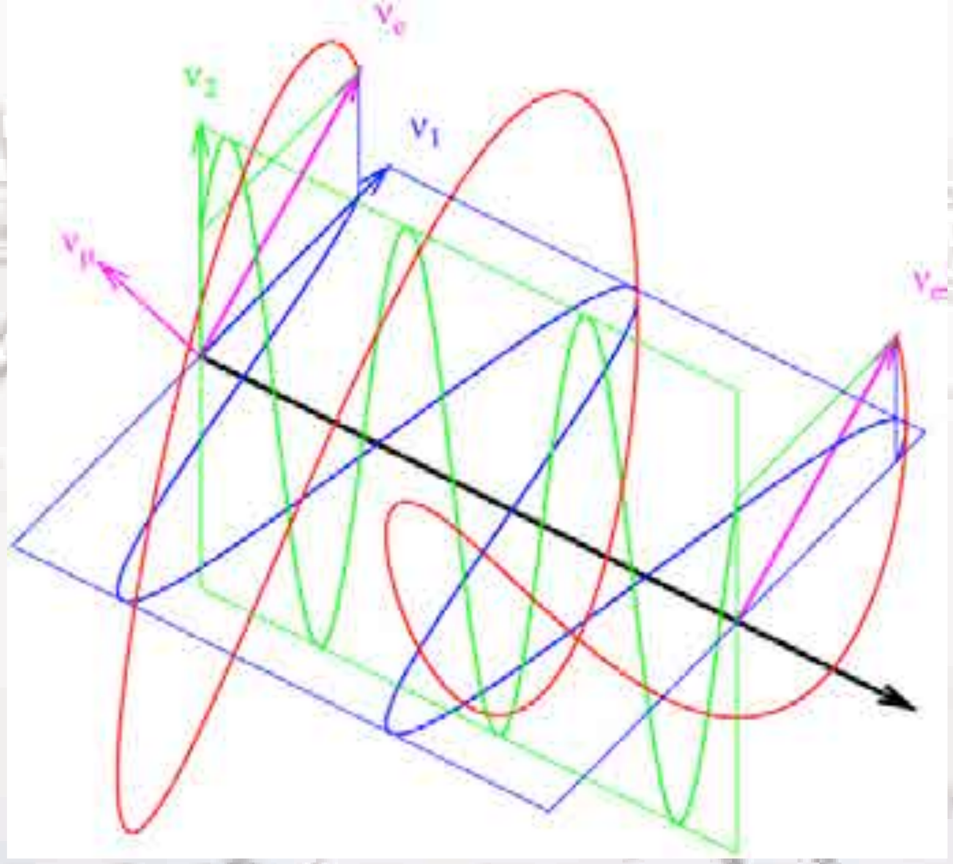
Next obstacles in precision neutrino oscillations: ν-Nucleus cross-section

F.Sánchez
IFAE Barcelona
Kavli-IPMU

Neutrino oscillations

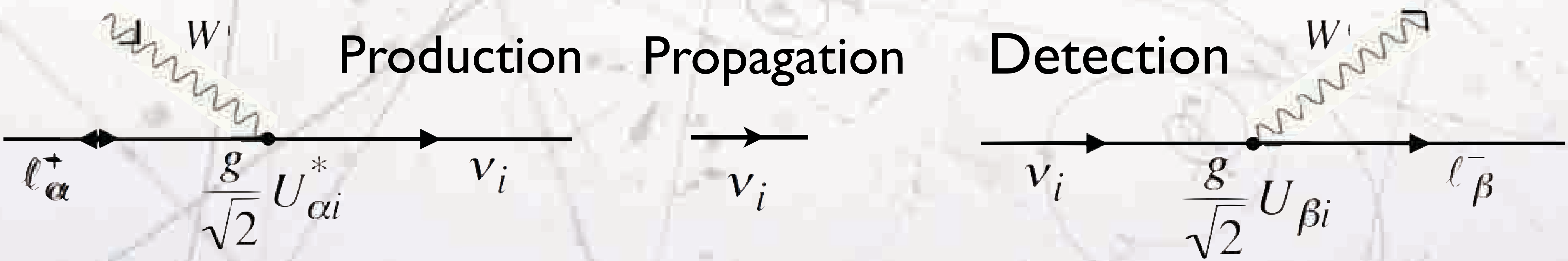


ν oscillations

Similar to quarks, flavour and Lorentz eigenstates of massive neutrinos are not identical.

The two eigenbases are related through the Pontecorvo-Maki-Nakagawa-Sakata matrix (U_{PNMS}).

$$U_{PNMS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$



Courtesy of B.Kayser

ν oscillations

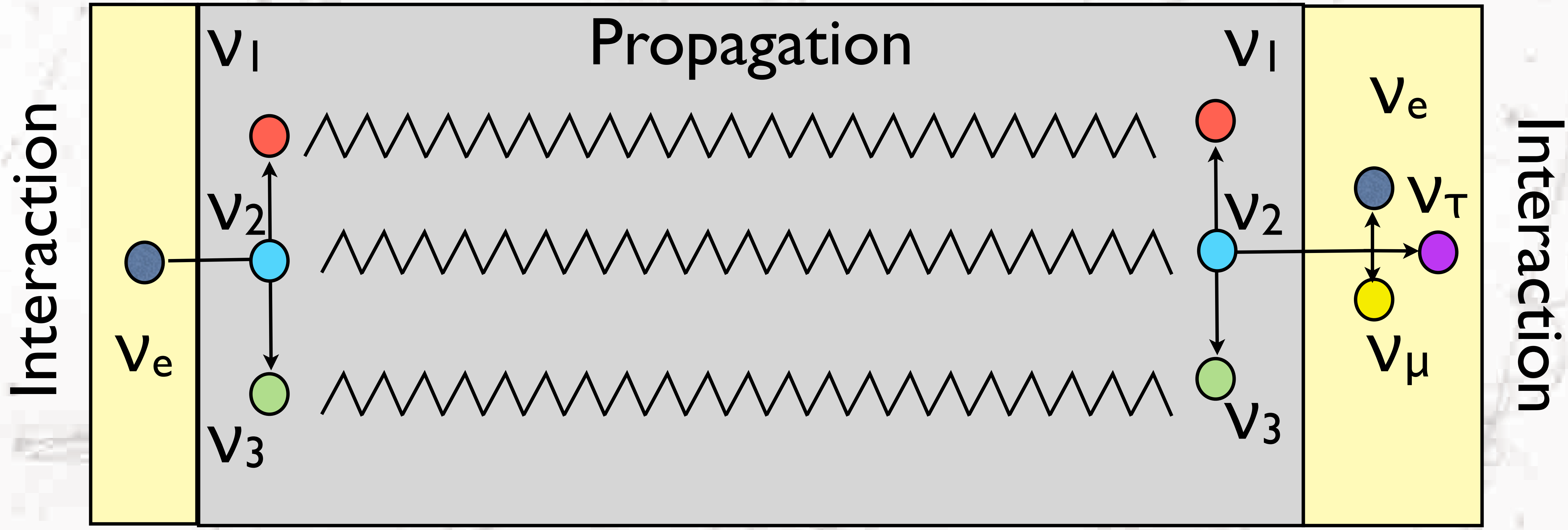
atmospheric — solar

$$U_{PNMS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{21} & \sin\theta_{21} & 0 \\ -\sin\theta_{21} & \cos\theta_{21} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} = U_{PNMS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

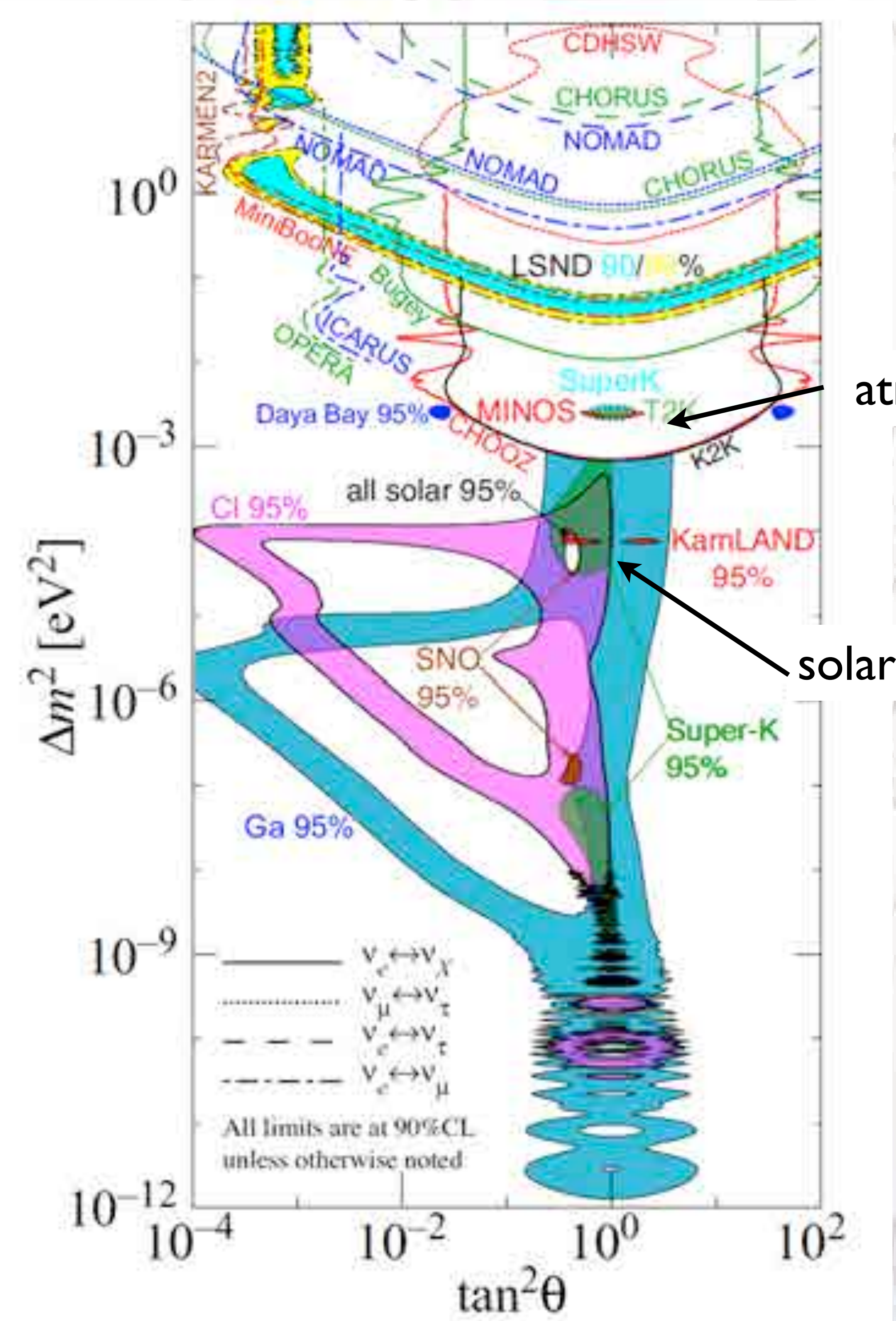
- With 3ν, there are 3 angles and 1 imaginary phase:
  - The imaginary phase allows for CP violation similar to the quark sector.
- There are also 2 values of Δm^2: traditionally Δm^2_{12} & Δm^2_{23}.

LBL concept


Interaction
Propagation
ν_1
ν_2
ν_3
ν_e
ν_1
ν_2
ν_3
ν_e
ν_τ
ν_μ
Interaction


pion
muon
neutrino
neutrino
0^{16}
electron
0^{15}

ν oscillations



Particle Data Group neutrino review

Status as of 2014

$$\Delta m^2_{12} = 7.54^{+0.26}_{-0.22}(10^{-5}eV^2)$$
$$|\Delta m^2_{23}| = 2.43 \pm 0.06(10^{-3}eV^2)$$
$$\sin^2\theta_{12} = 0.308 \pm 0.017$$
$$\sin^2\theta_{23} = 0.437^{+0.033}_{-0.023}(\Delta m^2 > 0)$$
$$\sin^2\theta_{23} = 0.455^{+0.039}_{-0.021}(\Delta m^2 < 0)$$
$$\sin^2\theta_{13} = 0.0234^{+0.0020}_{-0.0019}(\Delta m^2 > 0)$$
$$\sin^2\theta_{13} = 0.0240^{+0.0019}_{-0.0022}(\Delta m^2 < 0)$$
$$\delta = 1.39^{+0.29}_{-0.33}\pi$$

Next in ν oscillations

Next steps

- δ_{CP} accessible through:
  - comparison of appearance with reactor disappearance.
  - comparison of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$$\nu_\mu \rightarrow \nu_\mu$$
$$\nu_\mu \rightarrow \nu_e$$
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$$
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

- The θ_{23} octant:
  - The θ_{23} is close to 45° but, how close?, is $\theta_{23}<45°$ or $\theta_{23}<45°$?
- What is the absolute neutrino mass ? (Katrin?, Cosmology?,…)
- The mass hierarchy: is $m_3 > m_1$?

Next in ν oscillations

ACCURACY & PRECISION!

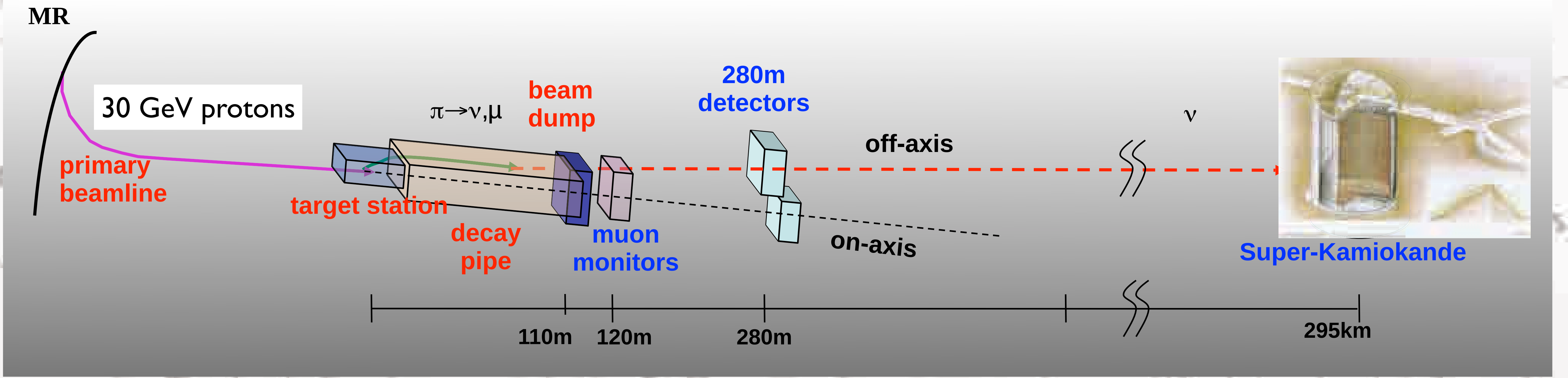
Next steps

- δ_{CP} accessible through:
  - comparison of appearance with … disappearance.
  - comparison of $\nu_\mu \rightarrow \nu_e$ ar…

$$\nu_\mu \rightarrow \nu_\mu$$
$$\nu_\mu \rightarrow \nu_e$$
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$$
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

- The θ_{23} octant:
  - The θ_{23} is c… 5° but, how close?, is θ_{23}<45° or θ_{23}<45°?
- What is … ute neutrino mass ? (Katrin?, Cosmology?,…)
- Th… ierarchy: is $m_3 > m_1$?

LBL concept



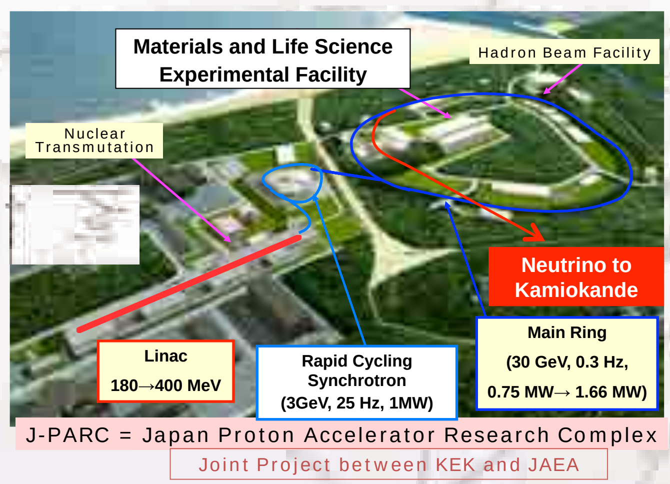
Beam

Near site detector

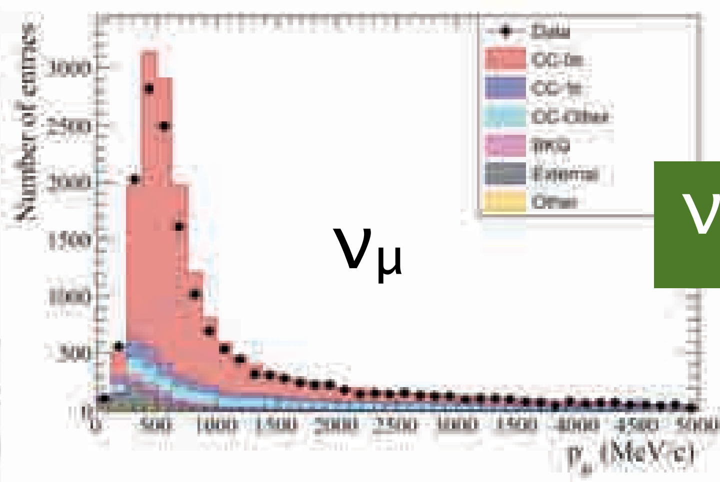
Far side detector

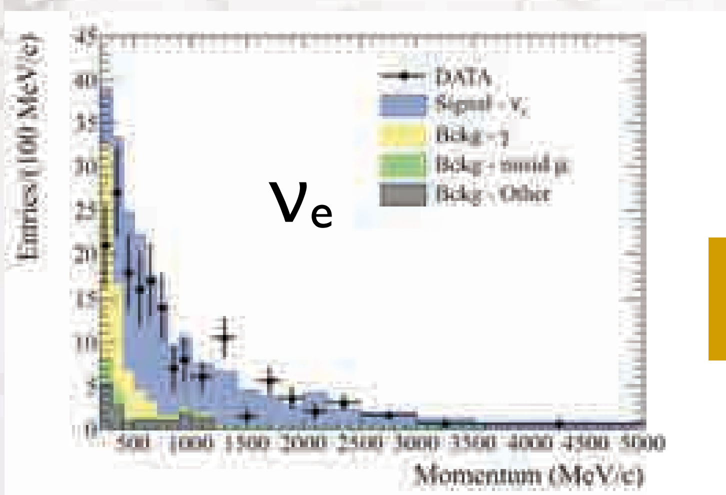
LBL concept

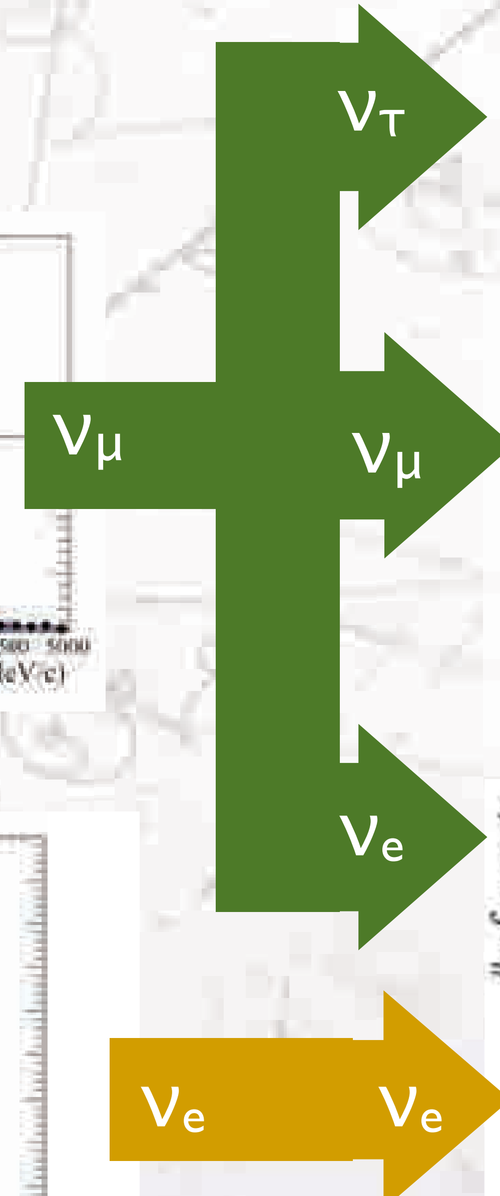
Proton beam



Near detector monitor

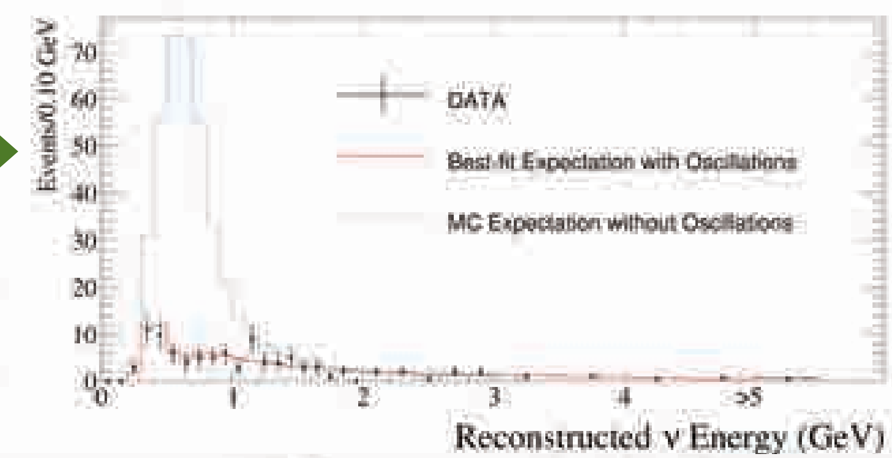


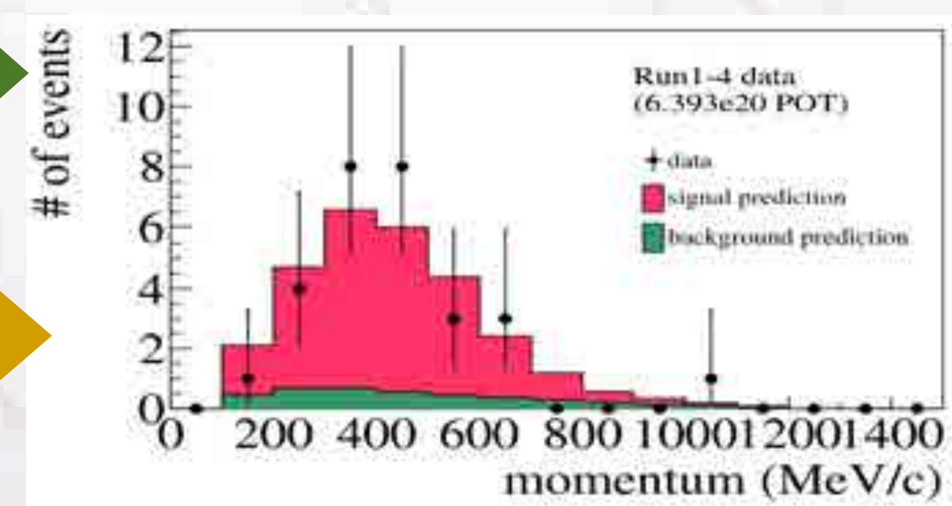




Far detector

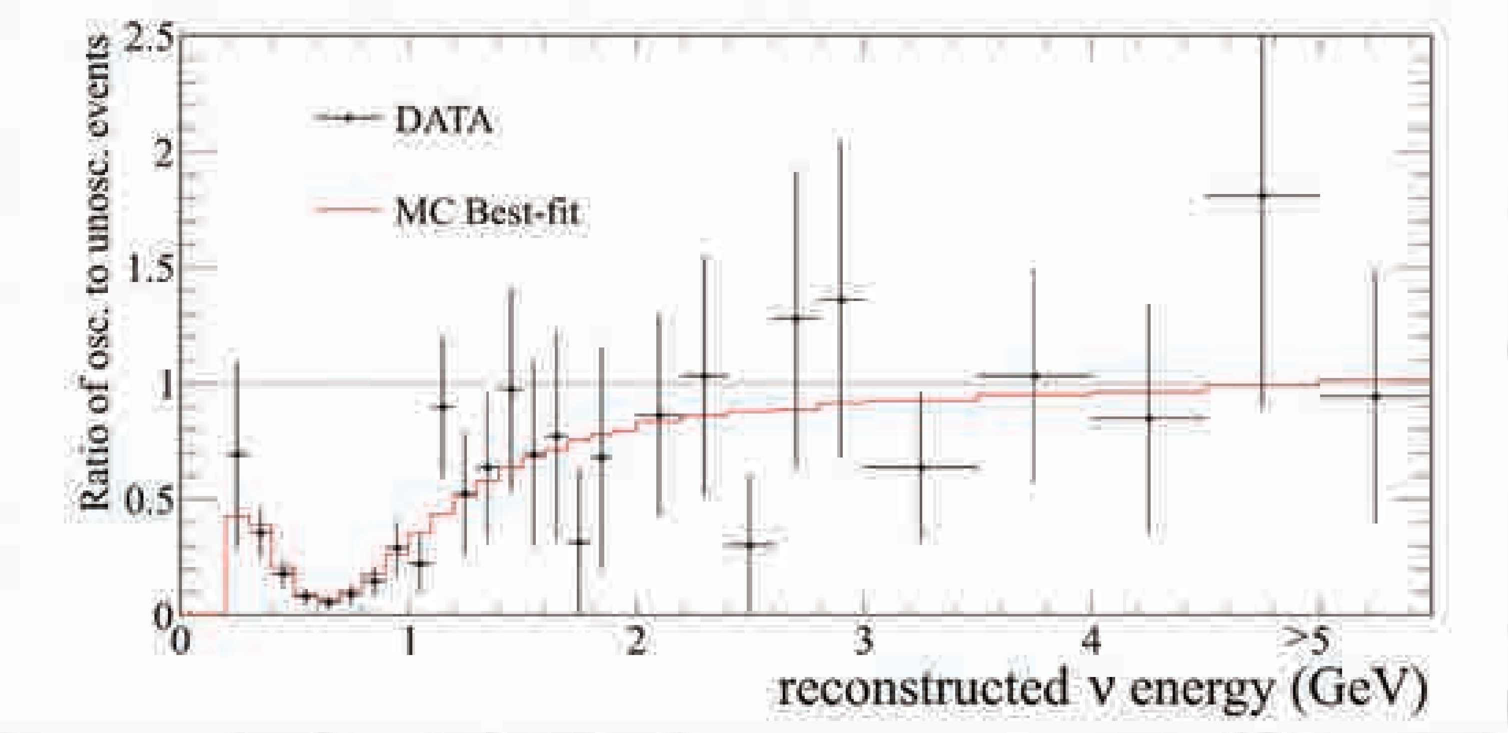
Invisible: ν´s are not energetic





LBL concept

$P_{osc}(E_\nu)$



- The observable is the disappearance/appearance of events as function of the ν energy.
- We have to reconstruct the energy of the neutrinos!!!!!

Cross-section problem

- The number of events depends on the cross-section:

$$N_{events}(E_\nu) = \sigma_\nu(E_\nu)\Phi(E_\nu)$$

- This is not so critical if we can determine the energy of the neutrino, since at the far detector

$$N^{far}_{events}(E_\nu) = \sigma_\nu(E_\nu)\Phi(E_\nu)P_{osc}(E_\nu)$$

- and it cancels out in the ratio as function of energy:

$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = P_{osc}(E_\nu)$$

Cross-section problem

- Since the neutrino energy is not monochromatic, we need to determine event by event the energy of the neutrino.
- This estimation is not perfect, we have the problem that the cross-section does not cancels out in the ratio.

$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

- The neutrino oscillations introduce differences in the flux spectrum and the ratio does not cancel the cross-sections.

Oscillation experiments require to know both $\sigma(E_\nu)$ & $P(E_\nu|E'_\nu)$

Both are related to cross-sections !!!!

Cross-section problem

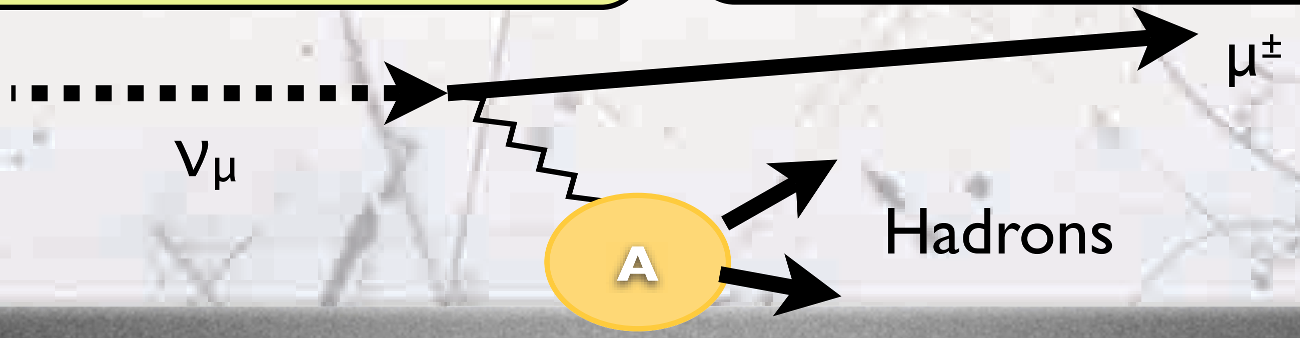
How to measure the neutrino energy ?

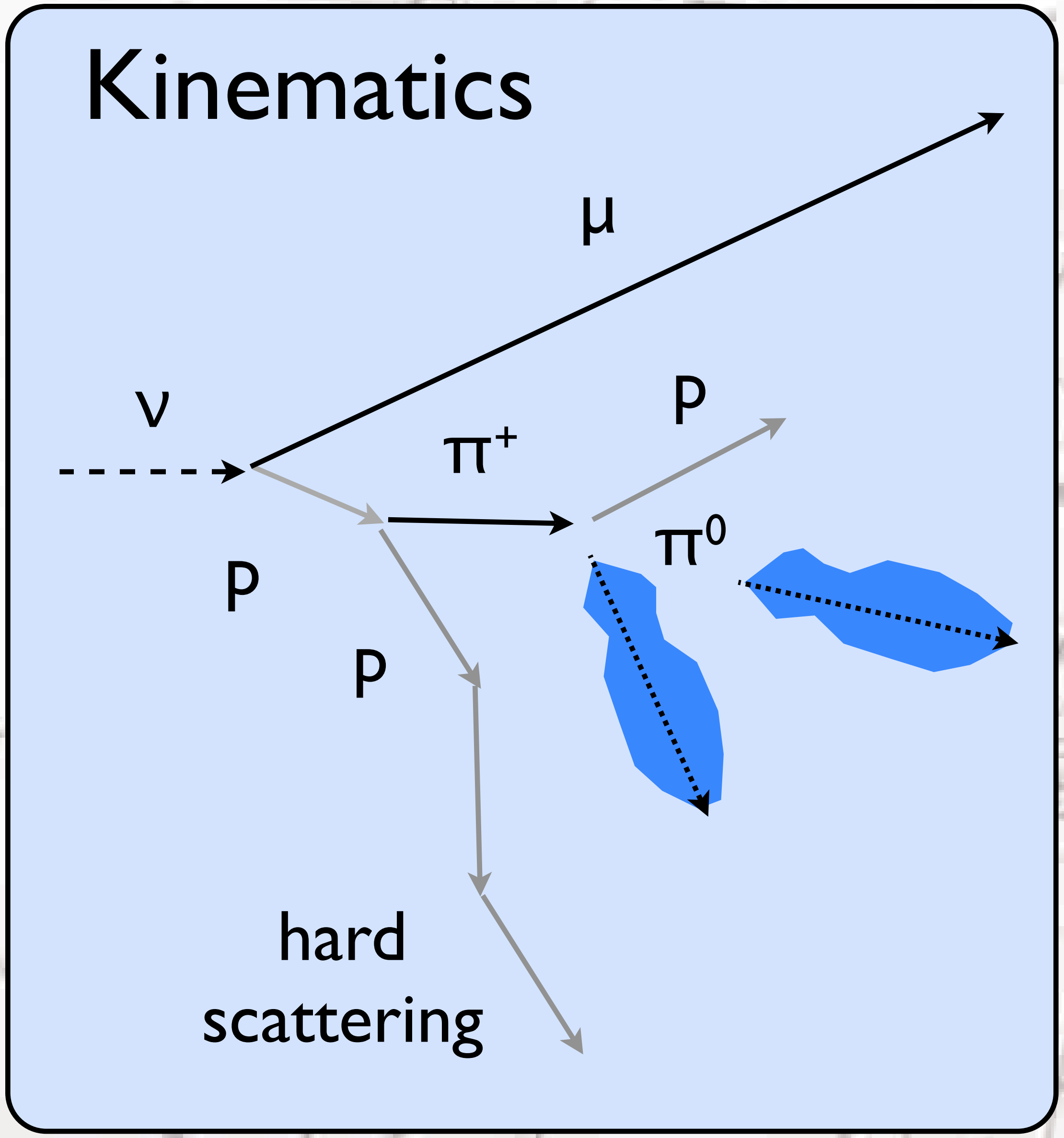
Low Energy ν's (≲2GeV)

- E_ν relies on the lepton kinematics.
- channel identification is critical:
  - Final State Interactions
  - hadron kinematics.
- Fermi momentum, Pauli blocking and bound energy are relevant contributions.

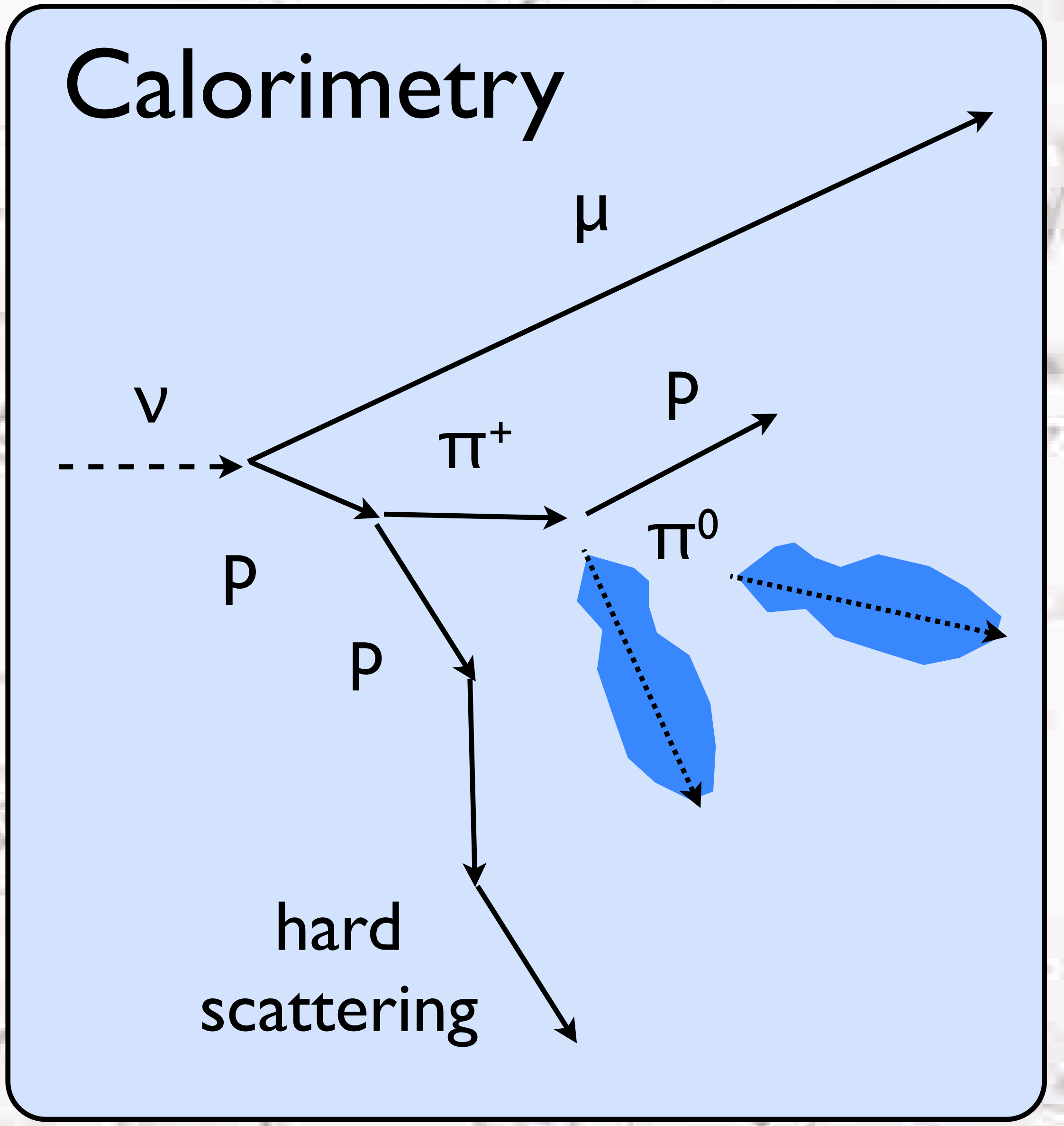
Medium-high Energy ν's (≳ 3GeV)

- $E_\nu = E_l + E_{hadrons}$ with $E_{hadrons} << E_l$
- Hadronic energy depends on modelling of DIS and high mass resonances.
- Hadronic energy depends on Final State Interactions.





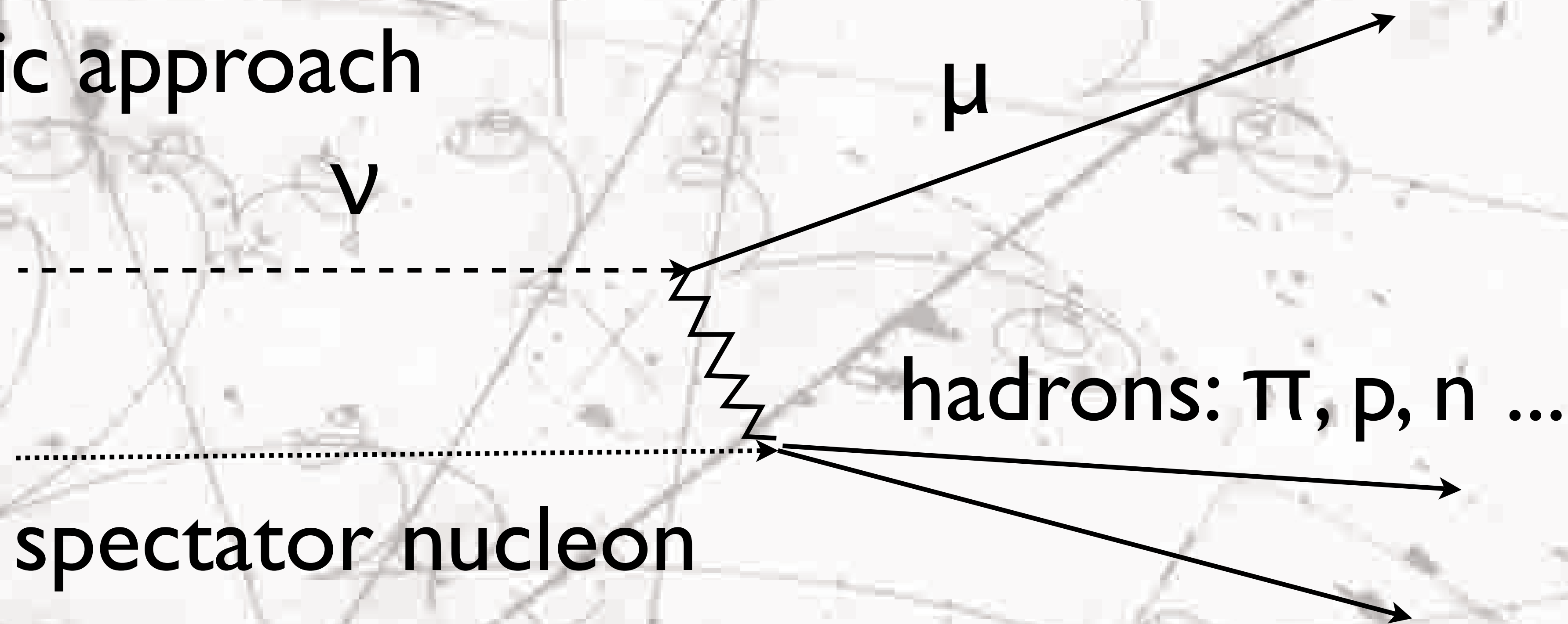
- Only a fraction of the energy is visible.
- Rely on channel interaction id.



- The visible energy is altered by the hadronic interactions and it depends on hadron nature.

Cross-section problem

Kinematic approach

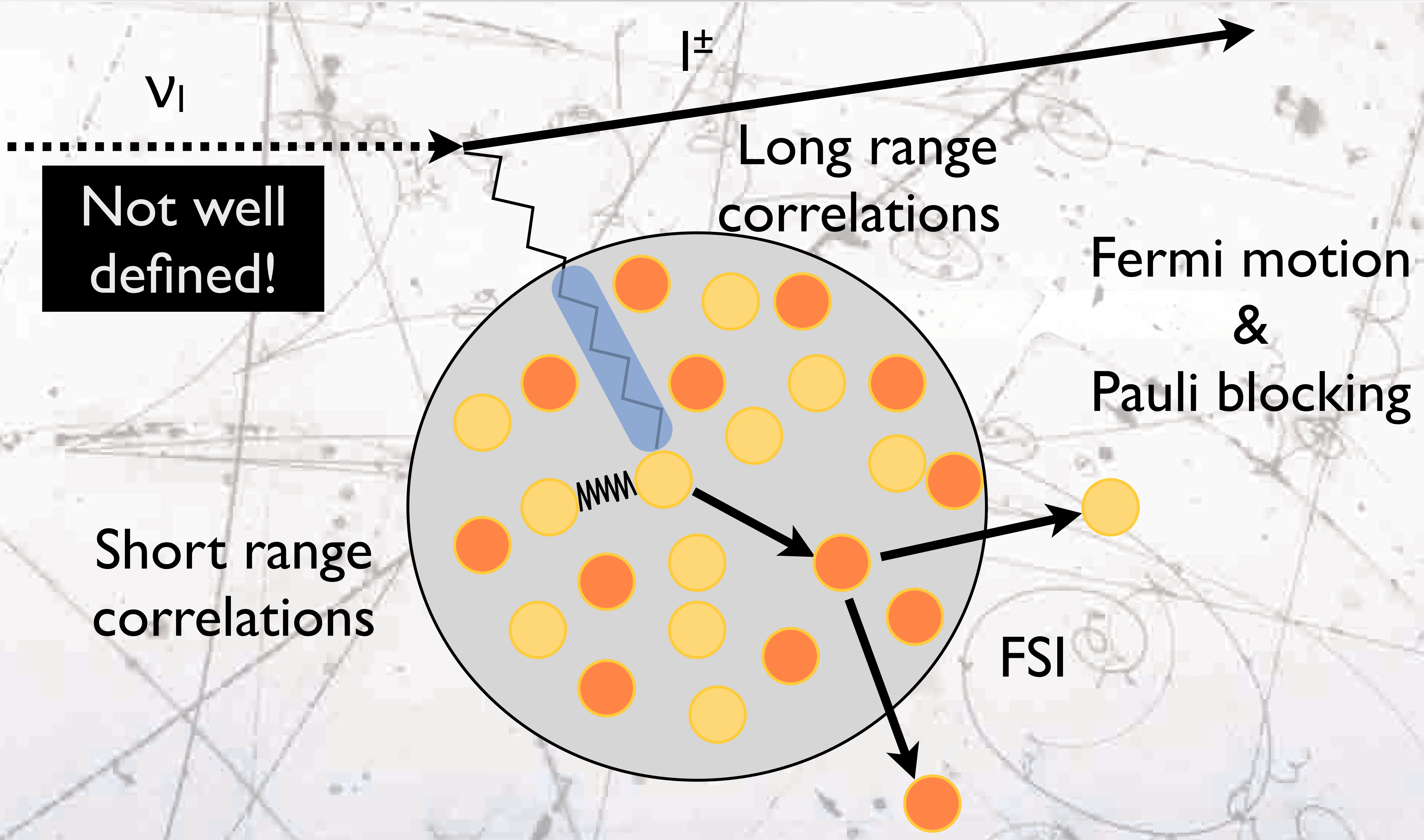


- Assume that the spectator nucleon is at rest ignoring Fermi Motion which is comparable to neutrino energy (250 MeV vs 600 MeV in T2K) or larger in models like Spectral functions. Need a good nuclear model.
- Assume that one of the hadrons is not seen and we know its identity (proton, pion, Δ, K, …). It can be one out of two or one out of one,.. Need to define the interaction channel: final state particles!
- Assume the neutrino direction is known (true in far detector, not so at near detector).
- Apply conservation of energy and momentum.

Partial summary

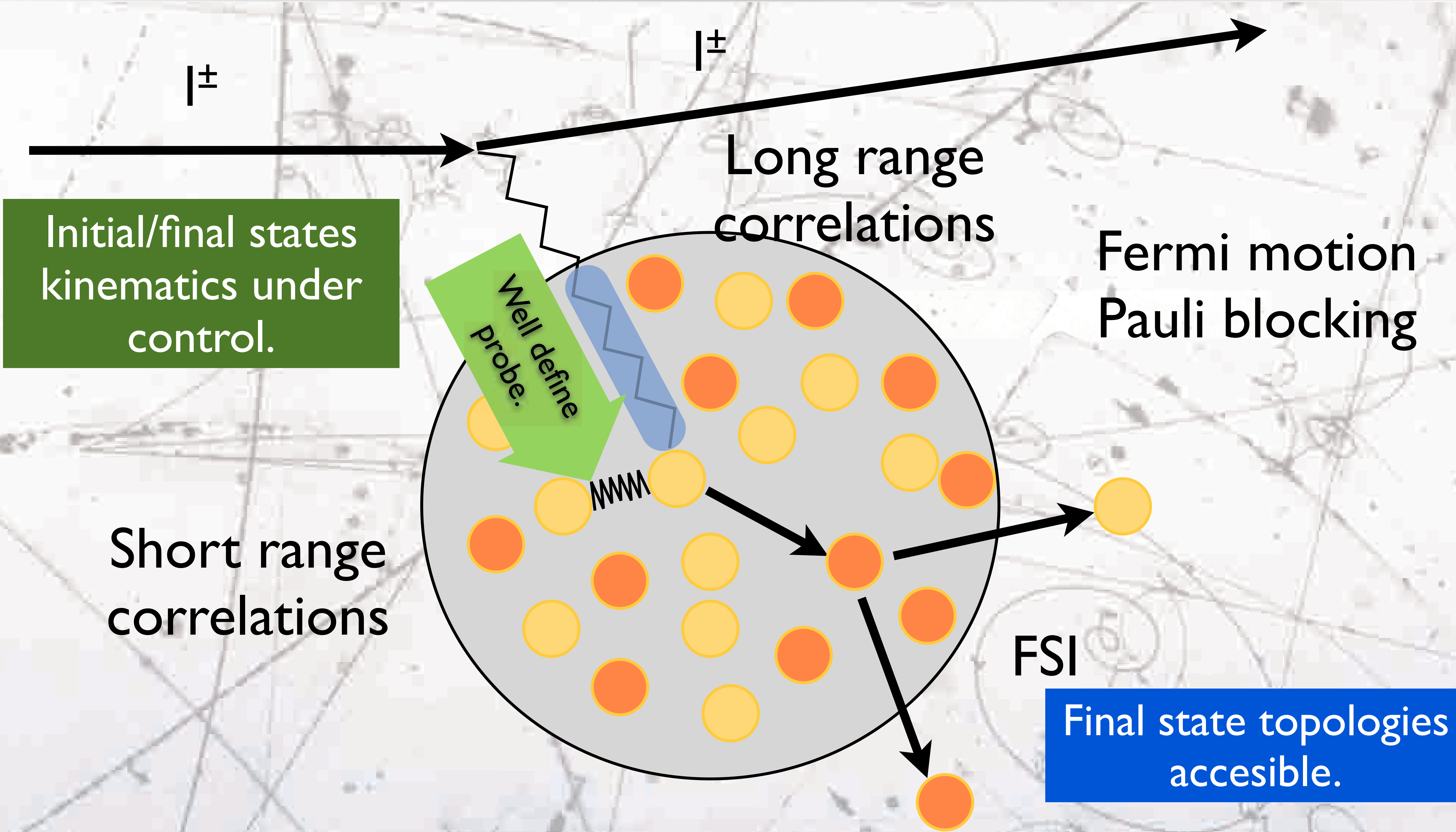
- LBL oscillation experiments requires an accurate calculation of the neutrino energy.
- Actually, we call it a cross-section problem but it is caused from our inability to:
  - precisely determine the neutrino energy event by event.
  - generate a mono-energetic neutrino beam.

The problem



ν_l
$l^{\pm}$
Not well defined!
Long range correlations
Fermi motion & Pauli blocking
Short range correlations
FSI

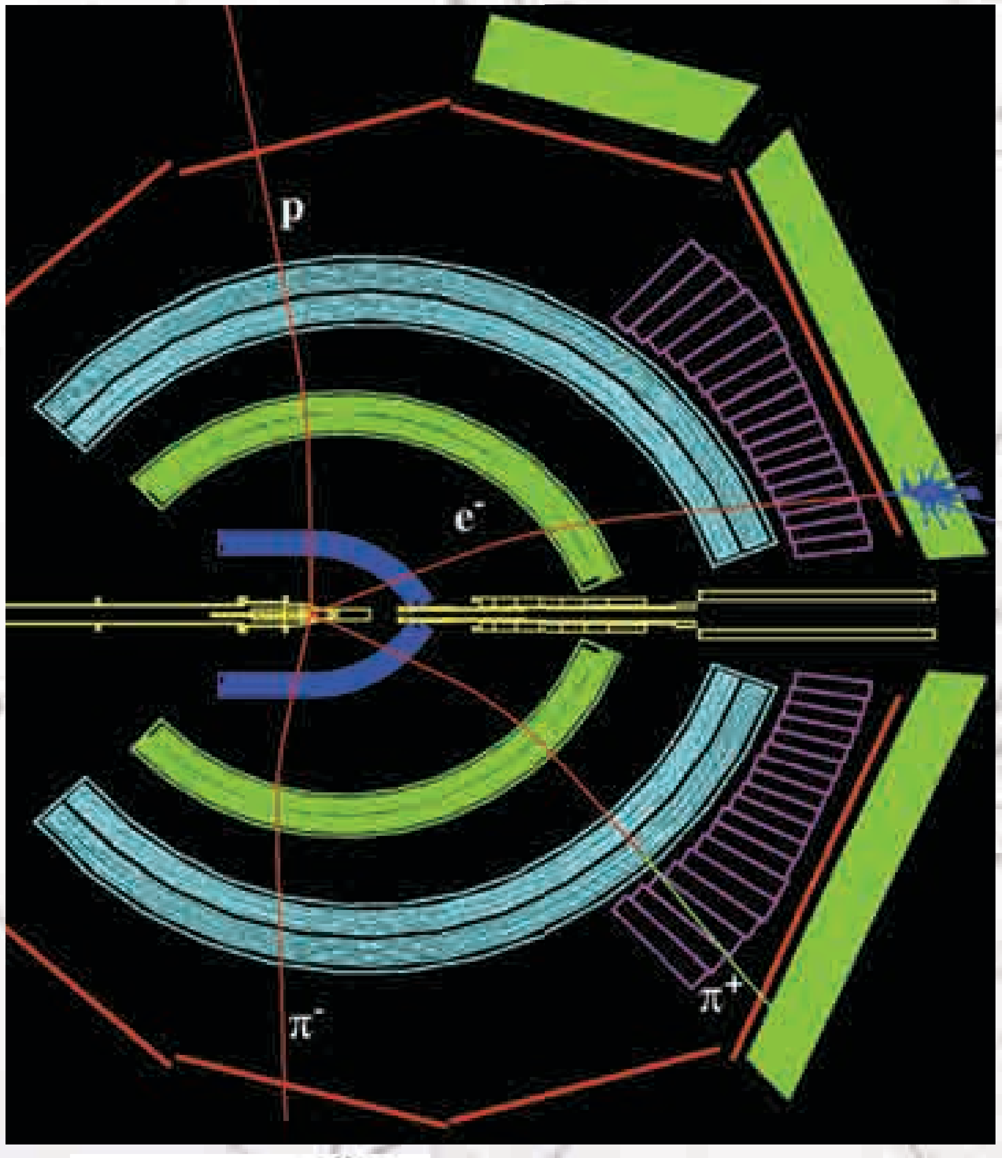
Electron scattering



Electron scattering

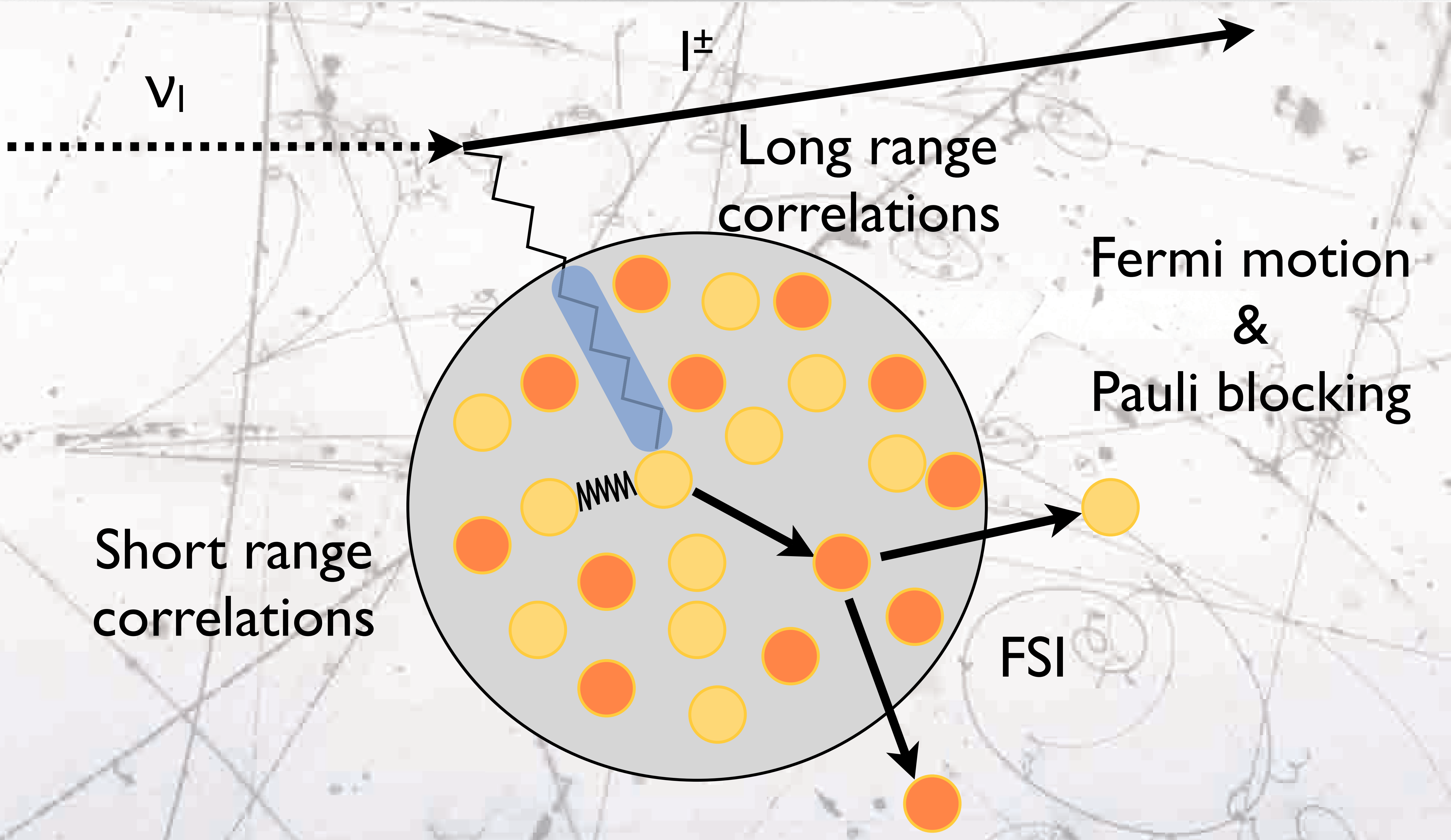
- This is similar to neutrino interactions with known initial conditions.
- But it is not the same:
  - only Vector current and not Axial current. This is only accesible trough neutrinos (or photon scattering in some cases).
  - Initial particle is charged.
  - Initial and final particles are electrons (light with respect to muon in relation to initial/final state radiation).
  - Detector is not full coverage (4π) and normally experiments ignored the hadron production.

Electron scattering



- Control on incident beam kinematics allow to:
  - Identify the channel: Elastic, resonant, etc…
  - Calculate the kinematics of hadronic final state (smeared by fermi-motion).
- This allows to understand the:
  - vector component of interaction.
  - effects of FSI and final state multiplicities.
- It is relevant to analyse electron and neutrino scattering based on the same MC to increase synergies between the two worlds.

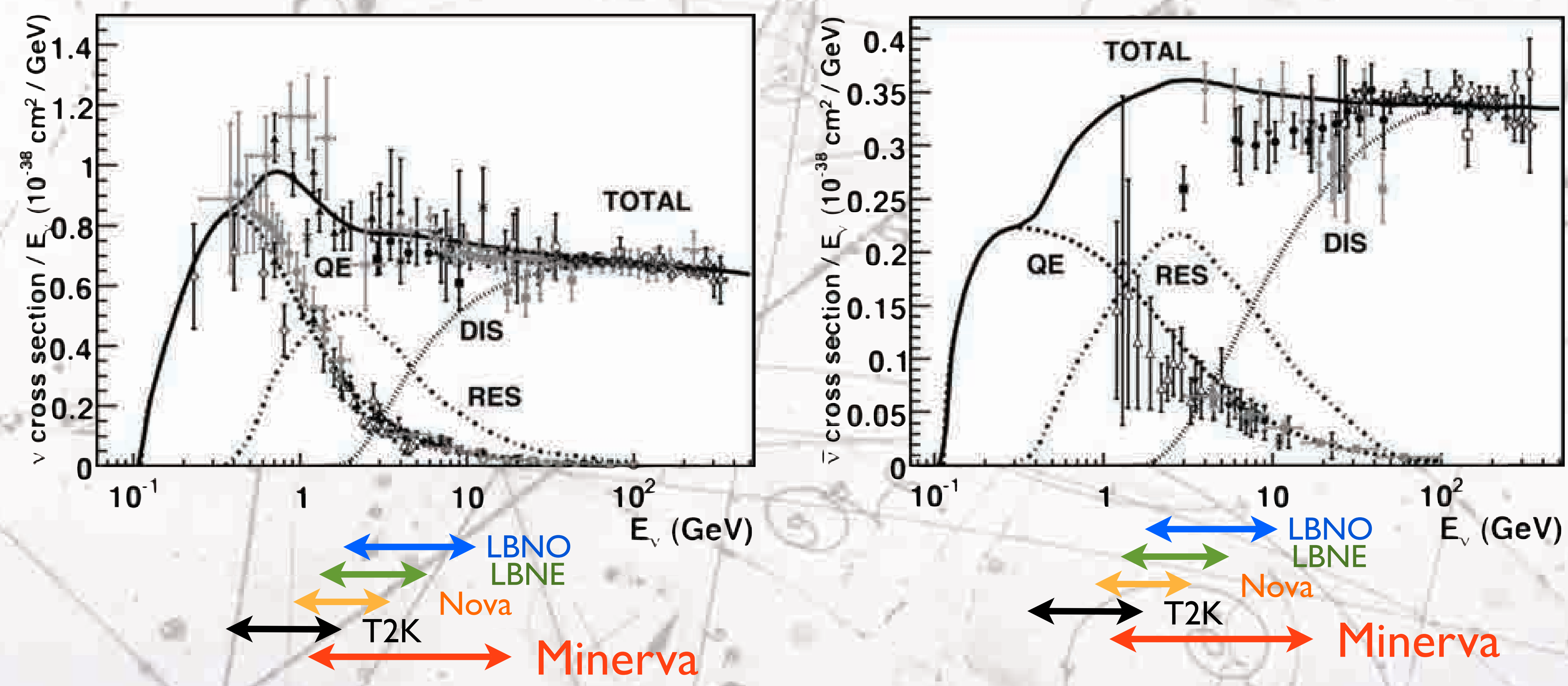
The problem



ν_l
$l^{\pm}$
Long range correlations
Fermi motion & Pauli blocking
Short range correlations
FSI

The problem

J.A.Formaggio, G.P.Zeller, Rev.Mod.Phys. 84 (2012) 1307

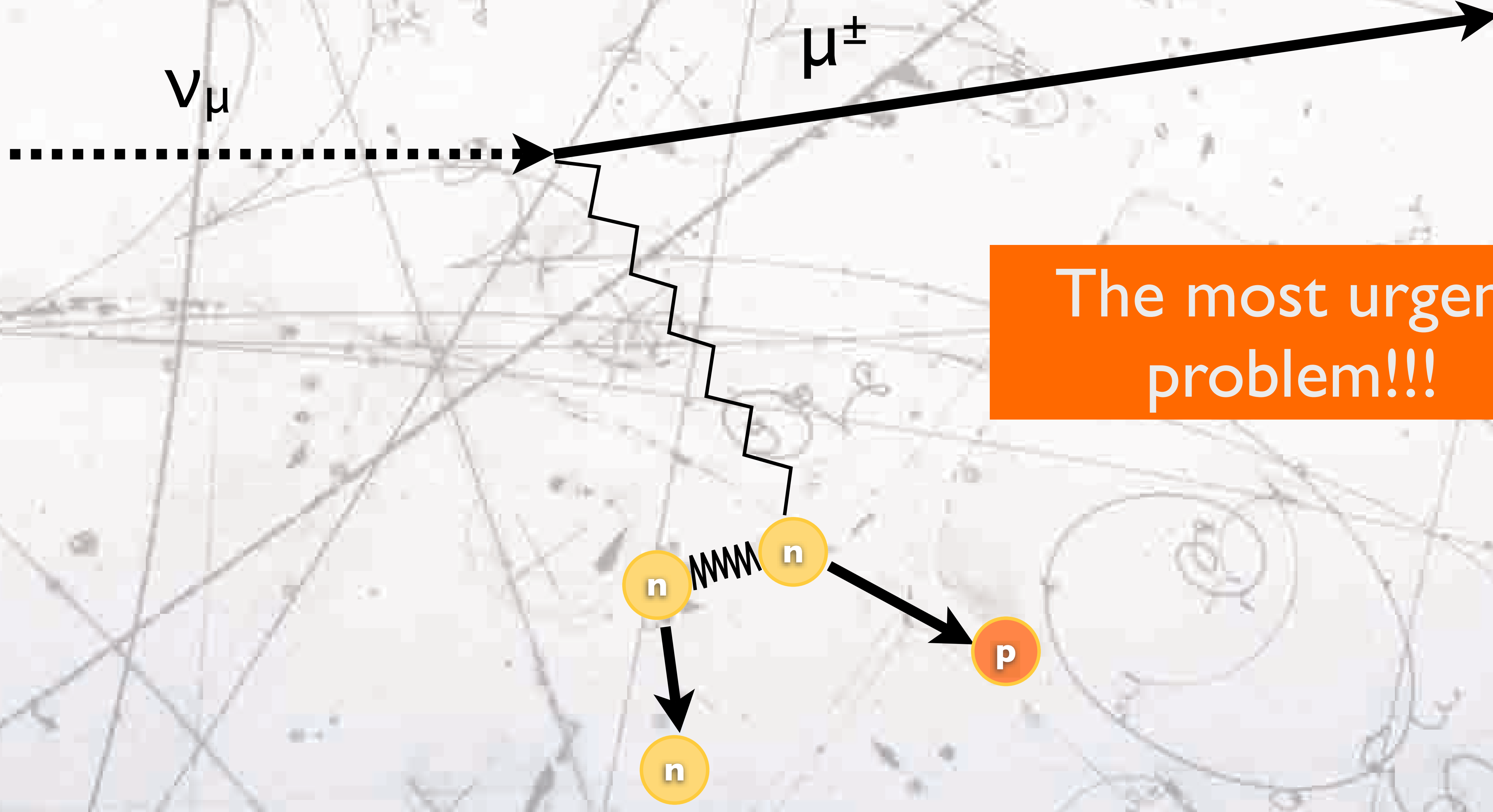


- Present and future oscillation experiments cover a region full of reaction thresholds and sparse data.

The shopping list

- Future CP violation measurements with Long Base Line neutrino beams require "ideally" the measurement of ν_μ, anti-ν_μ, ν_e and anti-ν_e
  - between ~500 MeV and ~10 GeV,
  - for (at least!) 4 nuclei: C, O, Fe and Ar. (Not all isoscalars!)
  - for ~10 exclusive channels:
    - QE, $1\pi^{0\pm}$, $N\pi^{0\pm}$, DIS both CC and NC.
  - Require a precise determination of the energy of the neutrino for the dominant(s) channel(s) at each energy.

CCQE + 2p2h



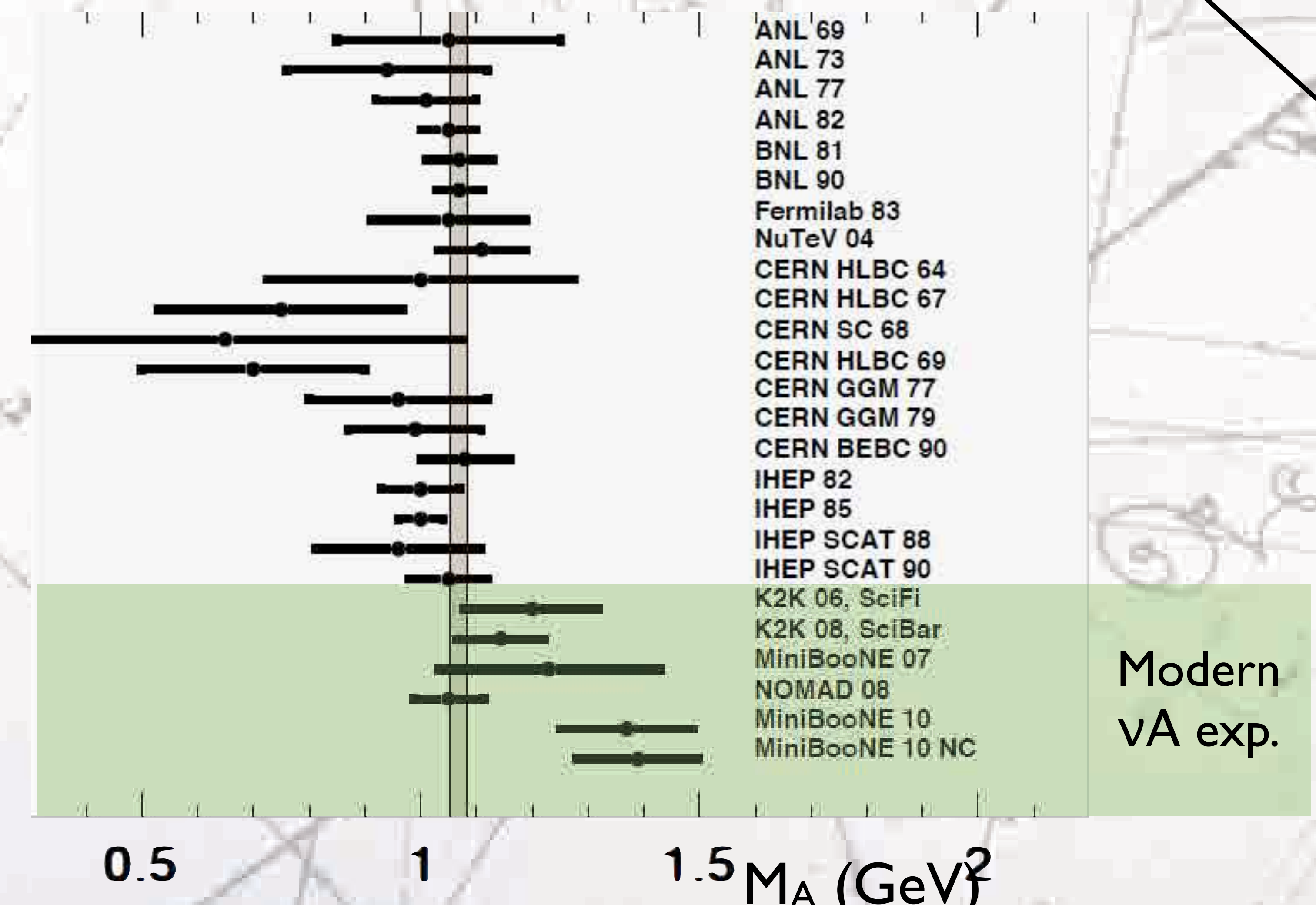
The most urgent problem!!!

Why CCQE ?

- It is the basic channel for neutrino oscillations at low energies (T2K)
- It is a clean signature (no pions produced) with simple neutrino energy reconstruction.
- Regardless its simplicity, the community faced many problems in the past:
  - Description of the axial component.
  - Disagreement among low and high energy experiments.

CCQE problems

$$F_A(q^2) = \frac{F_A(0)}{(1. - q^2/M_A)^2}$$

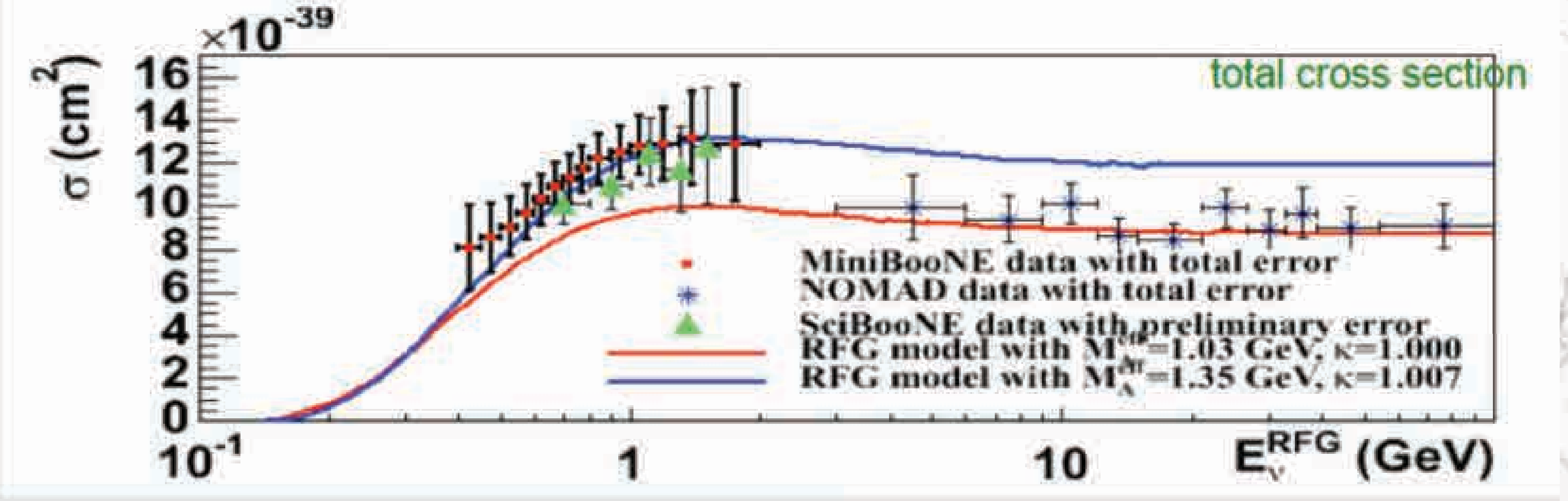


Bernard et al. 2002

- Vector current fixed by electron scattering.
- Axial current parametrised by dipole form factor with mass M_A.
- M_A increases the cross-section at the high-q2 region
- These effects are observed in νA experiments.
- Is M_A an effective parameter ?

CCQE problems

Difficult to concile the low and high energy results.

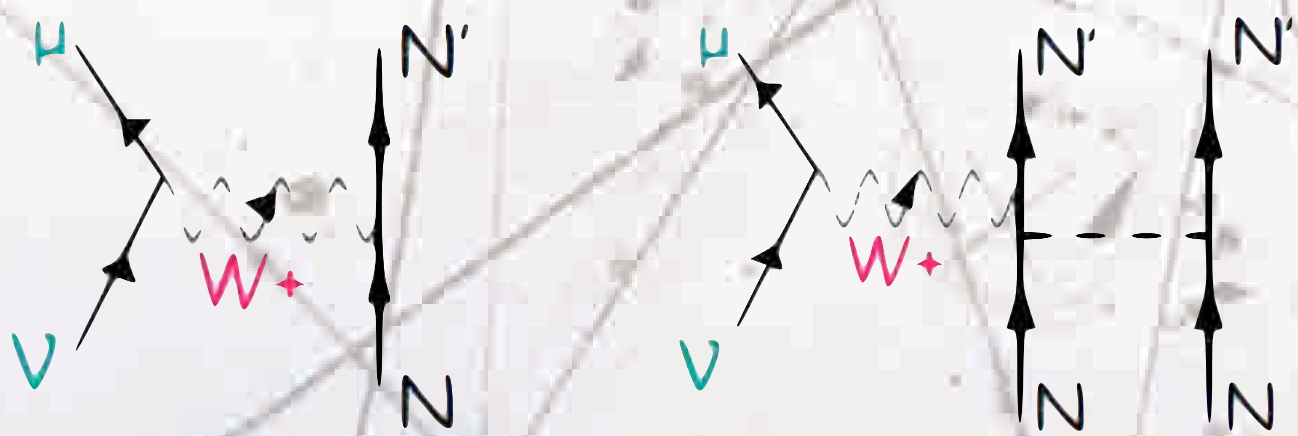


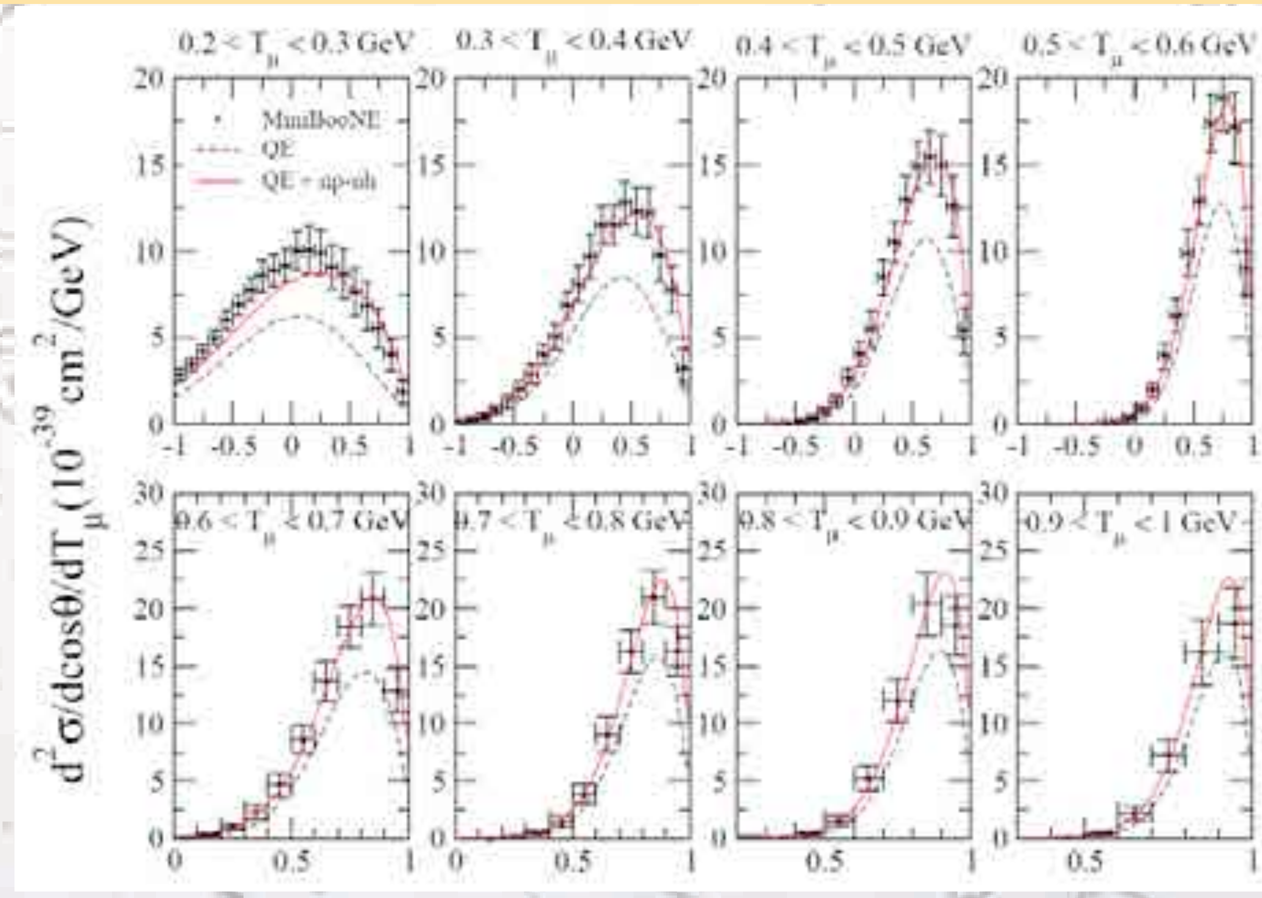
Experiments define CCQE in different manners (no proton, one proton,etc…) and sometimes develop analysis under certain model paradigm confusing the model comparison.

- MiniBoone published a double differential ν cross-section for events with no pions in final state (CCQE-like).
- Theorist profited from the clean data to realised that we were missing 20% of the cross-section !
- We need to add a new channel (CC-2p2h) !!!

CCQE

CC-2p2h



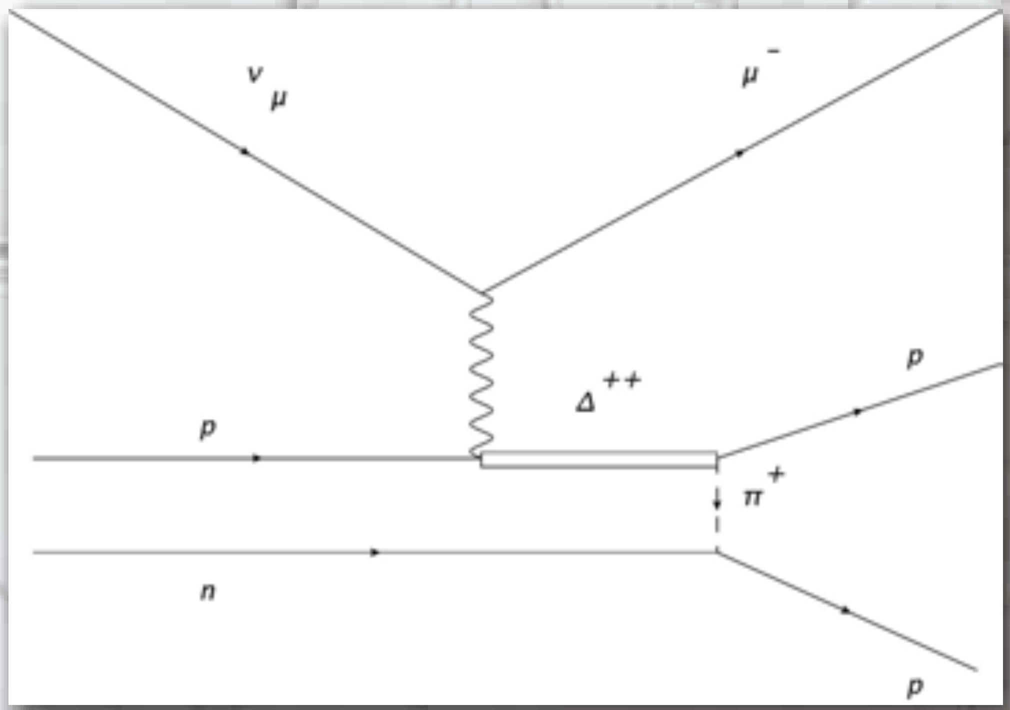


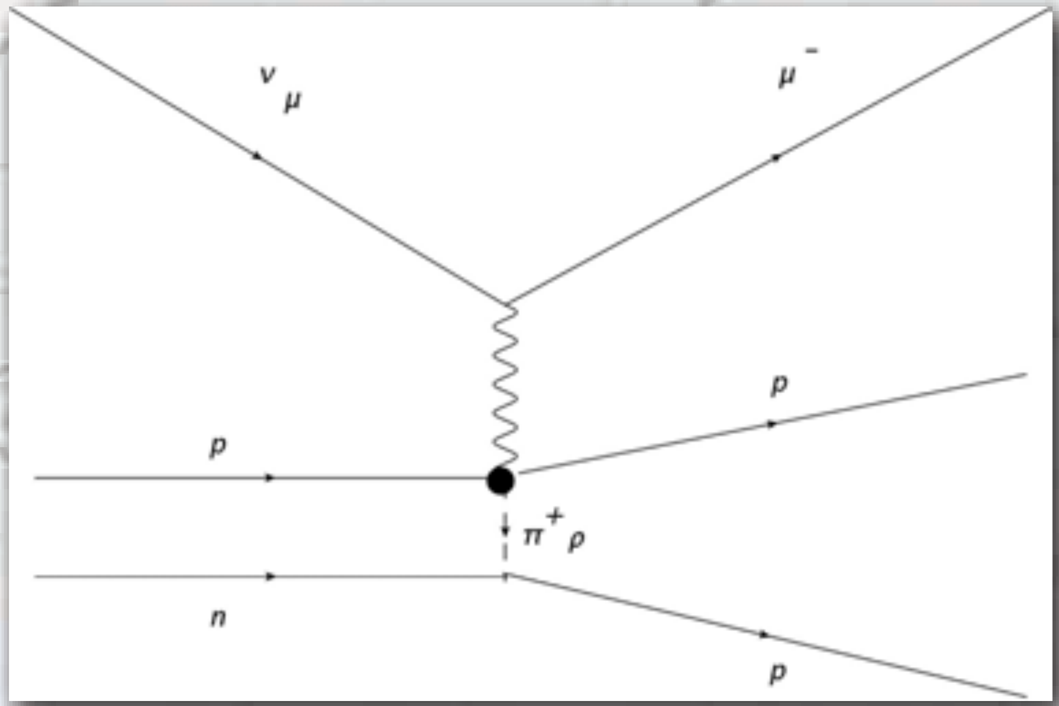
MiniBooNE, Phys. Rev. D 88 (2013) 032001

Martini et al. PRC 84 055502 (2011)

What is 2p2h?

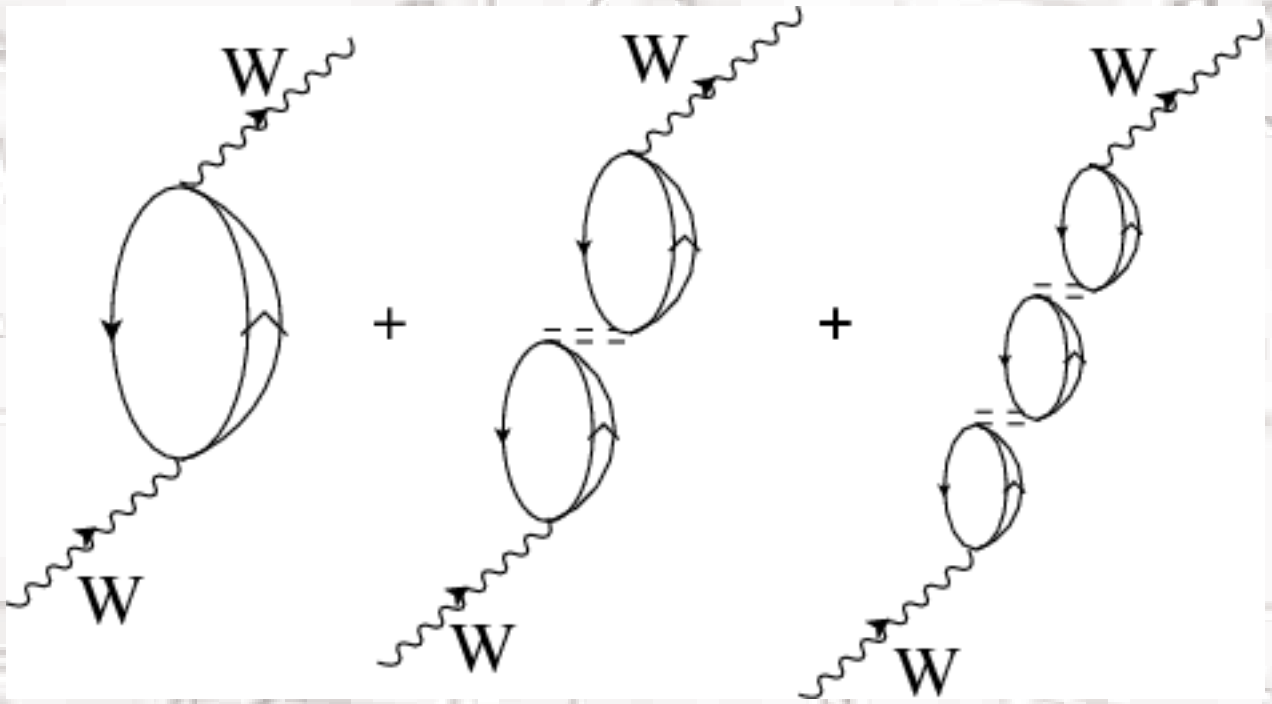
- 2p2h is basically the exchange of a meson between two close by nucleons in the nucleons with the emission of 2 nucleons.
- The pion can be produced in a contact point or through an intermediate virtual Δ^{++}.





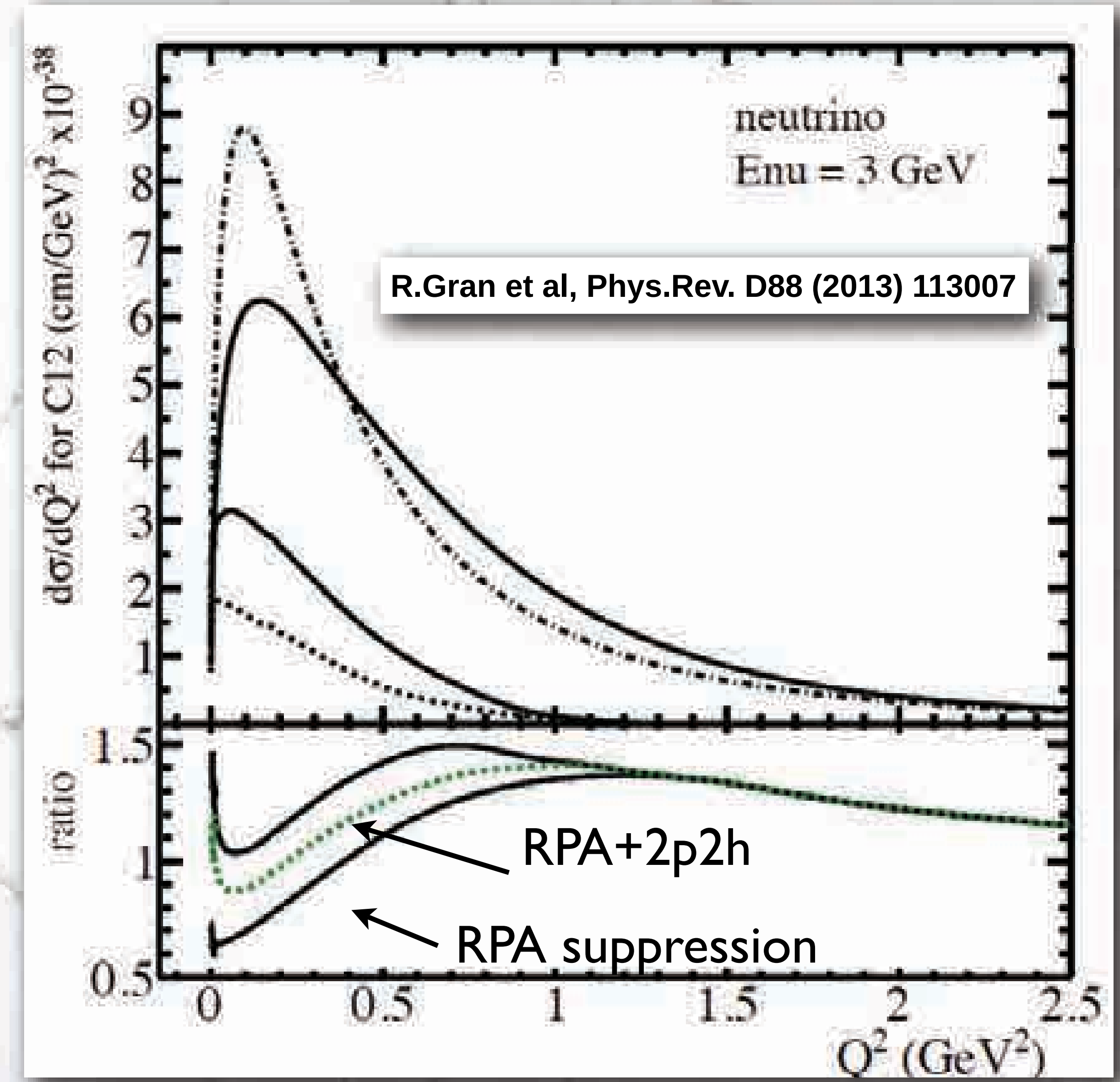
It is possible that the same process happens with the emission of one pion through high mass resonances!

Long range correlations: RPA



- Random Phase Approximation (RPA) is a mathematical approximation to describe the modification of the W self-energy in the presence of high density nuclear media.
- RPA alters the cross-section dependency with the q^2 (mass of the W propagator)

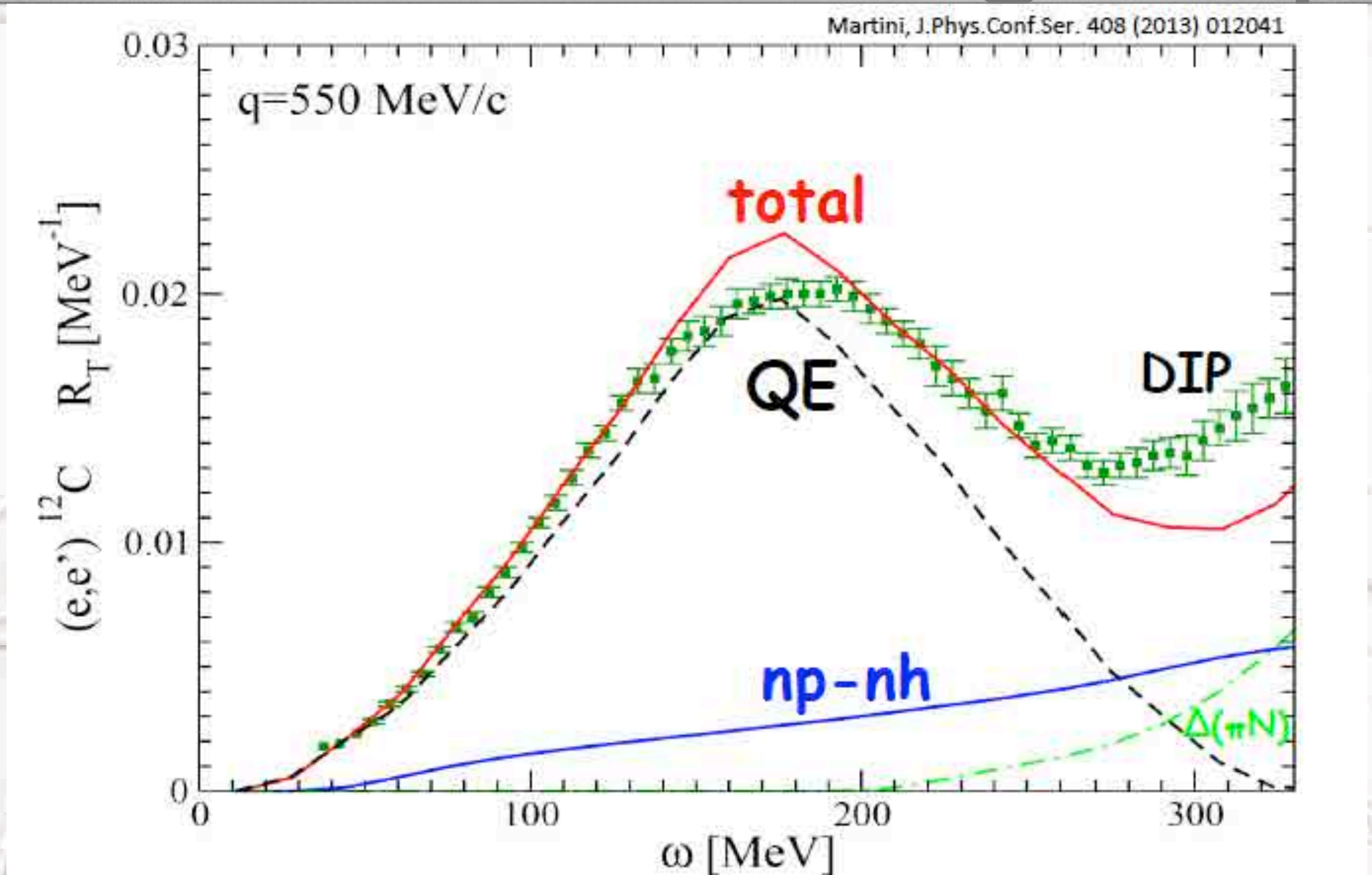
Short & Long Range



- RPA predicts a deficit at low Q^2 and enhancement at large Q^2.
- 2p2h fills the low Q^2 to compensate RPA and we see enhancement at low Q^2.

- The overall effect is that: 2p2h + RPA predicts large QE-like cross-section and enhancement at high Q^2.

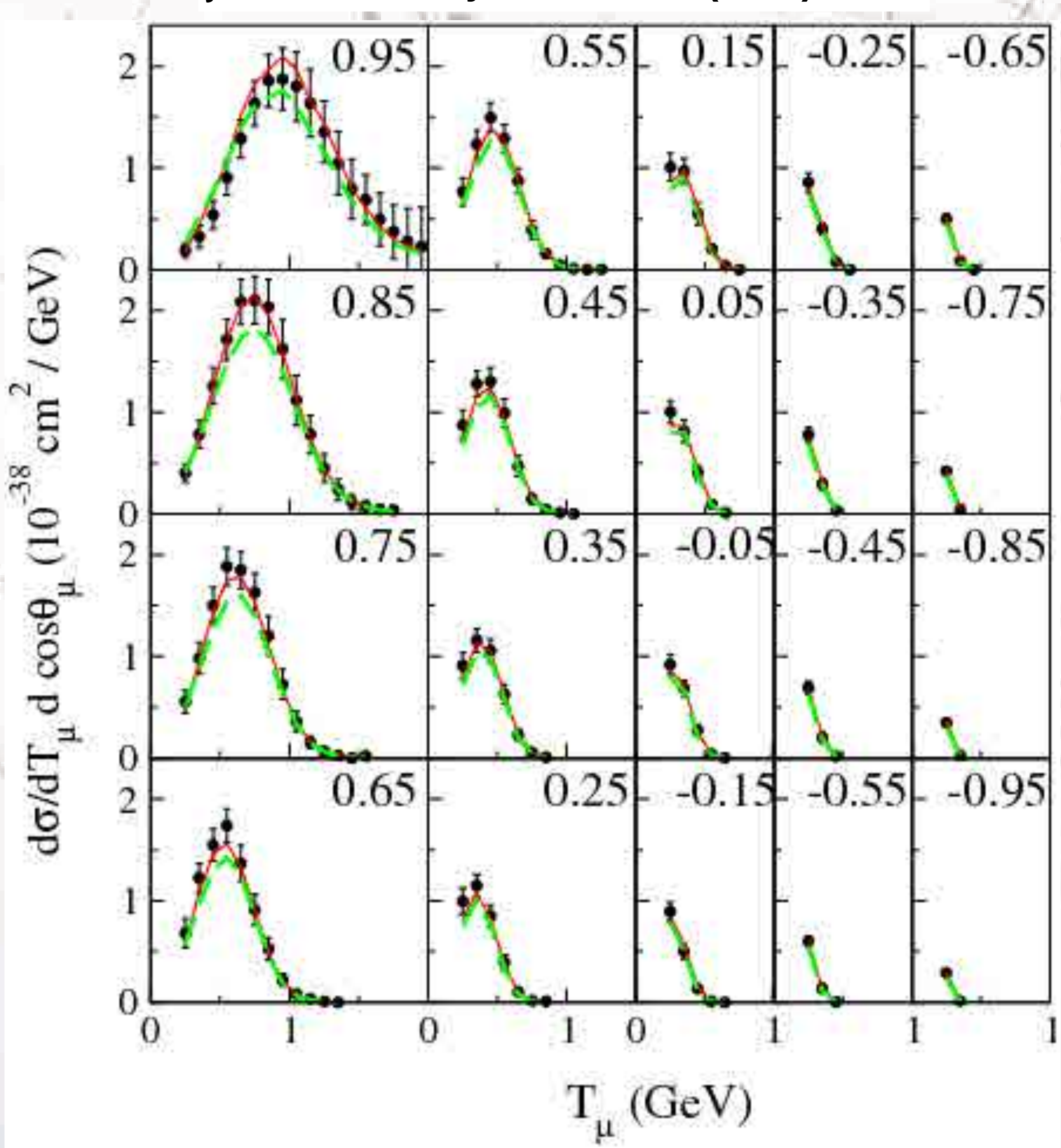
Electron Scattering & 2p2h

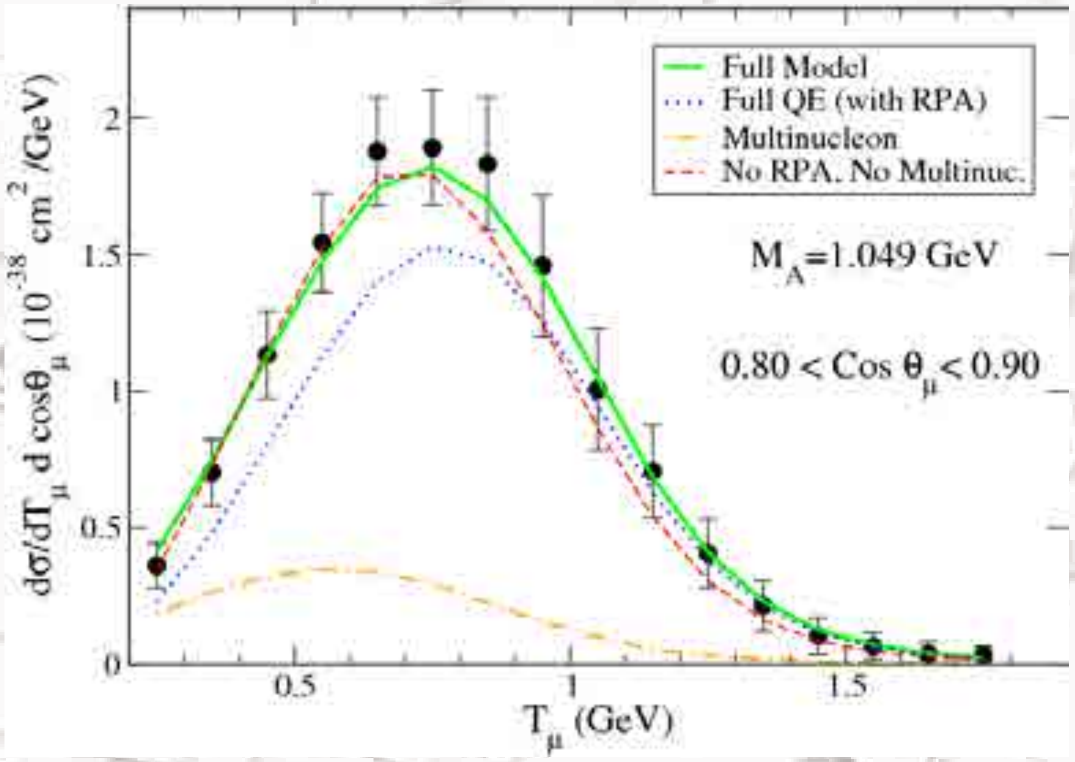


- This contribution was known to the electron scattering community for more than a decade.
- We needed double diferential (p_μ,θ_μ) data to observe np-nh with neutrinos.

Recovering M_A

J.Nieves et al. **Phys.Lett. B707 (2012) 72-75**





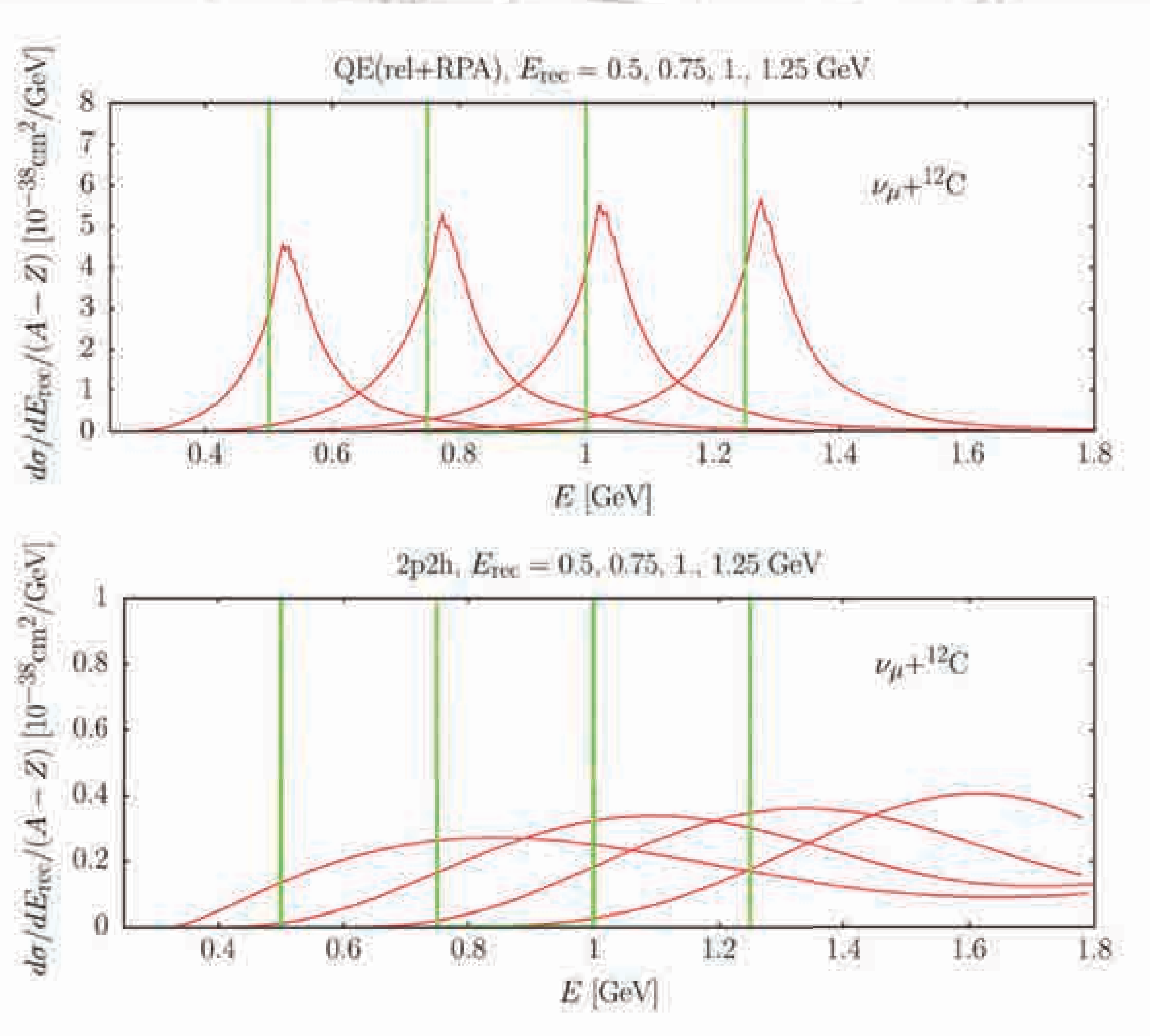
Data fits equally well to:

CCQE M_A = 1.31

CCQE MA = 1.05 + RPA + 2p2h

If so: what is the problem ?

2p2h and E_ν



PHYSICAL REVIEW D **85**, 113008 (2012)

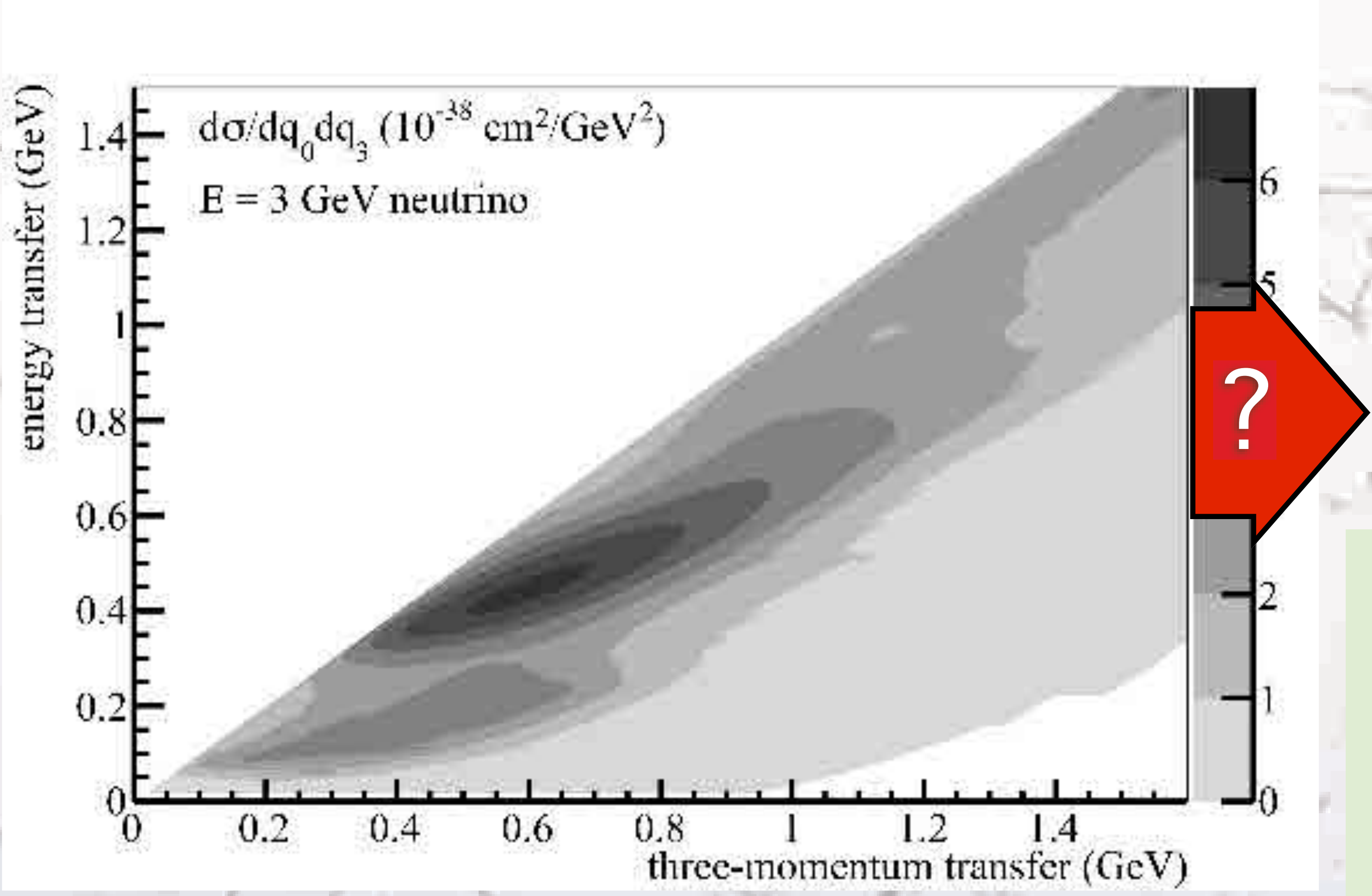
Effect of multi-nucleon (2p2h) interactions in the neutrino energy reconstruction.

- Recon values (E_ν)
- $P(E_\nu|E'_\nu)$

The problem is that the E_ν is wrongly reconstructed.

Limits of the model

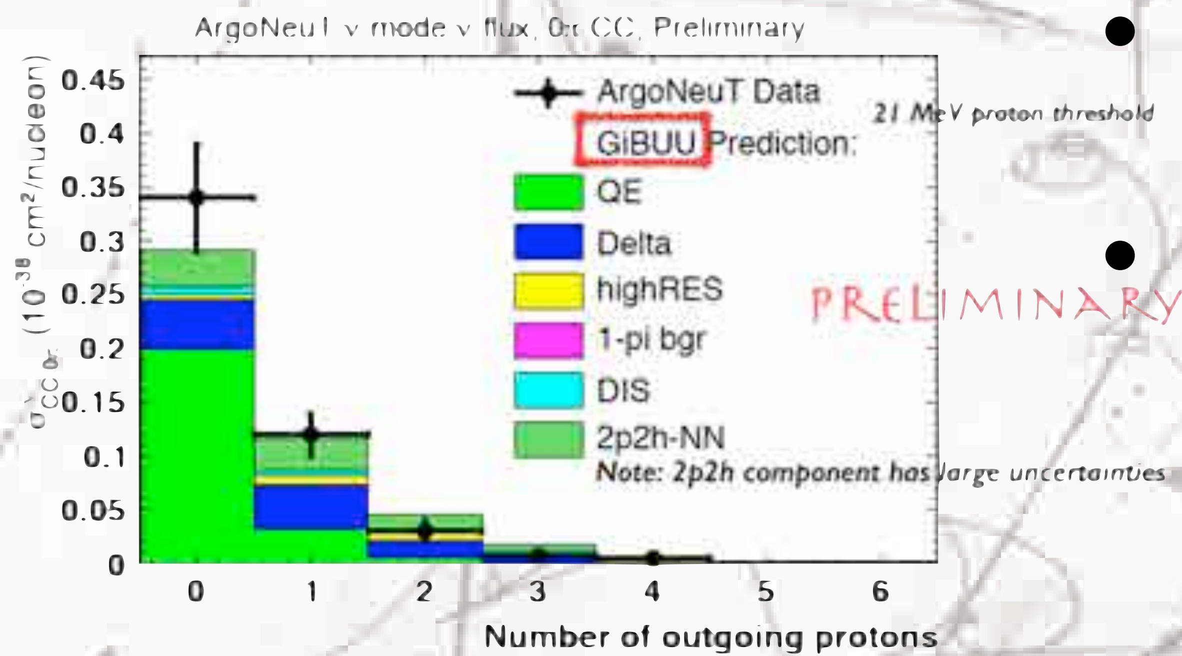
- The main problem with these models is that they are valid only in certain regions of the available kinematic space. Nominally, the low q^2 region.
- Extrapolations to the high q^2 region are complex since it implies a different treatment of the nucleus (relativistic, non-relativistic).
- Agreement with experiments might vary with the typical experiment energy.



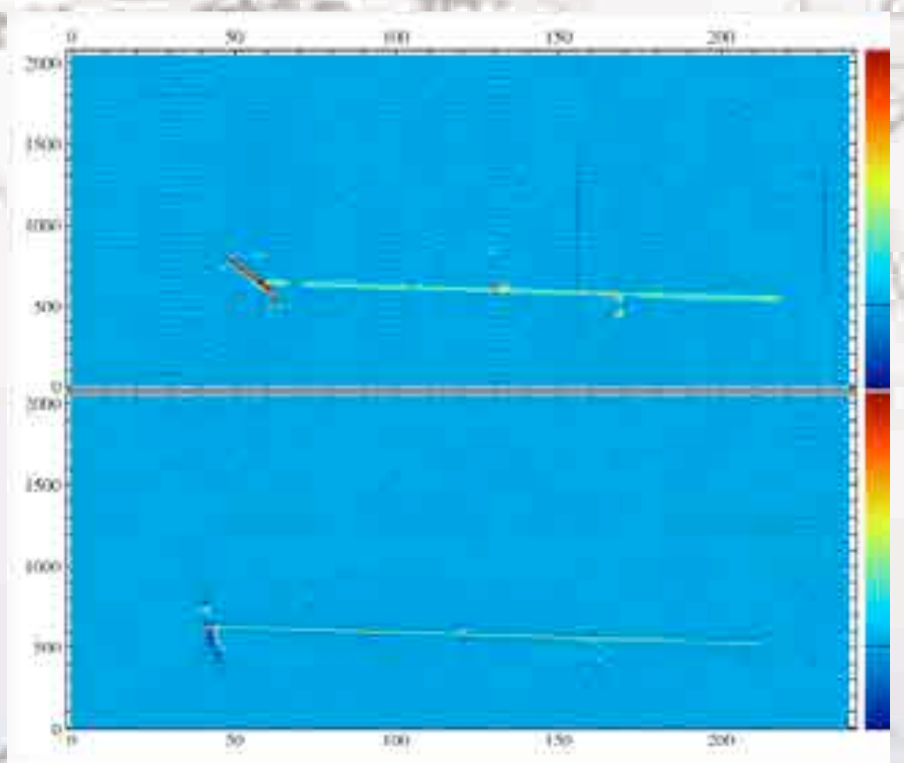
Gran, R. *et al.* Phys.Rev. D88 (2013) 11, 113007

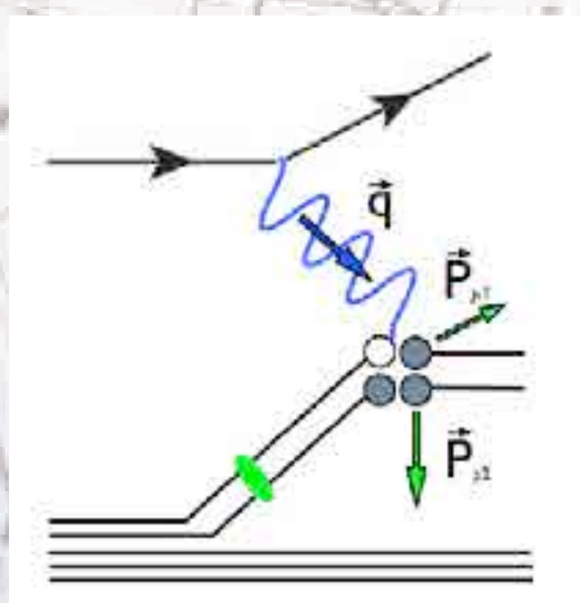
Proposed to use the momentum transfer to the nucleus as a reference cut and not neutrino energy.

Search for 2 proton

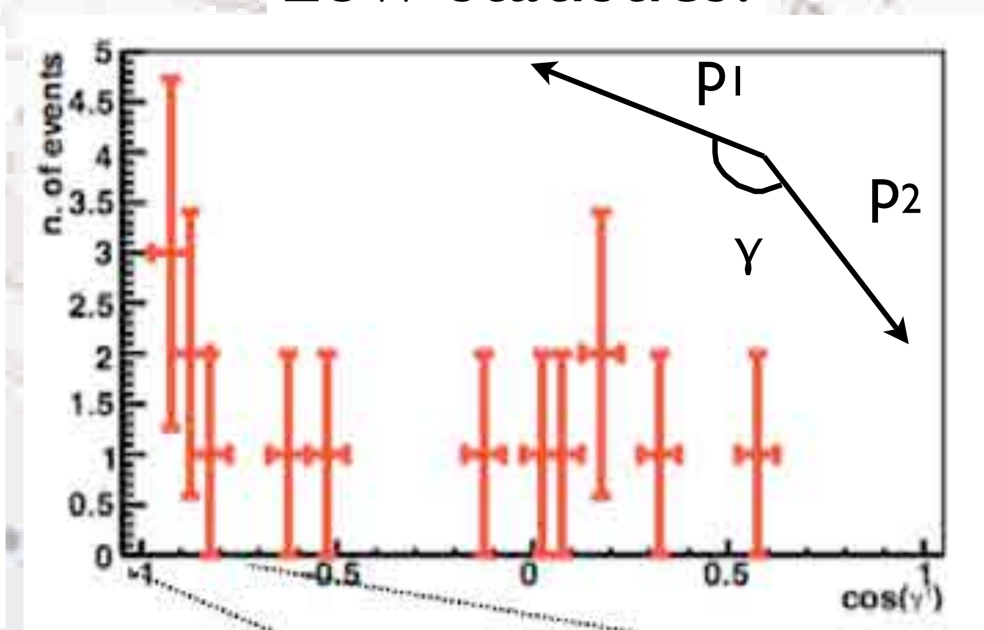


- LiqAr ArgoNeut has bubble chamber imaging capabilities to look into final states.
- It has first indications of correlated final state protons.
  - Spectral functions ? (~Initial state correlations)
  - 2p2h ? (~Final state correlations)
  - Both ?





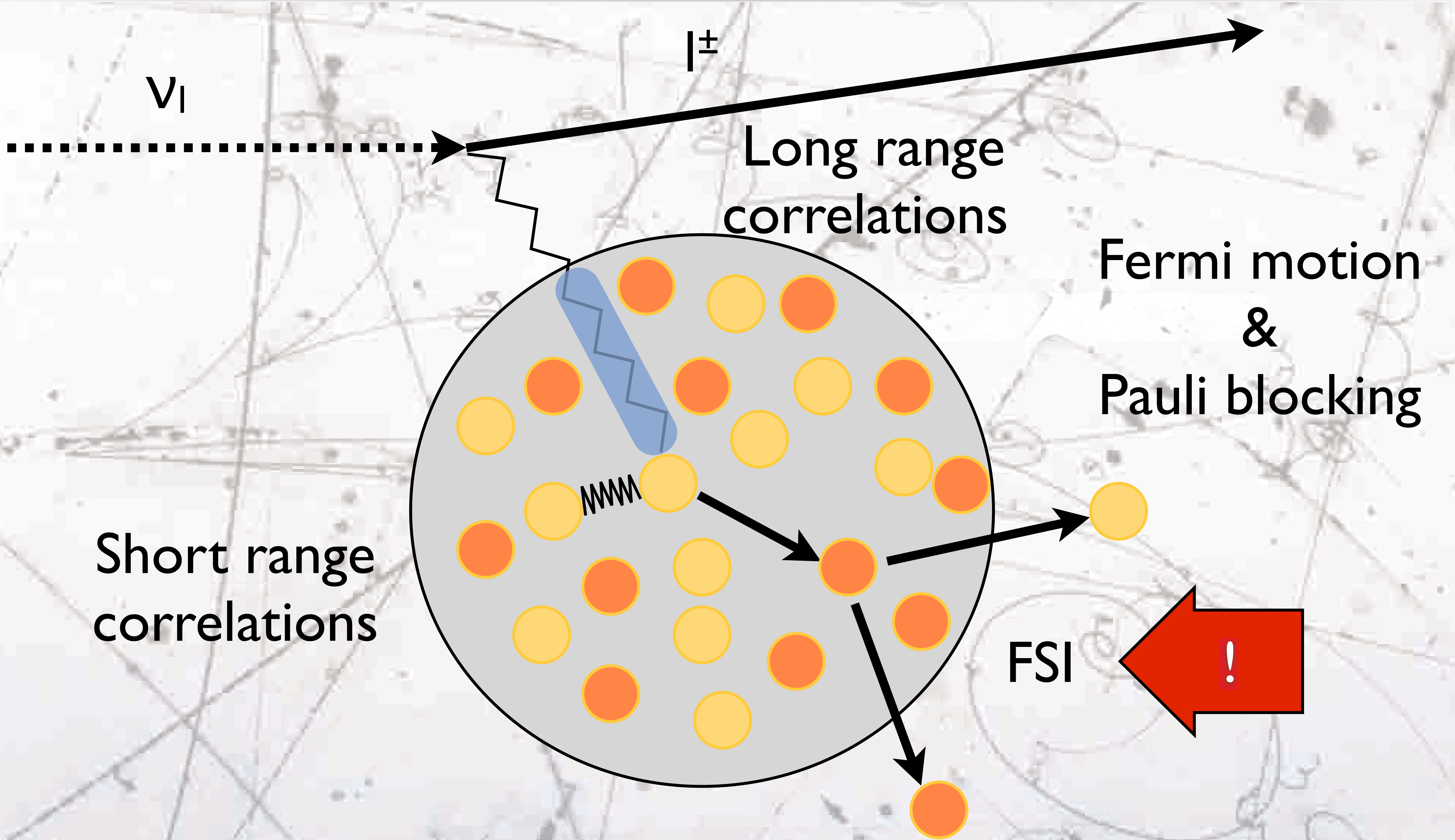
Low statistics!



CCQE-2p2h partial summary

- Revolution during the last 5 years!.
- Model is not yet settled due to nuclear contribution uncertainties.
- Lack of direct evidence (2 proton final state) of the 2p2h.
- Problems with the extension to large neutrino energy.

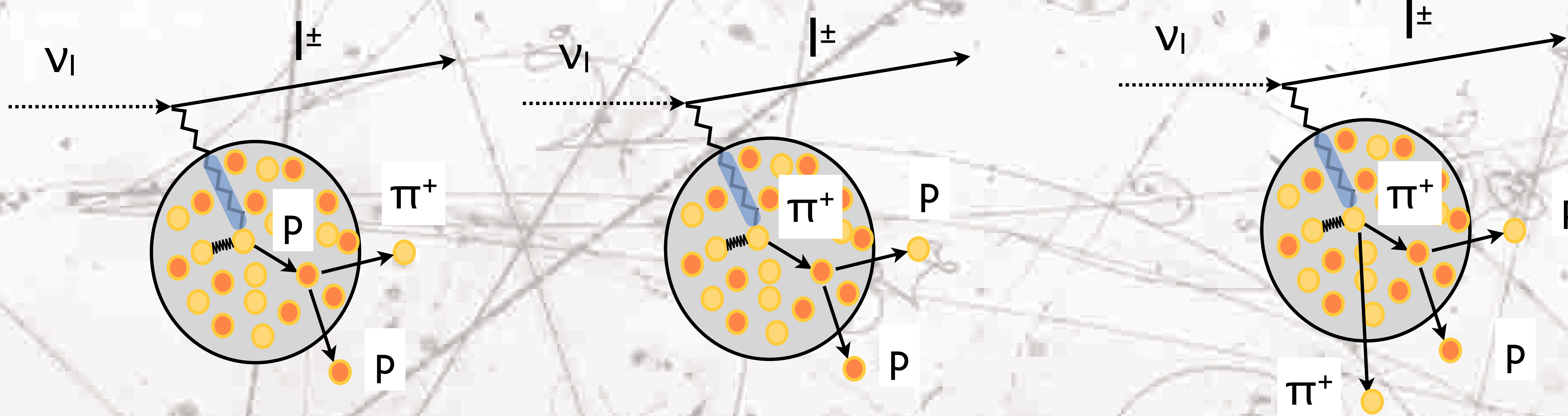
Final state interactions



Problem factorisation

- Example: events with $\mu^{-}+\pi^{+}$ in the final state.
- Topology is altered by FSI.

FSI alters the definition of the event



1.CCQE	1.CC1 π^{+}	1.CC 2π^{+}
2.proton in final state	2. π^{+} in final state	2. 2π^{+} in final state
3. p p -> p π^{+}	3. π^{+} p -> p p	3. π^{+} p -> p p

More on FSI...

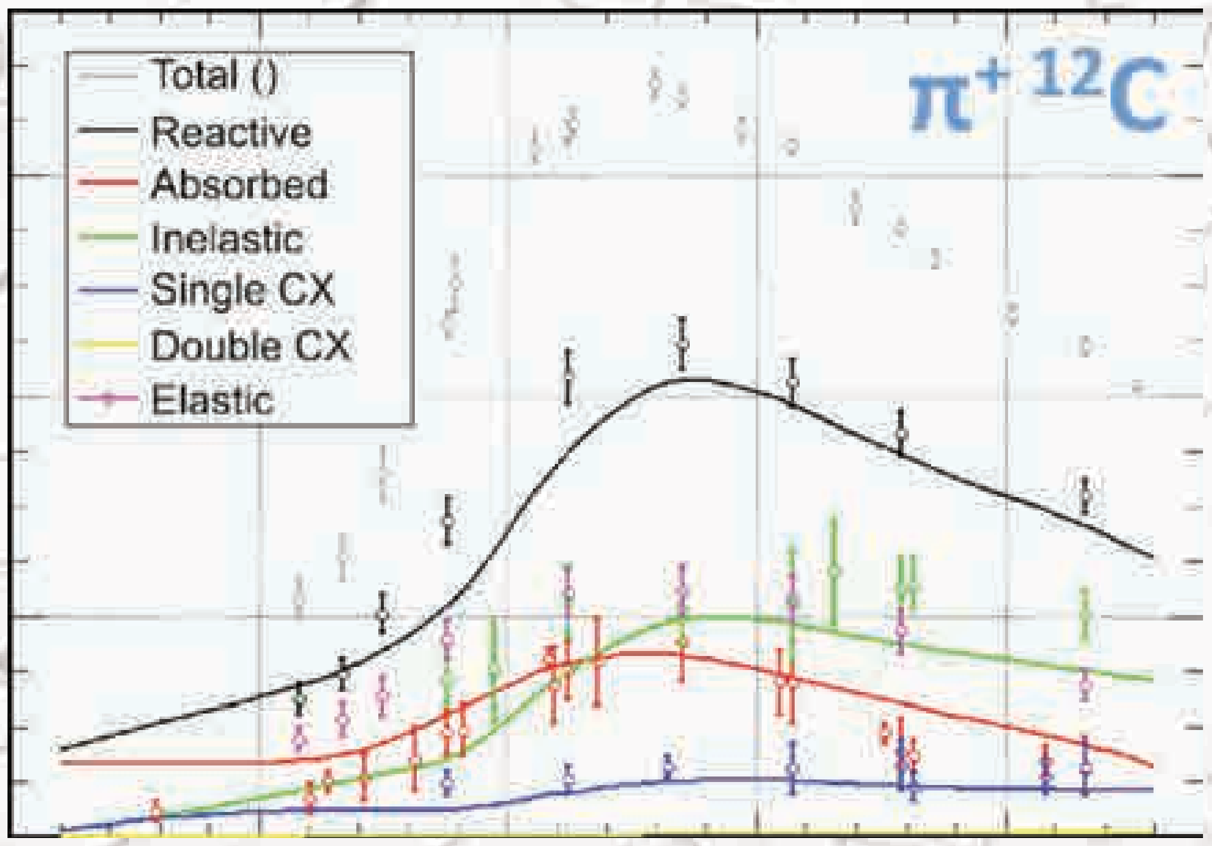
- Hadrons outside the nucleus will keep interacting altering the calorimetry.
- This is already part of the measurement program of WA105 but we need to measure exclusive channels and not only calorimetry.

This is already a dominant systematic @T2K

Specific experiment (DUET) is being run to reduce it.

Experimental results

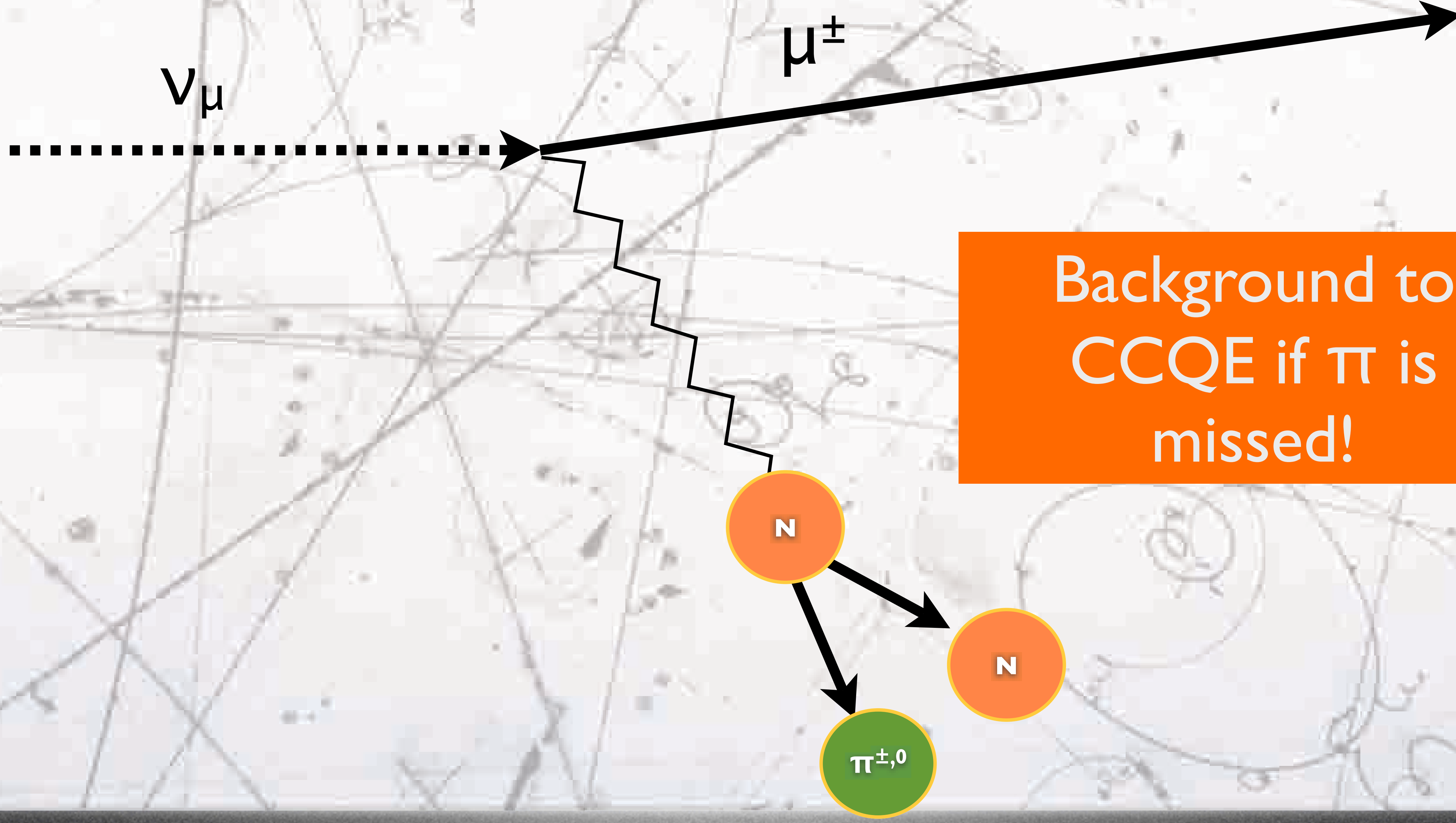
- Uncertainties from old experiments are large.
- These cross-sections do not cover the full range of interest in energy.
- Some of the results are inclusive.
- It is not obvious that and interaction of a hadron with a nucleus is the same for hadrons produced outside or inside the nucleus.



FSI partial summary

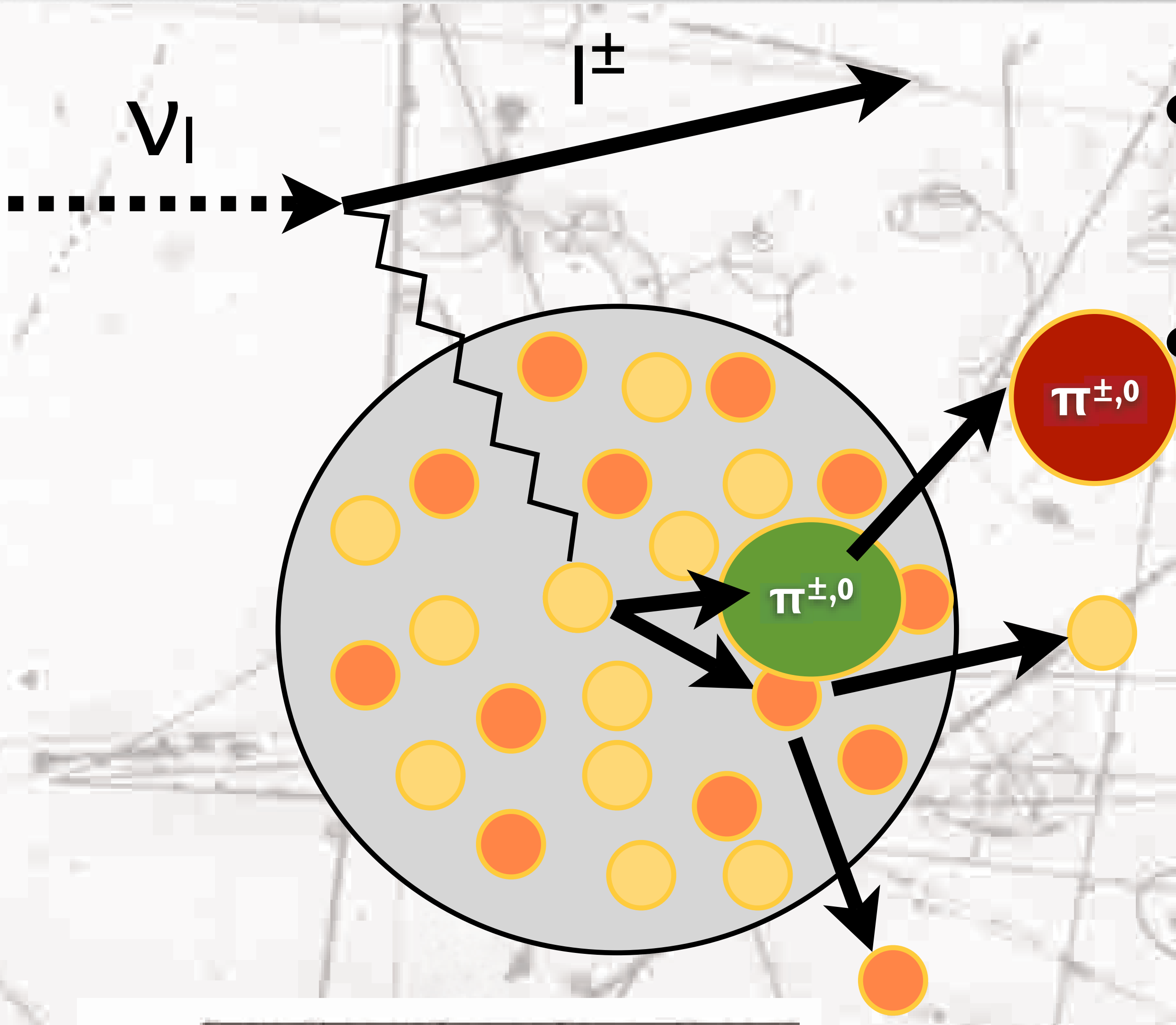
- Critical to the cross-section problem in nuclei.
- Sparse and non-precise data, it is also not available for all energies and all nuclei.
- Additional πA and pA experiments are needed to reduce uncertainties.
- Electron scattering might help to tune the "cascade" Monte Carlo models since the initial condition and energy is known.

CC1π

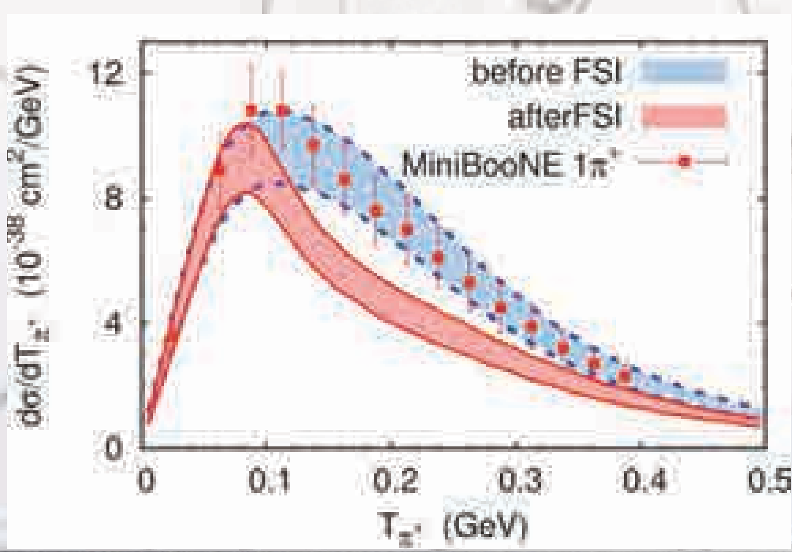


Background to CCQE if π is missed!

Signal definition

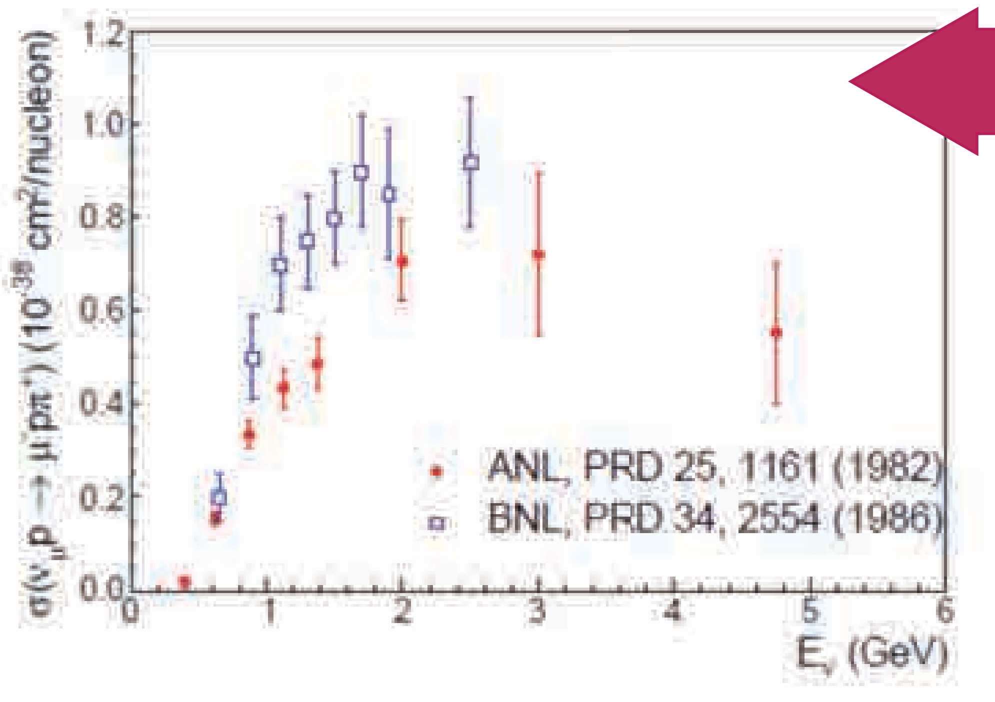


- Final state interactions alters the final state hadrons.
- Experiments make measurements for pion production:
  - @ nucleon level.
    - theoretically easy.
    - FSI correction by experiments, difficult to undo.
  - leaving the nucleus.
    - theorist need FSI model.
    - no experimental modelling bias.

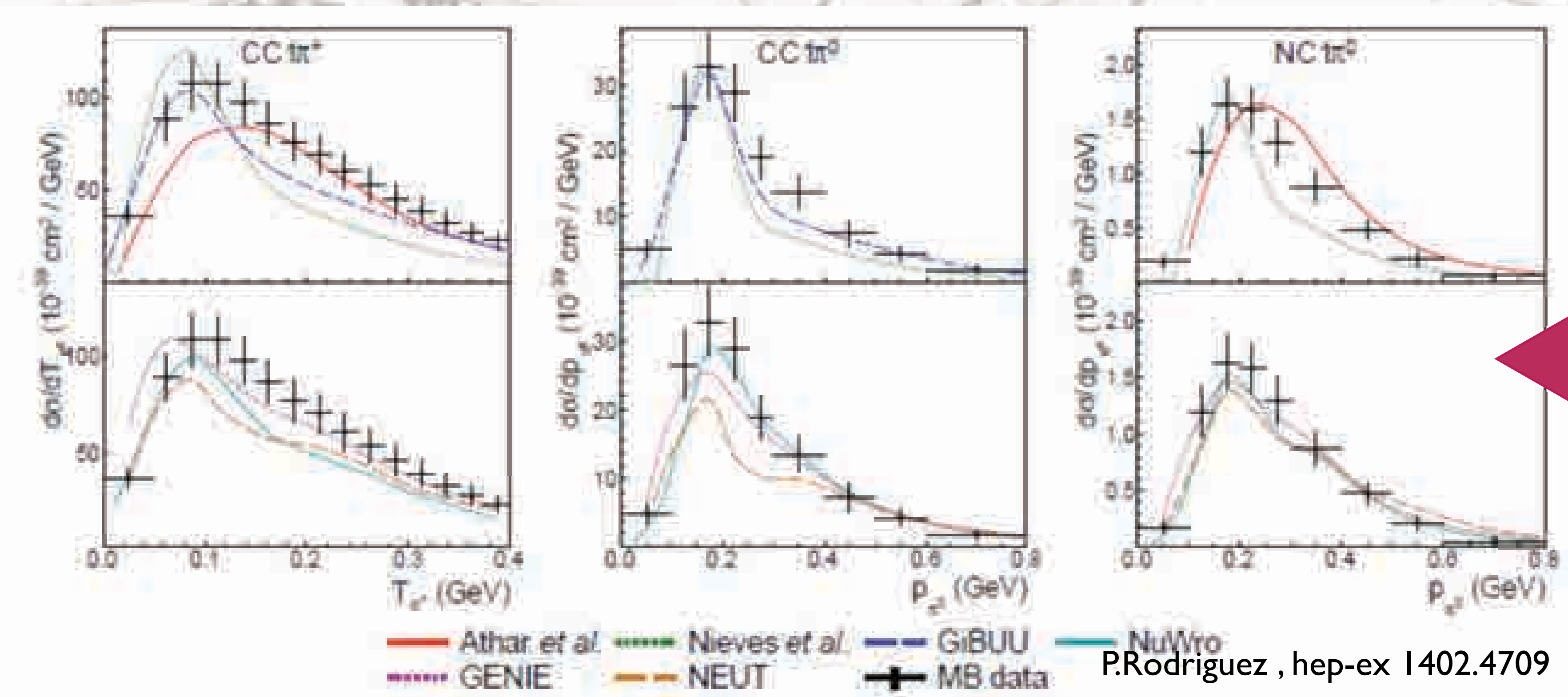


FSI is large

CCπ+,0 data



- Old deuterium data is inconsistent (probably flux)
- Difficult to tune MC models if the basic νp(νn) interaction is imperfect.
- FSI+nucleon model need to be tuned together (Large uncertainties in FSI!)



P.Rodriguez , hep-ex 1402.4709

- Models are not able to describe CC π+ π0 and NCπ0 together.

CC 1π

- It is more complex than CCQE and is not well understood:

ν-nucleon

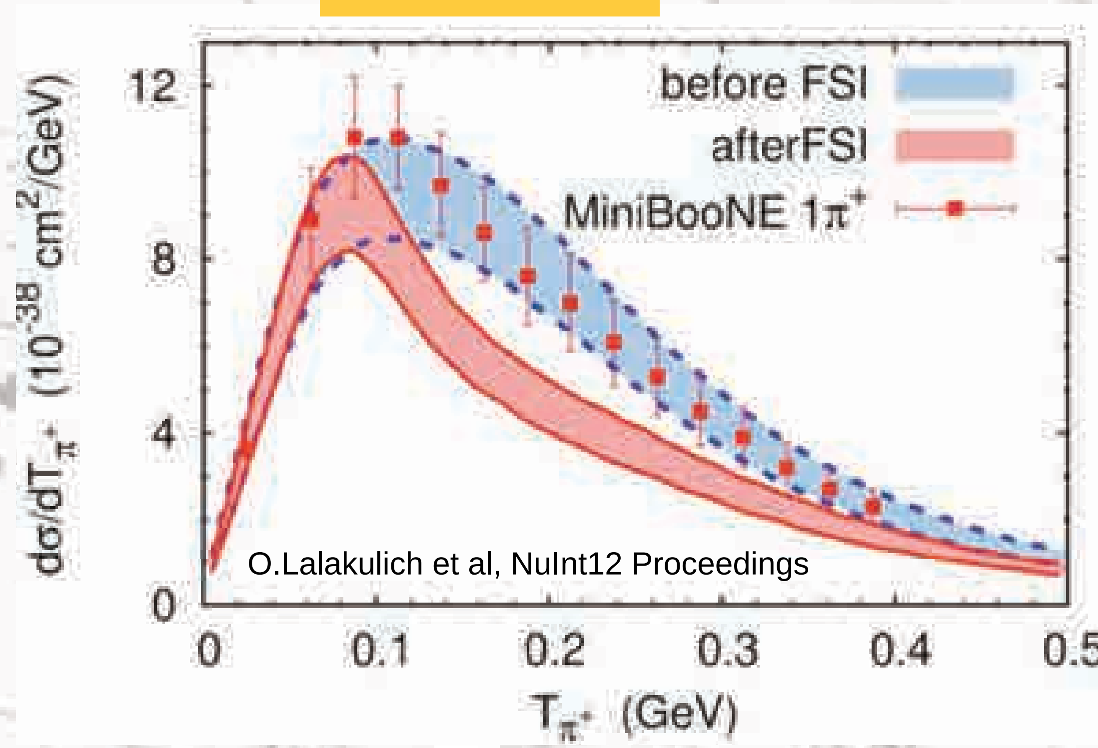
- $C^A_5(0)$ (interaction strength)
- resonant+ non-resonant + interference,
- transition to the forest of high mass resonances.

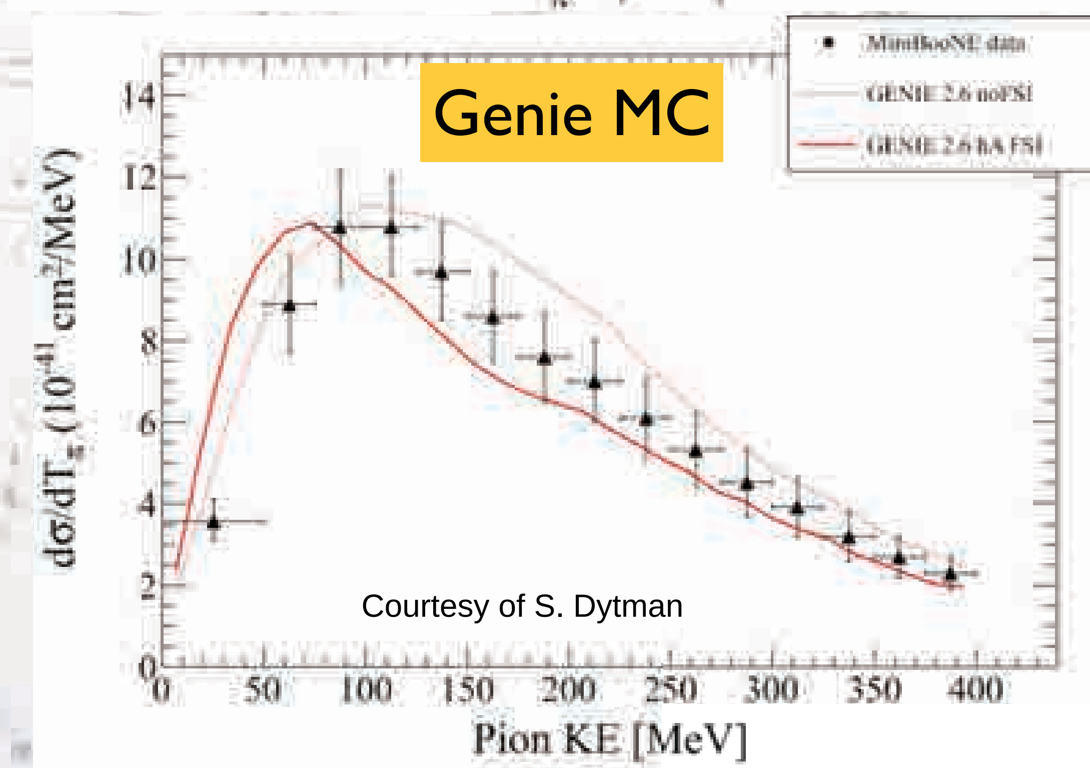
π-A

- Final state interactions

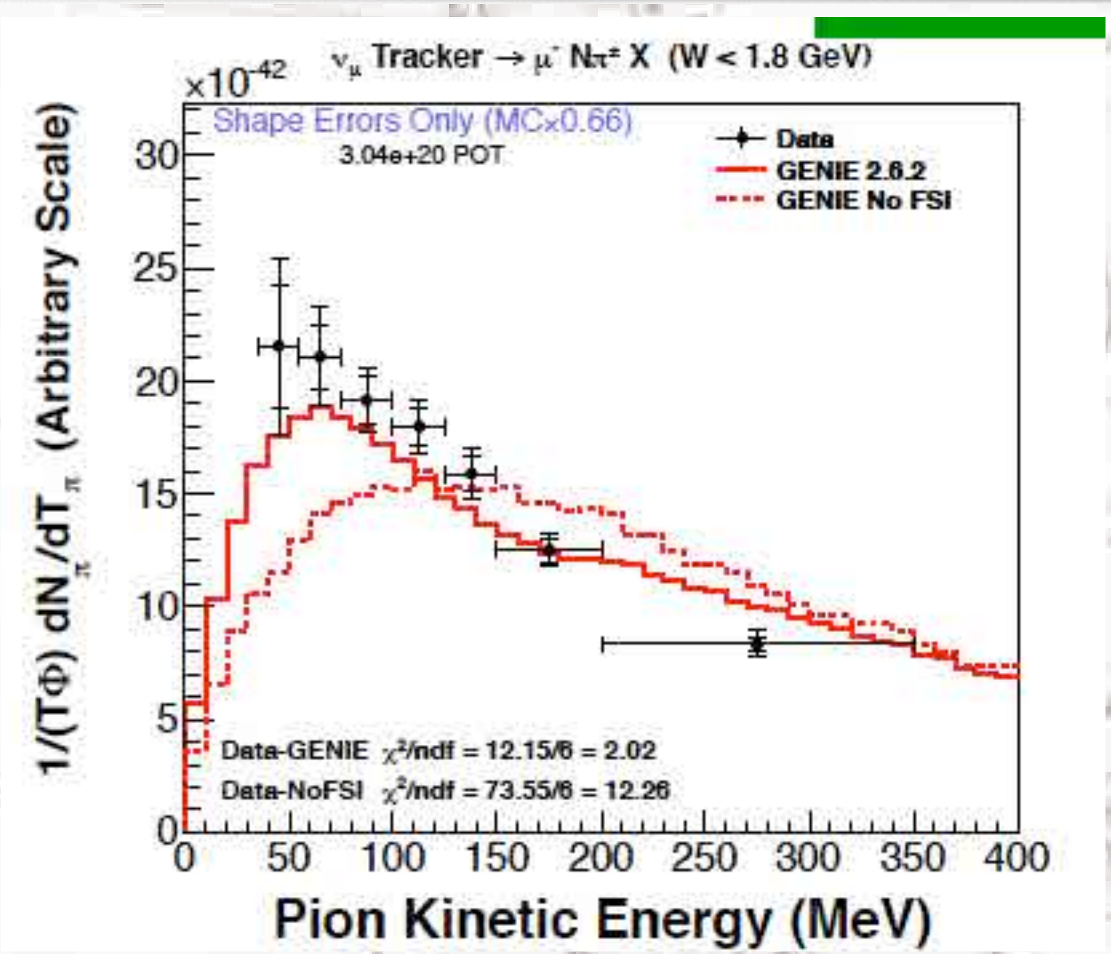
- Problem, poor agreement with MC predictions:
  - Data “seems” to prefer no nuclear absorption of pions!.

GIBUU MC

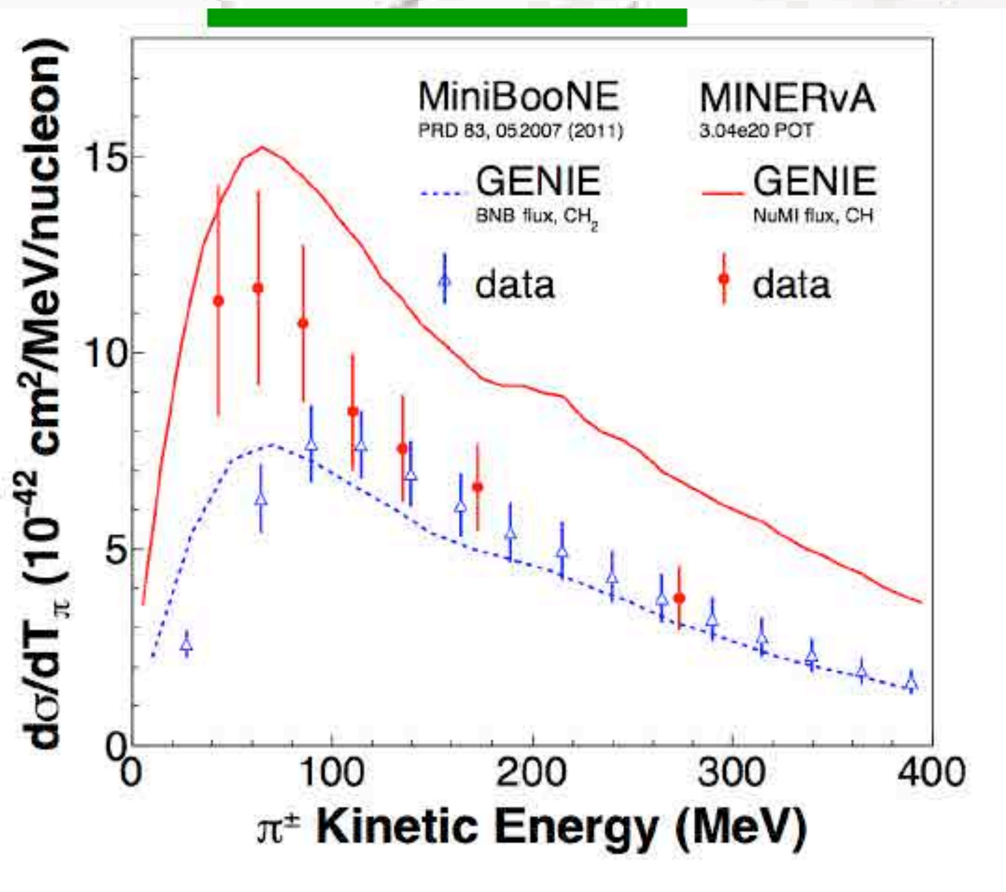




Minerva results



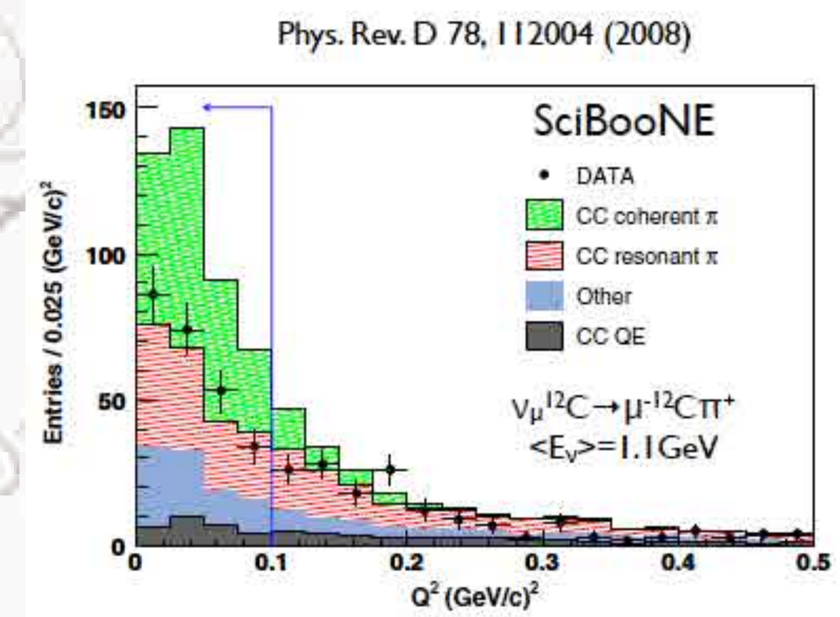
Minerva

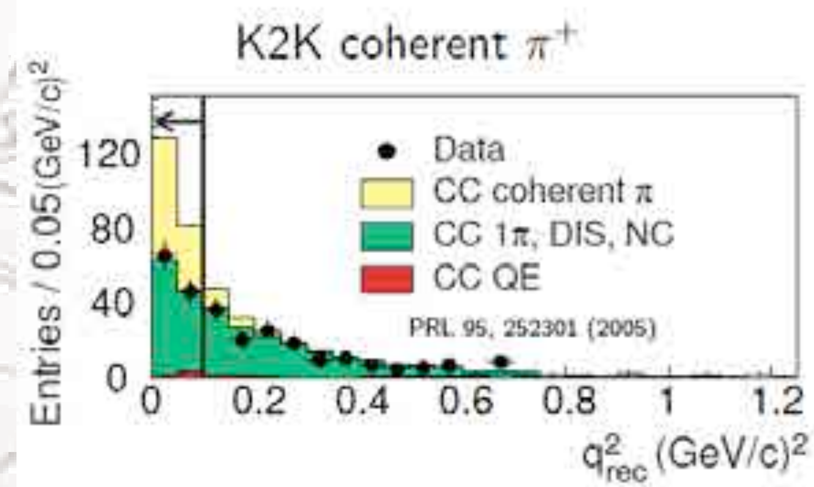


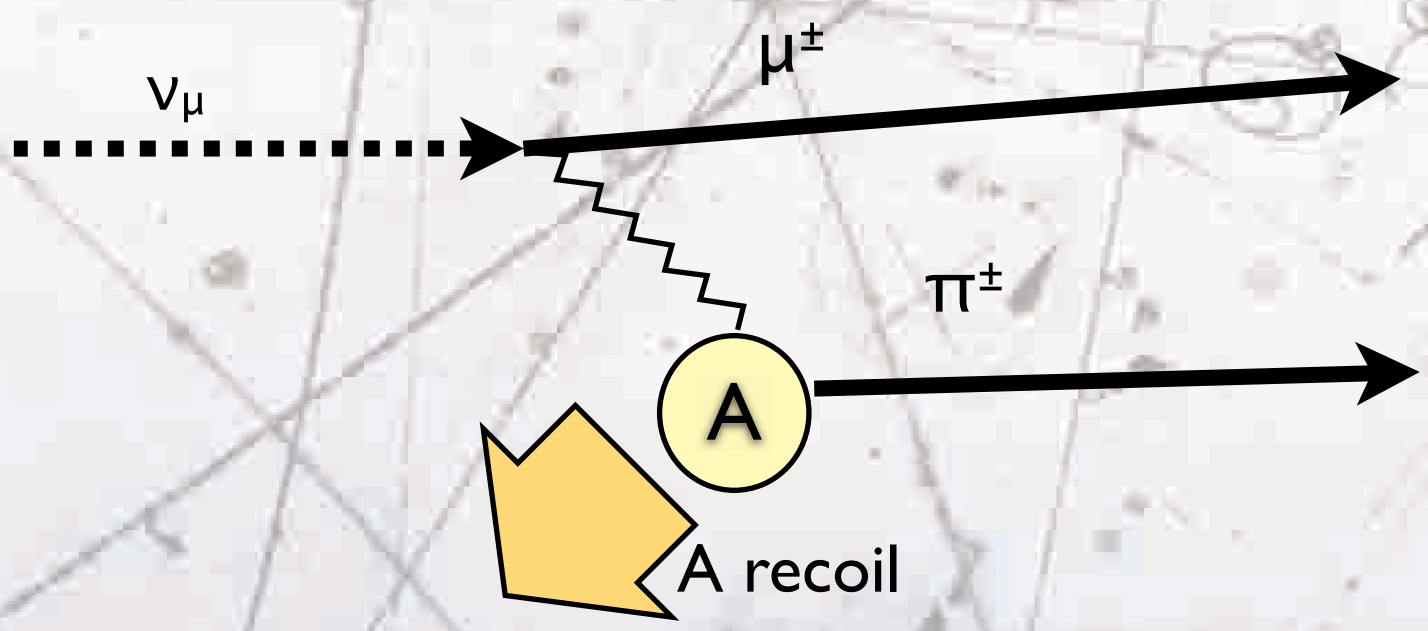
- Preliminary results show agreement with MC predictions & disagreement with MiniBoone data.
  - Minerva and MiniBoone are in a different energy region: backgrounds from large mass resonances?, ….
  - Minerva and MiniBoone detection technique is very different: Signal definition ?

CC 1π coherent

- The CC1π coherent has been an issue in neutrino interactions since a decade:
  - Low cross-section but concentrated at low q^2 !!!
  - the experiments were not able to find evidence at low energies.
- Some microscopic models predict that the coherent might help to understand the CC1π signal.





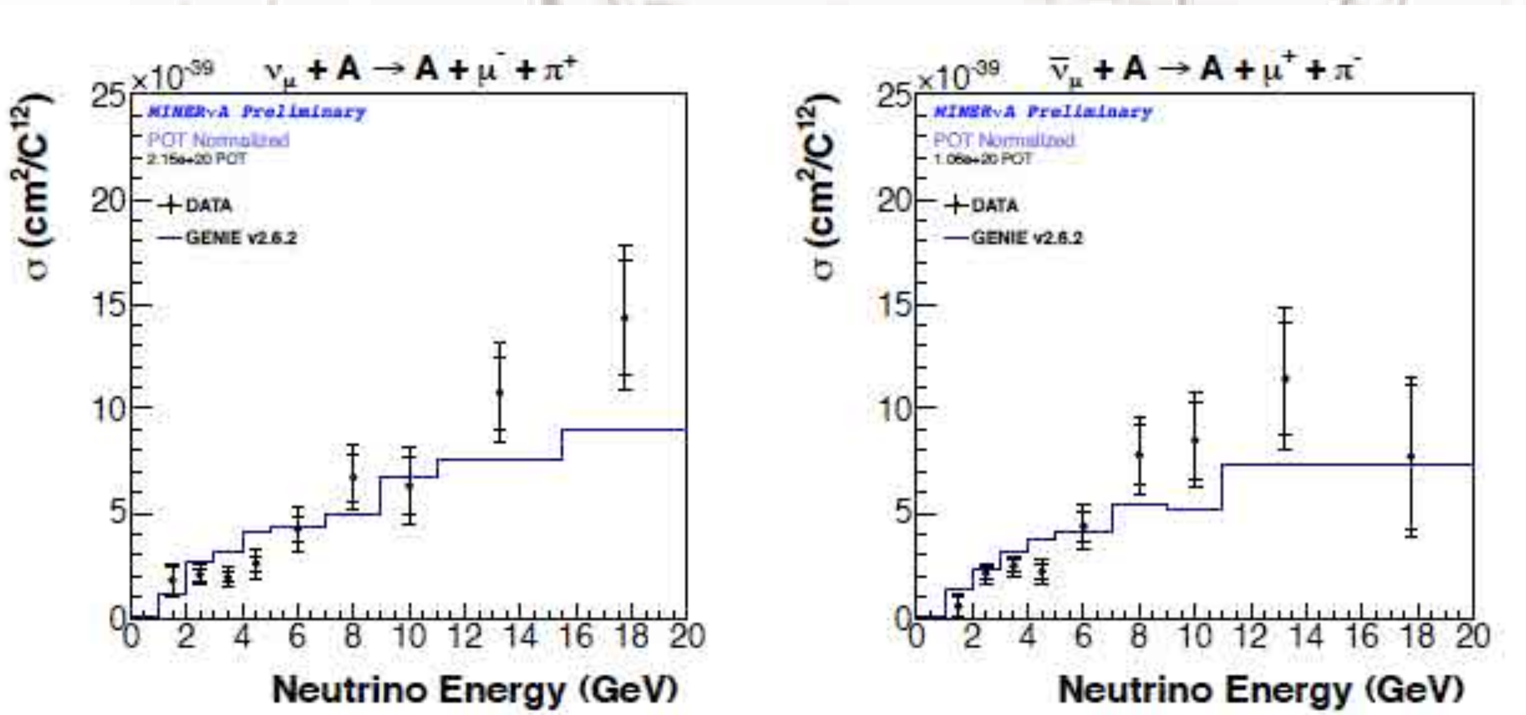


Low nuclear recoil (t)

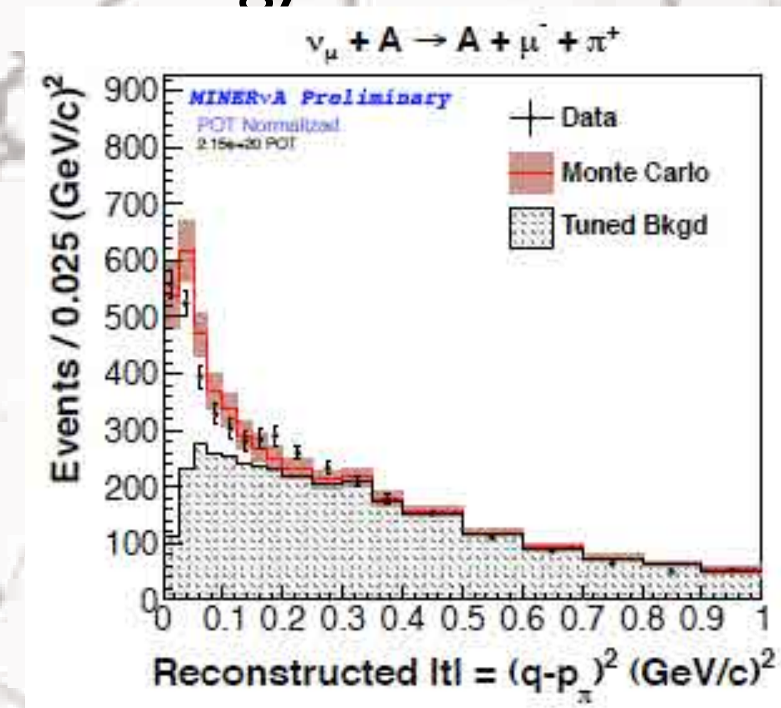
No nuclear breakup and no proton (vertex activity)

CC 1π coherent

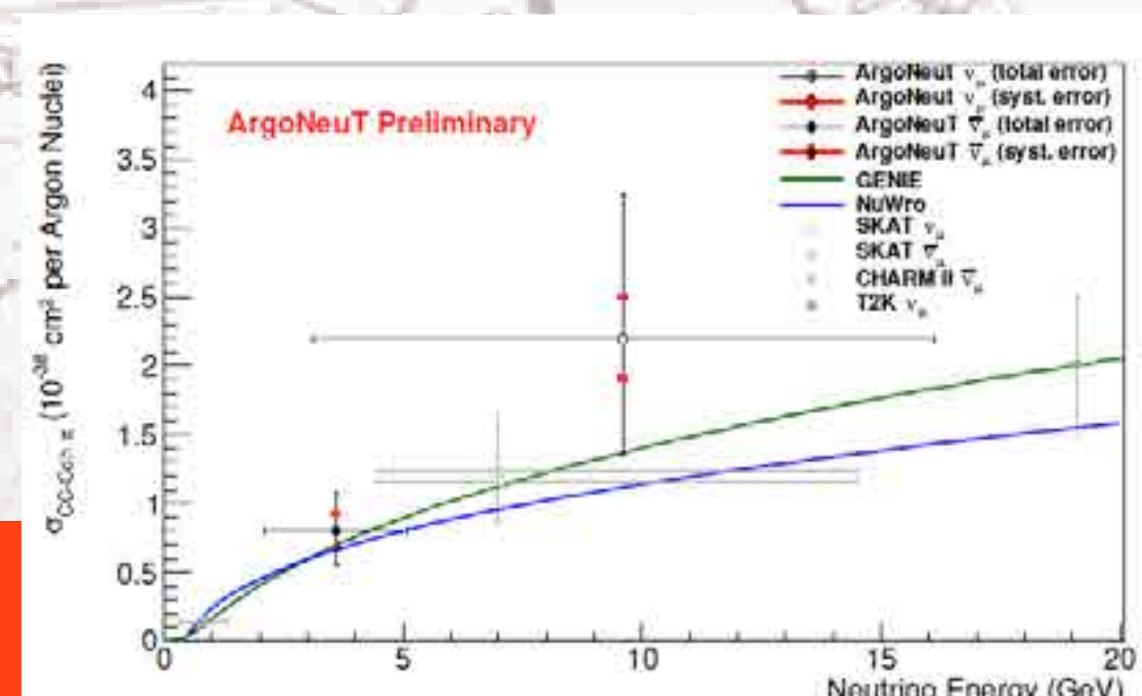
- Minerva from vertex activity & nuclear recoil energy



Minerva



- ArgoNeut from vertex activity.

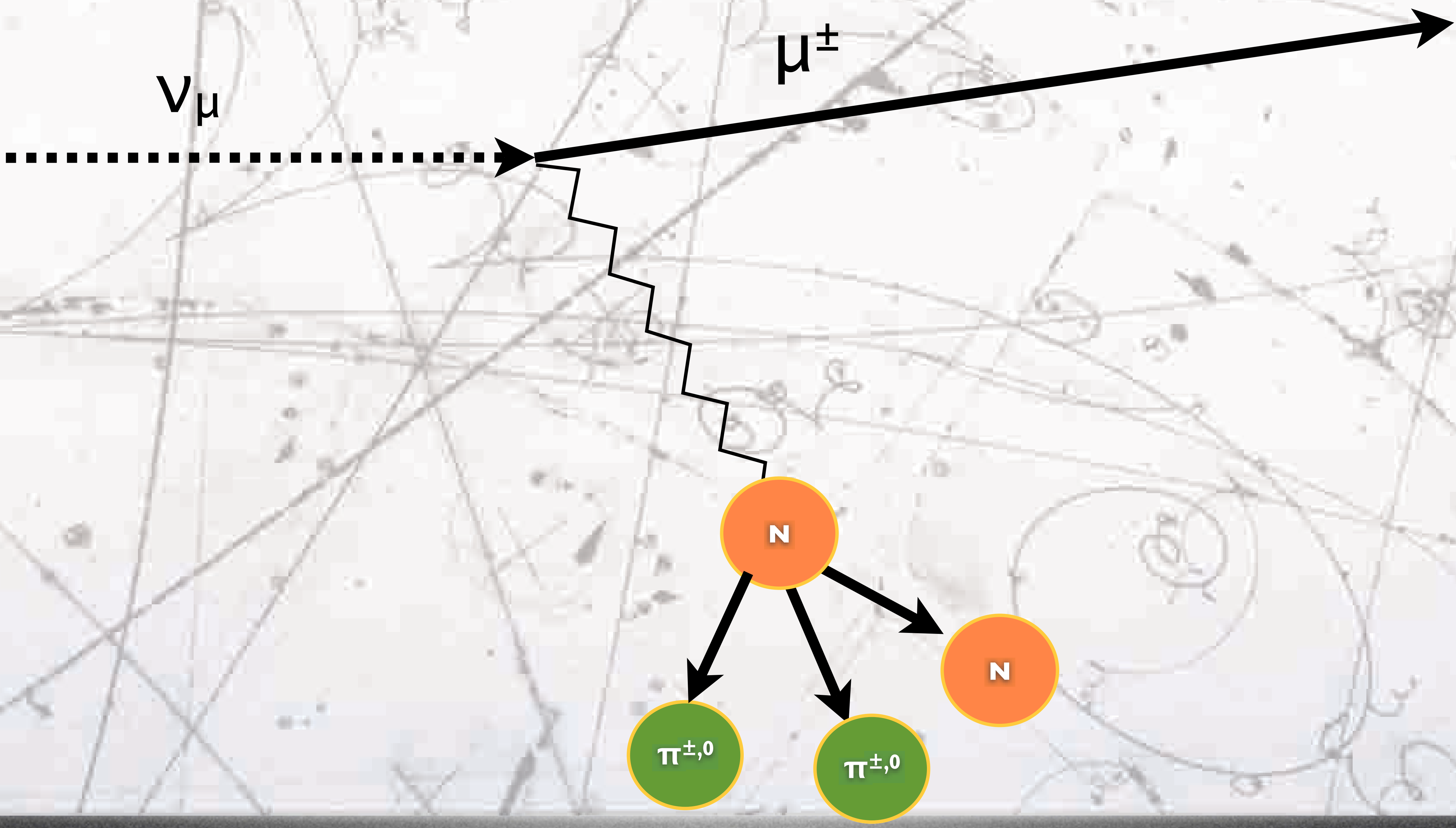


Good agreement with models except in the shape of nuclear recoil !

CC1π partial summary

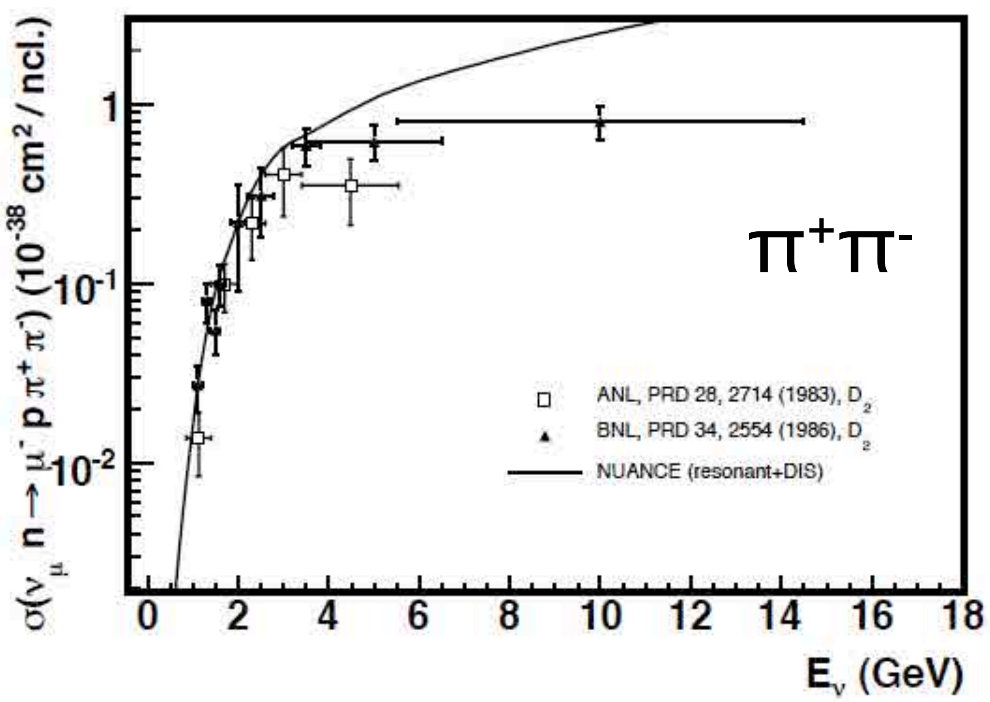
- CC1π is a difficult channel but it is the main background to other channels.
- Not well understood even at the nucleon level (old sparse data):
    - Nowadays it is almost impossible to make an active hidrogen(deuterium) active target detector.
- Large effects from FSI (π reinteractions!).

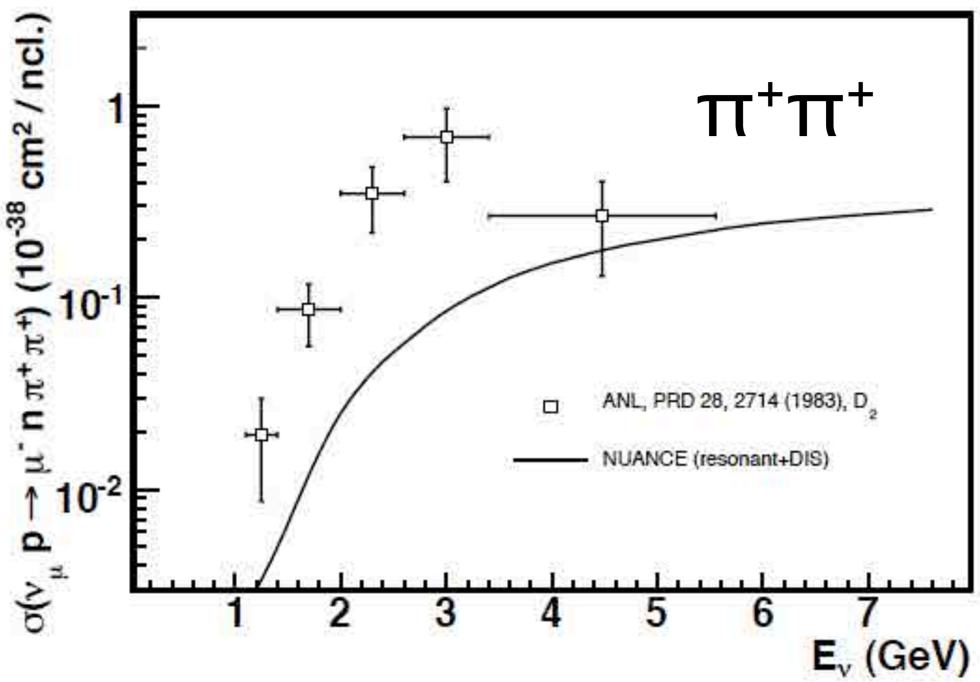
CC-Nπ

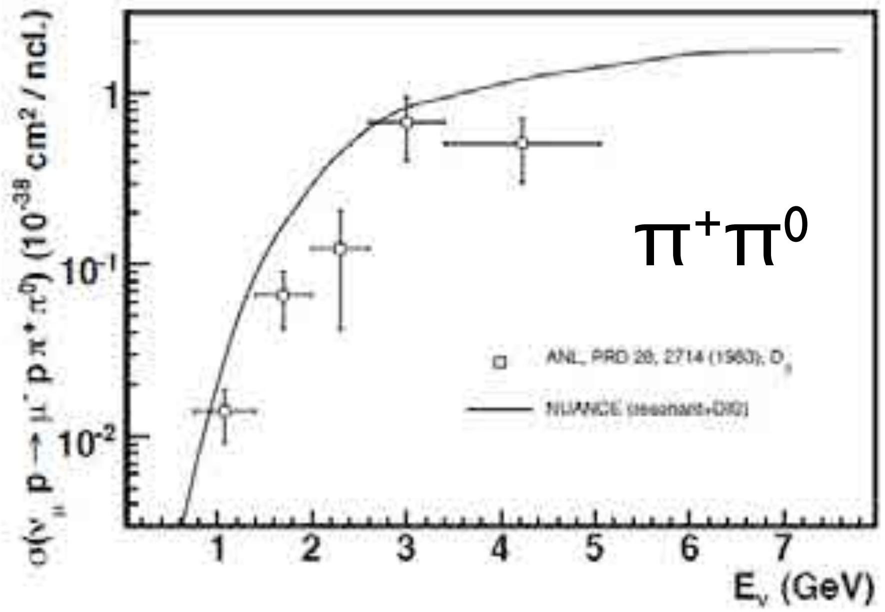


CC-Nπ

J.A.Formaggio, G.P.Zeller, Rev.Mod.Phys. 84 (2012) 1307

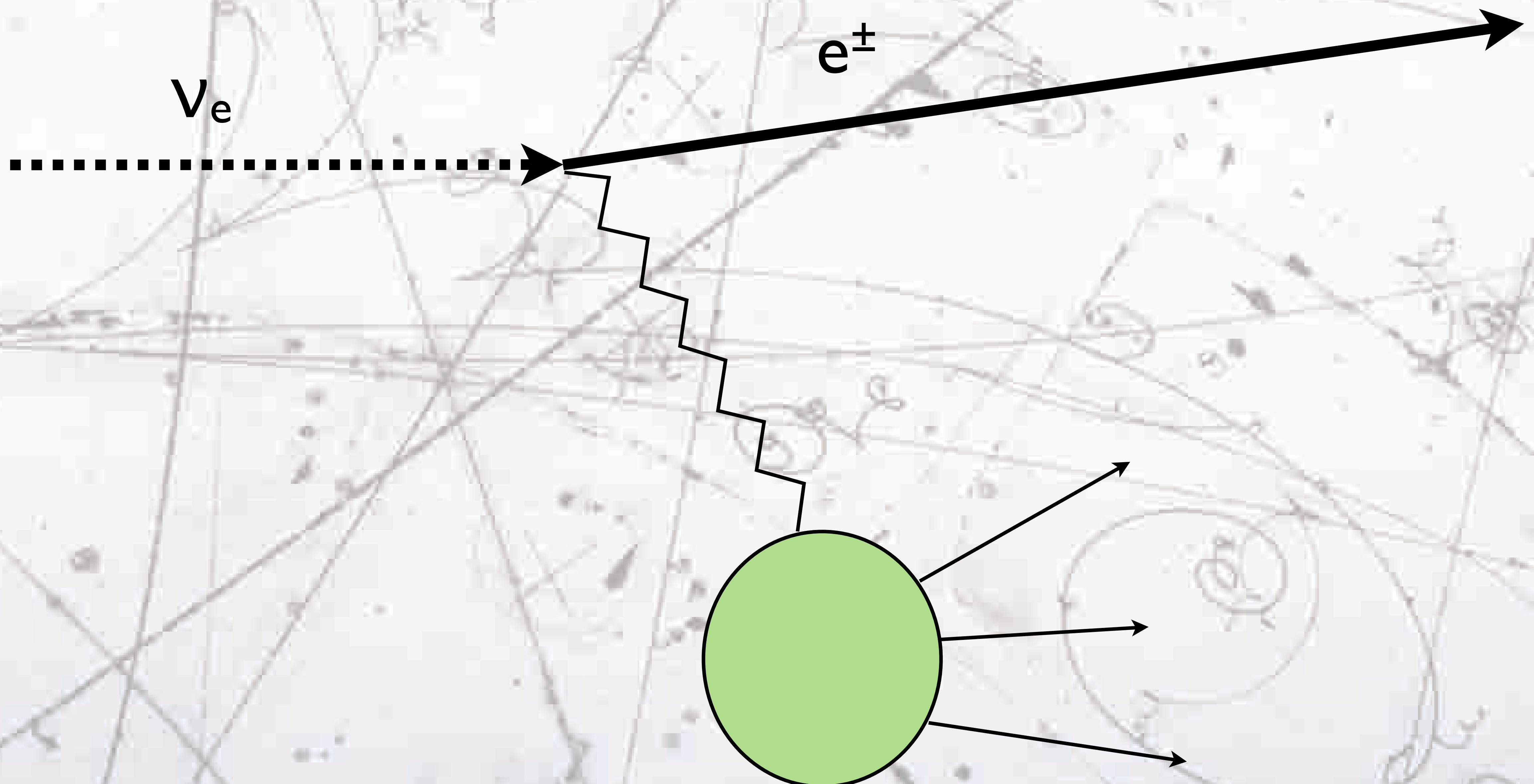






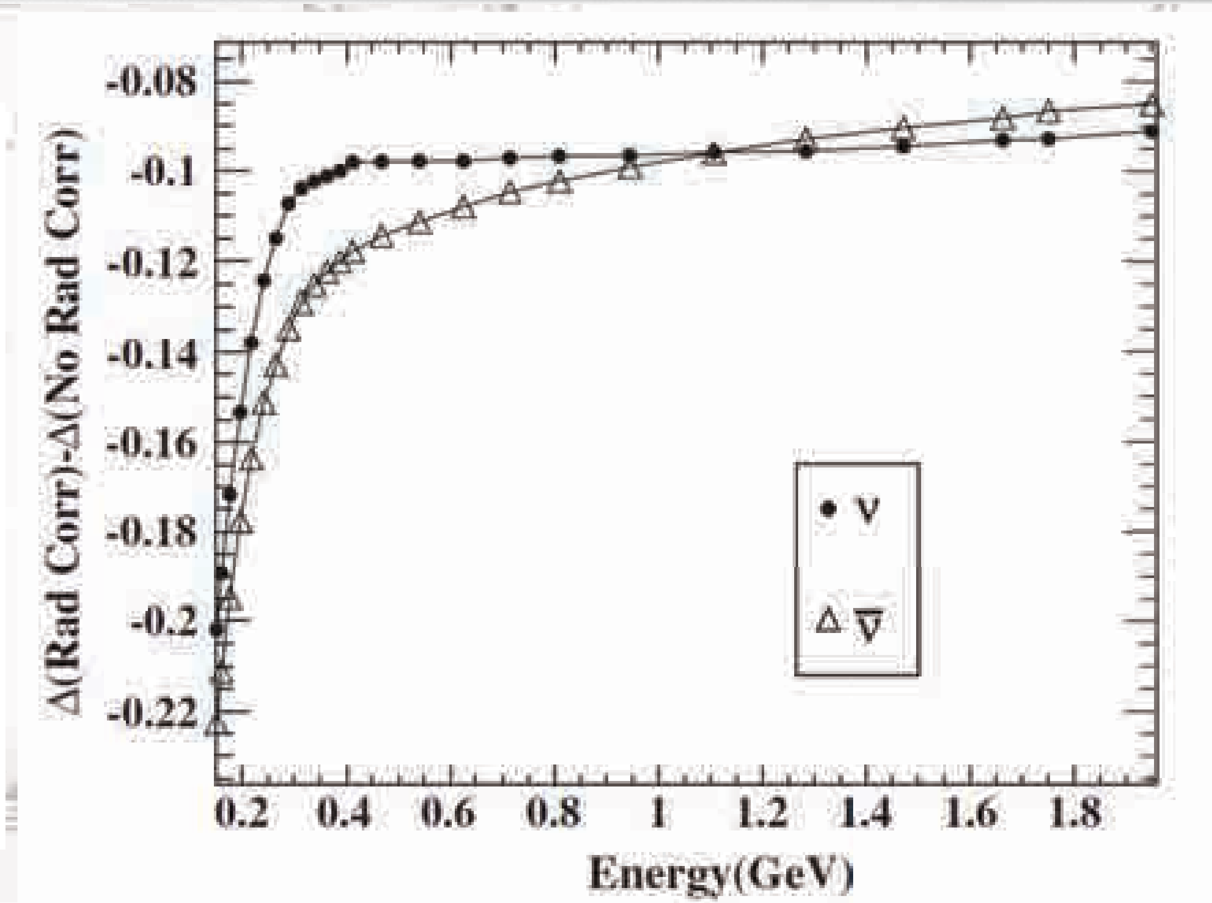
- This is a complex region with contributions from high mass Δ resonances and low ω DIS.
- There is no new data since ANL and BNL back to the 80's.
- No data in nuclei: difficult measurement due to FSI.
- No detailed pion kinematics available.
- Critical for LBNE and LBNO!.

Inclusive CC ν_e

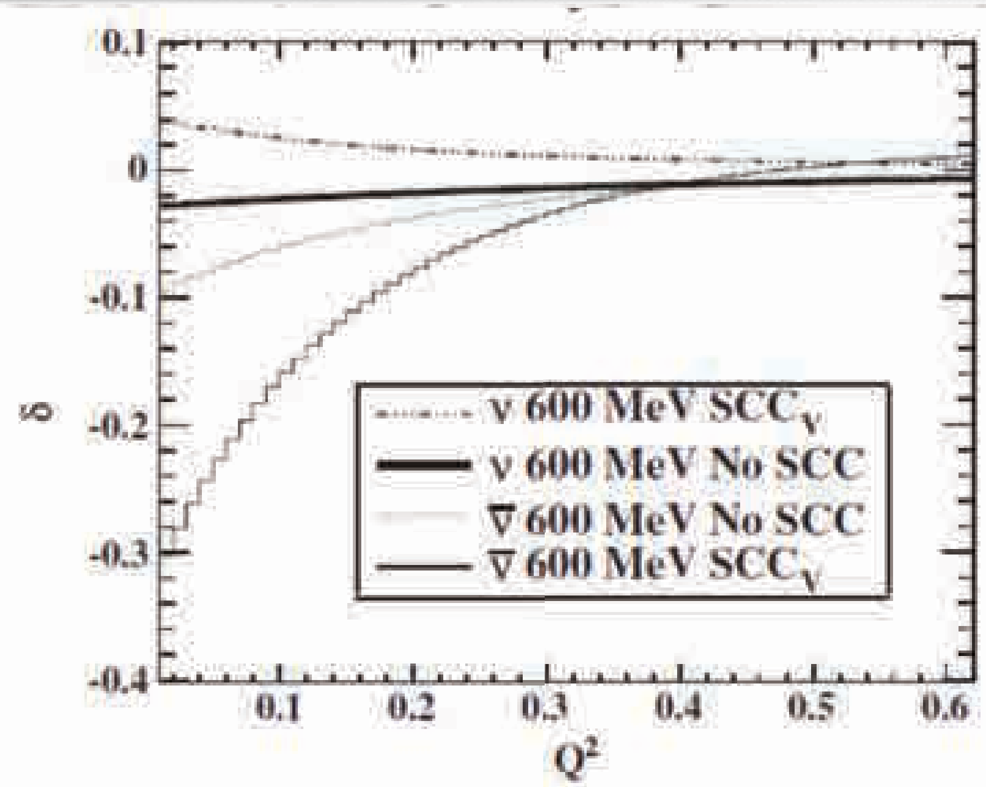


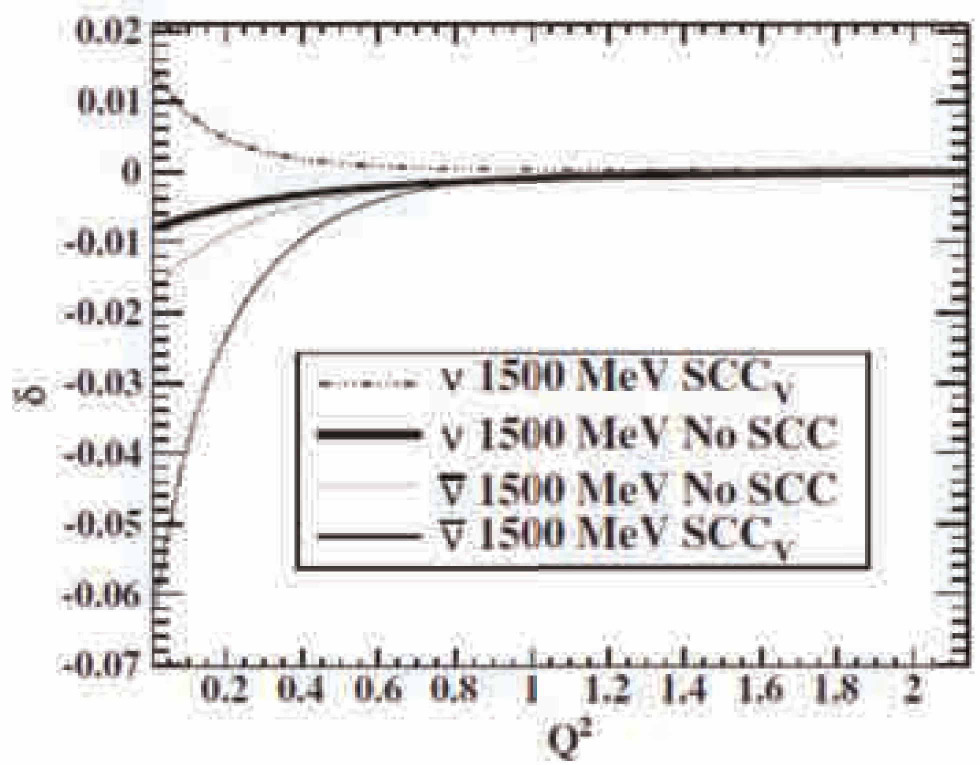
The ν_e problem

$$\Delta(E_\nu) \equiv \frac{\int dQ^2 \frac{d\sigma_\mu}{dQ^2} - \int dQ^2 \frac{d\sigma_e}{dQ^2}}{\int dQ^2 \frac{d\sigma_e}{dQ^2}}.$$



$$\delta(E_\nu, Q^2) \equiv \frac{\frac{d\sigma_\mu}{dQ^2} - \frac{d\sigma_e}{dQ^2}}{\int dQ^2 \frac{d\sigma_e}{dQ^2}}$$



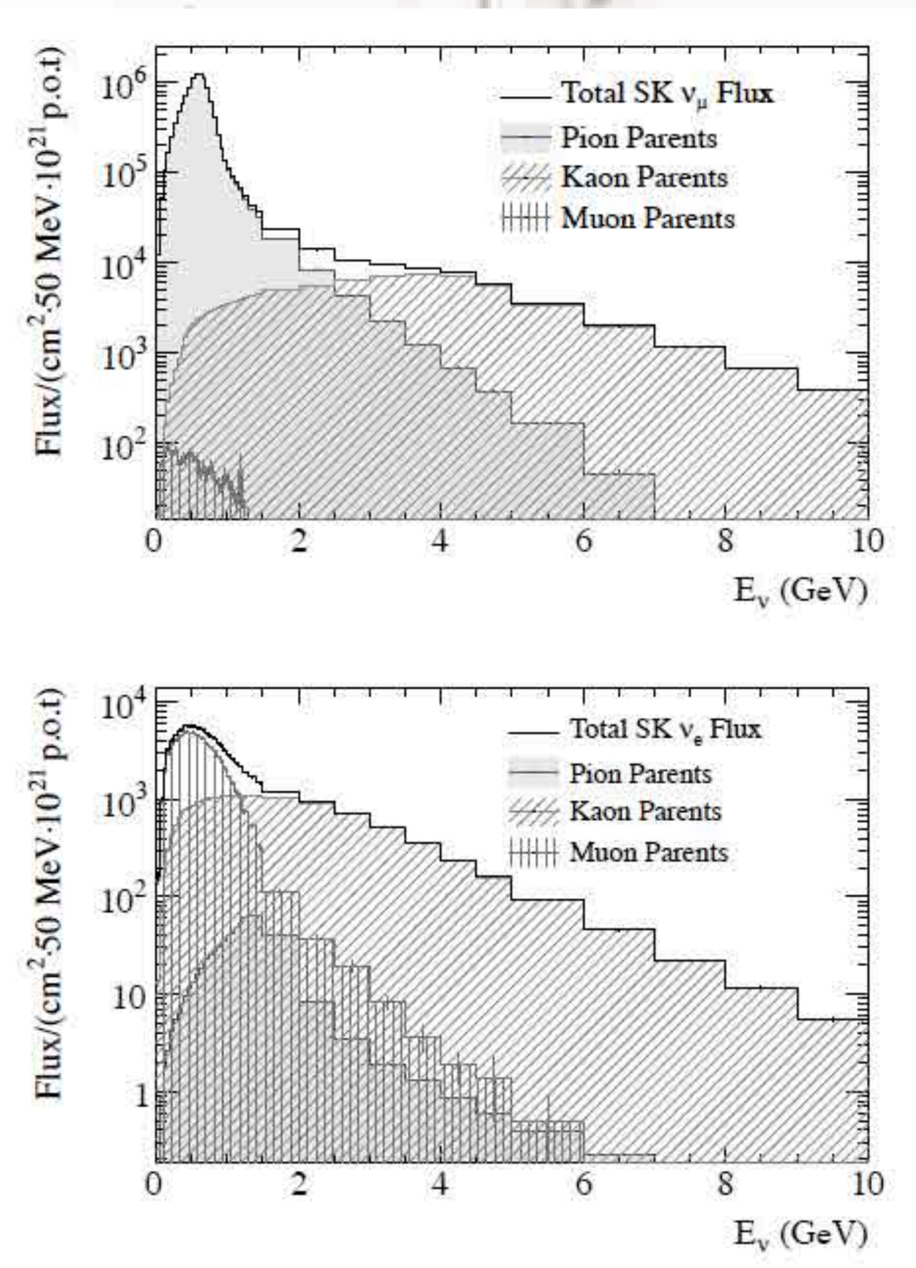


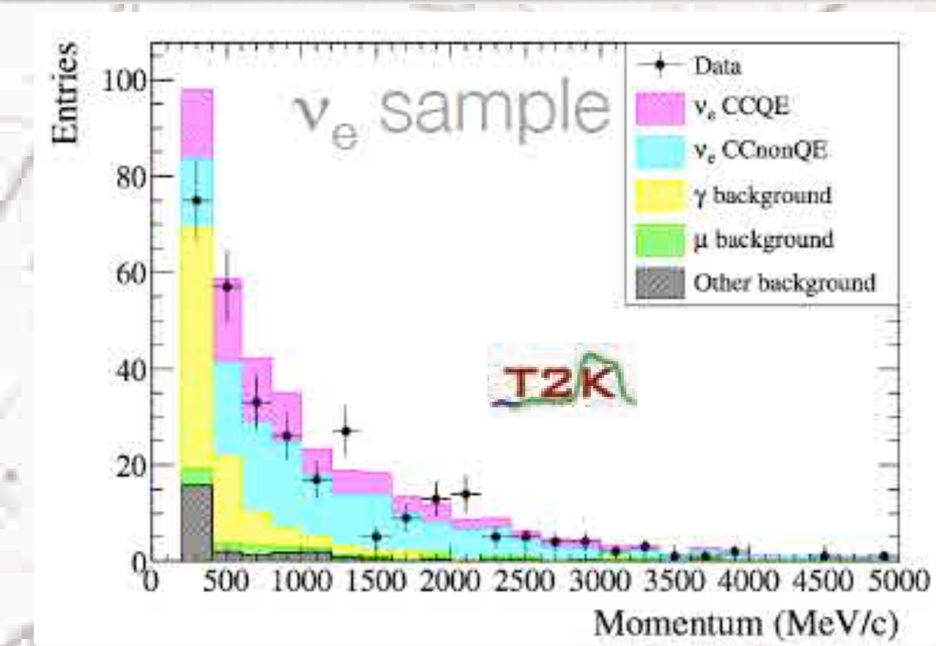
- Calculations show significant differences in the ratio of ν_e to ν_μ cross-sections due to:
  - form factors.
  - radiative corrections.
  - lepton mass.

Dominantes @ low E_ν (T2K)

PHYSICAL REVIEW D 86, 053003 (2012)

ν_e cross-sections





- Despite the relevance of the measurement, there are very little results (Gargamelle 1978!) :
  - Conventional beams provide small ν_e flux:
    - excellent PID.
    - large sample.
  - Two main flux contributions: μ decays and K decays.
  - The signal is masked by a large π^0 background from NC ν_μ. (~24% in the T2K selection)

T2K + μBoone

νStorm clean ν_e beam

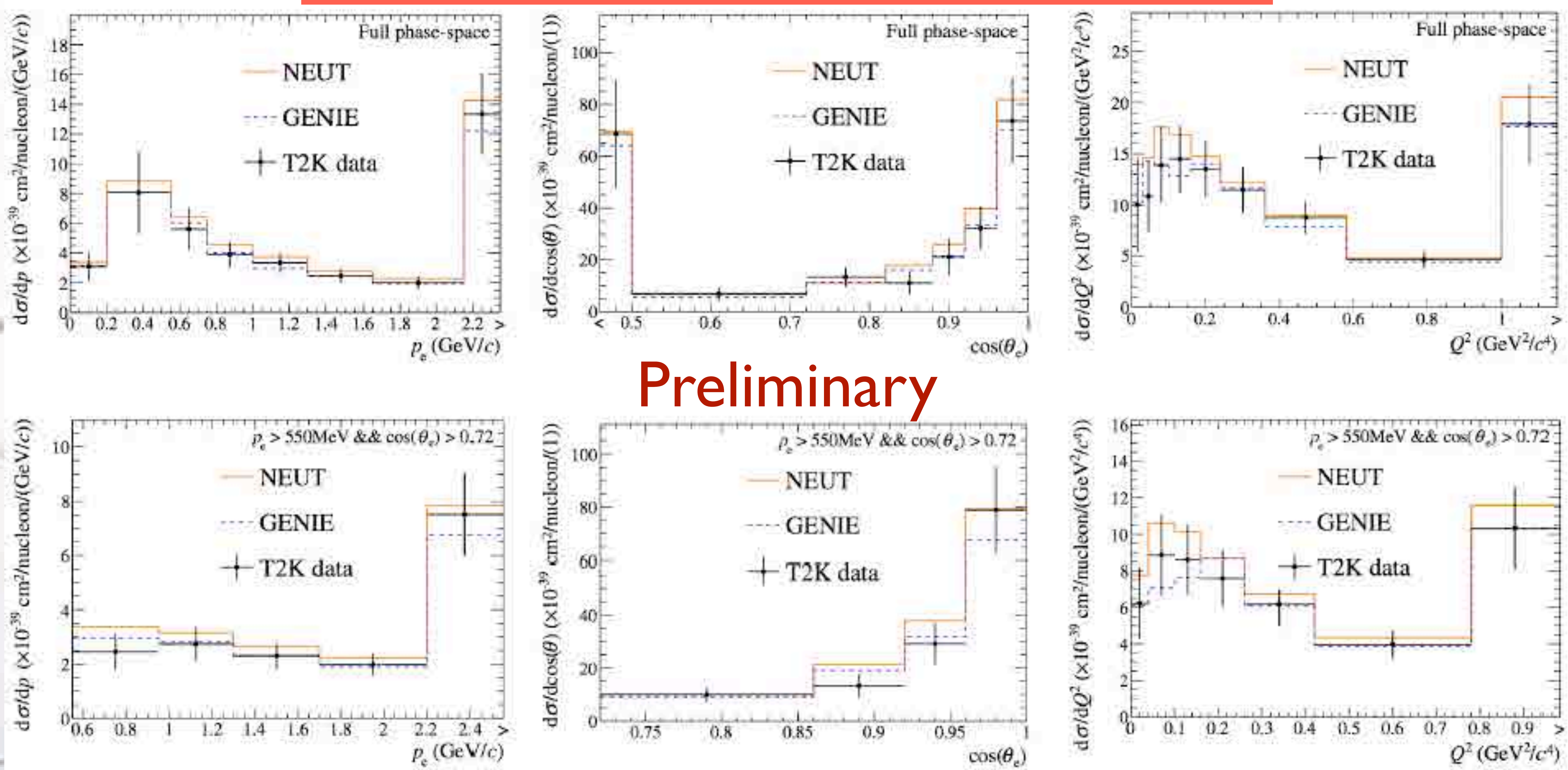
David Adey poster

CC inclusive ν_e

First measurement in 36 years!

low statistics & large background!

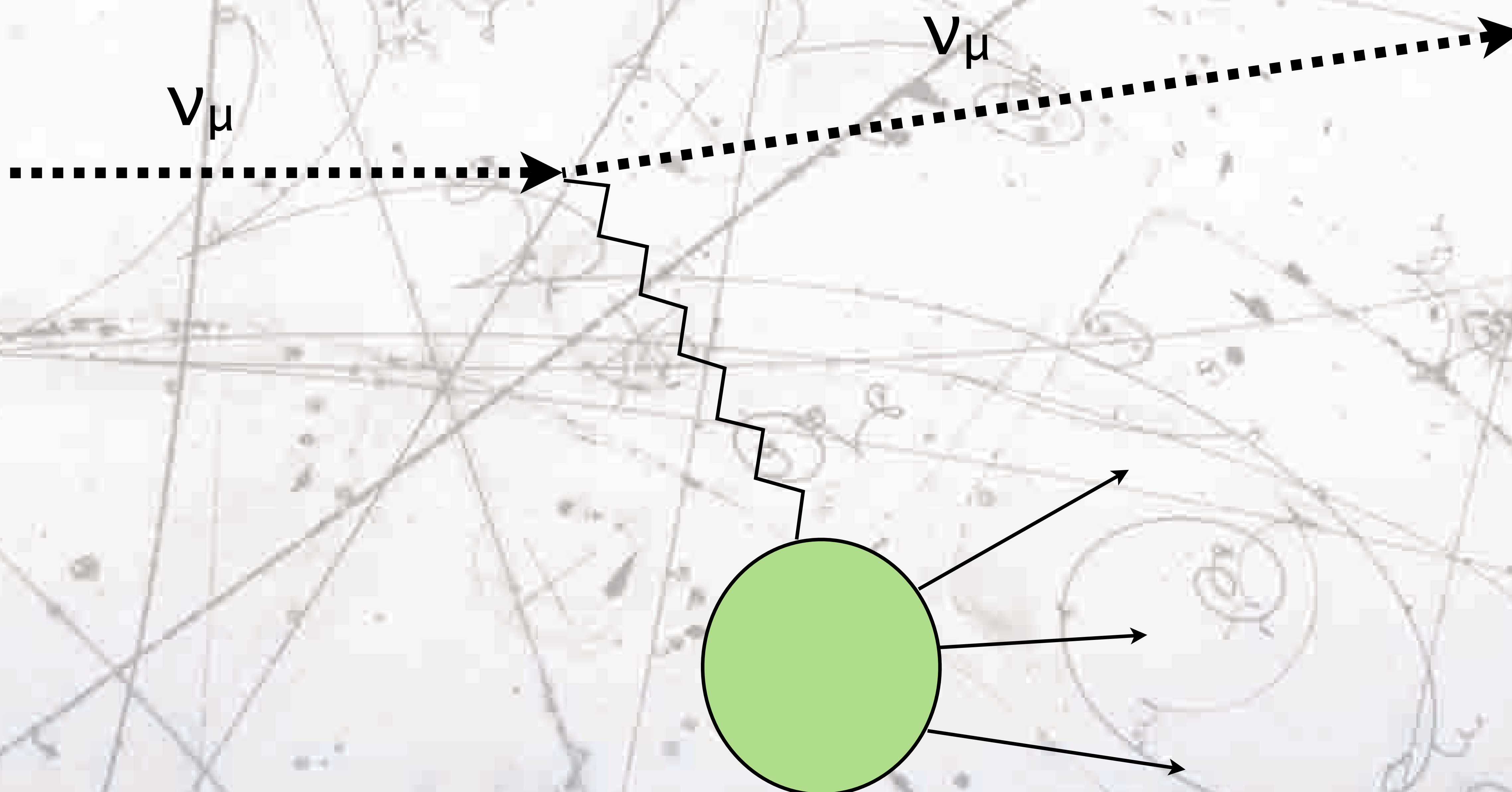
Nuint'14



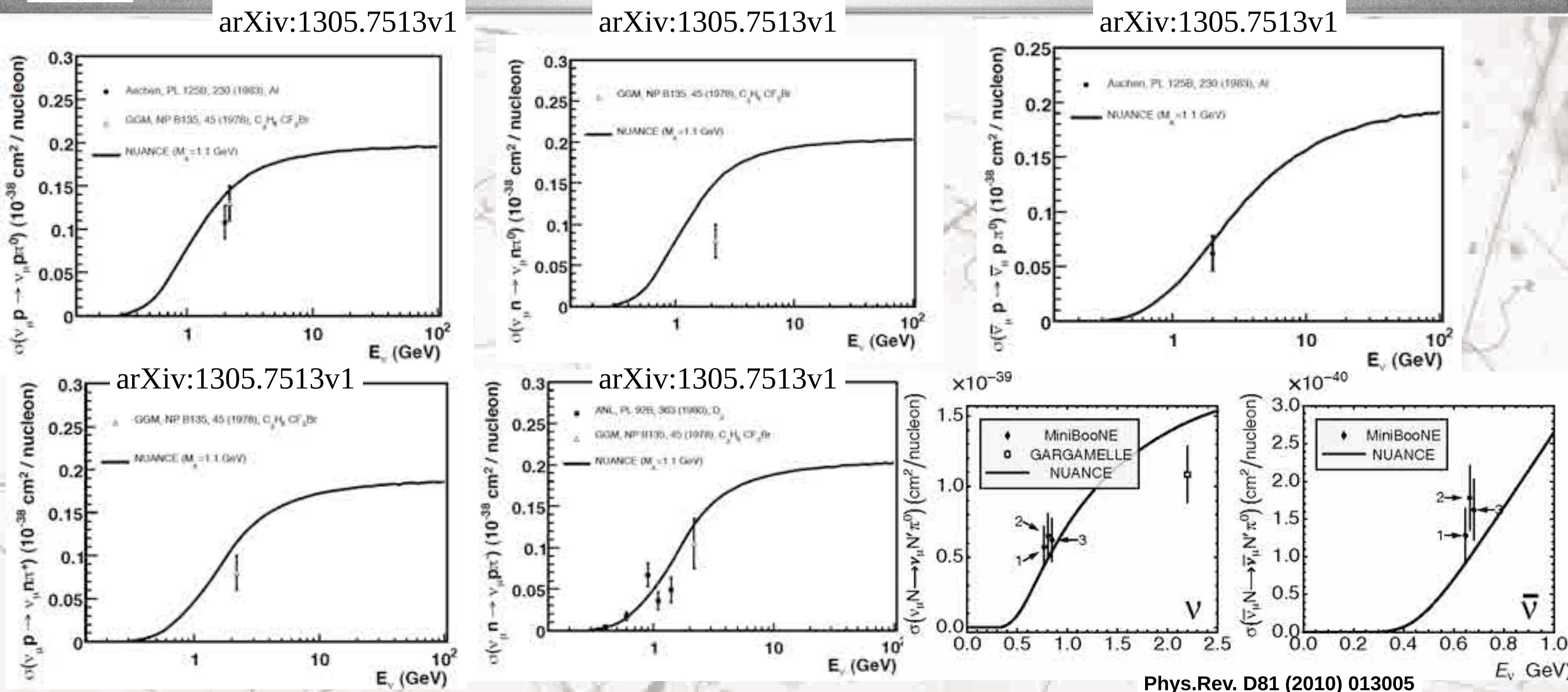
ν_e partial summary

- Expected differences between ν_e and ν_μ cross-sections at threshold.
- Critical for future experiments and CP violation search.
- Very difficult to make a pure ν_e beam although there are some new ideas popping up.

NC ν_μ



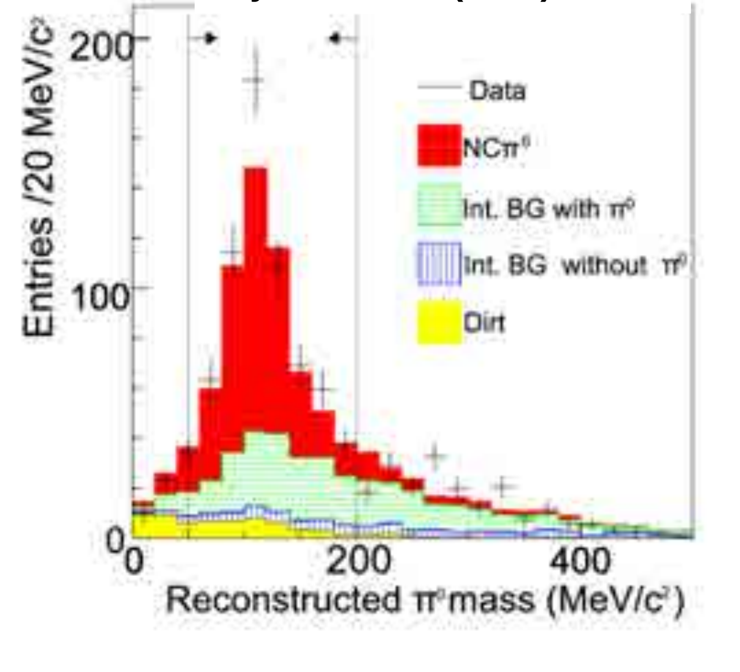
Existing data



- 30 years old and sparse data && MiniBoone (2009).
- No new results in Nuint'14.
- Important background for ν_μ disappearance ($NC\pi^+$) νe appearance. ($NC\pi^0$)
- ν sterile searches!

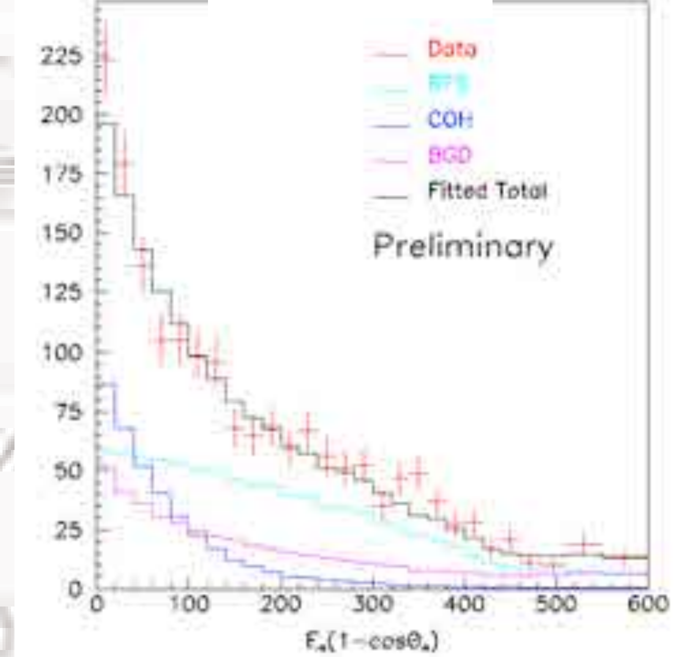
Recent results

Phys.Rev. D81 (2010) 033004



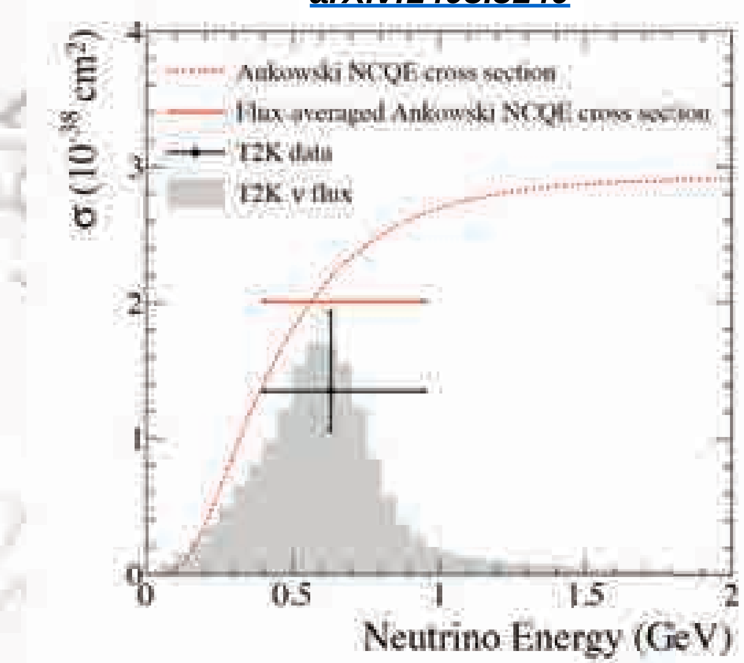
2010 SciBoone NCπ⁰/CC

arXiv:0806.2347



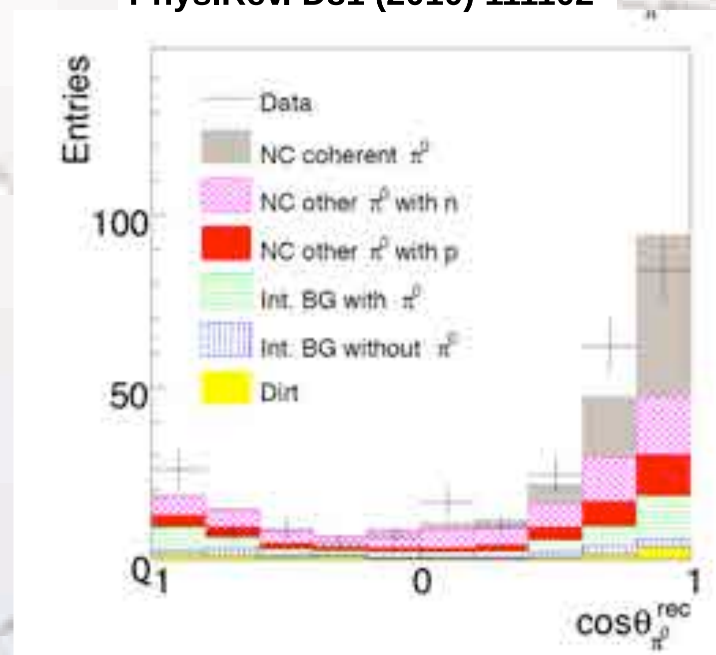
2008 MiniBoone NCπ⁰ Coherent.

arXiv:1403.3140



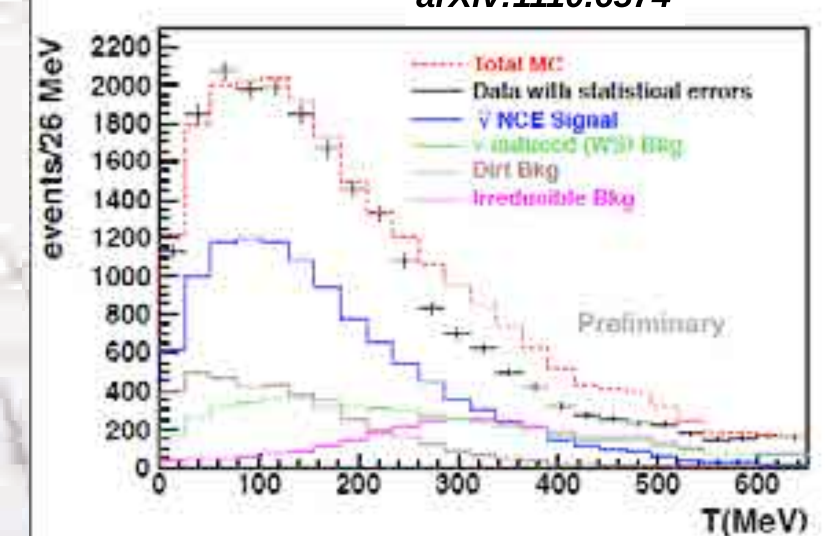
2014 T2K NC-QE from nuclear de-excitation γ rays.

Phys.Rev. D81 (2010) 111102

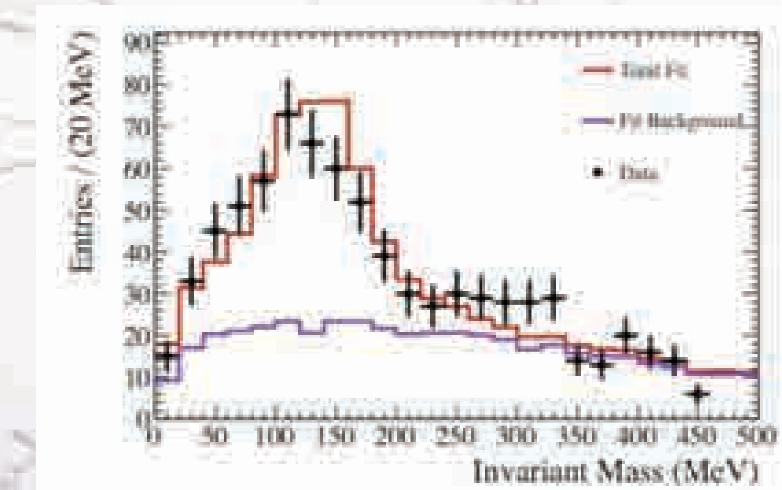


2010 SciBoone NCπ⁰ coh.

arXiv:1110.6574



2011 MiniBoone NC elastic.

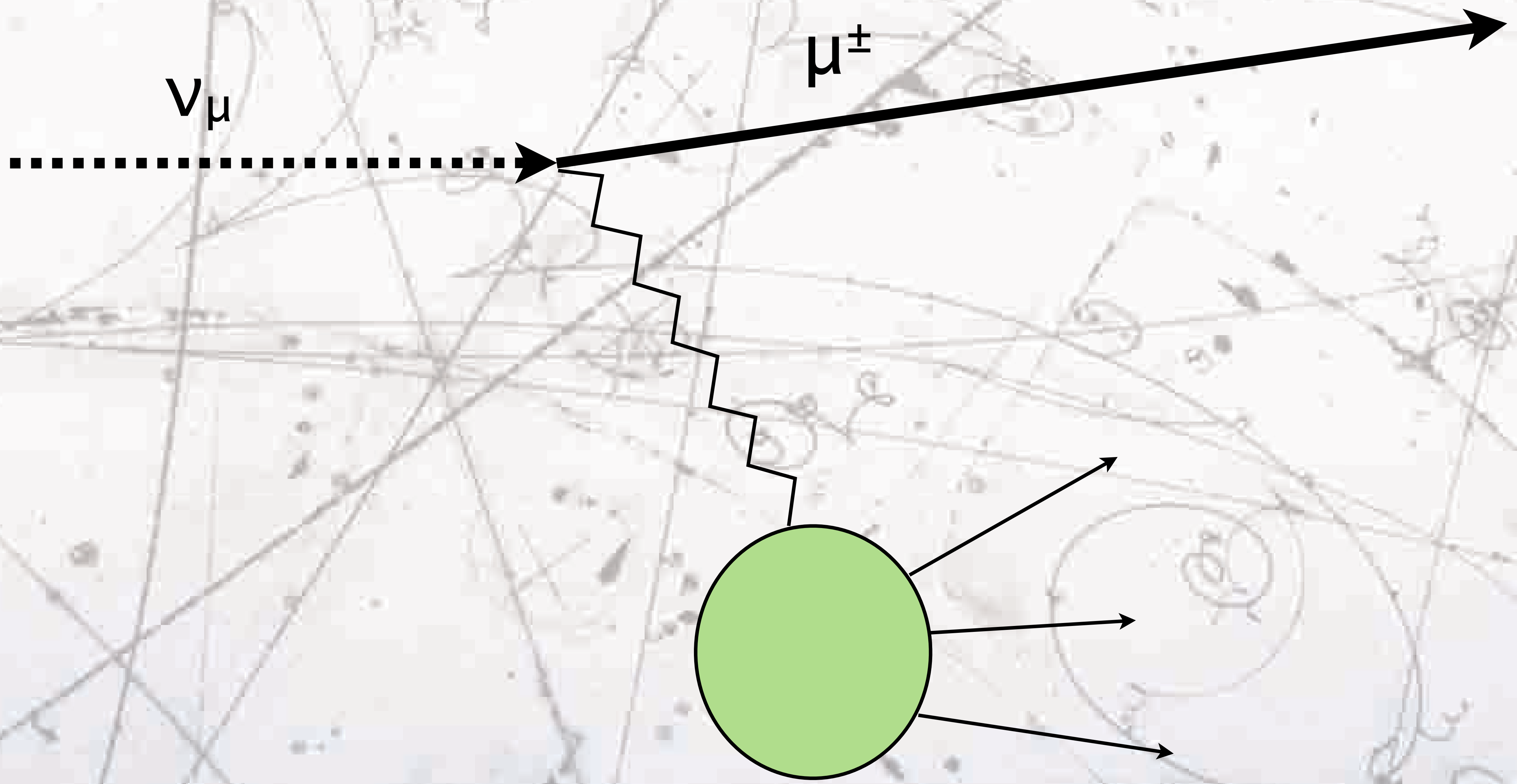


2014 T2K NC π⁰

NC partial summary

- Sparse and non precise measurements.
- NC-π is a background to oscillations (π mistaken for an electron or a muon).
- There is no way to make a neutrino energy prediction because the outgoing neutrino is not detectable.
- Modelling will rely on CC since this is a simple modification of the lepton current.

Monochromatic beam ?



Monochromatic beam

- Many of the problems in neutrino cross-section and neutrino oscillations comes from the reconstruction of the energy.
- Imaging you know precisely the response function of a detector:

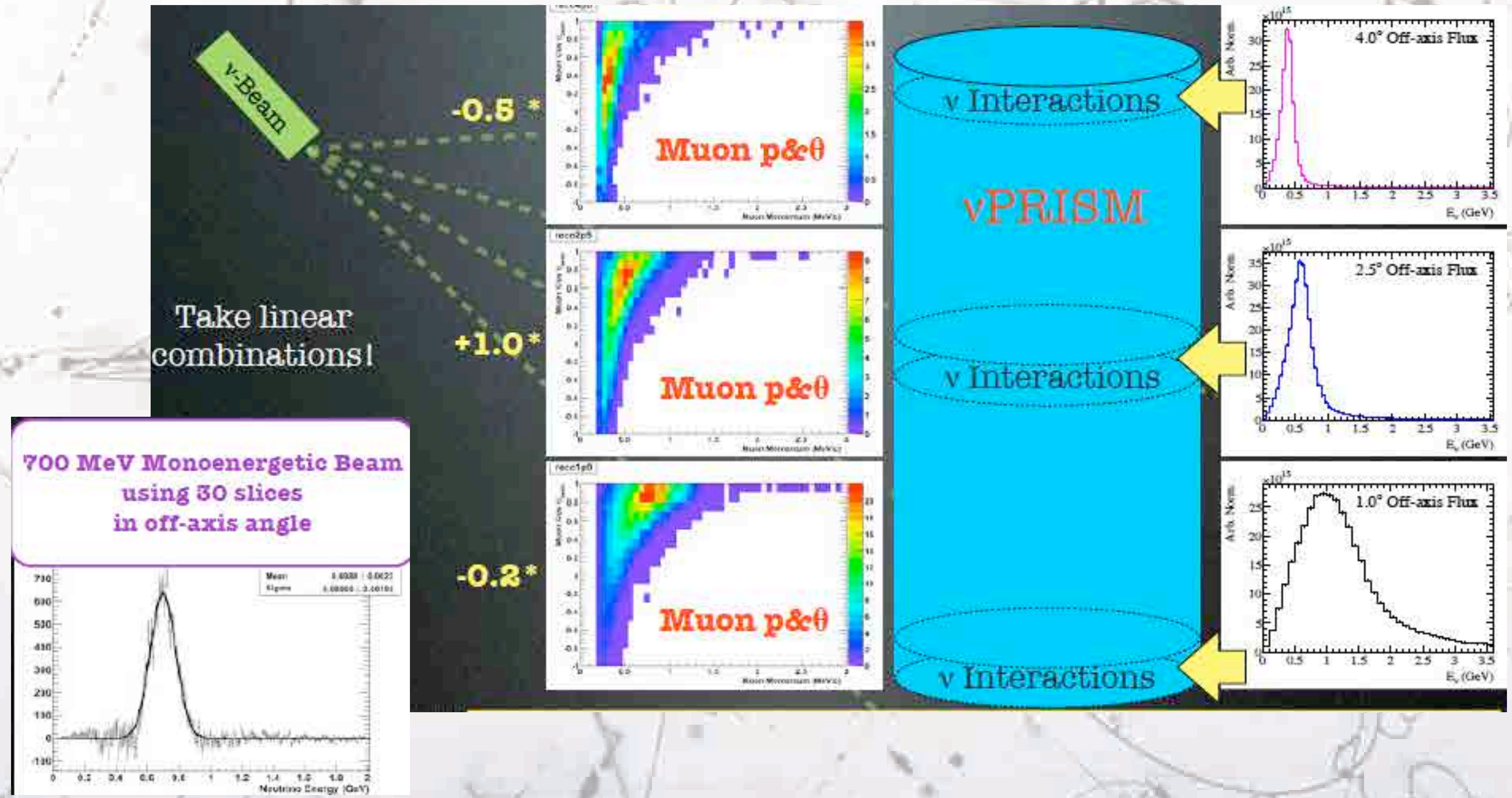
$$P(p_\mu, \theta_\mu | E_\nu)$$

- The oscillation result of the oscillation would be:

$$\int P(p_\mu, \theta_\mu | E_\nu) \times P_{osc}(E_\nu) \times \phi(E_\nu) dE_\nu$$

- and the cross-section problem is reduced/vanished.

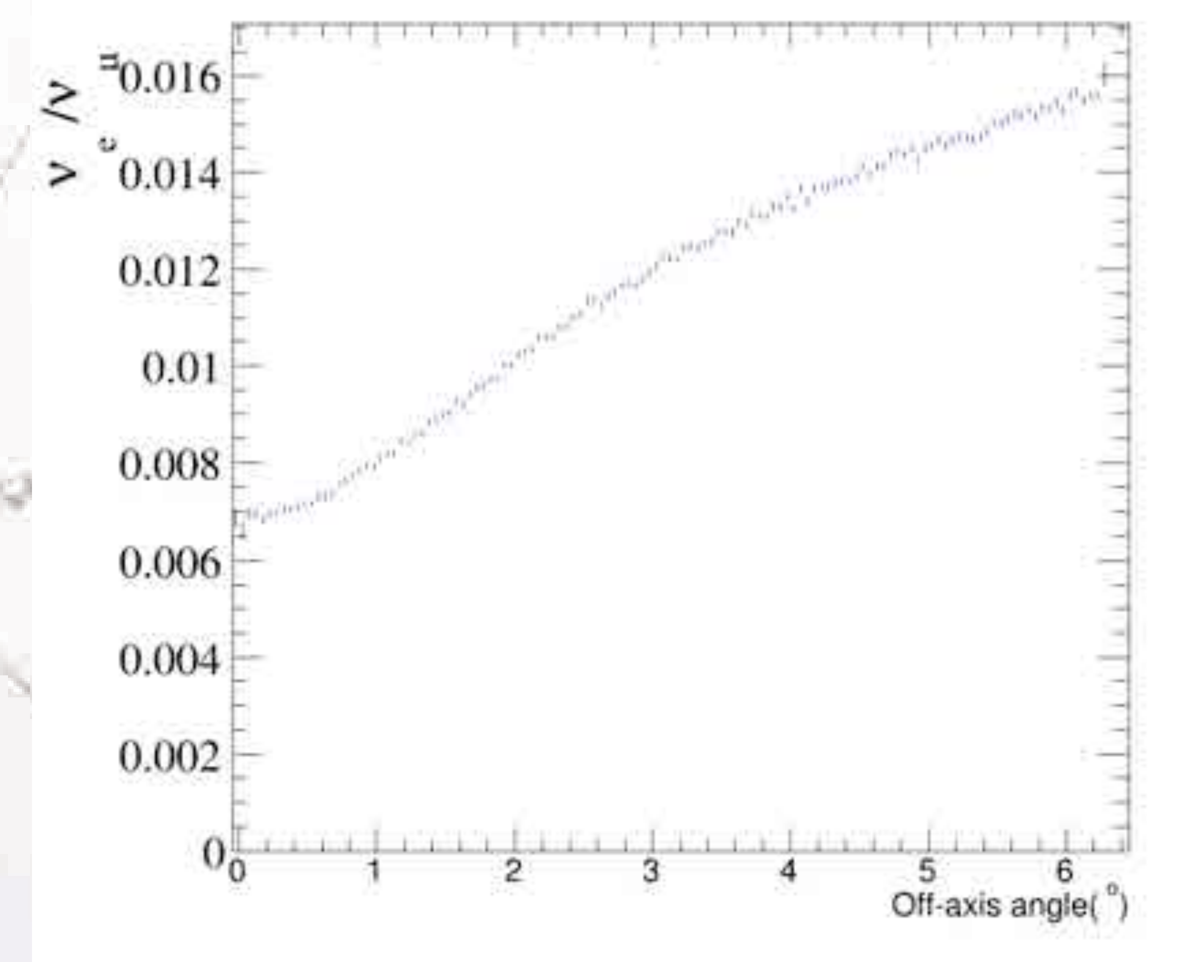
NuPrism

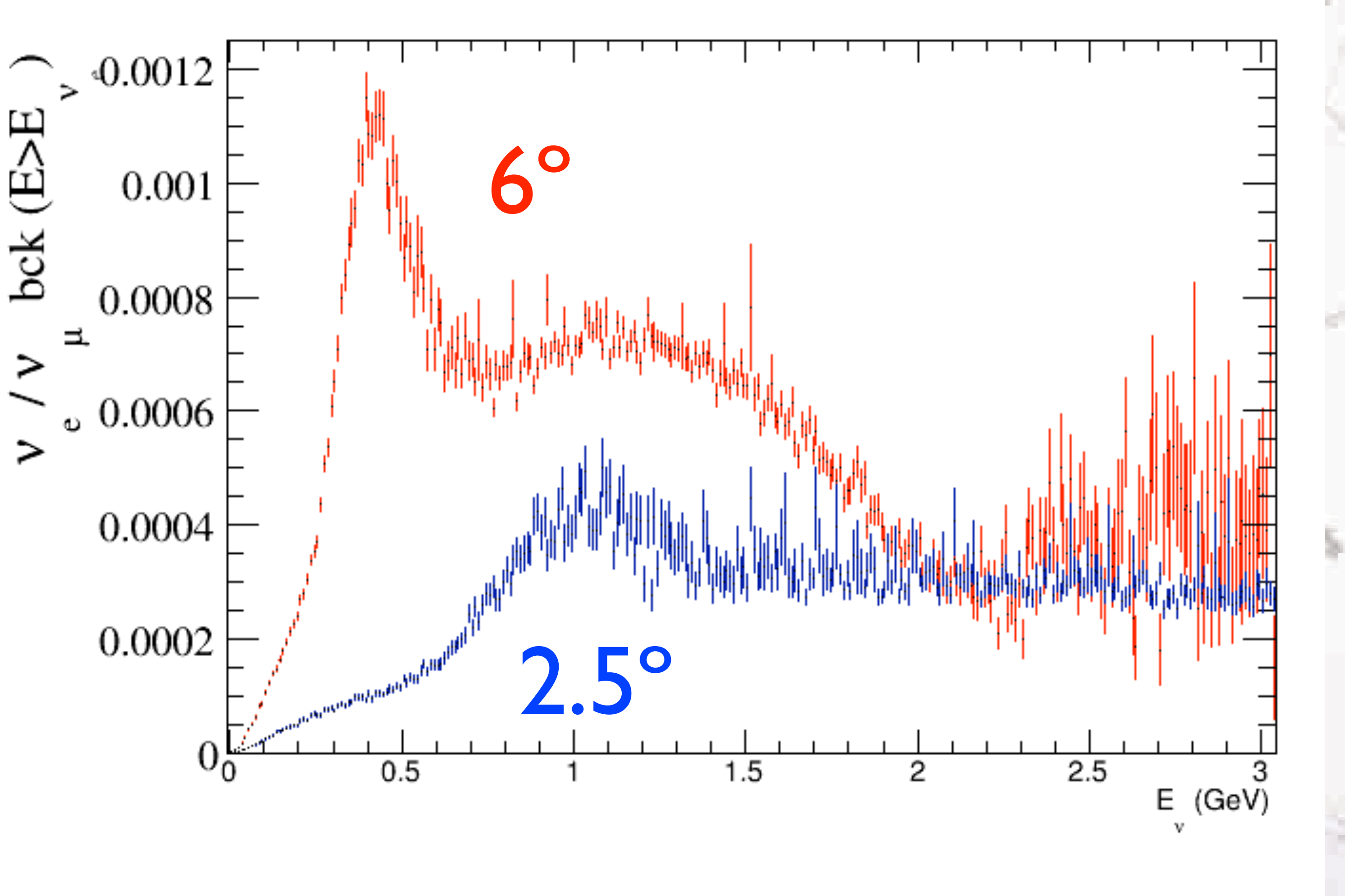


ν-Beam
-0.5 *
+1.0*
-0.2*
Take linear combinations!
Muon p&θ
Muon p&θ
Muon p&θ
ν Interactions
νPRISM
ν Interactions
ν Interactions
4.0° Off-axis Flux
2.5° Off-axis Flux
1.0° Off-axis Flux
700 MeV Monoenergetic Beam using 30 slices in off-axis angle
Neutrino Energy (GeV)

NuPrism and ν_e

- The proportion of electron neutrinos to muon neutrinos increase for high off-axis angles.

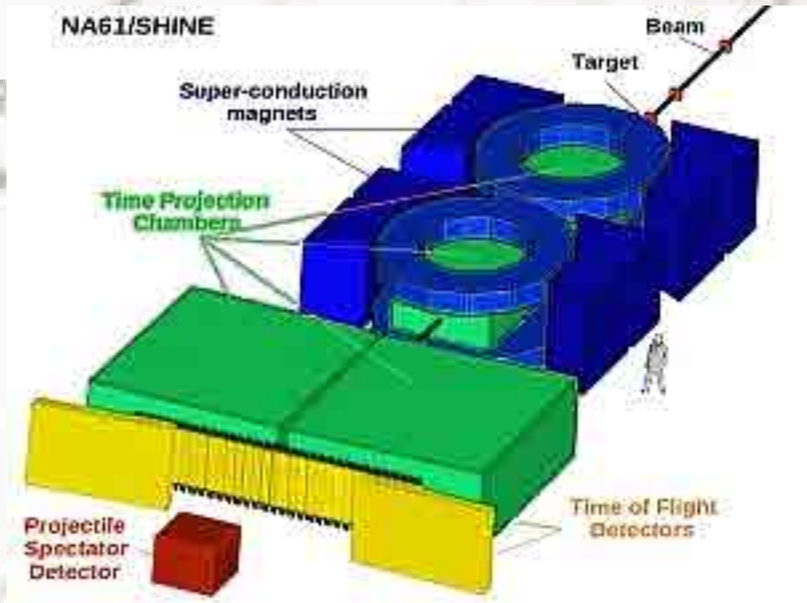


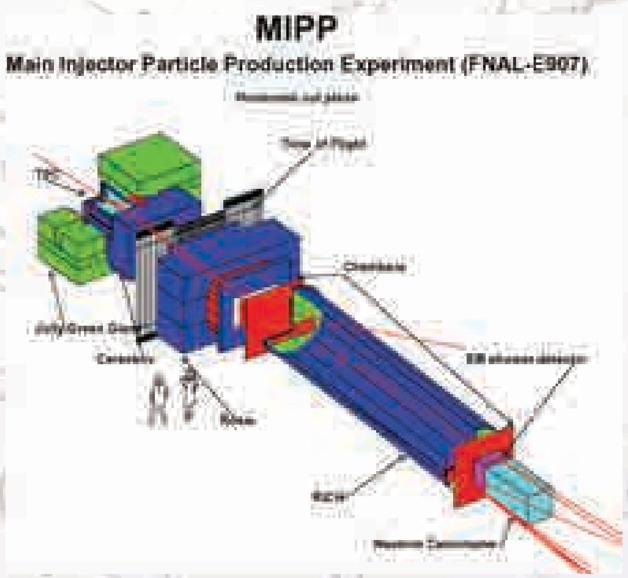


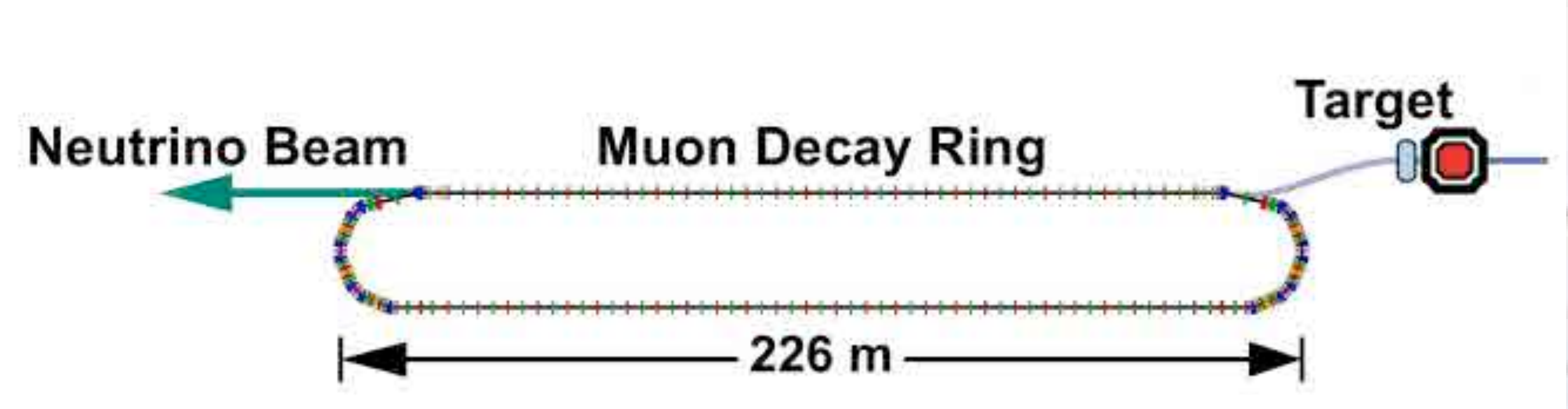
- It needs careful study but it looks like an affordable option to get a rather pure ν_e beam.

Beam systematics

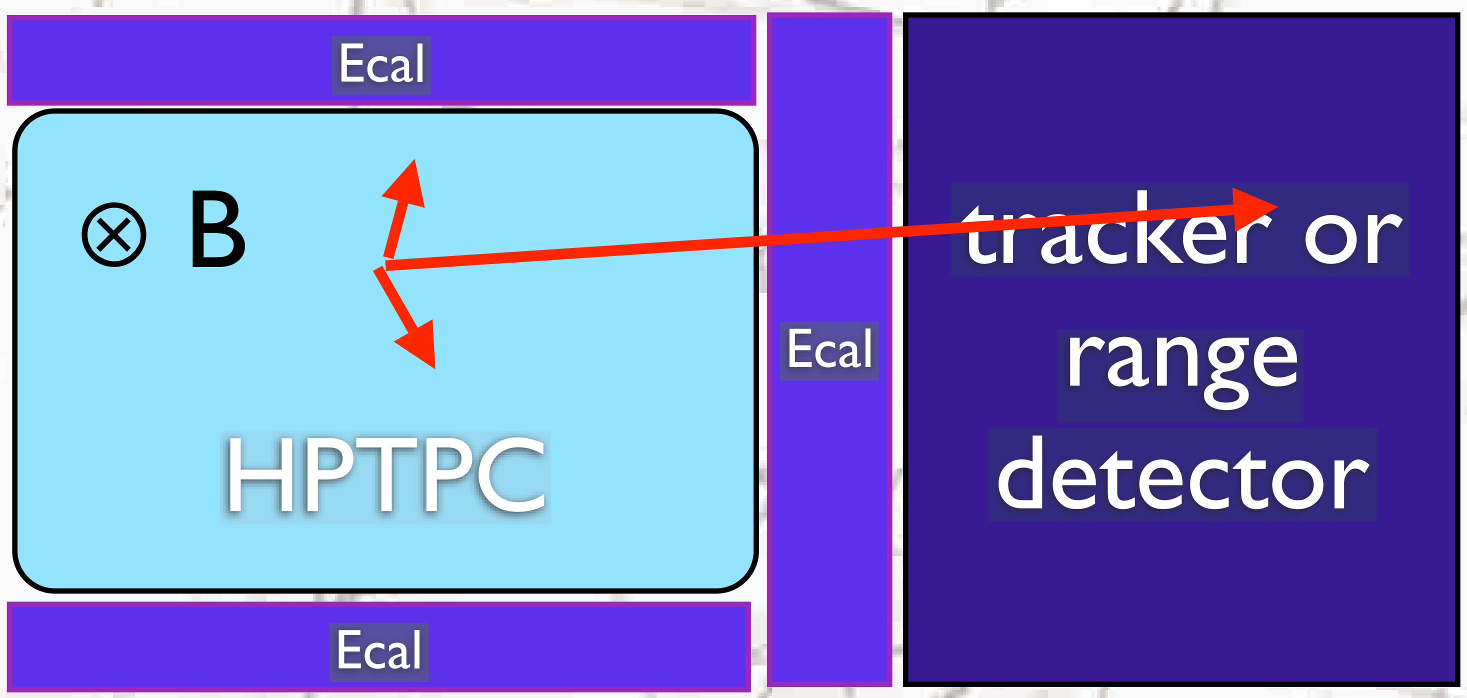
- I did not have time to talk about the importance of beam prediction systematics.
- Total flux and flux shape are crucial for precise cross-section measurements.
  - Hadro-production experiments: NA61 / MIPP. (talk A.Korzenev on Friday)
  - clean beam: NuStorm including electron neutrinos. (poster by D.Adey)







New Ideas: HPTPC

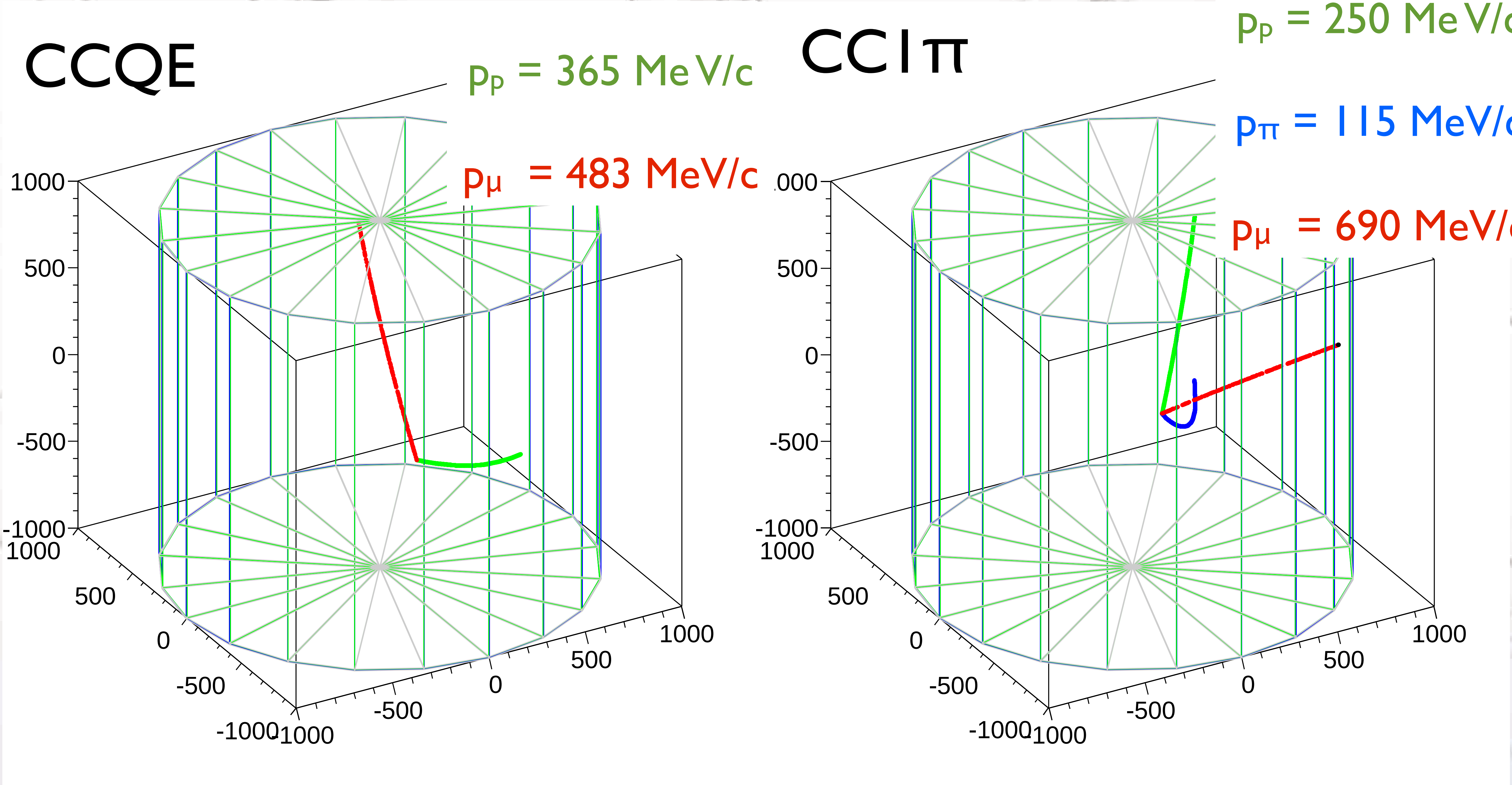


A moving detector ("a la NuPrism") or tuneable beam will help to reduce systematics.

A dream (?): a HPTPC filled with hydrogen and deuterium.

- TPC imaging capabilities.
- Interactions in the same gas (no passive material).
- Low momentum detected inside the TPC. Large momentum done with tracker chambers or range detector.
- Calorimeter for neutral energy containment.
- High pressure (~10 bars) to increase particle containment and # interactions.

New Ideas: HPTPC



Personal view

- If the cross-section model is incomplete or incorrect, the fitting of free parameter does not solve the problem (like M_A).
- There are two "convolved" contributions to the exclusive cross-sections:
  - free-nucleon cross-section (all reference data still from BNL and ANL).
  - effects of nucleon inside high density nuclear matter (from pion & nucleon cross-sections).
- Axial, scalar and pseudo-scalar form factors are based on models.
  - e^- scattering has no axial component, need ν data to derive them!.
- Better underlying theory. Theorist are requesting improvements in these measurements to be able to advance:
  - We need to repeat measurements in deuterium !!!!

Personal view

- If the cross-section model is incomplete or incorrect, the fitting of free parameter does not solve the problem (like M_A).
- There are two "convolved" contributions to the exclusive cross-sections:
    - free nucleon cross-section ... BNL and ANL).
    - ef... on & nucleon cross-sections).
- Axial, scalar and pseudo-scalar form factors are based on models.
    - e^- scattering has no axial component, need ν data to derive them!.

The problem is not the precise measurement of few parameters.

The problem is the validity of the cross-section model itself.

- Better underlying theory. Theorist are requesting improvements in these measurements to be able to advance:
    - We need to repeat measurements in deuterium !!!!

Shopping list

- I believe (and I am not the only one!) the community needs, parallel to the LBL oscillation, a consistent program of neutrino interaction cross-sections involving:

μBoone
Minerva

1. Experiments with several targets nuclei and/or low proton thresholds: ~100 MeV/c.

NA61
MIPP
NuStorm

   - Monochromatic or changeable neutrino beam (off-axis?) & hadro-production experiments.

2. Clean electron neutrino beam : NuStorm, off-axis NuPrism...

Common effort

3. Common MC tools and consistent models developed in close interaction with theorists.

Common effort

4. Electron and photon scattering experiments needs to be integrated in the process.

5. Need of a deuterium target measurement.

Shopping list

- I believe (and I am not the only one!) the community needs, parallel to the LBL oscillation, a consistent program of neutrino interaction cross-sections involving:

µBoone
Minerva

1. Experiments with several targets nuclei and/or low proton thresholds: ~100 MeV/c.

NA61
MIPP
NuStorm

   - Monochromatic or changeable neutrino beam (off-axis?) & hadro-production experiments.

2. Clean electron neutrino beam : NuStorm, off-axis NuPrism...

Common
effort

3. Common MC tools and consistent models developed in close interaction with theorists.

Common
effort

4. Electron and photon scattering experiments needs to be integrated in the process.

5. Need of a deuterium target measurement.

We need

1. better theoretical models.
2. data of better quality.
3. new detector concepts.
4. new beam concepts.

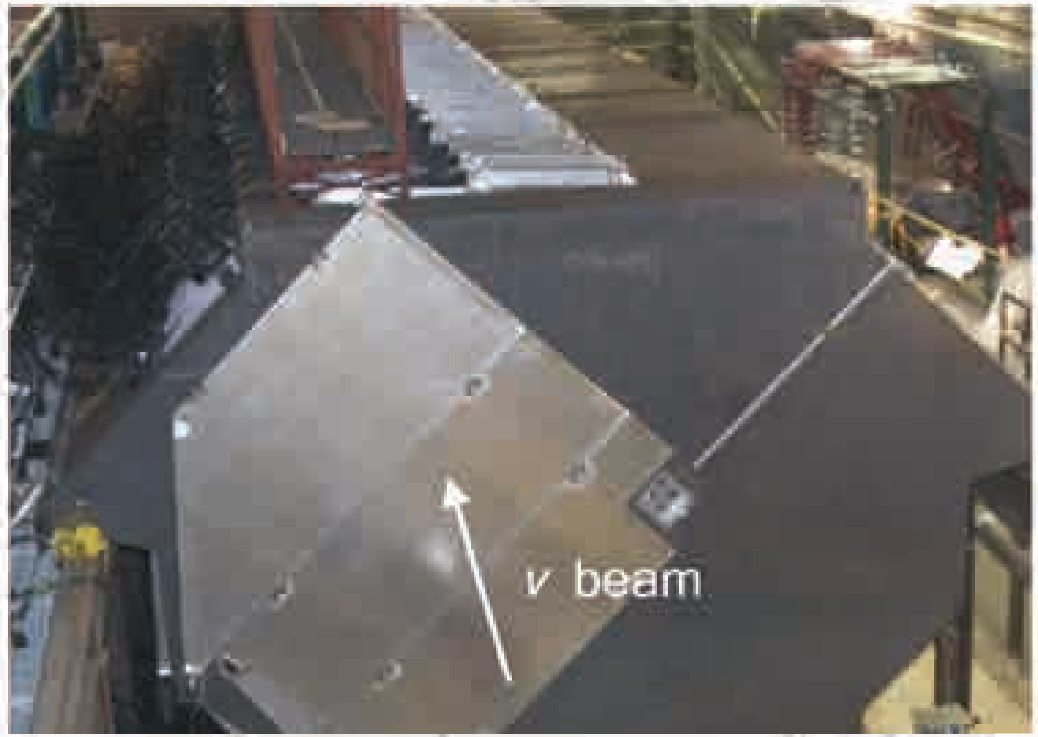
Backup and supporting slides

NusTEC

A Collaboration of HEP and Nuclear Experimentalists and Theorists Studying Low-energy Neutrino Nucleus Scattering Physics.

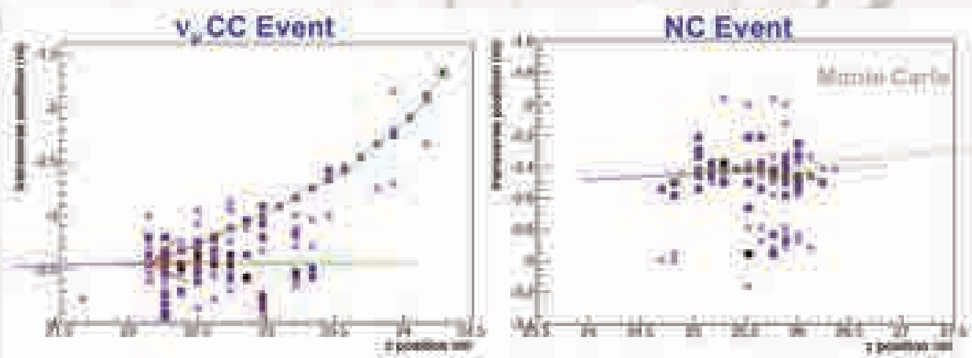
- **Neutrino Event Generators**
  - Coordinate theorist-experimentalist collaborative efforts to improve generators
- **Workshops**: Organize Community-wide Workshops when needed
  - Organization beginning on workshop to investigate np-nh/MEC nuclear effects
- **Training Programs**: Organize and run training programs.
- **Global Fits**: Combine results from multiple experiments to compare with and then, if necessary, modify a theory/model framework.

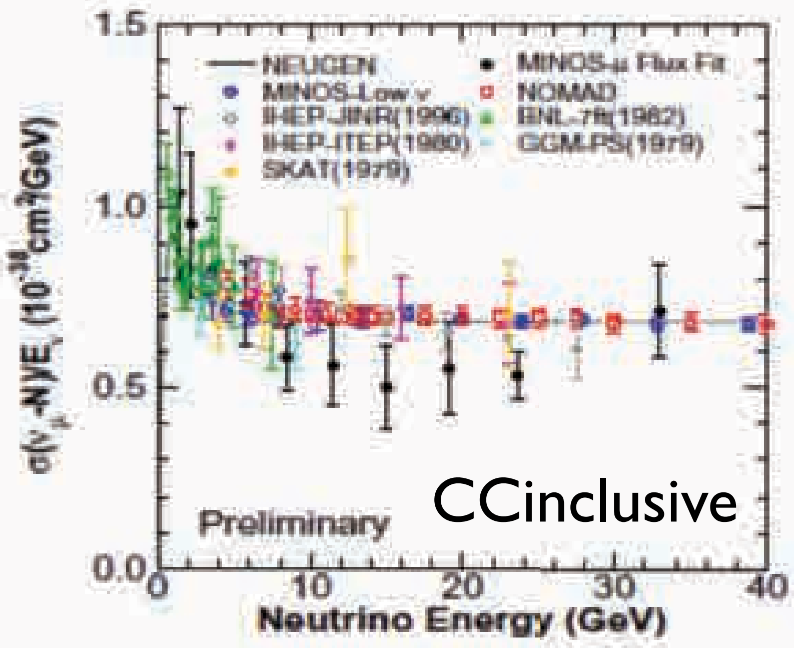
Near Minos

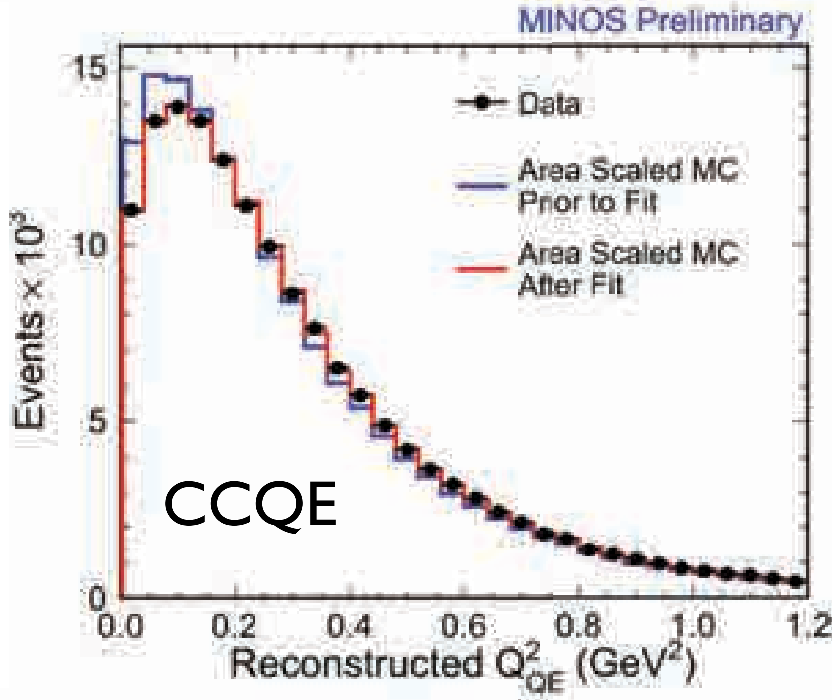


- Iron target.
- Magnetised.
- Large statistics.

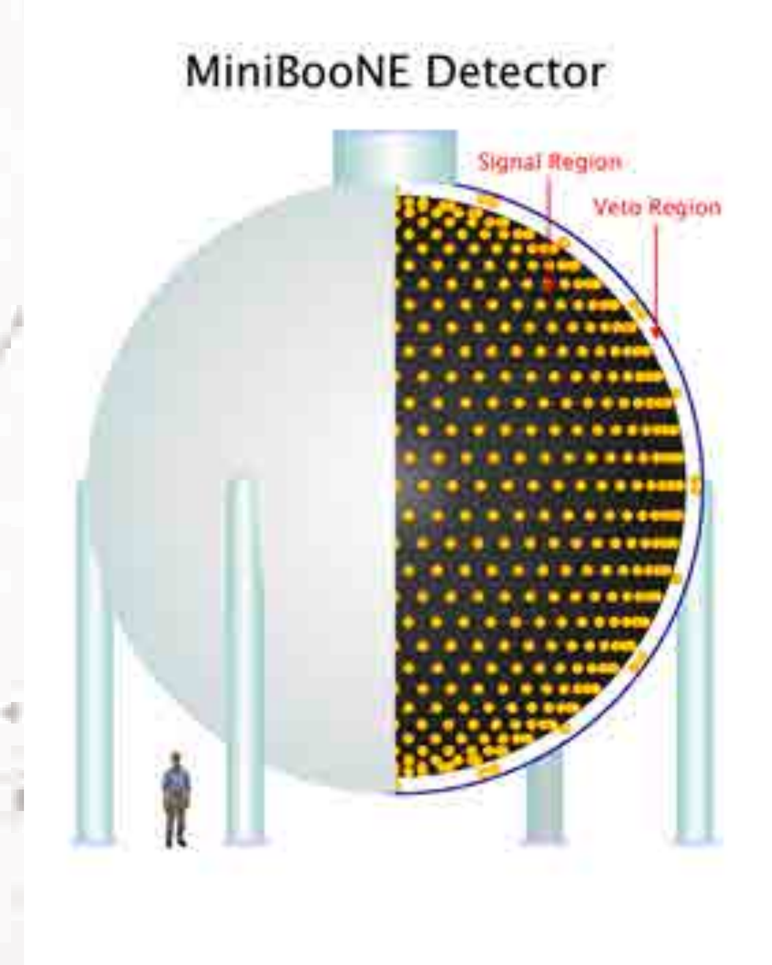
	M_A^{QE} (GeV)	E_μ Scale	M_A^{RES} (GeV)	k^{QE}_{Fermi}
Principal: $0 < Q^2 < 1.2$	1.21 +0.18 -0.10	0.996 +0.007 -0.015	1.10 +0.15 -0.16	1.10 +0.02 -0.03
Alternative: $0.3 < Q^2 < 1.2$	1.19 +0.19 -0.17	0.995 +0.008 -0.016	1.13 +0.17 -0.18	Not fit



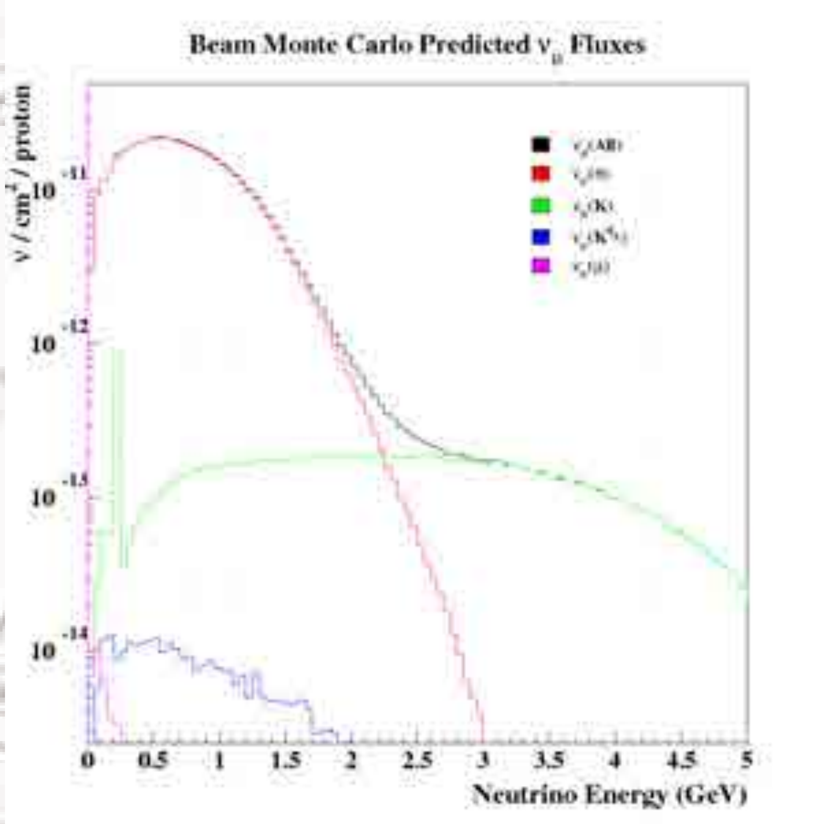


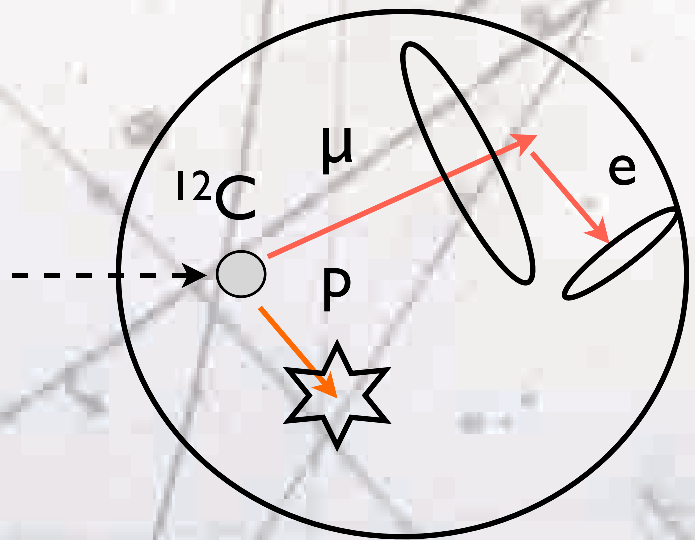


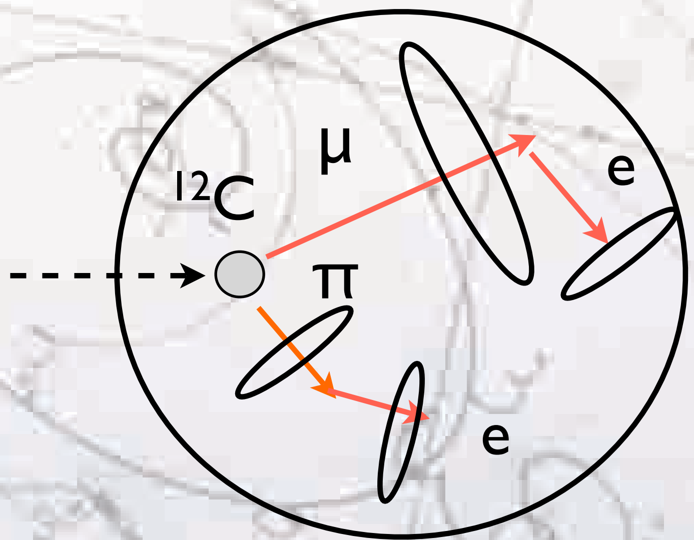
MiniBoone



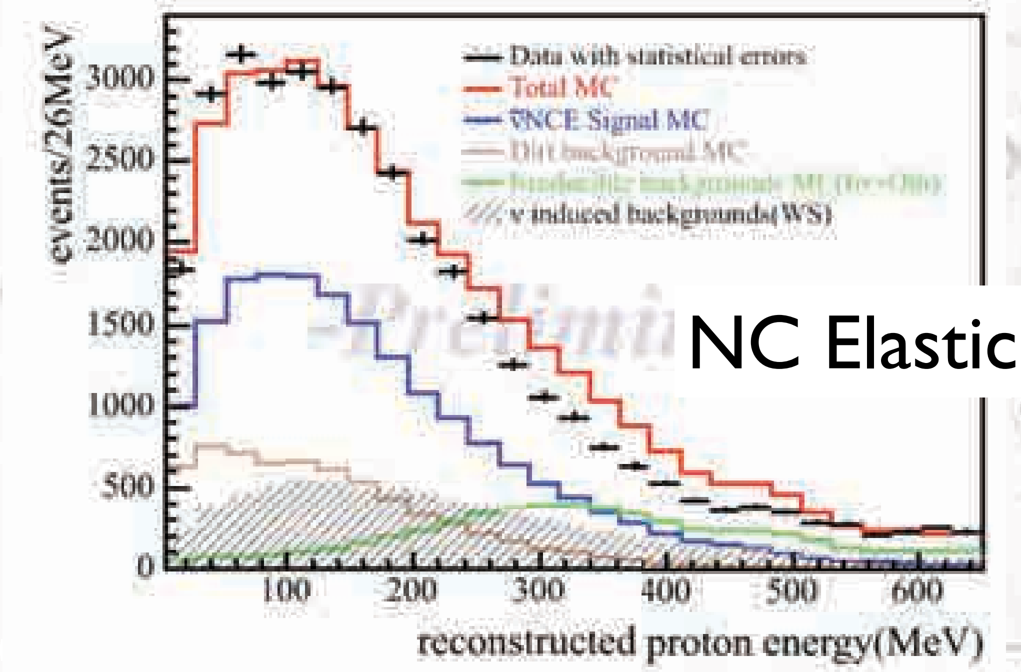
- 800 tons mineral oil Cherenkov detector.
- Boone neutrino line with sharp edge at 3 GeV.
- Flux constrained from HARP hadro-production experiment.
- ~450 Mev/c proton threshold.
- Excellent pion detection and tagging.
- Very large statistics.



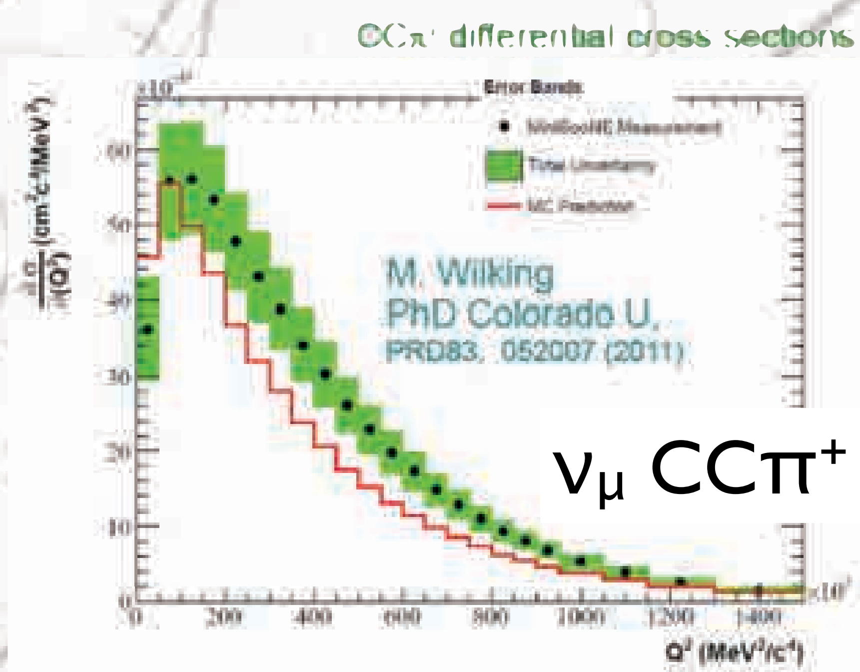




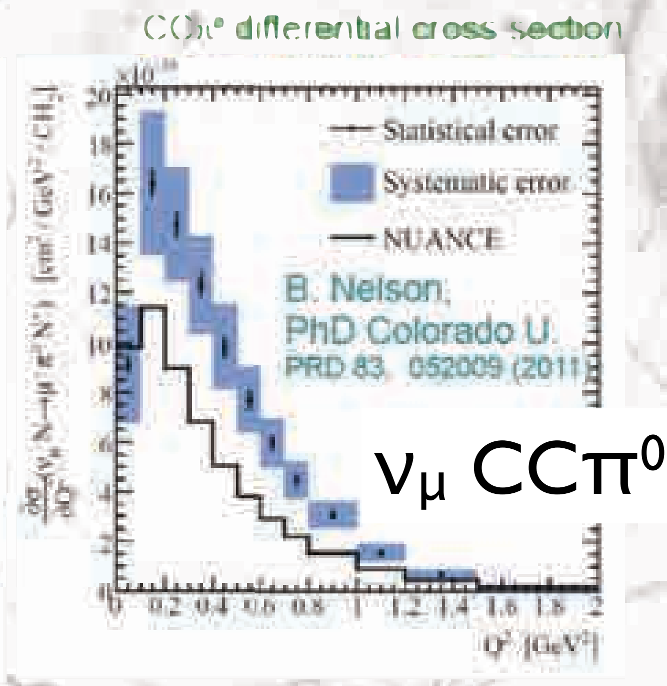
MiniBoone



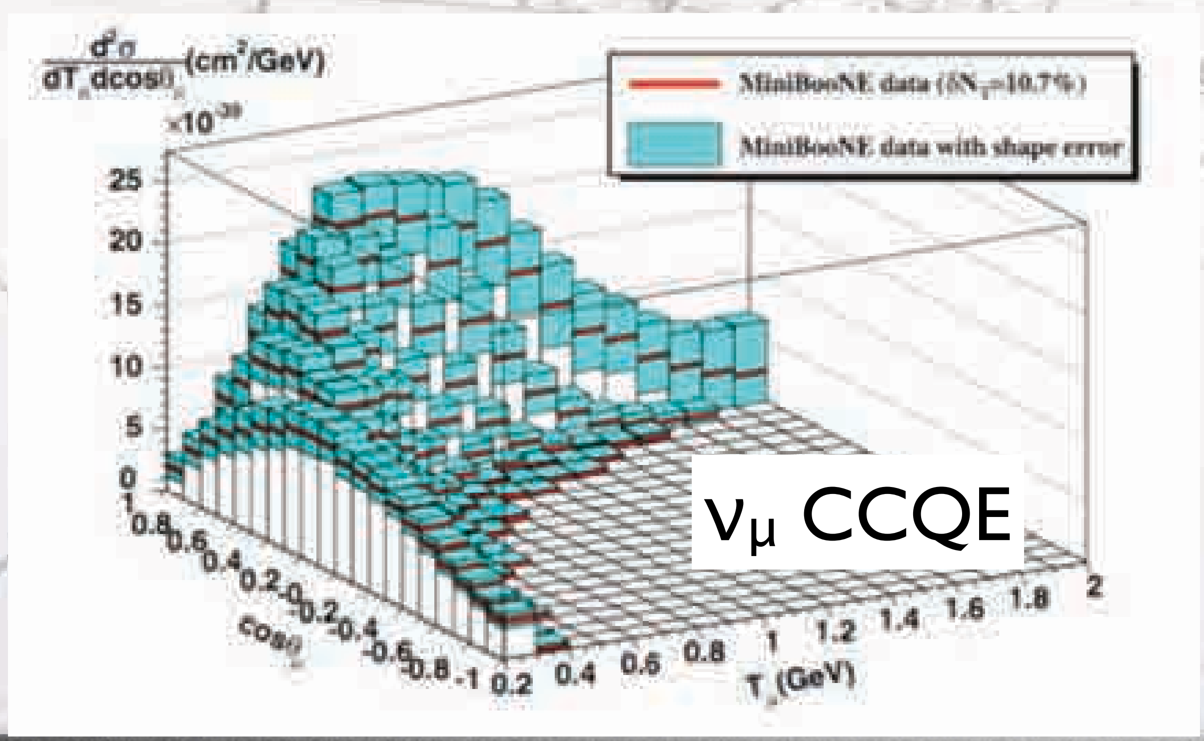
NC Elastic
events/26MeV
reconstructed proton energy(MeV)
Data with statistical errors
Total MC
νNCE Signal MC
Dirt background MC
ν induced backgrounds(WS)



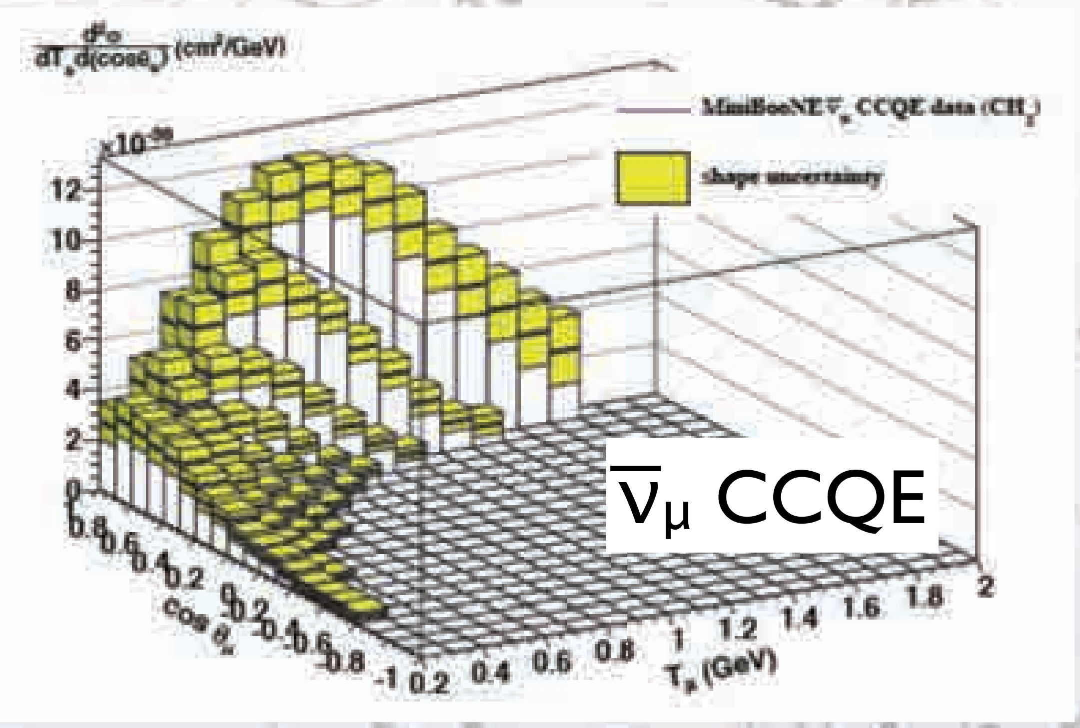
CCπ⁺ differential cross sections
ν_μ CCπ^+
M. Wilking
PhD Colorado U.
PRD83, 052007 (2011)
Error Bands
MiniBooNE Measurement
Total Uncertainty
MC Prediction
Q² (MeV²/c⁴)



CCπ⁰ differential cross section
ν_μ CCπ^0
Statistical error
Systematic error
NUANCE
B. Nelson,
PhD Colorado U.
PRD 83, 052009 (2011)
Q² [GeV²]



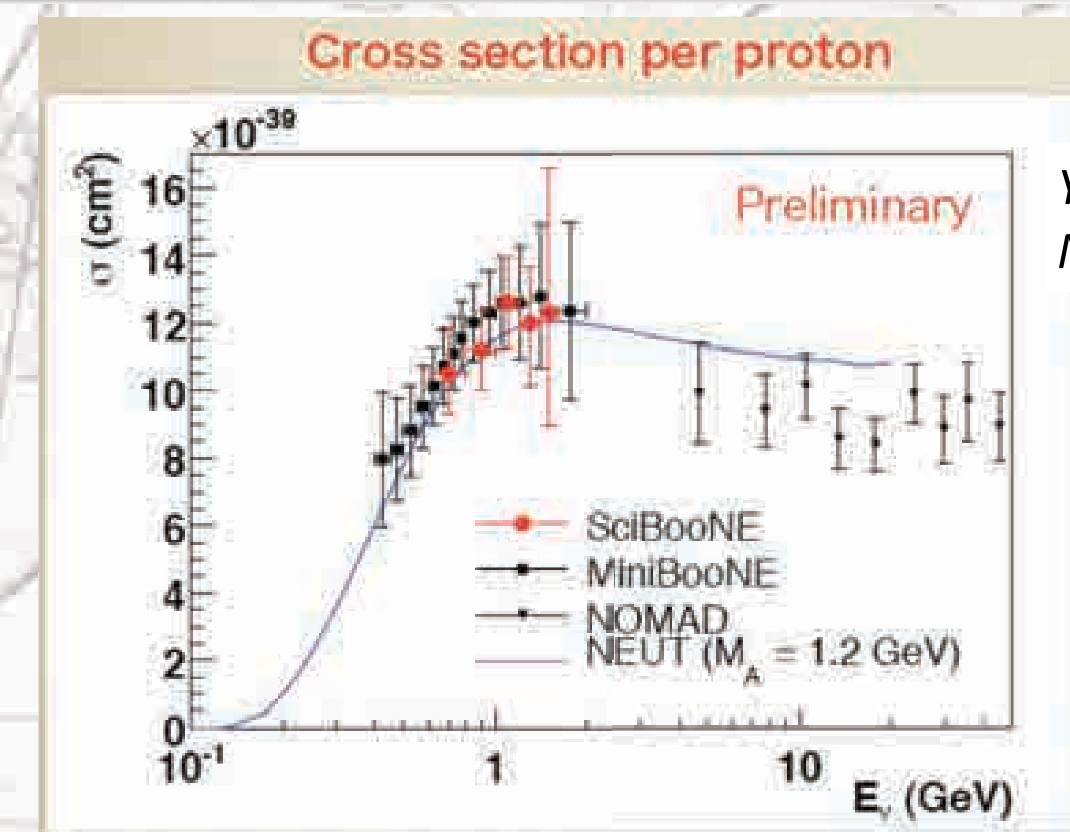
ν_μ CCQE
MiniBooNE data (δN_T=10.7%)
MiniBooNE data with shape error
T_μ(GeV)



$\bar{\nu}_\mu$ CCQE
shape uncertainty
T_μ (GeV)

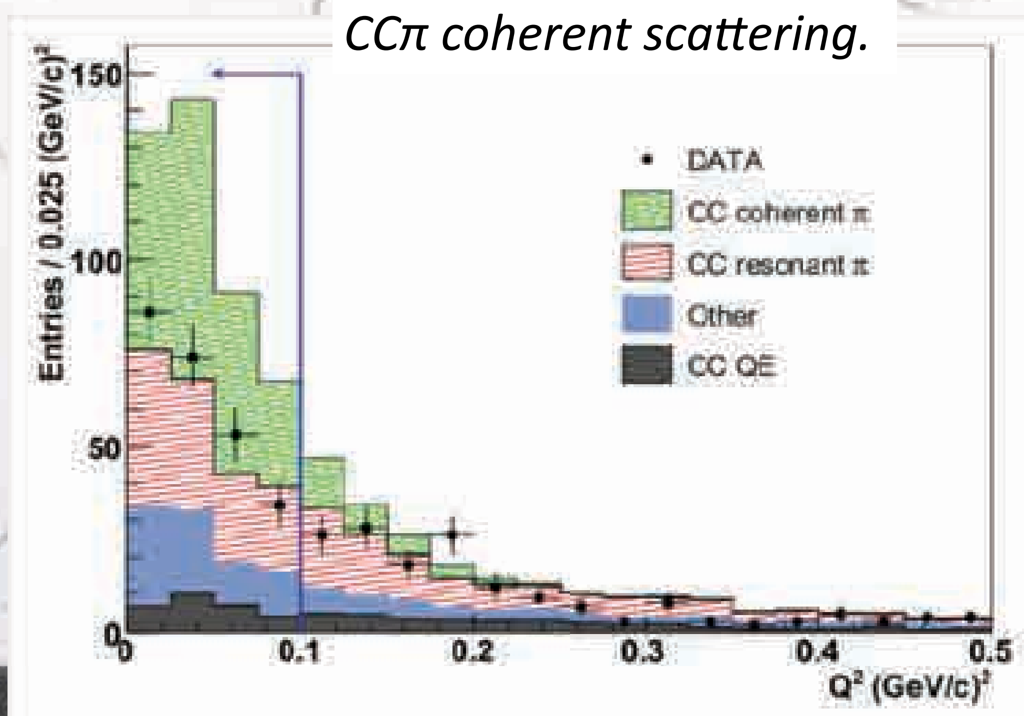
SciBoone

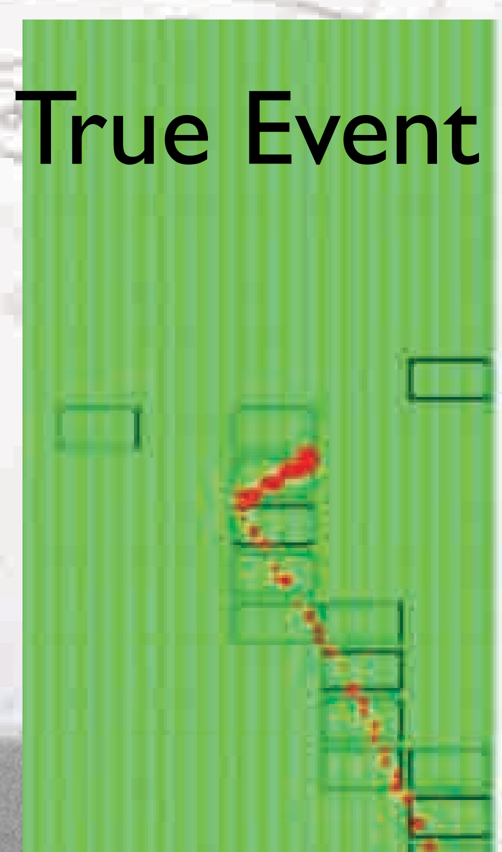
- Boone beam (< 3 GeV)
- Carbon target.
- Low proton tagging threshold (p > 450 MeV/c)
- Low statistics.
- Forward acceptance (> 60º)

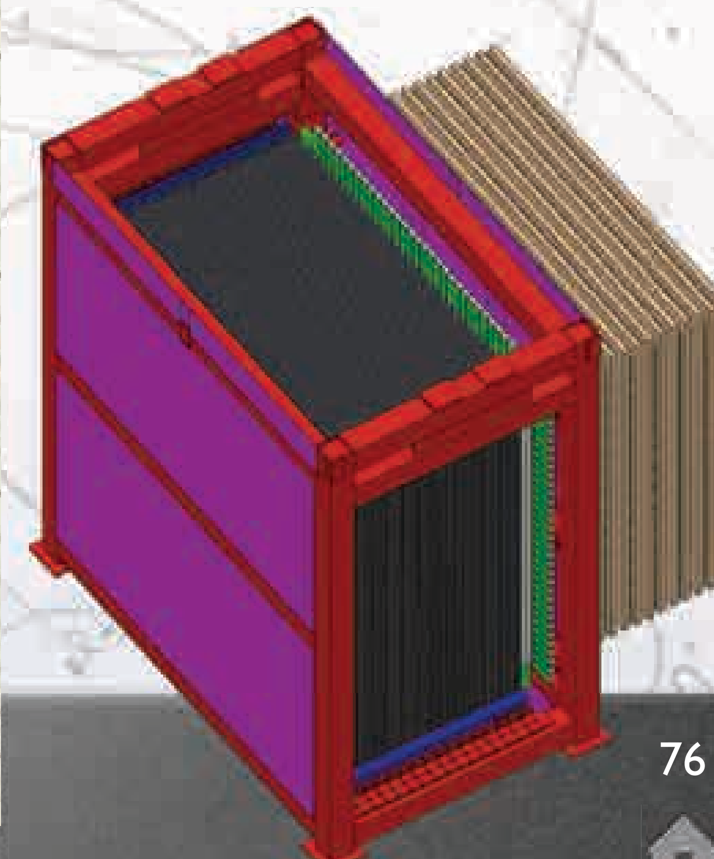


Y. Nakajima, NuInt11

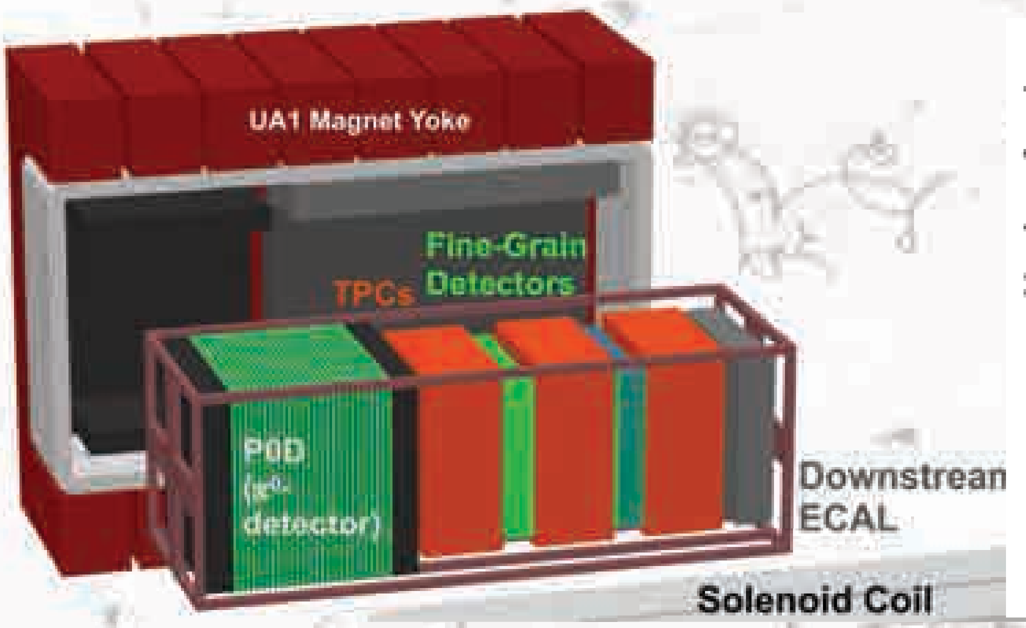
CCπ coherent scattering.

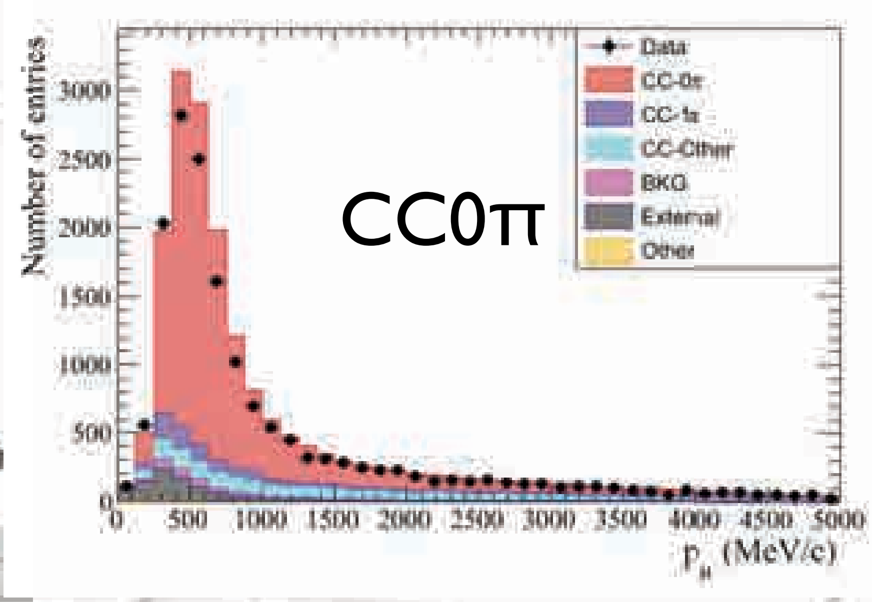


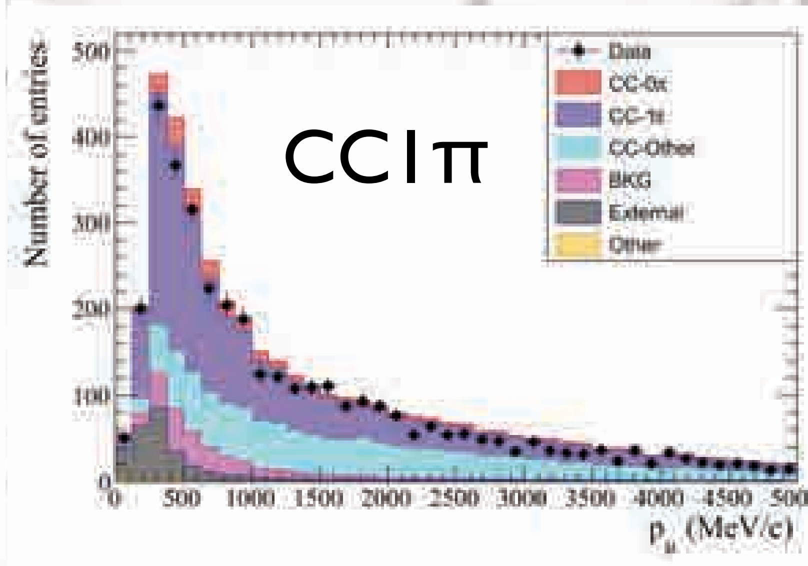




T2K/ND280

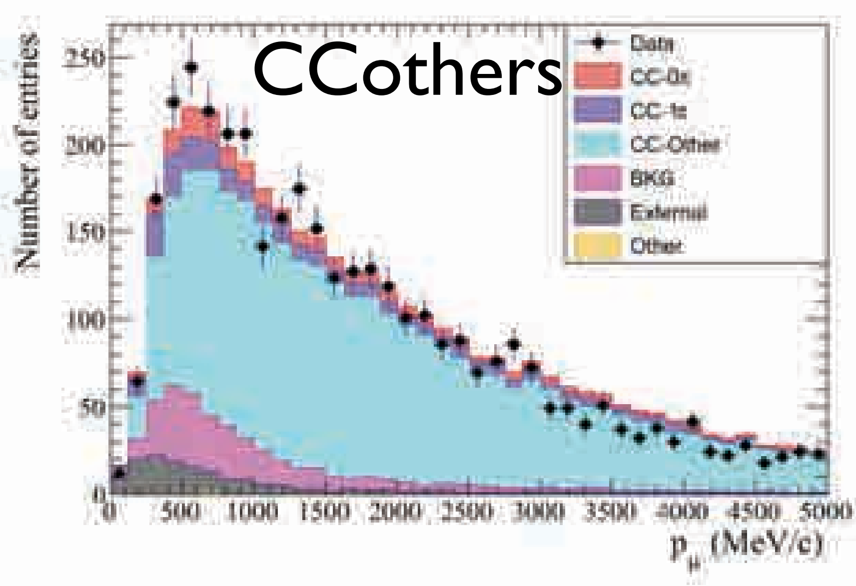




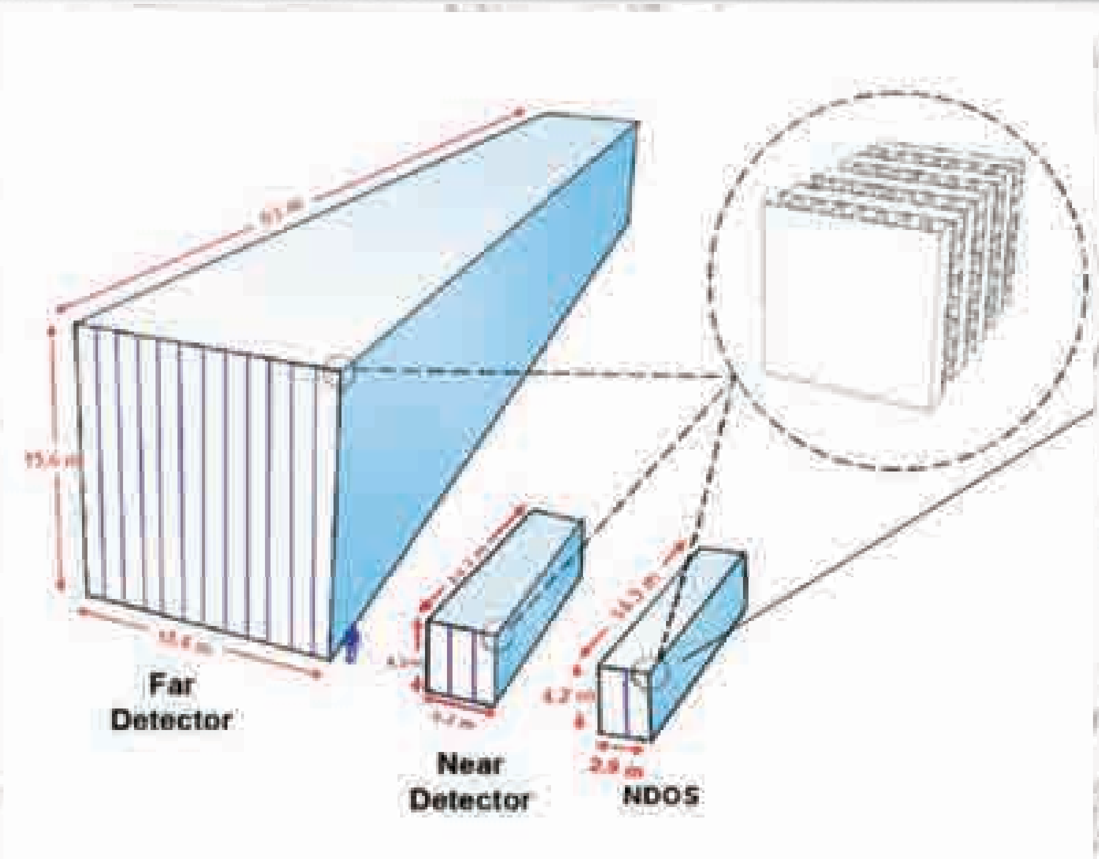


All detectors located within 0.2T UA1 magnet (charge sign determination):

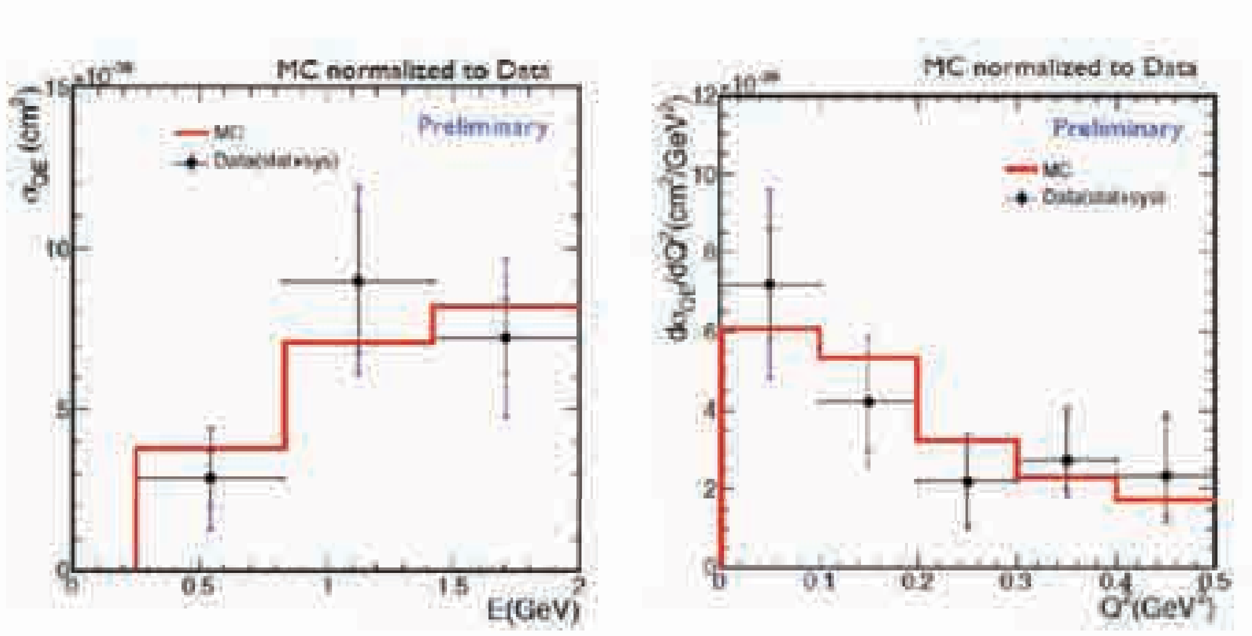
- 2 scintillator based tracking detectors (FGD) Nucl. Instrum. Meth. A 696, 1 (2012)
- 3 Ar - time projection chambers (TPC) NIM A 637, 25 (2011)
- P0D (triangular scintillator bars) Nucl. Instrum. Meth. A 686, 48 (2012))
- Electromagnetic calorimeters (ECALs JINST 8 P10019 (2013))
- Muon range detectors (scintillator in magnet, sMRD Nucl. Instrum. Meth. A 698, 135 (2013))

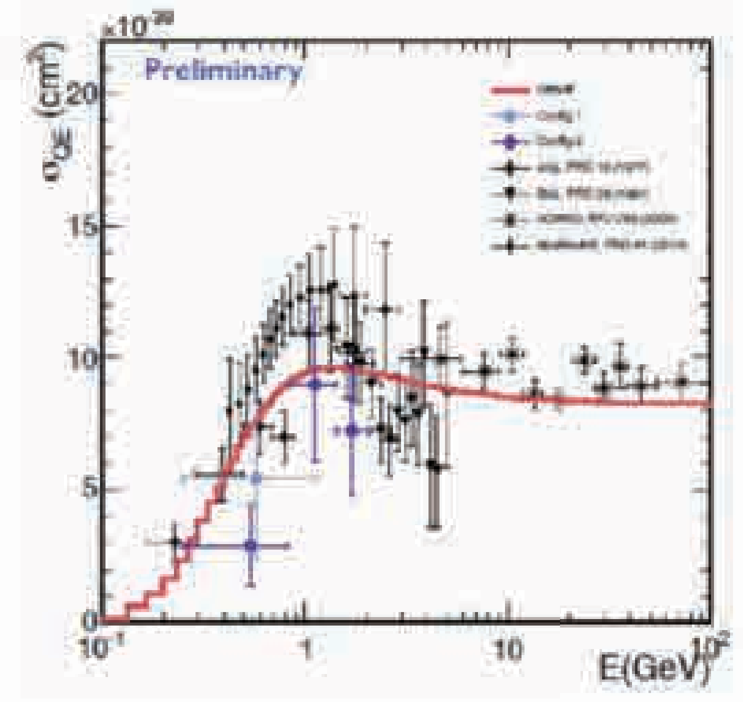


Nova ND



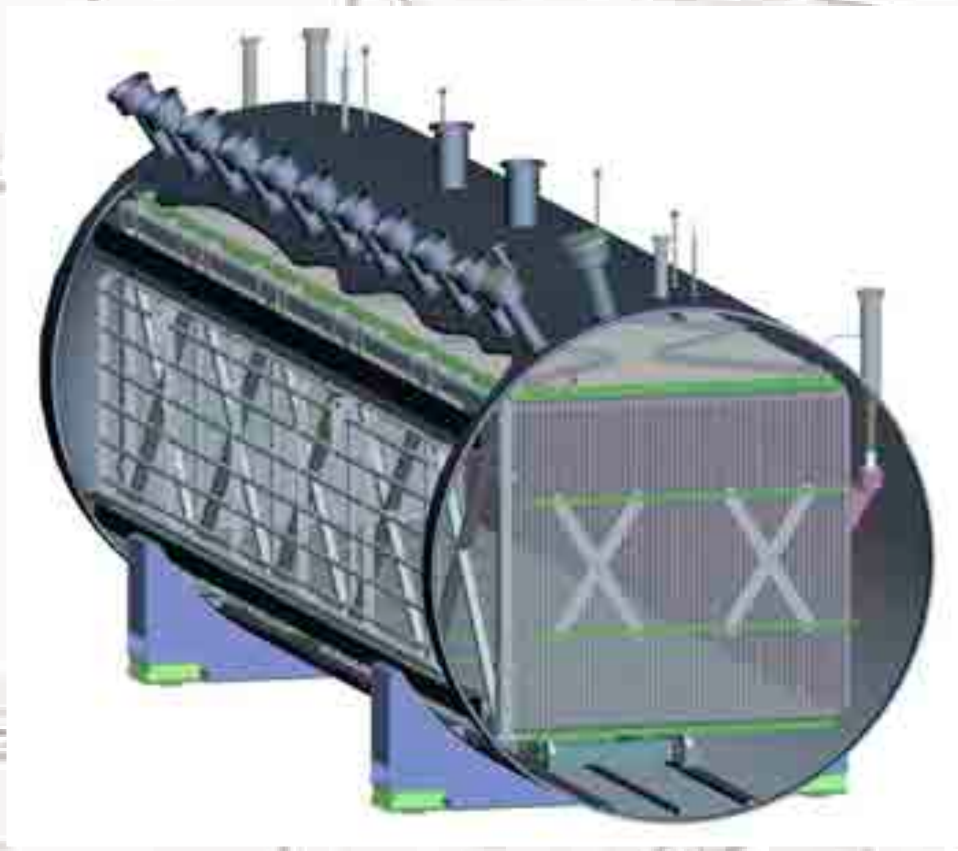
- Fully active target.
- Carbon target.
- Momentum by range.
- ND under construction.
- NDOS preliminary results.



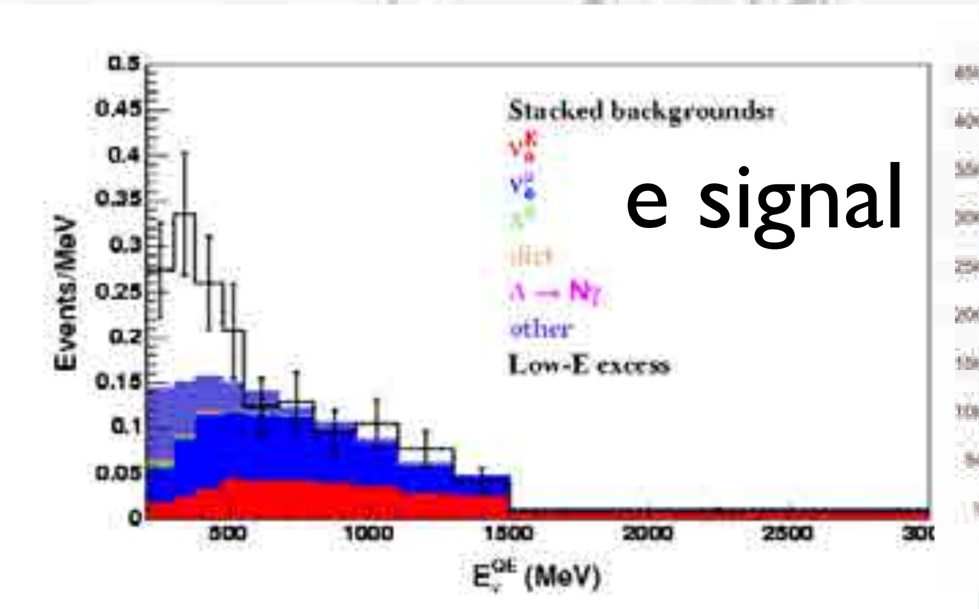


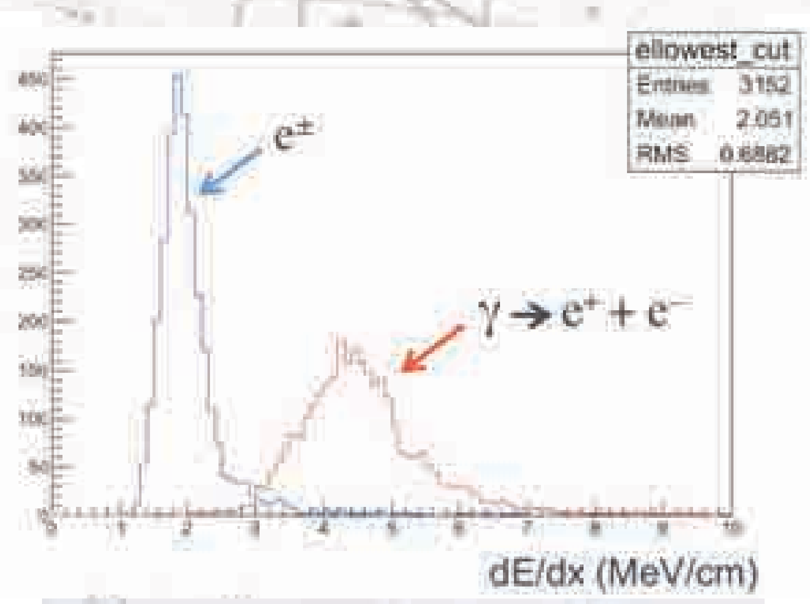
New results expected in the future

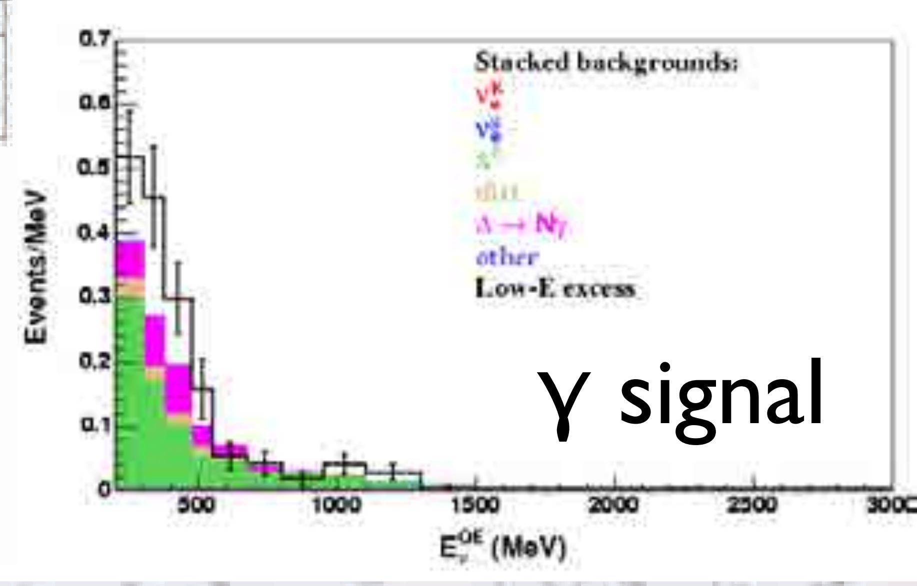
MicroBoone



- 60 ton fiducial volume LiqAr.
- Boone neutrino beam.
- Search for sterile neutrinos and study the low energy MiniBoone excess.
- Low momentum threshold for protons.
- Large mass!.
- no muon catcher!



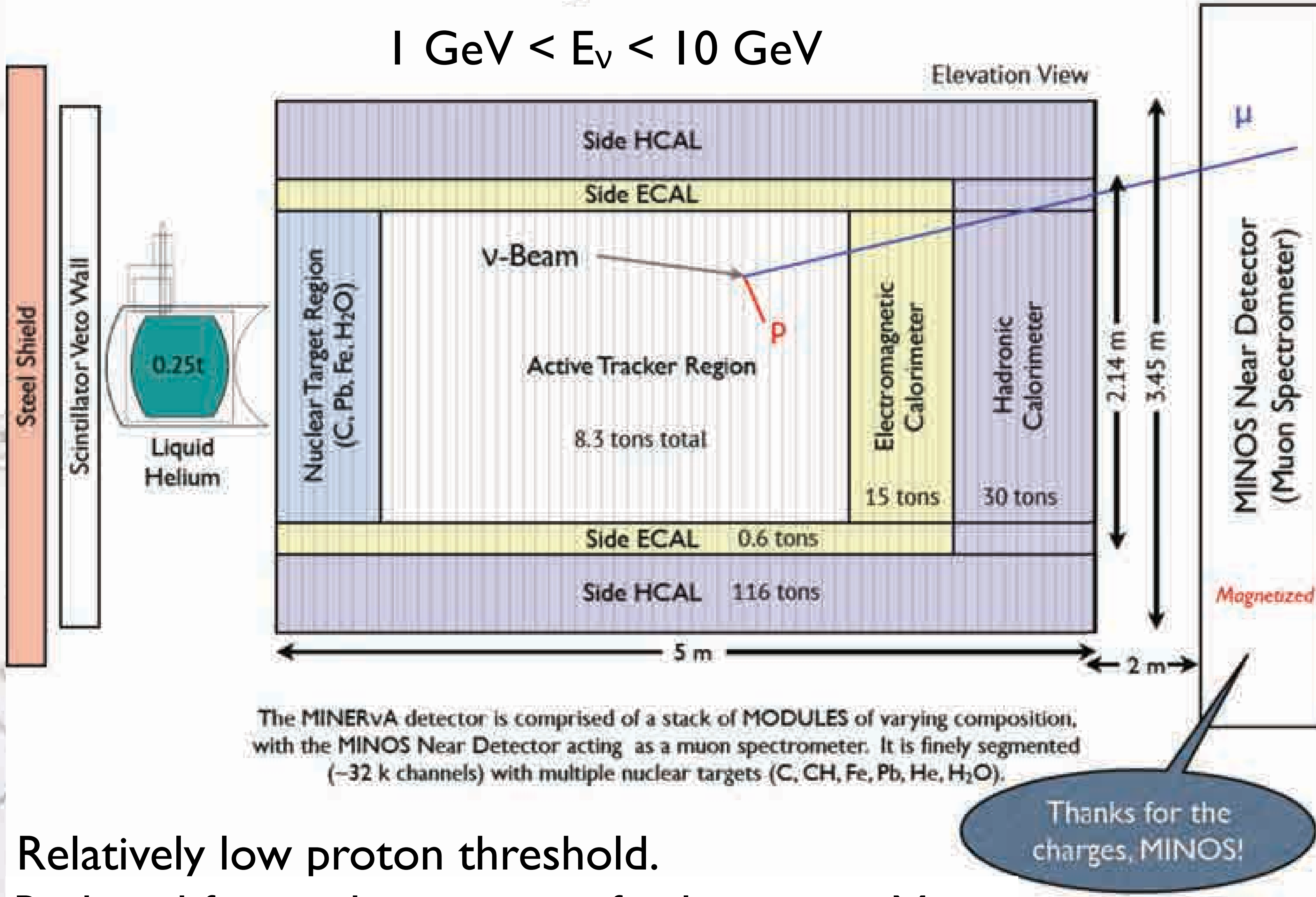




New results expected in the future

Minerva

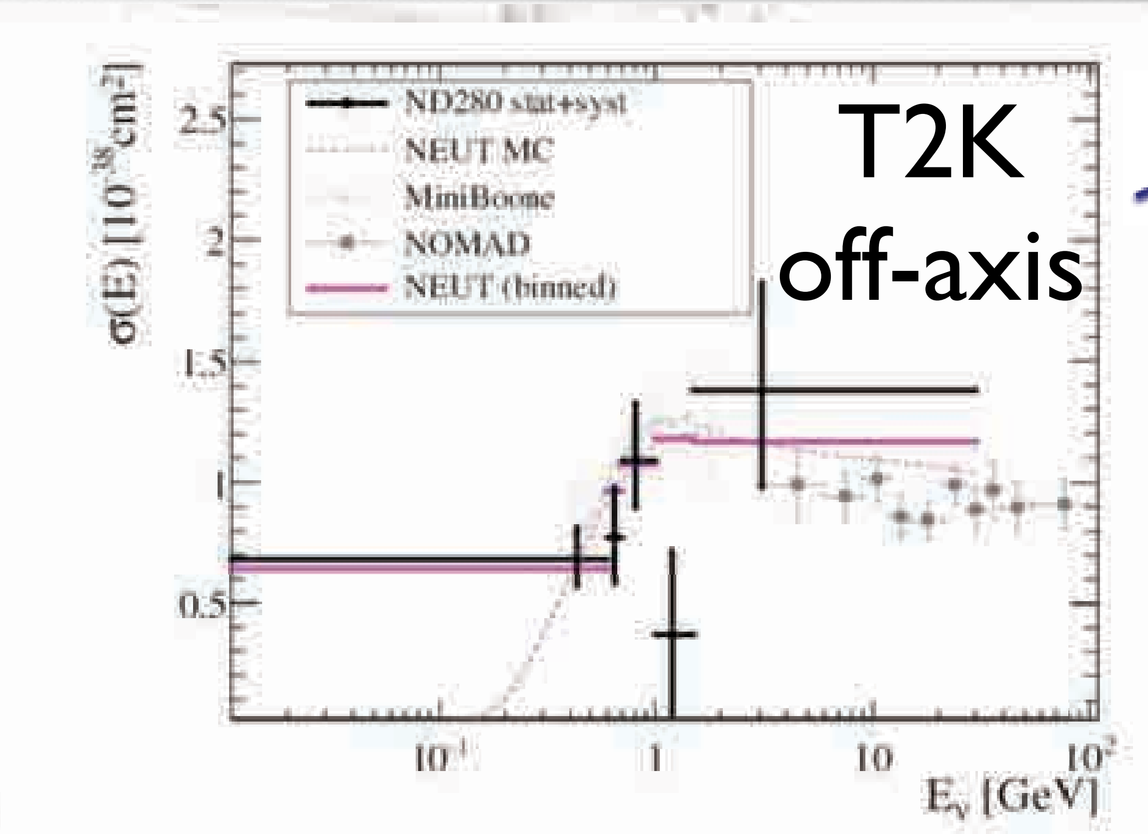
$1\ GeV < E_\nu < 10\ GeV$

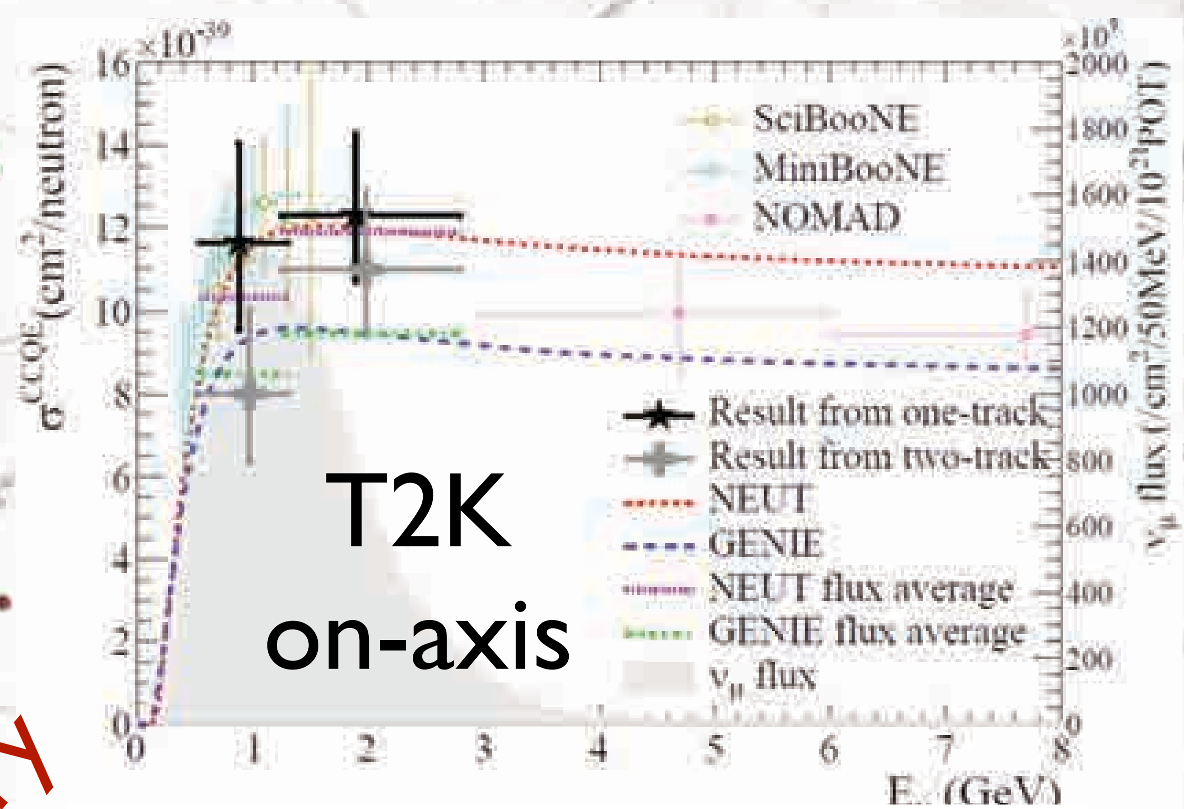


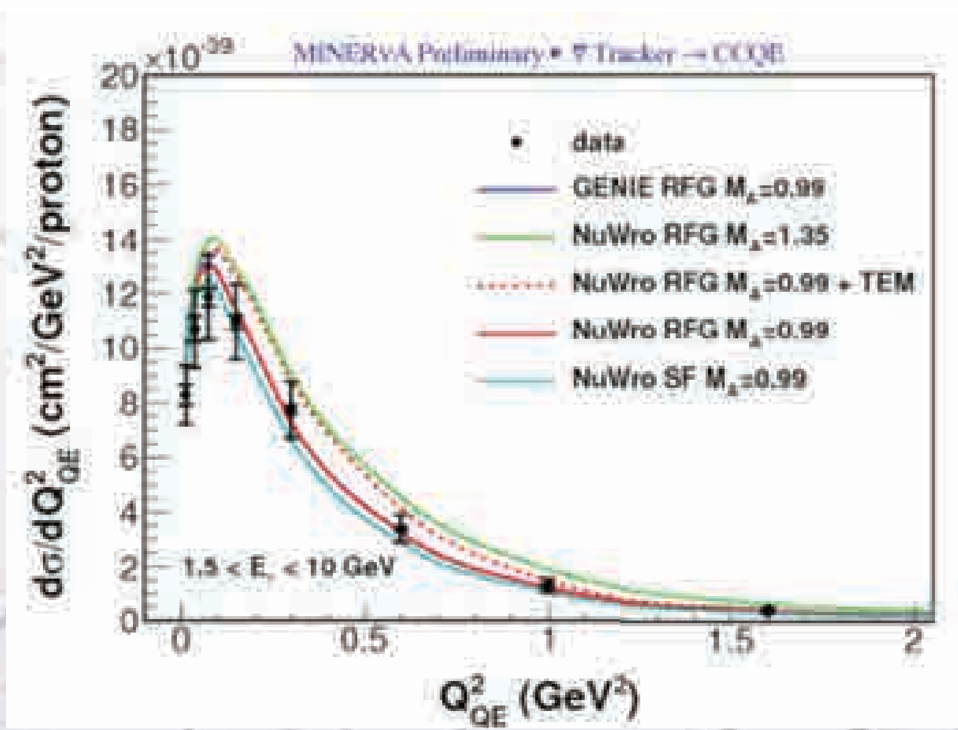
Relatively low proton threshold.

Reduced forward acceptance for leptons in Minos

Other CCQE

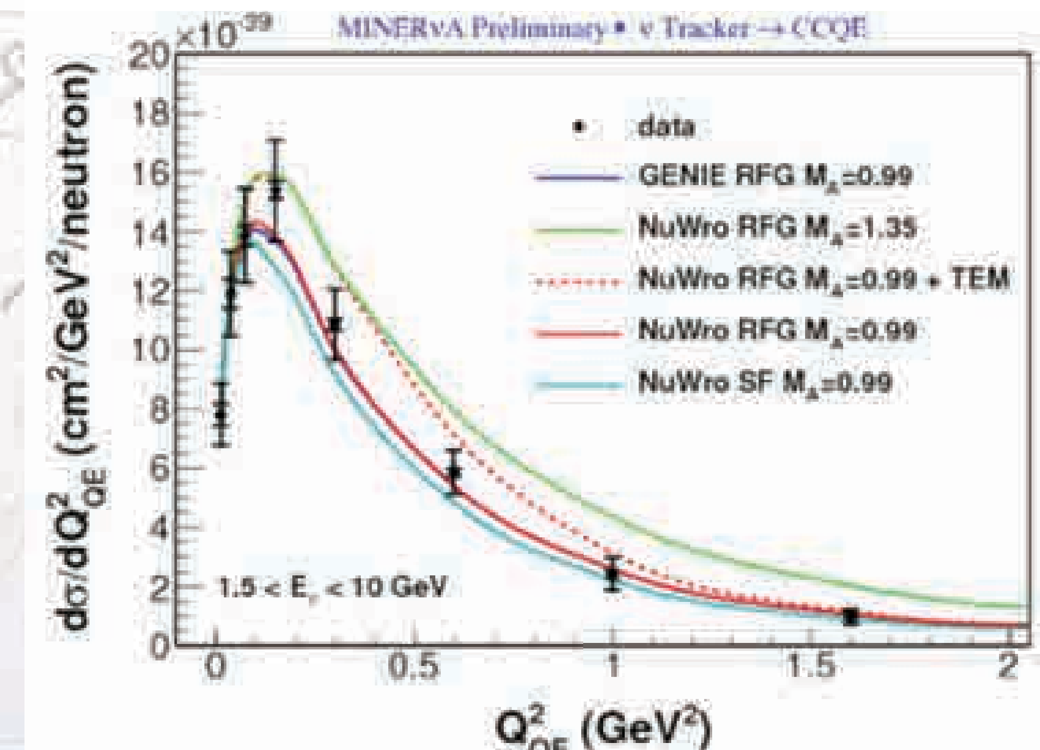




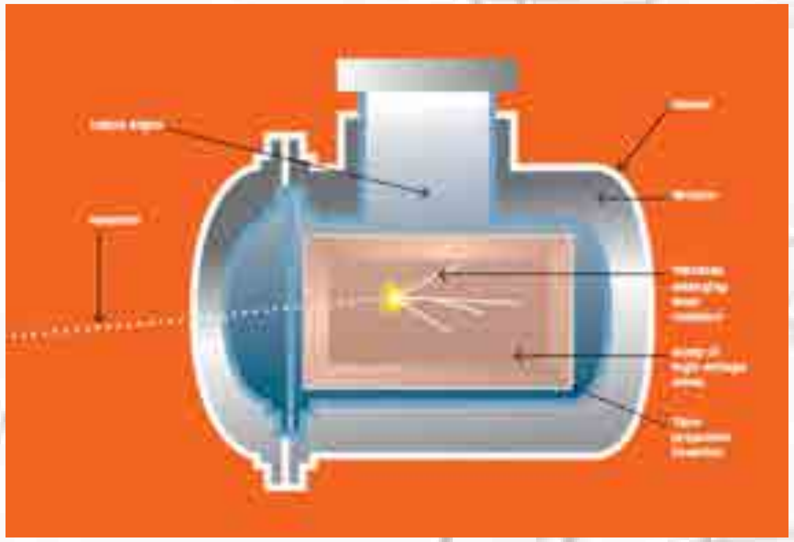


Preliminary

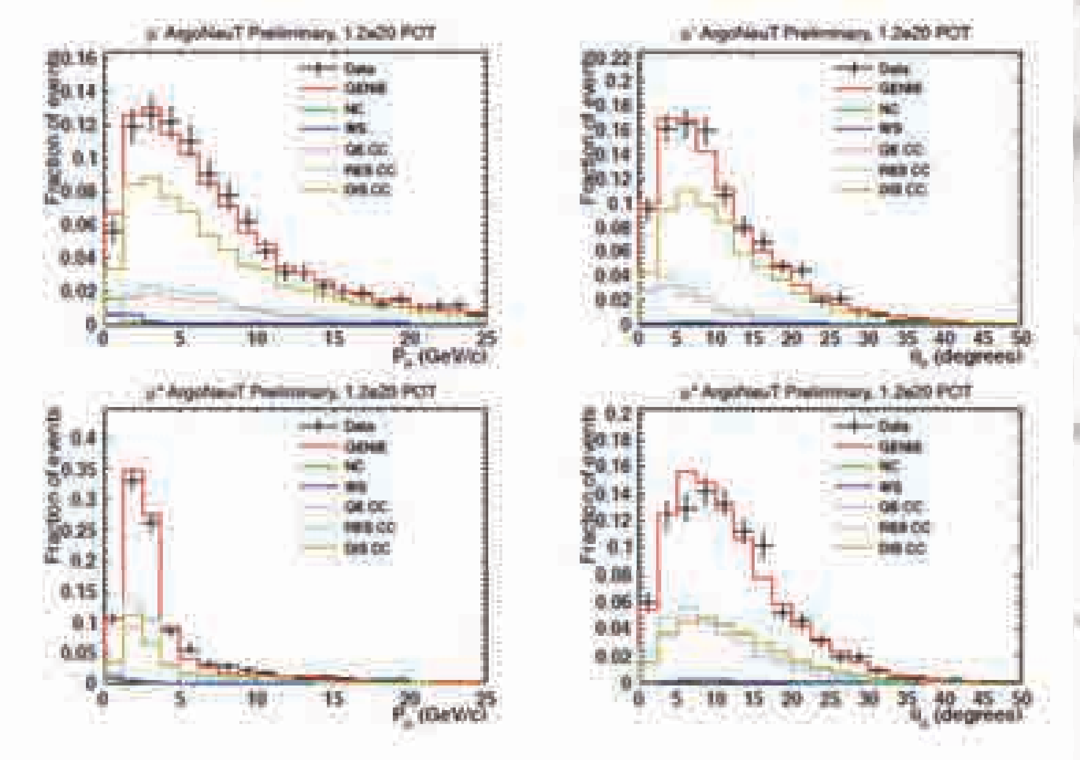
Minerva

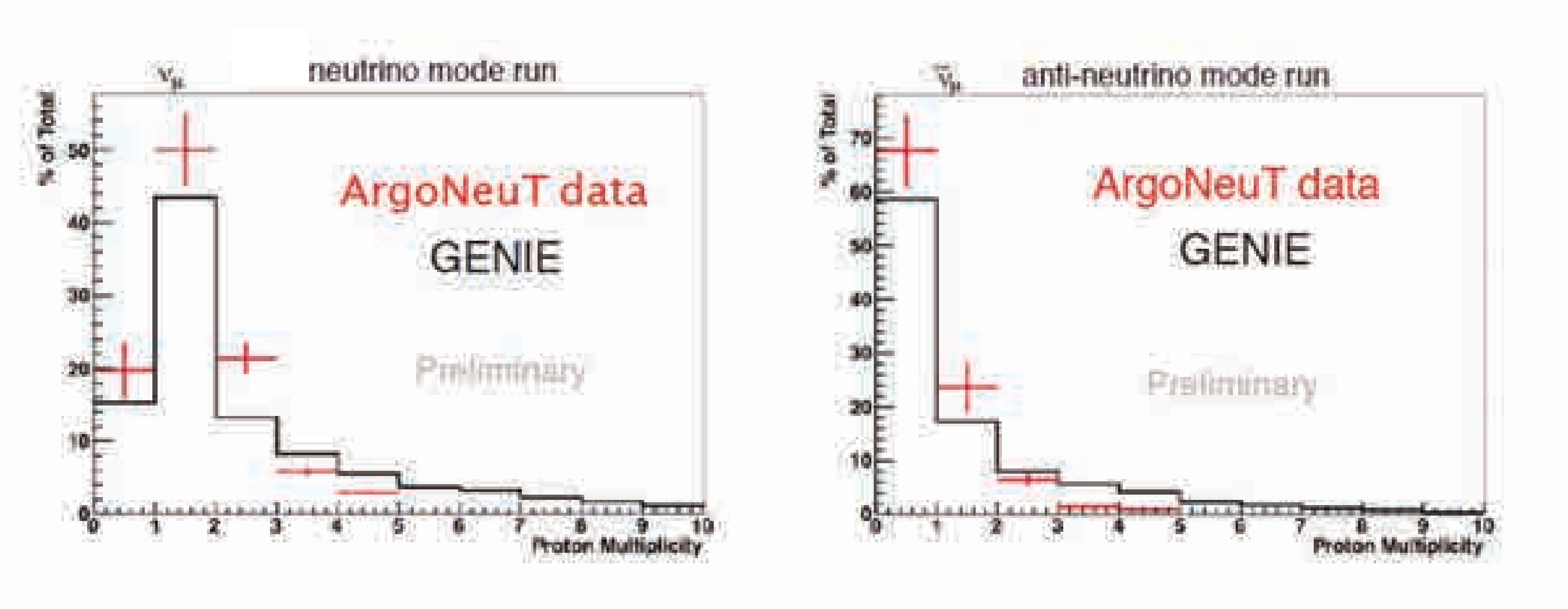


ArgoNeut

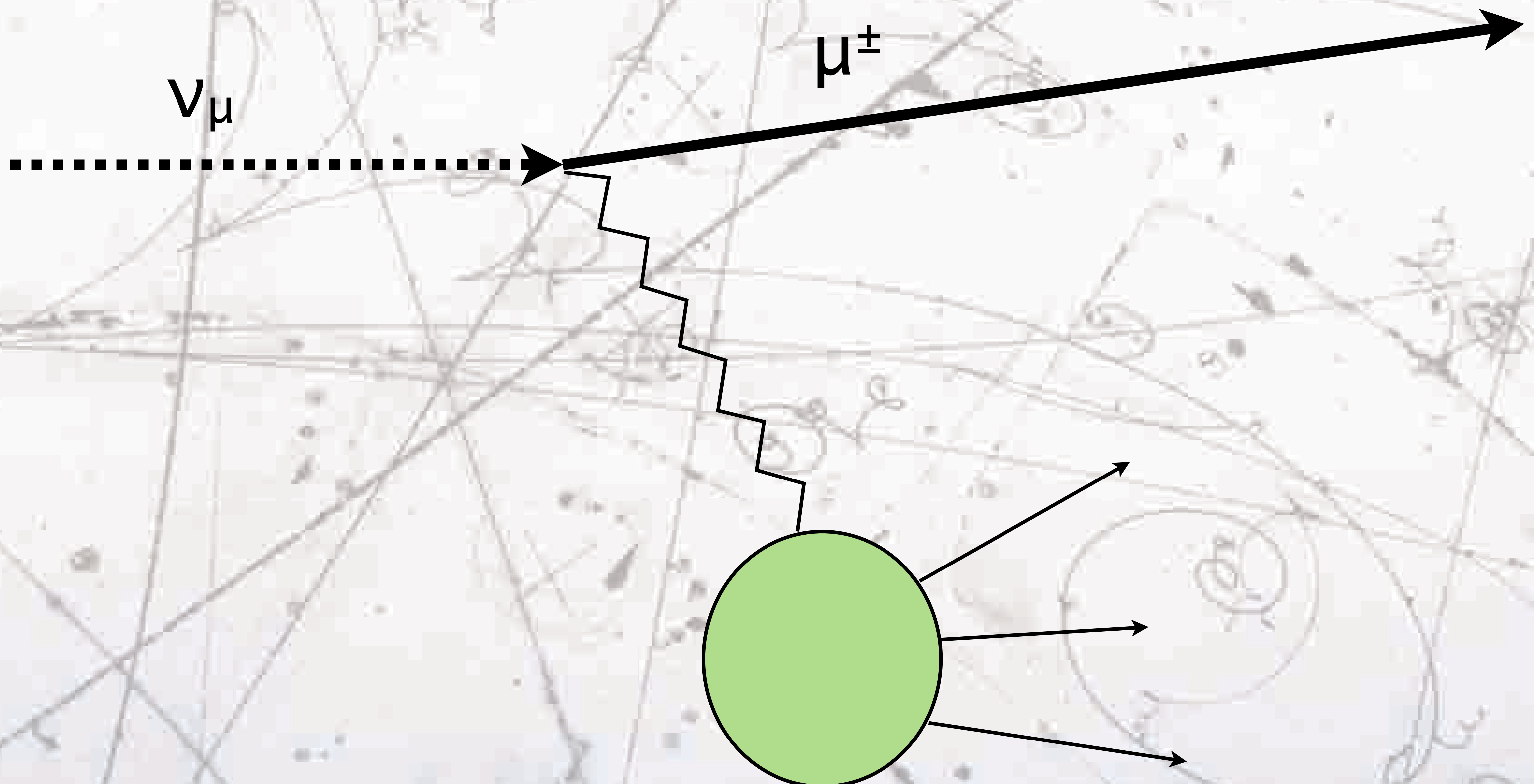


- LiqAr detector demonstrator: 240 kg.
- Boone neutrino beam.
- Low proton threshold.
- Operation: ~5 months.





Inclusive CC ν_μ



Why inclusive ?

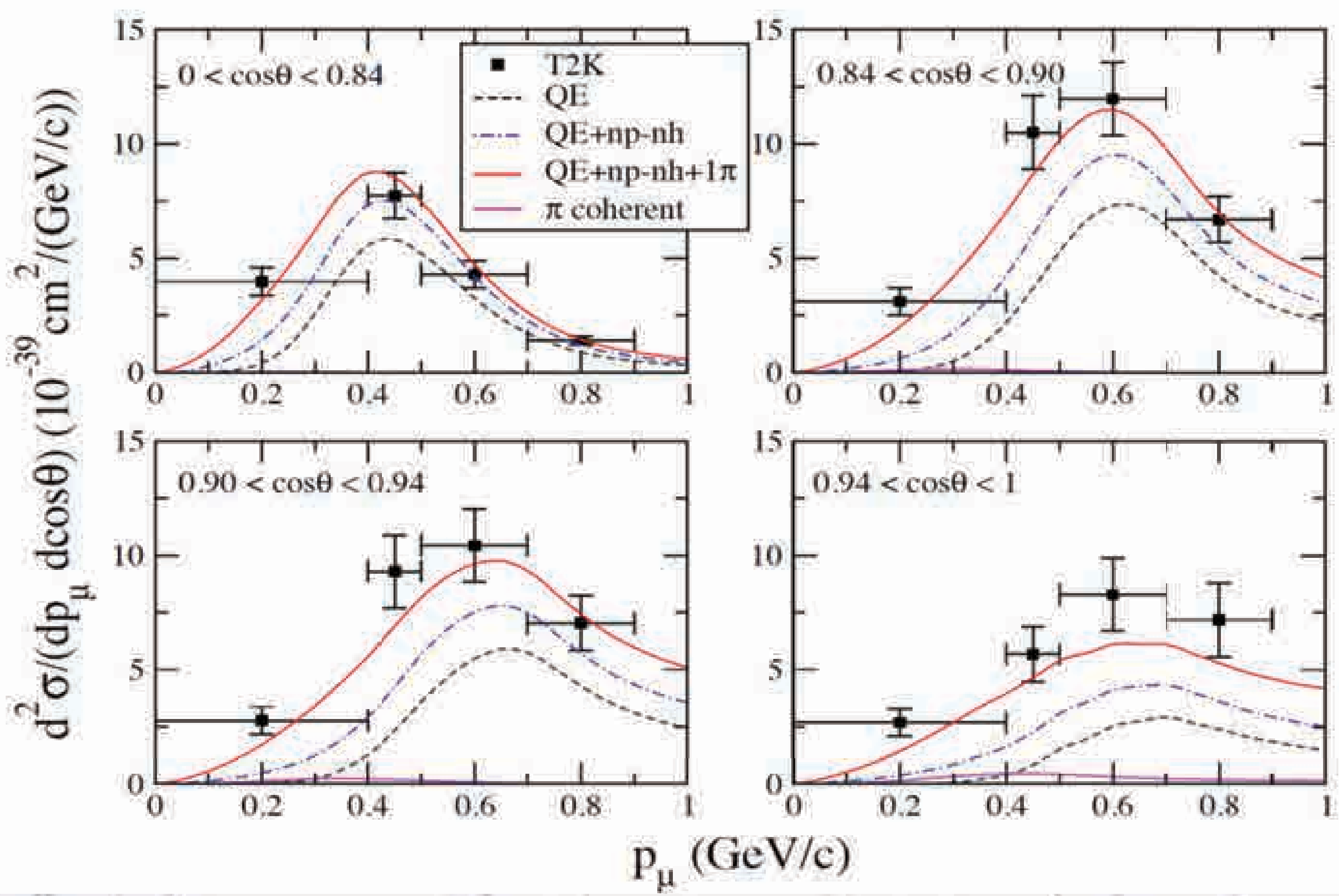
- Inclusive is a nice way for experiments to publish their data:
  - small theoretical bias.
  - "easy" to interpret from theorists.
  - easy to compare across experiments.
- The double differential (p_{μ},θ_{μ}) can be used to isolate reaction channels like CCQE and CC1π. (Martini et al. ***arXiv:1404.1490***)

It should be accompanied by the flux prediction + full covariance matrix.

CC inclusive T2K

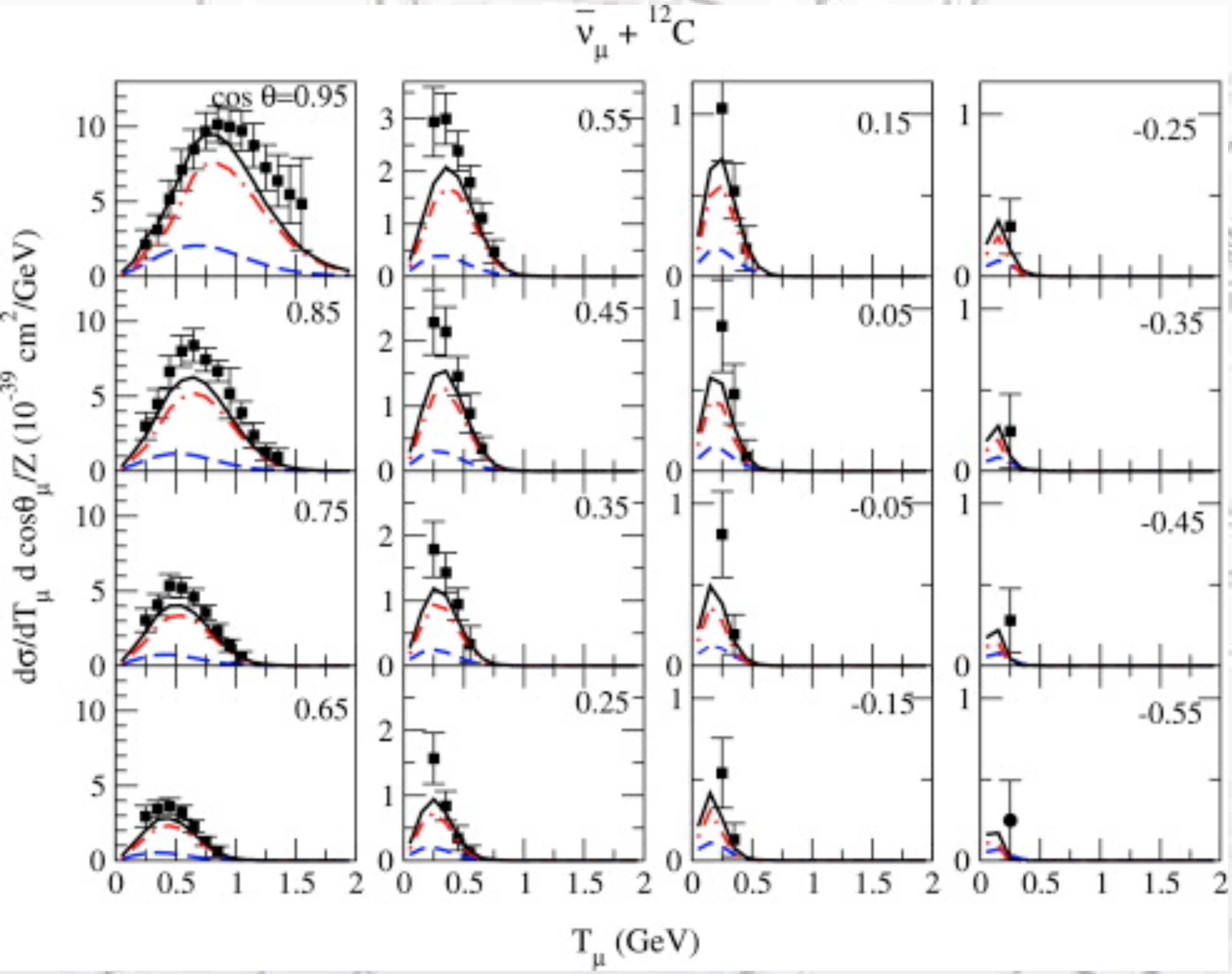
Phys.Rev. D87 (2013) 092003

Martini et al. *arXiv:1404.1490*



Near detector (ND280) double differential CC inclusive measurement and check with the Martini et al. model of CCQE and CC1π

MiniBoone antineutrinos

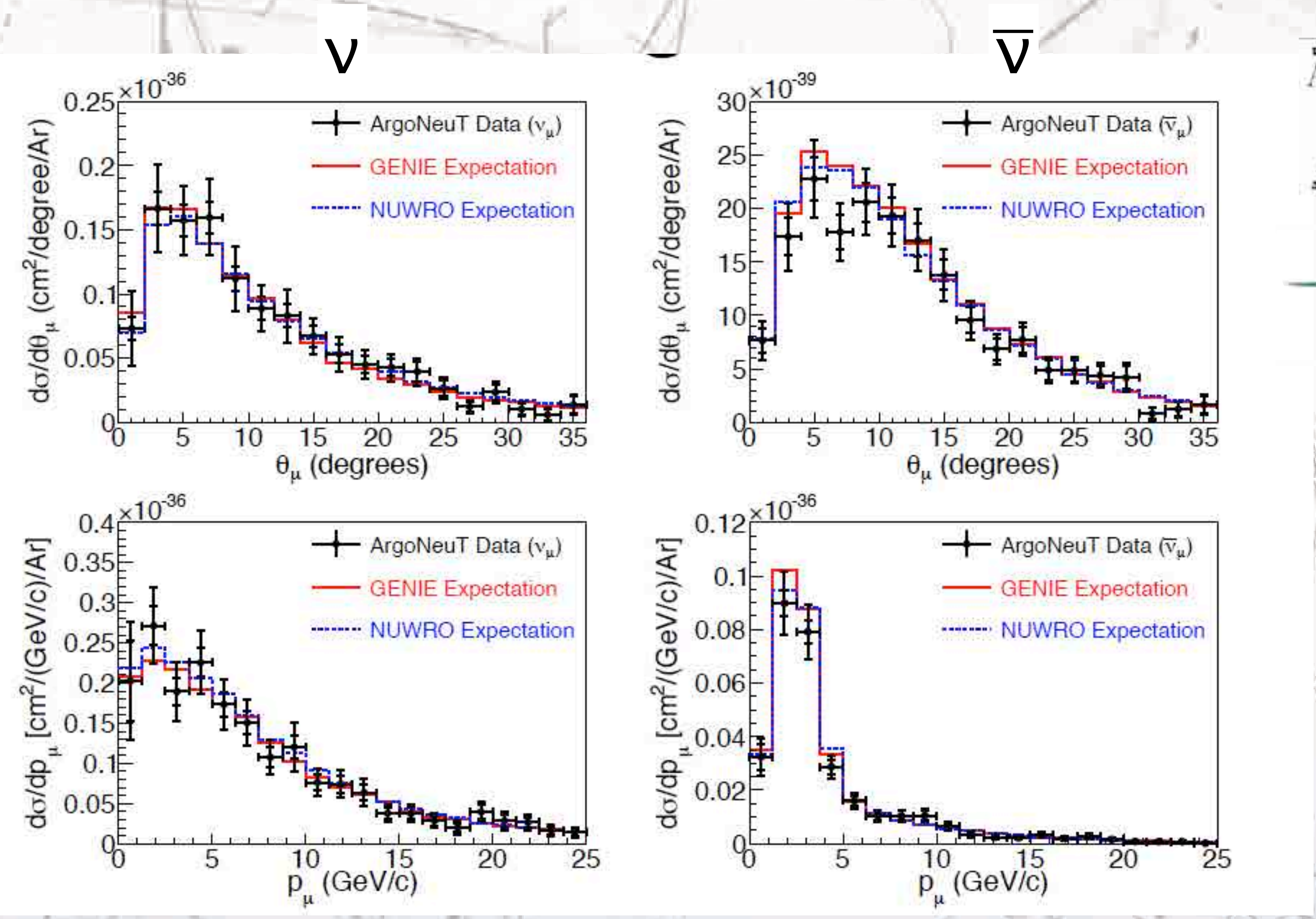


J. Nieves et al. , Phys.Lett. B721 (2013) 90-93

- Models with RPA+npnh also predicts anti-neutrino CCQE-like selection in MiniBoone.

MiniBooNe

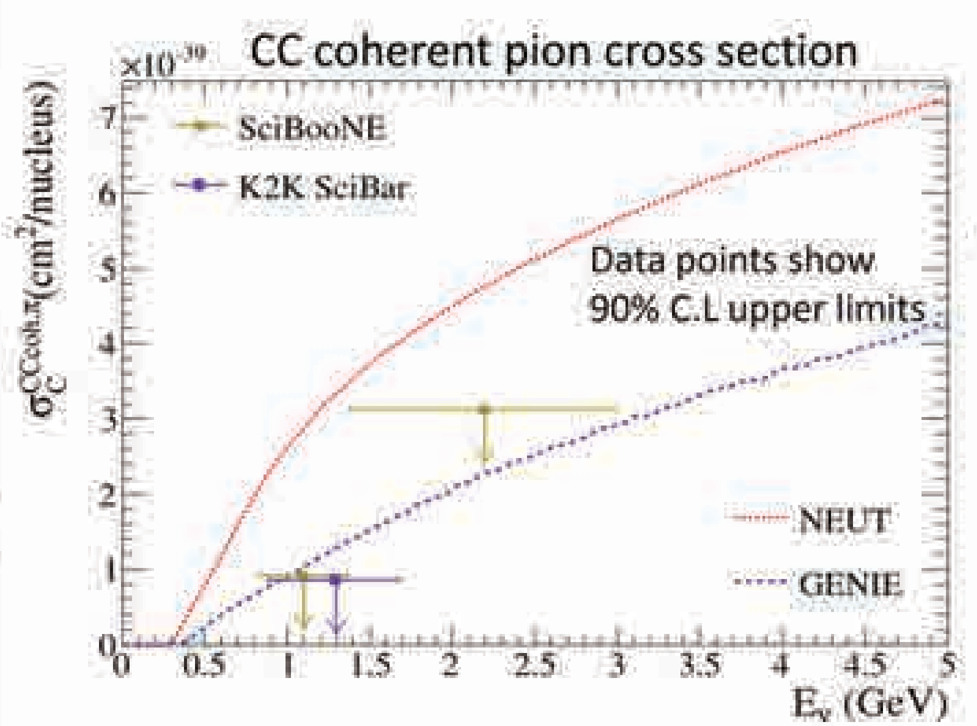
CC inclusive ArgoNeut

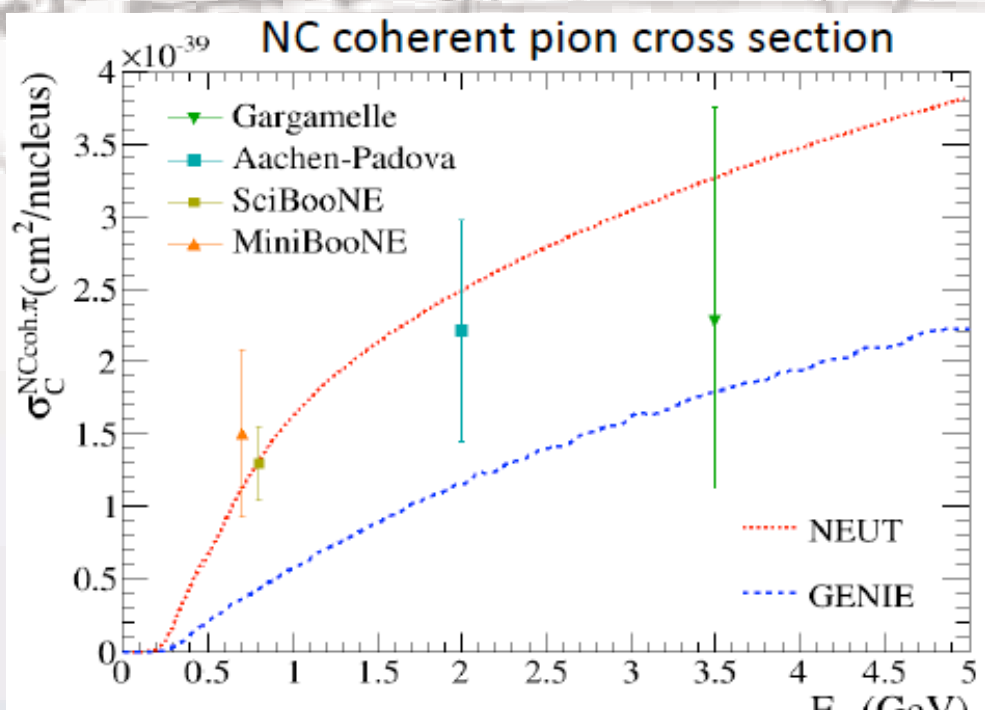


ArgoNeuT

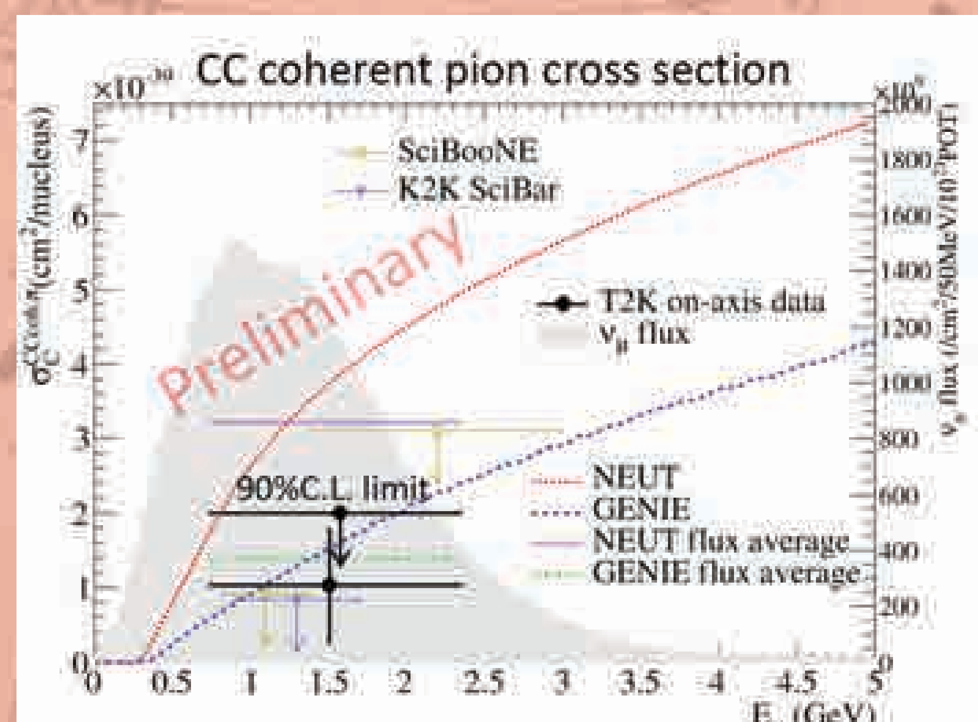
Nuint'14

CC 1π coherent





- Problem with models appear $E_\nu \sim 1$ GeV:
  - CC-coh not seen this energy.
  - Broken isospin relation prediction
    - CC-coh/NC-coh ~ 2.
- Large systematic errors from bck x-section modelling.



New T2K data with vertex activity

Nuint'14

Minerva A dependencies

- Minerva made the first CC inclusive measurement for neutrinos comparing different nuclear targets for different kinematic variables.
- This is very model independent and a nice input to model builders.
- See P.Rodrigues talk.

Minerva