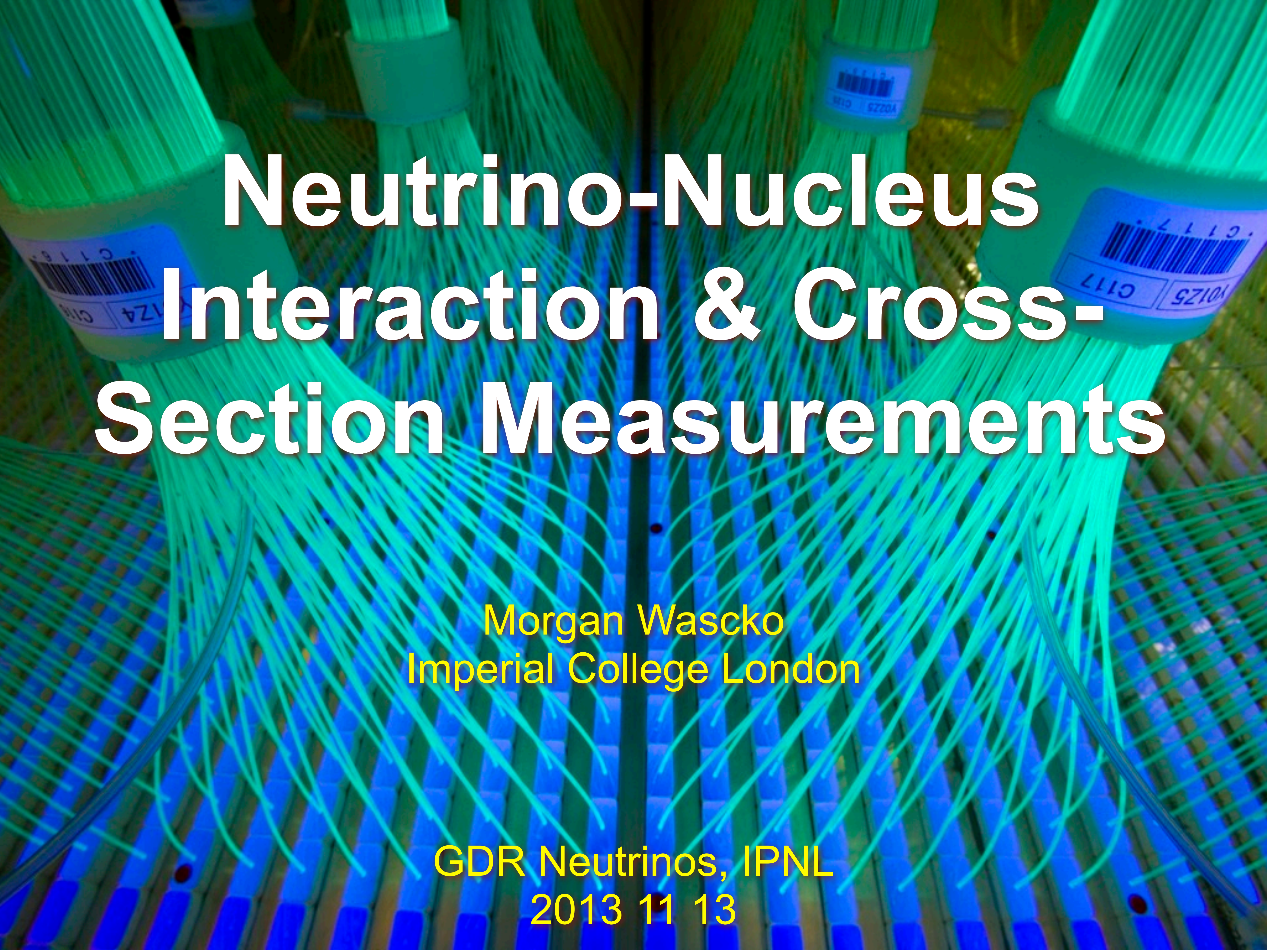


Neutrino-Nucleus Interaction & Cross-Section Measurements

Morgan Wascko
Imperial College London

GDR Neutrinos, IPNL
2013 11 13

Context & Message

- We have entered a new era of precision in neutrino physics
- The search for CP violation in neutrinos requires progress in reducing systematic errors due to neutrino interactions

- Neutrino experiments are using interaction models from the 1970s and 1980s to analyse 21st century data
- Testing 21st century models needs a new paradigm of data analysis:

model-independent measurements

Outline

- Historical Context
- Neutrino oscillation
- Quasi-Elastic Scattering
- Single pion production
- Model independent measurements
- Conclusion

Accelerator Neutrinos

- Accelerator neutrino experiments were born in the 1960s and came of age in the 1970s
- 1960s - First pion decay beam, first focussing horns
- 1970s - Development of big bubble chambers
- Discovery of 2nd generation of neutrinos and neutral currents

first accelerator neutrino beam

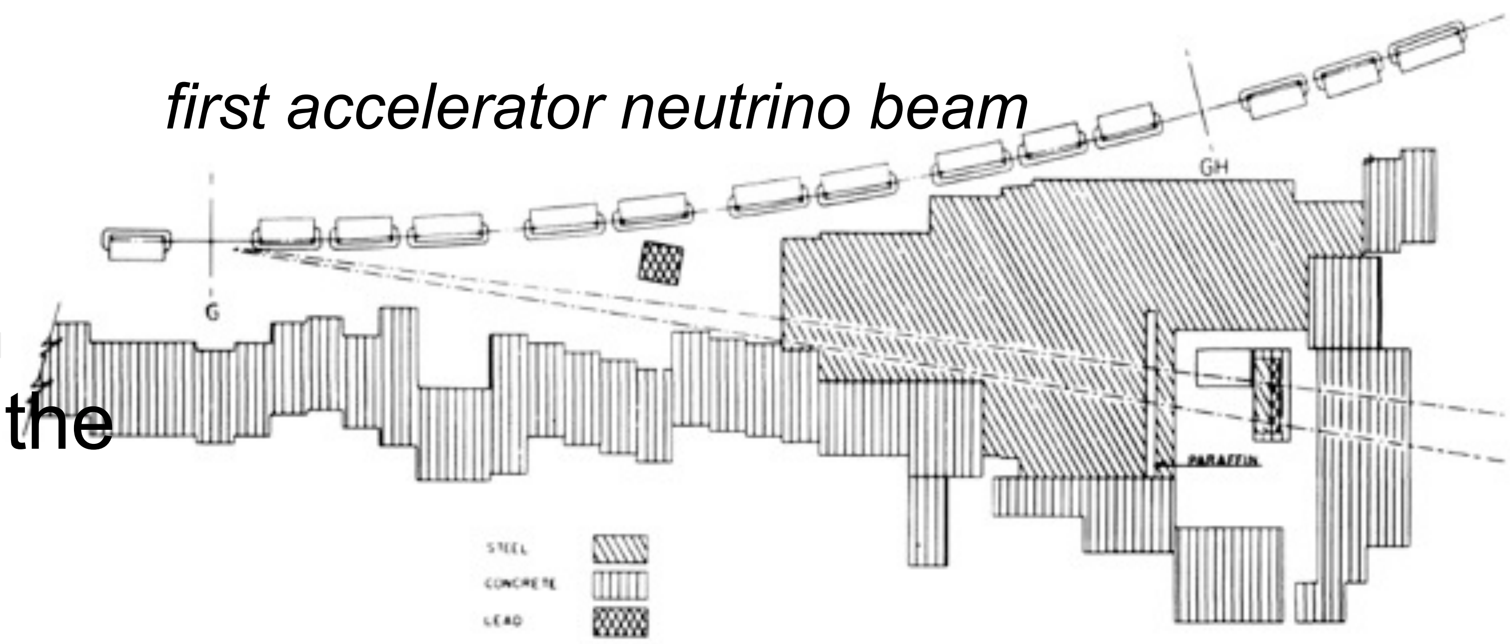
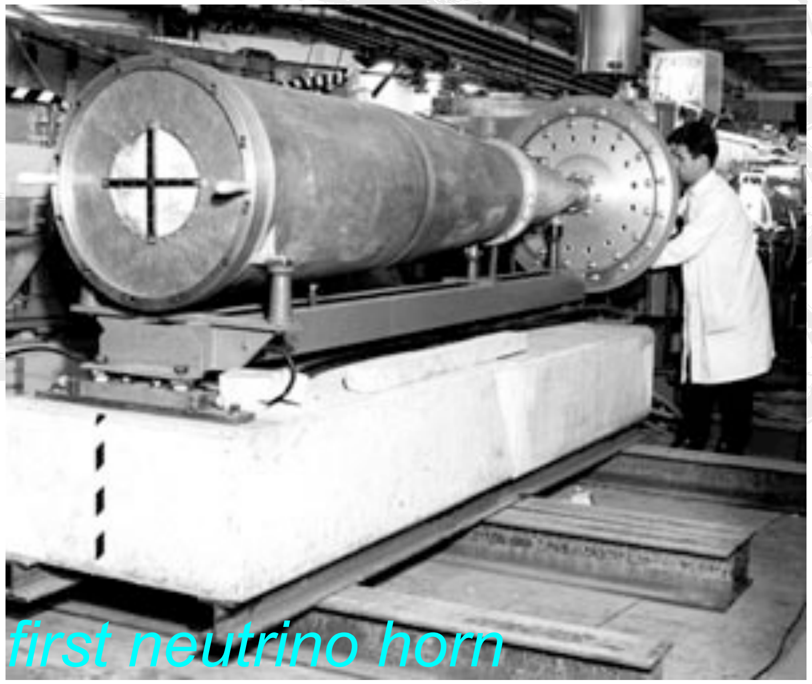
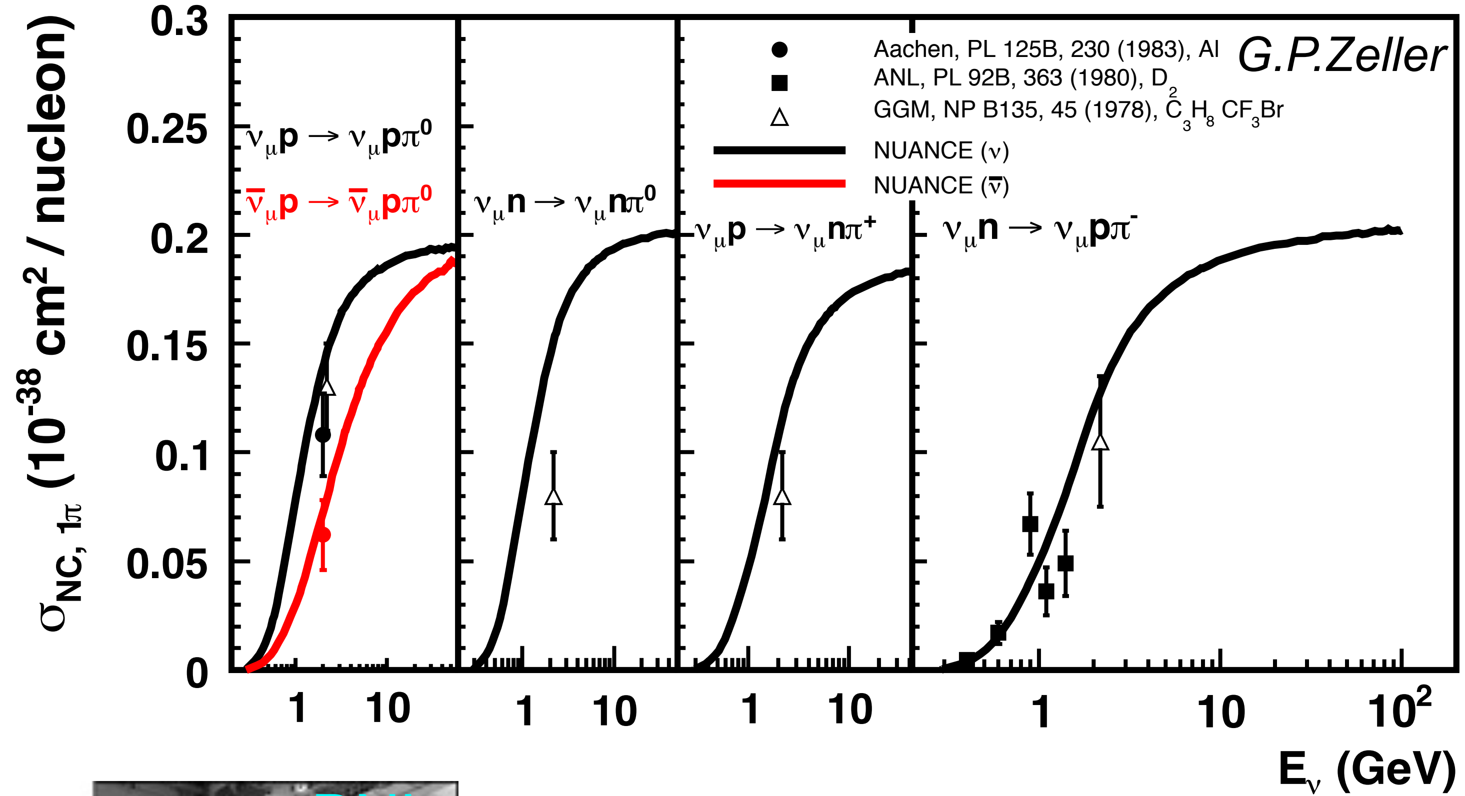


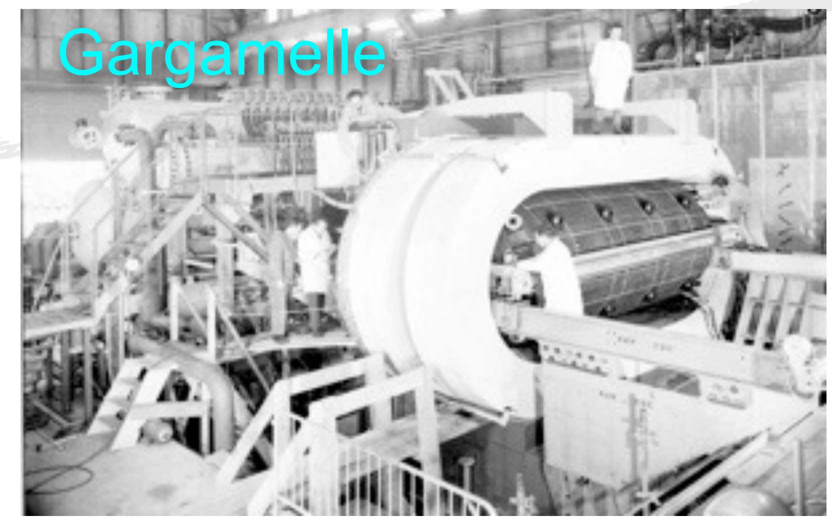
FIG. 1. Plan view of AGS neutrino experiment.

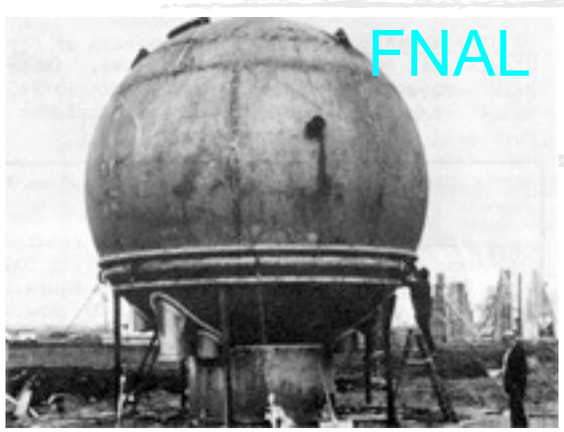


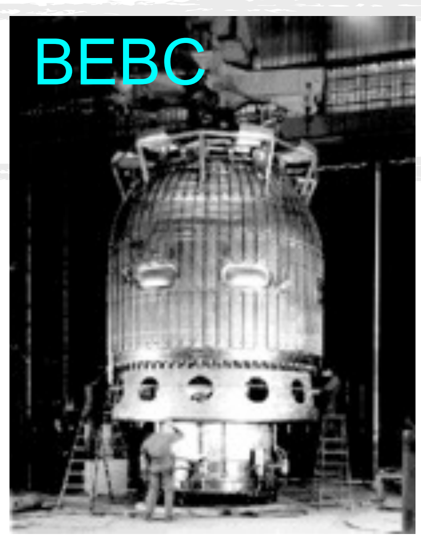
Early neutrino data

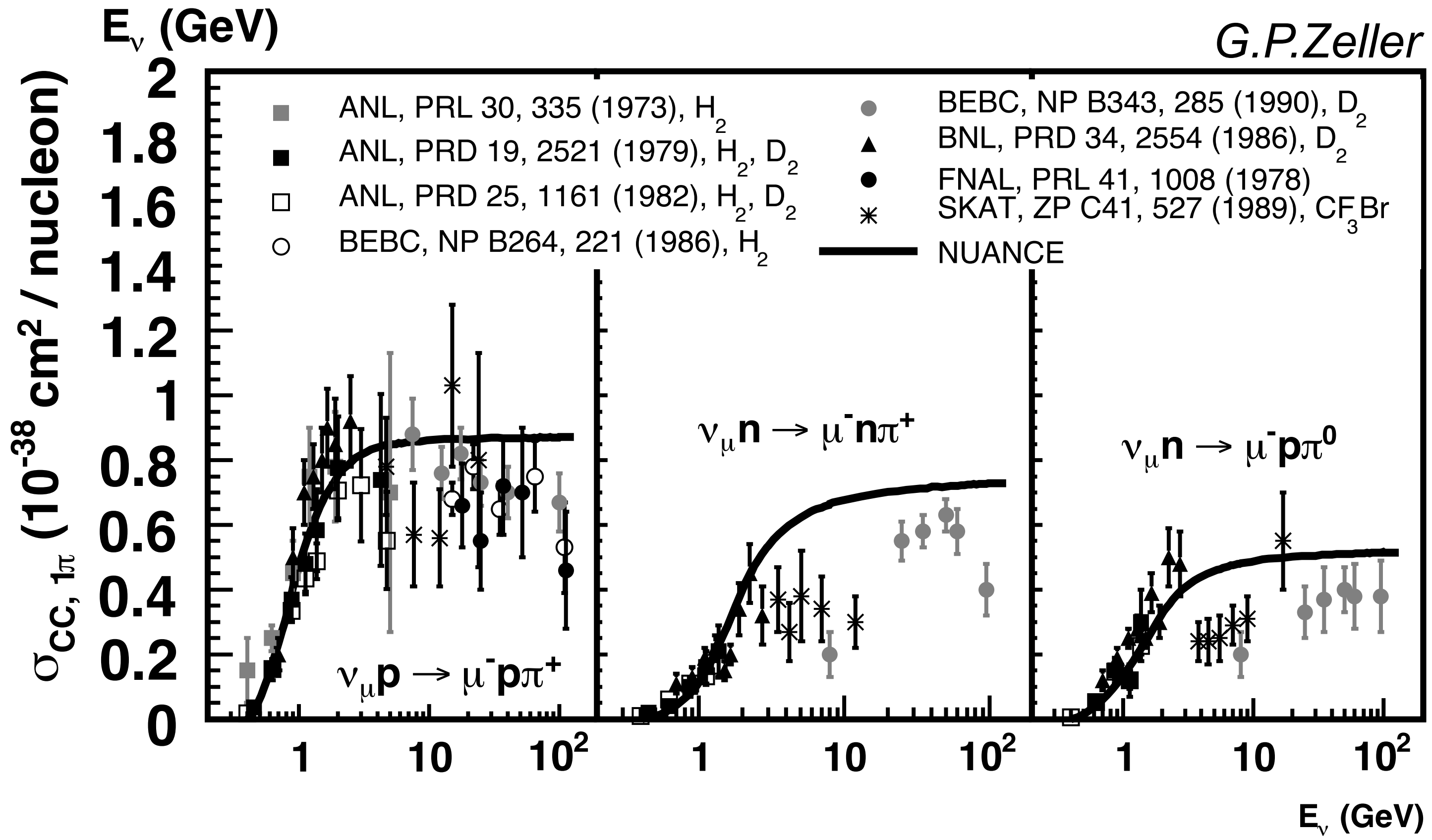


From discovery to (precision) measurements...

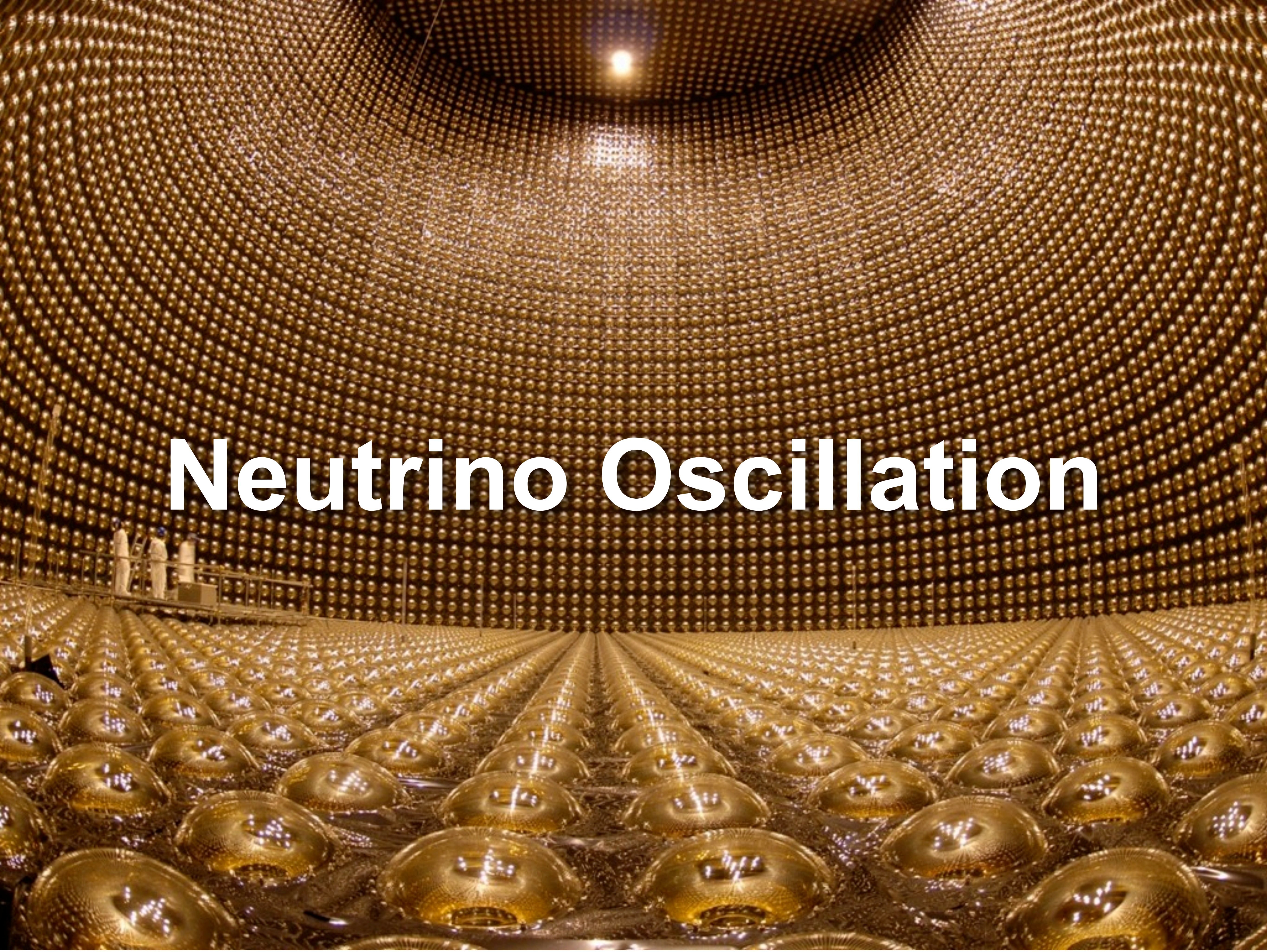








Plots from the PDG!

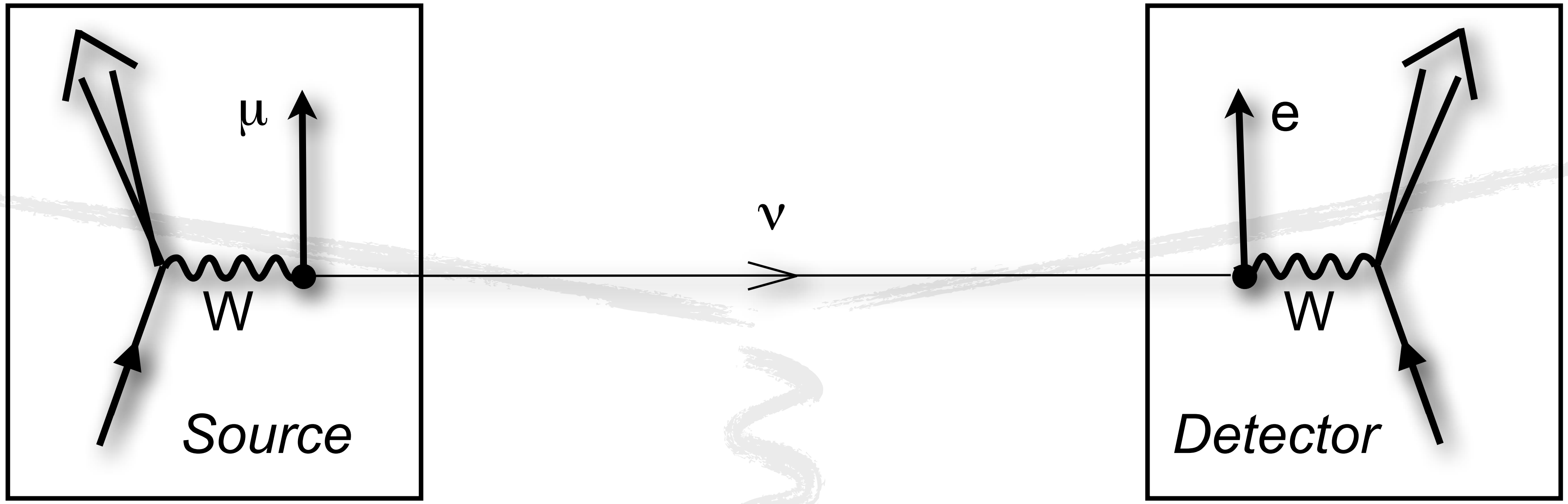

Neutrino Oscillation

Neutrino oscillation

Pontecorvo

Sov.Phys.JETP 6:429,1957

Sov.Phys.JETP 26:984-988,1968

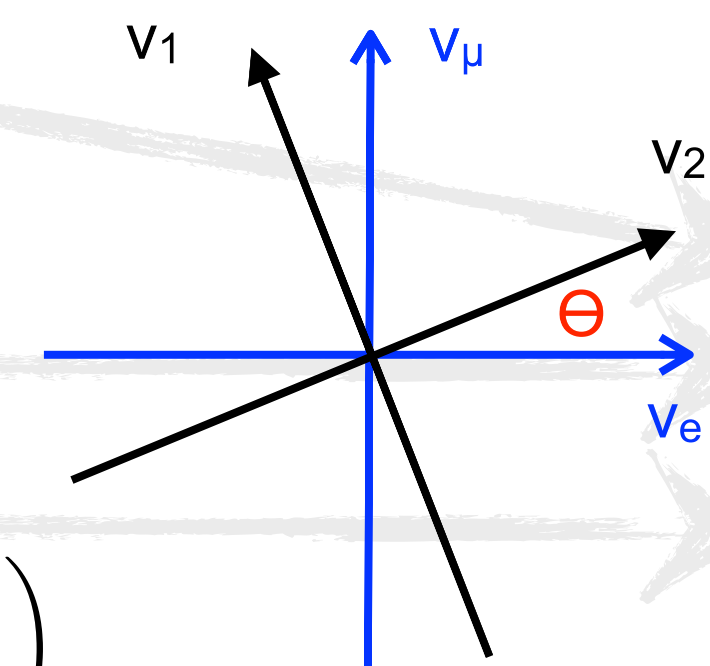


Maki, Nakagawa, Sakata

Prog.Theor.Phys. 28, 870 (1962)

Simple 2 neutrino example-
if weak eigenstates (ν_e, ν_μ) differ from mass eigenstates (ν_1, ν_2):

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



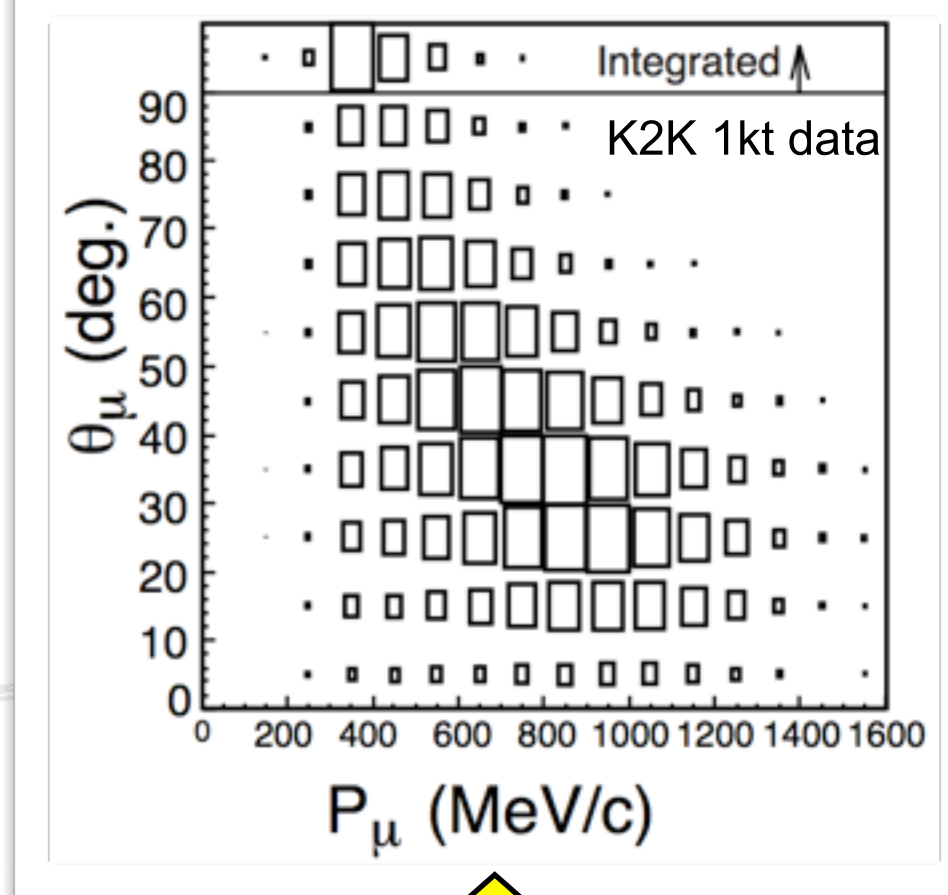
$$P_{oscillation}(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta sin^2 \left(\frac{1.27\, \Delta m^2(eV^2)\, L(km)}{E_\nu(GeV)} \right)$$

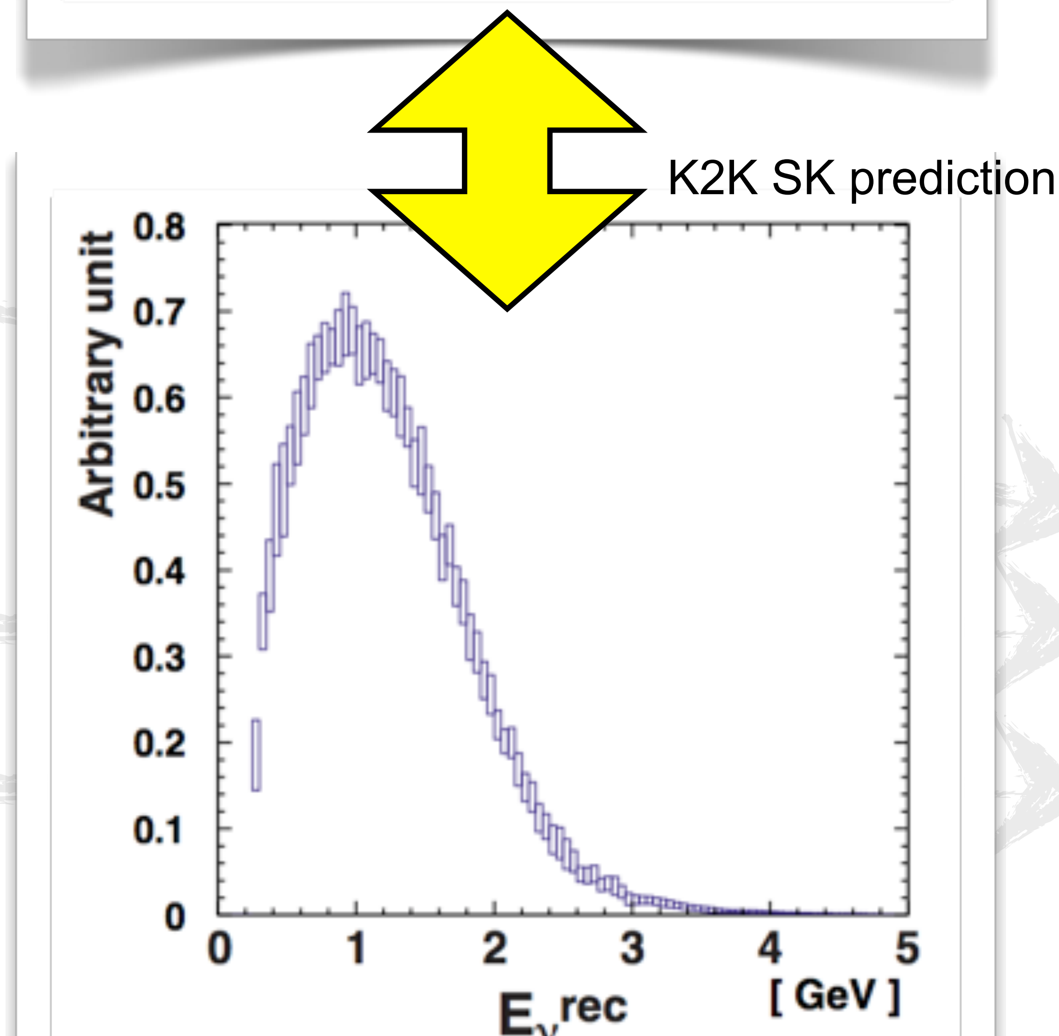
What do we need?

- Need to predict event rates and kinematics of final state particles
- Need to reconstruct neutrino energy accurately
  - Both kinematic and calorimetric reconstruction
- Need to accurately predict background contamination

➡Need precise neutrino-nucleus cross-sections

➡Need good models





Phys.Rev.D **74** 072003 (2006)

Xsecs and Oscillations

- Cross section models used by experiments cannot describe recent K2K, MiniBooNE, SciBooNE, MINERvA observations.
  - Leads to larger systematic uncertainties
- Model dependence will always be injected into data analysis
  - Energy, Q^2 reconstruction
  - Background subtraction
- Using these models will always give such uncertainties.
  - Need to use better models!

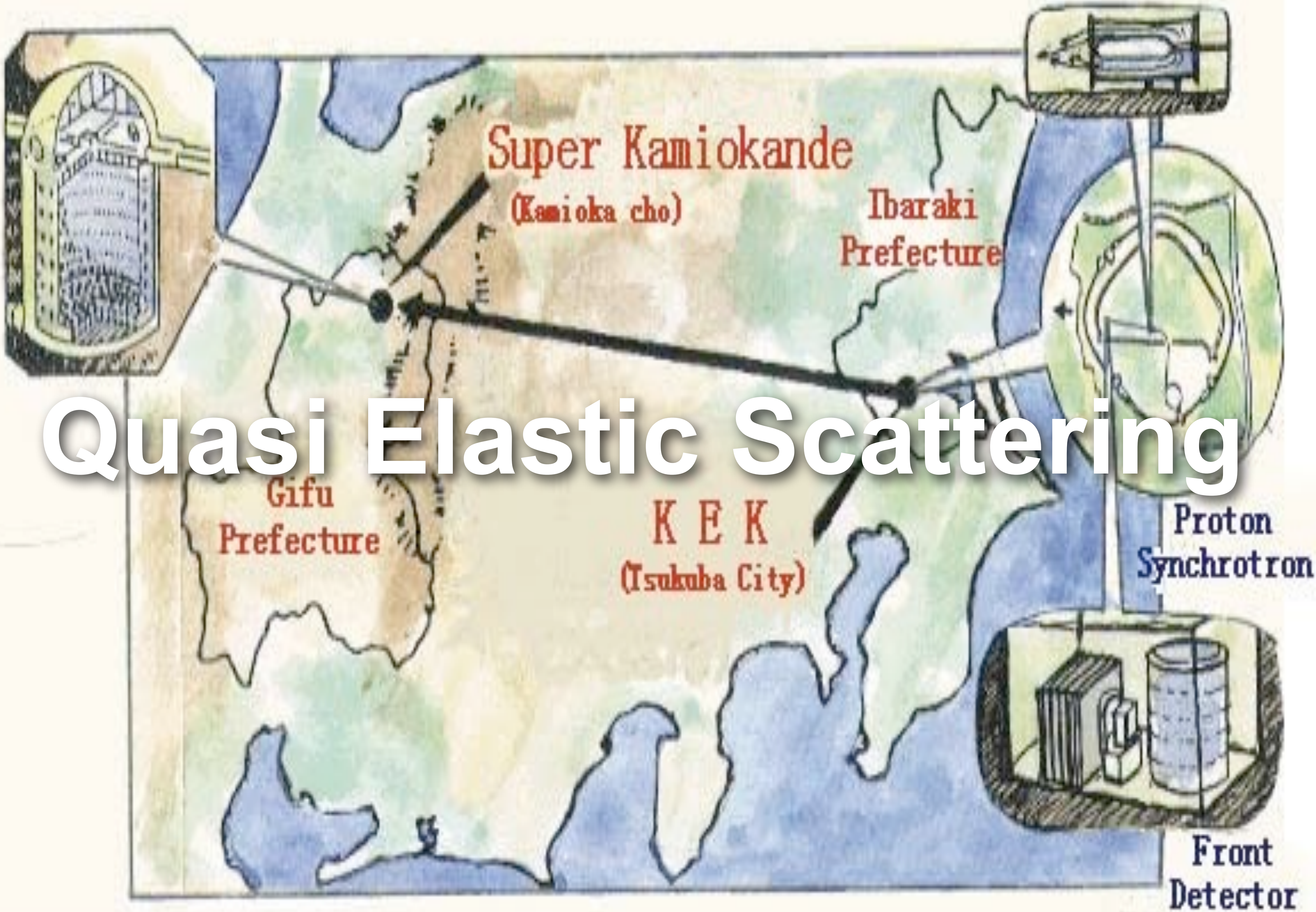
Systematic uncertainties reported by the world's most sensitive ν_e appearance experiments: MiniBooNE and T2K

Experiment	xsec err (%)	total err (%)
MiniBooNE (2007)	12.3	17.6
T2K (2012)	7.5	10.3

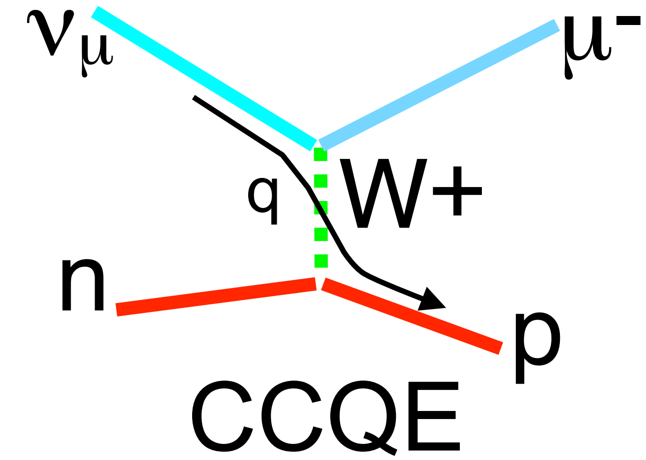
Conrad & Louis, FNAL Wine and Cheese Apr 11 2007

T. Nakaya, Neutrino 2012, Kyoto

Quasi Elastic Scattering



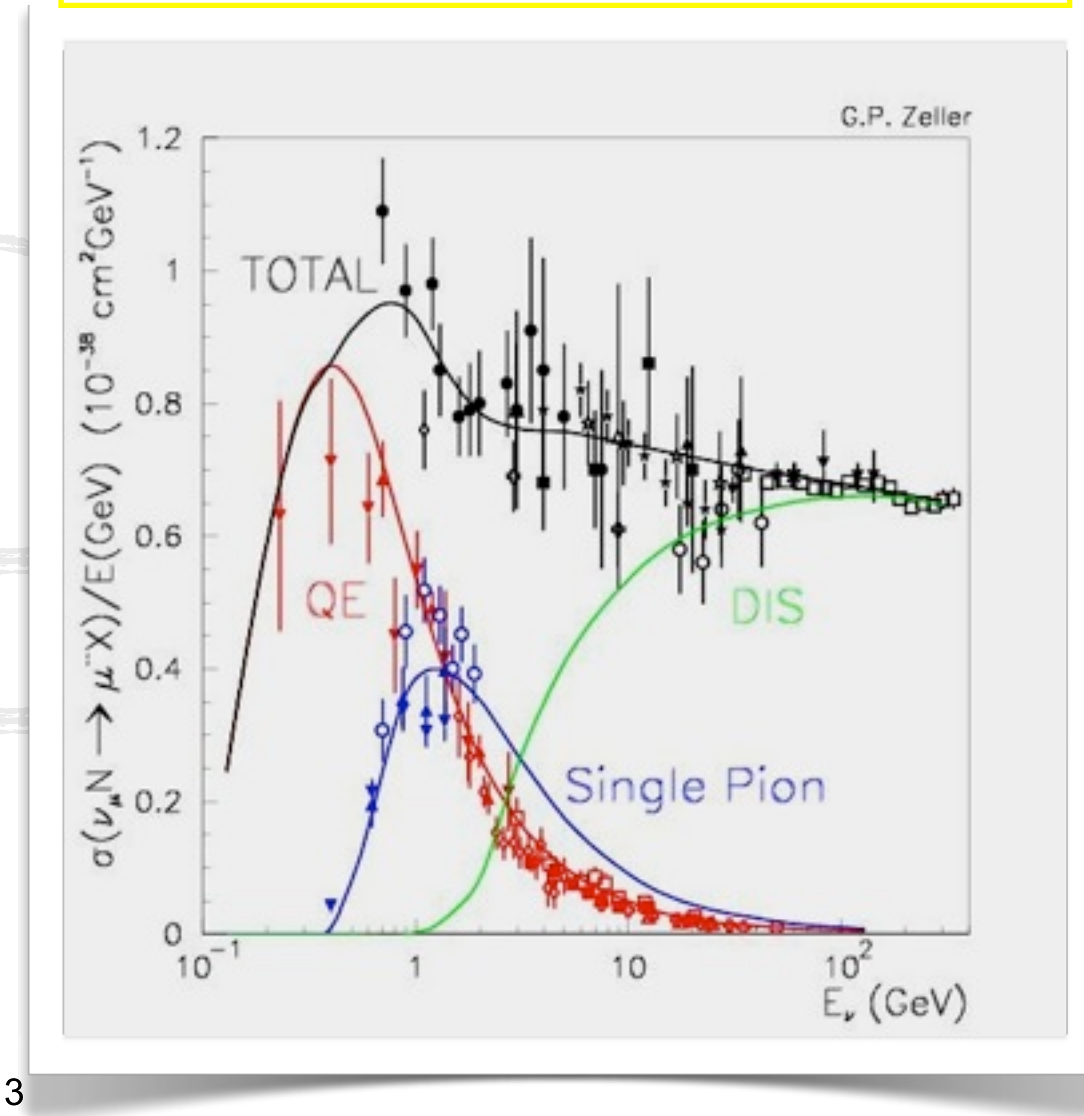
Quasi-Elastic Scattering



$$F_A(Q^2) = \frac{F_A(0)}{(1 - \frac{Q^2}{M_A^2})^2}$$

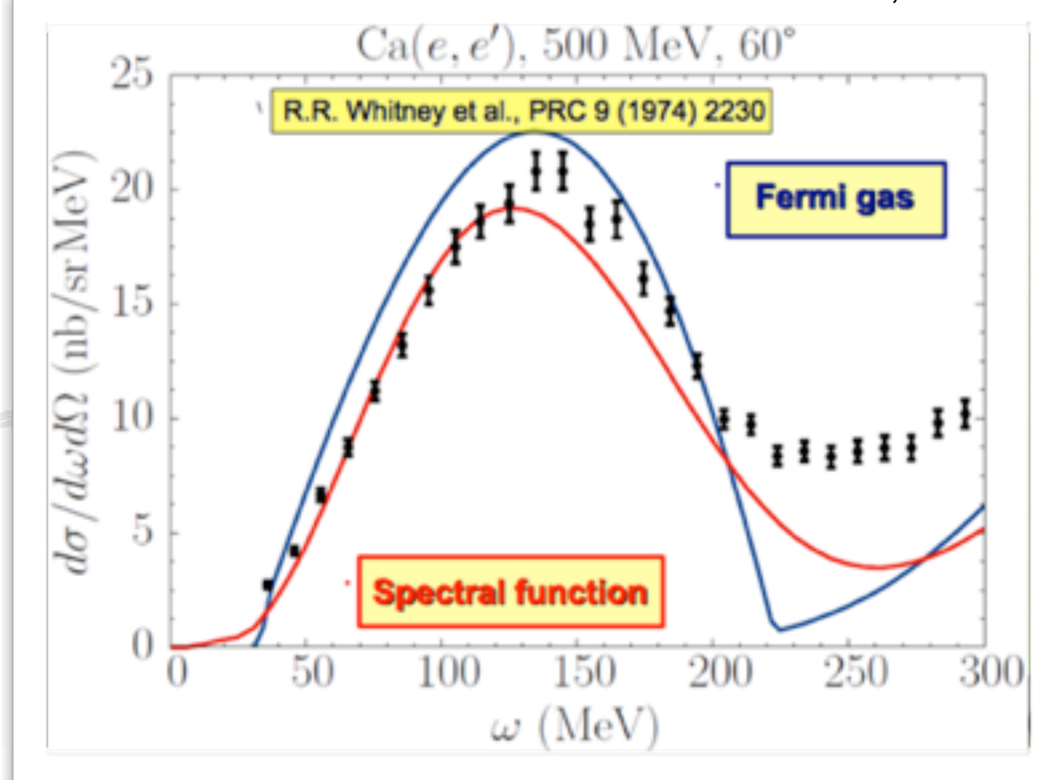
(where $Q^2 = -q^2$)

- Experiments use Llewellyn Smith formalism (1971)
- Form-factors parameterise nucleon weak charge distributions
  - F_V measured by electron scattering, F_P negligible due to kinematics, F_A assumed to be dipole
- Important for accelerator ν beams
  - Dominant process near 1 GeV
  - Simple energy reconstruction



Nuclear Models

Ankowski, NuInt09



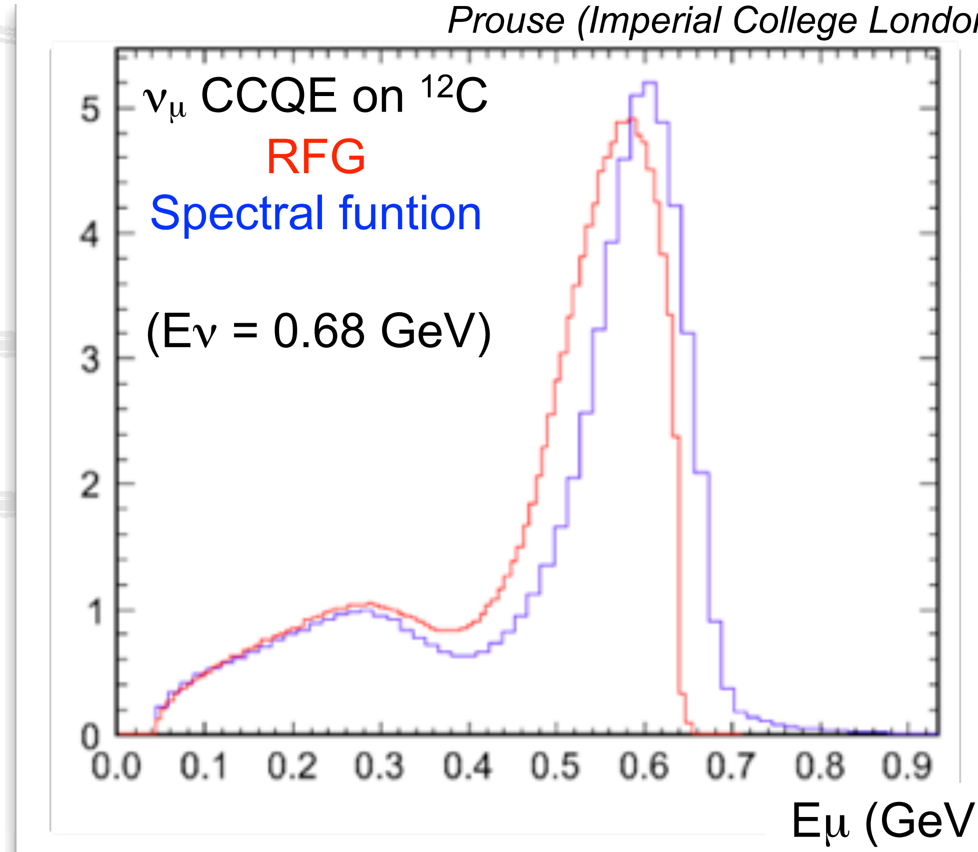
- Most experiments use RFG
  - Smith & Moniz (1971)

New Secretary of energy does not need citations anymore!

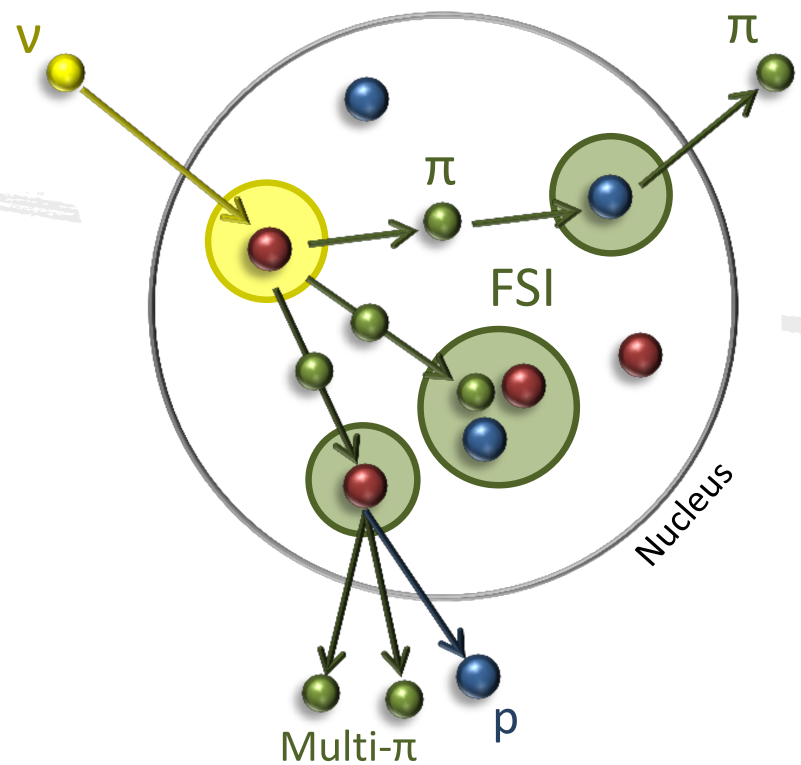
- Most theorists prefer something else
  - Spectral function
- Affects neutrino energy reconstruction!

➡ Impacts oscillation experiment!

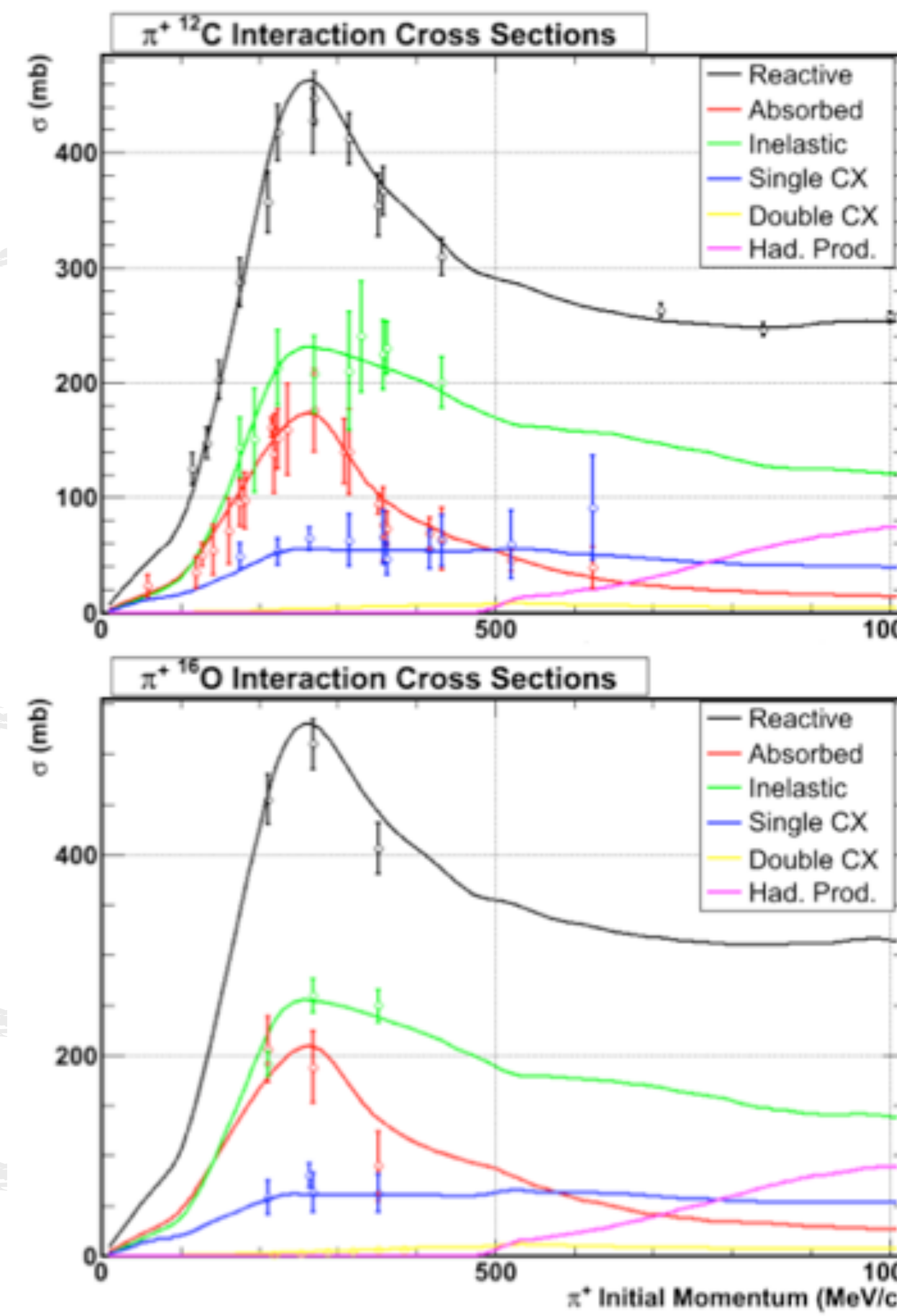
Prouse (Imperial College London)



Final State Interactions



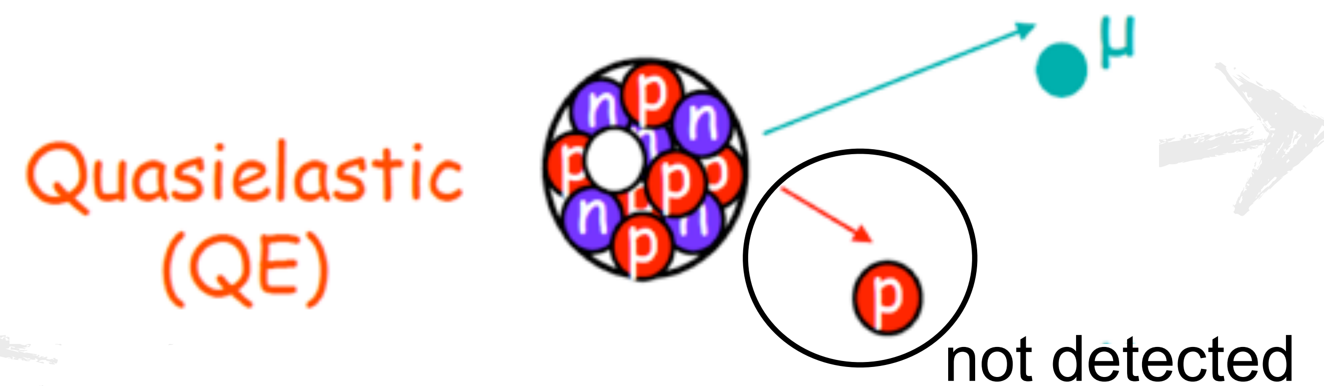
P. de Perio, NuInt11



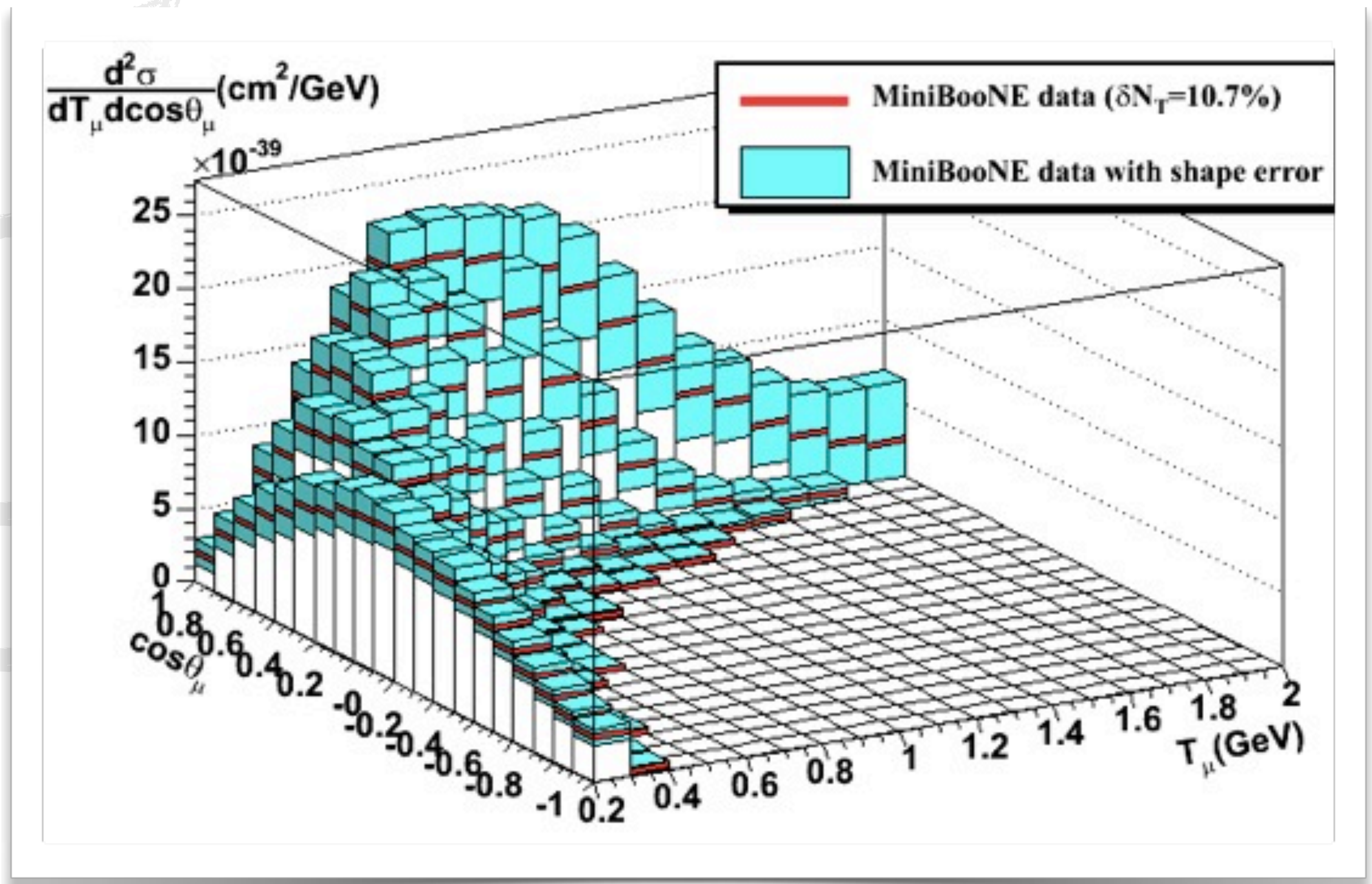
- Neutrino interaction products are created in the nuclear environment
- Need to simulate how they get out
  - Tune with external hadron data
  - Crucial piece of any analysis

MiniBooNE ν_μ CCQE

Diagram due to M. Martini

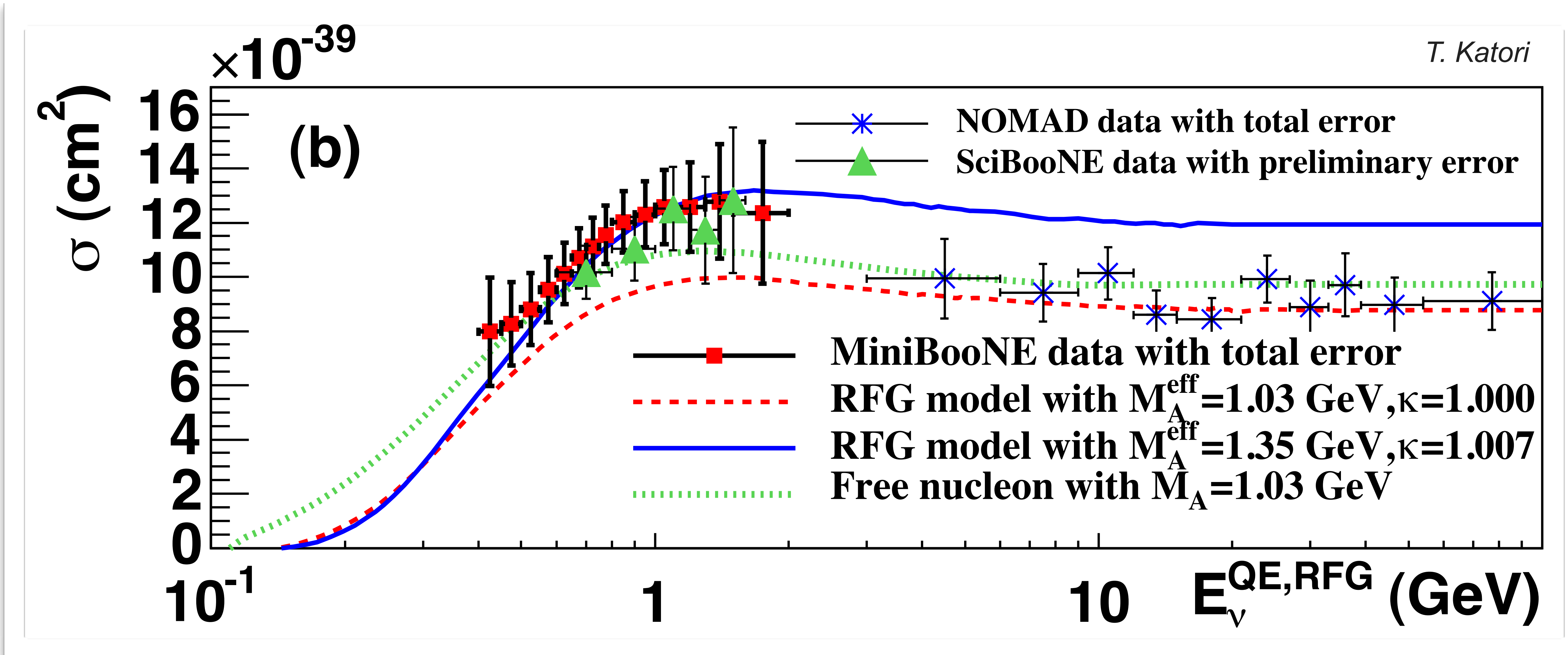


- Flux averaged double differential CCQE cross section
  - Depends critically on flux prediction, background estimation
- Most complete cross-section information possible based on the muon kinematics
- Incredibly useful input for theorists
  - 100+ citations!



PhysRevD **81** 092005 (2010)

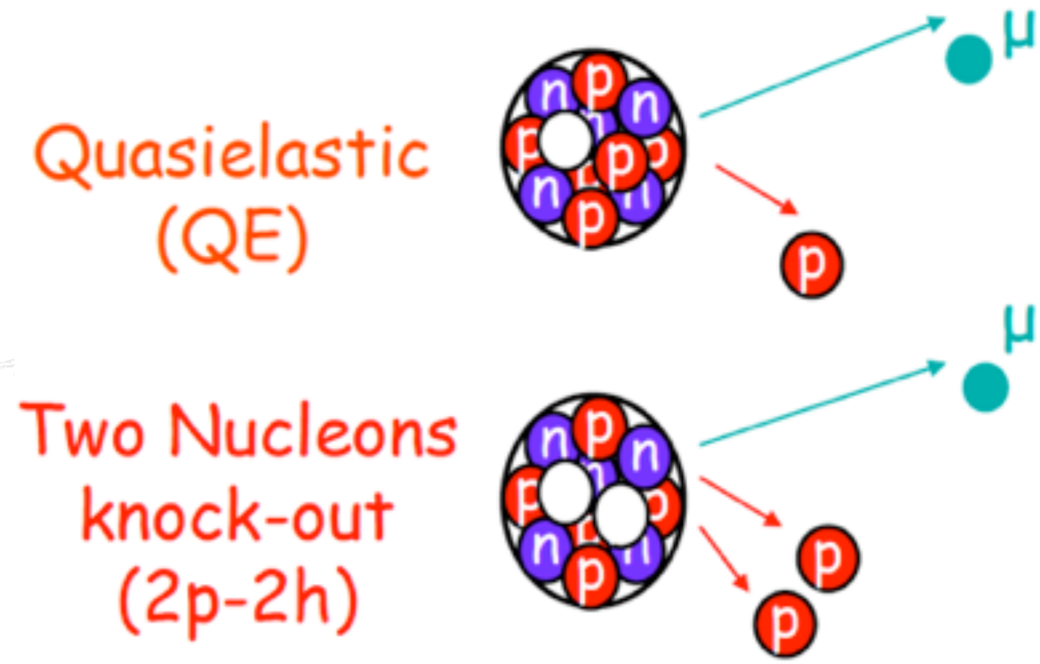
CCQE comparisons

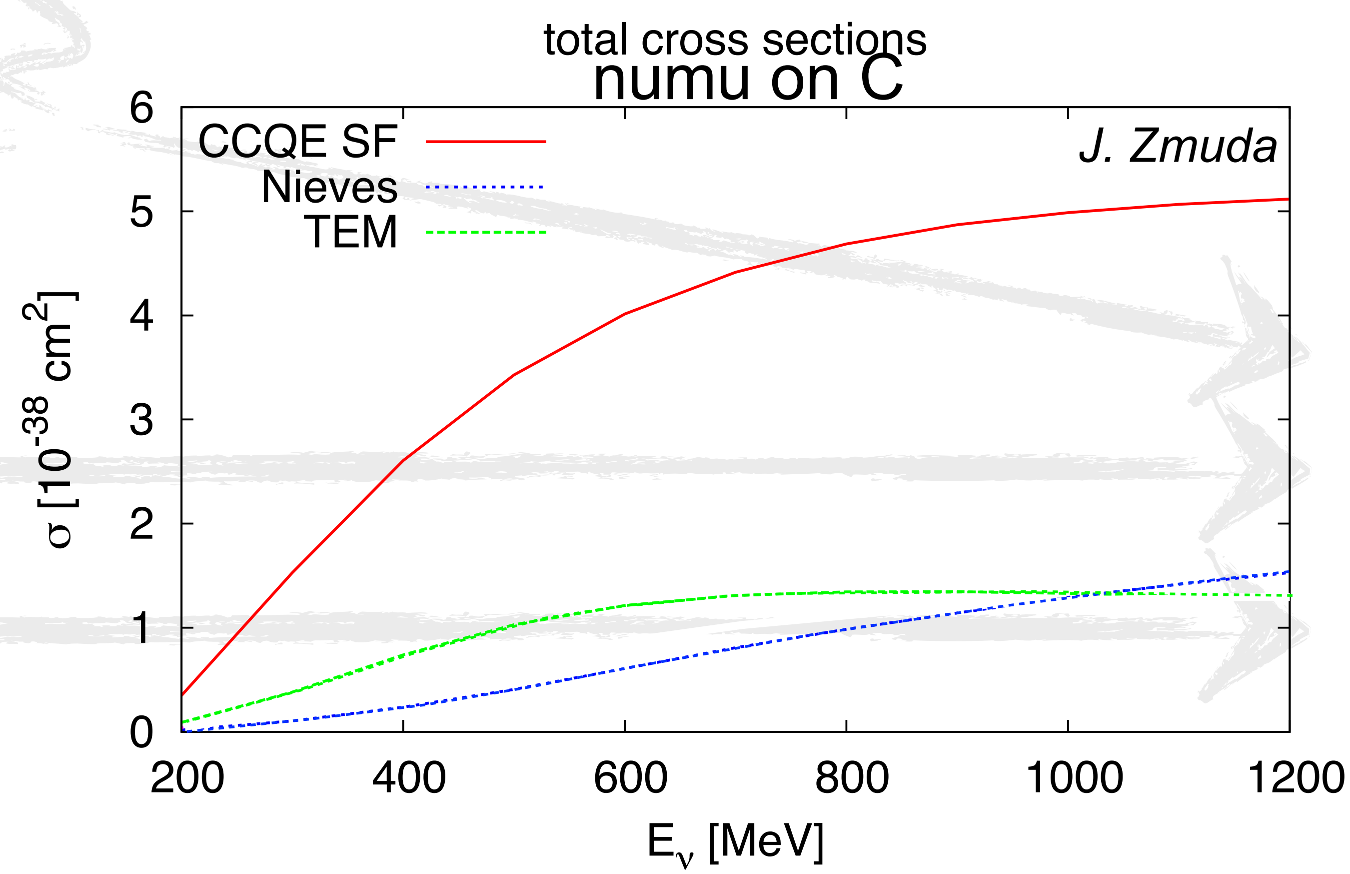


Significant discrepancies between BooNEs (~1 GeV) and NOMAD (~10 GeV).

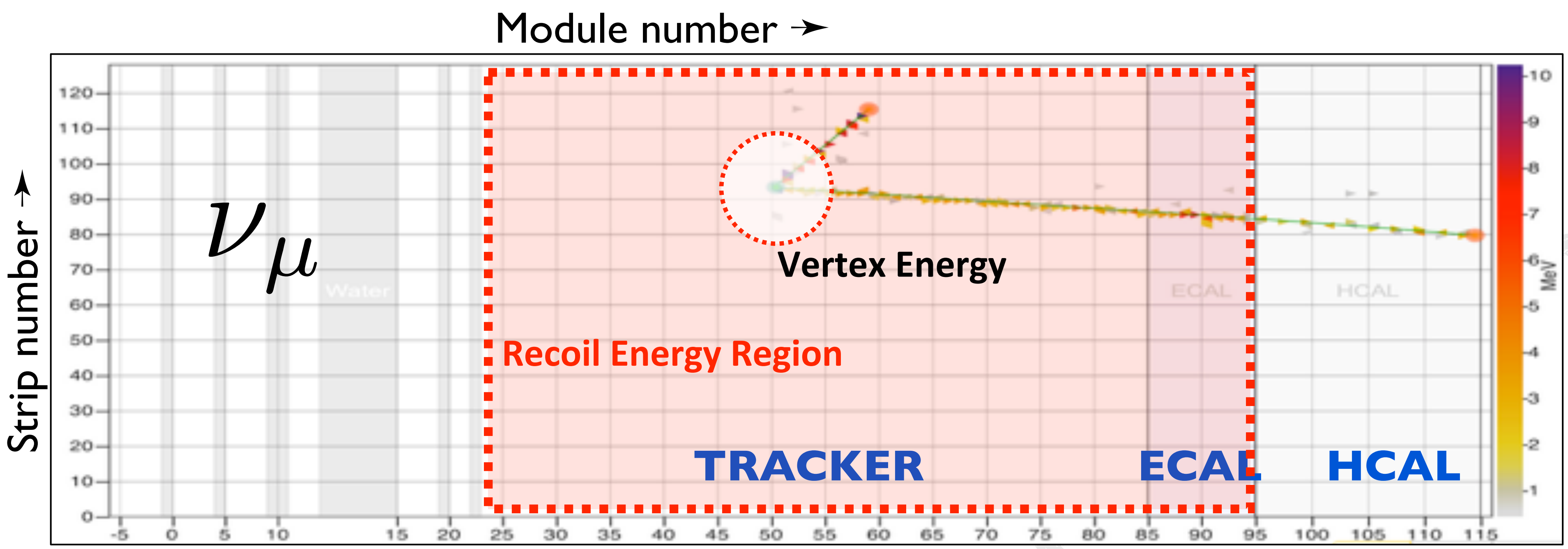
A "new" process?

- Solution to MinBooNE/NOMAD discrepancy : np-nh events?
  - First suggested by Martini *et al.* (IPNL)
- Neutrino interacts with correlated nucleons within the nucleus
- Evidence for such processes seen via enhancements in transverse cross sections in e-A scattering
- Multiple theoretical approaches being developed

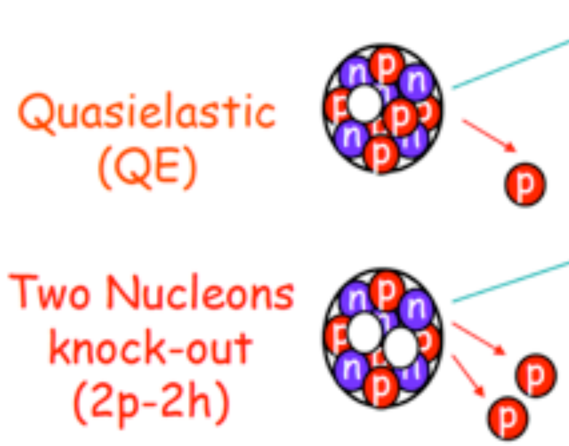


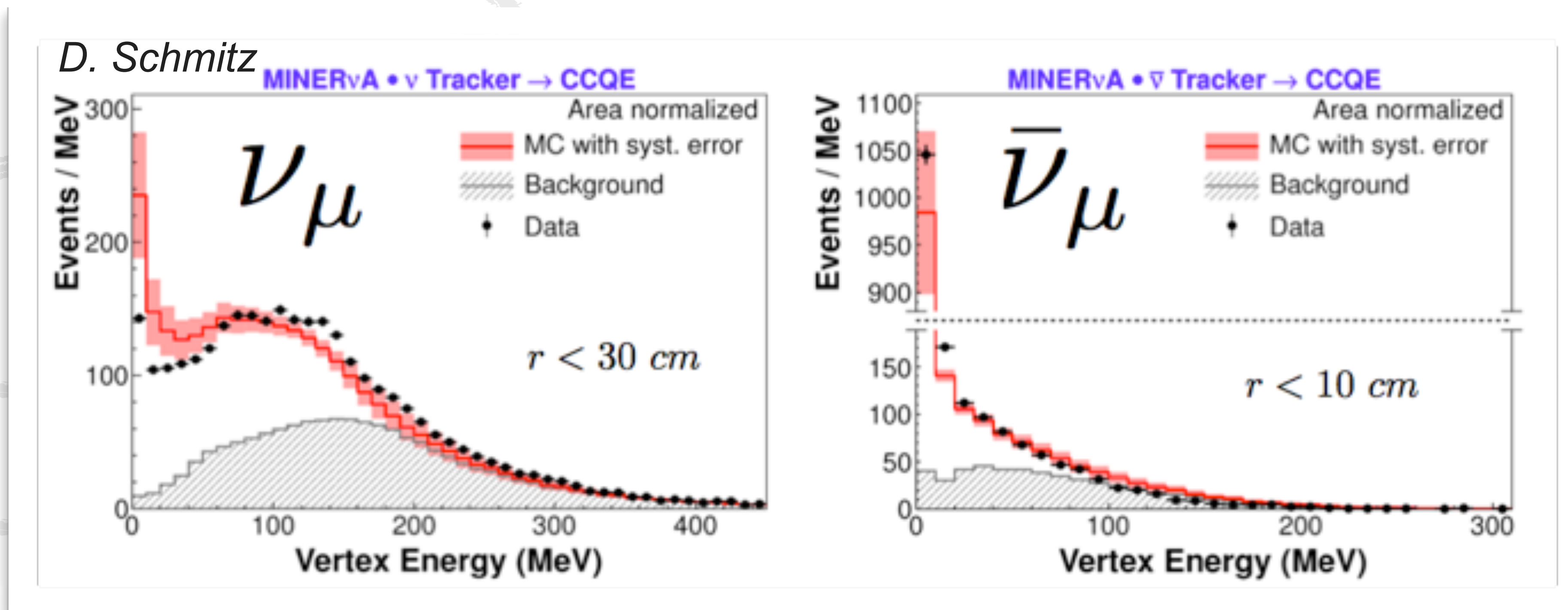


Support from MINERvA



MINERvA data: recoil hadron energy deposits in 10 cm and 30 cm radius from vertex



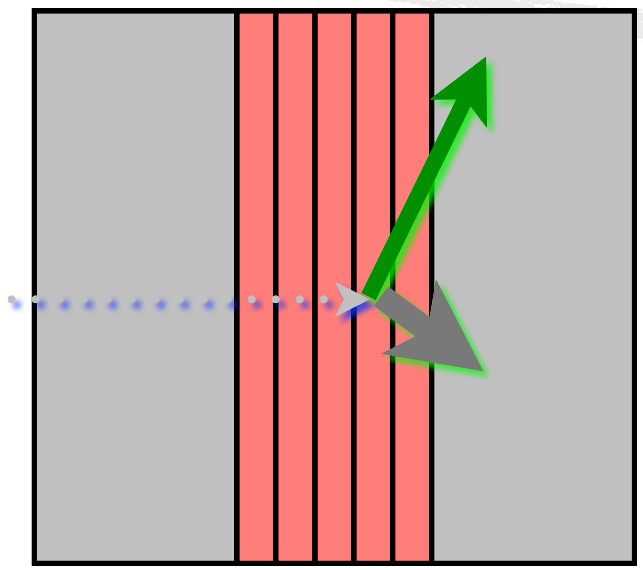


Neutrino data want more protons in 30 cm range

Antineutrino data want fewer protons in 10 cm range

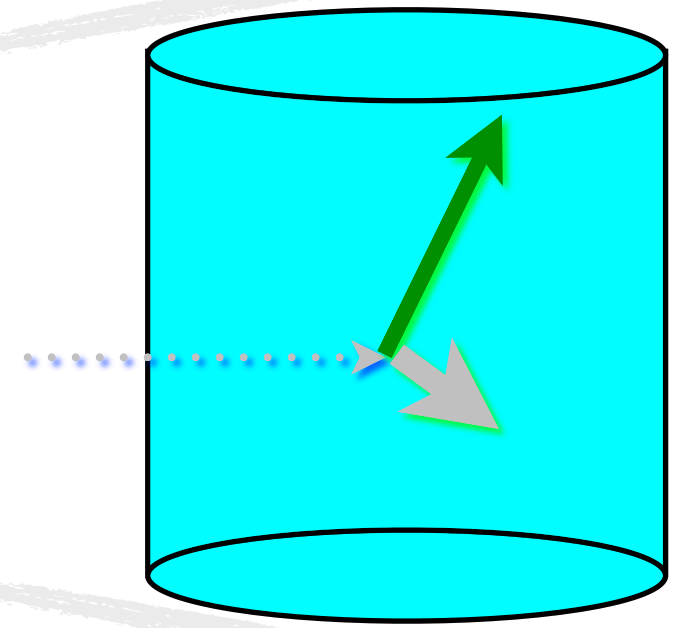
Effect on oscillation experiments

Segmented detector



Far detector rates tuned with near detector: *extrapolate xsec model parameters as well as flux factors*

Open-volume detector



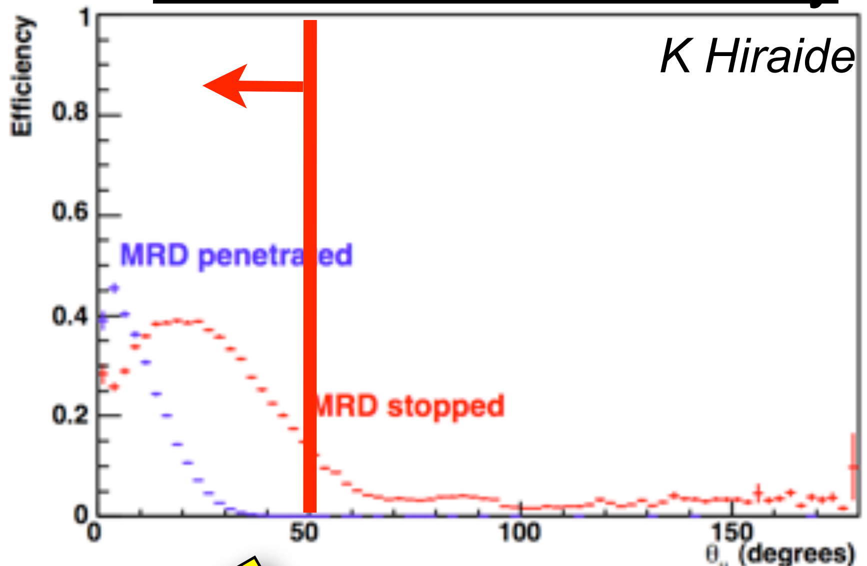
Loses acceptance at high angle;
No backwards muons.

Good acceptance over all angles;
2nd tracks often not seen.

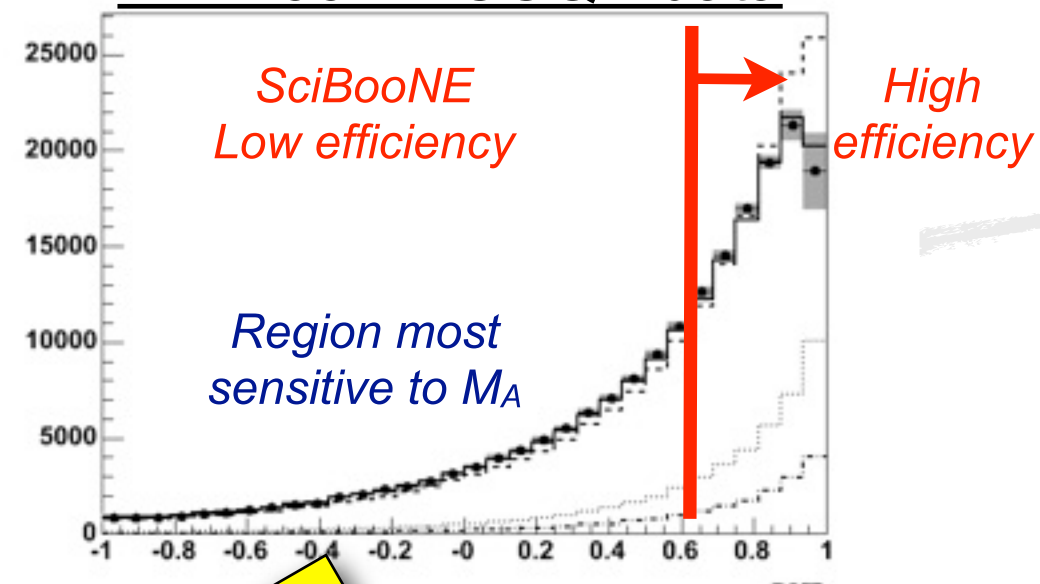
Example applies to:
T2K, MiniBooNE/SciBooNE,
possibly Hyper-K, LBNO & LBNE

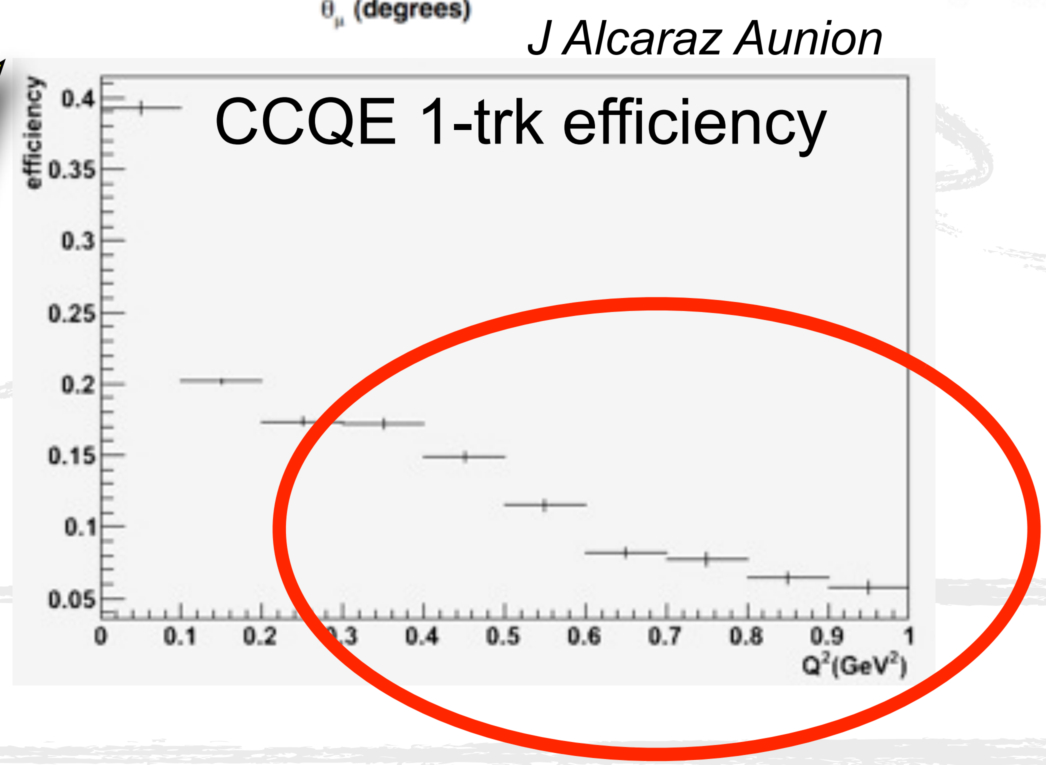
Different acceptances (1)

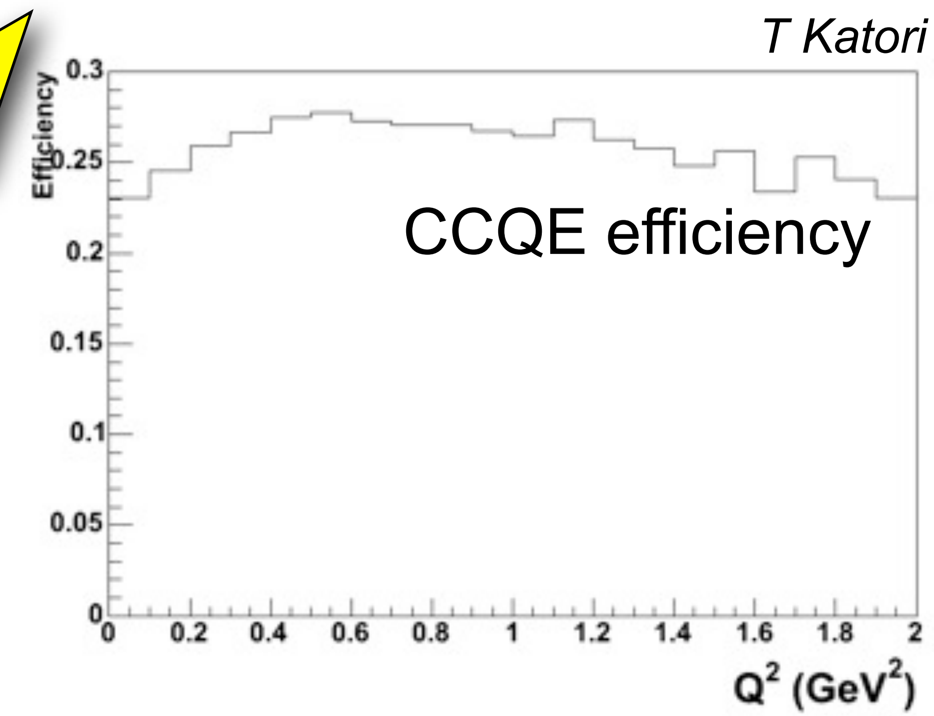
SciBooNE CC efficiency



MiniBooNE CCQE data





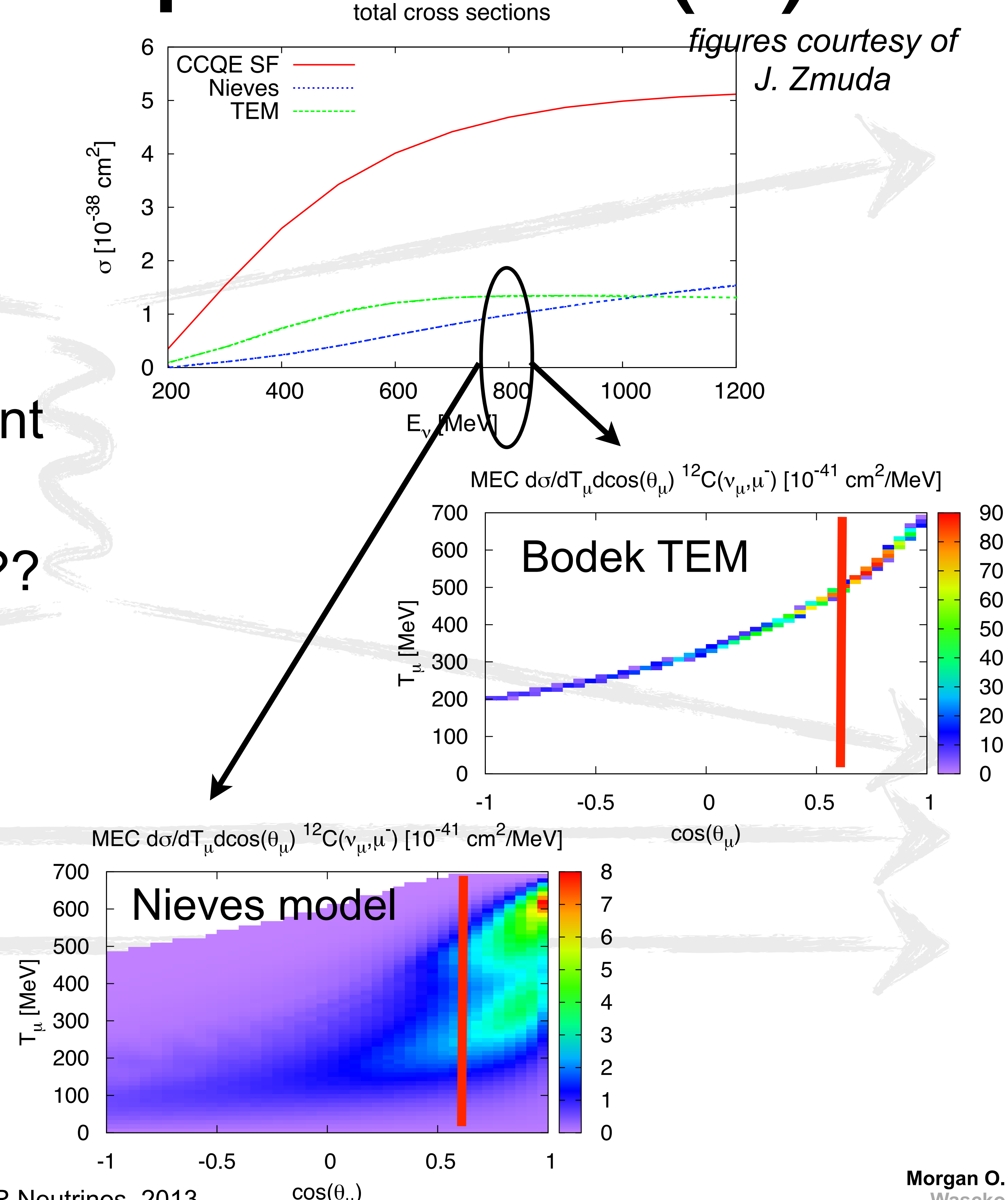


Non-zero efficiency over Q^2 range (& protons!) allow extrapolation because xsec model predicts kinematics over full phase space. Works great *as long as the model is correct*.

Different acceptances (2)

figures courtesy of J. Zmuda

- However, presence of un-modelled processes in data sample affects extrapolation
- Effects exacerbated by different kinematics in each model
  - Which one matches Nature??
- Changes neutrino energy reconstruction
- Near detector extrapolation cannot fix this even if it is identical to far detector!



Different acceptances (2)

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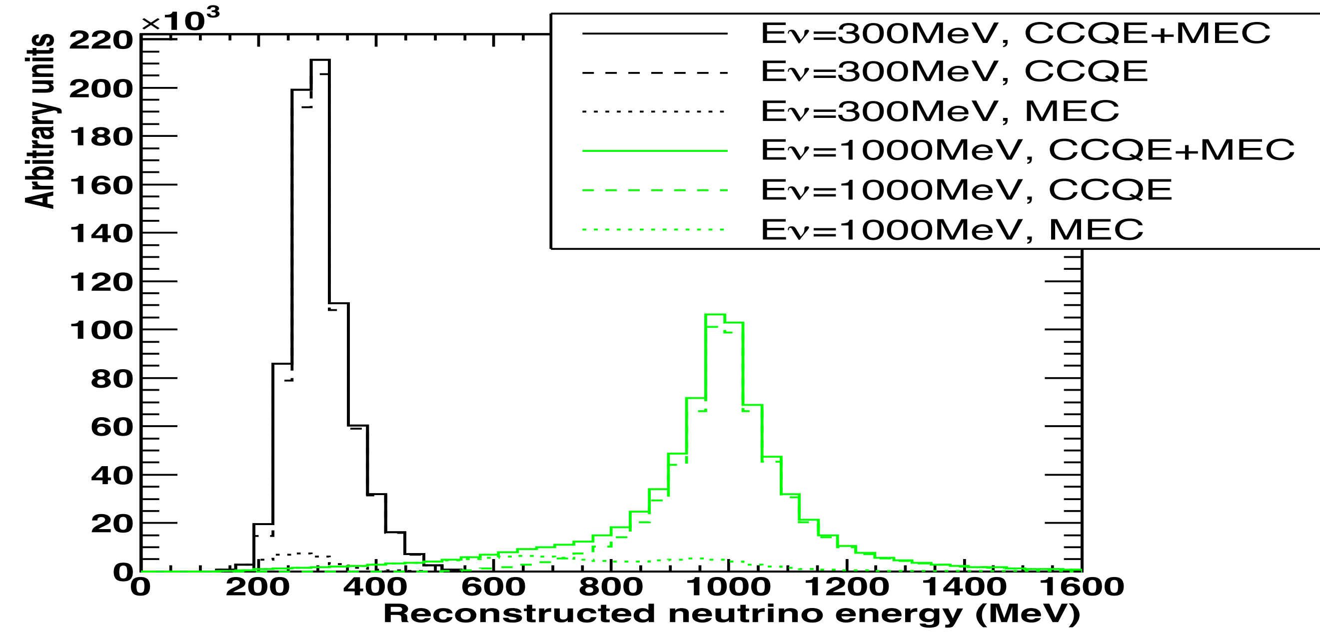
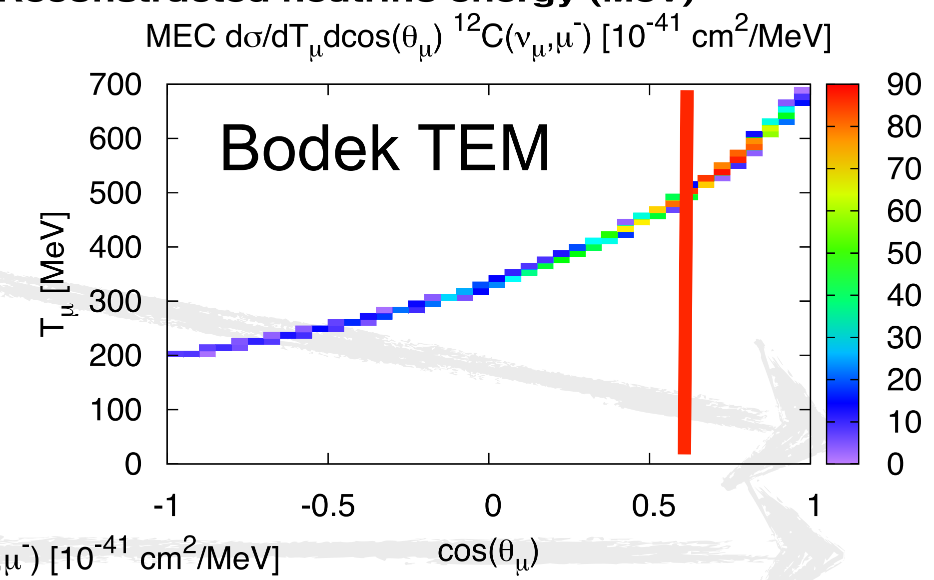
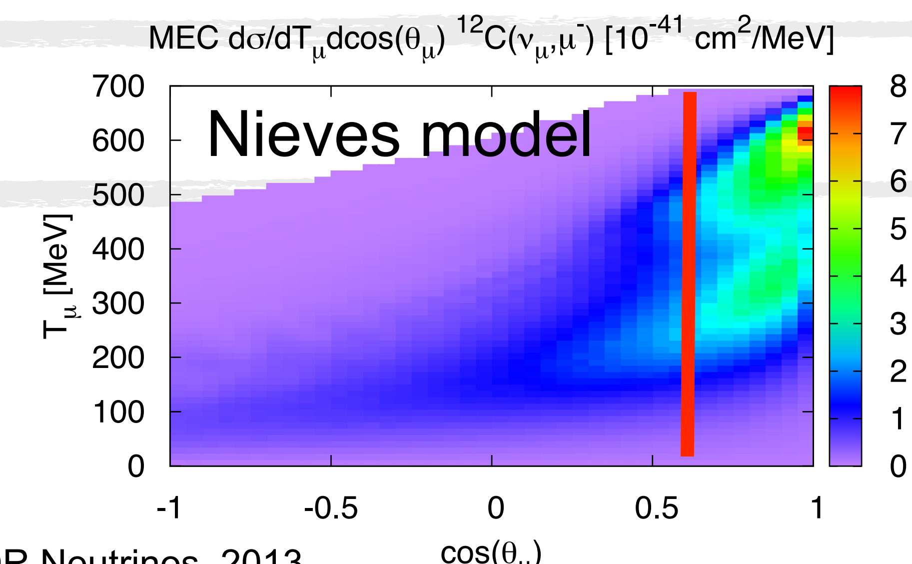


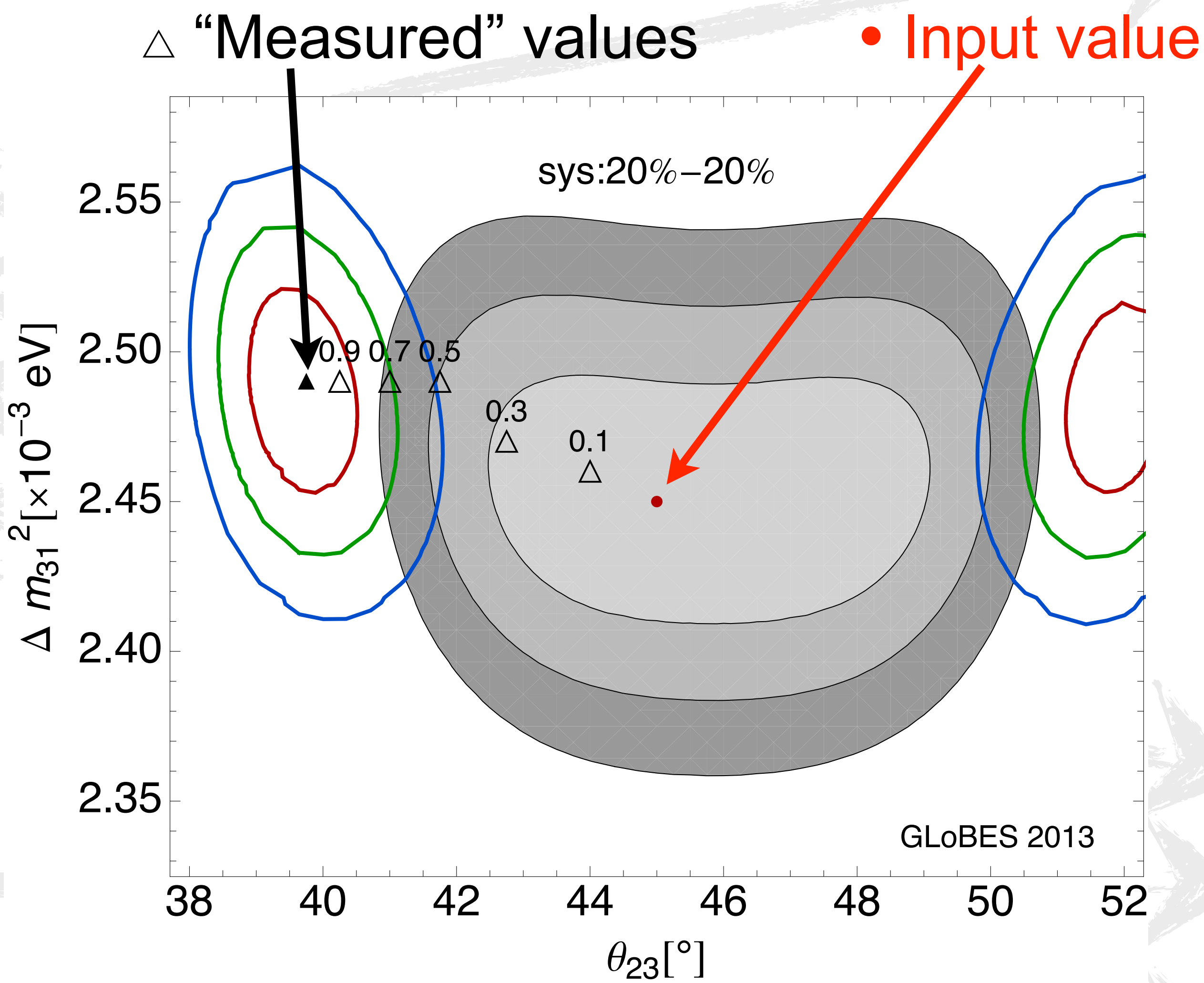


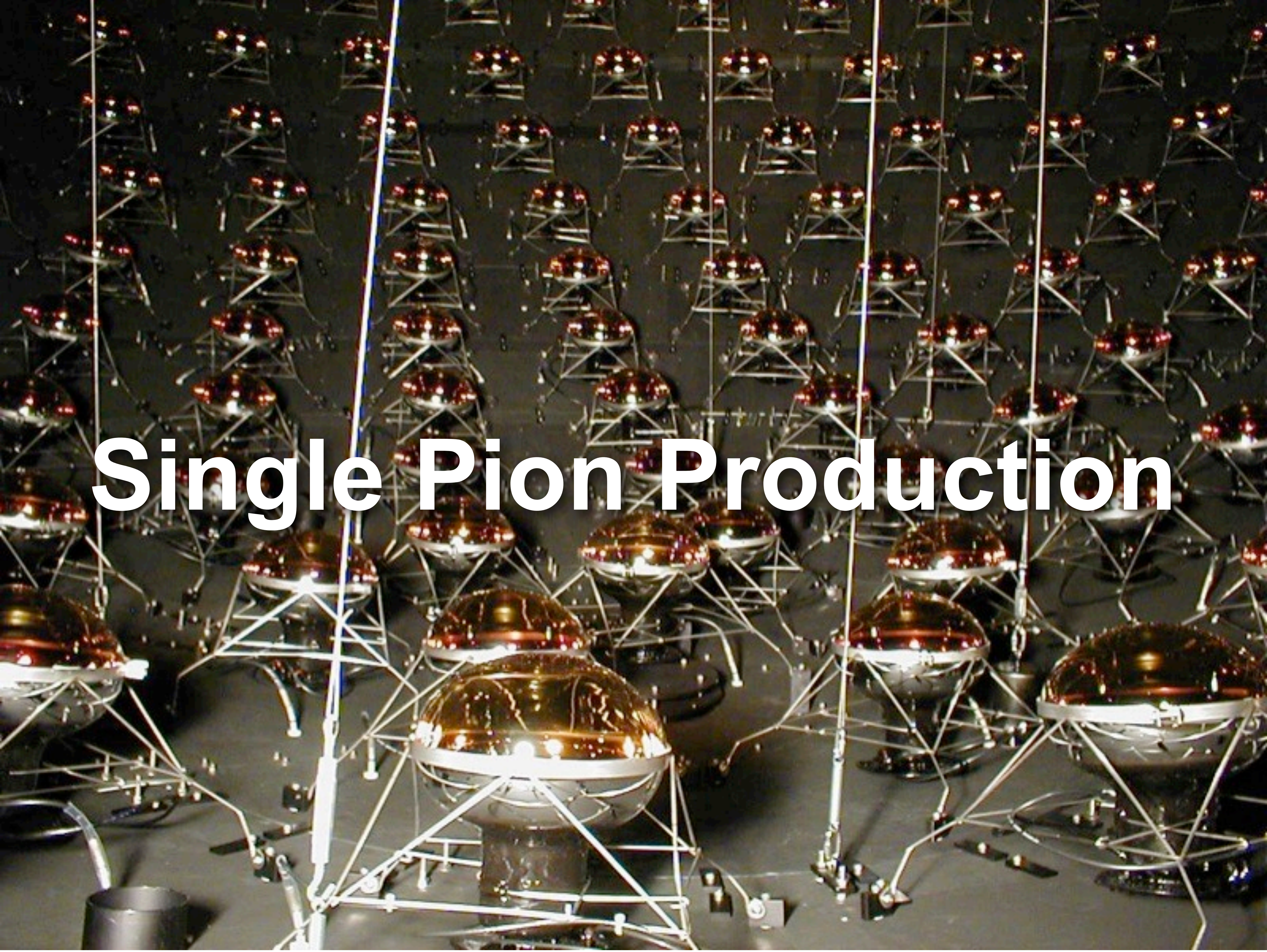


Effect on oscillation experiments

- Assuming a wrong model of np-nh (or any interaction) kinematics can change the measured value of neutrino oscillation parameters
  - E_ν reconstruction and event rates will be wrong
- Example: ν_μ disappearance with generic nuclear effects
  - Parameterise fraction of nuclear effects that are neglected
- Can shift the measured values of θ_{23} by 5° degrees and Δm^2_{31} by .05 eV^2
  - Can change interpretation: true maximal mixing can appear as non-maximal!

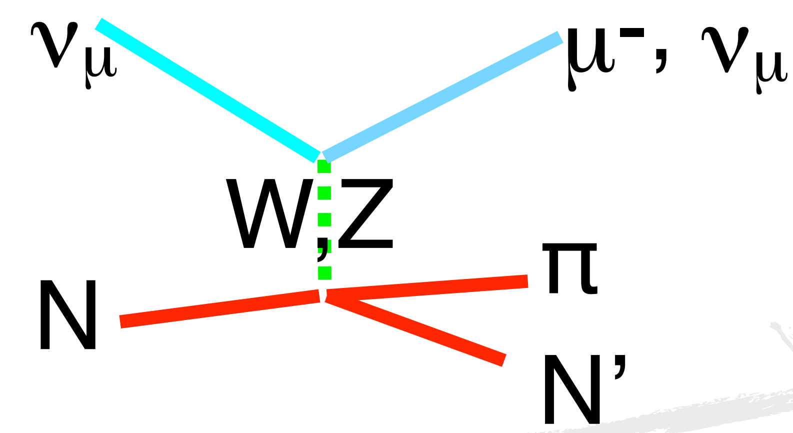
Coloma & Huber, arXiv:1307.1243 [hep-ph]



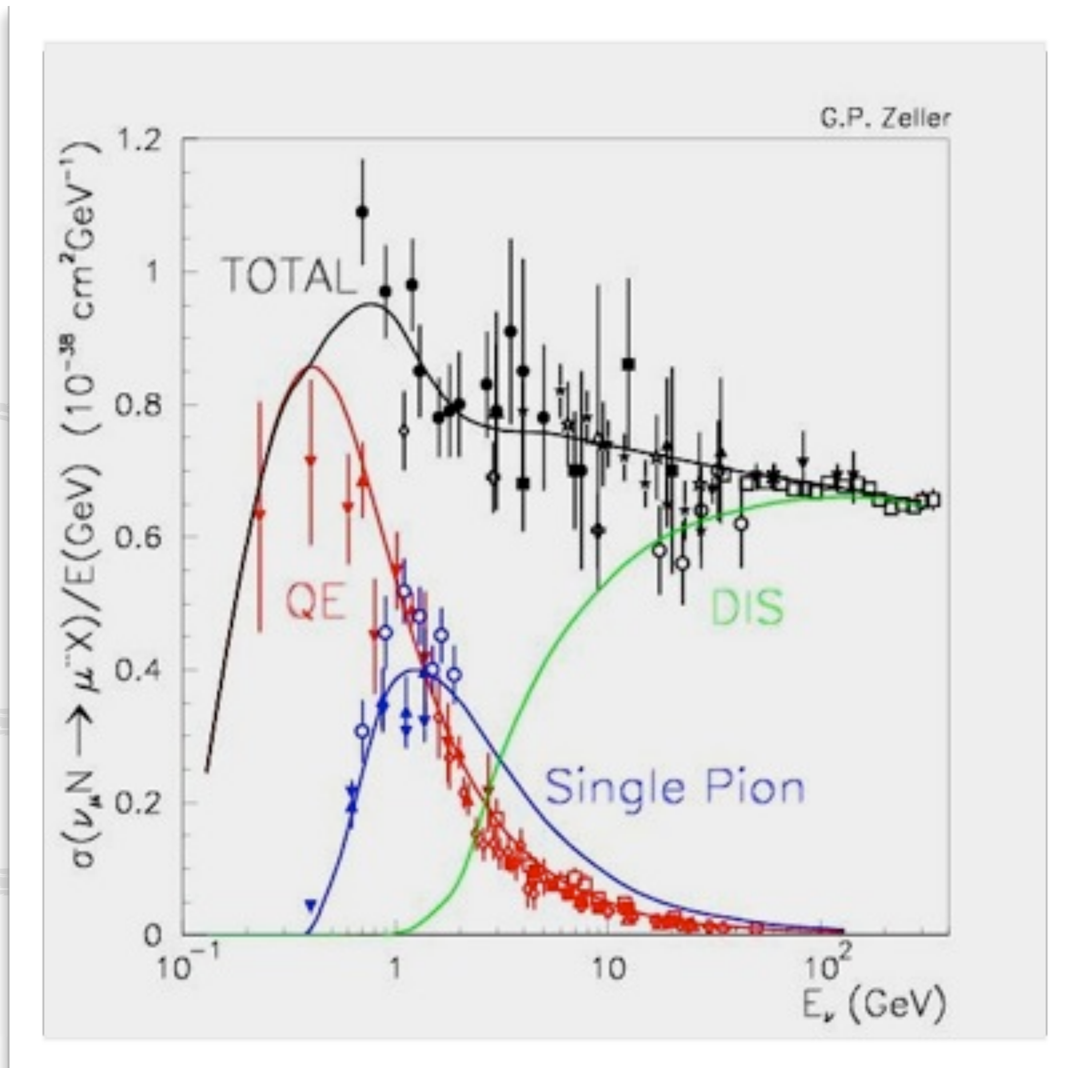


Single Pion Production

Single Pion Production



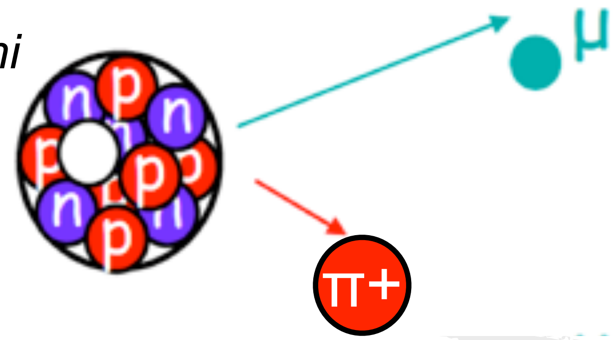
- Described by Rein-Sehgal model (1983)
- Again, form-factors parameterise nucleon weak charge distributions
- 18 resonances
- Model is tuned on data from 1970s
  - 2nd largest xsec near 1 GeV
  - Major background to CCQE
  - Previous measurements disagree!



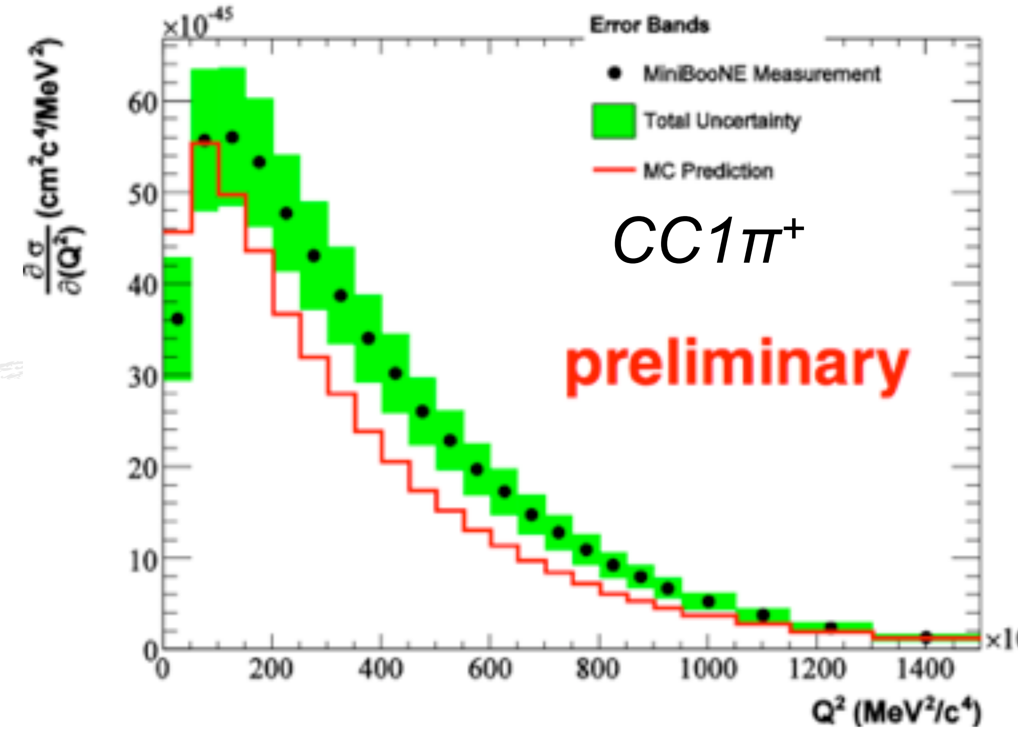
MiniBooNE data

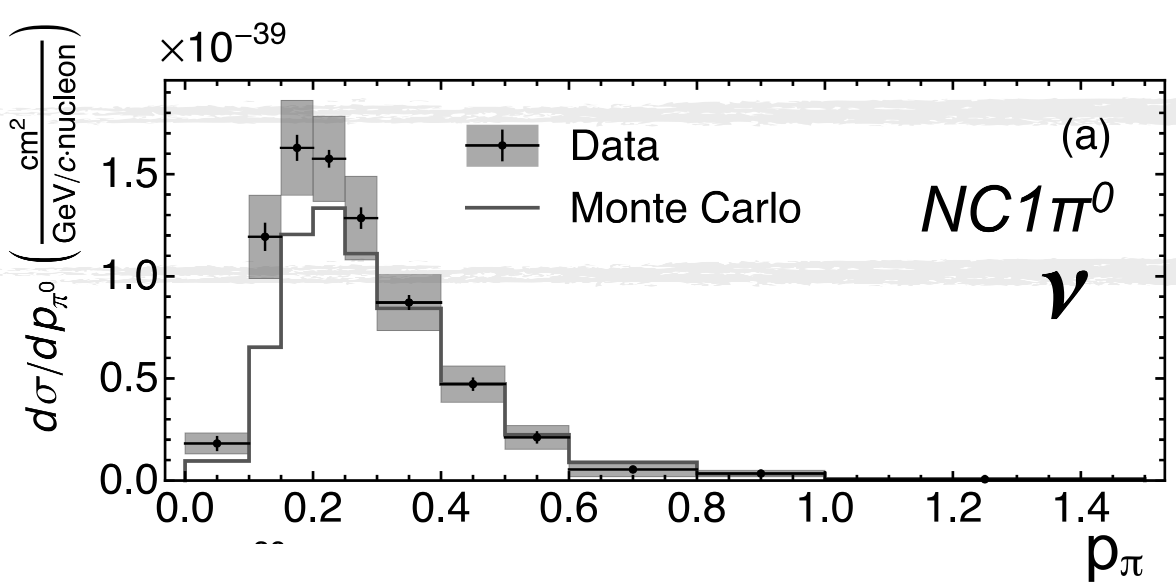
Diagram due to M. Martini

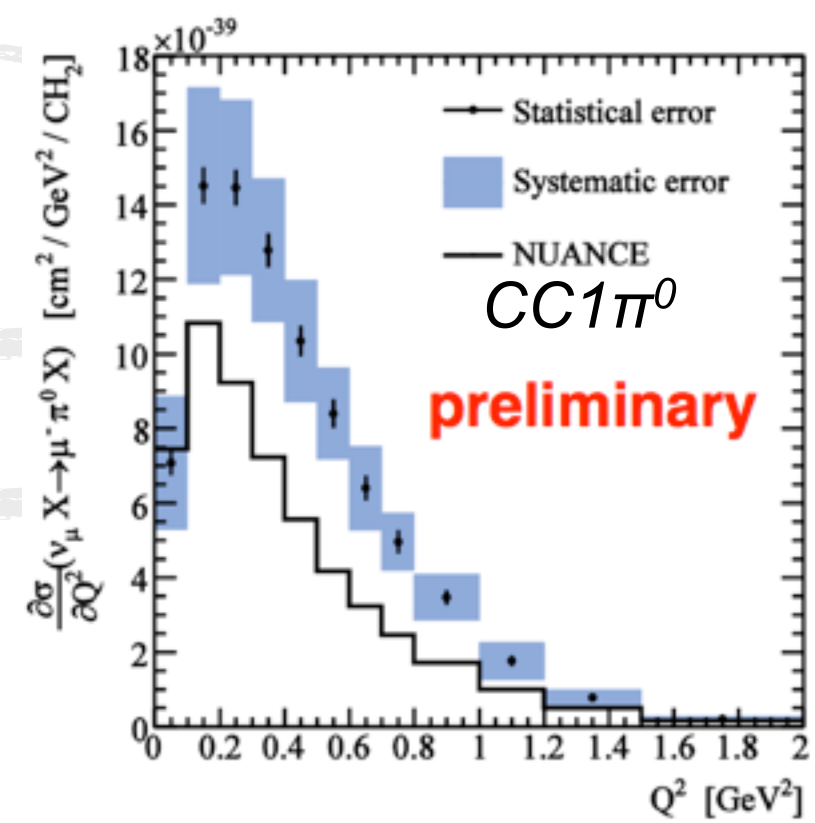
Single Pion
(CC1π+)



- MiniBooNE has published 3 world-leading papers on single pion production
- Signal definitions based on final state particles
  - model independence!



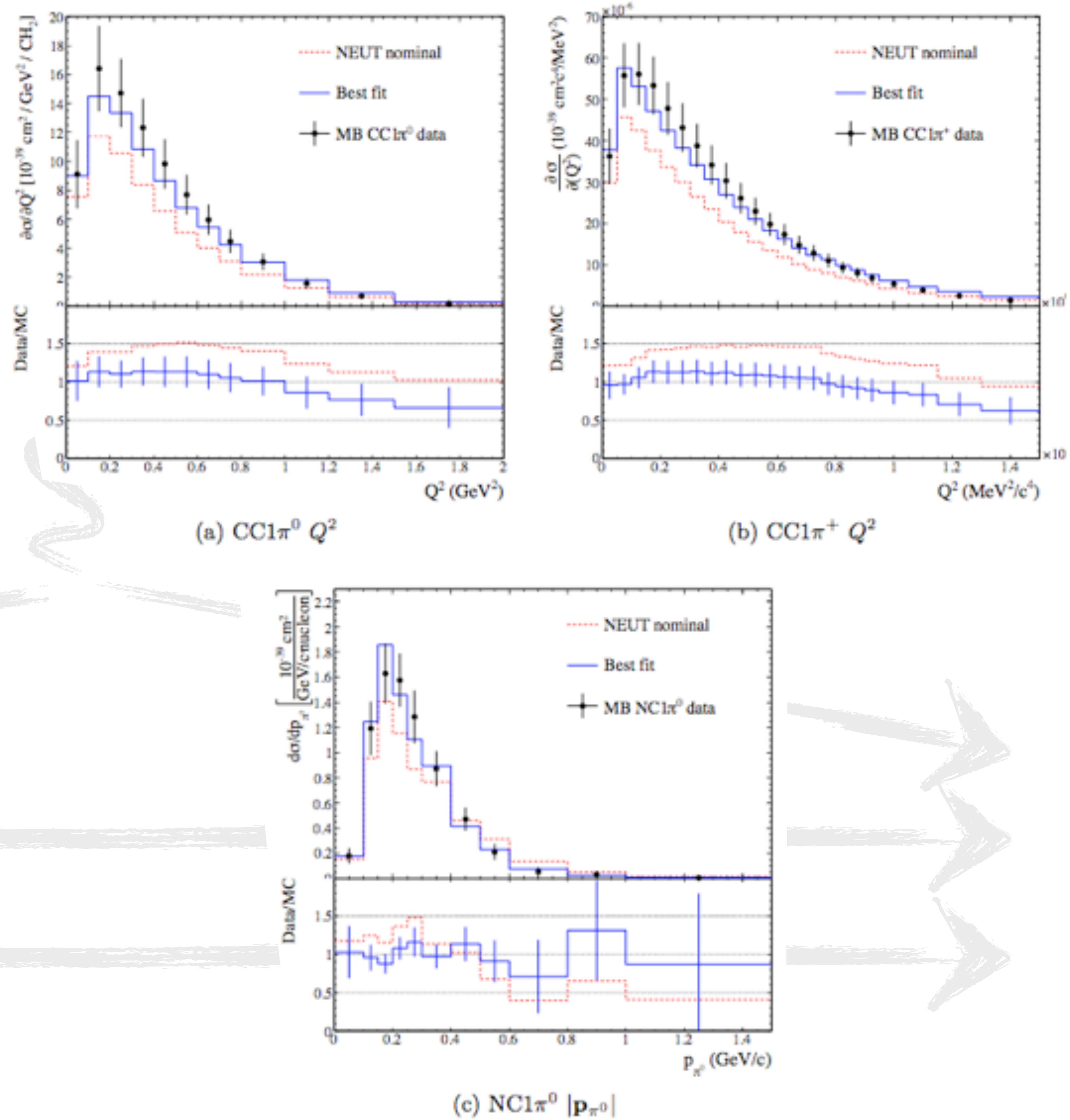




Simultaneous data fits

P. Rodrigues, NuFact12

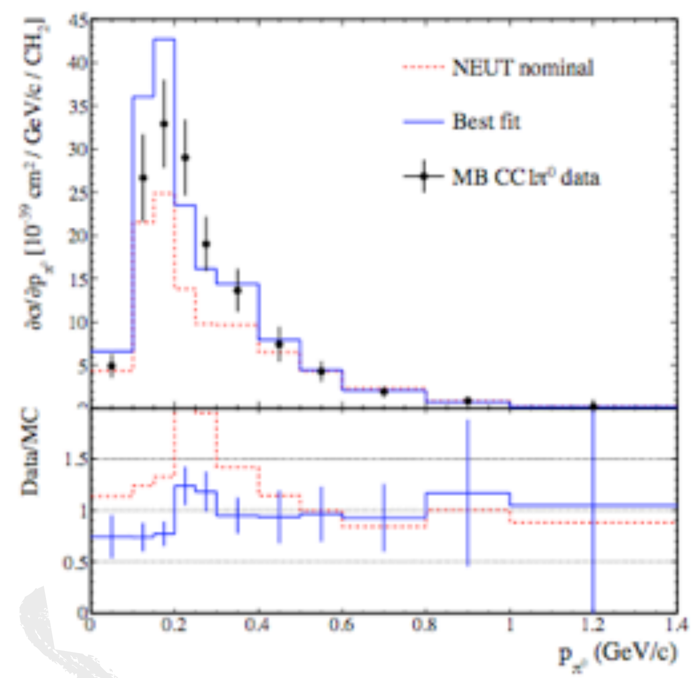
- T2K fits use all 3 data samples simultaneously with independent generator
- Poor agreement with Rein-Sehgal model
- For oscillation analysis, include *ad hoc* tuning parameters that break internal consistency of model
- Achieve good agreement in fitting variables



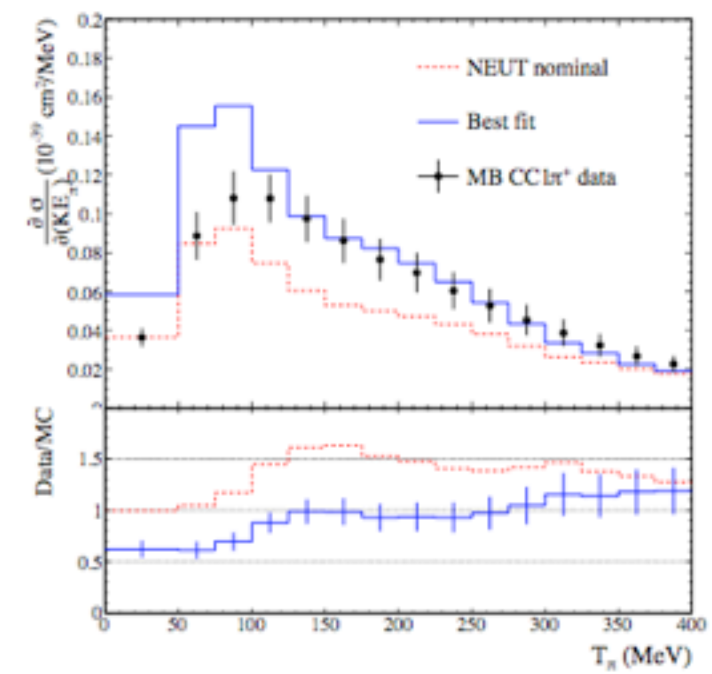
Non-fitting distributions

P. Rodrigues, NuFact12

- Unfortunately, other variables do not all agree well
- Must inflate systematic errors to cover data-model differences

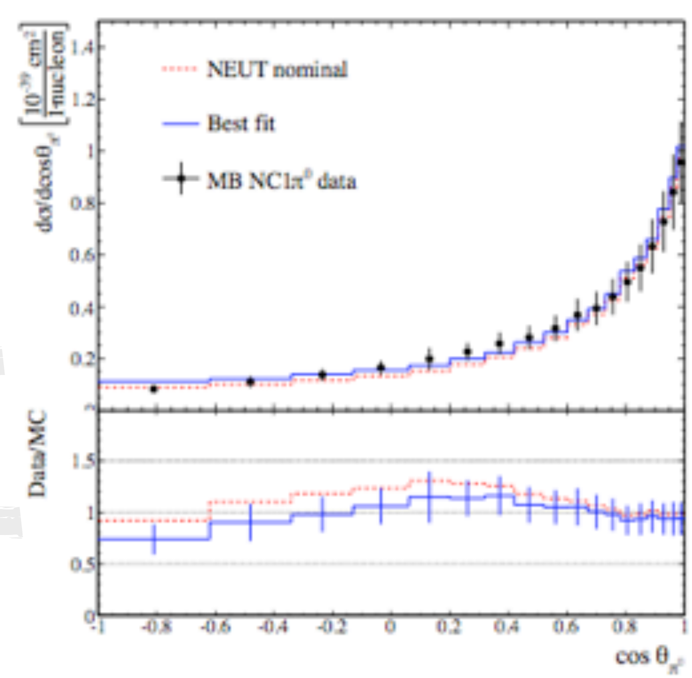


(a) CC1π^0 $|\mathbf{p}_{\pi^0}|$

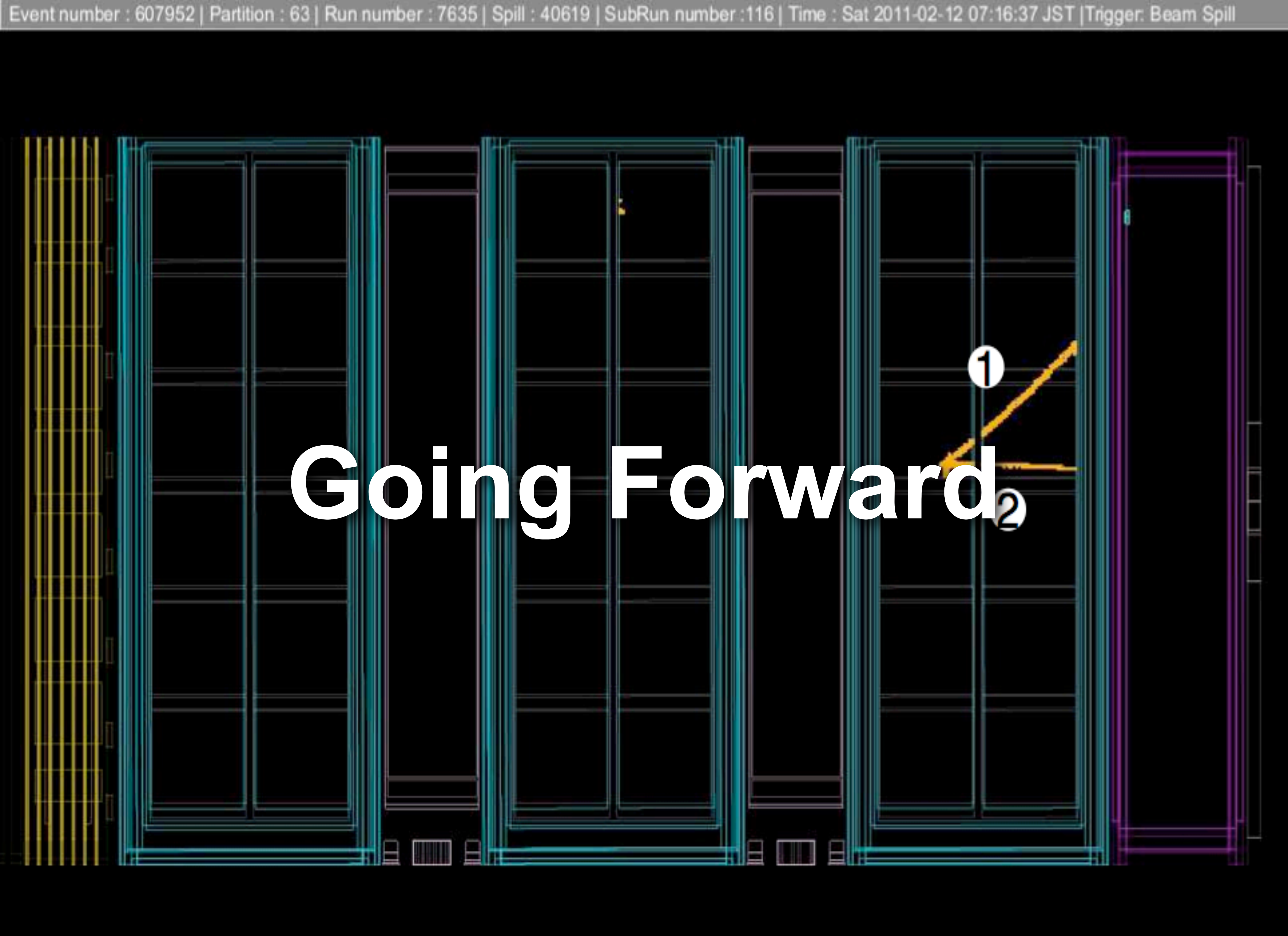


(b) CC1π^+ T_{π^+}

- Work proceeding on improved form factors and other model improvements
- High quality data samples inspire good new developments in theory and modelling

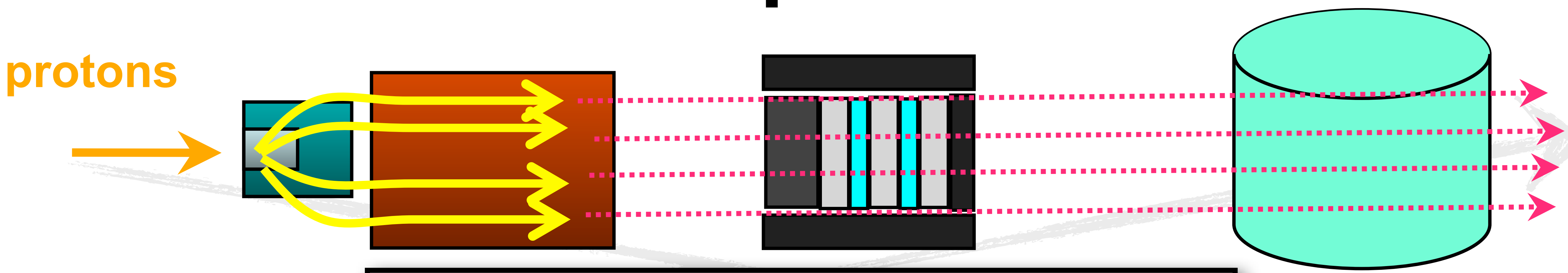


(c) NC1π^0 $\cos\theta_{\pi^0}$



Going Forward

Model Dependence?



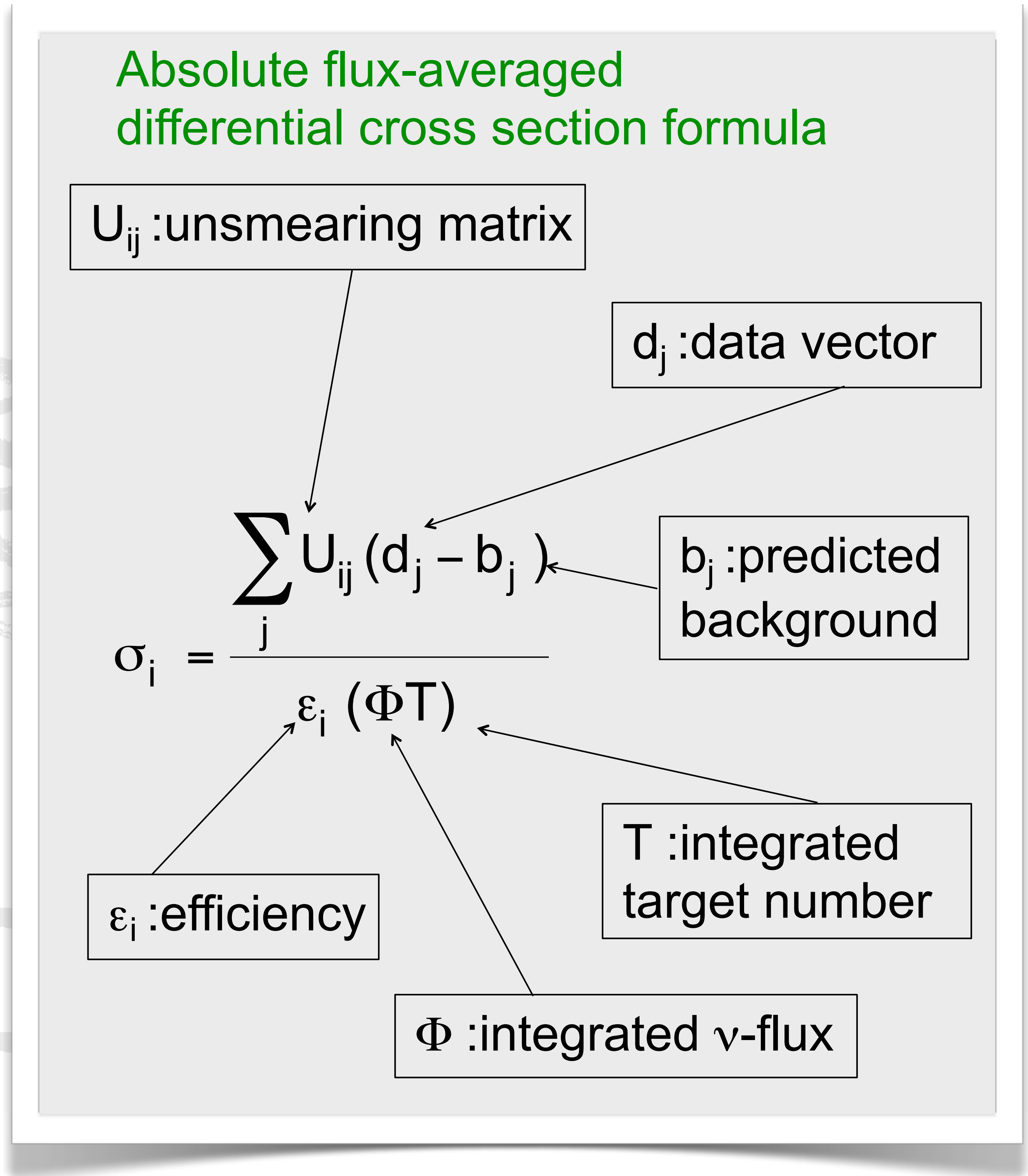
$$\Phi_\nu^{near}(E)\cdot\sigma^{near}(E)\cdot\varepsilon^{near}(E) \Leftrightarrow \Phi_\nu^{far}(E)\cdot\sigma^{far}(E)\cdot\varepsilon^{far}(E)$$

- Models are useful:
  - Relate final state particles to neutrino energy, estimate systematic errors.
  - Cannot do oscillation analysis without a model, but error cancellation only works if the model matches Nature!
- Ulrich Mosel's observation, NuInt11:
  - Theorist's paradigm: "A good generator MC does not have to fit the data, provided its model is correct"
  - Experimentalist's paradigm: "A good generator MC does not have to be correct, provided it fits the data"
- We need model independent measurements!
  - Provide enough info for later physicists to cleanly use data with a new model.
  - Confront each model with multiple data sets

What does model dependence mean?

- Distinguish between σ model and detector model
  - Any MC-derived quantity is, of course, model-dependent
- Restricting unsmearing, BG corrections, and efficiencies to detector MC quantities, not cross section processes is probably the best we can do
- This is why it's preferable to measure final state particle cross sections over process measurements

- NB: Could instead use multiplicative purity correction
  - Useful for highly correlated data: Peelle's Pertinent Puzzle



Show the whole story

- All neutrino data samples are rife with backgrounds.
  - MiniBooNE: CCQE $\leftrightarrow$ CC1π^+ $\rightarrow$ CC1π^0 $\rightarrow$? NC1π^0
  - but really: μ $\leftrightarrow$ μ+p $\leftrightarrow$ $\mu+\pi^+$ $\rightarrow$ $\mu+\pi^0$ $\rightarrow$? π^0
- Knowing what we do (about np-nh) from e-A experiments, we cannot have confidence in one without seeing all the others.
  - We've already learned that seeing them all isn't enough!
- For example, to extract M_A from neutrino data:
  - Requires nuclear model & background predictions match Nature.
  - Predicated on assumption that F_A is a dipole.

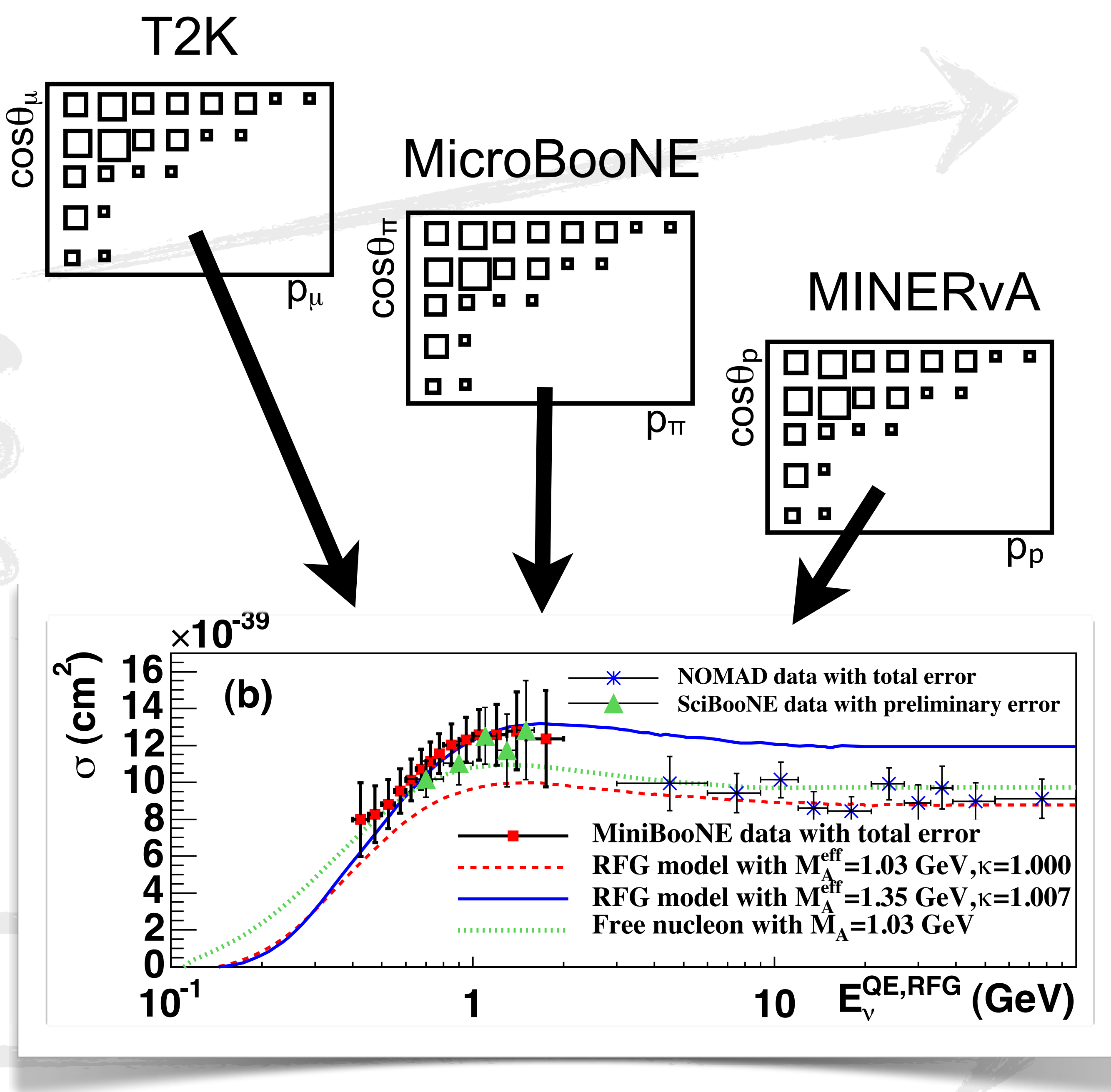
Experimenter's Wish List

1. np-nh models implemented in neutrino generator MCs
   - Neutrino experiments must develop event selection cuts using MC
   - Need to simulate interactions over all relevant energies and full phase space, which means need to use generators
2. Predictions for nucleon recoil multiplicities and spectra
   - True test of any model is comparison with data
   - Need to establish robust np-nh event signatures
   - Will need near detector designs with 4-pi coverage and very low recoil hadron energy thresholds (<5-10 MeV).
3. Role of np-nh interactions for pion production?

Conclusion

Growing Consensus

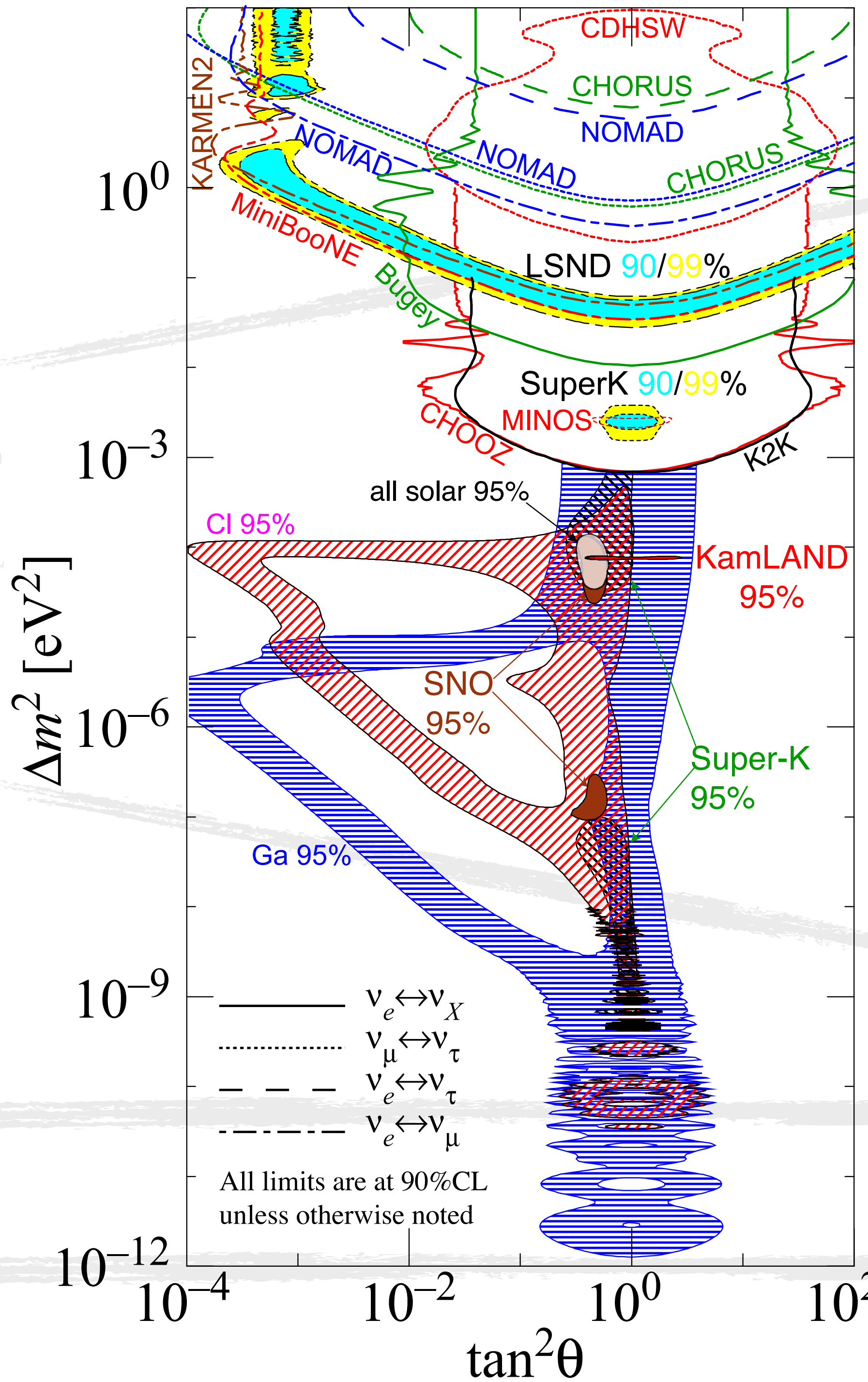
- We need broad coverage
  - Model independent measurements at many energies, nuclei
- Move away from process cross-sections
  - σ(CCQE), σ(CC res π), σ(CC coh π)
- Instead measure final state particle cross-sections
  - σ(CC), $\sigma(\mu)$, $\sigma(\mu$+p), $\sigma(\mu+\pi)$



With large value of θ_{13}, systematic errors will become the driving limitation for δ_{CP} searches!

Build a model-independent database

- Discovery of oscillation is robust because the effects are seen in many experiments, using many neutrino sources
  - Removes degeneracies & ambiguities, constrains systematic errors
- To find the best neutrino-nucleus interaction models—those that match Nature—we will need multiple techniques and technologies, and model-independent analyses



http://hitoshi.berkeley.edu/neutrino

Accelerators

Atmospherics

Reactors

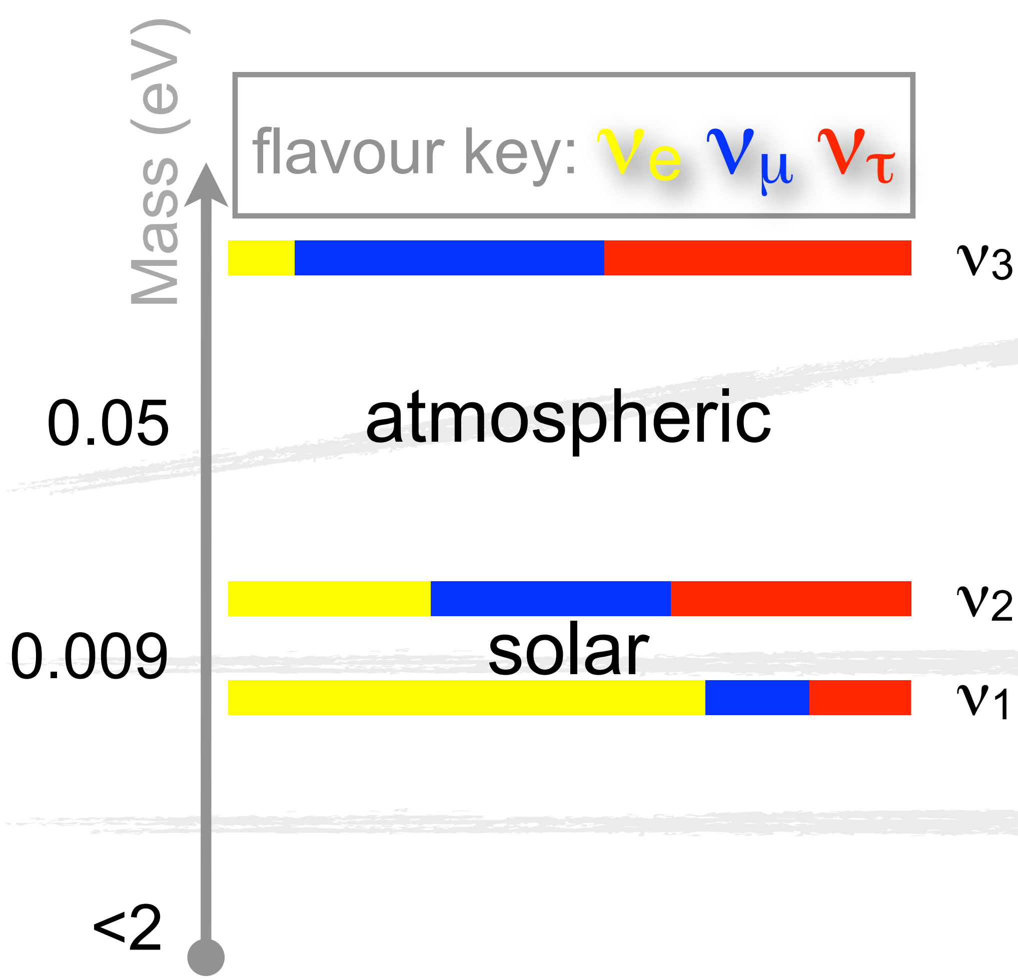
Solar


Thank you for your attention!
ご清聴ありがとうございました
水戸の梅の花

Current neutrino picture

flavour | *atmospheric* | *accelerator* | *solar* | *Majorana* | mass

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}e^{i\frac{\alpha_1}{2}} & 0 & 0\\ 0 & e^{i\frac{\alpha_2}{2}} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

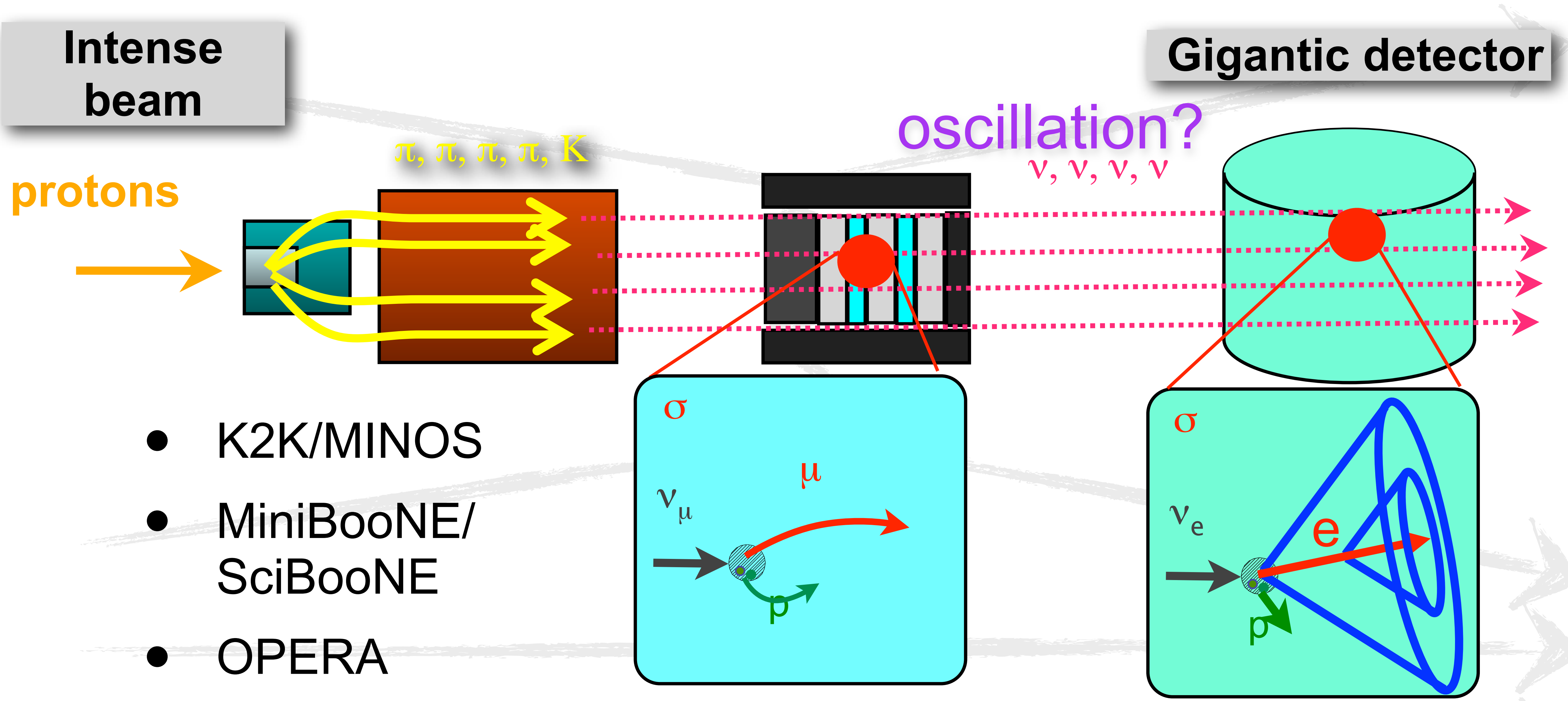


	VALUE
$\|\Delta m^2_{32}\|$	2.35±0.12 E-03 (eV^2)
Δm^2_{21}	7.58±0.24 E-05 (eV^2)
$\sin^2\theta_{12}$	0.31±0.018
$\sin^2\theta_{23}$	0.42±0.08
$\sin^2\theta_{13}$	~0.02±0.007
δ	?

Goal for next generation of experiments: **measure δ_{CP}**

Accelerator ν Experiments

Search for δ_{CP} by comparing $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$.

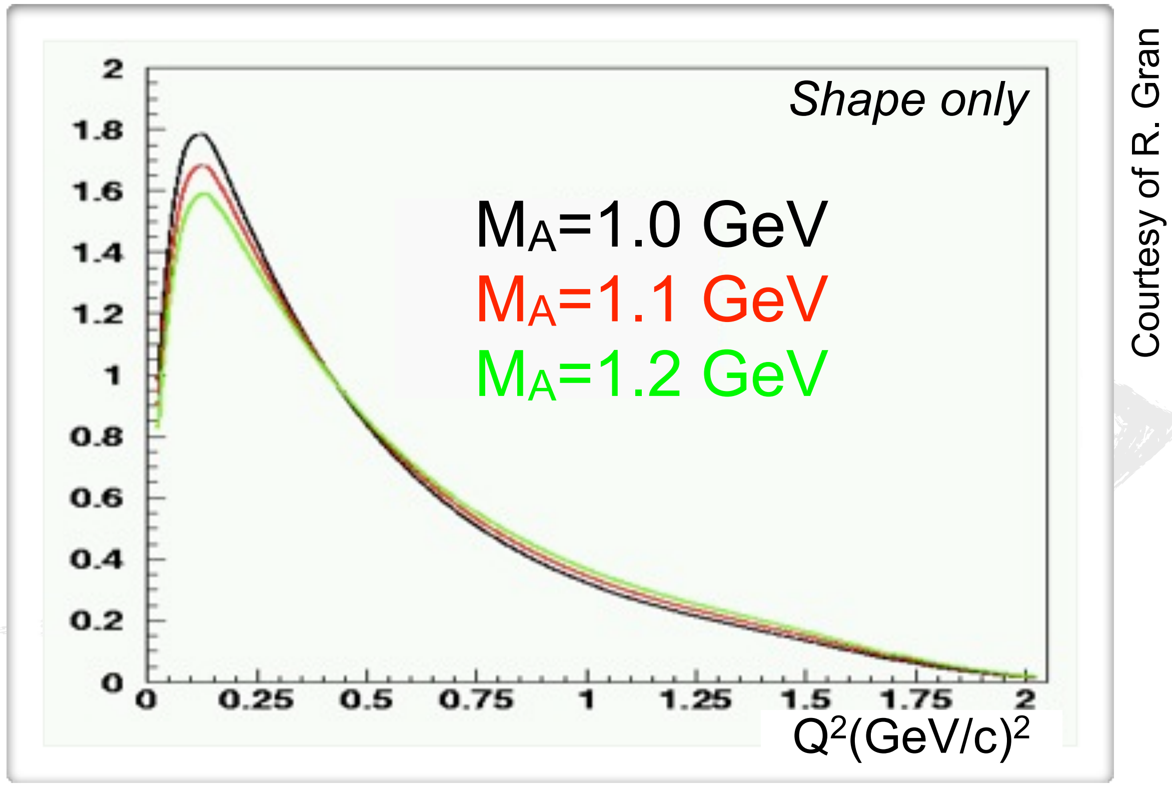


- K2K/MINOS
- MiniBooNE/ SciBooNE
- OPERA
- T2K/NOvA
- LBNE/LBNO/ T2HK

$$\Phi_\nu^{near}(E)\cdot\sigma^{near}(E)\cdot\varepsilon^{near}(E) \Leftrightarrow \Phi_\nu^{far}(E)\cdot\sigma^{far}(E)\cdot\varepsilon^{far}(E)$$

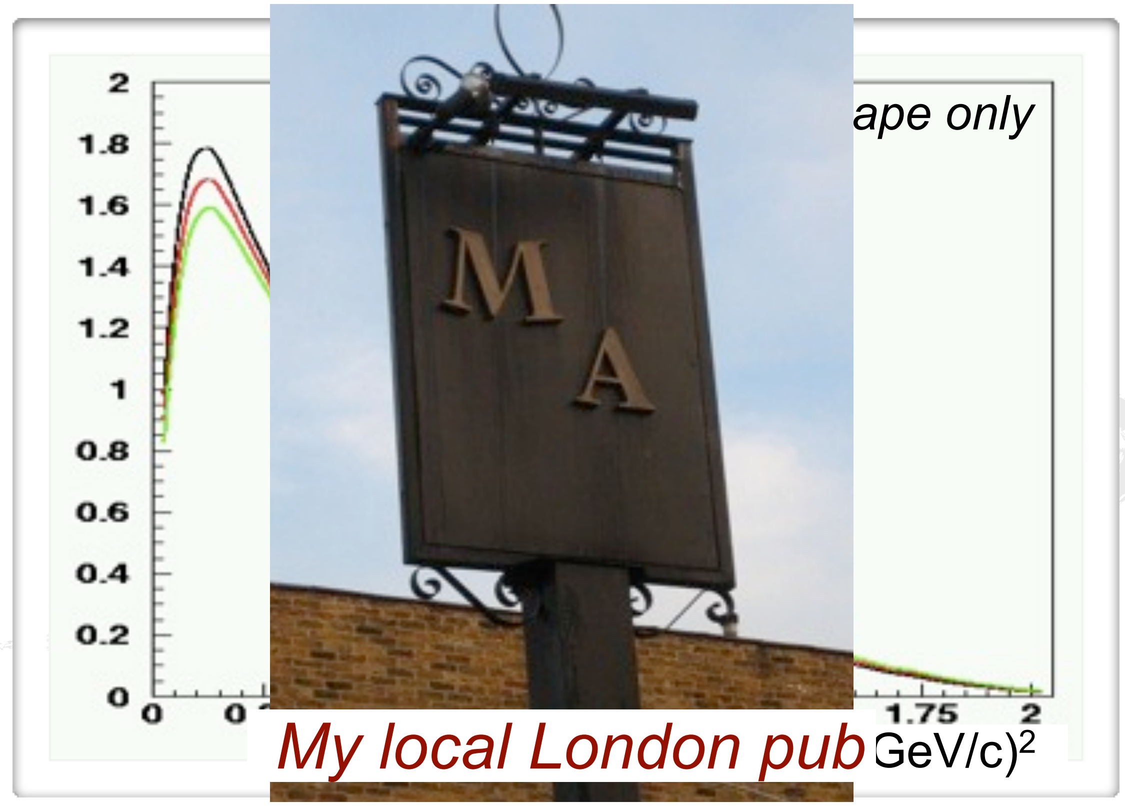
M_A fit results

- Value of M_A changes scale & shape of Q^2 distribution
- Recent measurements at low energy on nuclear targets favour high value of M_A
  - But not at high energy!
- Also show increased suppression at low Q^2
- F_A: not dipole form factor?
  - Is M_A an effective parameter?



Experiment	M_A Value (GeV)
World Average (n,p)	1.03±0.03
K2K SciFi (O)	1.20±0.12
K2K SciBar (C)	1.14±0.10
MiniBooNE (C)	1.35±0.17
MINOS (Fe)	1.19±0.17
NOMAD (C)	1.05±0.06

M_A fit results



Courtesy of R. Gran

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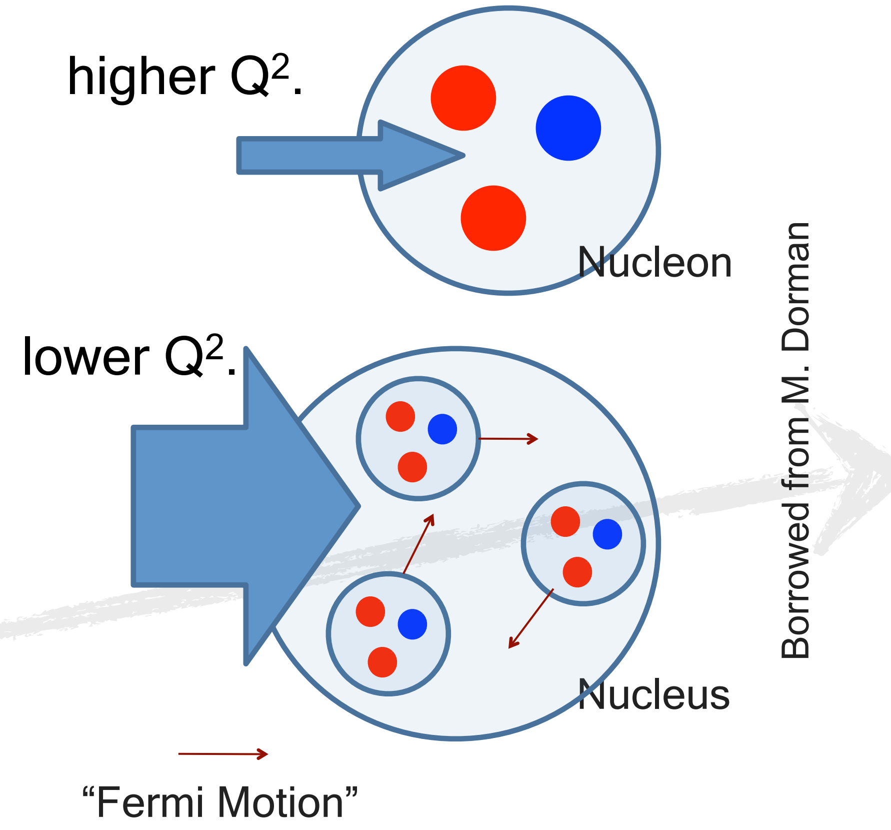
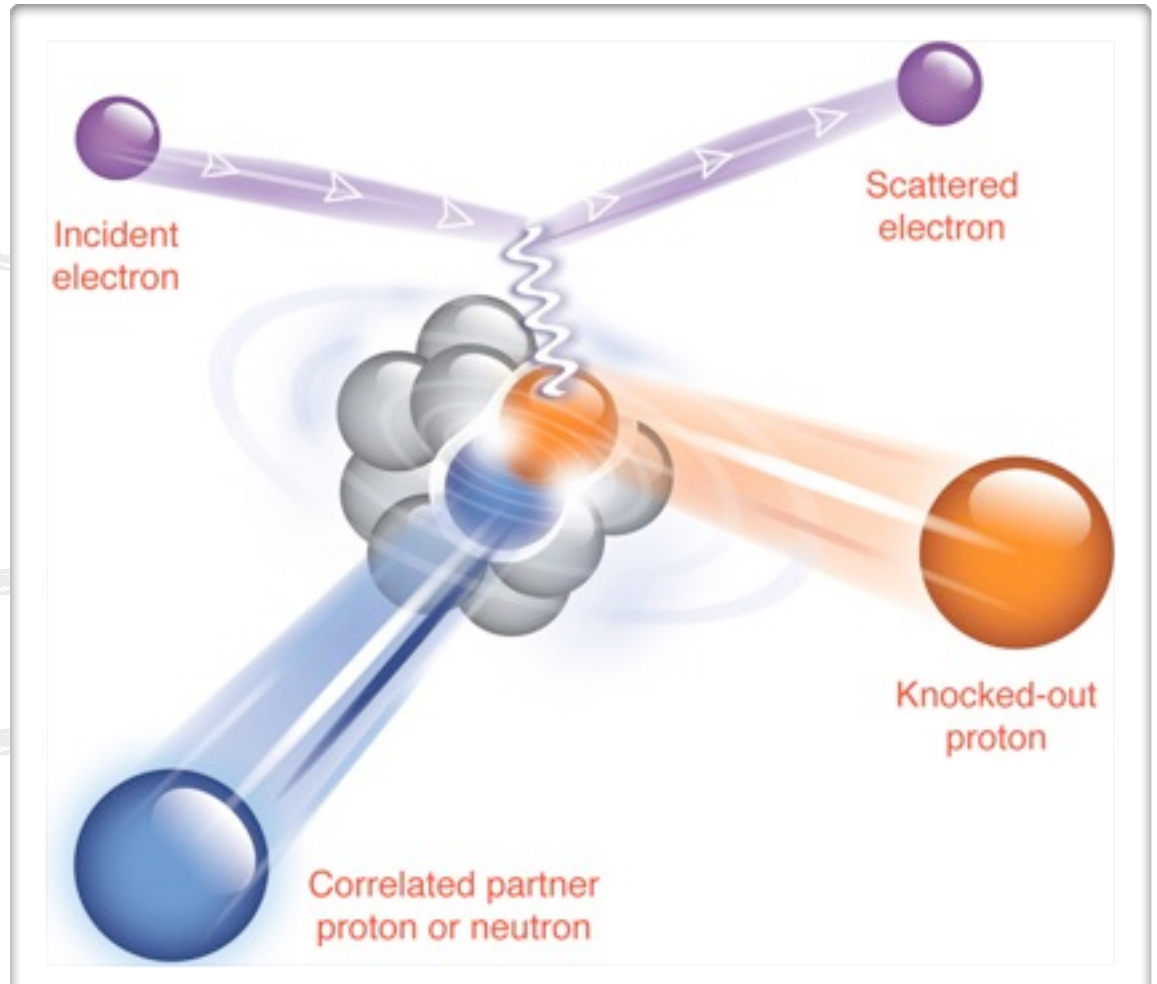
Impulse approximation

Nuclear effects discussed by O. Benhar

- Assume interaction involves only one nucleon
  - λ>1 fm for Q^2<1$(GeV/c)^2$
- Neutrino experiments assume quasi-free interactions
  - Are nucleons actually quasi-free? If not, could we tell?
- Can low Q^2 region be described by impulse approximation?





Science Vol.320. no.5882, pp.1476

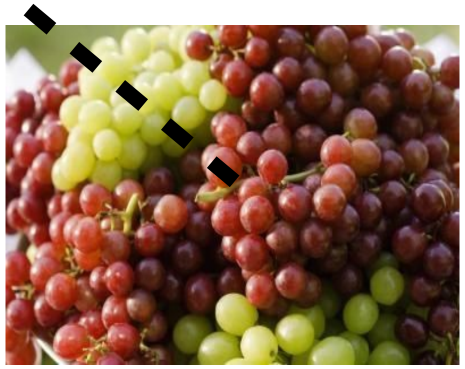
An analogy

lepton

neutrino

“probe”

detector: grapevine



Nuclei QEL: Hit a grape, knock it out

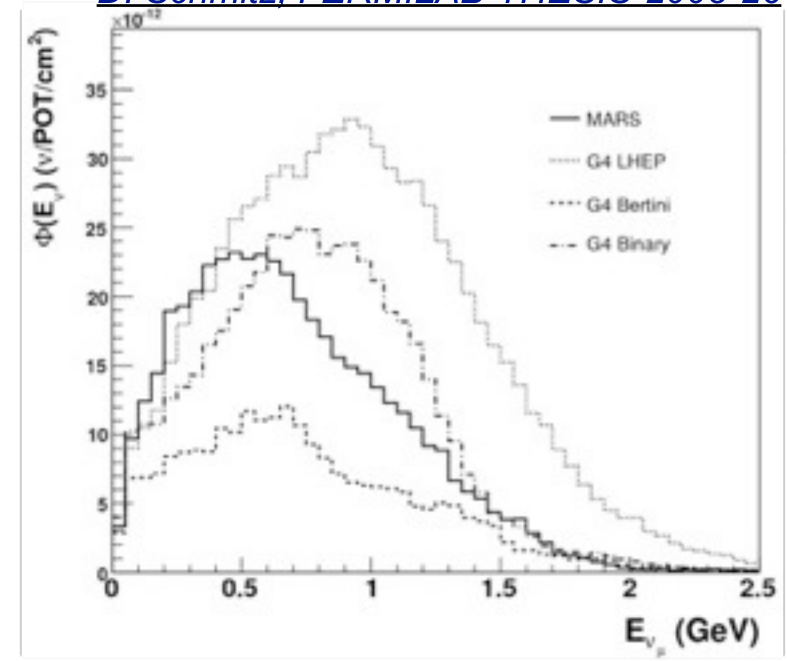
P. Stamoulis

Nuclei 2p2h: Hit a stem, knock both grapes!

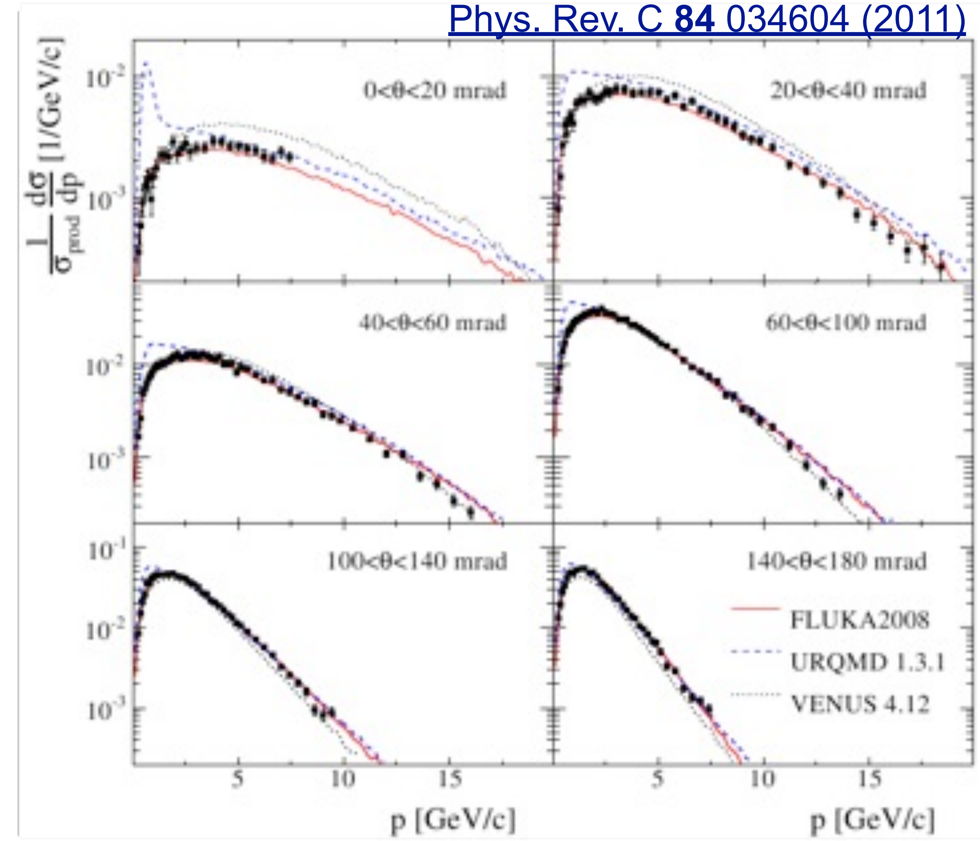
Flux Predictions

- Dedicated hadron production experiments have *revolutionised* neutrino flux predictions
- Top: range of MC MiniBooNE flux predictions with different hadron models
  - 8 GeV protons on beryllium
- Bottom: NA-61 pC→π^+X data used to tune T2K flux MC
- Of course, hadron production isn't magic
  - Still need primary & secondary beam monitoring, etc.

D. Schmitz, FERMILAB-THESIS-2008-26

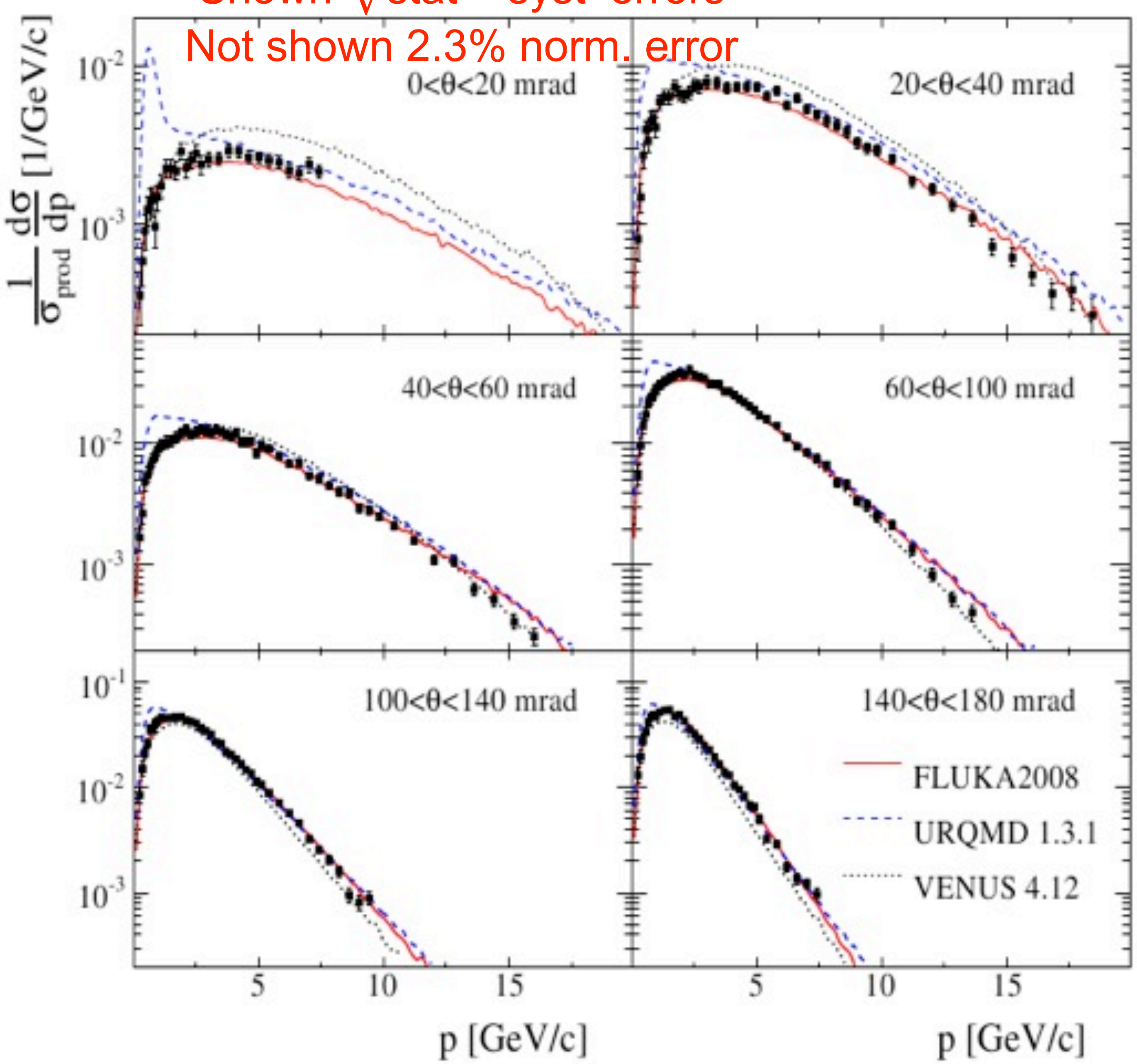


Phys. Rev. C **84** 034604 (2011)



NA61 pion data

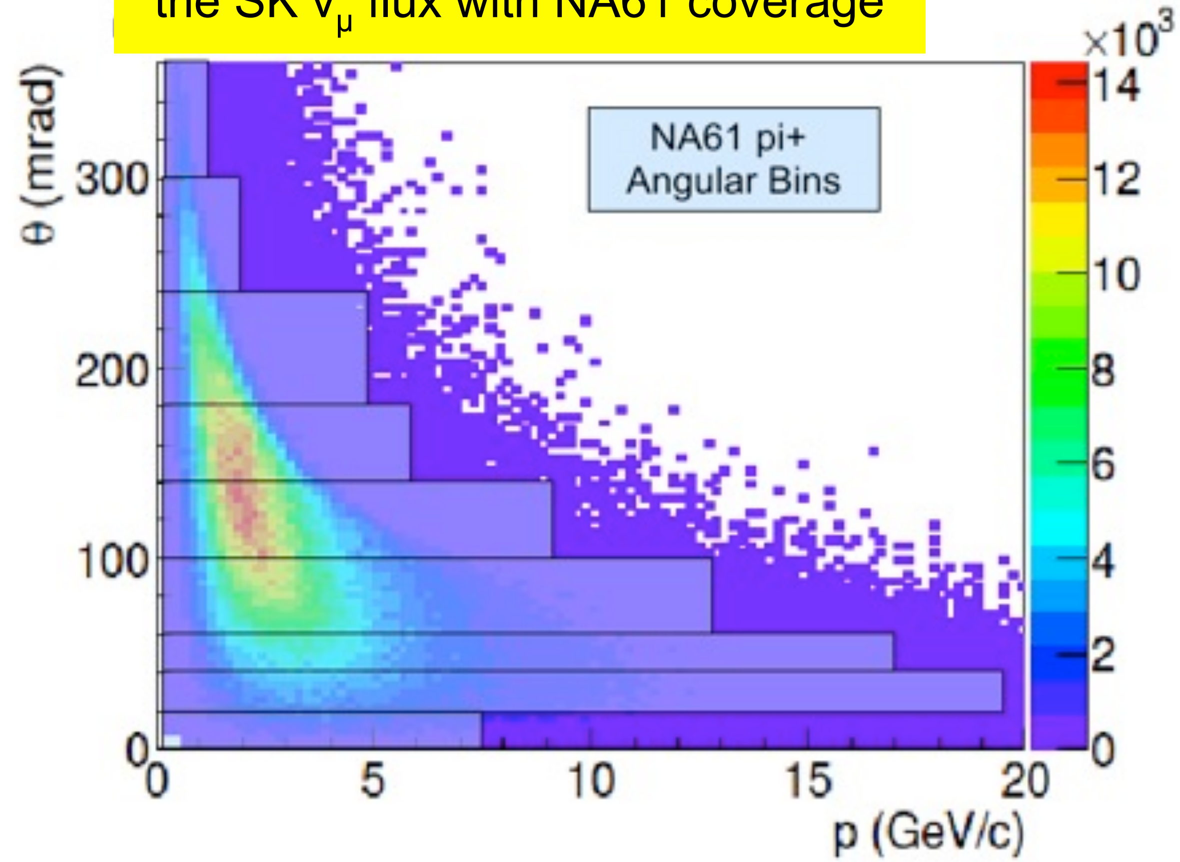
Shown $\sqrt{stat^2 + syst^2}$ errors
Not shown 2.3% norm. error



N. Abgrall et. al., arXiv:1102.0983 [hep-ex]
Accepted by Phys. Rev. C (2011)

NA61 experiment measures particle production from C at T2K beam energy (30 GeV)

Phase-space of pion contributing to the SK ν_μ flux with NA61 coverage



Covers almost all of the relevant pion phase-space for ν_μ production at T2K

- “But I love the 70s! I want to fit for M_A!”
- Me too! But let’s do the model independent measurements as well.
- Provide the data that theorists need to make our models better!