EXCELENCIA SEVERO OCHOA

Review of Neutrino Interactions

F.Sánchez
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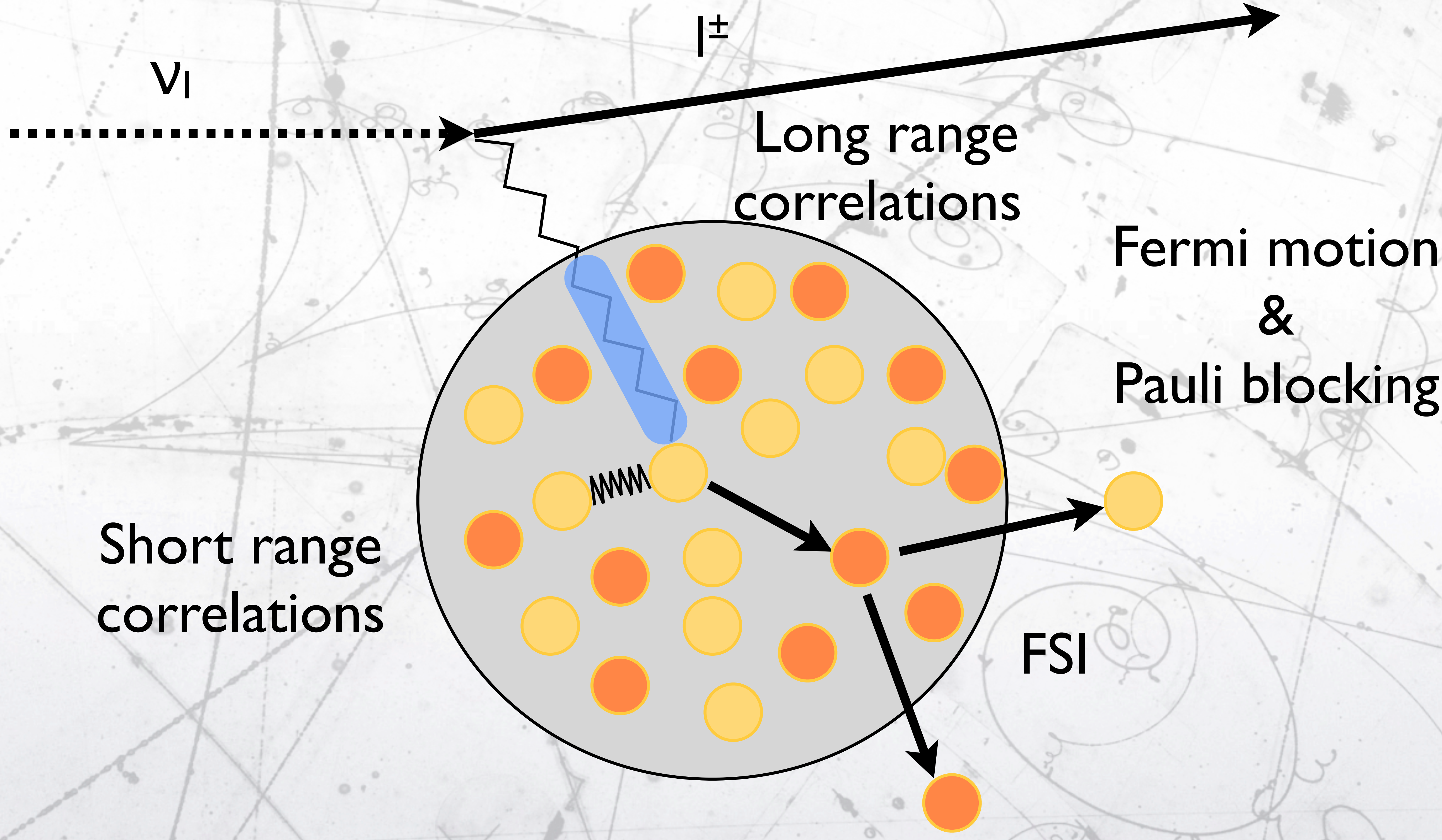
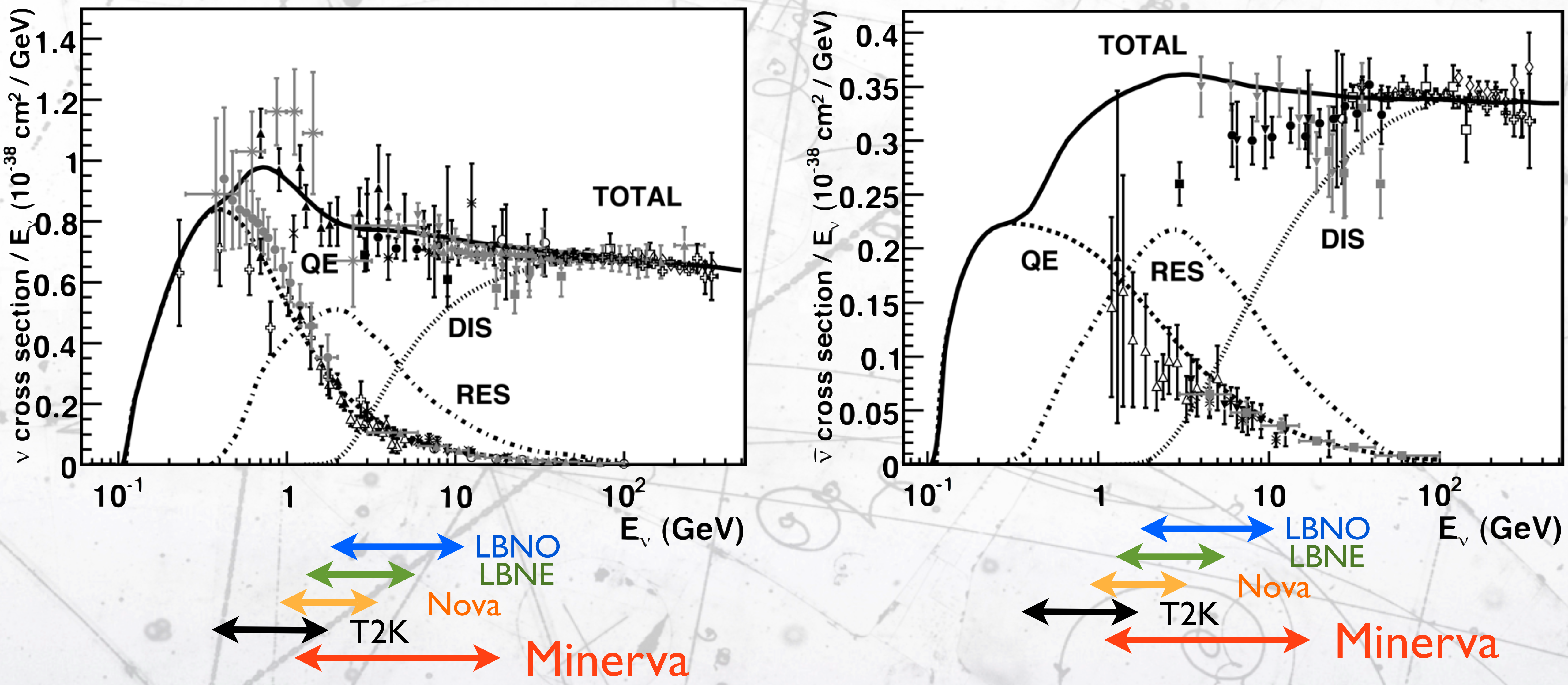
The problem



$l^{\pm}$
ν_l
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 problem

Neutrino flux is not monochromatic → Neutrino energy reconstruction

Low Energy (≲2 GeV)

- 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 (≳ 3 GeV)

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

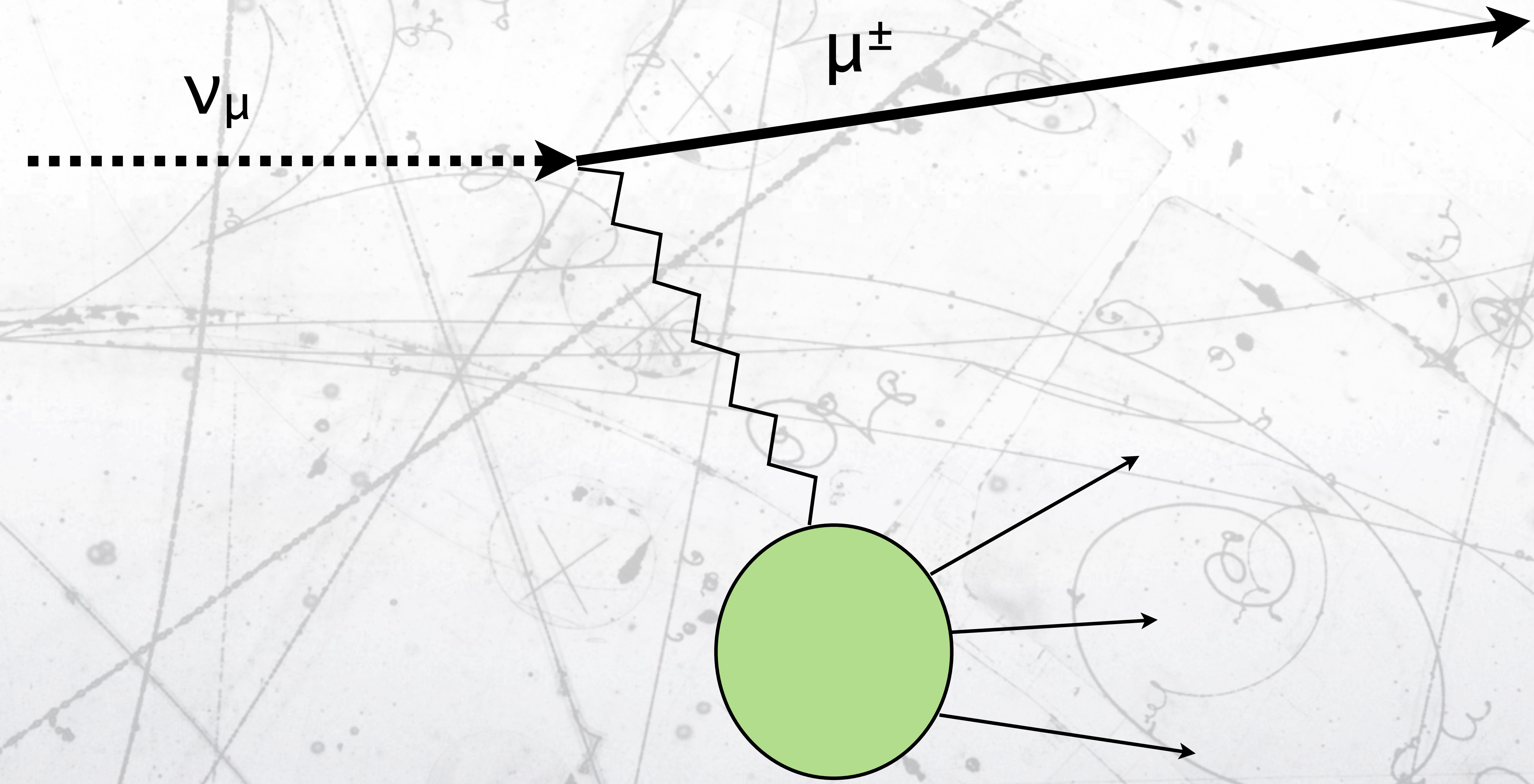
The problem

- 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!)
  - 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.

Outline

- Interaction channels:
  - Inclusive CC
  - CCQE + 2p2h
  - CC-1π
  - CC-Nπ + DIS
  - NC
  - Neutrino electrons!
- Electron scattering to the help!
- New approaches: NuPrism.
- NuSTEC
- Final (personal remarks).

Inclusive CC ν_μ

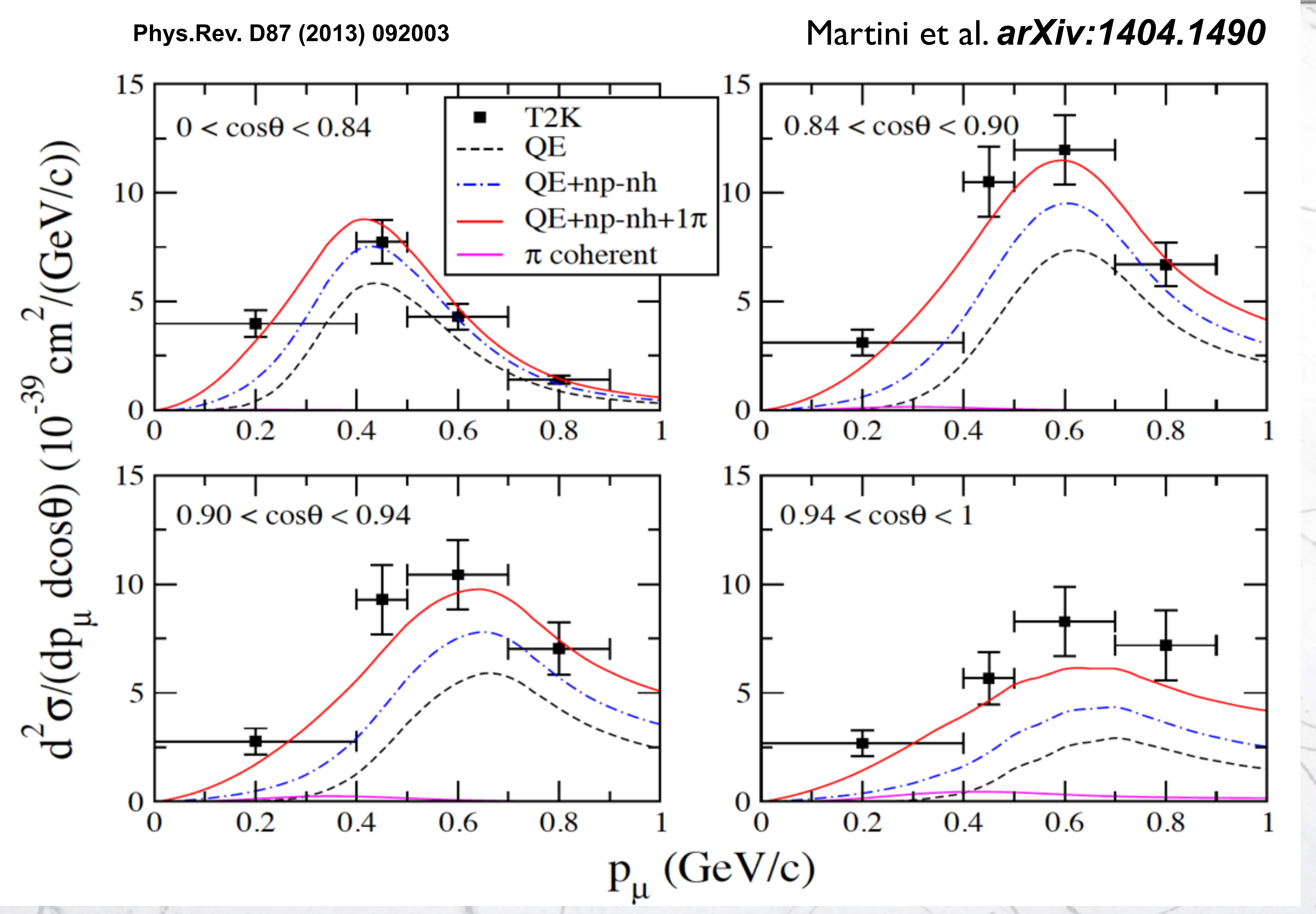


Why inclusive ?

- 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***)

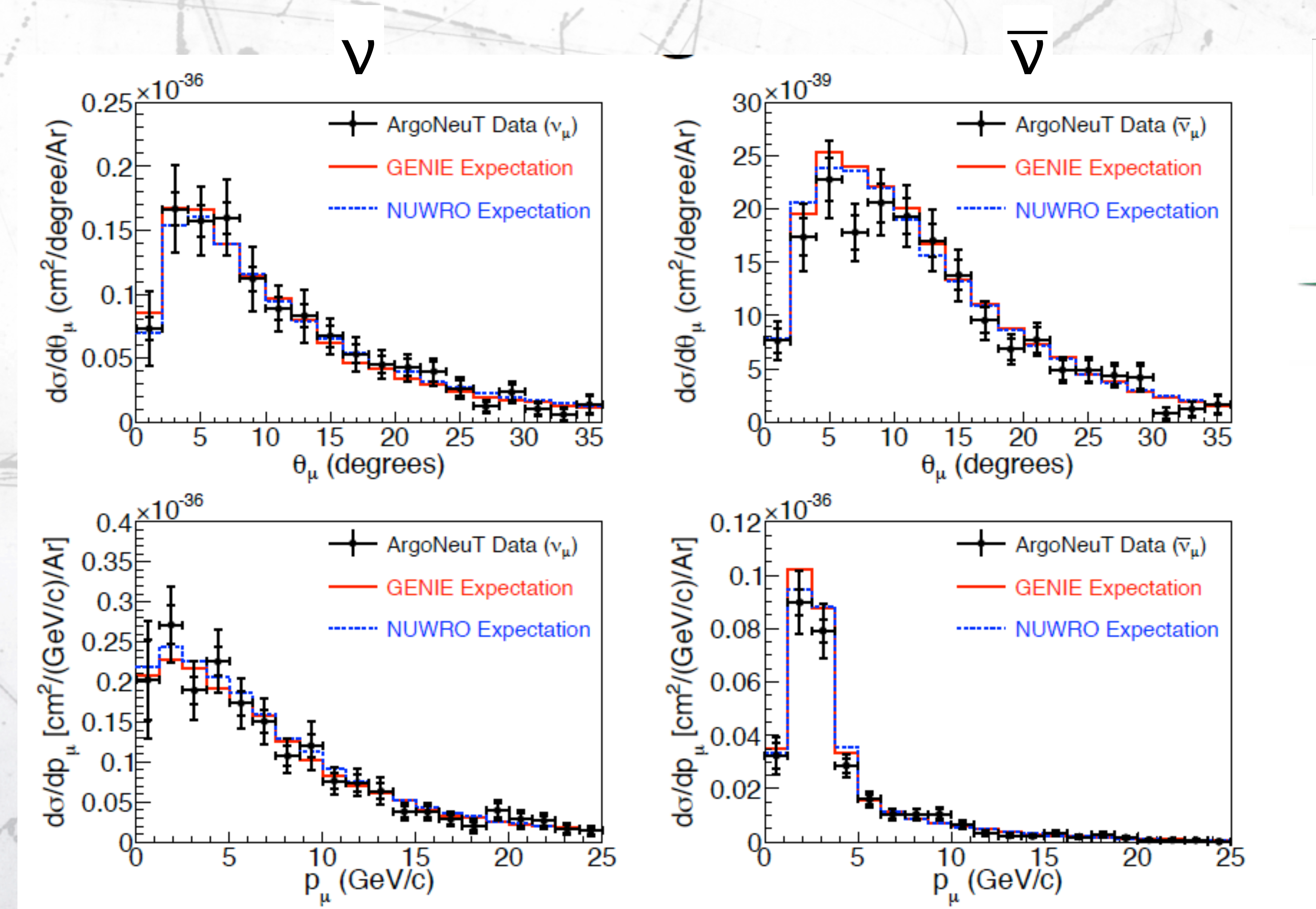
It should be accompanied by the flux prediction + full covariance matrix.

CC inclusive T2K



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

CC inclusive ArgoNeut

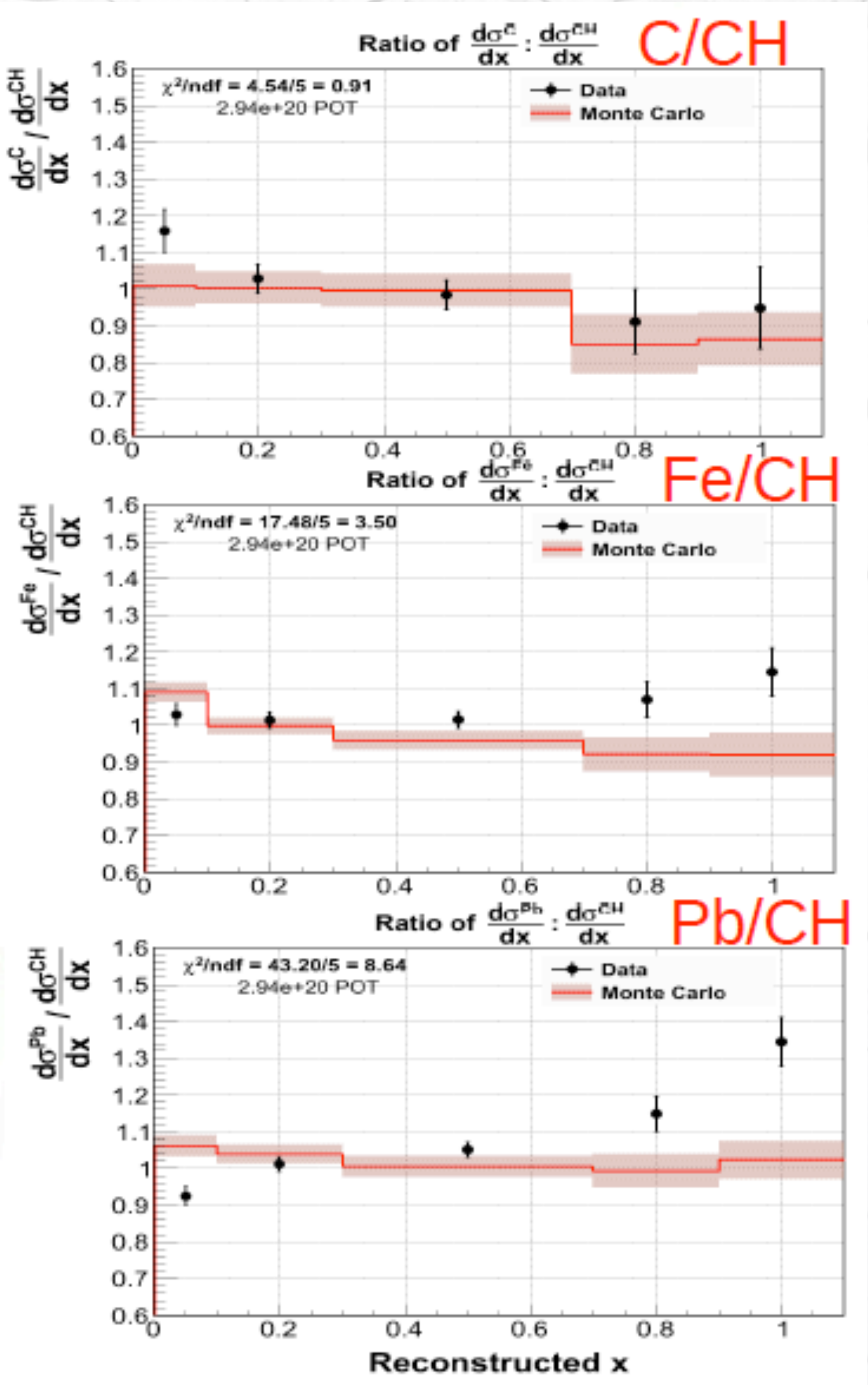


Minerva A dependencies

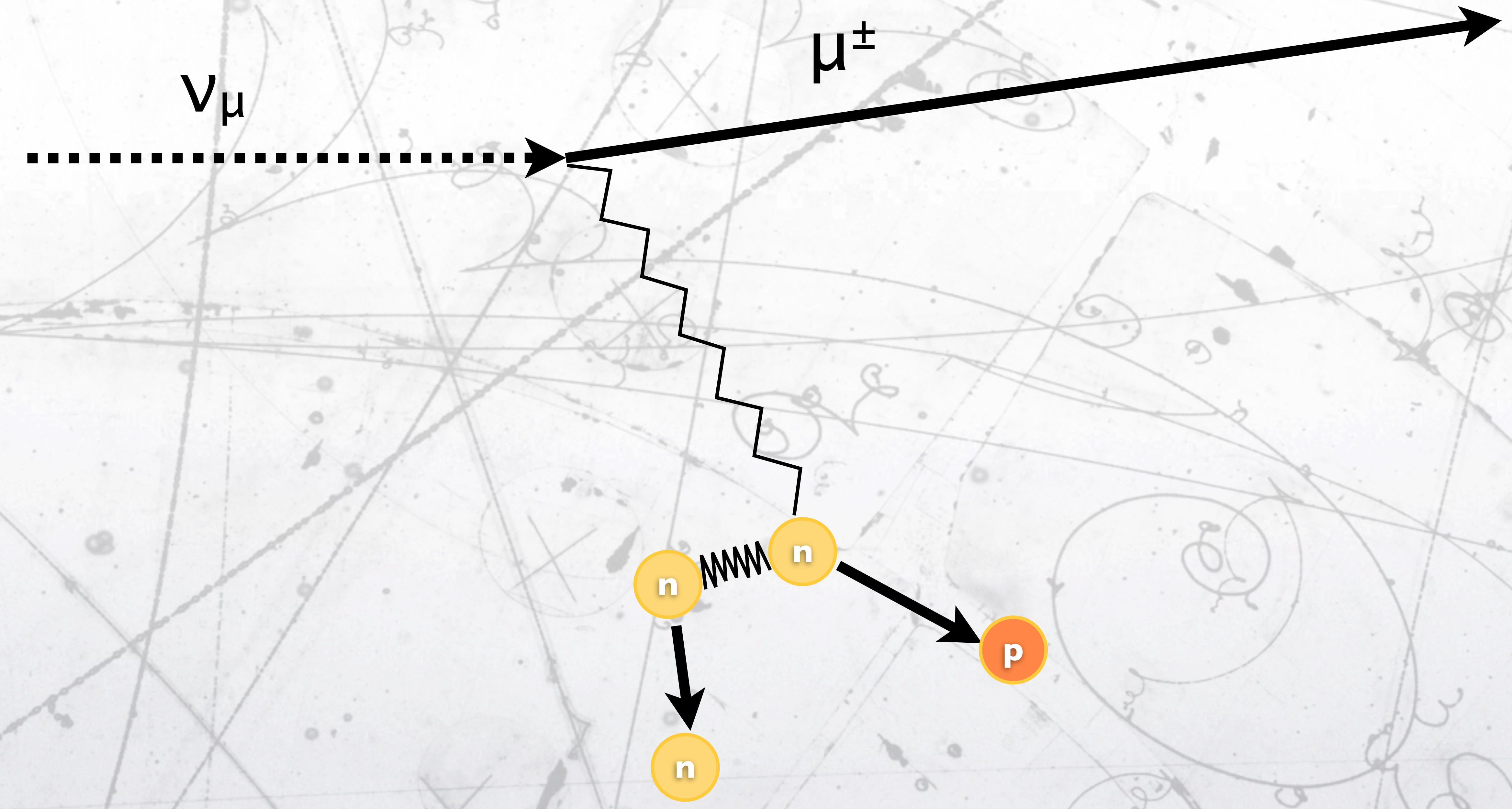
- Minerva made the first CC inclusive measurement for neutrinos comparing different nuclear targets for different kinematic variables.
- This is very model independent and a nice input to model builders.
- See P.Rodrigues talk.

Nuint'14

Minerva



CCQE + 2p2h

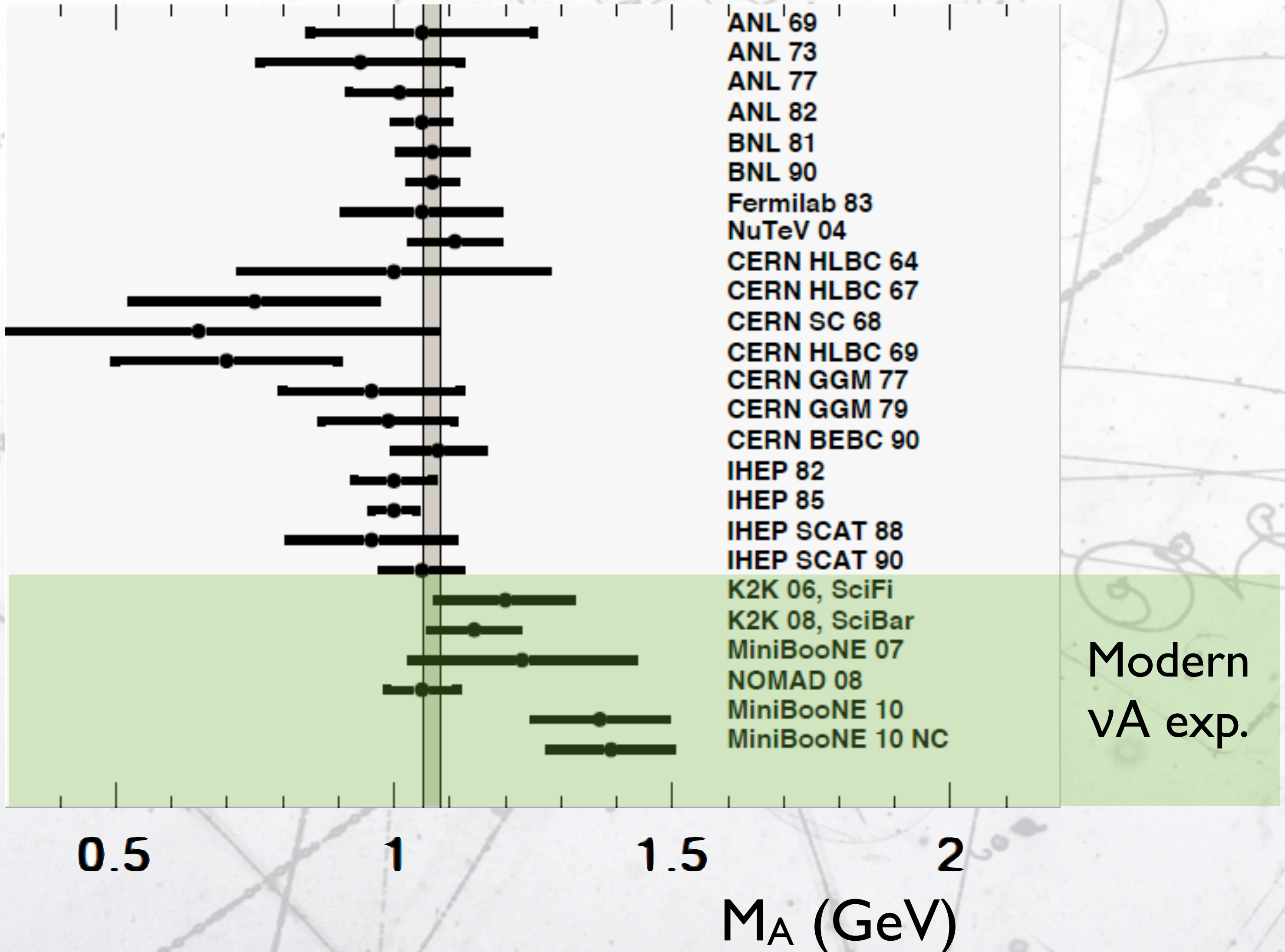


Why CCQE ?

- 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:
  - Effective axial mass.
  - Disagreement between low and high energy experiments.

CCQE problems

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

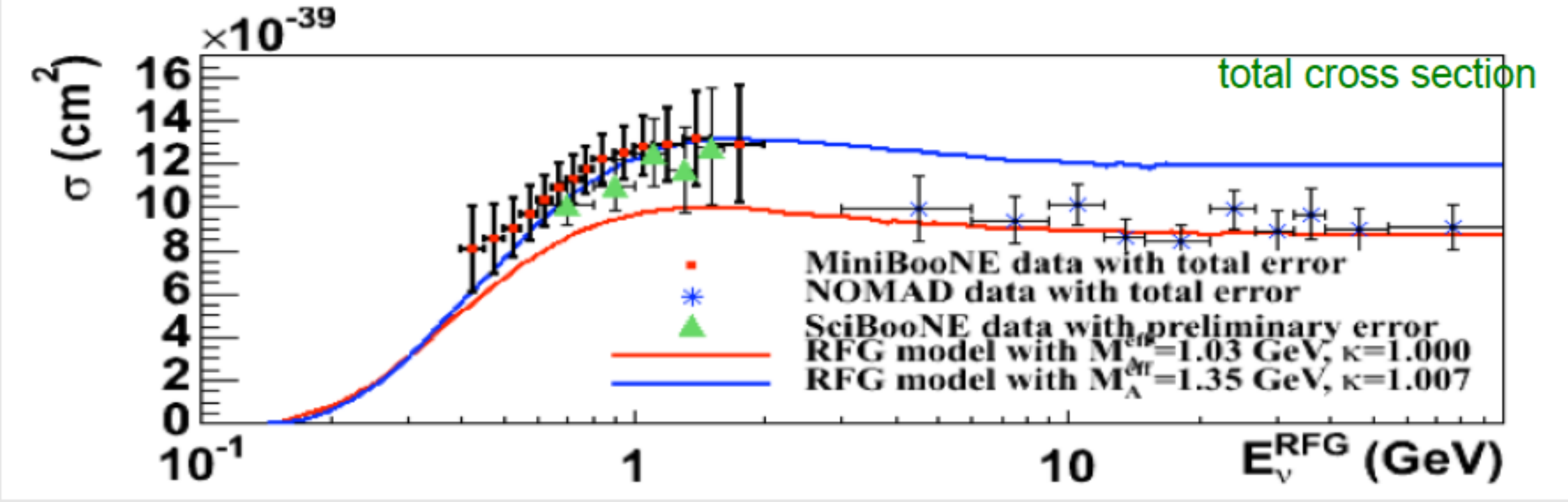


Bernard et al. 2002

- Total cross-section is almost lineal in M_A.
- M_A increases also the high-q2 region.
- Both effects are observed in νA experiments.
- Is M_A an effective parameter ?

CCQE problems

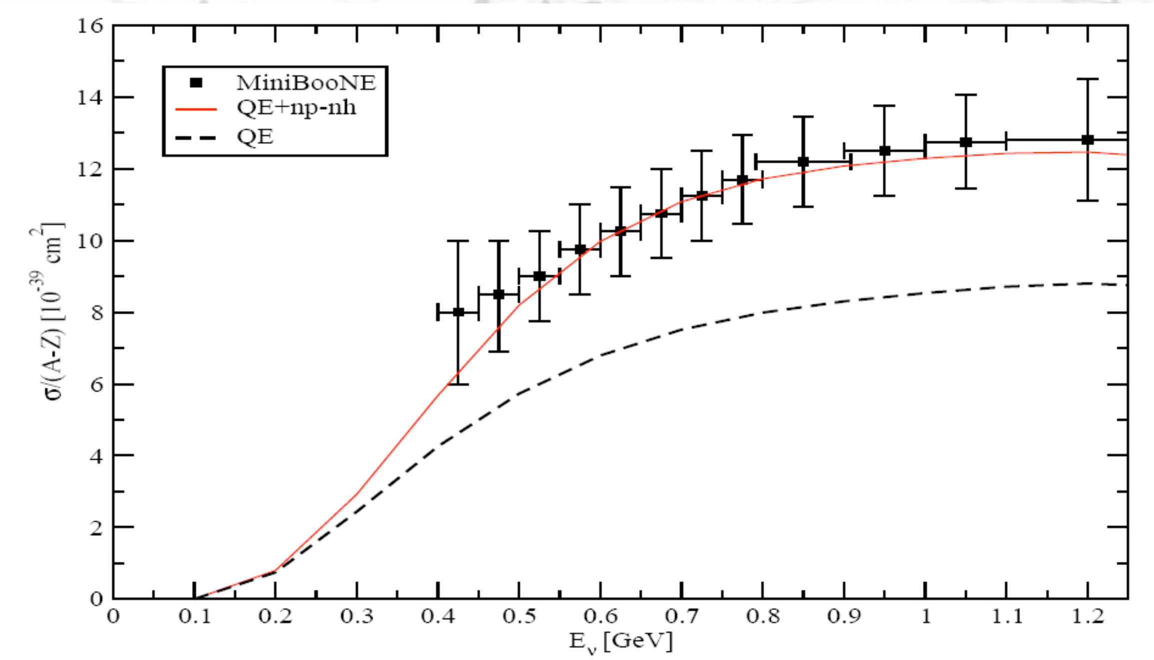
Difficult to concile the low and high energy results.

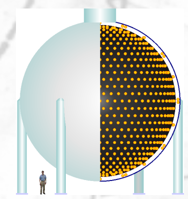


Experiments define CCQE in different manners (no proton, one proton,etc…) and sometimes develop analysis under certain model paradigm confusing the model comparison.

MiniBoone & 2p2h

Martini et al. PRC 84 055502 (2011)

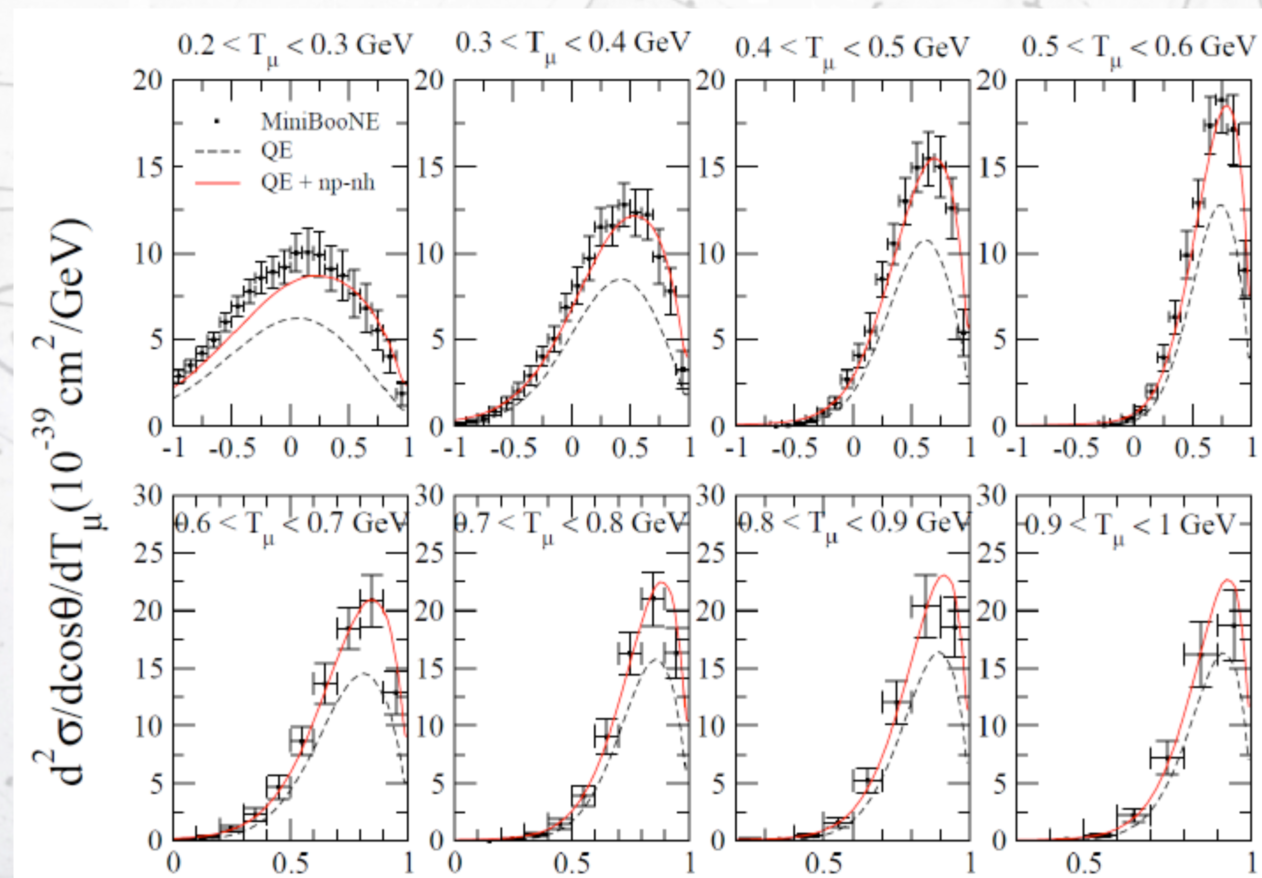




MiniBooNe

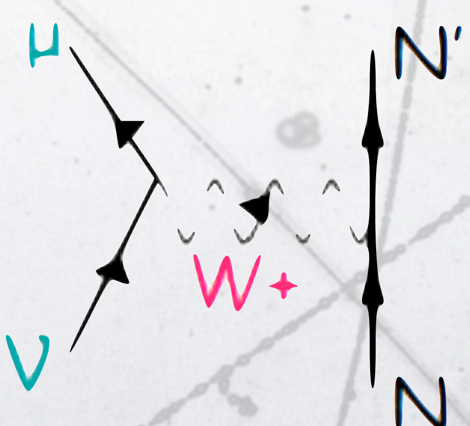
- MiniBoone published a double differential cross-section for events with no pions in final state (CCQE-like).
- Theorist profited from the clean data!.

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

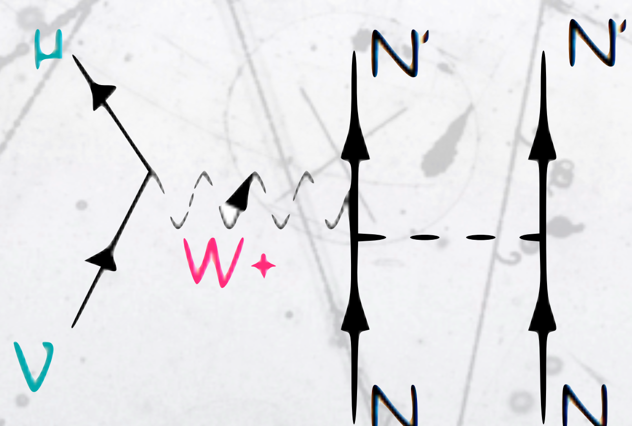


Martini et al. PRC 84 055502 (2011)

CCQE



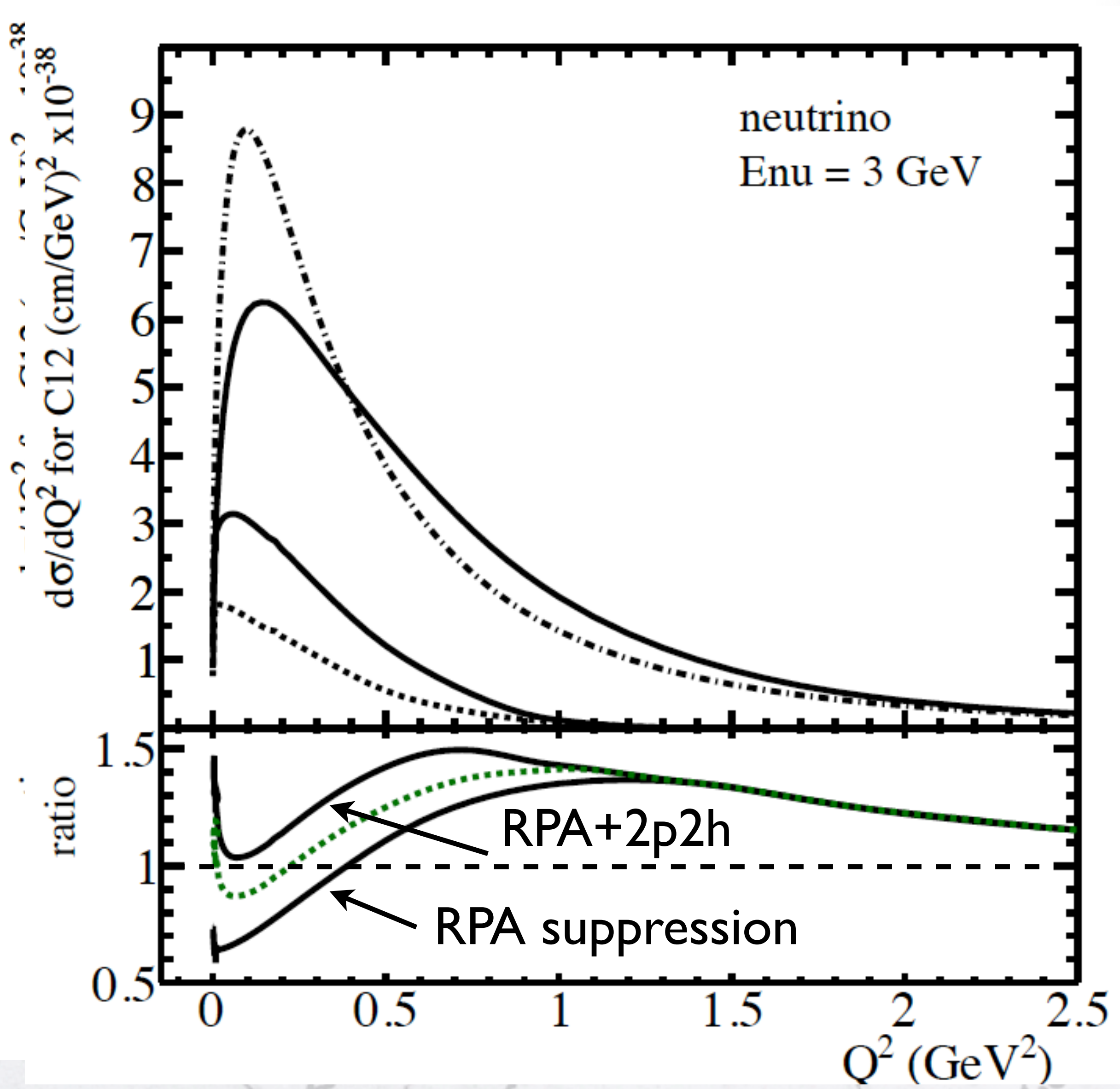
CC-npnh



See J.Sobczyk for details!

Long Range correlation

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

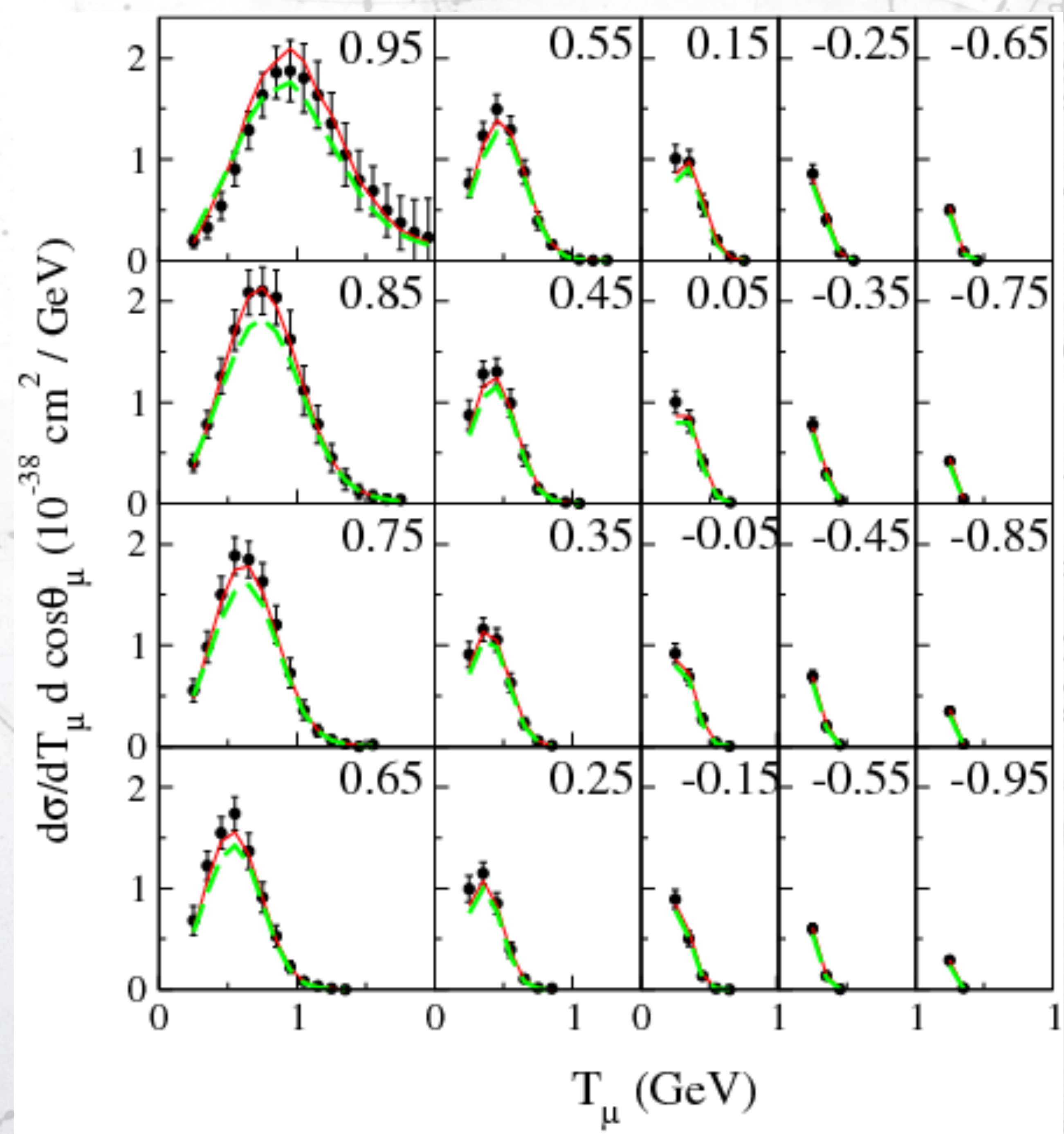


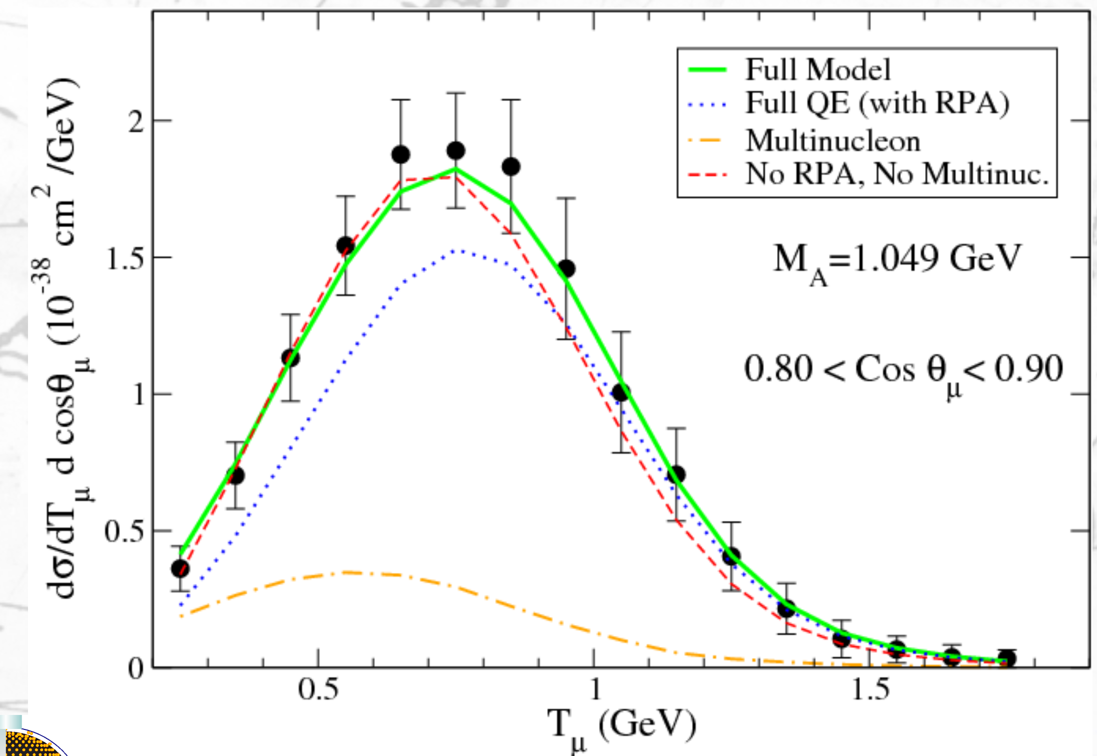
- Long Range Correlations are estimated with the Random Phase Approximation (RPA).
- It predicts a deficit at low Q^2 and enhance at large Q^2.
- 2p2h fills the low Q^2, so we see enhancement at low Q^2.

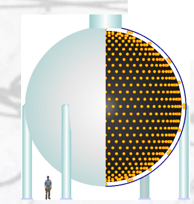
- The overall effect is that: 2p2h + RPA predicts large QE-like cross-section and enhancement at high Q^2.

Recovering M_A

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







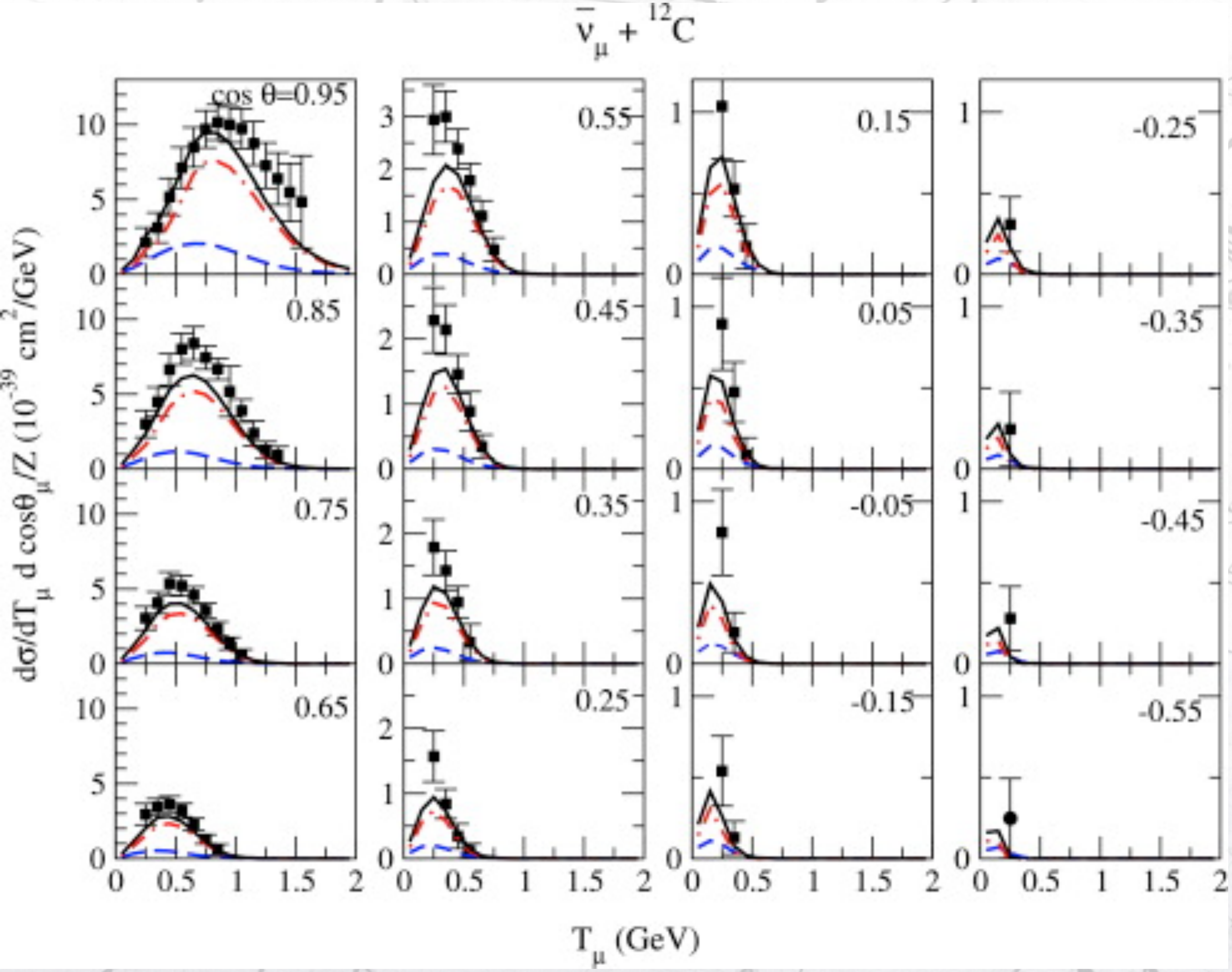
MiniBooNe

Data fits equally to

CCQE M_A = 1.31

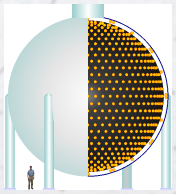
CCQE MA = 1.05 + RPA + 2p2h

MiniBoone antineutrinos



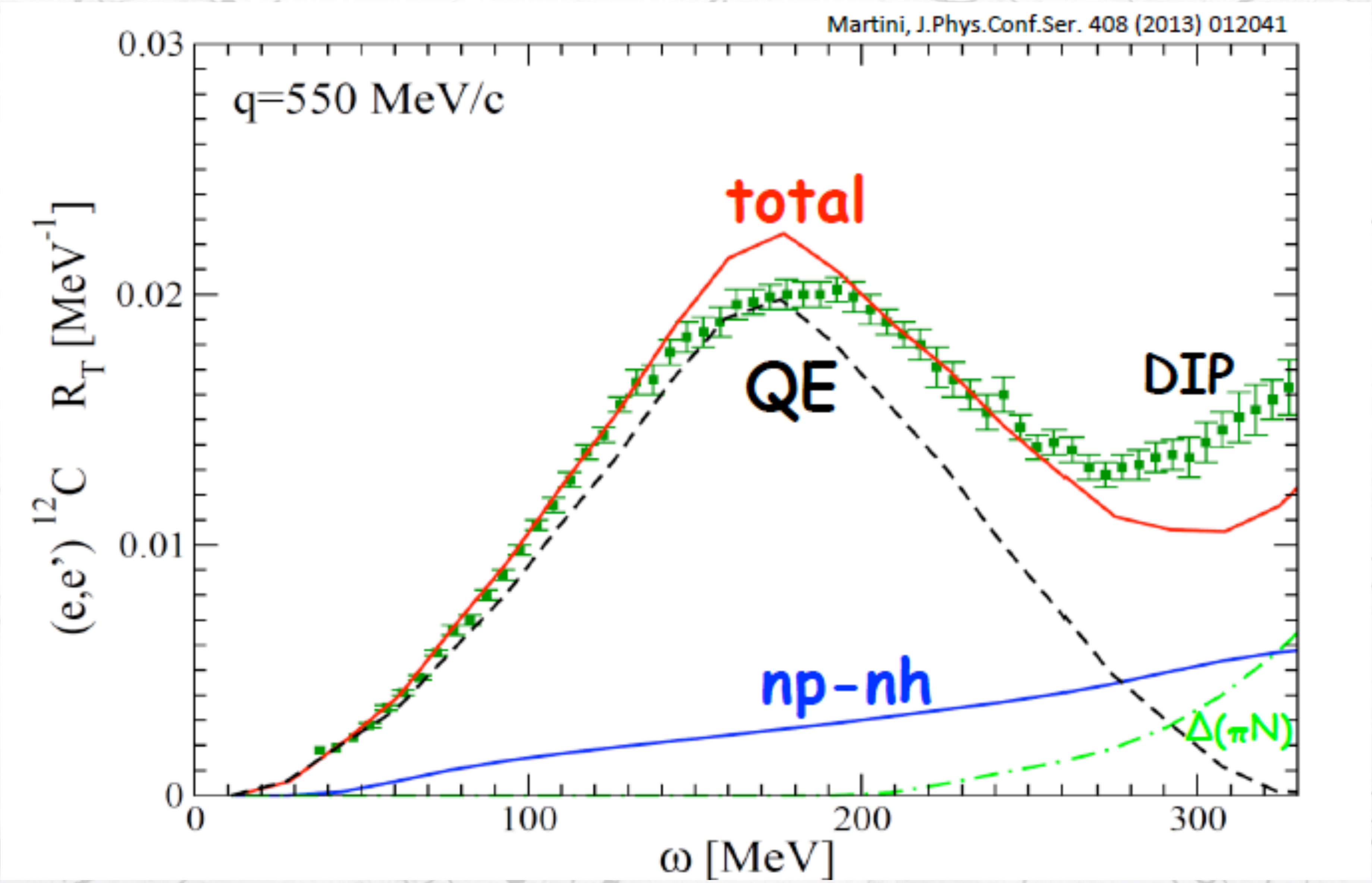
J. Nieves et al. , Phys.Lett. B721 (2013) 90-93

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



MiniBooNe

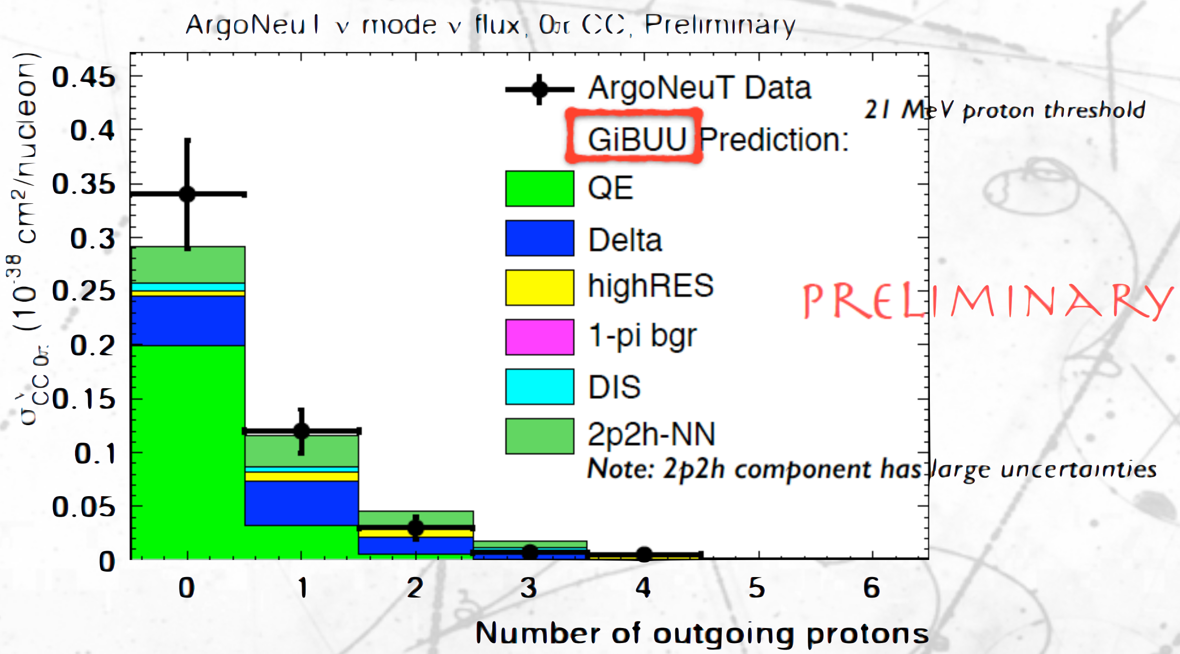
Electron Scattering & 2p2h



- 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.

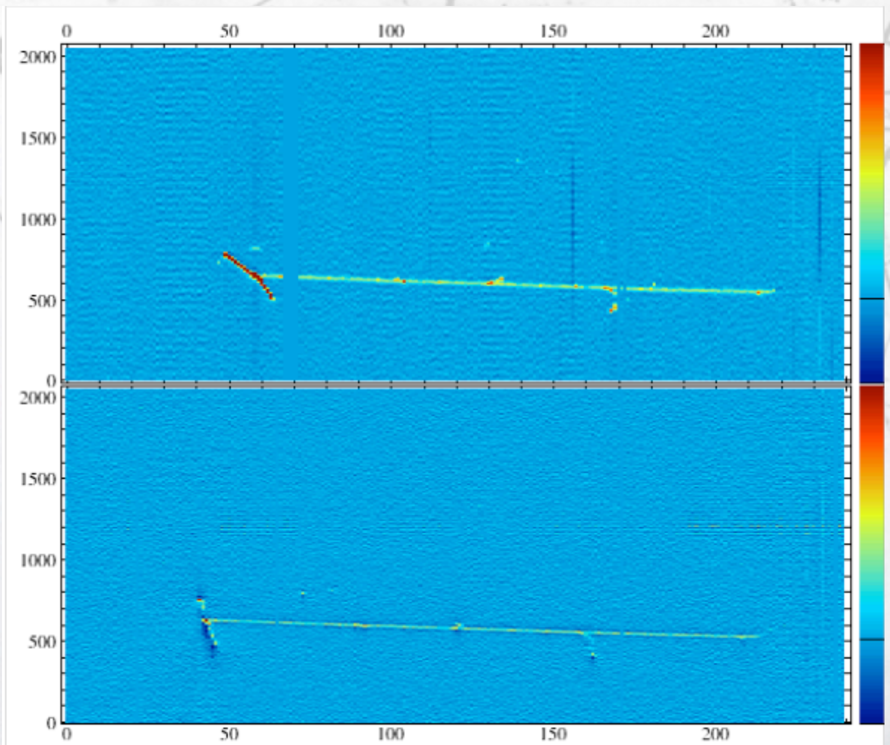
Search for 2 proton

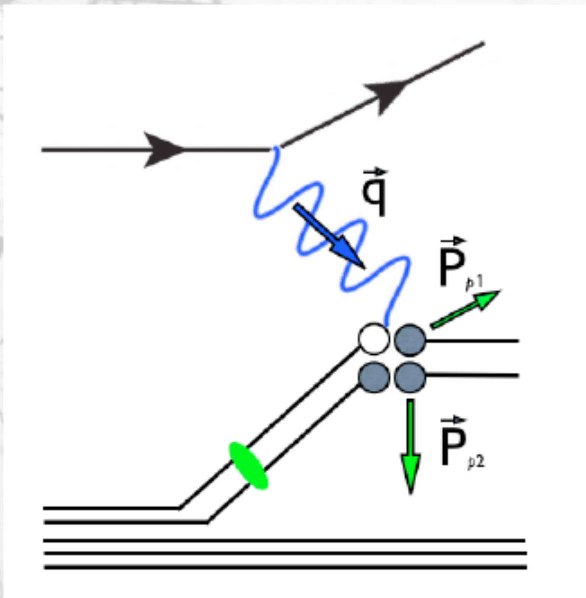


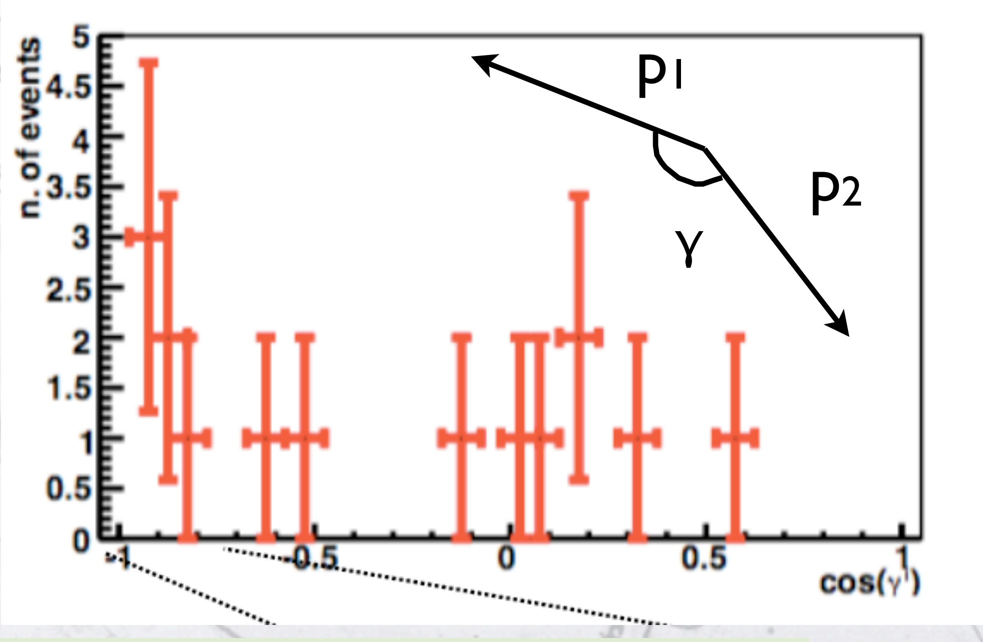
- LiqAr ArgoNeut has bubble chamber imaging capabilities to look into final states.
- It has first indications of correlated final state protons.
  - Spectral functions ?
  - 2p2h ?

Nuint'14

Strong debate @ Nuint'14

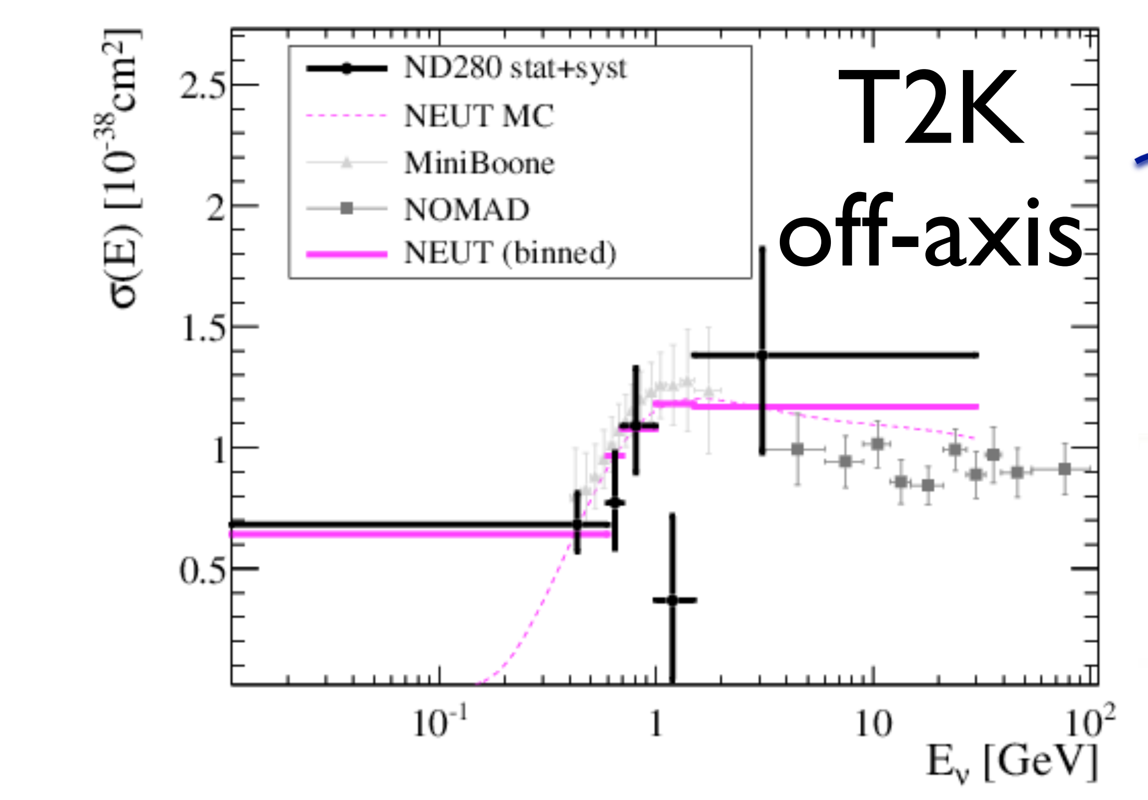




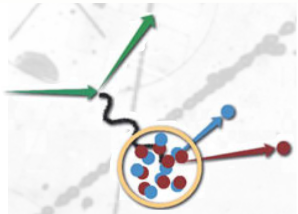


μBoone starts data taking soon!

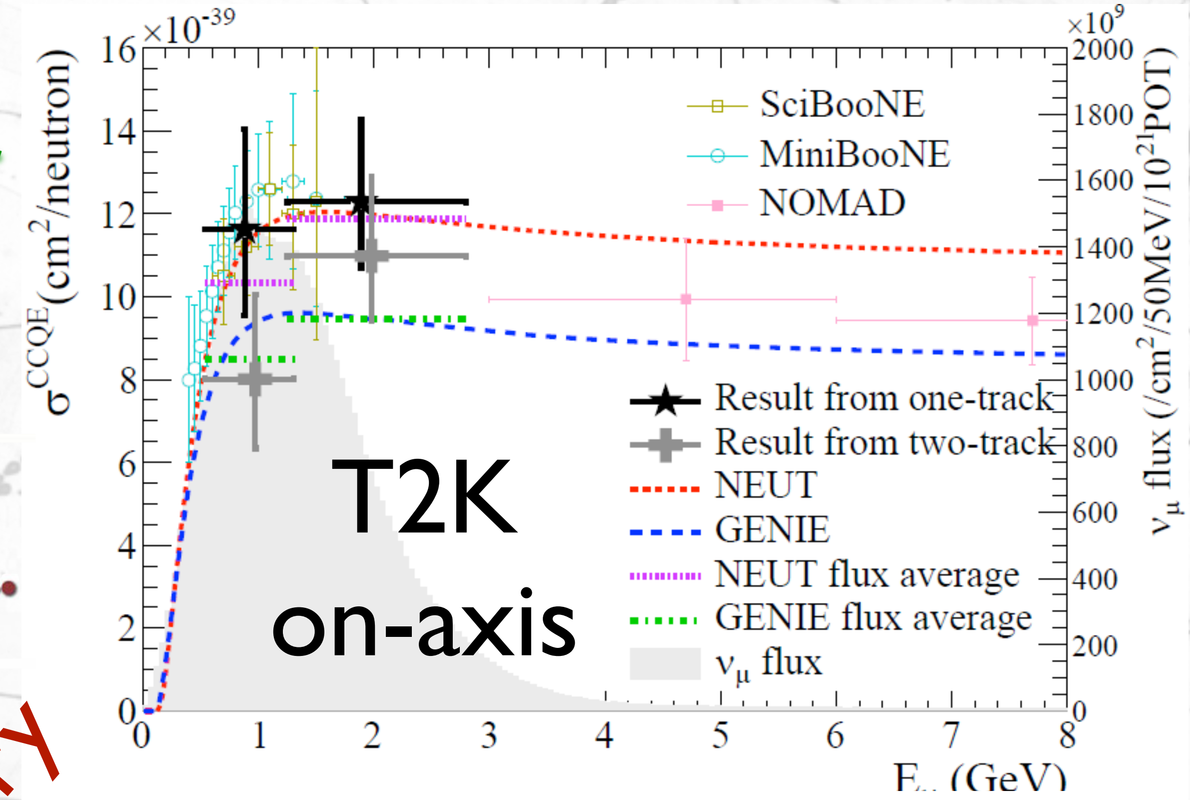
Other CCQE



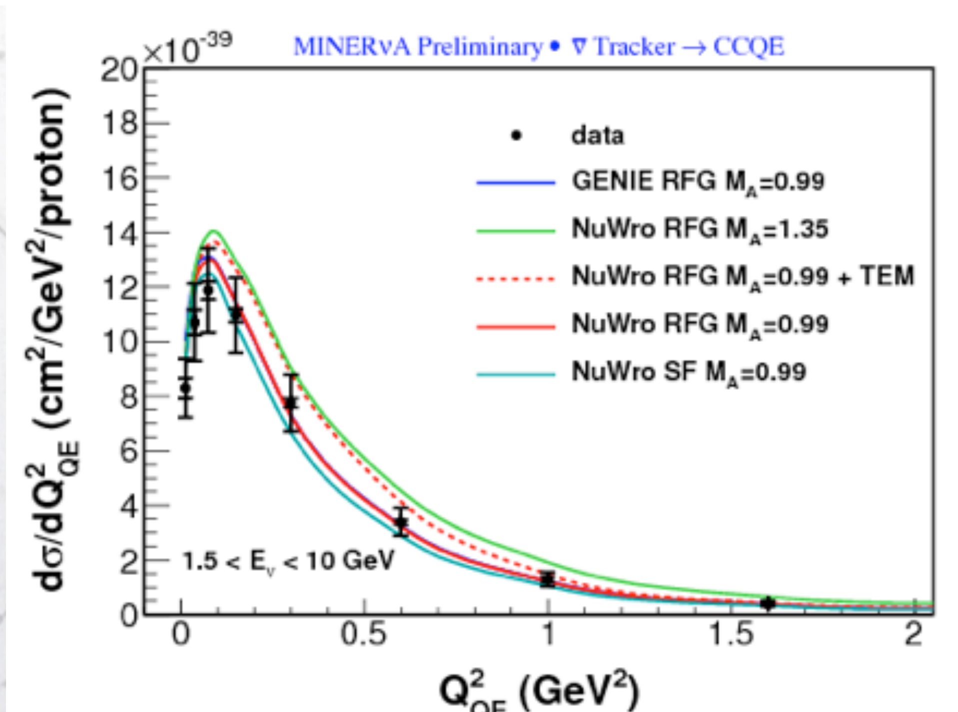
T2K



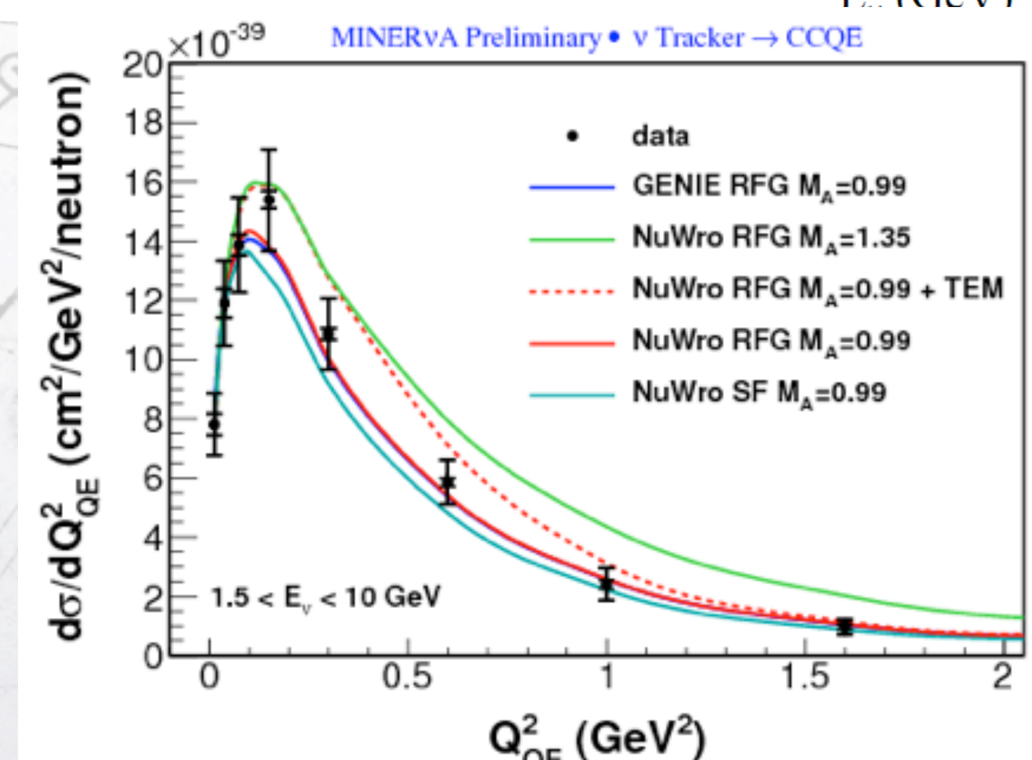
Nuint'14



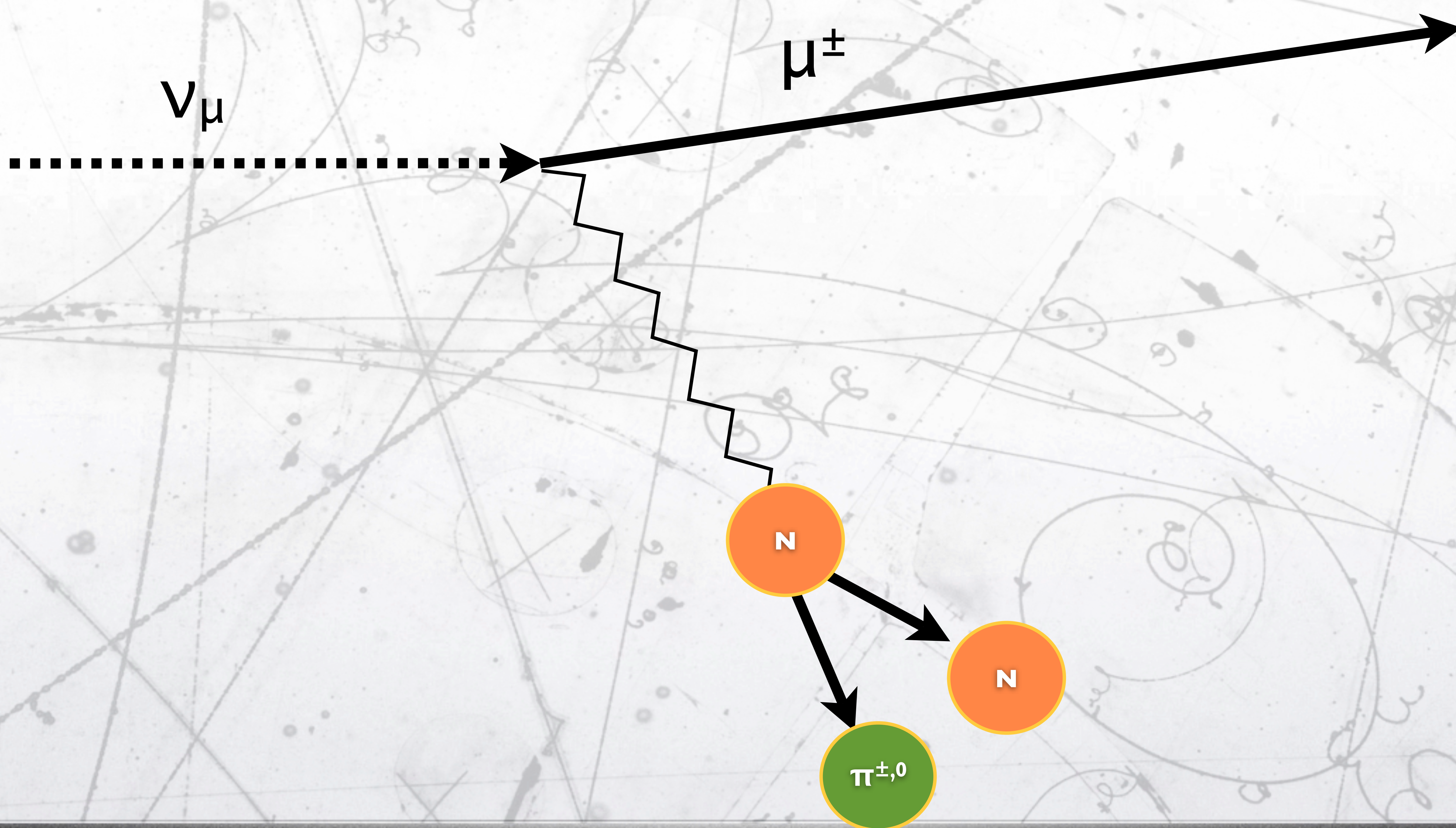
Preliminary



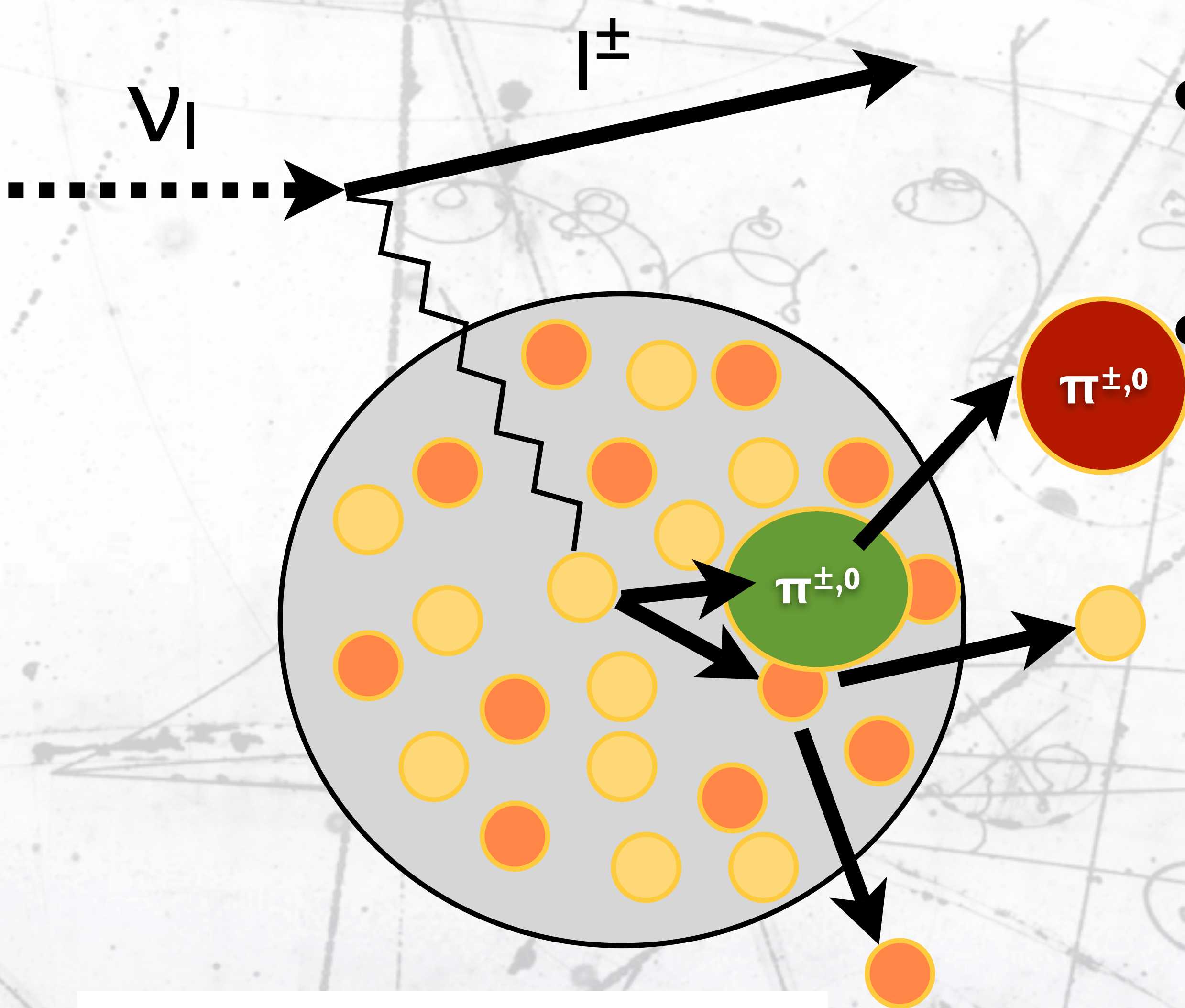
Minerva

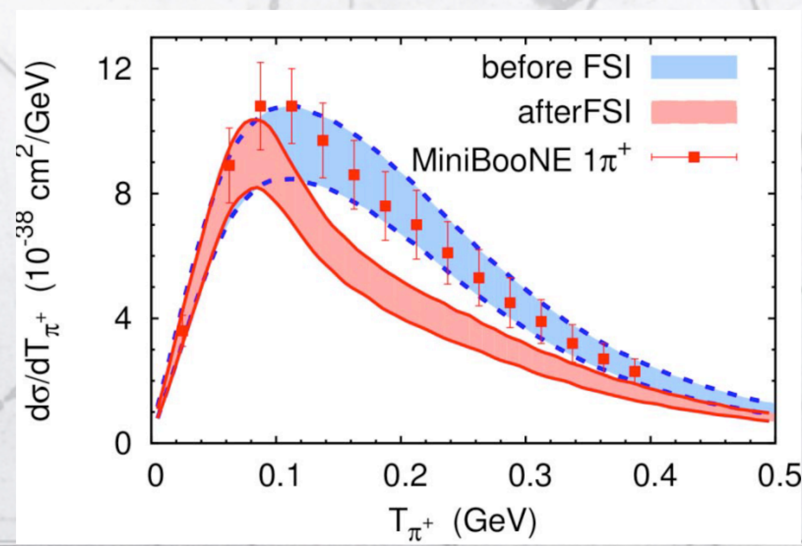


CC1π



Signal definition





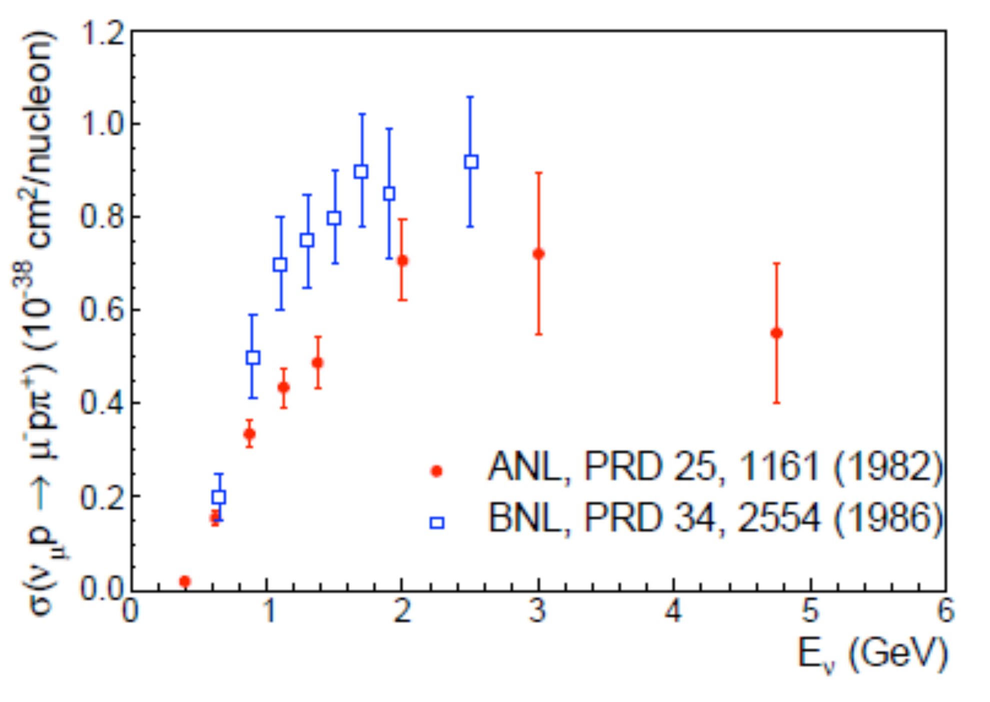
FSI is large

- Final state interactions alters the final state hadrons.
- Experiments make measurements for pion production:

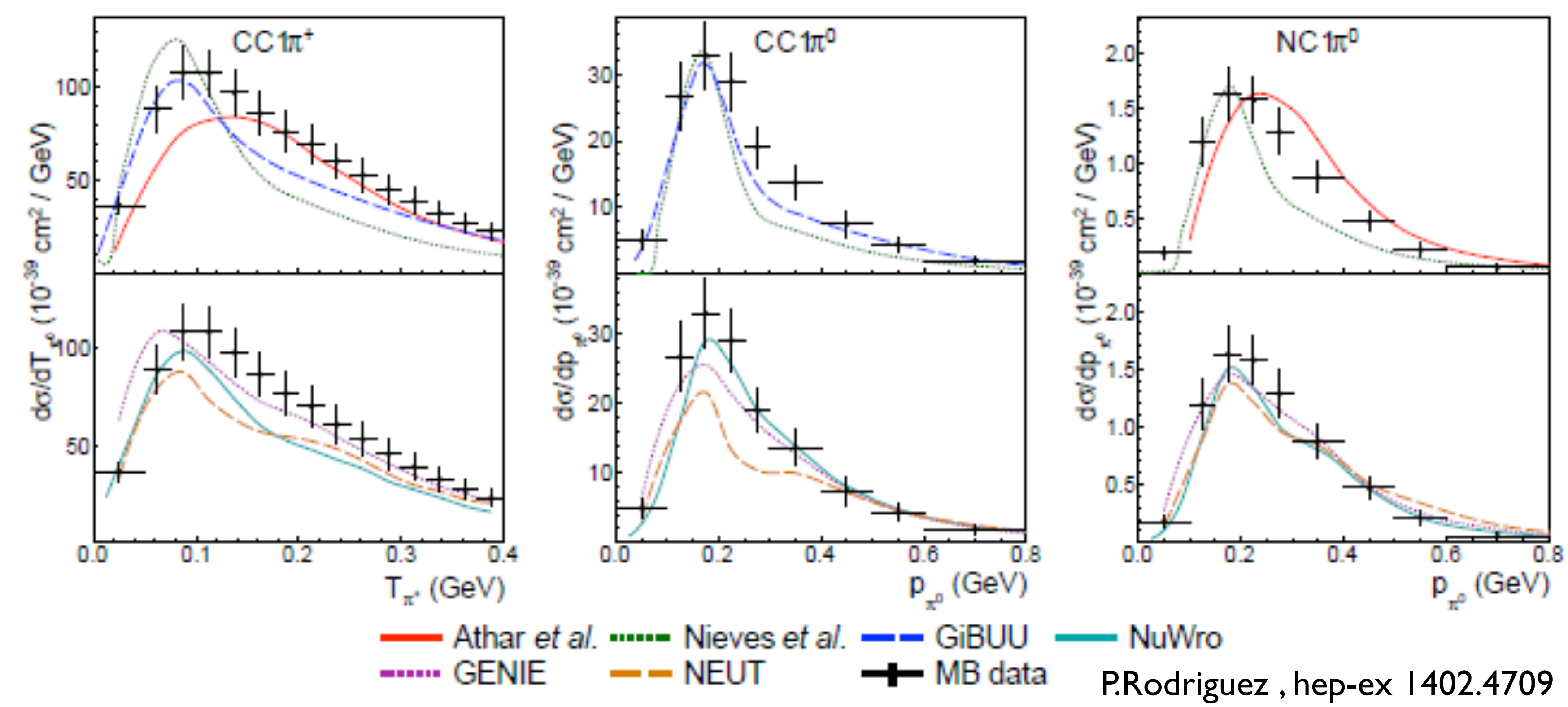
- @ nucleon level.
  - theoretically easy.
  - FSI correction by experiments, difficult to undo.

- leaving the nucleus.
  - theorist need FSI model.
  - no experimental modelling bias.

$CC\pi^{+,0}$ data



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



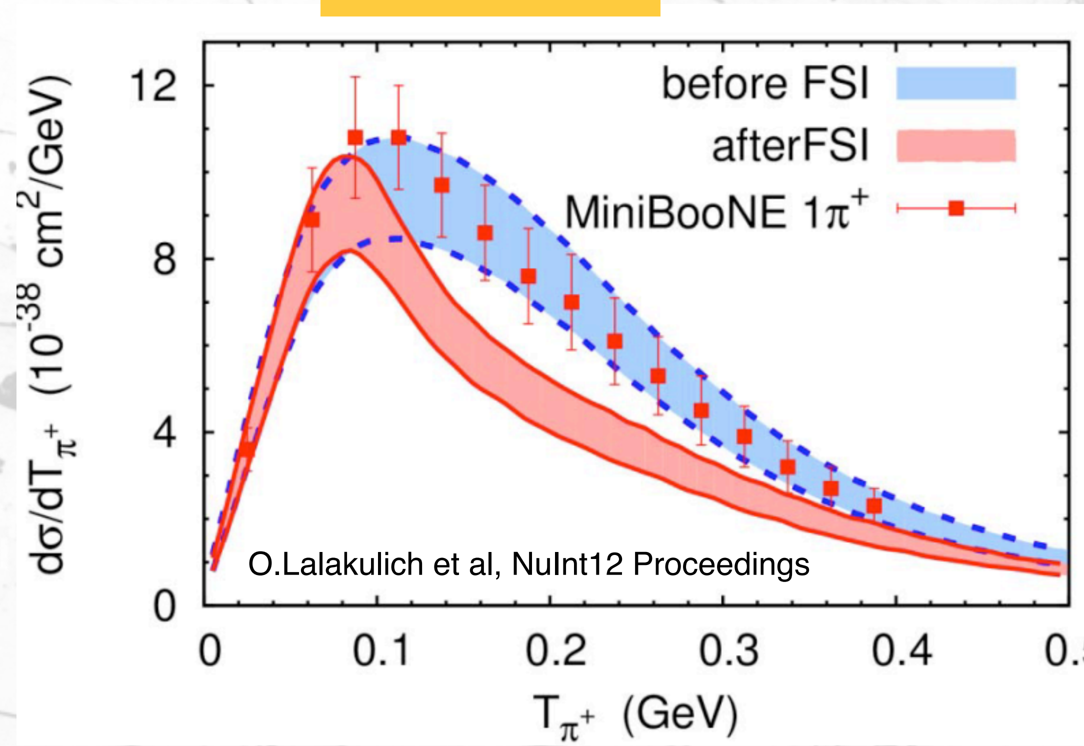
P.Rodriguez , hep-ex 1402.4709

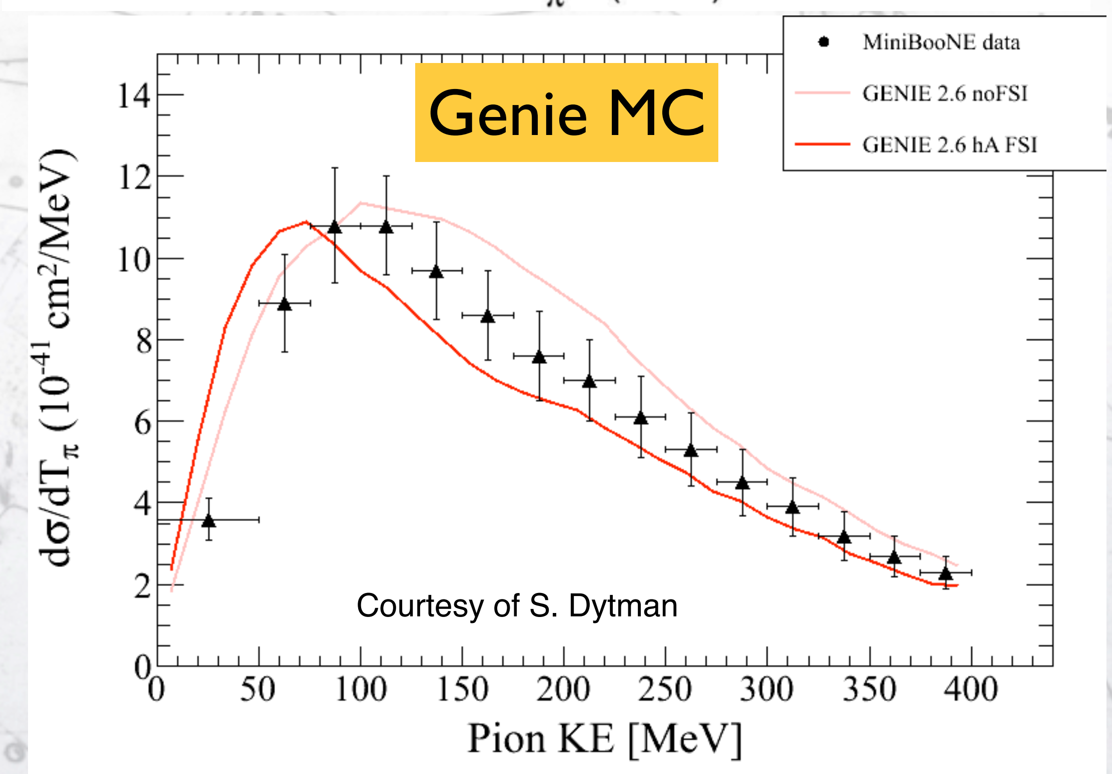
- Models are not able to describe CC π+ π0 and NCπ0 together.

CC 1π

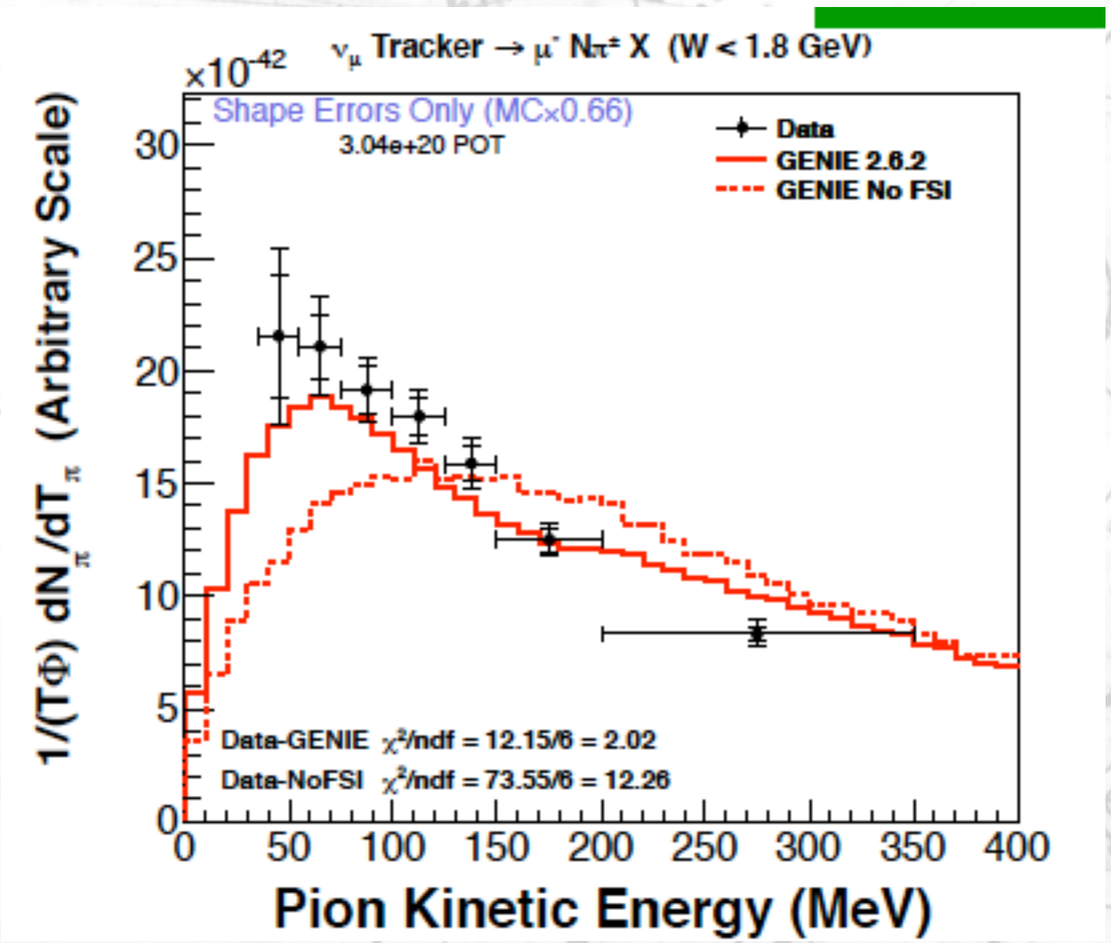
- It is more complex than CCQE. Not very well understood:
  - $C^A_5(0)$,
  - non-resonant+ interference,
  - FSI,
  - transition to high w resonances.
- It is dominated by MiniBooNE results.
- Problem: very poor agreement with MC predictions:
  - Data "seems" to prefer no nuclear absorption of pions!.

GIBUU MC

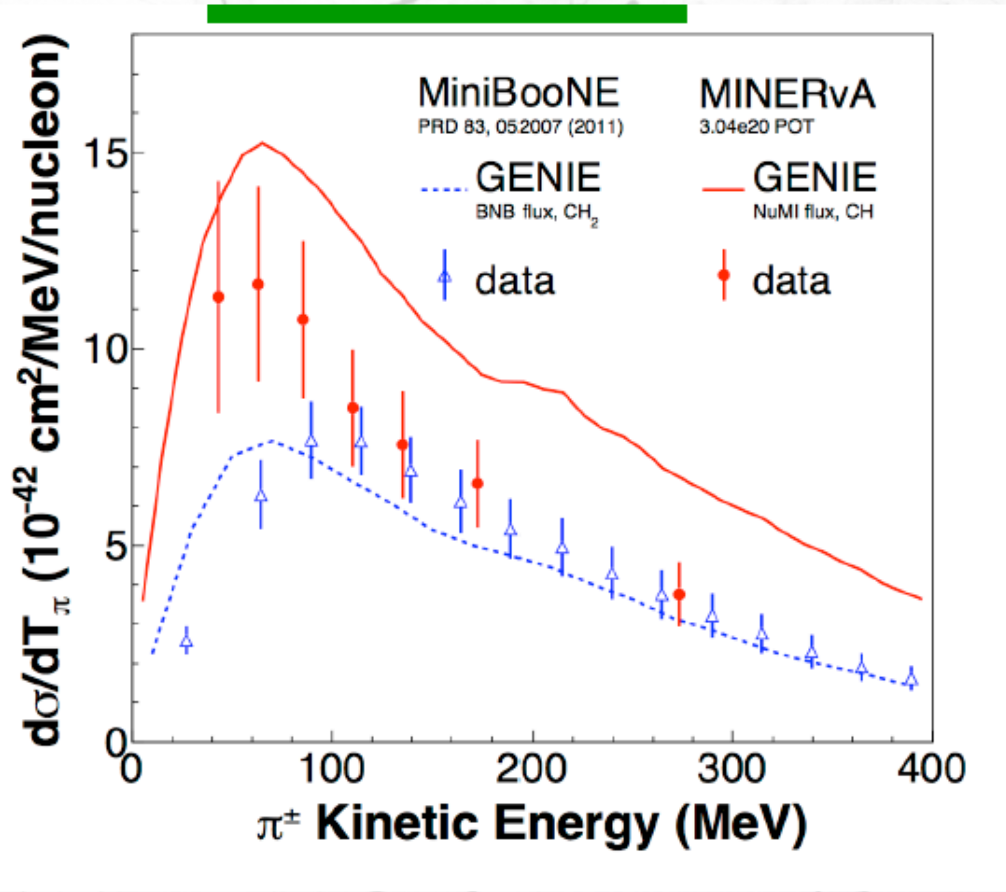




Minerva results



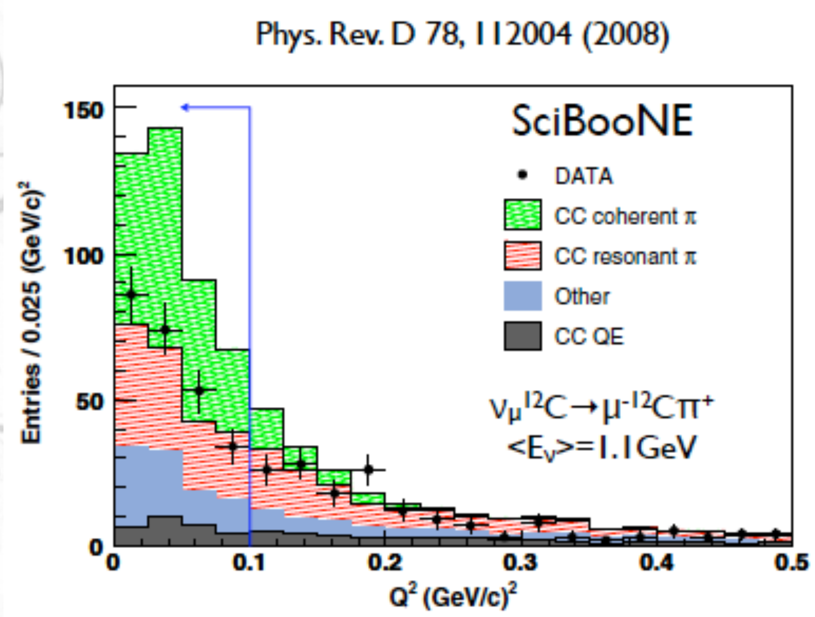

Minerva

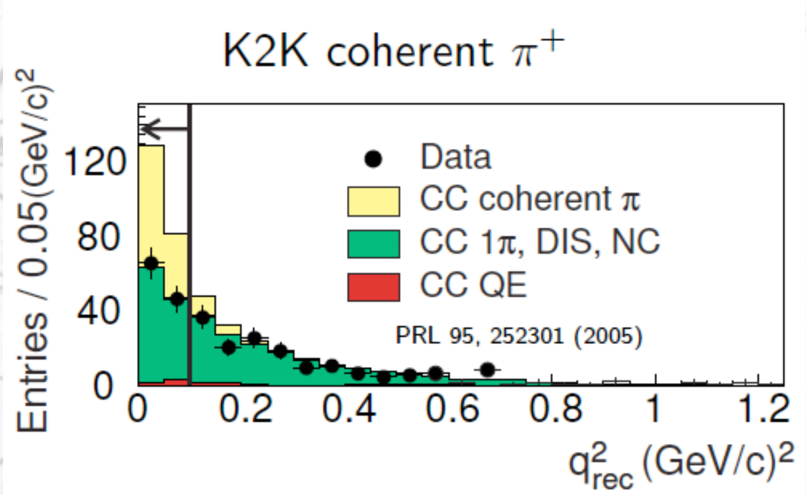


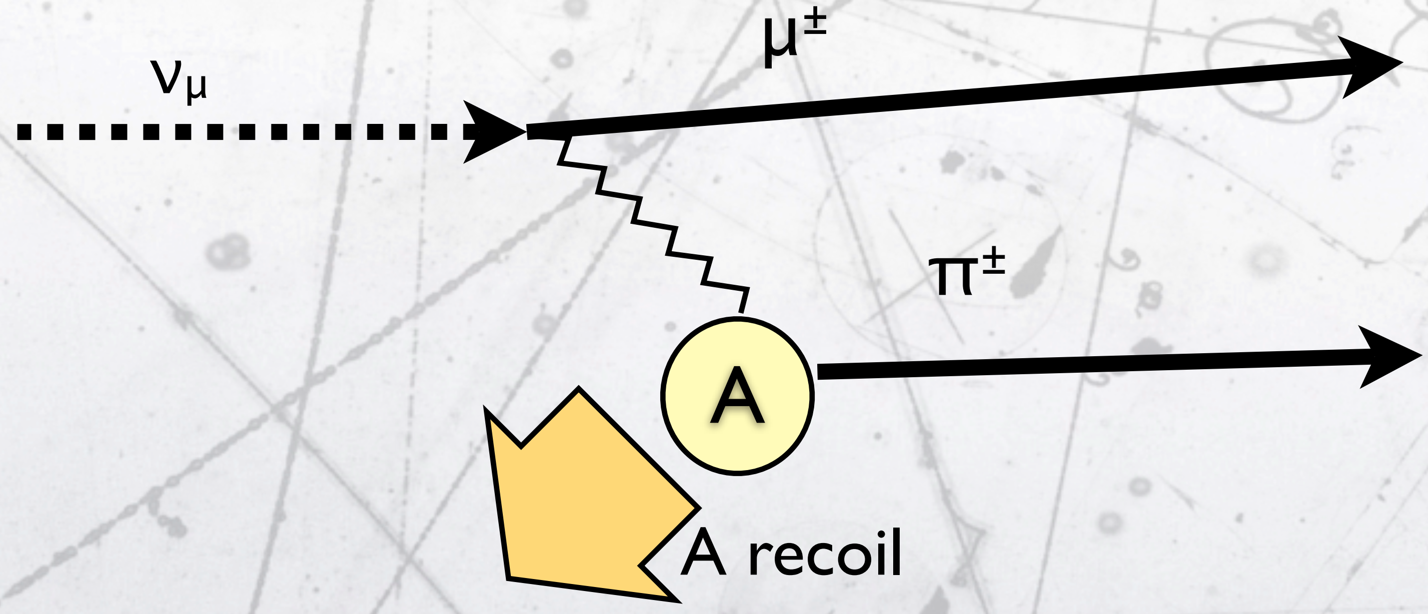
- Preliminary results show agreement with MC predictions & disagreement with MiniBoone data.
  - Minerva and MiniBoone are in a different energy region: backgrounds from large mass resonances?, ….
  - Minerva and MiniBoone detection technique is very different: Signal definition ?

CC 1π coherent

- The CC1π coherent has been an issue in neutrino interactions since a decade:
  - proposed to explained the deficit at low q^2 at K2K.
  - 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.





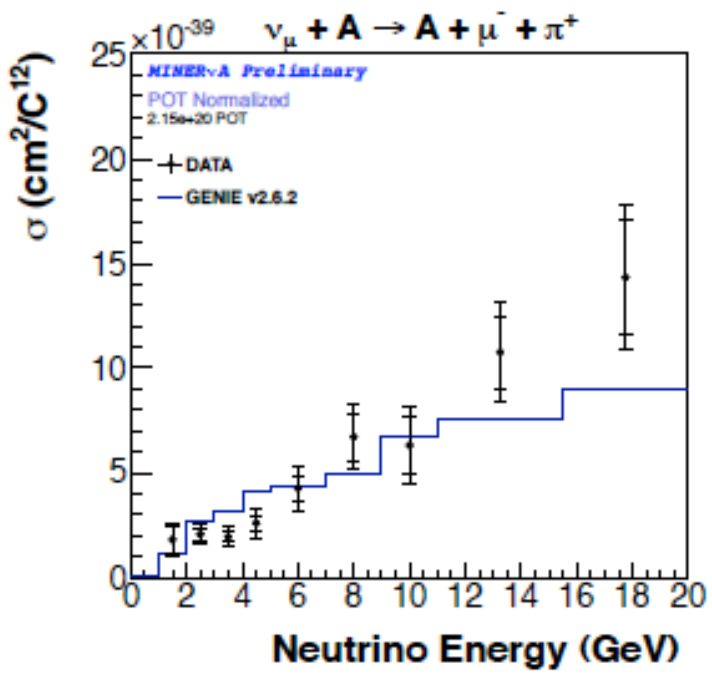


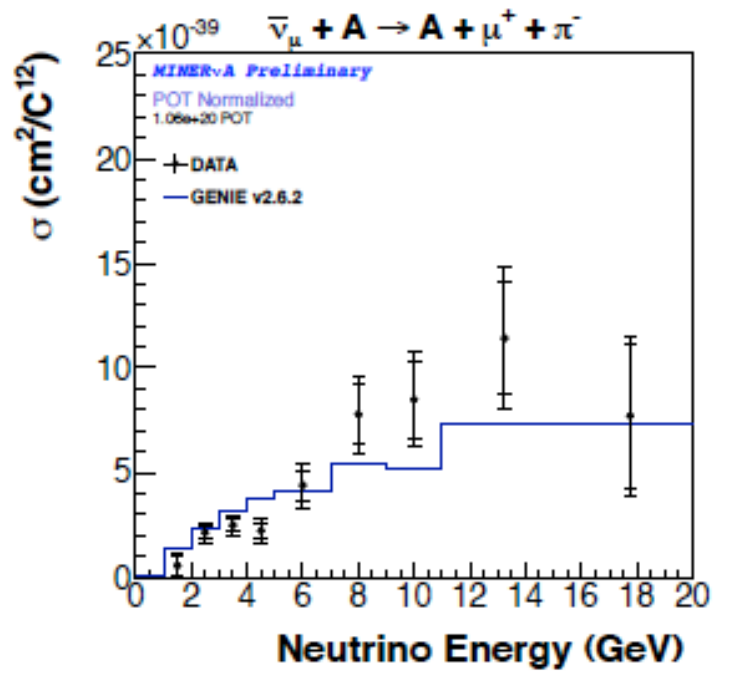
Low nuclear recoil (t)

No nuclear breakup and no proton (vertex activity)

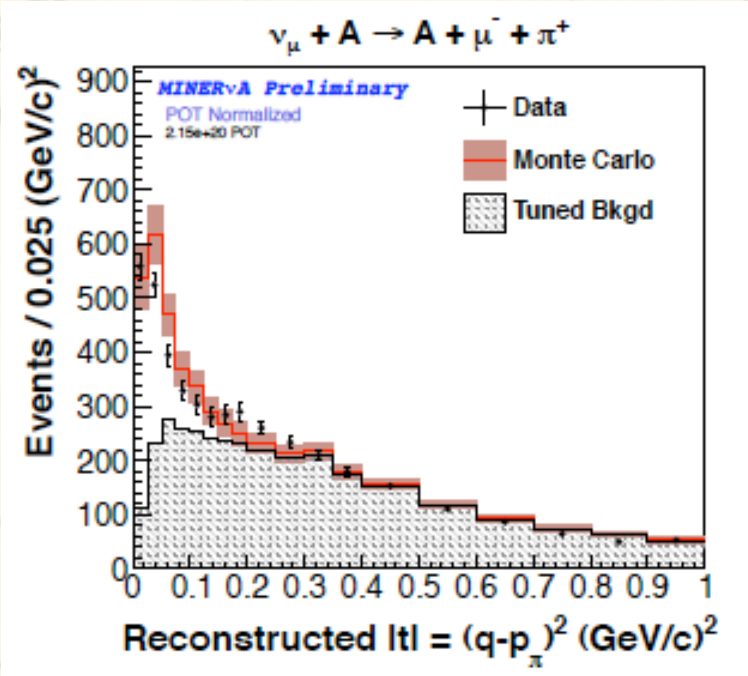
CC 1π coherent

- Minerva from vertex activity & nuclear recoil energy





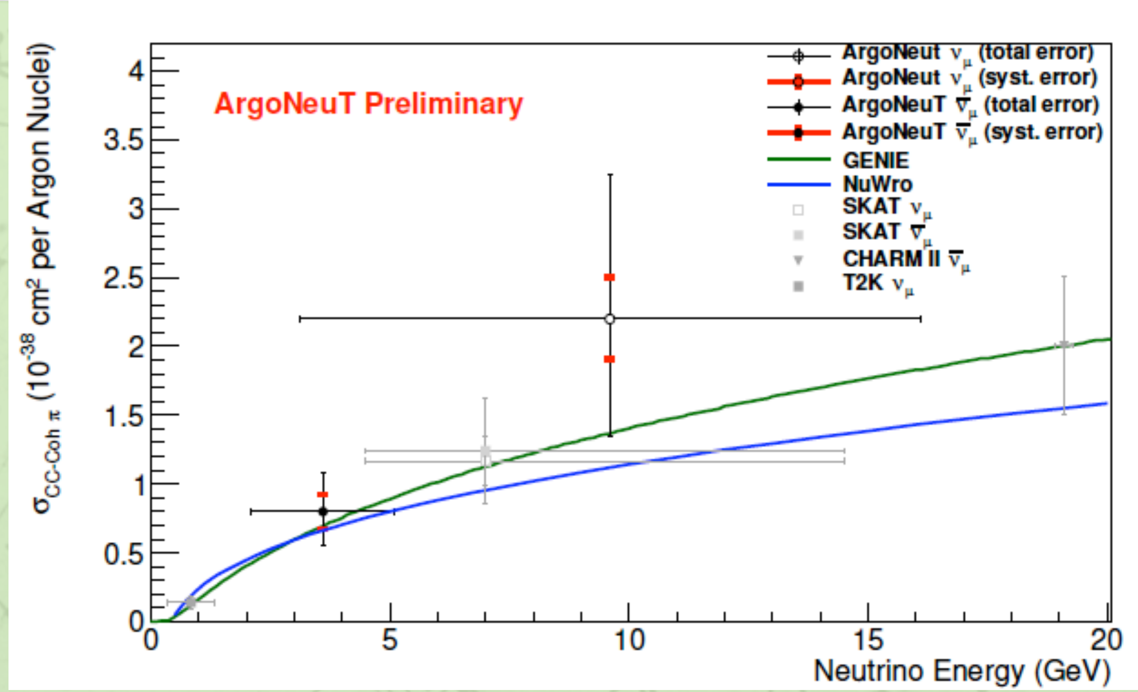
Minerva



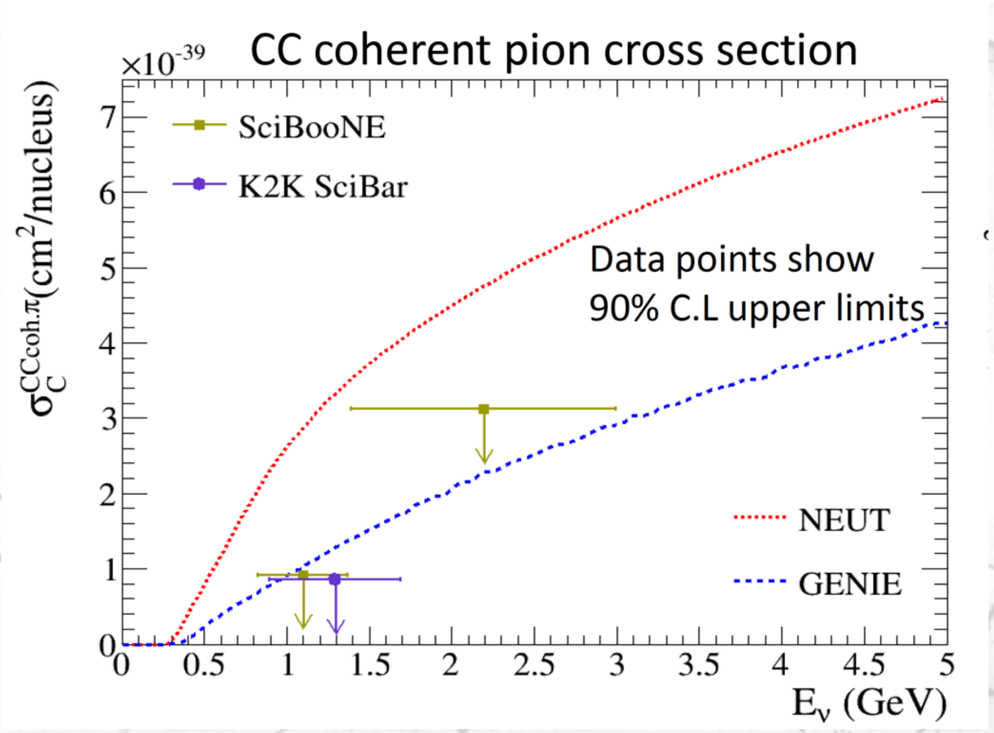
Nuint'14

- ArgoNeut from vertex activity.

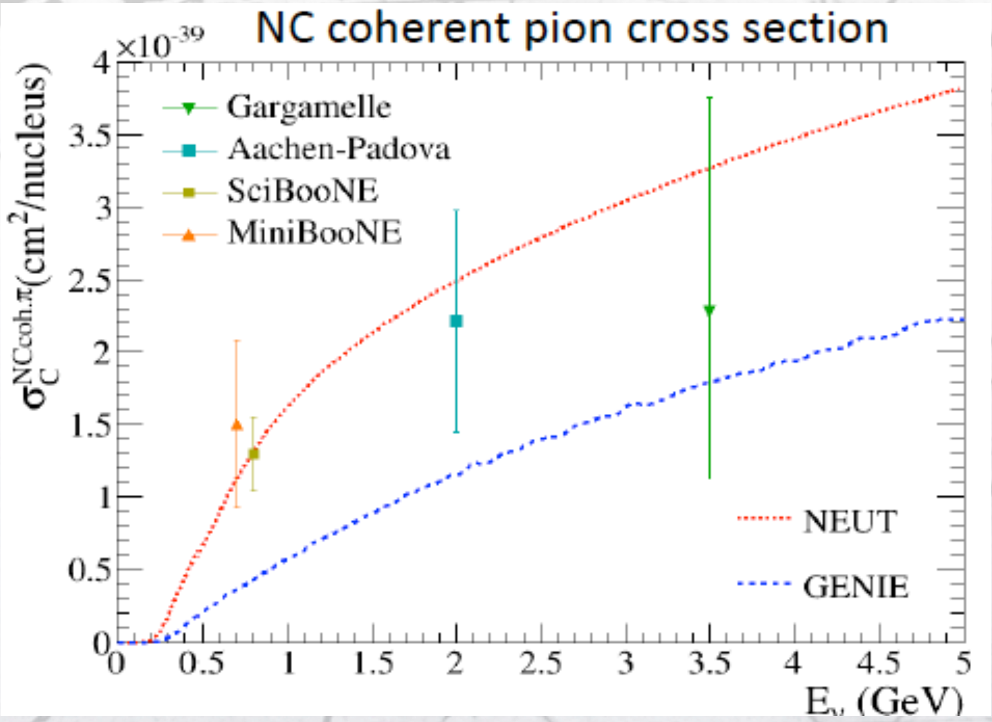
Good agreement with models!

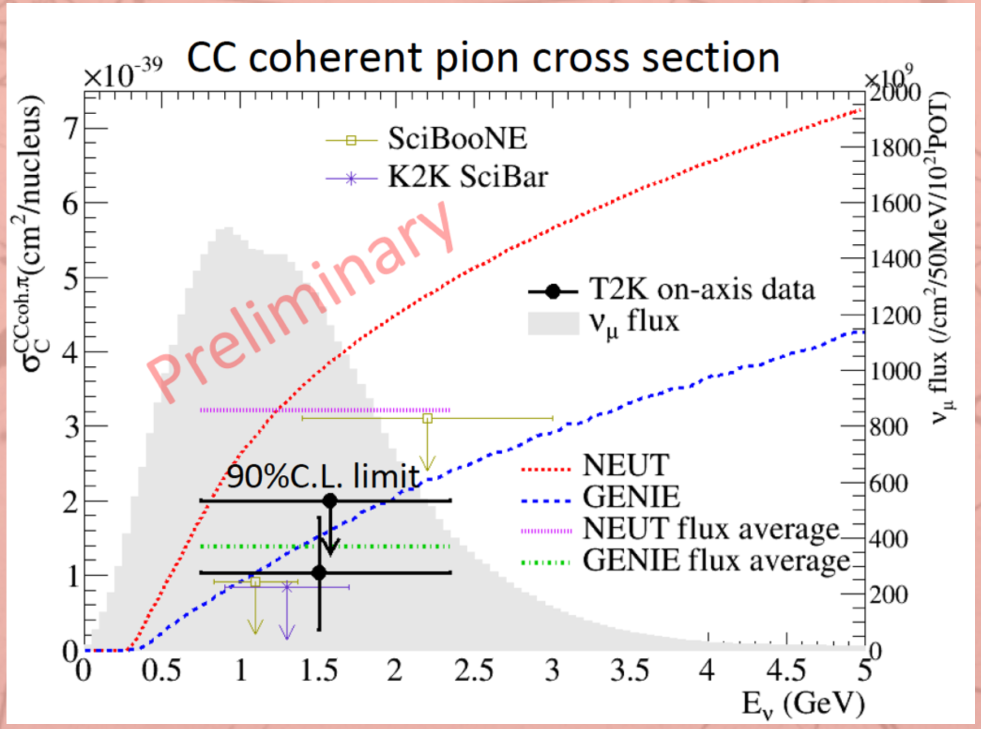


CC 1π coherent



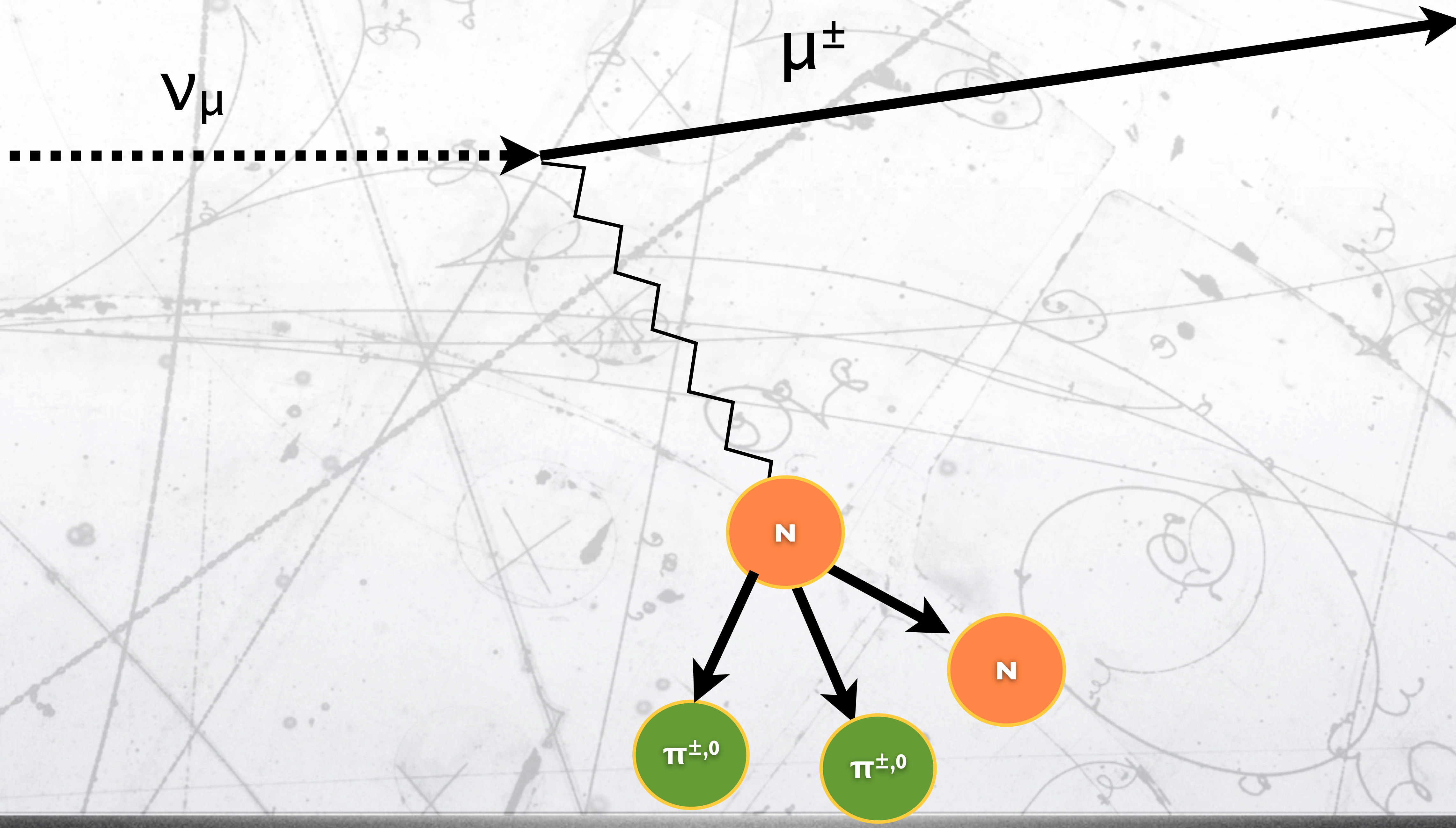
- Problem with models appear E_ν~1GeV:
  - CC-coh not seen this energy.
  - Broken isospin relation prediction
    - CC-coh/NC-coh ~ 2.
- Large systematic errors from bck x-section modelling.





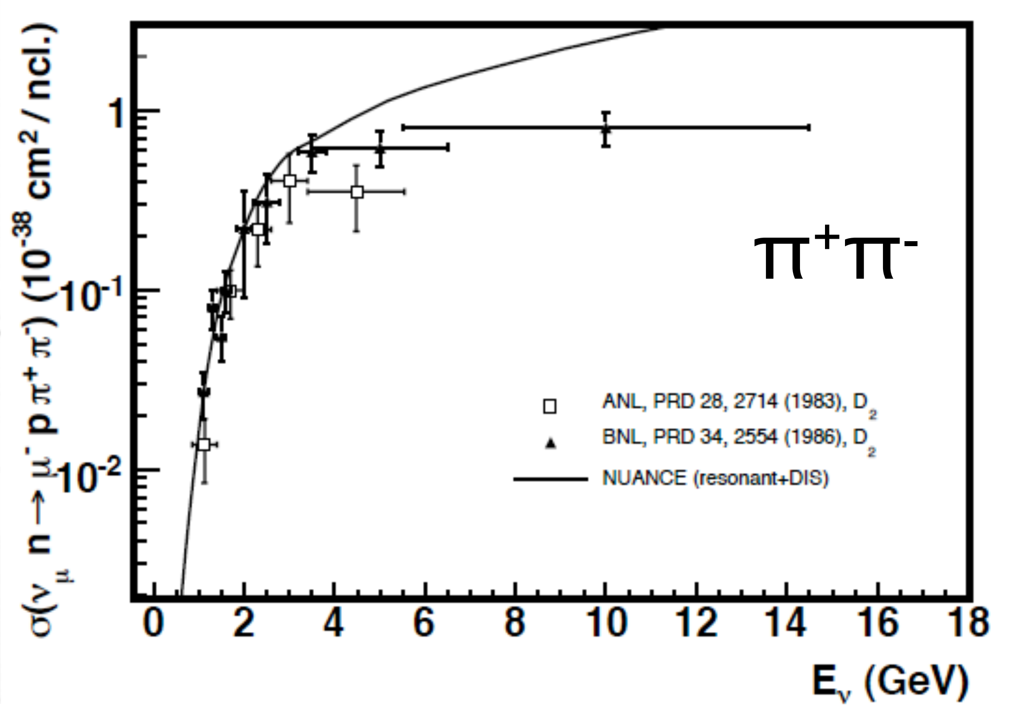
New T2K data with vertex activity

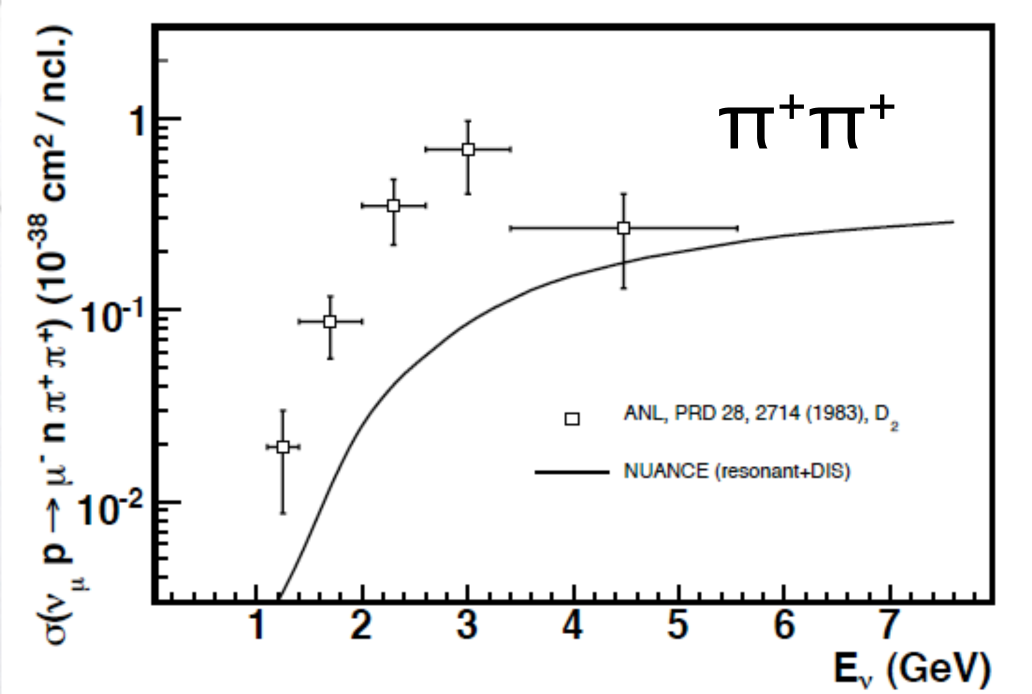
CC-Nπ

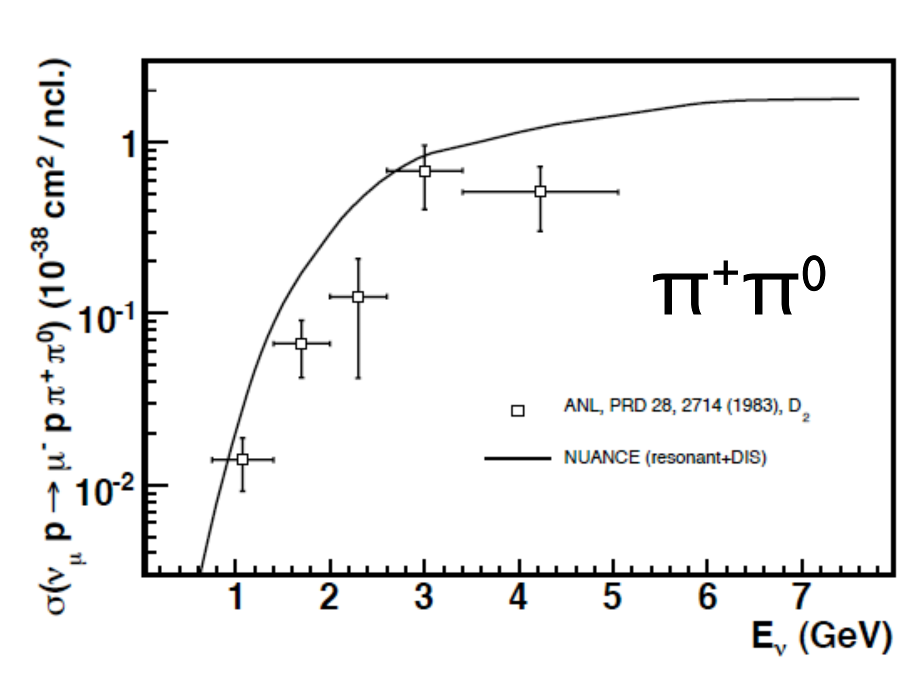


CC-Nπ

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

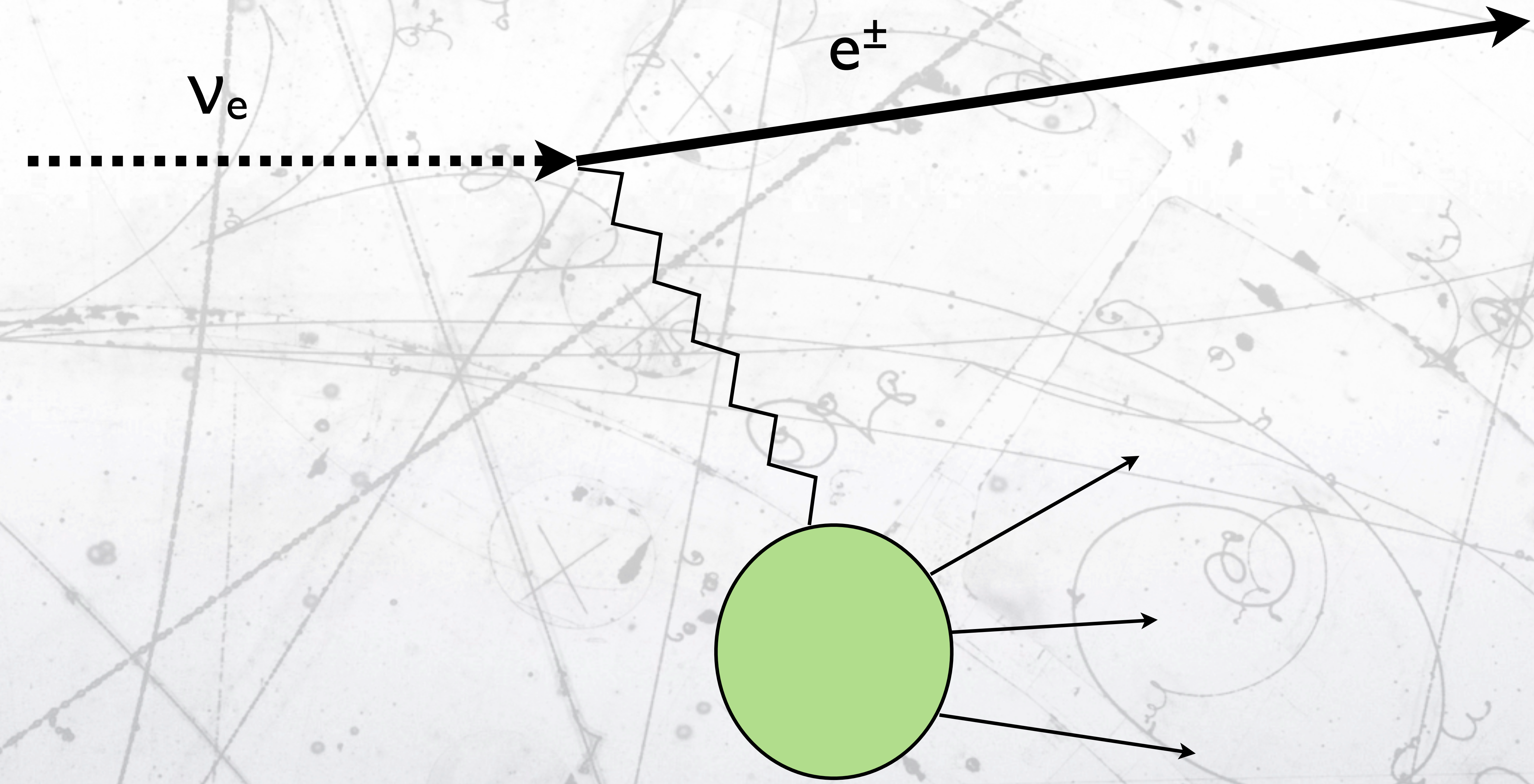




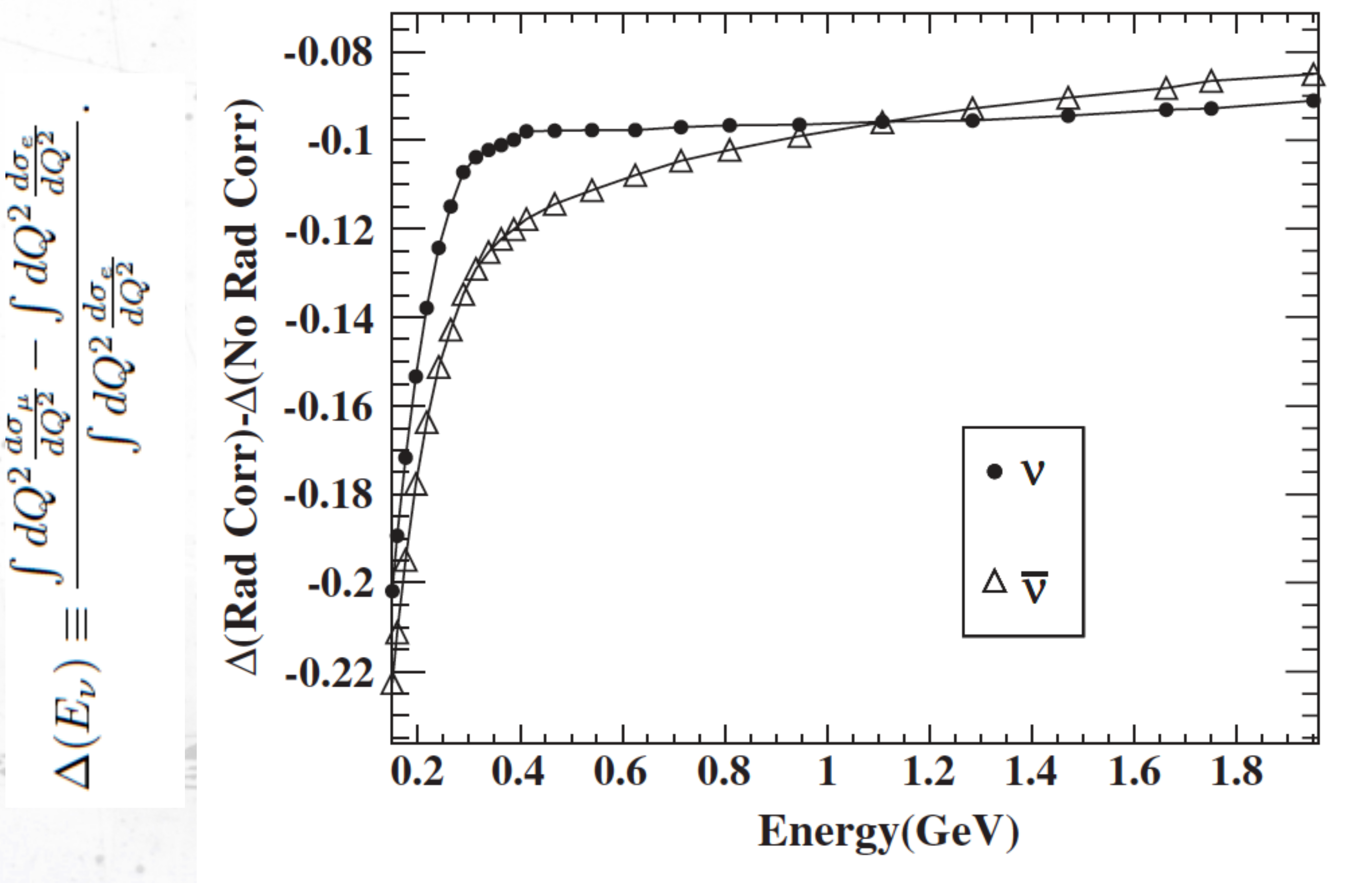


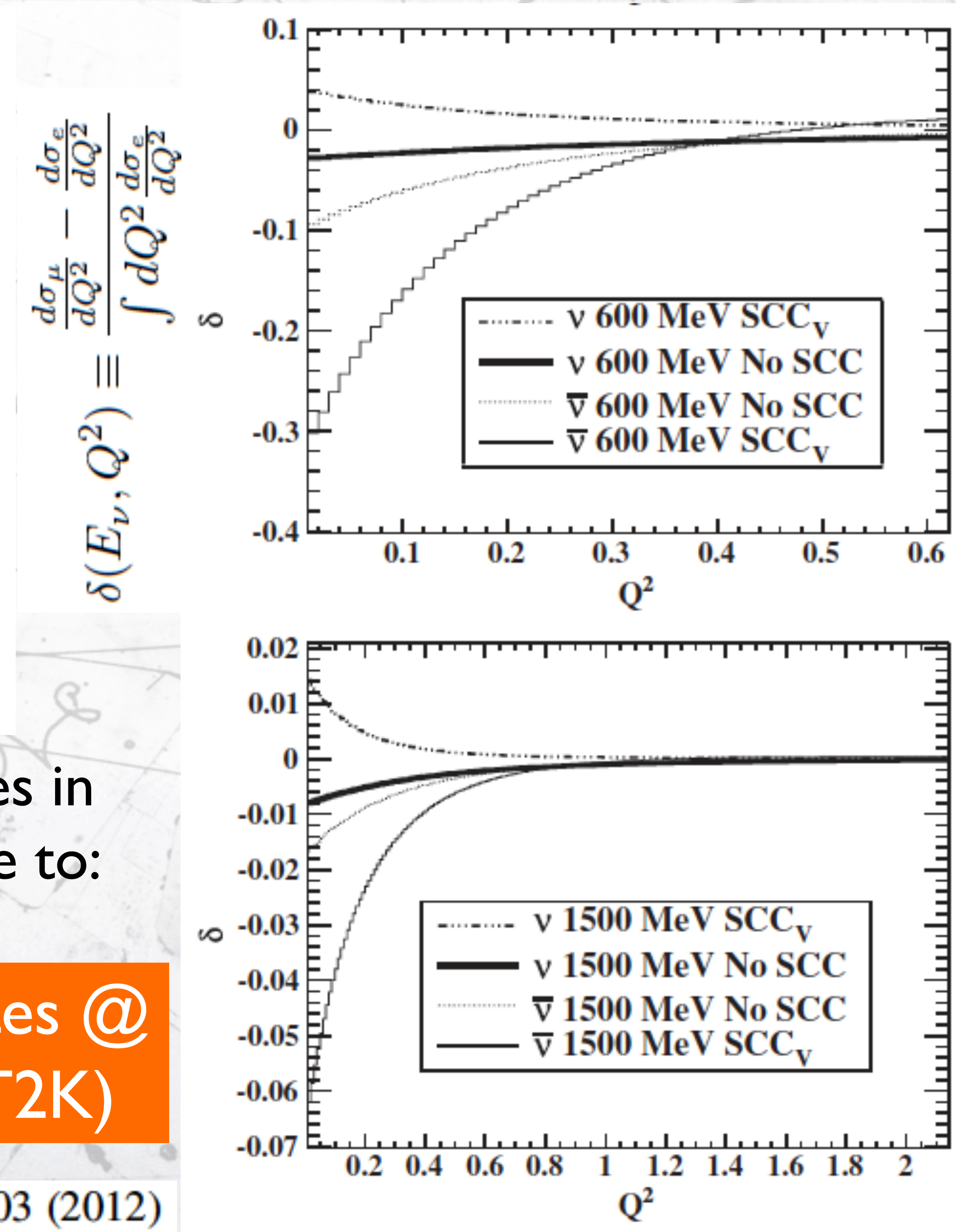
- This is a complex region with contributions from high mass Δ resonances and low ω DIS.
- There is no new data since ANL and BNL back to the 80's.
- No data in nuclei: difficult measurement due to FSI.
- No detailed pion kinematics available.
- Critical for LBNE and LBNO!.

Inclusive CC ν_e



The ν_e problem



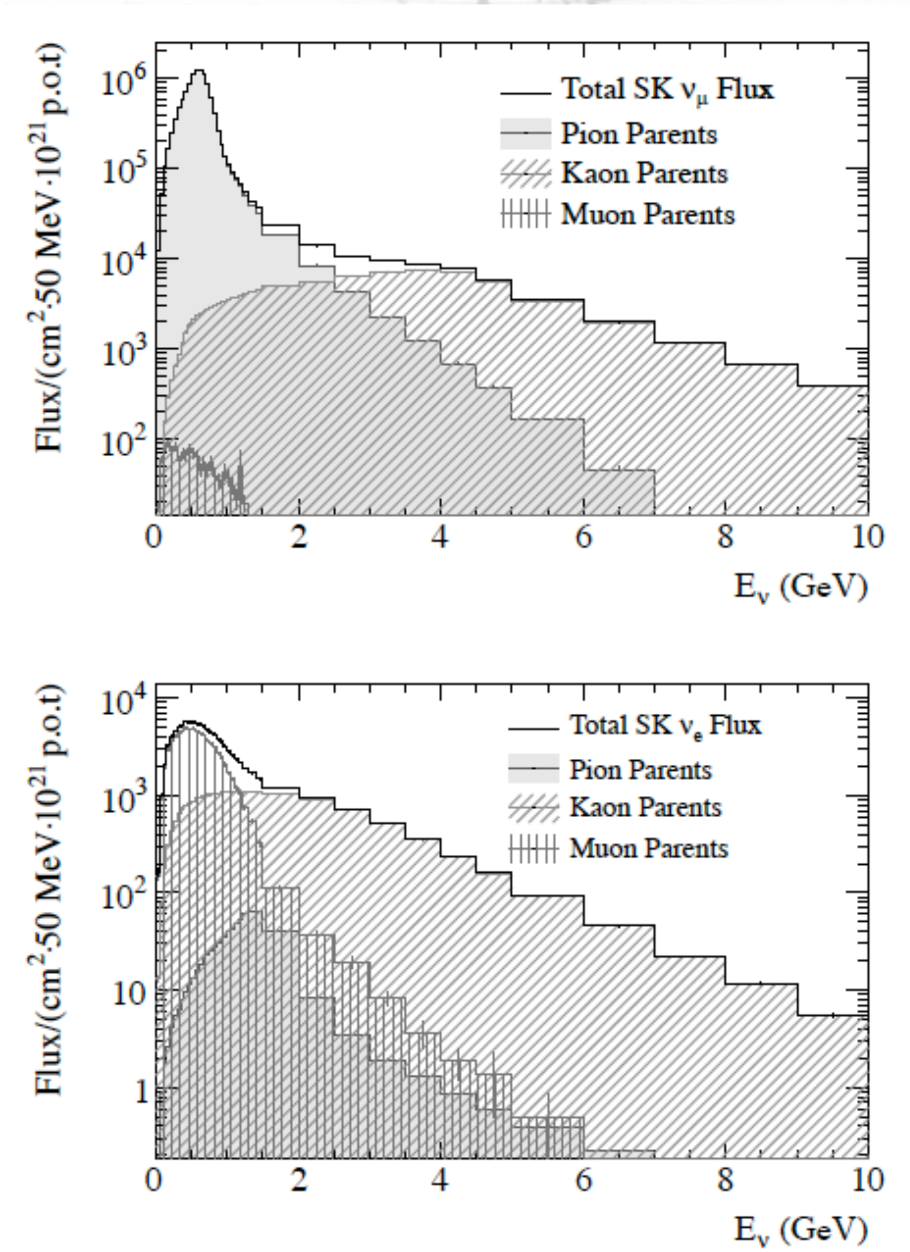


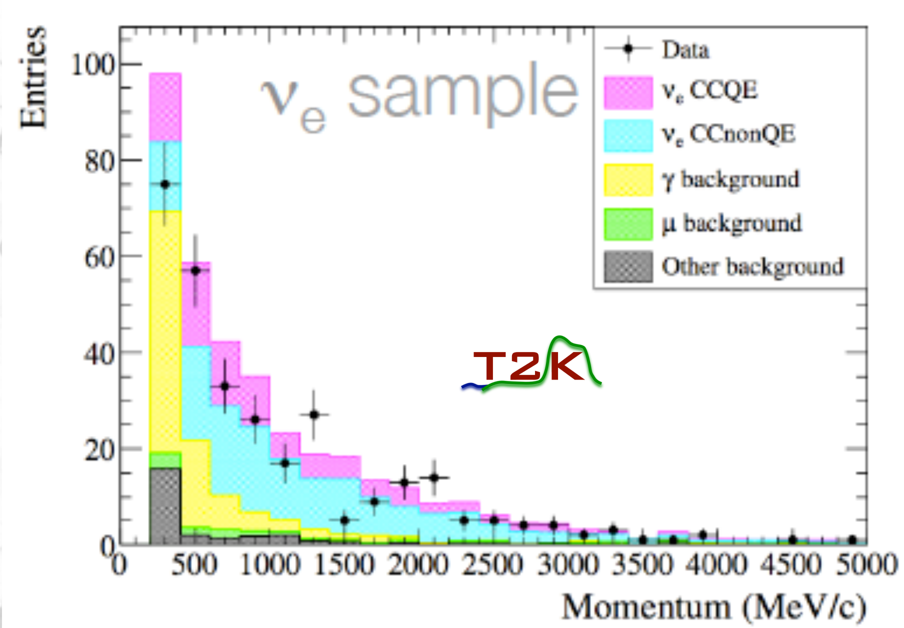
- Calculations show significant differences in the ratio of ν_e to ν_μ cross-sections due to:
  - form factors.
  - radiative corrections.
  - lepton mass.

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

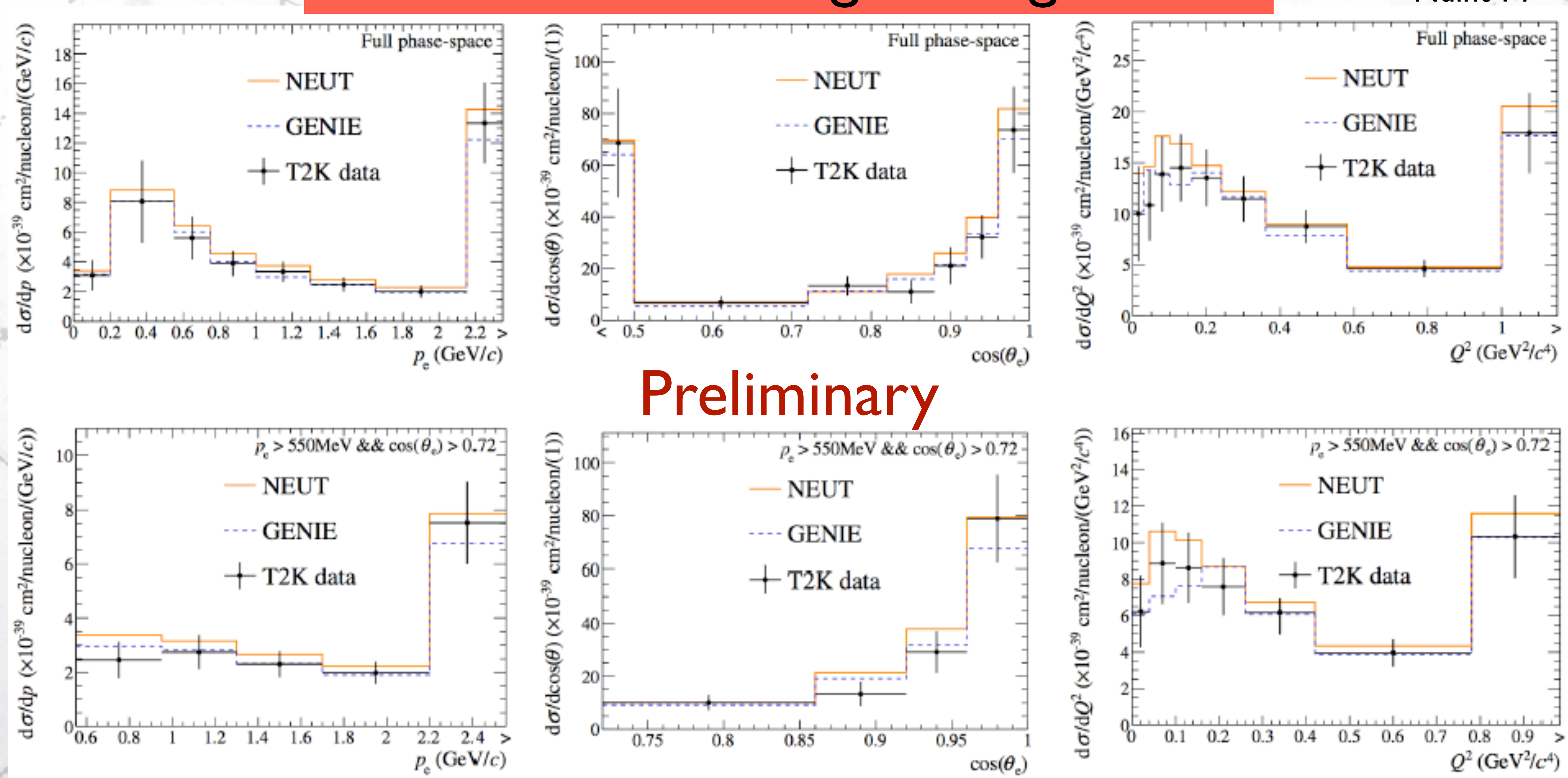
νStorm clean ν_e beam

David Adey poster

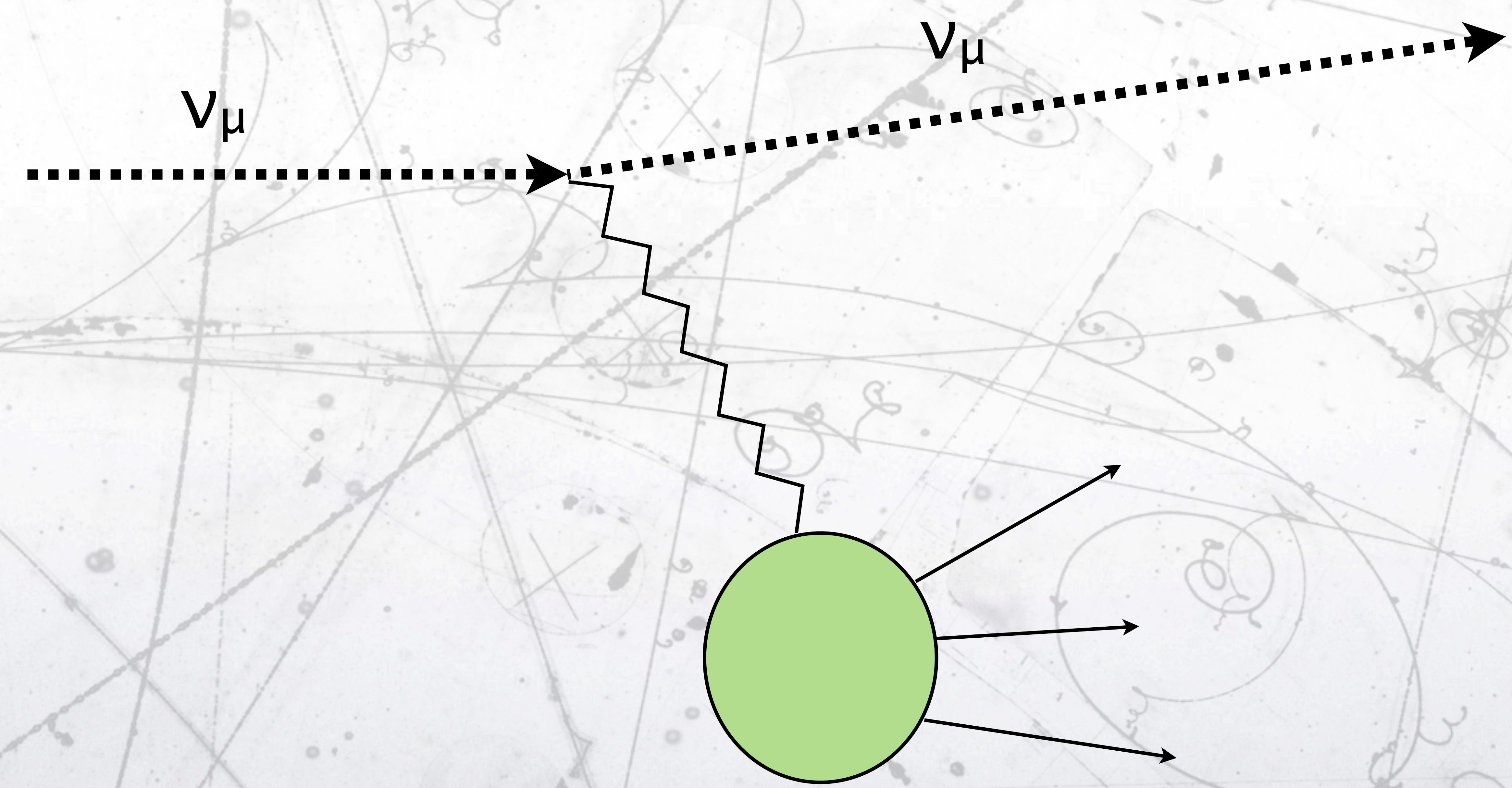
CC inclusive ν_e

First measurement in 36 years!

low statistics & large background!

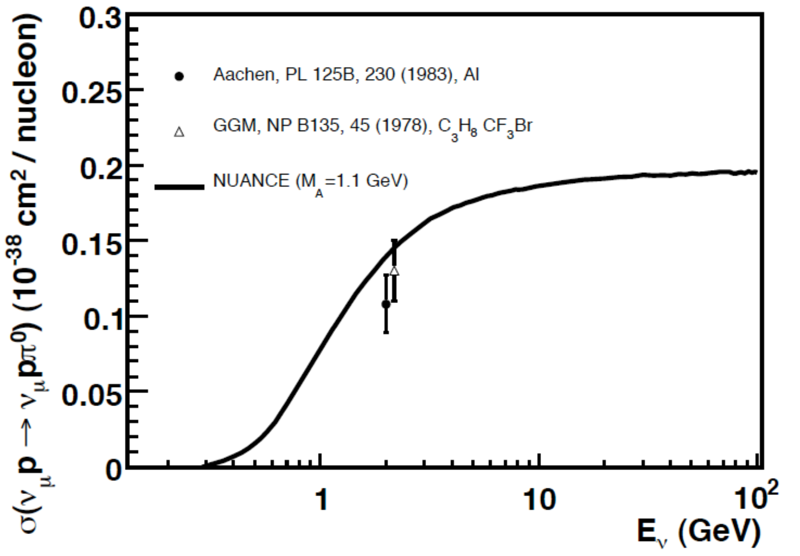


NC ν_μ

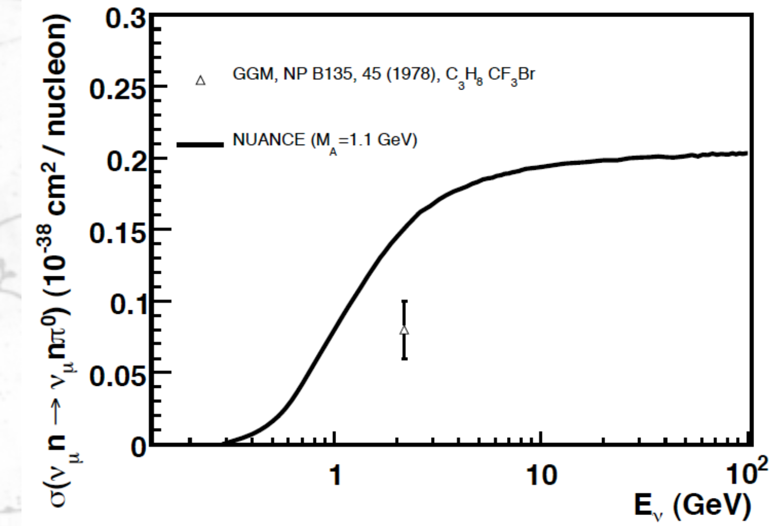


Existing data

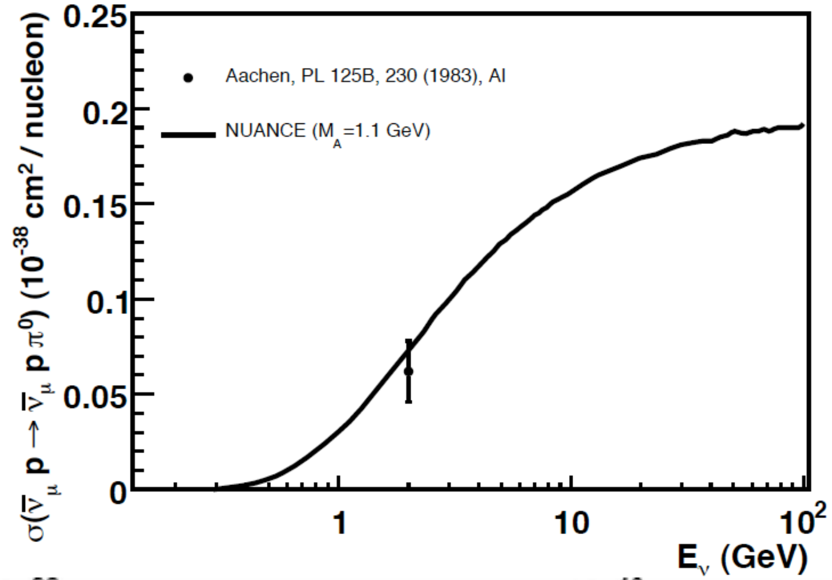
arXiv:1305.7513v1



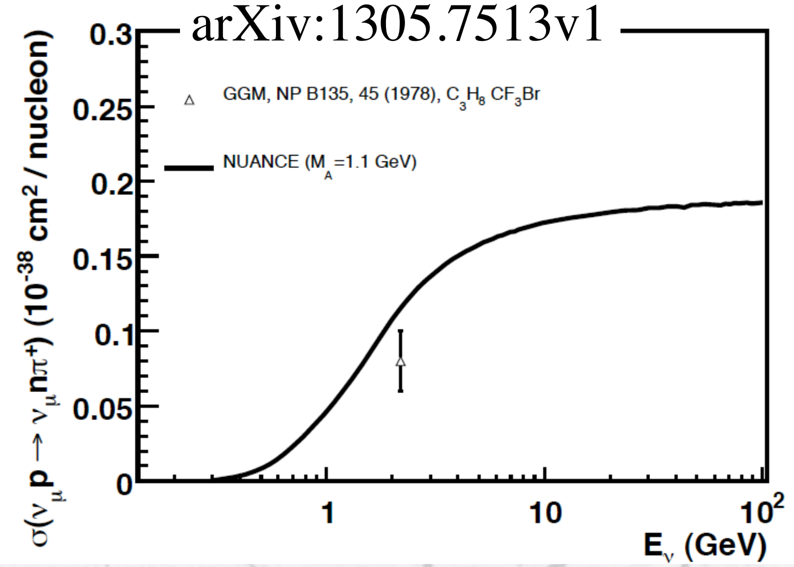
arXiv:1305.7513v1



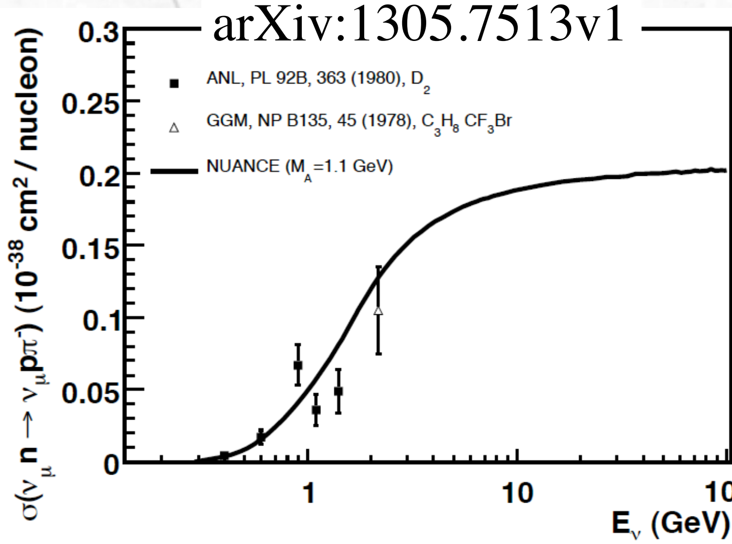
arXiv:1305.7513v1

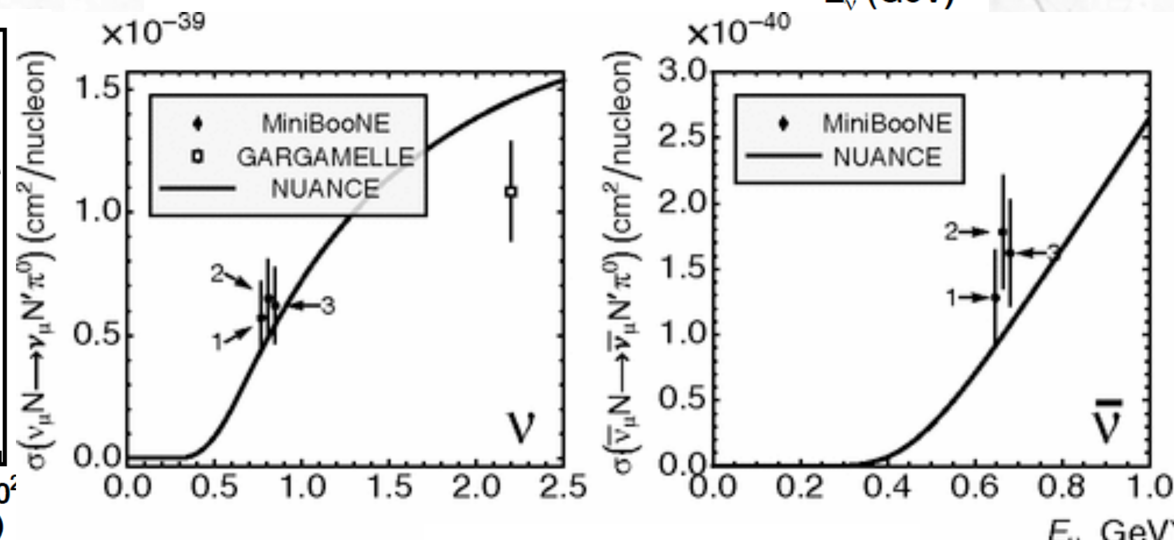


arXiv:1305.7513v1



arXiv:1305.7513v1

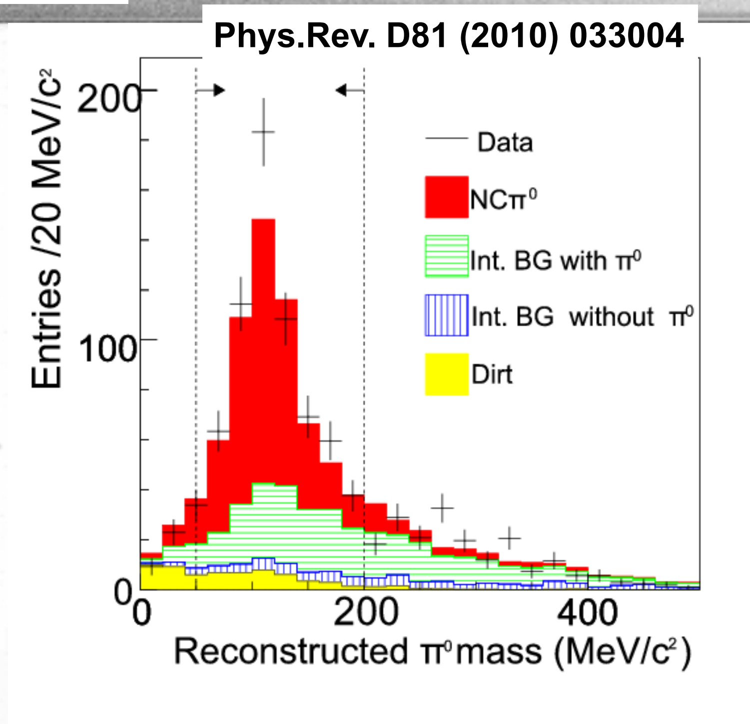




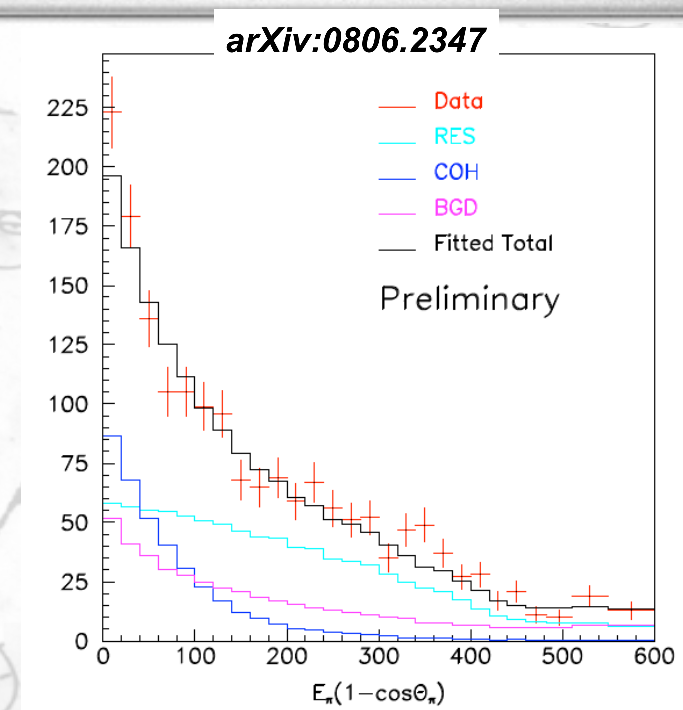
Phys.Rev. D81 (2010) 013005

- 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!

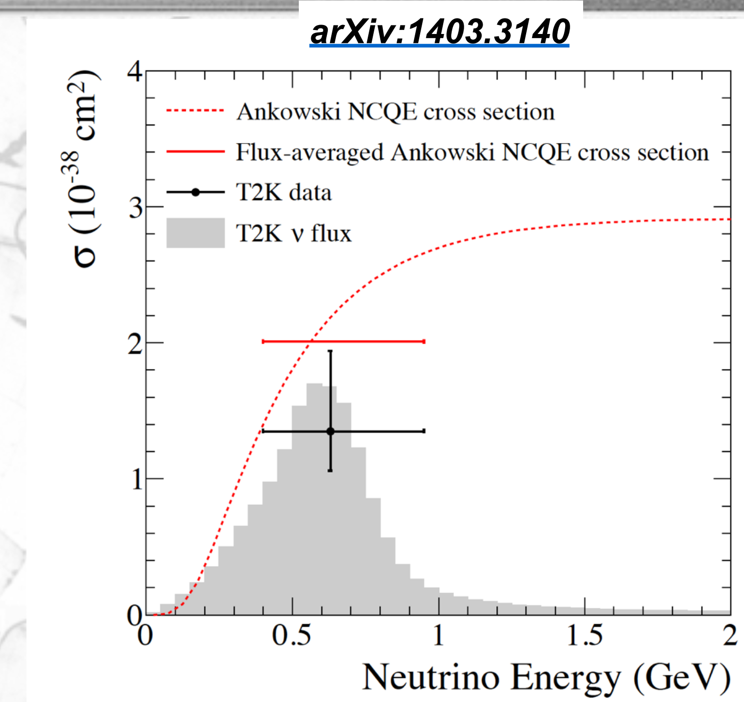
Recent results



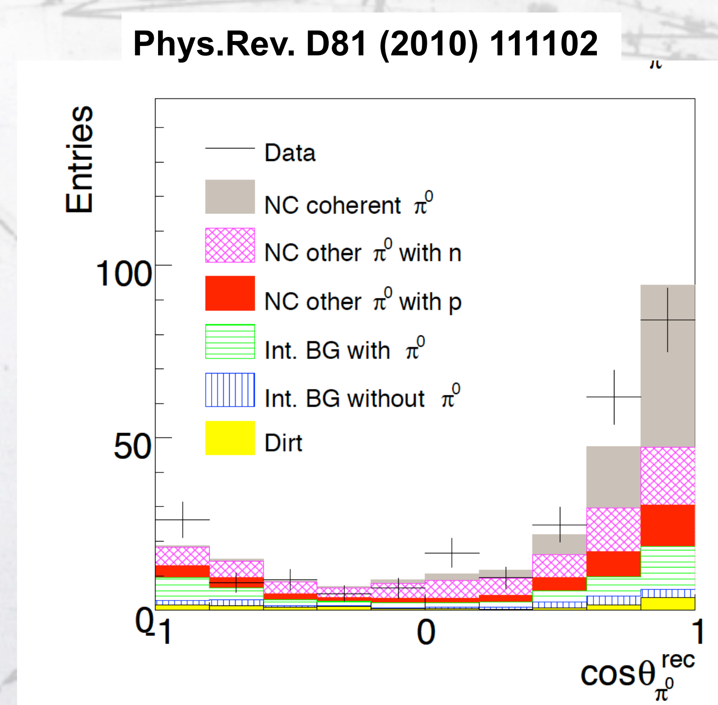
2010 SciBoone NCπ^0/CC



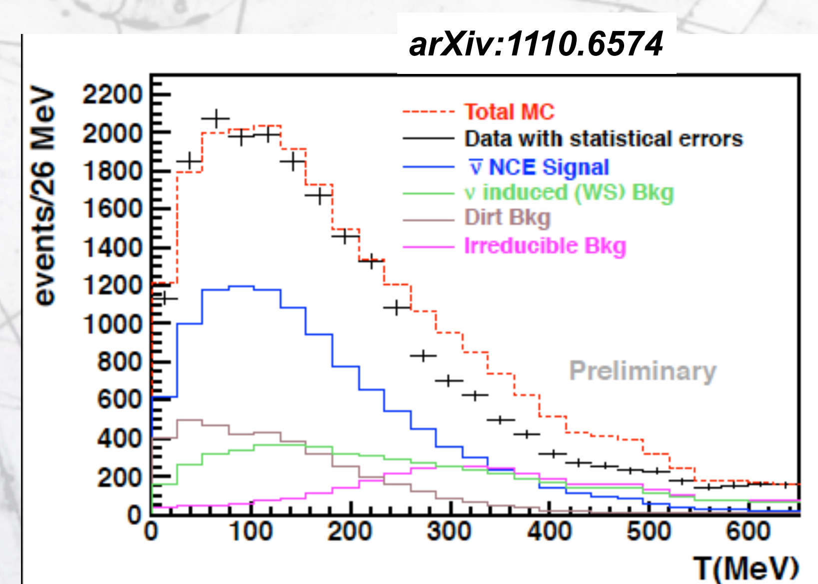
2008 MiniBoone NCπ^0 Coherent.



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



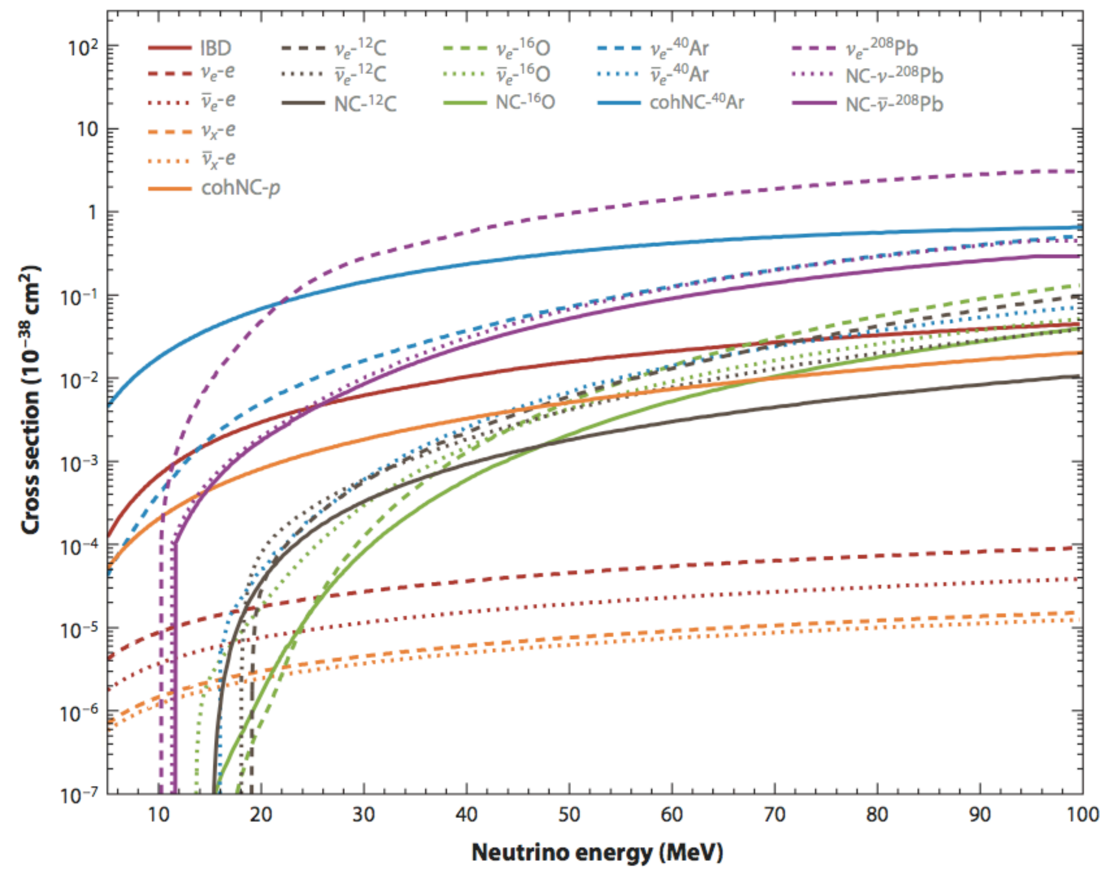
2010 SciBoone NCπ^0 coh.

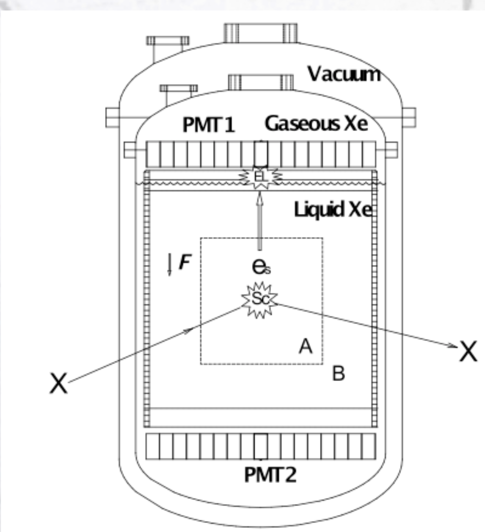


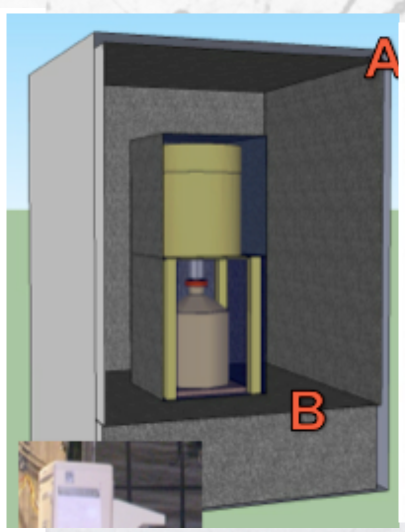
2011 MiniBoone NC elastic.

2014 T2K NC π^0 (poster)

Low energy NCcoherent



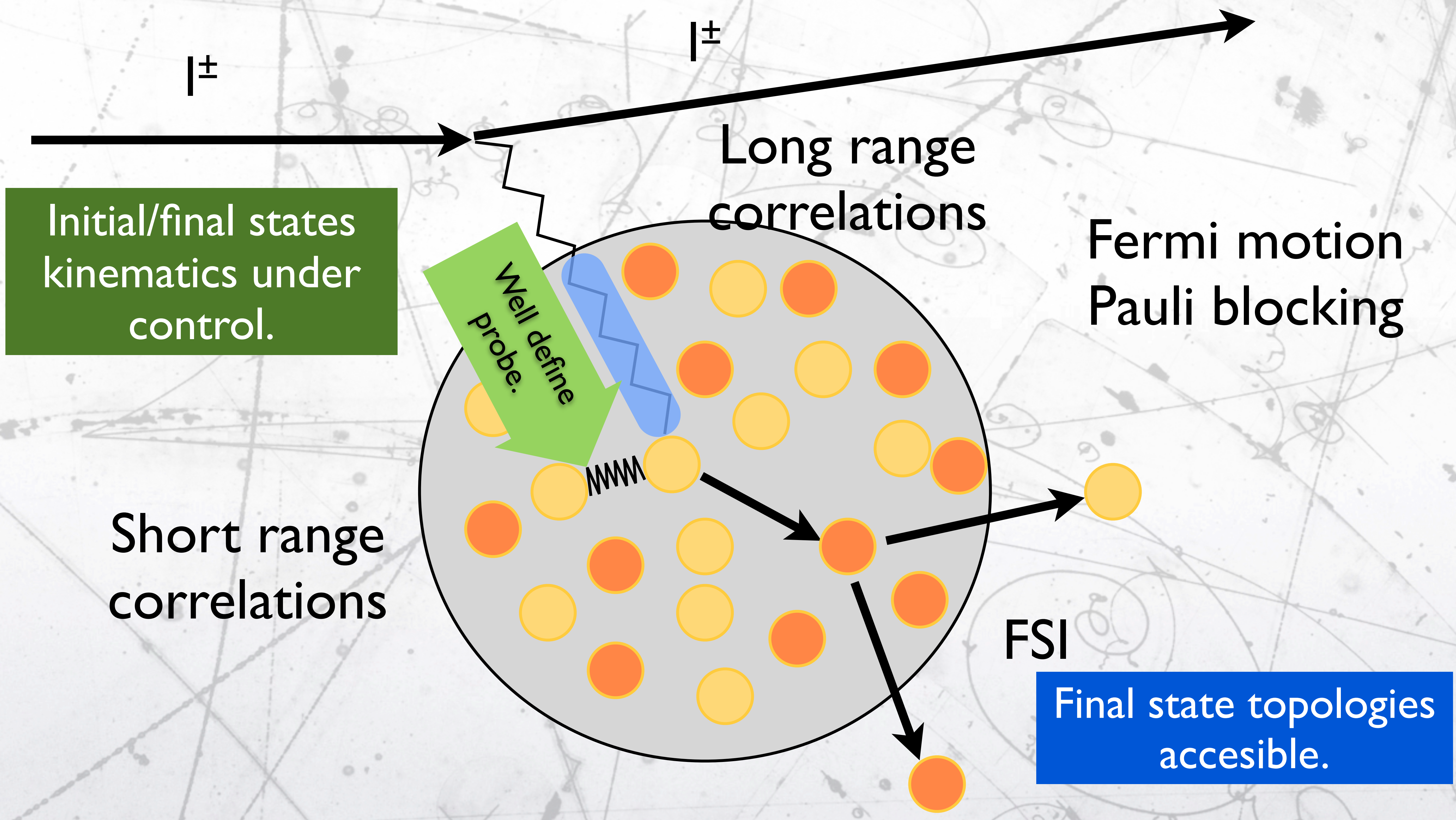




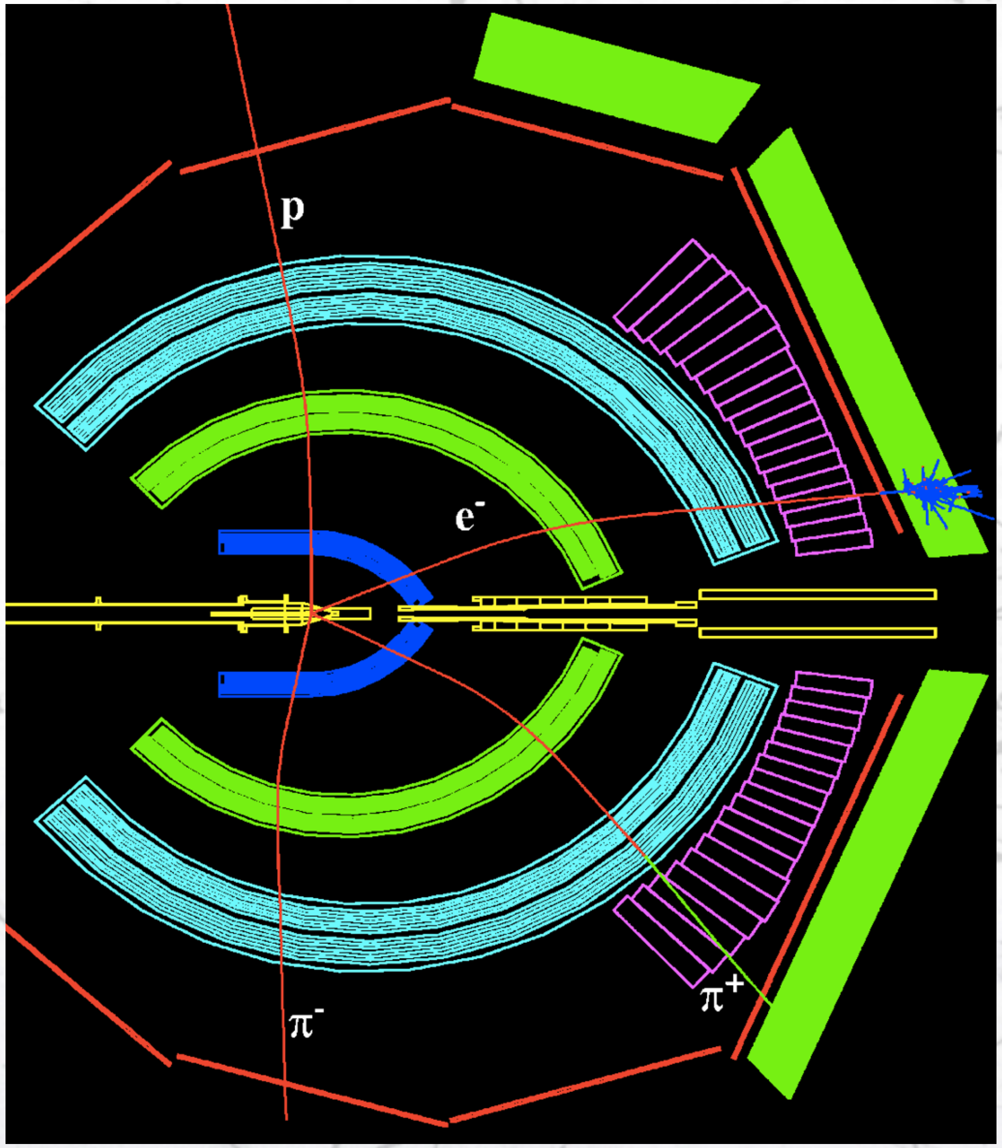
- Low energy (<100 MeV) Inverse beta decay and electron scattering is well known.
- Only 12C coherent scattering is measured (~10%).
- Future large LiqAr might explore the cross-section for SN burst and relic.
- It is also natural background for WIMP searches.
- COHERENT collaboration made a proposal to search for this interactions at pion stopping beam in SNS facility.

Session on Friday!

Electron scattering



Electron scattering

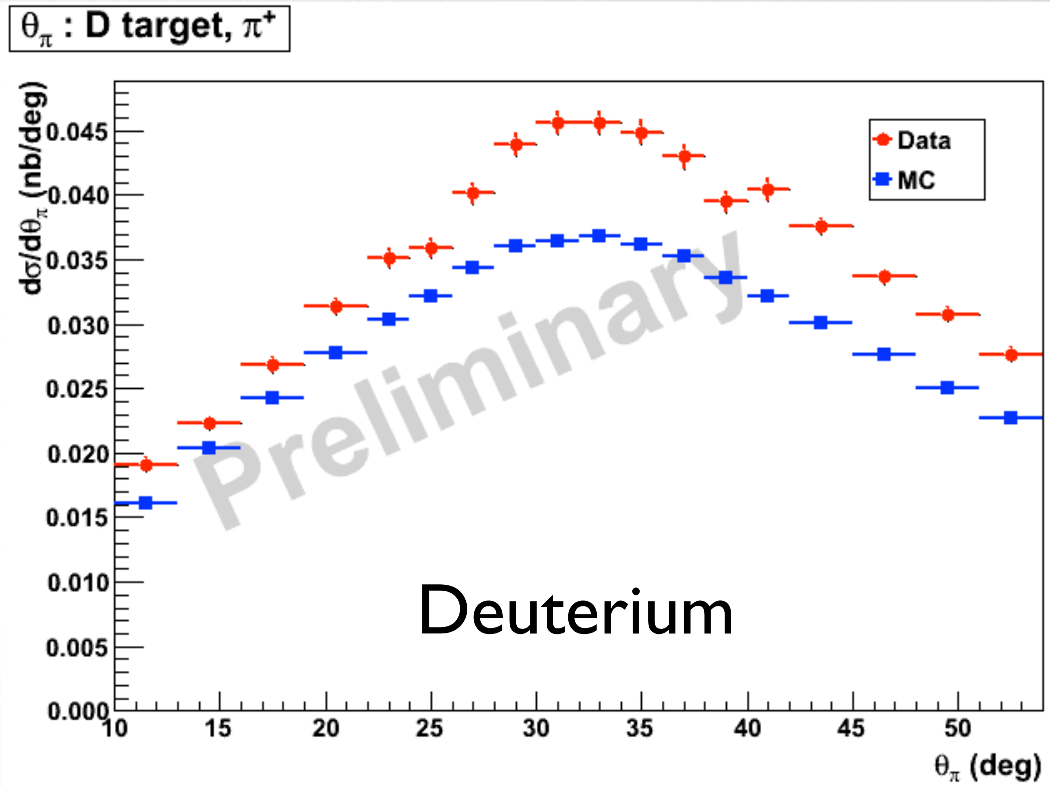


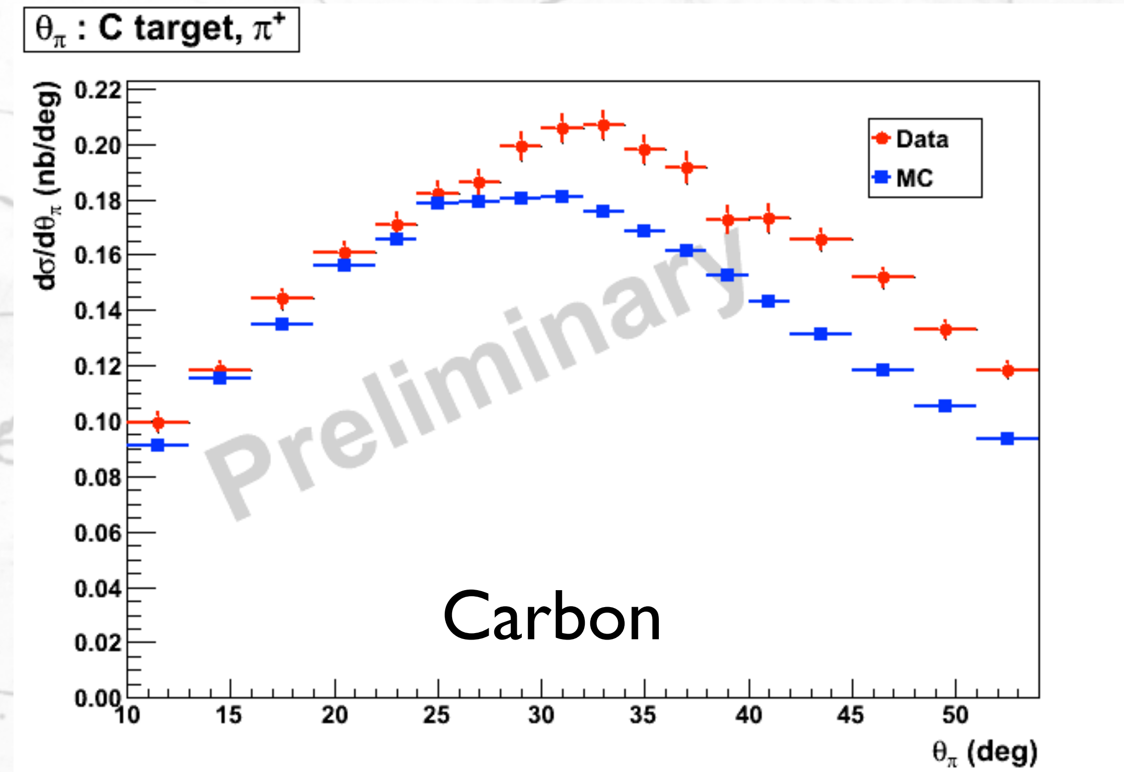
- Control on incident beam kinematics allow to:
  - Identify the channel: Elastic, resonant, etc…
  - Calculate the kinematics of hadronic final state (smeared by fermi-motion).
- This allows to understand the:
  - vector component of interaction.
  - effects of FSI and final state multiplicities.
-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

CLAS experiment at Jefferson Lab.

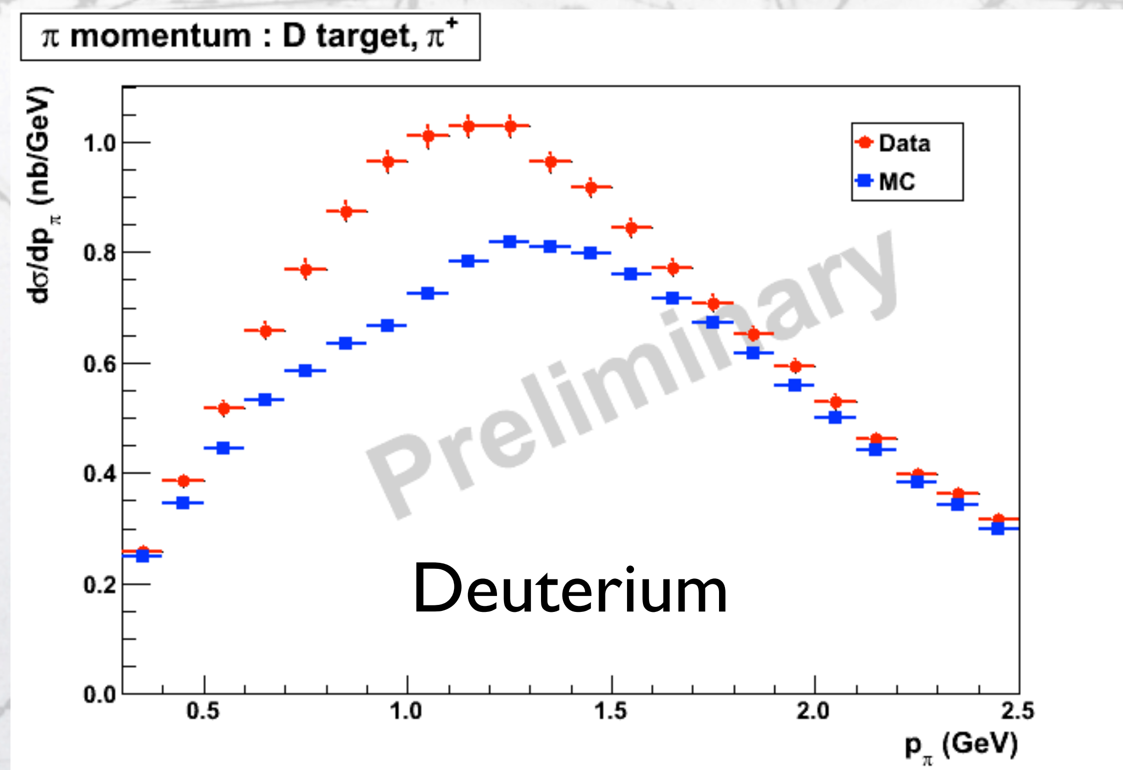
Data exists, analysis on going, manpower needed.

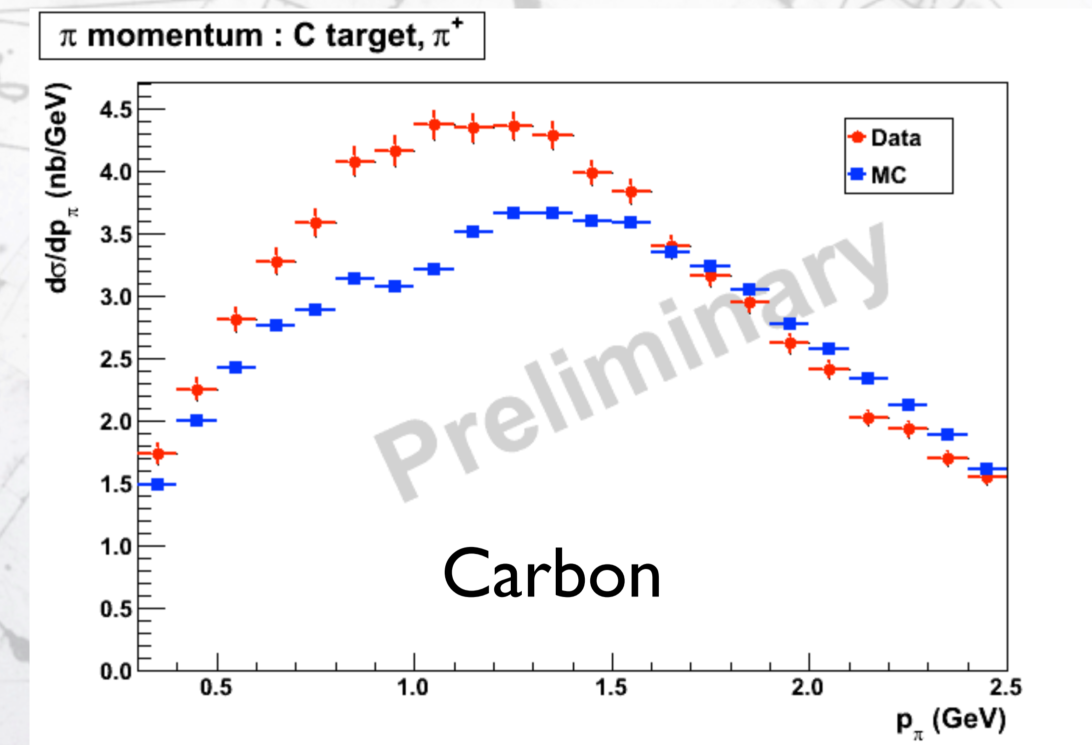
Electron scattering



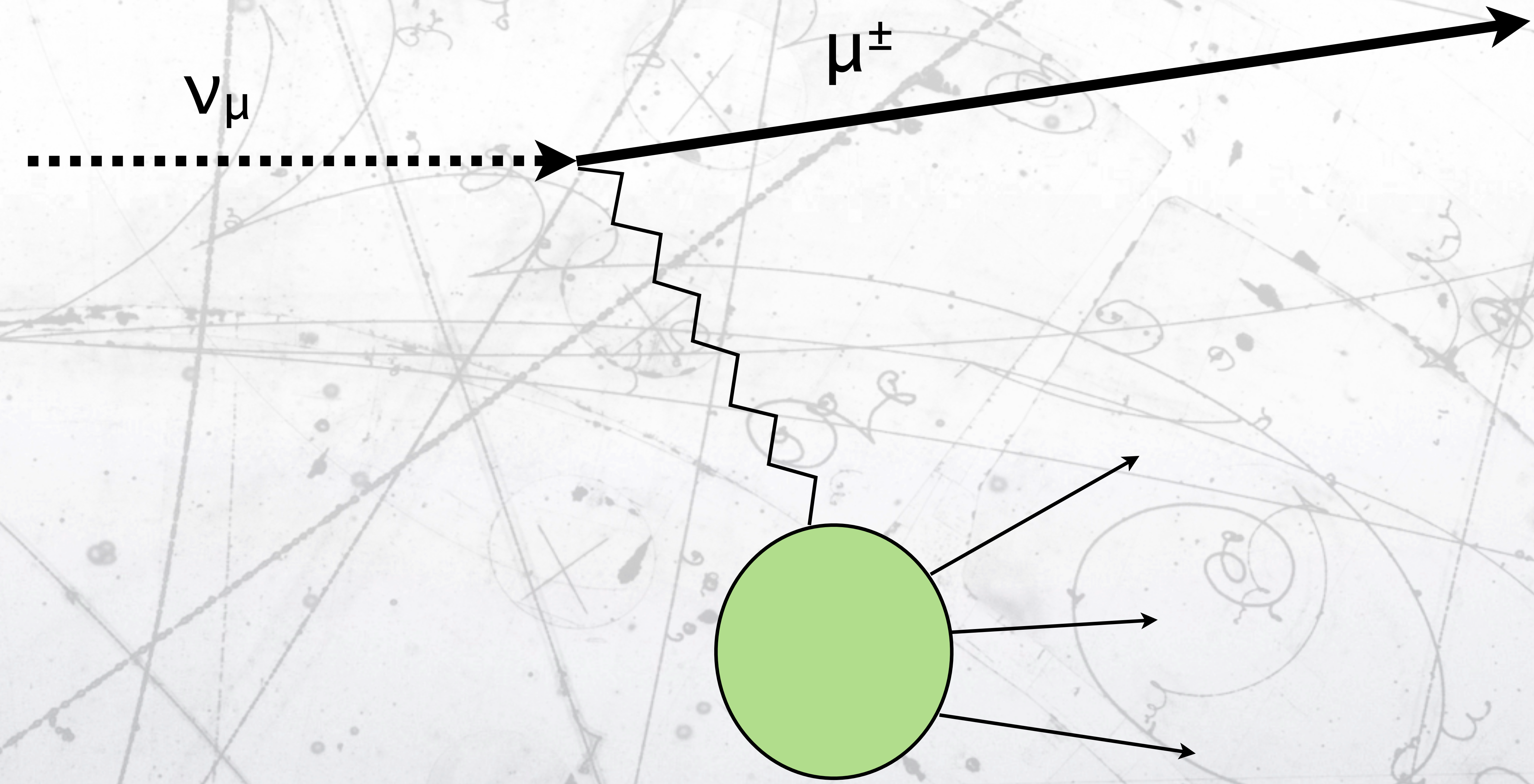


Nuint'14





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:

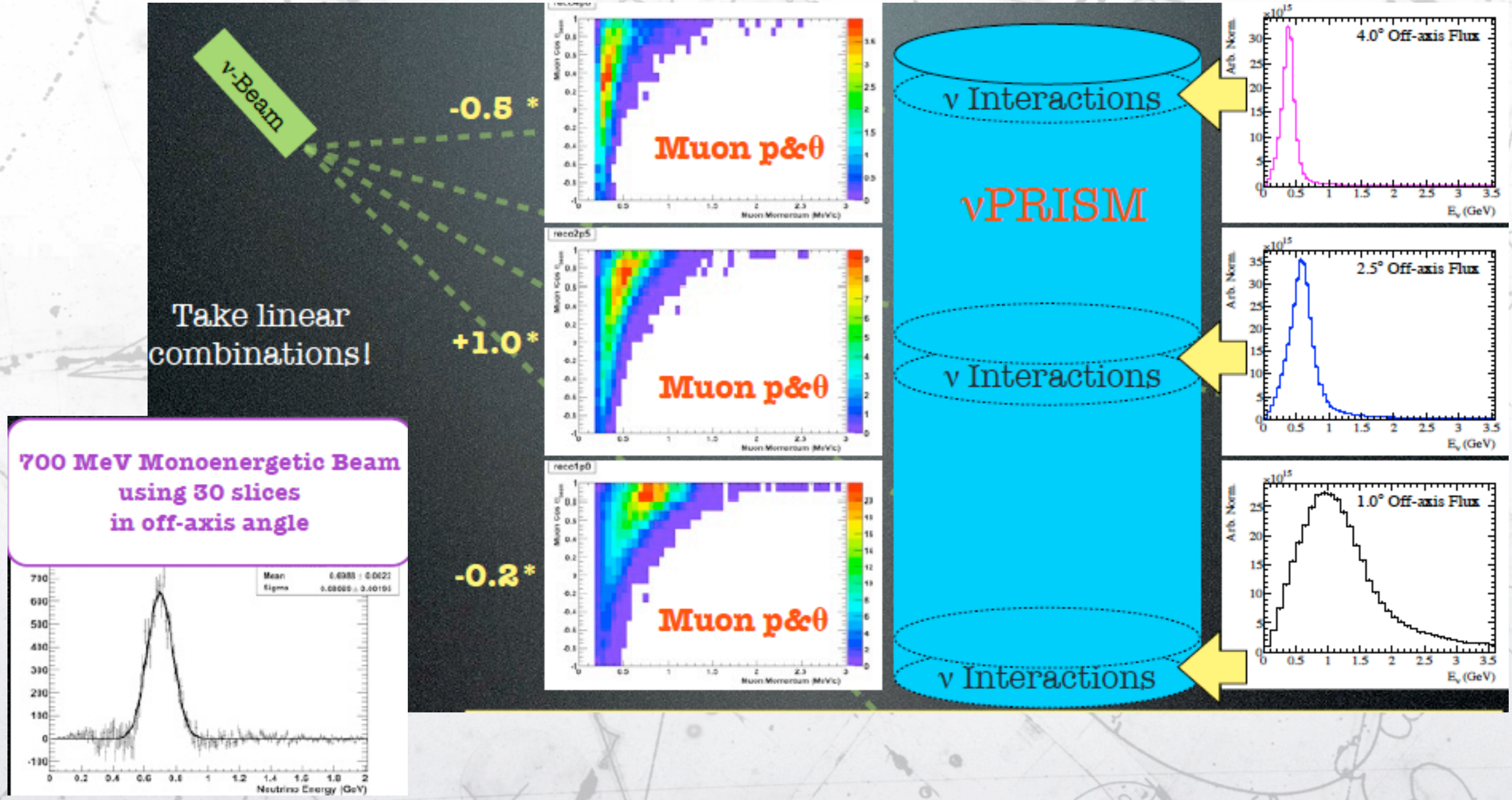
$$P(p_\mu, \theta_\mu | E_\nu)$$

- 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.

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
Arb. Norm.
E_ν (GeV)
700 MeV Monoenergetic Beam
using 30 slices
in off-axis angle
Neutrino Energy (GeV)

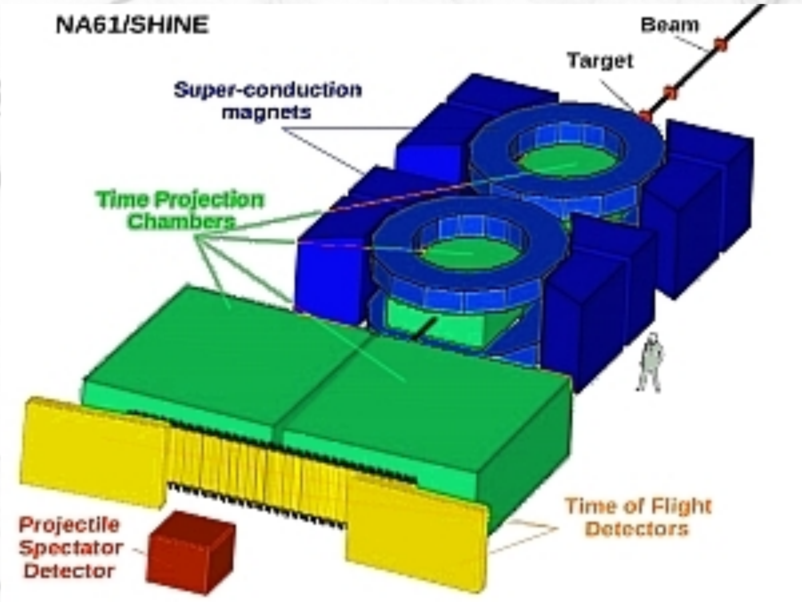
NusTEC

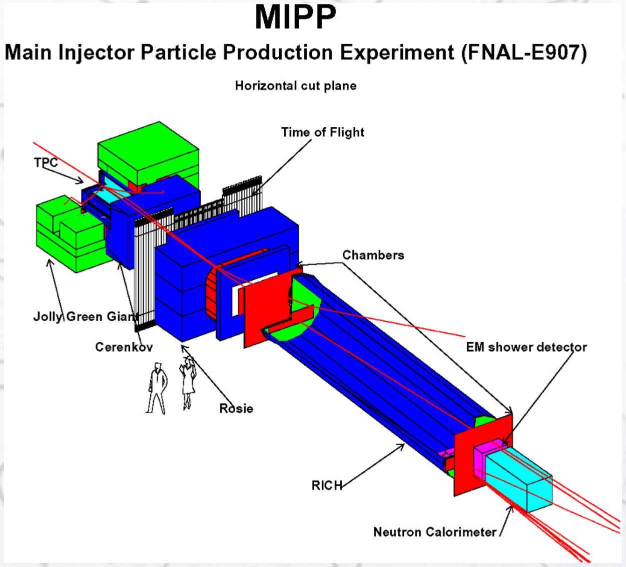
A Collaboration of HEP and Nuclear Experimentalists and Theorists Studying Low-energy Neutrino Nucleus Scattering Physics.

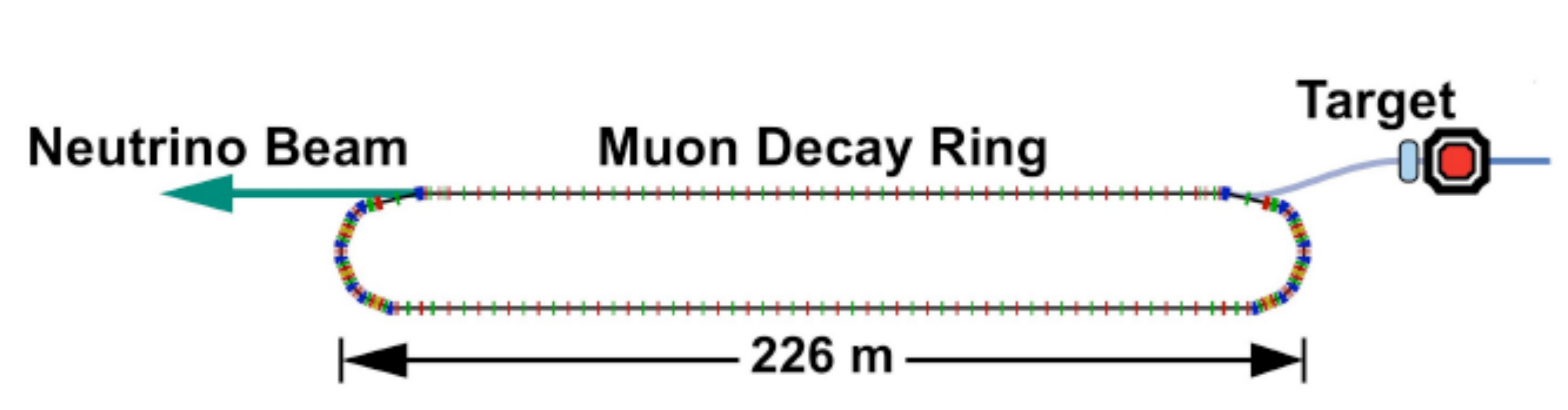
- **Neutrino Event Generators**
  - Coordinate theorist-experimentalist collaborative efforts to improve generators
- **Workshops**: Organize Community-wide Workshops when needed
  - Organization beginning on workshop to investigate np-nh/MEC nuclear effects
- **Training Programs**: Organize and run training programs in:
  - Neutrino Scattering Event Generators: University of Liverpool, 14 – 16 May
  - **Theory-oriented Neutrino-nucleus Scattering physics: Fermilab, 17 – 27 October.**
- **Global Fits**: Combine results from multiple experiments to compare with and then, if necessary, modify a theory/model framework.

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)







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 !!!!

My own conclusions

- 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.

NuSTEC

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

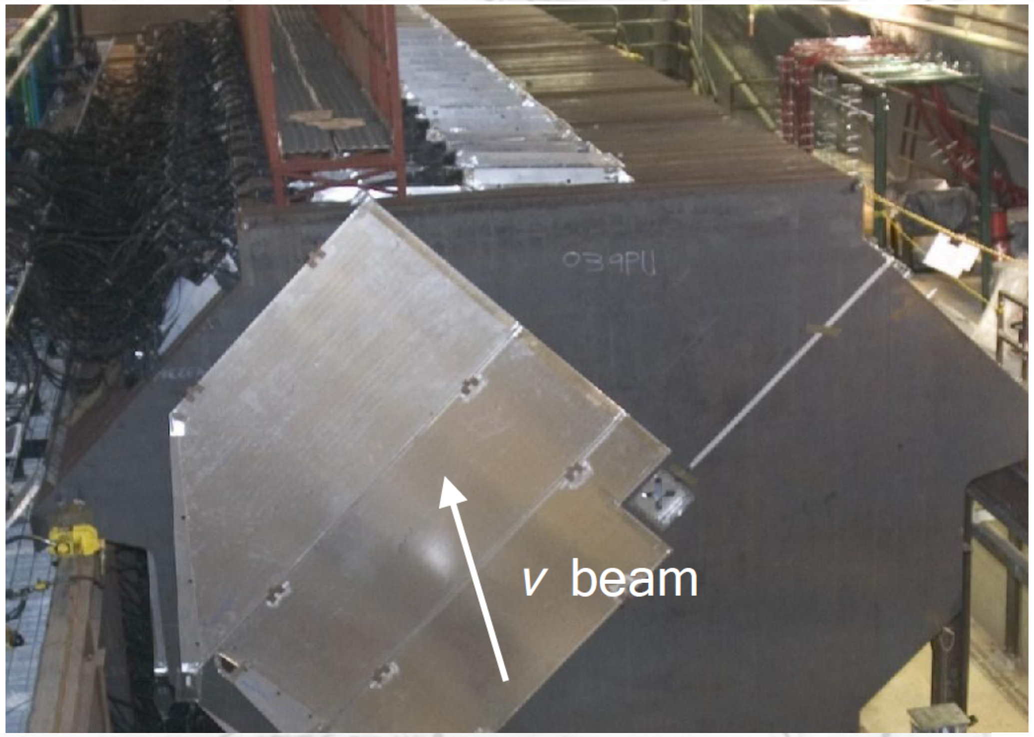
NuSTEC

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

5. Need of a deuterium target measurement.

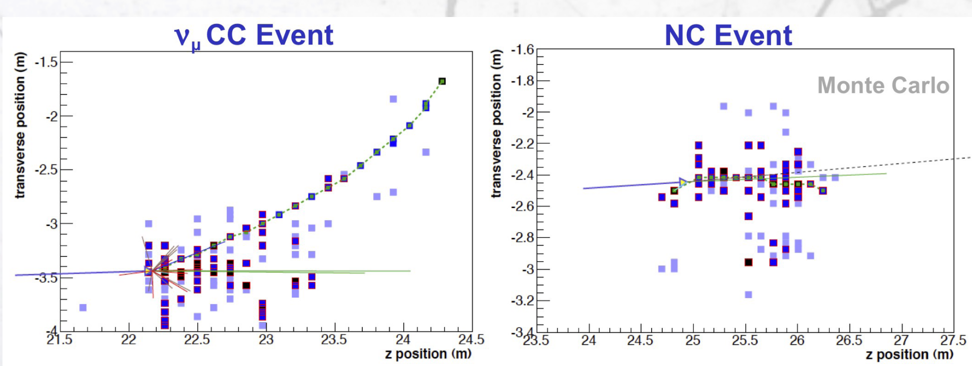
Backup and supporting slides

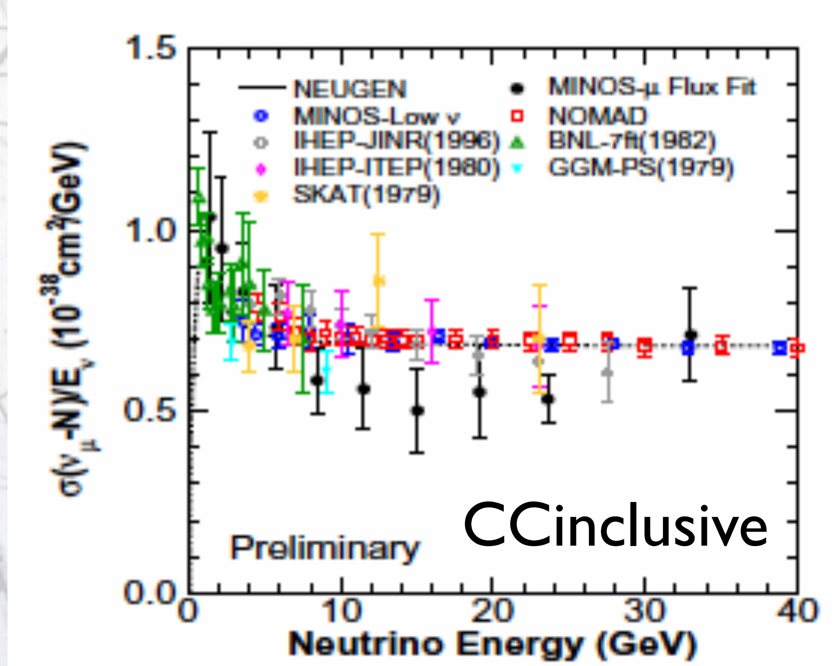
Near Minos

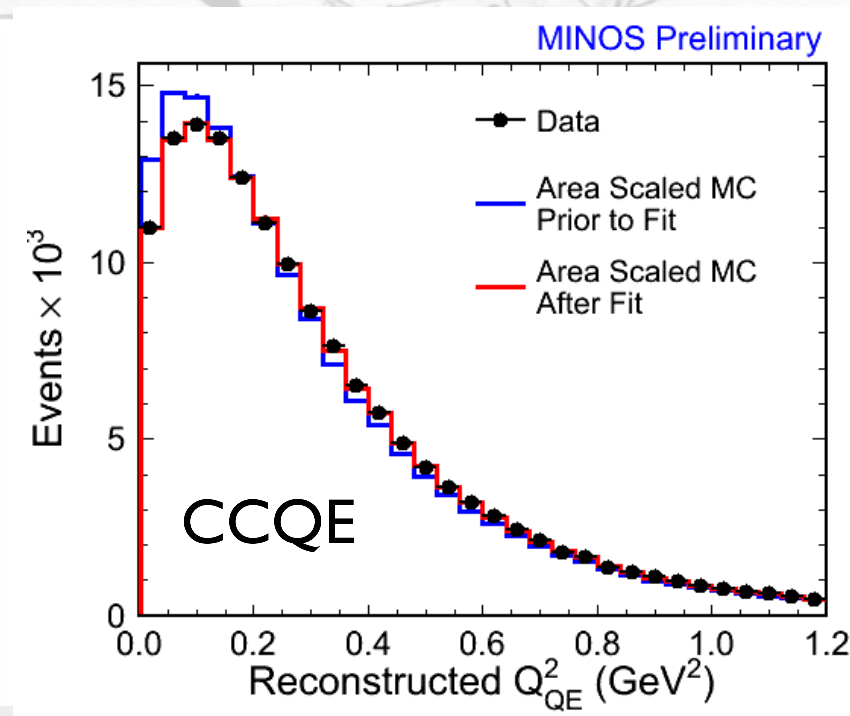


- Iron target.
- Magnetised.
- Large statistics.

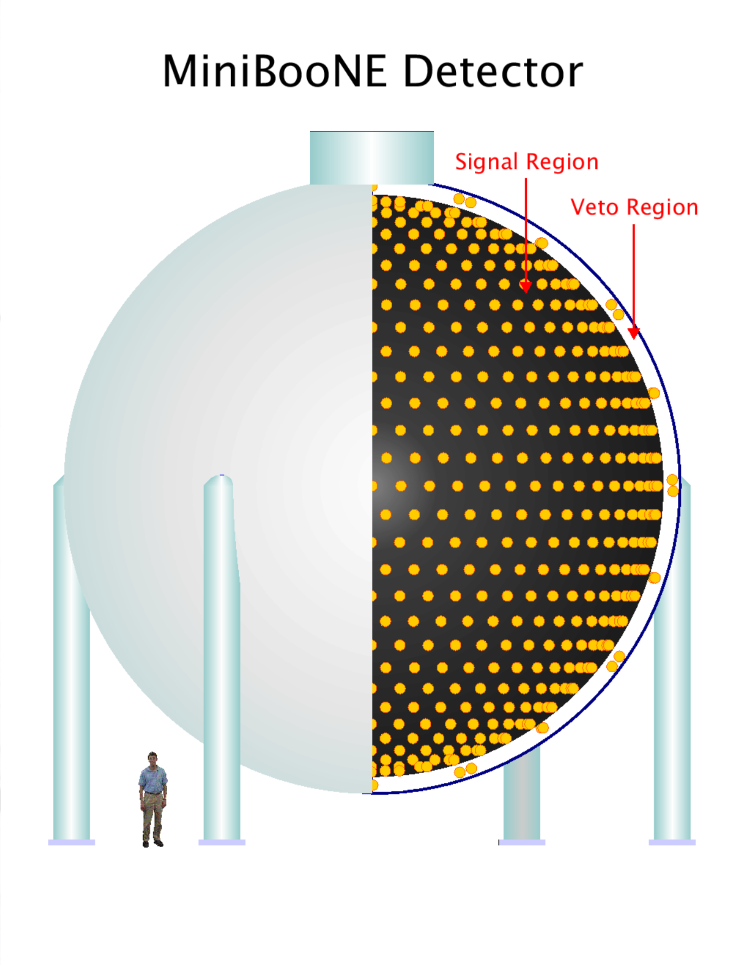
	M_A^{QE} (GeV)	E_μ Scale	M_A^{RES} (GeV)	k^{QE}_{Fermi}
Principal: $0 < Q^2 < 1.2$	1.21 +0.18 -0.10	0.996 +0.007 -0.015	1.10 +0.15 -0.16	1.10 +0.02 -0.03
Alternative: $0.3 < Q^2 < 1.2$	1.19 +0.19 -0.17	0.995 +0.008 -0.016	1.13 +0.17 -0.18	Not fit



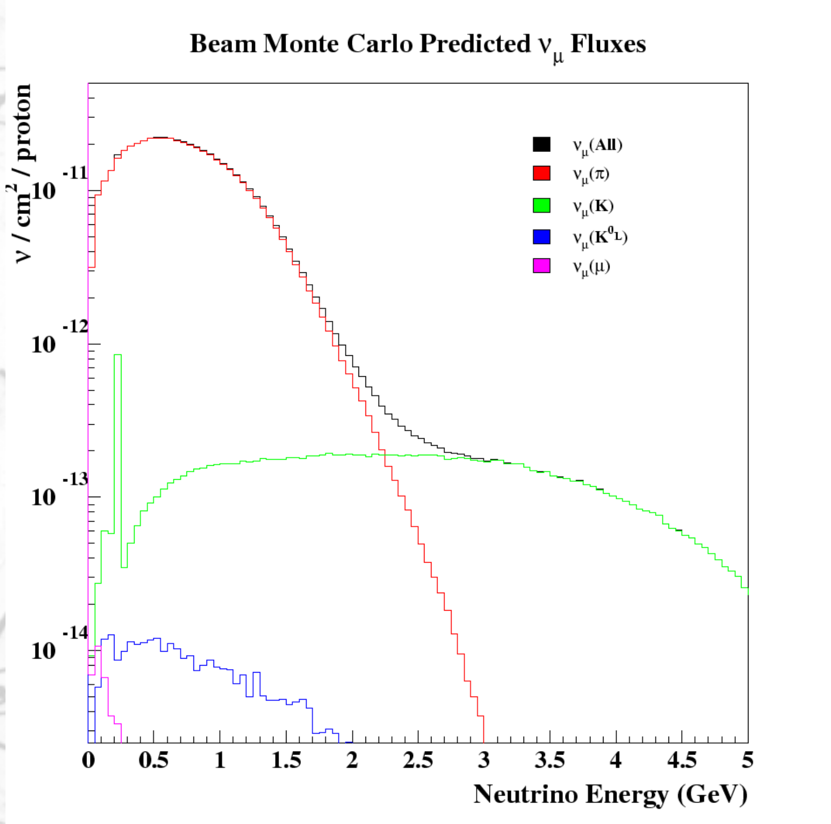


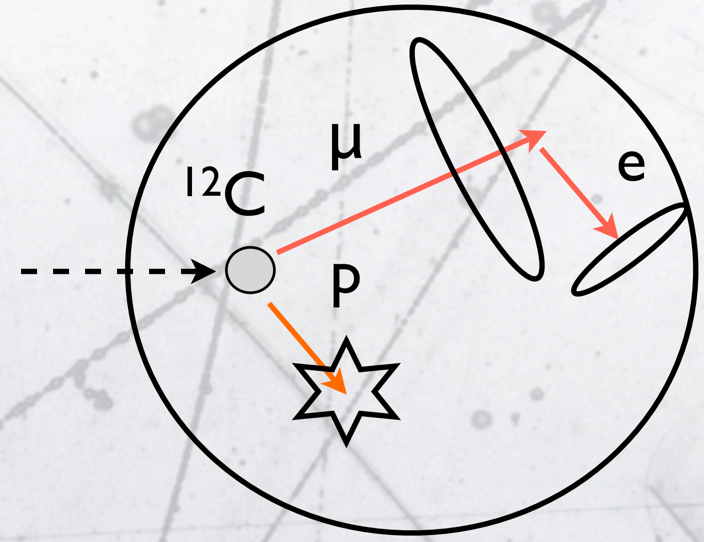


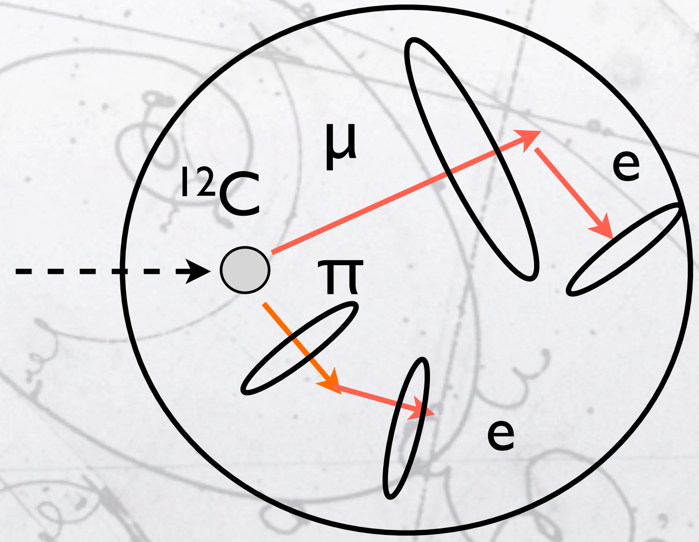
MiniBoone



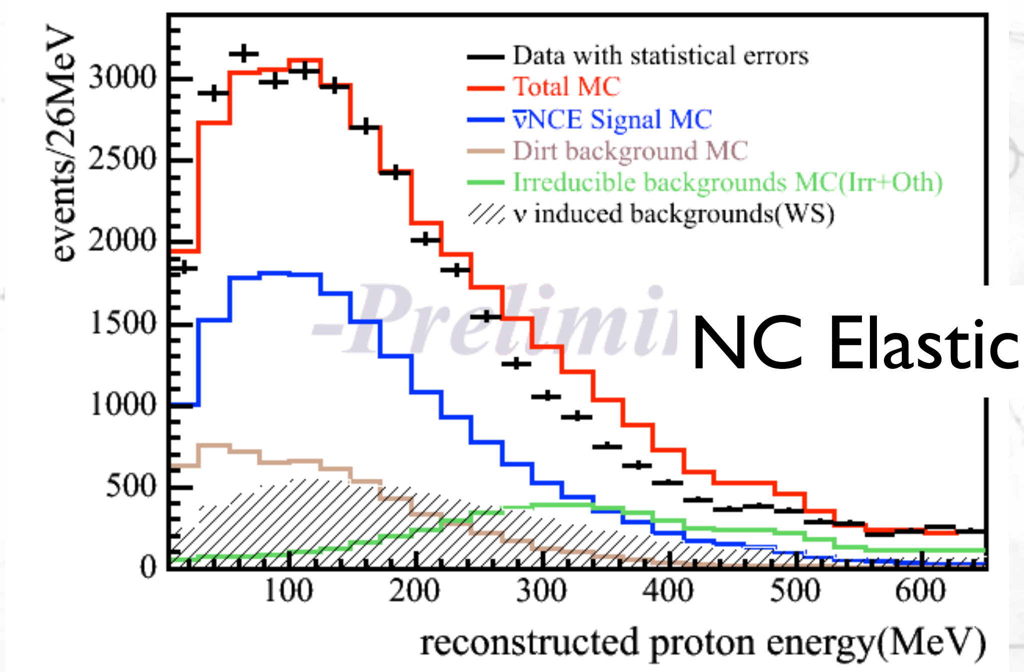
- 800 tons mineral oil Cherenkov detector.
- Boone neutrino line with sharp edge at 3 GeV.
- Flux constrained from HARP hadro-production experiment.
- ~450 Mev/c proton threshold.
- Excellent pion detection and tagging.
- Very large statistics.



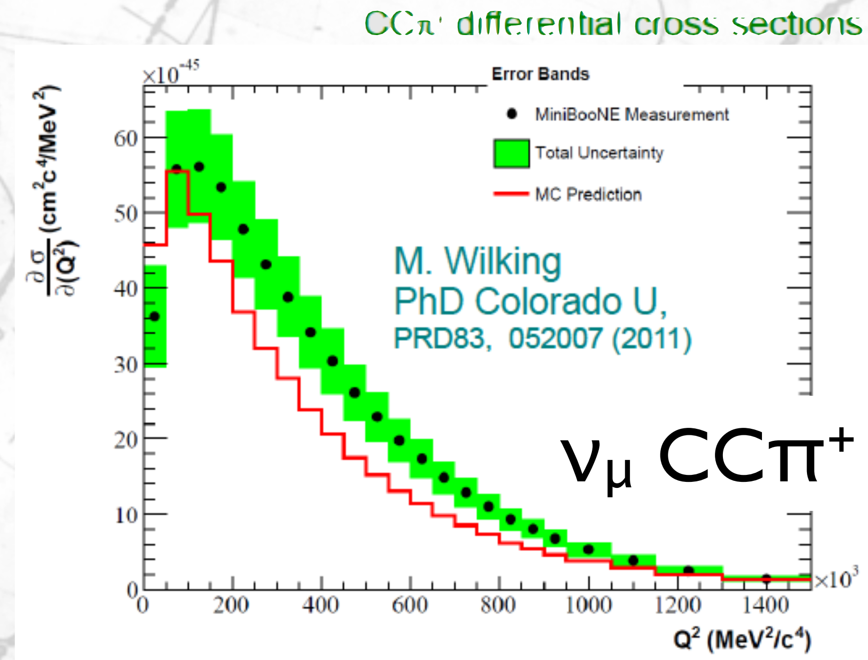




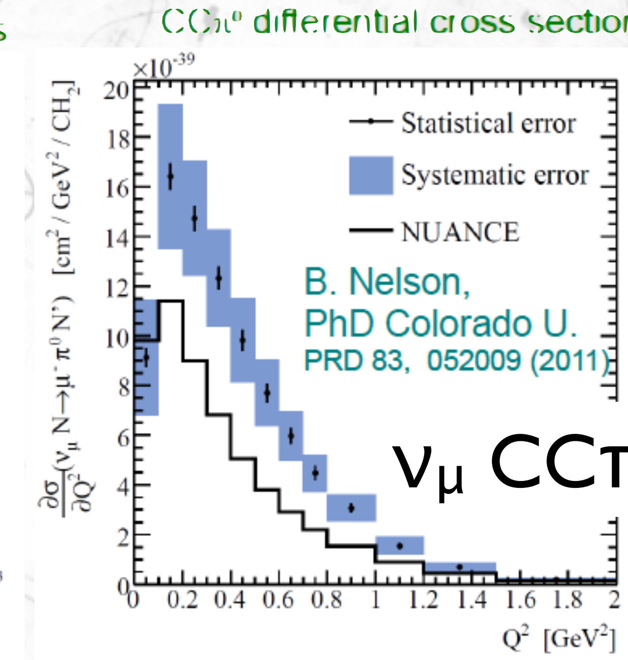
MiniBoone



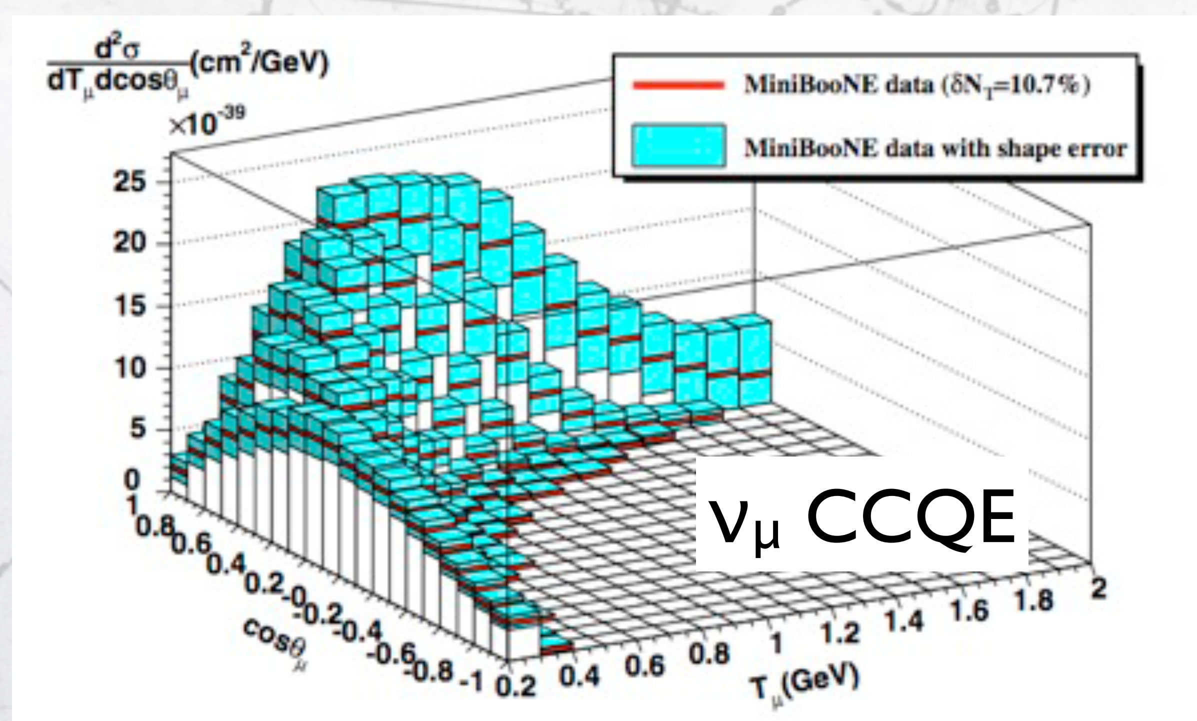
events/26MeV
Data with statistical errors
Total MC
νNCE Signal MC
Dirt background MC
Irreducible backgrounds MC(Irr+Oth)
ν induced backgrounds(WS)
-Prelimi
NC Elastic
reconstructed proton energy(MeV)



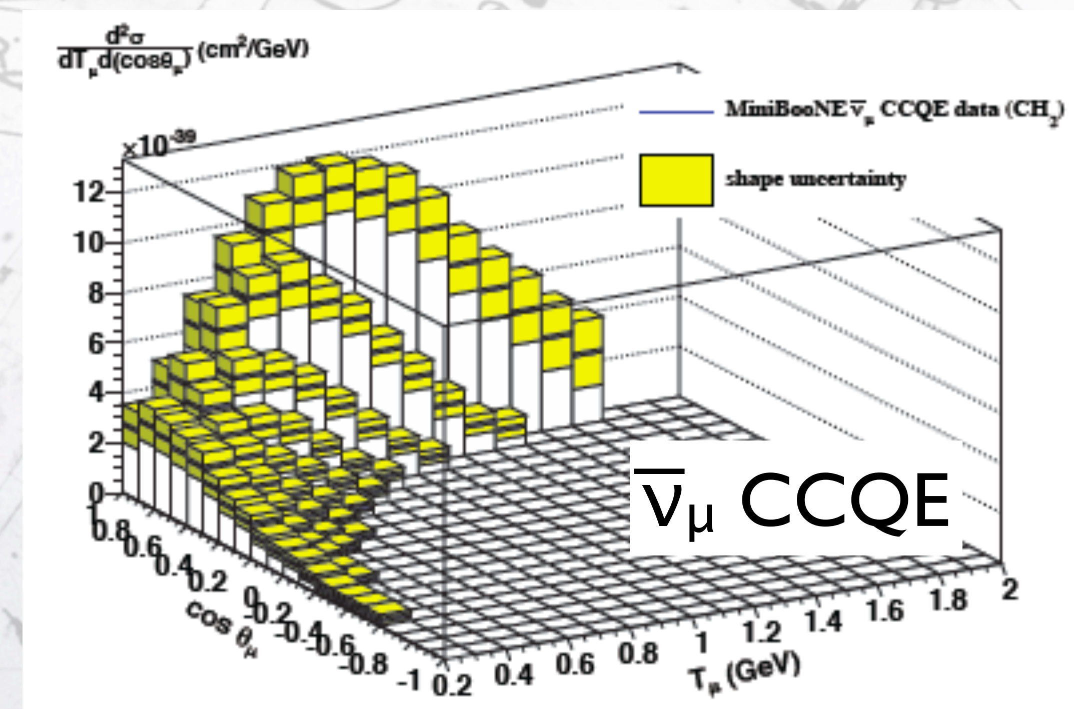
CCπ+ differential cross sections
Error Bands
MiniBooNE Measurement
Total Uncertainty
MC Prediction
M. Wilking
PhD Colorado U,
PRD83, 052007 (2011)
νμ CCπ+
Q² (MeV²/c⁴)



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



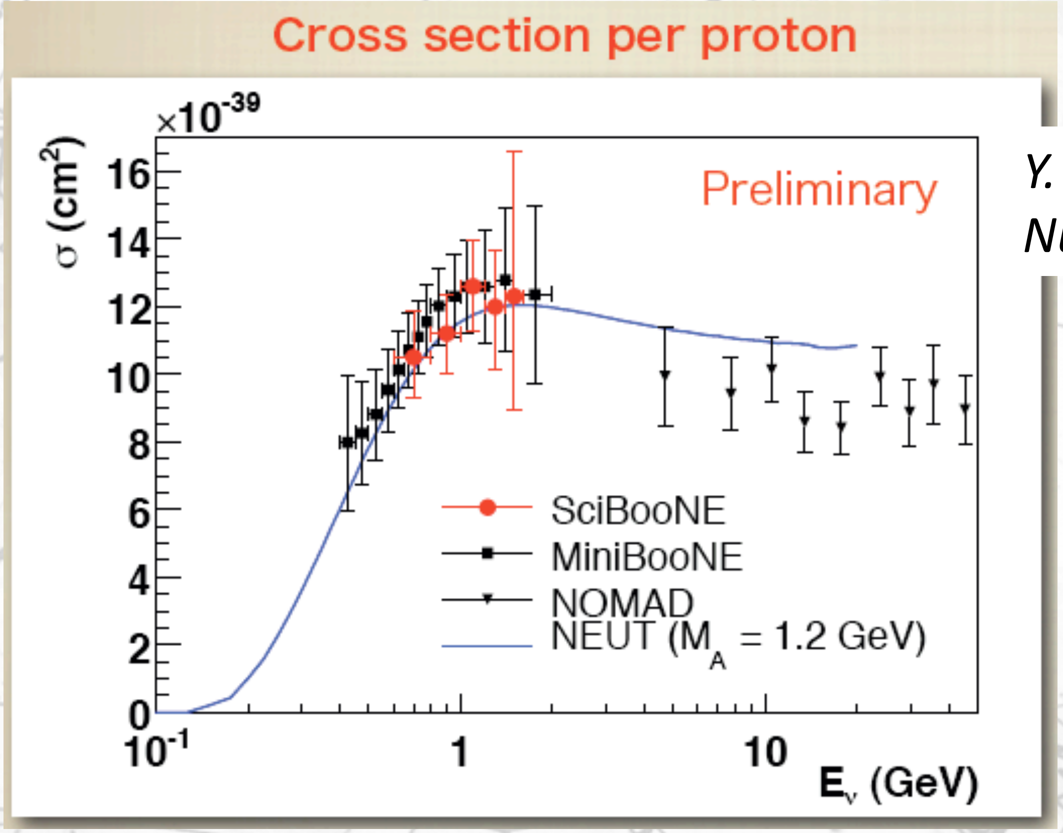
MiniBooNE data (δN_T=10.7%)
MiniBooNE data with shape error
νμ CCQE
T_μ (GeV)



MiniBooNE ν̄μ CCQE data (CH2)
shape uncertainty
ν̄μ CCQE
T_μ (GeV)

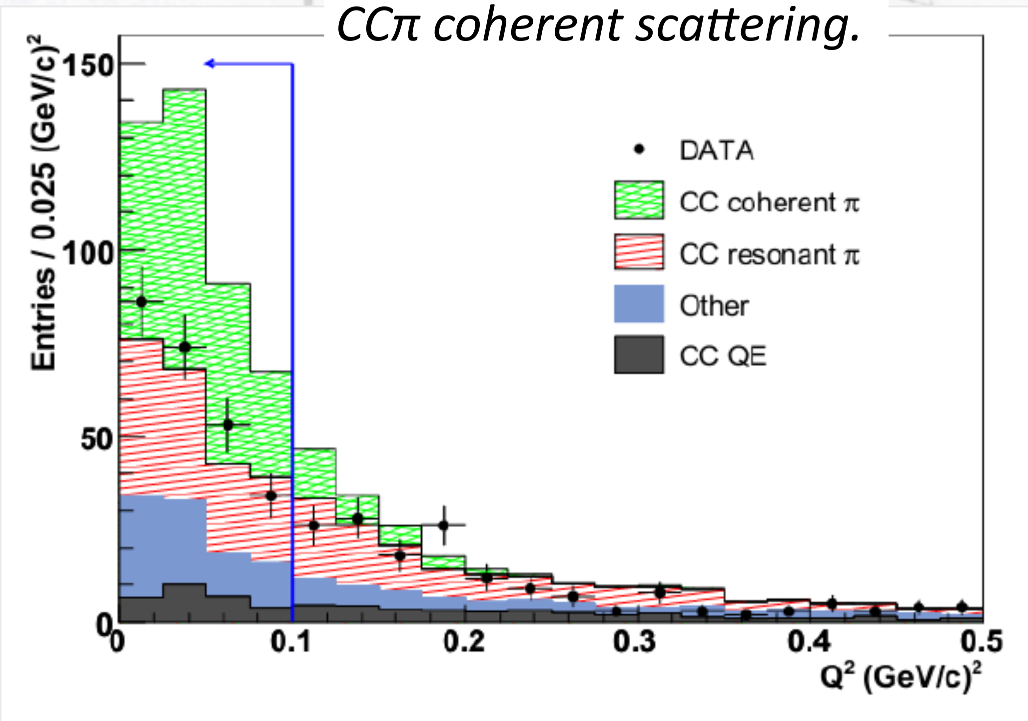
SciBoone

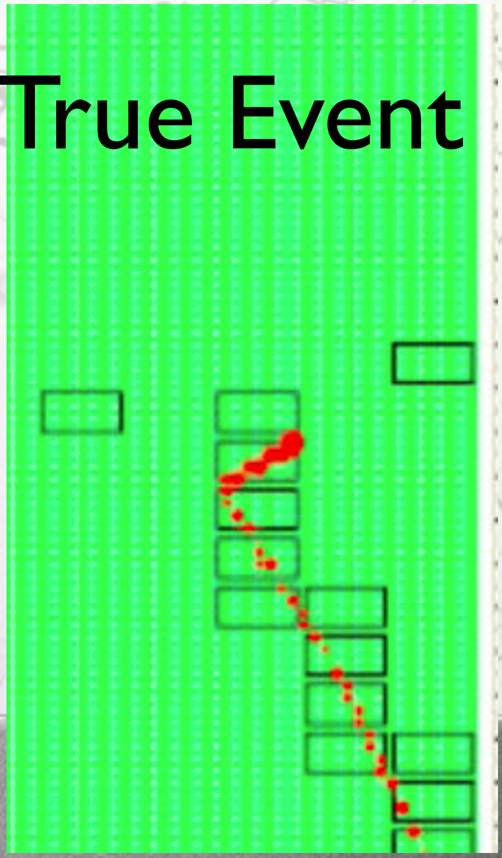
- Boone beam (< 3 GeV)
- Carbon target.
- Low proton tagging threshold (p > 450 MeV/c)
- Low statistics.
- Forward acceptance (> 60°)

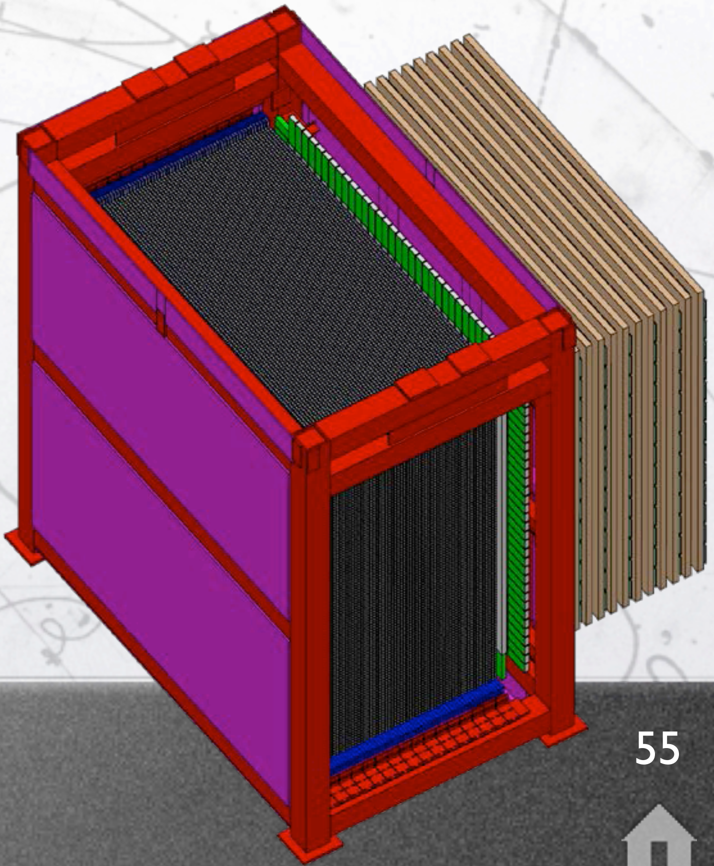


Y. Nakajima, NuInt11

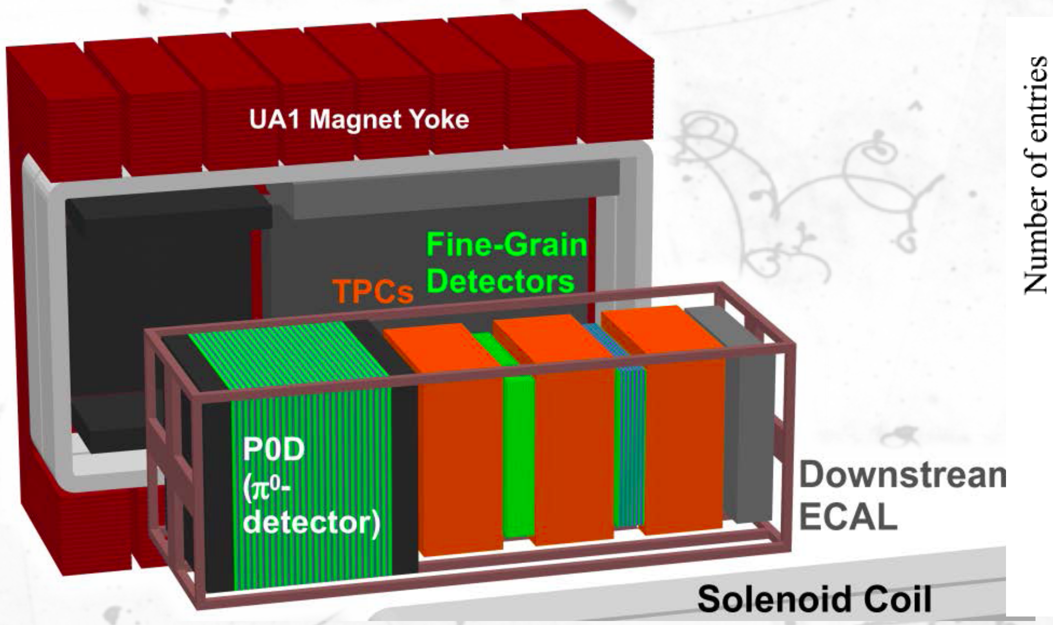
CCπ coherent scattering.

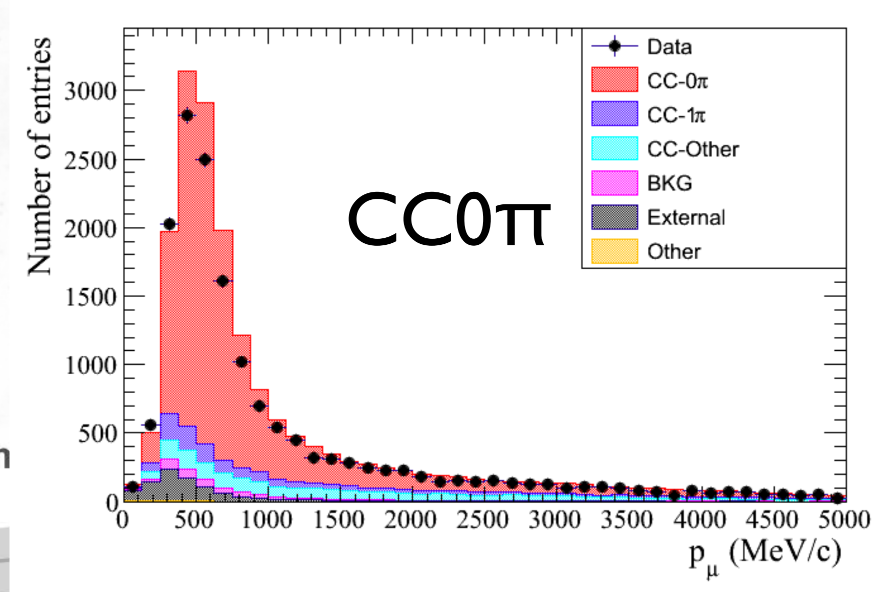


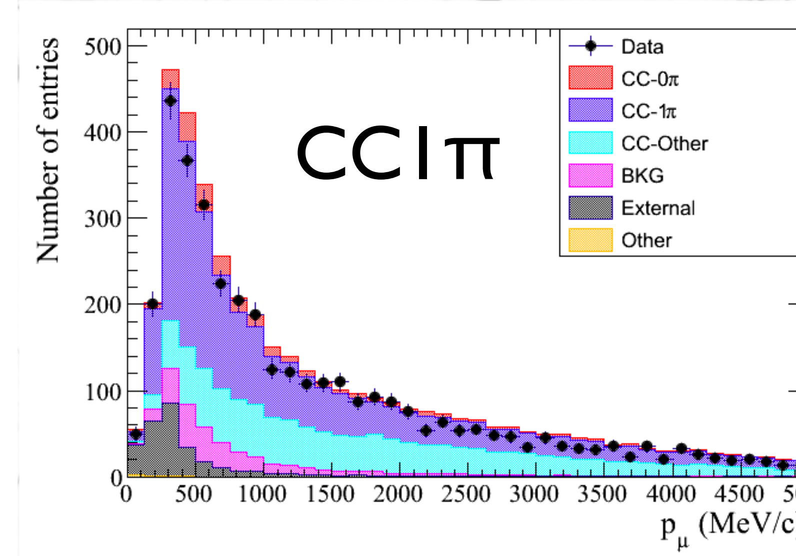




T2K/ND280

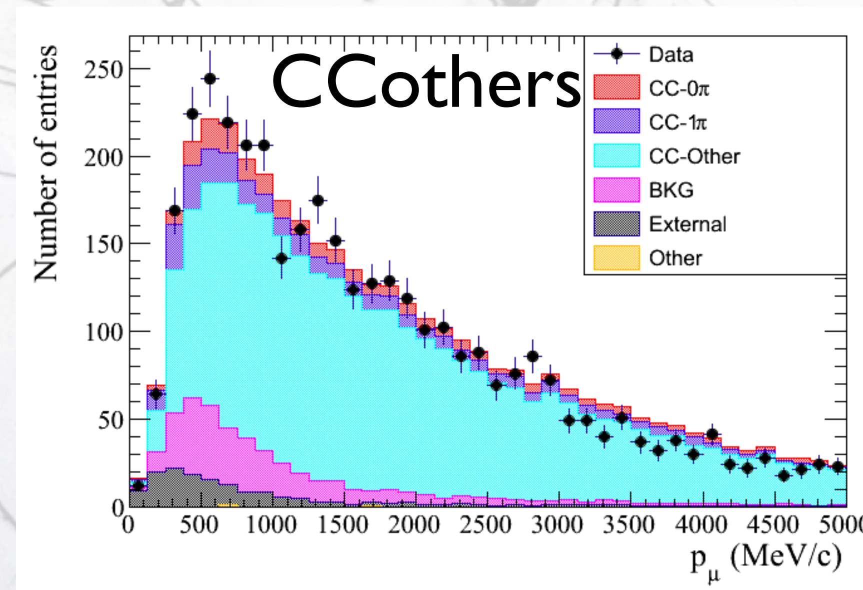




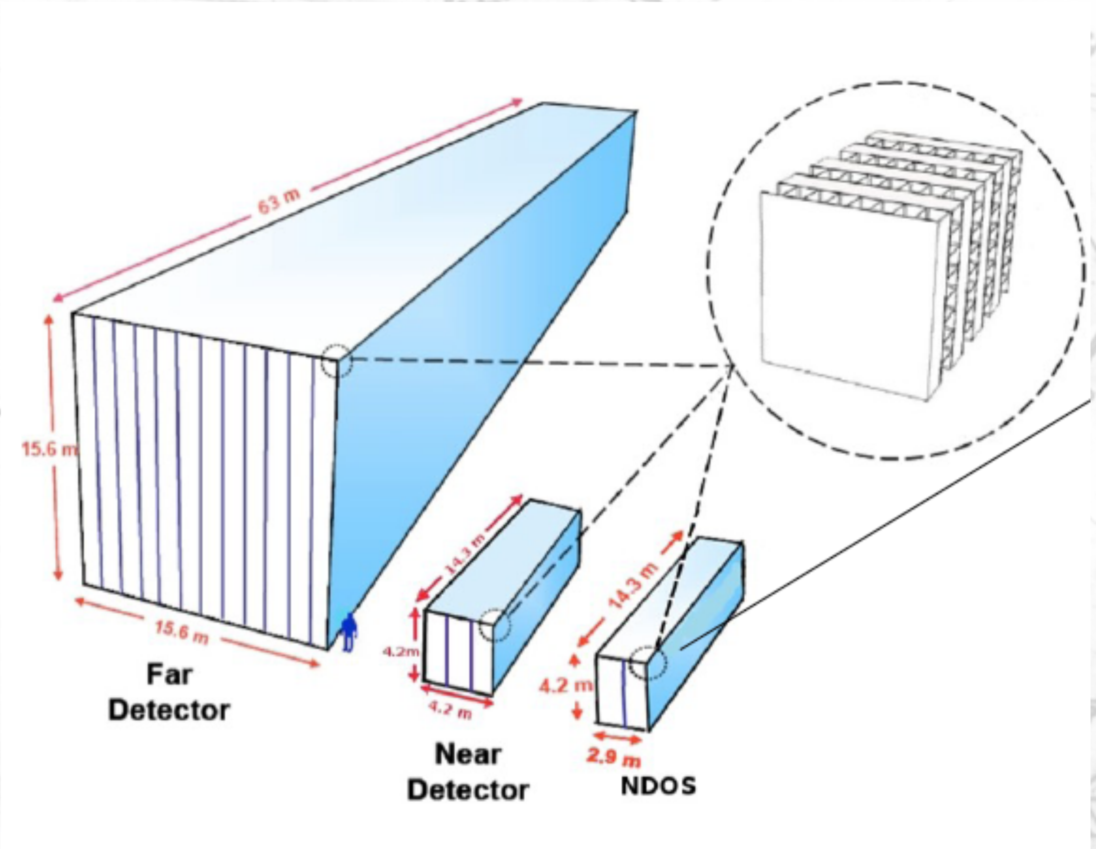


All detectors located within 0.2T UA1 magnet (charge sign determination):

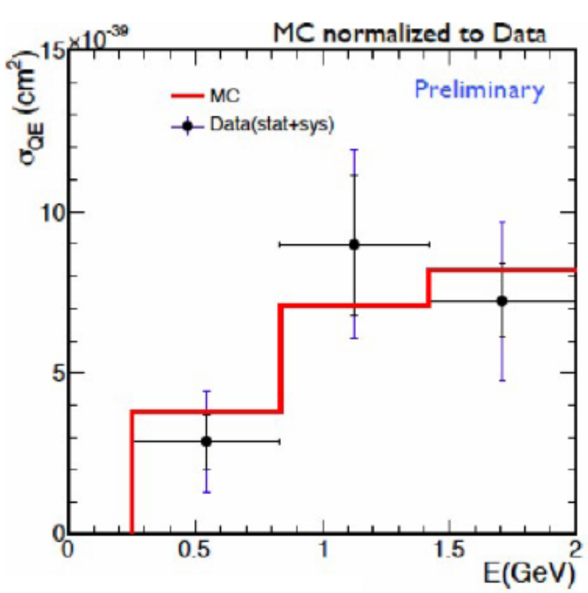
- 2 scintillator based tracking detectors (FGD) Nucl. Instrum. Meth. A 696, 1 (2012)
- 3 Ar - time projection chambers (TPC) NIM A 637, 25 (2011)
- P0D (triangular scintillator bars) Nucl. Instrum. Meth. A 686, 48 (2012))
- Electromagnetic calorimeters (ECALs JINST 8 P10019 (2013))
- Muon range detectors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

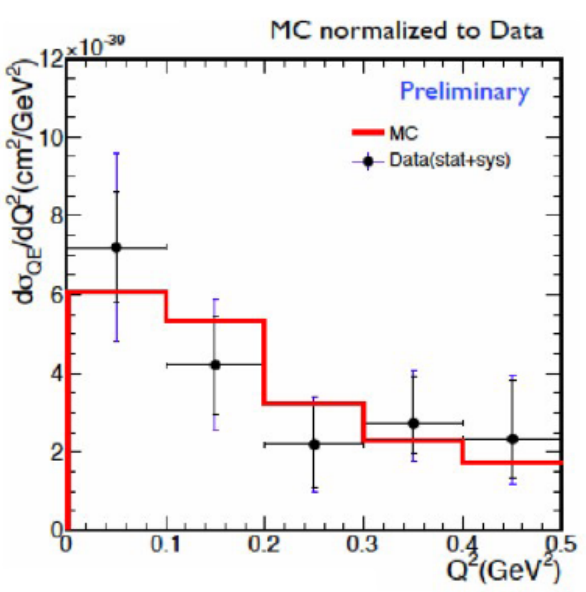


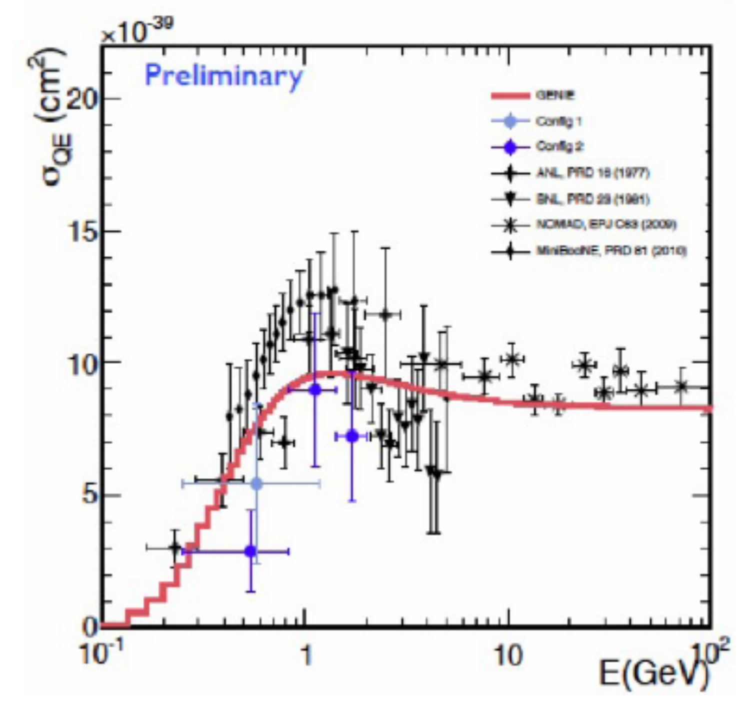
Nova ND



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

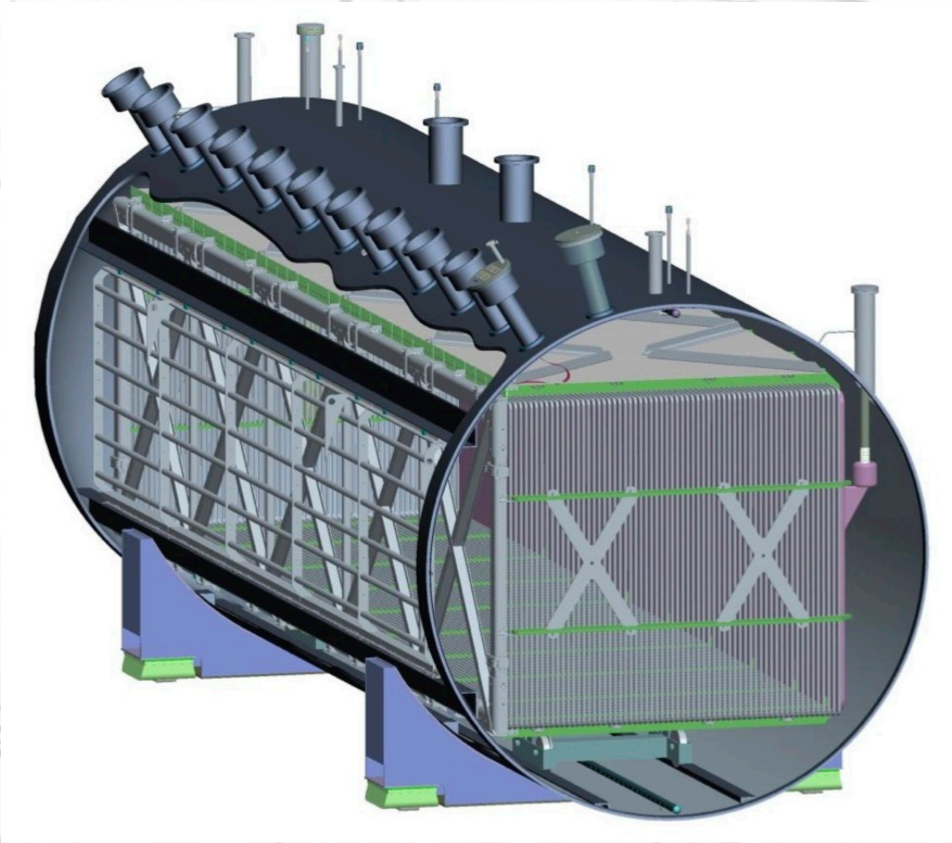




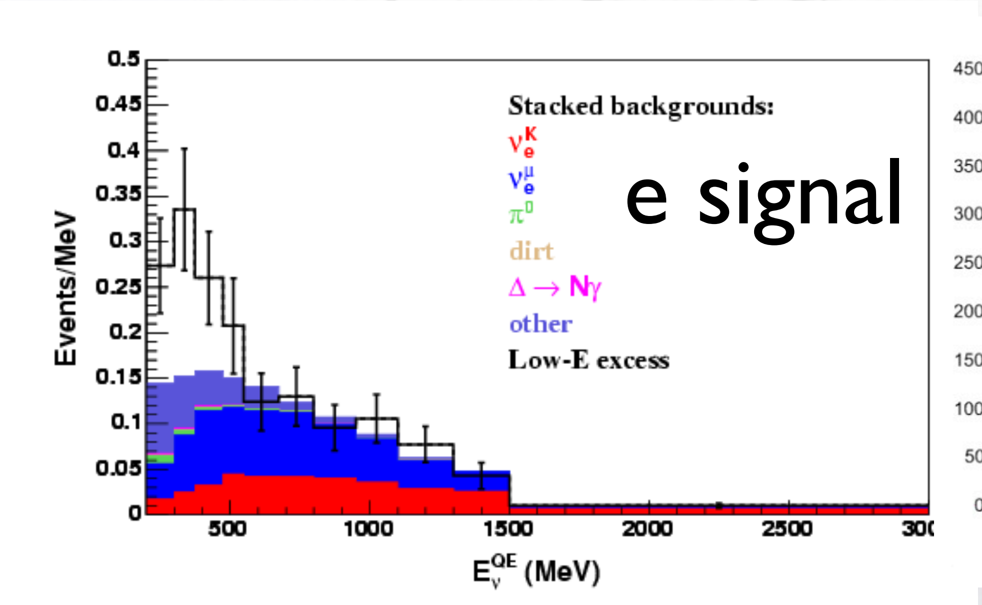


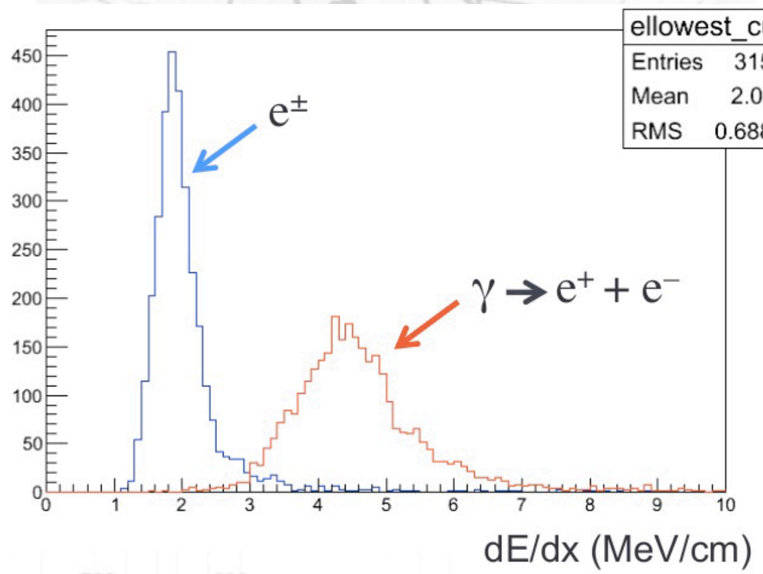
New results expected in the future

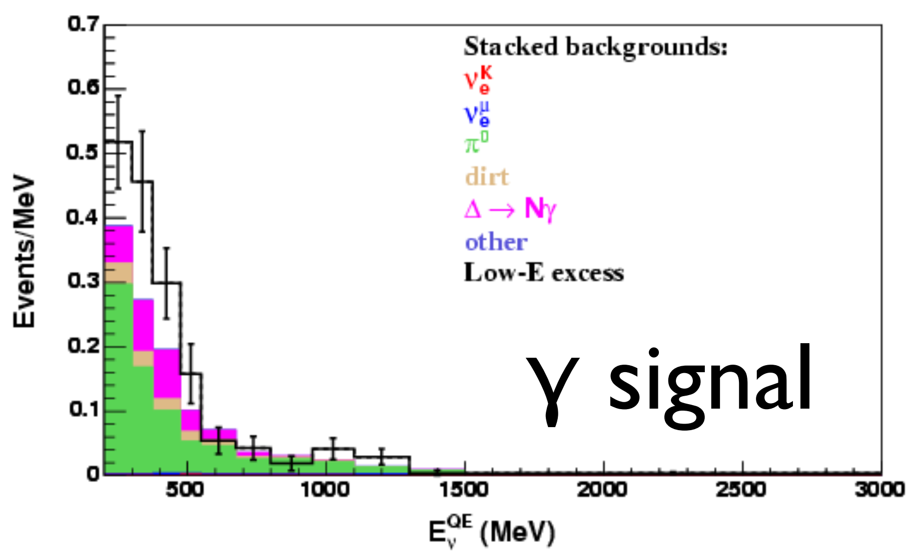
MicroBoone



- 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!

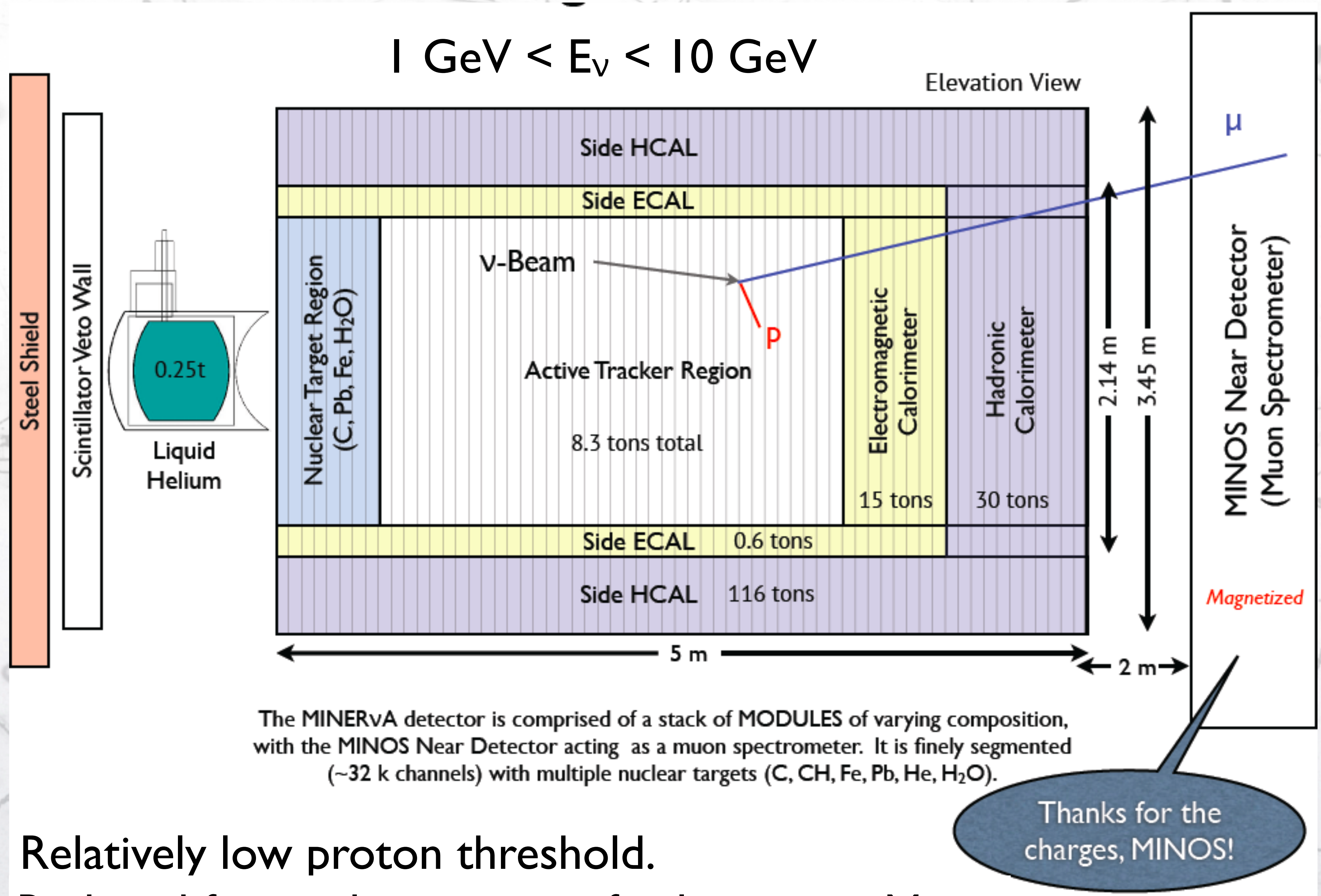






New results expected in the future

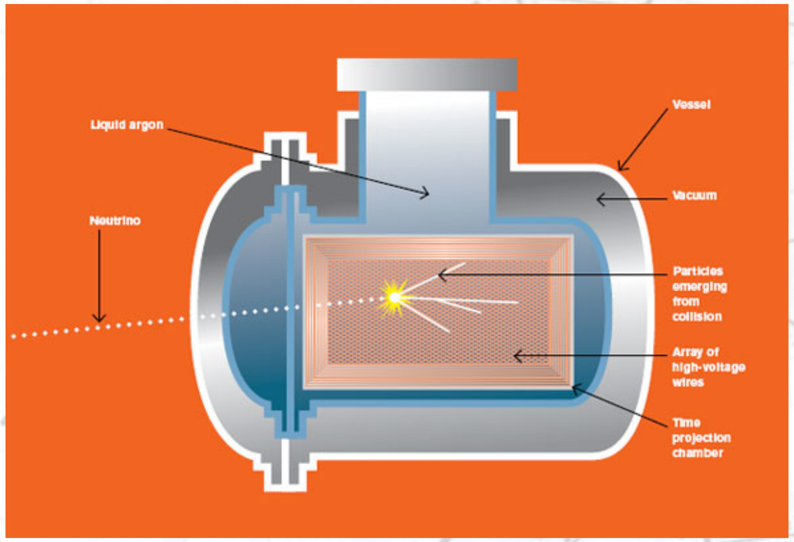
Minerva



Relatively low proton threshold.

Reduced forward acceptance for leptons in Minos

ArgoNeut



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