Neutrino Interactions around 1GeV/c: experiments

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Outlook

- Cross-sections and future oscillation experiments.
- Experiments
- Status and prospects: CC and NC
- Conclusions

Oscillation experiments

- The existing "validated" data on oscillations is based on neutrino disappearance.
- In conventional beams, we measure before and after oscillations: cross-sections and fluxes are "cancelled".
- One problem comes from the different neutrino flux-shape and neutrino induced backgrounds.

$$\frac{Signal(\Phi') - Bck(\Phi')}{Signal(\Phi) - Bck(\Phi)}$$

- Exclusive cross-sections has to be known as a function of Energy, this is specially critical close to production thresholds.
- At this level a precise understanding of "exclusive" neutrino cross-sections is critical.

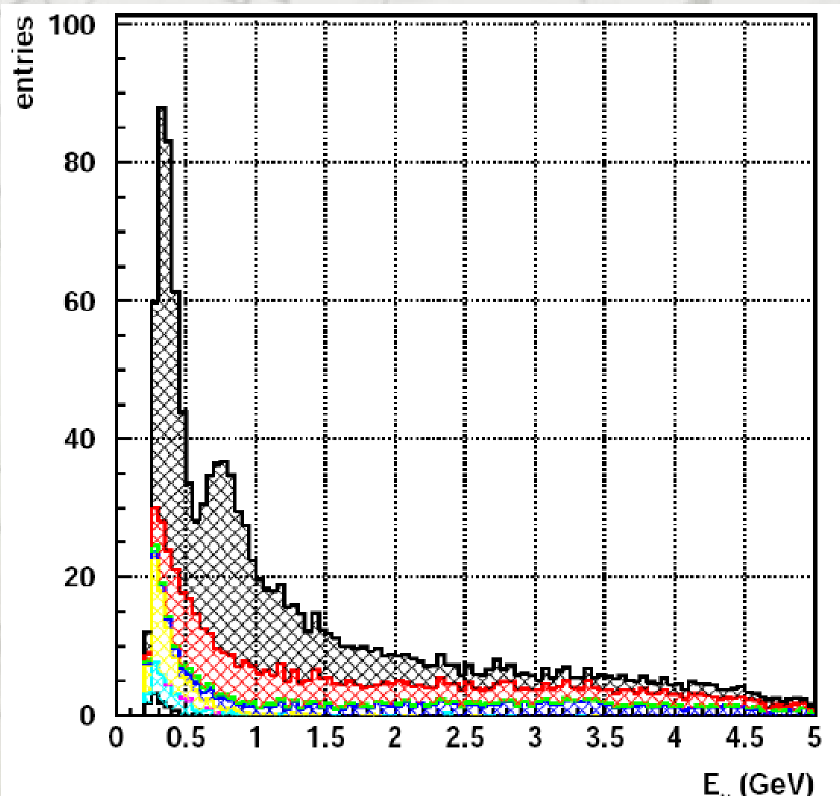
Oscillation experiments

- Next goal of oscillation experiments aims at appearance (Minos, Nova, MiniBoone, T2K) and better precision (DoubleChooz).
- The requirements in precision (up to 1% or lower in some cases) and the existence of 2 neutrino spices makes it even more complex:
  - We have to measure 2 independent cross-sections with two fluxes.
- Sometimes, we have no sample of the appeared neutrino specie:
  - This is specially critical for low energy beta-beams (ν_e->ν_μ) with neutrino interactions close to threshold.

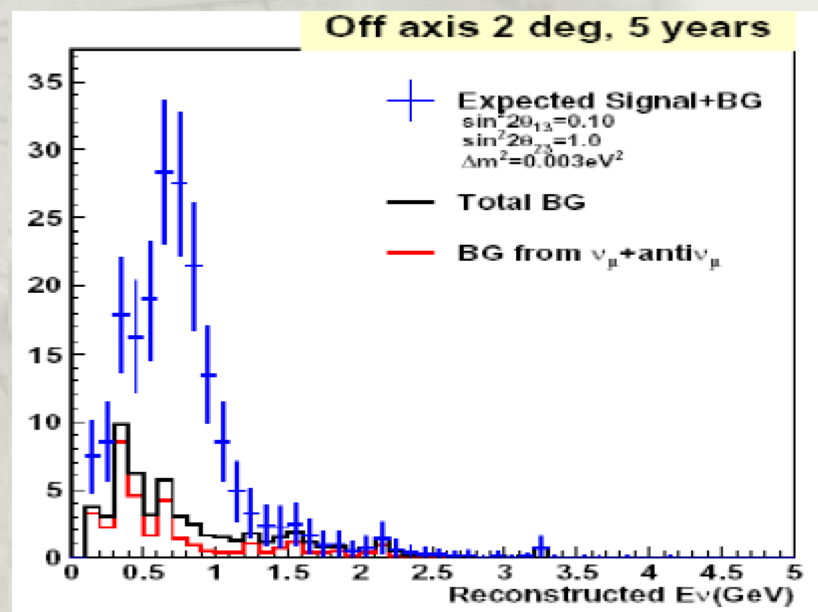
Oscillation experiments

- We need to know:
  - The neutrino flux in the case of conventional beams: using experiments like HARP or Mipp.
  - Exclusive cross-sections, including final state particle kinematics for all neutrinos species.
  - Same for neutrinos and anti-neutrinos.
- In case of low energy neutrinos, the nuclear target material is also important:
  - Cross-section changes due to nuclear effects
    - Cross-section as a function of energy and q^2 and A.
  - Final state interactions.

Example: T2K case



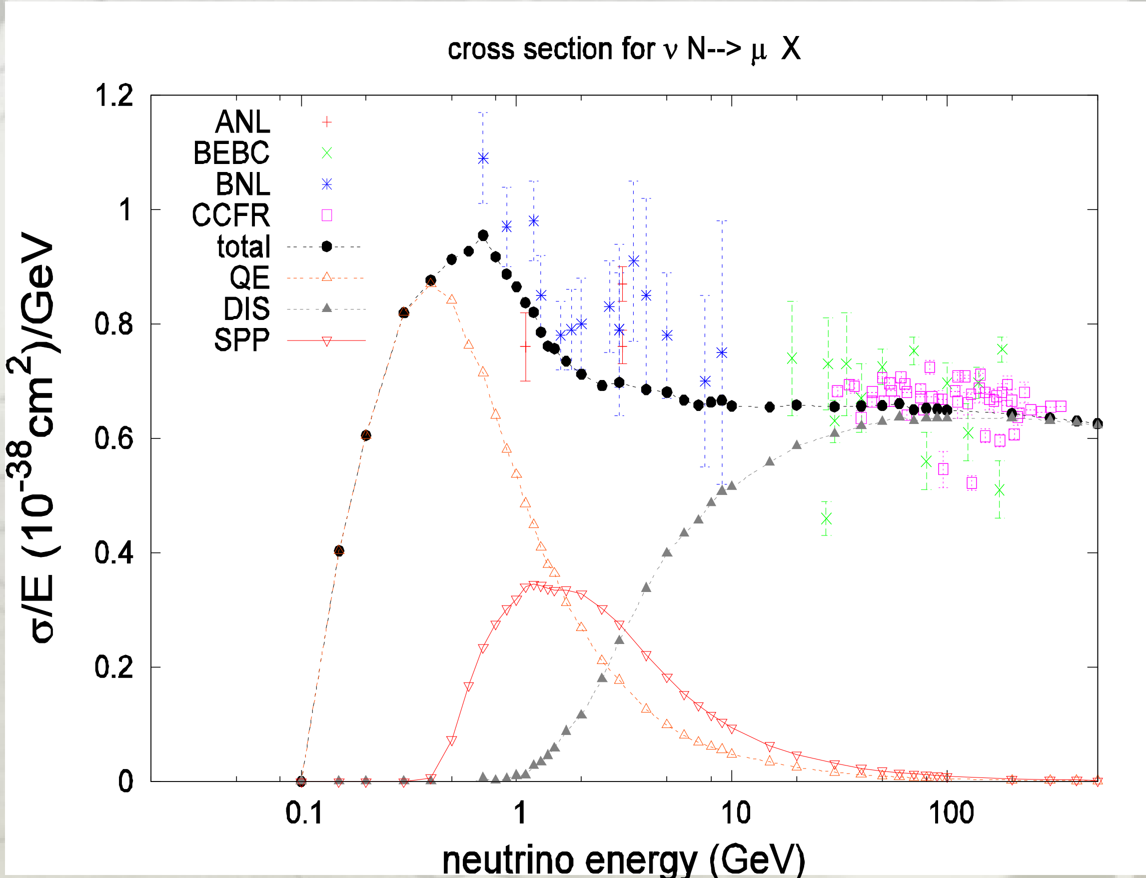
- Reconstructed energy at SK for 1 ring-like event.
  - Black: CCQE
  - Red: CC1p
  - Yellow: NC1p



~40% of background in ν_e appearance is due to NC-$1\pi^0$

Cross-sections

- From 0.2GeV to 5GeV/c neutrino cross-sections crosses several production thresholds:
  - CCQE (~200 MeV)
  - CCD (~700 MeV)
  - DIS (~2 GeV)
- CC Coherent pion production is very poorly known in the full energy rage.



Experimental data is worse at low energies.

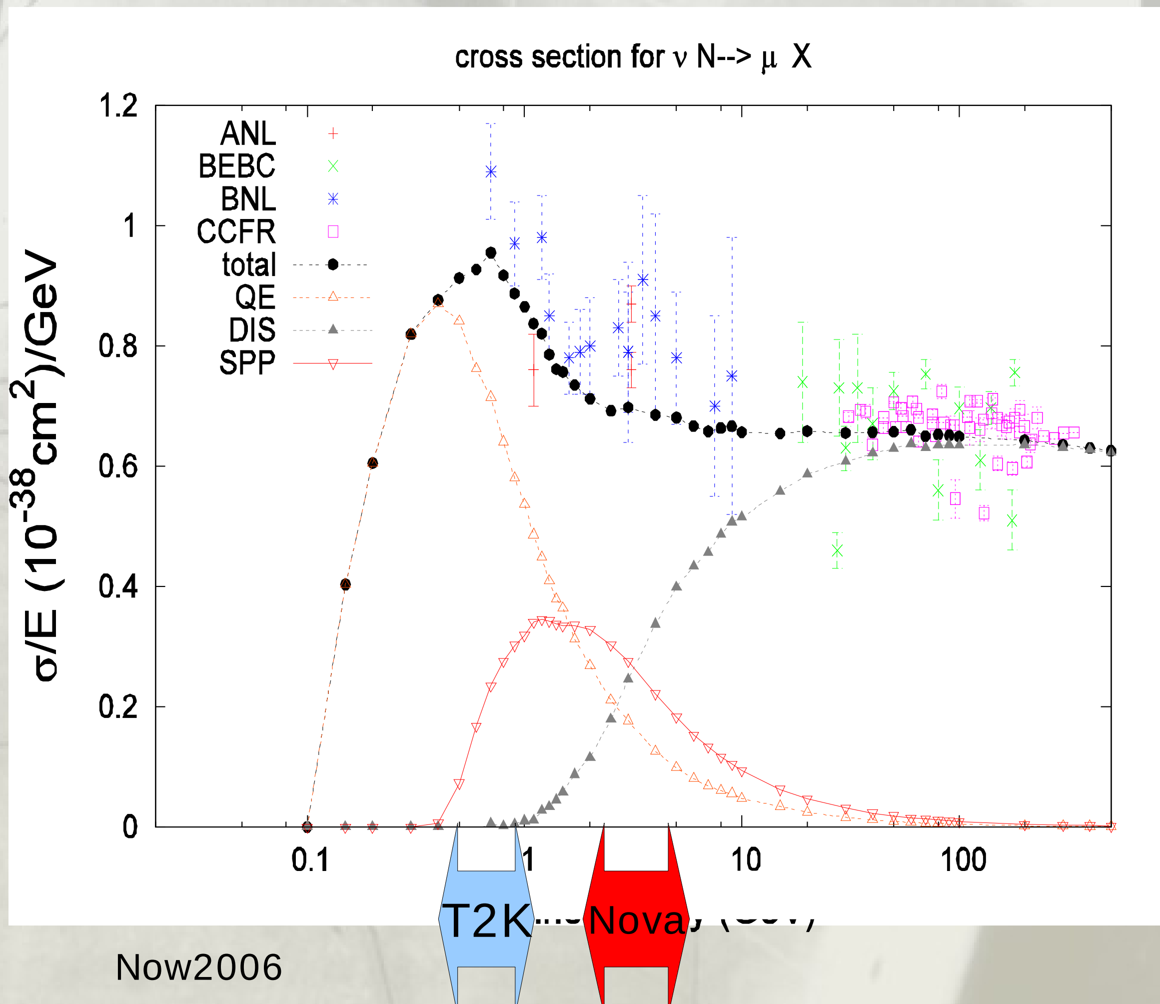
Cross-sections & oscillation experiments

T2K

- ~700 MeV
- CCQE dominant
- Current uncertainties:
  - CC ~20%
  - NC ~50%

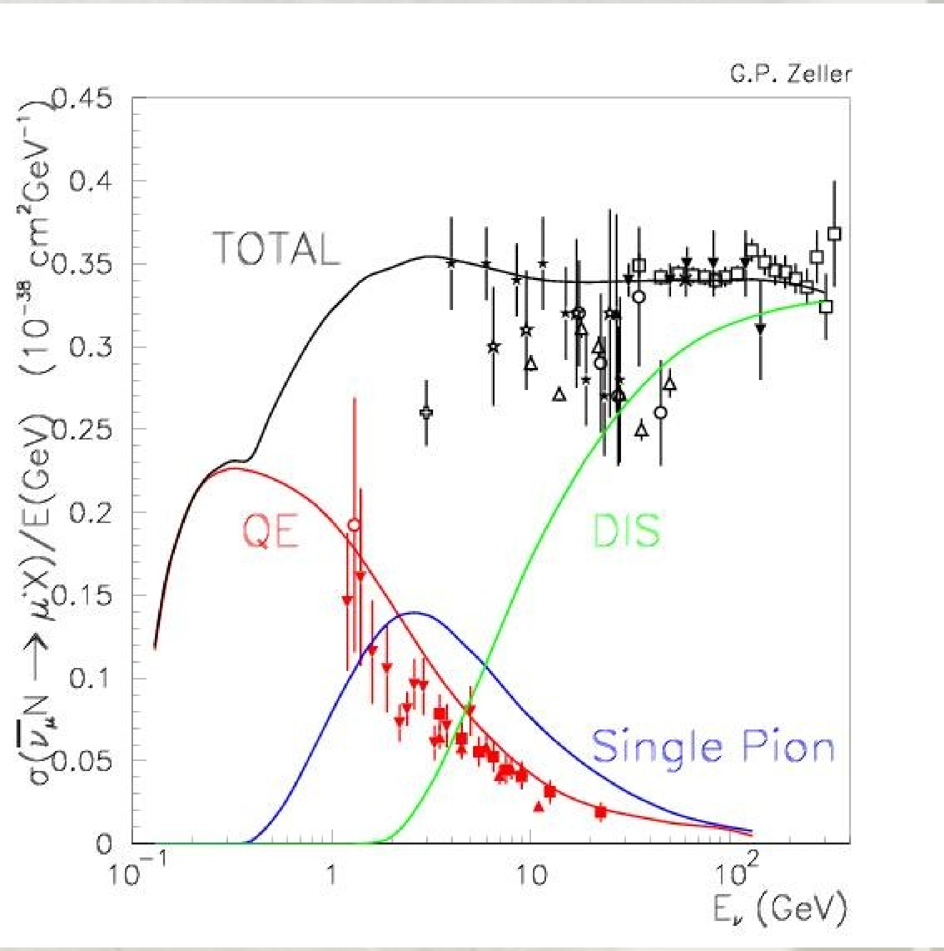
Nova

- 2-4 GeV
- CC resonant important
- Current uncertainties:
  - CC ~30%
  - NC ~50%



Anti-neutrino Cross Sections

- Needed for observation of CP violation in lepton sector.
- The current experimental situation is very poor up to ~100 GeV.
- Next generation of experiments aims at improving measurements.



Experiments - Overview

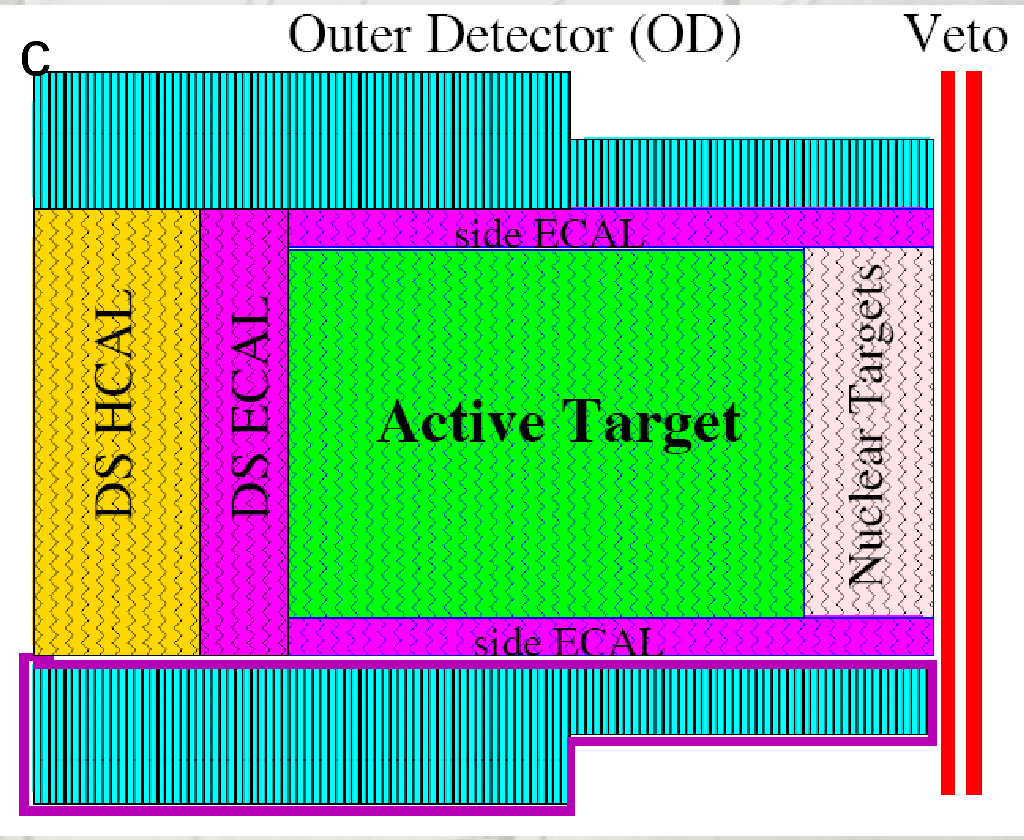
Recent/Current Measurements

- MiniBooNE
  - Energy 0.8 GeV
  - Mineral oil (C target)
- K2K near detector
  - Energy 1.2 GeV
  - Suite of near detectors
    - 1 kt - oxygen
    - SciFi - oxygen
    - SciBar - carbon
- NOMAD
  - Energy: 5-70 GeV
  - C target
- MINOS Near Detector
  - Energy: 2-12 GeV
  - Fe target

Future Measurements

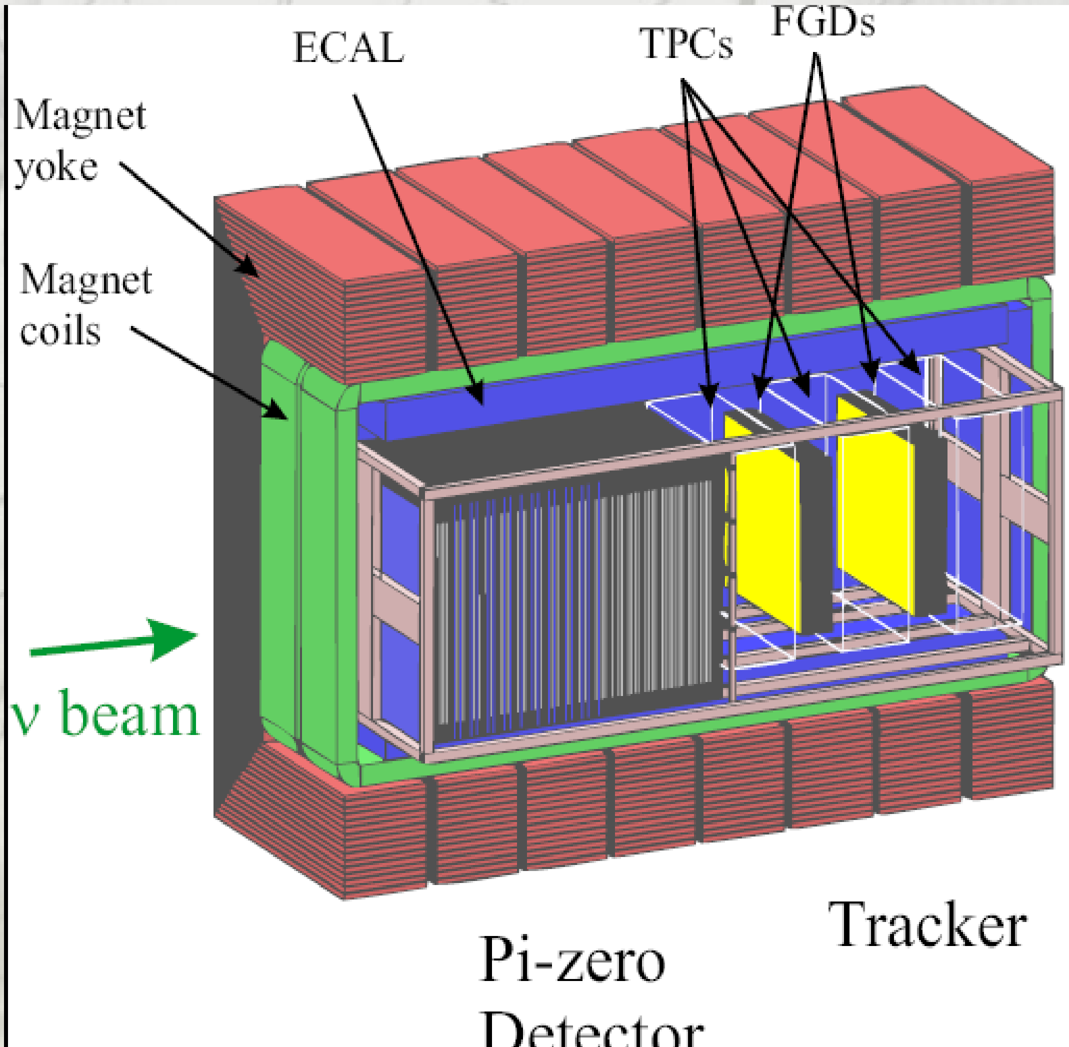
- SciBooNE
  - Energy 0.8 GeV
  - SciBar detector
    - Carbon target
- MINERνA
  - Possible Energies:
    - 3, 7, 12 GeV
  - Multiple nuclear targets
- T2K near detector
  - Energy from 0.5 to few GeV.
  - C and O targets

Experiments - Minerva



- Active target: tracking calorimeter
- Momentum from range.
- PiD from dE/dx
- Several targets.

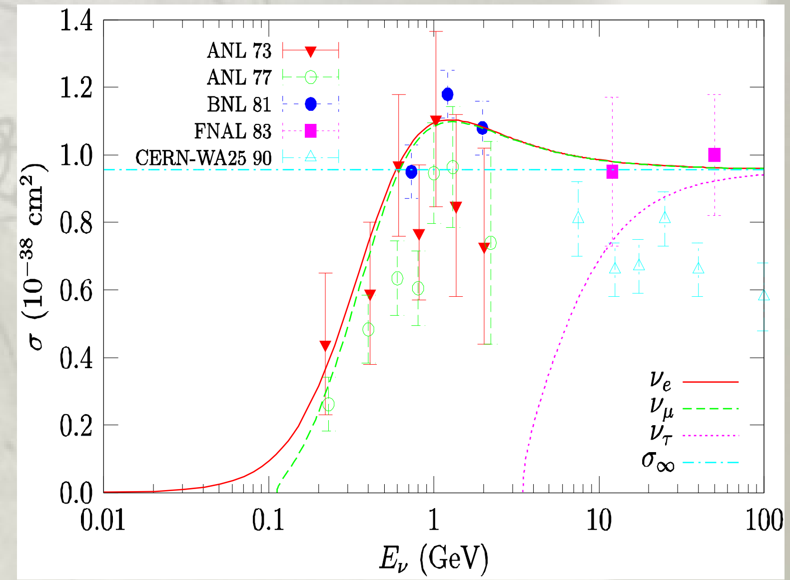
Experiments - T2K



- Magnetic field
- Active target + light tracker --> better for low energies
- PiD from dE/dx + ECAL
- Dedicated π^0. detector

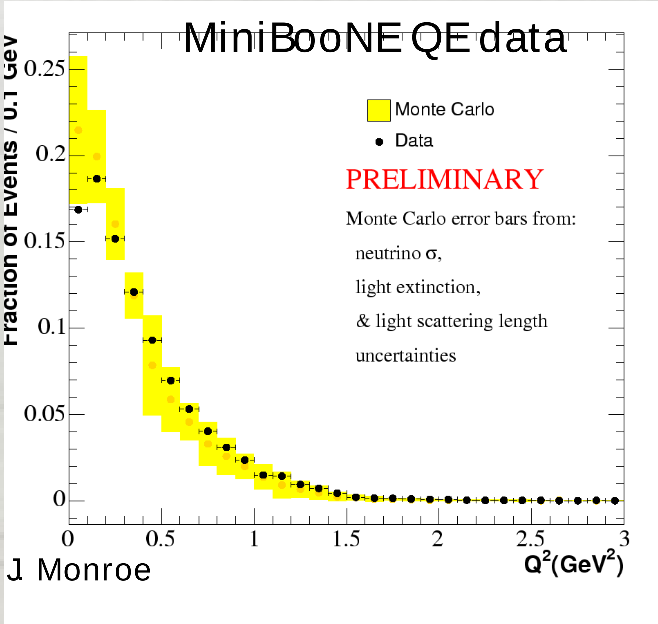
CC Quasi-elastic

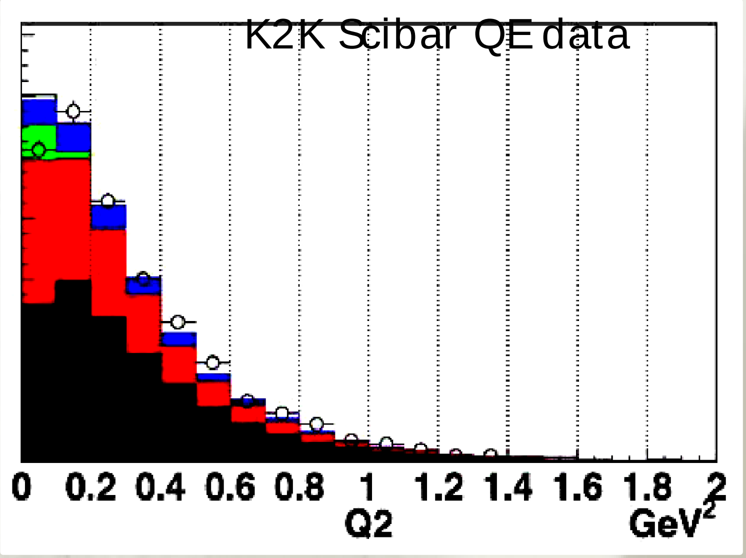
- Experiments need more than cross-sections to operate.
- For the CCQE case:
  - Theory based on CVC and PCAC.
  - Vector form factors from electron scattering.
  - Dipole Axial from factor with a free parameter: Axial Mass.
  - Nuclear effects based on simple Fermi motion and Pauli blocking models--> large impact at low q^2.
  - Poor knowledge at threshold with large nuclear uncertainties.



CCQE: low q^2 deficit

- High statistics sample of CCQE events and event purity in K2K and MiniBoone.
- Data/MC disagreement at low Q^2
  - Signature of nuclear effects?
  - Background? (due to reconstruction method background tends to be at low q^2)
  - Both detectors have low-A target (C,O)





CCQE: MA values

- Large discrepancies.
- Two methods: q^2 shape and cross-section.

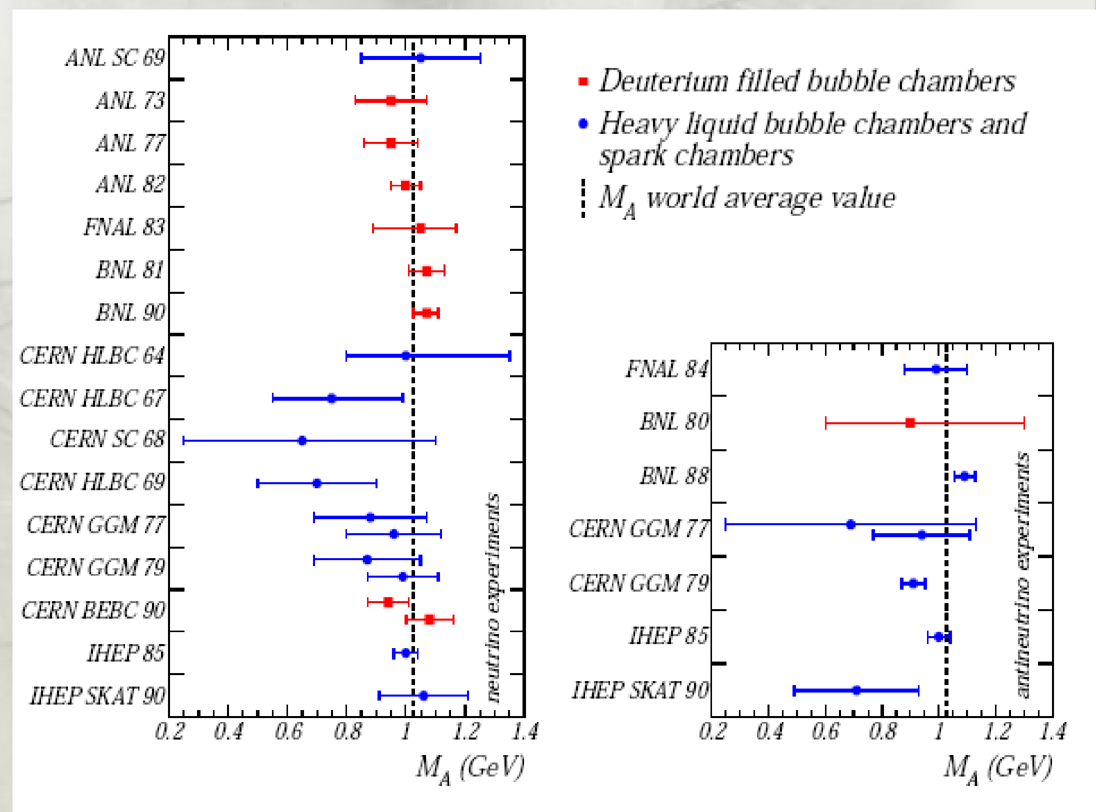
Should they agree?

New results from K2K are large:

MA = 1.2 ± 0.12

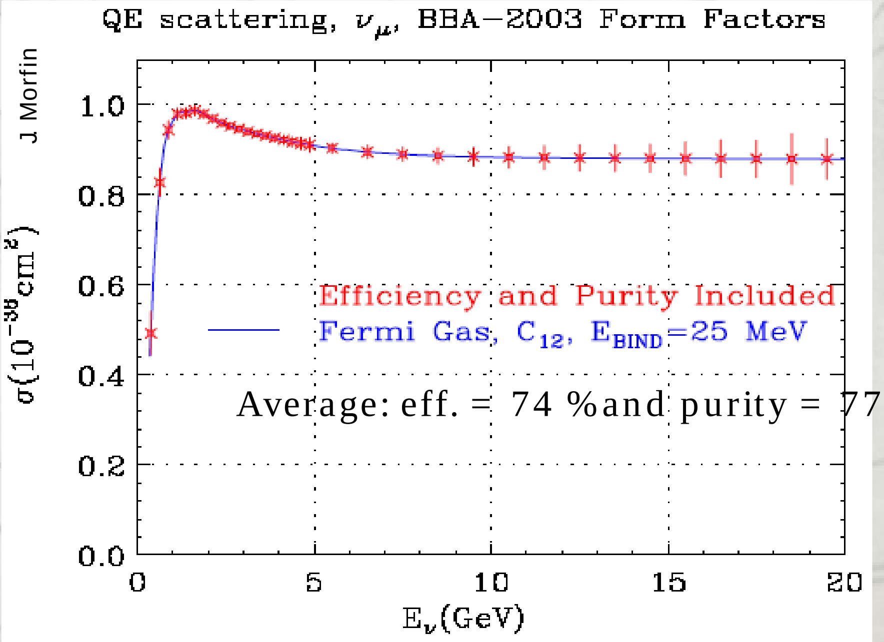
but <u>the systematic erros are dominant.</u>

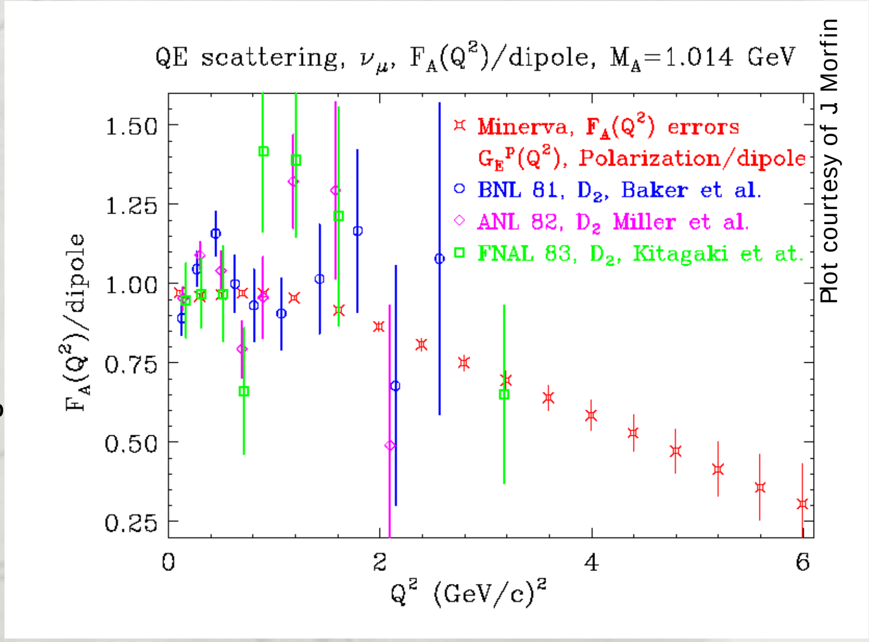
New data from K2K and MiniBoone comming soon.



V.Lyubushkin

CCQE: MINERνA





- **Expect ~800 K events**
- Precision determination of axial vector form factor (F_A), particularly at high Q^2
- Study of A-dependence (C, Fe and Pb targets)
- T2K can also contribute but with very low energy, so it will be more sensitive to nuclear effects.

CC-resonance

3 CC channels for neutrino reactions:

$$\nu + p \rightarrow l^- + p + \pi^+$$
$$\nu + n \rightarrow l^- + p + \pi^0$$
$$\nu + n \rightarrow l^- + n + \pi^+$$

Dominant contributions comes from:

$$\nu + p \rightarrow l^- + \Delta^{++} \rightarrow l^- + p + \pi^+ \qquad \bar{\nu} + p \rightarrow l^+ + \Delta^0 \rightarrow l^+ + p + \pi^-$$
$$\nu + n \rightarrow l^- + \Delta^+ \rightarrow l^- + p + \pi^0 \qquad \bar{\nu} + p \rightarrow l^+ + \Delta^0 \rightarrow l^+ + n + \pi^0$$
$$\nu + n \rightarrow l^- + \Delta^+ \rightarrow l^- + n + \pi^+ \qquad \bar{\nu} + n \rightarrow l^+ + \Delta^- \rightarrow l^+ + n + \pi^-$$

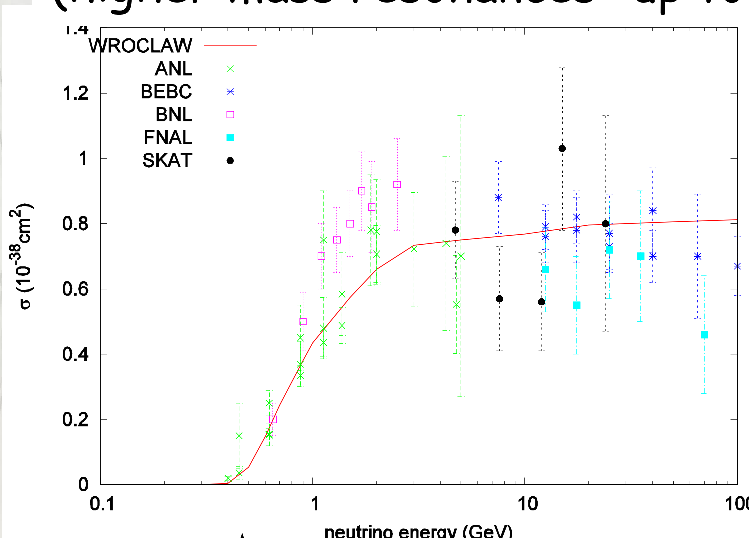
They can be related by isospin relations except for nuclear corrections.

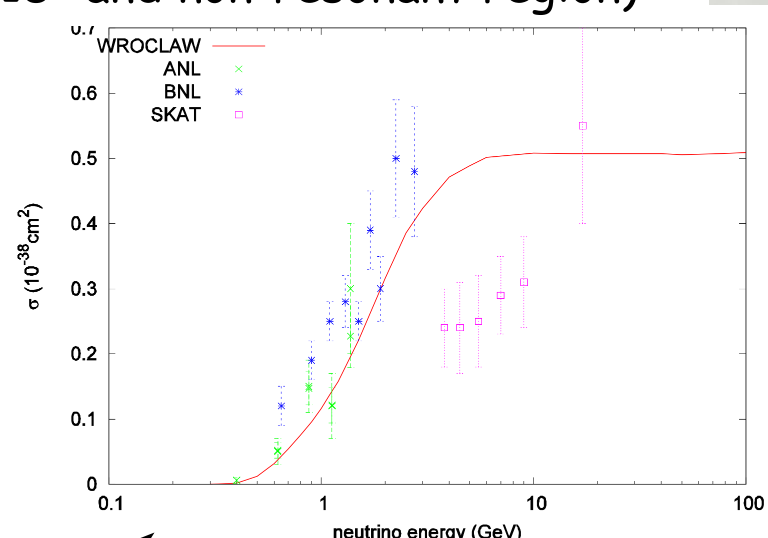
- Theory is built as a mixture of electron data, free parameter and theory as in CCQE.
- One problem are the high W resonances above the 1232 (Axial + Vector)
- The relative amount of them and the transition to the DIS is poorly known.

CC-1π

The overall cross sections for CC1π (with the W ≤ 2 GeV cut):

It is not well measured and it depends on the W cut
(higher mass resonances –up to 18- and non-resonant region)

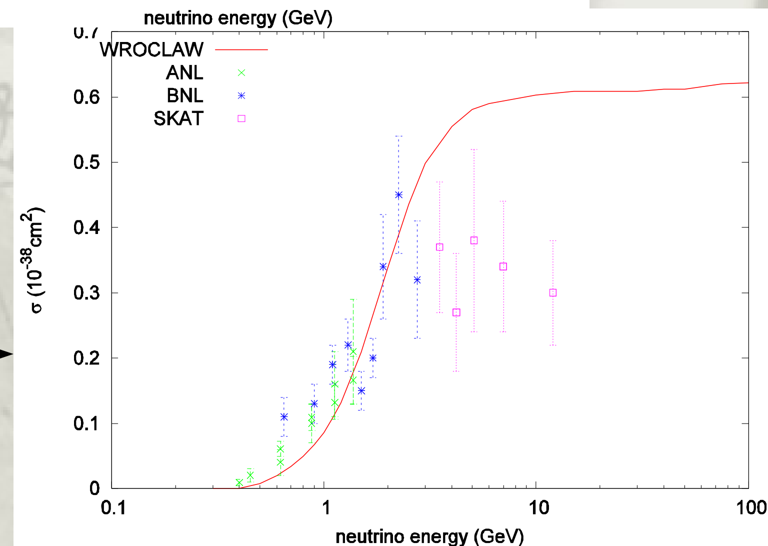




$$\nu + p \rightarrow l^- + p + \pi^+$$

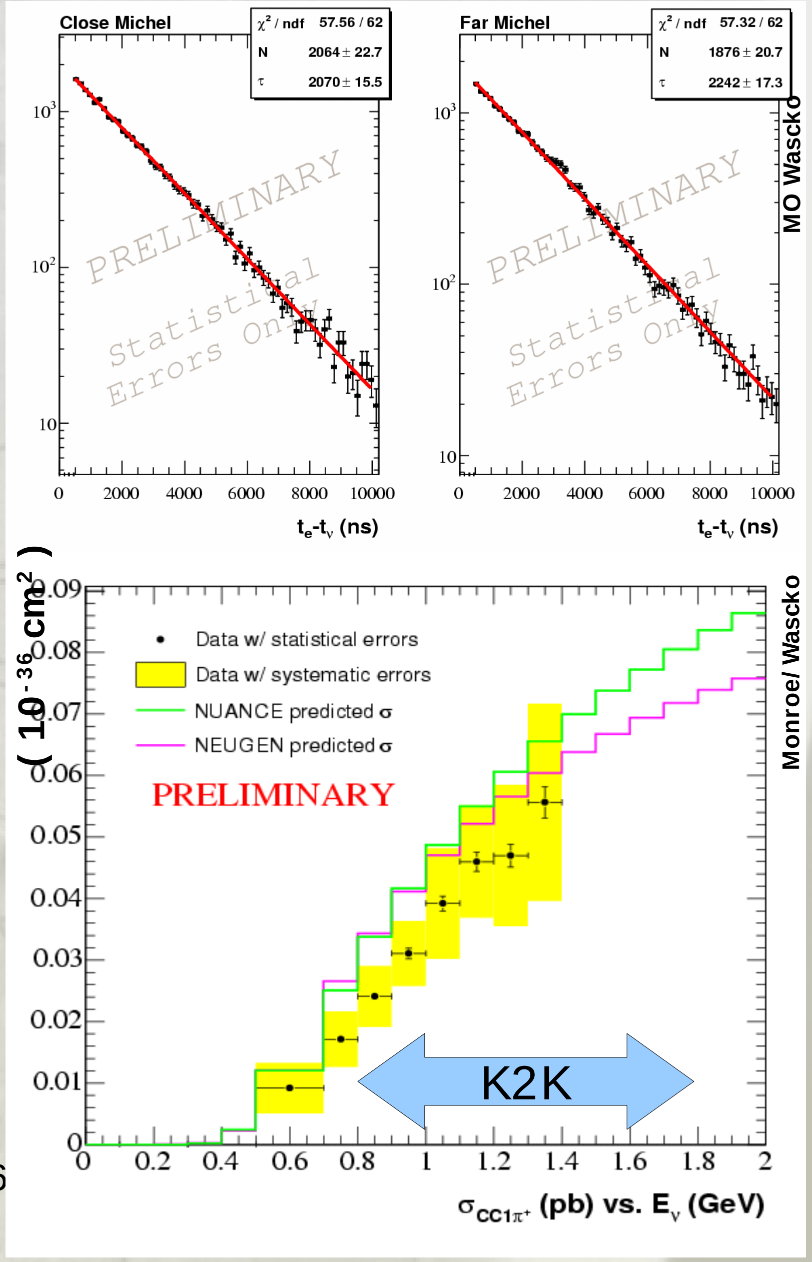
$$\nu + n \rightarrow l^- + p + \pi^0$$

$$\nu + n \rightarrow l^- + n + \pi^+$$



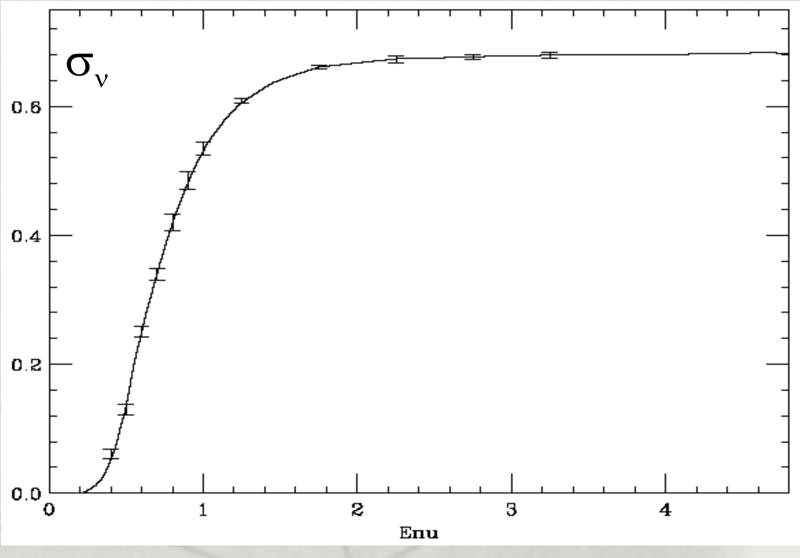
CC1π: MiniBooNE

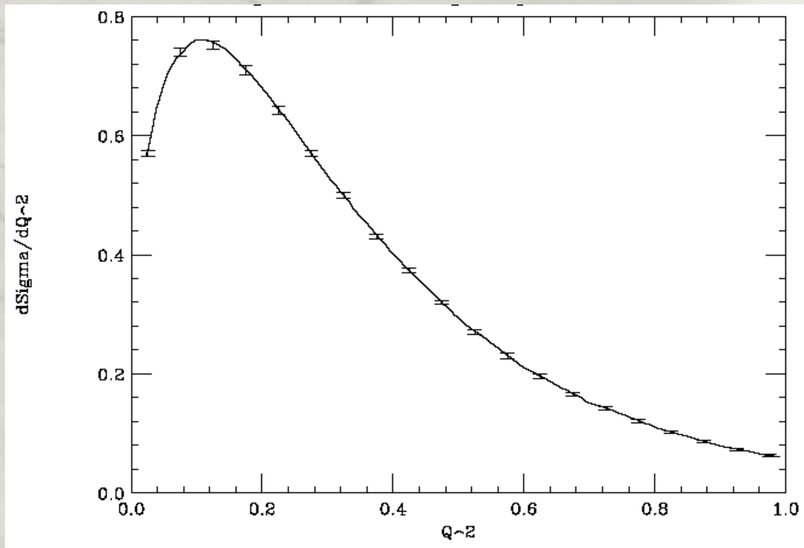
- MiniBooNE selects CC1π events by searching for two Michel electrons
  - High event purity
- Measure cross-section ratio of CC1π/CCQE
- K2K-SciBar is also measuring this cross-section ratio for energies above ~700 MeV. (in preparation).
- We need more than the absolute cross-section…



CC1π: MINERνA & T2K

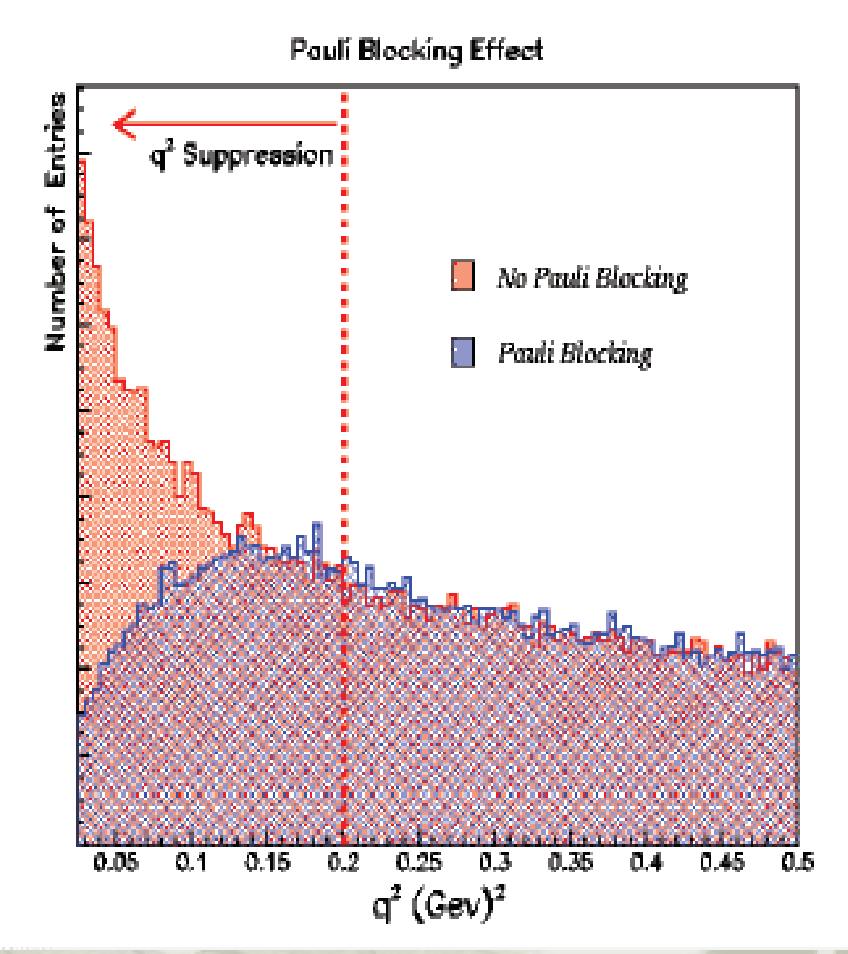
- Expect 1.6M total resonant, 1.2M 1π
  - Precision measurement of σ and dσ/dQ for individual channels
  - Detailed comparison with dynamic models, comparison of electro- & photo production,
  - the resonance-DIS transition region
  - Study of nuclear effects and A-dependence.
  - Measurement of CC1π axial form factors.
- T2K will also have a large statistics (~1M) at the threshold energies.
  - Q^2 and W distributions.

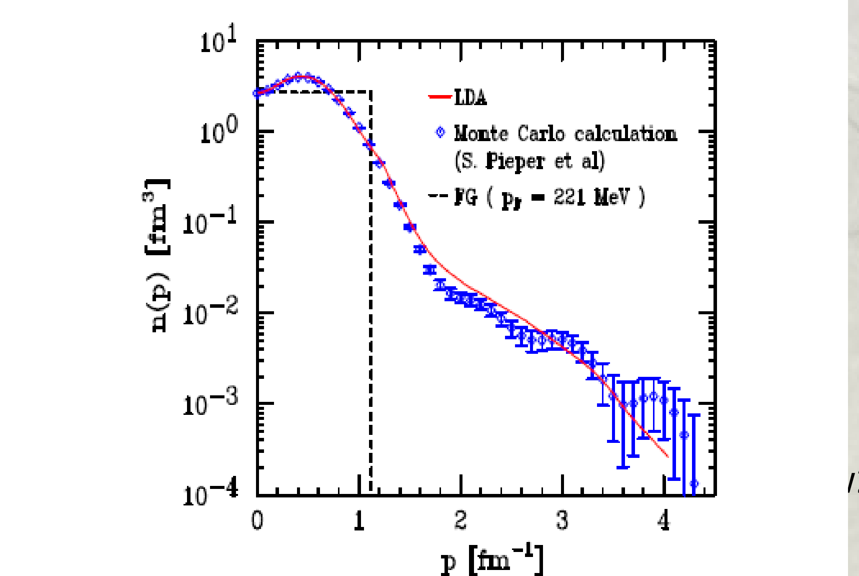




Nuclear effects

- Fermi motion and Pauli blocking affect the cross-section at low q^2 and also introduce and additional smearing in the reconstruction of neutrino energy.





FSI on pions

The hadrons suffer interactions changing nature and kinematics of the particles before leaving the nucleus.

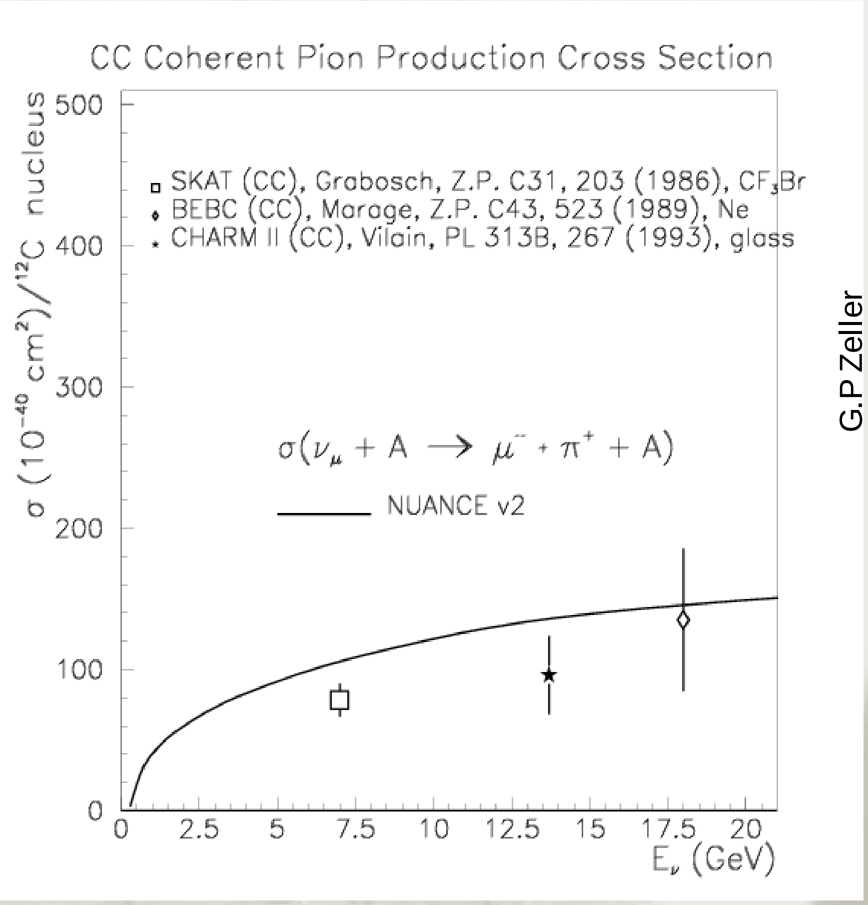
The hadron part is background in some oscillation channels (normally in NC).

Poorly known (±30% in MC) and difficult to measure.

Int. Mode	0 proton	1 proton	2 protons
CCN_{events}	2050	57516	12586
$CC-QE$	0.3%	88.1%	86.1%
$CC-p\pi^+$	22.6%	7.2%	8.2%
$CC-p\pi^0$	5.6%	2.2%	2.3%
$CC-n\pi^+$	58.2%	0.5%	0.8%
$CC-Coh$	0.0%	0.0%	0.0%
$CC-N\pi$	3.4%	0.2%	0.4%
$CC-DIS$	2.3%	0.6%	0.6%
NCN_{events}	12799	16149	3477
$NC-n\pi^0$	6.6%	1.1%	1.8%
$NC-p\pi^0$	0.8%	4.9%	5.1%
$NC-p\pi^-$	0.5%	3.2%	3.2%
$NC-n\pi^+$	3.7%	0.8%	1.0%
$NC-Coh$	0.0%	0.0%	0.0%
$NC-N\pi$	0.2%	0.3%	0.4%
$NC-\Lambda K^+$	0.2%	0.0%	0.0%
$NC-DIS$	0.4%	0.5%	0.6%
$NC-Ep$	0.0%	67.7%	60.5%
$NC-En$	86.5%	20.5%	26.1%

CC1π: Coherent Pion Production

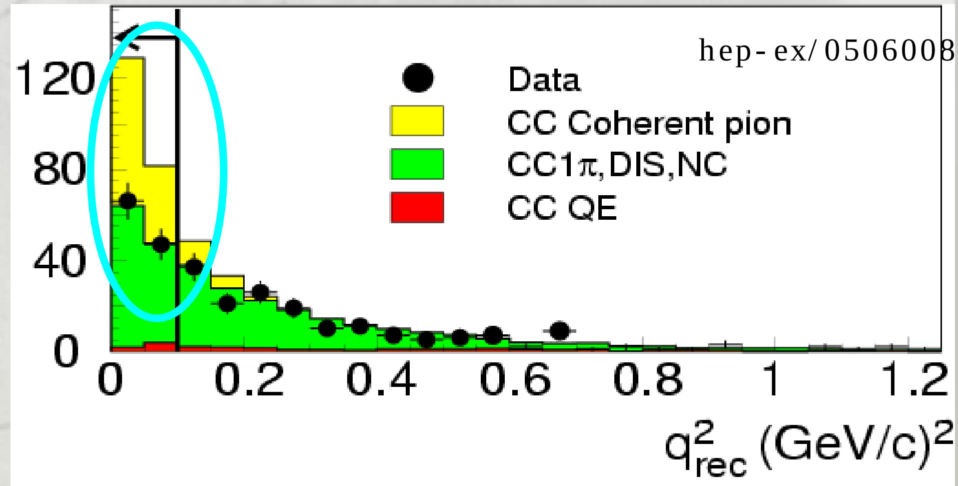
- Neutrino interacts coherently with entire nucleus
- Low momentum transferred to nucleus
- Muon, pion peaked in forward direction
- Depends on A
- Similar cross section for ν, $\bar{\nu}$

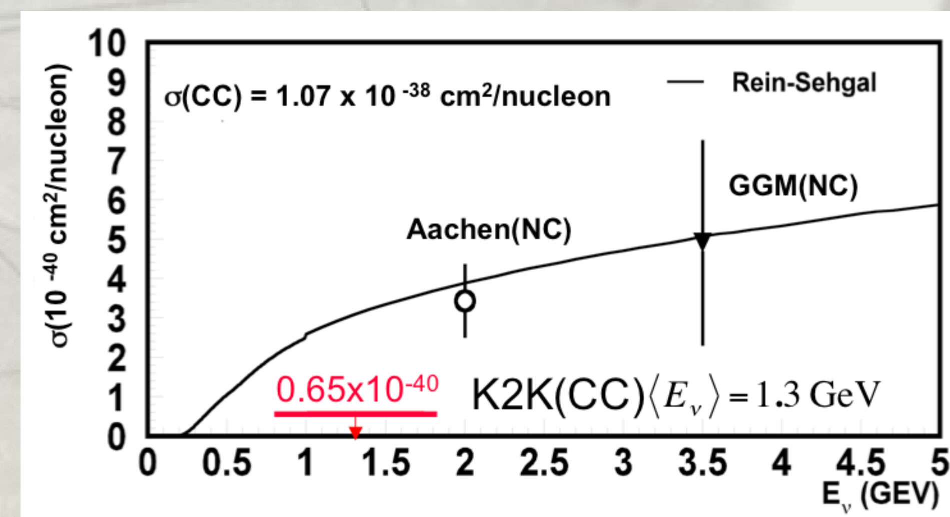


G.P Zeller

CC Coherent π: K2K

- SciBar detector data
  - Carbon target
  - PRL 95, 252301 (2005)
- Select events with two reconstructed tracks, consistent with μ,π
  - Low activity in vertex
- MC predicts excess events at low Q^2
- Fitting Q^2 distribution yields 7.6±50.4 events
  - Expect 470 from plain Rein-Sehgal model. Modified models predict lower yields.
- No evidence for coherent production





Tanaka

New analysis in preparation with better sensitivity.

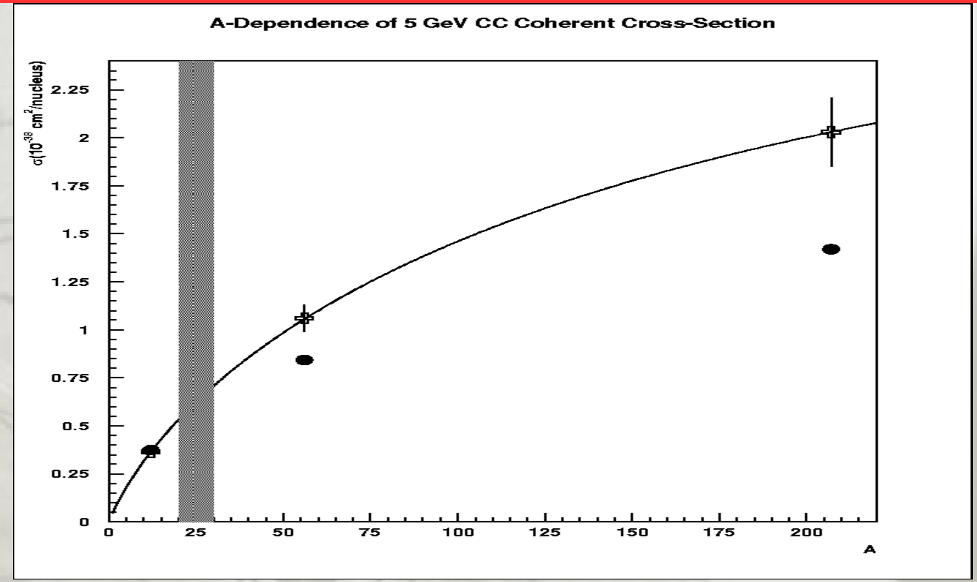
Coherent π: MINERνA & SciBoone

Several models to explain the deficit

- Rein-Sehgal
- Paschos
- Oset

- Experimentalist need the full kinematics of the event, not only the cross.sections.

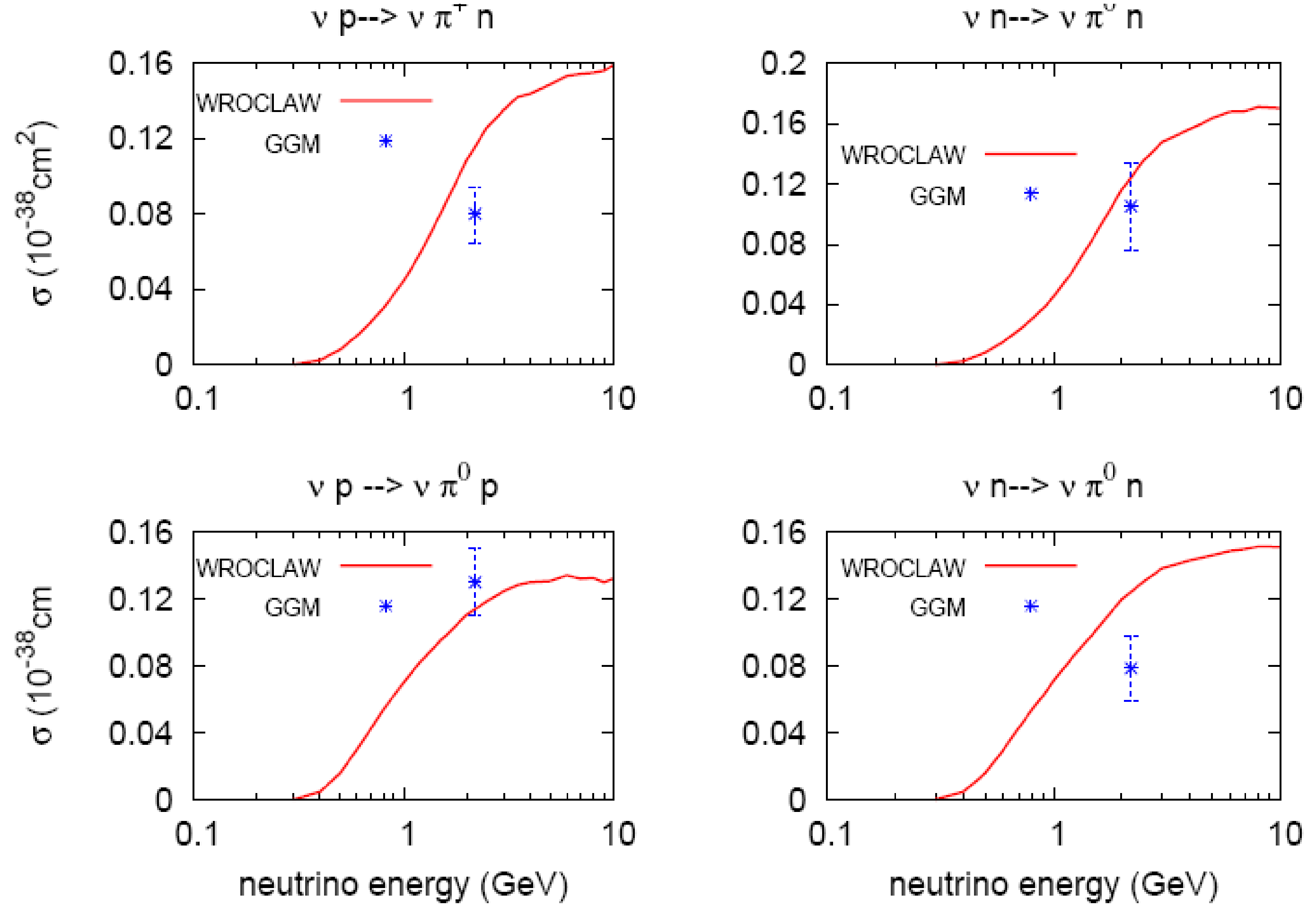
MINERνA's nuclear targets allow the first measurement of the A-dependence of σ_{coh} across a wide A range



SciBoone will run with antineutrinos: improved sensitivity.

NC-1π

Very little is known about NC pion production:



(NC π^0 and π^{+-} production are important backgrounds!)

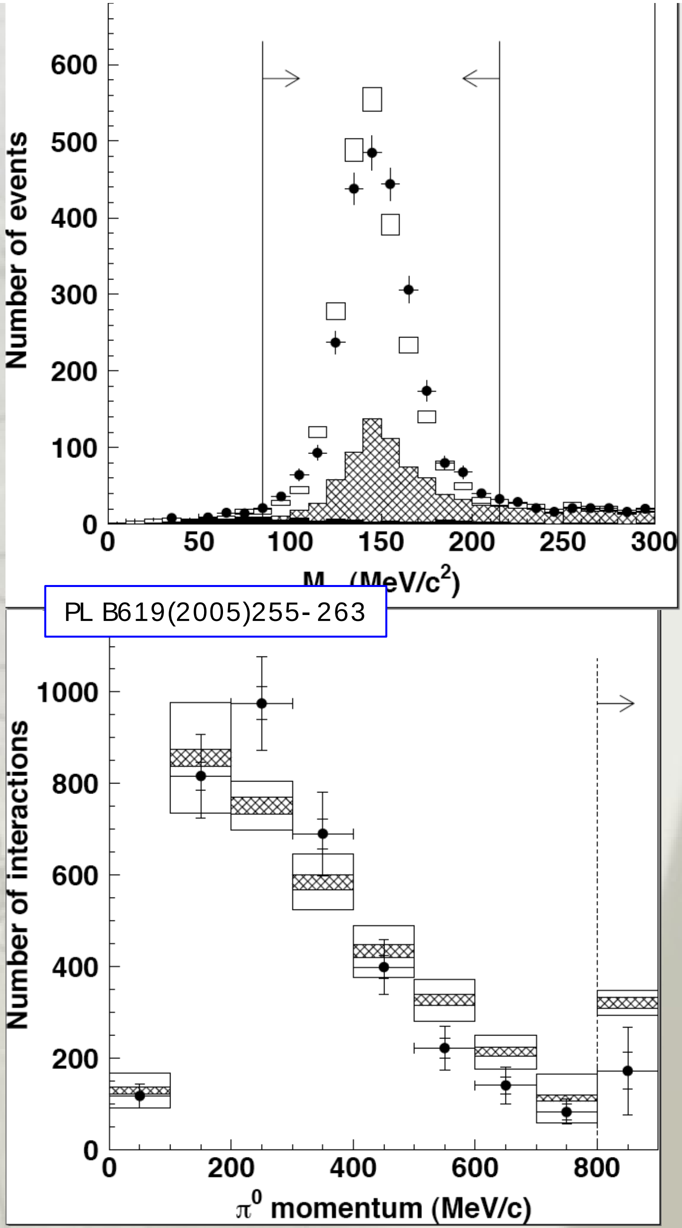
NC1π^0: K2K

New analysis with C target in preparation.

- 1kt detector
  - Oxygen target
  - PLB 619, 255 (2005)
- Good data/MC agreement in the ratio of NC1π^0/CC events:

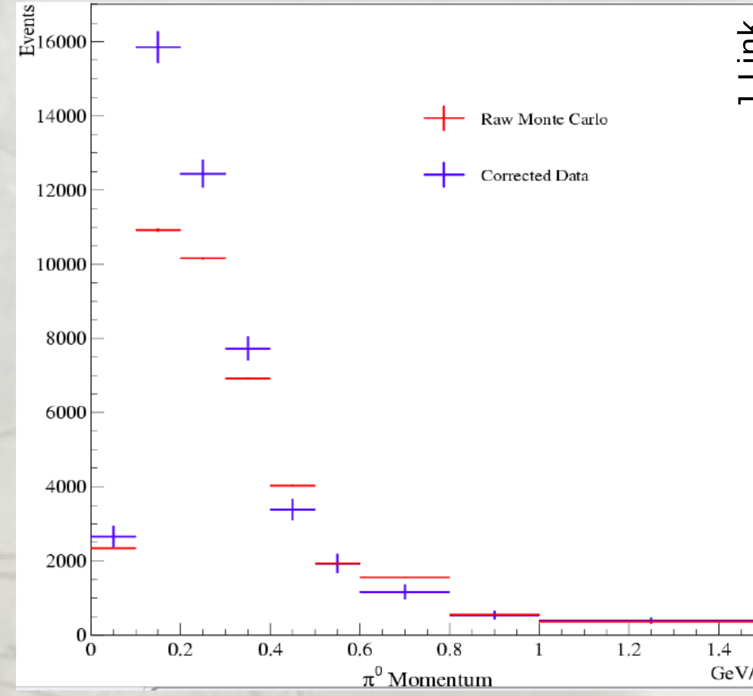
  $\sigma_{NC1\pi 0}/\sigma_{CC\text{-}all}$ =0.064±0.001 ±0.007

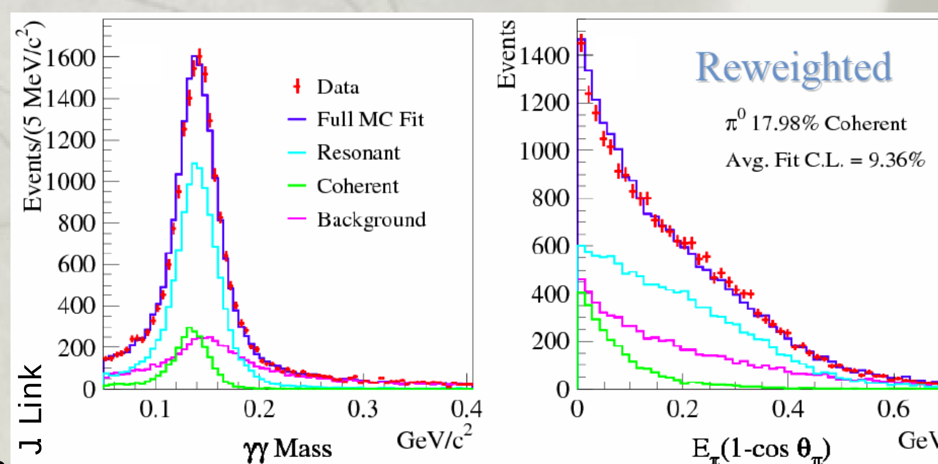
  MC:0.065
- Observe difference in $p_{\pi 0}$ distributions of data &MC
  - NC1π^0 backgrounds come from asymmetric decays



NC1π^0: MiniBooNE

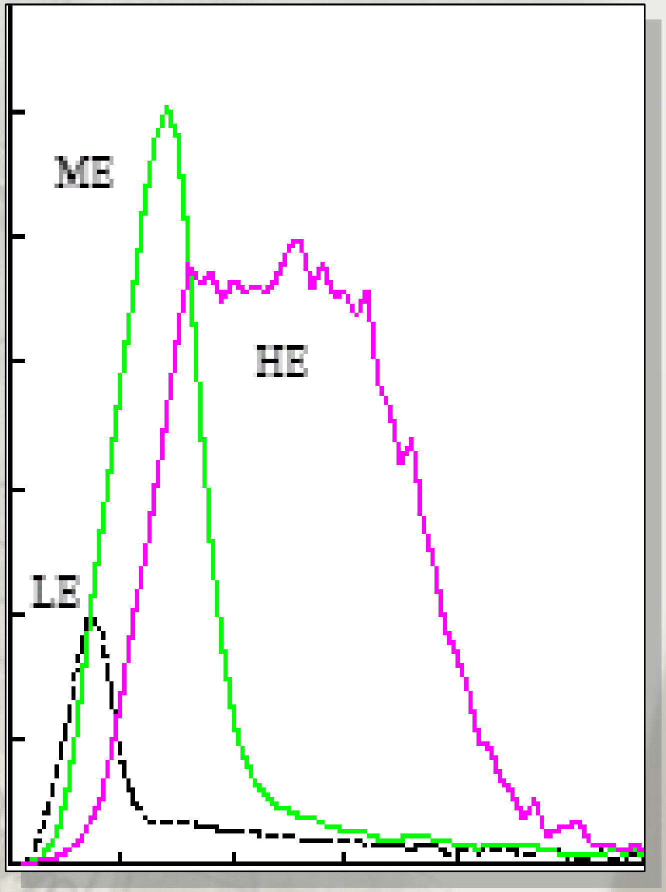
- Like K2K, slight MC/data *shape* disagreement in $p_{\pi 0}$
- Reweight MC according to observed $p_{\pi 0}$ spectrum
- 2D fit to angular distribution and π^0 mass to extract coherent fraction
  - Use NUANCE, Rein& Sehgal
- Find reduced, but non-zero, coherent fraction
  - Differs from CC coherent limit set by K2K!





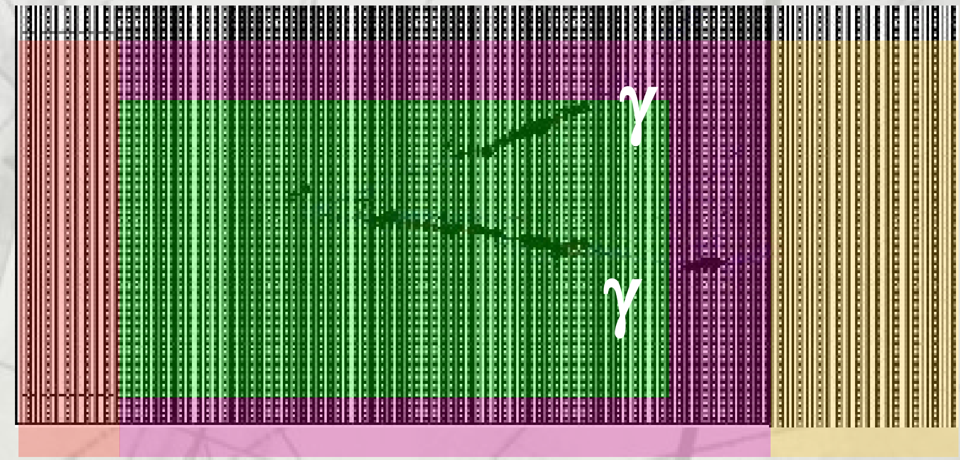
Neutral currents

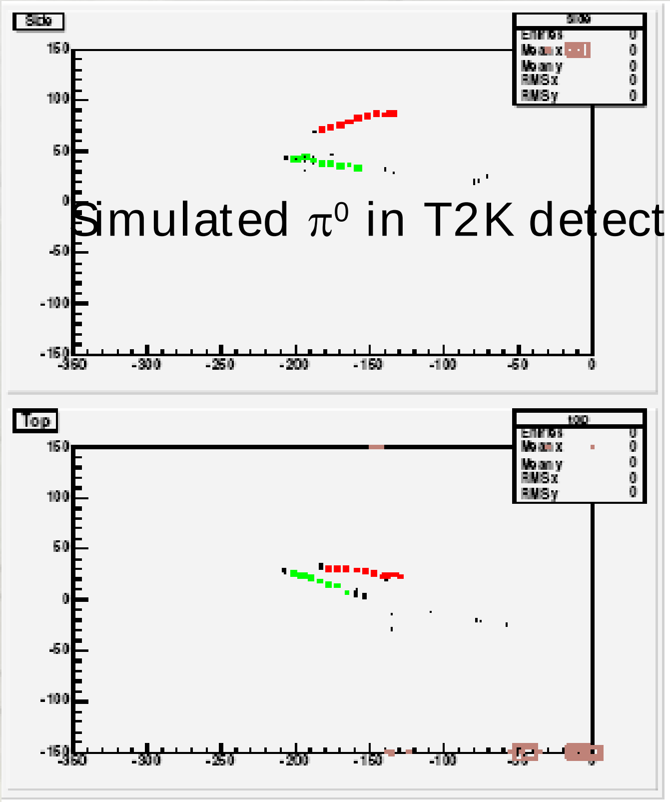
- Need an energy dependency:
  - Minerva: variable beam.
  - SciBoone/K2K: same detector, 2 beams.
  - T2K shows a running energy across the detector: enough?



NC1π^0: MINERνA & T2K

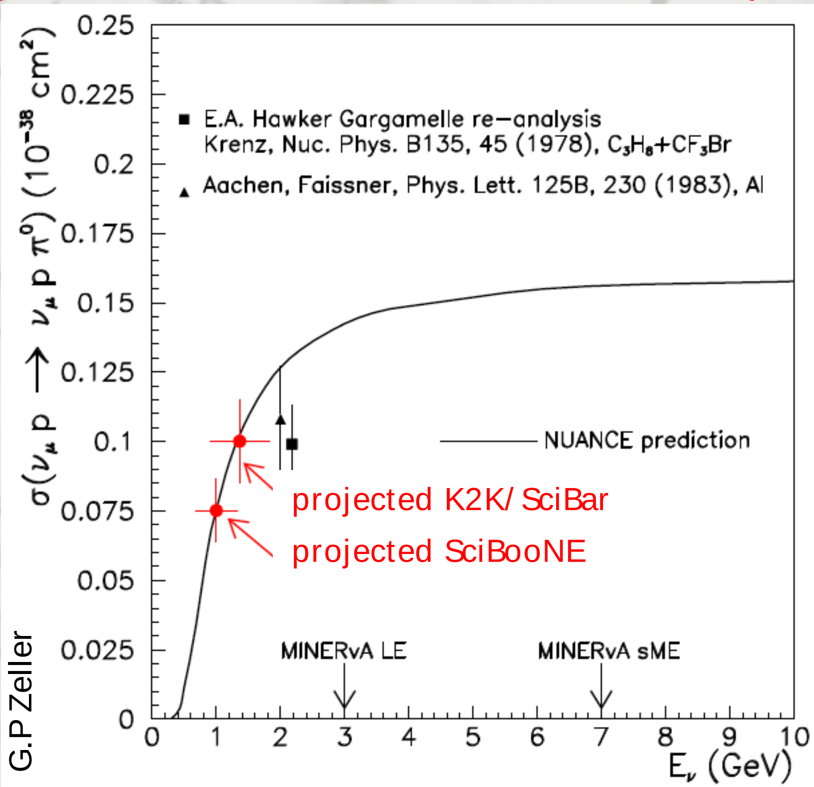
Simulated π^0 in MINERνA detector

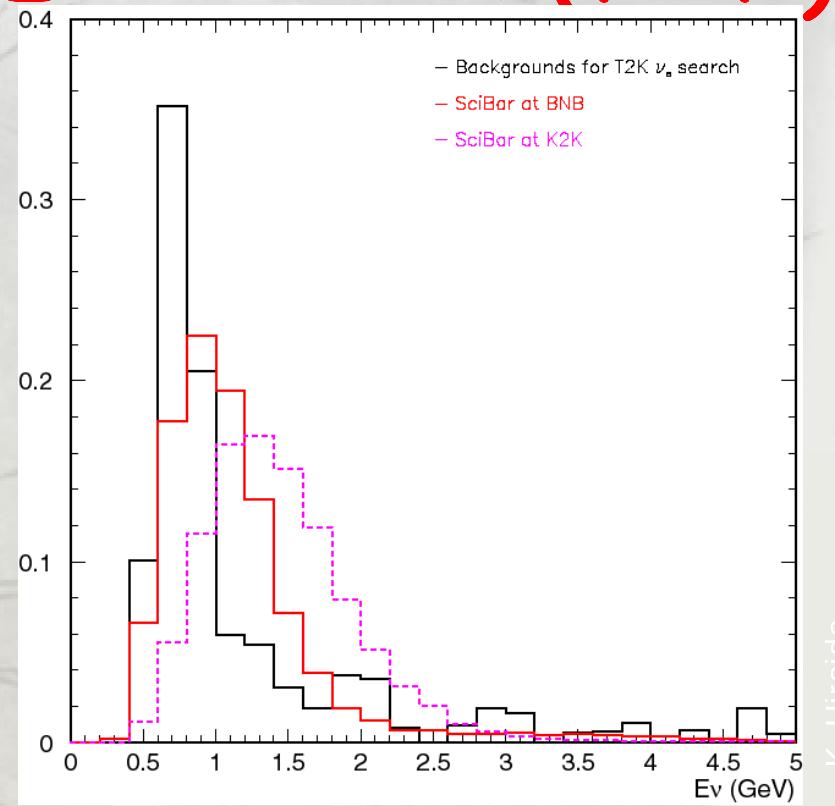




- Clean identification of π^0's
- Extremely good π momentum reconstruction
- Minerva: Running in >1 energy mode would allow understanding of NC1π^0 background.
- Detector in T2K designed to measure the neutral pion production in Carbon and water.

NC1π^0: SciBooNE + SciBar(K2K)





- Exactly the same detector used to measure NC1π^0 in two beams different beams.

Antineutrinos: T2K&SciBoone

- Very useful for measurements beyond antineutrino oscillations:
  - MA & CC-QE studies
  - CC1π
  - Coherent podiction is enhanced in antineutrinos.
- The main problem with antineutrinos is the large intrinsic neutrino background.
- SciBoone will run with antineutrinos.
- T2K is able to run with neutrinos and antineutrino beams and it is the only one of the new generation equiped with a magnetic field.

I did not mention

- DIS Measurements
  - NuTeV
  - NOMAD
  - MINOS
  - MINERνA
  - T2K-ND?
- τ channels
  - OPERA, ICARUS
- Charm production (key for neutrino factory)
    - Nomad
    - Minerva …

Conclusions

- The knowledge of the low energy neutrino cross-section (<5Gev) is critical for the next generation of neutrino oscillation experiments.
- We are lacking knowledge on the absolute cross-sections, nuclear effects, final state kinematics...
- A new generation of experiments: near detectors of oscillation experiments or devoted ones.

Conclusions

- The new experiments:
  - Large estatistics (T2K,Minerva,SciBoone, MiniBoone)
  - Magnetic field (T2K)
  - Neutrino and antineutrino runs (SciBoone, T2K?)
  - Variable neutrino spectrum.