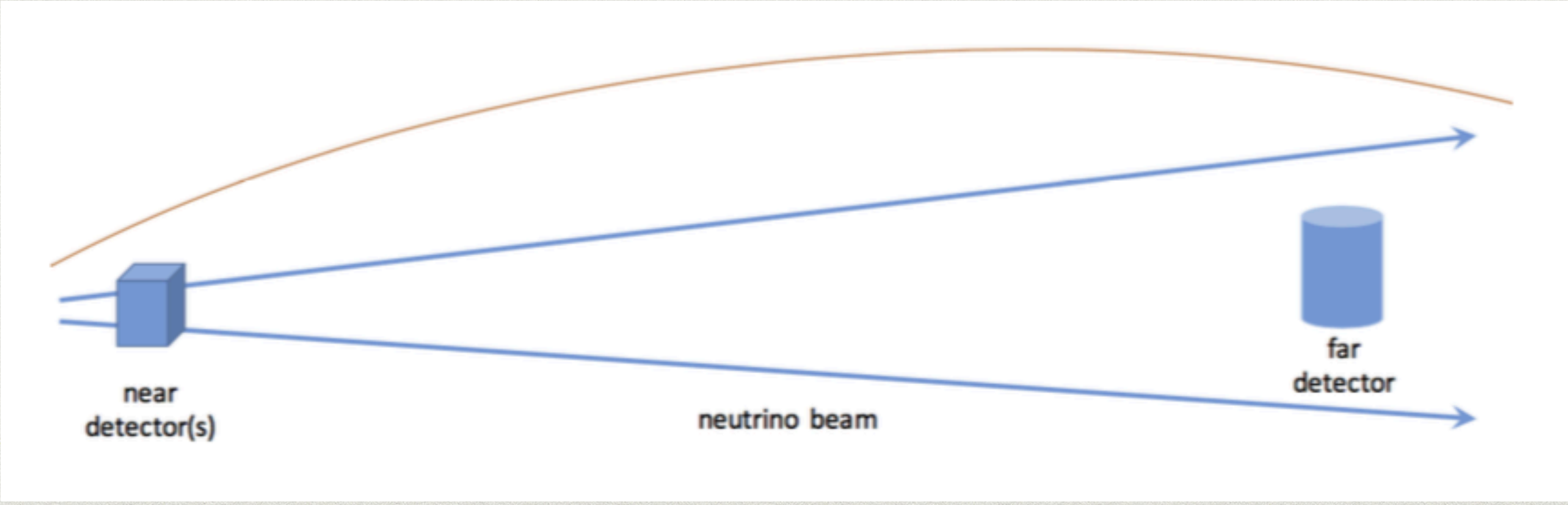
- **Can not describe in any detail as part of this talk**
  - Different approaches owing to variety of detection techniques, calibration systems etc
- **Generally well-motivated, but multi-fragmented and not very rigorous approach**
  - Reasonably predictive MC models
  - Data (often different from neutrino data)
    - Beam tests
    - Calibration systems
    - Standard candles (cosmic muons, Michel electrons)
    - Control samples
- Can play an important role
  - In may cases, drive the **ultimate sensitivity ceiling**

(*) Broadly defined to include all aspects of detector response and calibration, reconstruction and data reduction

Multi-detector experiment paradigm

Making oscillation measurements at ~few % level while model is known to ~30%?

Using multiple detectors at different baselines to mitigate the worst uncertainties



<u>Near to Far extrapolation:</u>

A **data-driven estimate** of the un-oscillated event rate at the Far detector

2 analysis paradigms: **Indirect** and **direct** extrapolation

Multi-detector experiment paradigm - Simplified picture

$$N^{obs}_{\nu_f}(E_r) \propto \sum_{\nu_i} \int dE_t \frac{d\Phi_{\nu_i}(E_t)}{dE_t} P^{\nu_i \to \nu_f}_{osc}(E_t; \vec{\alpha}) \epsilon_{\nu_f}(E_t) \sum_A w_A \sum_i \int dK^n_t \frac{d^n \sigma^i_{\nu_f A}(E_t, K^n_t)}{dK^n_t} R_i(E_r; E_t, K^n_t)$$

(over)simplify as

$$N^{obs} \propto \Phi \times P_{osc} \times \epsilon \times \sigma$$

At "Far" detector

$$N^{obs}_{Far} \propto \Phi_{Far} \times P_{osc} \times \epsilon_{Far} \times \sigma_{Far}$$

At "Near" detector (too near for oscillation)

$$N^{obs}_{Near} \propto \Phi_{Near} \times \epsilon_{Near} \times \sigma_{Near}$$

For identical detectors

$$\frac{N^{obs}_{Far}}{N^{obs}_{Near}} \propto \frac{\Phi_{Far}}{\Phi_{Near}} \times P_{osc} \times \overbrace{\frac{\epsilon_{Far}}{\epsilon_{Near}}}^{\approx 1} \times \overbrace{\frac{\sigma_{Far}}{\sigma_{Near}}}^{\approx 1} \Rightarrow$$

for "identical" detectors

$$\boxed{N^{obs}_{Far} \propto N^{obs}_{Near} \frac{\Phi_{Far}}{\Phi_{Near}} \times P_{osc}}$$

Limitations

No such thing as ”functionally identical” detectors

Near detector closer to source and at shallower depth

- Different beam-related and cosmic backgrounds
- Different flux (line source vs point source, oscillations!)

High event rate in the Near hall often necessitates different technology

- Uncorrelated detector systematics between Near and Far detectors
- Different acceptance from the (usually 4π) Far detector
- Different nuclear targets

Unavoidable reliance on models -> non-trivial systematics

Reliance on models

EXAMPLE: ELECTRON-(ANTI)NEUTRINO CROSS-SECTIONS

- Large observed value θ_{13} of is a mixed blessing
  - **Large appearance rate** for electron (anti)neutrinos

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

Phys. Rev. D64 (2001) 053003

Leading term

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

"+" for antineutrino

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

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

  - But **small CP asymmetry**

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

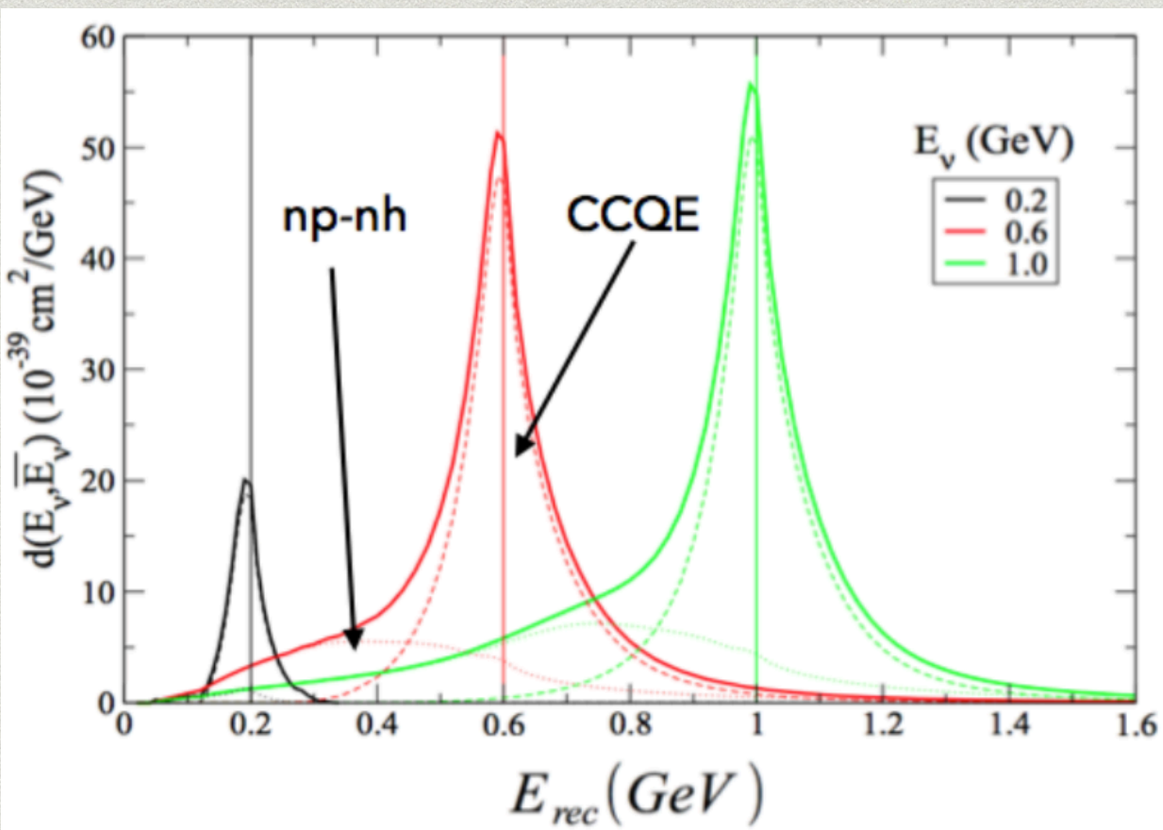
- **"Signal" systematics** (e.g. electron (anti)neutrino cross-sections) **important**
  - But oscillation "signal" absent from ND
  - Intrinsic electron (anti)neutrinos component low and a different energy

Reliance on models

EXAMPLE: NEUTRINO ENERGY RECONSTRUCTION

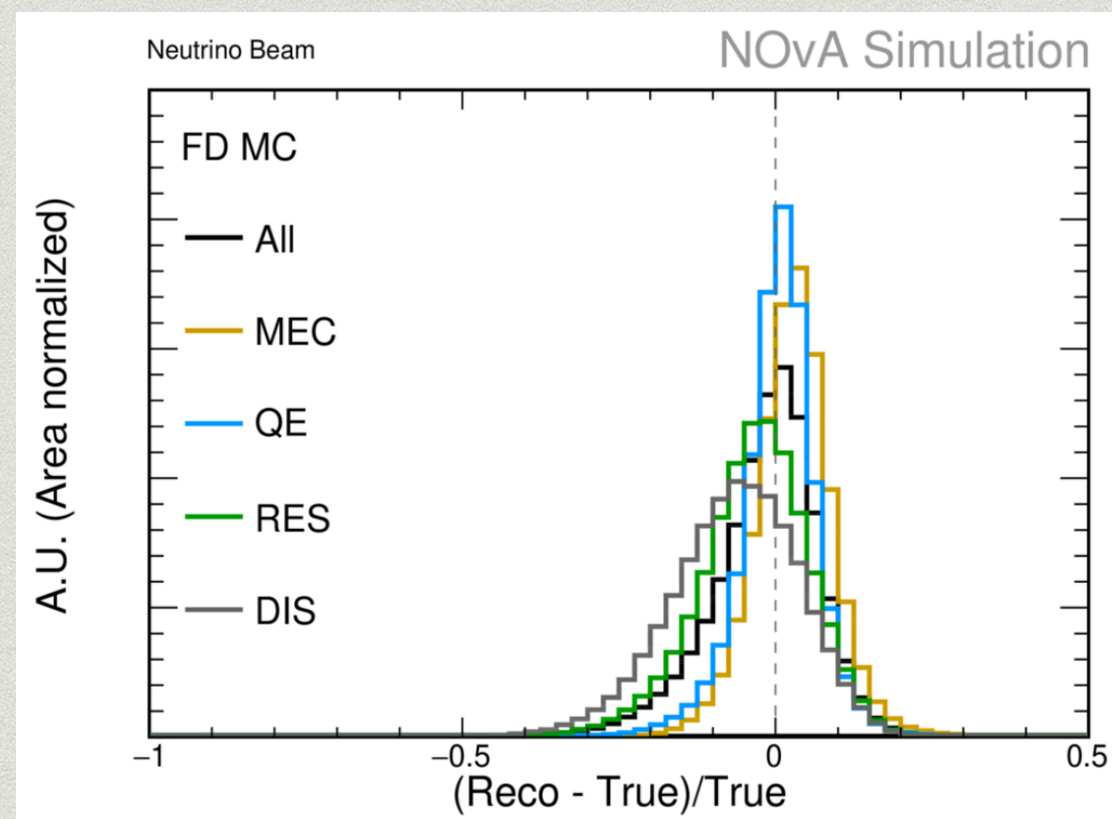
For lower-energy experiments relying on **QE-enhanced samples**, reconstructed energy is critically influenced by

- Modelling of **pion absorption**, and
- Modelling of **collective effects (2p2h)**



[M.Martini]

Higher-energy experiments using **calorimetric** energy reconstruction, even if perfectly calibrated for single particles, are critically influenced by **particle content of simulated hadronic showers**.

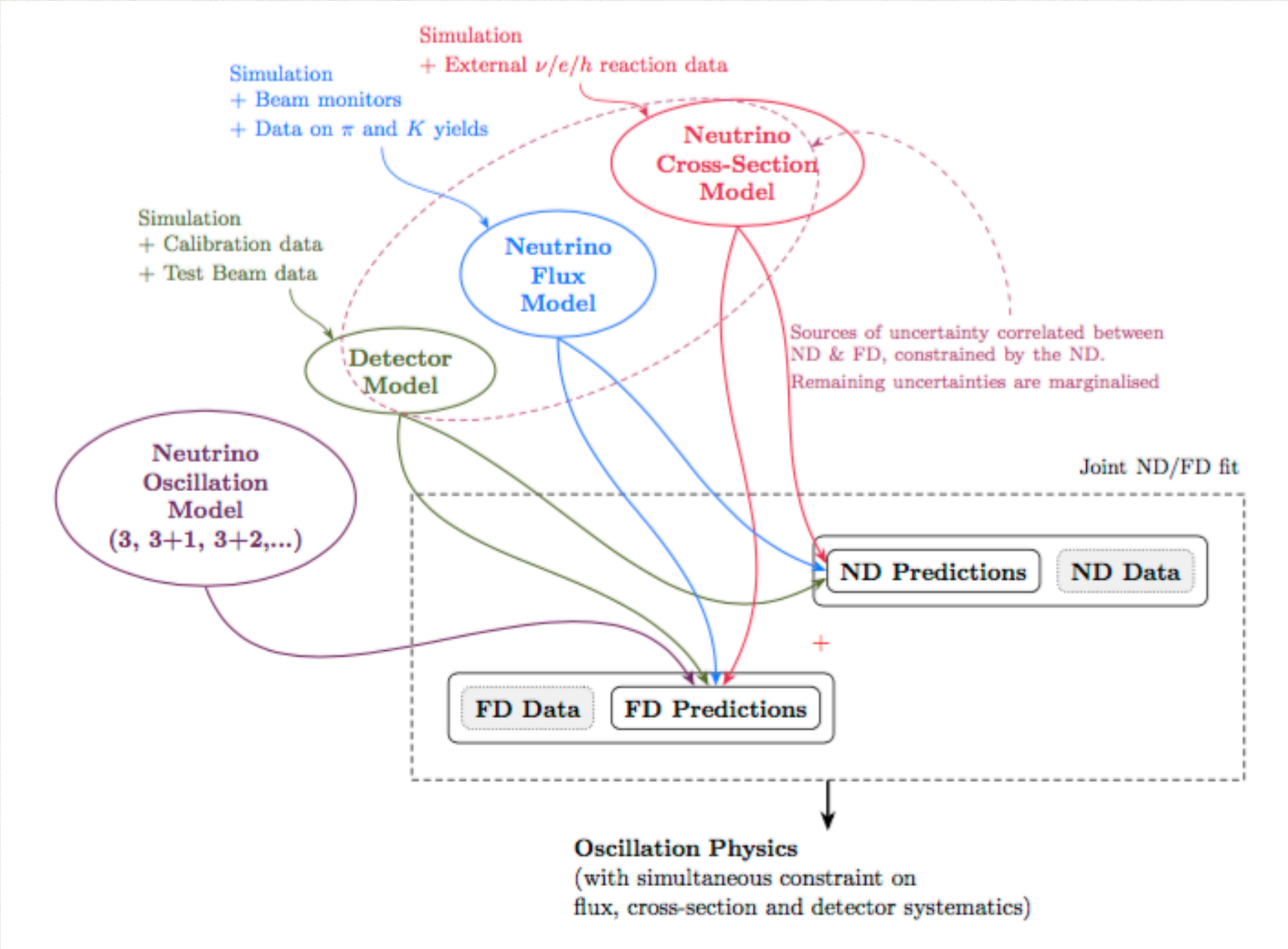


[J.Wolcott, NuFact18]

Indirect extrapolation

Convolved models of flux, cross-section and detector response, with parameterised uncertainties, are fit to ND and FD.

Implementation: **Joint ND/FD fit** or a **2-step fit**: a) ND-only fit to provide model tune and constrained systematics, followed by b) FD-only fit using ND fit model and uncertainties.



Pros:

- Method attempts to disentangle the effects of flux and cross-section systematics.

Cons:

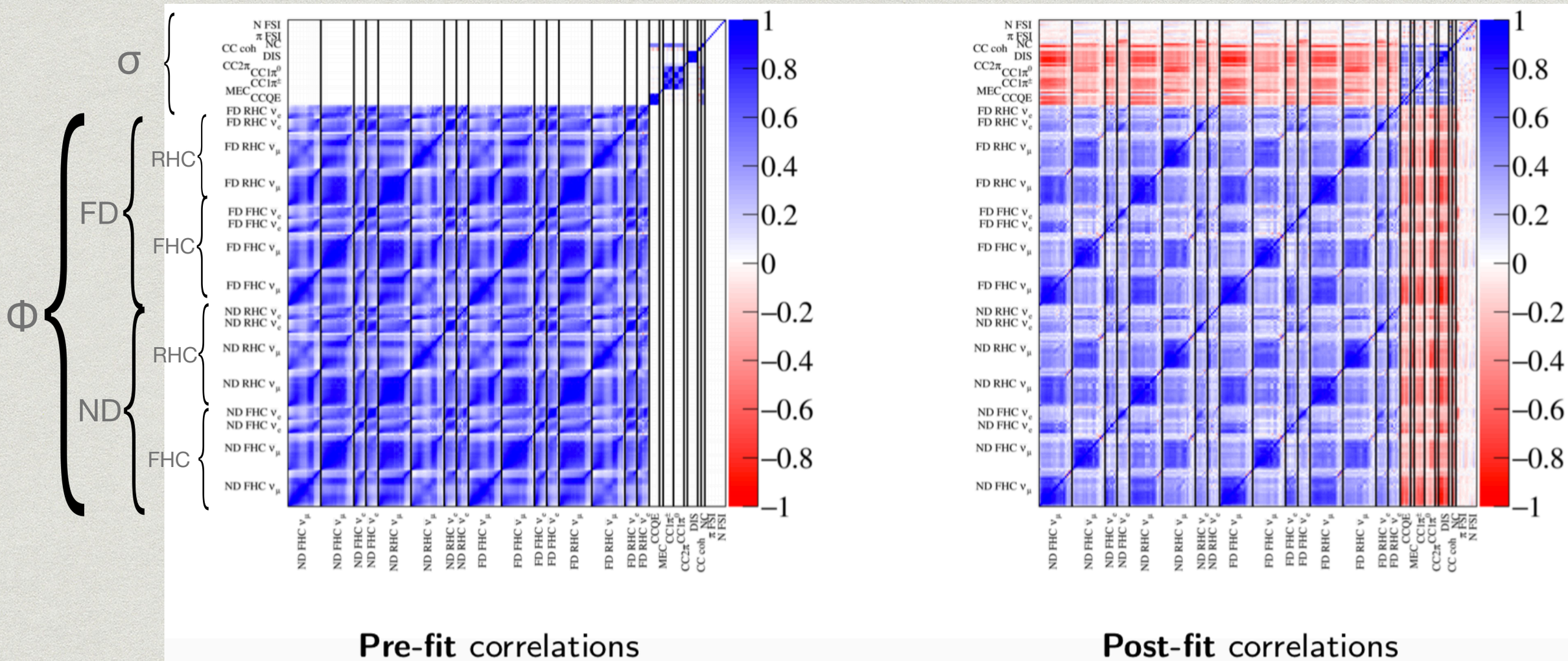
- ND data may not be well described by fit model.
- Possible overfitting a concern

Indirect extrapolation

Convolved models of flux, cross-section and detector response, with parameterised uncertainties, are fit to ND and FD.

Breaking flux, cross-section and efficiency degeneracies

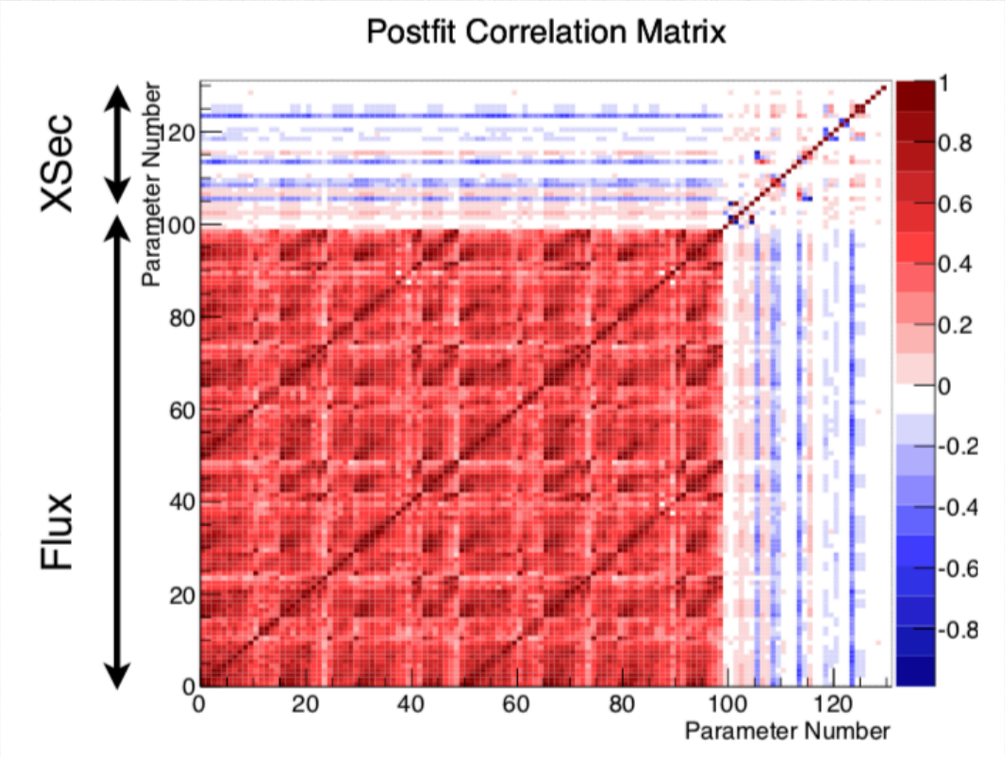
Flux and cross-section parameters become anti-correlated: Constraint is event rate.



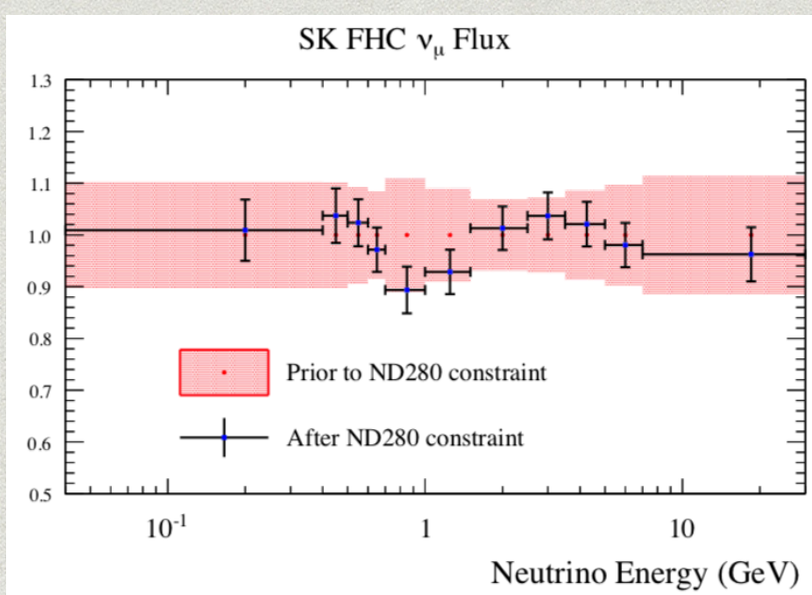
[Example from some earlier VALOR fit group for DUNE]

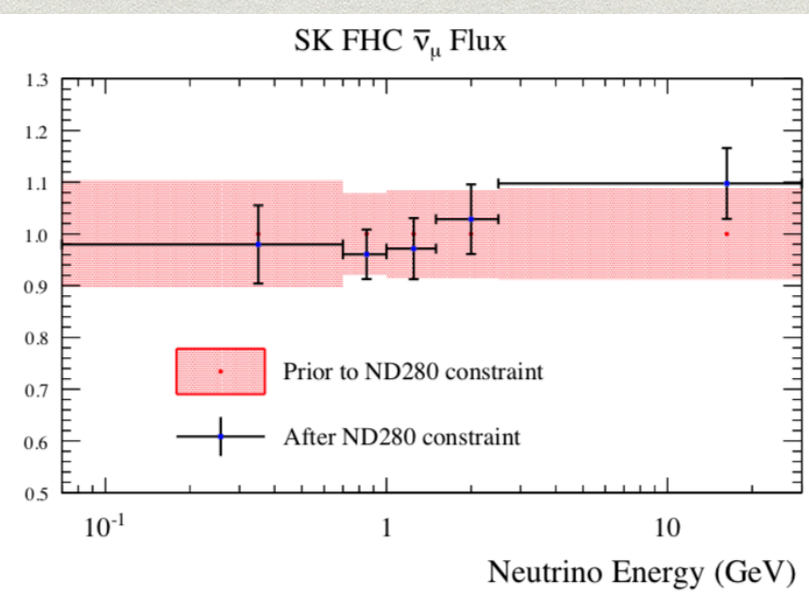
Indirect extrapolation

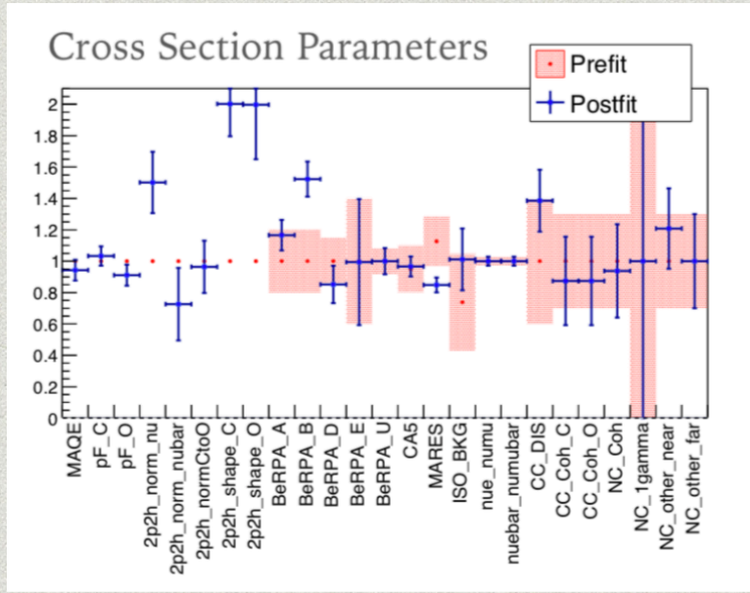
Model tuning and systematic error constraints in T2K oscillation analysis



	1-Ring μ		1-Ring e		
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.
SK Detector	2.40	2.01	2.83	3.80	13.15
SK FSI+SI+PN	2.21	1.98	3.00	2.31	11.43
Flux + Xsec constrained	3.27	2.94	3.24	3.10	4.09
E_b	2.38	1.72	7.13	3.66	2.95
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.61
NC1γ	0.00	0.00	1.09	2.60	0.33
NC Other	0.25	0.25	0.15	0.33	0.99
Osc	0.03	0.03	2.69	2.49	2.63
All Systematics	5.12	4.45	8.81	7.13	18.38
All with osc	5.12	4.45	9.19	7.57	18.51







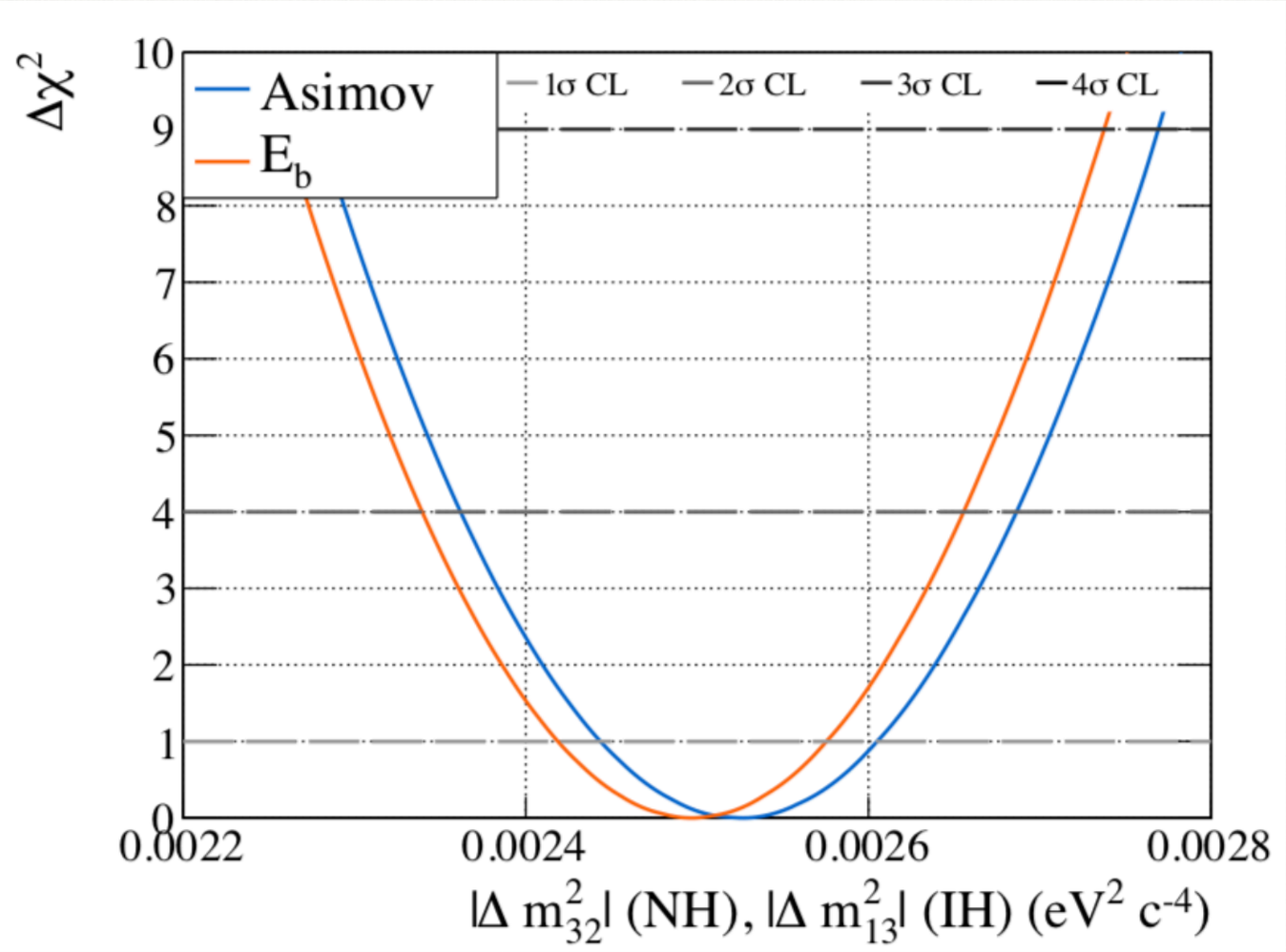
Testing impact of model dependencies and missing systematics

Generate ND and FD pseudo-data with alternative model

Fit pseudo-data using the MC (baseline model) used for the standard analysis.

Checking oscillation parameter biases

If substantial, in terms of the current statistical uncertainty, add extra systematic parameters.



[D.Sgalaberna, NuFact18]

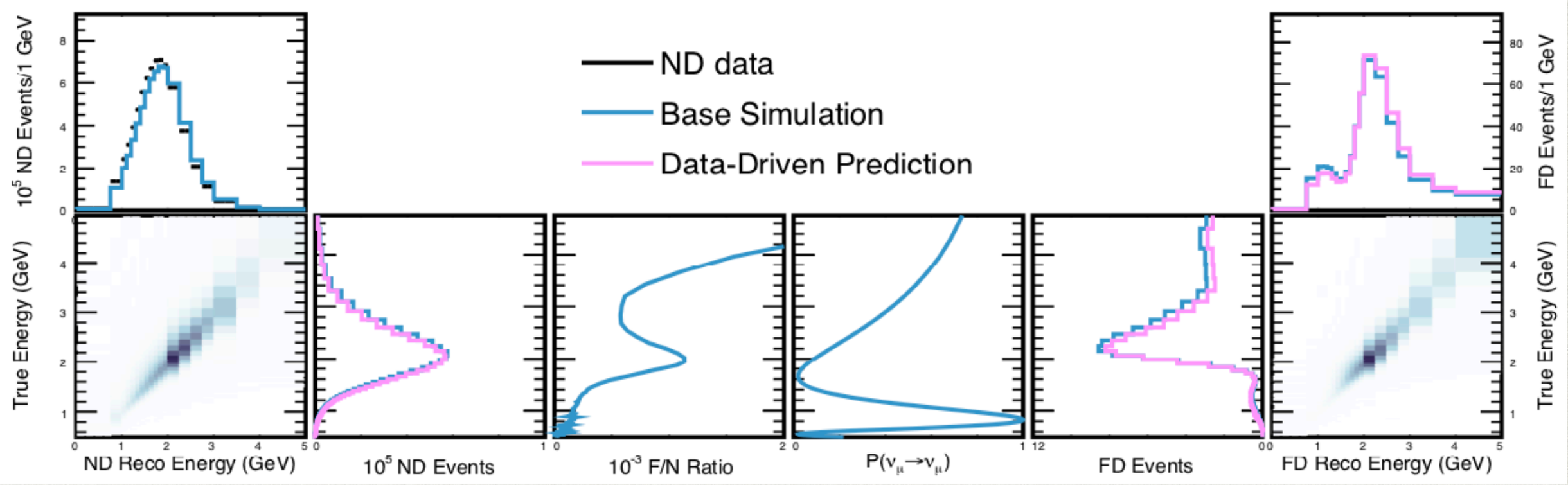
Above, an example from T2K where binding energy was determined to have non-negligible impact on the squared-mass splitting Δm^2_{32}.

Added new systematic parameter, smearing the likelihood to include effects on Δm^2_{32}.

Direct extrapolation

An alternative approach, hides much under the carpet.

Limited range of applicability and systematically less robust (personal opinion).

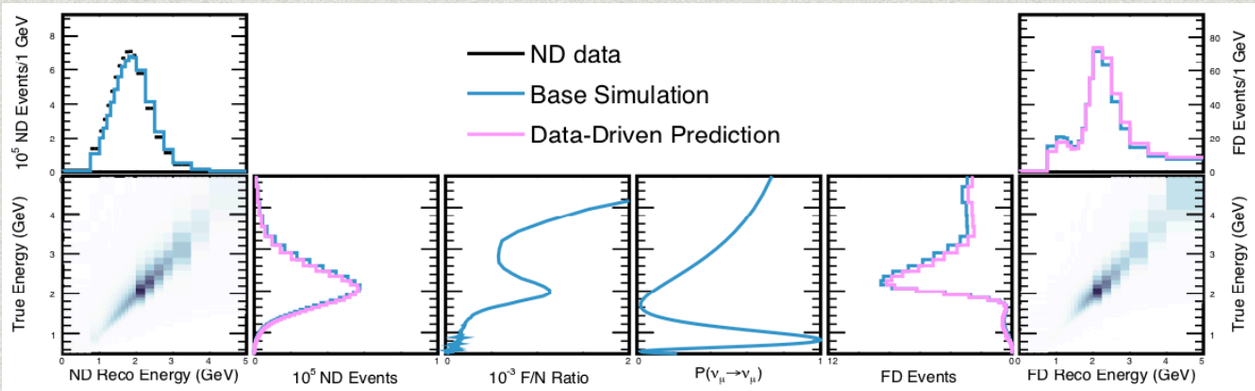


[M.Sanchez, Neutrino18]

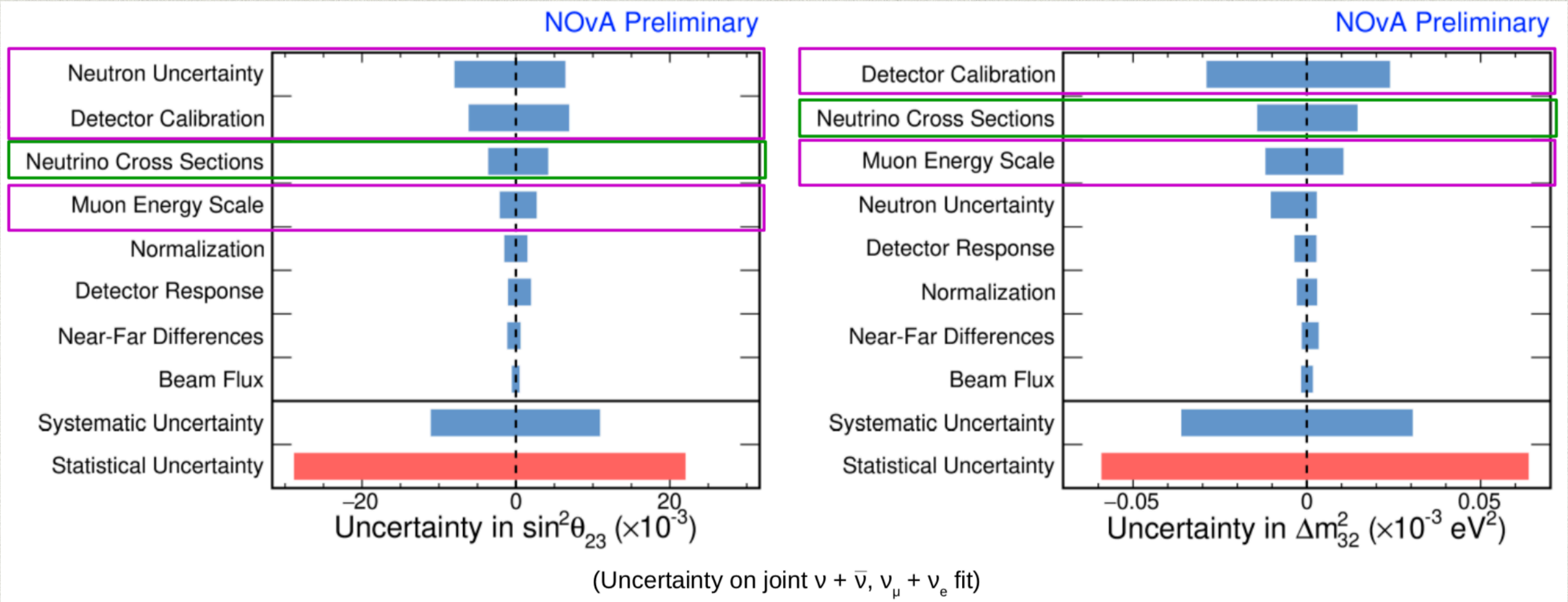
Pros: Extrapolates data - Bypasses some of the concerns related with overfitting or poor description of data by model.

Cons: No attempt to disentangle flux, cross-section and detector effects - loses connection with underlying model and can not identify the source of the differences between base simulation and data-driven prediction.

Testing error cancellation and propagating systematic effects



- Unknown unknowns in data: Replace ND data with ND model with variations and test extend of error cancelation.
- Known unknowns in MC: Repeating the analysis for each systematic, and use difference to nominal extrapolated MC as nuisance parameter.

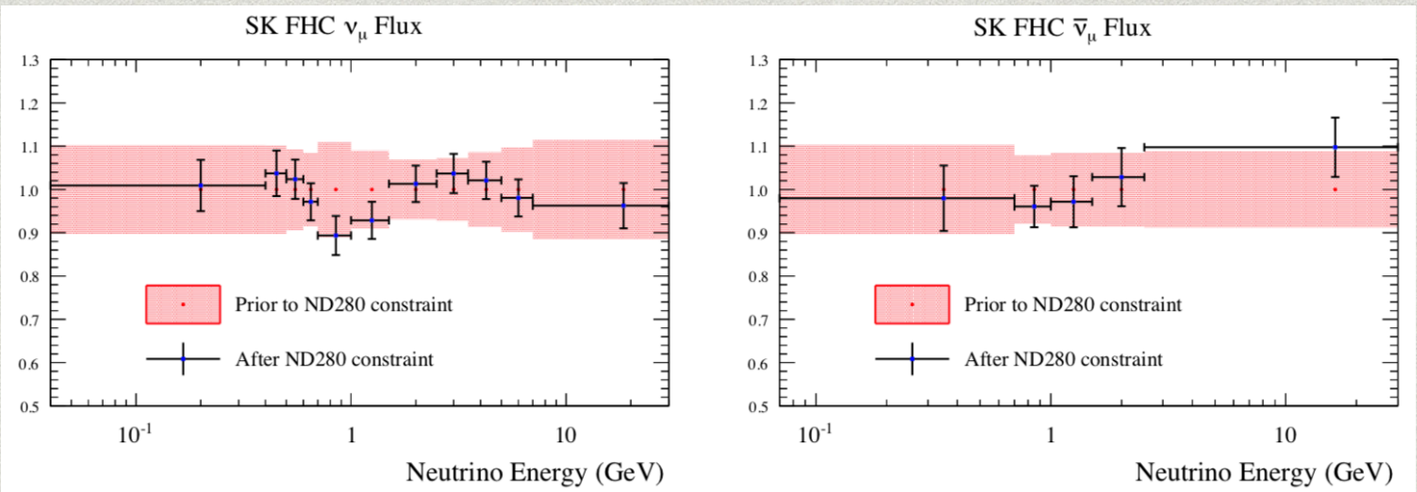


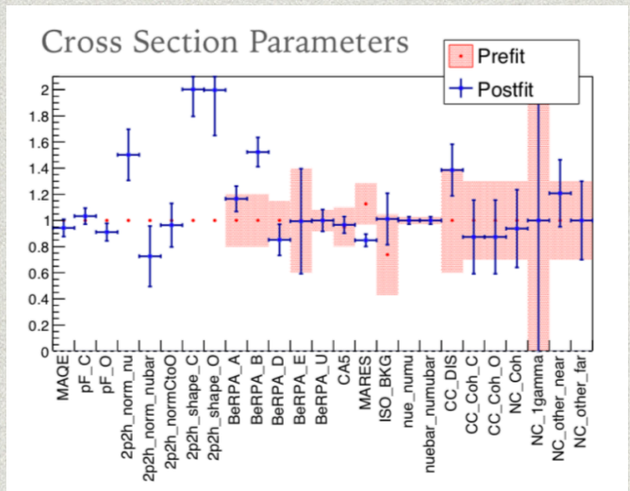
[J.Wolcott, NuFact18]

Error reduction -> better understanding?

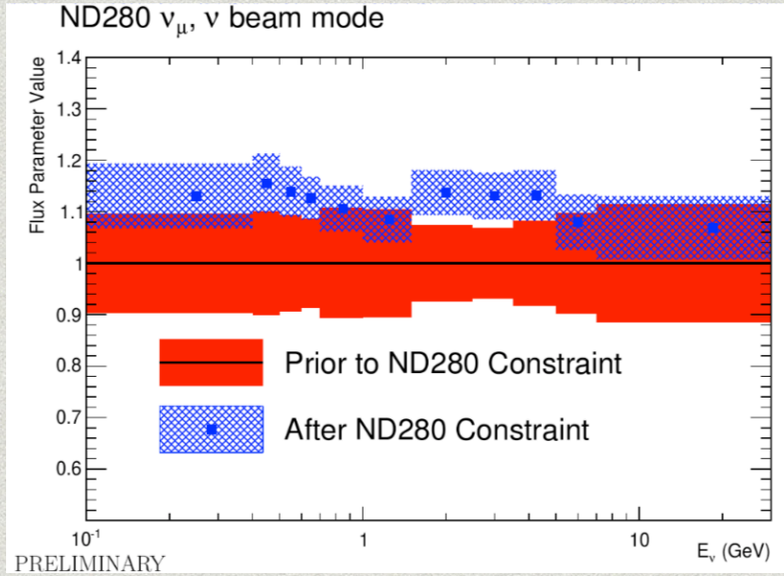
Experiments demonstrate substantial systematic error reduction (~30% -> ~5-8%)
In particular, the impact of key physics systematics correlated between ND and FD reduced to ~2-3%!

For example, current T2K ND results pull nuclear (2p2h) modelling parameters, leaving flux close to nominal

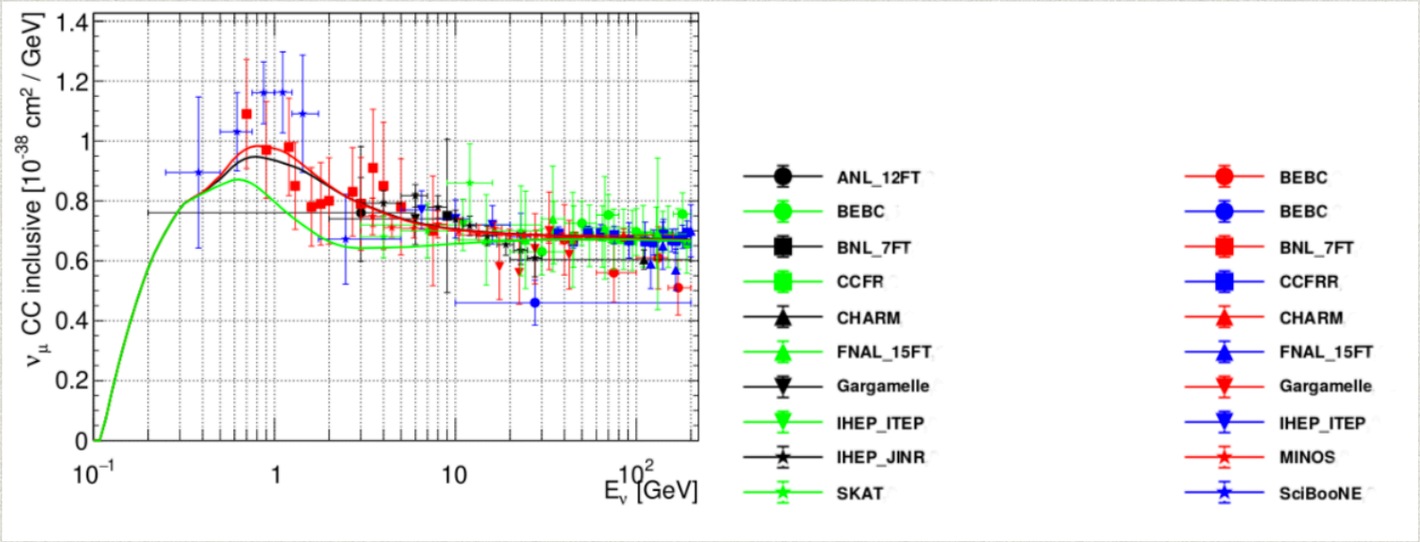




But previous results pulled the flux instead

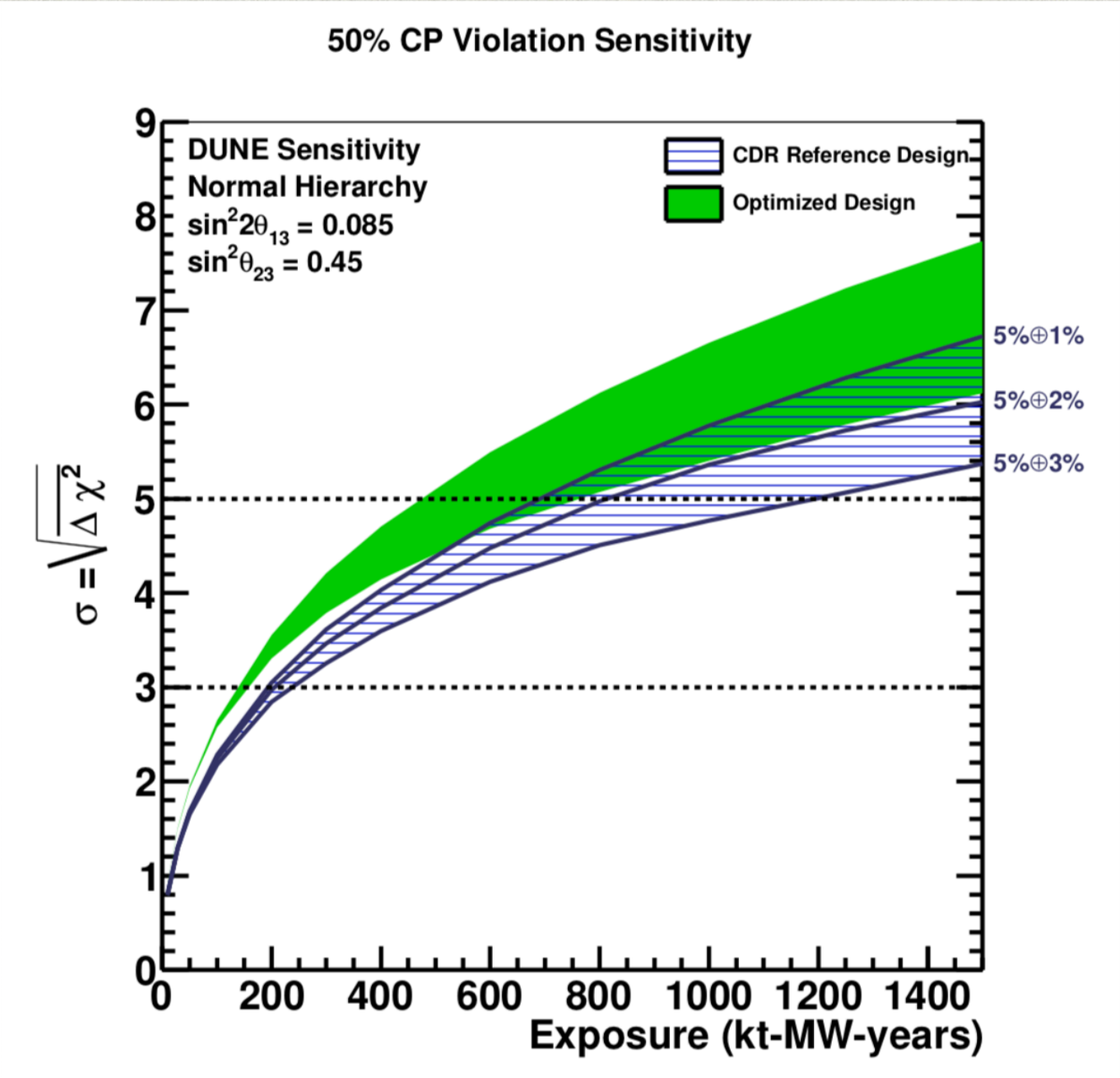


Is it different from tensions seen in GENIE free-nucleon cross-section fits, that have nothing to do with either T2K flux or nuclear modelling?



Could PHYSTAT-\nu 2029 look back at this as another case where we were misled and missed correct physics?

Requirements of future experiments



Stringent systematic requirements:

~1% on the uncorrelated error

between muon and electron neutrinos.

Likely have to go beyond demonstrating CPV?

- Identifying CPV origin, if not pure δ_{CP}.
- Resolving new anomalies / New physics?

Will require **redundancy of information** and, further, unprecedented control over systematics to **claim a major discovery**.

Unsure that we design detectors and an external measurement programme to deliver what will be required.

Neutrino-nucleus interactions a weak link

No real progress unless we get more creative at breaking the convolution:

$$N^{exp}_{\nu_f}(E_r) \propto \sum_{\nu_i} \int dE_t \frac{d\Phi_{\nu_i}(E_t)}{dE_t} P^{\nu_i \to \nu_f}_{osc}(E_t; \vec{\alpha}) \epsilon_{\nu_f}(E_t) \sum_A w_A \sum_i \int dK^n_t \frac{d^n \sigma^i_{\nu_f A}(E_t, K^n_t)}{dK^n_t} R_i(E_r; E_t, K^n_t)$$

Summary

- Modern experiments made outstanding progress constraining systematics
- Currently, analyses of LBL accelerator experiments are statistically limited
- However, we can all feel the pain ahead.

- In the area of neutrino flux, a rigorous programme of external and in-situ measurements keeps flux systematics under control.
- In interaction modelling, however, there are several experimental puzzles, somewhat poor practices and no clear path to deliver a level of understanding that can underpin discovery.