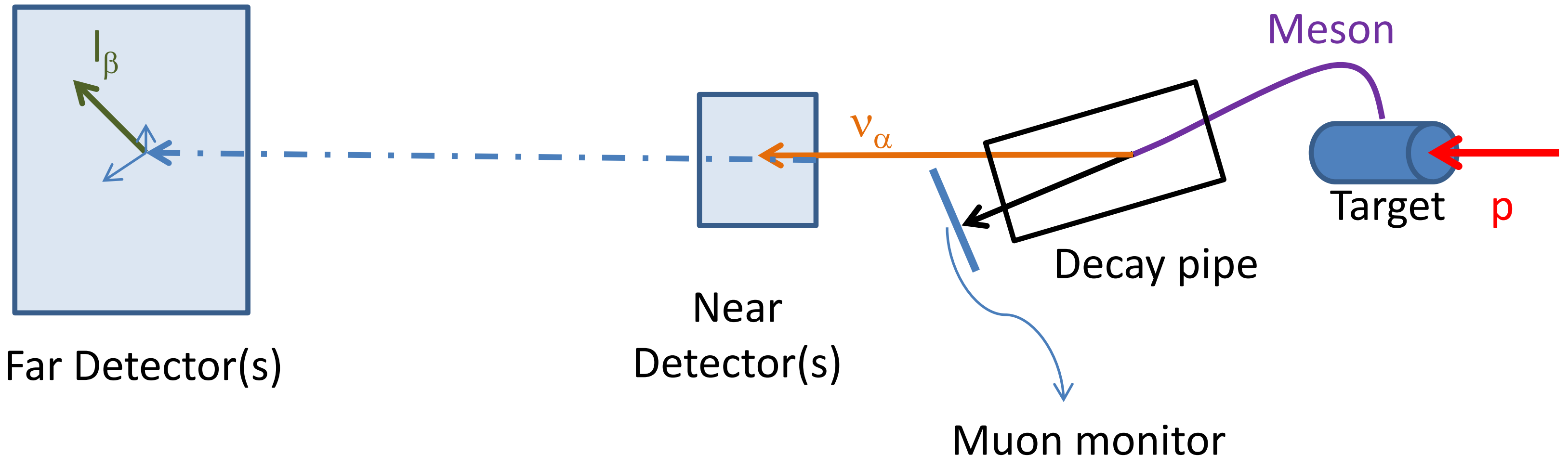
Cross Sections: The Beginning And End

A Talk In Two Parts

Ryan Terri (QMUL)
IoP Half-Day Meeting
7 November 2012

Generic Long-Baseline Experiment Schematic (Not To Scale)



Protons from beam collide with target
Mesons produced from this collision
Mesons are focused into a decay pipe producing neutrinos & their lepton pair
Near detector(s) characterize the beam & try to measure relevant cross sections
Far detector(s) detect interactions from beam neutrinos after oscillations have occurred
Use all of this information to extract oscillation parameters (e.g. θ_{13}, mass hierarchy)

HADRON PRODUCTION

Meson Production

Normally want a pure ν_μ beam in long- baseline (LBL) experiments to study $\nu_\mu \rightarrow \nu_{e,\mu,\tau}$

Many contributions to the flux:

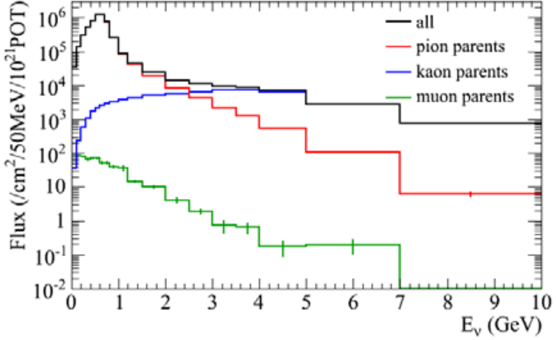
$\pi \rightarrow \mu\nu_\mu$

$K^\pm \rightarrow \mu\nu_\mu$ or $K^\pm_{(e \text{ or } \mu)3}$

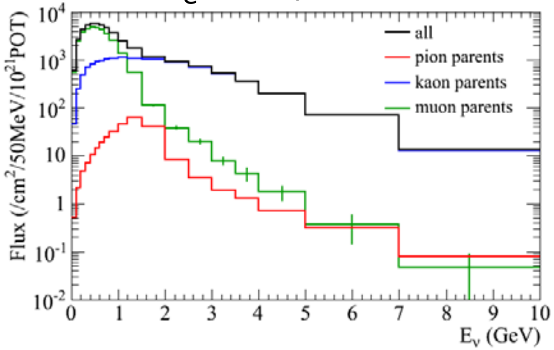
$K^0 \rightarrow \pi\mu\nu_\mu$ or $\pi e \nu_e$

$\mu \rightarrow e\nu_\mu\nu_e$

T2K ν_μ flux prediction:



T2K ν_e flux prediction:



T2K: hep-ex 1211.0469

How do we measure these contributions to the flux?

- Muon monitors at end of decay pipe
  - Energy-dependent (μs must make it to the monitor)
- Near detector
  - Want them to be capable of detecting more than one neutrino flavour and, preferably, the antiparticles
- External Experiment
  - Does not need to worry about effects from target station, horn, and decay pipe
  - Focuses only on hadron production

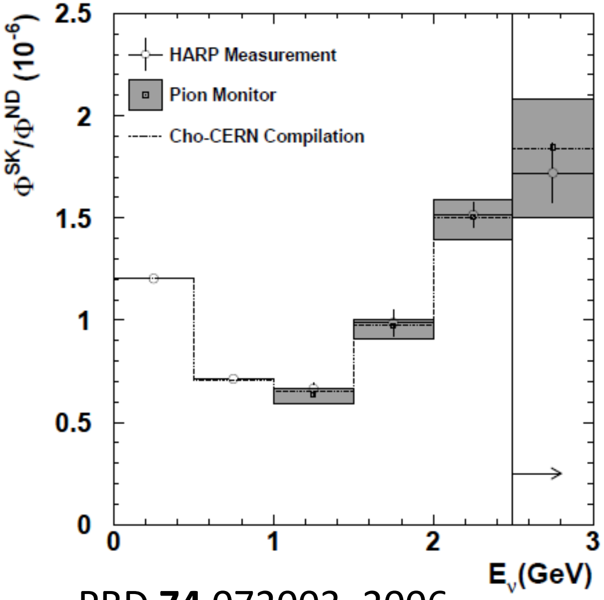
External Experiments

Can reduce flux related errors for overall flux uncertainty and near-to-far flux extrapolation

- First done in LBL experiments by K2K, now done for all long-baseline experiments

External experiments	LBL experiments
HARP/CERN-PS214 1.5-15 GeV beam	(Mini-, Sci-, Micro-)BooNE (Fermilab) K2K (KEK to Super-Kamiokande)
NA20 & SPY/NA56 400-450 GeV beam	NOMAD, CHORUS CNGS (OPERA, ICARUS)
NA-49/CERN SPS 160 GeV beam	MINOS (Fermilab to Soudan)
SHINE/NA61 30-160 GeV beam	T2K (J-PARC to Super-Kamiokande) NuMI (MINERvA, NOvA)

K2K:

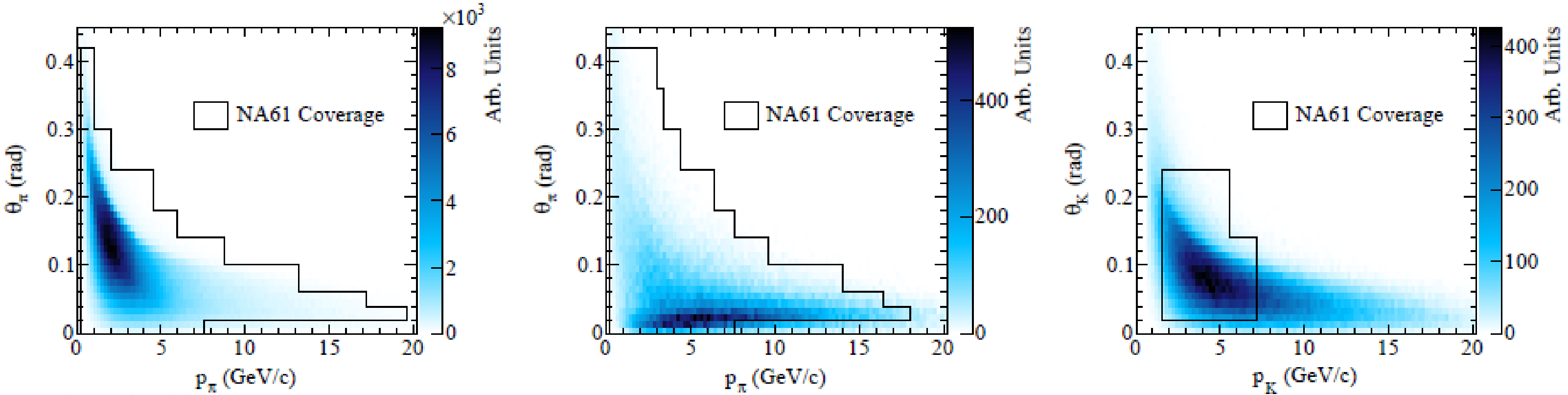


PRD **74** 072003, 2006

Goal to reduce uncertainties to <5% for overall flux normalization; <3% for near-to-far extrapolation

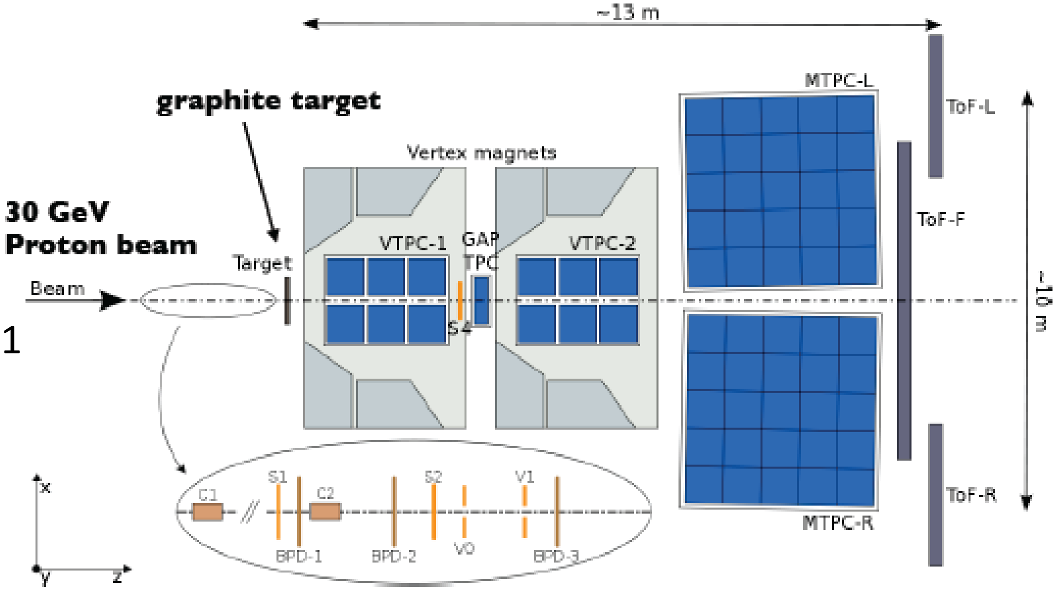
Example: NA61/SHINE

Overlap in phase space of meson production:



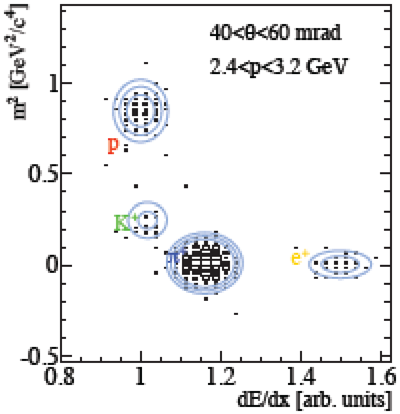
T2K: hep-ex 1211.0469

(a) π^+ (b) π^- (c) K^+



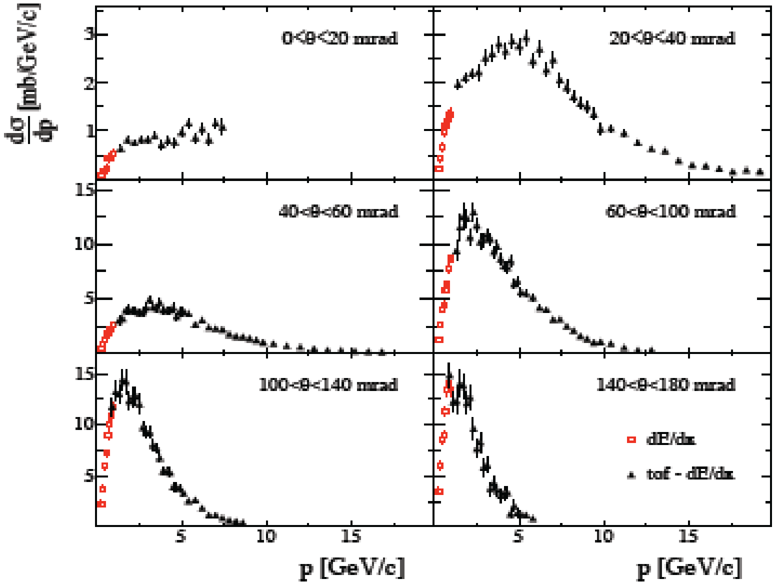
PRC **84** 034604,2011

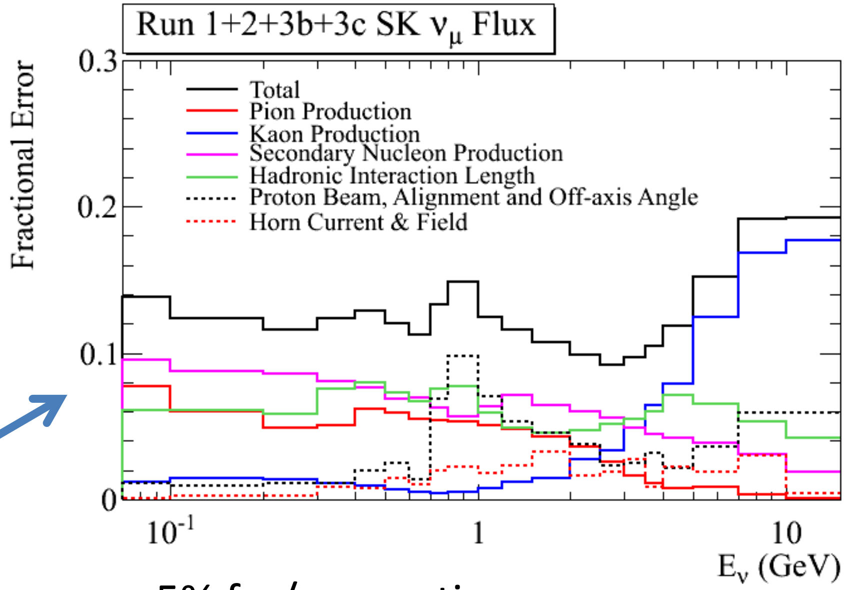
Example: NA61/SHINE



Good particle PID to reduce errors on differential production (time-of-flight & dE/dx)

π^+:





<5% far/near ratio error from including this analysis

4% on total production

S. Murphy, NuFact 2012

Who Will Need To Have An External Hadron Production Experiment?

Or: who will be using a conventional beam?

T2HK (extension of T2K in Japan w/ Hyper-Kamiokande (HK) as the far detector) (Nakaya for HK)

LBNE (USA) (Evans)

GLADE (USA) (Evans)

LBNO (Europe) (McCauley)

NESSIE (Short-baseline sterile ν search at CERN)

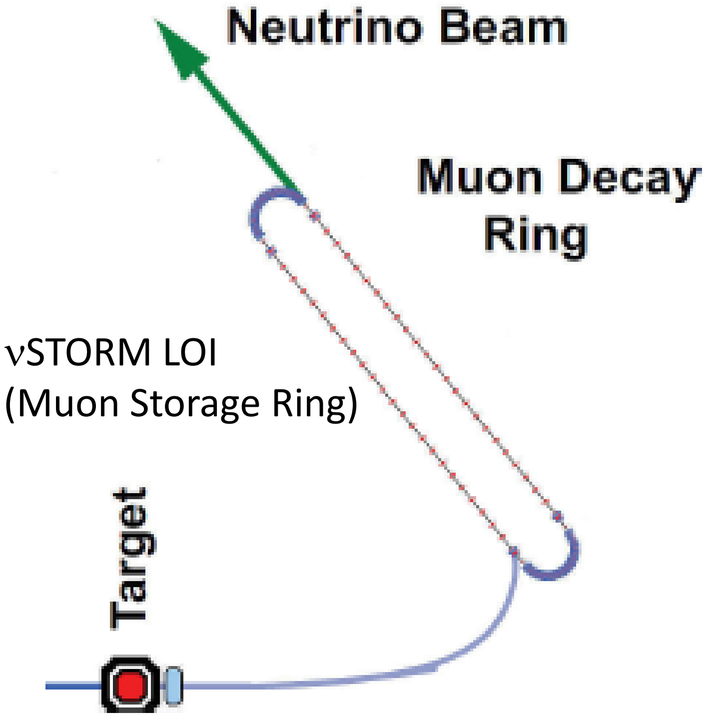
*Remember: T2K, MINOS, NOvA, MiniBooNE, ArgoNeuT and others already are using external experiments

Mauri, XXIV Recontres de Blois

Is There A Way to Avoid External Experiments?

Well, yes.

Neutrino factories & β-beams:



νSTORM LOI
(Muon Storage Ring)

e.g. νSTORM (Fermilab)

Provide very pure neutrino beams

Little flux error since the decay processes that produce the neutrinos are well-known

Due to high boost (e.g. γ≈1500), highly collimated beam

See talk later on today from K. Long

PART II: NEUTRINO CROSS SECTIONS

Why is the neutrino-nucleon cross section important?

Far detector: reconstruct neutrino energy to extract oscillation parameters via either outgoing lepton kinematics (assuming charged current quasi-elastic (CCQE)):

$$\boxed{E_\nu^{rec} = \frac{m_N E_\mu - \frac{1}{2} m_\mu^2}{m_N - E_\mu + p_\mu \cos\theta_\mu}}$$

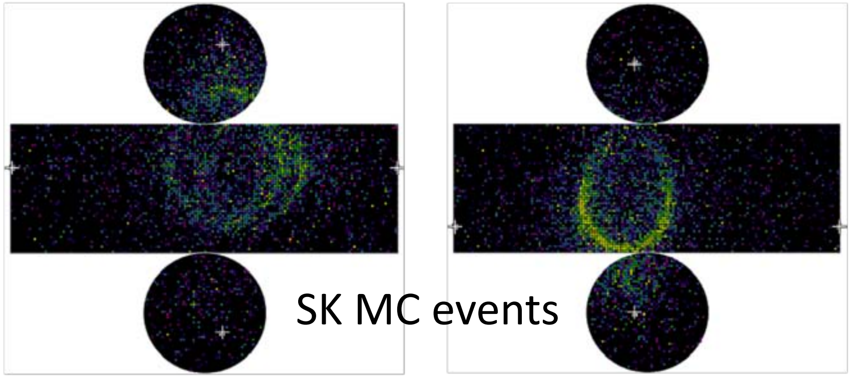
or calorimetry, though moving into using only lepton kinematics for analyses

Near detector: measure processes contributing to signal and/or background, or just to figure out what's happening in this energy range ignoring neutrino oscillations

Signal & background processes both need to be well-understood

$\nu_\mu \rightarrow \nu_\mu$:
Signal: ν_μCCQE interaction
Some backgrounds: ν_μCC1$\pi^\pm$, NC1$\pi^\pm$, antiν_μCC

$\nu_\mu \rightarrow \nu_e$:
Signal: ν_eCC
Some backgrounds: beam ν_eCC, NC1π^0


SK MC events

CC = charged current
NC = neutral current

Which Cross Sections Matter?

Depends on the experiment:

T2HK ~300 km → $E_\nu \approx 0.6$ GeV (CCQE is dominant)

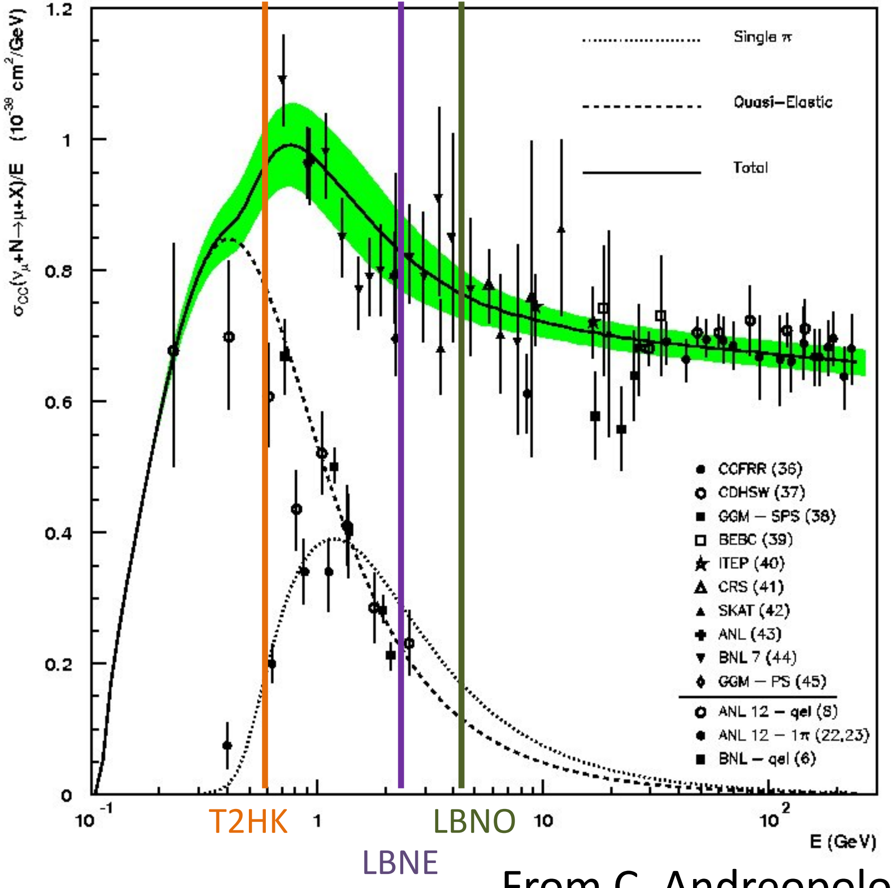
LBNE ~1500 km → $E_\nu \approx 2.5$ GeV

LBNO ~2300 km → $E_\nu \approx 4.5$ GeV

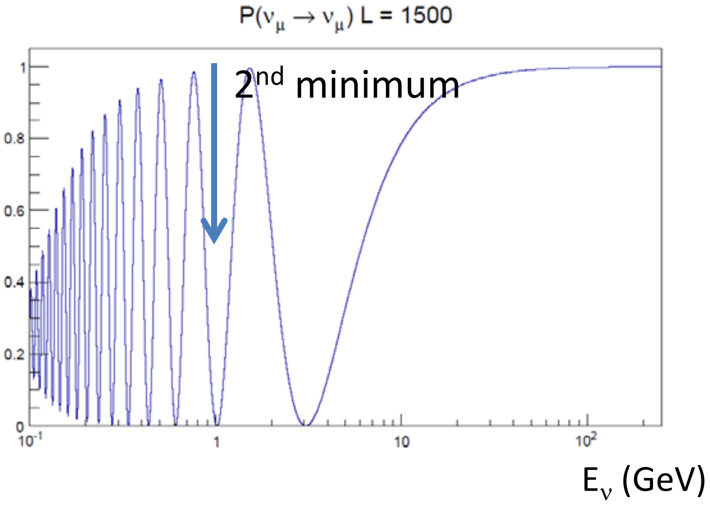
These are for the first ν_μ disappearance minimum

The desire to see the second minimum just means we need to understand the lower energy cross sections as well

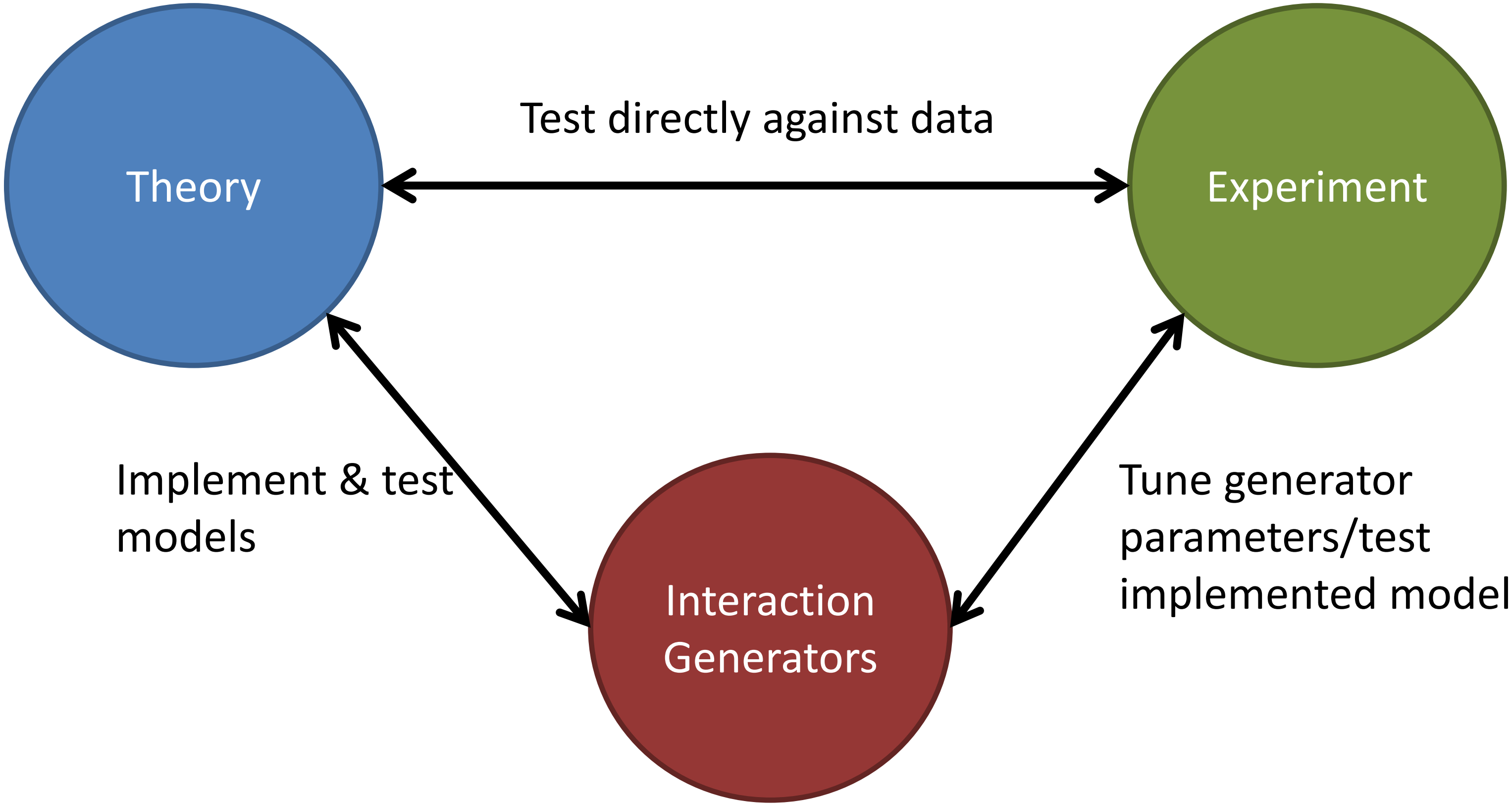
ν_μCC cross sections



From C. Andreopolous



How Is The Data Understood?



Test directly against data

Theory

Experiment

Implement & test models

Interaction Generators

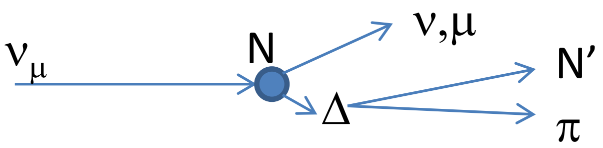
Tune generator parameters/test implemented models

Lots of discussion amongst various members of the community needed

Models For A Generic Event Generator

Have base set of models from which we draw our understanding of the physics
Most have a variation on this theme:
(Quasi-)elastic scattering: Llewellyn Smith + relativistic Fermi gas (Smith Moniz, Nucl.Phys. B43, 605 (1972))

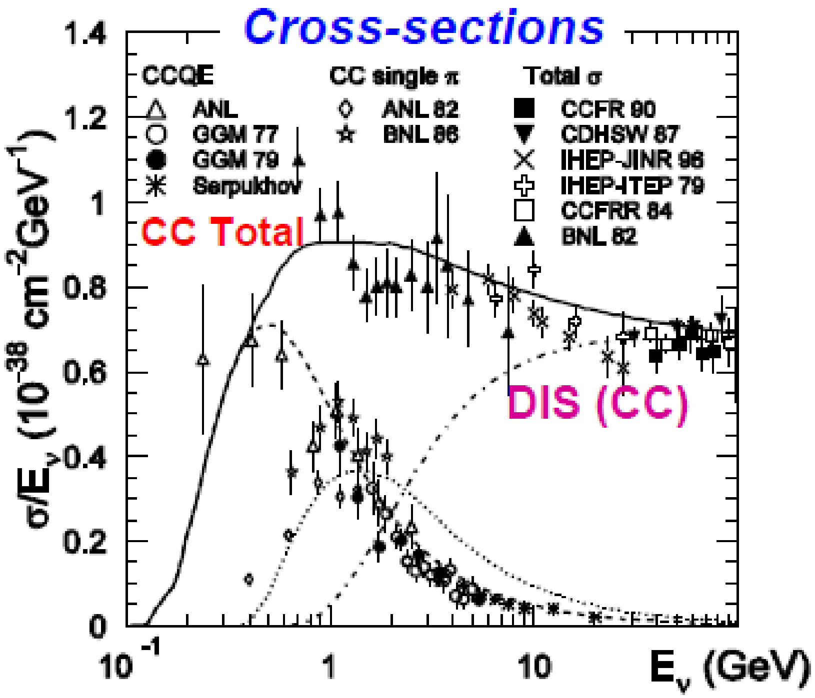
Resonant production: Rein & Sehgal (Ann.Phys.133, 79 (1981))



Coherent pion production: Rein & Sehgal (Phys.Lett.B657:207-209,2007)

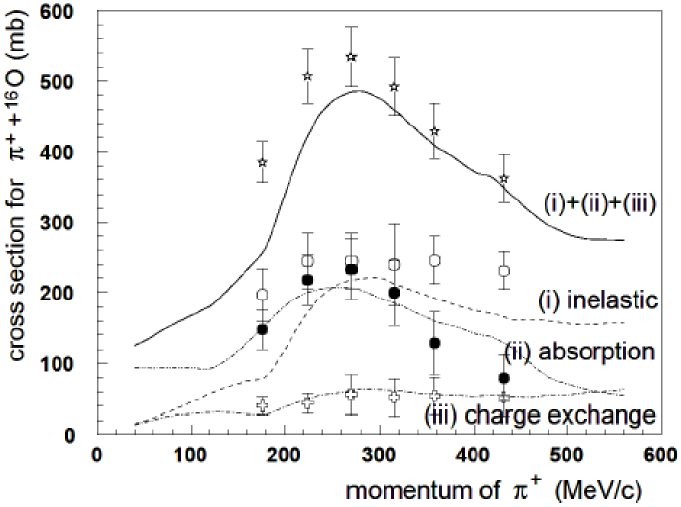
DIS: GRV98 PDFs w/ Bodek-Yang scaling for x (GRV: Eur.Phys.J. C5, 1998, BY multiple, e.g. hep-ph 1012.0261)
Intranuclear effects: cascade model

Inputs For A Generic Event Generator



From Y. Hayato

Pion scattering, from Y. Hayato

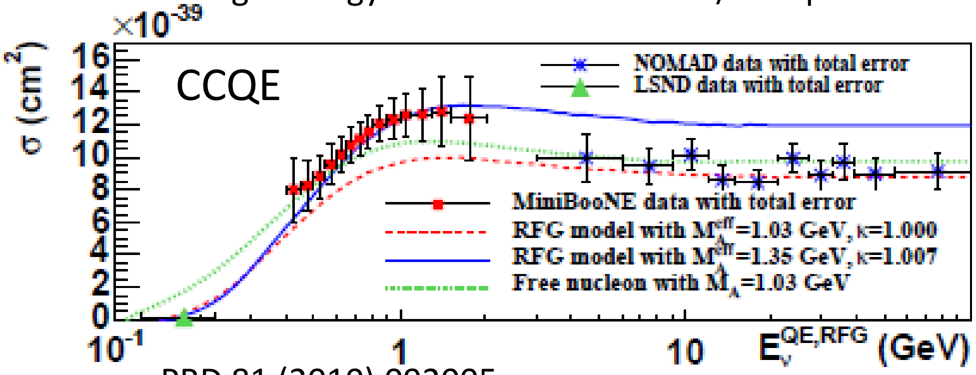


These models are not produced in a vacuum

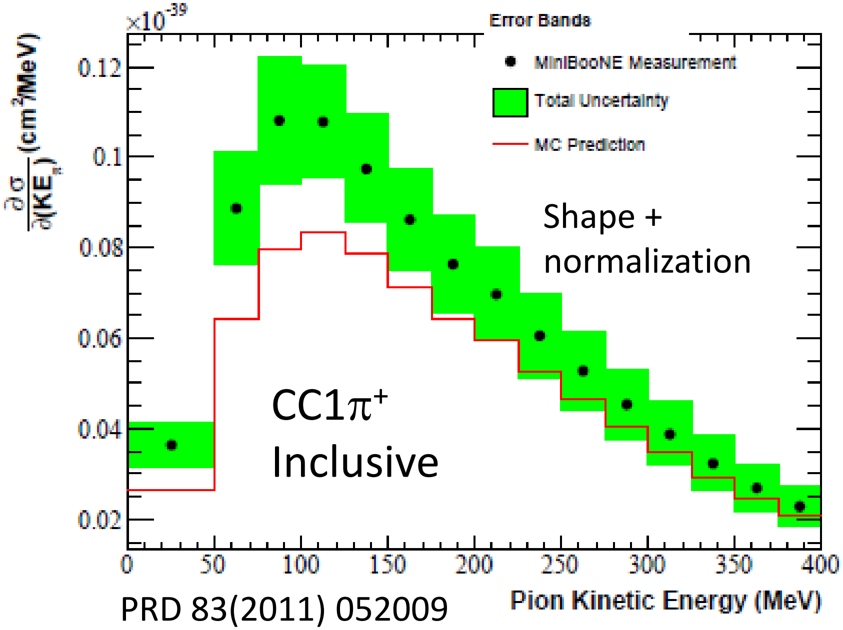
Various parameters tuned to older xsec data sets, electron scattering data, and pion-nucleon scattering

Problem At Lower Energies ($E_\nu \approx 1$ GeV)

Low & high energy data not consistent w/ one parameter

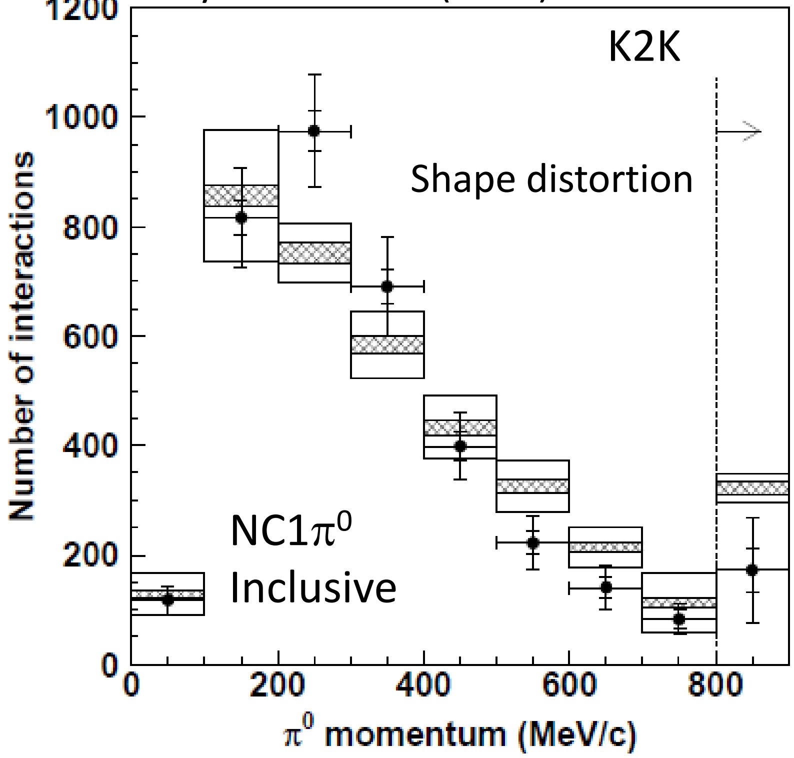


PRD 81 (2010) 092005



PRD 83(2011) 052009

Phys. Lett. B619 (2005) 255-262



And I'm not even mentioning CC coherent pion production

Why The Discrepancy?

Low energy region affected more by nuclear environment

Can’t get away with idea that neutrino interacts w/ independent nucleon in this energy regime, need better model for this

Problem of definition: What do we mean when we describe a certain interaction type? How does that affect our interpretation of the data?

Are these models actually complete? Are we missing some type of interaction that can reduce/explain the discrepancy?

Are the models tuned properly?

Example: CCQE (1/4)

Llewellyn Smith Model (target nucleon rest frame):

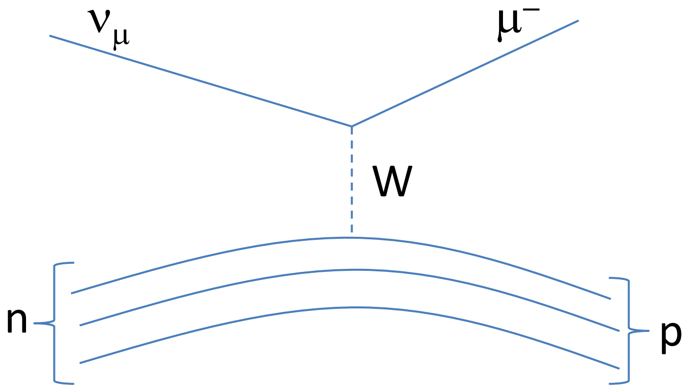
$$\boxed{\frac{d\sigma^{\nu,\,\overline{\nu}}}{dQ^2} = \frac{M^2 G_F^2 cos^2\theta_c}{8\pi E_\nu^2} \times \left[A(Q^2) \mp \frac{(s-u)B(Q^2)}{M^2} + \frac{C(Q^2)(s-u)^2}{M^4}\right]}$$

s,u = Mandelstam variables

A,B,C contain vector & axial form factors

$$\boxed{\mathcal{F}_A(q^2) = \frac{g_A}{\left(1+\frac{Q^2}{M_A^2}\right)^2}}$$

Dipole approximation, not from first principles

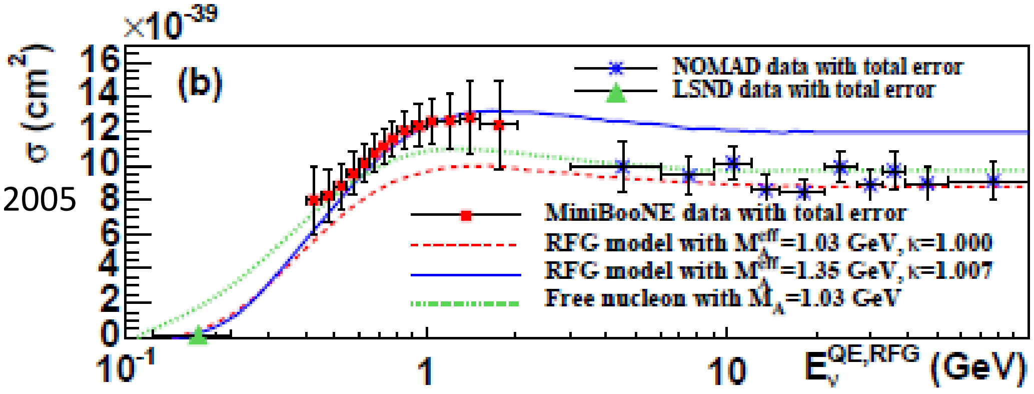


Theoretical definition

To simulate nuclear targets, use relativistic Fermi gas (RFG) model

Outgoing proton undergoes nuclear effects in nuclear environment via cascade model, resulting in some events having a pion in the final state

Example: CCQE (2/4)



PRD 81 (2010) 092005

Problem is, experiments have to use a different definition of CCQE than theorists

$\nu_\mu+n\rightarrow\mu+p$ (see Feynman diagram)

$\nu_\mu+X\rightarrow\mu+X'+0\pi$ (MB)

$\nu_\mu+X\rightarrow\mu+X'+0\pi$ + no vertex activity

$\nu_\mu+X\rightarrow\mu+X'+0\pi+0\gamma$+no vertex activity

$\nu_\mu+X\rightarrow\mu+p+X'+0\pi$ (NOMAD)

Etc.

These are all based on what is observed by your detector in the final state of the interaction

Possible background comes from $\nu_\mu+n\rightarrow\mu+\Delta$, $\Delta\rightarrow p+\pi$, π is absorbed in the nucleus, p is not observed

MiniBooNE unfolded its data after subtracting backgrounds (some data driven), so it should be closer to the theory definition of CCQE

Example: CCQE (3/4)

Experiment	M_A Measured (GeV/c^2)
World Average (p,n)	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

Table from Y. Hayato, NuInt 2012

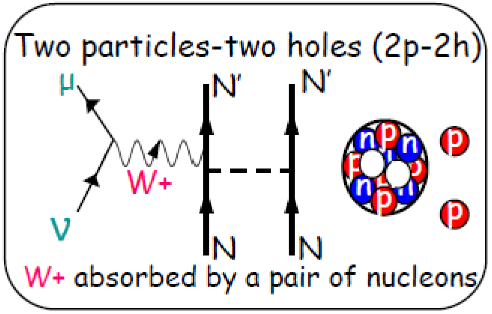
Nuclear environment plays a larger role in cross sections <2 GeV

Is M_A sacred? (Depends on who you ask)

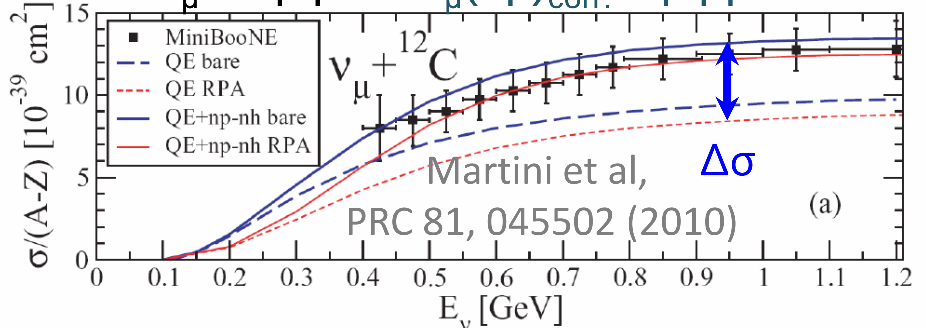
In the **bold** measurements, M_A becomes a rug with which to sweep our ignorance under and is more of an effective parameter than a fundamental one (that doesn't mean M_A is physical, though)

Example: CCQE (4/4)

Plenty of models have arisen to explain the MiniBooNE CCQE data
Most popular is np-nh (lots of work on this in the last few years)

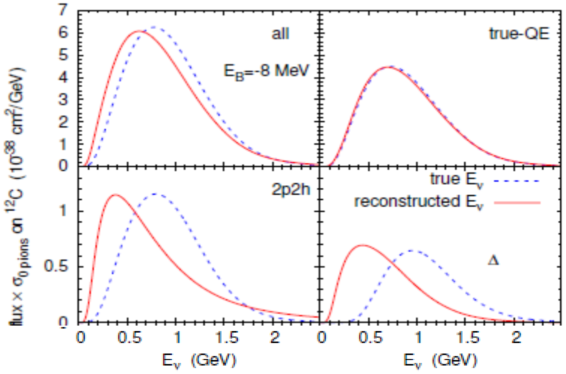


$\nu_\mu n \rightarrow \mu^- p$ $+ \nu_\mu (np)_{corr.} \rightarrow \mu^- pp$



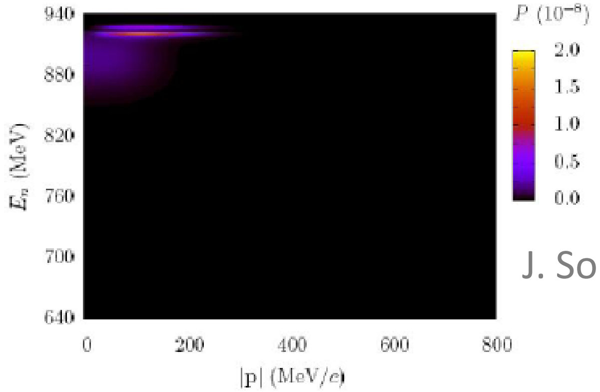
Martini et al,
PRC 81, 045502 (2010)

Spectral Function rather than Fermi Gas for nuclear environment



Lalakulich & Mosel,
arXiV:208.3678

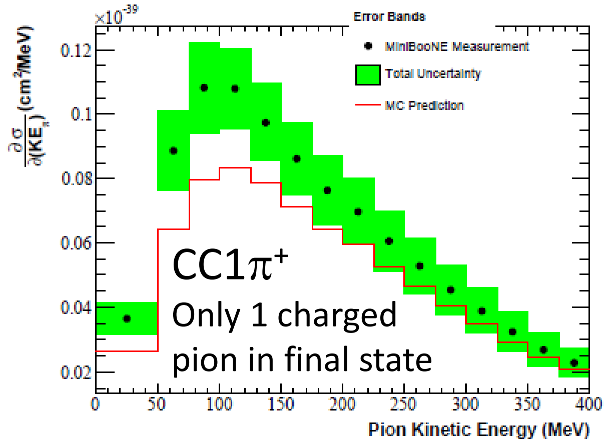
Still have to worry about energy reconstruction since these types of interactions are actually occurring



J. Sobczyk

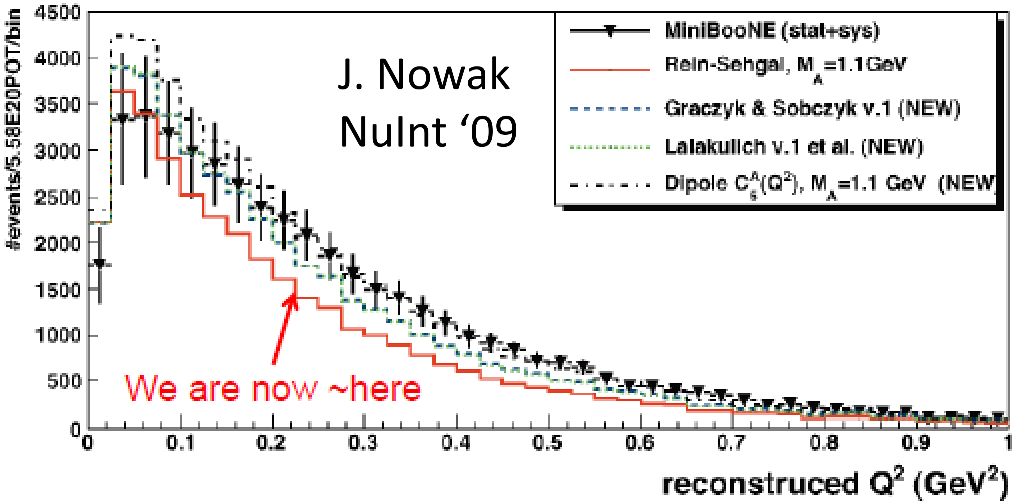
Calculated from first principles ("no free parameters")

Other Possible Places For Improvement



$CC1\pi^+$

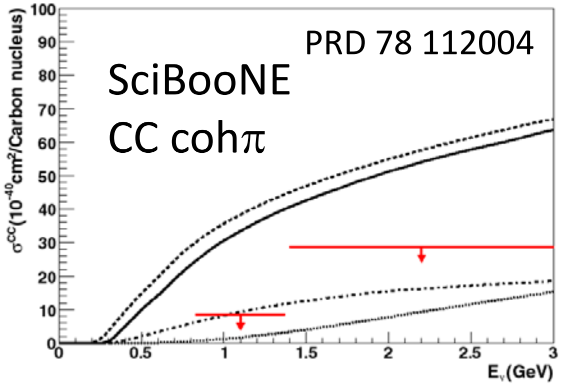
Only 1 charged pion in final state



J. Nowak NuInt '09

We are now ~here

Retuning of the Rein & Sehgal model's parameters should bring better agreement to this (and other 1π) picture(s)

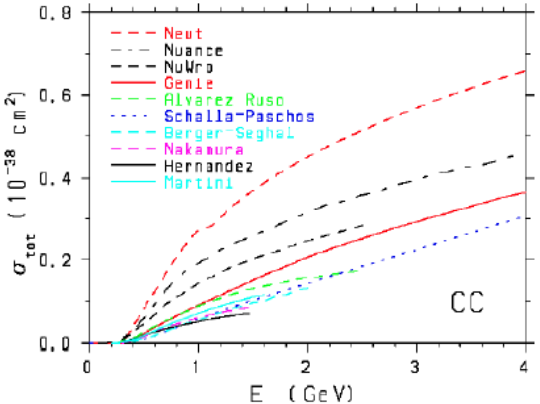


PRD 78 112004

SciBooNE

CC cohπ

Boyd *et al*. AIP Conf. Proc. 1189

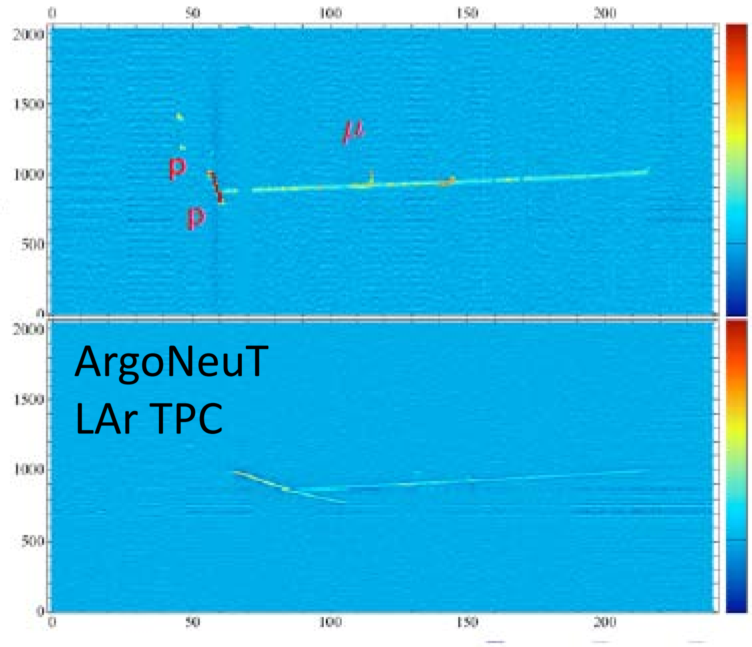


Also use more recent πA scattering data for additional tuning of intranuclear effects

Microscopic Models?

This Is All Right Now, What About In the Future?

Szelc, NuInt 2012



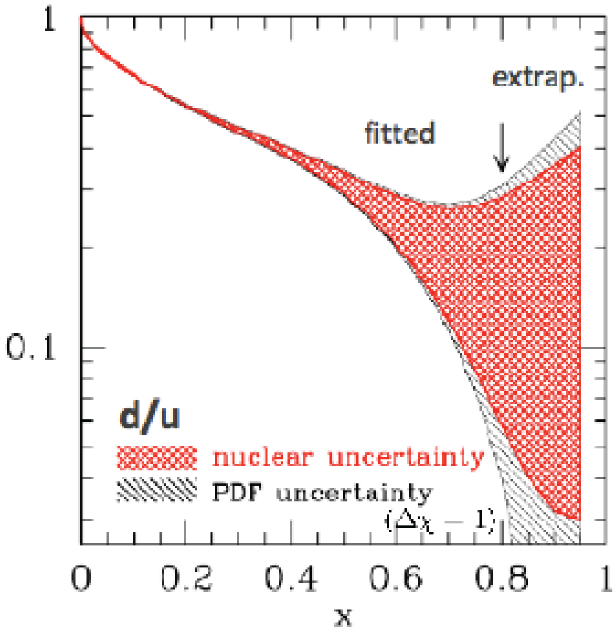
ArgoNeuT
LAr TPC

2p?!?

Start looking at a greater number of exclusive final states experimentally

Can start to resolve nuclear effects and continue testing various models

With some future experiments in region where DIS turns on, need to understand PDFs in high-x, low Q^2 region



Morfin,
NuInt 2012

A Path

Theorists:

Not only develop model, but provide way to implement for use in experiments

- Either in generator or vectors that can be put directly into detector simulator
- Need to move beyond investigating outgoing lepton kinematics (i.e. nuclear effects)

Generator providers:

Figure out how to implement models w/ proper outgoing nucleon kinematics before & after final state effects

- Validate that it is reasonable

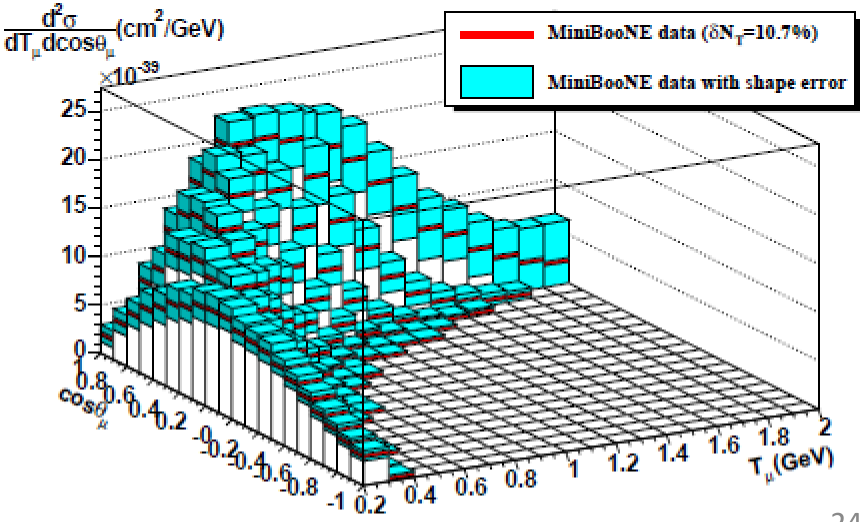
Experimentalists:

Do best to provide model-independent measurements (or be explicit on the model)

Data releases of not only cross section measurements, but also fluxes and complete errors also needed (including correlations between datasets)

- i.e. follow & improve on lessons from MB

PRD 81 (2010) 092005



Some Current & Future Xsec Experiments

Plenty of experiments will help increase our understanding now and in the near future:

T2K
MiniBooNE
SciBooNE
ArgoNeuT
MINERνA

Currently taking data

νSTORM
LBNO
LBNE
NESSIE

Proposed

And as you've seen, there's plenty of work for everyone to do, especially when you go back to considering possible impact on oscillation analyses

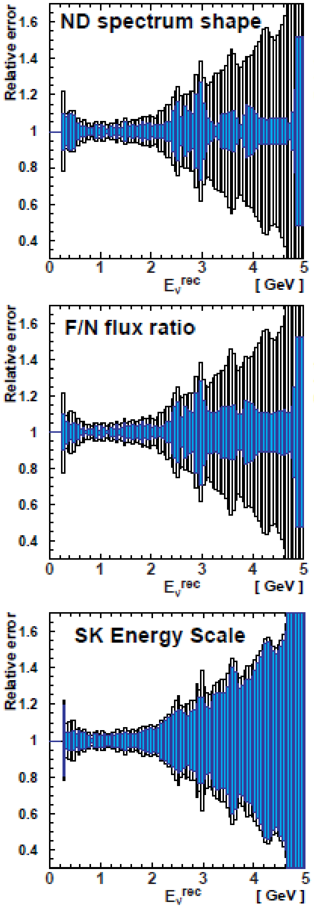
Summary

- Greater understanding of the flux through cooperation with external hadron production experiments needed to nail down the neutrino flux
    - True for current method of neutrino beam production, not so much once only one particle type is decaying
- Neutrino-nucleus interactions need more study
    - Lots of data-model discrepancies, some of which directly affects how we understand oscillation signals & backgrounds
    - Lots of ideas on how to better understand them for the next generation of experiments
        - Still need to measure them for each experiment to cancel some systematics as well as add to overall body of knowledge we need for understanding these interactions

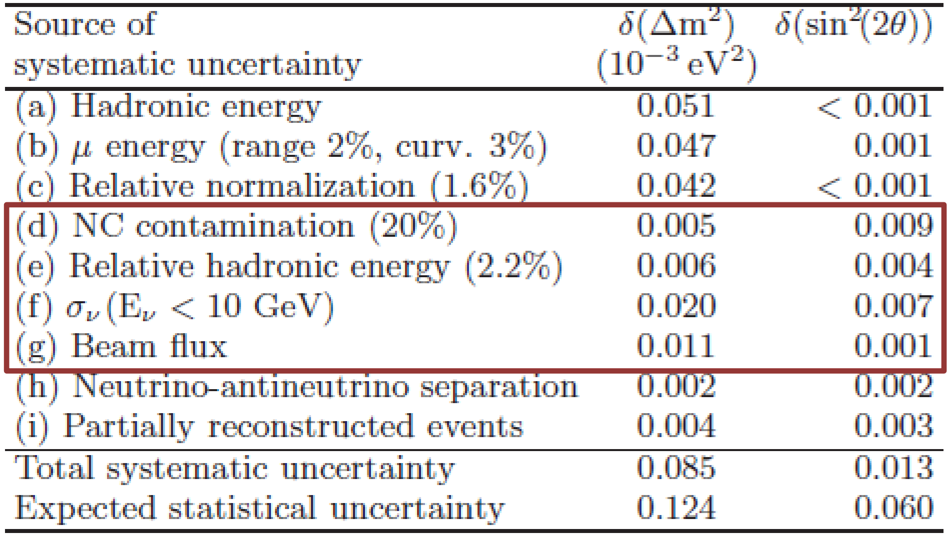
BACKUPS

Which Systematic Errors Am I Concerned About?

K2K ν_μ disappearance (PRD 74: 072003 (2006))



MINOS (PRL 106:181801 (2011))



Source of systematic uncertainty	$\delta(\Delta m^2)$ (10^{-3} eV^2)	$\delta(\sin^2(2\theta))$
(a) Hadronic energy	0.051	< 0.001
(b) μ energy (range 2%, curv. 3%)	0.047	0.001
(c) Relative normalization (1.6%)	0.042	< 0.001
(d) NC contamination (20%)	0.005	0.009
(e) Relative hadronic energy (2.2%)	0.006	0.004
(f) $\sigma_\nu (E_\nu < 10$ GeV$)$	0.020	0.007
(g) Beam flux	0.011	0.001
(h) Neutrino-antineutrino separation	0.002	0.002
(i) Partially reconstructed events	0.004	0.003
Total systematic uncertainty	0.085	0.013
Expected statistical uncertainty	0.124	0.060

T2K ν_e appearance (PRL 107:041801 (2011))

Error Source	Flux	Near Detector	Near Detector Stats.	Xsec	SK	Total
Size (%); $\sin^2 2\theta_{13} = 0.1$	**8.5**	+5.6/-5.2	2.7	**10.5**	9.4	+17.6/ -17.5