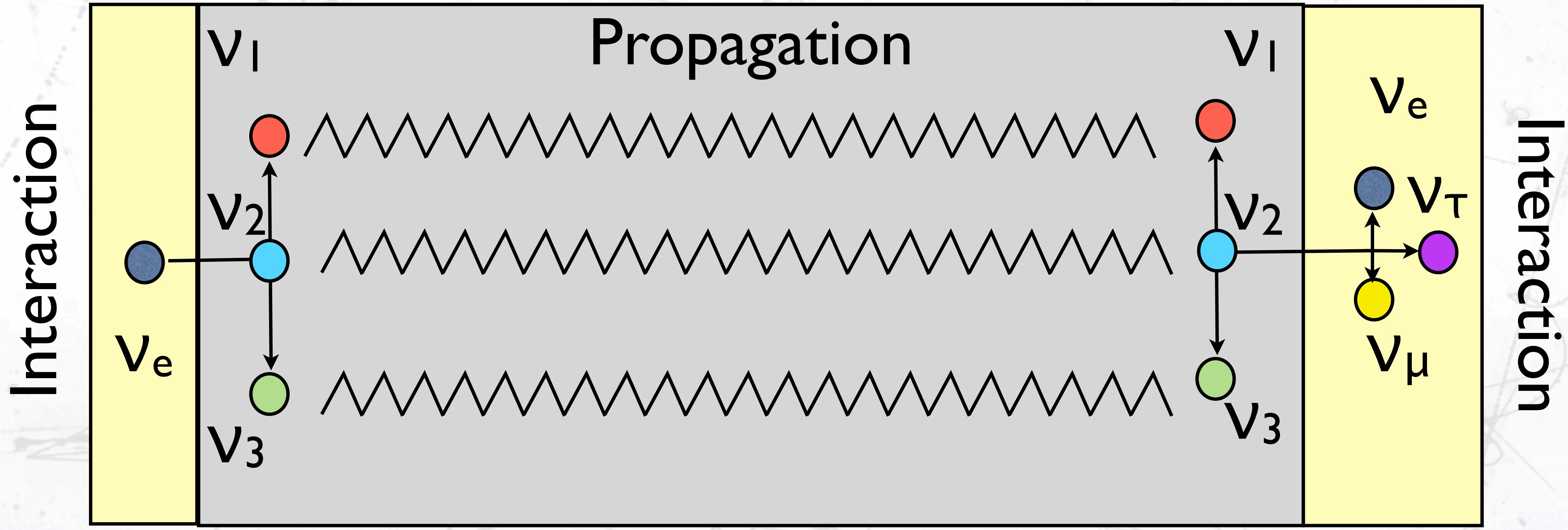
ν-Nucleus cross-sections

F.Sánchez
IFAE Barcelona

LBL concept

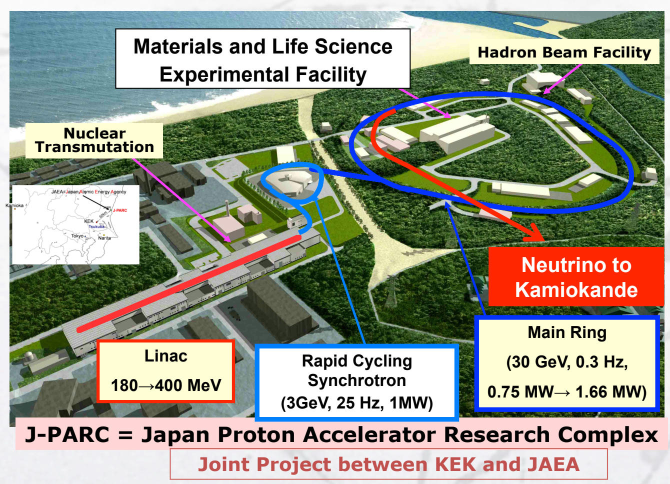


Interaction
Propagation
Interaction
ν_e
ν_1
ν_2
ν_3
ν_1
ν_2
ν_3
ν_e
ν_τ
ν_μ

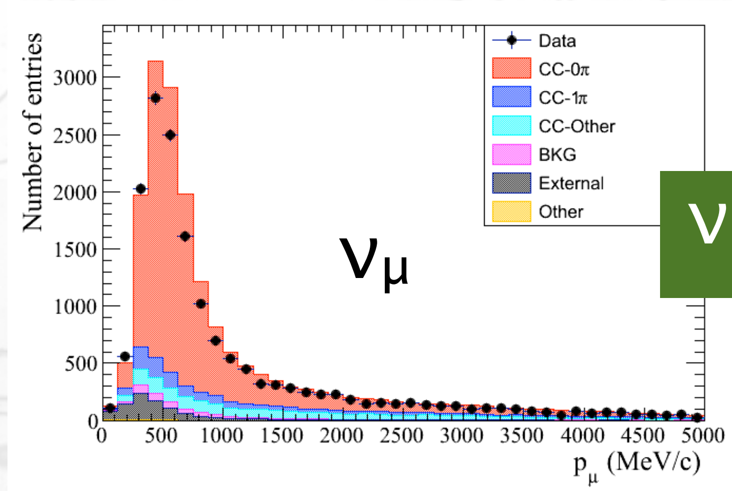
pion
muon
neutrino
neutrino
O^{16}
electron
O^{15}

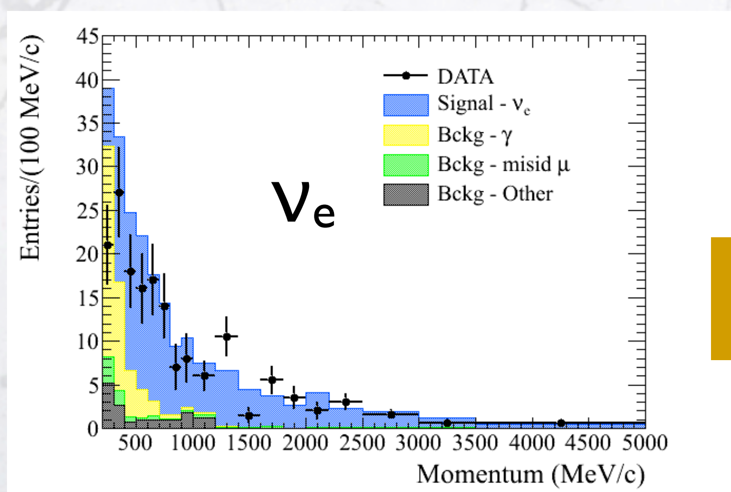
LBL concept

Proton beam



Near detector monitor





ν_τ

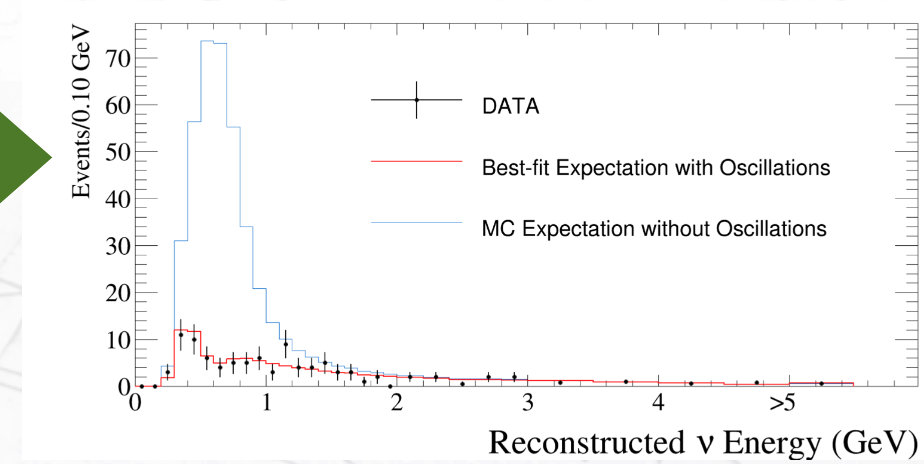
ν_μ ν_μ

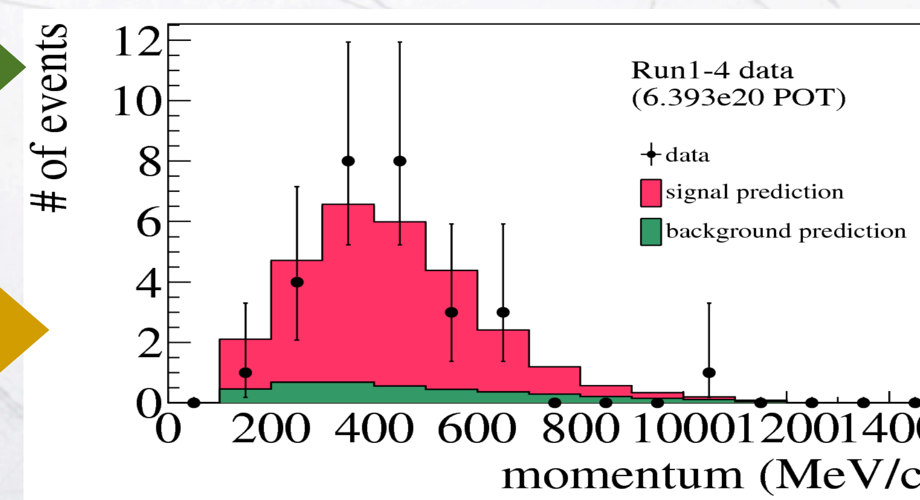
ν_e

ν_e ν_e

Far detector

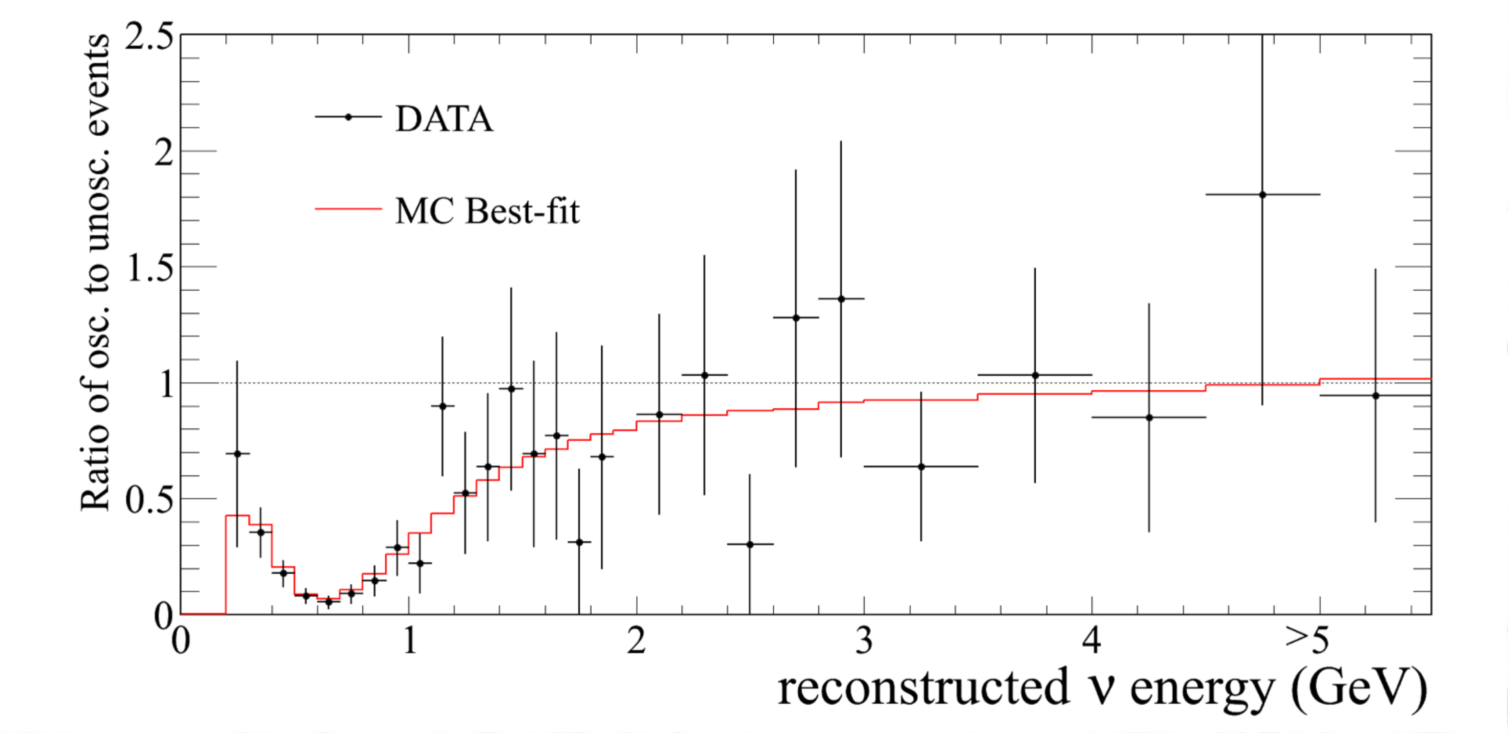
Invisible: ν´s are not energetic





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 ?

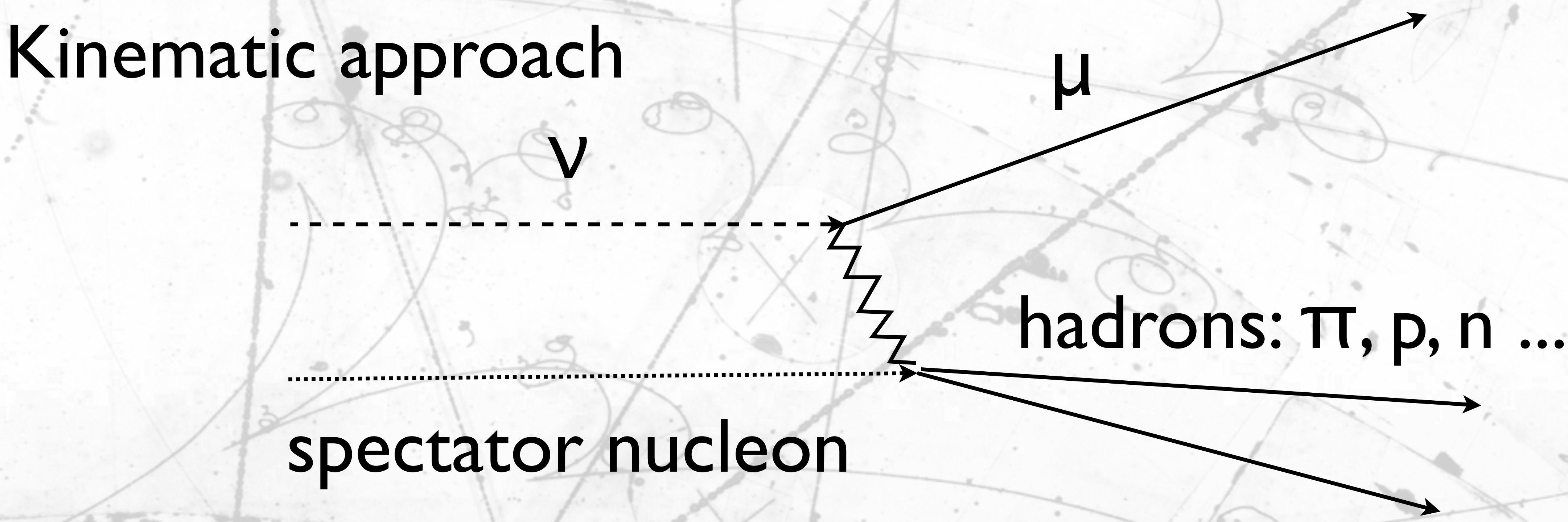
Low Energy ν's (≲2GeV)

- 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.

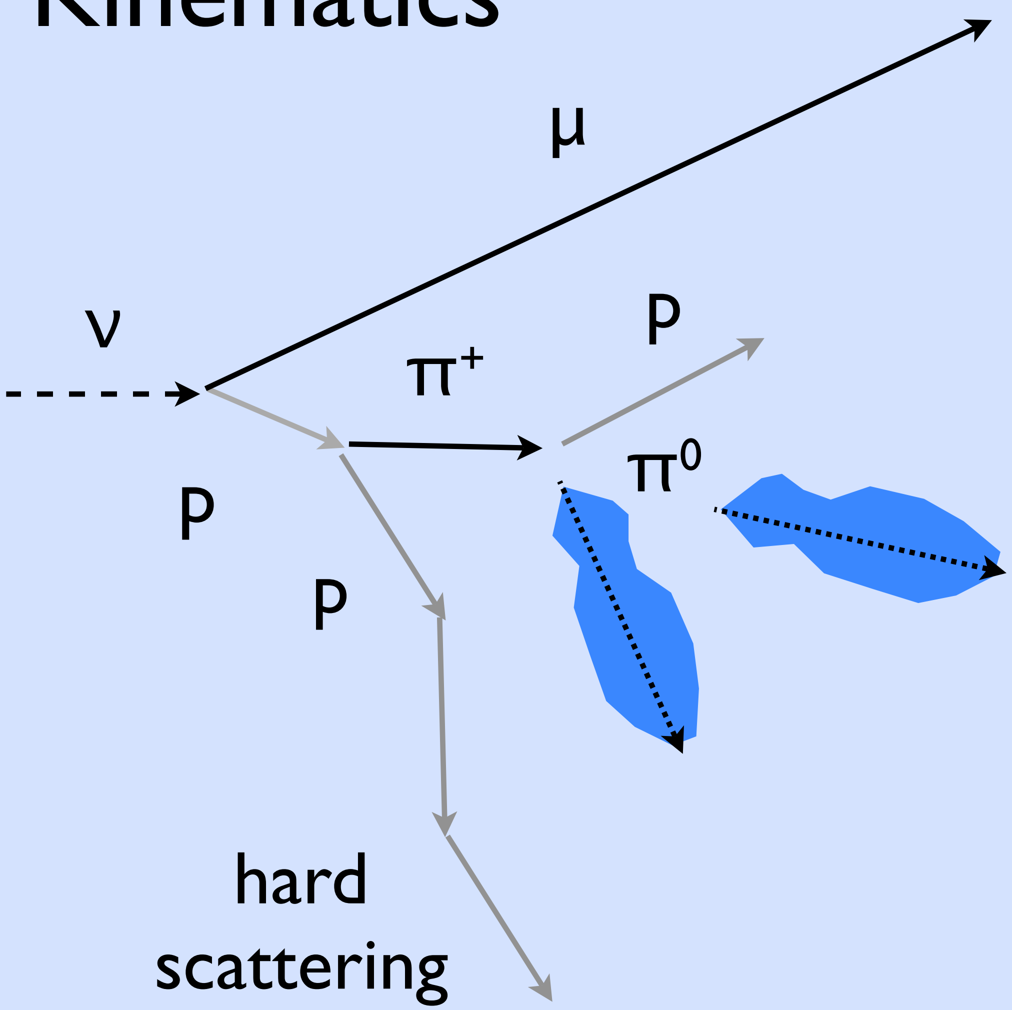
Cross-section problem



- 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.

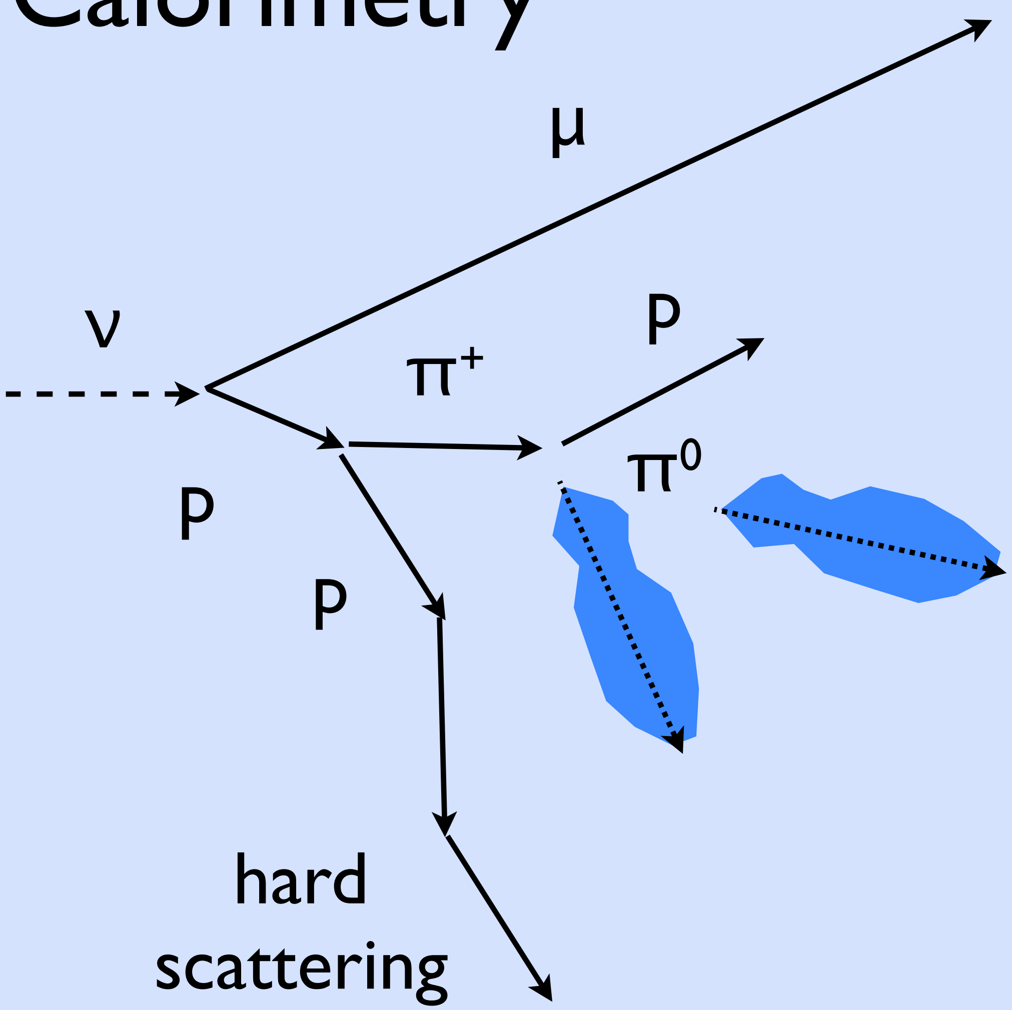
Cross-section problem

Kinematics



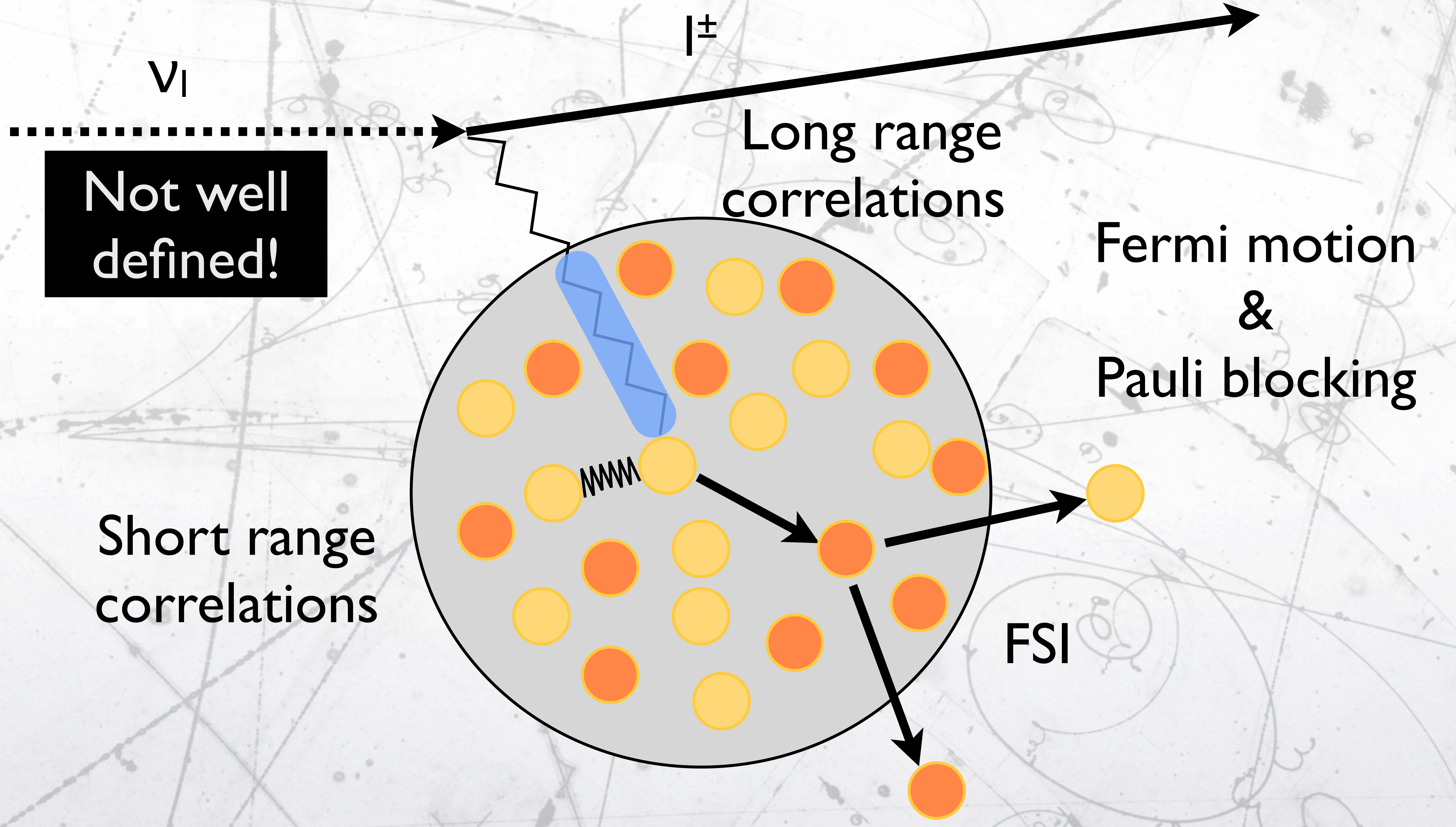
- Only a fraction of the energy is visible.
- Rely on channel interaction id.

Calorimetry



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

The interaction

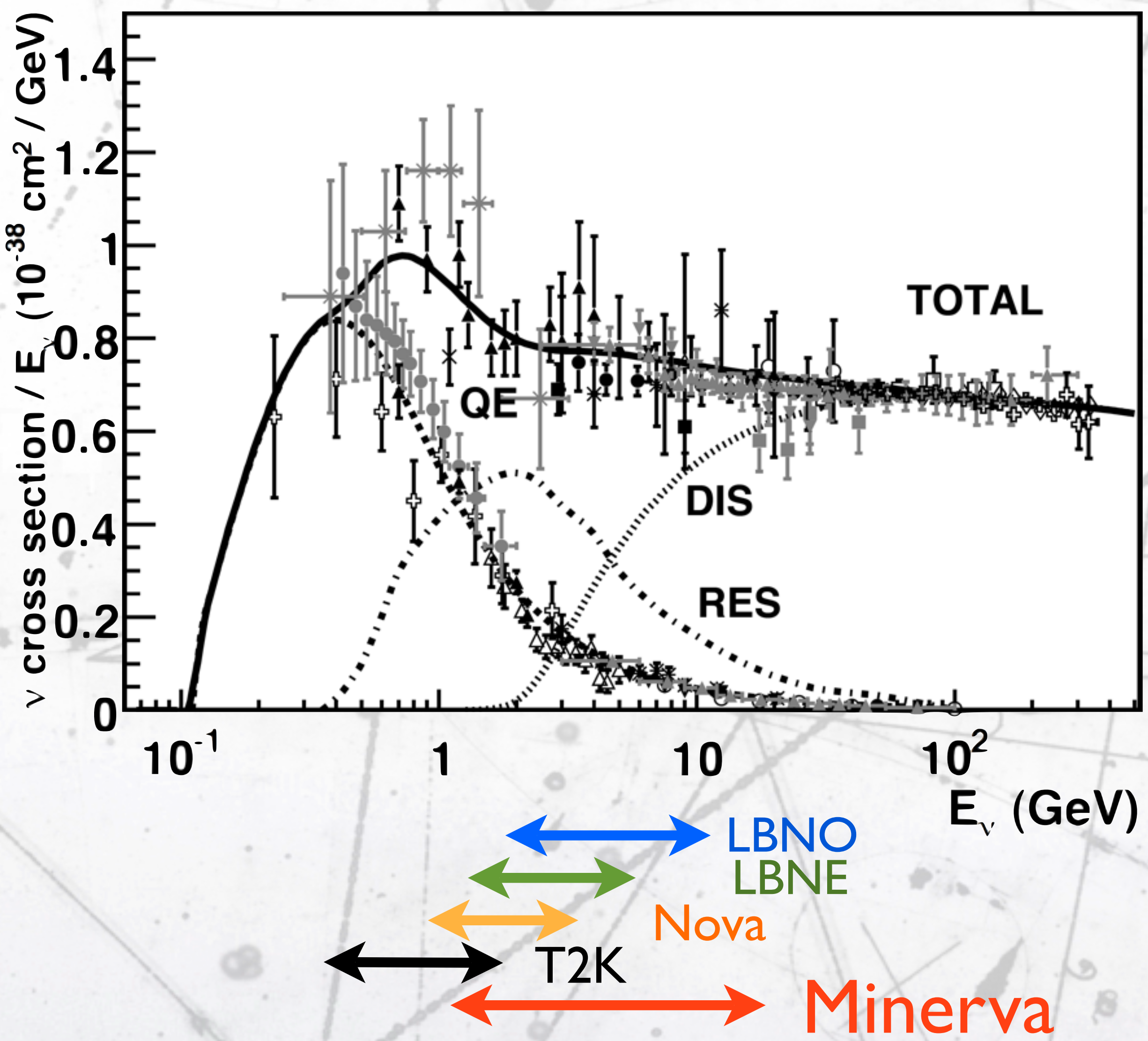


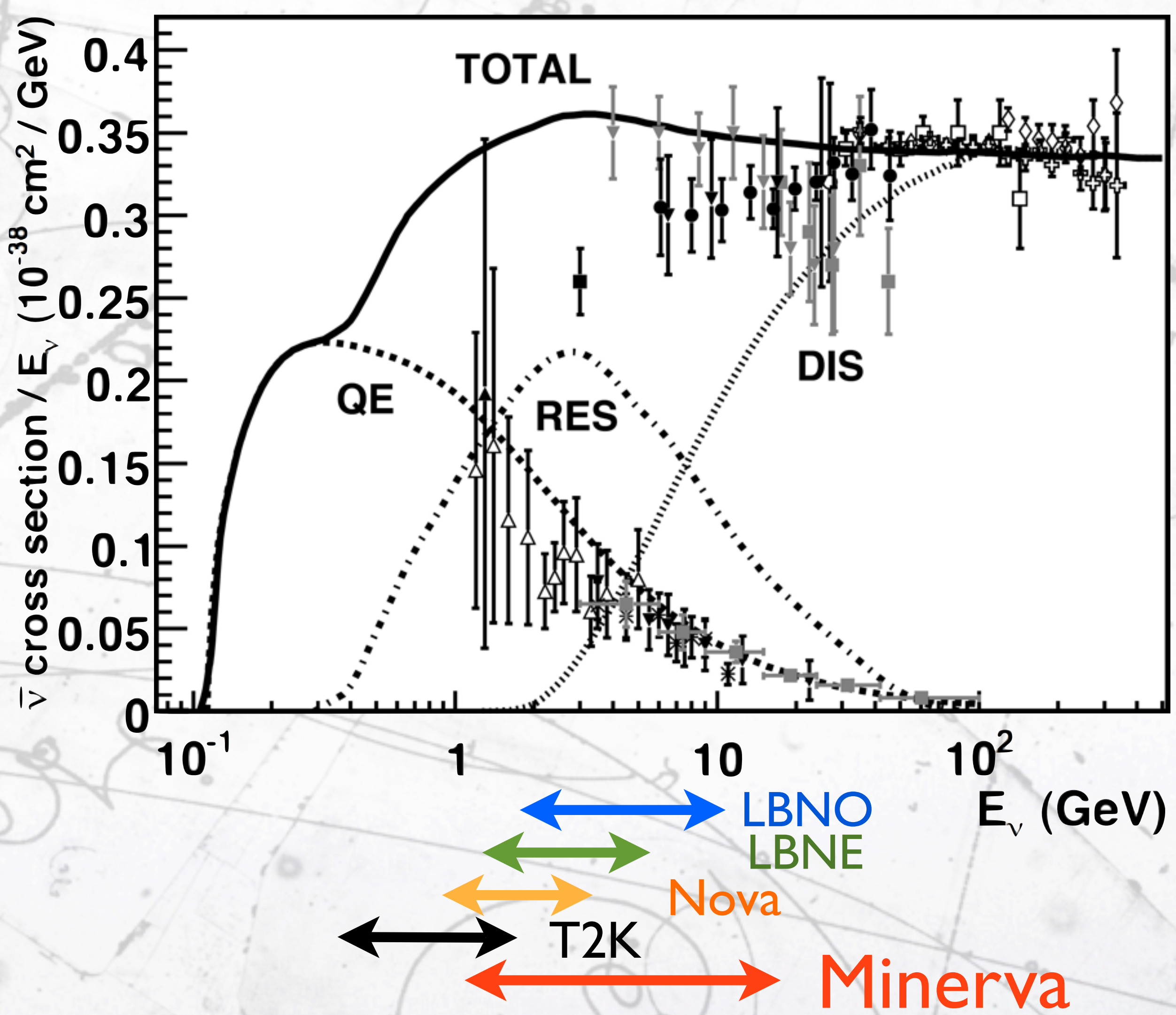
The interaccions

$CCQE$	$\nu_\mu n \rightarrow \mu^- p$
$CC1\pi$	$\nu_\mu p \rightarrow \mu^- \Delta^{++} \rightarrow \mu^- \pi^+ p$
	$\nu_\mu n \rightarrow \mu^- \Delta^{+} \rightarrow \mu^- \pi^+ n$
	$\nu_\mu n \rightarrow \mu^- \Delta^{+} \rightarrow \mu^- \pi^0 p$
$CCN\pi$	$\nu_\mu N \rightarrow \mu^- \Delta^{+,++} \rightarrow \mu^- N' \pi\pi ...$
$CCDis$	$\nu_\mu N \rightarrow \mu^- N' \pi, \pi, ...$

The xsec problem

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



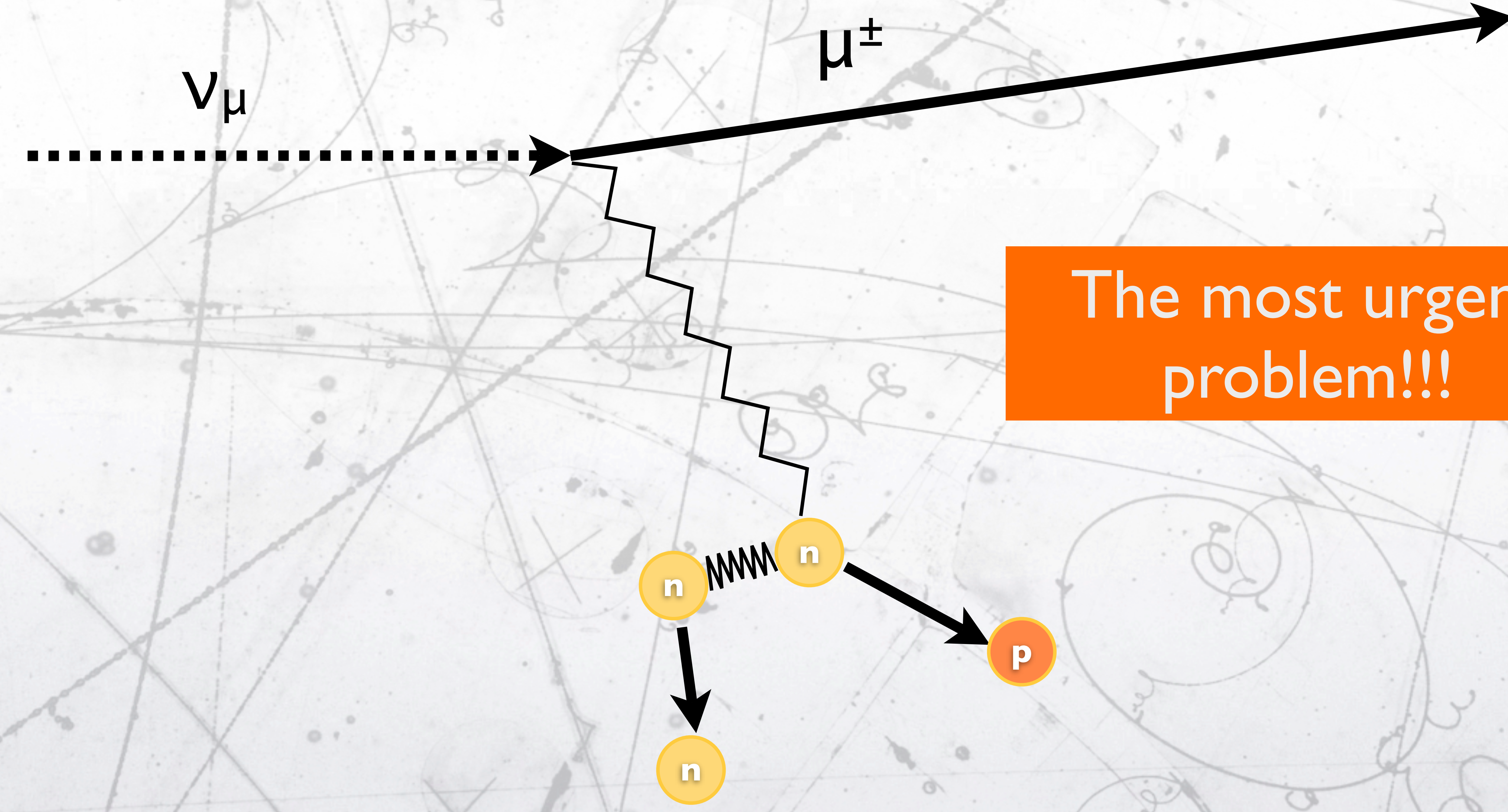


- Present and future oscillation experiments cover a region full of reaction thresholds and sparse data.

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!!!

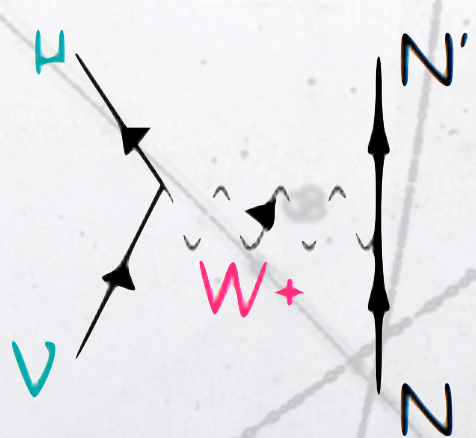
Why CCQE ?

- 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.

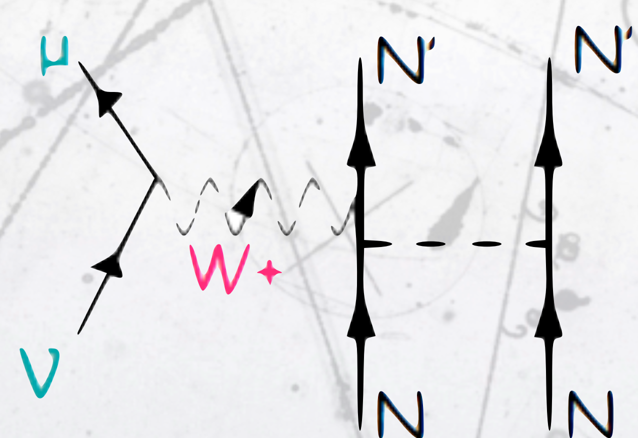
MiniBoone & 2p2h

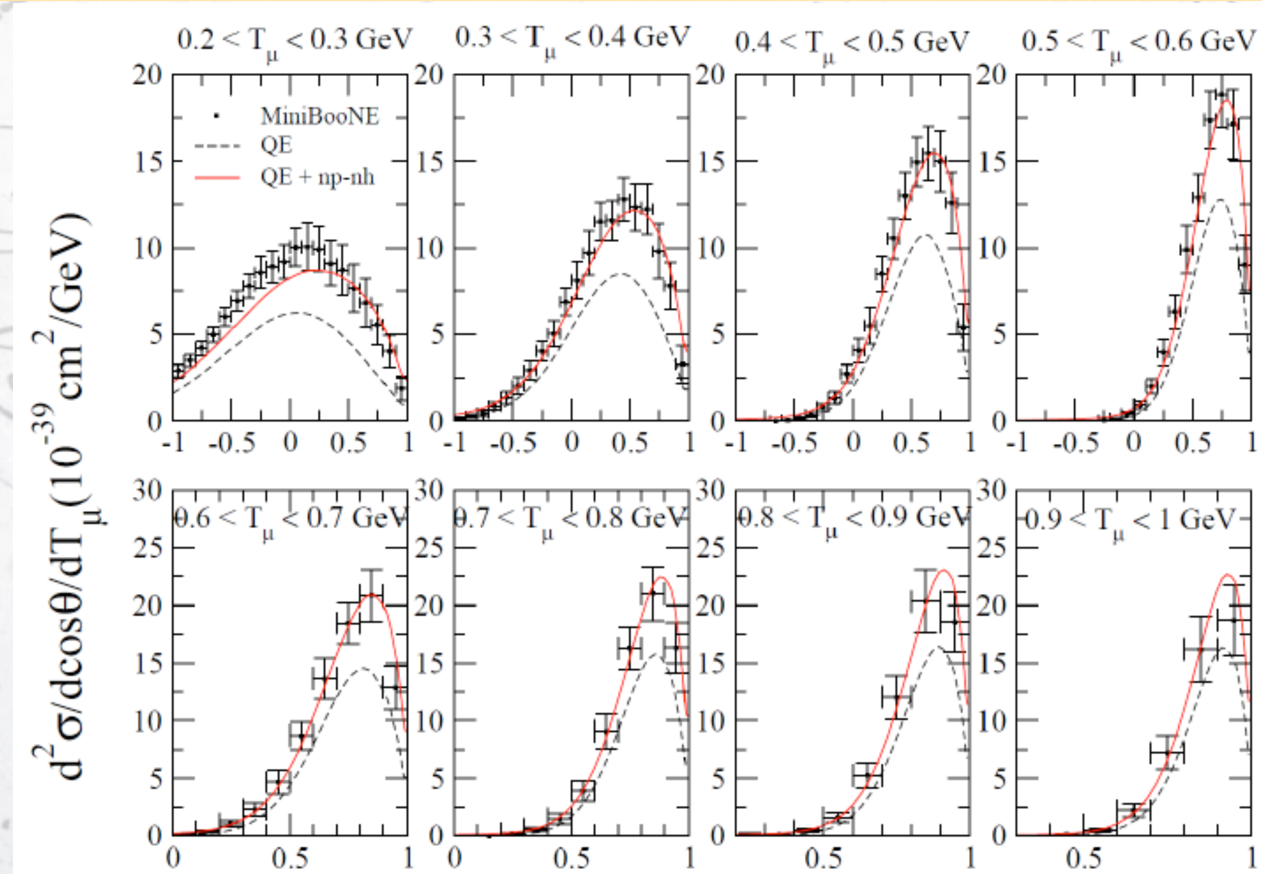
- MiniBoone published a double differential ν cross-section for events with no pions in final state (CCQE-like).
- Theorist profited from the clean data to realised that we were missing 20% of the cross-section !
- **We need to add a new channel (CC-2p2h) !!!**

CCQE



CC-2p2h



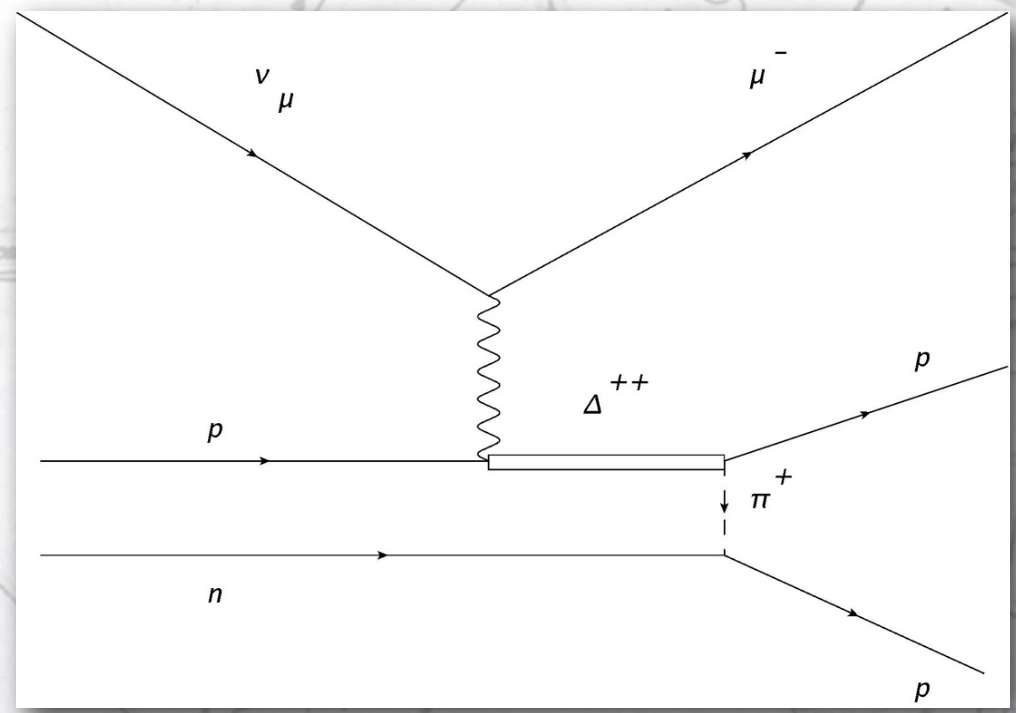


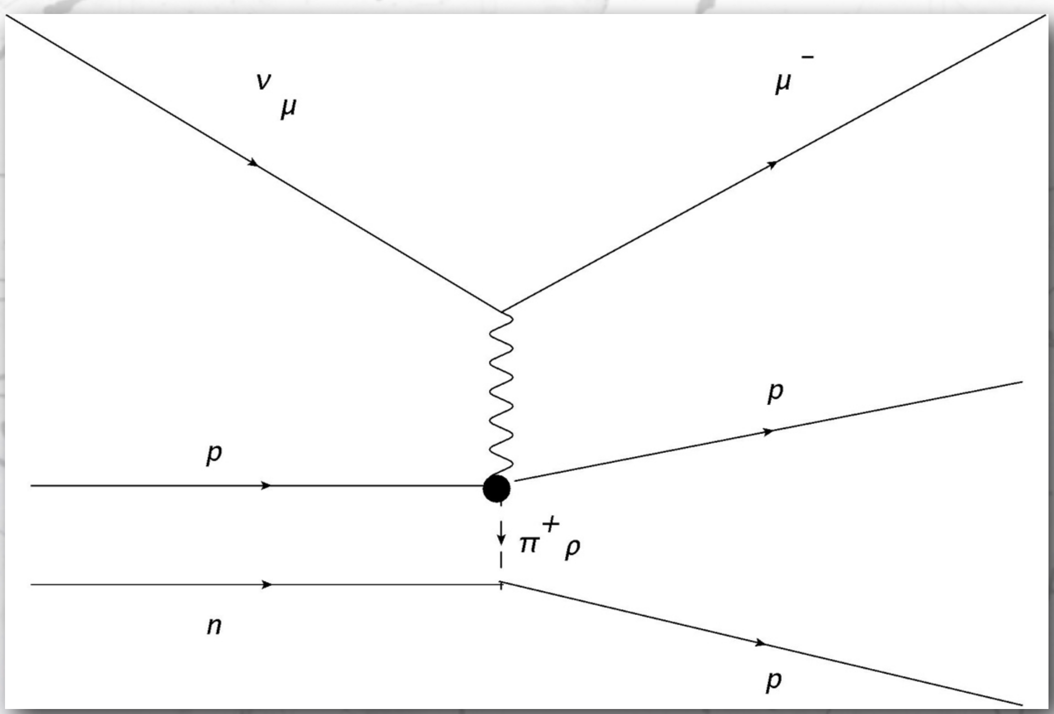
MiniBooNE, Phys. Rev. D 88 (2013) 032001

Martini et al. PRC 84 055502 (2011)

What is 2p2h?

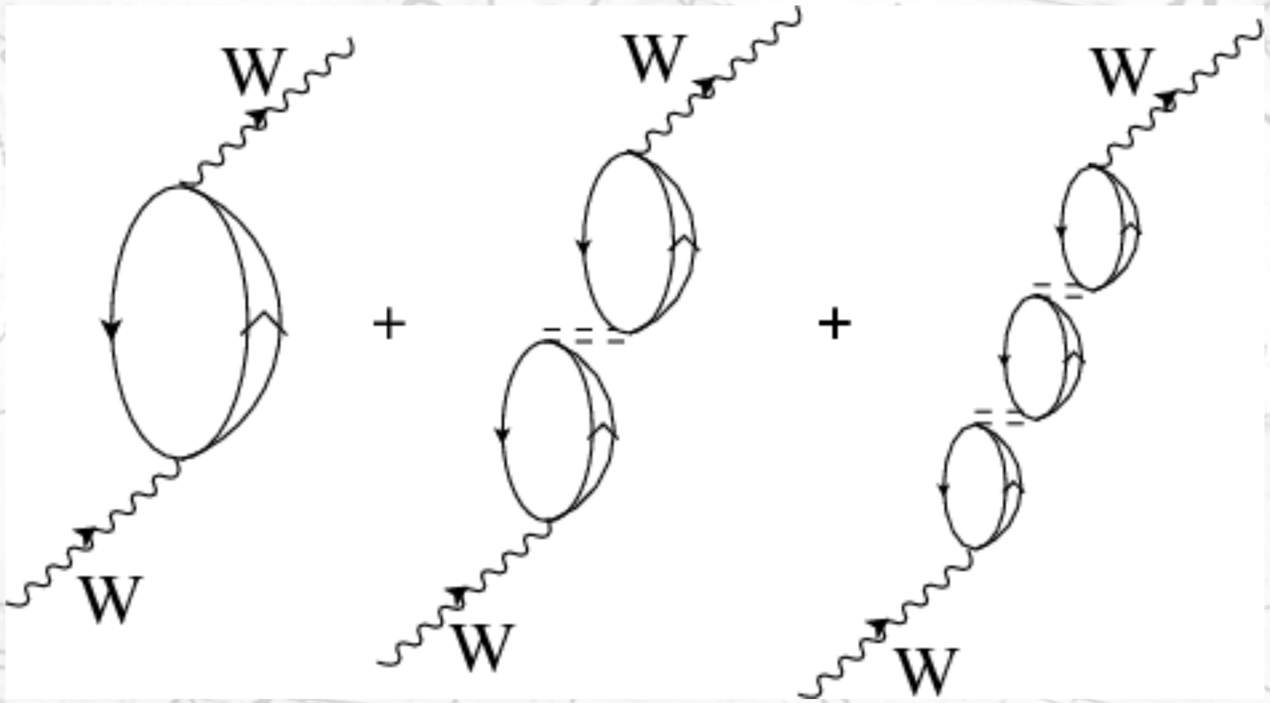
- 2p2h is basically the exchange of a meson between two close by nucleons in the nucleons with the emission of 2 nucleons.
- The pion can be produced in a contact point or through an intermediate virtual Δ^{++}.





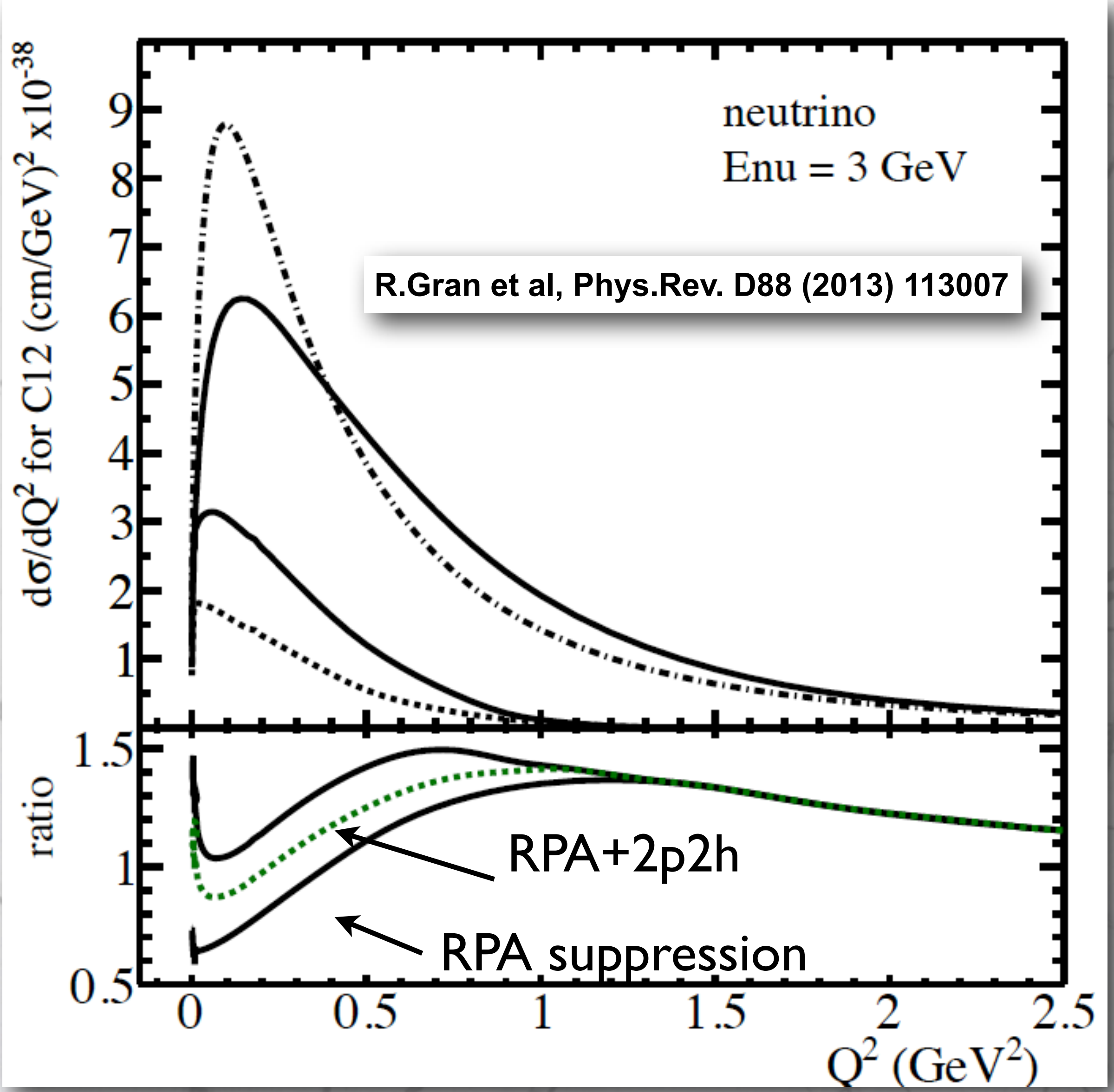
It is possible that the same process happens with the emission of one pion through high mass resonances!

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)

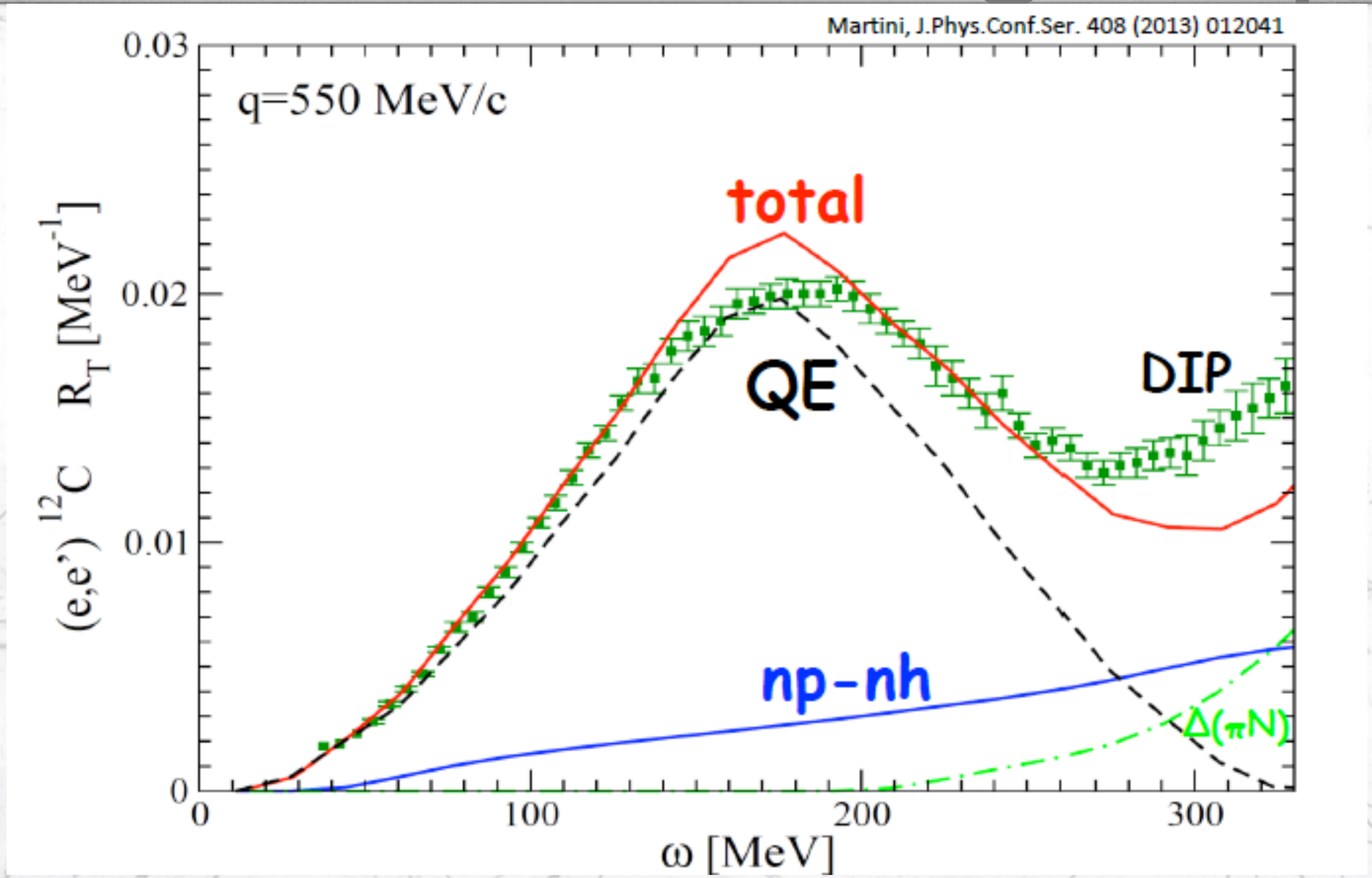
Short & Long Range



- 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.

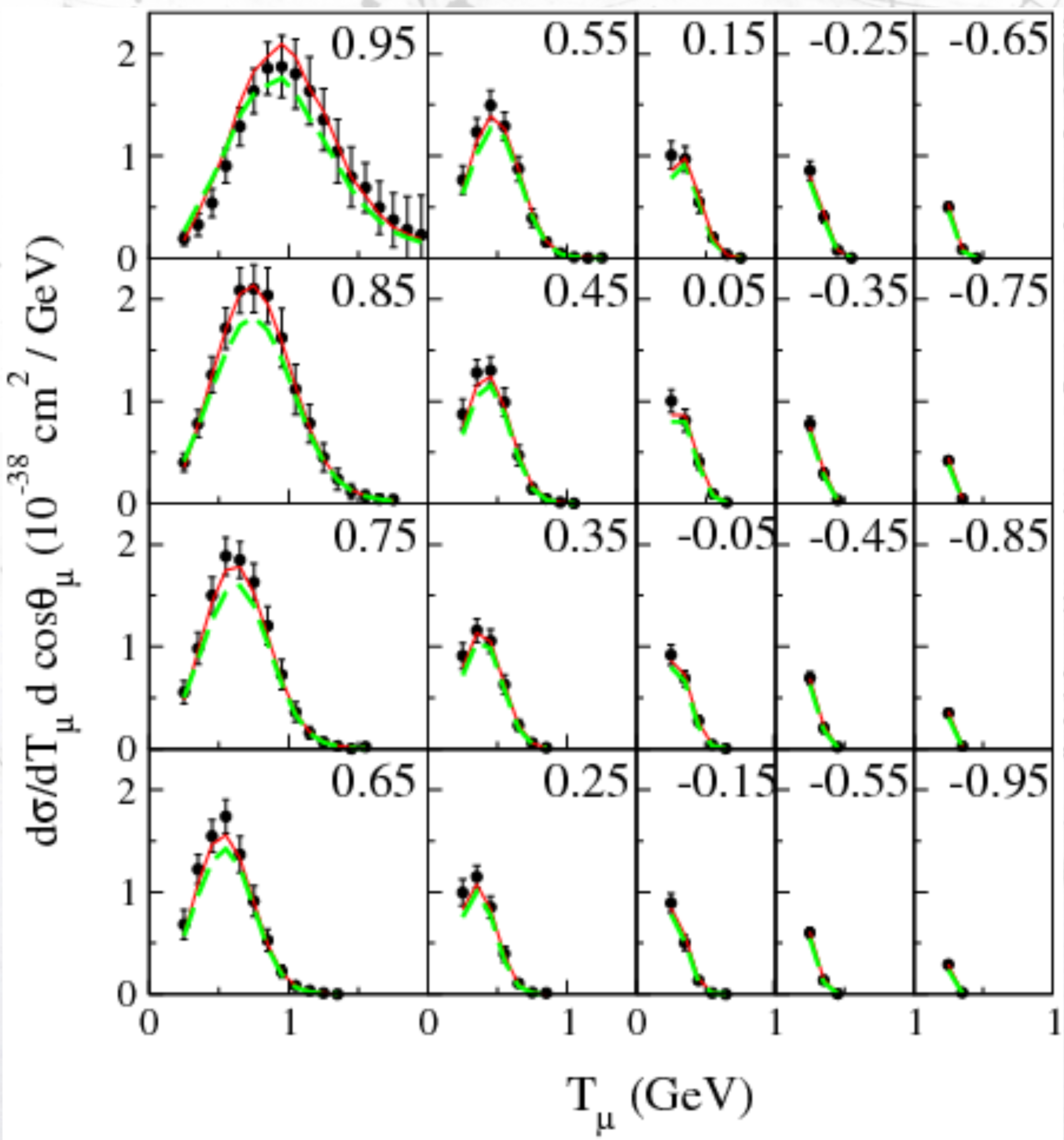
Electron Scattering & 2p2h

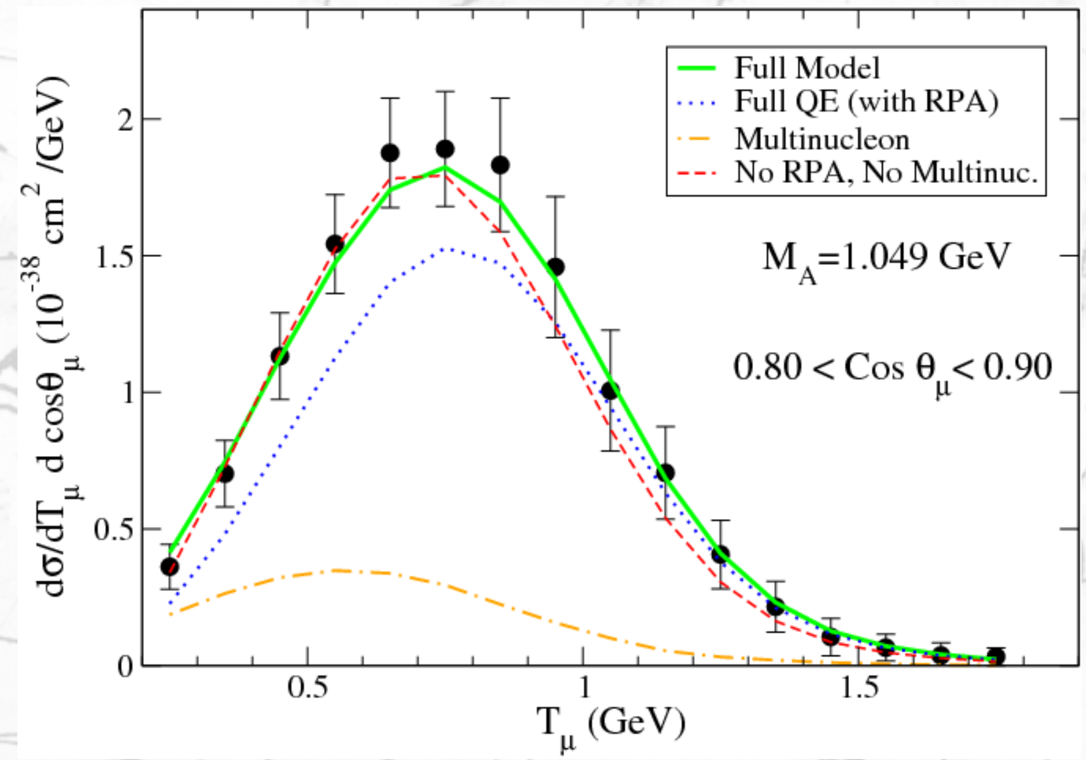


- This contribution was known to the electron scattering community for more than a decade.
- We needed double diferential (p_μ,θ_μ) data to observe np-nh with neutrinos.

Recovering M_A

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





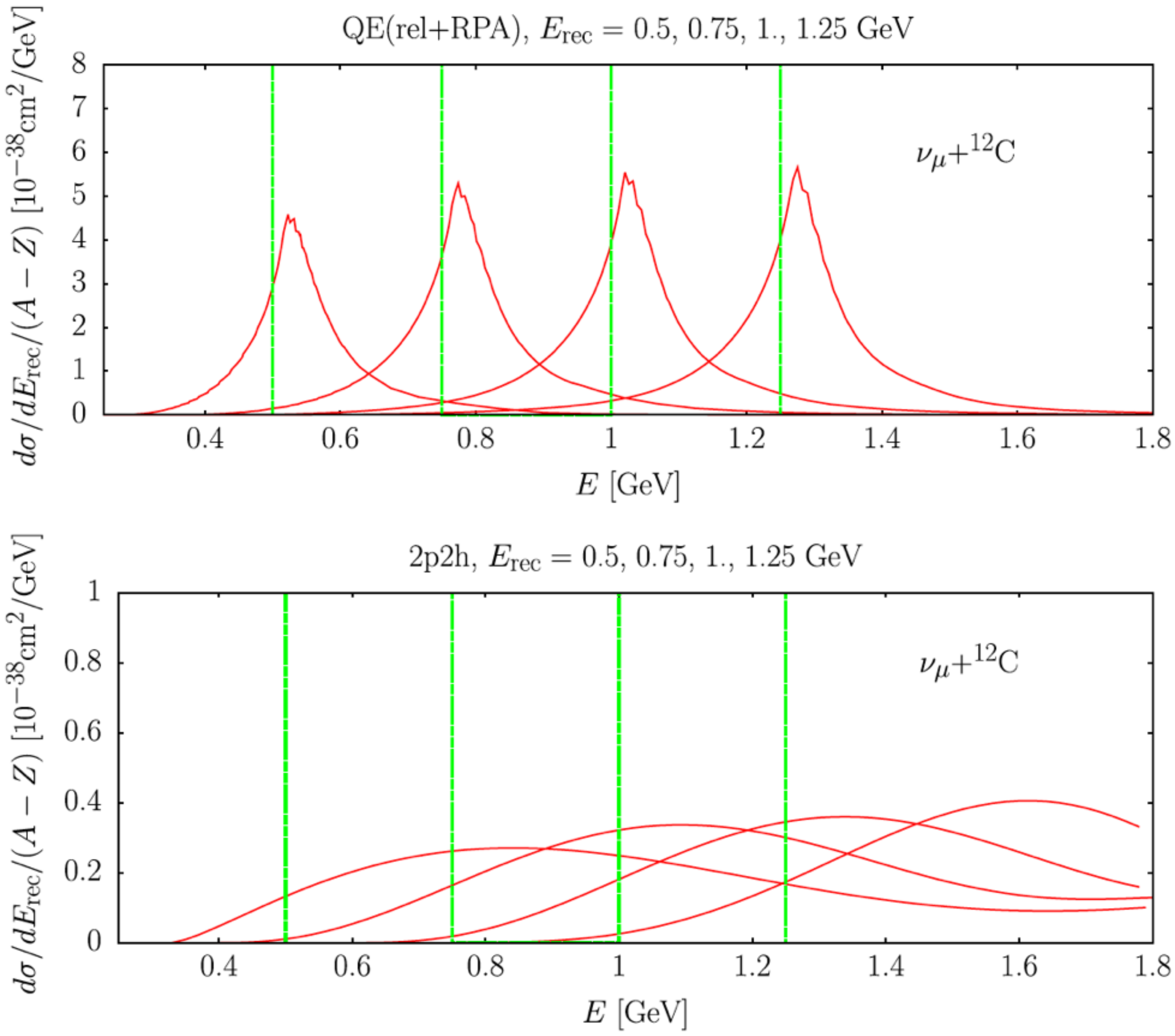
Data fits equally well to:

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)

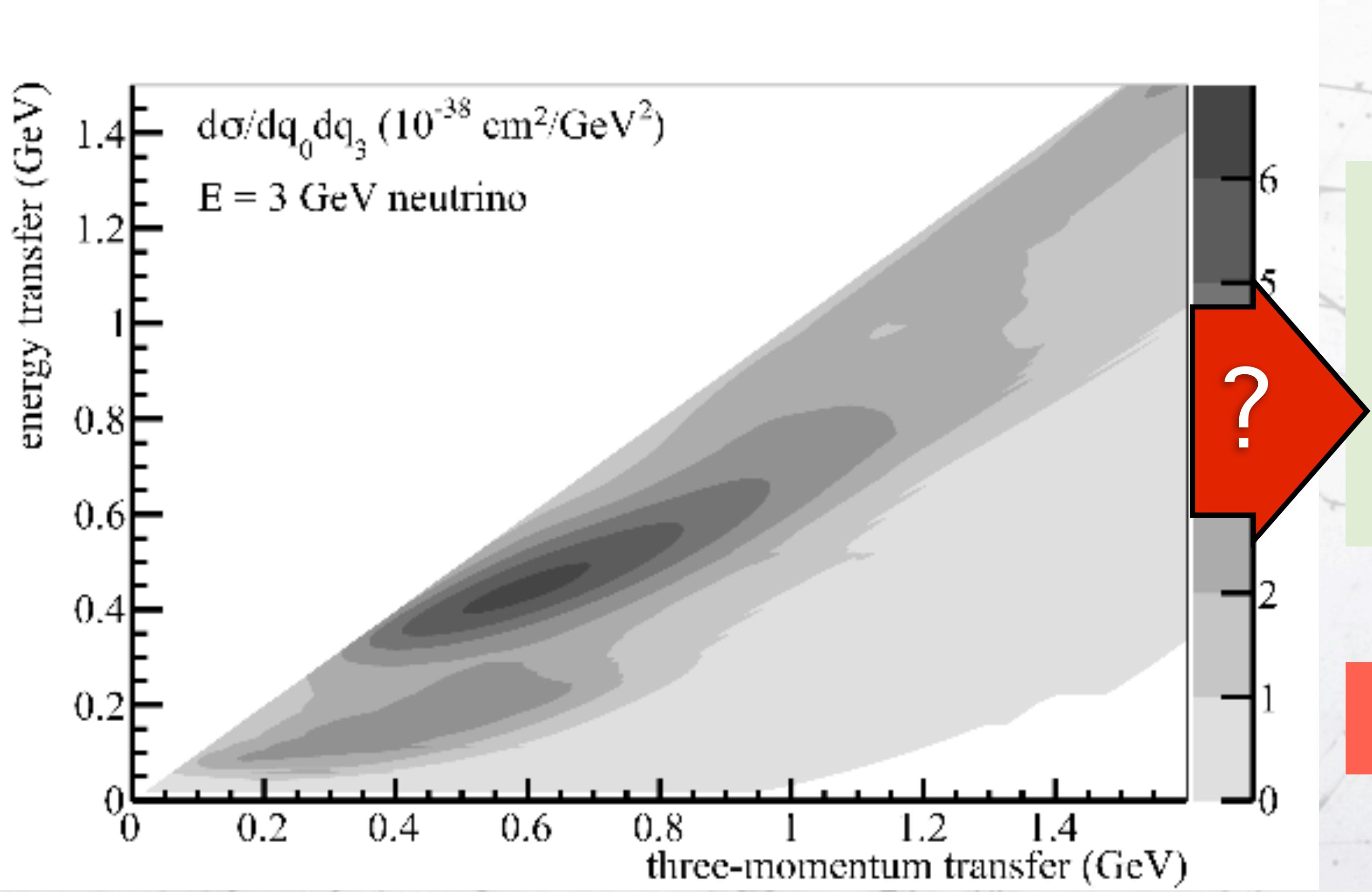
Effect of multi-nucleon (2p2h) interactions in the neutrino energy reconstruction.

- 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, etc...).
- Agreement with experiments might vary with the typical experiment energy.

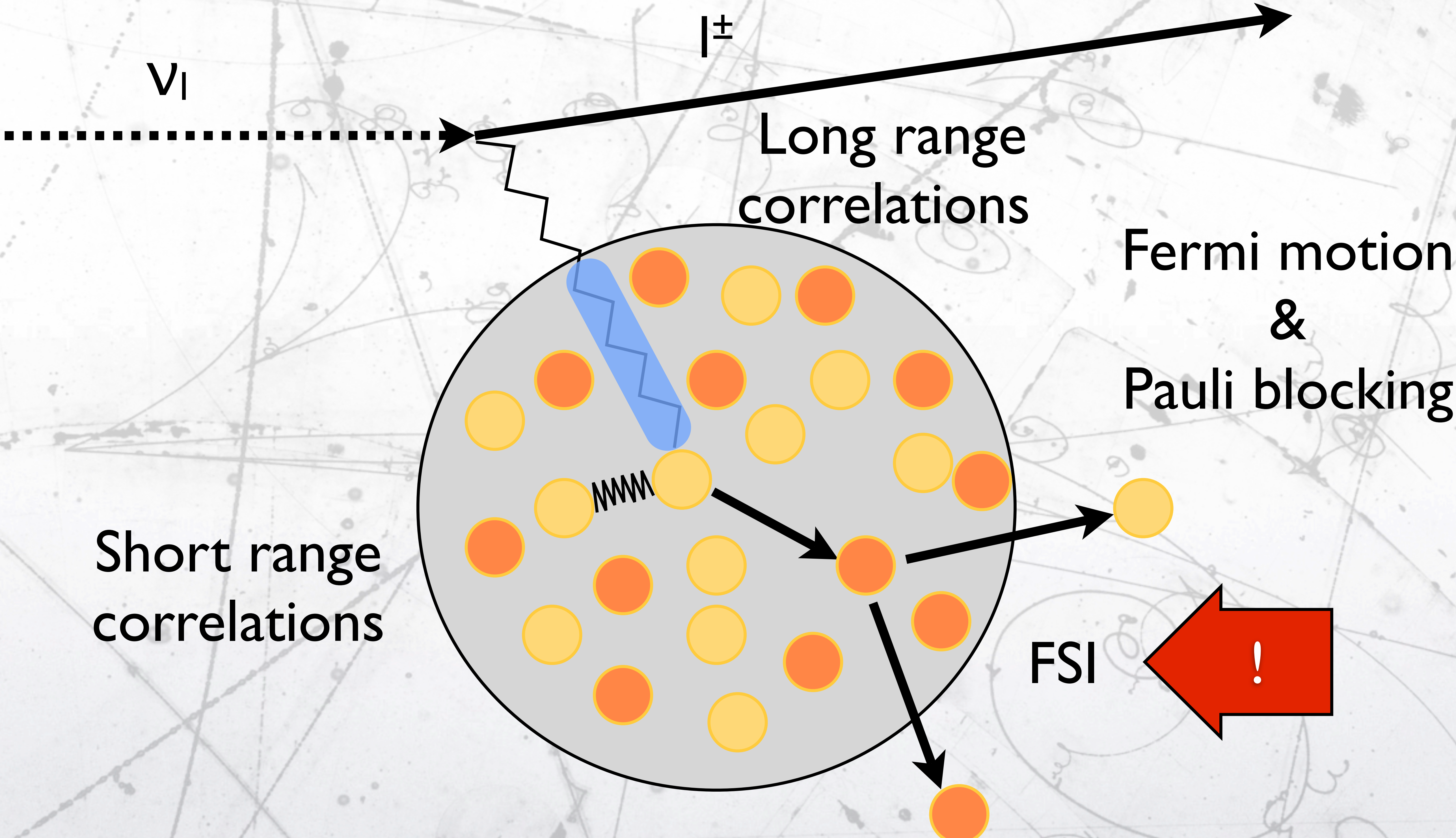


Gran, R. *et al.* Phys.Rev. D88 (2013) 11, 113007

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

Theorists are needed!

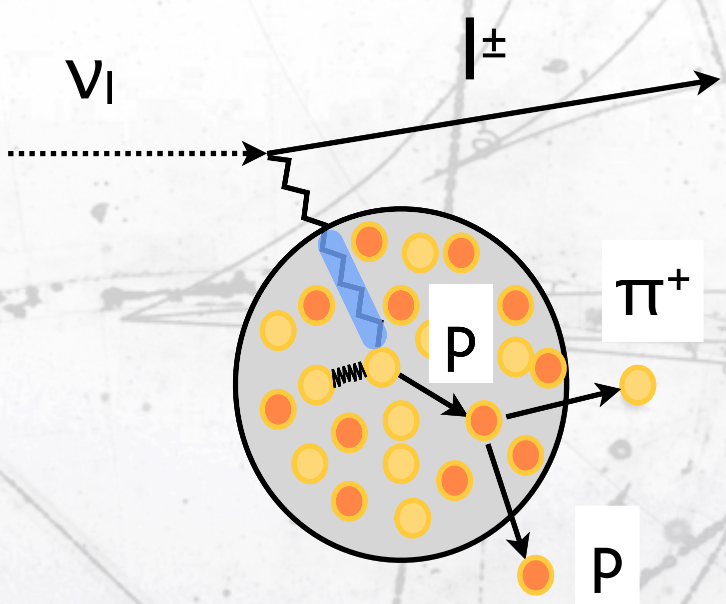
Final state interactions



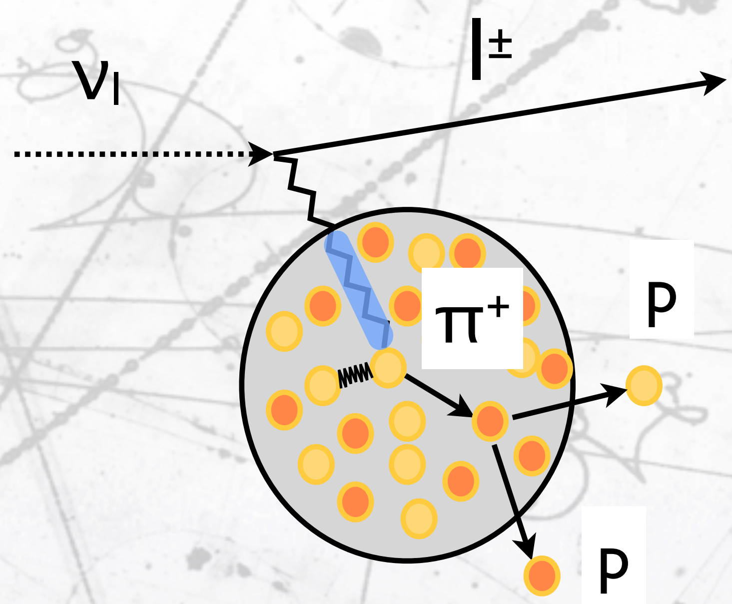
Problem factorisation

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

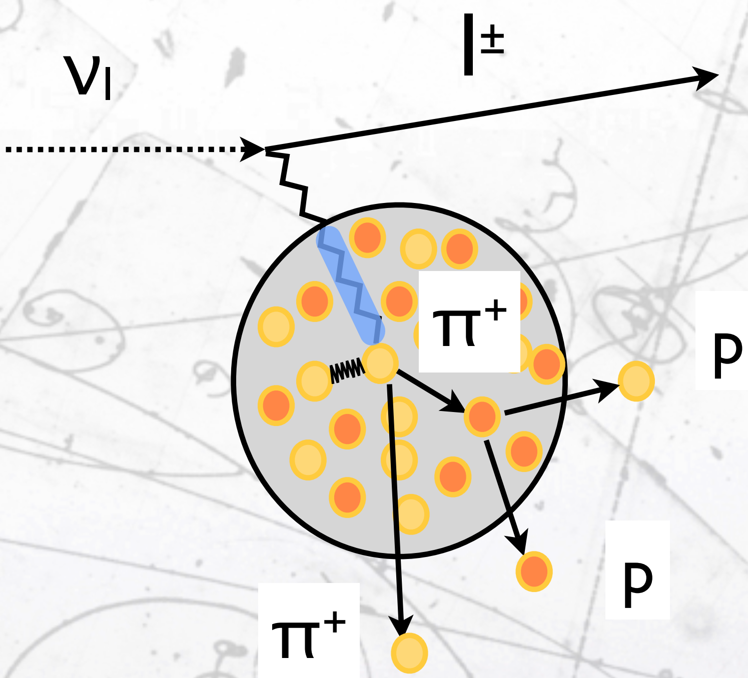
FSI alters the definition of the event



1. CCQE
2. proton in final state
3. p p -> p π^+



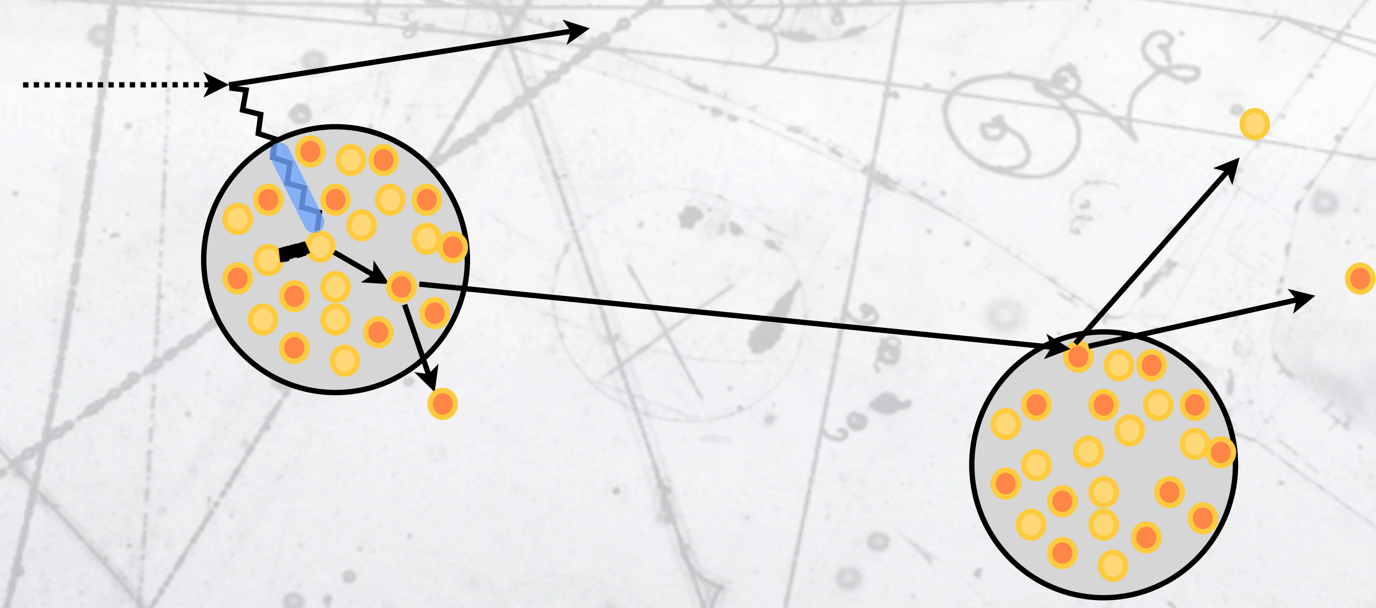
1. CC1 π^+
2. π^+ in final state
3. π^+ p -> p p



1. CC $2\pi^+$
2. $2\pi^+$ in final state
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.



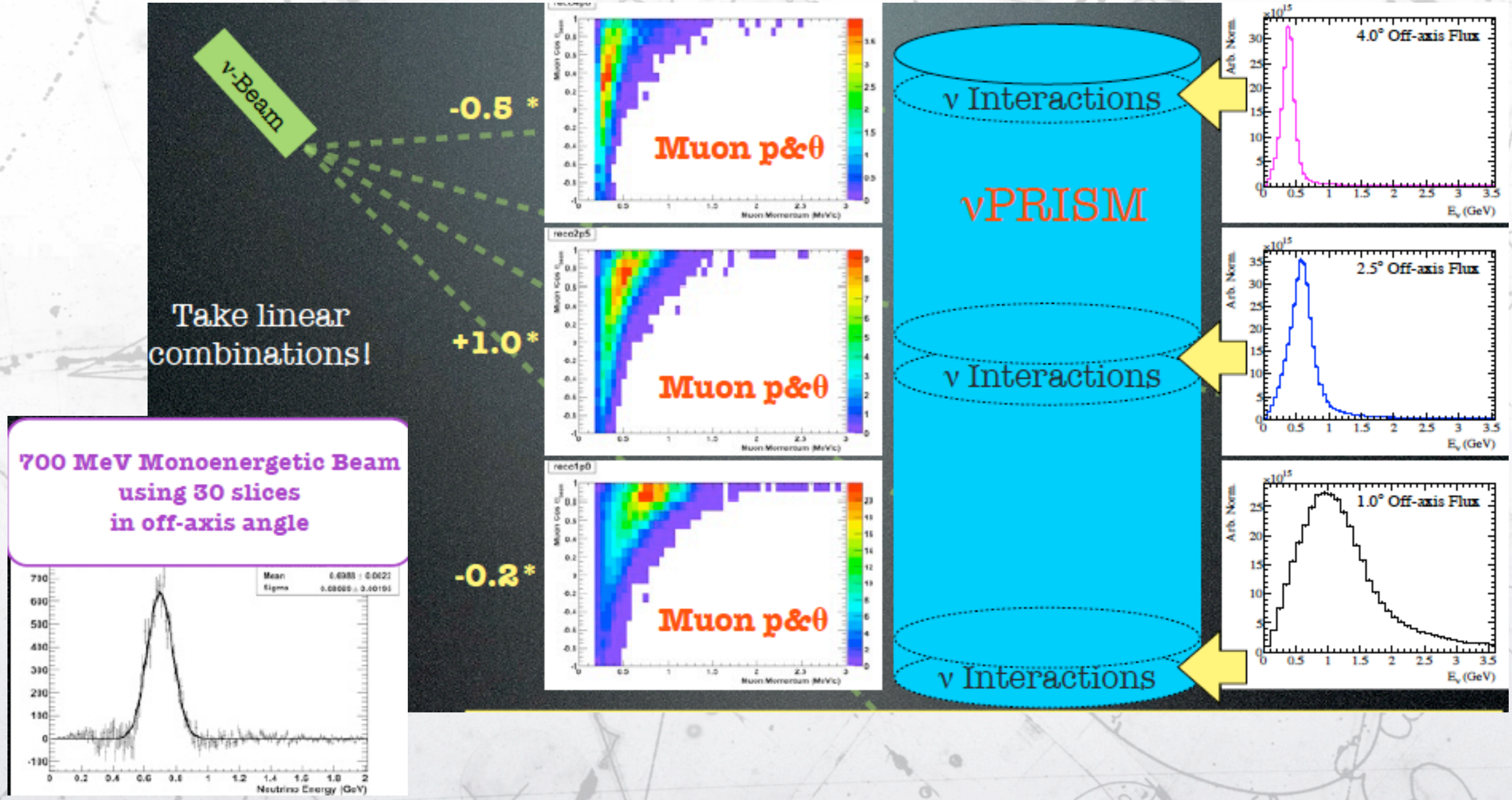
This is already a dominant systematic @T2K

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

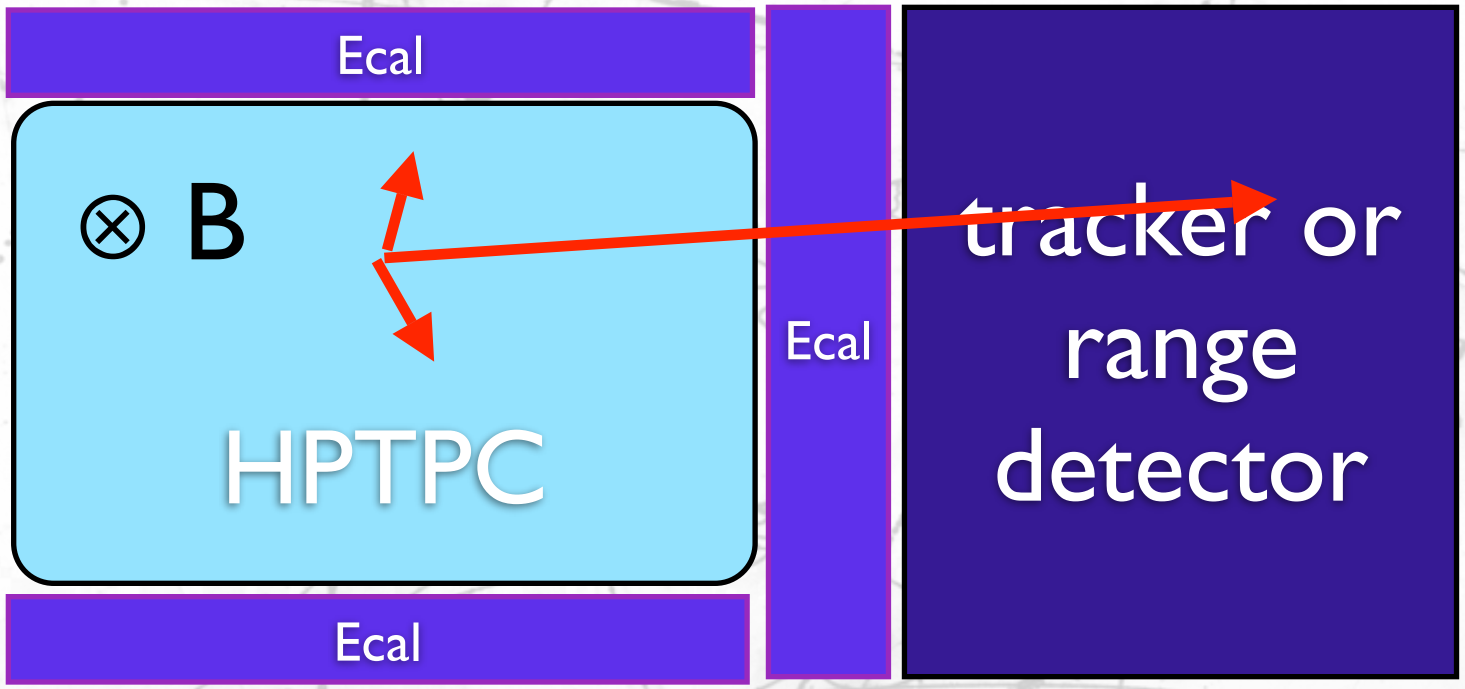
How to measure them?

- Monochromatic neutrino beam!
  - Or at least a variable neutrino spectra.
- Detector sensitive to the low energy hadron component: count protons/pions, topologies,…
- Experiments to measure proton and pion scattering with nuclei.
- Several nuclei targets to be able to factorize the nuclear dependencies:
  - Re-do hydrogen/deuterium measurements.

NuPrism


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

New Ideas: HPTPC

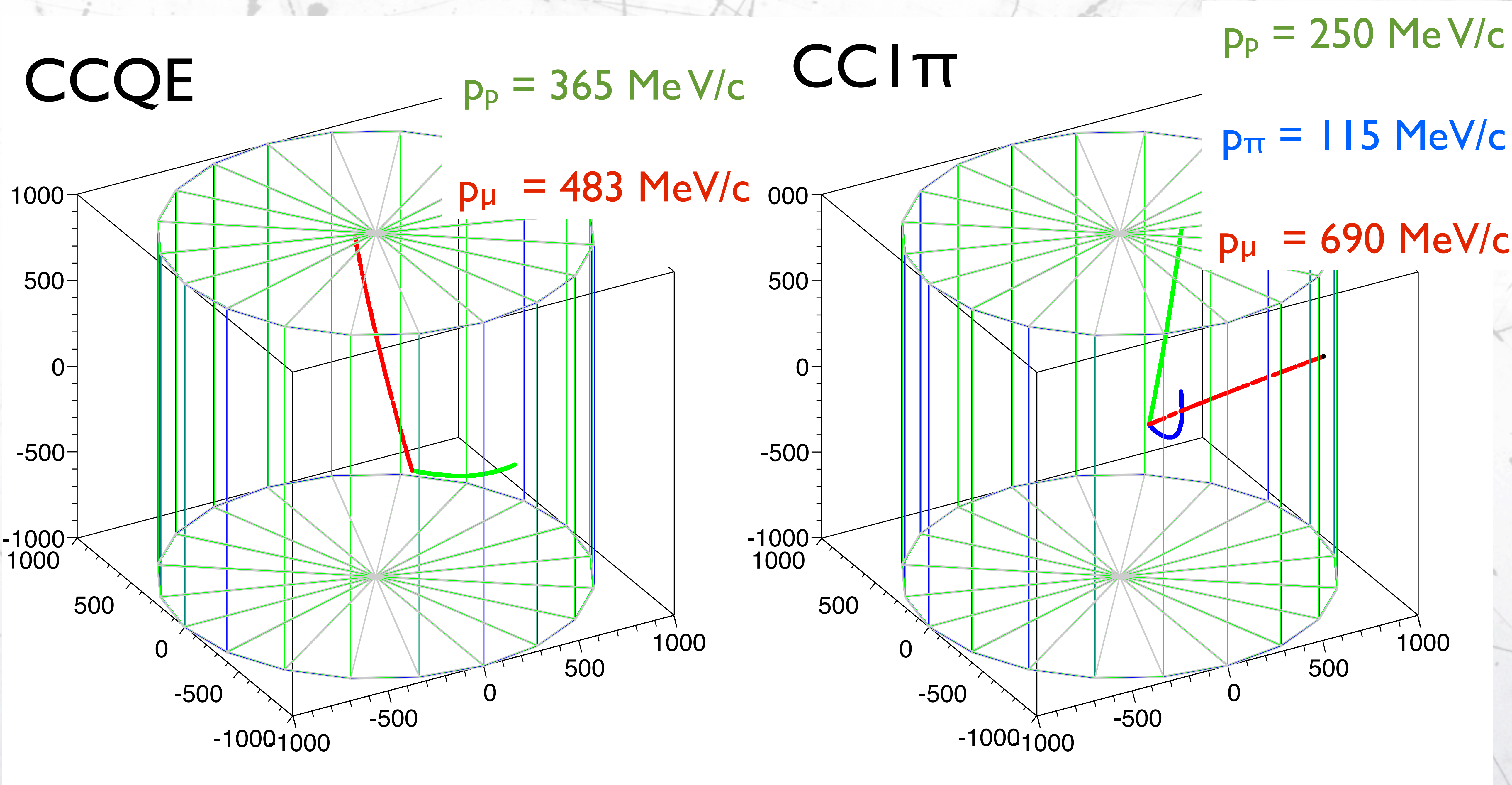


A moving detector ("a la NuPrism") or tuneable beam will help to reduce systematics.

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.
- Several gases: He, Ne, Ar, CF4….

New Ideas: HPTPC

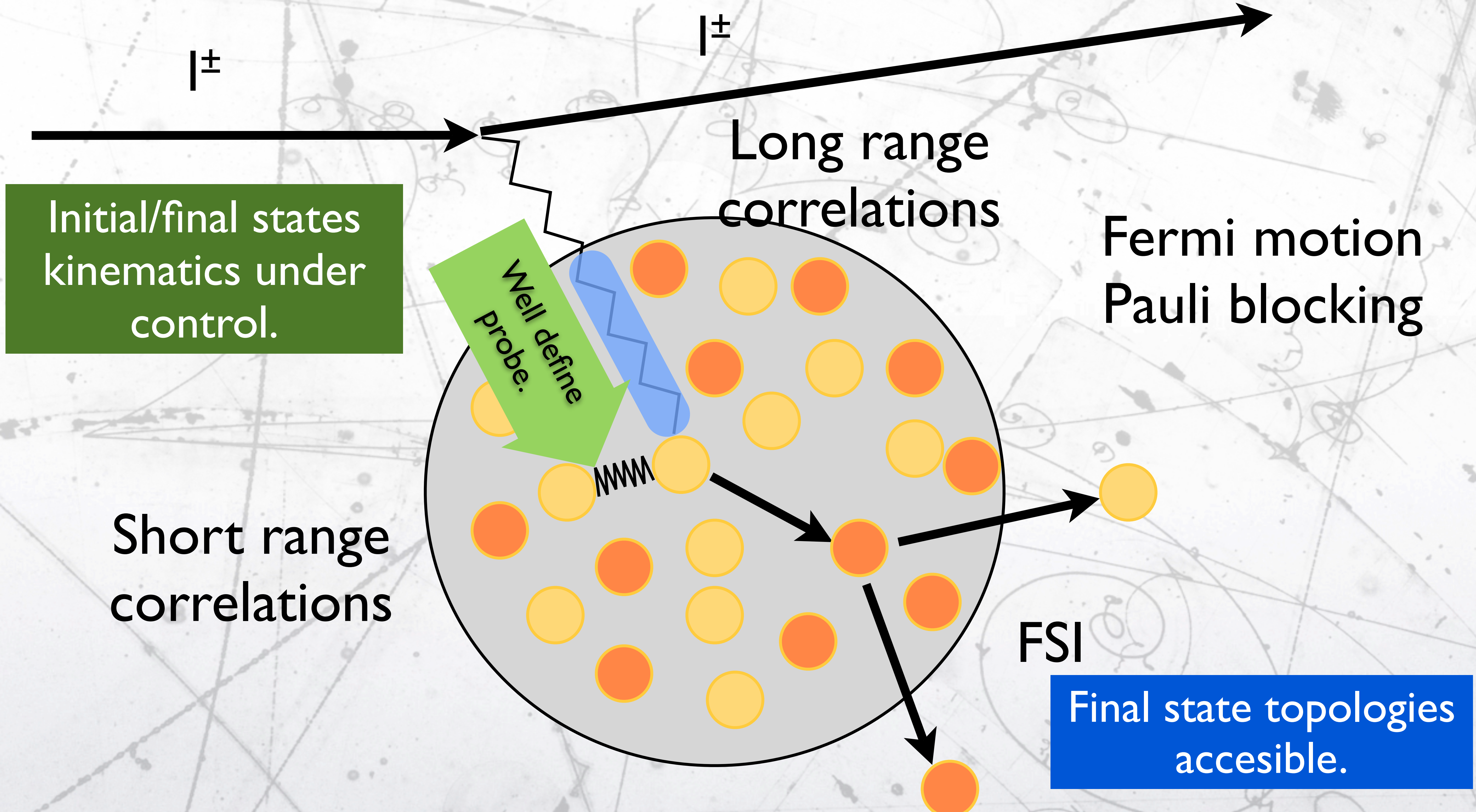


New Ideas

- IFAE proposed the idea of the HPTPC to T2K and now it is collecting interest from several institutions around the world (UK, France, Italy, Germany, Switzerland, USA, Canada, Japan,…) to propose an experiment in FNAL.
- We are investigating options to finance the design studies using Fet-Open.
- The call will include both experimentalist and model-builders.

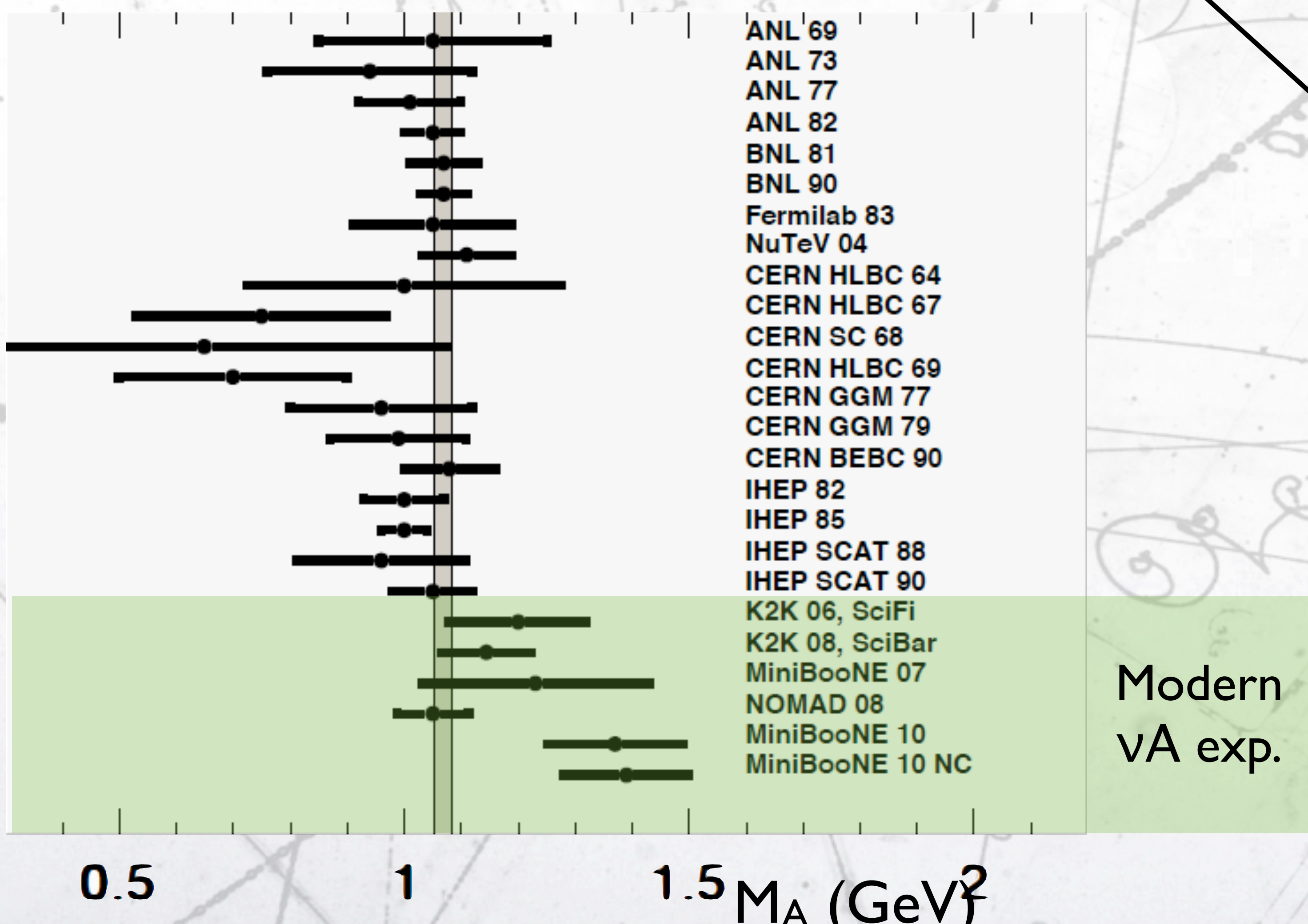
Backup and supporting slides

Electron scattering



CCQE problems

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

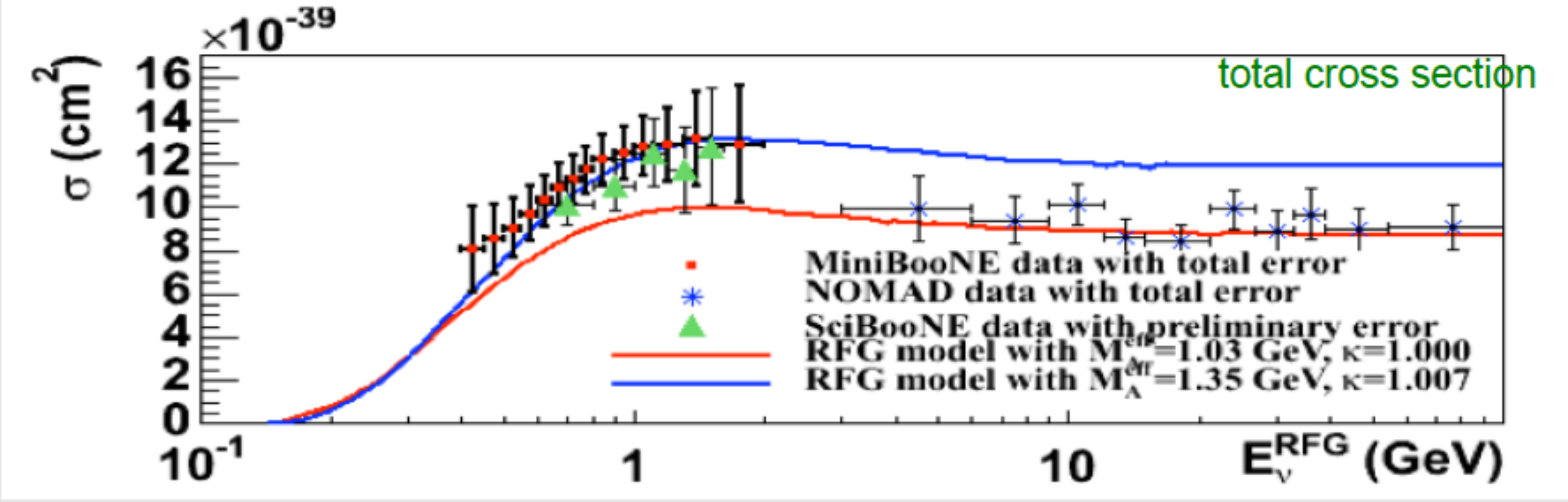


Bernard et al. 2002

- 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.



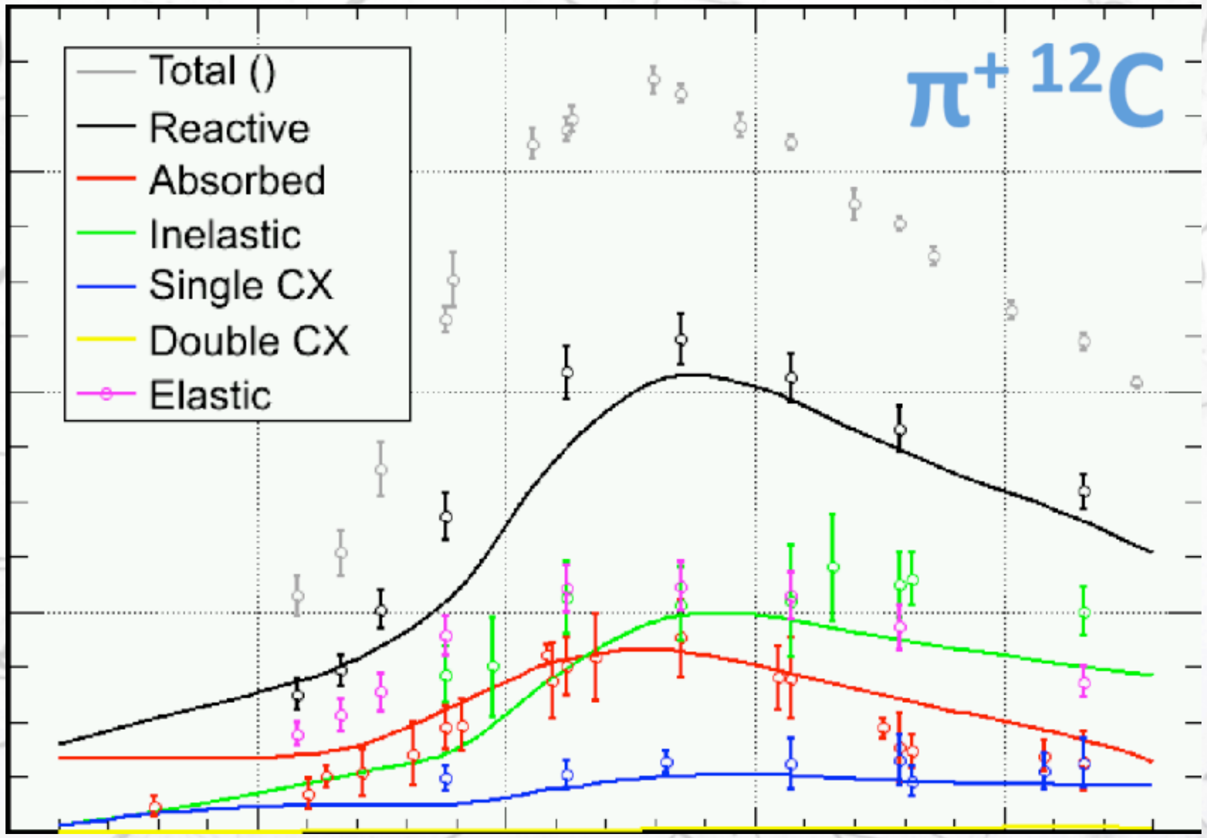
Experiments define CCQE in different manners (no proton, one proton,etc…) and sometimes develop analysis under certain model paradigm confusing the model comparison.

Electron scattering

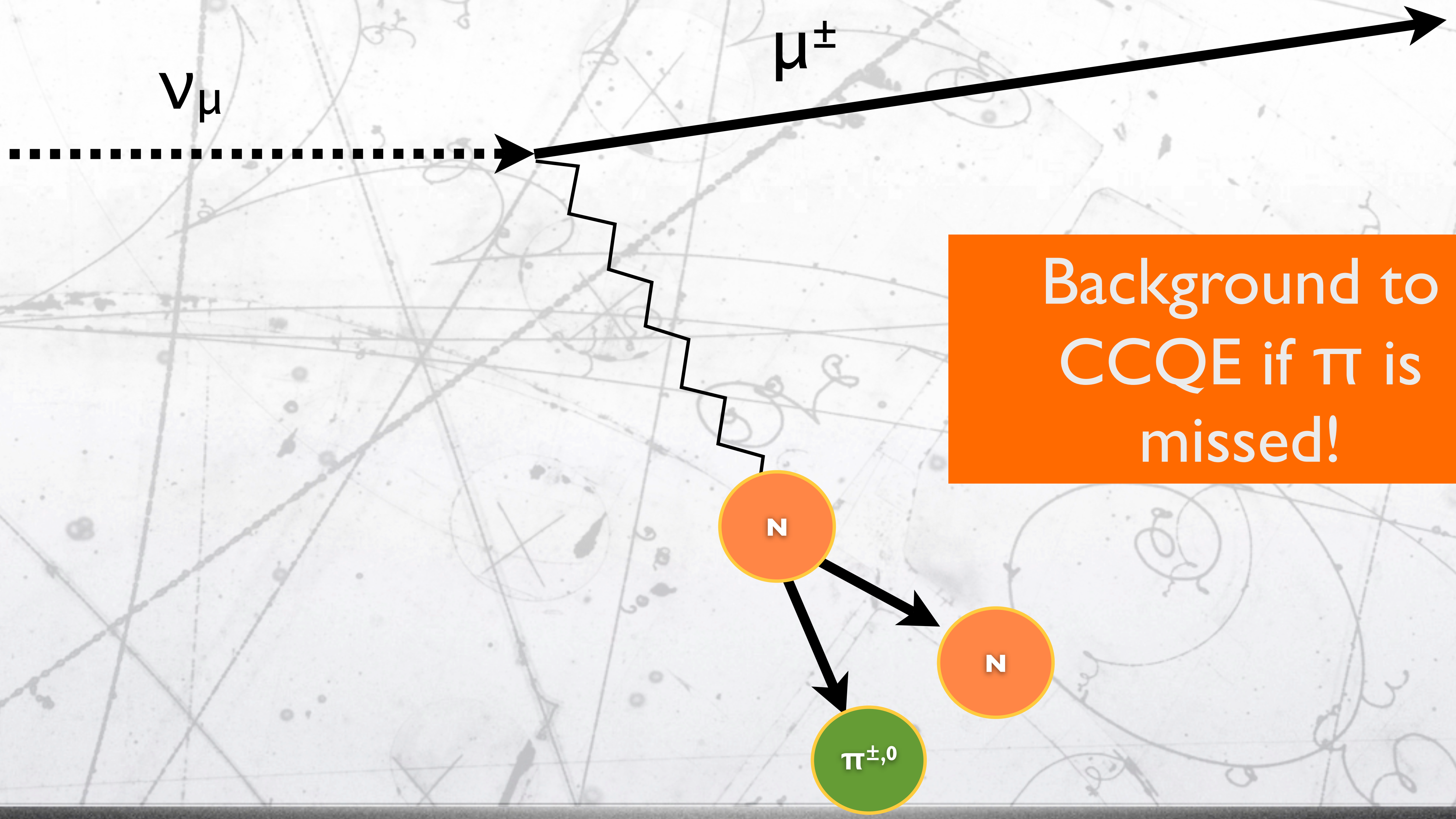
- This is similar to neutrino interactions with known initial conditions.
- But it is not the same:
  - only Vector current and not Axial current. This is only accesible trough neutrinos (or photon scattering in some cases).
  - Initial particle is charged.
  - Initial and final particles are electrons (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.

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.

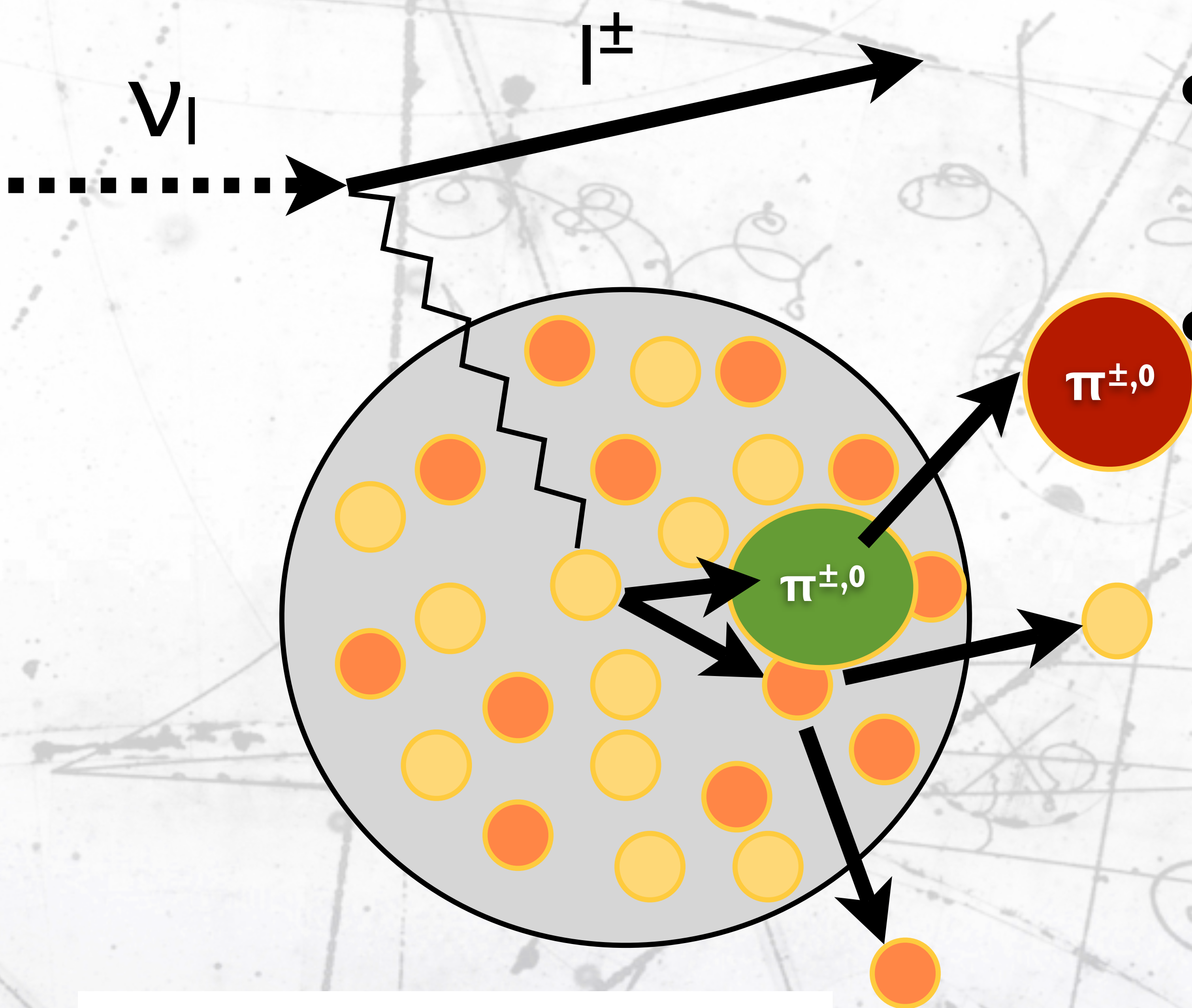


CC1π

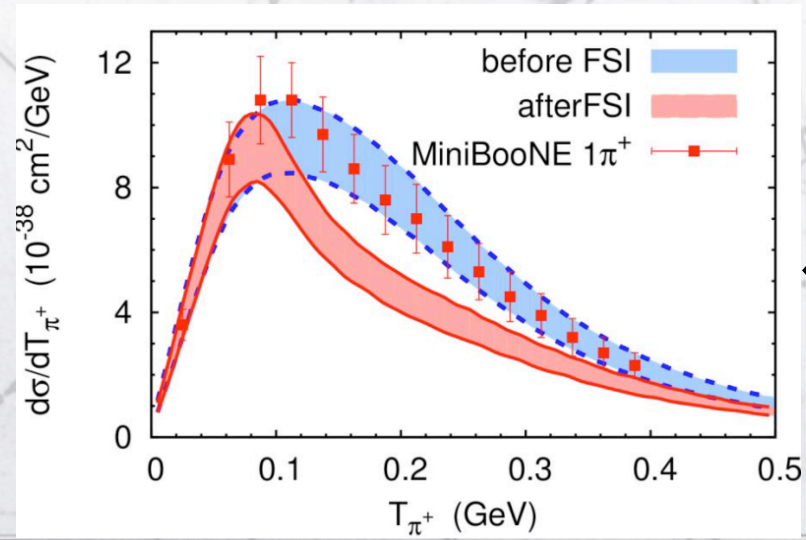


Background to CCQE if π is missed!

Signal definition

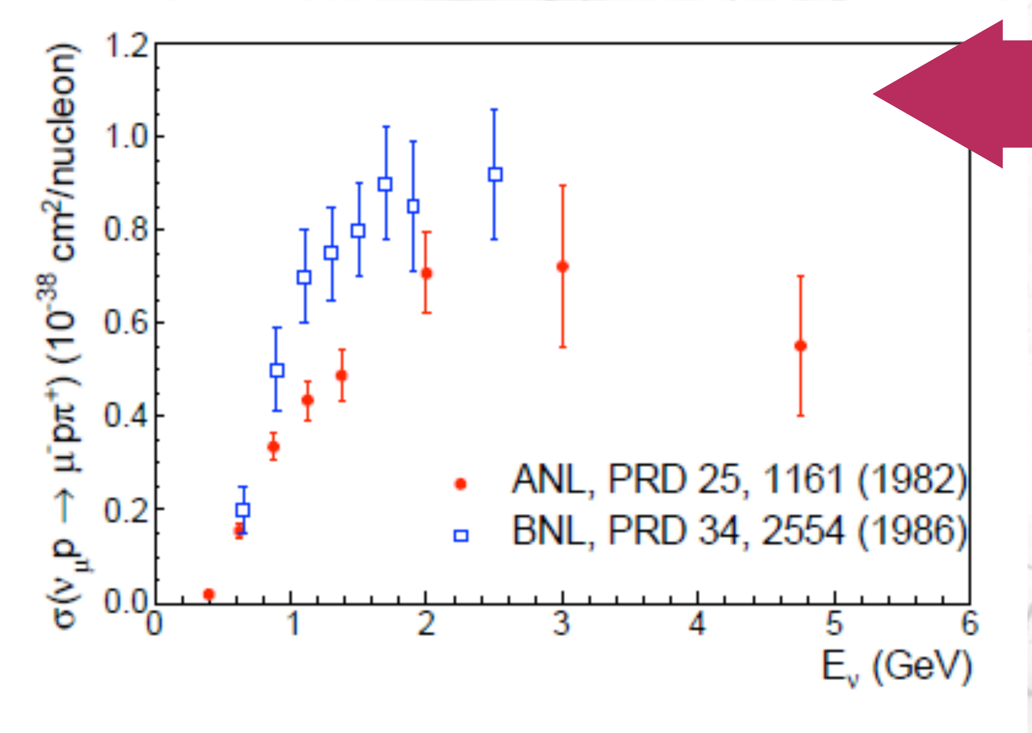


- Final state interactions alters the final state hadrons.
- Experiments make measurements for pion production:
  - @ nucleon level.
    - theoretically easy.
    - FSI correction by experiments, difficult to undo.
  - leaving the nucleus.
    - theorist need FSI model.
    - no experimental modelling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

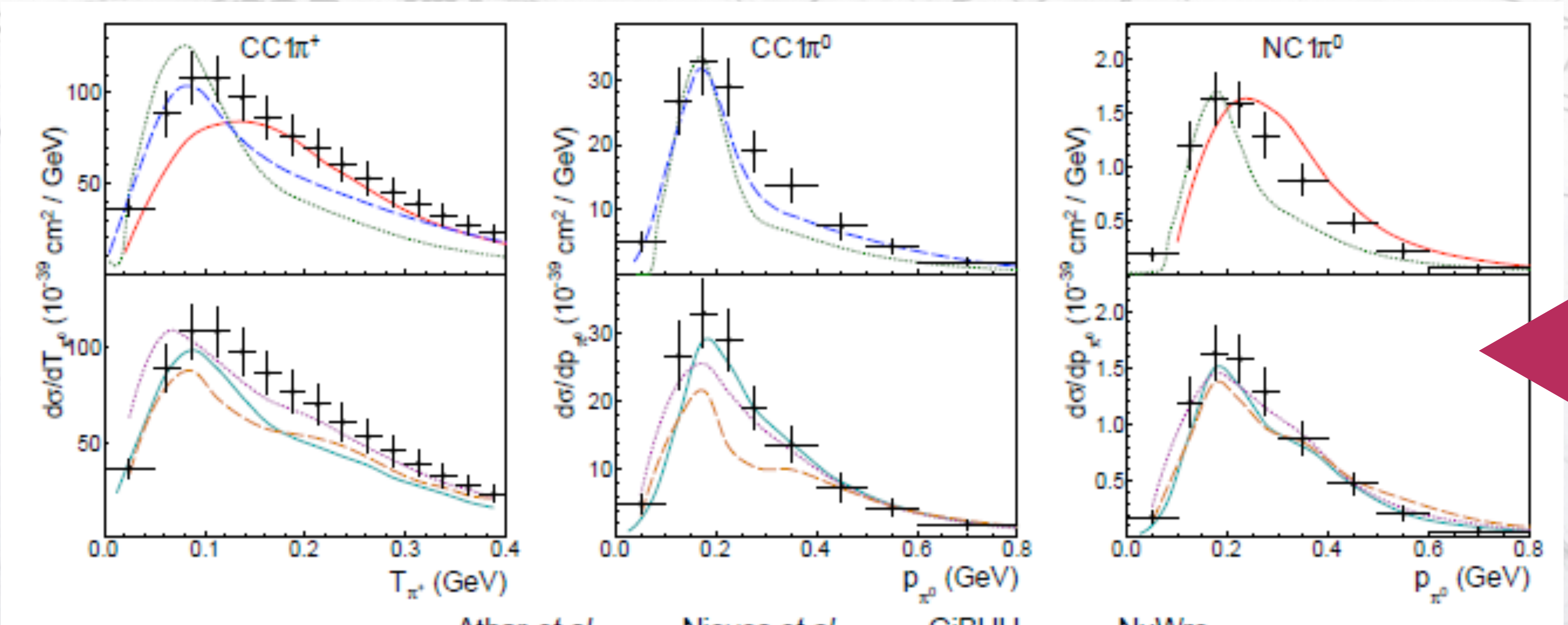


FSI is large

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

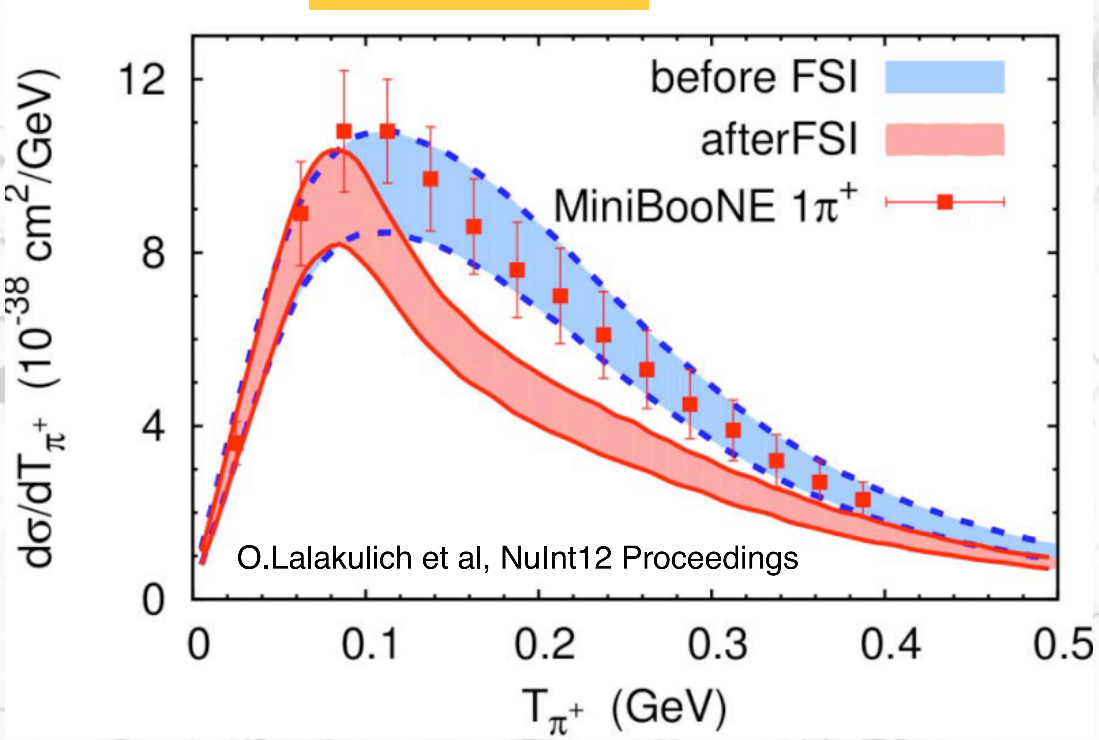
  - $C^A_5(0)$ (interaction strength)
  - resonant+ non-resonant + interference,
  - transition to the forest of high mass resonances.

π-A

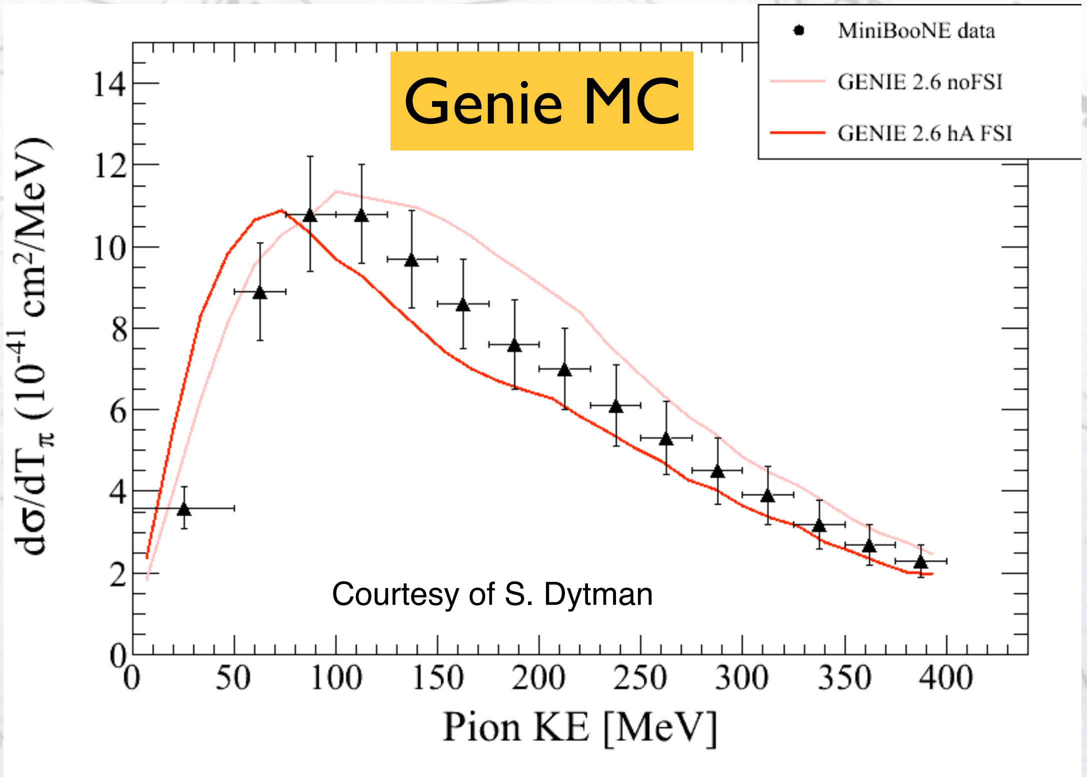
  - Final state interactions

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

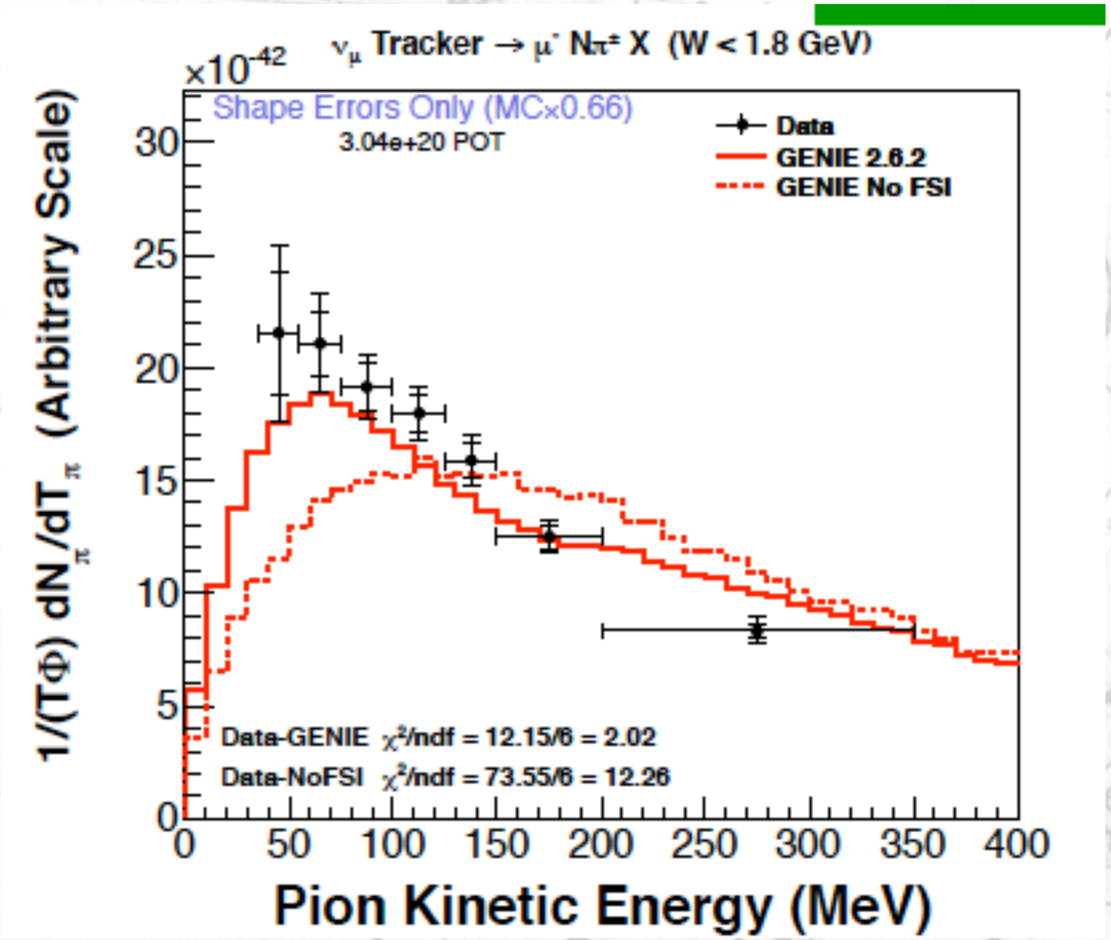
GIBUU MC



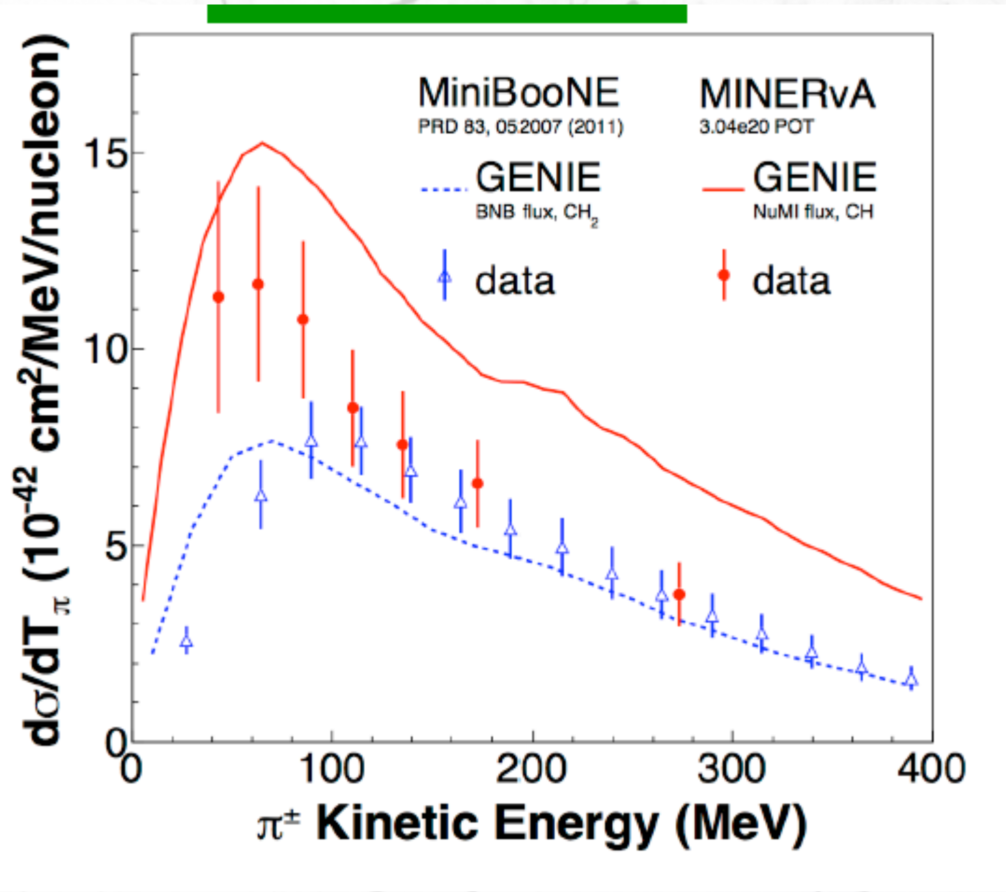
Genie MC



Minerva results



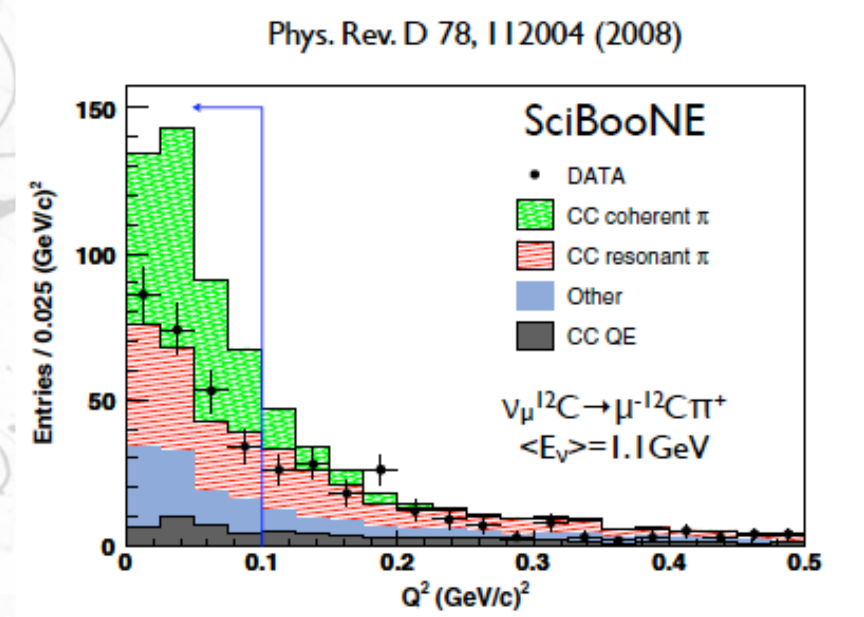
Minerva

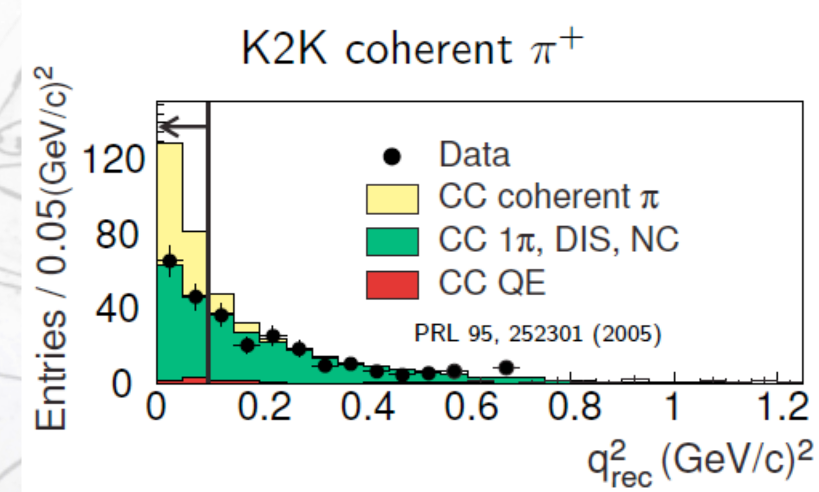


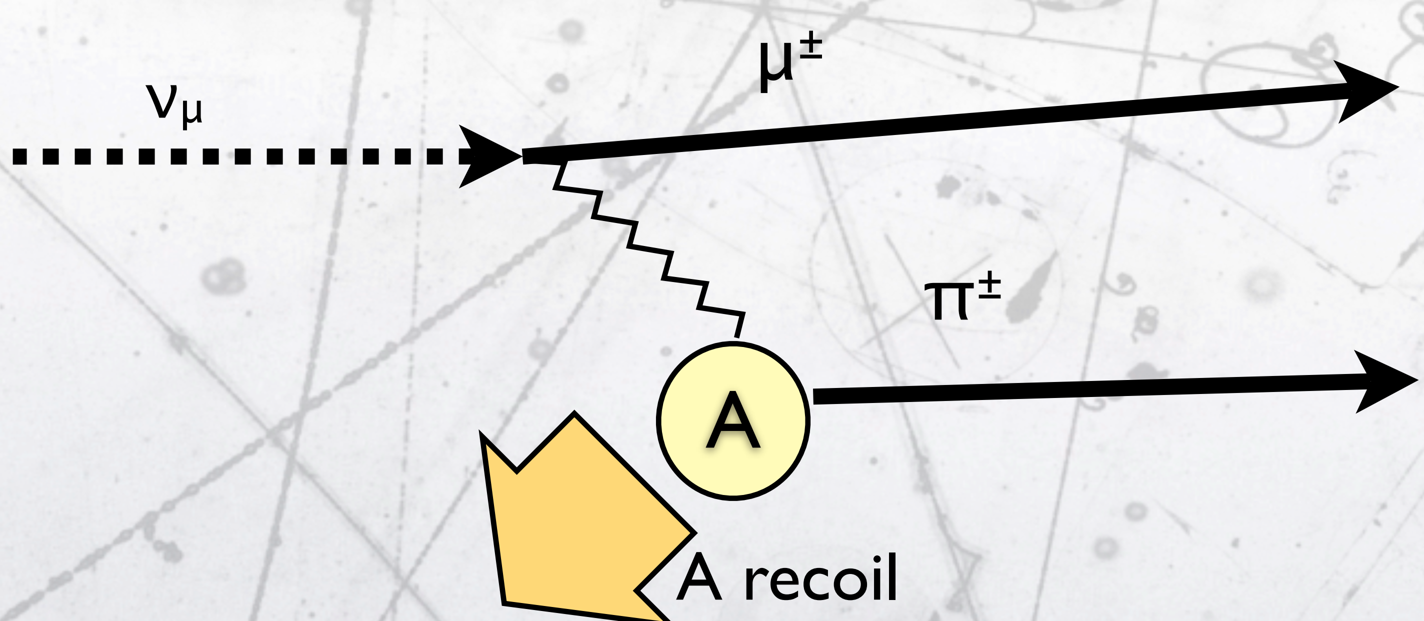
- Preliminary results show agreement with MC predictions & disagreement with MiniBoone data.
  - Minerva and MiniBoone are in a different energy region: backgrounds from large mass resonances?, ….
  - Minerva and MiniBoone detection technique is very different: Signal definition ?

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.





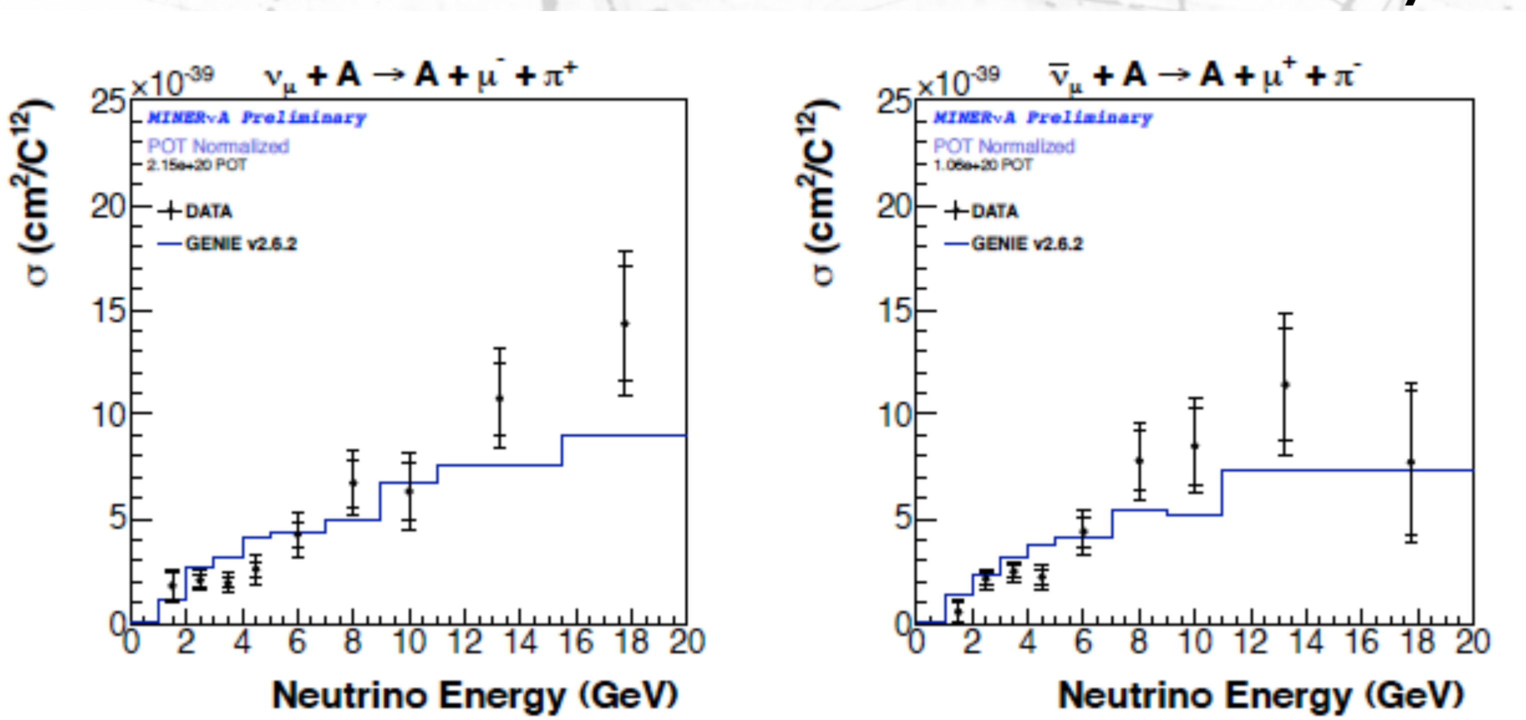


Low nuclear recoil (t)

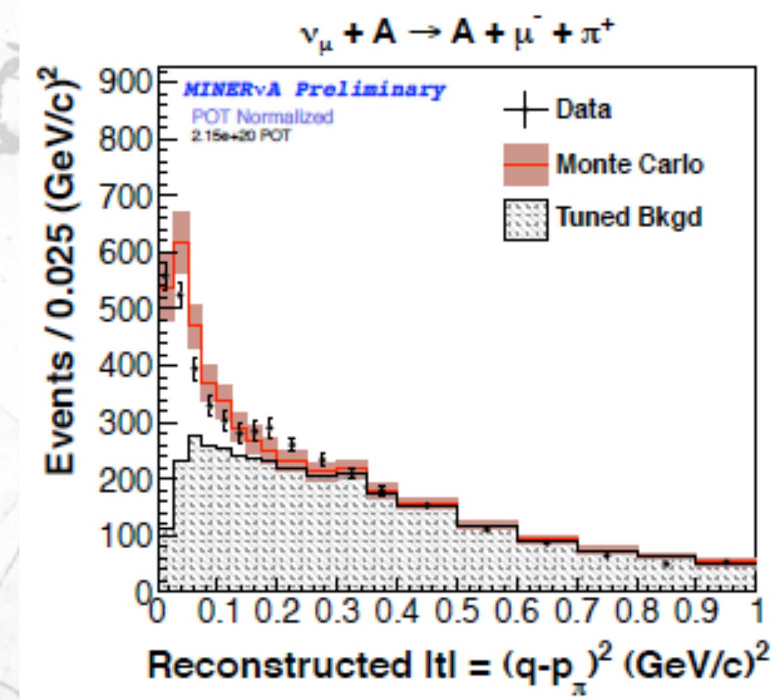
No nuclear breakup and no proton (vertex activity)

CC 1π coherent

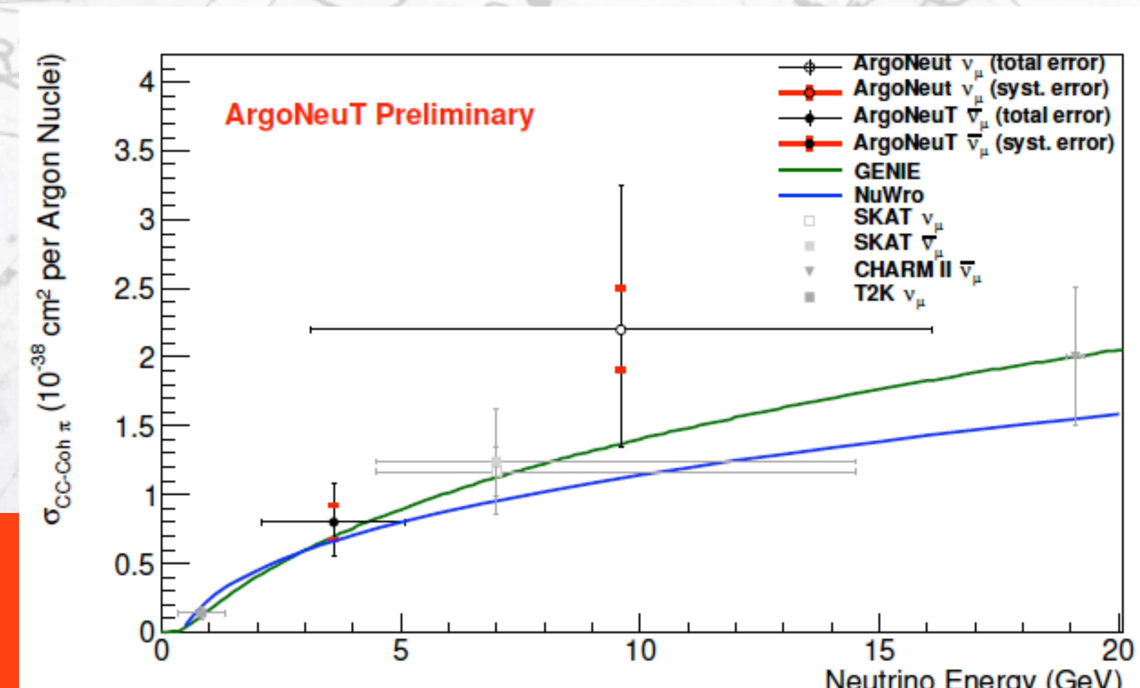
- Minerva from vertex activity & nuclear recoil energy




Minerva



- ArgoNeut from vertex activity.

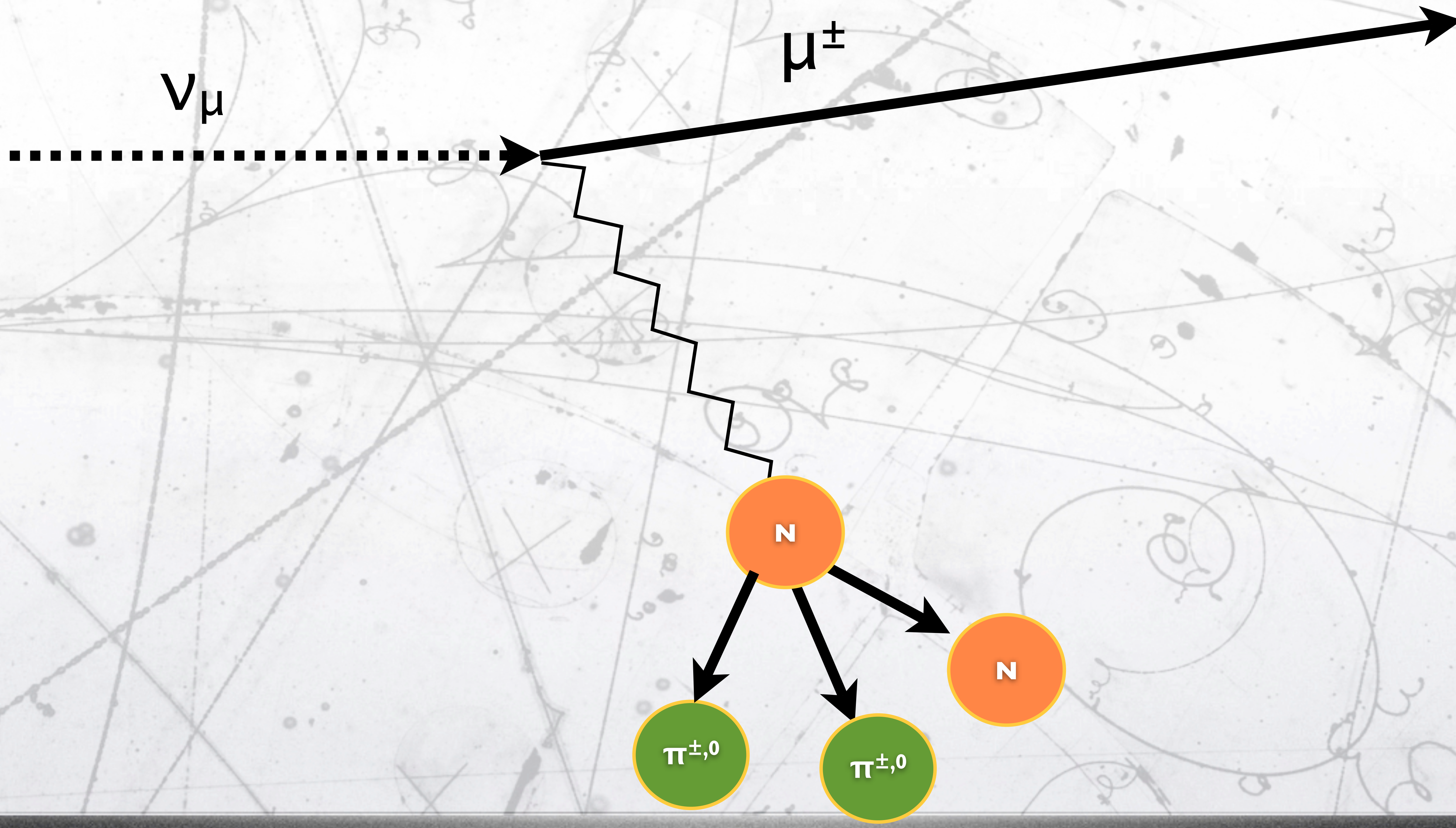


Good agreement with models except in the shape of nuclear recoil !

CC1π partial summary

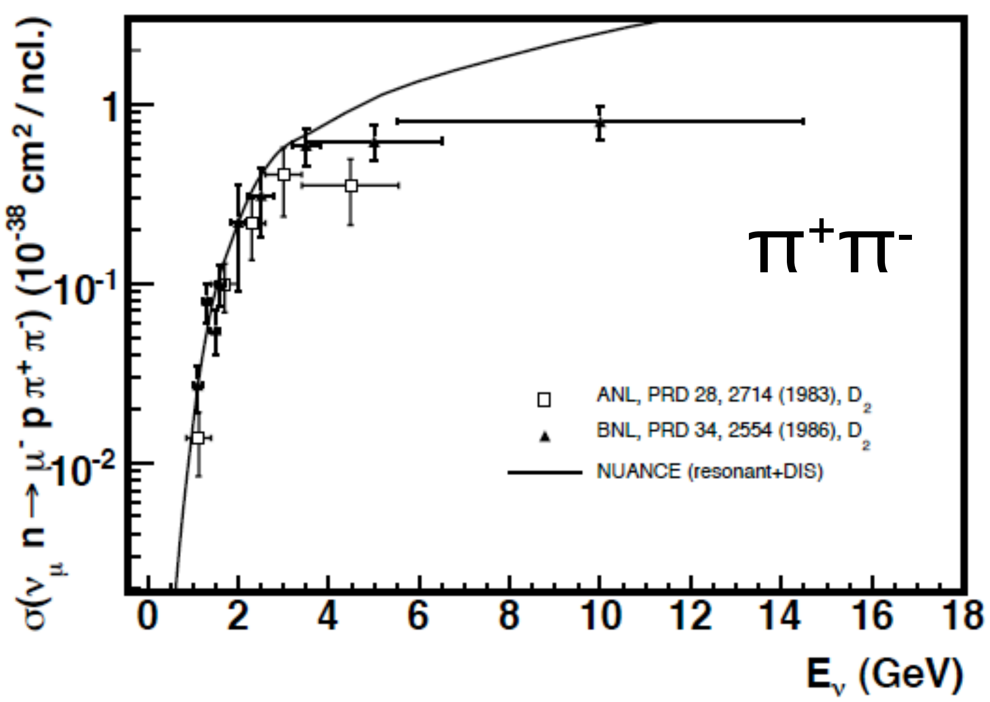
- CC1π is a difficult channel but it is the main background to other channels.
- Not well understood even at the nucleon level (old sparse data):
  - Nowadays it is almost impossible to make an active hidrogen(deuterium) active target detector.
- Large effects from FSI (π reinteractions!).

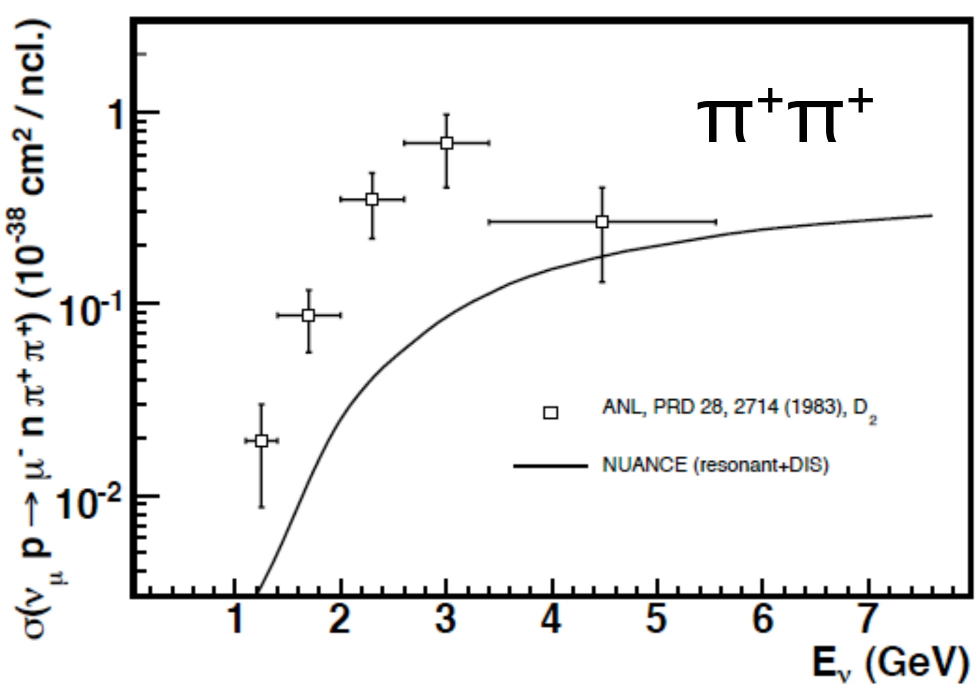
CC-Nπ

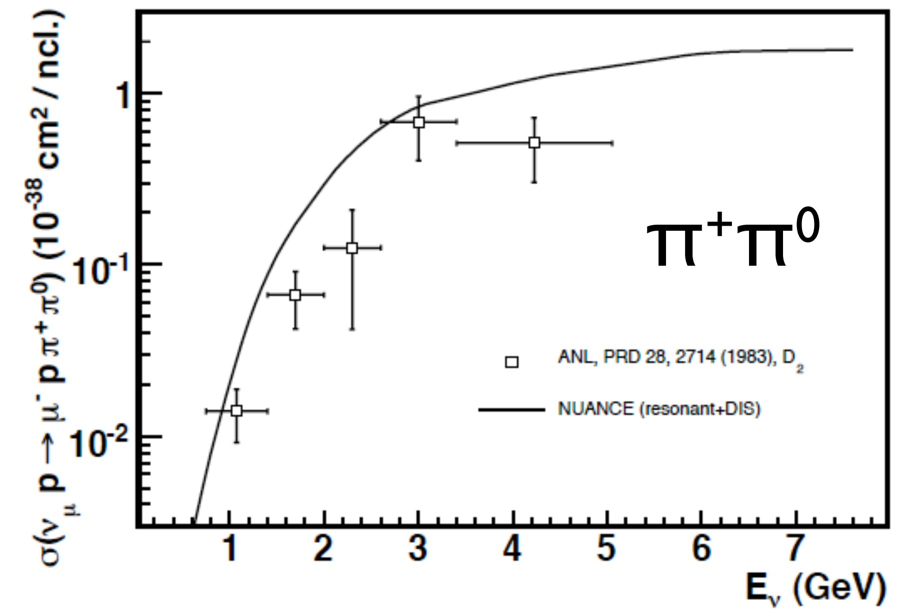


CC-Nπ

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

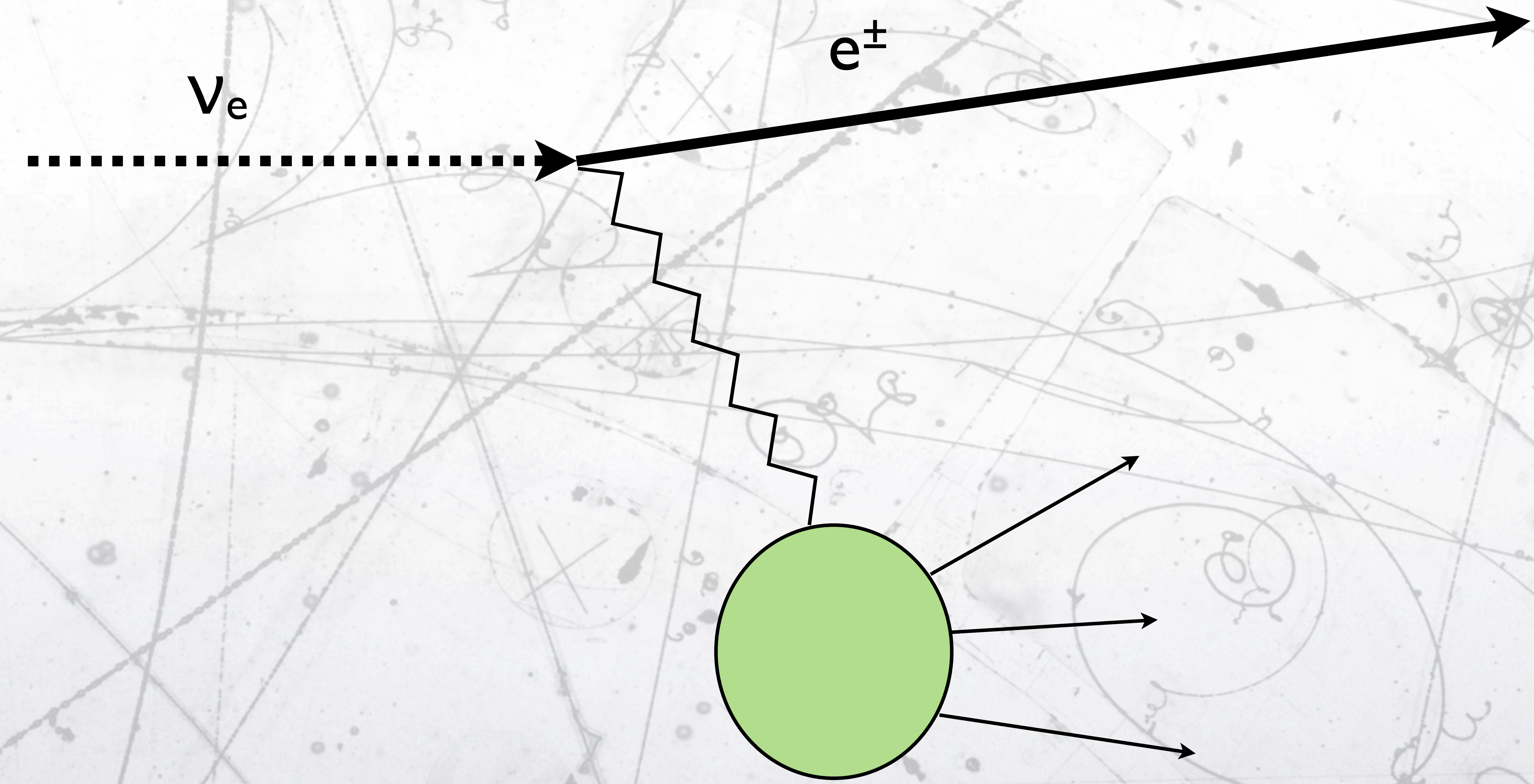




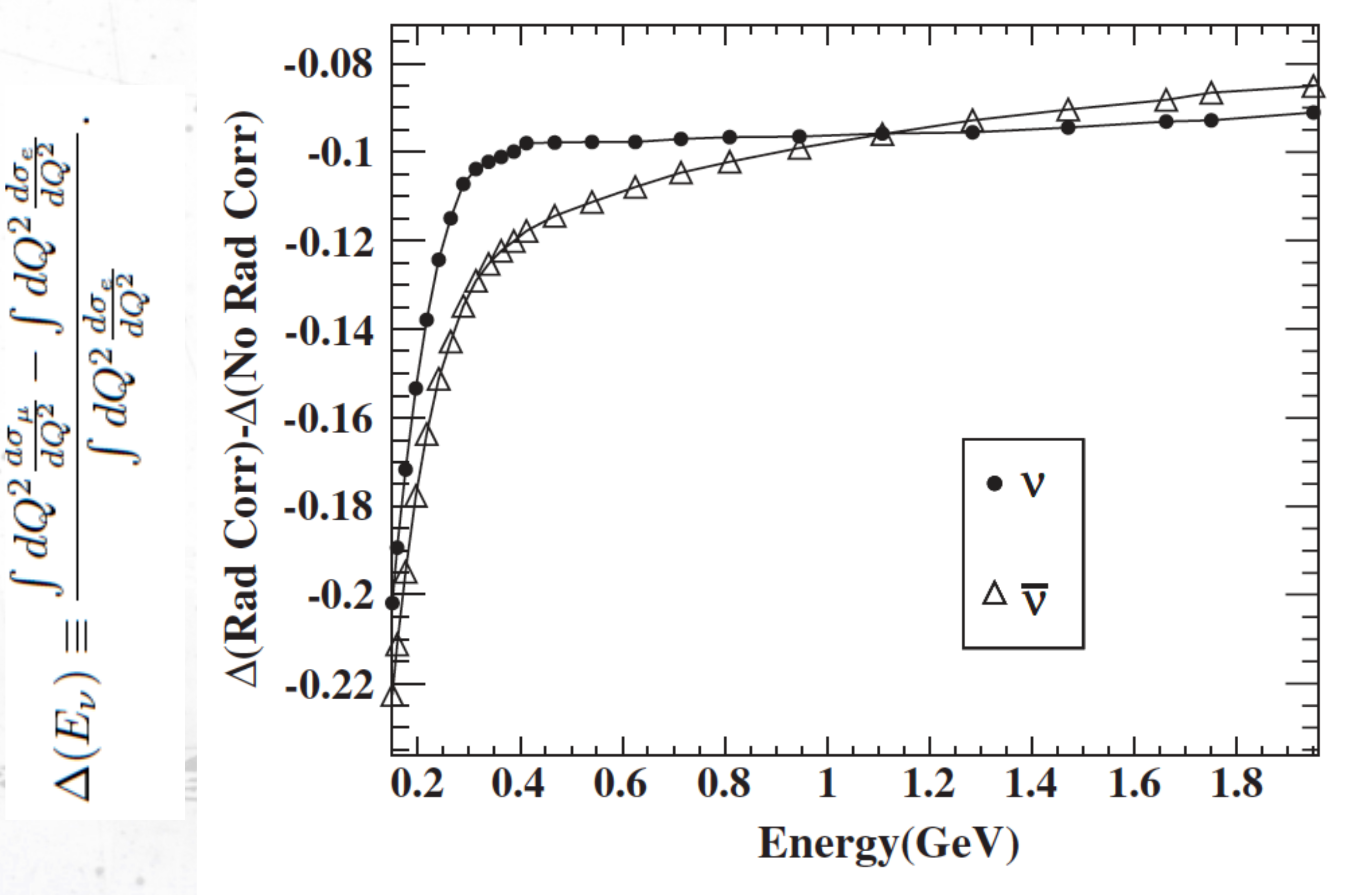


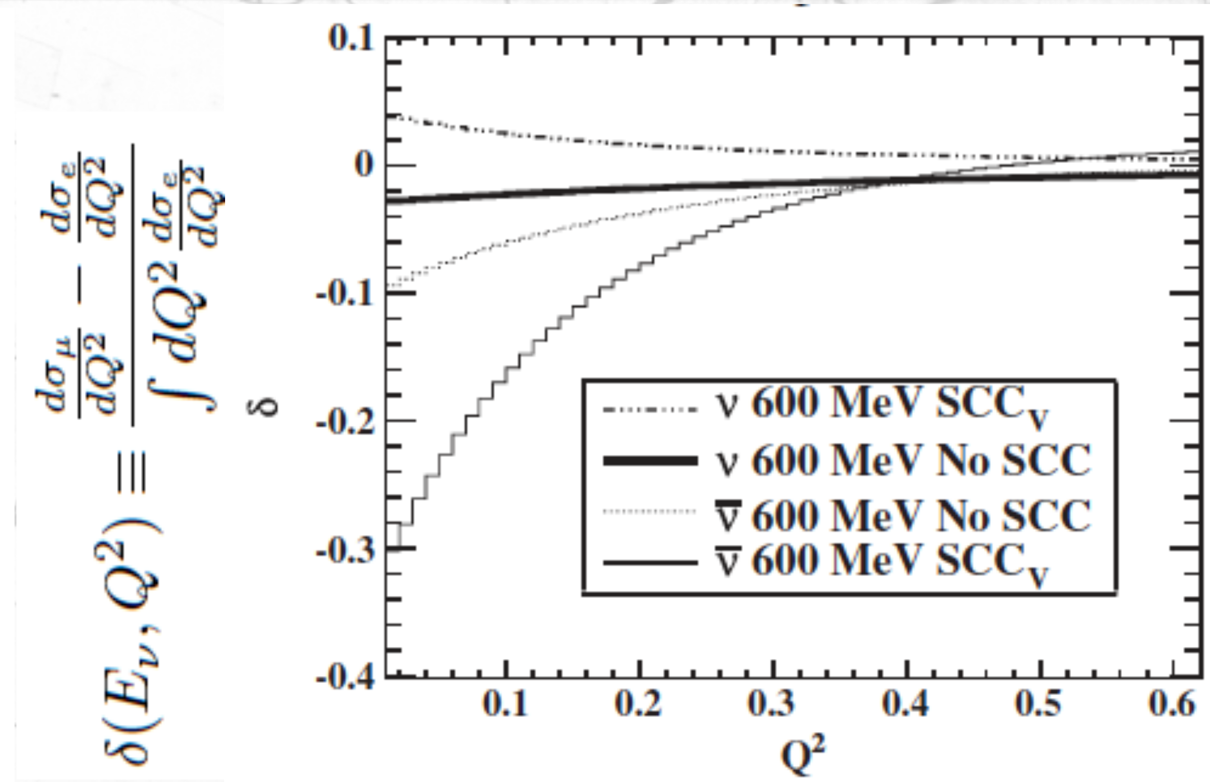
- This is a complex region with contributions from high mass Δ resonances and low ω DIS.
- There is no new data since ANL and BNL back to the 80's.
- No data in nuclei: difficult measurement due to FSI.
- No detailed pion kinematics available.
- Critical for LBNE and LBNO!.

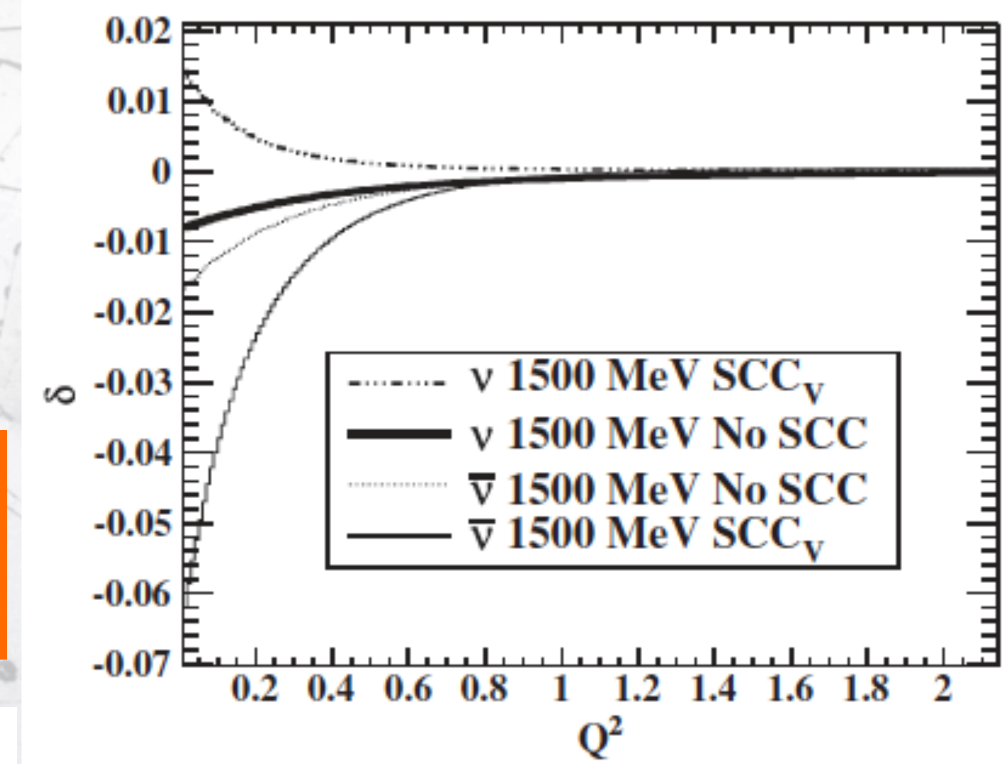
Inclusive CC ν_e



The ν_e problem





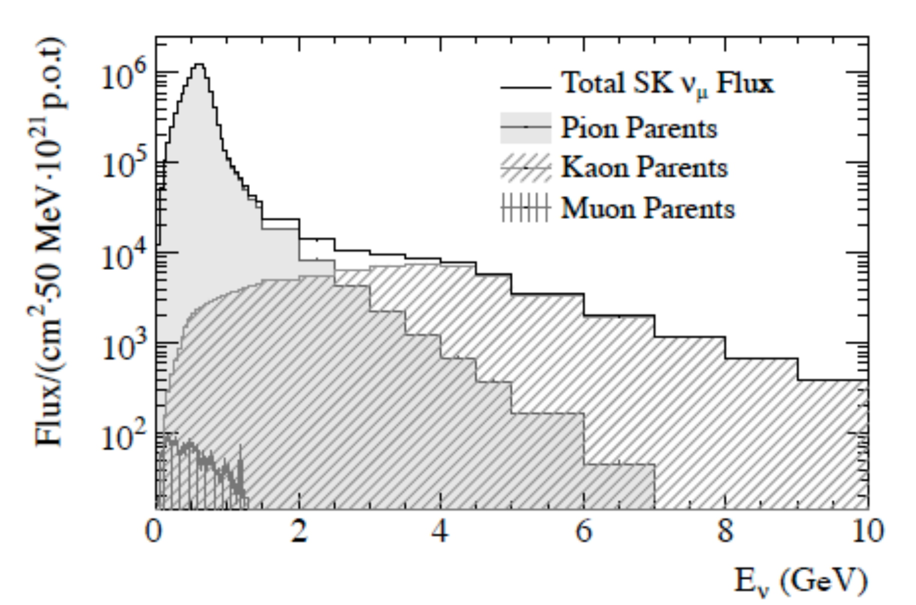


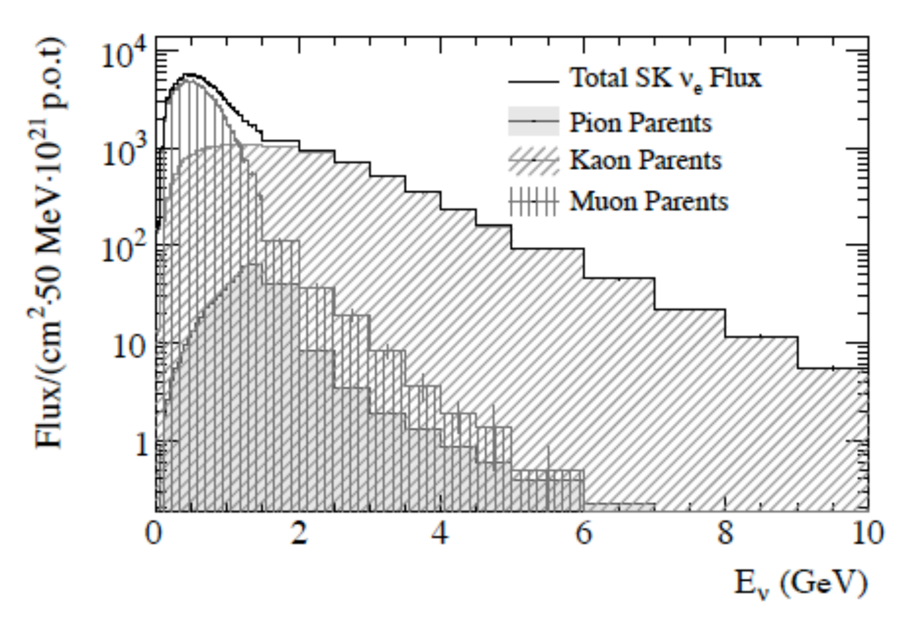
- Calculations show significant differences in the ratio of ν_e to ν_μ cross-sections due to:
  - form factors.
  - radiative corrections.
  - lepton mass.

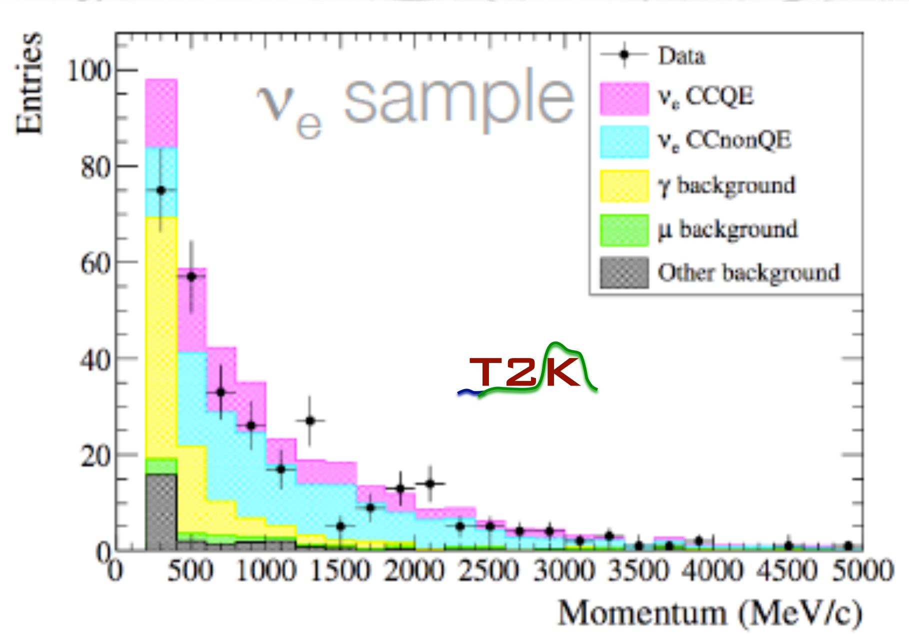
Dominantes @ low E_ν (T2K)

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

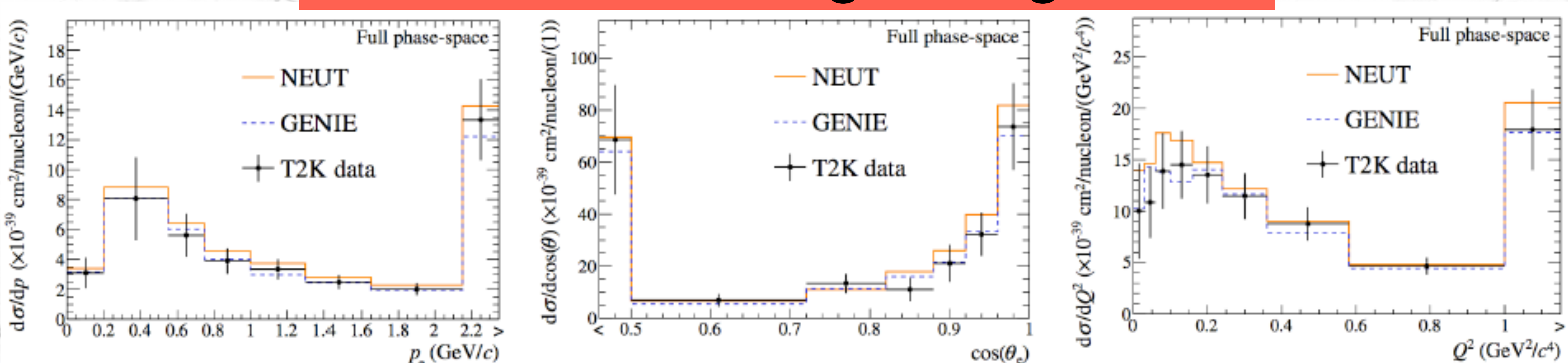
David Adey poster

CC inclusive ν_e

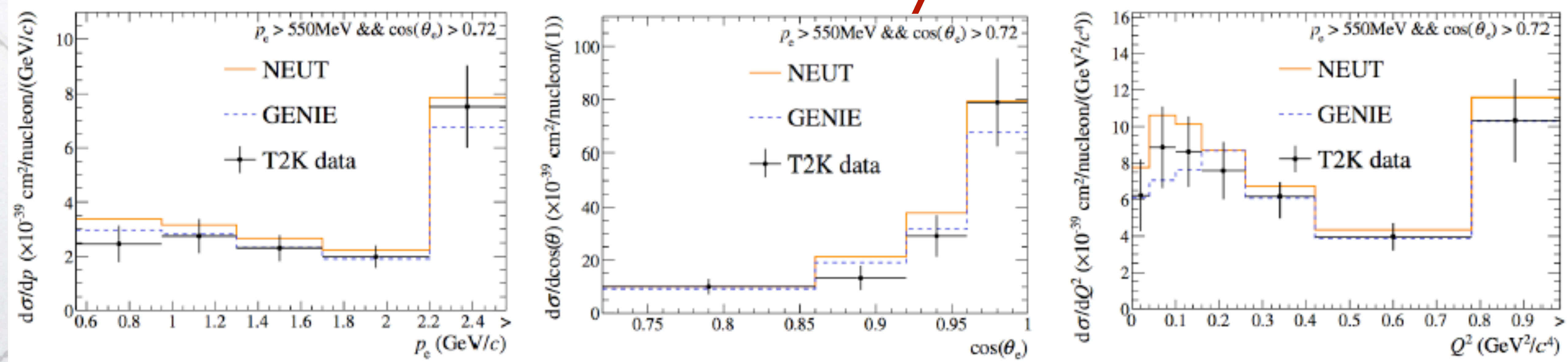
First measurement in 36 years!

low statistics & large background!

Nuint'14



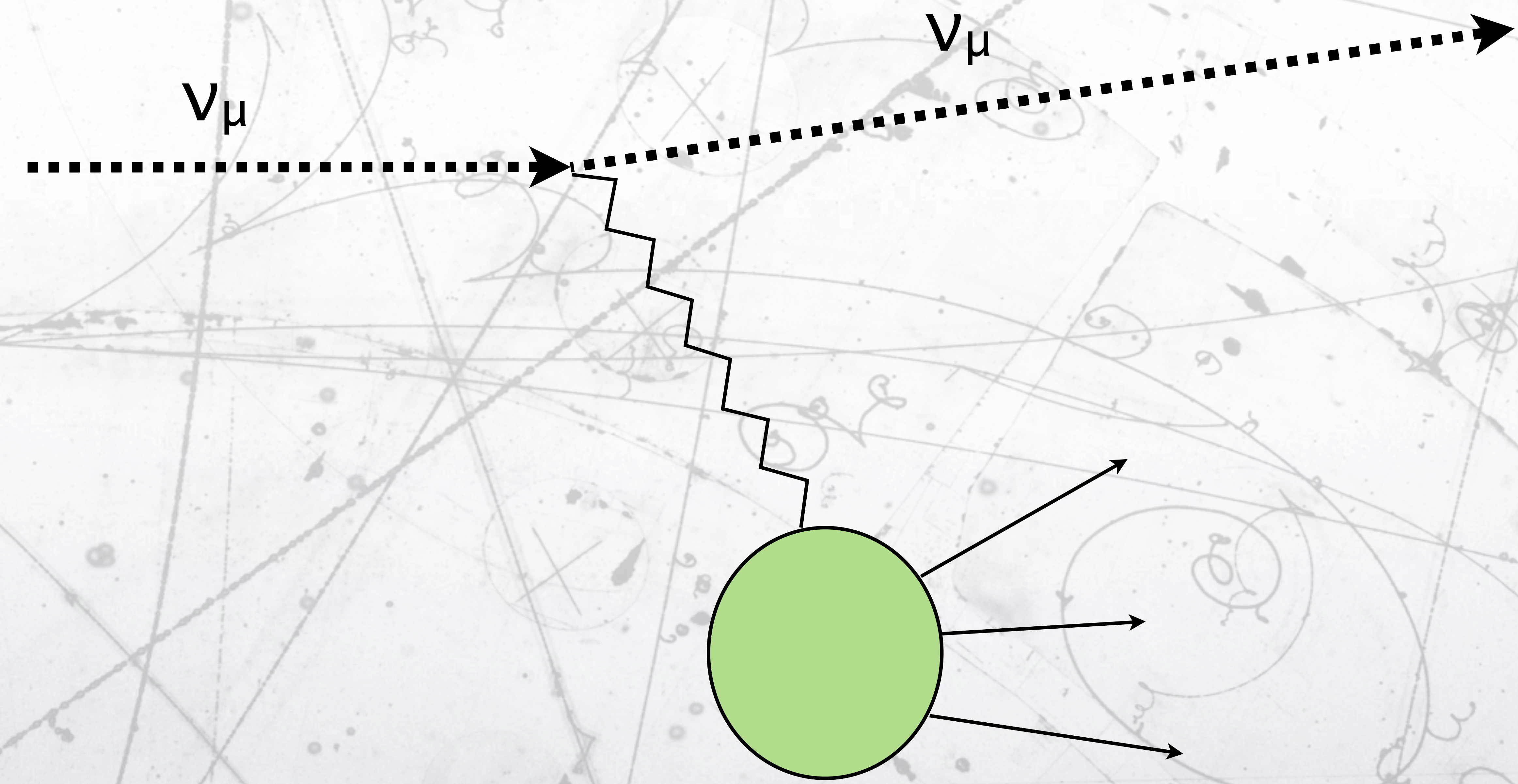
Preliminary



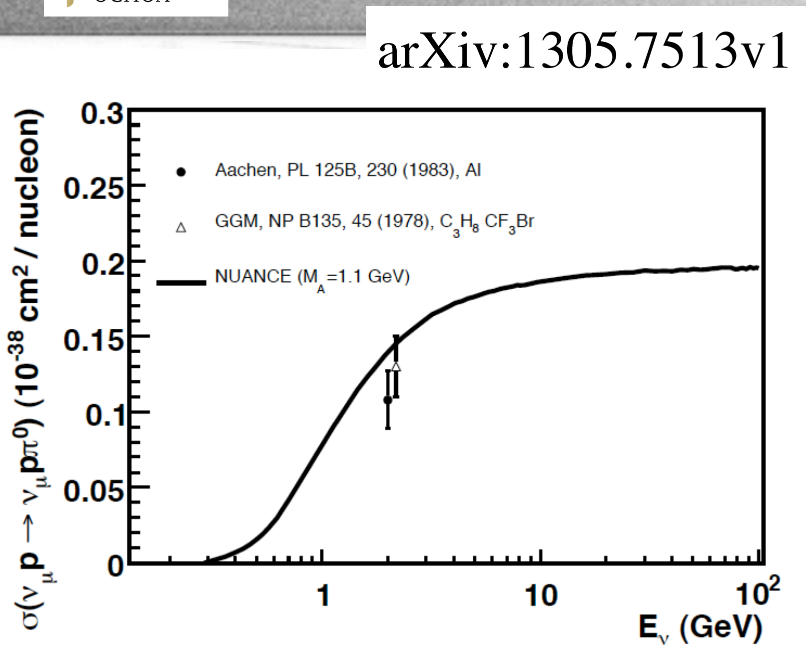
ν_e partial summary

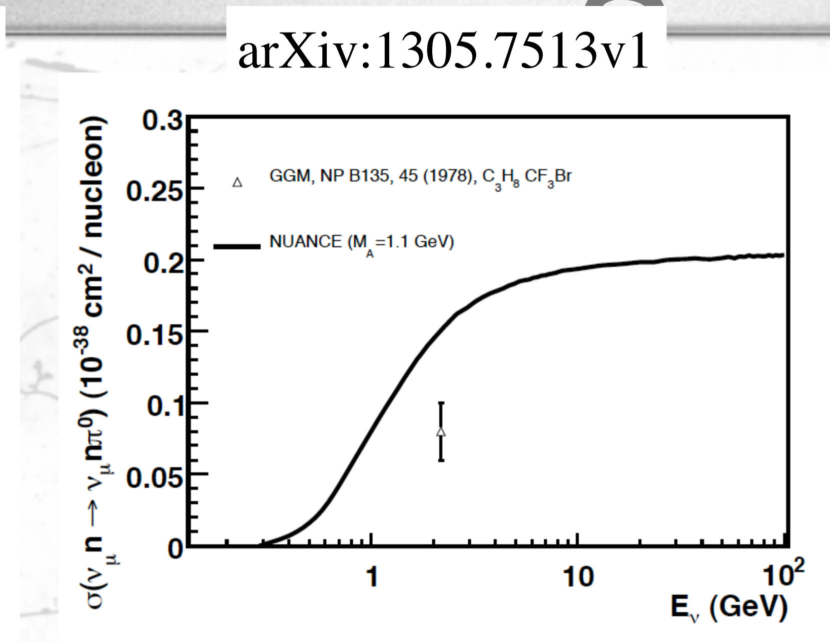
- Expected differences between ν_e and ν_μ cross-sections at threshold.
- Critical for future experiments and CP violation search.
- Very difficult to make a pure ν_e beam although there are some new ideas popping up.

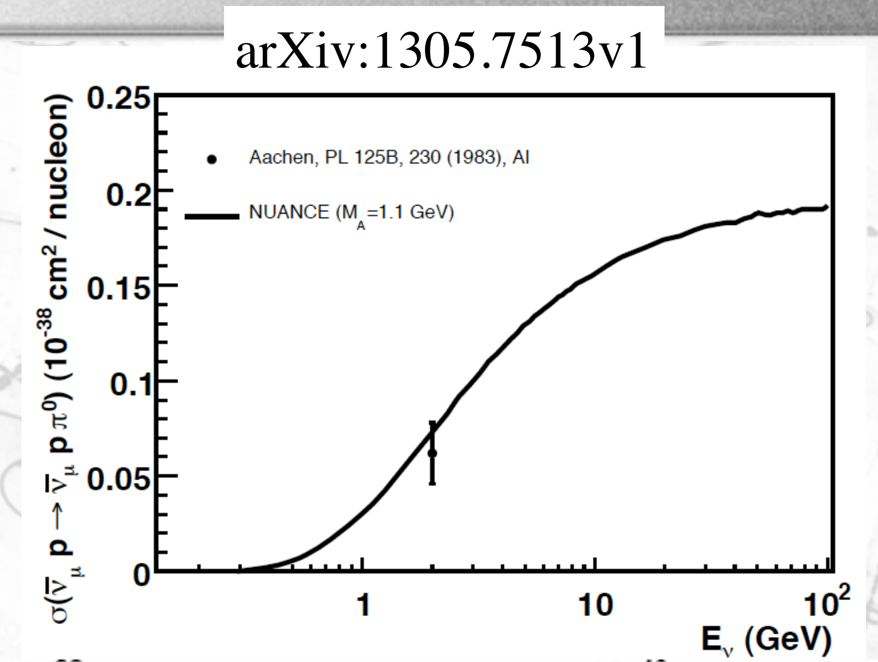
NC ν_μ

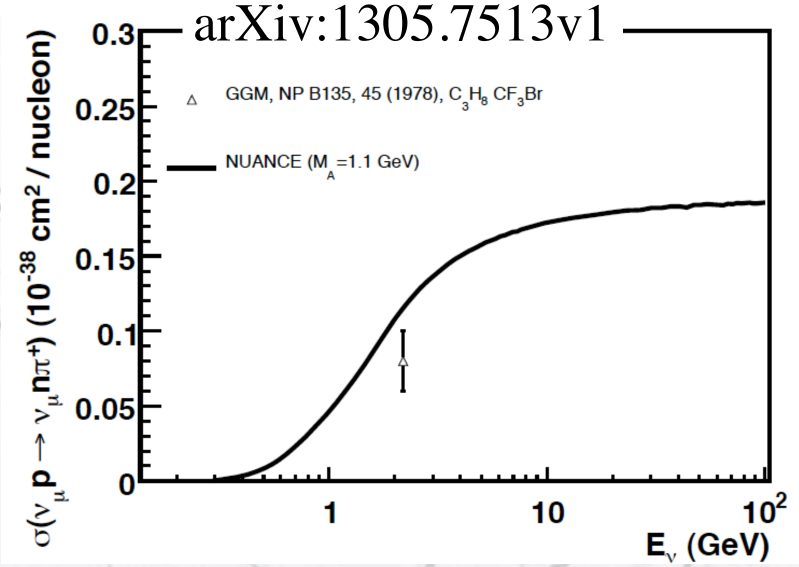


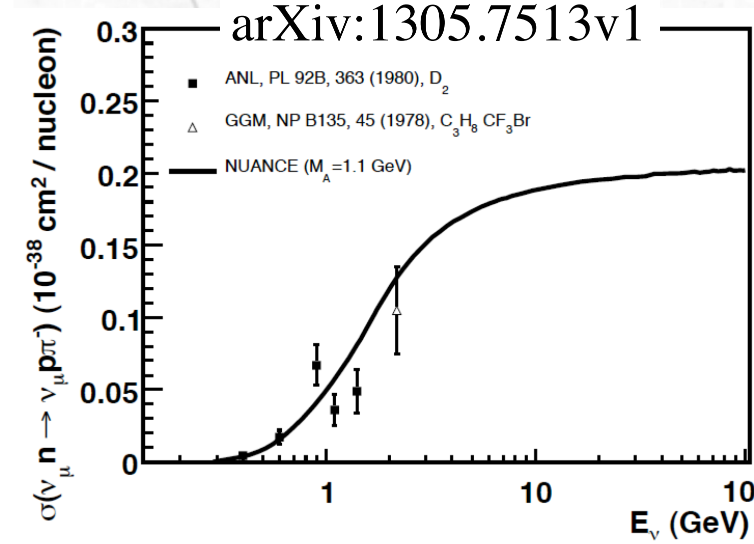
Existing data

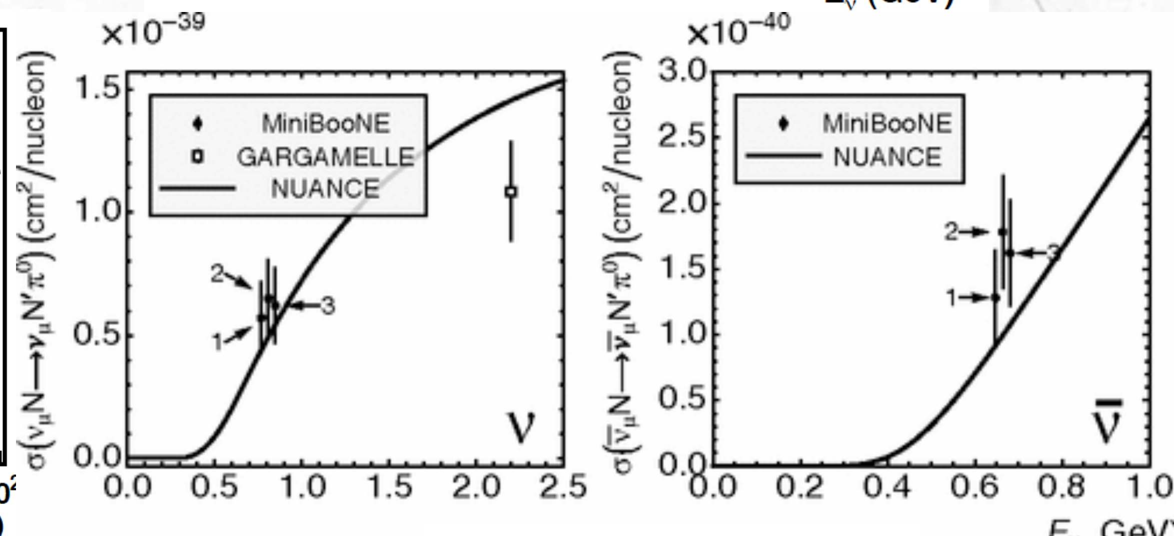








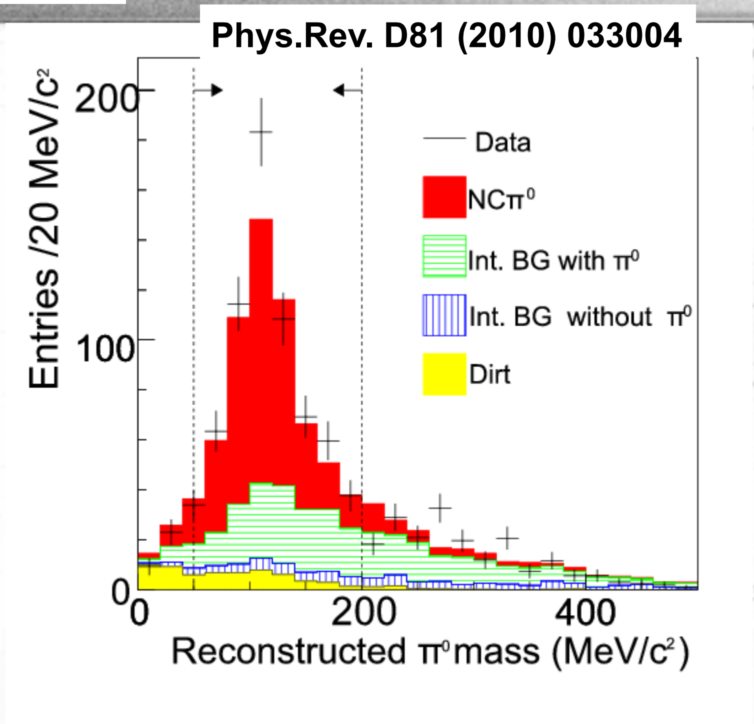




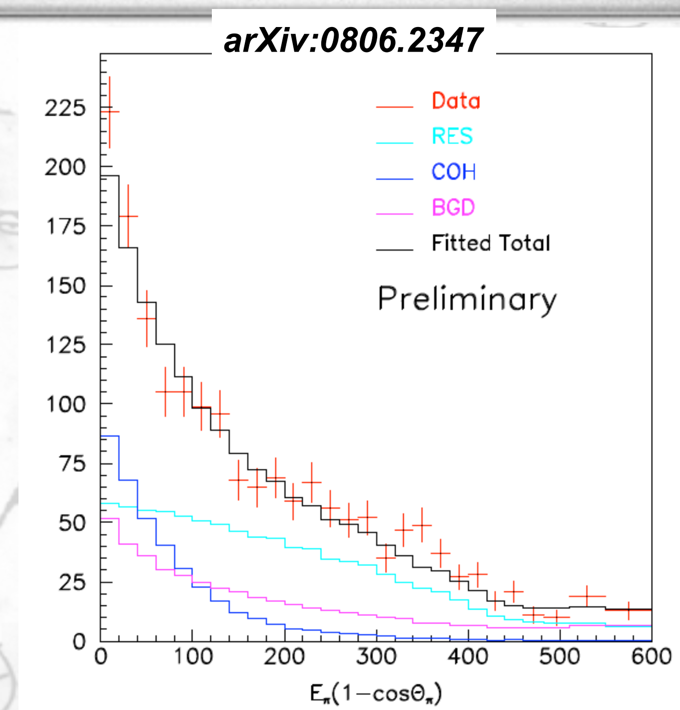
Phys.Rev. D81 (2010) 013005

- 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!

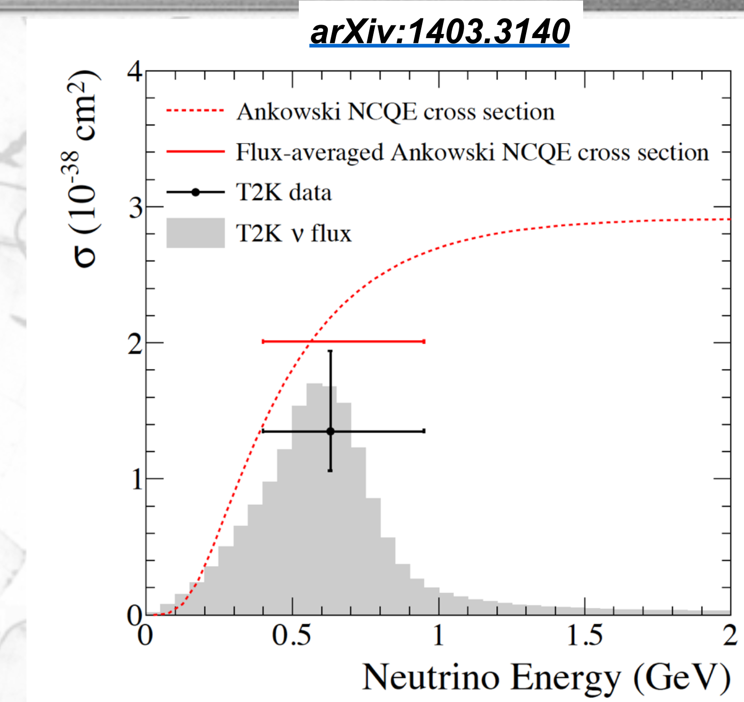
Recent results



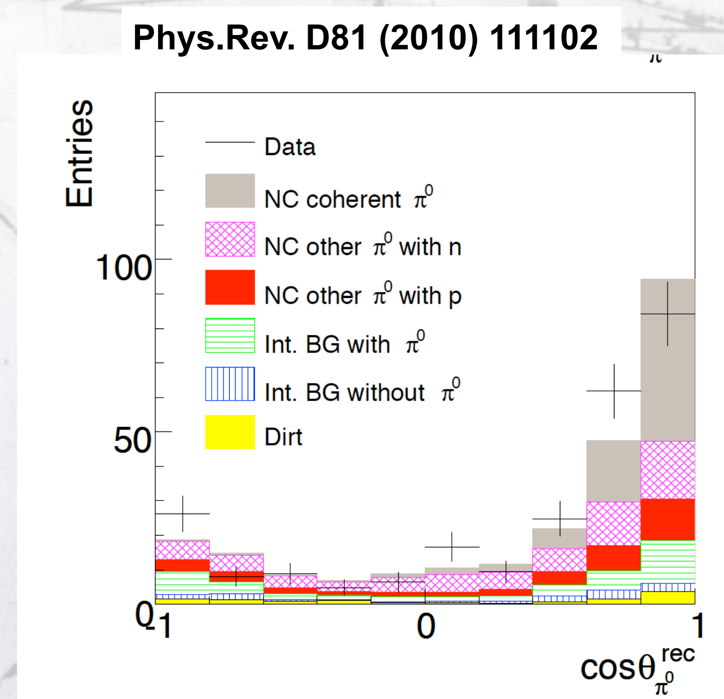
2010 SciBoone NCπ⁰/CC



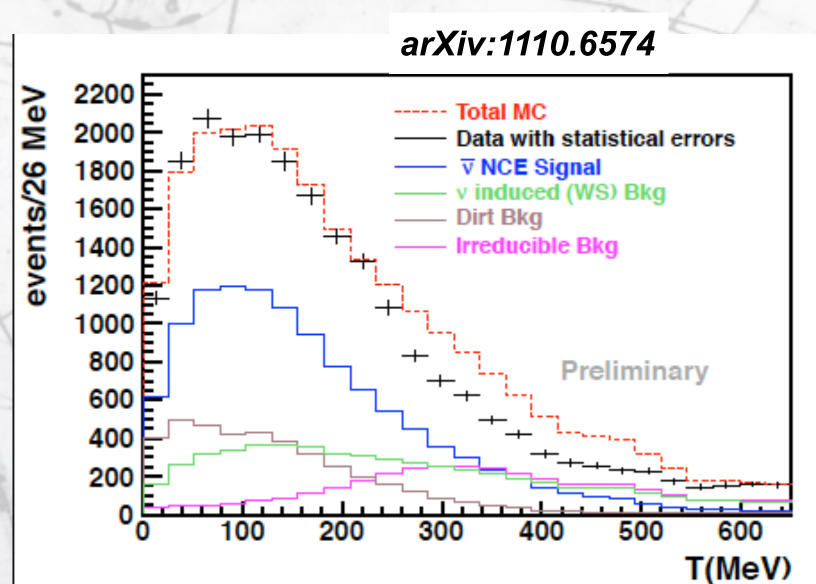
2008 MiniBoone NCπ⁰ Coherent.



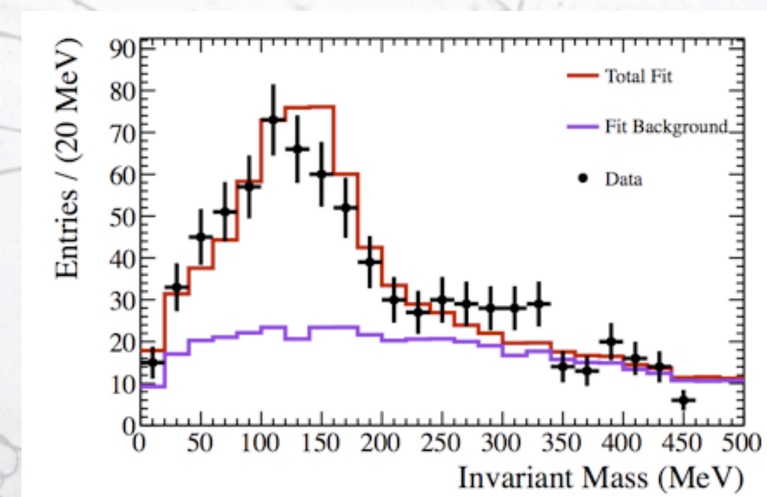
2014 T2K NC-QE from nuclear de-excitation γ rays.



2010 SciBoone NCπ⁰ coh.



2011 MiniBoone NC elastic.

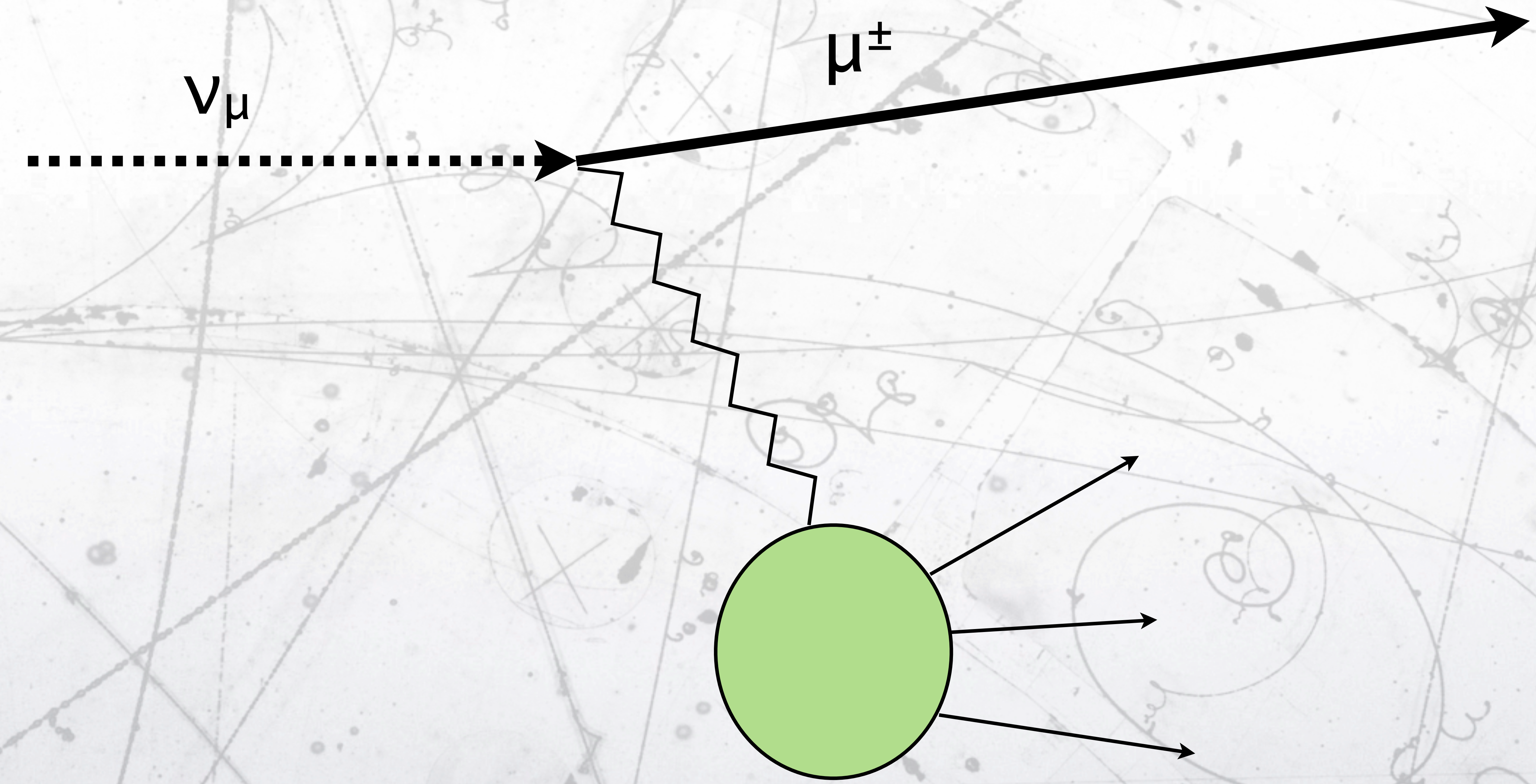


2014 T2K NC π⁰

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:

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

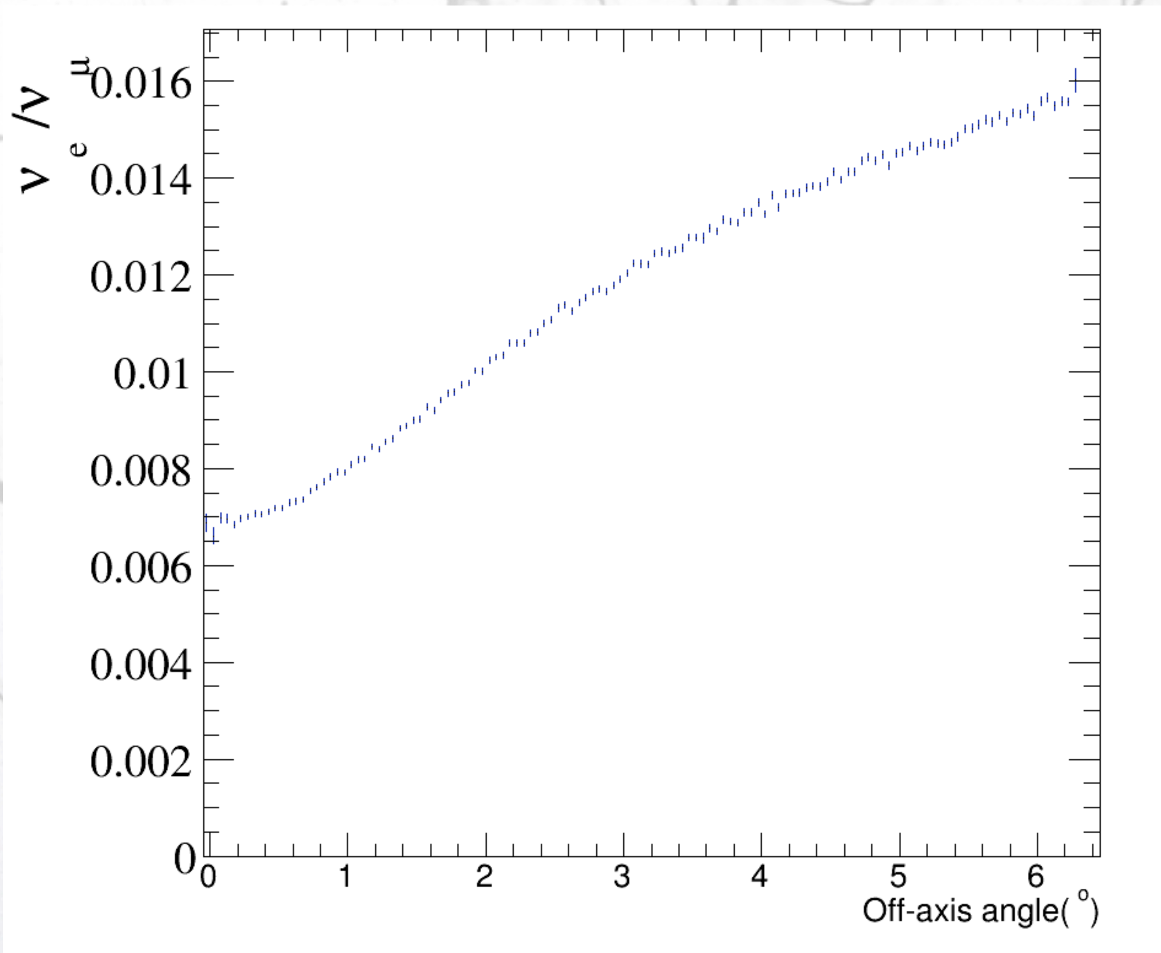
- The oscillation result of the oscillation would be:

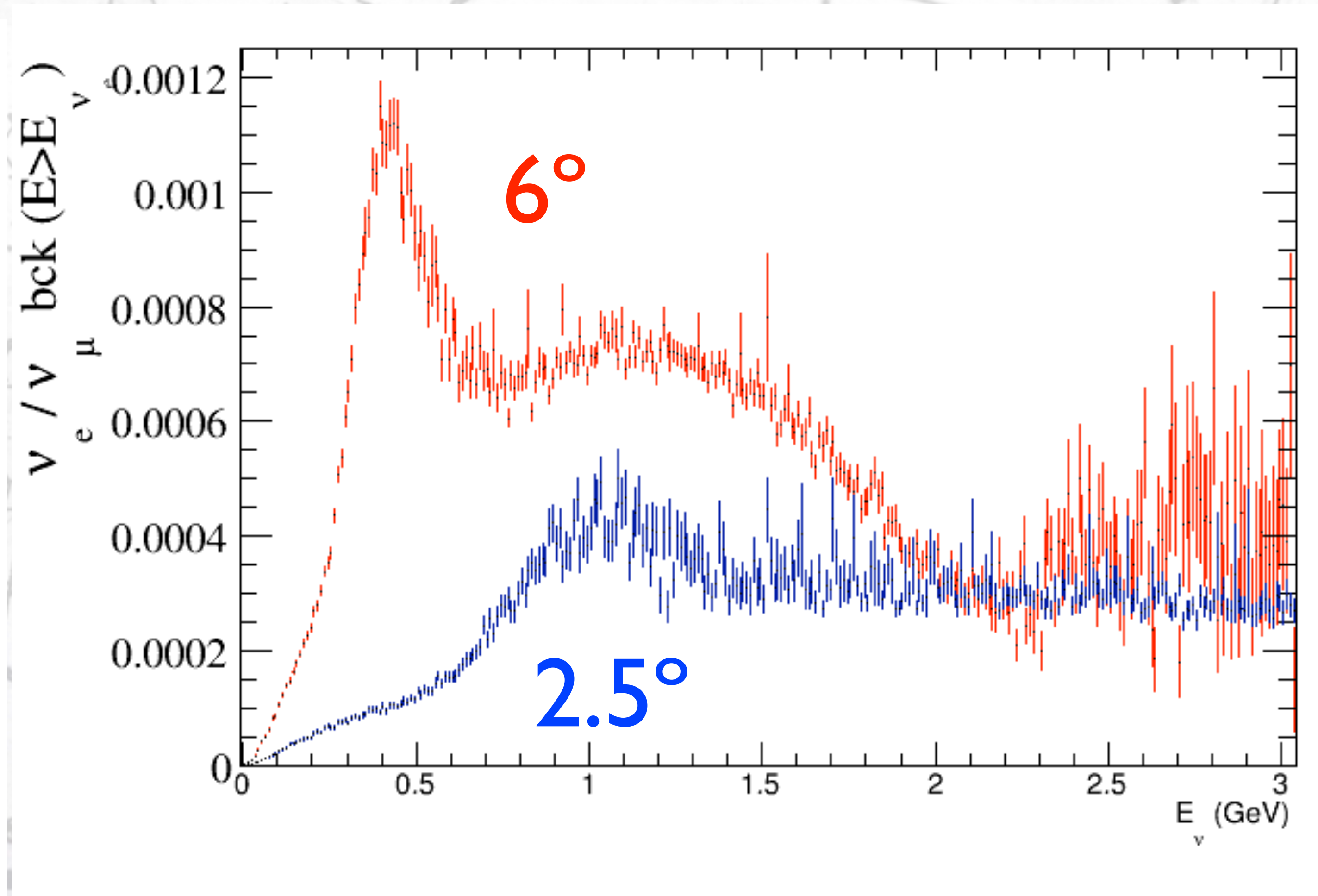
$$\int P(p_\mu, \theta_\mu | E_\nu) \times P_{osc}(E_\nu) \times \phi(E_\nu) dE_\nu$$

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

NuPrism and ν_e

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

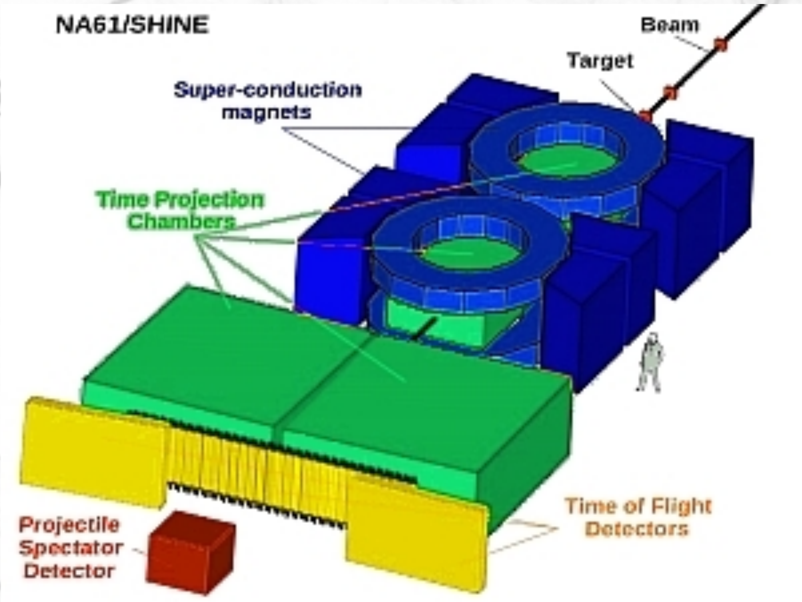


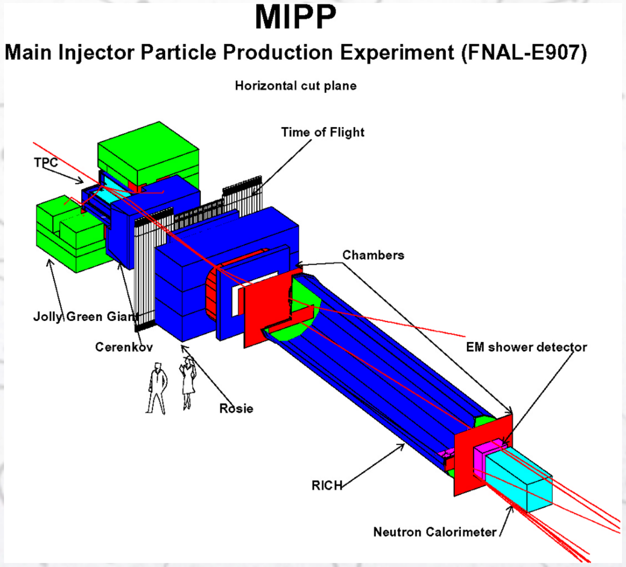


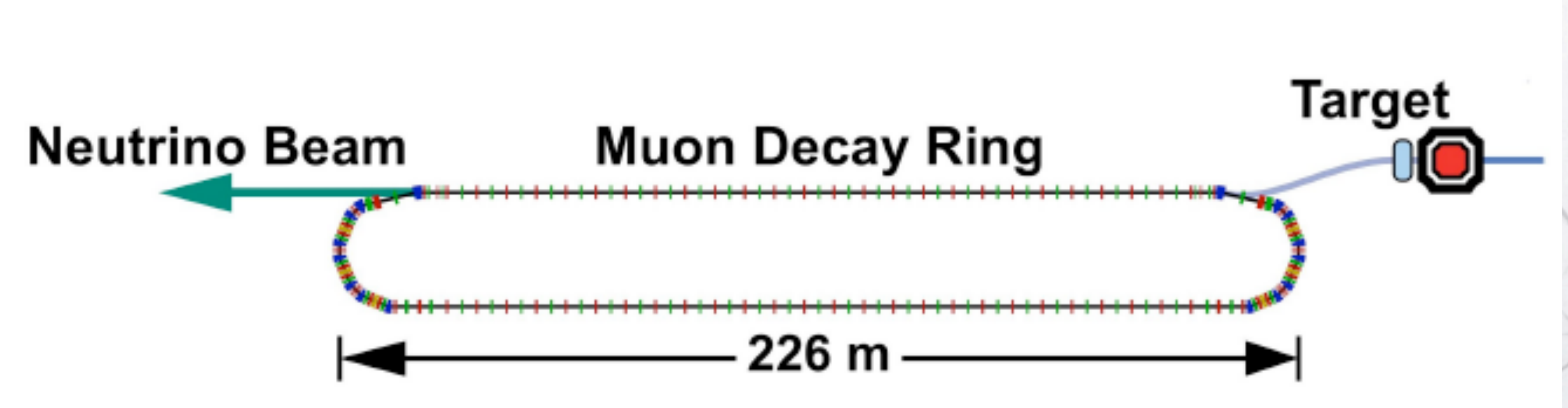
- It needs careful study but it looks like an affordable option to get a rather pure ν_e beam.

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)







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 !!!!

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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.

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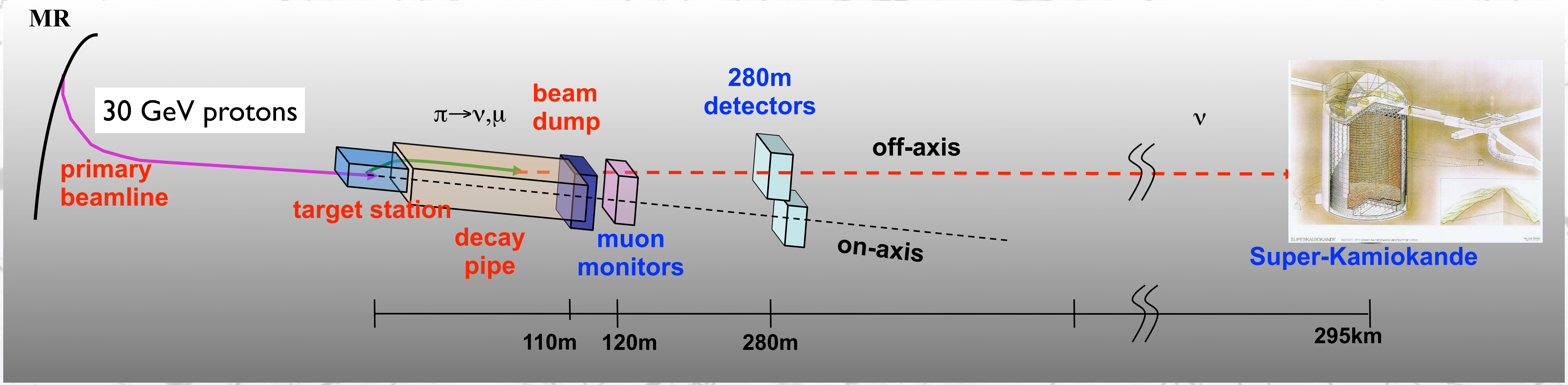
We need
1. better theoretical models.
2. data of better quality.
3. new detector concepts.
4. new beam concepts.

LBL concept



Beam

Near site detector

Far side detector

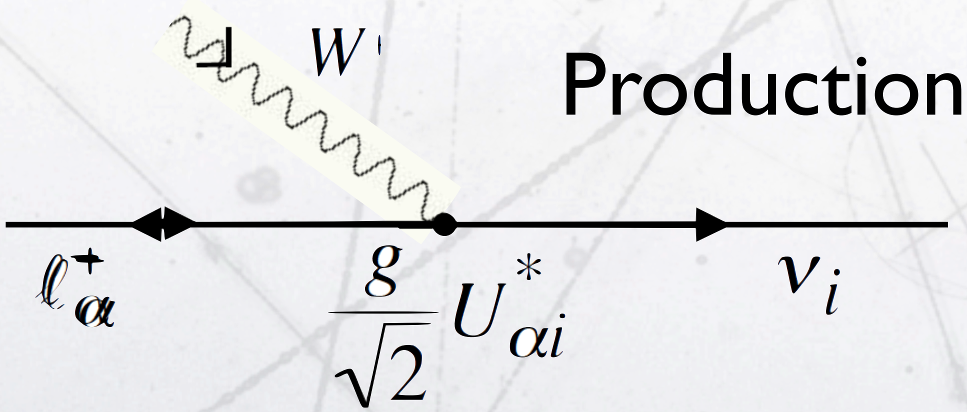
ν oscillations

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

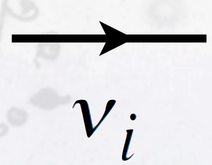
The two eigenbases are related through the Pontecorvo-Maki-Nakagawa-Sakata matrix (U_{PNMS}).

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

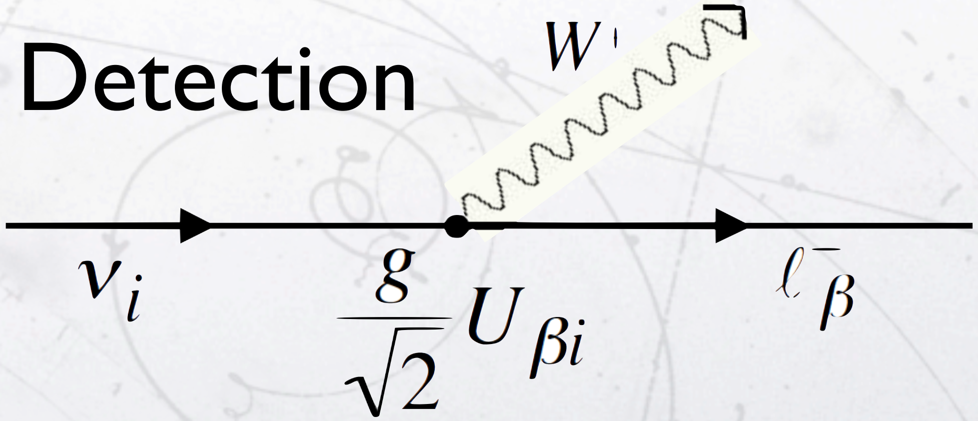
Production



Propagation



Detection



Courtesy of B.Kayser

ν oscillations

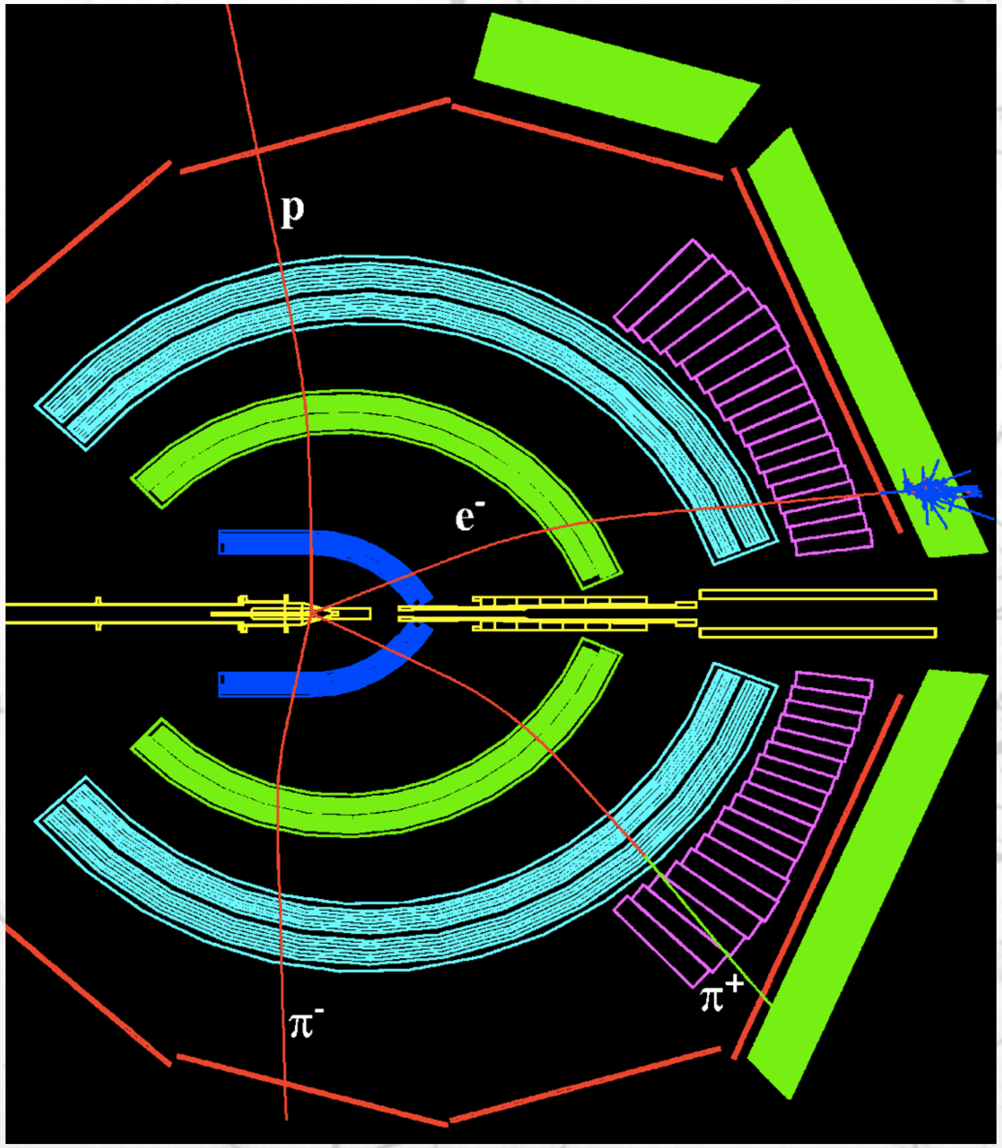
atmospheric   solar

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

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

- 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}.

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.