The state of neutrino Cross-sections

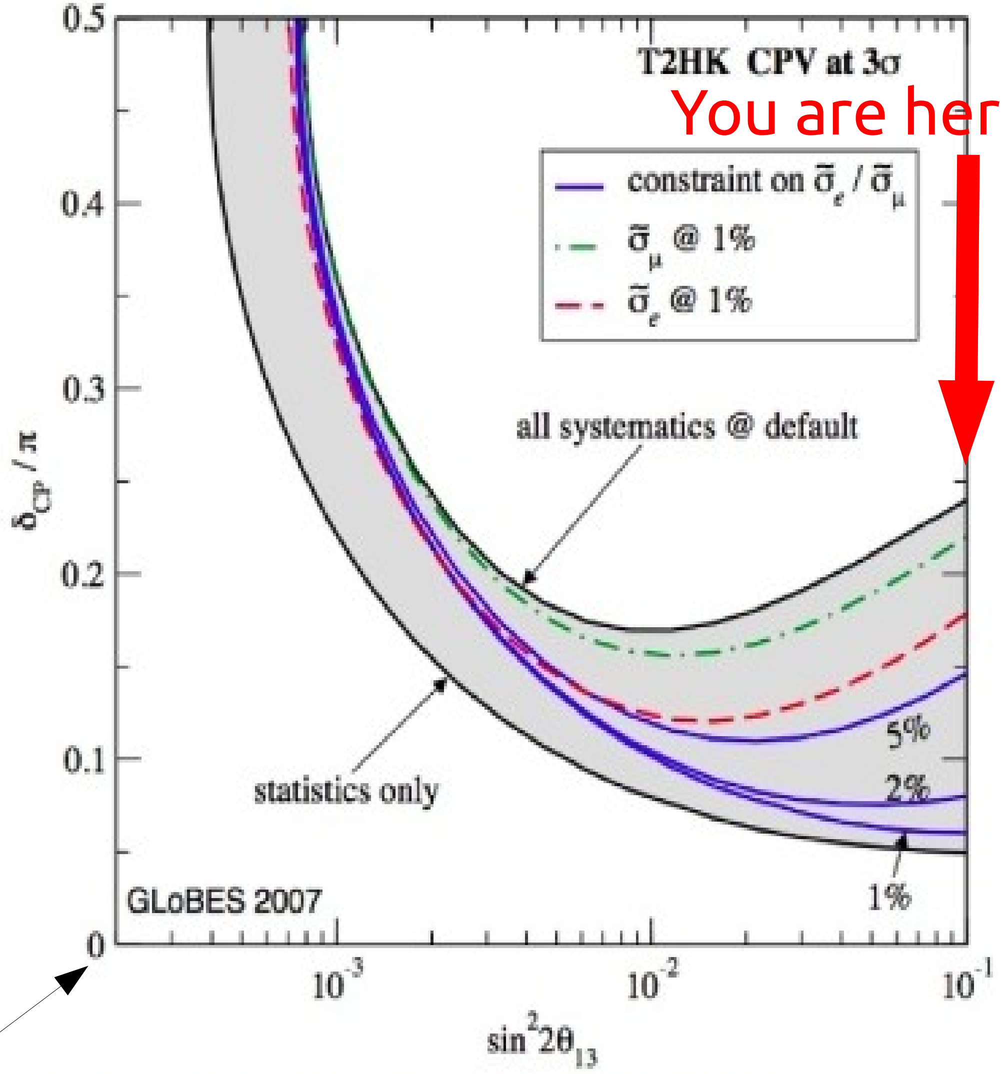
- Why do we want to do cross-section measurements?
- What is the current state of cross-section measurements?
- What we'd like to do

THE UNIVERSITY OF WARWICK

S. Boyd, CERN νStorm Discussion, 15/11/12

Why should we care about x-sections?

- Recent large θ_{13} result opens up possibility of
  - Mass heirarchy measurement
  - CP violation measurement
- Experiments will be looking for $\nu_\mu \leftrightarrow \nu_e$ and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations.
- Need to understand $\bar{\nu}_\mu, \bar{\nu}_e$ cross sections as asymmetry is small for large θ_{13}
- Some geometries require%-level precision on low energy σ



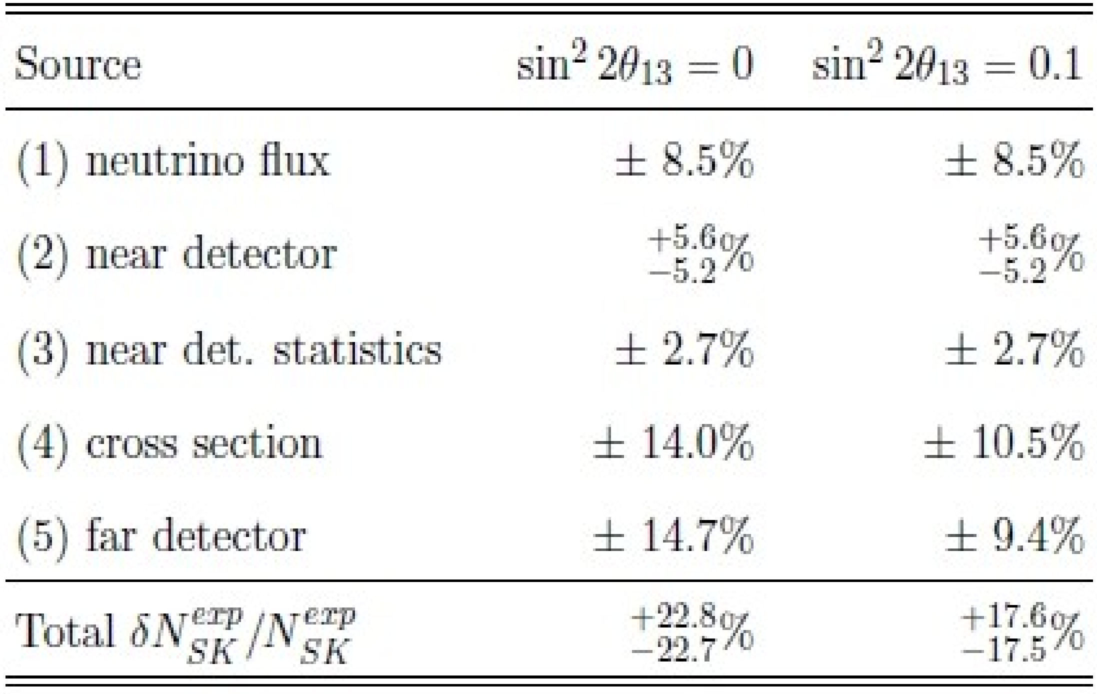
You are here!

For T2HK-like experiment

Huber, Mezzetto, Schwetz, 0711.2950 [hep-ph]

Example: T2K Systematic Errors

Systematic errors for T2K θ_{13} measurement



Source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) neutrino flux	$\pm$ 8.5%	$\pm$ 8.5%
(2) near detector	$^{+5.6}_{-5.2}\%$	$^{+5.6}_{-5.2}\%$
(3) near det. statistics	$\pm$ 2.7%	$\pm$ 2.7%
(4) cross section	$\pm$ 14.0%	$\pm$ 10.5%
(5) far detector	$\pm$ 14.7%	$\pm$ 9.4%
Total $\delta N_{SK}^{exp}/N_{SK}^{exp}$	$^{+22.8}_{-22.7}\%$	$^{+17.6}_{-17.5}\%$

Error on Far/Near Flux ratio
Absolute errors ~ 15%

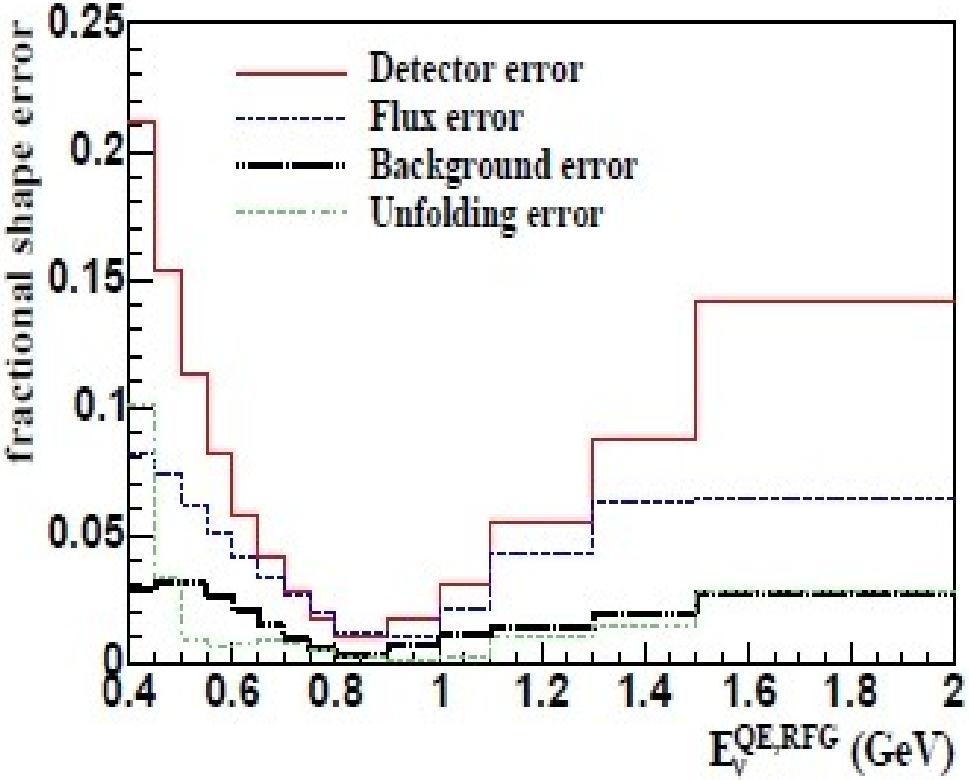
$\sigma(\nu_e)/\sigma(\nu_\mu) \approx 6\%$

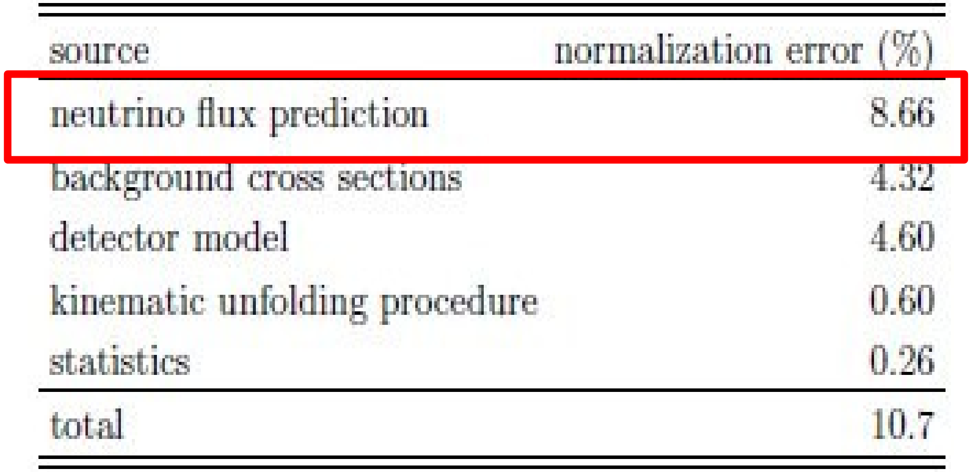
FSI+
Initial State ~ 6%

NB – These are errors based on an analysis of ratios so absolute cross section errors partially cancel

Phys. Rev. Lett 107, 041801

Example : MiniBooNE CCQE





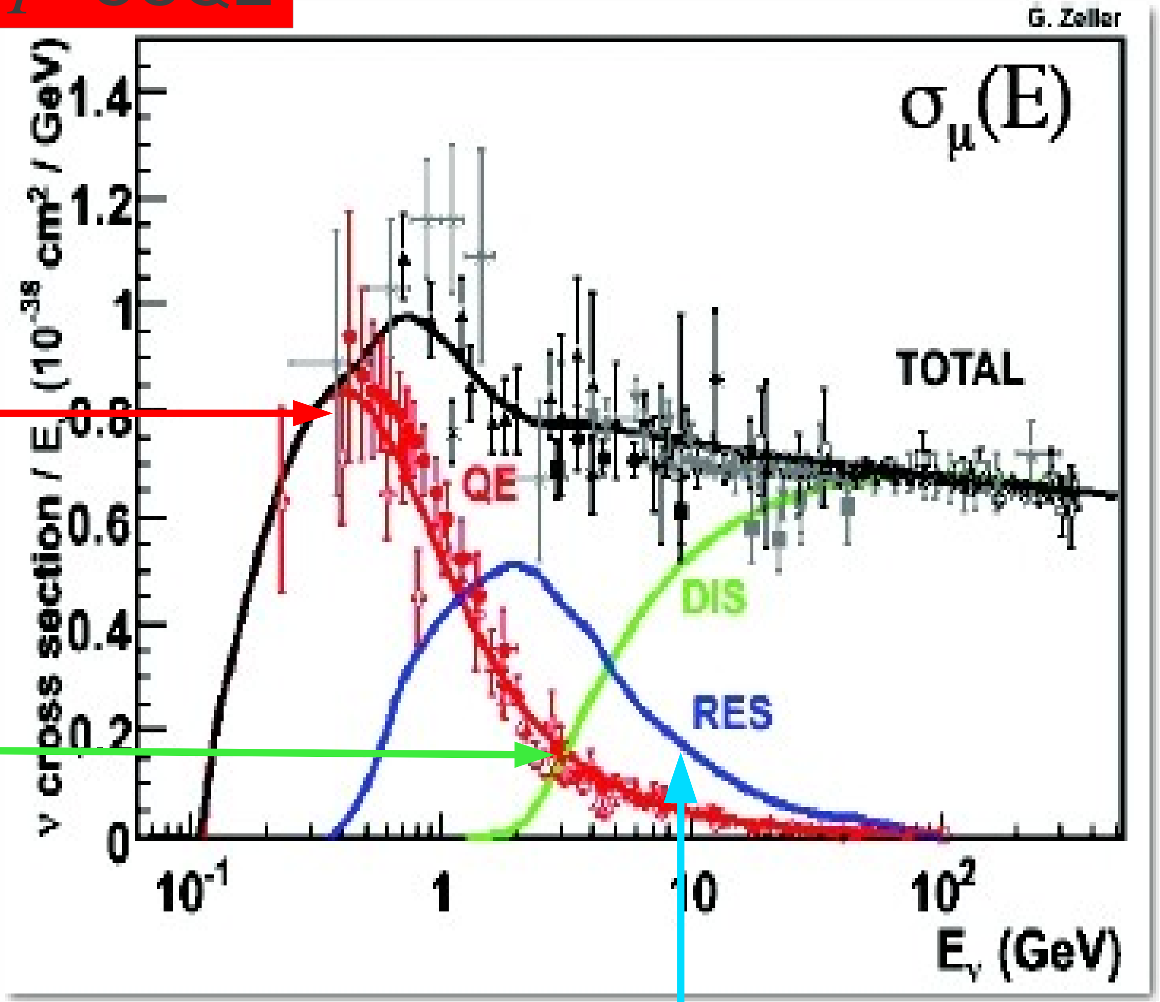
source	normalization error (%)
neutrino flux prediction	8.66
background cross sections	4.32
detector model	4.60
kinematic unfolding procedure	0.60
statistics	0.26
total	10.7

- Fractional shape error for MiniBooNE CCQE analysis
- Total normalisation uncertainty

A. A. Aguilar-Arevalo et al. [MiniBooNE Collaboration],, Phys. Rev. D81, 092005 (2010)

Cross-sections – the state of play

$\nu_\mu + n \rightarrow \mu^- + p$ CCQE



ν_μ

“Transition Region”

$\nu_\mu + N \rightarrow \mu^- + N' + \pi$ Single pion

Which cross sections do we care about?

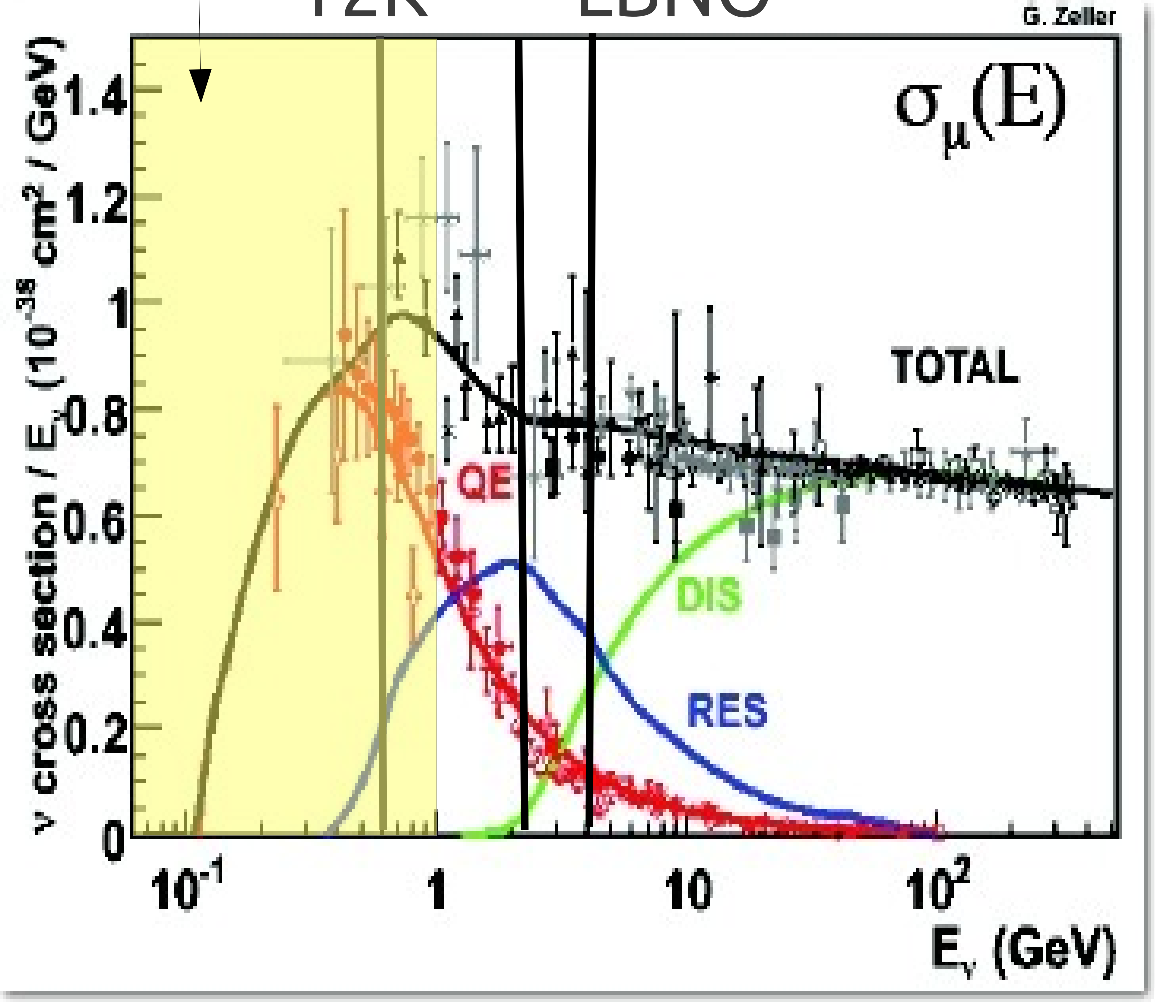
- All of them – region of interest is around 0.1 – 10 GeV
- Measurements looking at 2nd oscillation maximum will want to go down in energy as well

>2nd oscillation maxima

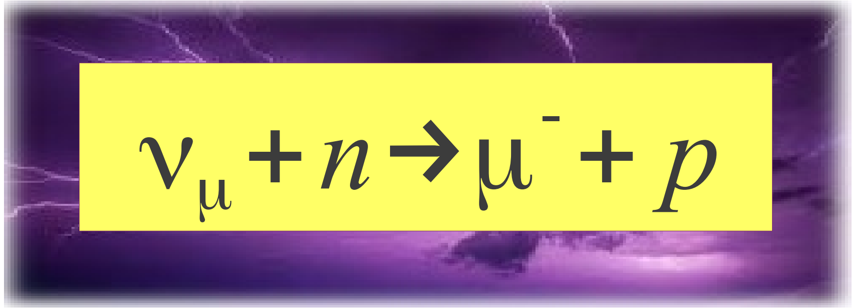
LBNE

T2K

LBNO



Case Study : QE scattering



$$\nu_\mu + n \rightarrow \mu^- + p$$

As excellent example of why we shouldn't assume ν cross sections are well in hand

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

with the functions A, B and C parametrised in terms of the vector and axial-vector form factors

$$F_{A,V}(Q^2) = \frac{g_{A,V}}{\left(1+\frac{Q^2}{M_{A,V}^2}\right)^2}$$

Couplings set by behaviour of currents at $Q^2=0$ (CVC and PCAC)

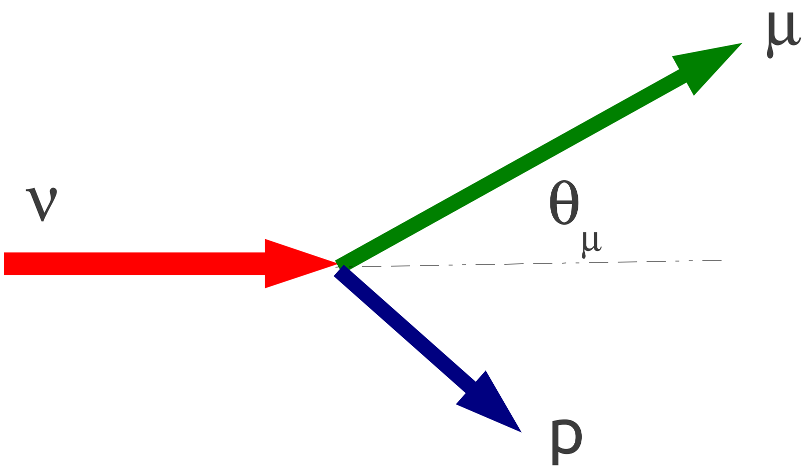
Vector and Axial vector masses must be measured

NB This is an ansatz....

M_V measured in electron scattering

M_A measured in neutrino scattering

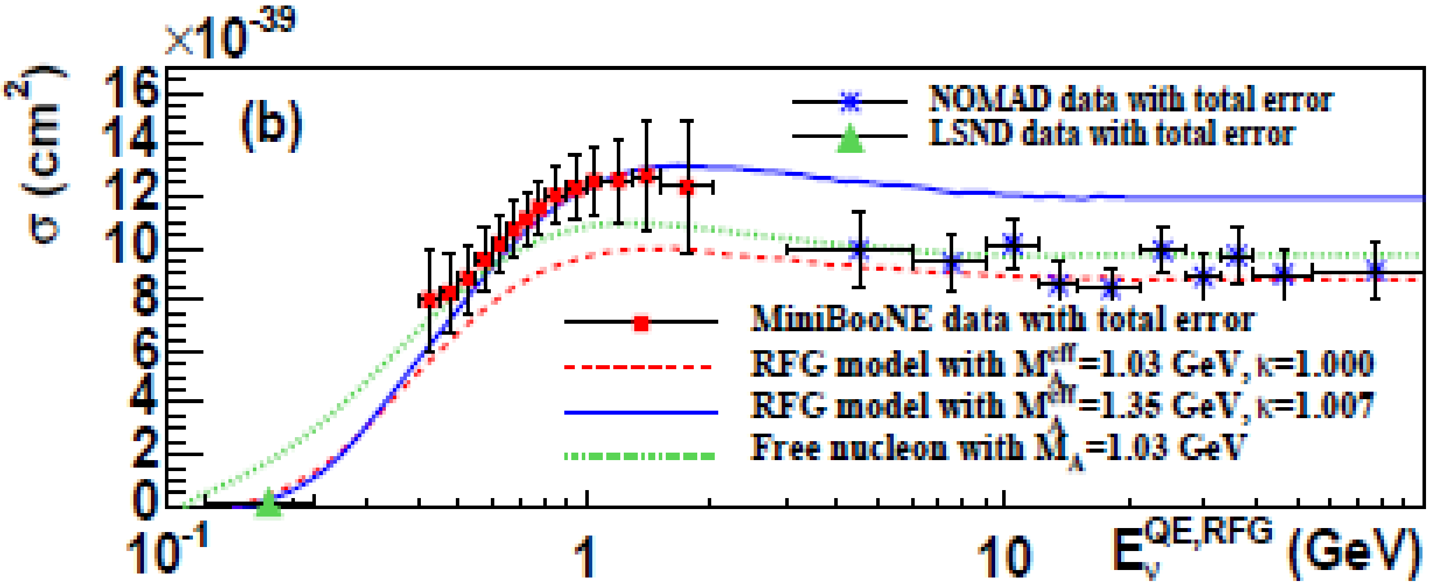
Why is this channel important?



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

- neutrino energy reconstructed using final state lepton or calorimetry and fits for oscillation parameters.
- CCQE is quasi-2-body. E_ν can be estimated just from lepton kinematics.
- Sometimes considered to be a “Standard Candle” and used to normalise other processes.

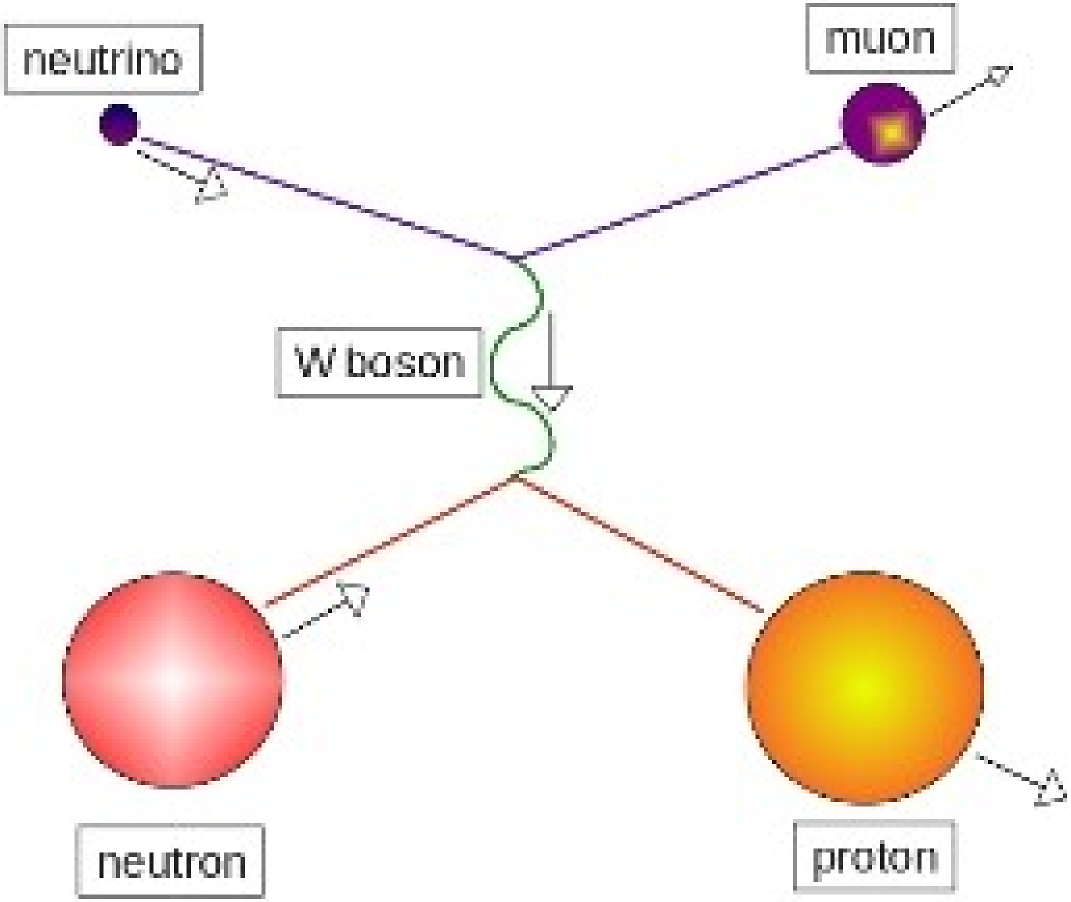
CCQE Definition



Theoretical definition : one muon and one proton in FS
Experimental definition : one muon and no pions (miniBooNE)
one muon, one proton, no pion (NOMAD)
one muon, no pions and no vertex activity
…
other signals based on topology visible in detector

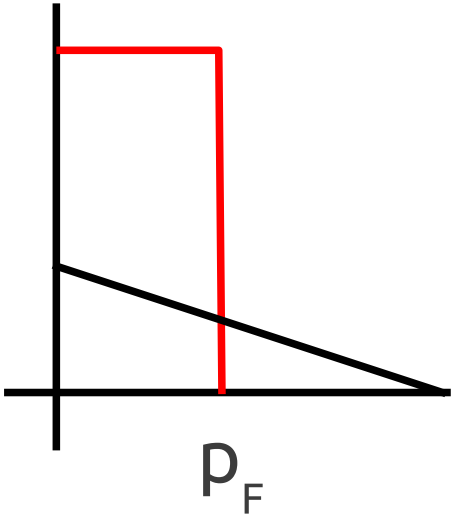
Experiments measure QE-like, *not* QE

CCQE – What we like to think it is



CCQE – What we like to think it is*

Initial State:
Relativistic
Fermi Gas



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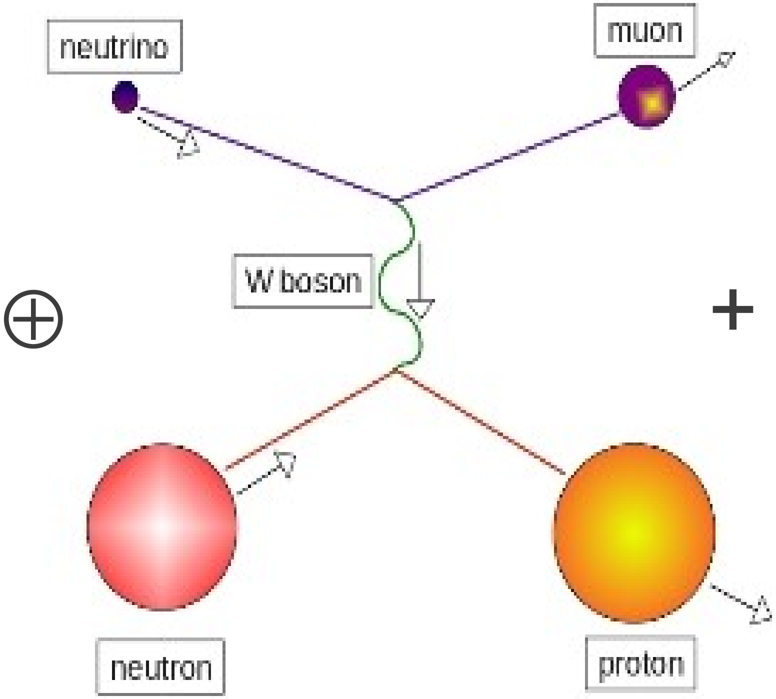

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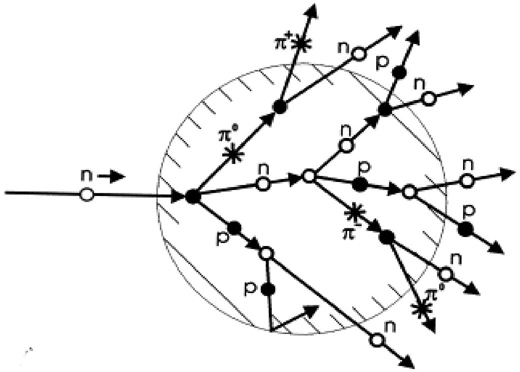
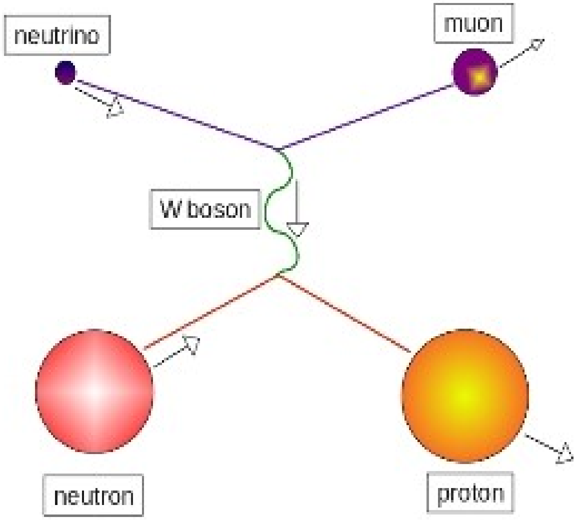
Final State:
Cascade Model



* if feeling a bit clever

CCQE – What is seems to involve now



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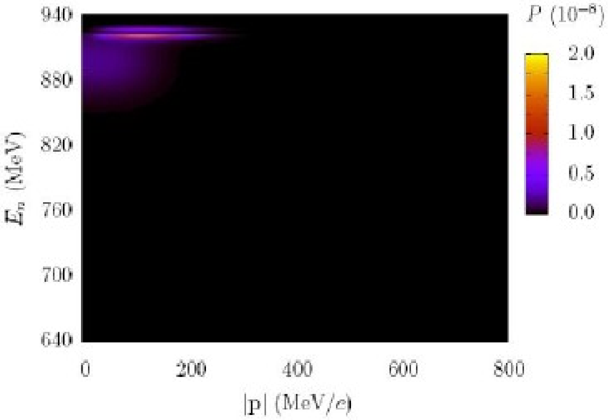
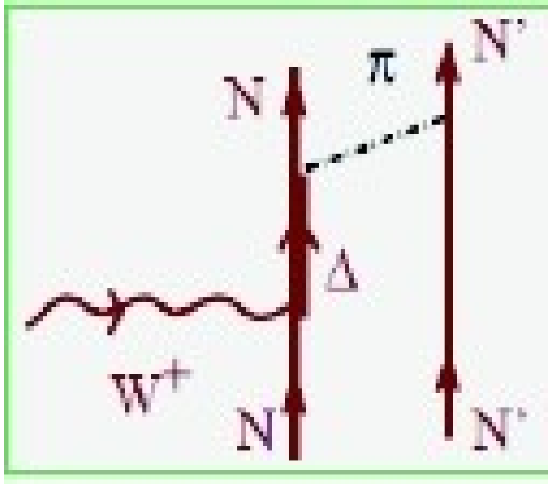


Spectral Functions

⊕

2p-2h effects



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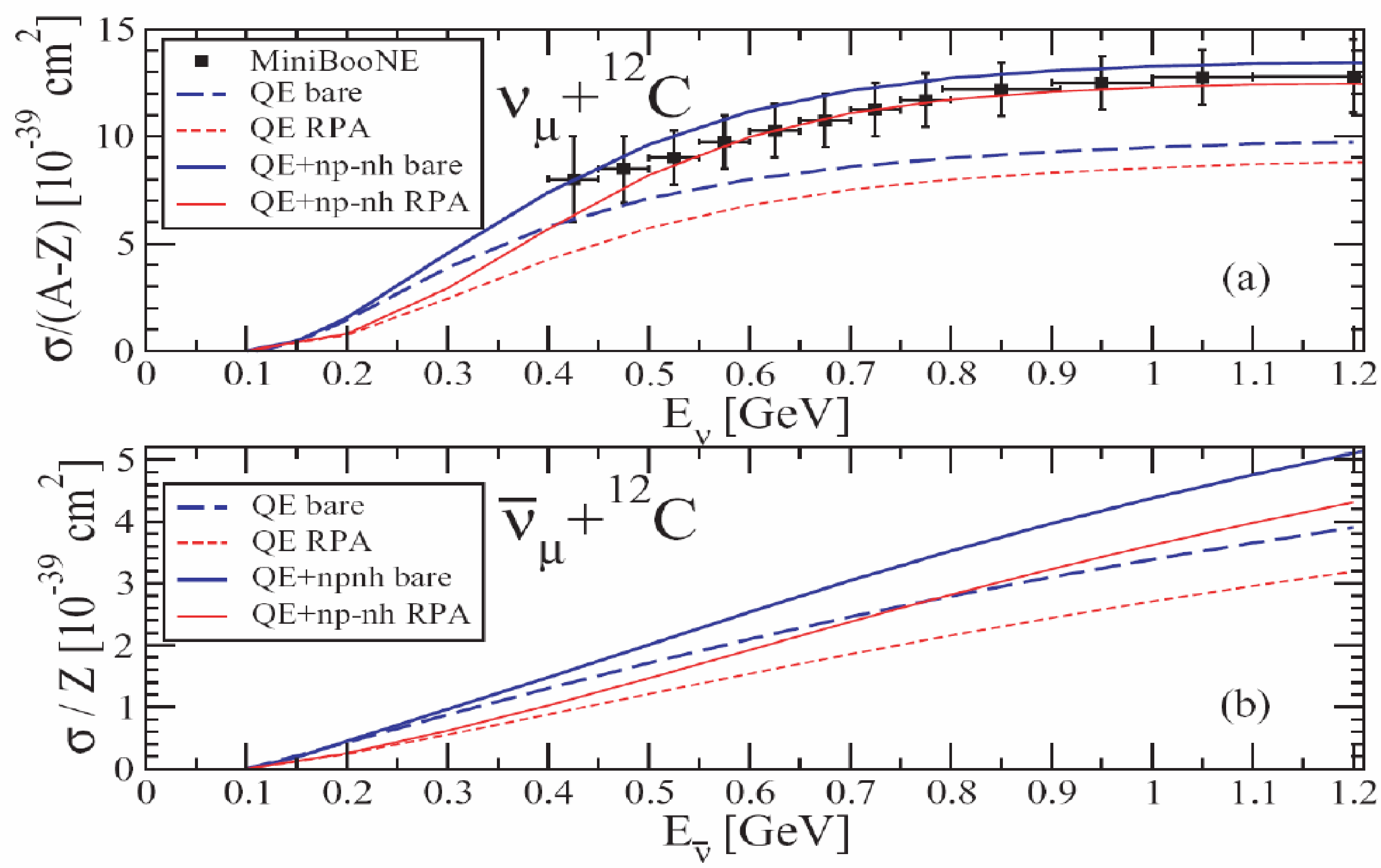
Cascade Models
In-medium effects

How big are these nuclear effects?



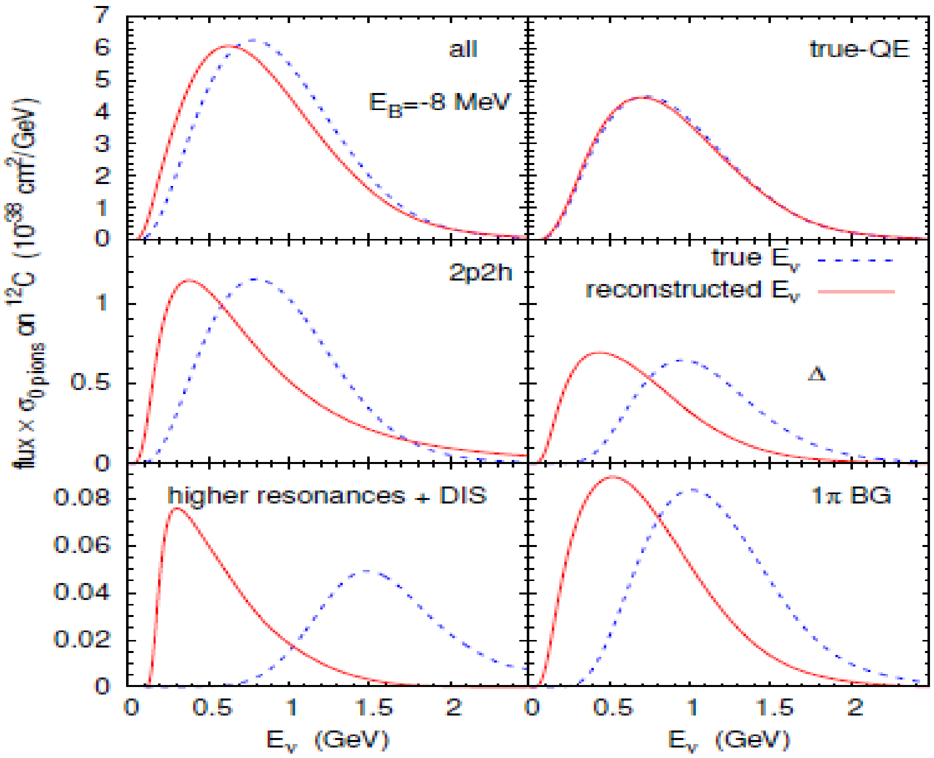
Martini et al, PRC 81, 045502 (2010)

Models good up to ~ 1.5 GeV
No prediction of nucleon kinematics

Another problem

Reconstructed E_ν

True E_ν

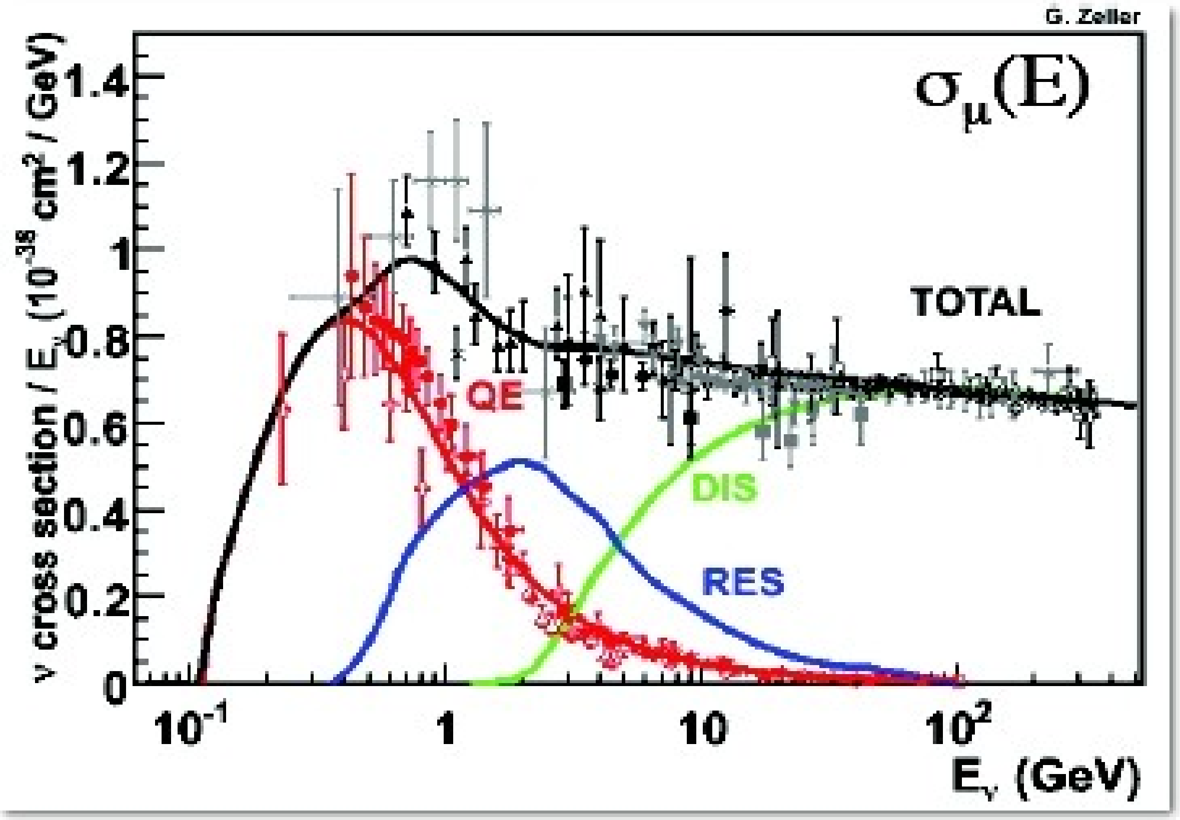


- Impacts E_ν determination
  - important for oscillation studies
- Effects could be different between ν and $\bar{\nu}$
  - Could be interpreted as a spurious CP effect

- QE scattering is still not understood – we could be missing a sizeable (and energy dependent) part of the cross section
- more measurements are needed

Single pion production

Resonant pion production dominates σ at a few GeV



$$\nu_\mu + p \rightarrow \Delta^{++} + \mu^-$$

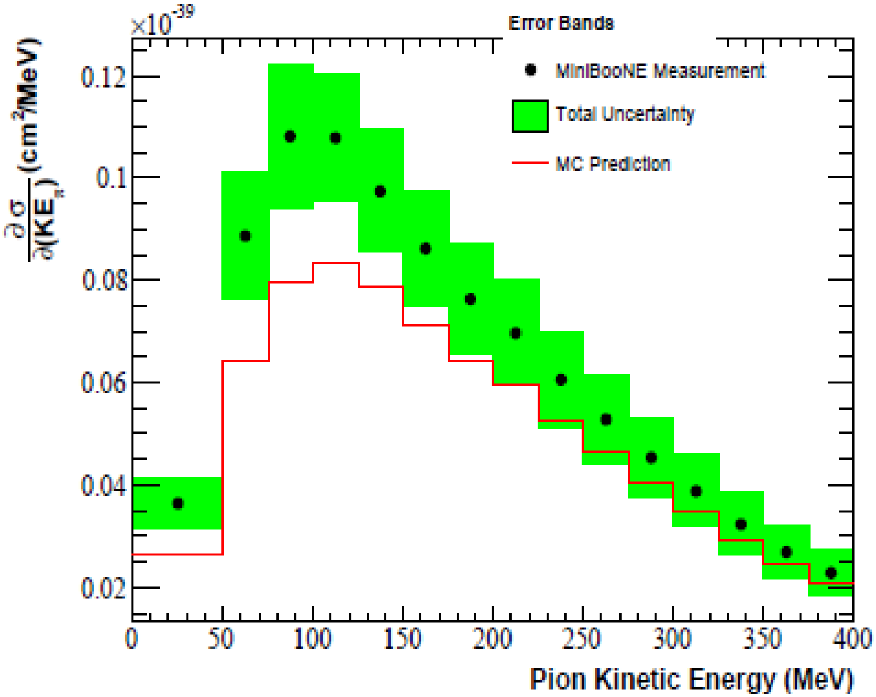
$$\hookrightarrow p + \pi^+$$

Decays can also be to multi-pion states, other resonance, photons,...

Single pion production

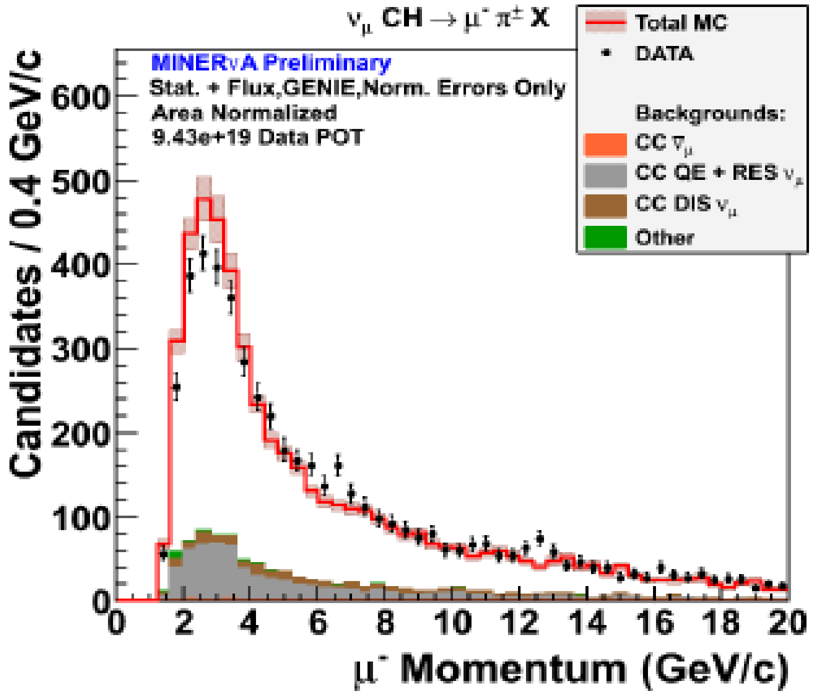
$$\nu_\mu + X \rightarrow \mu^- + N + \pi$$

- Significant background to CCQE(like) channel



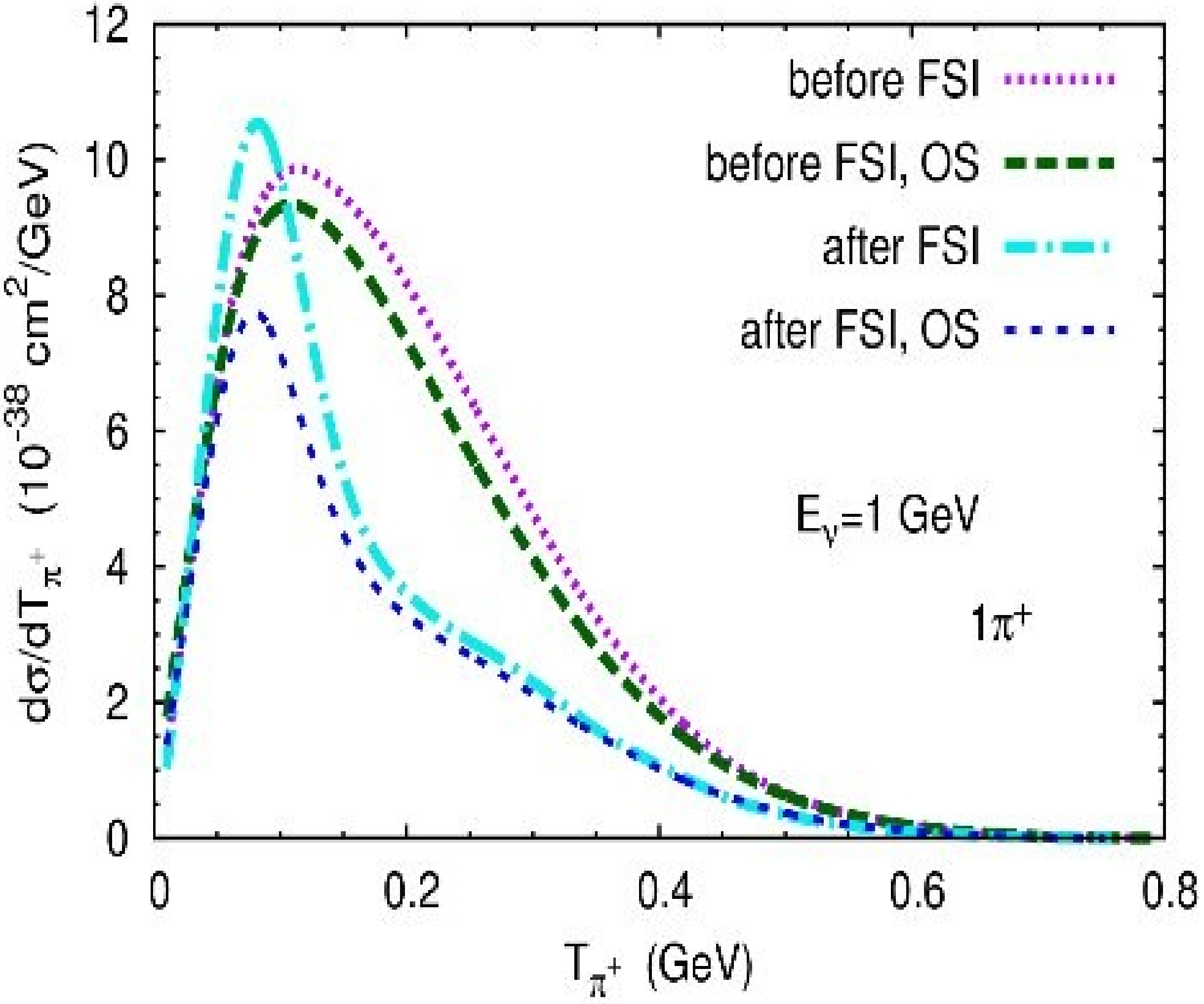
MiniBooNE : CC 1 π^+ (only 1 visible pion in final state)

- Sensitive probe of Final State effects but hard to disentangle from hard process



MINERvA : CC 1 π^+ X (at least 1 visible pion in final state)

Effect of Final State Interactions



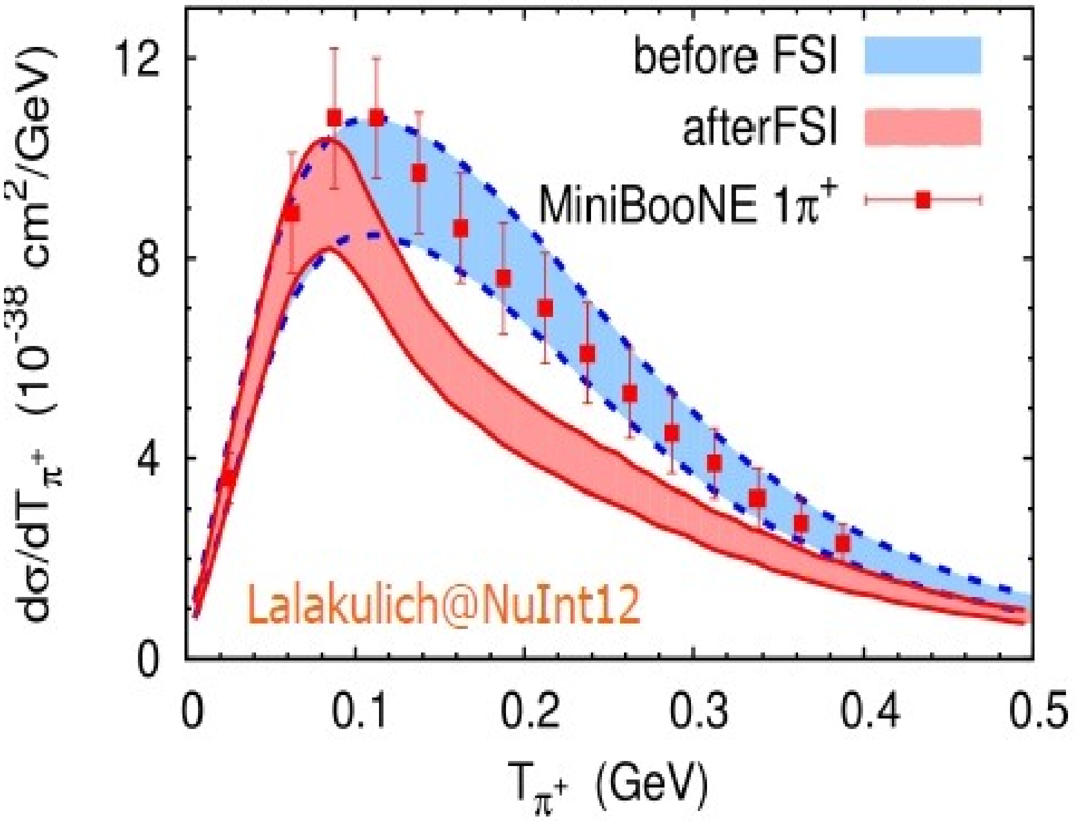
- OS : Oset-Salsedo modification

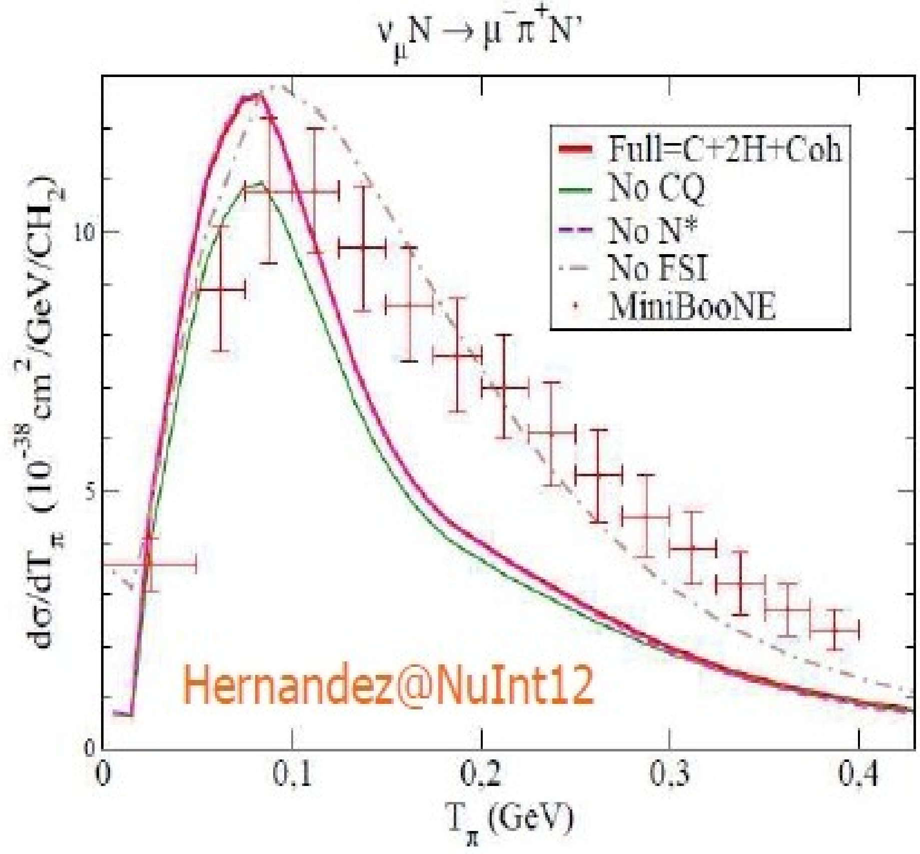
  In-medium Δ width broadening

Lalakukich, NuInt12

Single pion production

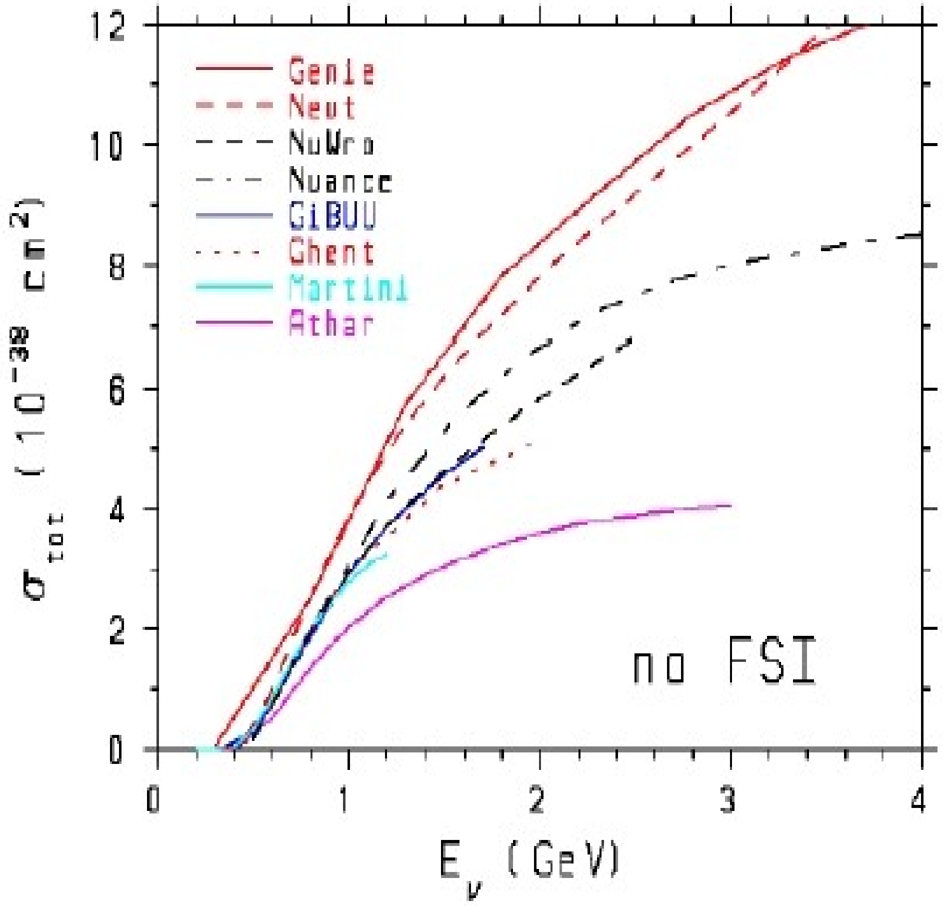
- State of the art calculations describe better the data without FSI





But....but....we know FSI effects should be there....???

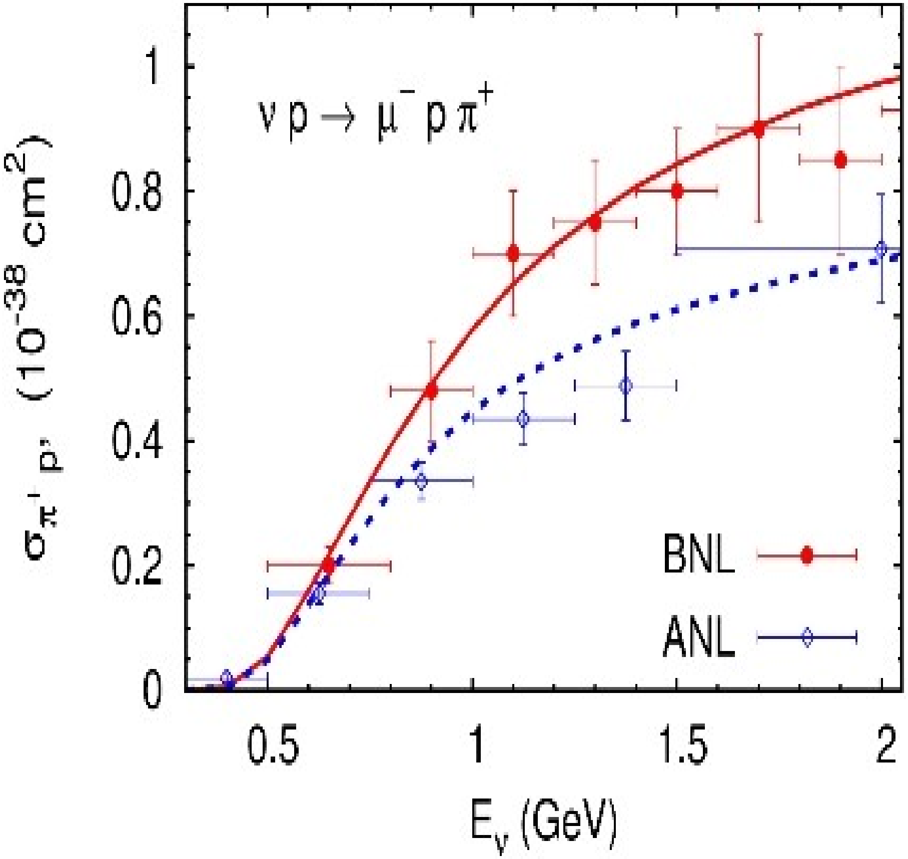
Single pion production



Boyd et al., AIP Conf. Proc. 1189

- Current models differ at the free nucleon level.
  - Non-resonant effects
  - N-resonance transition form factors
  - Delta in-medium corrections
- Not much point trying to get FSI model right using single pion data, if the input model is wrong.
- Current generators use Rein-Seghal model. This is incorrect at low energies.

Single pion production

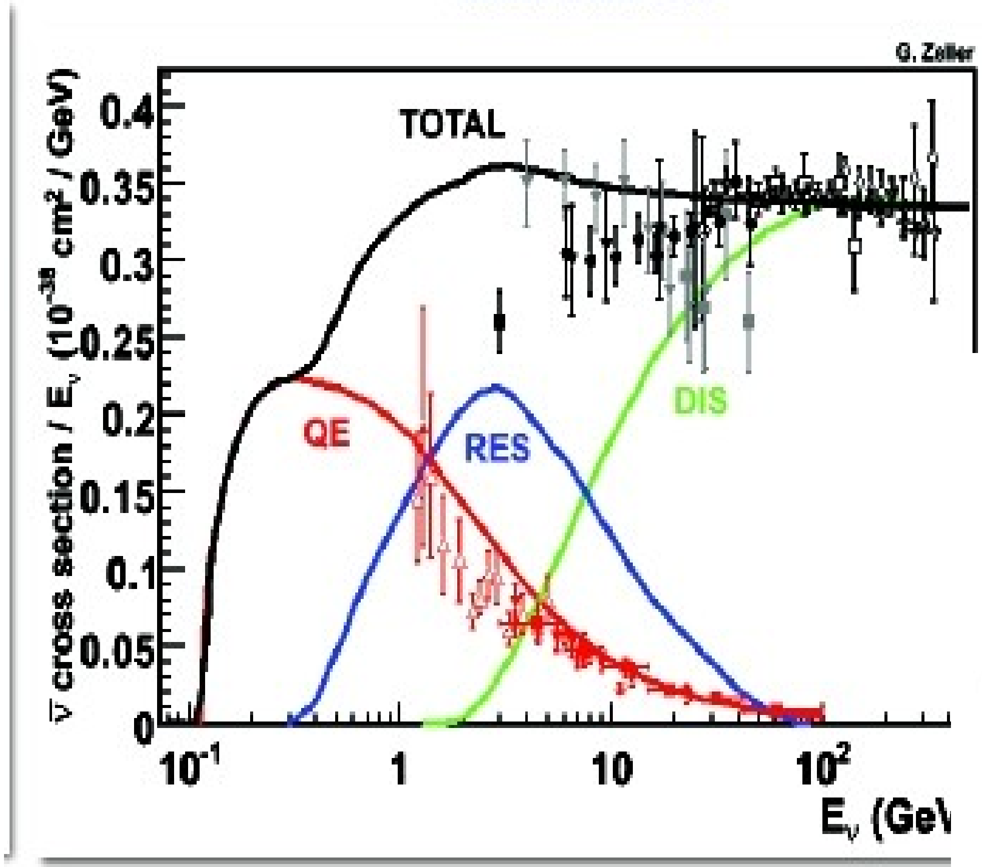


- Best measurement of initial σ comes from ANL & BNL (D_2)
- These differ by 20%.
- Theoretical models differ in how they treat this
  - Average?
  - Choose one?

"New π production measurements on H or D would help a lot"

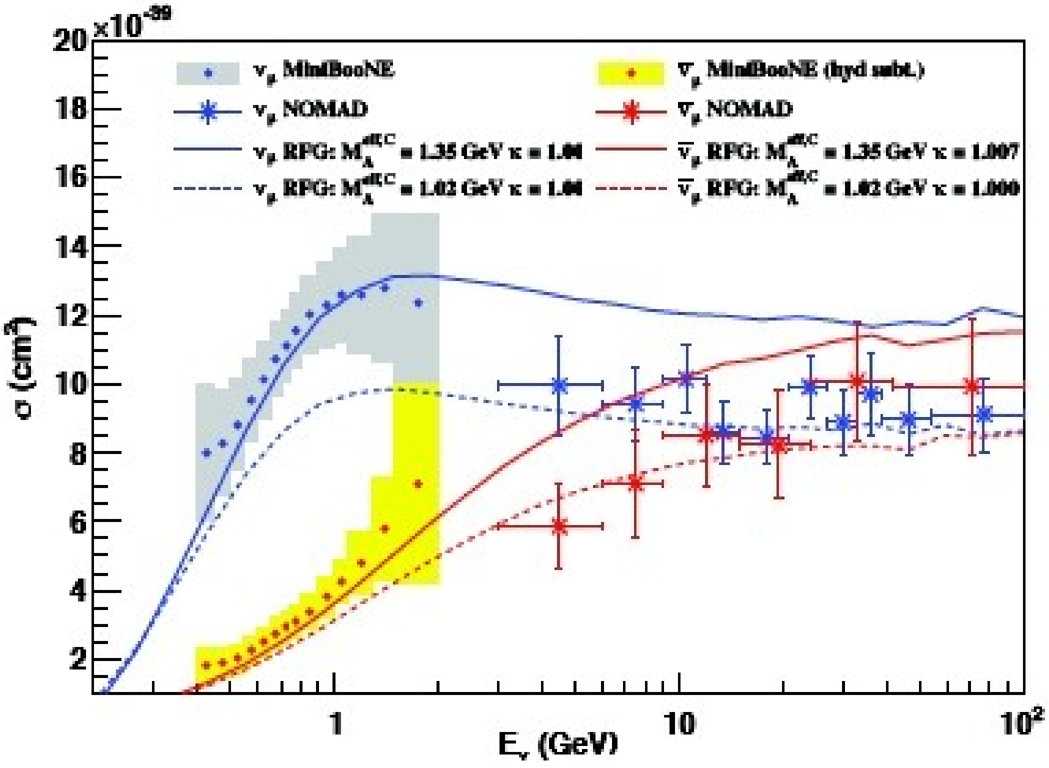
Significant work needed on this channel

Antineutrino Cross-sections



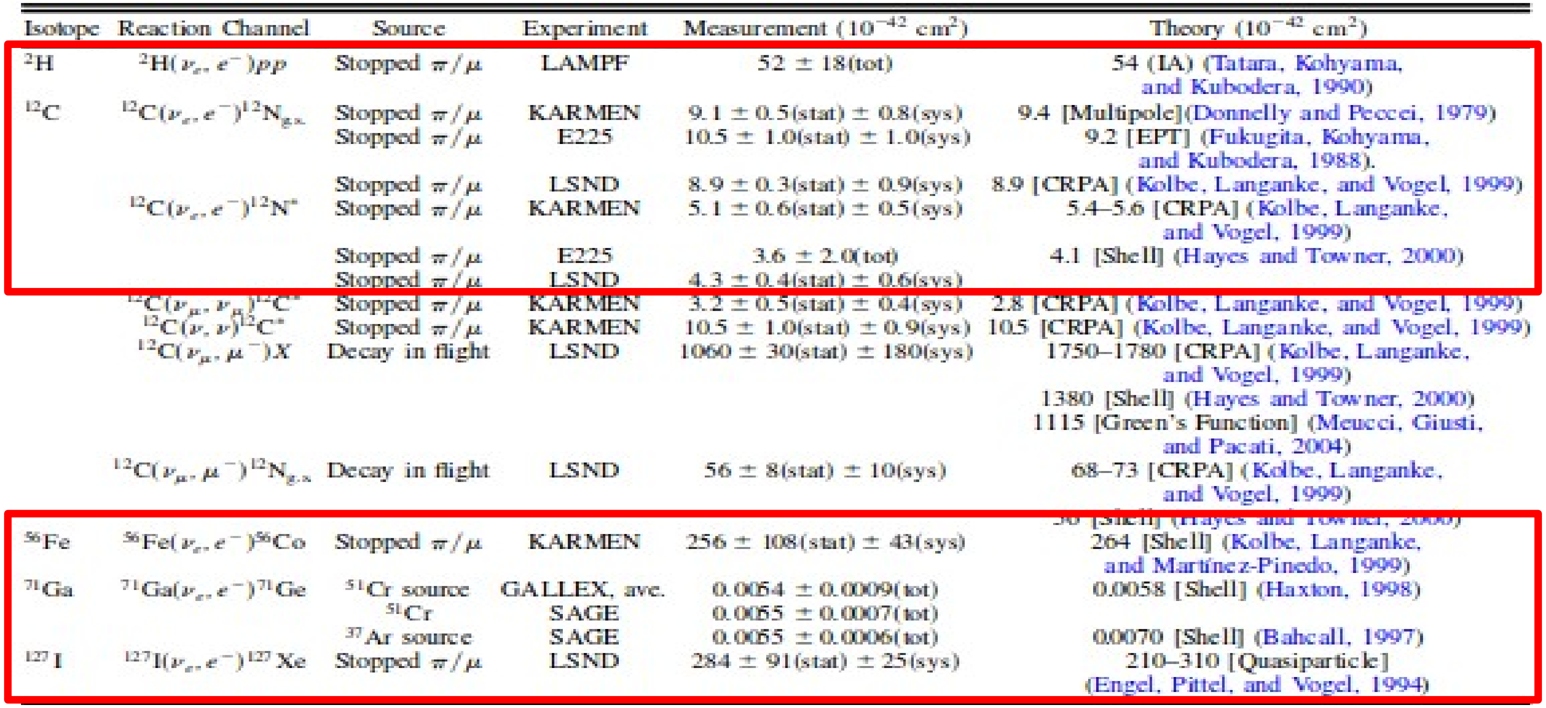
Total cross section

CCQE-like,MiniBooNE,
NuInt 2012



ν_e Cross-section

There is very little ν_e data available, not least because we try to minimise the number of ν_e in accelerator beams.



Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
^{2}H	^{2}H$(\nu_e, e^-)pp$	Stopped π/μ	LAMPF	52 ± 18(tot)	54 (IA) (Tatara, Kohyama, and Kubodera, 1990)
^{12}C	^{12}C$(\nu_e, e^-)^{12}$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, Kohyama, and Kubodera, 1988).
		Stopped π/μ	LSND	8.9 ± 0.3(stat) ± 0.9(sys)	8.9 [CRPA] (Kolbe, Langanke, and Vogel, 1999)
	^{12}C$(\nu_e, e^-)^{12}$N*	Stopped π/μ	KARMEN	5.1 ± 0.6(stat) ± 0.5(sys)	5.4–5.6 [CRPA] (Kolbe, Langanke, and Vogel, 1999)
		Stopped π/μ	E225	3.6 ± 2.0(tot)	4.1 [Shell] (Hayes and Towner, 2000)
		Stopped π/μ	LSND	4.3 ± 0.4(stat) ± 0.6(sys)	
	^{12}C$(\nu_\mu, \nu_\mu)^{12}$C*	Stopped π/μ	KARMEN	3.2 ± 0.5(stat) ± 0.4(sys)	2.8 [CRPA] (Kolbe, Langanke, and Vogel, 1999)
	^{12}C$(\nu, \nu)^{12}$C*	Stopped π/μ	KARMEN	10.5 ± 1.0(stat) ± 0.9(sys)	10.5 [CRPA] (Kolbe, Langanke, and Vogel, 1999)
	^{12}C$(\nu_\mu, \mu^-)X$	Decay in flight	LSND	1060 ± 30(stat) ± 180(sys)	1750–1780 [CRPA] (Kolbe, Langanke, and Vogel, 1999) 1380 [Shell] (Hayes and Towner, 2000) 1115 [Green's Function] (Meucci, Giusti, and Pacati, 2004)
	^{12}C$(\nu_\mu, \mu^-)^{12}$N$_{g.s.}$	Decay in flight	LSND	56 ± 8(stat) ± 10(sys)	68–73 [CRPA] (Kolbe, Langanke, and Vogel, 1999) 56 [Shell] (Hayes and Towner, 2000)
^{56}Fe	^{56}Fe$(\nu_e, e^-)^{56}$Co	Stopped π/μ	KARMEN	256 ± 108(stat) ± 43(sys)	264 [Shell] (Kolbe, Langanke, and Martínez-Pinedo, 1999)
^{71}Ga	^{71}Ga$(\nu_e, e^-)^{71}$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$(\nu_e, e^-)^{127}$Xe	Stopped π/μ	LSND	284 ± 91(stat) ± 25(sys)	210–310 [Quasiparticle] (Engel, Pittel, and Vogel, 1994)

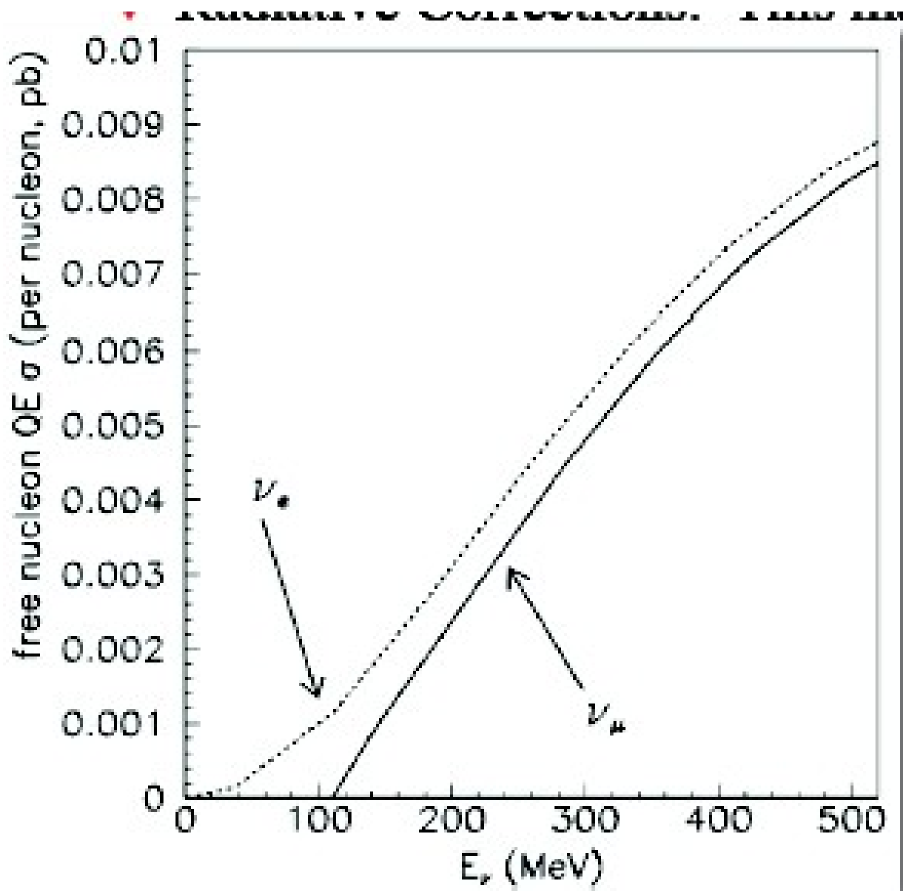
< 50 MeV

~ 700 keV

All σ at very low energies (reactors/decay-at-rest)

Differences between ν_e and ν_μ

- QE Scattering dominates at second oscillation maximum
- Kinematic differences from μ/e mass threshold
- Radiative corrections
- Second class currents and form factor differences
- Relative weight of nuclear response can change as lepton tensor changes → nuclear effects are different for neutrino and antineutrino



What do we need to clean this up?

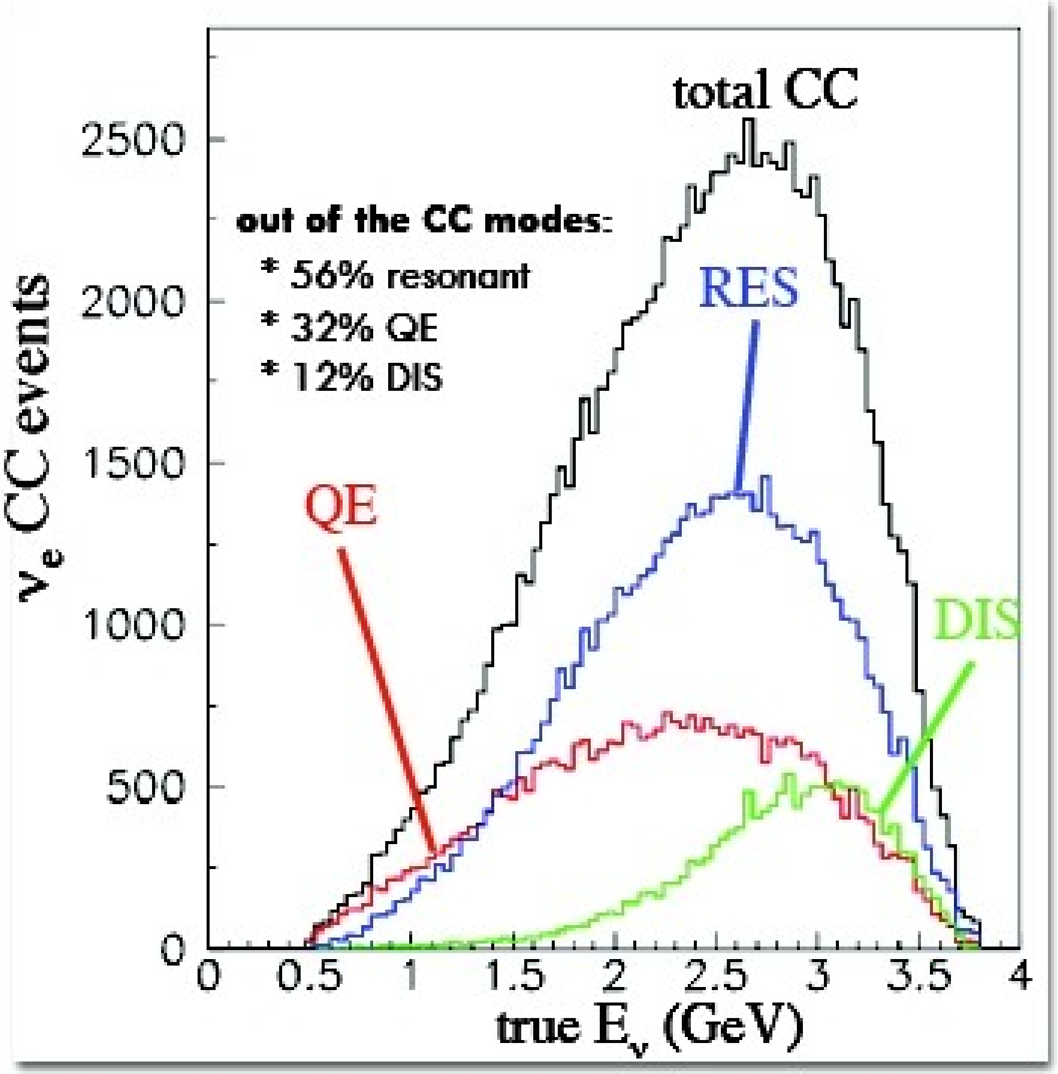
- Detectors capable of excellent PID and imaging of the interaction vertex
- Mutiple target measurements – especially on H or D
- Much better precision : either a better beam or a precisely known standard candle process to normalise against

There are no standard candles at a few GeV....

poss. exception : neutrino-electron NC scattering

Event composition

ν_e in a 3.8 GeV μ^+ beam



μ^+ beam

Channel	# Events
Anti ν_μ NC	845,000
ν_e NC	1,388,000
Anti ν_μ CC	2,146,000
νε CC	3,960,000

For 1E21 POT / 100 Tons of C^{12} @ 50 m

Summary

- σ in few-GeV range are not nearly as well known as at high or low energies.
- These cross sections embody one of the largest systematic errors for oscillation experiments.
- We have no realistic standard candle in this energy regime. Old data is proving difficult to interpret.
- A νStorm facility is the only one capable of making ν_μ and ν_e cross section measurements with the precision needed for CP violation measurements

νStorm Facility

Should think of this as a facility for multiple experiments, rather than an experiment itself. What would we want a detector to do?

- Photon thresholds down to 50 MeV or less
- Proton KE threshold down to 20 MeV
- Charged particle tracking in magnetic field
- Full topology reconstruction
- Neutrino energy reconstruction
- Electron / Proton / Mip identification
- Multiple target materials : Al, C, Pb, Fe, Ar, ?
- Low-Z targets : D, H ?
- Other requirements...

A single detector cannot meet all these criteria.

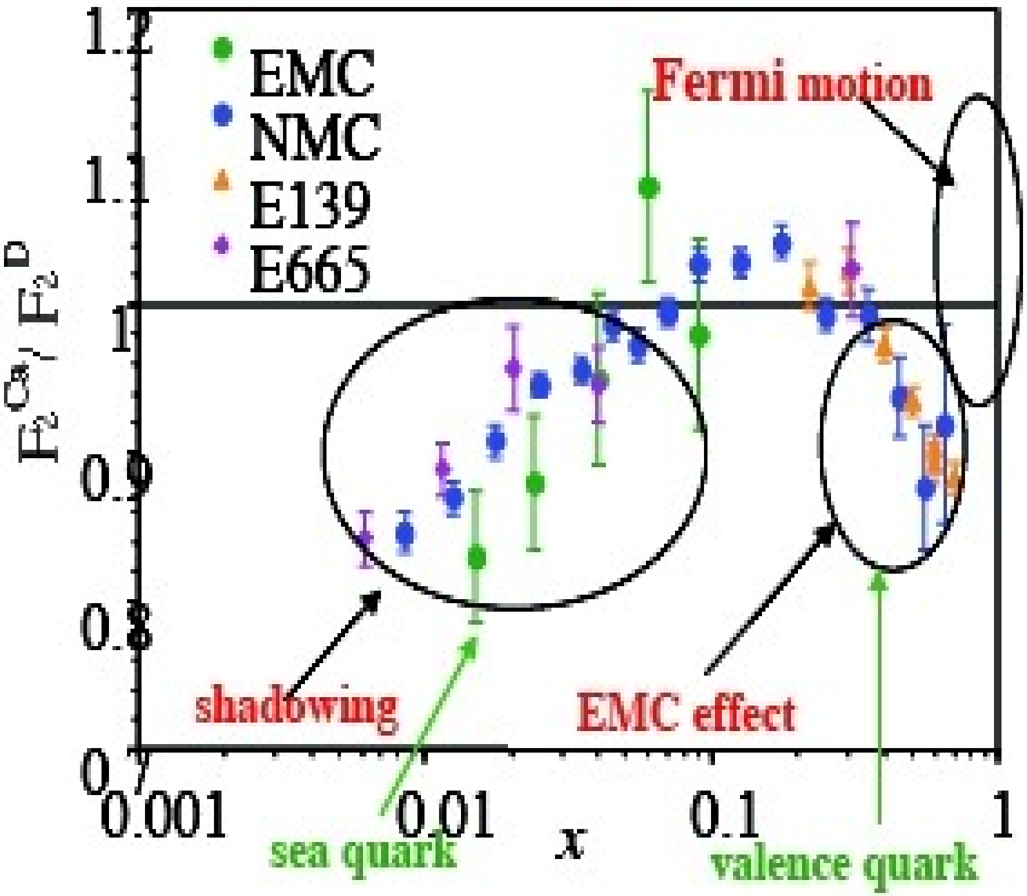
1)Liquid Argon TPC

2)Active tracking detector

3)Low-Z detector

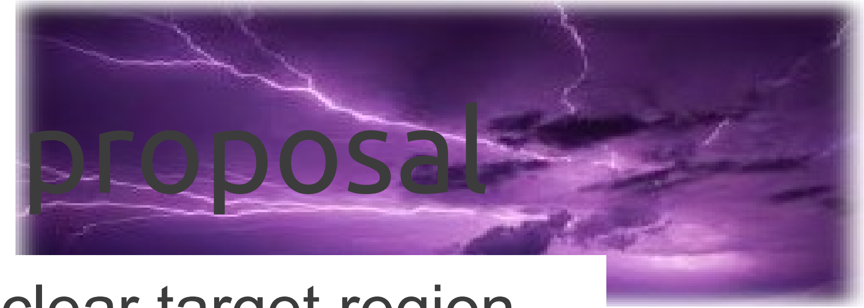
High Energy

There are even issues that still haven't been resolved at high energy in the deep inelastic regime



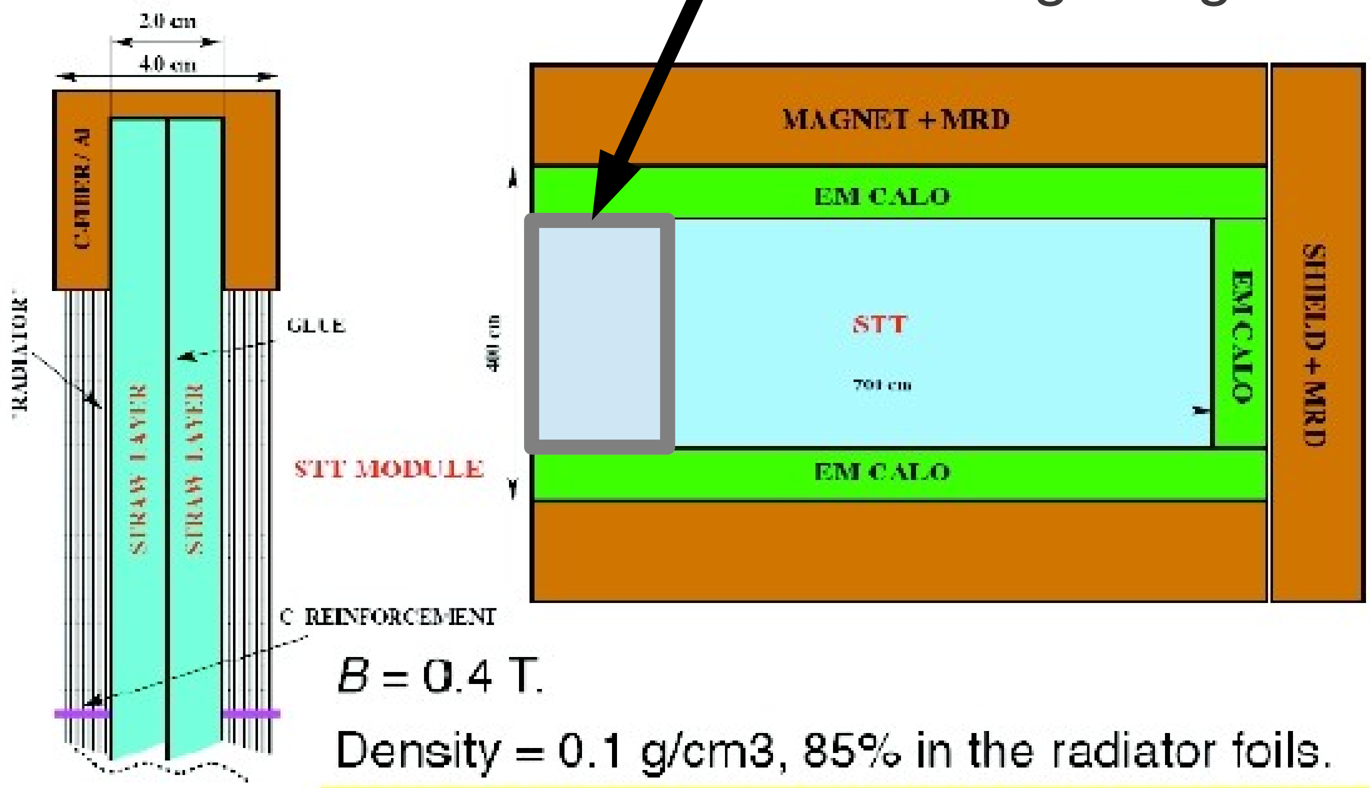
- F_2 changes as a function of A. However, this has only been measured in μ/e-A
- Presence of axial-vector current can change the dependence.
- Very slight indication that this is the case from CTEQ.

Current tracker proposal



- **HighRes – Mishra/Petti**

Nuclear target region



$B = 0.4$ T.

Density = 0.1 g/cm3, 85% in the radiator foils.

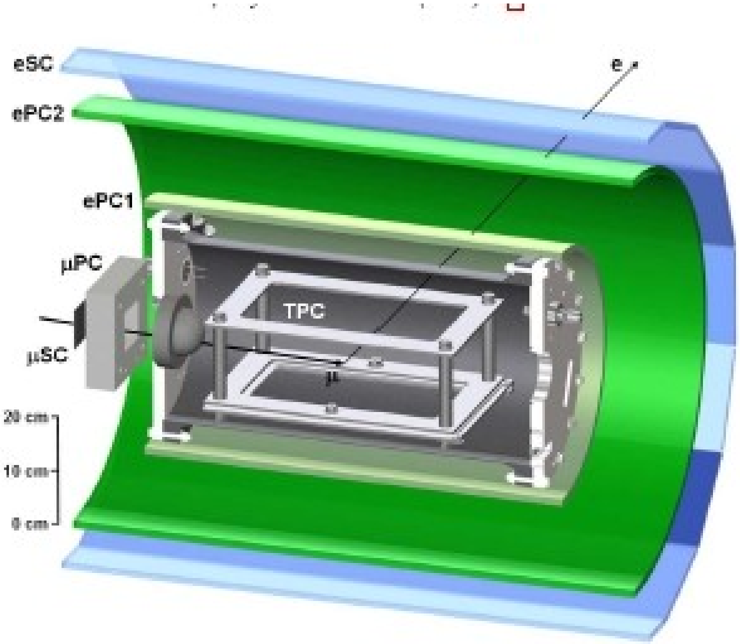
Transition Radiation ↔ Electron ID ⇒ γ (w. Kinematics)
dE/dx ↔ Proton, π, K ID
Magnet/Muon Detector ↔ μ

Straw tube idea does not yet convince me
Would like to see performance numbers...

Low Z detector?

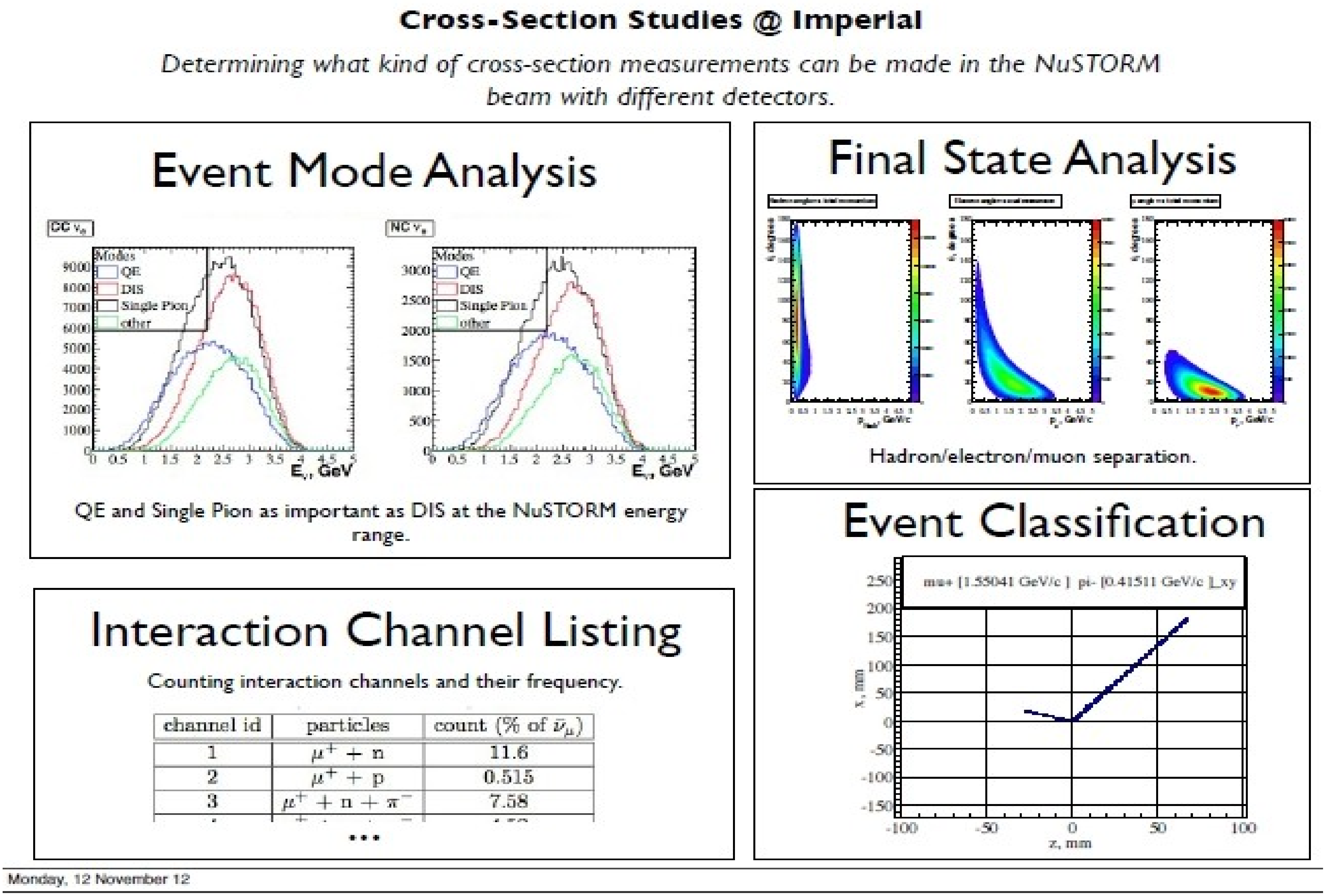
- Lot's of work to get data on high Z targets : C, Brass, Pb, Fe etc
- But theorists are pleading for precise, low Z data

Modern version of bubble chamber?



MuCap 10 bar H gas TPC run @ PSI

Pressurised gaseous H TPC?



Cross-Section Studies @ Imperial

Determining what kind of cross-section measurements can be made in the NuSTORM beam with different detectors.

Event Mode Analysis

QE and Single Pion as important as DIS at the NuSTORM energy range.

Final State Analysis

Hadron/electron/muon separation.

Event Classification

Interaction Channel Listing

Counting interaction channels and their frequency.

channel id	particles	count (% of $\bar{\nu}_\mu$)
1	$\mu^+ + n$	11.6
2	$\mu^+ + p$	0.515
3	$\mu^+ + n + \pi^-$	7.58

...

Monday, 12 November 12

Characterisation studies starting at Imperial – Ed Santos

CCQE Cross section as usually implemented

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

with the functions A, B and C defined in terms of the vector and axial-vector form factors

$$F_{A,V}(Q^2)=\frac{g_{A,V}}{\left(1+\frac{Q^2}{M_{A,V}^2}\right)^2}$$

Couplings set by behaviour of currents at $Q^2=0$ (CVC and PCAC)

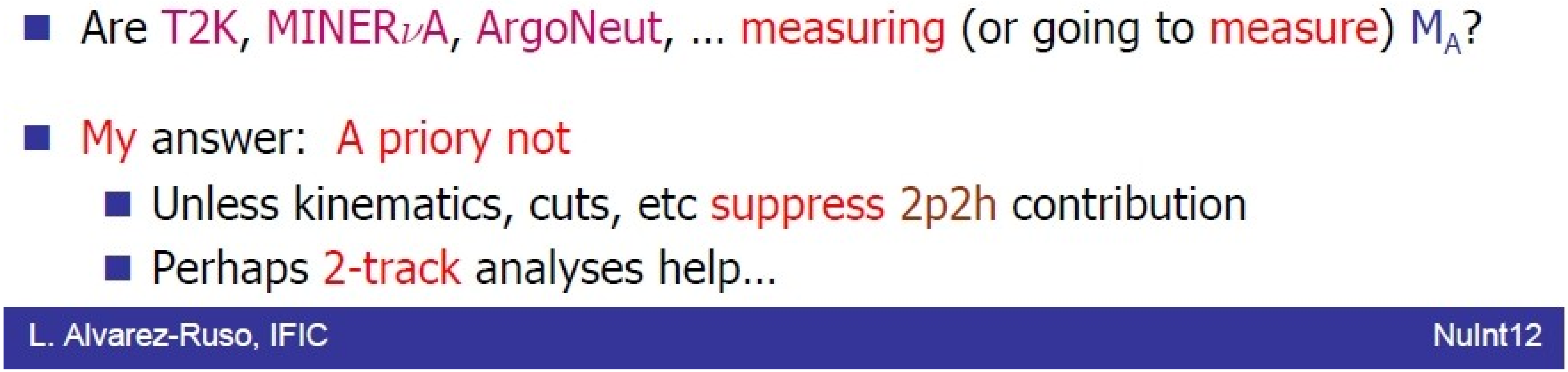
Vector and Axial vector masses must be measured

NB This is an ansatz....

M_V measured in electron scattering

M_A measured in neutrino scattering

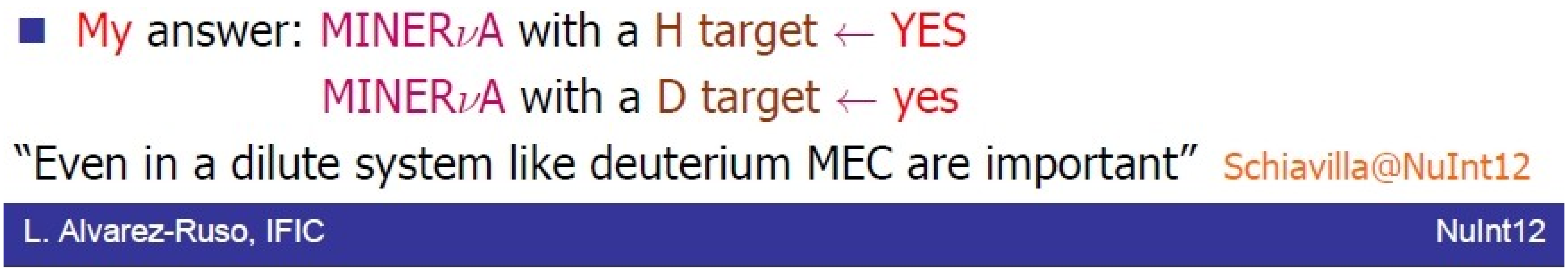
Another measurement of M_A? Really?



- Are T2K, MINERνA, ArgoNeut, … measuring (or going to measure) M_A?
- My answer: A priory not
  - Unless kinematics, cuts, etc suppress 2p2h contribution
  - Perhaps 2-track analyses help…

L. Alvarez-Ruso, IFIC NuInt12

Plea from theorists for low-Z scattering data – preferably Hydrogen



- My answer: MINERνA with a H target ← YES

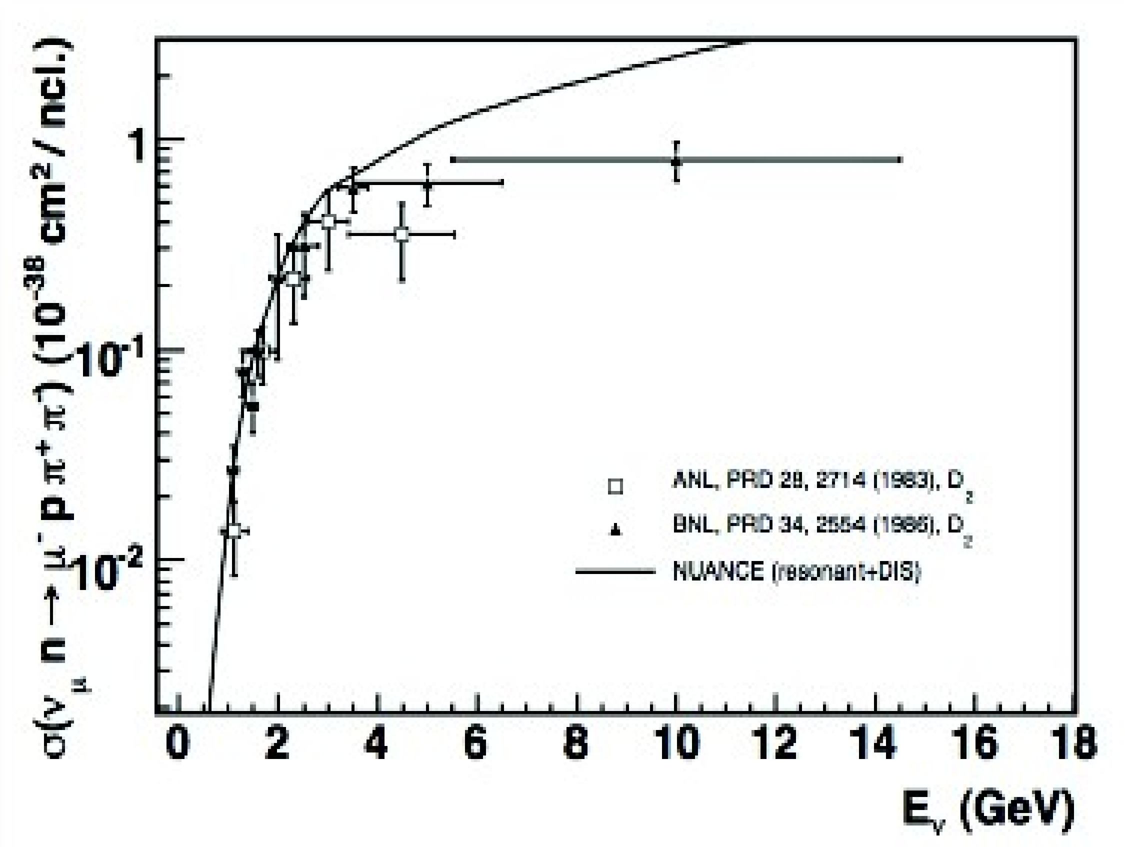
  MINERνA with a D target ← yes

"Even in a dilute system like deuterium MEC are important" Schiavilla@NuInt12

L. Alvarez-Ruso, IFIC NuInt12

Multi-pion production

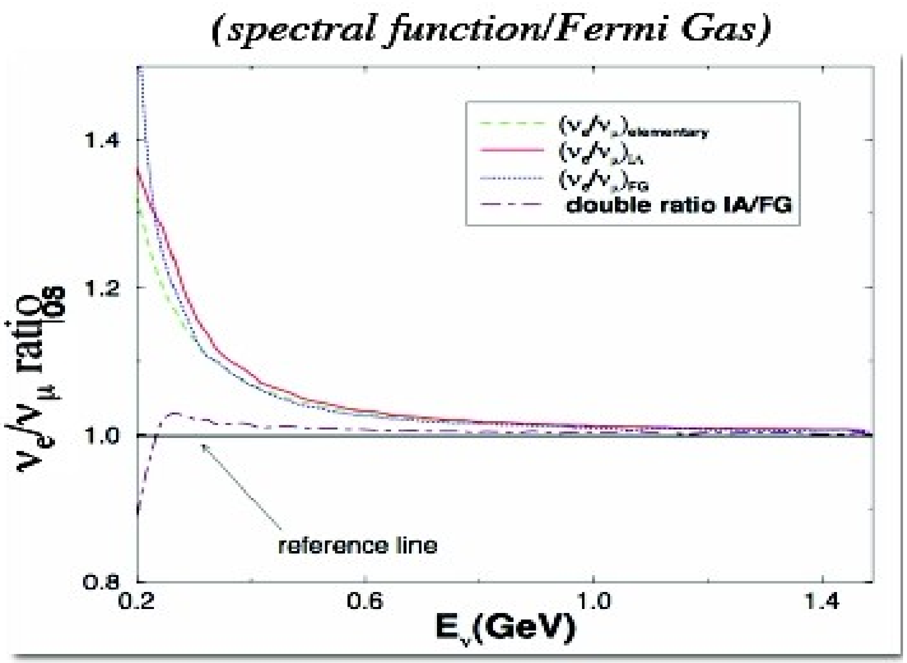
Contains contributions from resonant single-pion, DIS and the transition region (Res → DIS)

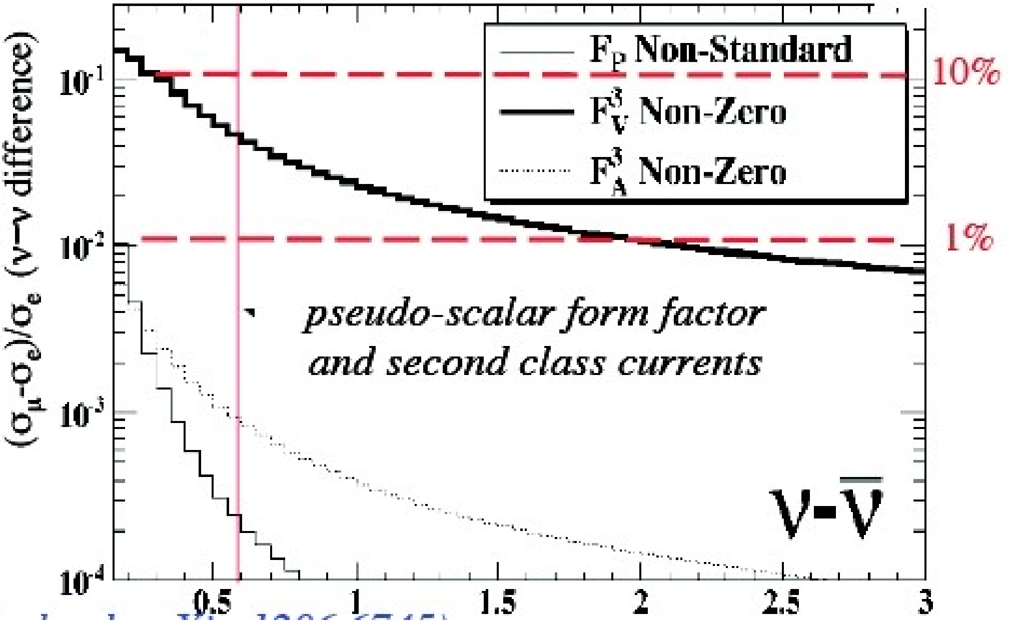


- Only existing data from ANL/BNL D_2 bubble chambers

Differences between ν_e and ν_μ

- Kinematic differences from μ/e mass threshold
- Radiative corrections which haven't been calculated
- Second class currents and form factor differences – usually ignored but are proportional to lepton mass
- Relative weight of nuclear response can change as lepton tensor changes

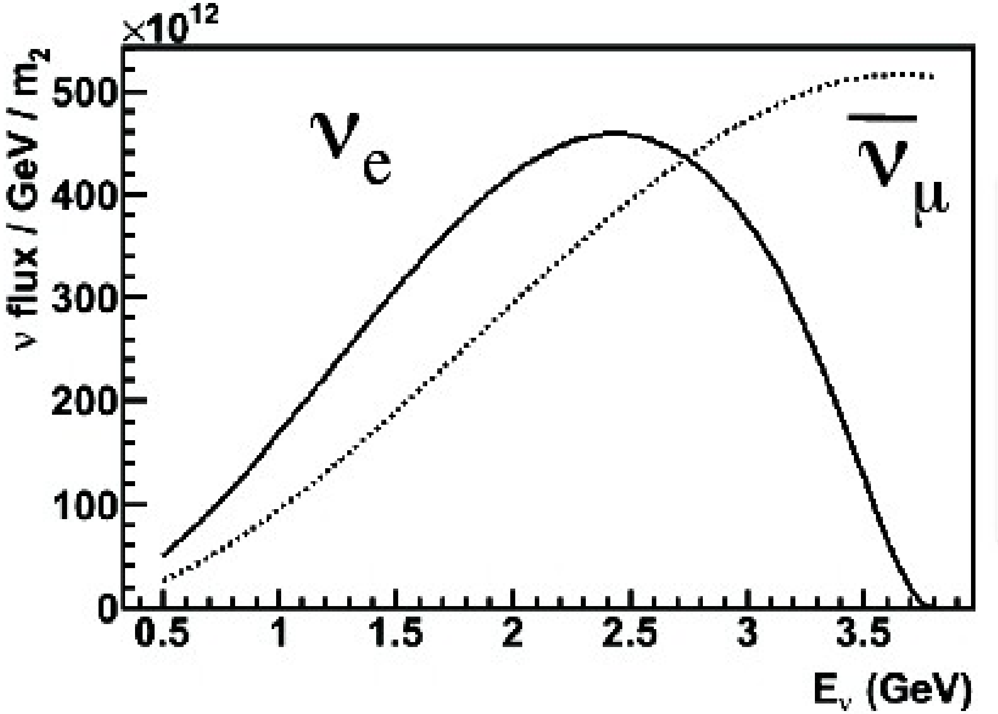




S. Zeller – nuStorm workshop

Day-McFarland: Phys.Rev. D86 (2012) 053003

νStorm Beam



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

(thanks to Sam Zeller and Chris Tunnell!)

$$\mu^- \rightarrow \nu_\mu + \overline{\nu_e} + e^-$$

$$\mu^+ \rightarrow \overline{\nu_\mu} + \nu_e + e^+$$

- Precisely known neutrino energy spectrum
- $\delta(\phi(E)) \sim 1\%$
- Note : Won't help with the energy reconstruction issues – but will if combined with the right target and detector.

To M_A or not to M_A

$$F_A(q^2) = \frac{g_{A,V}}{\left(1+\frac{Q^2}{M_{A,V}^2}\right)^2}$$

$M_V^2 = 0.71\ GeV^2$

Experiment	M_A (GeV/c^2)
World Average	1.03 ± 0.03
K2K (O)	1.20 ± 0.12
K2K (C)	1.14 ± 0.21
MiniBooNE (C)	1.35 ± 0.17
NOMAD (C)	1.05 ± 0.06
MINOS (Fe)	1.19 ± 0.17

- Nuclear environment is important below 2 GeV
- Many measurements use M_A to soak up ill-known nuclear effects
- Why assume a dipole? Is that even right

  (Answer : no, it's probably not)