νSTORM AND LONG-BASELINE NEUTRINOS

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Fermilab

νSTORM Workshop
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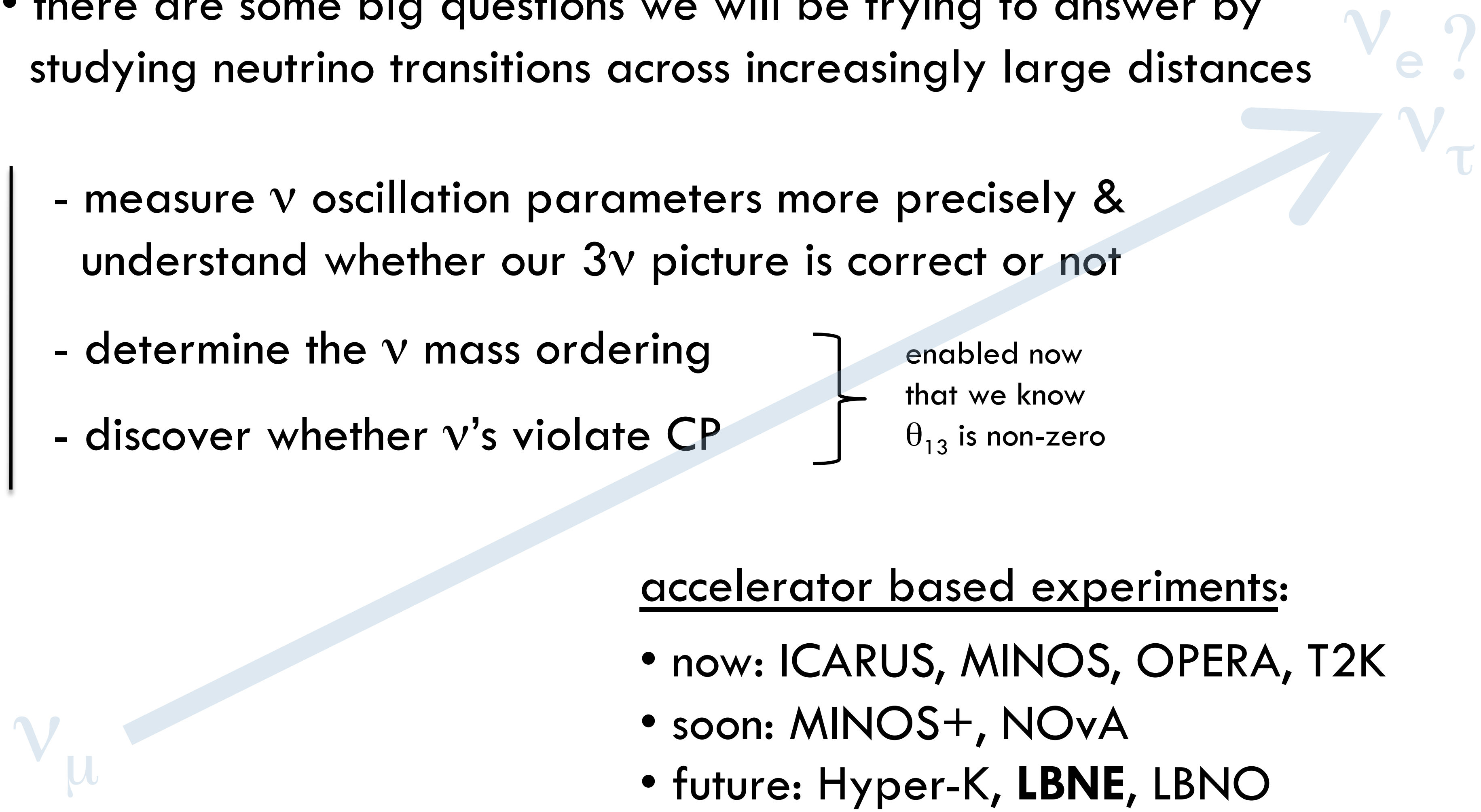
- there are some obvious synergies
- will focus on the unique information that νSTORM can provide on on $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$ interaction cross sections as it relates to LBL physics

Long-Baseline Neutrino Physics



- there are some big questions we will be trying to answer by studying neutrino transitions across increasingly large distances

  - measure ν oscillation parameters more precisely & understand whether our 3ν picture is correct or not
  - determine the ν mass ordering
  - discover whether ν's violate CP

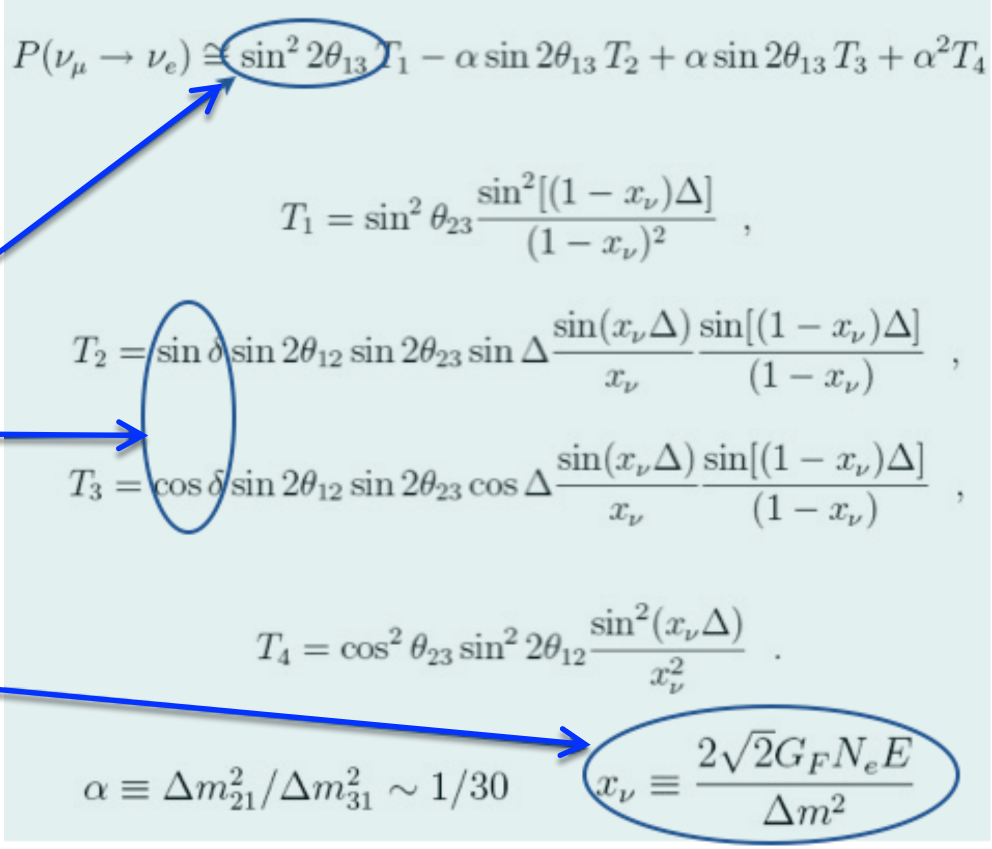
enabled now that we know θ_{13} is non-zero

<u>accelerator based experiments</u>:

- now: ICARUS, MINOS, OPERA, T2K
- soon: MINOS+, NOvA
- future: Hyper-K, **LBNE**, LBNO

Oscillation Formula

- in order to be sensitive to these effects (MH and $\cancel{C}P$), LBL exps will be looking for the conversion of ν_μ to ν_e (and $\overline{\nu}_\mu$ to $\overline{\nu}_e$) over large distances



θ_{13} is the "gate-keeper"

CP violating phase, δ

matter effects
neutrino mass ordering

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13}\, T_1 - \alpha \sin 2\theta_{13}\, T_2 + \alpha \sin 2\theta_{13}\, T_3 + \alpha^2 T_4$$

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x_\nu)\Delta]}{(1-x_\nu)^2} \,,$$

$$T_2 = \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x_\nu\Delta)}{x_\nu} \frac{\sin[(1-x_\nu)\Delta]}{(1-x_\nu)} \,,$$

$$T_3 = \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x_\nu\Delta)}{x_\nu} \frac{\sin[(1-x_\nu)\Delta]}{(1-x_\nu)} \,,$$

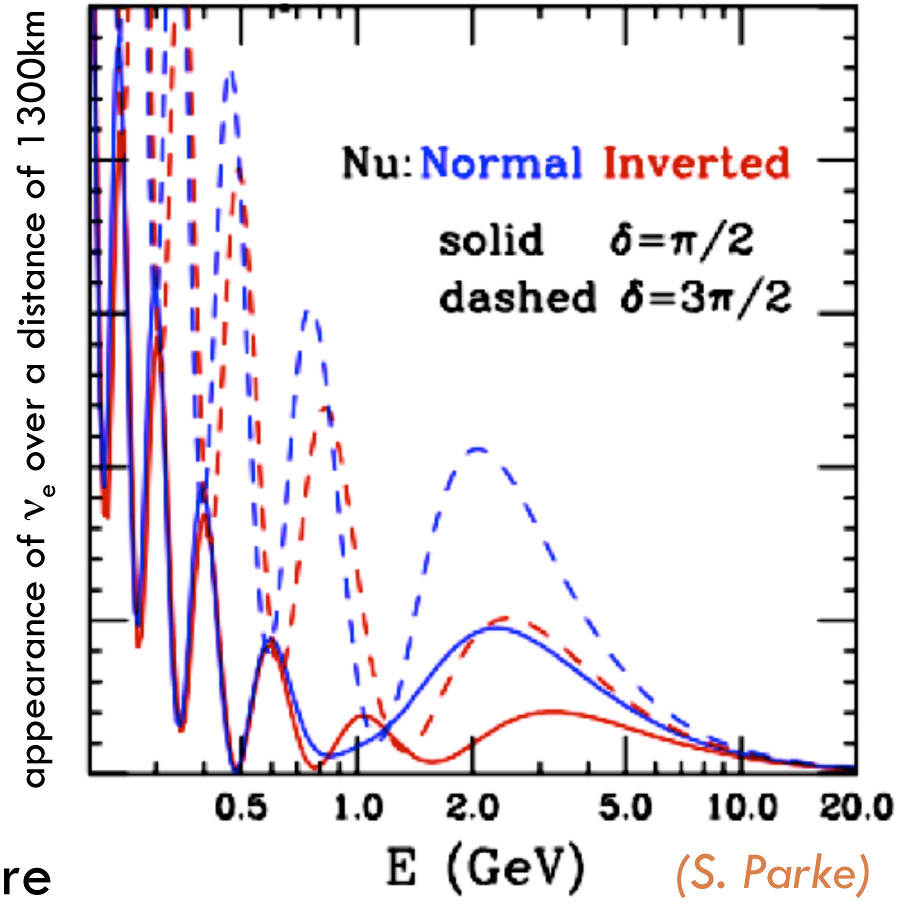
$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x_\nu\Delta)}{x_\nu^2} \,.$$

$$\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} \sim 1/30 \qquad x_\nu \equiv \frac{2\sqrt{2}G_F N_e E}{\Delta m^2}$$

How Do We Do This?

- measure spectrum of ν_e observed
- MH effect largest in 1st osc max
  $\cancel{CP}$ effect largest in 2nd osc max
- need to to probe a range of ν E's to disentangle various effects
- examine for <u>both neutrino and antineutrino</u> scattering
- no longer trying to simply observe a signal, but want to actually measure distortions in both ν_e and $\overline{\nu}_e$ due to mass ordering and $\cancel{CP}$

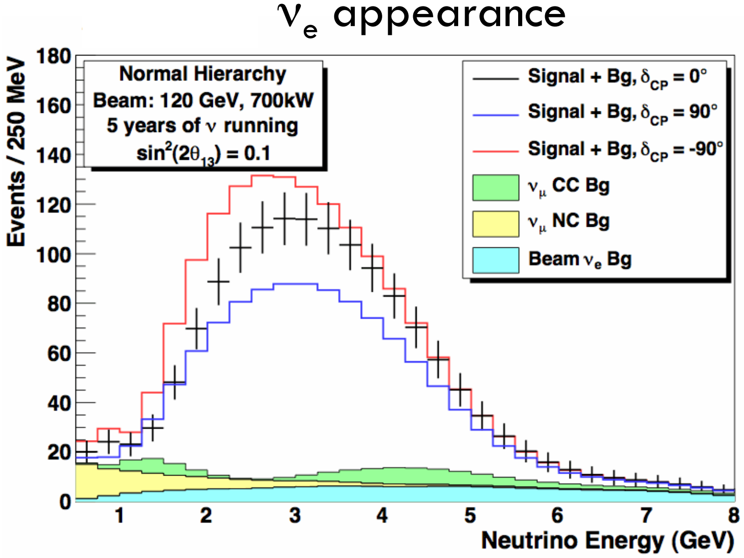
in pictorial form:



(S. Parke)

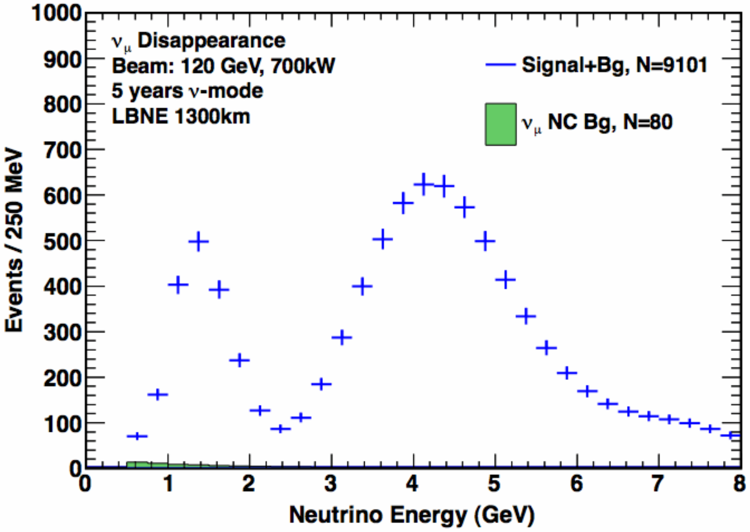
Example: LBNE

(E. Worcester, Z. Isvan)



ν_e appearance

examples of what signals might look like in a 34kton LAr TPC at 1300km



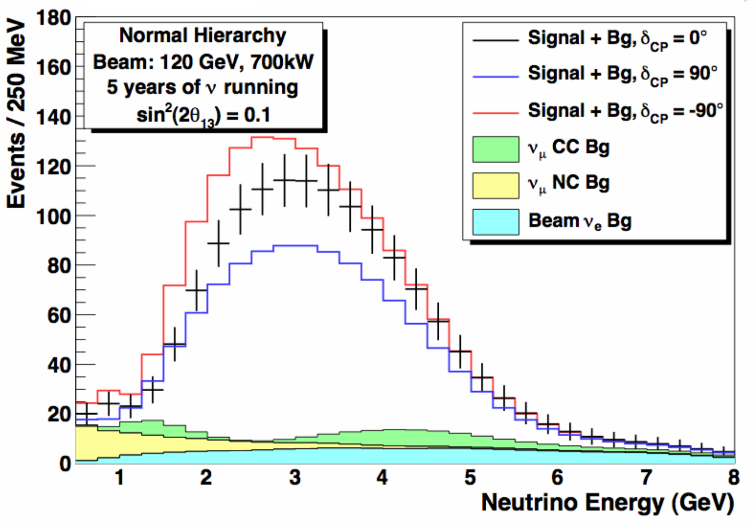
ν_μ disappearance

- <u>goals</u>:
  - measure full oscillation pattern in both channels, precisely constraining mixing angles, mass differences
  - search for $\not{C}P$ both by measuring δ_{CP} and by explicitly observing differences between ν and $\overline{\nu}$ oscillations
  - cleanly separate matter effects from CP-violating effects

Example: LBNE

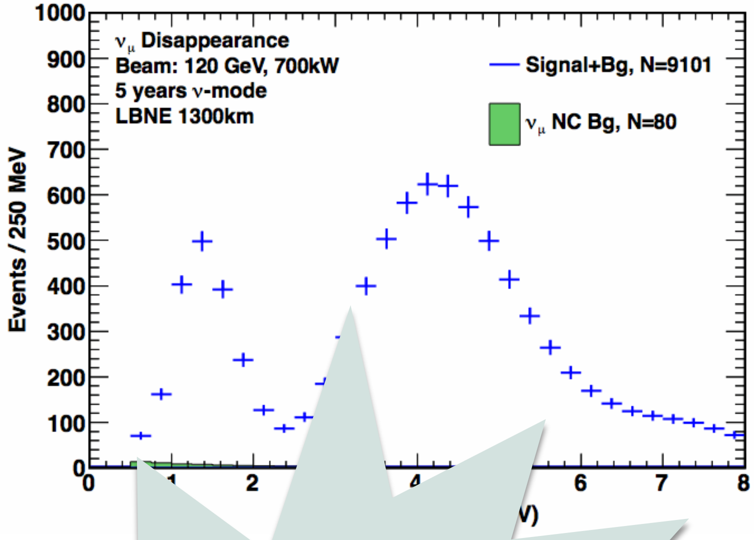
(E. Worcester, Z. Isvan)

ν_e appearance



examples of what signals might look like in a 34kton LAr TPC at 1300km

ν_μ disappearance

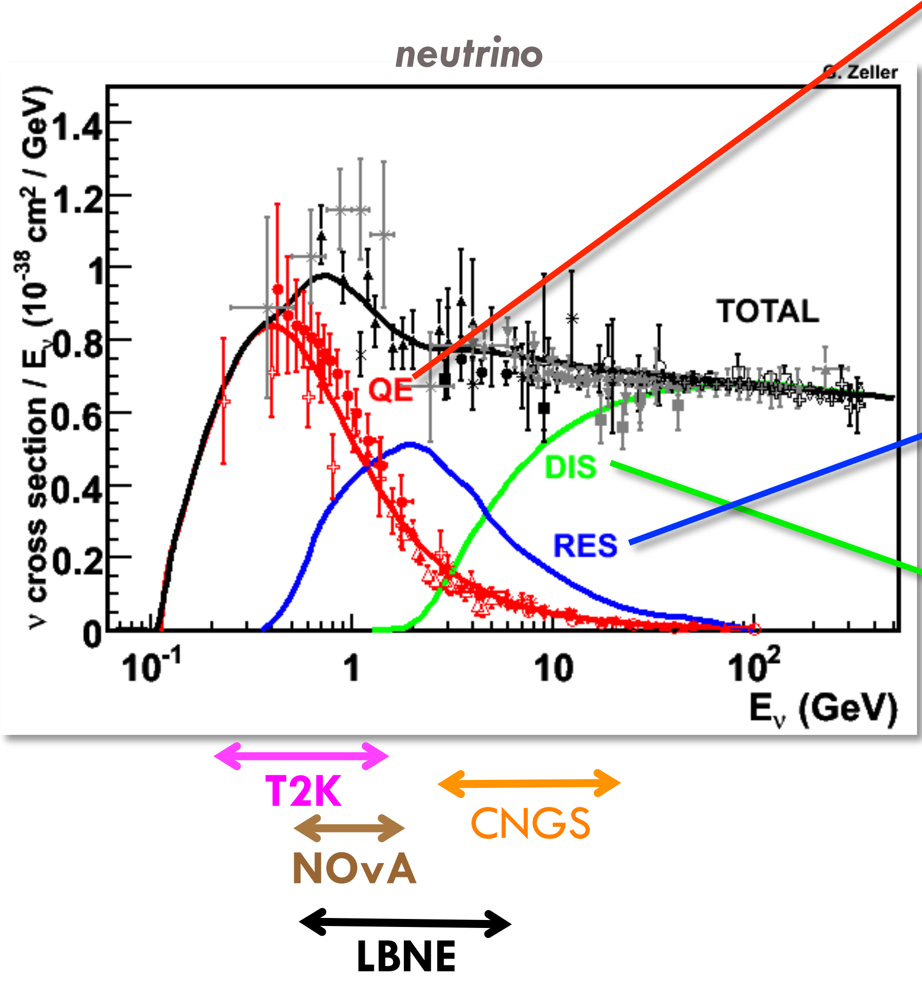


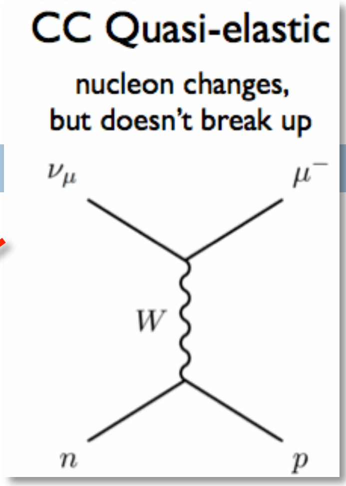
interested in energies from ~0.5 to 6 GeV

- goals:
  - measure full oscillation pattern in bo
    precisely constraining mixing angles, m
  - search for $\not{C}P$ both by measuring δ_{CP} a
    observing differences between ν and $\overline{\nu}$
  - cleanly separate matter effects from CP-viol ting ffects

Complicated Region

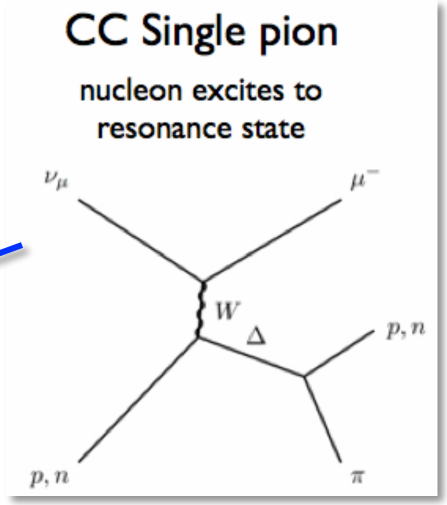
(event samples contain contributions from multiple reaction mechanisms)





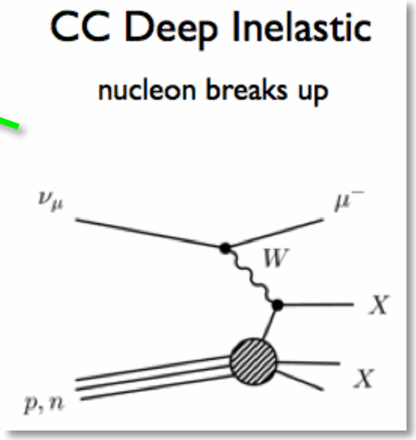
CC Quasi-elastic

nucleon changes, but doesn't break up



CC Single pion

nucleon excites to resonance state

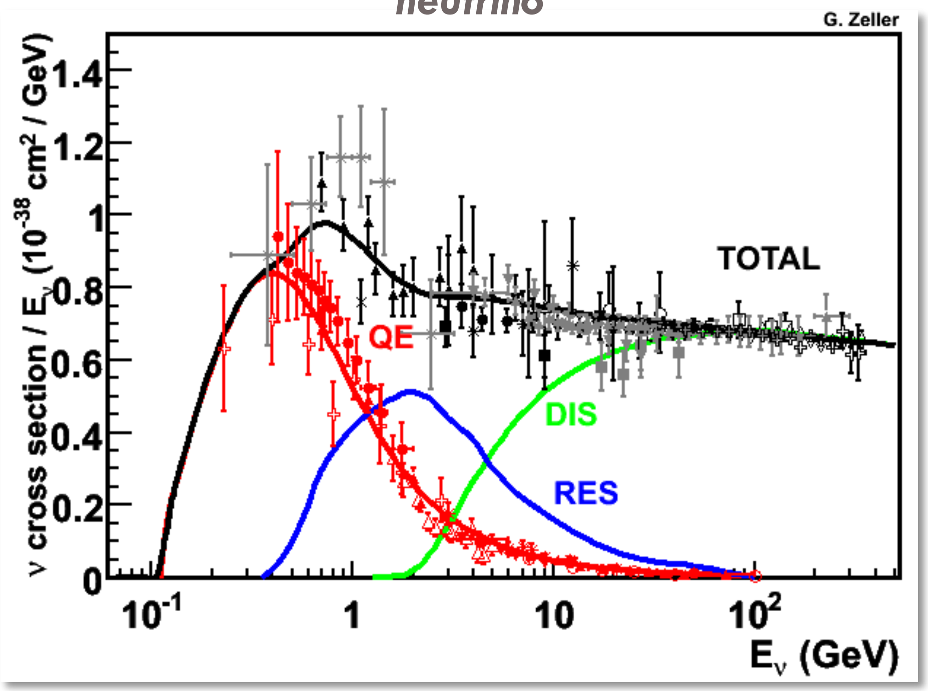


CC Deep Inelastic

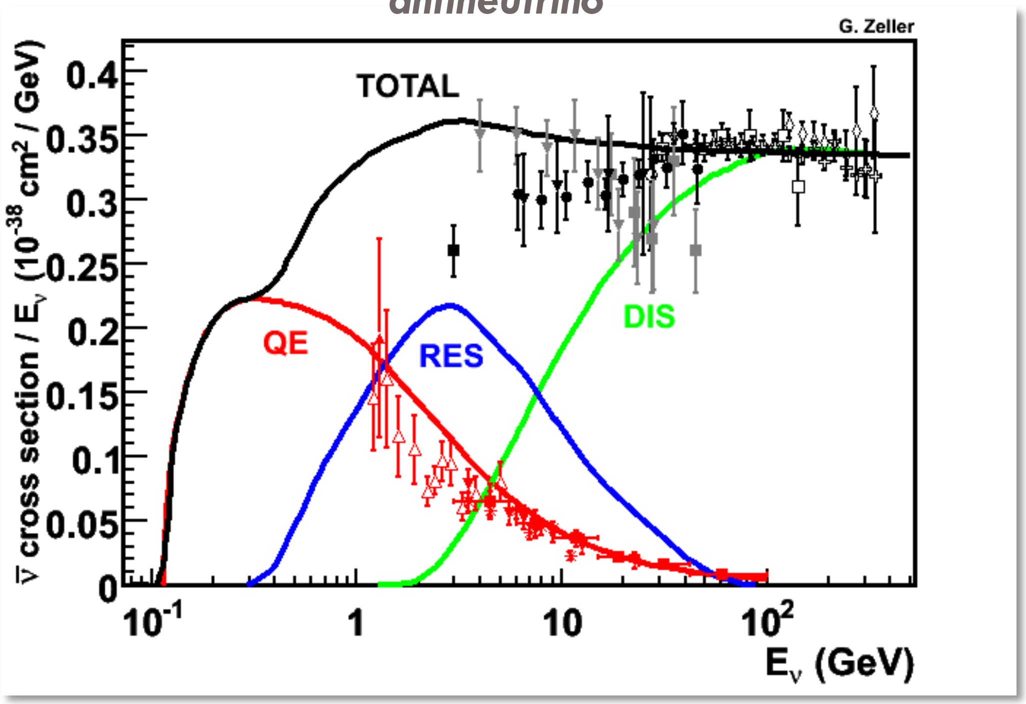
nucleon breaks up

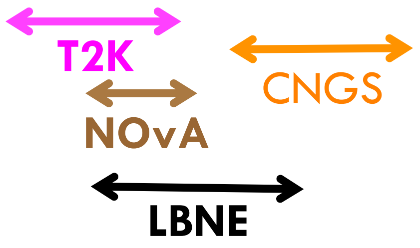
Current Knowledge

neutrino



antineutrino

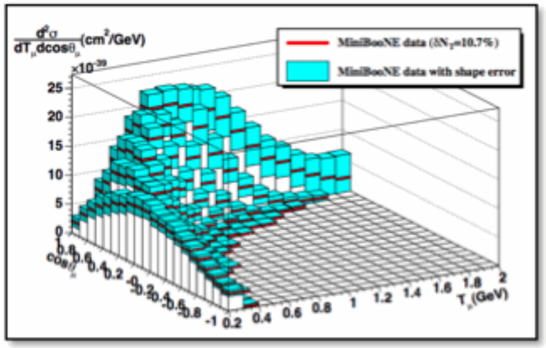




- σ_ν's are not particularly well-constrained in this region but situation has been improving *(availability of much higher statistics data on nuclear targets!)*

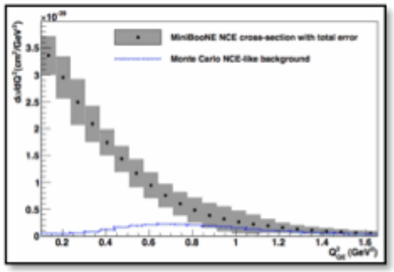
MiniBooNE

- has made some of the 1st measurements of full kinematics for these reactions



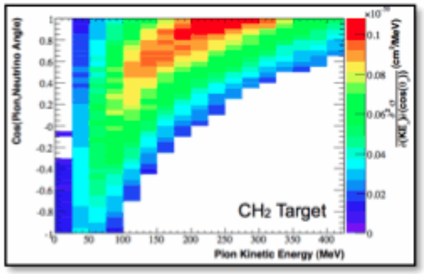
quasi-elastic scattering

- Phys. Rev. Lett. **100**, 032301 (2008)
- Phys. Rev. **D81**, 092005 (2010)



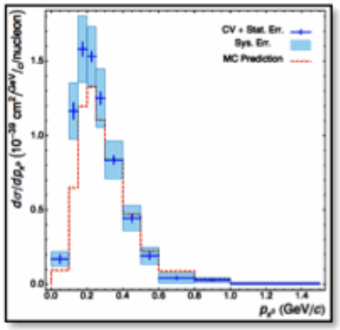
NC elastic scattering

- Phys. Rev. **D82**, 902005 (2010)



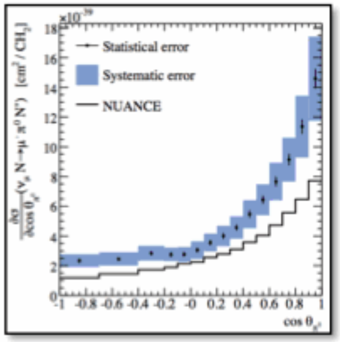
CC π^+ production

- Phys. Rev. Lett. **103**, 081801 (2009)
- Phys. Rev. **D83**, 052007 (2011)



NC π^0 production

- Phys. Lett. **B664**, 41 (2008)
- Phys. Rev. **D81**, 013005 (2010)



CC π^0 production

- Phys. Rev. D83, 052009 (2011)

- *also, σ_ν measurements from ArgoNeuT, ICARUS, K2K, MINERνA, MINOS, NOMAD, NOνA ND, SciBooNE, T2K ND!*

- want to pick one example to help motivate why σ_ν are important

QE Scattering

- QE scattering is just one example that we shouldn't assume that we know everything about ν interaction cross sections

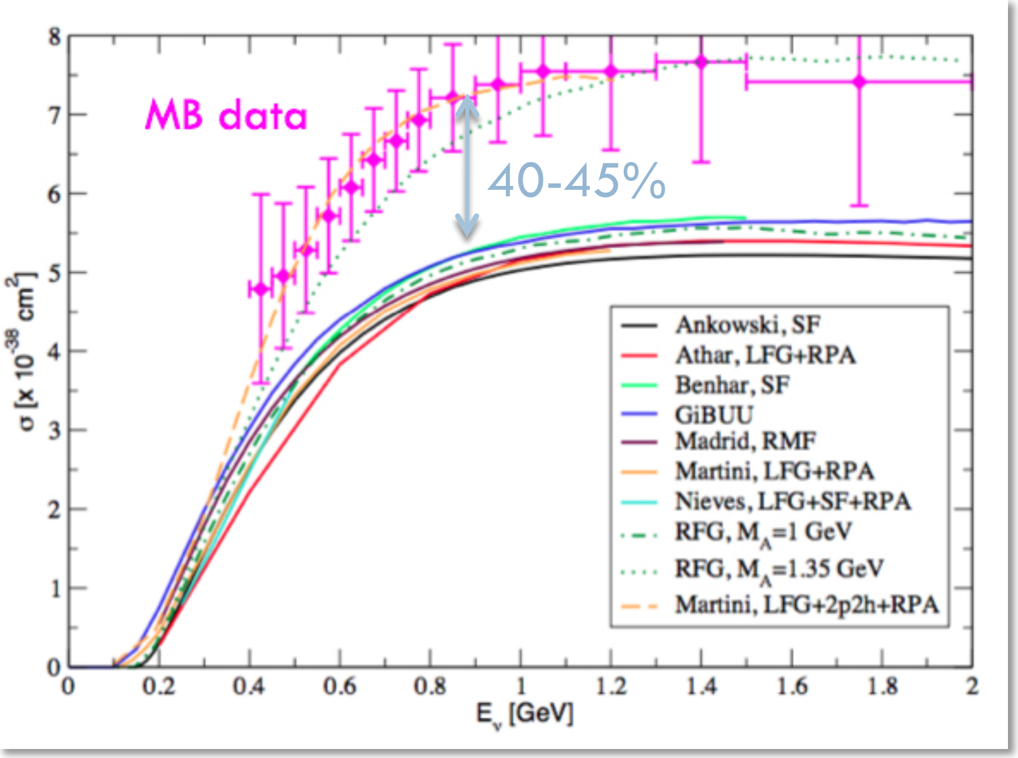
- plus, has been a hot topic lately

  MiniBooNE data is the 1st time have measured the ν QE σ on a nuclear target below 2 GeV

- σ's are appreciably larger than conventional approaches

  (increased QE rates also seen in K2K, MINOS, SciBooNE)

- community has been working to understand these results

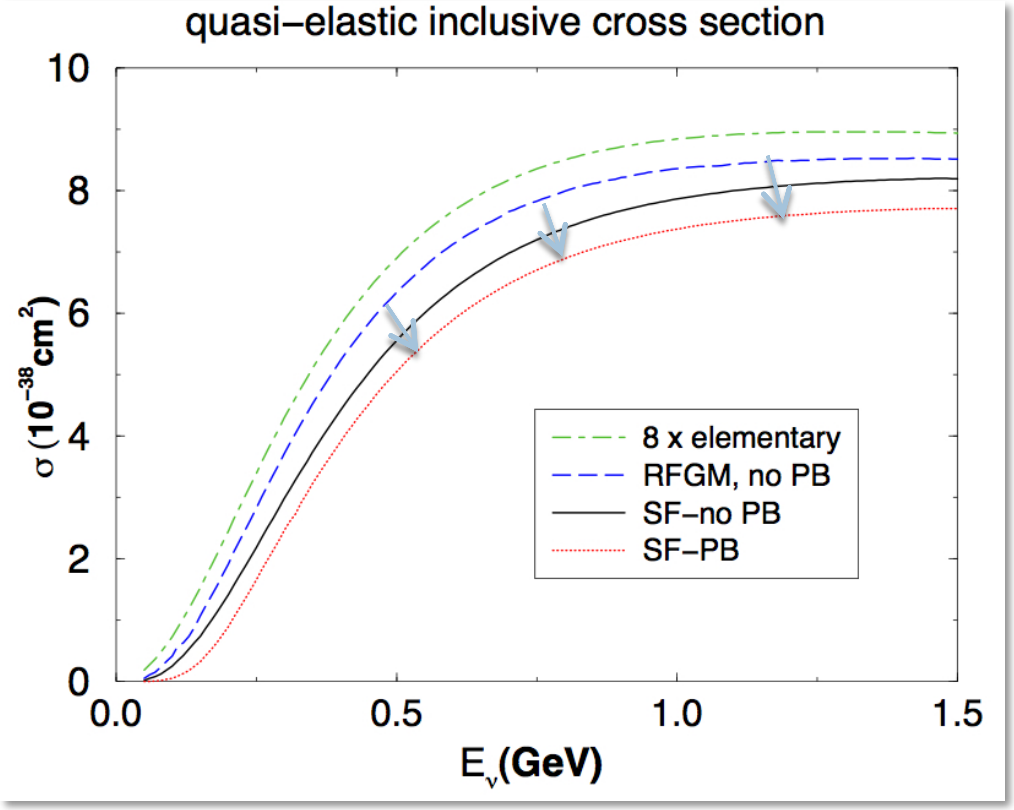


(L. Alvarez-Ruso, NuFact11)

QE Scattering

$\nu_\mu\, n \longrightarrow \mu^-\, p$

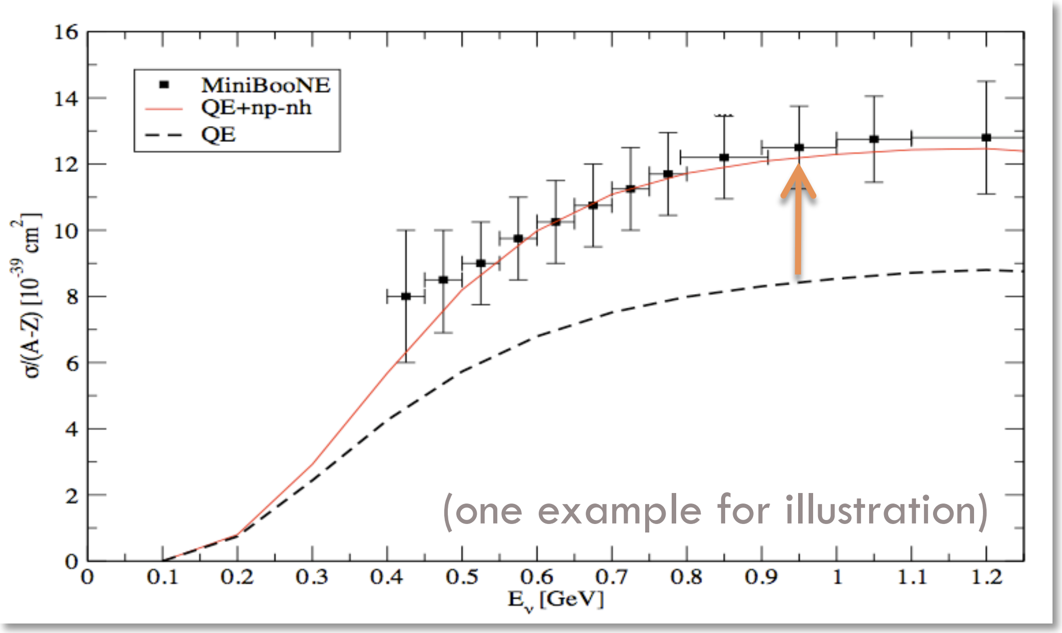
- caused problems because has long been thought that nuclear effects <u>decrease</u> the σ



(O. Benhar, arXiv:0906.3144)

“New” Source of Nuclear Effects?

- while traditional nuclear effects decrease σ_ν, it has been appreciated that there are processes that can increase the total yield



(one example for illustration)

(Martini et al., arXiv:1202.4745)

- increased σ stemming from fact that the incoming ν can interact with *more than one* nucleon in the target nucleus

  (i.e., effects not included in the independent particle approaches we have been using for decades)

- *has been known in e^- scattering*

  *Carlson et al., PRC **65**, 024002 (2002)*

What Does This All Mean?

- in this one example, even something as simple as QE scattering isn't as simple as we thought
  - *discovered a "new" source of nuclear effects that can significantly increase the σ*
  - *idea that could be missing ~40% of σ in our neutrino simulations is a big deal*
- good news: expect larger event yields
- bad news: need to understand the underlying physics

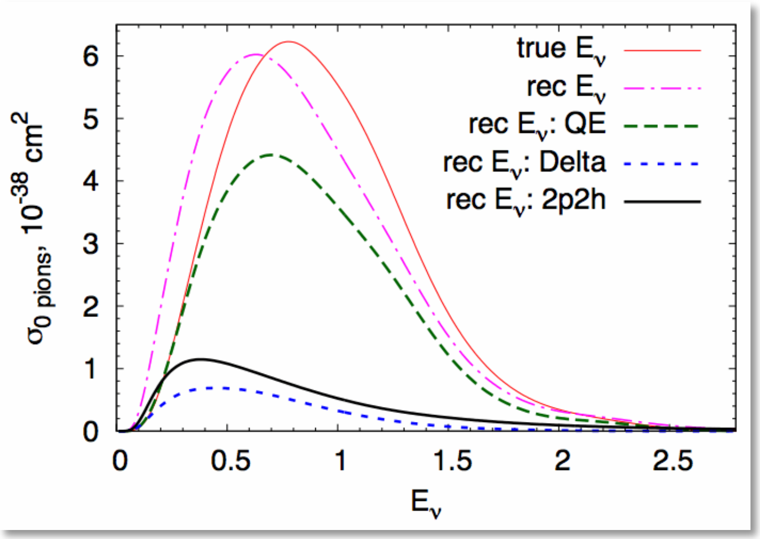
(1) impacts E_ν determination

ex: Mosel/Lalakulich 1204.2269, Martini *et al.* 1202.4745, Lalakulich *et al.* 1203.2935, Leitner/Mosel PRC81, 064614 (2010)

(2) effects will be different for ν vs. $\overline{\nu}$

(at worse, could produce a spurious $\cancel{CP}$ effect)

(3) could impact ν_μ and ν_e differently?

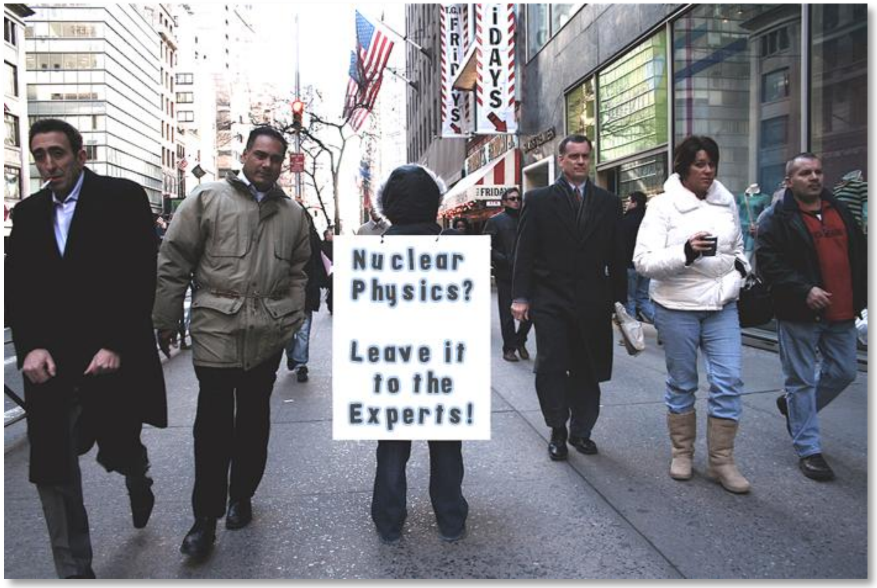


(Lalakulich, Gallmeister, Mosel, 1203.2935)

Theory Calculations In the Past Year

- this is something that needs to get sorted out and people are working hard on this …

  - Lalakulich, Mosel, arXiv:1208.3678
  - Bodek *et al.*, arXiv:1207.1247
  - Ankowski, PRC 86, 024616 (2012)
  - Butkevich, arXiv:1204.3160
  - Lalakulich *et al.*, arXiv:1203.2935
  - Mosel, arXiv:1204.2269, 1111.1732
  - Barbaro *et al.*, arXiv:1110.4739
  - Giusti *et al.*, arXiv:1110.4005
  - Meloni *et al.*, arXiv:1203.3335, 1110.1004
  - Martini *et al.*, arXiv:1202.4745, 1110.0221, 1110.5895, PRC 81, 045502 (2010)
  - Paz, arXiv:1109.5708
  - Sobczyk, arXiv:1201.3673, 1109.1081, 1201.3673
  - Nieves *et al.*, PRD 85, 113008 (2012), 1106.5374, 1110.1200, PRC 83, 045501 (2011)
  - Bodek *et al.*, arXiv:1106.0340
  - Amaro, *et al.*, arXiv:1112.2123, 1104.5446, 1012.4265, PL B696, 151 (2011)
  - Antonov, *et al.*, arXiv:1104.0125
  - Benhar, *et al.*, arXiv:1012.2032, 1103.0987, 1110.1835
  - Meucci *et al.*, arXiv:1202.4312, PRC 83, 064614 (2011)
  - Ankowski *et al.*, Phys. Rev. **C83**, 054616 (2011)
  - Alvarez-Ruso, arXiv:1012.3871
  - Martinez *et al.*, Phys. Lett **B697**, 477 (2011) + …

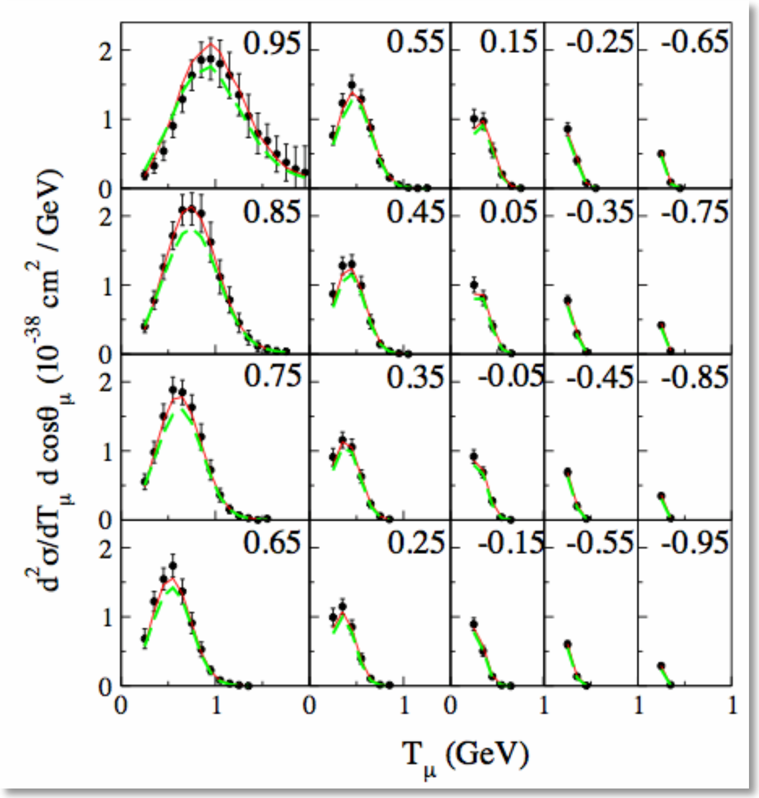


- >50 theoretical papers on the topic of QE ν-nucleus scattering in the past year or so

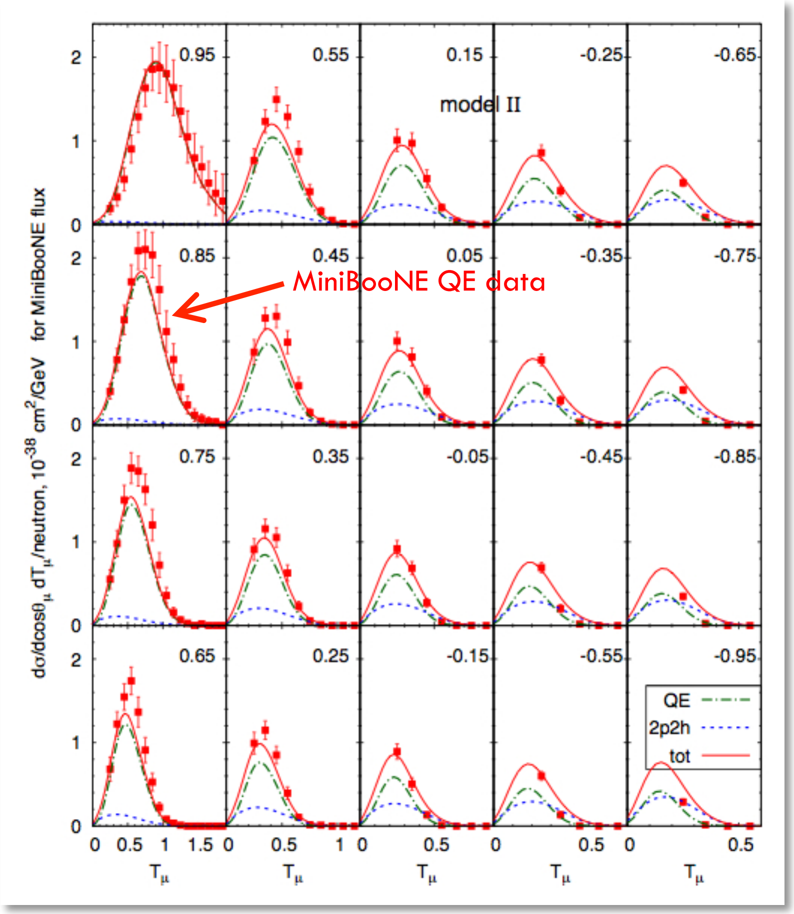
(disclaimer: this is not a complete list!)

$d^2\sigma/dT_\mu d\theta_\mu$

- this is the 1st time we've had this sort of information available



Nieves, Simo, Vacas, PL ***B707****, 72 (2012)*



MiniBooNE QE data

Lalakulich, Gallmeister, Mosel arXiv:1203.2935

- we need measurements at other E_ν, A, plus hadronic side, and ν_e's!

Neutrino Scattering on Nuclei

- I bring this up because this isn't just boiler plate physics

- this is why the σ_ν program at MINERνA is so important
  \+ LAr *(ArgoNeuT, MicroBooNE, ICARUS)* + NDs *(NOνA, T2K)*

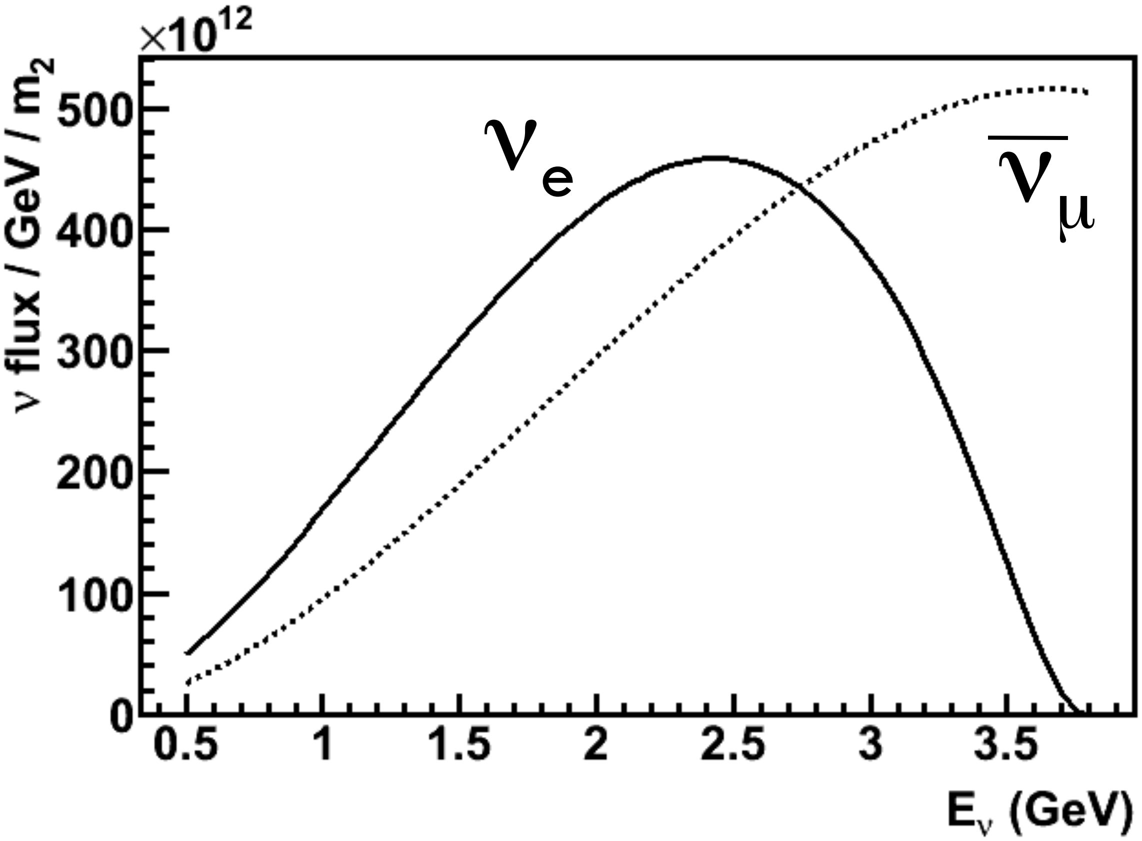
- these σ_ν measurements are being made in accelerator-based beams produced for ν oscillation physics $\Longrightarrow$ predominantly ν_μ by construct

  1 - do not have measurements of ν_e cross sections *(infer from ν_μ)*

  2 - σ_ν uncertainties limited by knowledge of incoming ν flux
  (uncertainties in π, K production in the beam are a limiting factor)

- these are two areas where νSTORM can play an important role

νSTORM Neutrino Beam



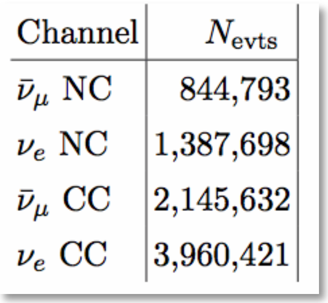
3.8 GeV μ^+ stored, 150m straight, flux at 100m

(thanks to Chris Tunnell!)

- provides well-known beams of neutrinos & antineutrinos

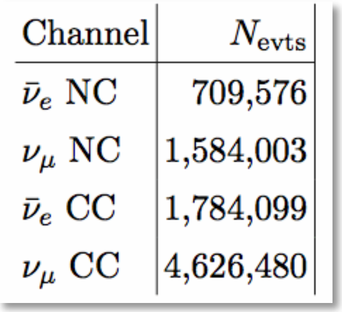
- and a unique high statistics source of ν_e's

μ^+



Channel	N_{evts}
$\bar{\nu}_\mu$ NC	844,793
ν_e NC	1,387,698
$\bar{\nu}_\mu$ CC	2,145,632
ν_e CC	3,960,421

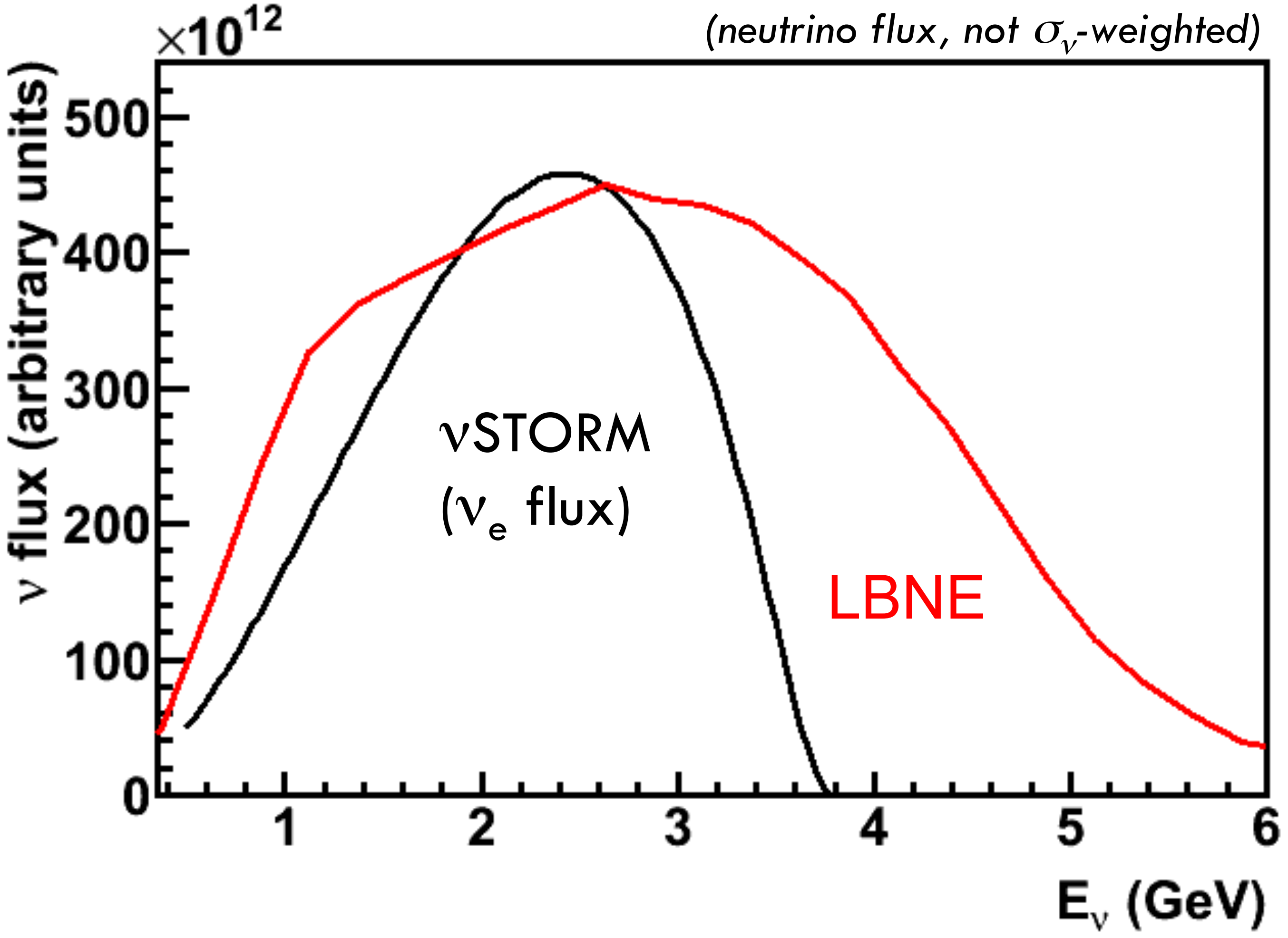
μ^-



Channel	N_{evts}
$\bar{\nu}_e$ NC	709,576
ν_μ NC	1,584,003
$\bar{\nu}_e$ CC	1,784,099
ν_μ CC	4,626,480

event rates per 1E21 POT, 100 ton at 50m

Direct Comparison



- in LBNE, care about neutrino energies from ~0.5 to 6 GeV
- νSTORM nicely overlaps a large fraction of this region!

- νSTORM can make some important ν_e measurements as input (also ν_μ)

What Do We Know About ν_e Cross Sections?

- have seen that there have been some interesting results being unearthed by new investigations of ν_μ scattering (ex. QE), so what do we know about ν_e's?

- our current information on ν_e (and $\overline{\nu}_e$) cross sections comes from 3 main sources … scattering measurements made on:

  (1) free protons (IBD)
  (2) deuterium
  (3) + a few other nuclear targets (mostly carbon)

- will spend a few slides on surveying what we know about ν_e σ's since this is not something we typically talk about

Inverse Beta Decay

- important reaction for detection of solar and reactor neutrinos

- IBD cross section measured in reactor experiments in mid 80's-90's

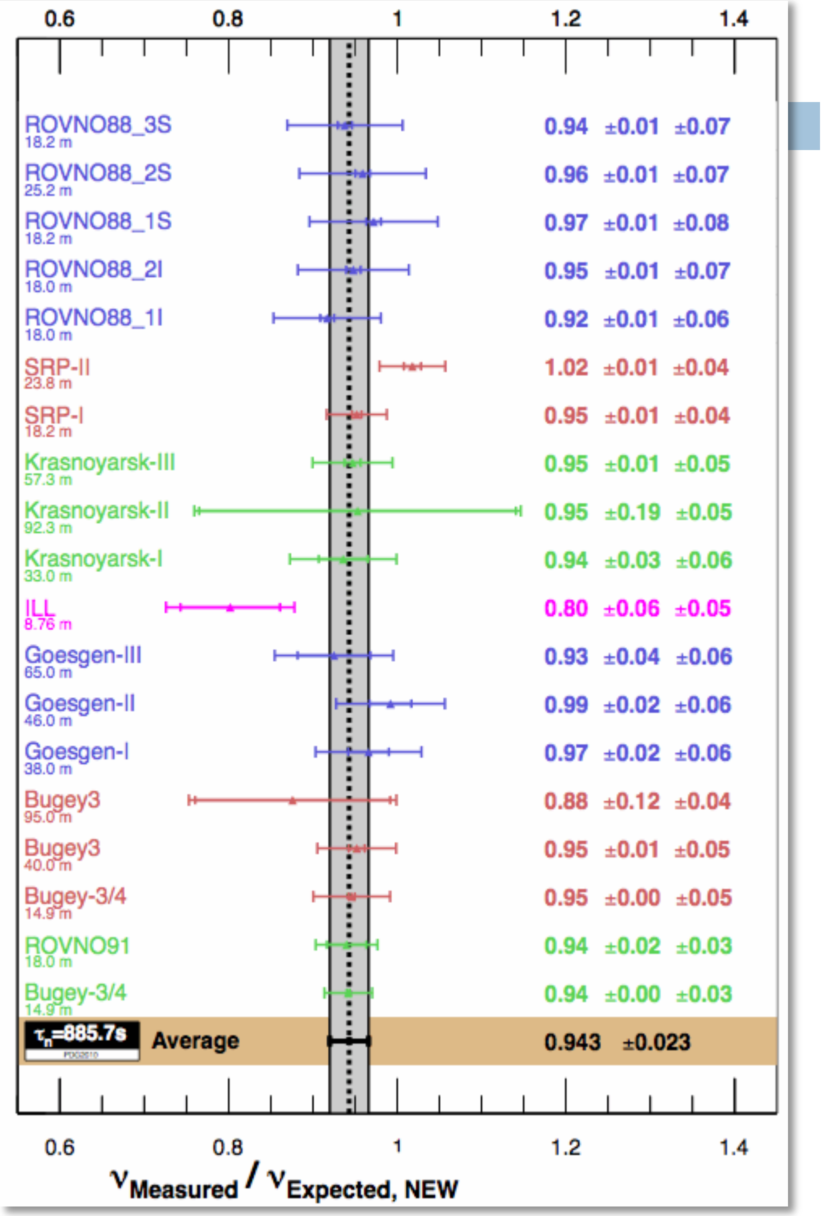
  (possible at short distances <100m from the reactor where oscillation effects are negligible)

$$\overline{\nu}_e\, p \longrightarrow e^+ n$$

- consistent to within ~5% of the theoretical calculations

- ~10 MeV so not really the energies we care about for LBL ν physics

- what about more complex targets?



(Formaggio & Zeller, Rev. Mod. Phys. 2012)

Deuterium

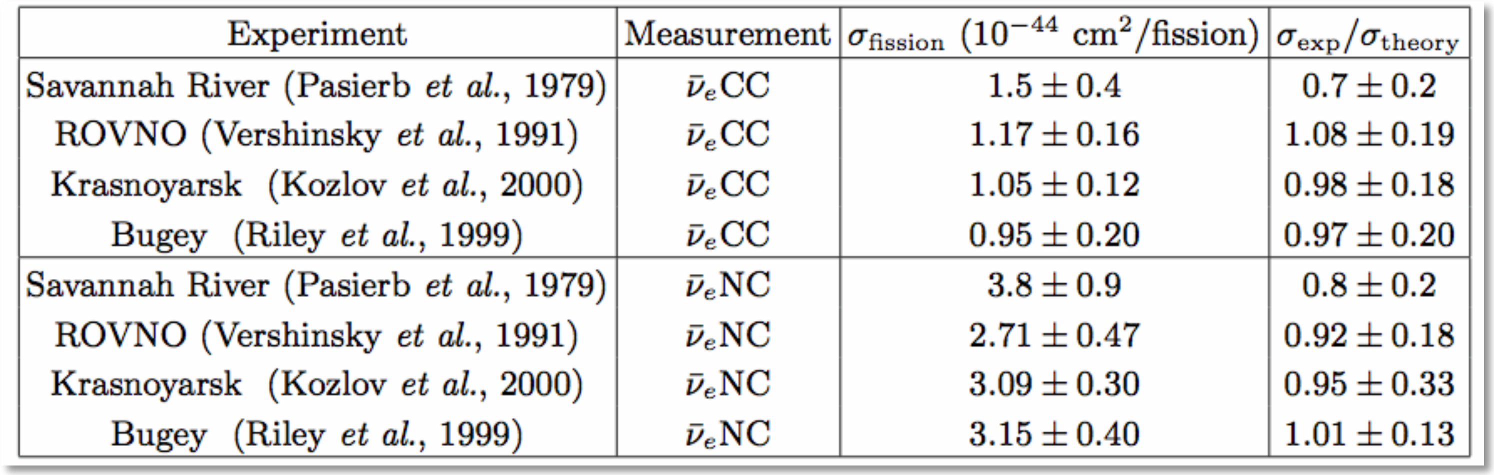
- particularly important role in solar neutrino oscillations (e.g., SNO)
- only one measurement of ν_e cross section on deuterium

  (Willis et al., PRL 44, 522 (1980), LAMPF stopped μ^+ beam)

$$\sigma(\nu_e\, d \rightarrow e^- \, p\, p) = (0.52 \pm 0.18) \times 10^{-40}\, \text{cm}^2$$

(35% measurement)

- several measurements of $\overline{\nu}_e$ cross section on deuterium from reactors



Experiment	Measurement	σ_{fission} $(10^{-44}\ \text{cm}^2/\text{fission})$	$\sigma_{\text{exp}}/\sigma_{\text{theory}}$
Savannah River (Pasierb *et al.*, 1979)	$\bar{\nu}_e$CC	1.5 ± 0.4	0.7 ± 0.2
ROVNO (Vershinsky *et al.*, 1991)	$\bar{\nu}_e$CC	1.17 ± 0.16	1.08 ± 0.19
Krasnoyarsk (Kozlov *et al.*, 2000)	$\bar{\nu}_e$CC	1.05 ± 0.12	0.98 ± 0.18
Bugey (Riley *et al.*, 1999)	$\bar{\nu}_e$CC	0.95 ± 0.20	0.97 ± 0.20
Savannah River (Pasierb *et al.*, 1979)	$\bar{\nu}_e$NC	3.8 ± 0.9	0.8 ± 0.2
ROVNO (Vershinsky *et al.*, 1991)	$\bar{\nu}_e$NC	2.71 ± 0.47	0.92 ± 0.18
Krasnoyarsk (Kozlov *et al.*, 2000)	$\bar{\nu}_e$NC	3.09 ± 0.30	0.95 ± 0.33
Bugey (Riley *et al.*, 1999)	$\bar{\nu}_e$NC	3.15 ± 0.40	1.01 ± 0.13

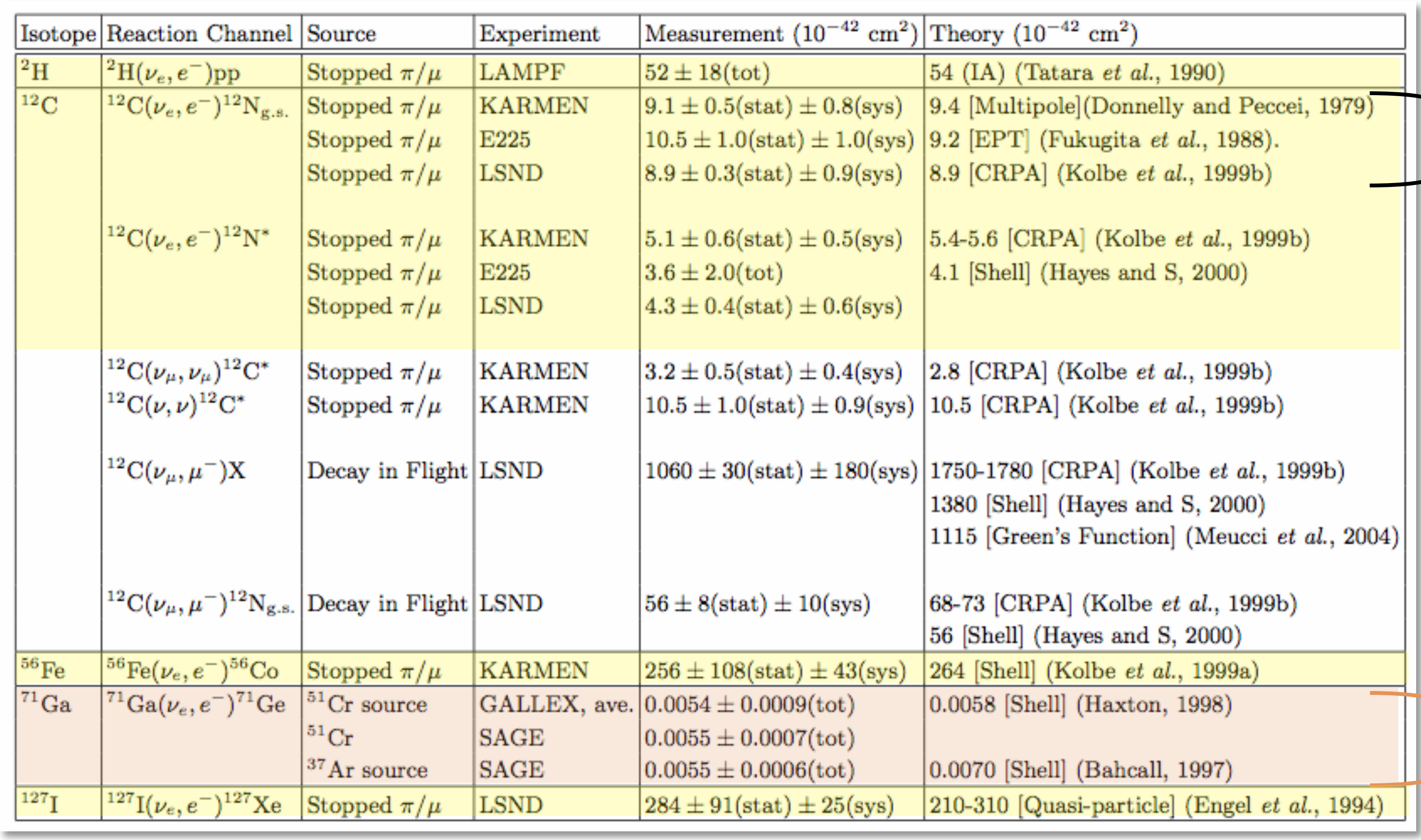
(Formaggio & Zeller, Rev. Mod. Phys. 2012)

(~20% measurements)

- again, all at very low E_ν

Other Nuclear Targets

- ν_e measurements from stopped π/μ (< 50 MeV) and radiological sources
- flux-averaged cross section measurements



Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
^{2}H	^{2}H(ν_e, e^-)pp	Stopped π/μ	LAMPF	52 ± 18(tot)	54 (IA) (Tatara *et al.*, 1990)
^{12}C	^{12}C(ν_e, e^-)^{12}N$_{g.s.}$	Stopped π/μ	KARMEN	9.1 ± 0.5(stat) ± 0.8(sys)	9.4 [Multipole](Donnelly and Peccei, 1979)
		Stopped π/μ	E225	10.5 ± 1.0(stat) ± 1.0(sys)	9.2 [EPT] (Fukugita *et al.*, 1988).
		Stopped π/μ	LSND	8.9 ± 0.3(stat) ± 0.9(sys)	8.9 [CRPA] (Kolbe *et al.*, 1999b)
	^{12}C(ν_e, e^-)^{12}N*	Stopped π/μ	KARMEN	5.1 ± 0.6(stat) ± 0.5(sys)	5.4-5.6 [CRPA] (Kolbe *et al.*, 1999b)
		Stopped π/μ	E225	3.6 ± 2.0(tot)	4.1 [Shell] (Hayes and S, 2000)
		Stopped π/μ	LSND	4.3 ± 0.4(stat) ± 0.6(sys)	
	^{12}C(ν_μ, ν_μ)^{12}C*	Stopped π/μ	KARMEN	3.2 ± 0.5(stat) ± 0.4(sys)	2.8 [CRPA] (Kolbe *et al.*, 1999b)
	^{12}C(ν, ν)^{12}C*	Stopped π/μ	KARMEN	10.5 ± 1.0(stat) ± 0.9(sys)	10.5 [CRPA] (Kolbe *et al.*, 1999b)
	^{12}C(ν_μ, μ^-)X	Decay in Flight	LSND	1060 ± 30(stat) ± 180(sys)	1750-1780 [CRPA] (Kolbe *et al.*, 1999b)
					1380 [Shell] (Hayes and S, 2000)
					1115 [Green's Function] (Meucci *et al.*, 2004)
	^{12}C(ν_μ, μ^-)^{12}N$_{g.s.}$	Decay in Flight	LSND	56 ± 8(stat) ± 10(sys)	68-73 [CRPA] (Kolbe *et al.*, 1999b)
					56 [Shell] (Hayes and S, 2000)
^{56}Fe	^{56}Fe(ν_e, e^-)^{56}Co	Stopped π/μ	KARMEN	256 ± 108(stat) ± 43(sys)	264 [Shell] (Kolbe *et al.*, 1999a)
^{71}Ga	^{71}Ga(ν_e, e^-)^{71}Ge	^{51}Cr source	GALLEX, ave.	0.0054 ± 0.0009(tot)	0.0058 [Shell] (Haxton, 1998)
		^{51}Cr	SAGE	0.0055 ± 0.0007(tot)	
		^{37}Ar source	SAGE	0.0055 ± 0.0006(tot)	0.0070 [Shell] (Bahcall, 1997)
^{127}I	^{127}I(ν_e, e^-)^{127}Xe	Stopped π/μ	LSND	284 ± 91(stat) ± 25(sys)	210-310 [Quasi-particle] (Engel *et al.*, 1994)

next page

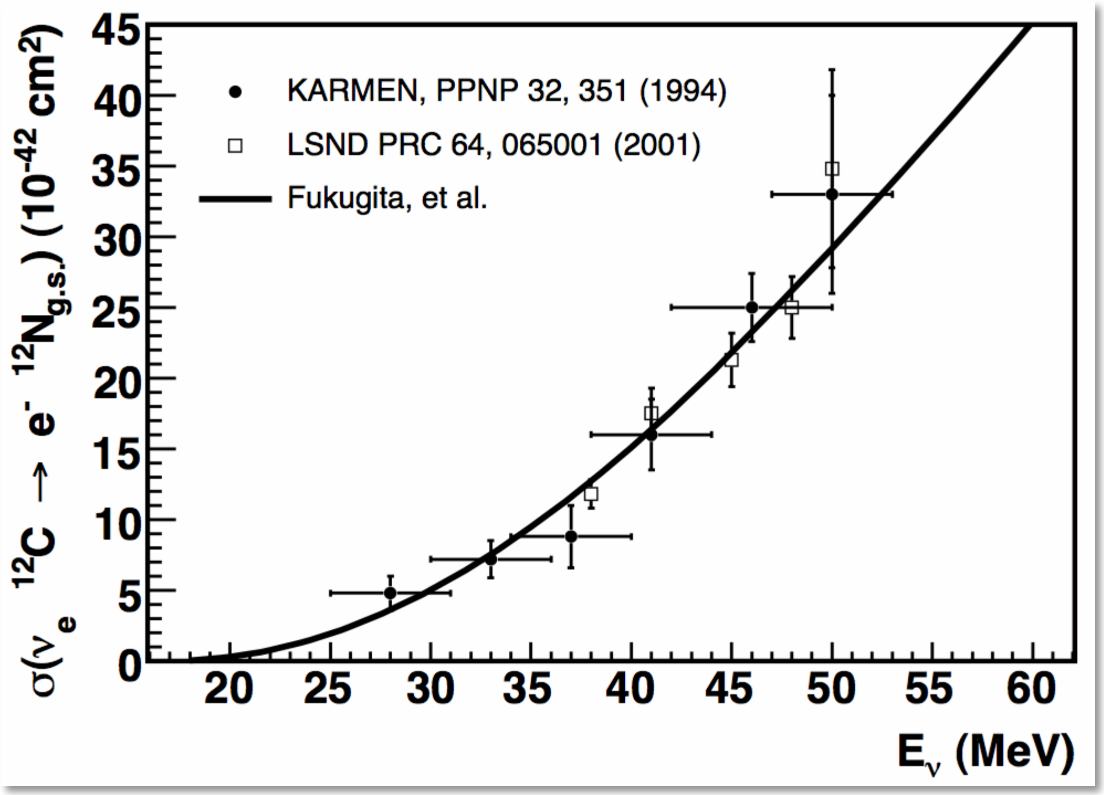
~700 keV

Formaggio & Zeller, Rev. Mod. Phys. 2012)

Carbon

- only existing check of E_ν-dependence of ν_e cross section: KARMEN and LSND measured ground state transition from μ DAR neutrinos

$\nu_e\,^{12}C \rightarrow e^-\,^{12}N_{g.s.}$



(Formaggio & Zeller, Rev. Mod. Phys. 2012)

Carbon

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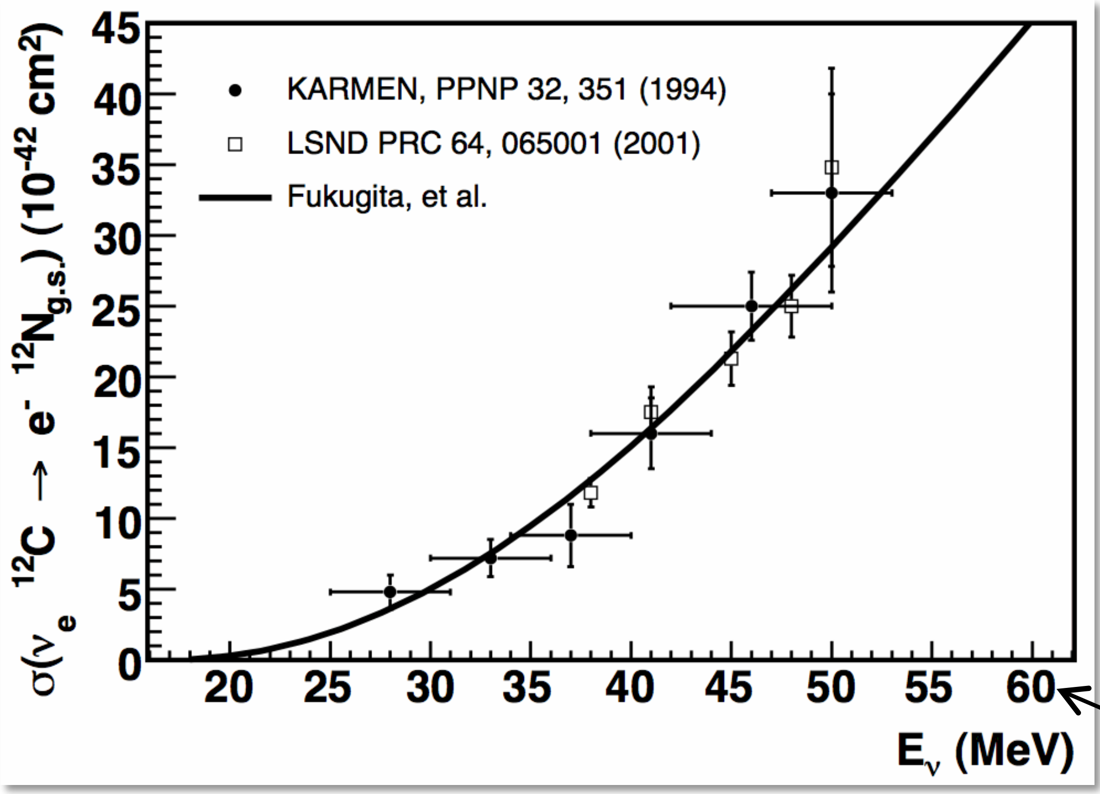


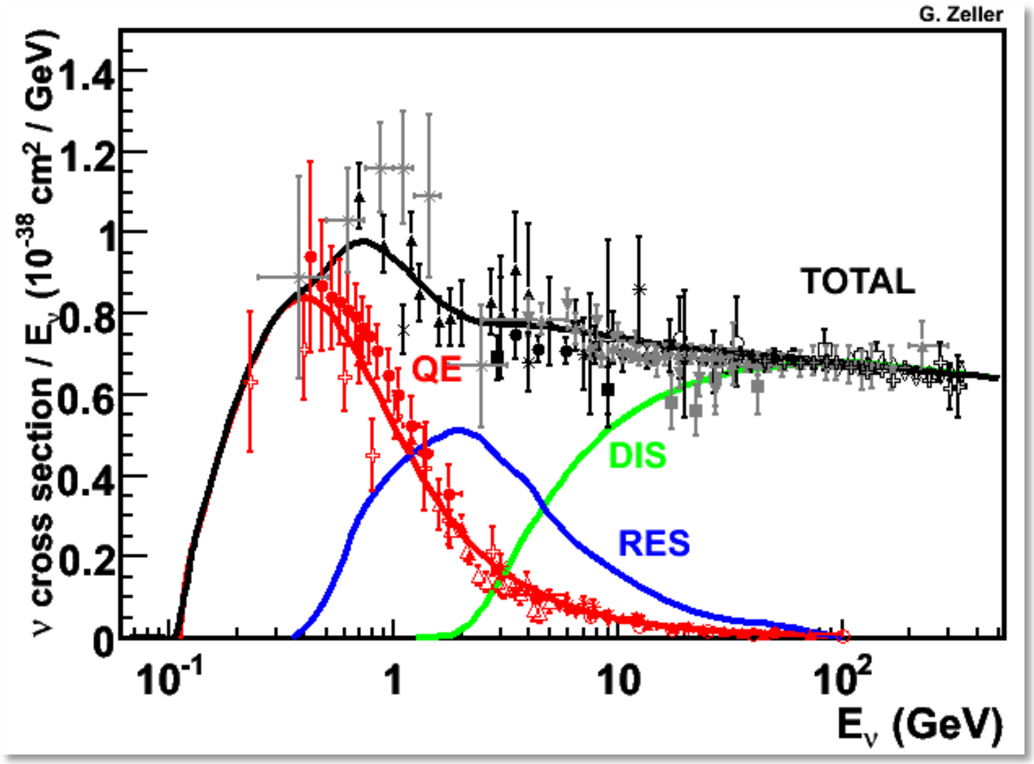
(Formaggio & Zeller, Rev. Mod. Phys. 2012)

$$\nu_e\,^{12}C \rightarrow e^-\ ^{12}N_{g.s.}$$

- there are not many ν_e σ measurements
- ones that exist are all below ~50 MeV
- the bulk of measurements are flux-averaged
- would really like to have this type of spectral info

Moving Forward

Wish list



↔ **LBNE**

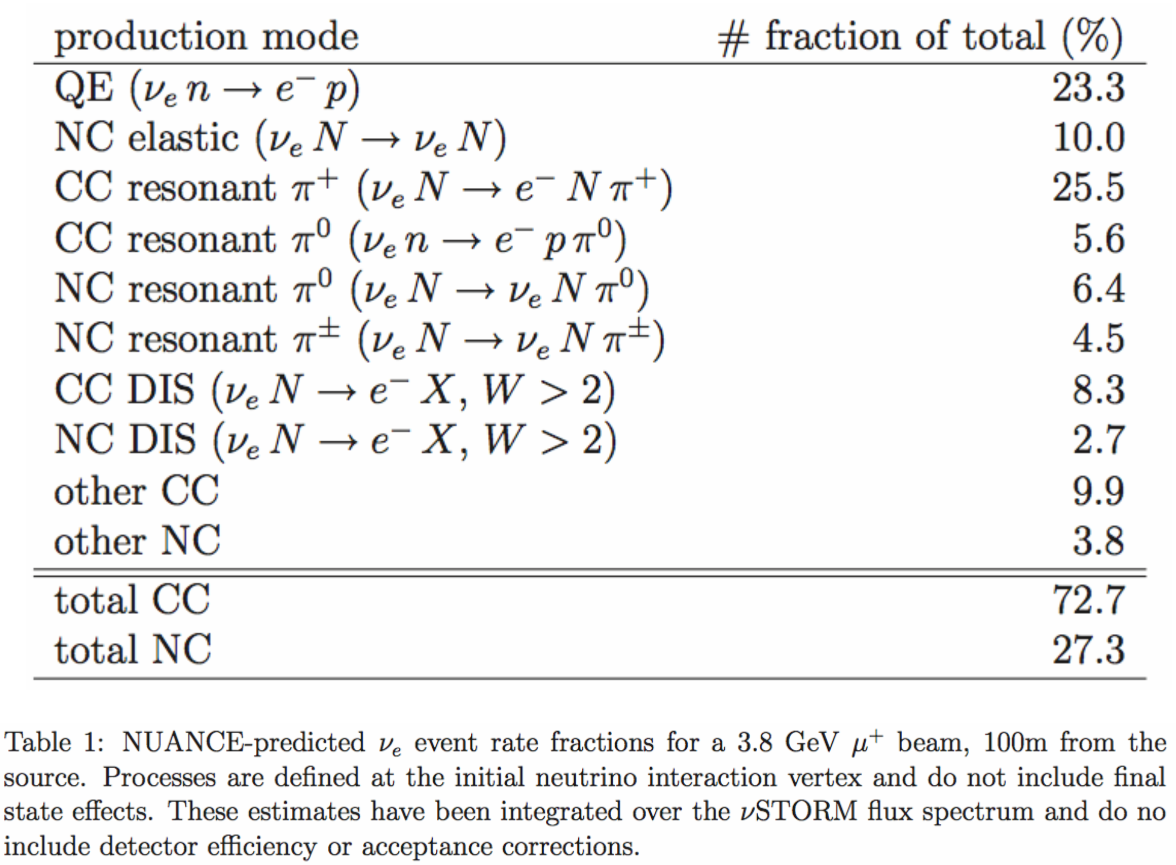
one would really like:

(1) a check of ν_e σ at higher energies ~ 1 GeV

(2) precise knowledge of E_ν dependence of ν_e σ; in particular, need to model multiple contributions to accurately predict energy spectrum of a ν_e oscillation sample for LBL physics

ν_e Event Fractions in νSTORM

- sources of ν_e events produced by νSTORM 3.8 GeV μ^+ beam



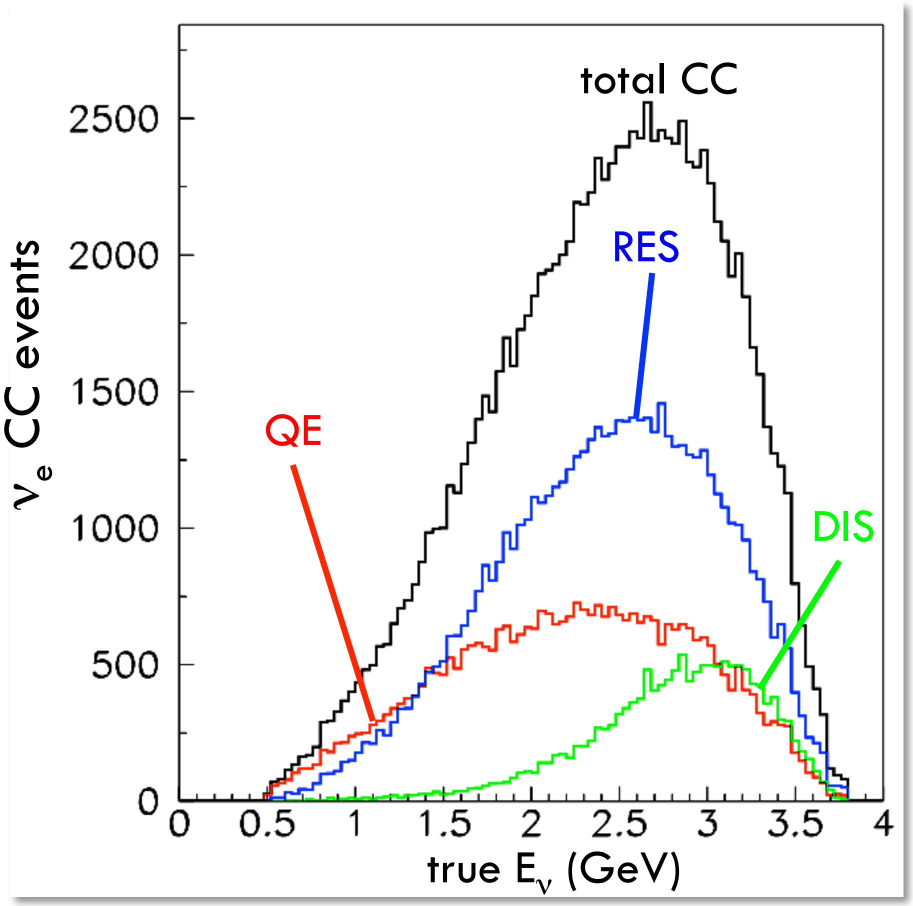
production mode	# fraction of total (%)
QE ($\nu_e\, n \rightarrow e^-\, p$)	23.3
NC elastic ($\nu_e\, N \rightarrow \nu_e\, N$)	10.0
CC resonant π^+ ($\nu_e\, N \rightarrow e^-\, N\, \pi^+$)	25.5
CC resonant π^0 ($\nu_e\, n \rightarrow e^-\, p\, \pi^0$)	5.6
NC resonant π^0 ($\nu_e\, N \rightarrow \nu_e\, N\, \pi^0$)	6.4
NC resonant $\pi^\pm$ ($\nu_e\, N \rightarrow \nu_e\, N\, \pi^\pm$)	4.5
CC DIS ($\nu_e\, N \rightarrow e^-\, X$, $W > 2$)	8.3
NC DIS ($\nu_e\, N \rightarrow e^-\, X$, $W > 2$)	2.7
other CC	9.9
other NC	3.8
total CC	72.7
total NC	27.3

Table 1: NUANCE-predicted ν_e event rate fractions for a 3.8 GeV μ^+ beam, 100m from the source. Processes are defined at the initial neutrino interaction vertex and do not include final state effects. These estimates have been integrated over the νSTORM flux spectrum and do no include detector efficiency or acceptance corrections.

similar to reactions of interest in LBNE oscillation region

ν_e Event Fractions in νSTORM

- sources of ν_e events produced by νSTORM 3.8 GeV μ^+ beam



out of the CC modes:

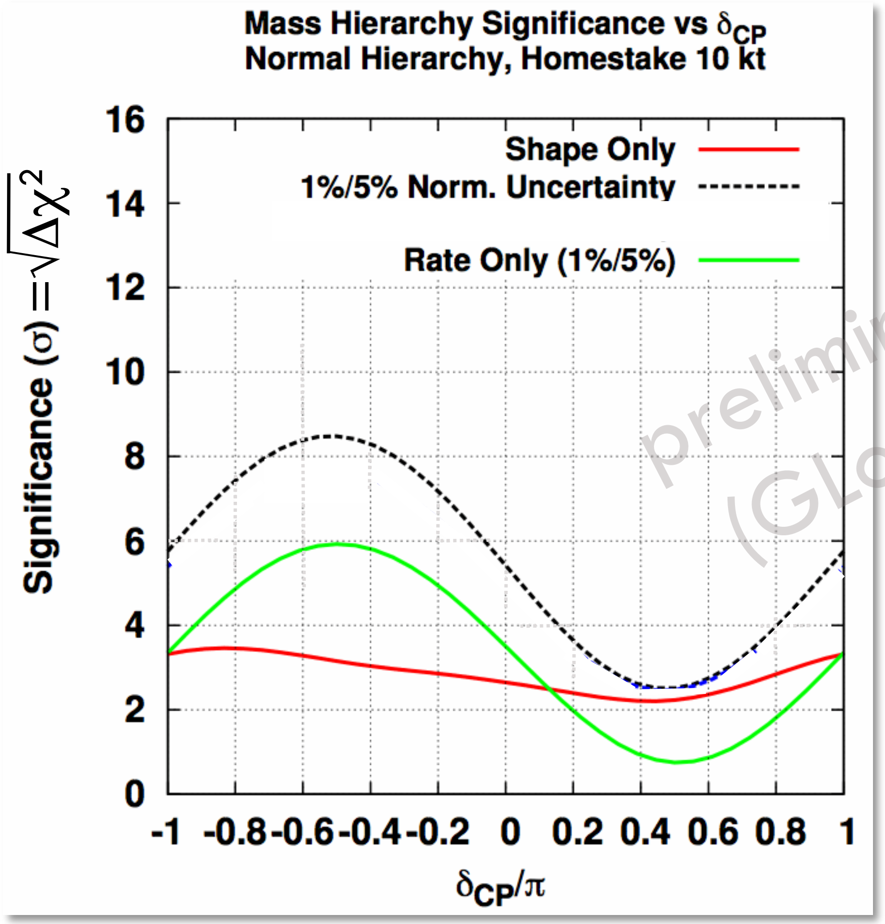
* 56% resonant
* 32% QE
* 12% DIS

- each of these processes have different models, different final states, different E_ν-dep

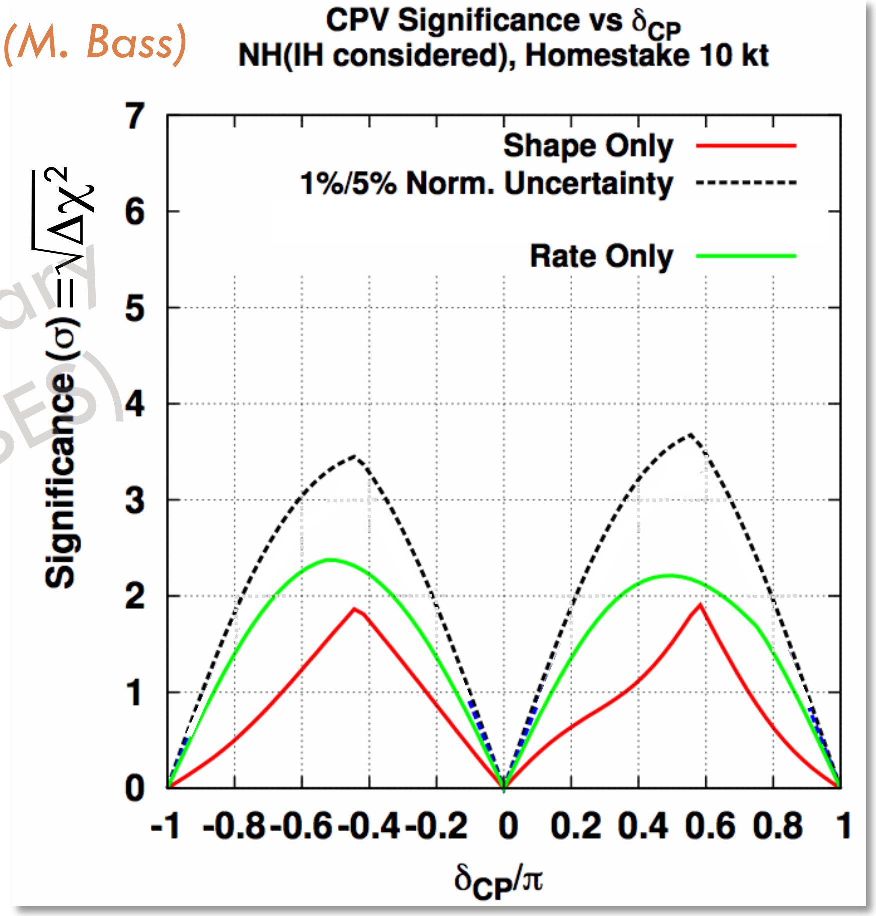
- how important is this?

($\overline{\nu}_\mu$ sample: 52% resonant, 40% QE, 8% DIS)

How Much Do We Rely on Spectral Info?

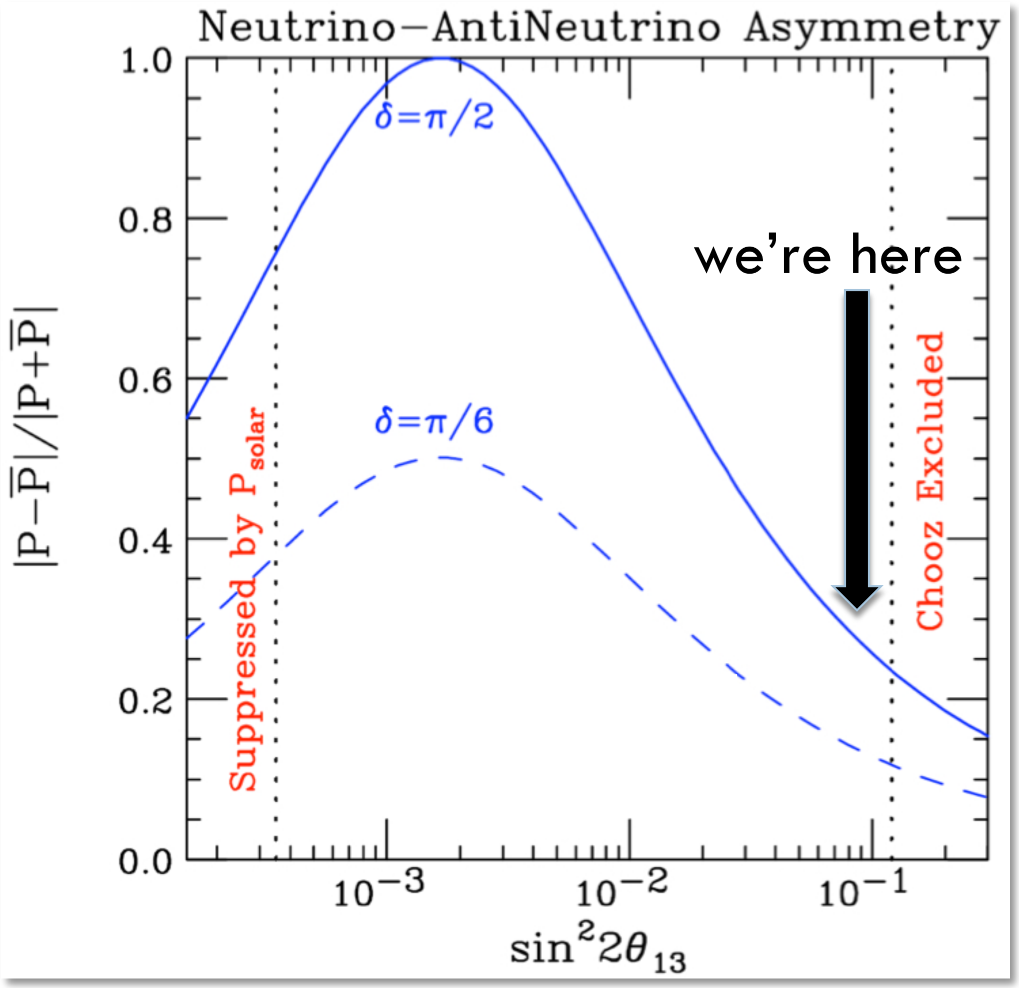


(M. Bass)



- these are not just counting experiments anymore, will increasingly rely on how well we know event spectra $\Longrightarrow \sigma(E_\nu)$ from 0.5-6 GeV

Also Need to Know $\bar{\nu}_e$



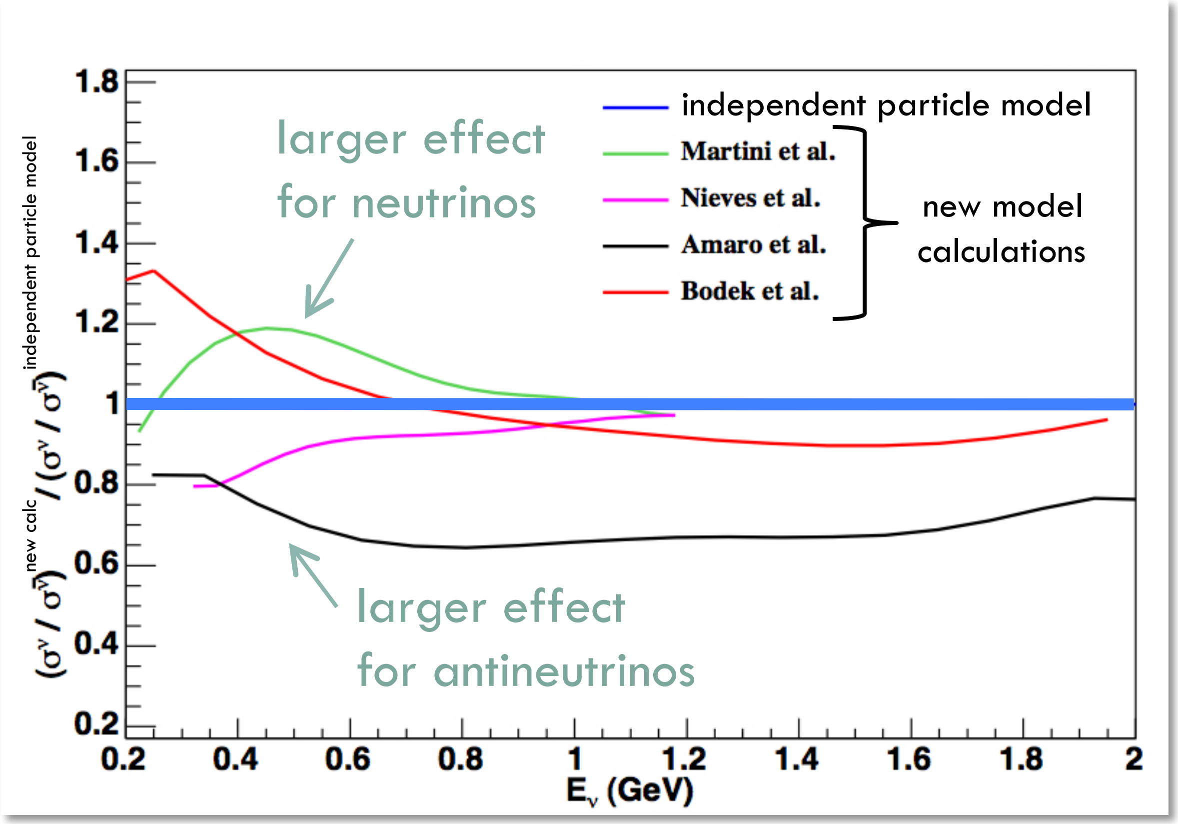
(not including matter effects & backgrounds)

(S. Parke)

- large θ_{13} means we can expect large signals
- but it also means that the asymmetry we're trying to detect is very small
  (asymmetry ~ $1/\sin\theta_{13}$)
- large θ_{13} isn't making our life any easier
- $\sin^2 2\theta_{13}$~0.1 means we will be trying to detect a ν_e-$\bar{\nu}_e$ difference on the order of ~20% or less (depending on δ)

Antineutrino/Neutrino QE Ratio

- current models give different predictions for $\bar{\nu}_\mu/\nu_\mu$ QE scattering
  (for ex., for LBNE we assume we will know this ratio to ~1%)



- the situation is unclear and will need to get resolved …

- certainly, better data on ν_e and $\bar{\nu}_e$ will be important for future $\cancel{C}P$ measurements

(J. Grange)

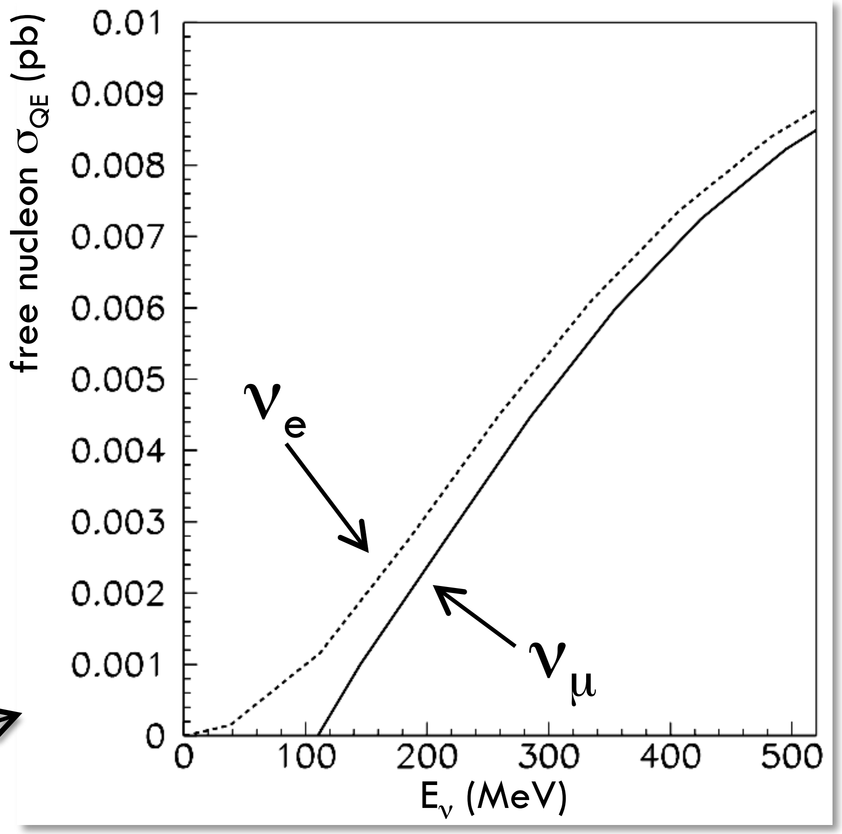
ν_e/ν_μ Cross Sections

- $\sigma(E_\nu)$, σ's for various contributing reactions, and $\overline{\nu}/\nu$ can all of course be constrained with ν_μ measurements (e.g., MB, MINERνA, μB, etc.)

- weak interaction is flavor universal to infer ν_e from ν_μ

- given dearth of ν_e measurements, how robust is our knowledge of ν_e/ν_μ ratio? this is something we rely on simulations for …

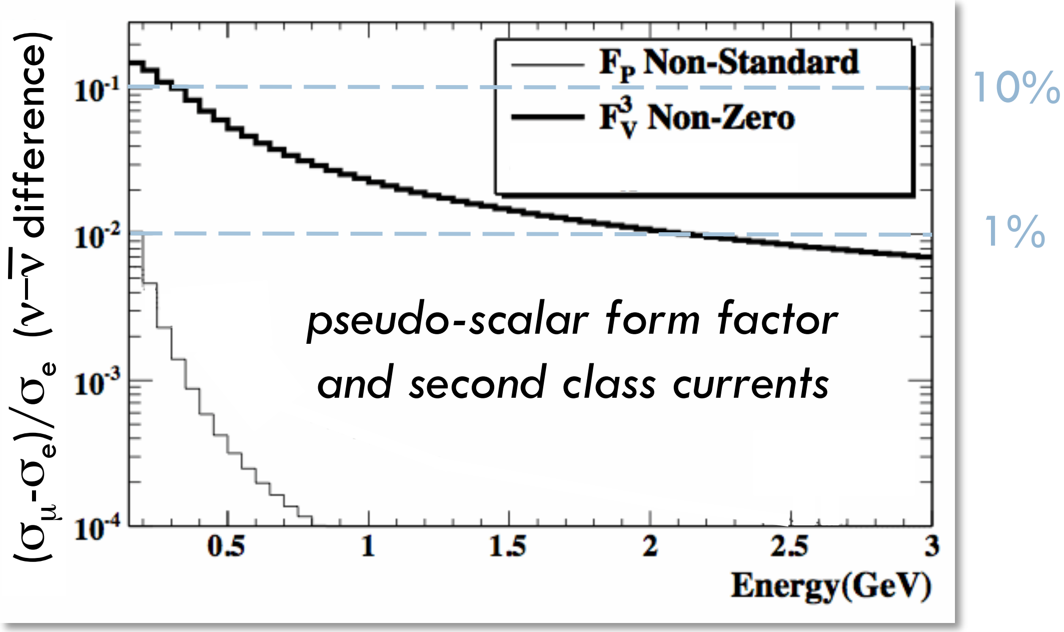
- <u>step 1</u>: take into account effect of kinematic limits (m_{lepton})



ν_e/ν_μ Cross Sections

- there are effects not included in event generators that can impact ν_e and ν_μ scattering off nucleons differently *(before any nuclear effects are added)*

(M. Day, K. McFarland, arXiv:1206.6745)



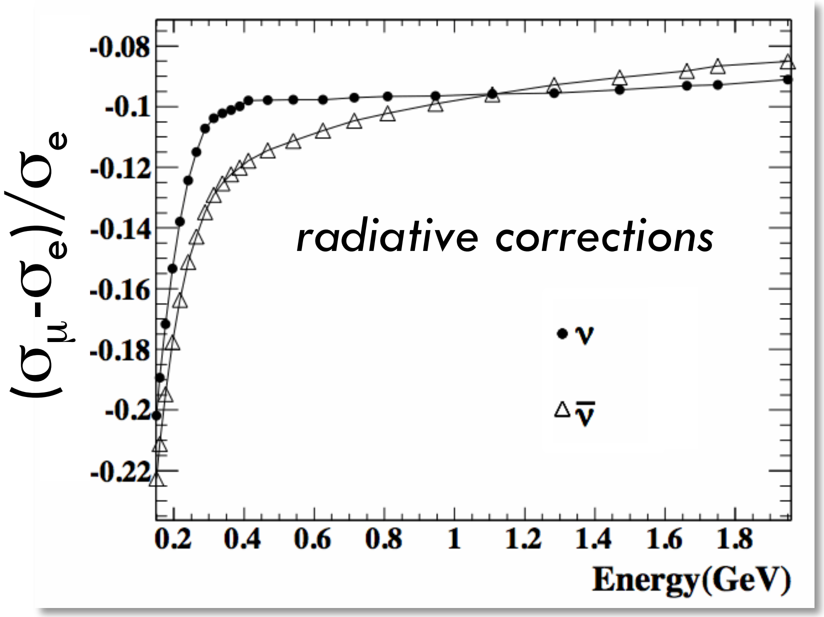
pseudo-scalar form factor and second class currents

effect of the FFs on ν_e/ν_μ can be different for neutrinos & antineutrinos

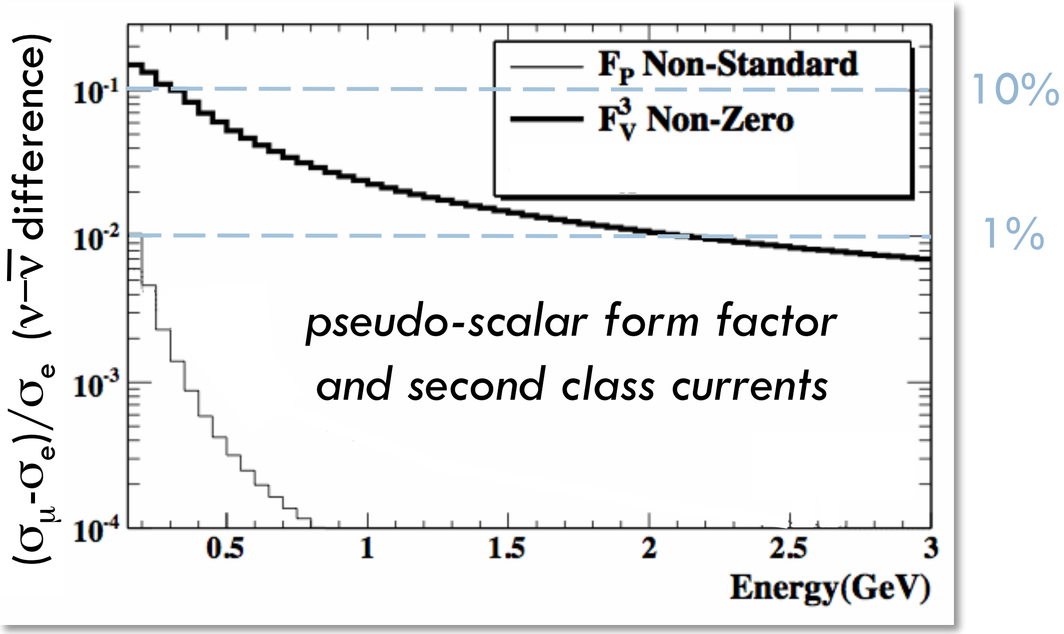
ν_e/ν_μ Cross Sections

- there are effects <u>not</u> included in event generators that can impact ν_e and ν_μ scattering off nucleons differently *(before any nuclear effects are added)*

(M. Day, K. McFarland, arXiv:1206.6745)



radiative corrections

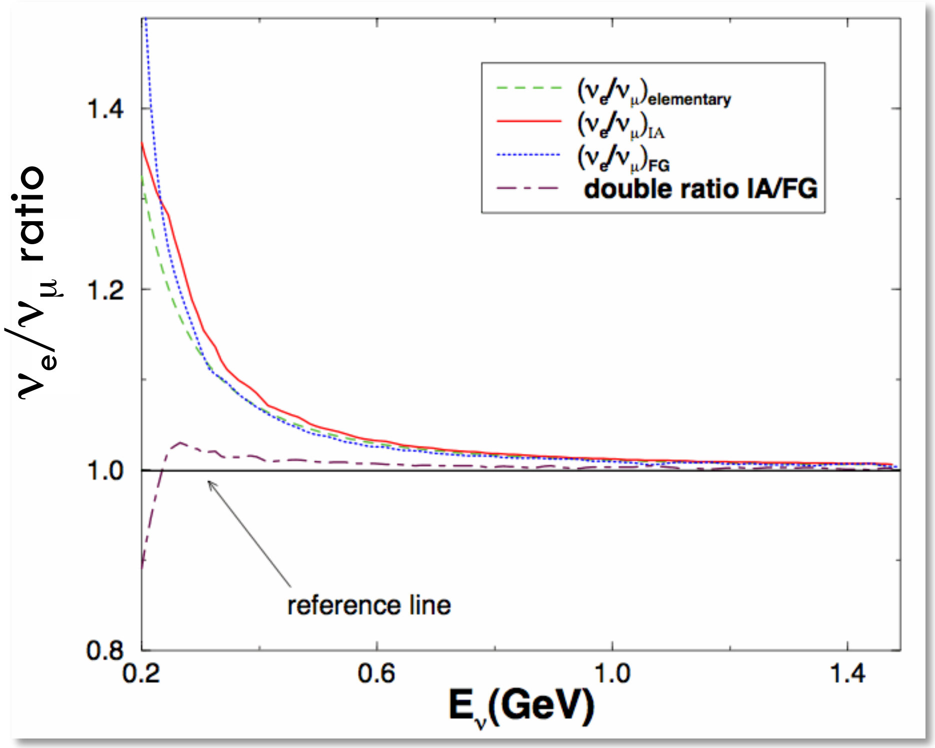


pseudo-scalar form factor and second class currents

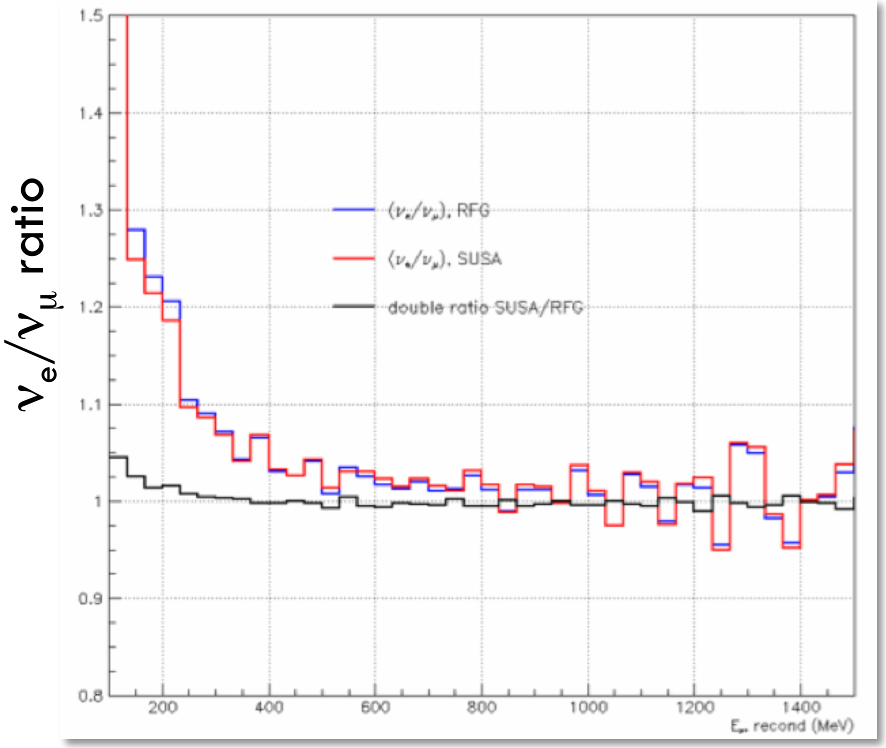
- would be nice to have a high stats sample of ν_e to actually test this *(i.e., that our procedure for extrapolating from ν_μ to ν_e is robust)*

Nuclear Effects

(spectral function/Fermi Gas)



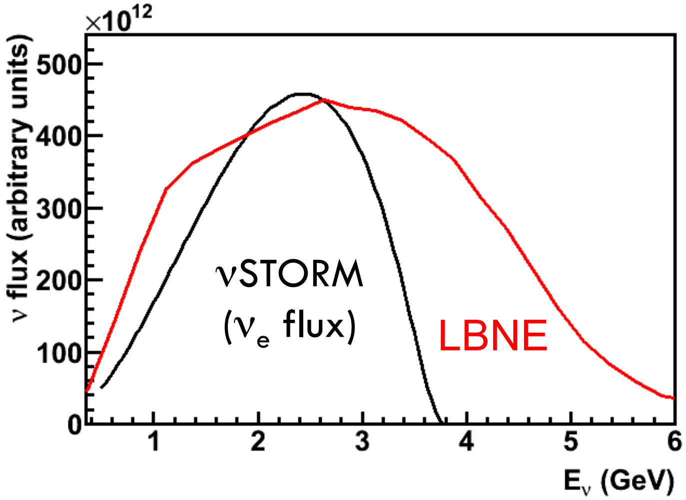
(superscaling/Fermi Gas)



- for standard calcs, up to 5% differences on ν_e/ν_μ ratio < 200 MeV
- more recent worry: could nuclear effects that we are not presently modeling (e.g., multi-nucleon states) be dramatically different for ν_e vs. ν_μ?

Conclusions

- **a possible σ_ν program with νSTORM presents a unique opportunity**
  - *can uniquely measure ν_e and ν_μ (and $\overline{\nu}$) rates in a single experiment*
    only way to get large samples of ν_e interactions → important calibration source!
  - *provides a known beam flux and flavor composition*
    very powerful cross-check of existing σ_ν knowledge



- **covers a similar energy range as LBNE**
  - would be the 1st ν_e σ measurements in this region
  - *existing ν_e, $\overline{\nu}_e$ σ measurements are limited,*
    all at DAR and reactor energies (< 50 MeV)

- would be prudent to have a cross-check on our assumptions about ν_e, $\overline{\nu}_e$ cross sections as we embark on rather ambitious programs to measure MH and $\cancel{CP}$ with long-baseline neutrinos