Experimental implications on neutrino cross-sections (just) below 1 GeV

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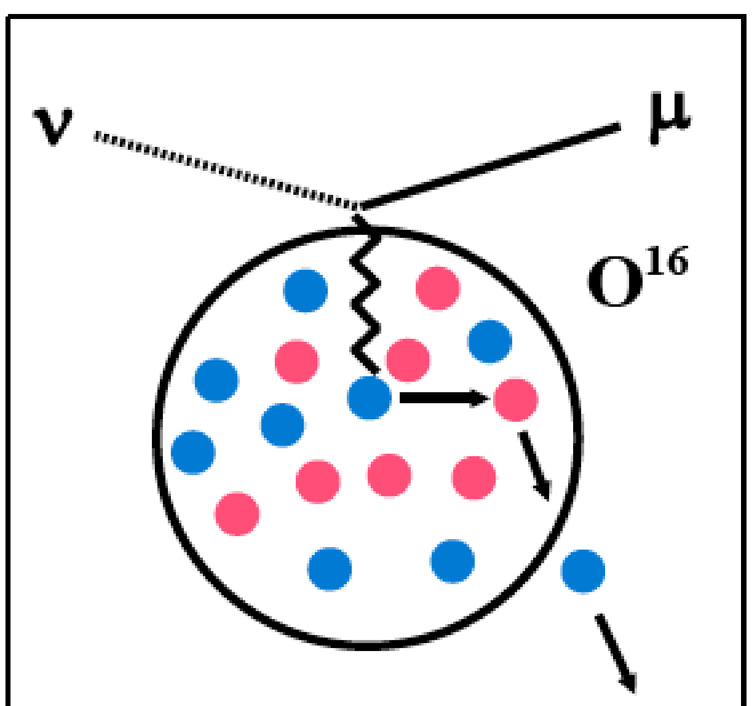
Outline

- Reminder: why is this important?
- What do we need to measure?
- How is it done?
- Can we do it better?
- Conclusions.

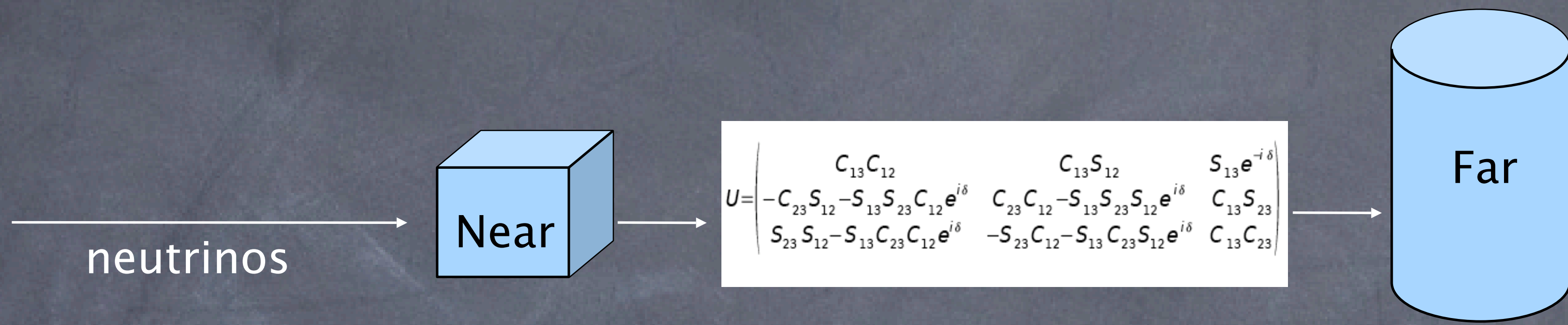
Why is this so important?

- Neutrino interactions are intimately related to the study of neutrino oscillations.
- The neutrino flavour is always determined via its interaction.



$$U=\begin{pmatrix} C_{13}C_{12} & C_{13}S_{12} & S_{13}e^{-i\delta} \\ -C_{23}S_{12}-S_{13}S_{23}C_{12}e^{i\delta} & C_{23}C_{12}-S_{13}S_{23}S_{12}e^{i\delta} & C_{13}S_{23} \\ S_{23}S_{12}-S_{13}C_{23}C_{12}e^{i\delta} & -S_{23}C_{12}-S_{13}C_{23}S_{12}e^{i\delta} & C_{13}C_{23} \end{pmatrix}$$

Why is this so important?



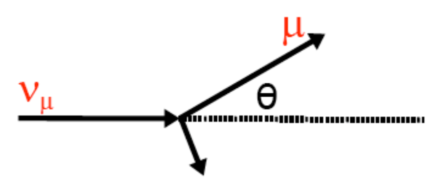
$$\phi_\nu(E) = \frac{N_{signal}(E) - N_{back}(E)}{\sigma_\nu^{signal}(E)} = \frac{N_{signal}(E) - \sigma_\nu^{back}(E)\phi_\nu(E)}{\sigma_\nu^{signal}(E)}$$

$$OSC_\nu(E) = \frac{N_{signal}^{far}(E) - N_{back}^{far}(E)}{\sigma_\nu^{signal}(E)\phi_\nu^{far}(E)}$$

- In oscillation experiments we are interested in the flux prediction.
- To do that, we have to know the background in the near detector as a function of the energy.
  - Need at least the relation of cross-sections between background and signal as a function of energy.
- The flux from near to far is distorted via the oscillation and the dynamics of the beam --> it is not trivial to extrapolate from near to far

Why is this so important?

- Neutrino energy reconstruction @ ~1 GeV.
- Use the CC-QE: $\nu_\mu\, n \to p\, \mu$.
- This is a two body final state, E can be obtained with angle and momentum of muon.



$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos(\Theta_\mu)}$$

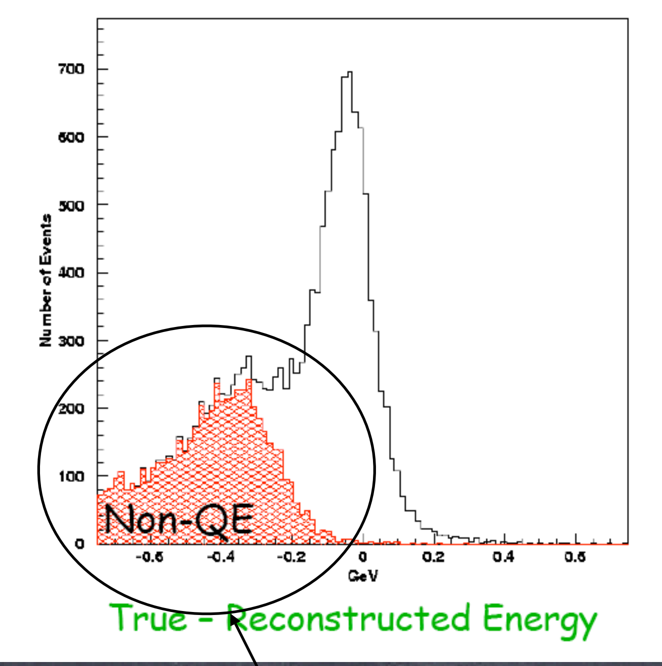
m_N = Neutron mass

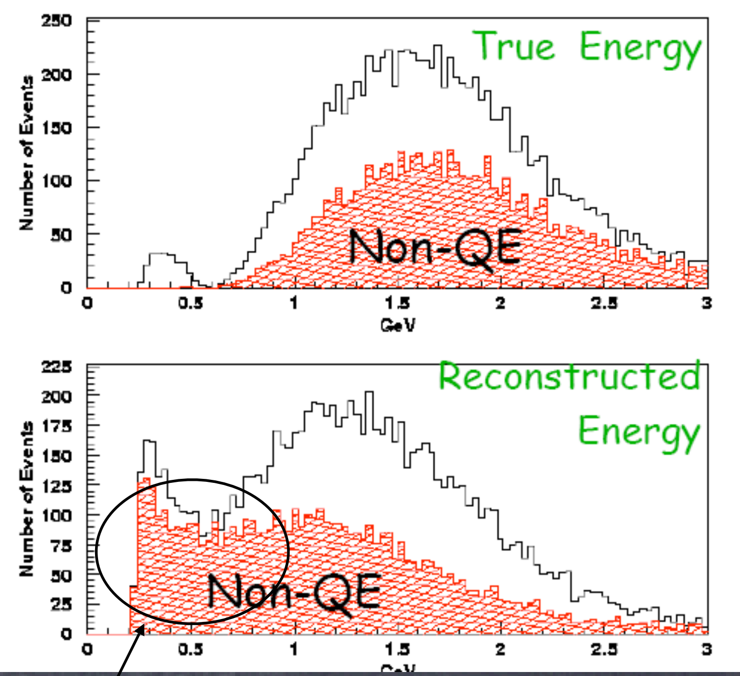
E_μ = Muon energy

m_μ = Muon mass

p_μ = Muon momentum

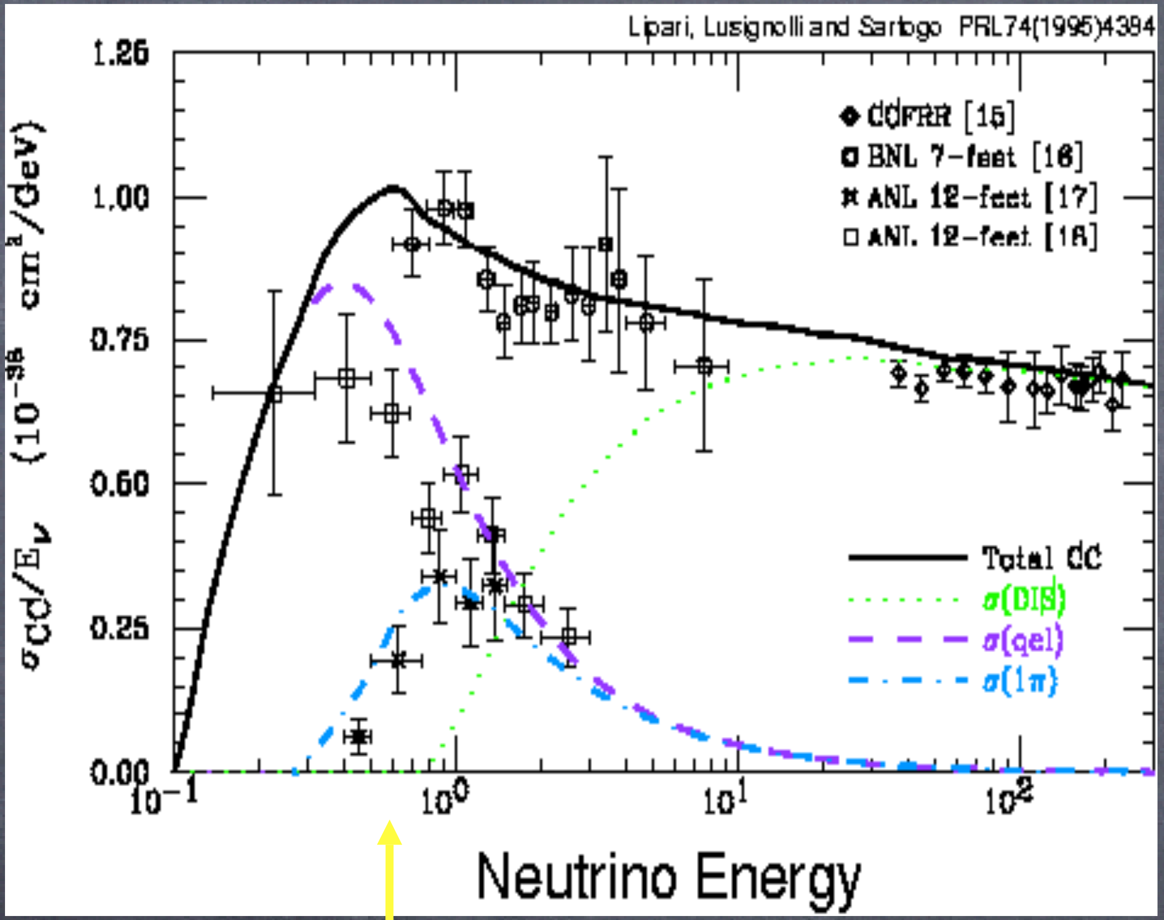
Θ_μ = Muon angle wrt beam





The Non-QE background provoques a distortion in the reconstructed spectrum

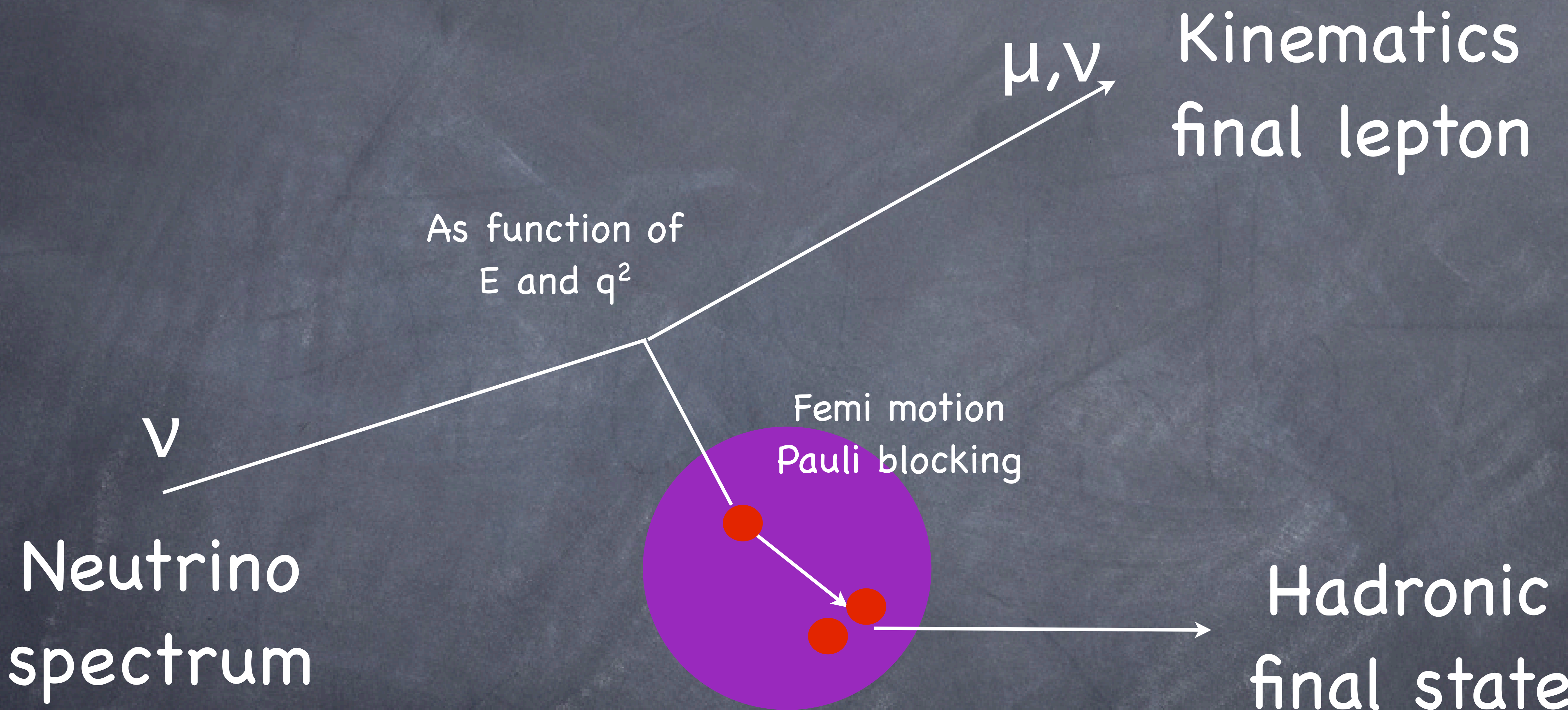
Why is this so important?



300 Km --> ~600 MeV
T2K baseline

- The GeV region is a complex admixture of neutrino interaction thresholds.
- Little knowledge of cross-sections.
- Even less knowledge on the details, mainly nuclear re-interactions:
  - event topologies.

What do we need to measure?



What do we need to measure?

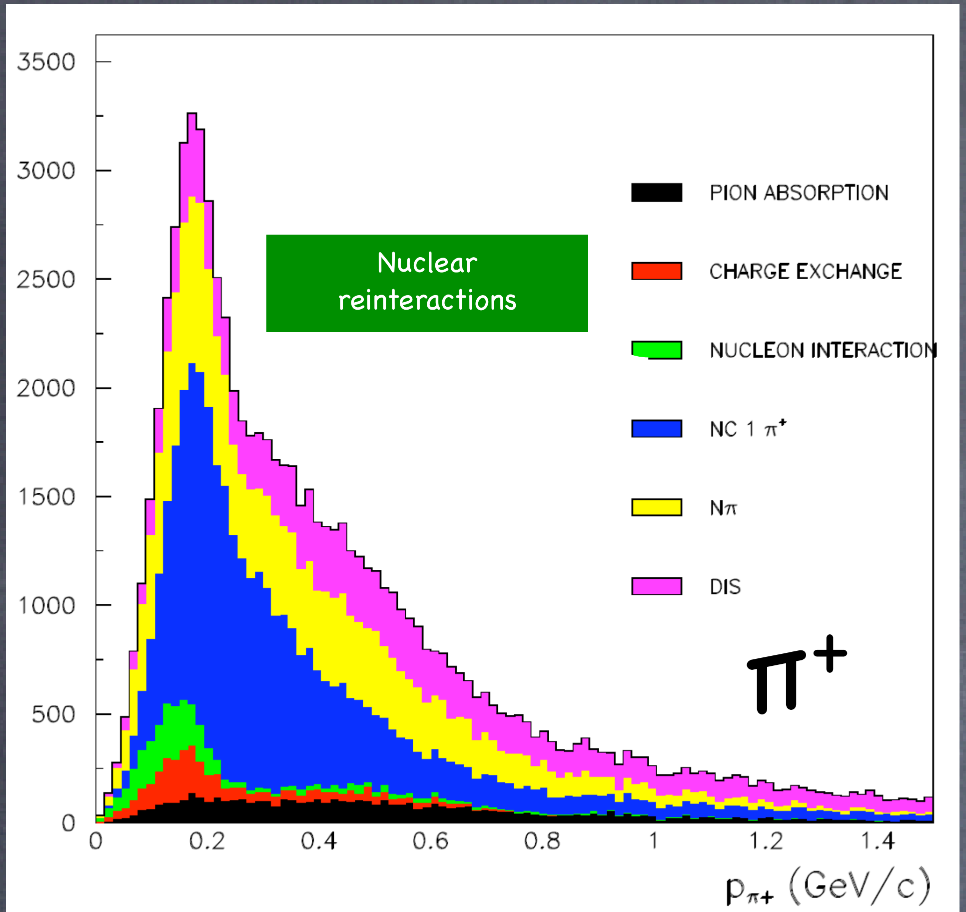
- The final lepton kinematics gives information on the neutrino energy and q^2. But!, there are some approximations:
  - Assume CCQE
  - Assume neutron target at rest.
- Also provides information on the neutrino-nucleon cross-section:
  - Axial mass, $\sigma(E)$, etc...

What do we need to measure?

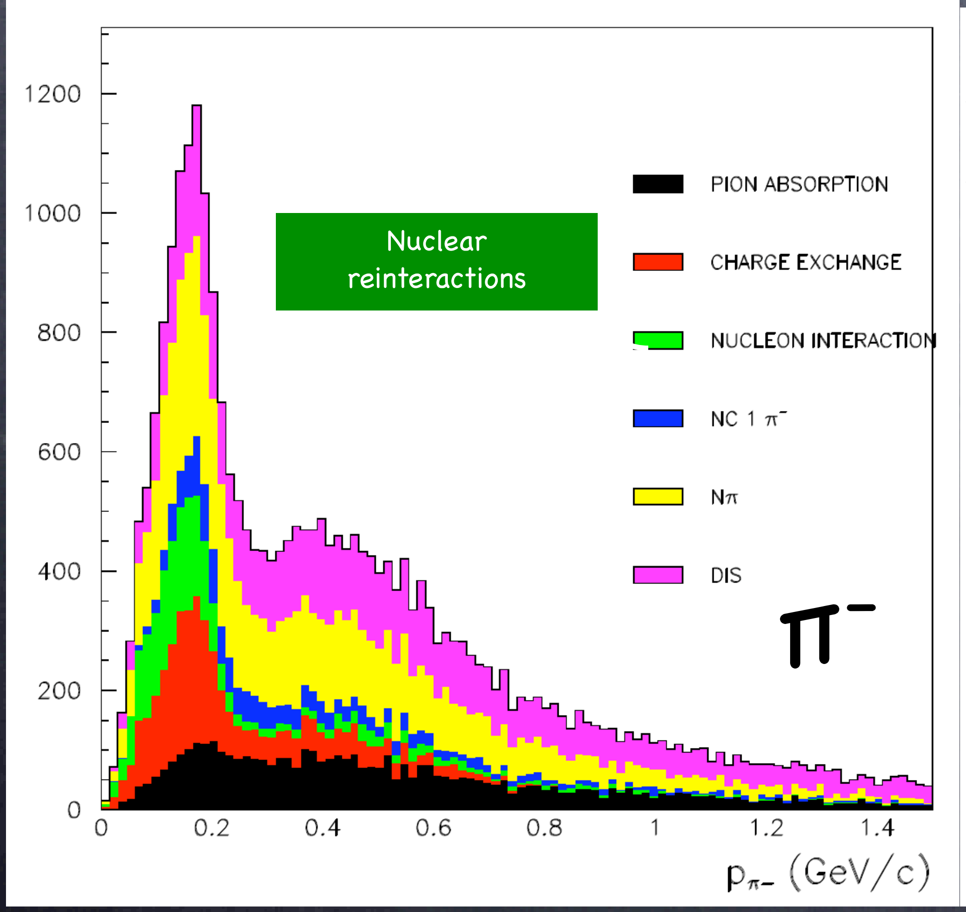
- The final hadronic state helps in defining the interaction type: CCQE, CC1π,etc...
- They also carry “some” information about the target nucleons.
- But!, everything is distorted by the nuclear re-interactions.

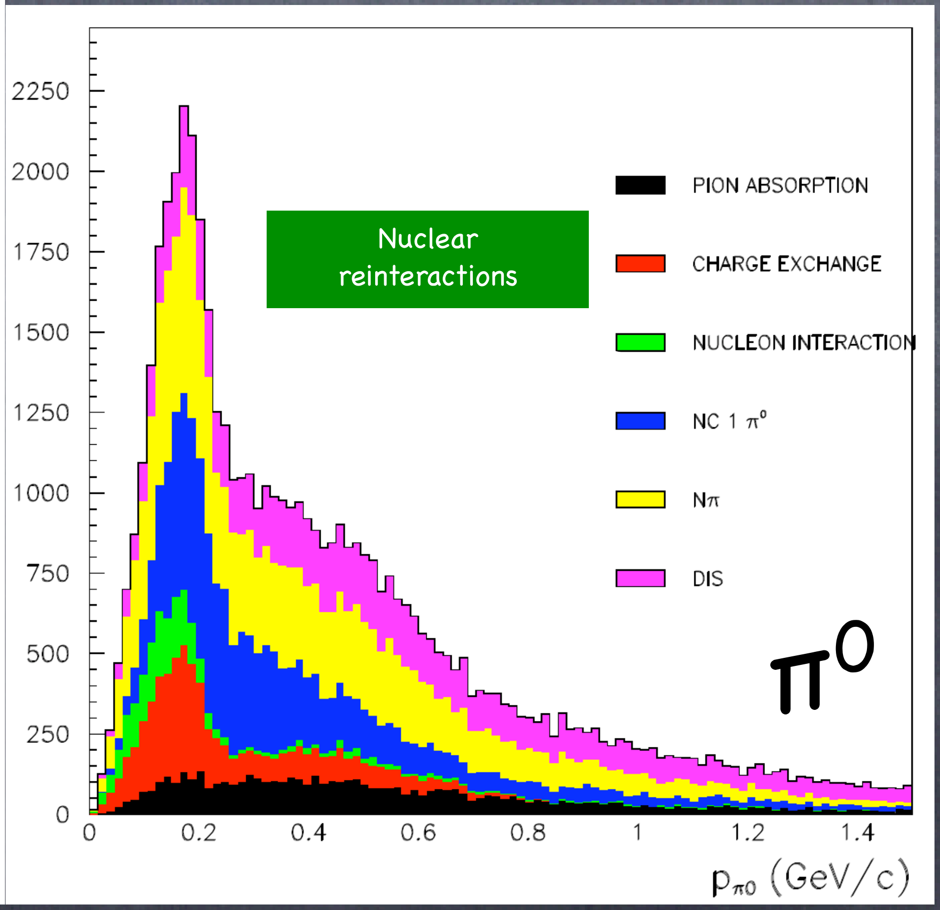
Nuclear re-interactions limit out ability to identify the reaction channel.

Nuclear rescattering



- The nuclear re-scattering also changes the π^0, that is relevant to ν_e appearance experiments.





<u>Pion reactions</u>

Pion absorption

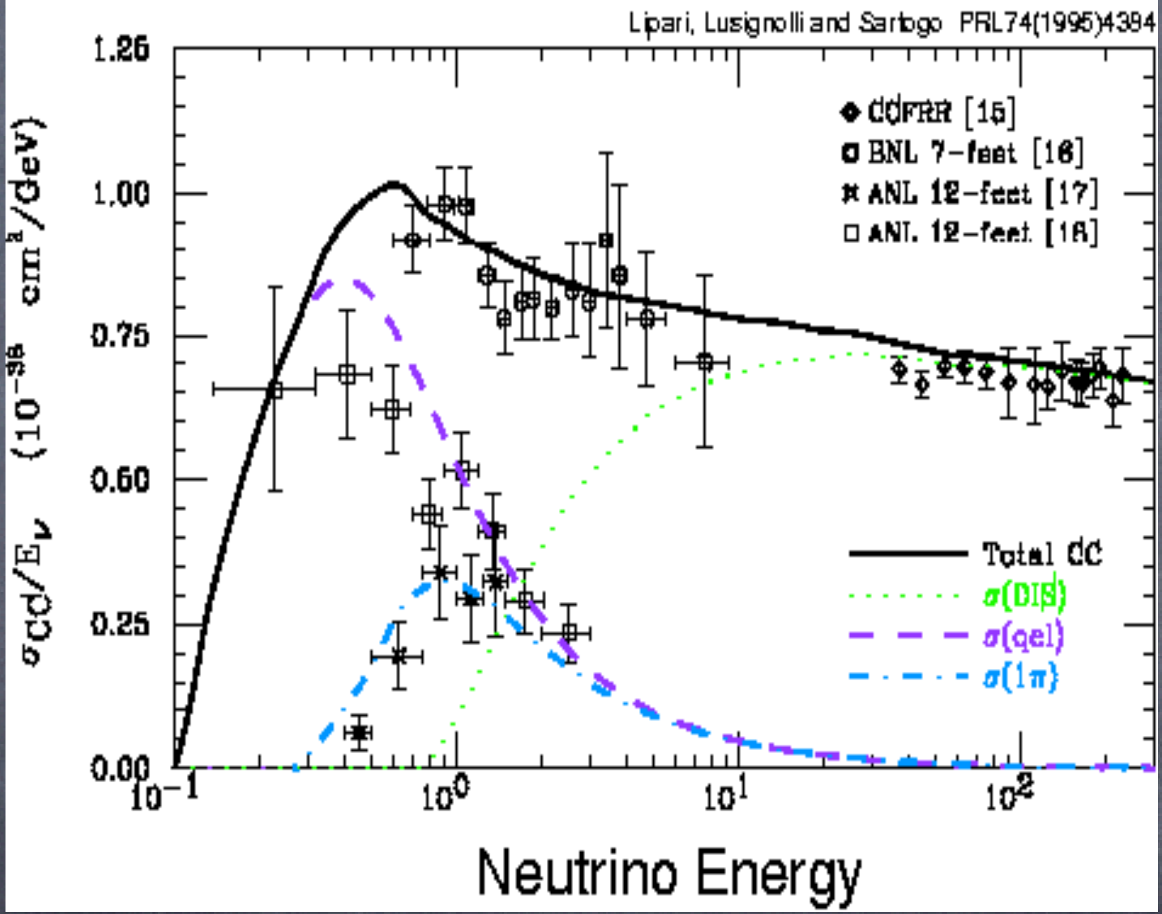
Pion scattering

Charge exchange

CCQE

- This is the dominant cross section at low energies.
- This is also the experimental way to reconstruct the neutrino energy under certain assumptions.

Status of cross-sections



CCQE

- The actual models used by experimentalists is the Lewelling-Smith with vector and axial form factors.
  - The vector form factors are obtained from electron scattering.
  - The axial form factor is assumed to be dipolar and the value measured in neutrino experiments via q^2 and/or cross-section.
- This model seems to work nicely above 1GeV.
- Recent calculations show large deviations of this model for neutrino energies below 500MeV.
- What about the region from 0.5 to 1 GeV ?

M_A CCQE

- M_A is the way to parametrize the q^2 dependency of the cross section. Effective parameter.
- Several assumptions:
  - This is the only parameter.
  - It is dipolar form factor, while vector form factors show a more complex q^2 dependency.
- The model do not take into account most of the nuclear effects that are important at low energies.
- It is always related to the description of the vector form factors.

Next generation should depart from dipole mode

M_A CCQE

- The relevance of M_A for oscillations comes from the fact that it changes the q^2 distribution and so the acceptance of detectors: p_μ and θ_μ.
- Different acceptance in near and far detector appears as systematics in the oscillation parameters.

M_A CCQE

- Easier to measure at high energy, but: can it be extrapolated to lower energies?.
- Problems at low energies:
  - nuclear effects are important (low q2)
  - Selection of CCQE:
    - the larger the q2 the largest the probability to observe the proton in the detector.
    - the usual two track selection bias the sample towards high q^2 and it does it convolving the nuclear re-interactions.

M_A CCQE

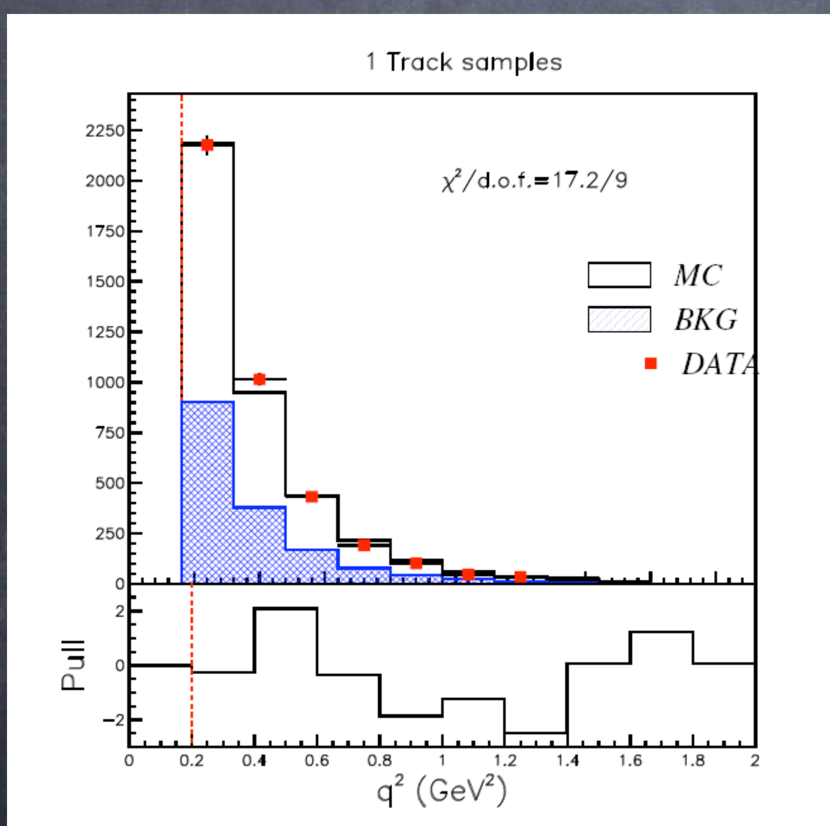
K2K

MA = 1.20 ± 0.12

Phys. Rev. D74, 052002 (2006).

MA= 1.144 ± 0.077(fit)
+0.078 -0.072 (syst)

aip conference procc. 967, 117 (2007)

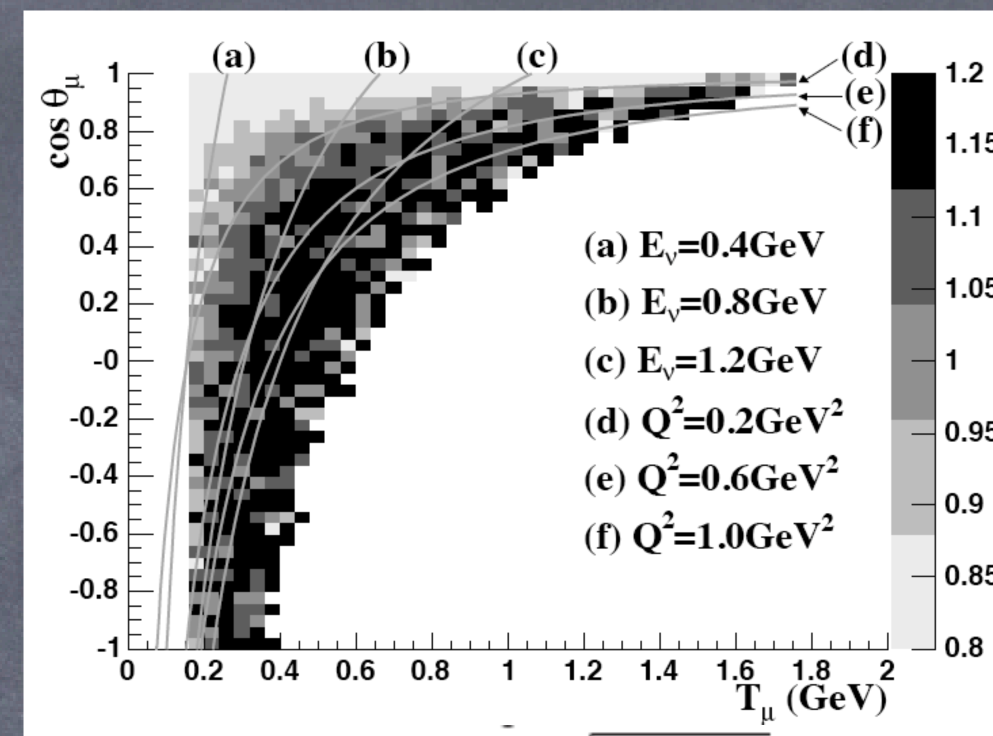


Remove events below 0.2GeV^2

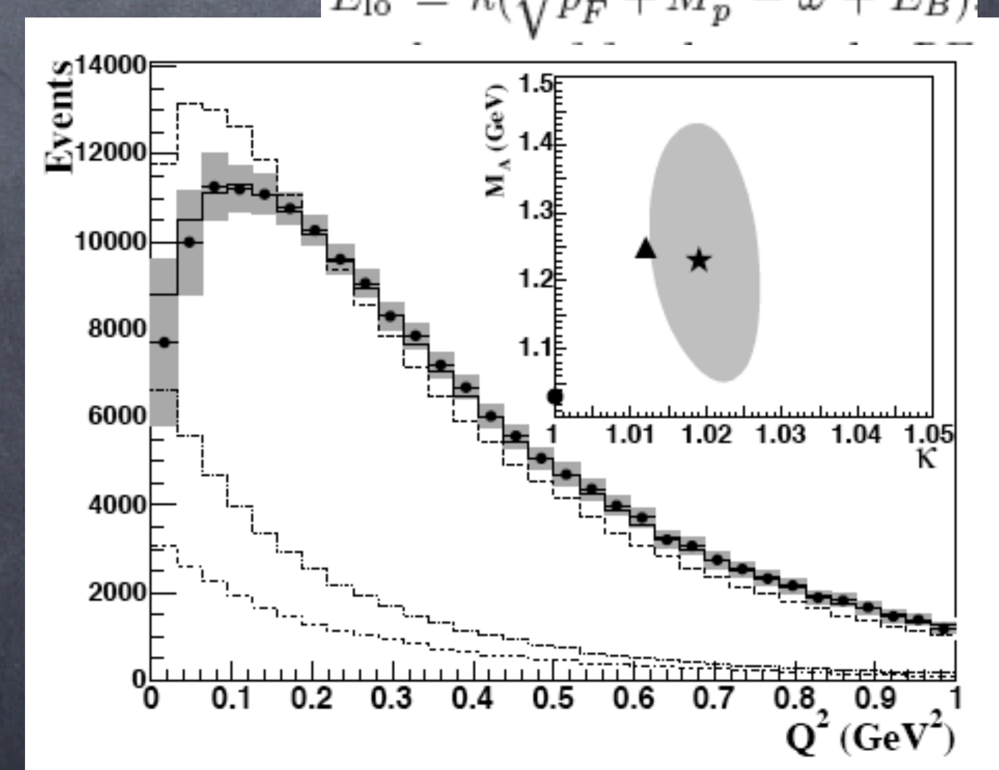
MiniBoone

MA = 1.23 ± 0.20

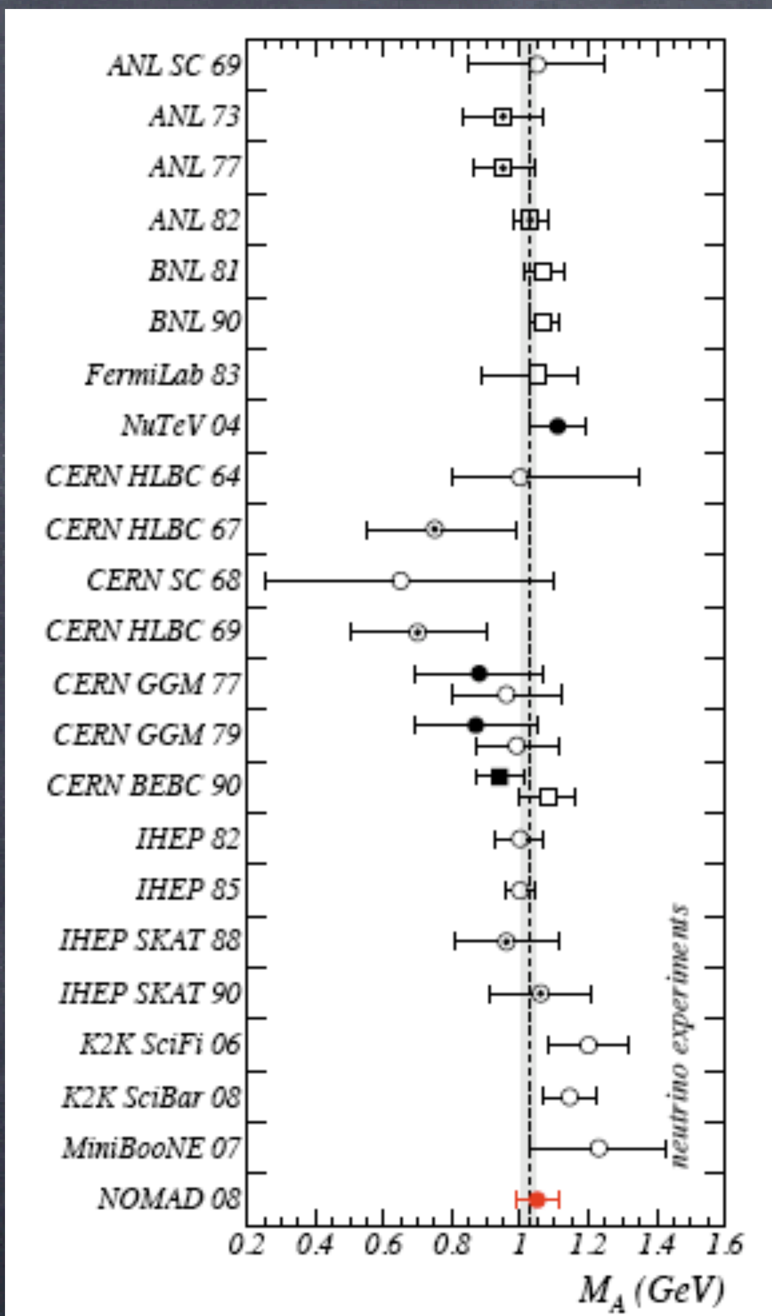
Phys. Rev. Lett. 100, 032301 (2008)



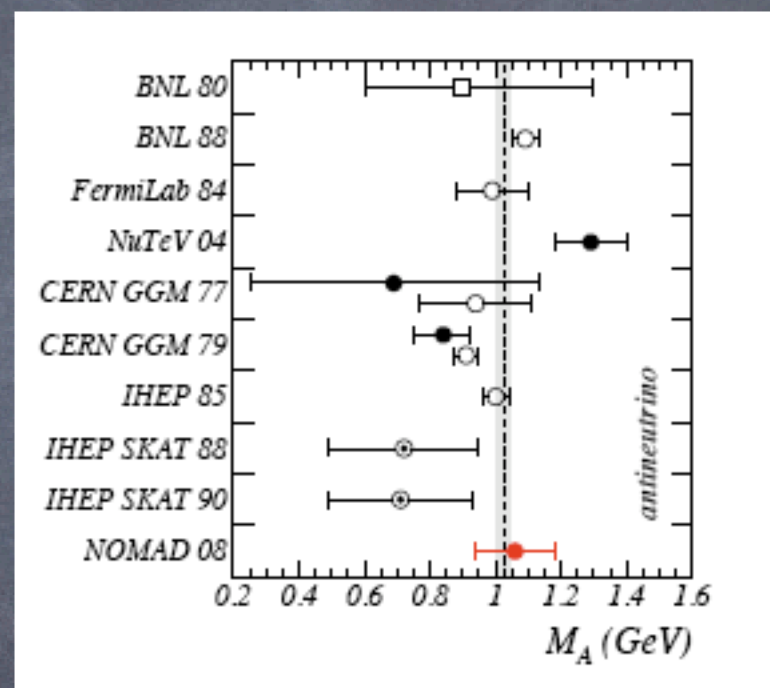
$$E_{lo} = \kappa(\sqrt{p_F^2 + M_p^2} - \omega + E_B)$$



CCQE MA



hep-ex:08124543



- Recent result from NOMAD at higher energies for neutrinos and antineutrinos.
- $M_A = 1.05 \pm 0.02 \pm 0.06$ (GeV) from q^2 and cross-sections.
- Picture is not yet clear. M_A is large for lower energies:
  - Dipole form factor?
  - Nuclear effects?
  - Detector systematics?
- This shows the fact the MA is an effective parameter with little validity across experiments.

Energy reconstruction

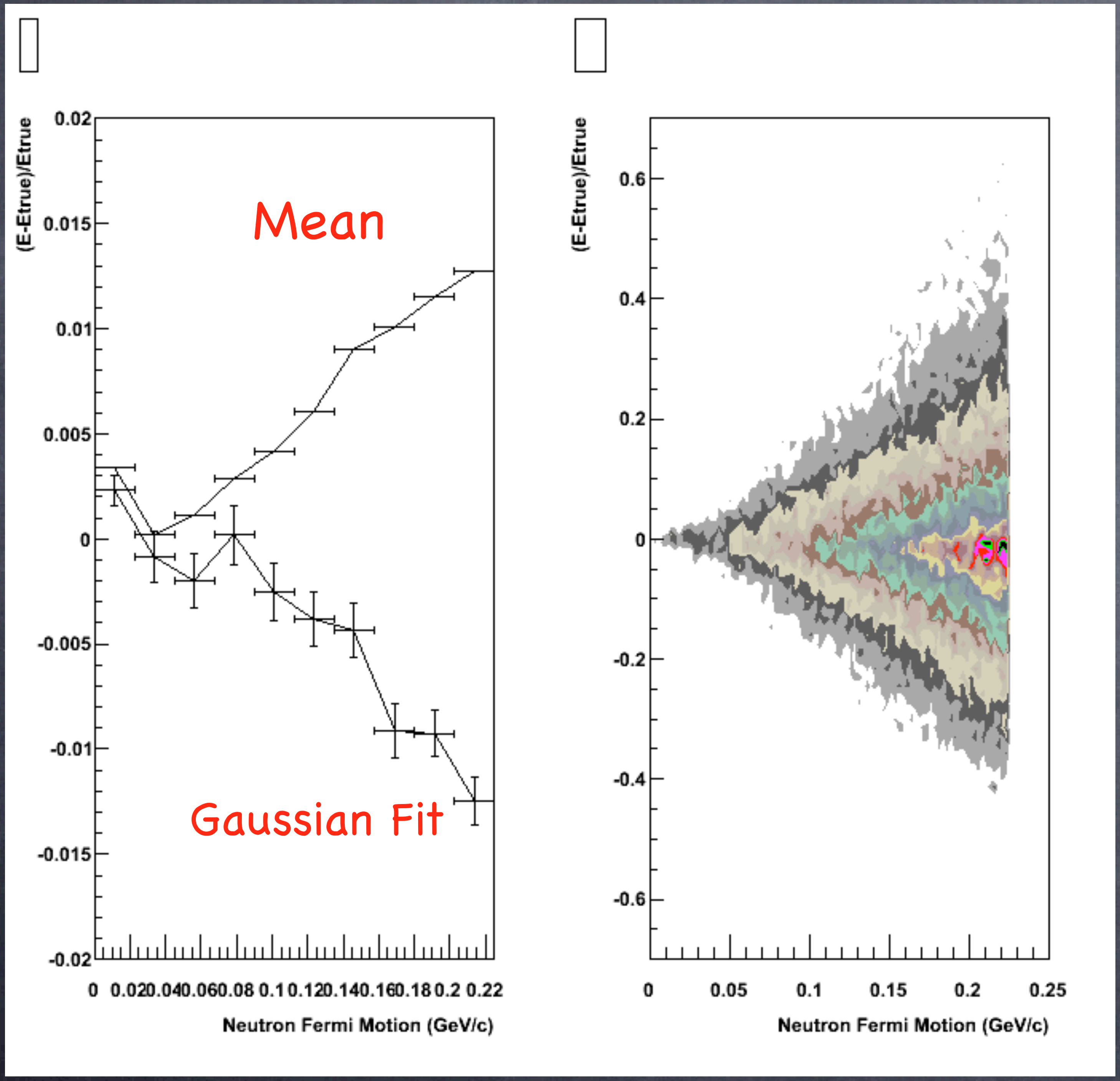
$$E_\nu = \frac{m_n E_\mu + \frac{m_p^2 - m_n^2 - m_\mu^2}{2}}{m_n - E_\mu + P_\mu \cos\theta_\mu}$$

- Assumptions:
  - single neutron target at rest.
  - Known neutrino direction.
  - Fix bind energy in m_n.
  - Free proton in the nuclear media.

Energy reconstruction

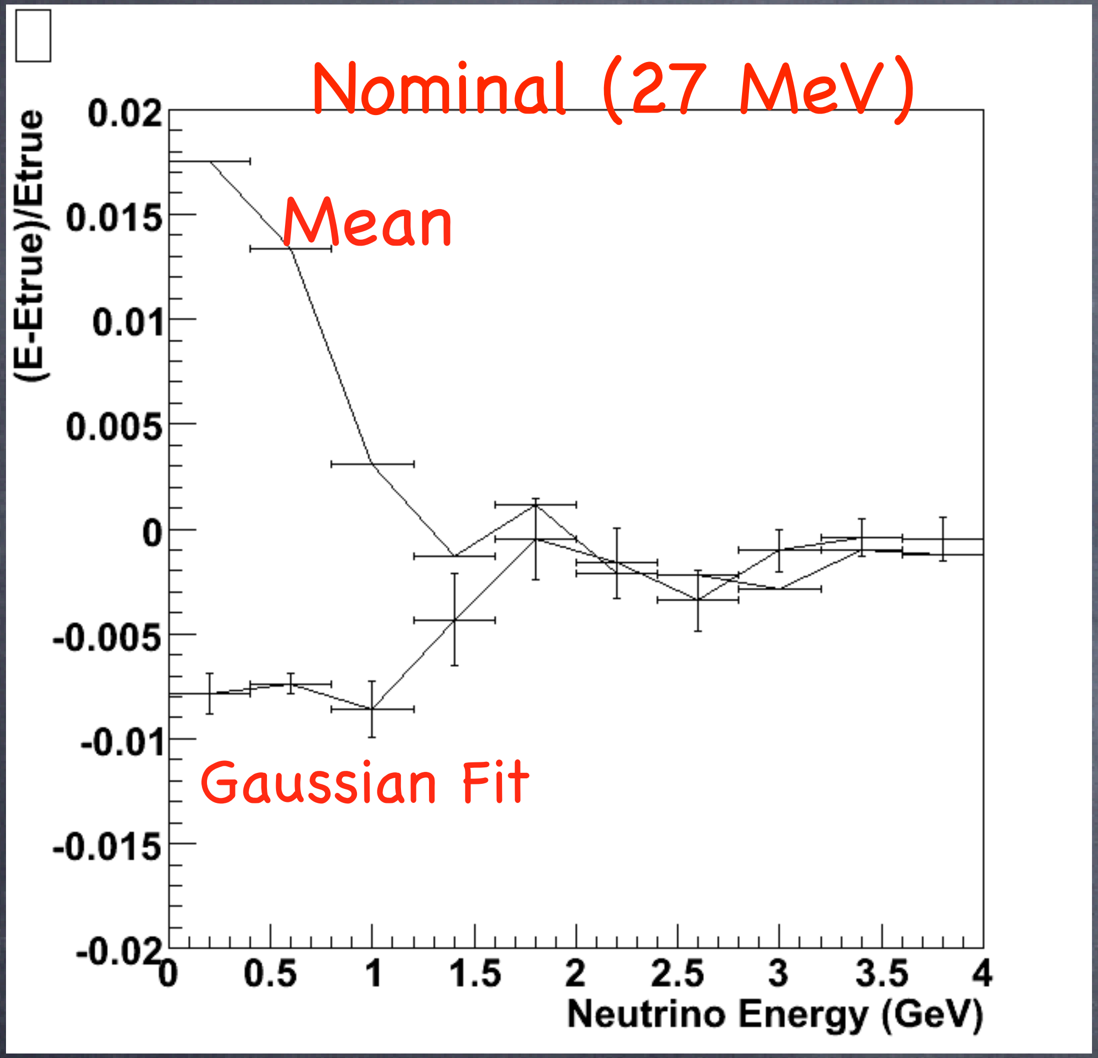
- In oscillation experiments, the near and far detectors follow the same reconstruction model cancelling systematics.
- However, systematic shifts in energy reconstruction might add a fixed systematic error in Δm^2_{23}.
- The systematic shifts might also introduce a bias in the q^2 reconstruction affecting our interpretation of the CCQE physics at different neutrino energies.

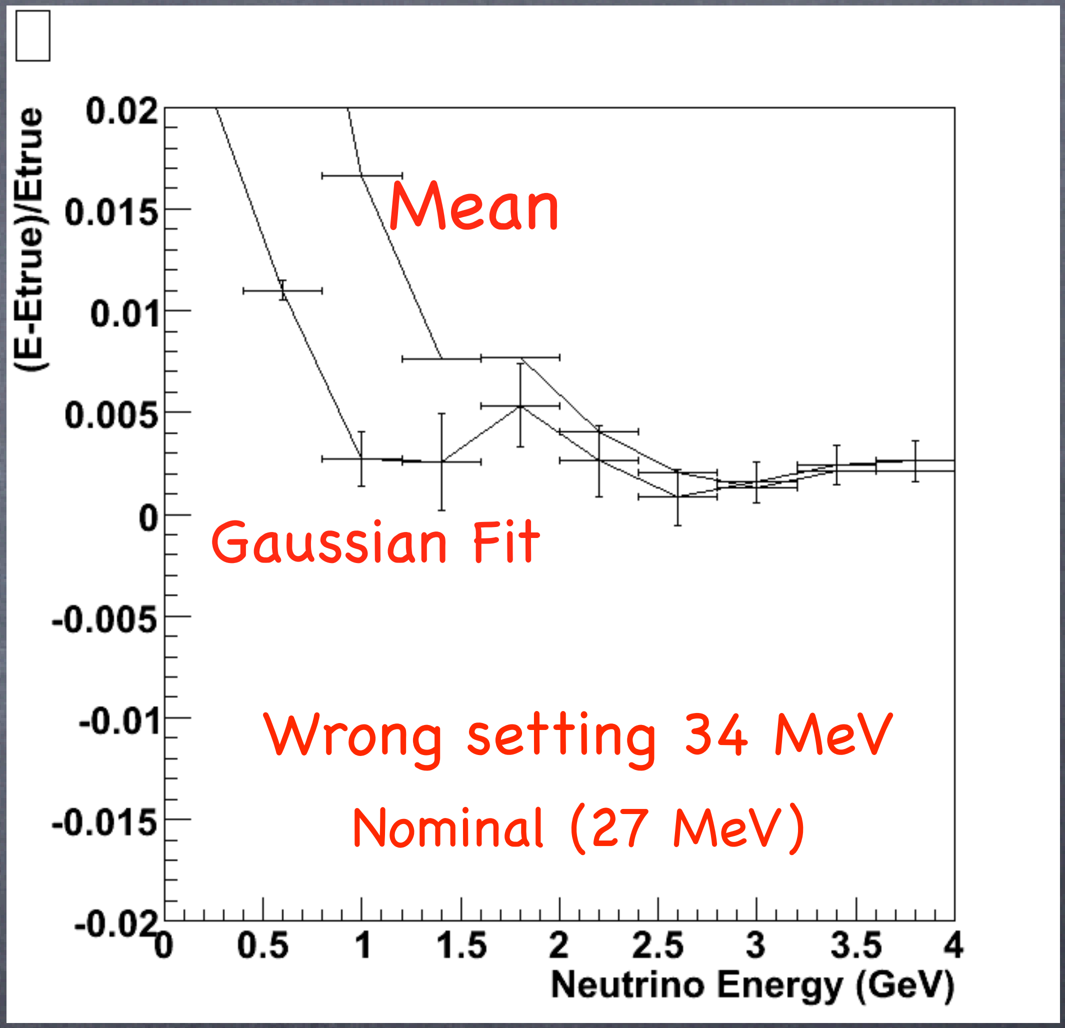
Energy Bias vs Fermi Motion



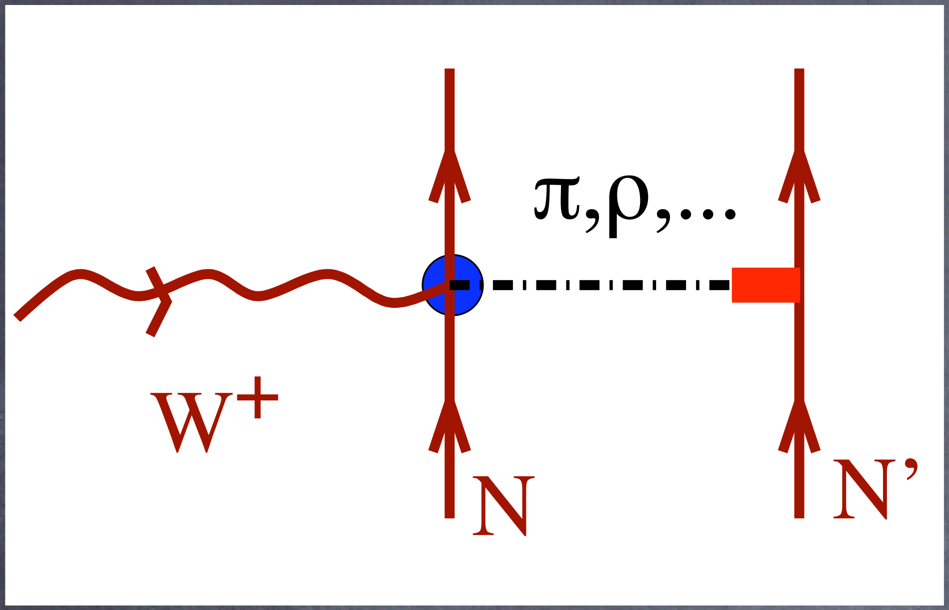
- Energy bias produced from the ignored Fermi Motion.
  - The bias tends to 0 for small Fermi Motion.
- What will happen for a model beyond Fermi Gas model like spectral functions ?

Effect of bind energy

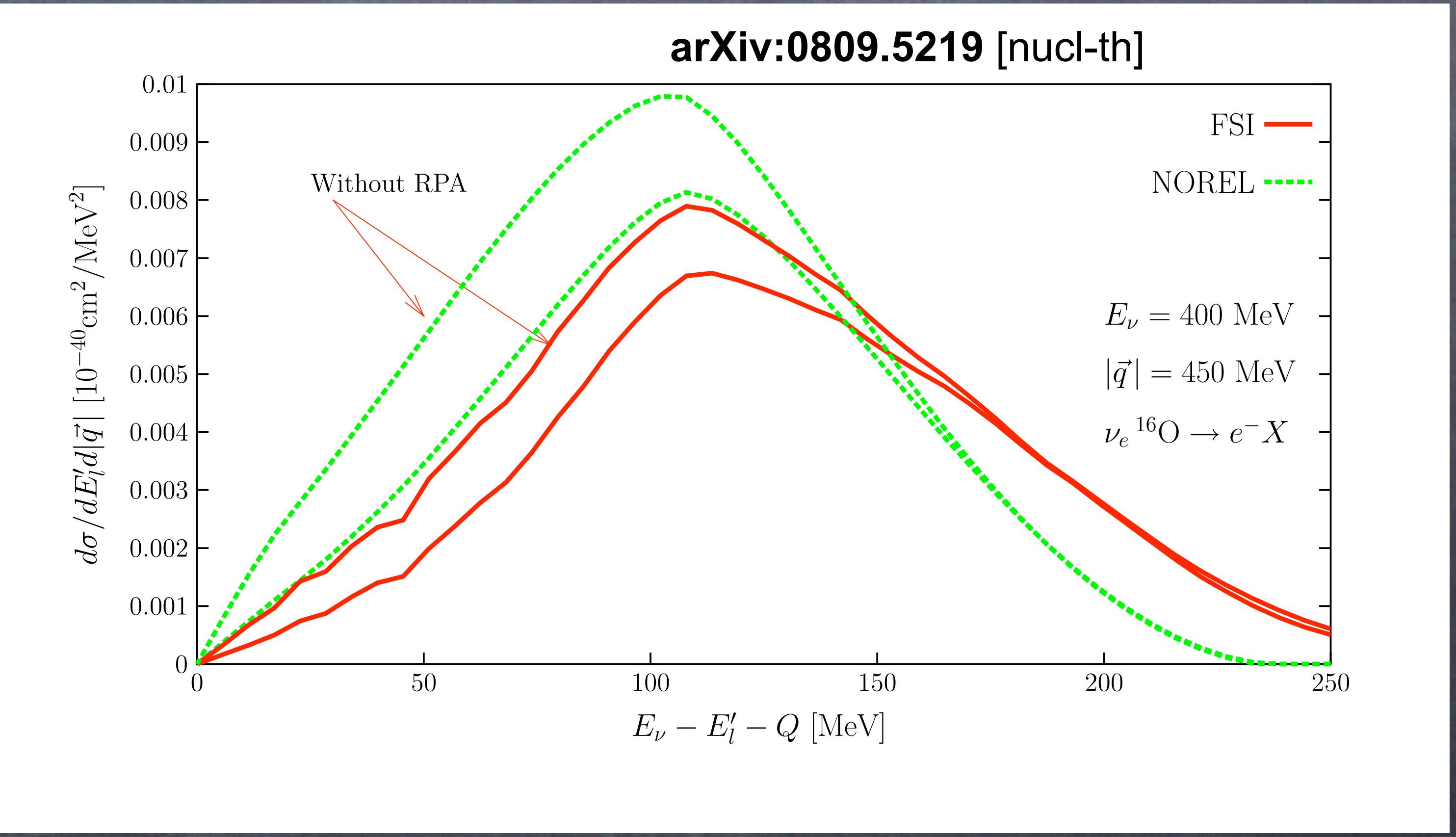




Additional possible effects



- The QE interactions has contributions of interactions with two nucleons and large range correlations (RPA). In this case the energy reconstruction might be incorrect.



- FSI (nucleon nuclear dressing) also alters the energy reconstruction.

Experimental effects

- Nuclear interactions alter the composition of the final state -> change of channel identification.
- Unknown fraction of backgrounds in the signal could lead to misinterpretation of observed effects.
    - systematics in background predictions could be large.

CC1π

- Second most important cross section.
  - Main background to CCQE reactions.
- It might allow the neutrino energy reconstruction, at least for the Δ^{++} production that is dominated by the 1232 resonance.

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:

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

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

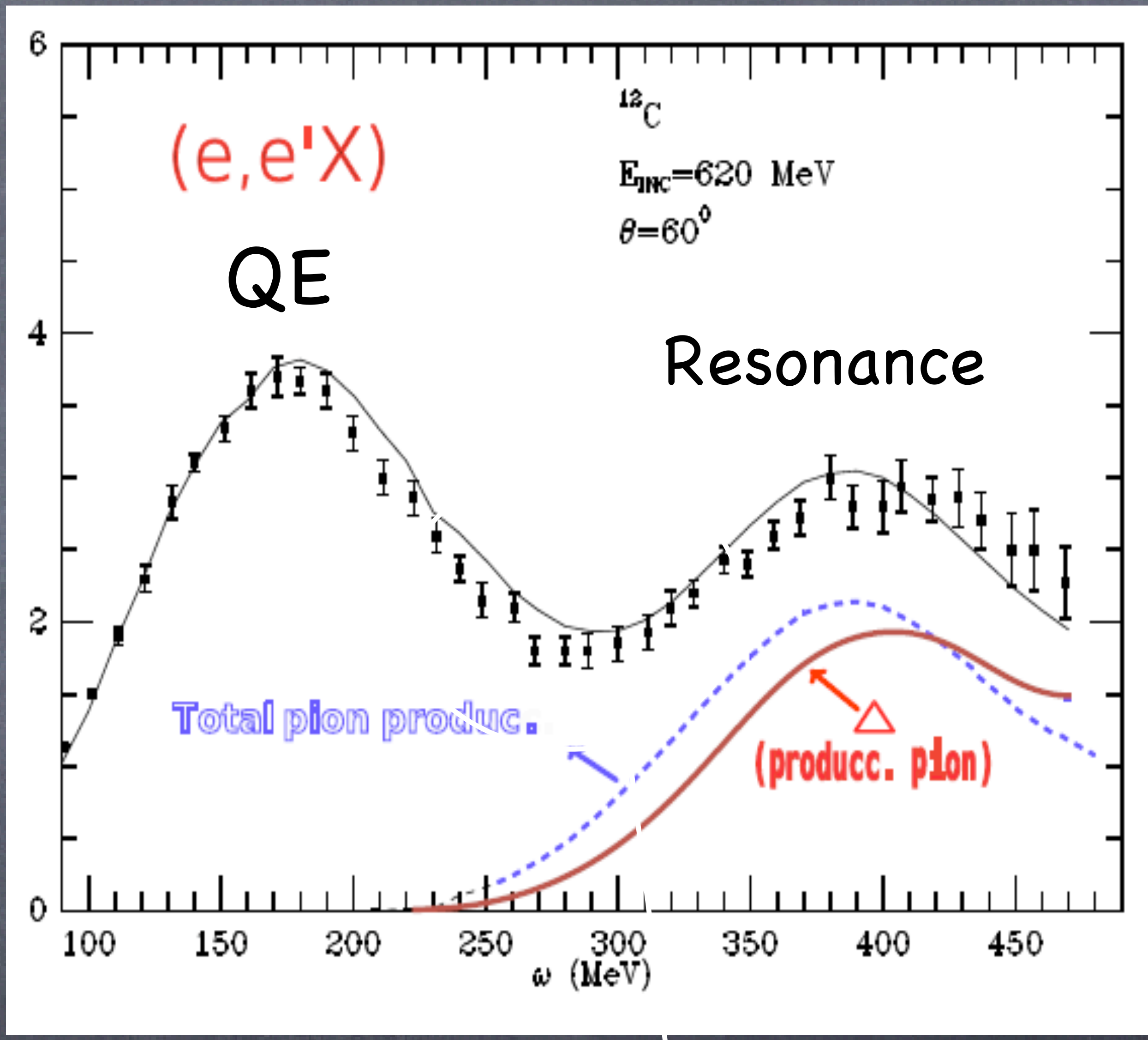
They can be related by isospin relations except for nuclear corrections.

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

CCQE CC1π

E.Hernandez et al. hep-ph/0701149

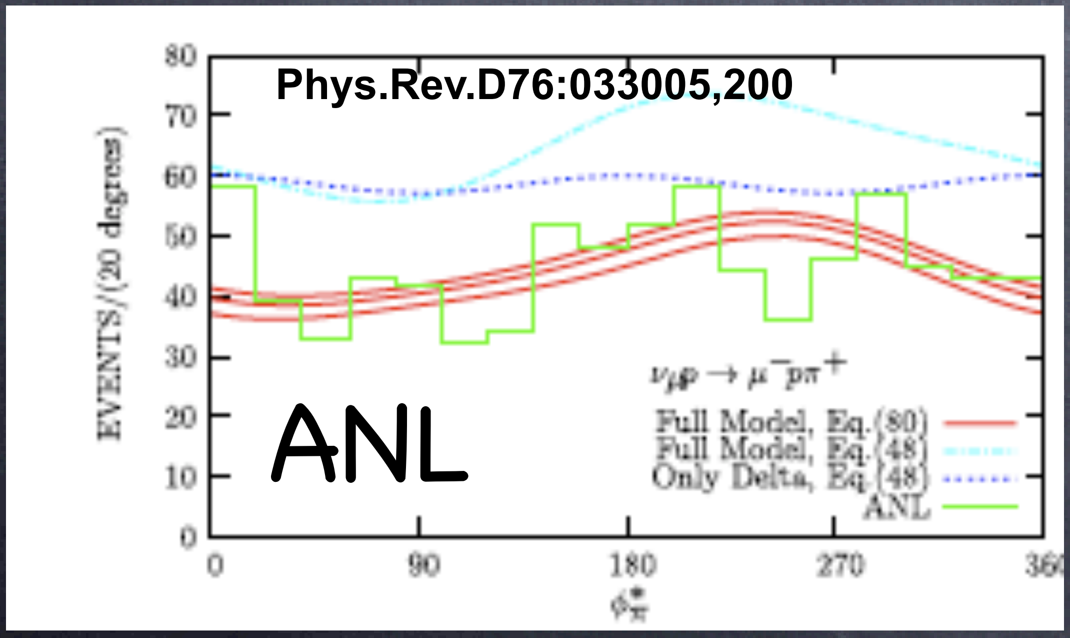
- New models in the market that predicts a sizeable contribution of non-resonant contribution to single pion production:
  - Non-resonant π production
- This is known in electron scattering since long.
- This is specially relevant at threshold.
- Detectable with polarization of final Δ.
  - Need to adress this point in future experiments.

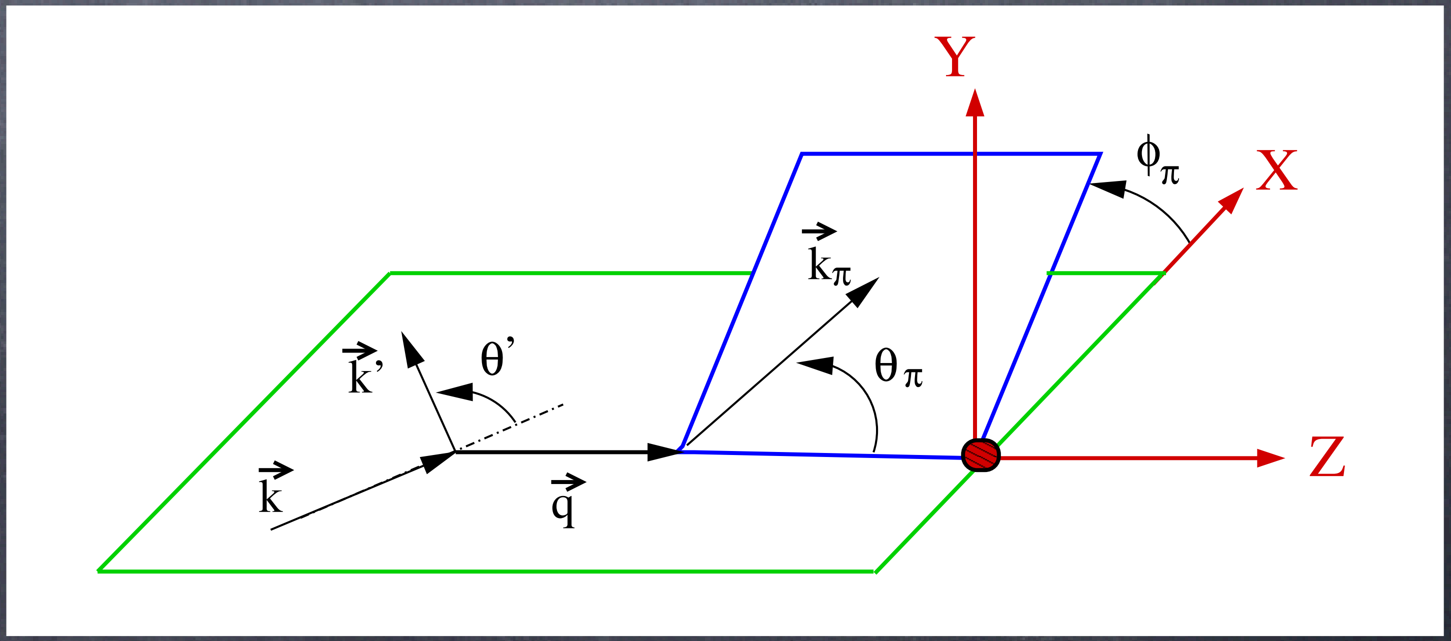


The intermediate region is not well reproduced by QE + Δ

CC-1π measurements

- How to measure the non-resonant contribution.
  - The interference of resonant and non-resonant produce a P violating observable.
  - This can be used to constrain ratio's for both π^+ and π^0.
  - This is not done since ANL. Next generation might be able to measure it again as function of neutrino energy.





CC1π

- The measurements are based in two methods:
  - Detecting the final π^+(MiniBoone) and π^0(K2K & MiniBoone) final states (production+reinteractions).
    - Lower systematics.
    - More difficult interpretation.
    - Contribution from detector mass reinteractions.
  - Based on the lepton kinematics: π^+(K2K MiniBoone). The nuclear reinteractions enter in event selection.
    - Easier to interpret.
    - Larger systematics.
    - Not suitable to check theoretical models.

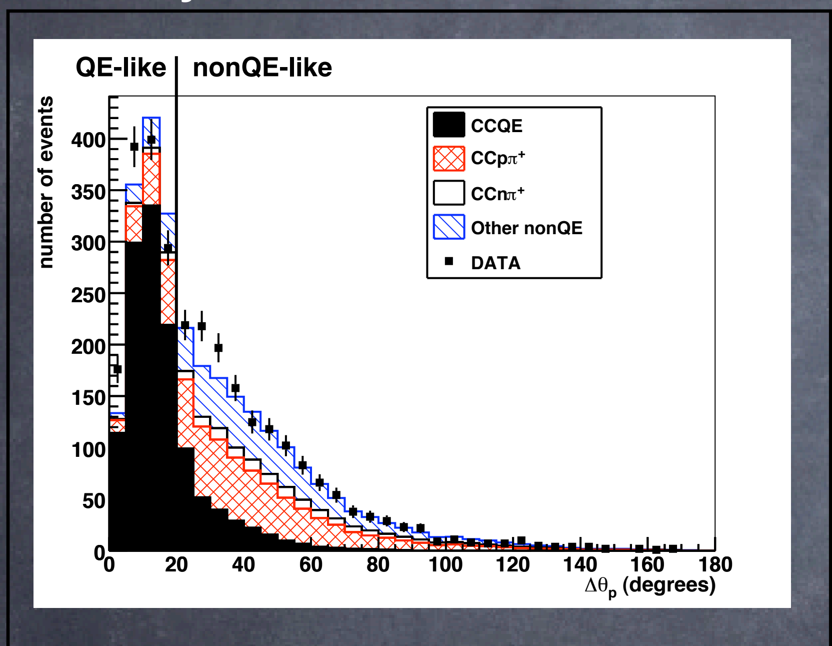
How many times the pion leaves nucleus?

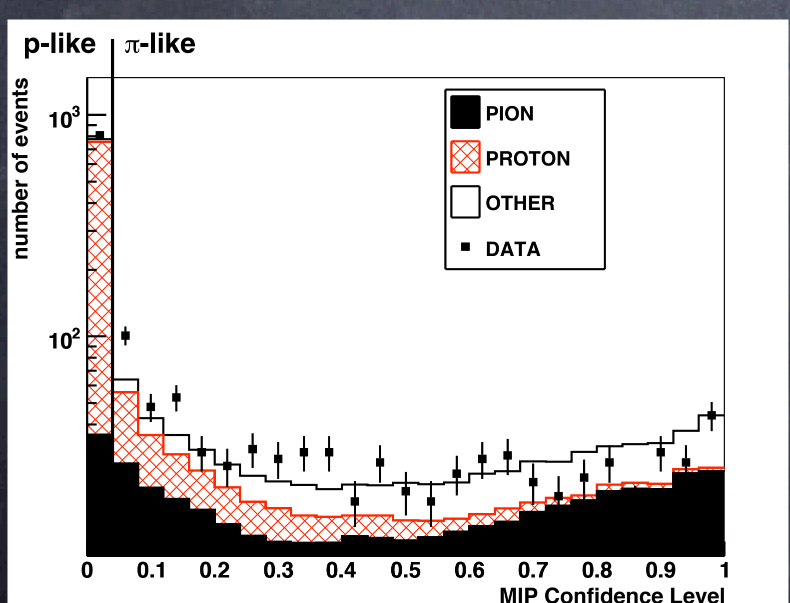
How many times the pion is produced inside the nucleus?

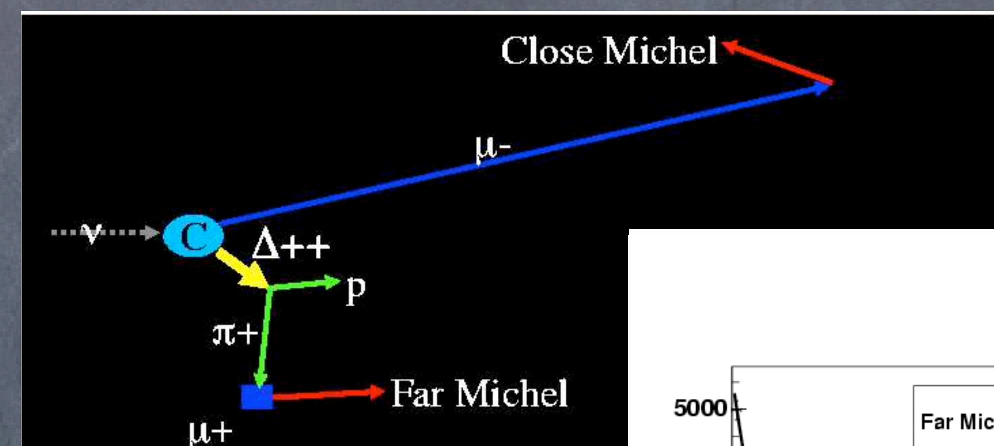
CC1π

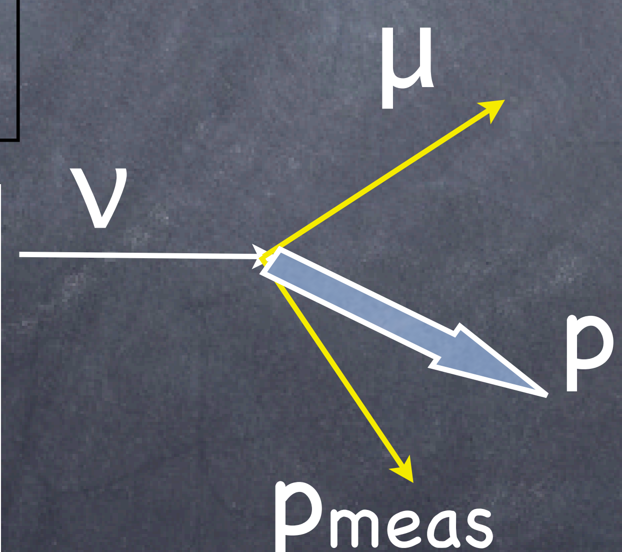
- K2K and MiniBoone uses different methods to detect the π^+ --> different systematics.

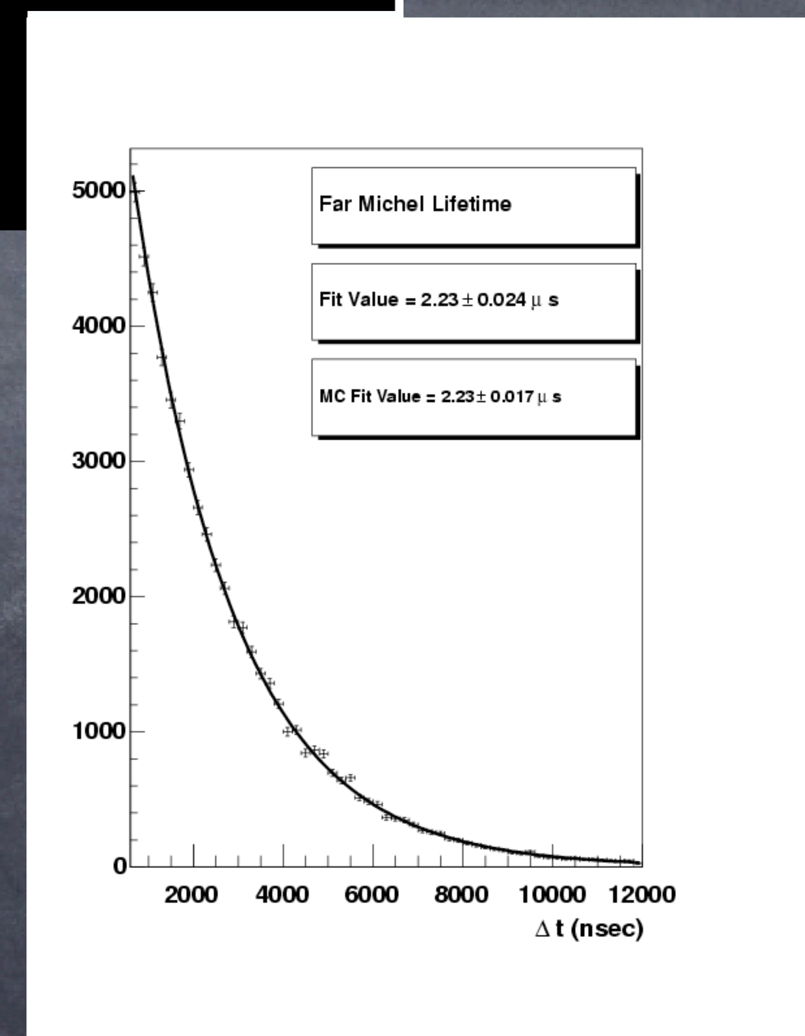
Phys.Rev.D78:032003,2008.





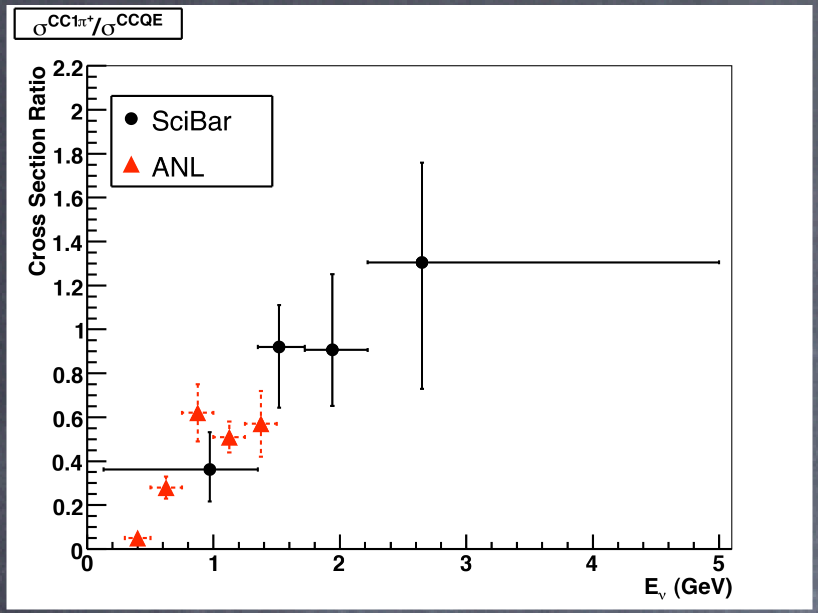






CC1π

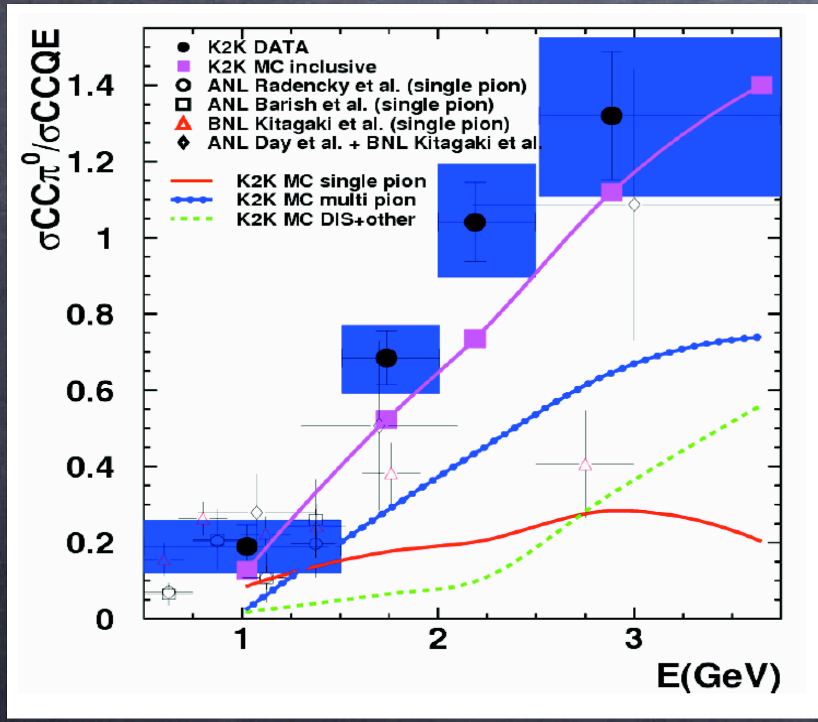
K2K



Nucleon

π^+

Phys.Rev.D78:032003,2008.



Nucleus

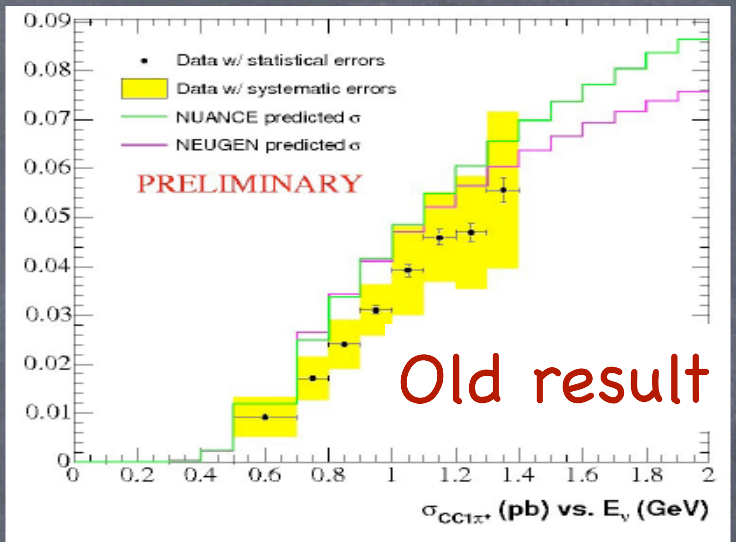
π^0

K2K,
Nuint07

MiniBoone

Nucleus?

π^+



MiniBoone,
Nufact06

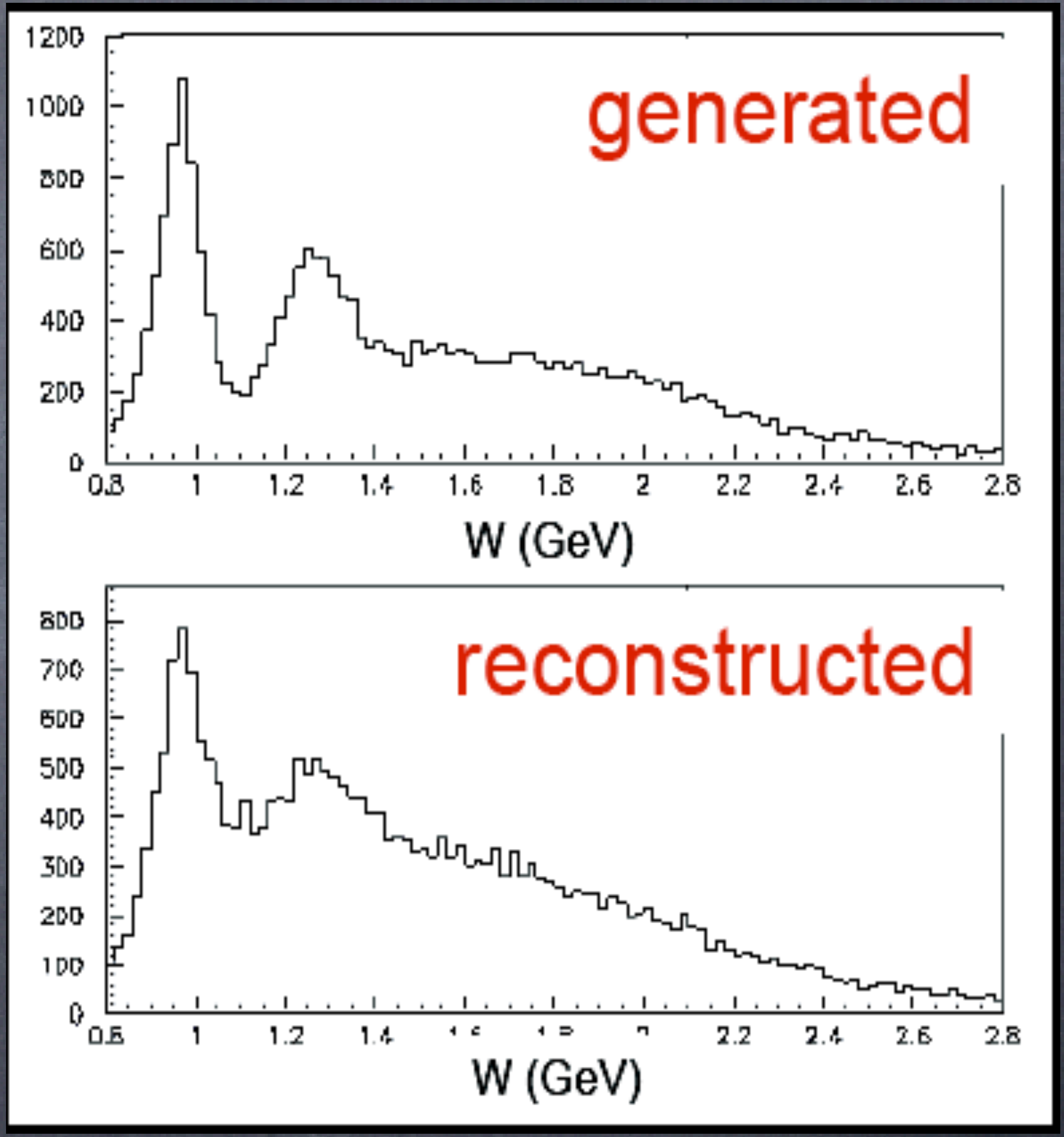
M_A CC1π

- This is not very well measured as CCQE.
  - CC1π was considered background.
- It is still important because it defines the (p_μ,θ_μ) map and so the reconstructed energy as CCQE and event acceptance.
- It is a more difficult measurement because of:
  - Non-resonance contribution
  - Several contributing resonances
  - large backgrounds from CCQE
  - effect of nuclear re-interactions in selection

CC1π

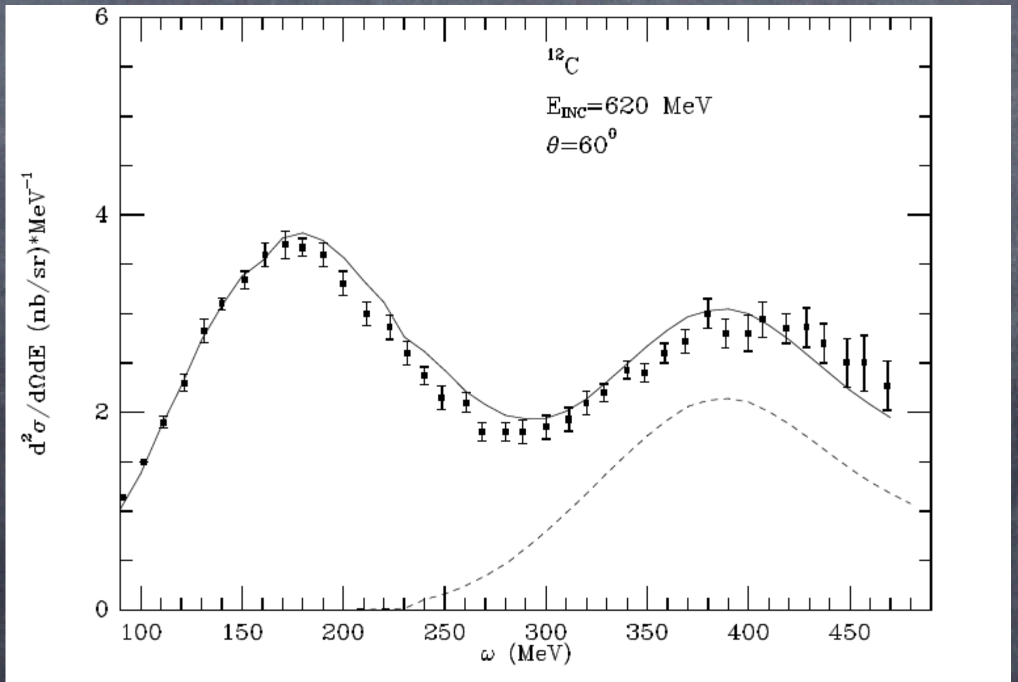
Minerva, Nuint07

- There is no measurement of the resonance production since time of bubble chambers.
- This is only possible in the case of $p\pi^+$ final state and probably radiative decays.
- Also difficult to interpret from Nuclear modification of Delta's.



Transitions

- CCQE-CC1π
  - contributions from RPA, nNN and non-resonant pion production.
  - well known and modeled in electron scattering.
  - we need to establish this experimentally in neutrino scattering.



$e + {}^{12}C \rightarrow e' + X$

Transitions & Beyond

- CC1π-CCNπ-DIS
  - Resonances with many pions.
  - non-resonant with >2 pions.
  - (D)IS at low energies
    - Bodek-Yang corrections
    - high twist
    - shadowing
    - etc..

Based in old data

How to interface with nuclear re-scattering ?

CC-coh π measurements

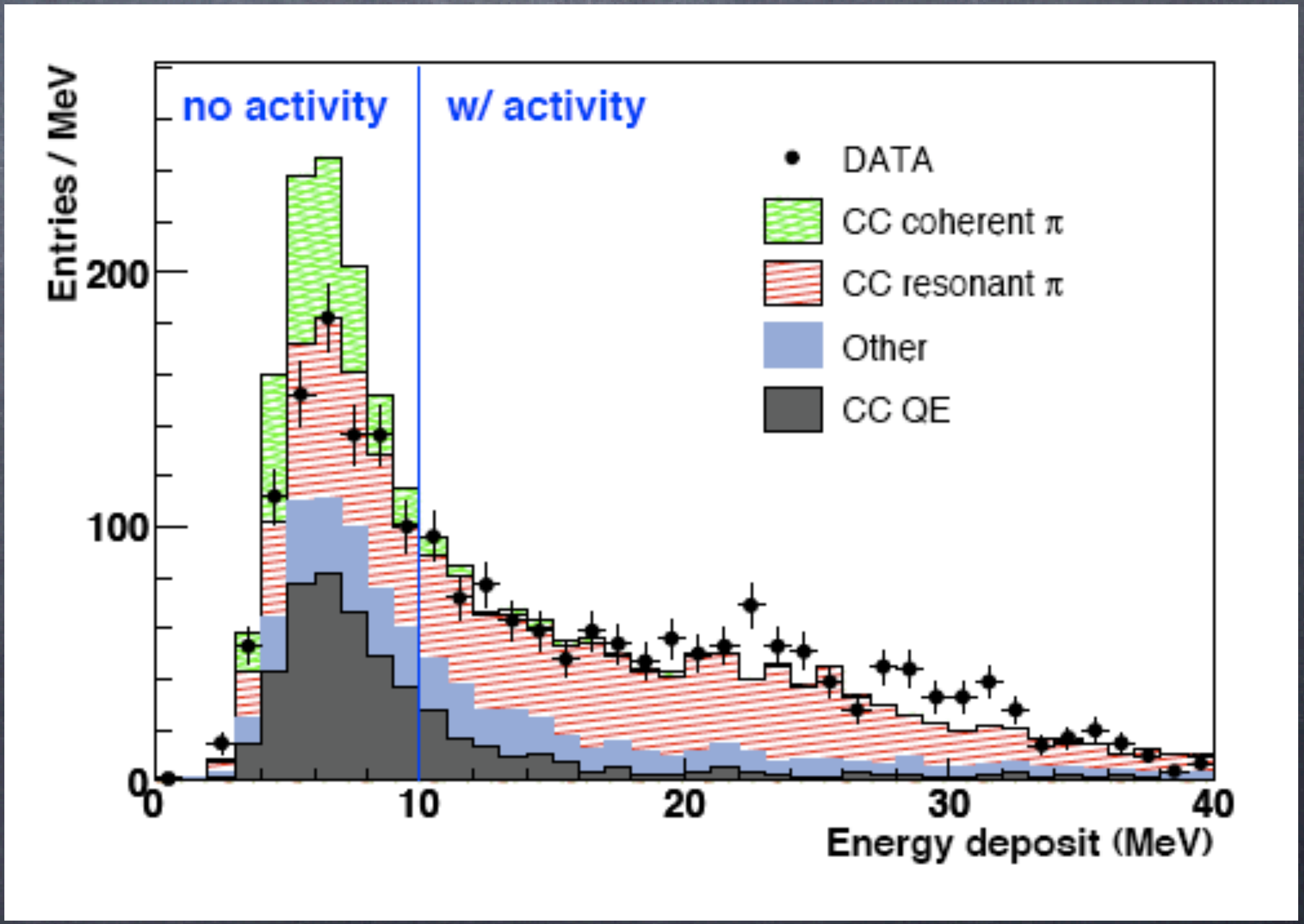
- Recently the measurement of the coherent charged pion production show a lower yield than expected (K2K & SciBoone)
- Small corrections from muon mass (Phys. Lett. B 657, 207 (2007)) did not compensate difference with original Rein-Sehgal (Nucl. Phys. B 223, 29 (1983).)
- Some other models(Phys.Rev. D 74, 054007 (2006)) do not account for the experimental result.
- There are other models in the market (Phys.Rev.D79:013002,2009) that predicts lower values.
    - This is actually very interesting because it links the value directly to the amount of resonant production in CC1π via the value of axial form factor $C^A_5(0)$
    - It is also interesting because of predicted the relation NCπ^0 and CCπ^+ do not match the experimental results from MiniBoone.
- This can be an interesting laboratory to understand CC interactions at low energies.

CC-coh π measurements

- Reaction measured at K2K and SciBoone.
- The main ingredient is the detection of vertex activity:
  - No vertex activity means:
    - No low energy proton emitted.
    - nucleus is not broken.

Phys.Rev.D78:112004,2008.

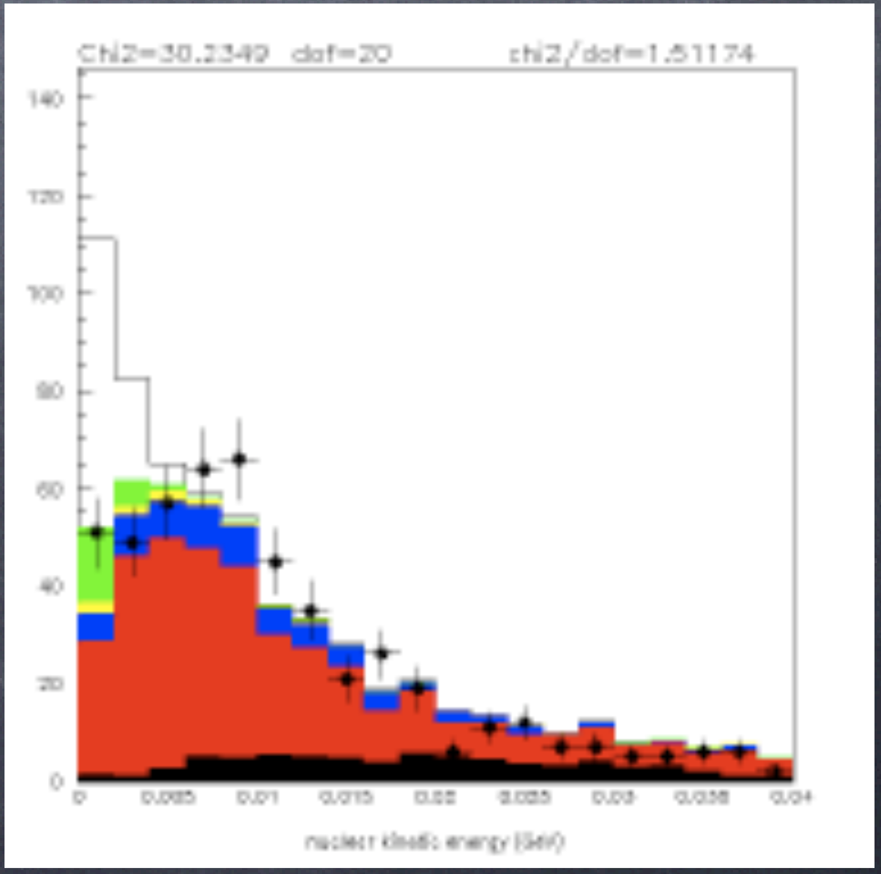
$$\frac{\sigma(\text{CC coherent } \pi)}{\sigma(\text{CC})} < 1.36 \times 10^{-2}$$



CC-coh π measurements

- The measurements can be improved by reconstructing the kinetic energy of the nucleus (t) . For coherent, this value should be around zero.
- Cut independent to activity cut.
- This can be done using the muon energy and direction, neutrino direction and pion energy and direction. This is a independent and more powerful way to identify coherence.

$$T'_N = \frac{(E_\mu + E_\pi)\left(E_\mu + E_\pi - |p_\mu| c\cos\theta_{\nu\mu} - |p_\pi| c\cos\theta_{\nu\pi}\right)}{m_N c^2 - (E_\mu + E_\pi - |p_\mu| c\cos\theta_{\nu\mu} - |p_\pi| c\cos\theta_{\nu\pi})} - \frac{(E_\mu E_\pi - |p_\mu||p_\pi| c^2 \cos\theta_{\mu\pi}) + \frac{(m_\mu c^2)^2 + (m_\pi c^2)^2}{2}}{m_N c^2 - (E_\mu + E_\pi - |p_\mu| c\cos\theta_{\nu\mu} - |p_\pi| c\cos\theta_{\nu\pi})}$$



Neutral currents

- Neutral currents are important for sterile neutrino oscillation analysis and as background to electron neutrino appearance.
- There is also an important measurement topic: nuclear ΔS. (I won't mention it but it is very challenging from the theoretical and experimental points of view).
- The measurement is highly complicated since we have to rely on our knowledge of the nuclear recoils and re-interactions.
- From this aspect, the minimum is to measure the NC event topologies.

Neutral currents as background

- π^+ may mimic the signal of a single muon if charge is not measured.
- This is specially critical at low energies where the muon has low energy similar to the pions in neutral currents.
- π^+ are produced mainly in Δ^+ in NC. This is similar to the Δ^+ in CC and can be related via isospin, but CC has a large background from Δ^{++}
- Detector with charge identification and PiD might help in this analysis.

Do not forget about high mass resonances !!!!

Neutral currents as background

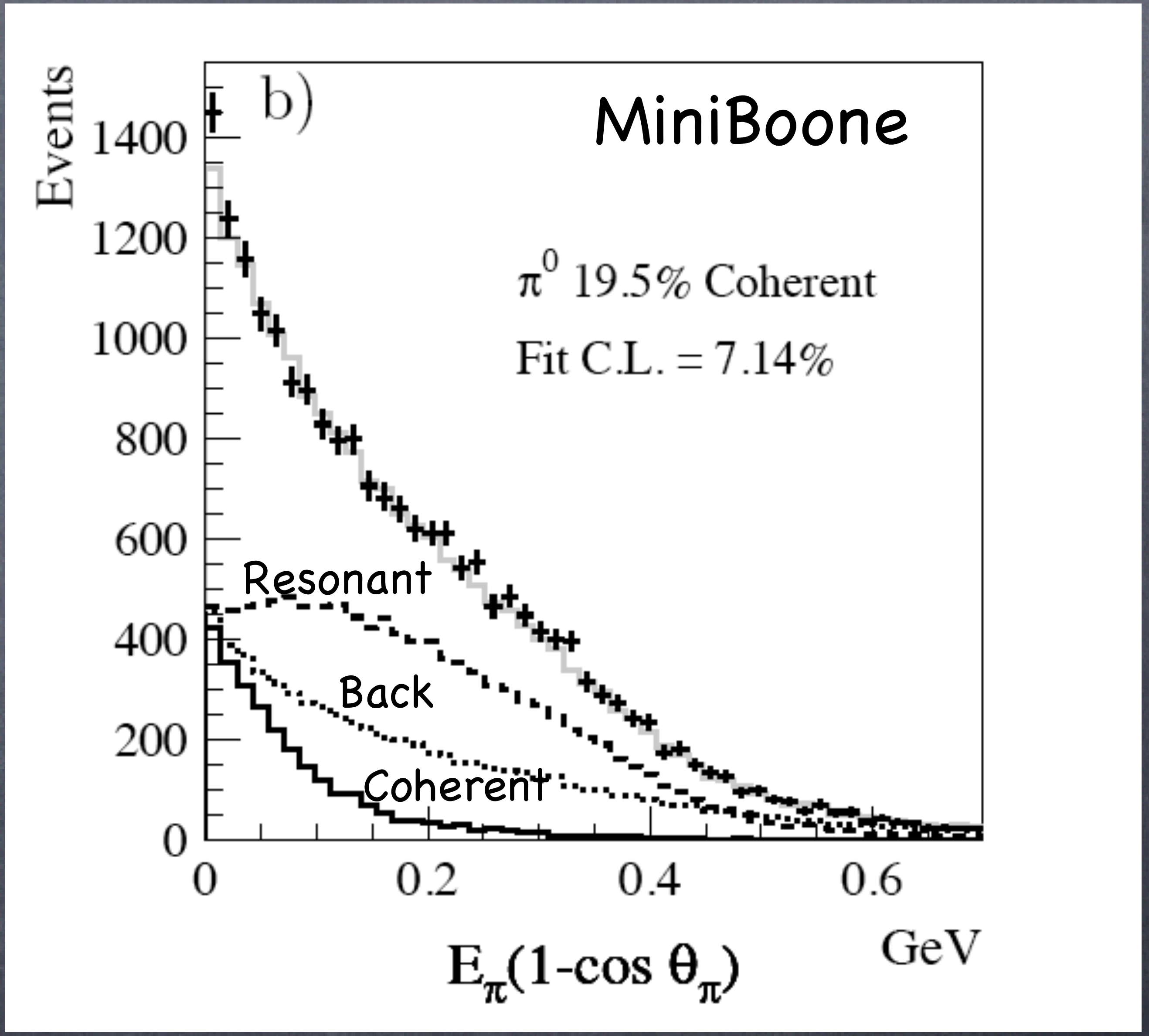
- π^0 may mimic the signal of a single electron.
- This is specially critical at low energies where the electron has low energy similar to the pions in neutral currents and one of the gammas from π^0 can be missed.
- π^0 are produced mainly in Δ^0 (~1.9%) and Δ^+(~2.3%) in NC. CC only has Δ^+ production making the relation between the NC & CC very difficult.
- NC-π^0 detection is experimentally challenging.

Do not forget about high mass resonances !!!!

Neutral current coherent

Phys. Lett. B. 664, 41 (2008)

- Very difficult measurement.
- Very little handles beyond the kinematics of neutral pion.
- Large background.
- MC-theory model predicting the shape of $E_\pi(1\text{-}\cos\theta_\pi)$.
- Probably need other means to constrain non.coherent contribution: CC-resonant, etc...

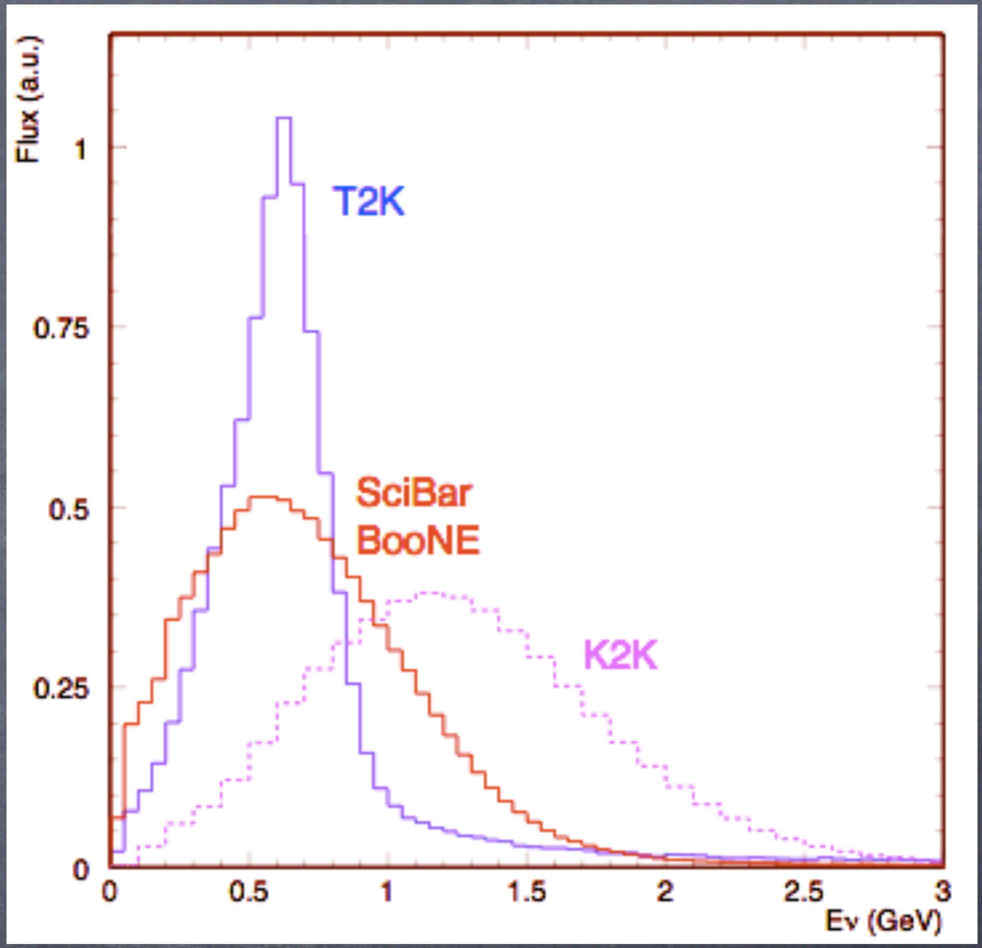


What do we need?

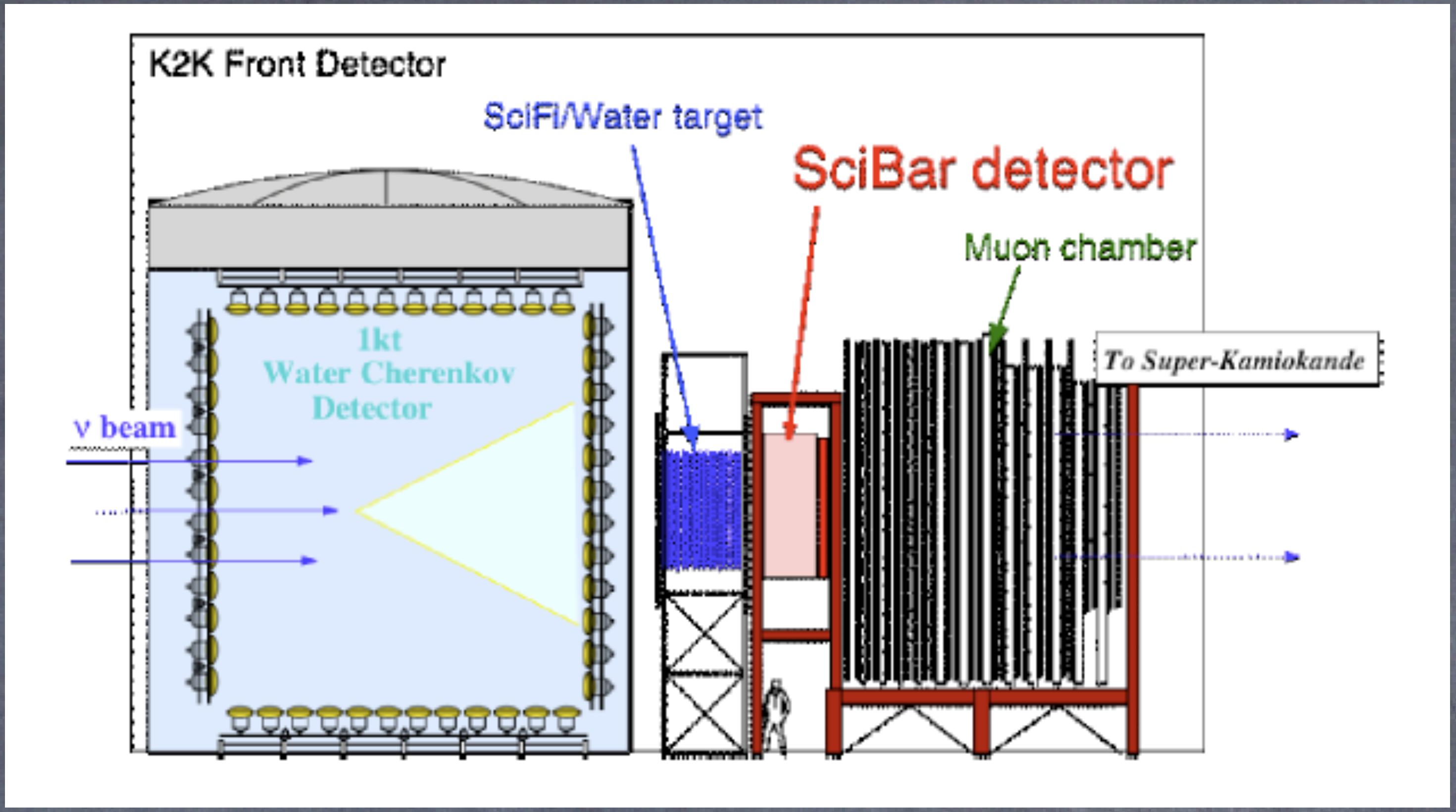
- Muons.
  - That's easy.
  - need good momentum scale.
  - moderate momentum resolution.
- Charged pions.
  - PID via charge, dE/dx and Michel electrons.
    - Difficult in dense materials due to hadronic interactions.
- Neutral pions
  - Experimental challenge at low energies.
- protons (what do we learn from protons?)
  - Difficult: short range.

How was it recently done ?

- K2K
  - E > 1 GeV.
  - Several detectors: water, scintillator, ...
- SciBoone
  - SciBar from K2K at lower energies.
- MiniBoone
  - Scintillator cherenkov at low energies.

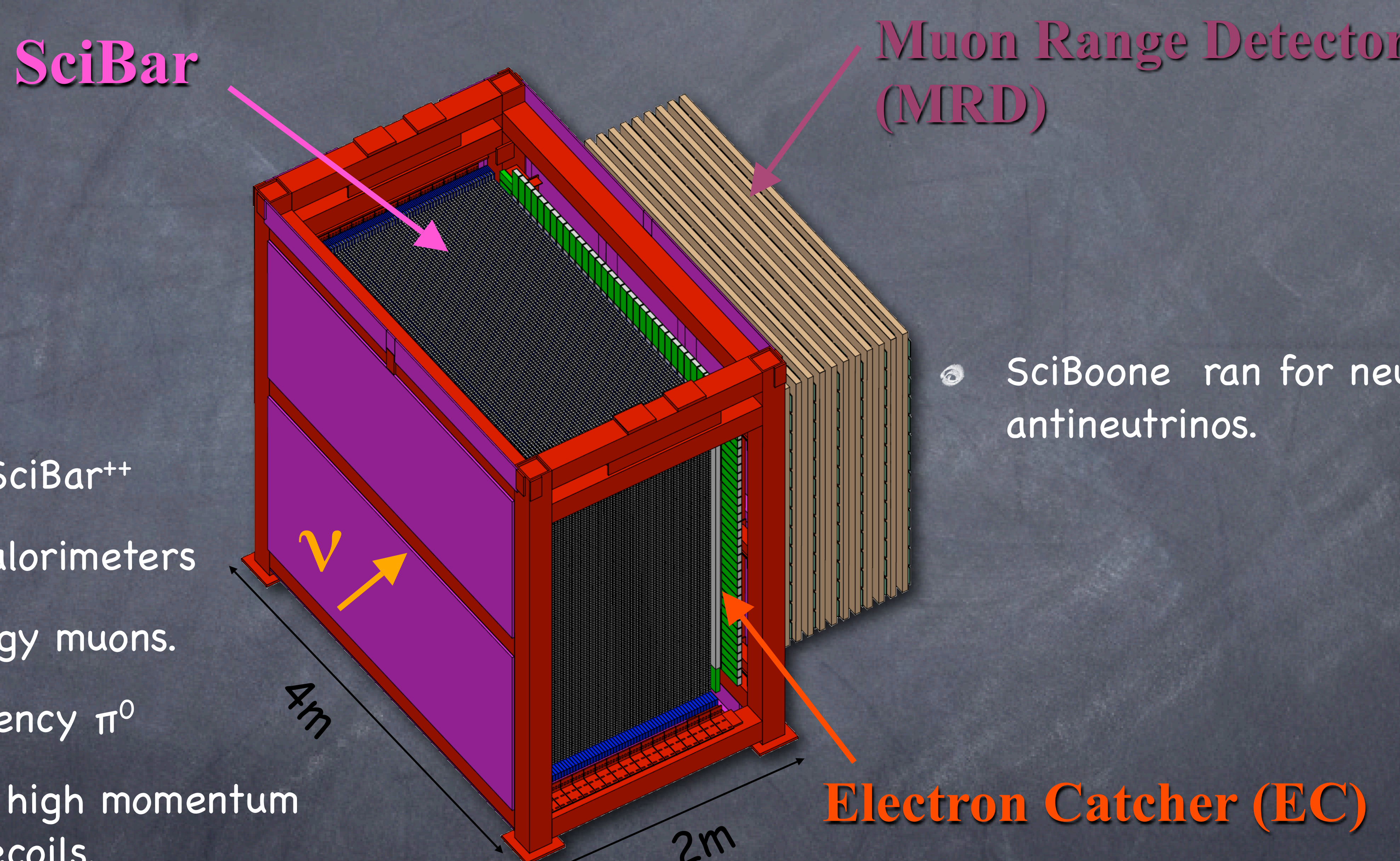


K2K



- 1Kt
  - water cherenkov.
  - low energy muons.
  - Good efficiency π^0
  - No access to nuclear recoils.
  - 4π acceptance.
- SciFi & SciBar
  - tracker calorimeters
  - High energy muons.
  - Bad efficiency π^0
  - Access to high momentum nuclear recoils.
  - forward acceptance.

SciBoone

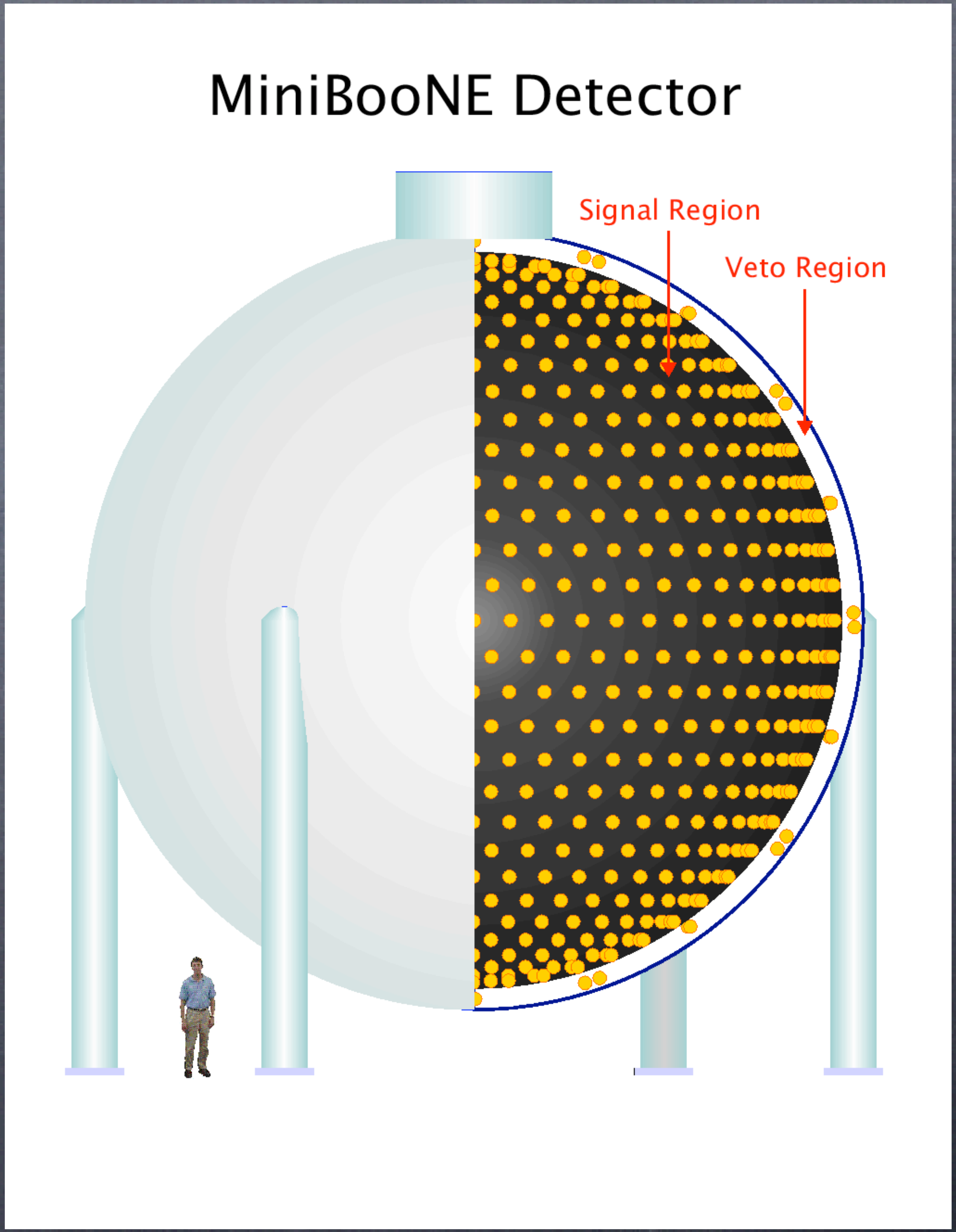


- SciBoone ran for neutrinos and antineutrinos.

- SciBoone == SciBar^{++}
  - tracker calorimeters
  - High energy muons.
  - Bad efficiency π^0
  - Access to high momentum nuclear recoils.
  - forward acceptance.
  - Better capability for Michel electrons: π^+ & μ.

MiniBoone

- Cherenkov detector + scintillator light.
- Low energy muons.
- Good π^0 efficiency.
- Good at identifying π^+ via Michel Electrons.
- No charge: π^+ <-> μ confusion.
- Neutrino and antineutrino run.
- Low reconstruction capabilities for nuclear recoils (except π^0)

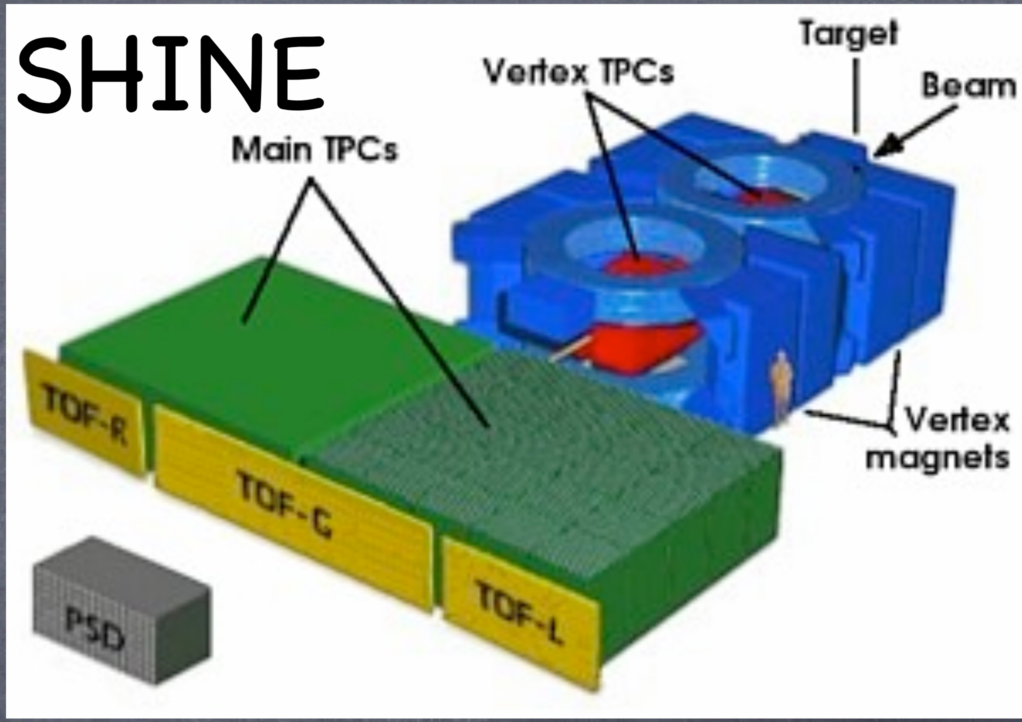


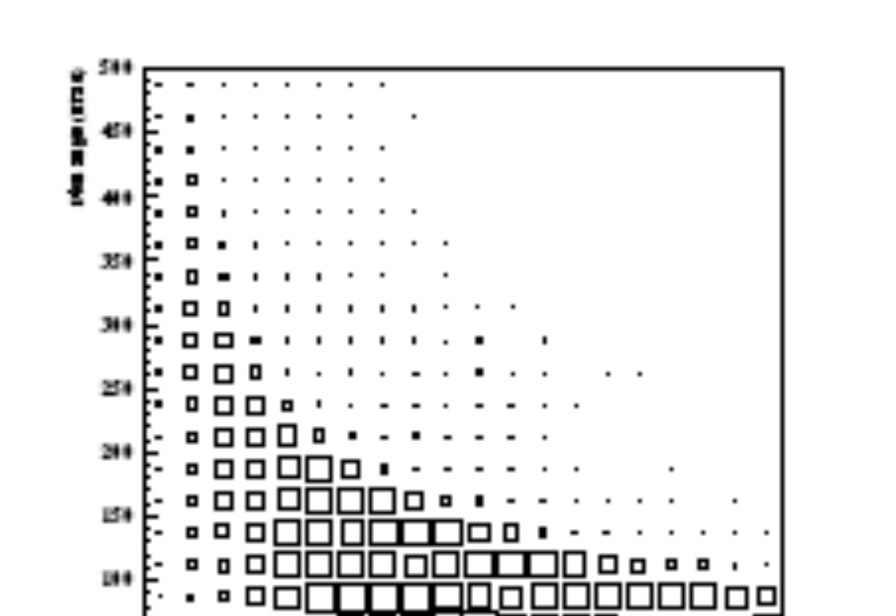
Can we do it better?

- Hadroproduction experiments.
  - neutrino flux shape.
  - neutrino absolute flux.
- T2K
- Minerva (Higher Energy, I do not mention here but:
  - nuclear mass dependency
  - nice energy range.
  - We need it for consistent modelling of data.

HadroProduction experiment

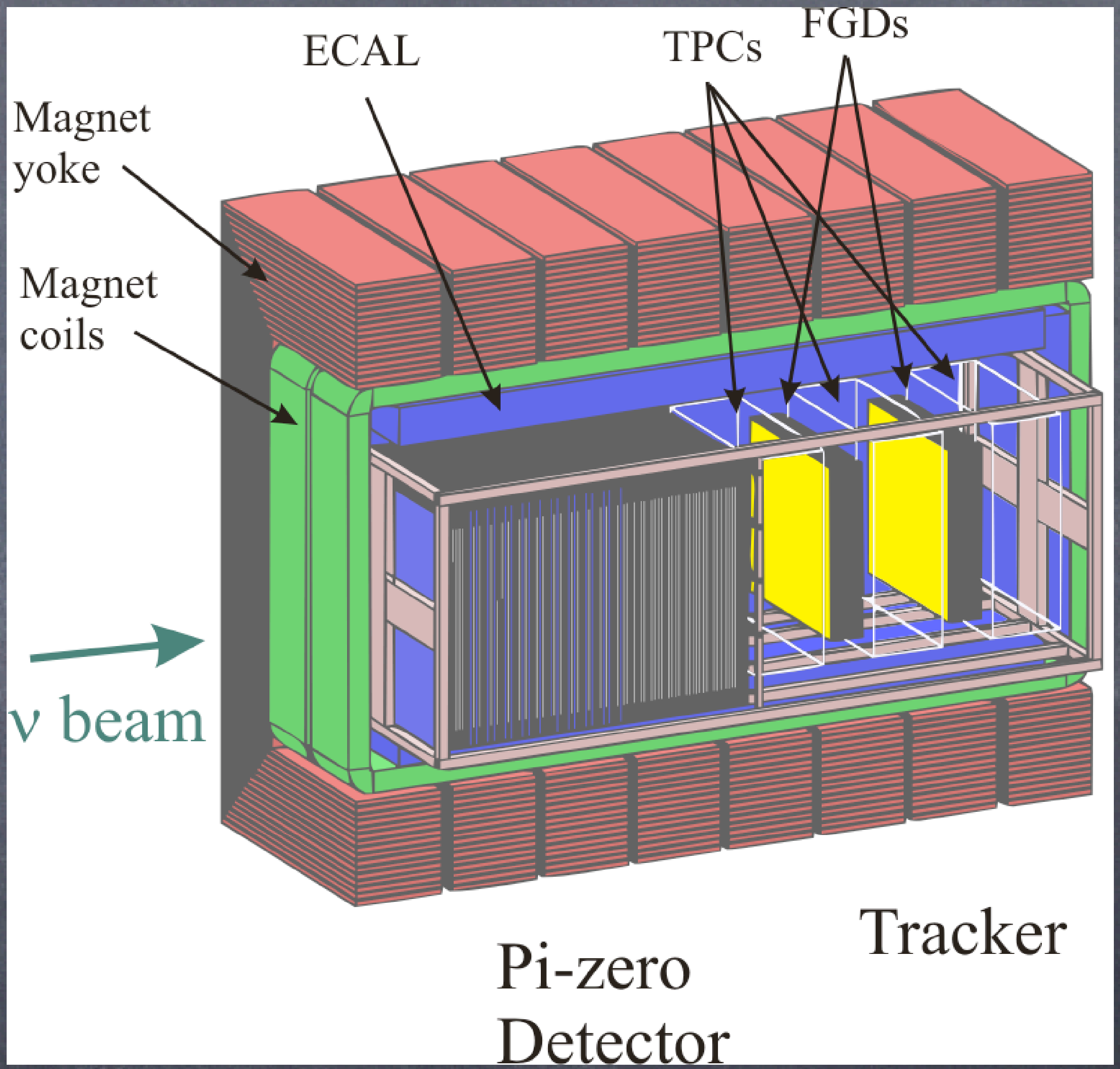
- Measure the production of pions (p_π,θ_π) in a neutrino beam target replica.
- Introduce this information in the beam MC to compute flux with high precision.
- This is very important for oscillation physics but also for cross-sections since they constrain flux.
  - We measure always $\sigma_\nu\Phi_\nu$.
- Shine (NA61) collaboration is performing the measurement for T2K.





T2K (ND280m)

- Large statistics neutrino beam. (Antineutrinos in the future?)
- Off-axis: narrow spectrum + running of energy along the detector.
- Advanced near detector:
  - tracks with low hadronic recoil threshold.
  - 4π acceptance.
  - neutral pions.
  - Magnet: Charge sign.
  - PID from: dE/dX & Michel Electrons.
  - Good momentum resolution (TPC)



Help from electron scattering

- Many lessons have been learned in electron scattering.
- Some how we are behind them in our nuclear models.
- Already some parameters are incorporated in our monte-carlos:
  - vector form factors.
- Do we need to be more agressive and request for specific measurements?:
  - i.e. nuclear re-scattering with well define initial conditions.
- To which level we are sensitive to all these details in neutrino physics ?. (My personal view is that we need MC to check this point).

Conclusions

- Still many points open to understand interactions of neutrinos below 1GeV.
- Large theoretical effort below ~0.5GeV --> need integration in MC.
- Large effort at few GeV region.
- It seems that 0.5 to 1 is a “bit” orphan.
- Nuclear effects (initial and final state) are basic for precision oscillation experiments.
- Transition regions and non-standard interactions are also relevant (RPA, νNN, non resonant pion, etc...)

Conclusions

- Experimentally we need:
  - Good PiD for pions (dE/dx, Michel electrons) and protons.
  - Detectors with charge determination.
  - low momentum threshold detection (low density).
  - Good π^0 detection efficiency.
  - Hadroproduction experiments to decouple σ_ν from Φ_ν.
  - large statistics and many exclusive channels to relate final topologies and interactions into fundamental cross-sections.

Conclusions

- Theoretically we need:
    - Recipes how to correlate measurements.
    - More complete description of cross.sections in Monte Carlos.
    - Import electron scattering information and lessons in our models.
    - Directions (Models) of what is really relevant to be measured.

09 NUINT
May 18th-22nd 2009 Sitges(Spain)
6th International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region
Confronting theory, models & data
Electron scattering and its connections to neutrino-nucleus interactions
Current and future neutrino experiments
CC and NC quasi-elastic scattering
Single pion production
Deep and not-so-deep inelastic scattering
The path forward: theory vs. experiments needs
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