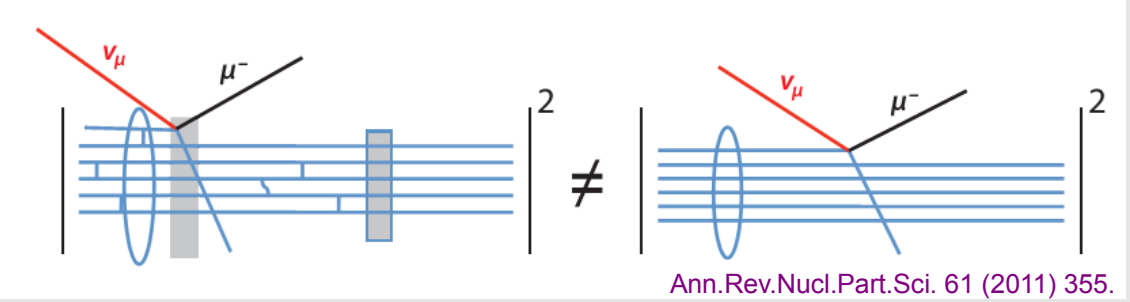
Snowmass on the Mississippi a.k.a CSS 2013

(Nu4) **Neutrino Interactions**
subgroup conveners: Jorge Morfin (FNAL), Rex Tayloe (Indiana)

Neutrino Interactions (nu4)
Working group summary

Outline:

- Physics
- Experiments/Facilities
- Theory effort
- Conclusions



Ann.Rev.Nucl.Part.Sci. 61 (2011) 355.

Neutrino interactions: Physics Topics

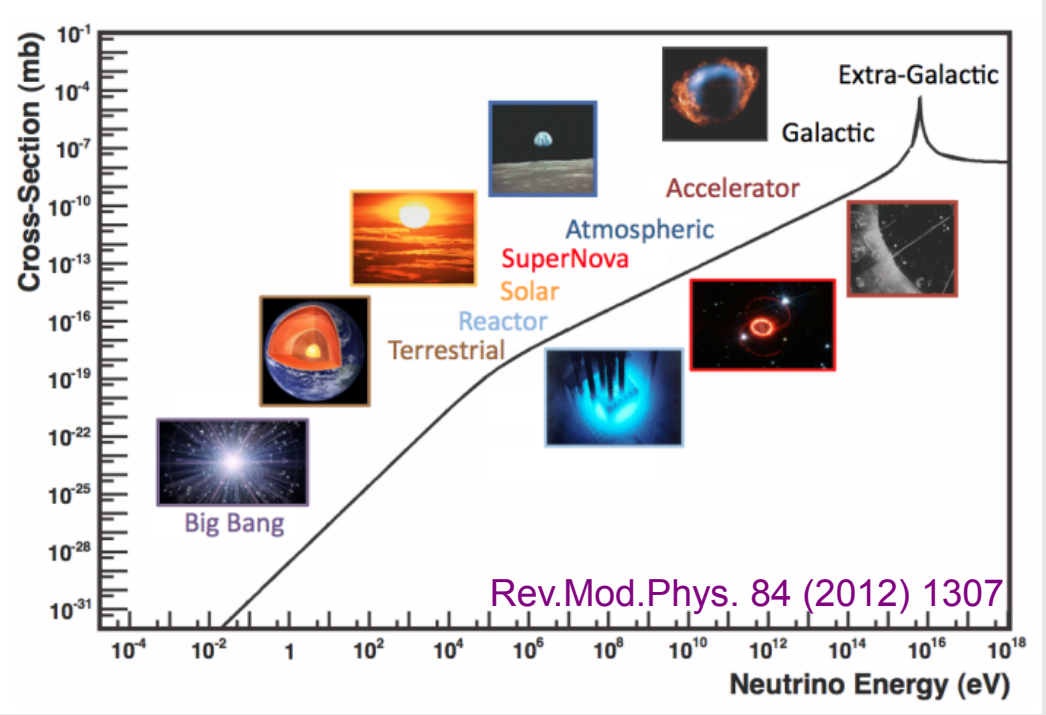
Presented in 2 major energy ranges..

"intermediate"-energy regime (~0.1-10GeV)

- CCQE scattering
  - E_ν reconstruction with nuclear targets and oscillations
  - multinucleon correlation
- CC π production
- NC π, γ resonant/coherent production
- ν_μ, ν_e cross section differences

"low-energy" regime (~1-100MeV)

- supernova physics
- coherent elastic ν nucleus scatterng (CENNS)



Neutrino-interactions and Oscillations

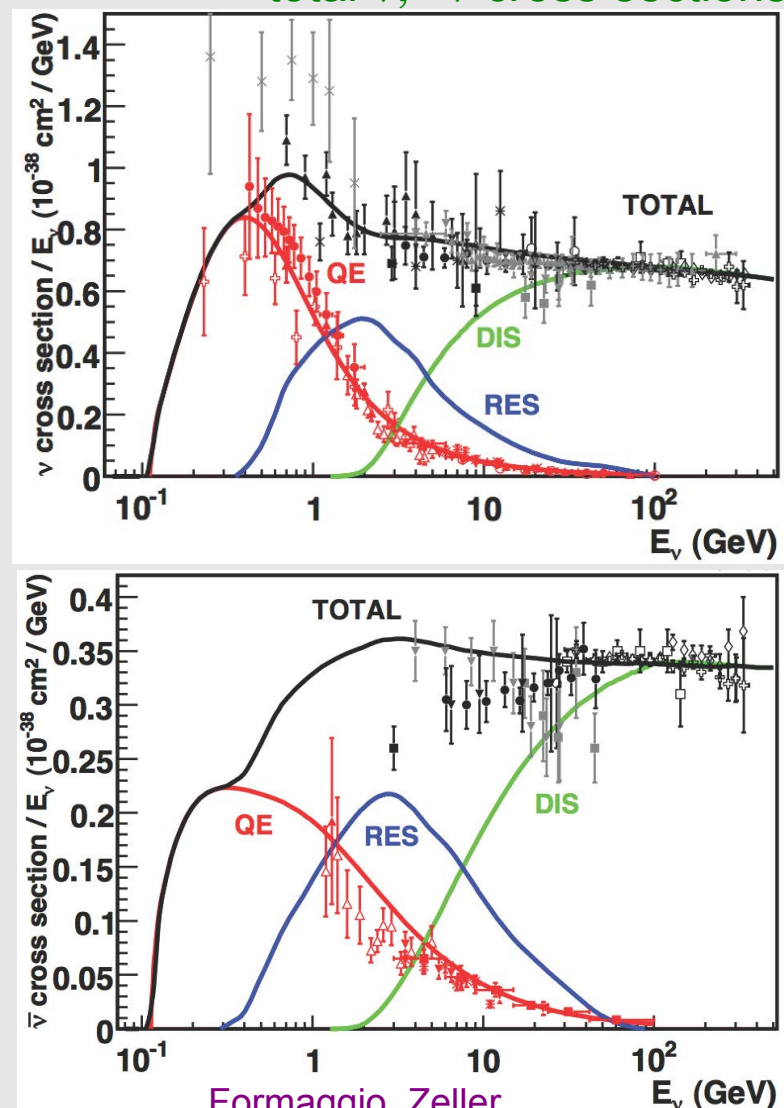
Oscillation experiments need improvement to our current understanding of ν–A scattering at E_ν ~ 1-10 GeV

- eg: MINOS(+), MiniBooNE, T2K, NOvA, LBNE, etc
  - especially for *precision* (e.g. 1%) measurements
  - and/or small oscillation probabilities (e.g. 0.1%)

Significant challenge for ν experiments:
- non-monoenergetic and poorly-known beams
- large backgrounds
- nuclear scattering (bound nucleons)

Requires: Precise/accurate measurements and models to enable a complete theory, valid over wide range of variables (reaction channel, energy, final state kinematics, nucleus, etc)

total ν, $\bar{\nu}$ cross sections



Formaggio, Zeller
Rev.Mod.Phys. 84 (2012) 1307

Neutrino-*nucleus* scattering

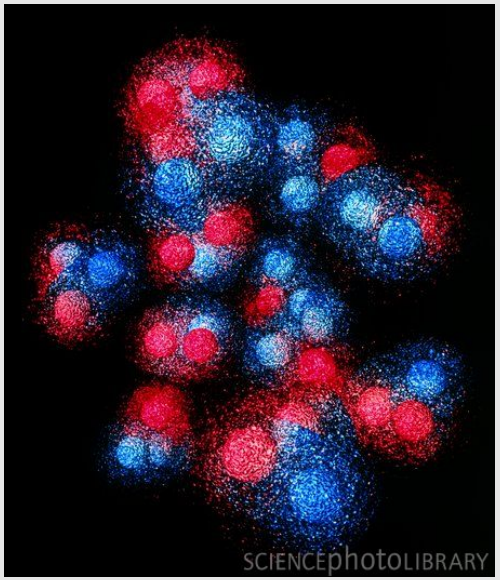
E_ν reconstruction in oscillation experiments

- Neutrino experiments require nuclear targets
- At ~1GeV, the nucleus is complex and impulse approximation (free nucleons) is not adequate (as seen in recent data)
- increases scattering rate.. .
- but more importantly introduces error in E_ν reconstruction
- and adds error in oscillation parameter extraction.

- E_ν reconstruction is model dependent, need correct model

- Need to know what ν is recoiling from!
- (and final state effects)

exhibit A: carbon



MiniBooNE ν CCQE total cross section

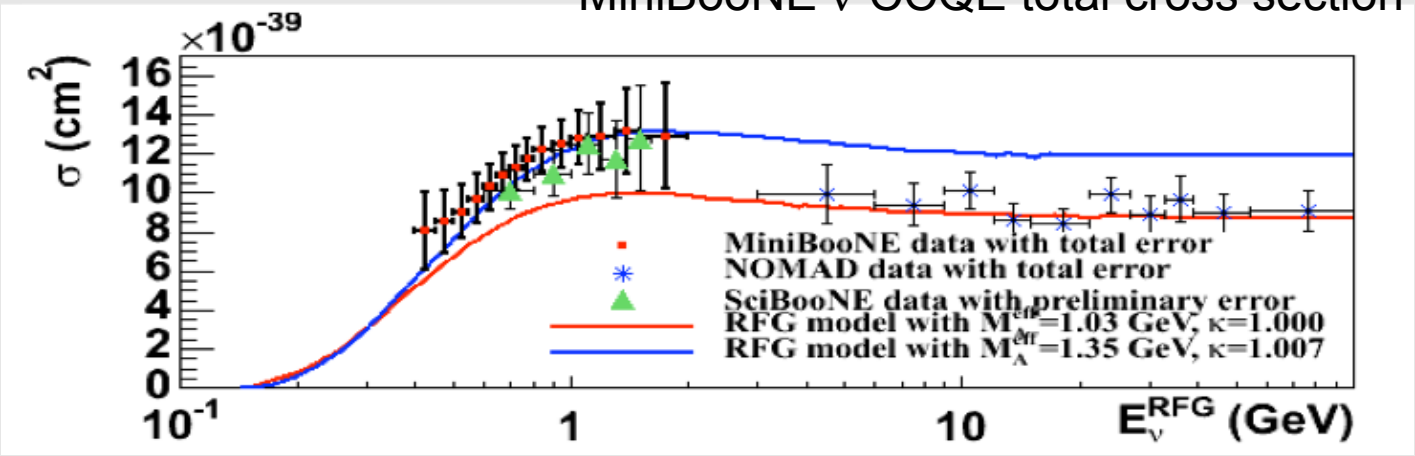
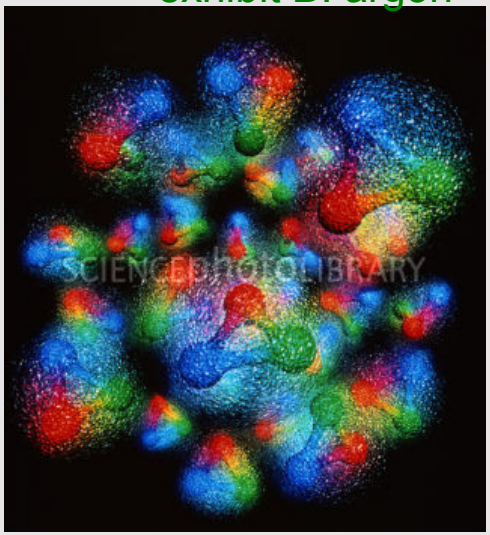


exhibit B: argon*



* actually silicon, but you get idea

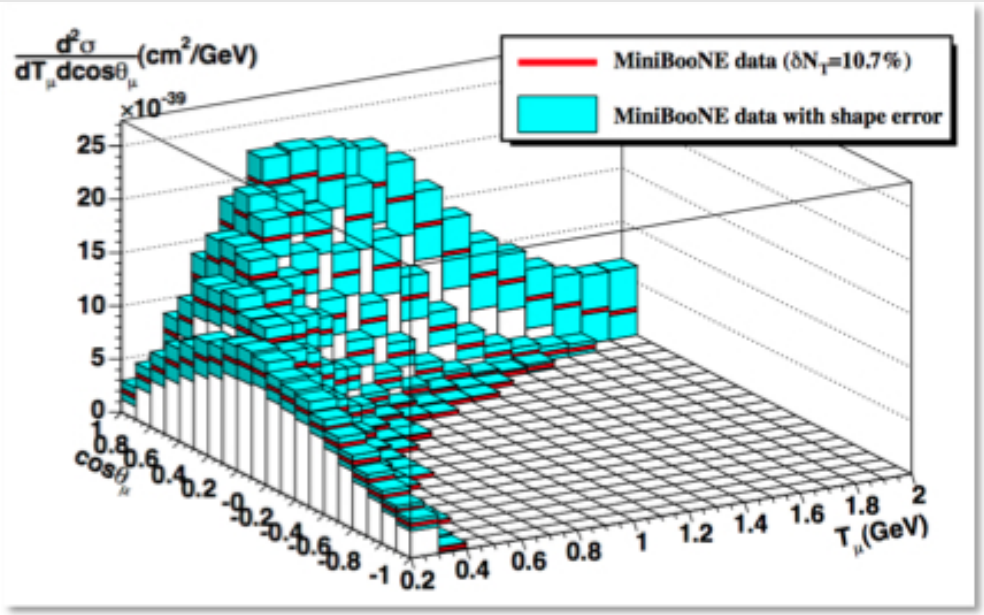
Neutrino-*nucleus* scattering

- E_ν reconstruction is model dependent, need correct model

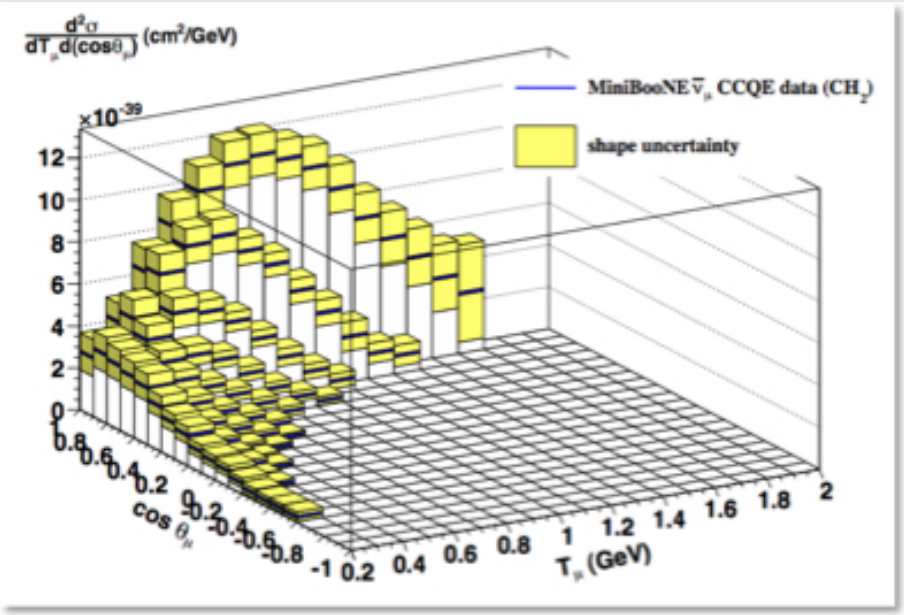
- Must go beyond total cross section measurements (σ vs E_ν is not solid observable) Thus less model-depending observable important to resolved this.

- Eg: diff xsections in muon kinematics

MiniBooNE double diff. xsections neutrino antineutrino



PRD 81, 092005 (2010)



arXiv:1301.7067

Neutrino-*nucleus* scattering

E_ν reconstruction in oscillation experiments

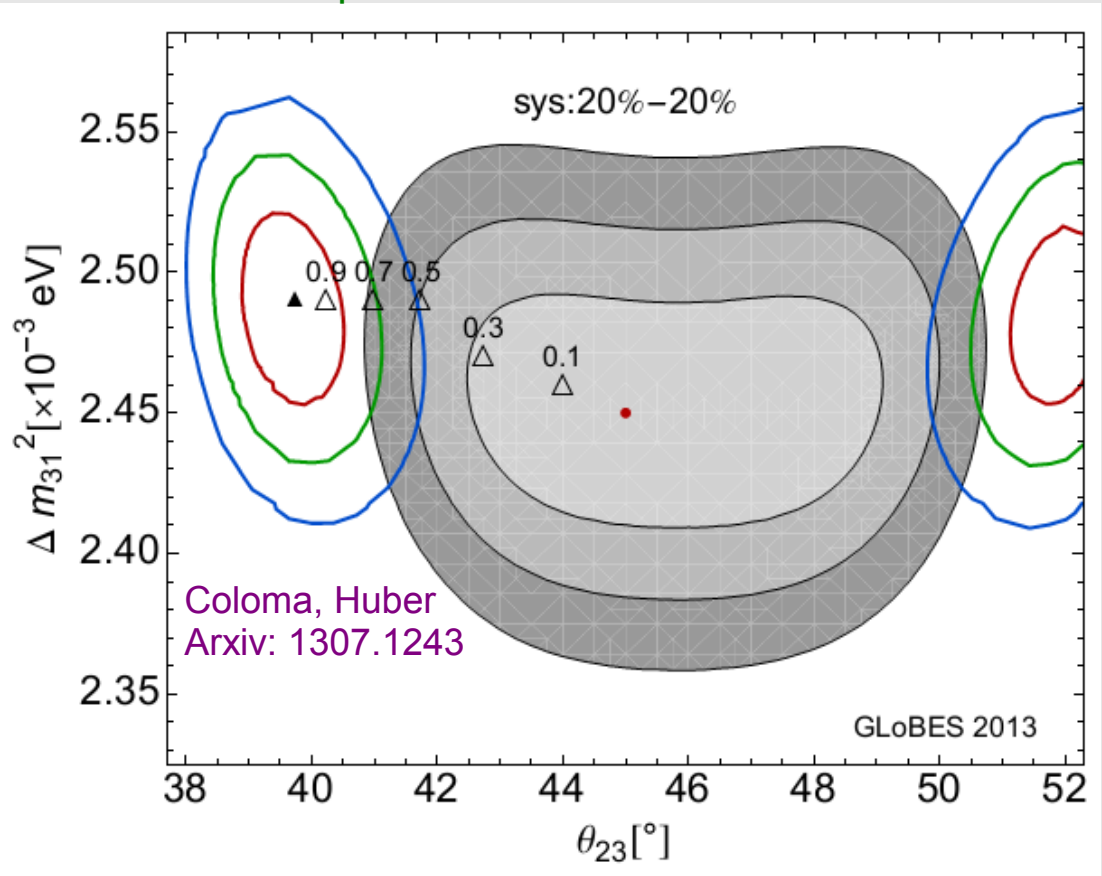
Without an accurate ν–A scattering model, E_ν can be misconstructed and bias extracted oscillation parameters.

Recent quantitative study shows bias of $\Delta\theta_{23}$ ~2° (3σ) for 30% nuclear effects (as indicated in MB data).

- effect not removed …
  - with near/far ratios...
  - or hadronic energy measurements

Coloma, Huber (1307.1243) study:
- T2K, only lepton detected
- ν_μ disapearance, 5 yrs data
- ideal near detector
- 20% flux errors

Oscillation parameter extraction and nuclear effects



Neutrino-*nucleus* scattering

Ultimately will need complete theory/model/generator for sufficient simulations of oscillation experiments.
Including:
  nuclear effects, final state interactions, hadronic energy/multiplicity....

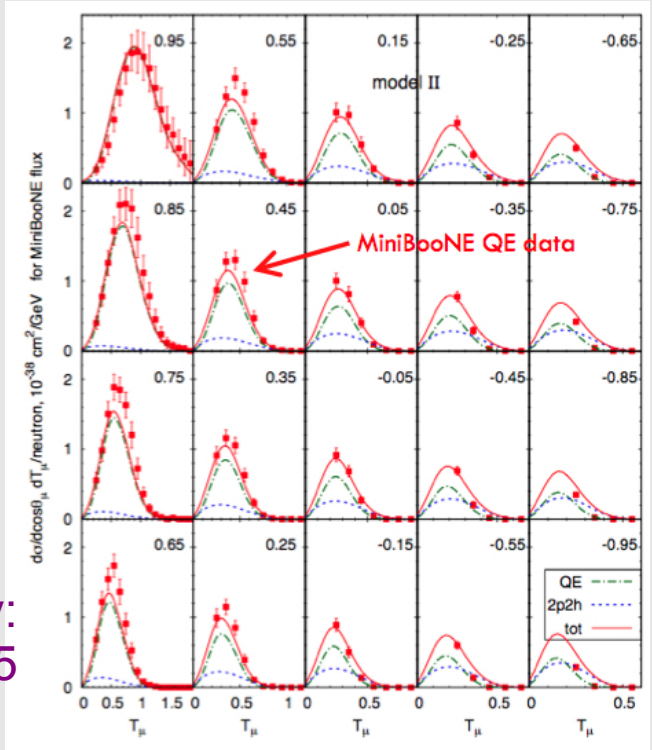
Good that the physics is also interesting...

EG:
- MB data explained by multinucleon scattering?
- same as effects as seen in e-scattering(?)
- new data is coming soon: MB $\bar{\nu}$ CCQE, Minerva (consistent with MB evidence for 30% multi nucleon effects)

However, more needed to understand these nuclear effects.. especially from argon

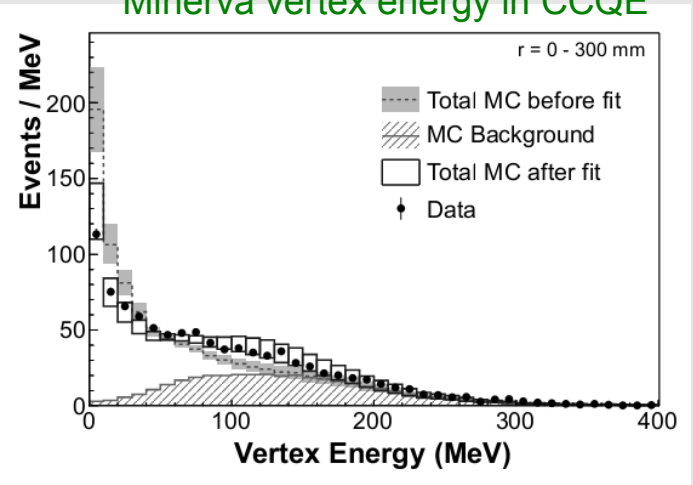
Upcoming data:
- Minerva
- T2K
- microboone

fits to MB CCQE diff xsections



arXiv: 1203.2935

Minerva vertex energy in CCQE



Neutrino interactions and CP violation

Ultimately, δ_{CP} may be limited by cross section uncertainties, in particular those between

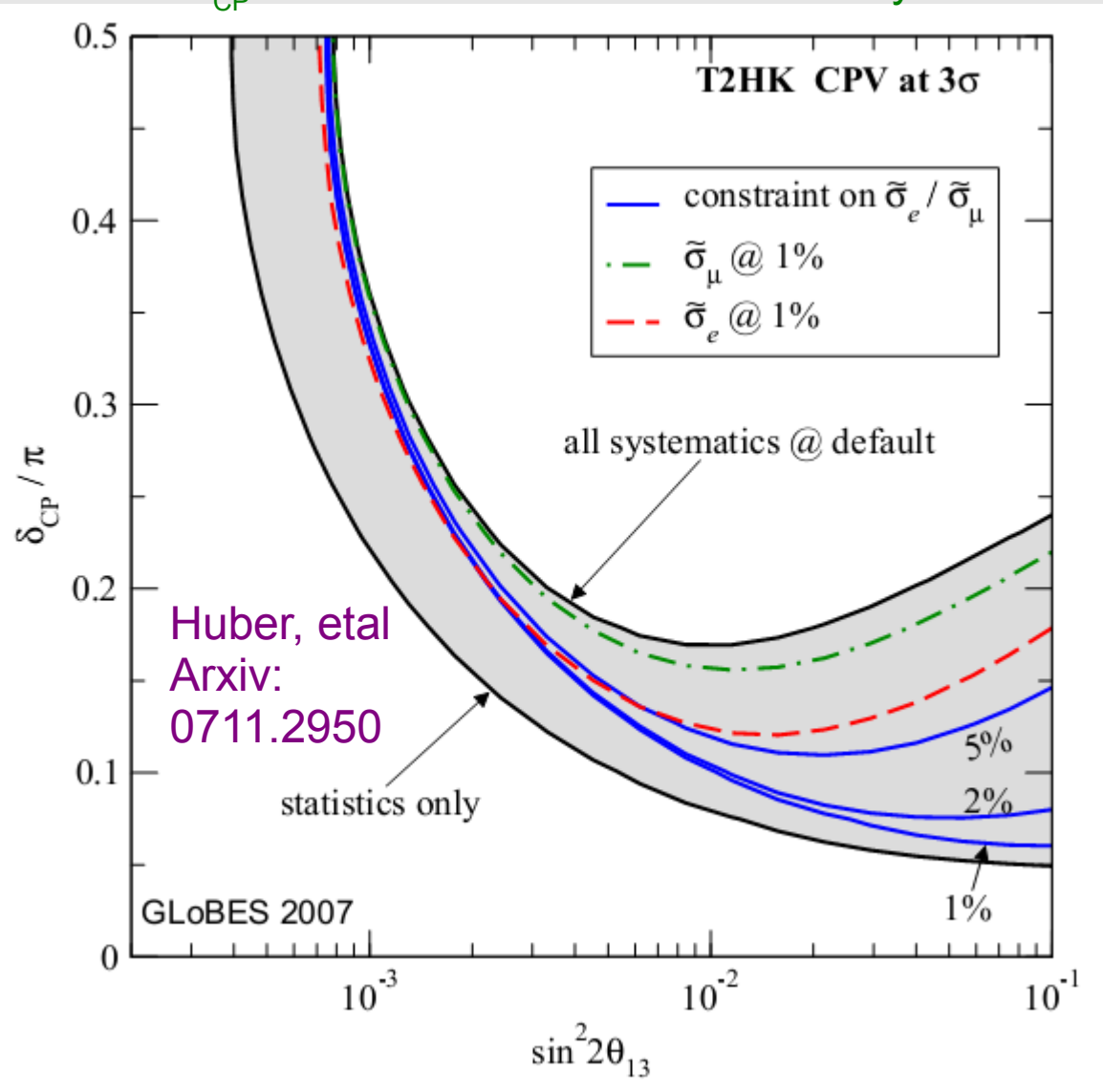
ν_μ/ν_e $\nu/\bar{\nu}$

- CP asymmetry goes as $1/\sin\theta_{13}$

Requires measurements of ~1 GeV ν_e crosssections!

νStorm
(muon storage ring!)

δ_{CP} sensitivites and cross section systemics



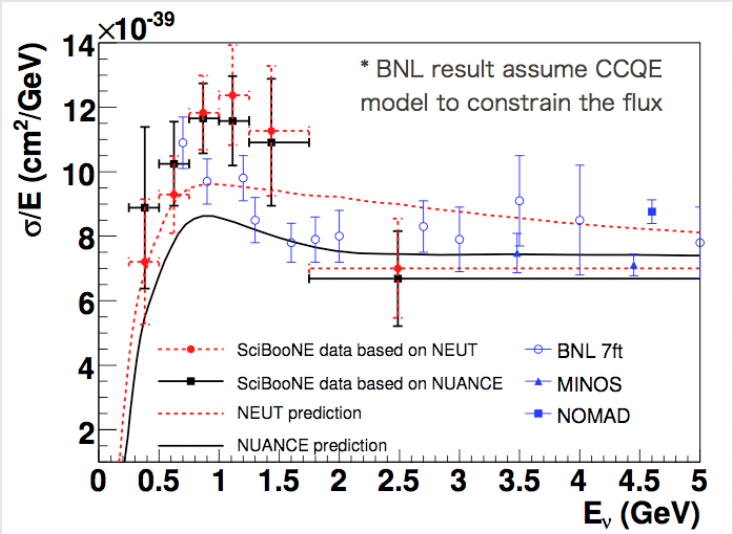
Neutrino interactions at intermediate energies

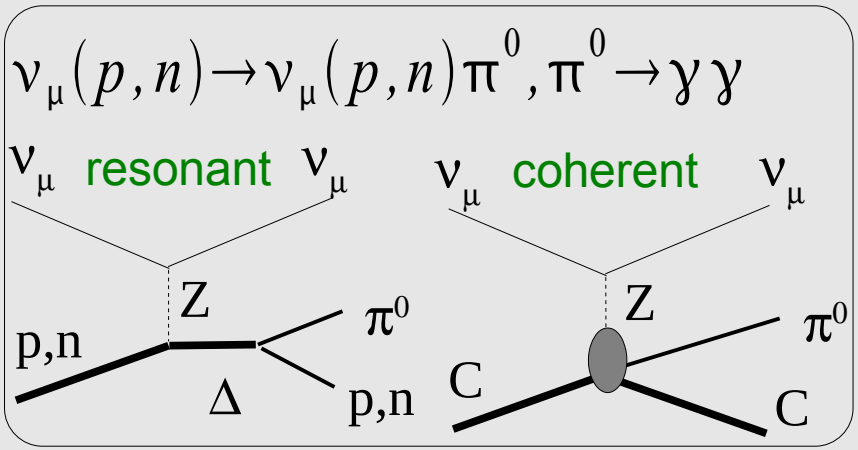
More topics/ experiments in this energy range (~200-10GeV)

- ν neutral-current (NC) elastic (NCel)
- ν CC production of π^+, π^0
- ν CC inclusive scattering
- ν NC production of neutral pions
- ν NC production of photons
- νDIS

- on a range of targets
- ideally on H/D targets,
  (to get at the bare-nucleon physics)

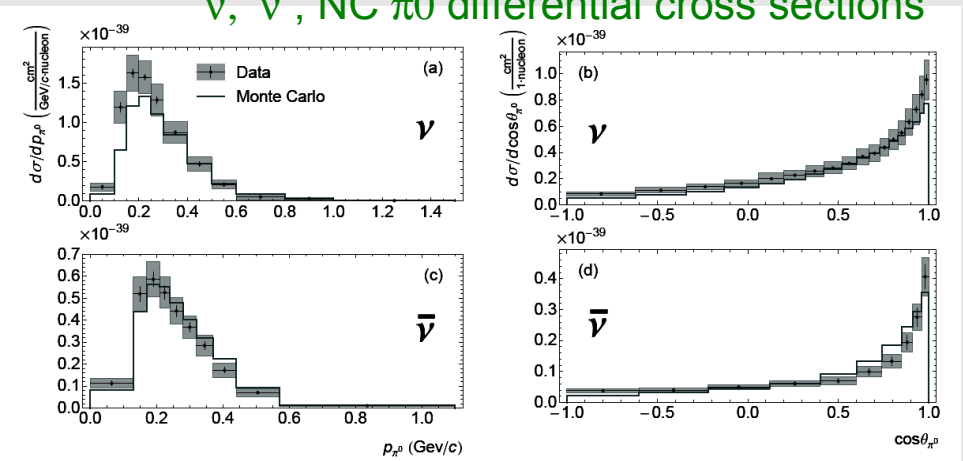
SciBooNE ν CC inclusive cross section





NCπ^0 production

ν, $\bar{\nu}$, NC π0 differential cross sections



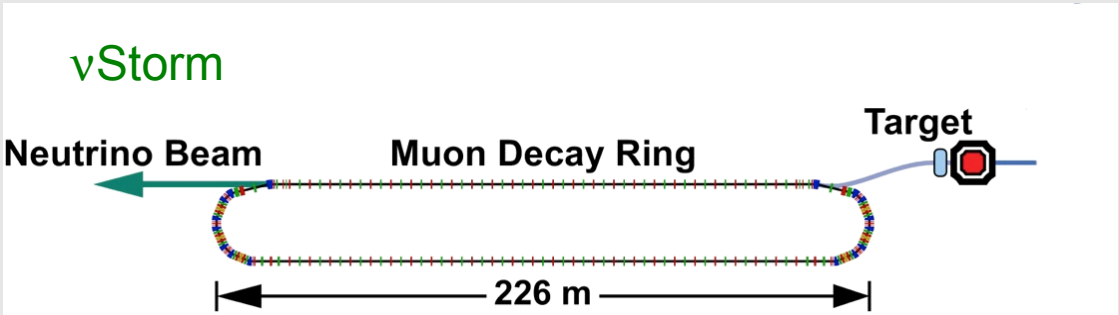
Neutrino interactions at intermediate energies

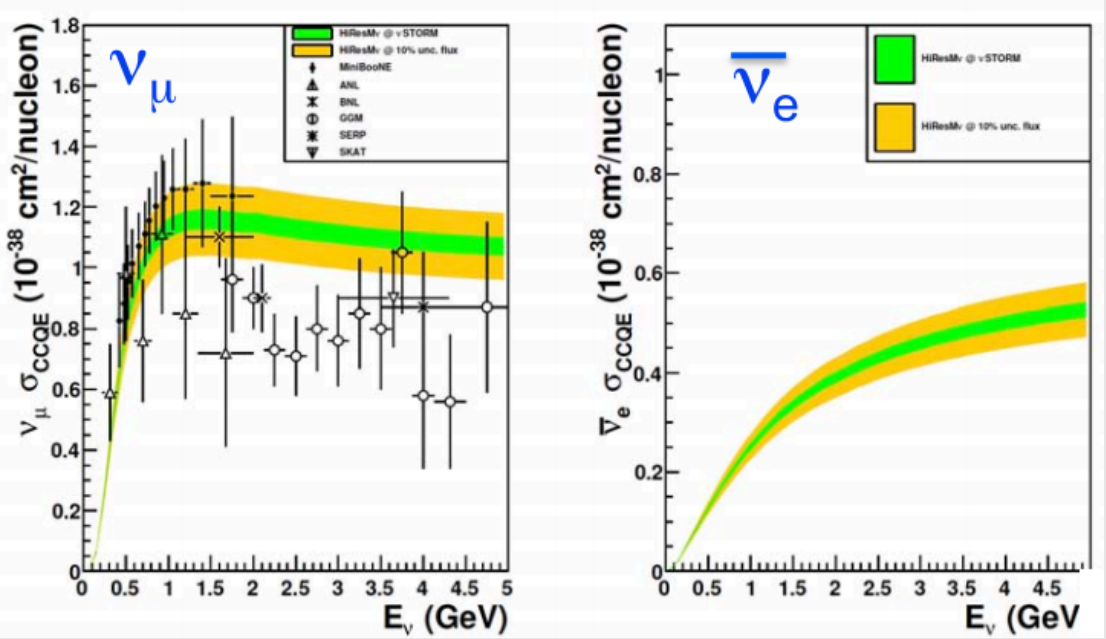
Experiments in this energy range can significantly add to our understanding of this physics:

built/approved :
- MINERvA, T2K, MINOS+, NOvA, microBooNE

proposed:
- SciNOvA,
- MiniBooNE+
- nuStorm,
- LBNE near detector

using these facilities:
- Fermilab: Booster ν line, NuMI, LBNE beam, νStorm, ProjX





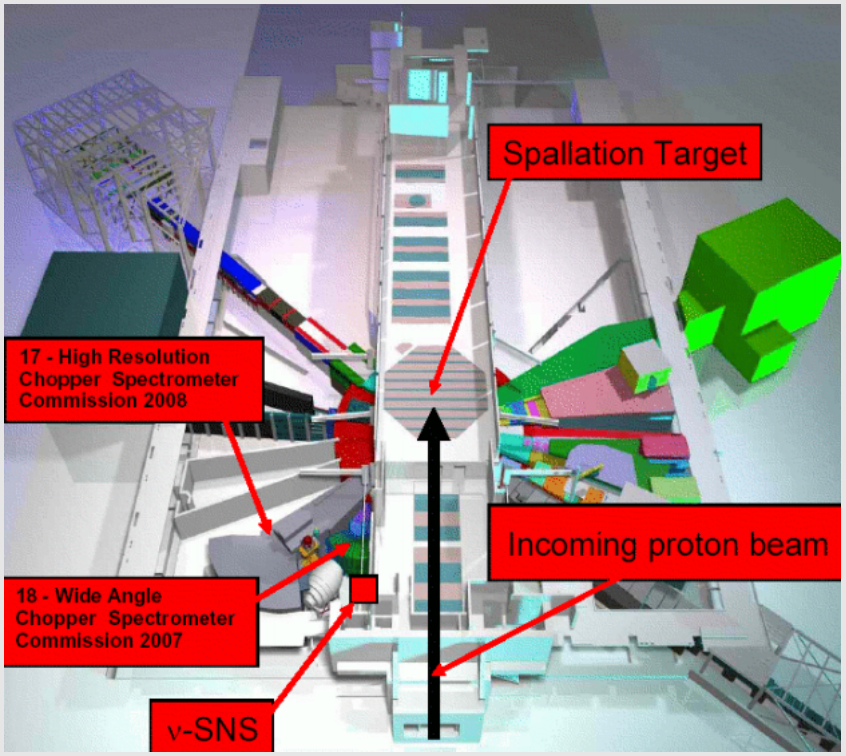
Neutrino interactions at low energy

At ~1-100MeV, multiple physics opportunities exist for important ν scattering topics

- ν-A inelastic scattering for supernova physics at SNS

- ν-A elastic coherent scattering (CENNS) at SNS, Fermilab, and reactors

SNS at ORNL



Neutrino interactions at low-E: Supernova physics

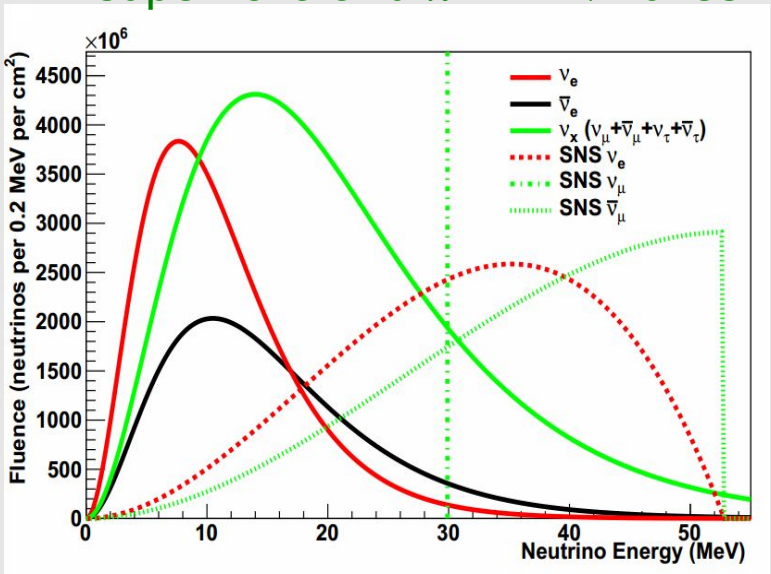
- ν-A inelastic scattering for supernova physics
  - for better understanding of supernova core-collapse processes <u>and</u> detection of supernova ν

- of important nuclei, only ^{12}C measured (to 10%) in this energy range
- particularly important to know response of large liqAr detectors to supernova

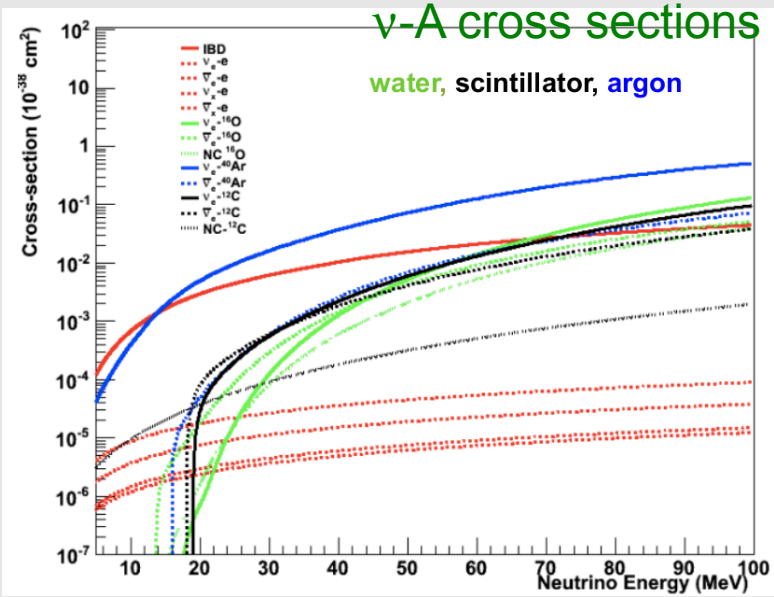
Experiments:
- liquid scintillator detector and/or liqAr at SNS or ProjX

Could provide beneficial connections with cosmic frontier

supernova and π DAR ν fluxes



ν-A cross sections



Neutrino interactions at low energy:CENNS

- ν-A elastic coherent scattering (CENNS)
  - important for understanding an ultimate limit to DM searches, and offers possibiltiy for SM, weak-nuclear tests.

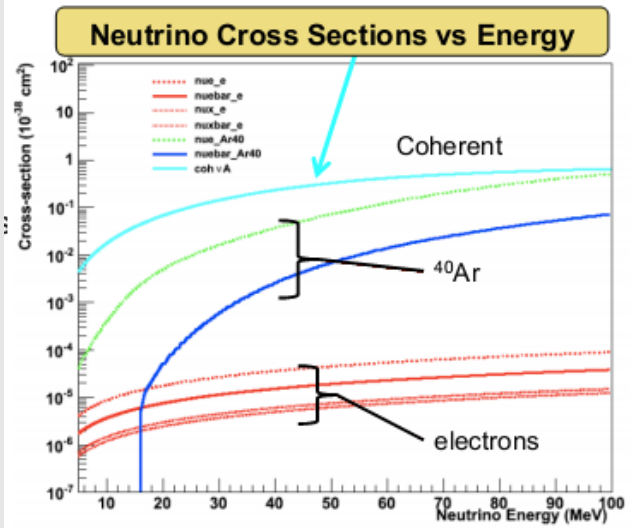
- for large nucleus (like argon)

$$E_\nu \lesssim \frac{hc}{R_N} \cong 50 \text{ MeV}$$

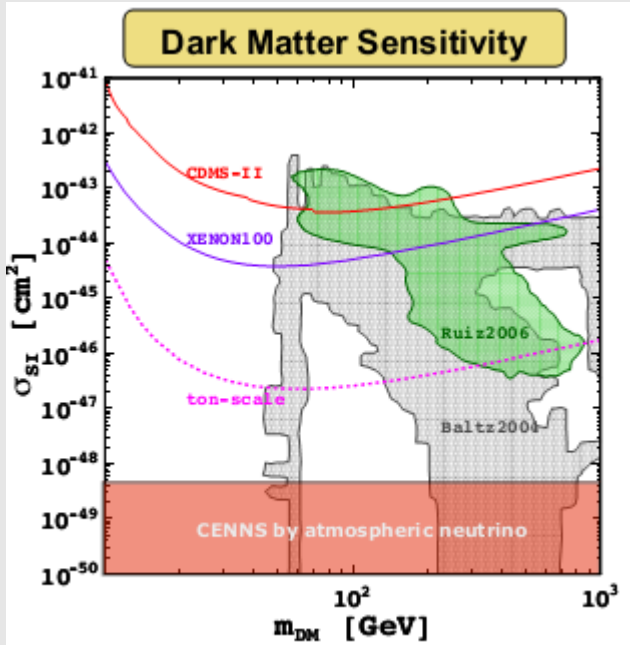
- large cross section, however, small nuclear recoil energy (~10keV)

$$E_r^{\max} \simeq \frac{2E_\nu^2}{M} \simeq 50 \text{ keV}$$

- never been observed, however low-threshold DM detector technology makes it now conceivable



K. Scholberg at Coherent NCvAs mini-workshop at FNAL



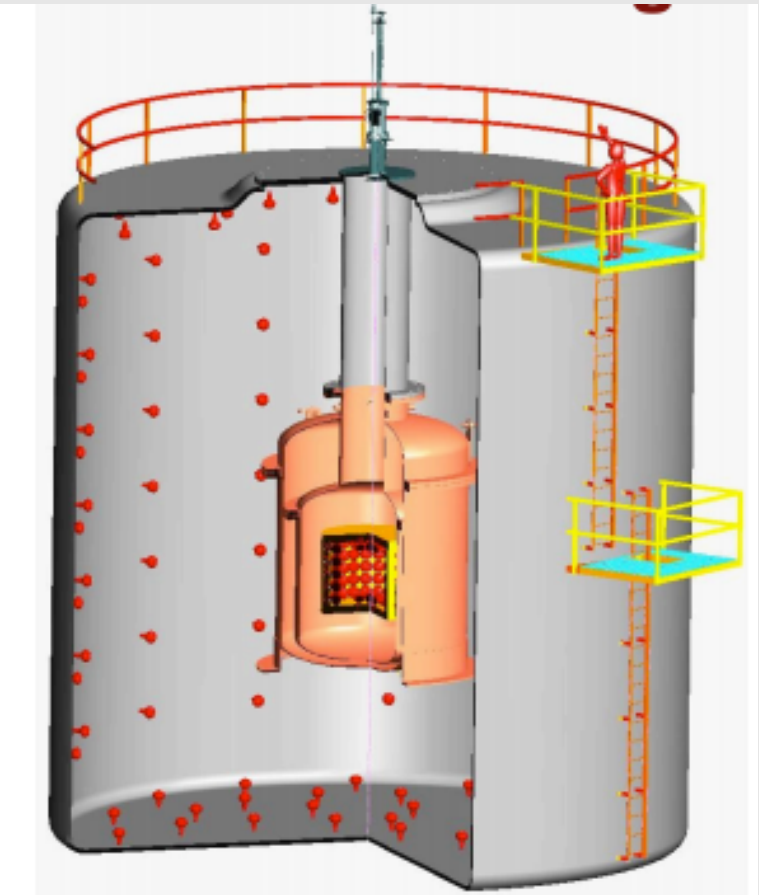
J. Yoo at Coherent NCvAS mini-workshop at FNAL

Neutrino interactions at low energy:CENNS

Experimental possibilities are numerous:
- CENNS at
  - FNAL at 90deg to Booster ν beamline
  - SNS with Germanium, Cesium-iodide, LiqAr, LiqXe
  - reactors with these technologies

- has possibilities for reactor monitoring (see nu7 group)

Also overlaping interest with cosmic frontier



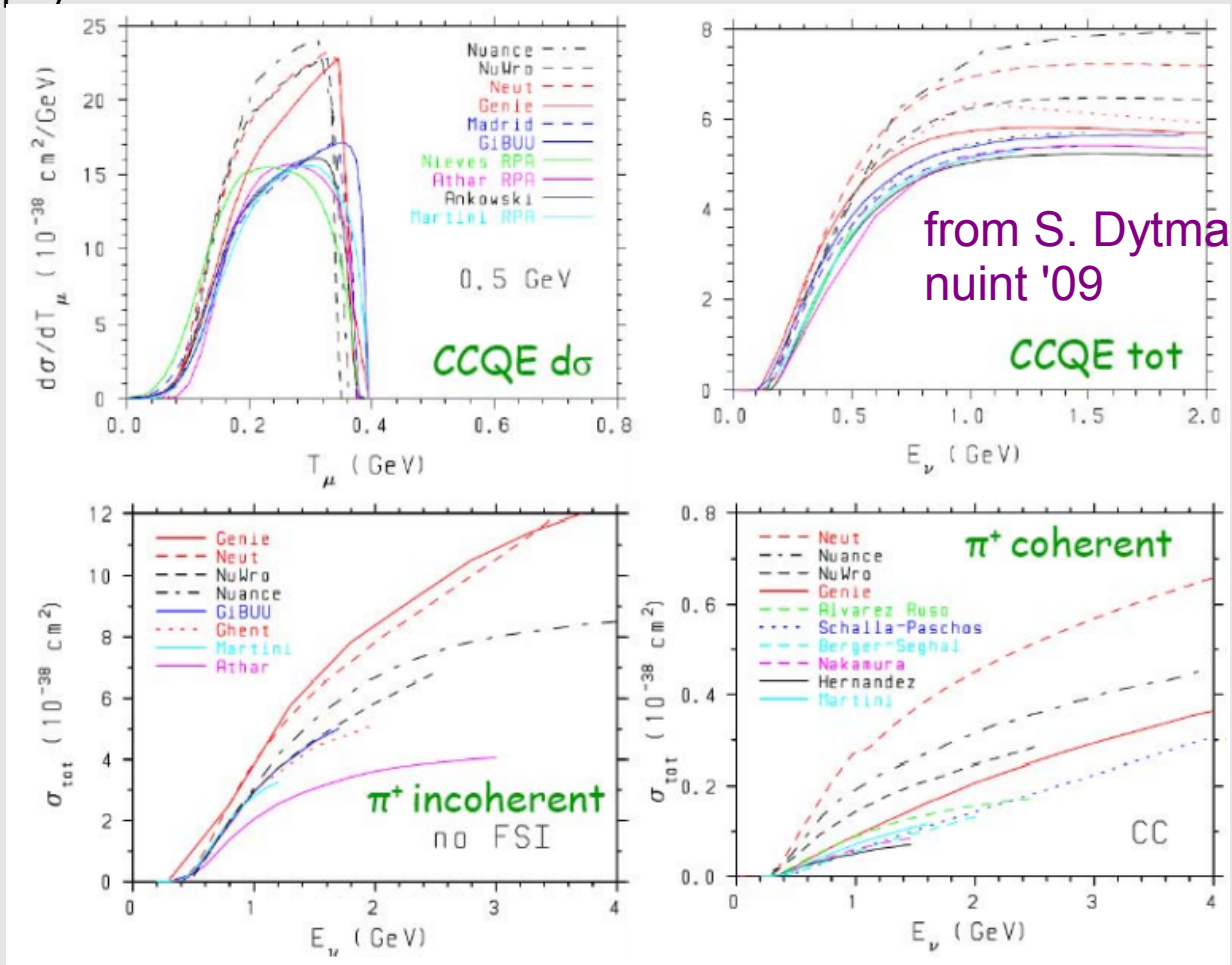
possible ~1ton liqAr CENNSdetector at Fermilab

Neutrino interactions: theory and modeling efforts

A concerted theory/phenomenological/generator effort will be required to
- digest the data that these experiments will provide (

- produce quantative and complete models for both the "pure" and "ν engineering" physics issues.

- This will require reasonable support



from S. Dytman, nuint '09

Whitepapers

The interest in ν interactions is large and varied
- ~20 whitepapers received so far
- Summarized at SLAC in 4 sessions (and in this talk and in neutrino chapter of writeup).

(Working Group Nu4) Neutrino Interactions
- C. Mariani, "Study of Neutrino Cross Sections and Nuclear Model"
- A. Bolozdynya, Y.V. Efremenko, K. Scholberg, "Perspectives to Search for Neutrino-Nuclear Neutral Current Coherent Scattering" (overlap with Nu5, Nu6, Nu7)
- A. Datta, A. Rashed "Non-Standard Interactions in nutau-nucleon scattering"
- J. Conrad et al., "Whitepaper on Cyclotrons as Drivers for Precision Neutrino Experiments" (overlap with Nu1, Nu7)
- U. Mosel, "Thoughts on Improving Event Generators and Theoretical Calculations of Neutrino-Nucleus Interactions"
- S. Brice et al., "Measuring CENNS in the Low Energy Neutrino Source at Fermilab"
- A. Bernstein et al., "Observation of Coherent Neutrino-Nucleus Scattering at a Nuclear Reactor" (overlap with Nu7)
- P. Barton et al., "Searches for CENNS at the Spallation Neutron Source"
- A. Bolozdynya et al., "Opportunities for Neutrino Measurements at the Spallation Neutron Source" (overlap with Nu6)
- O. Palamara, K. Partyka, F. Cavanna, "Neutrino-Nucleus Cross Sections: Development of Tools for Reconstruction of Exclusive Topologies in LAr TPC Experiments"
- R.J. Wilson for the LBNE collaboration, "Opportunities for Precision Neutrino Physics and Constraining Oscillation Systematics with an LBNE Near Detector"
- S. Dytman and H. Gallagher, "Improving Neutrino-Nucleus Event Generators"
- E. Santos and K. Long on behalf of the nuSTORM collaboration, "Cross Section Measurements at nuSTORM" (overlap with Nu1)
- C. Mauger et al., "NuMI Running with the LANL LDRD Liquid Argon TPC" (overlap with Nu1)
- C. Mauger et al., "Neutron Running with a Liquid Argon TPC to Study Neutrino-Argon Final State Interactions and Cosmogenic Backgrounds Important for LBNE" (overlap with Nu1, Nu6)
- G. Sinnis et al., "Measuring Neutrino Cross Sections on Argon for Supernova Neutrino Detection" (overlap Nu6)
- R. Cooper et al., "A Measurement of Neutrino-Nucleus Scattering in a Narrow Band Beam: SciNOvA" (overlap Nu1)
- M.E. Christy, "Precision Studies of Nucleon Structure and Medium Modifications with Neutrino Beams"
- G. Garvey, "Improved Neutrino-Nucleus Event Generators"

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(Nu4) **Neutrino Interactions**
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Neutrino Interactions (nu4) conclusions:

Goals:

Better understand ν-quark/nucleon/nucleus interactions over range of energies/targets

- to aid/improve ν oscillations searches/measurements
- interesting nuclear/particle/IF/CF physics

Challenges:

- new/improved data of last 10 years show fairly serious gaps in understanding
- broad-band beams, nuclear targets, quark/nucleon/nuclear DOF

Requires:

- New experiments and requisite facilities
- Improved theory/phenomenology efforts

backups/notes/spares

Neutrino interactions: areas of overlap

neutrino scattering physics is quite relevant to all other neutrino areas....
(not surprising as that is we dont see non-interacted neutrinos)
Especially for
- oscillations (as described above) energy reconstruction
- with nu6 (astro) ultra-high-energy neutrinos
- with nu7 (nus and society), CENNS and reactor monitoring
- with the cosmic frontier, especially through CENNS and what nu scattering teaches us about dark matter scattering.