# Experimental studies of low energy charged current neutrino interactions

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# Outline

This talk focuses on new results in the few GeV-neutrino energy region.

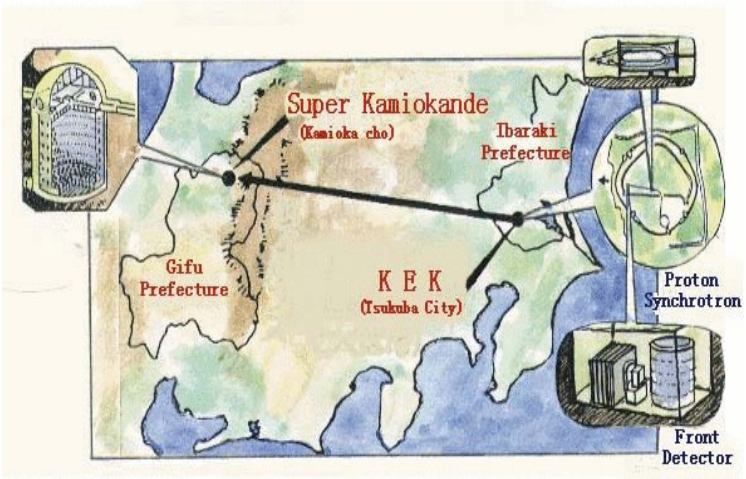
- Recent experiments:
  - K2K, MiniBooNE, SciBooNE.
- Results on:
  - CC quasi-elastic
  - CC resonance production
  - CC coherent pion production
- Conclusions
- Outlook

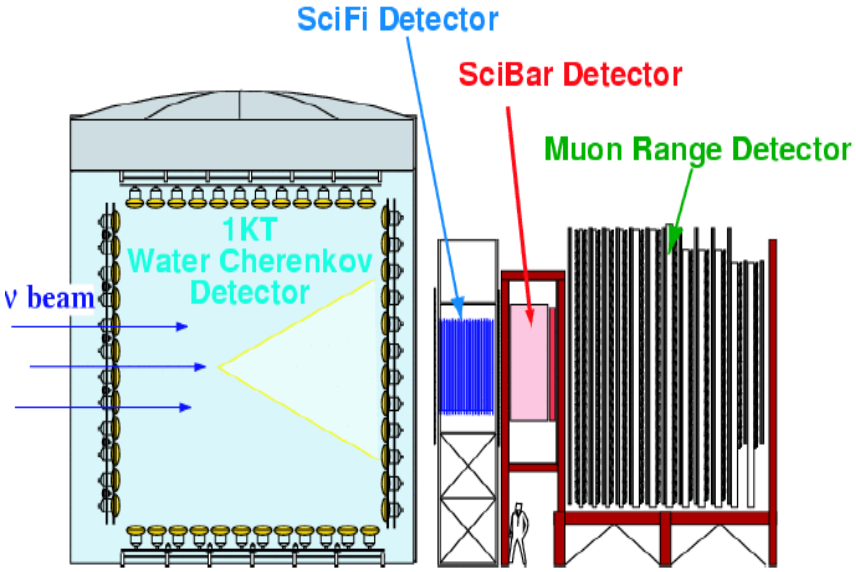
# Brief experimental description of

# K2K, MiniBooNE and SciBooNE

# K2K Experiment

- Experiment type: neutrino oscillation experiment
- Main goal: measure the $\nu_\mu$ disappearance.
- Run Period: 1999-2004
- $<E_\nu>=1.2$ GeV
- Detector type(near detector):
  - 1Kt detector: Cherenkov detector
  - SciFi-detector: Segmented tracker
  - SciBar-detector: Segmented tracker
- Main nuclear target:
  - SciFi (water/aluminum):Oxygen
  - 1Kt Detector (water): Oxygen
  - SciBar (scintillator) :Carbon
- Statistics: ~$10^4$ $\nu$ interactions



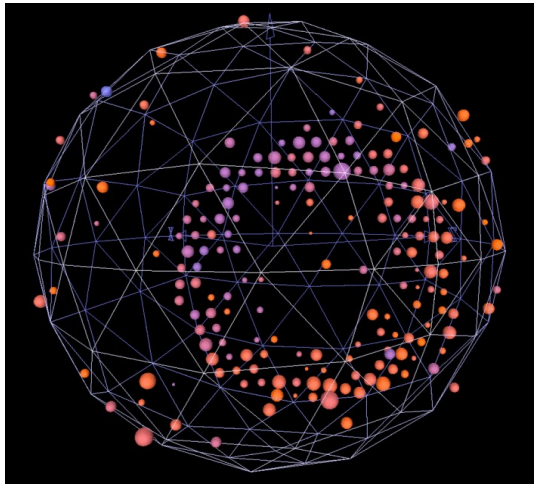




*K2K-Near Detector*

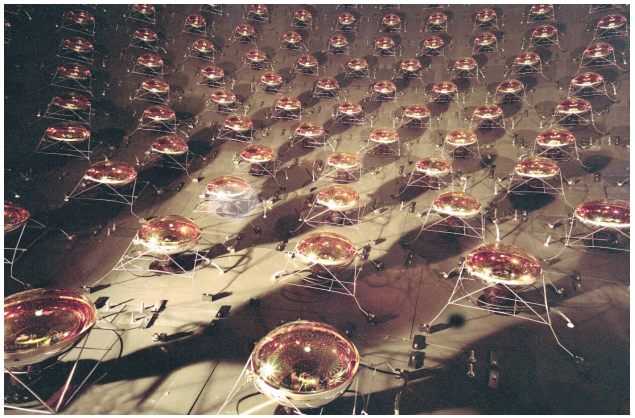
# MiniBooNE



- *Experiment type: neutrino oscillation experiment*
- *Main goal:* to confirm/rule out the LSND results.
- *Run Period: 2002 - present*
- $<E\nu>$=0.8 GeV
- *Detector type*: spherical cherenkov detector
- *Main nuclear target (mineral oil)* : Carbon
- *High statistics*: ~$10^6$ $\nu$ interactions (200k CCQE events)
- Fiducial Volume:~450 ton (5 m radius)



*MiniBooNE event Display.*

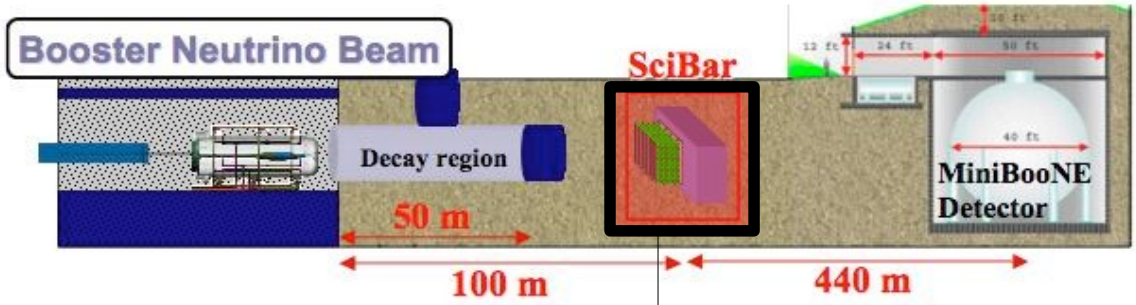


*MiniBooNE PMT's*

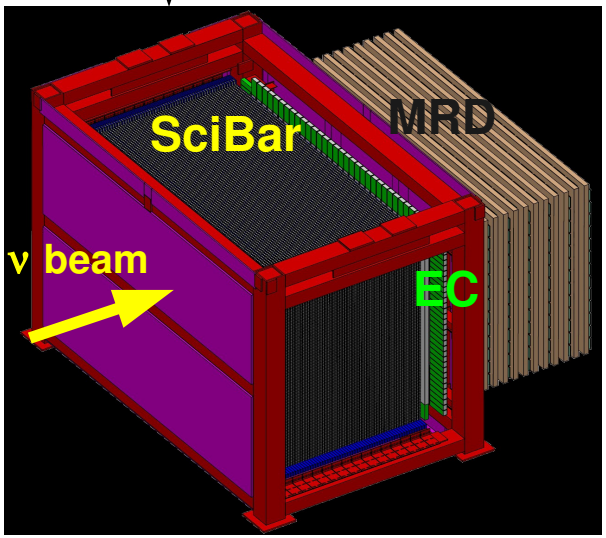
# SciBooNE



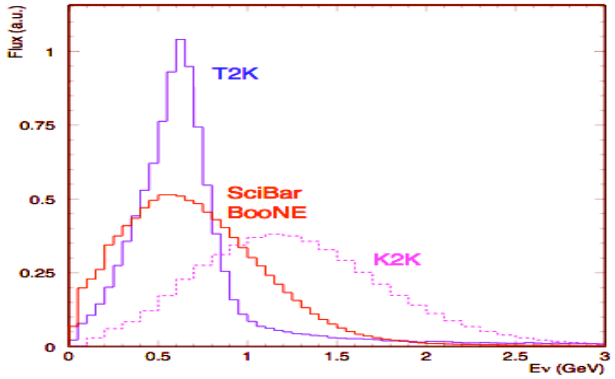
- *Type: neutrino scattering experiment*
- *Main goal:* designed to measure **the ν and $\bar{\nu}$ cross section** at low energies.
- *Run Period: June 2007 - present*
- *<Enu>*=0.8 GeV (FNAL BNB).
- *Detector type*: tracker detector.
- *Main nuclear target*: Carbon (iron also available).
- *High statistics*: ~$10^4$ CC events
- Fiducial Volume: ~10 tons

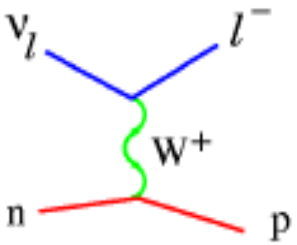



*SciBooNE Neutrino Beam Line.*

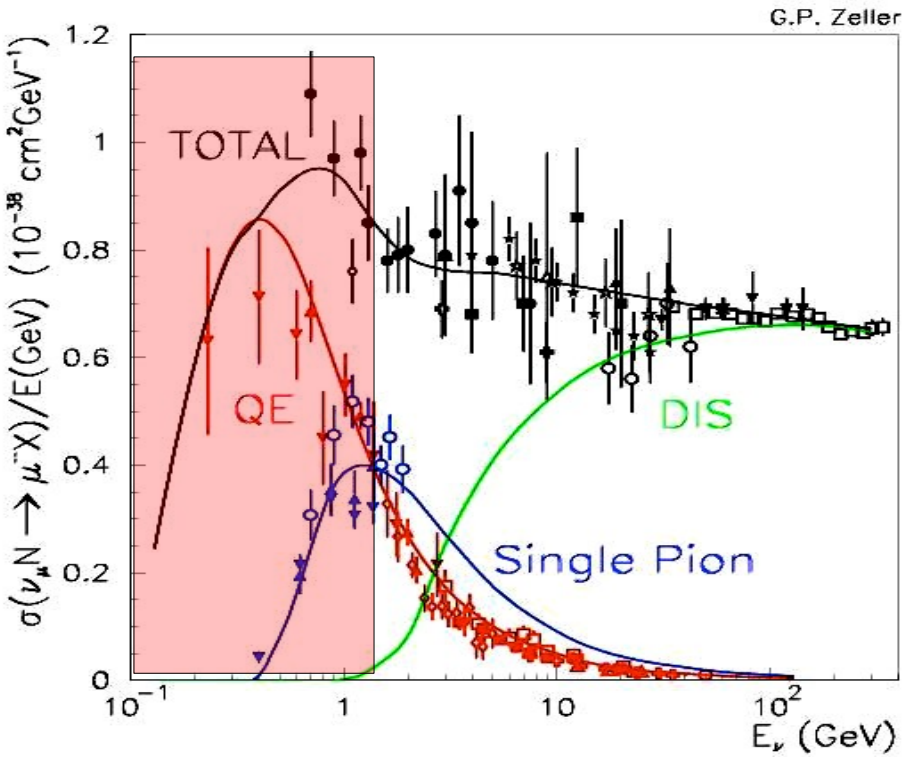



*SciBooNE detectors*

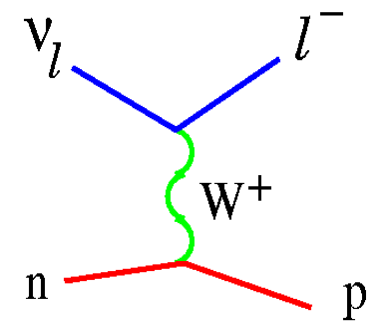





# CC Quasi-Elastic



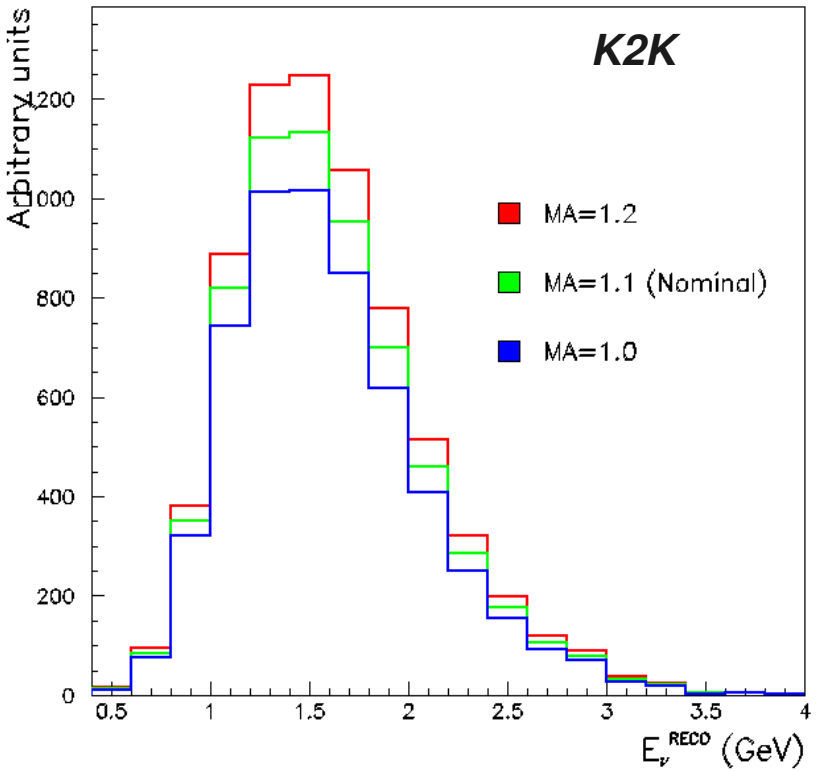
In the Llewellyn Smith formalism, the differential cross section of this process is described as follows:




$$\frac{d\sigma}{dQ^2} = \frac{m_N^2 G_F^2 |V_{ud}|^2}{8\pi(\hbar c)^4 E_\nu^2}[A(Q^2) \pm B(Q^2)\frac{(s-u)}{m_N^2} + \frac{C(Q^2)(s-u)^2}{m_N^4}]$$

- Where A, B and C are expressed in terms of two vectors (f1,f2) and one axial ($F_A$) form factors.
- The vector form factors can be obtained from electron scattering experiments.
- The axial form factor is assumed to have a dipole form:
  - $F_A(q^2) = \frac{F_A(0)}{(1+q^2/M_A^2)^2}$ , where F(0) is obtained from beta decay.
- The only free parameter to calculate σ is the $M_A$ (axial mass).

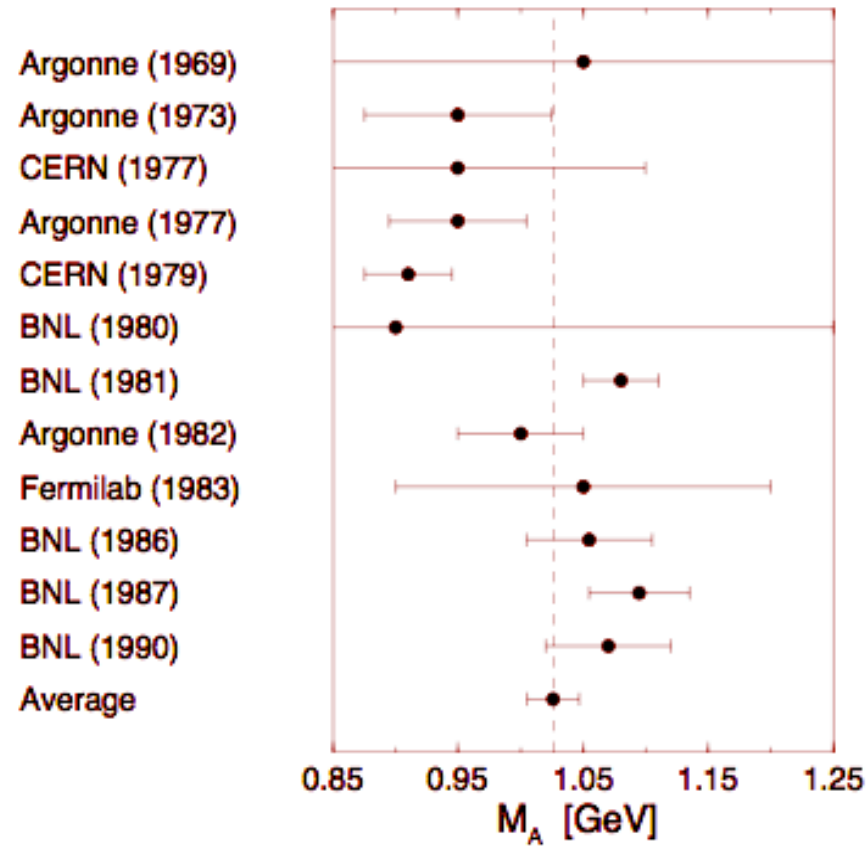
- $M_A$ effects:
  - Change the cross section.
  - Modify the $Q^2$ shape.
- Two ways to determine $M_A$:
  - $Q^2$ shape:
    - Advantage: Does not require flux normalization.
  - Total cross section




*Neutrino $\sigma$ .vs. neutrino energy for different $M_A$ values in the MC.*

# Past Experiments

- *Run Period* :1969-1990
- *Main targets:* deuterium, propane/freon, aluminum.
- *Detector types:* Bubble chambers, segmented trackers.
- *Statistics:*~$10^3$ $\nu$ interactions (poor statistics!)




*hep-ph/0107088v1*

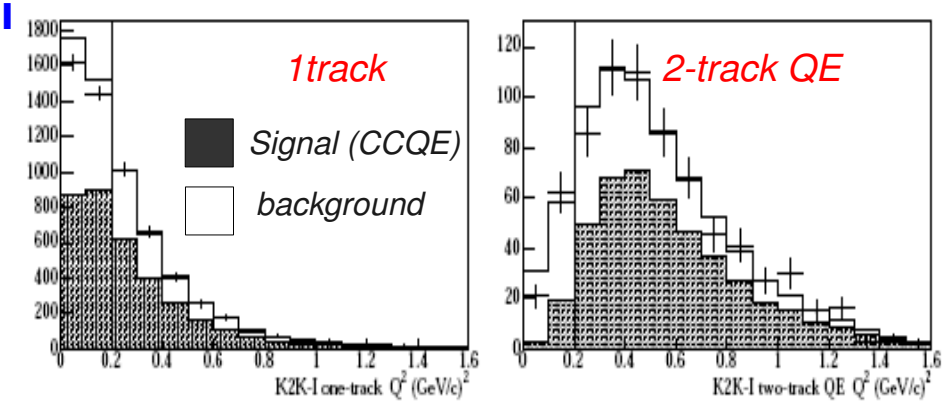
**World average:**
**MA** = 1.026 ± 0.021 **GeV**

# K2K: SciFi && SciBar

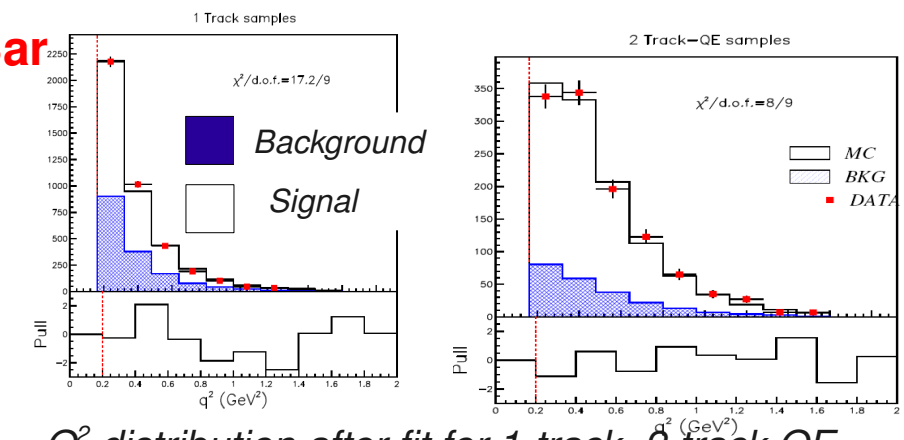


- Fit the shape of Q2 distribution.
- ***A deficit at low-$Q^2$ region was observed.***
- $Q^2$<0,2 $GeV^2$ region is not used for the fit to reduce uncertainties from nuclear effects.
- Compatible results between each other but higher than the world average.
- Dominant systematic uncertainties coming from momentum scale and ν-flux shape.

**SciFi**




**SciBar**




*$Q^2$ distribution after fit for 1-track, 2-track QE .*

| Sources of uncertainty | Error in MA |
|---|---|
| Muon momentum scale | 0.07 |
| Relative Flux and normalization | 0.06 |
| $M_A$ 1-π | 0.03 |
| nonQE/QE | 0.03 |
| Proton rescattering | 0.03 |
| Statistics | 0.03 |
| Total | 0.12 |

*SciFi* *hep-ph/0603034v1*

**SciFi (oxygen):**

**MA = (1.20 ± 0.12) GeV**

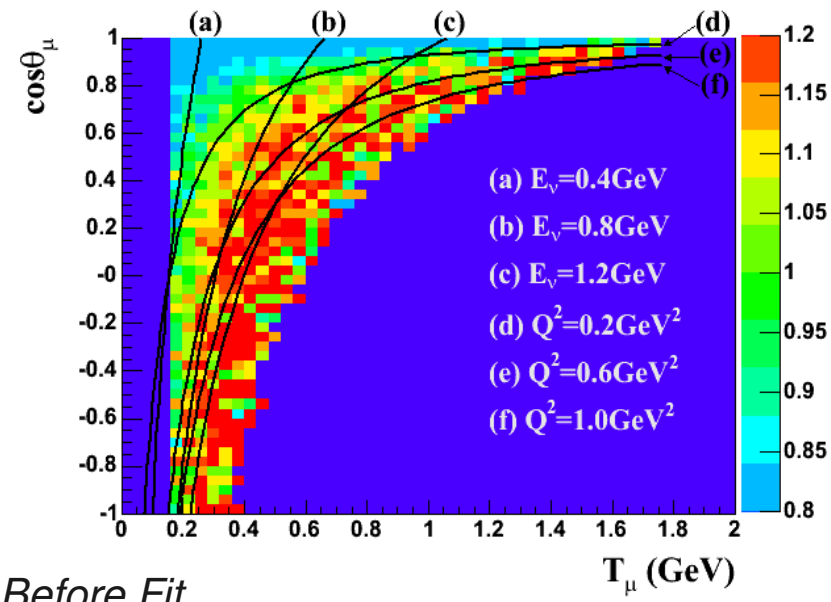
**SciBar (Carbon):**

**$M_A$ = 1.144 +- 0.077(fit)**

**+ 0.078 -0.072 (syst)**

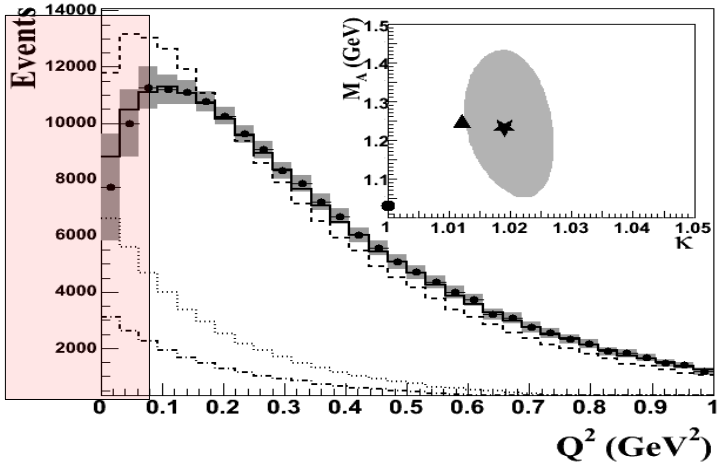
- High statistics: 2D histogram using μ-angle and μ-Energy.
- Data/MC disagreement follows the $Q^2$ lines not the Eν lines. Then, the discrepancy comes from the $\sigma_{\nu\mu}$, not from νμ– flux prediction.
- DATA deficit at low $Q^2$ region but with different treatment:
  - Tuning the RFG model: (κ): to control the strength of the Pauli suppression.

data/MC ratio in RFG




*Before Fit*

*T. Katori, Nuint07*




*(PRL 101, 032301 (2008))*

# MiniBooNE

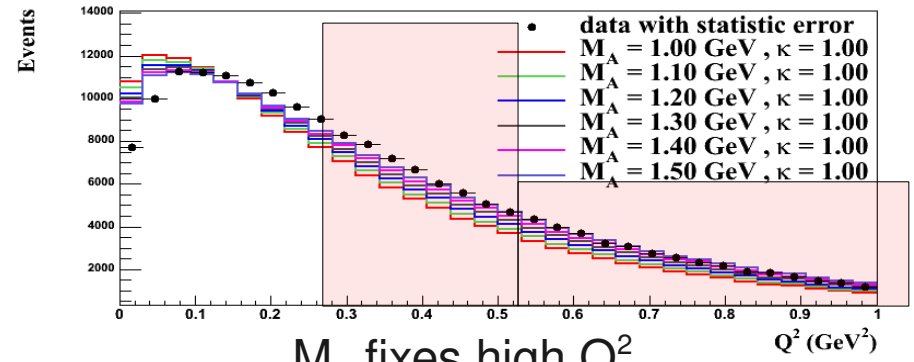


- Pauli Blocking parameter ($\kappa$) fix the low $Q^2$ region.
- $M_A$ is fixing the high $Q^2$ region.
- The dominant systematic uncertainties comes from the detector model.

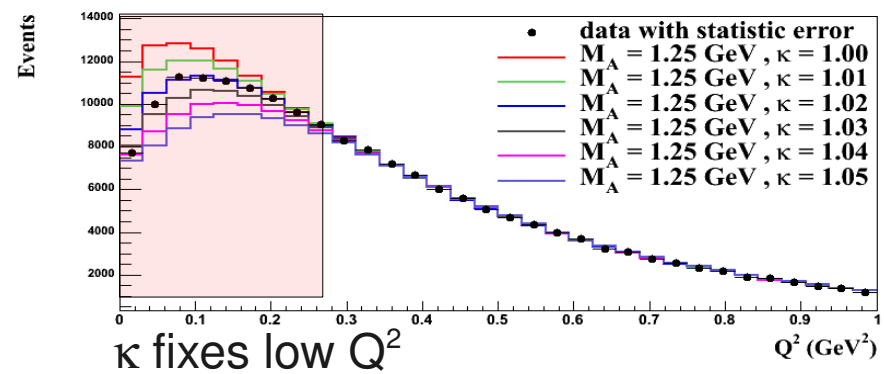
| error source | $\delta M_A^{\text{eff}}$ | $\delta\kappa$ |
|---|---|---|
| data statistics | 0.03 | 0.003 |
| neutrino flux | 0.04 | 0.003 |
| neutrino cross sections | 0.06 | 0.004 |
| detector model | 0.10 | 0.003 |
| CC $\pi^+$ background shape | 0.02 | 0.007 |
| total error | 0.20 | 0.011 |

*Uncertainties of $M_A$ and the Pauli blocking parameter in the fit.*

*Q2 shape of the backgroun d events*

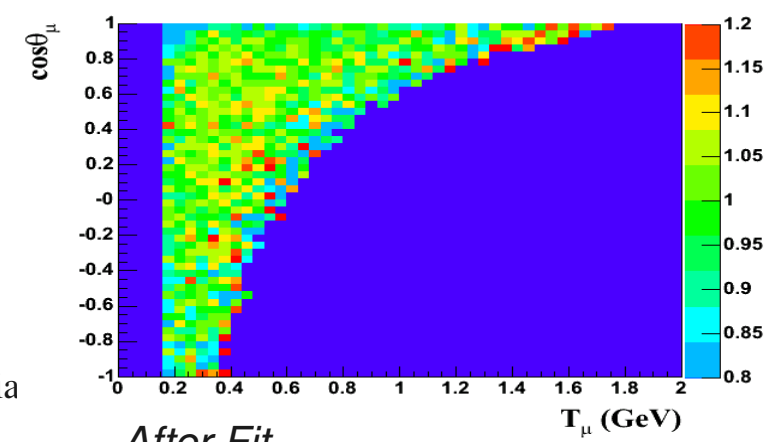



$M_A$ fixes high $Q^2$




$\kappa$ fixes low $Q^2$

*T. Katori, NuInt07*




*After Fit*

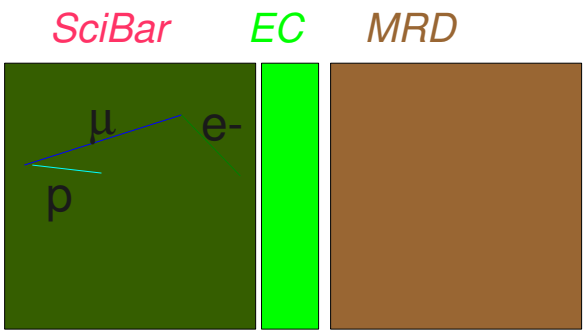
**$M_A$ = 1.23 ± 0.20(stat+sys)**

**$\kappa$ = 1.019 ± 0.011(stat+sys)**

First look at $\nu$ data!

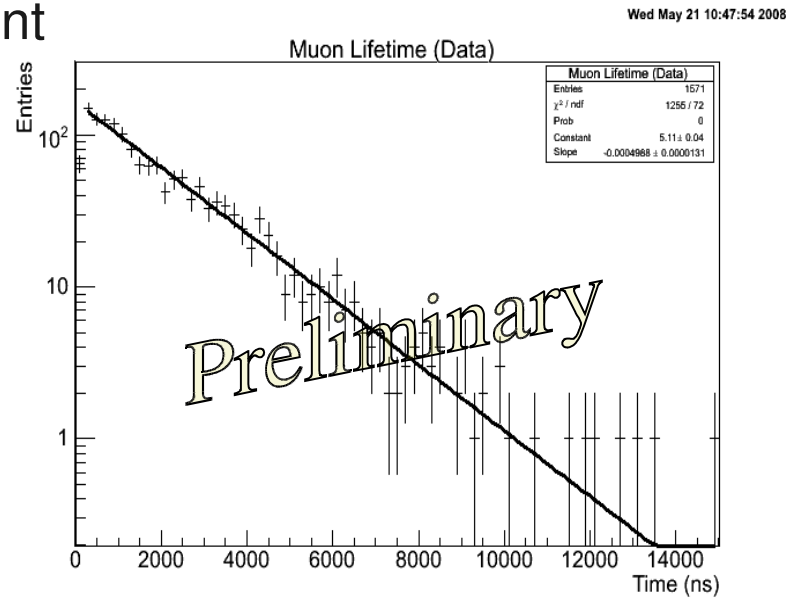


2 independent analyses, covering all the $E_\nu$ spectrum.




**SciBar contained muons (low energy events):**

- Events completely contained in SciBar.
- The SciBar stopped muons are tagged using Michel e- information.
- Muon lifetime: (2.003+-0.047)x$10^{-6}$s ( is in agreement with Suzuki et al., PRC 35 ,(1987) ).



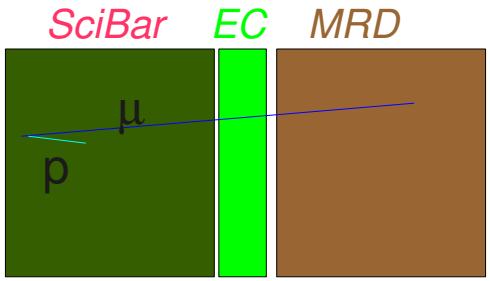

*Muon lifetime distribution for CCQE sample selection.*

# SciBooNE

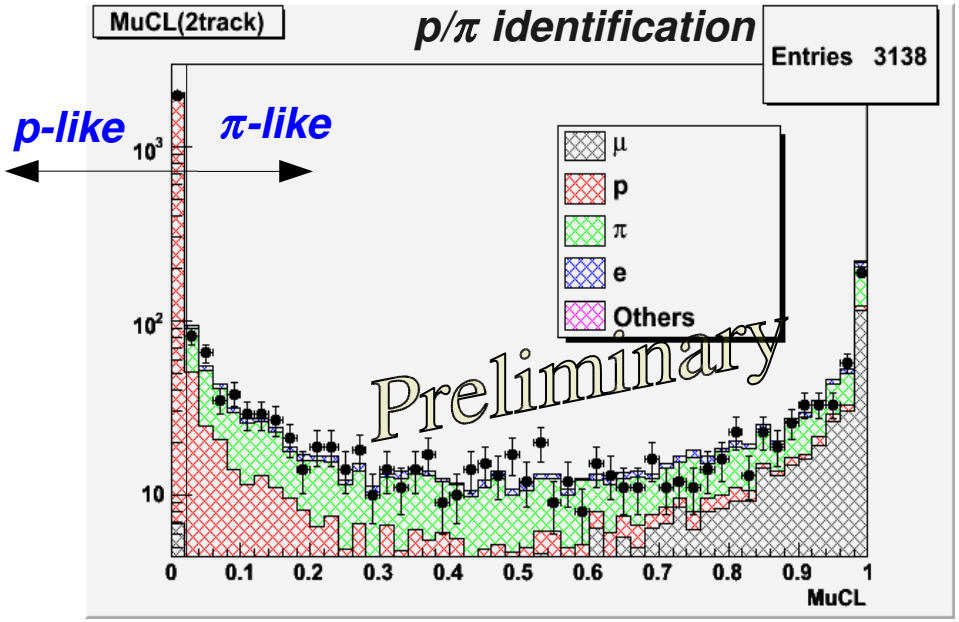
First look at $\nu$ data!

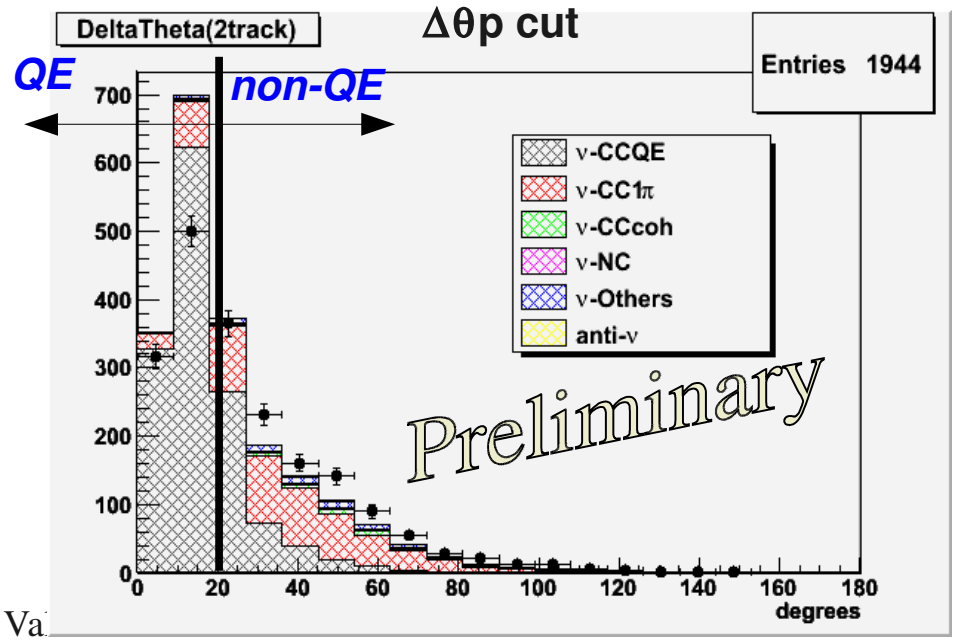
$\nu_\mu$ CCQE-$M_A$

**SciBar-MRD matched muons (high energy events):**




- SciBar-MRD matched track required (μ-like track), high energy events .
- 1-track sample (~66% Purity)
- 2-track sample (~**90% Purity!!!**):
  - p/π identification by dE/dx for 2nd track.
  - Δθp cut (<20 degrees): this cut shows a data deficit for low angles (under study!).




Statistical -only errors

First look at $\nu$ data!

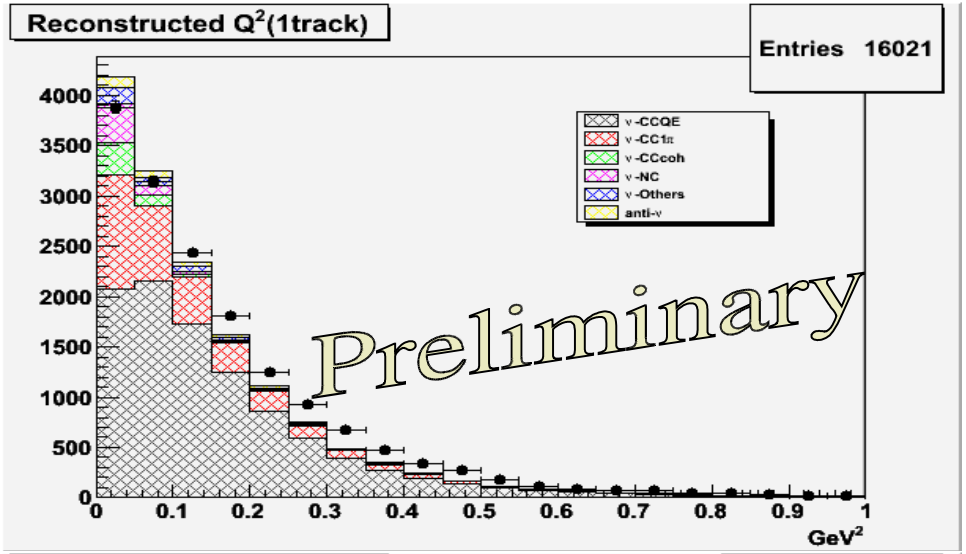


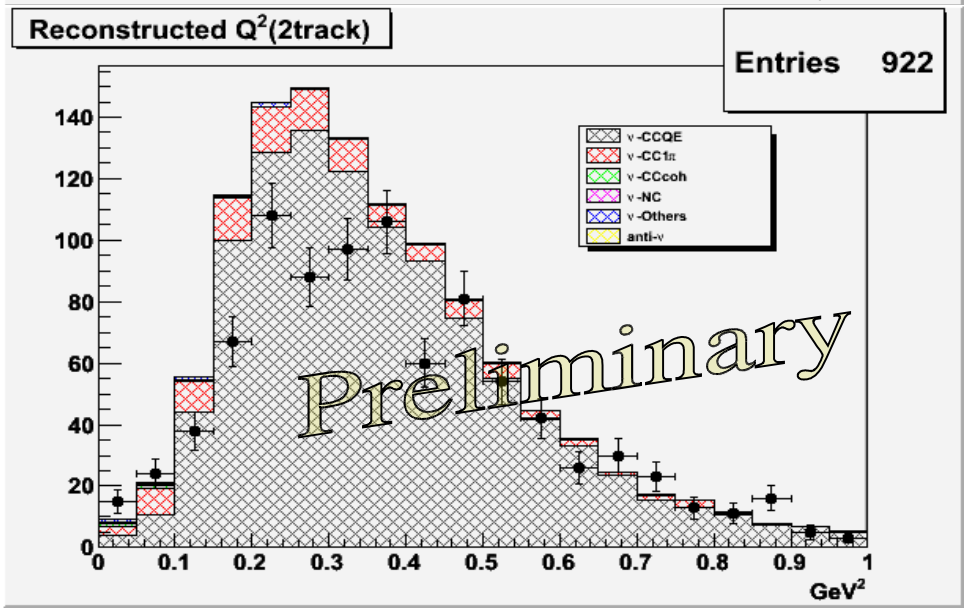
Analysis:

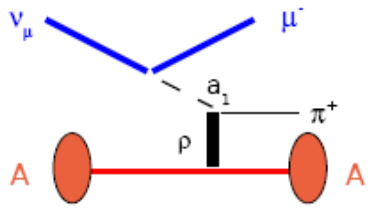
**SciBar-MRD matched muons**:

- All $Q^2$ region is covered:
  - **Low $Q^2$** by 1-track sample (~16,000).
  - **High $Q^2$** by 2-track sample (~1,000).
    - Between $0.2 < Q^2 < 0.5$ GeV$^2$, a DATA/MC disagreement (under study).
- fit $Q^2$ shape to obtain the $M_A$ value.
- Fit for $Q^2>0$ GeV$^2$. This will require some strategy:
  - Using the Pauli suppression parameter (like MiniBooNE)
  - Study other strategies.....

***NEUT with MA=1.1 GeV$^2$***



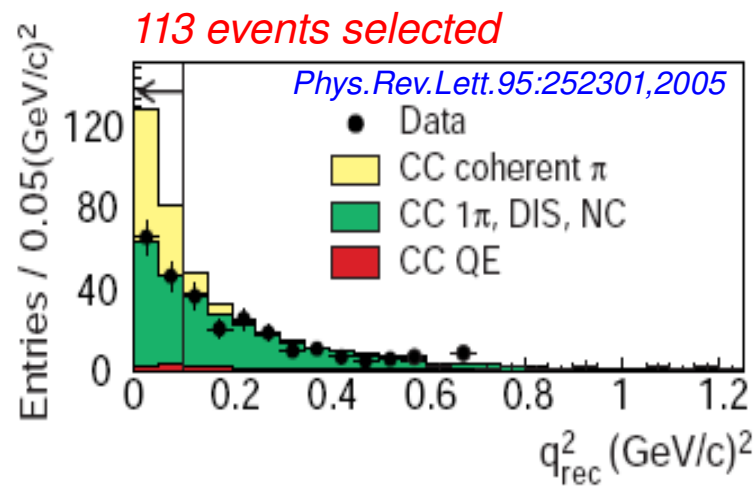



# CC coherent production

# K2K-SciBar

## $\nu_\mu$ CC coherent $\pi^+$ production

- σ(CC-coh)/σ(CC-inclusive) ratio measured.
- Rein and Sehgal model for CC coherent π production (on NEUT).
- Results are consistent with non-existence of CC coherent π at K2K neutrino energies (1.3 GeV)
- Main systematic uncertainties:
  - nuclear effects (π–absorption and elastic scattering)
  - neutrino interaction models ($M_A$ variation...).

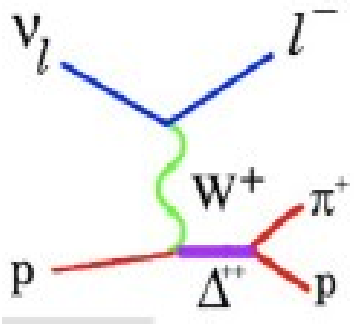



*Reconstructed q2 in the final sample.*

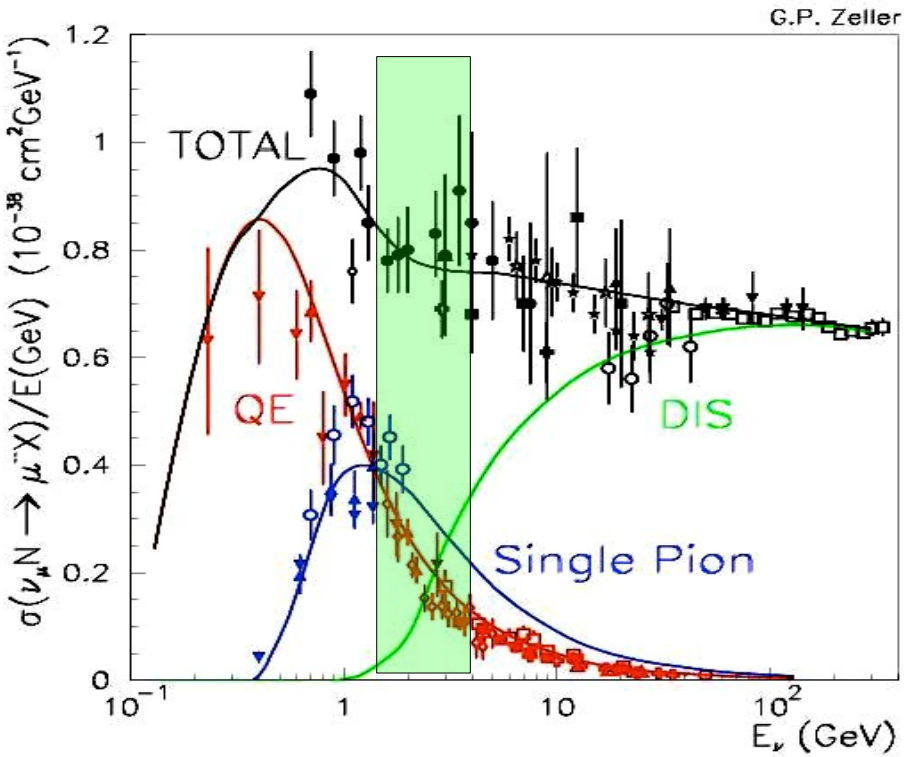
$$\sigma(\text{CC coherent } \pi)/\sigma(\nu_\mu \text{CC}) < 0.60 \times 10^{-2}.$$

*at 90% C.L.*

| Error source | Uncertainty of σ ratio ($\times 10^{-2}$) | |
|---|---|---|
| Nuclear effects | +0.23 | −0.24 |
| Interaction model | +0.10 | −0.09 |
| CC1π suppression | +0.14 | — |
| Event selection | +0.11 | −0.17 |
| Detector response | +0.09 | −0.16 |
| Energy spectrum | +0.03 | −0.03 |
| Total | +0.32 | −0.35 |



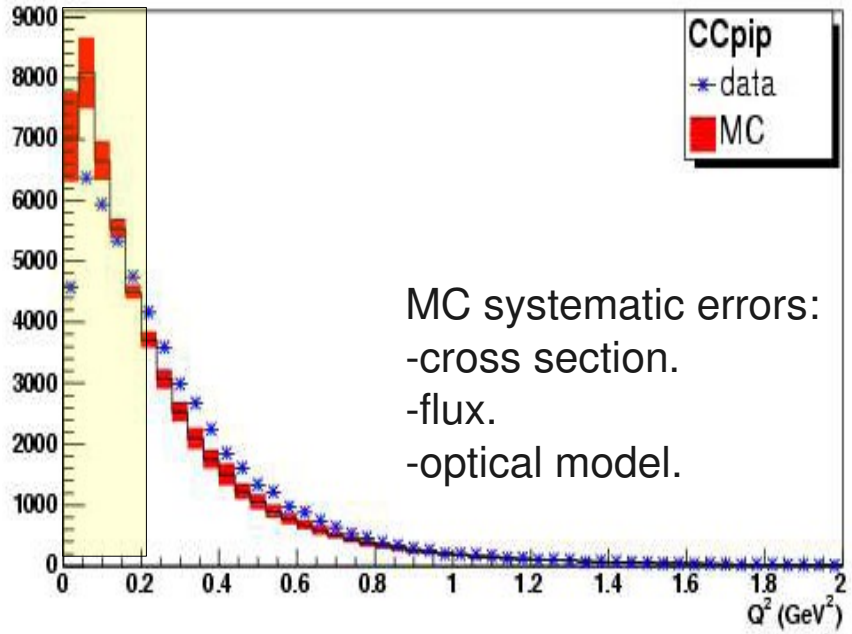

# CC resonance production



# MiniBooNE

$\nu_\mu CC1\pi^+$

- NUANCE neutrino generator with original Rein-Sehgal formalism for resonance and coherent model.
- Data/MC disagreement at low Q2 region :
  - Missing nuclear effects?
  - Fermi Gas Model?
  - Others.....
- Work on going, improved results expected soon..




*B.T.Fleming Nuint07*

# K2K-SciBar

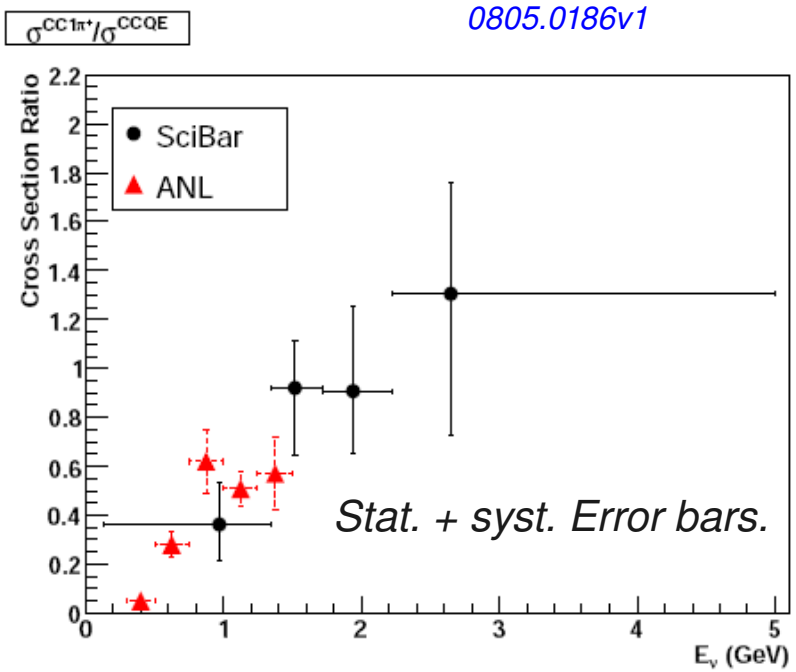
$\nu_\mu CC1\pi^+$

(for extended description look forward to L. Whitehead talk )

- Calculate the $\sigma$ -ratio (Re=$\sigma[CC1\pi] / \sigma[CCQE]$).
- (avoiding uncertainties from nu-flux prediction)
- Re= $0.734 \pm 0.086(\mathrm{fit})^{+0.076}_{-0.103}(\mathrm{nucl})^{+0.079}_{-0.073}(\mathrm{syst})$

  0805.0186v1
- Largest systematic uncertainties:
  - Modeling final state interactions ($\pi$-absorption, $\pi$-scattering, p re-scattering...)
  - Uncertainty on $M_A$ value.

0805.0186v1




*SciBar σ ratio vs Eν compared to ANL data.*

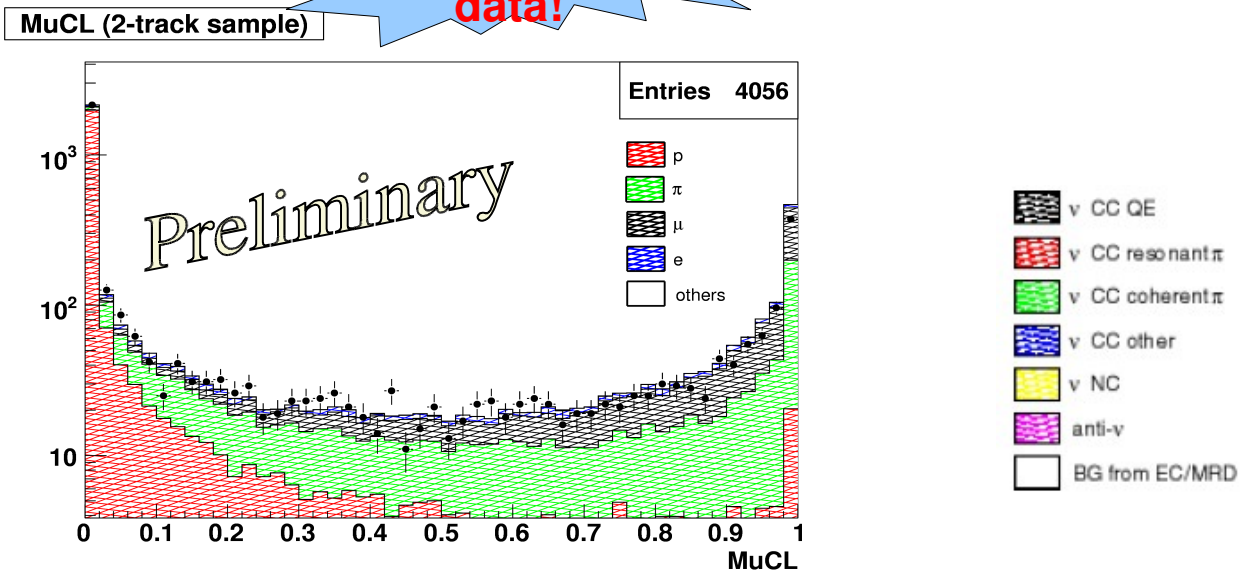
# SciBooNE

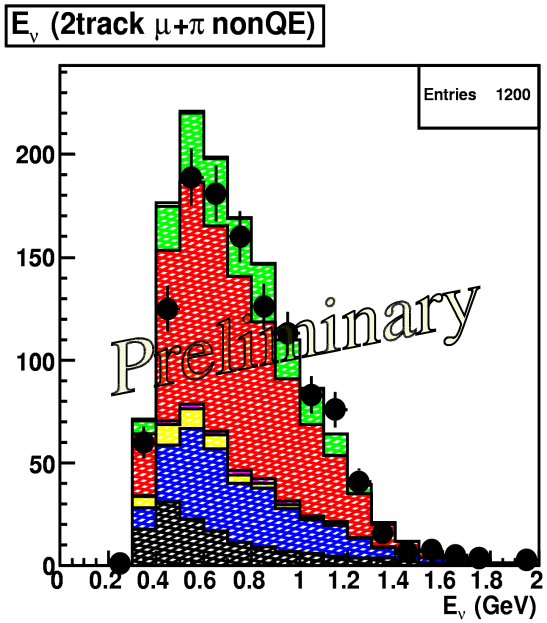
First look at $\nu$ data!

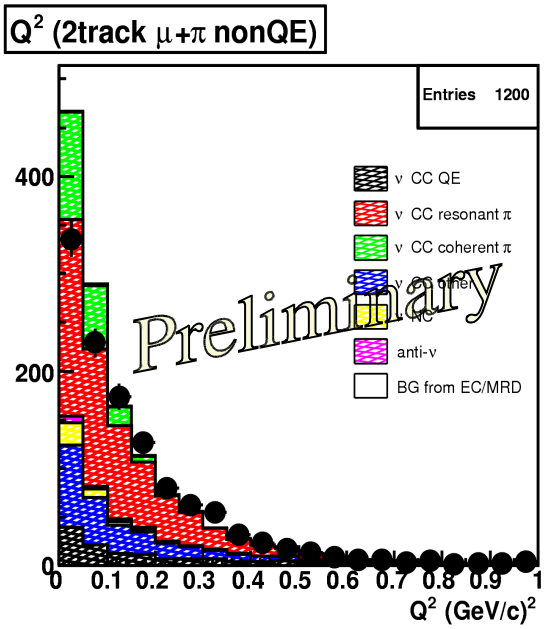
$\nu_\mu CC1\pi^+$

## $CC1\pi^+$ event selection

- 2 tracks selection
- $p/\pi$ separation by dE/dx..
- $\Delta\theta p$ cut.
- Statistics: ~1,200 events
- Sample Purity: ~66%




*Eν and $Q^2$ distribution for 2-track non-QE μ+π*

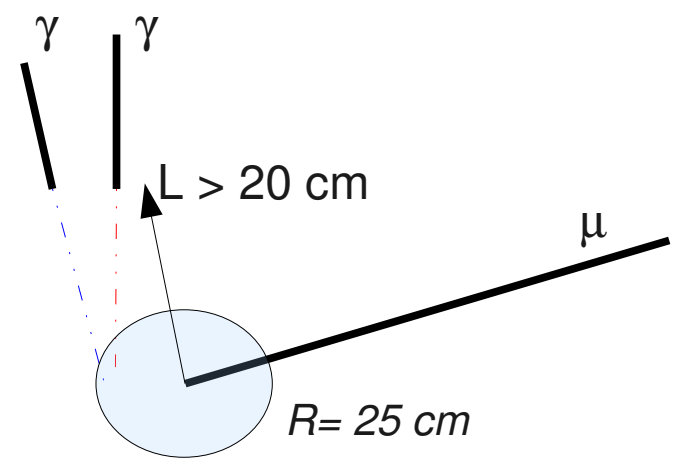
## Analysis

- We observed the familiar deficit at low Q2 .

# $CC\pi^0$

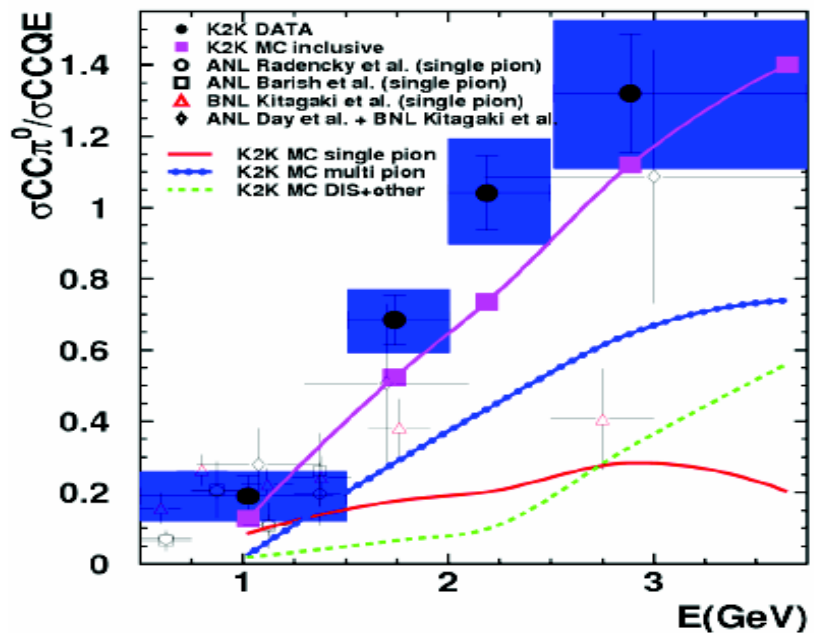
## CC inclusive $\pi^0$ event selection:

- Signal definition:
  - $\pi^0$ from $\nu$–interaction vertex or from re-interactions inside of the target nucleus.
- 3 tracks:1 $\mu$-like, 2 $\gamma$ showers (reconstructed SciBar+EC ).
- Vertex disconnection for $\gamma$ showers.
- $\gamma$ showers pointing to vertex.
- Sample Purity ~ 60% (479 events)




## Results:

- The ratio $\sigma(CC\pi^0)/\sigma(CCQE)$ seems to be larger than the NEUT predictions but consistent with previous results.



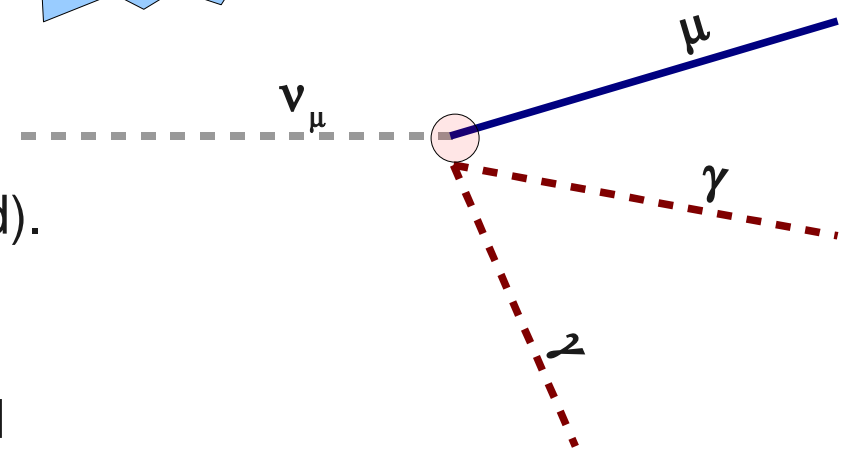

*C. Mariani, NuInt07*

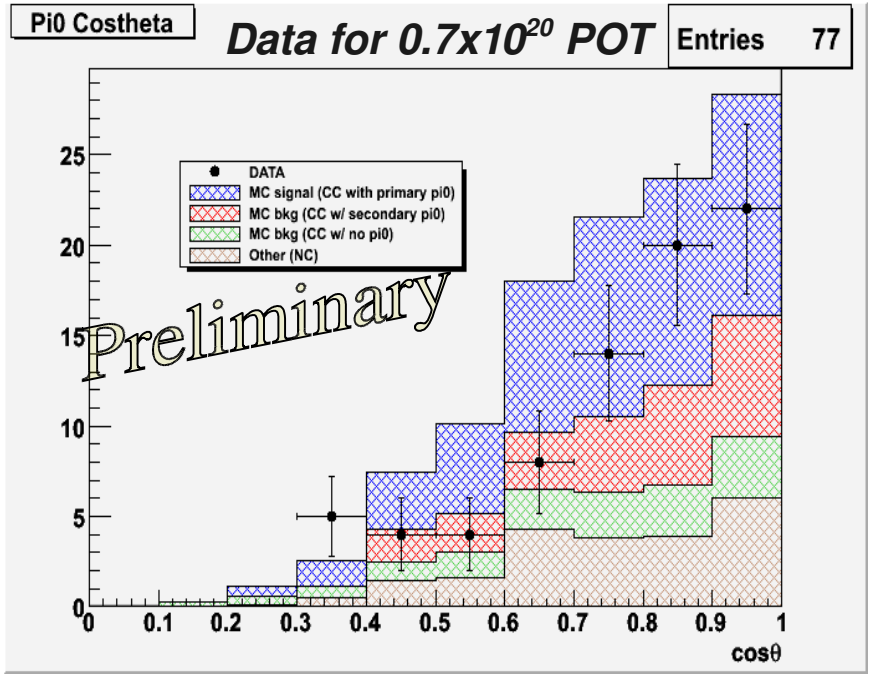
# SciBooNE

First look at $\nu$ data!

## $\nu_\mu CC1\pi^0$

- Signal definition:
  - $\mu$ with primary $\pi^0$'s ($\pi^0$ absorption and secondary $\pi^0$'s are considered background).
- Sample selection:
  - 3 tracks : $\mu$ and 2 $\gamma$ showers (reconstructed in SciBar detector only).
  - $\gamma$ showers on time with $\mu$-like track (<100 ns).
  - $\gamma$ showers disconnected from vertex.
- Sample purity ~47%
- The statistics will be improved with next reconstruction improvements.
- But preliminary results show a data deficit in the $CC\pi^0$/CC-inclusive ratio compared to MC .




*Reconstructed $\pi^0$ angle (with respect to the $\nu$-beam)*

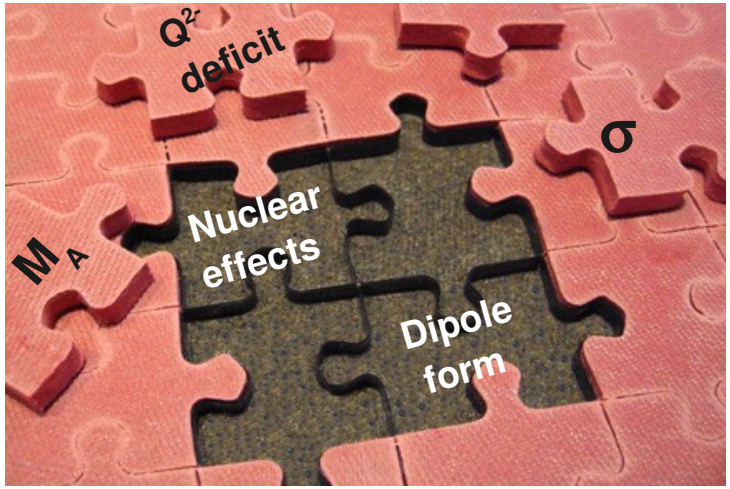
# Conclusions

# Conclusions

- Observed a data deficit at low Q2 for CCQE and CC1pi
  - MiniBooNE CCQE analysis: tunning the RFG model
  - K2K-CC-coh analysis: no evidence for CC-coherent pion production
- MA higher than historical:
  - Nuclear effects with heavy nuclei? Axial dipole form?
- *Accuracy of recent high-statistics results typically dominated by the systematic uncertainties, in particular:*
  - *Models of nuclear effects.*
  - *$\nu$-flux prediction.*
  - *Energy scale and detector response.*

# OutLook

- More data (with high statistics) are coming up to help solving this puzzle:
  - MiniBooNE results in $\bar{\nu}$ mode.
  - All SciBooNE results in $\nu$ and $\bar{\nu}$ mode.
  - *MinervA (next year):*
    - *Different nuclear targets: study in more detail the nuclear effects.*
    - *Cover a wide neutrino energy region.*
  - *T2K (April 2009).*




**Exciting moment for experimental and theoretic physicists in this field!**

# Thanks for your attention!

*Cómo la liáis!!*

podemos....que gran turrón que gran turrón.

*Jose luis Alcaraz-Aunion*
*alcaraz@ifae.es*

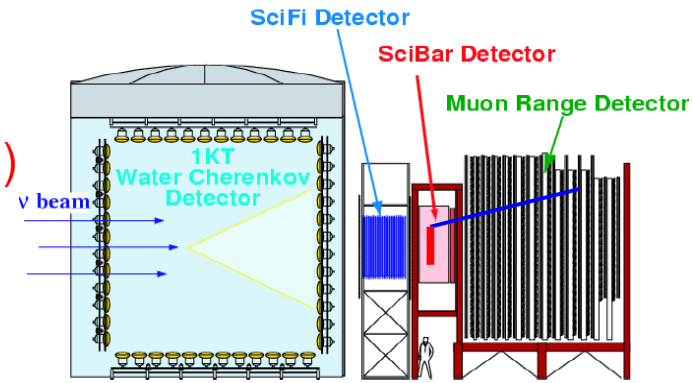
# backup

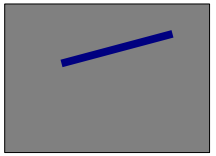
# K2K: SciFi && SciBar

CCQE event selection:

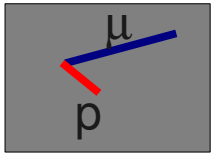
(both using the same strategy for event selection)

- 1 track ( muon-like track)
  - for CCQE events with non-reconstructed proton track).
- 2-track CCQE enriched sample:
  - $\Delta\theta p$ cut:
    - Is a kinematic cut (using $\mu$ information).
    - Allow to separate CCQE from CC1$\pi$.
- Sample Purity:
  - SciFi ~63%.
  - SciBar 75%(1track), 84% (2tracks)

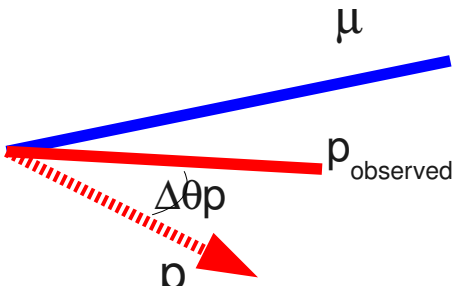


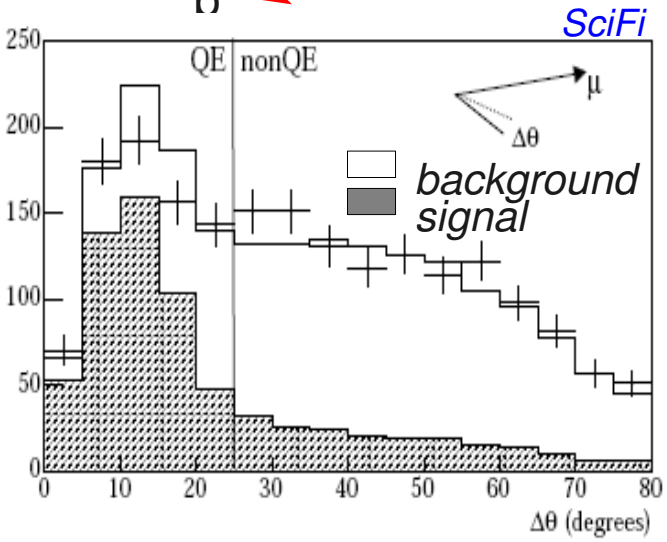



*1 track sample*




*2 track sample*



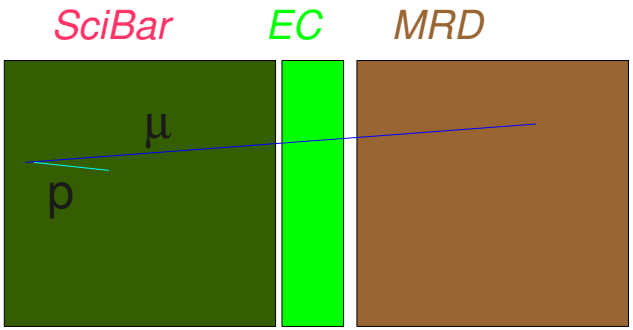



# SciBooNE

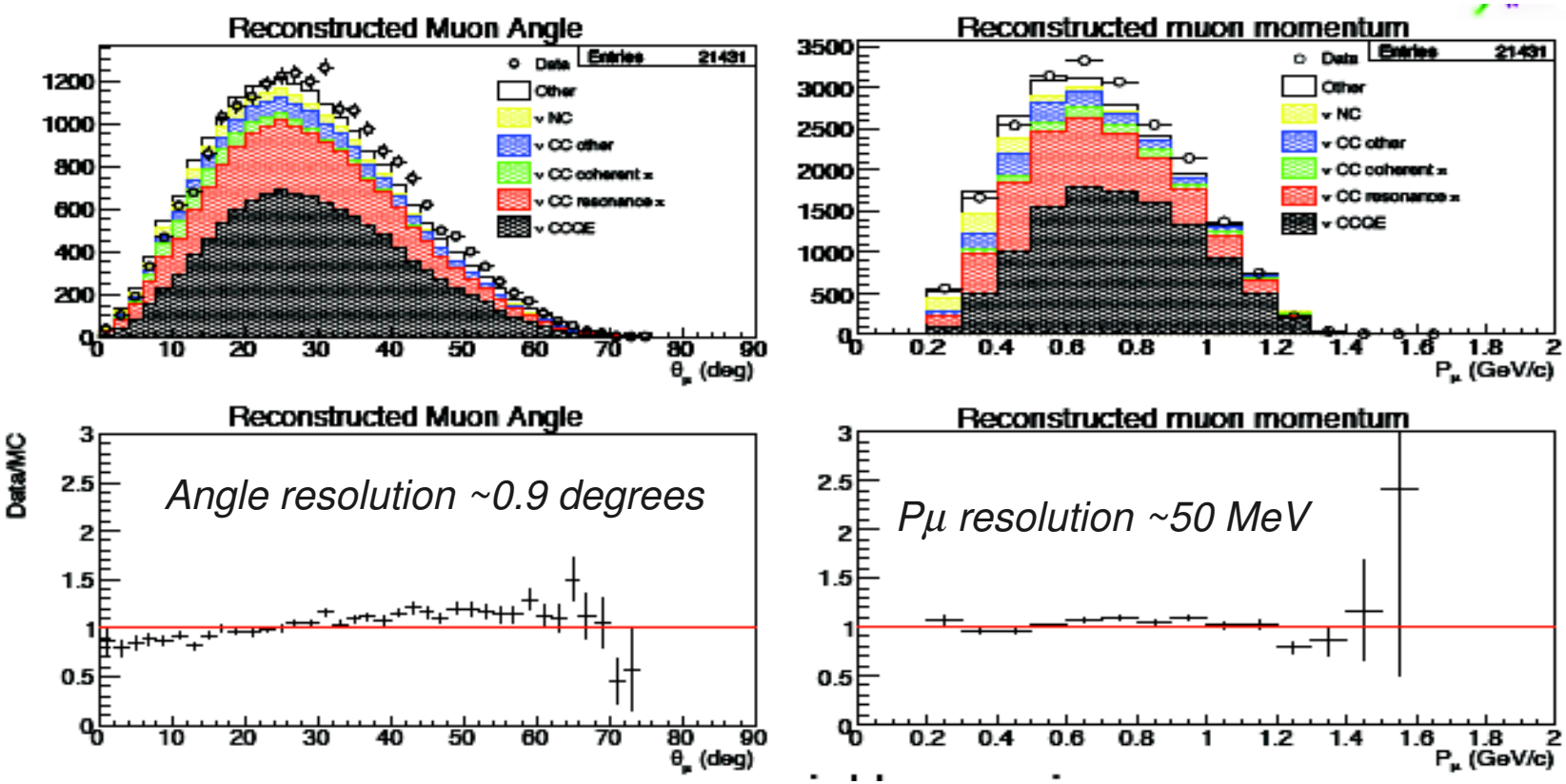
First look at $\nu$ data!

$\nu_\mu$ CC-inclusive

Good shape agreement between data/MC for CC inclusive sample.

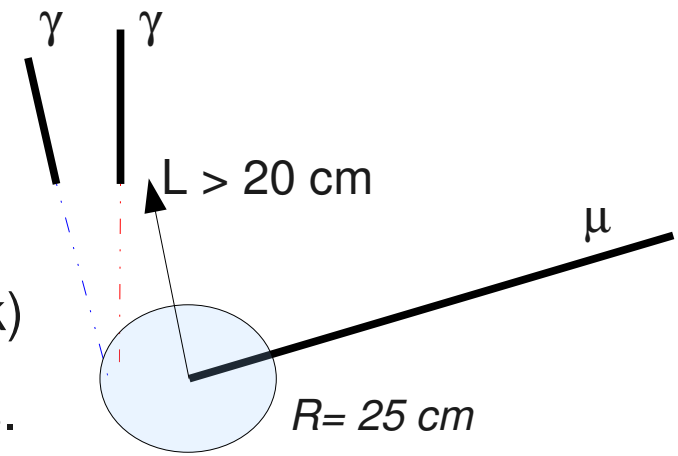



## MRD stopped sample



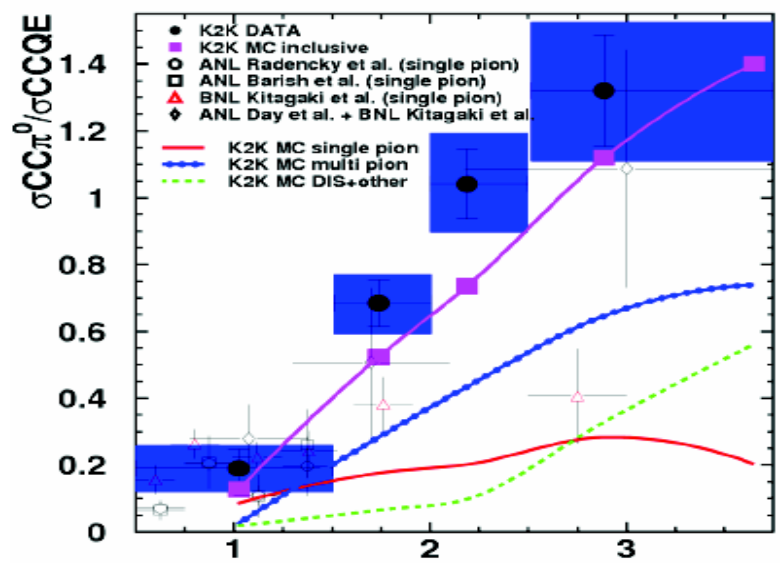
## CC inclusive $\pi^0$ event selection:

- Signal definition: 1 or more $\pi^0$ from $\nu$-interaction vertex or re-interactions inside of the nucleus.
- 3 tracks: 1 $\mu$-like track (SciBar-MRD matched track) & 2 disconnected, but pointing to the vertex, tracks.




## Results:

- The ratio $\sigma(CC\pi^0)/\sigma(CCQE)$ seems to be larger than the NEUT predictions but consistent with previous results.




*C. Mariani, NuInt07*

# MiniBooNE: Pauli blocking parameter (κ)



- NUANCE: using Relativistic Fermi Gas model (nuclear model).
- Tunning the RFG model to control the effect of Pauli Blocking.
- κ modifies the lowest bound energy of a nucleon just above the Fermi momentum.

$$E_{hi} = \sqrt{p_F^2 + M_n^2} \qquad E_{lo} = \kappa\left(\sqrt{p_F^2 + M_p^2} - \omega + E_B\right)$$

**$E_{hi}$**:upper bound energy of an initial nucleon on the Fermi surface.

**$E_{lo}$**: lowest bound energy of the initial nucleon leading to a final nucleon just above the Fermi momentum.

**$E_B$**: binding energy

**w**: energy transferred to the nucleon.

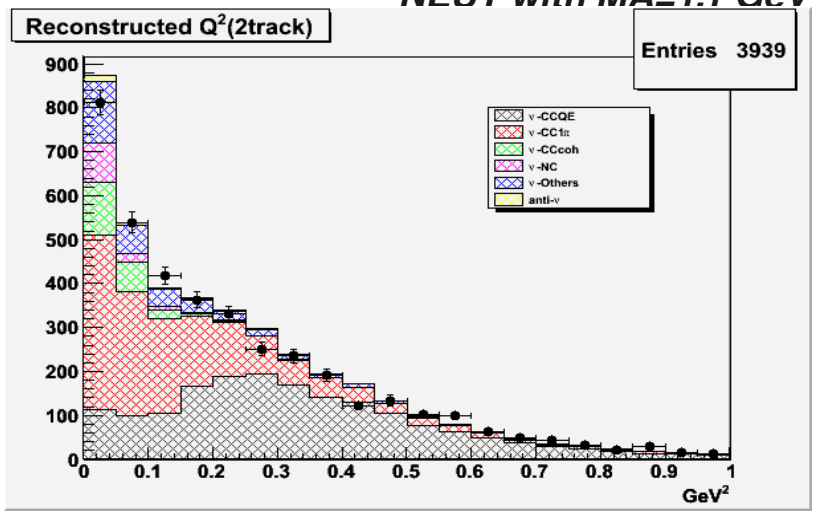
# SciBooNE

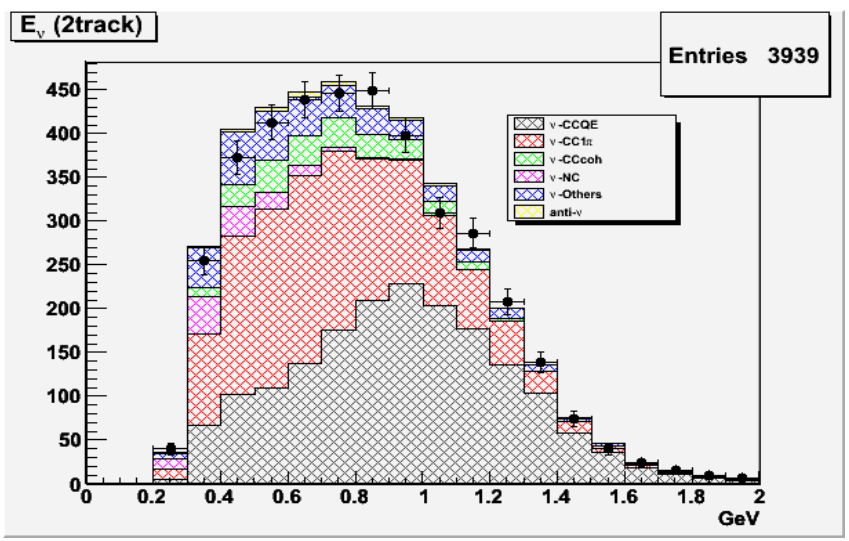
First look at $\nu$ data!

# $\nu_\mu$ CCQE-$M_A$

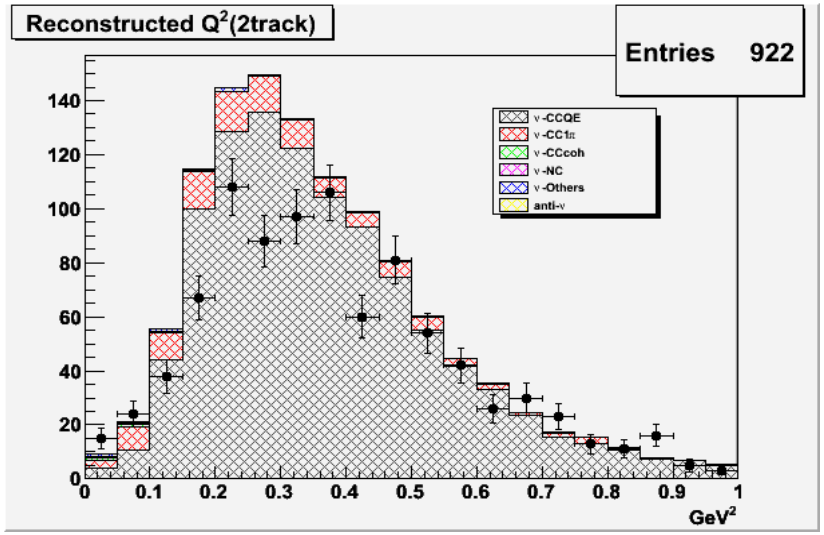
## BEFORE CUTS

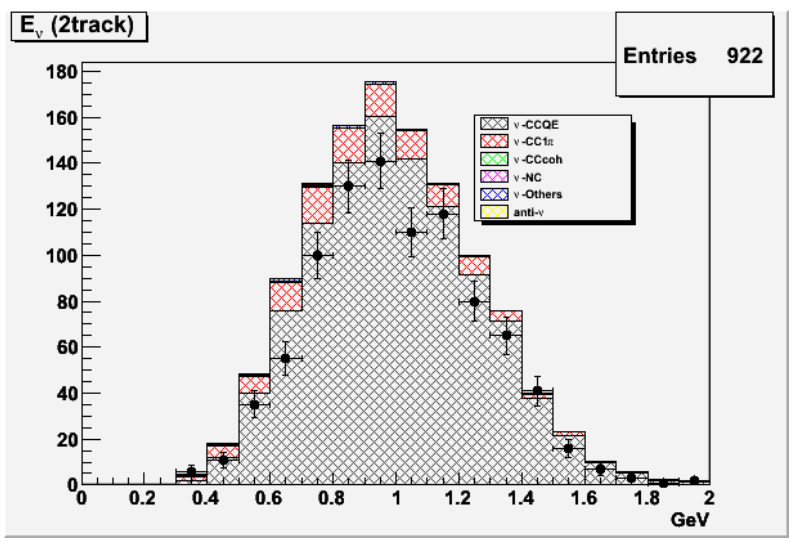
*NEUT with MA=1.1 GeV²*




## AFTER CUTS



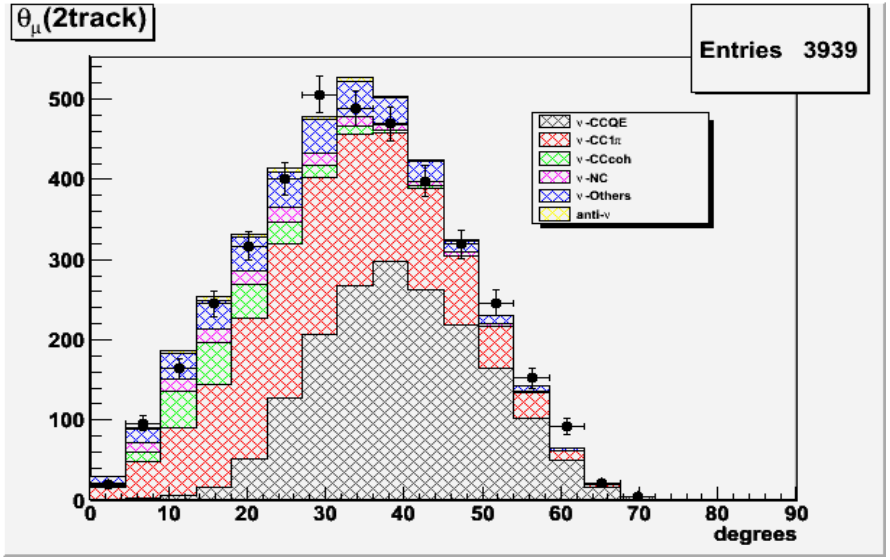



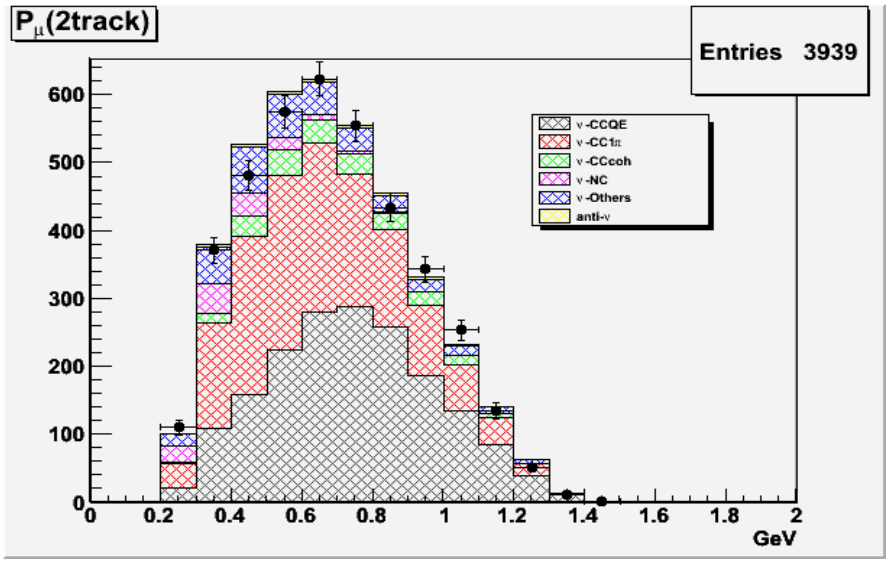
# SciBooNE

First look at $\nu$ data!

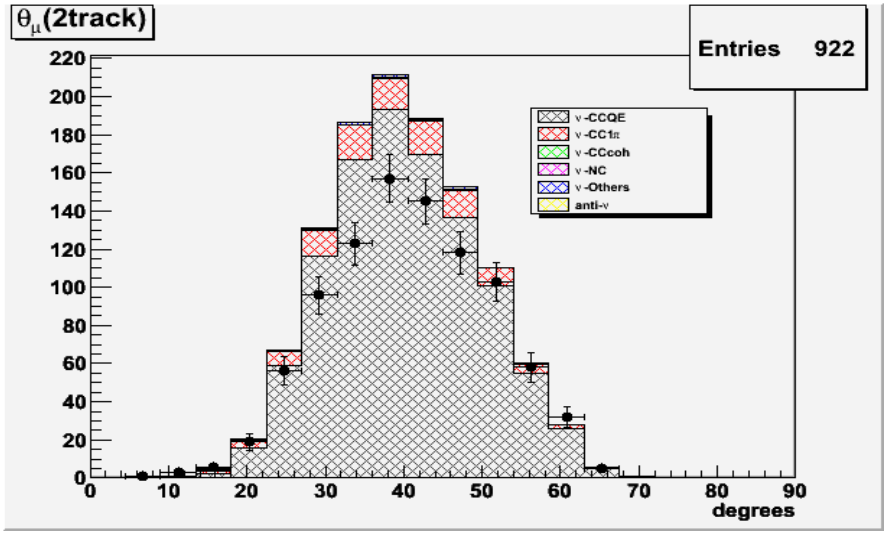
# $\nu_\mu$ CCQE-$M_A$

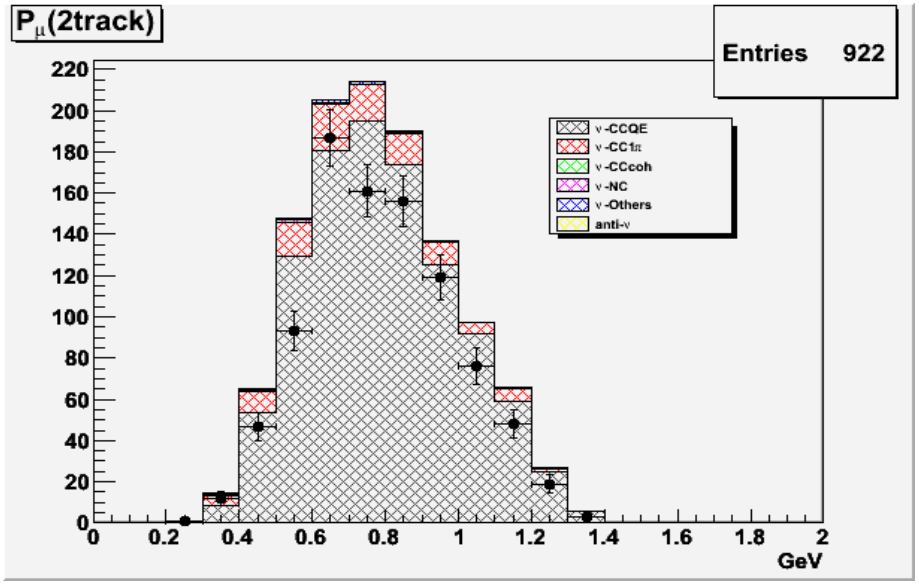
## BEFORE CUTS




## AFTER CUTS

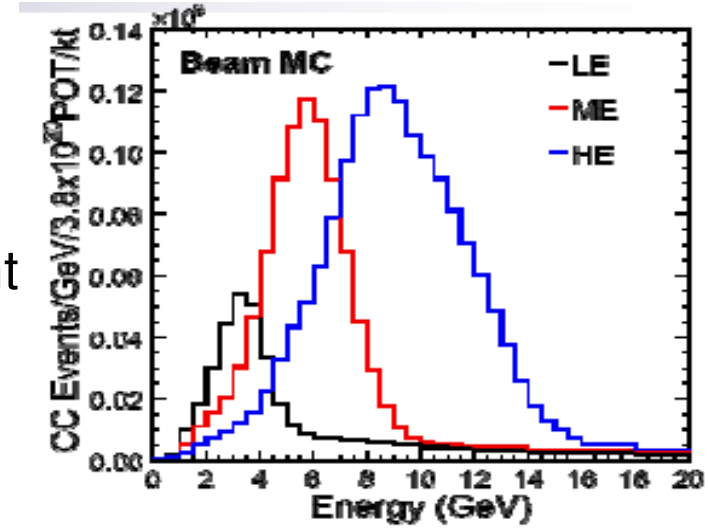


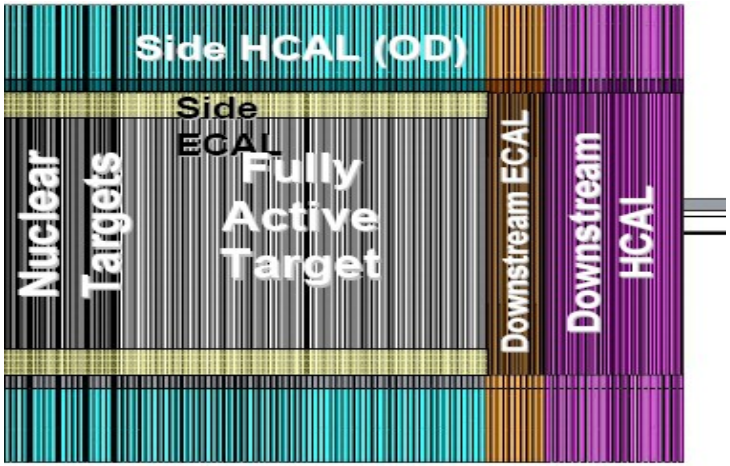
# MINERνA



- *MINERvA: Main Injector Neutrino Experiment v-A.*
- *Experiment type: neutrino scattering experiment*
- *Main goal:* precision neutrino interaction measurement over a wide range of neutrino energies.
- <Eν>= Low energies and Medium energies.
- High statistics (~9M CC events):
  - 4x10E20 POT in LE (1 year).
  - 12x10E20 POT in ME (3 years).
- *Detector type*: segmented tracker.
- *Detector installation and commissioning: 2009*.
- *Different nuclear targets: Carbon, Iron and Lead.*
  - *Study nuclear effects in different targets (He -> Pb).*

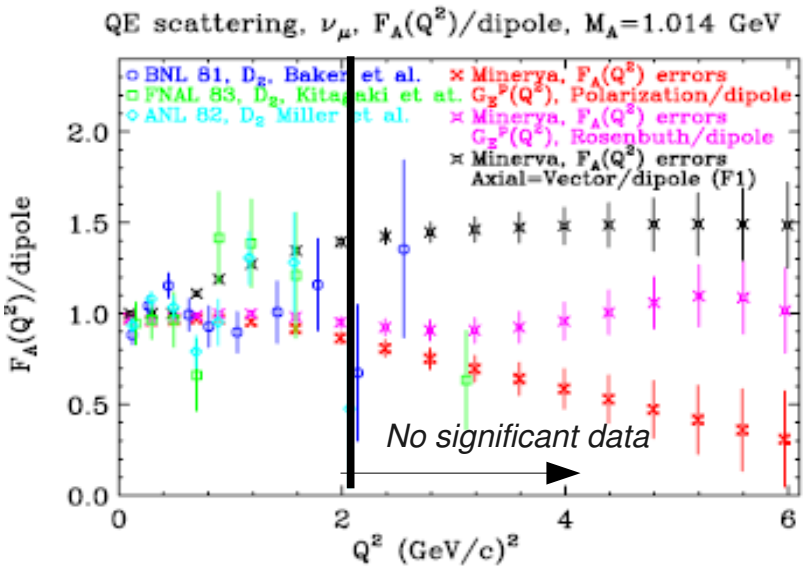



*Eν distribution for 3 different NuMI beam configuration.*

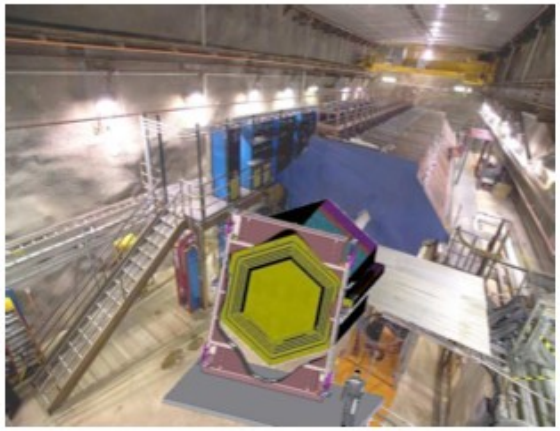


# MINERνA

- The large neutrino energy spectrum will allow to test the different models to the Axial form factor (is not a perfect dipole form)
- Study the nuclear effect and form factor for a range of light to the heavy nuclei (He to Pb.)
- The hadronic region of the detector is prepared to contained all the hadronic energy: capability to measure with precision the pion resonance production.

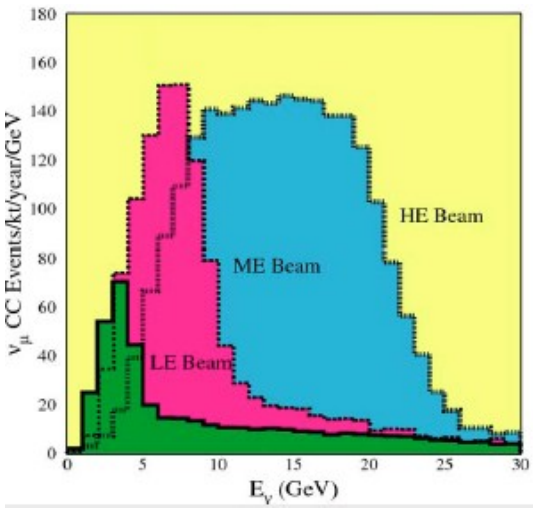



*Minerva predictions on the deviation of dipole form for 3 models (Polarization/dipole, Rosenbuth/dipole and Vector/dipole)*

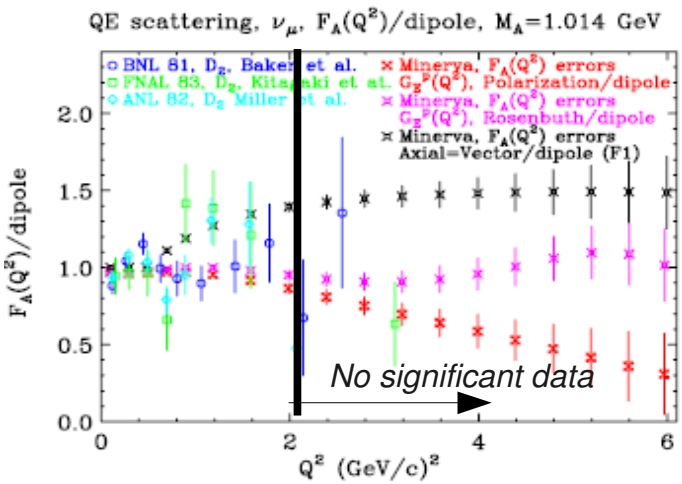


# MINERνA: Main Injector Neutrino ν experiment ν-A

- *Experiment type: neutrino scattering experiment*
- <Eν>= LE(~3GeV-1year operation) and ME(~7GeV-3years operation).
- High statistics (~9M CC events).
- *Different nuclear targets: He,Carbon, Iron and Lead.*
  - *Detail study of nuclear effects in different targets .*
- *dipole form deviation studies at high Q2 region.*
- *Precise measurements of CC-coherent with different targets.*
- *Scheduled to take-data: 2009!*




*Eν distribution for 3 different NuMI beam set up.*

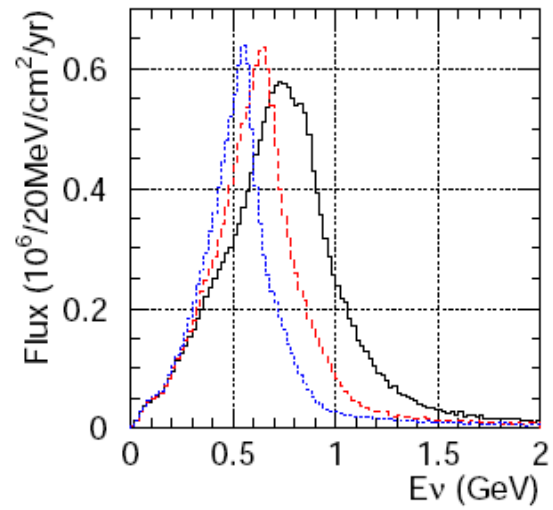



*Minerva predictions on the deviation of dipole form for 3 models (Polarization/dipole, Rosenbuth/dipole and Vector/dipole)*

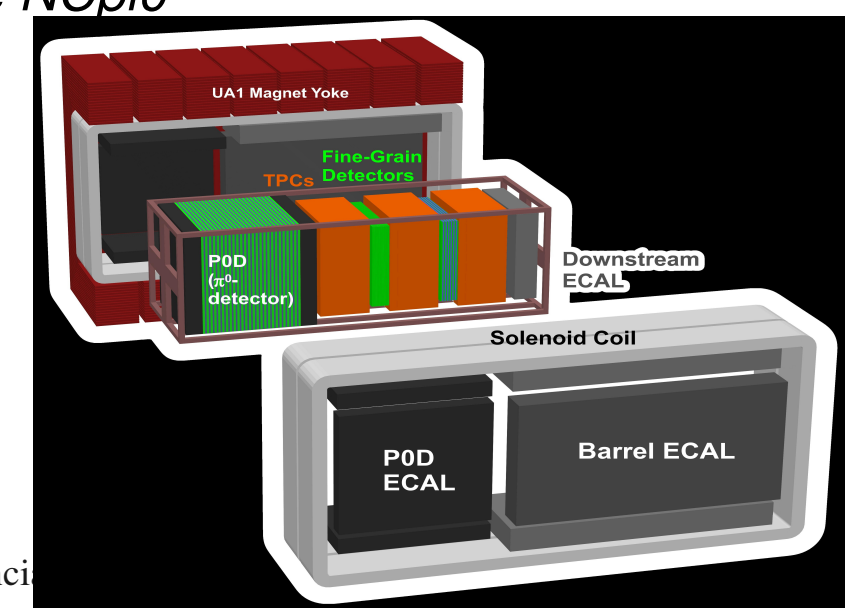
# T2K-ND280



- Precise measurements of CCQE interactions (initial flux):
  - momentum scale systematic ~ 2%
  - High angle and momentum resolution (TPCs and magnet spectrometer)
- *Nuclear targets: $H_2O$, Carbon.*
- *P0D: Specific detector designed to measure the NCpi0 neutrino interactions (background in SK).*
- *Scheduled to take-data: April 2009!*




*Eν distribution for different off axis configurations.*




*T2K ND280 near detector*