Physics prospects for neutrino-nucleus cross-sections

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Neutrino oscillations

- Neutrino oscillation experiments are carried out by comparing neutrino interactions at a near and far sites.
- 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

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

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

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

Neutrino oscillations

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

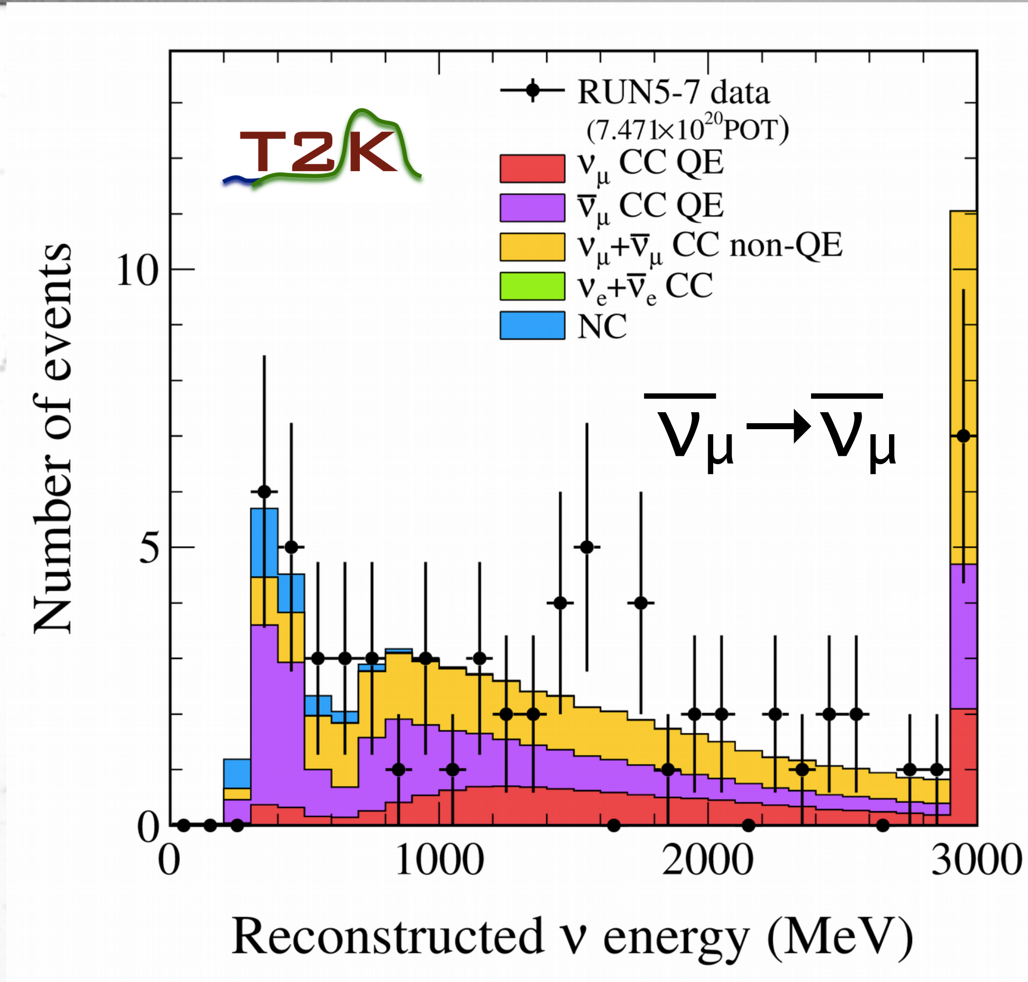
$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

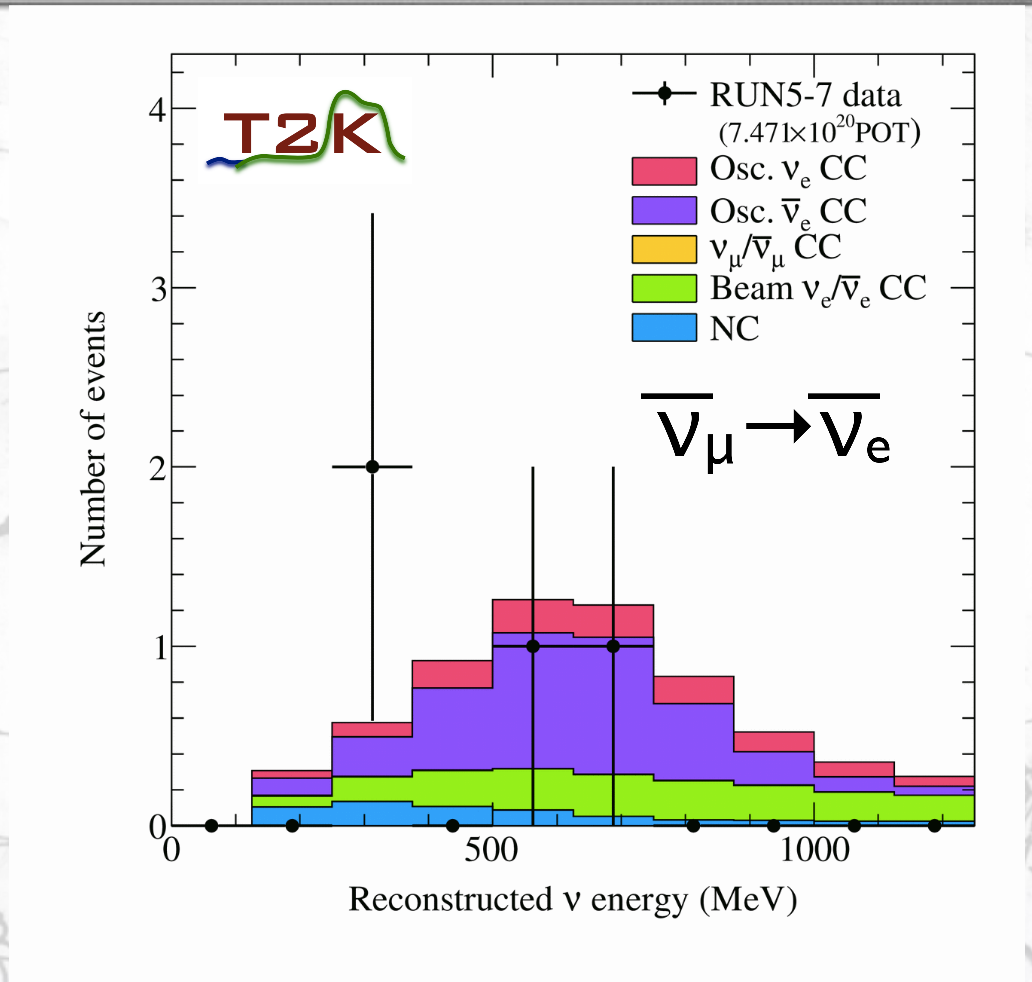
- The neutrino oscillations introduce differences in the flux spectrum and the ratio does not cancel the cross-sections.

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

$P(E_\nu|E'_\nu)$ is not caused by a mere detector smearing.

Backgrounds





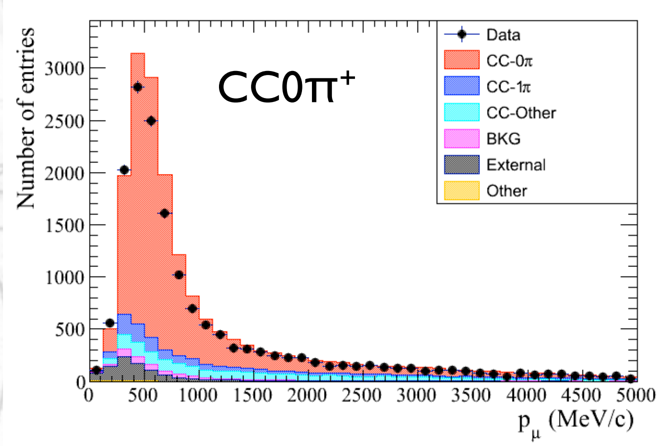
- Far detector also have several sources of backgrounds:
  - wrong sign backgrounds (neutrinos vs. antineutrinos).
  - NC interactions populating low energy bins.
  - Wrong interaction channel leading to biased energies.

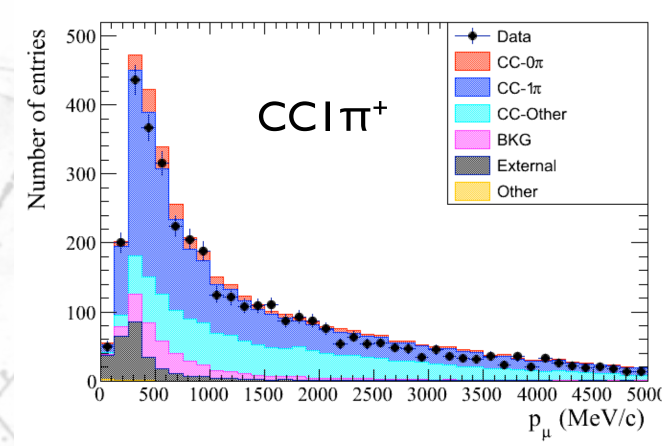
Neutrino Flux

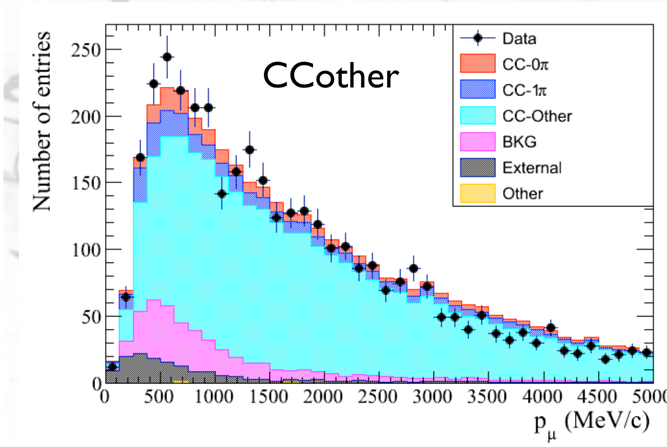
- The neutrino flux has to be obtained from the near detector.
- Dedicated hadro-production experiments help but not sufficient: target, horn and decay volume description.
- The only tool we have to calibrate all these parameters is with a near detector using neutrino interactions.
  - Cross-sections are the key to the problem.
  - But, also the source of most of our problems.
- Other alternatives are possible to complement the measurement (ν e^- scattering). Minerva is exploring this option.

Near detector

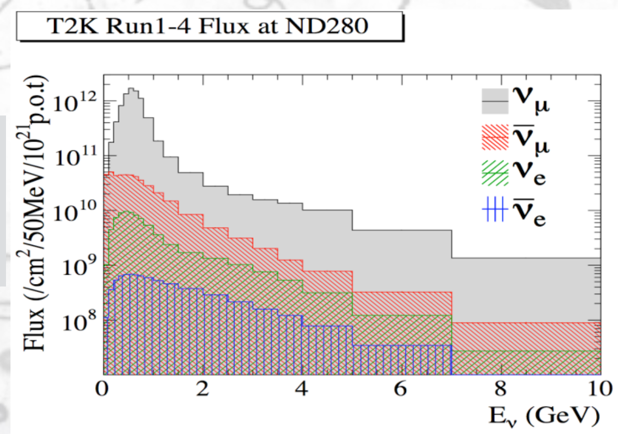
Near detector data



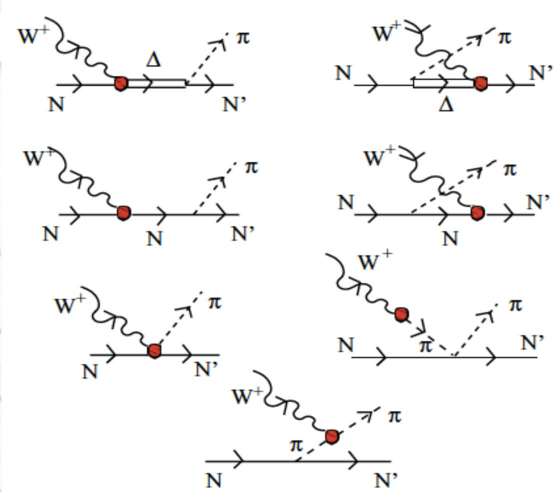




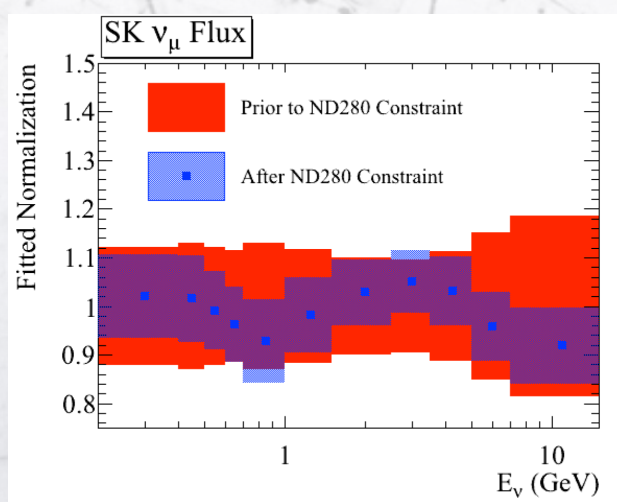
⊕ Hadron production flux prediction



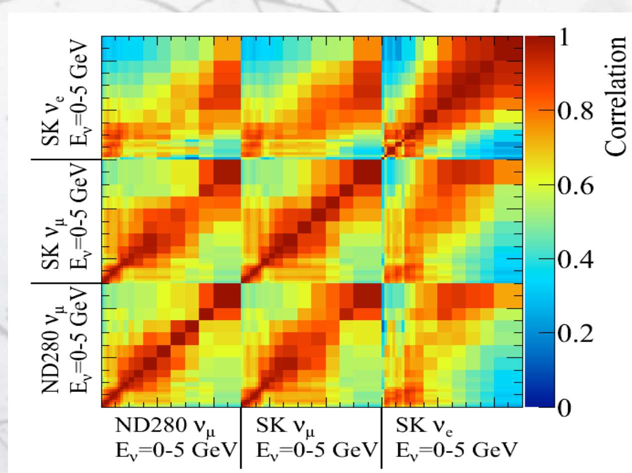
⊕ Cross-section model



= Corrected flux and cross-section model



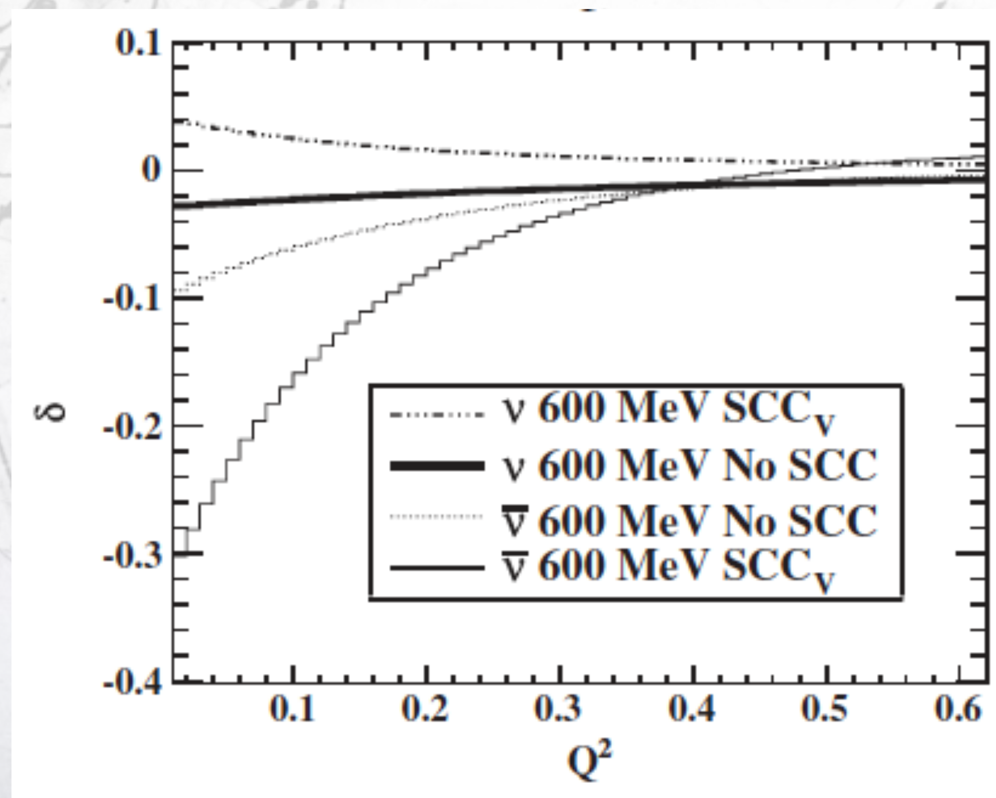
& correlation



Neutrino Electron

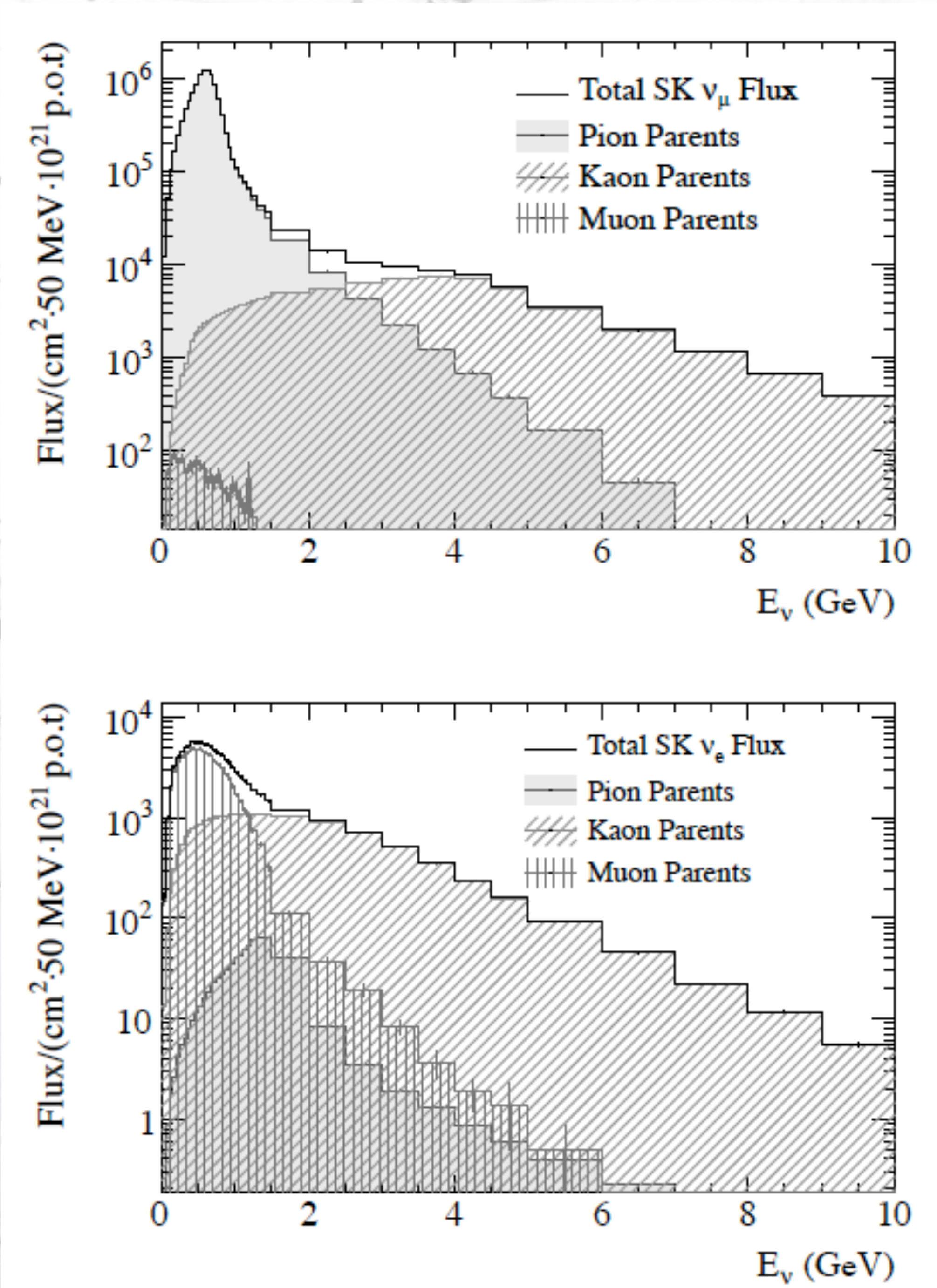
- CP violation requires in addition the knowledge of the ratio $\sigma(\nu_\mu)/\sigma(\nu_e)$ for neutrinos and anti-neutrinos.
- The ratio does not need to be trivial due to the Breemstrahlung and convolution with nuclear effects.

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



PHYSICAL REVIEW D **86**, 053003 (2012)

Neutrino Electron



- Conventional neutrino beams are very bad places to perform this measurement:
  - Low flux with respect to muon neutrinos.
  - Production process is very different:
    - ν_e mainly from muon and kaon decays
    - ν_μ mainly from pion decays.

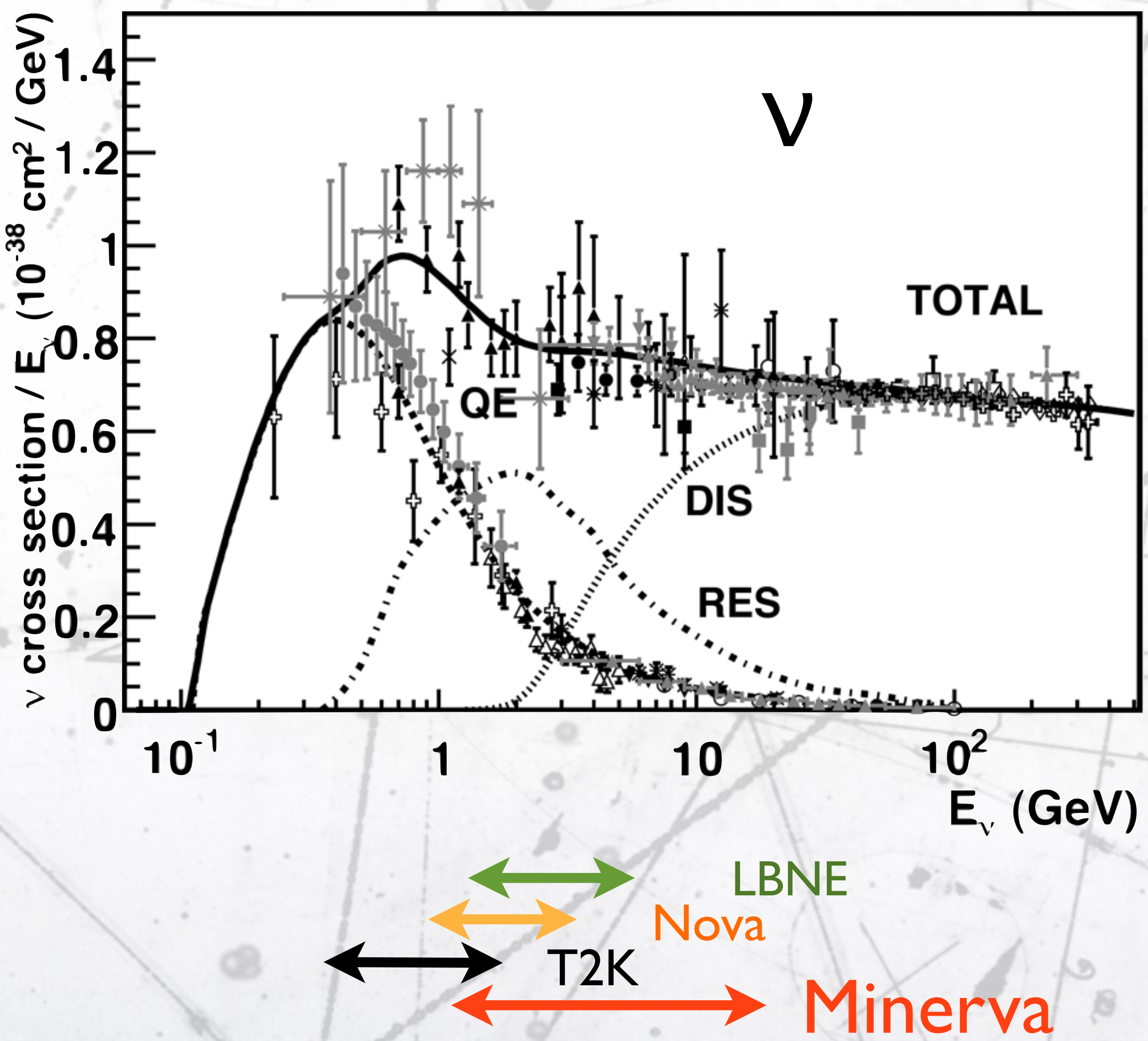
Neutrino interactions

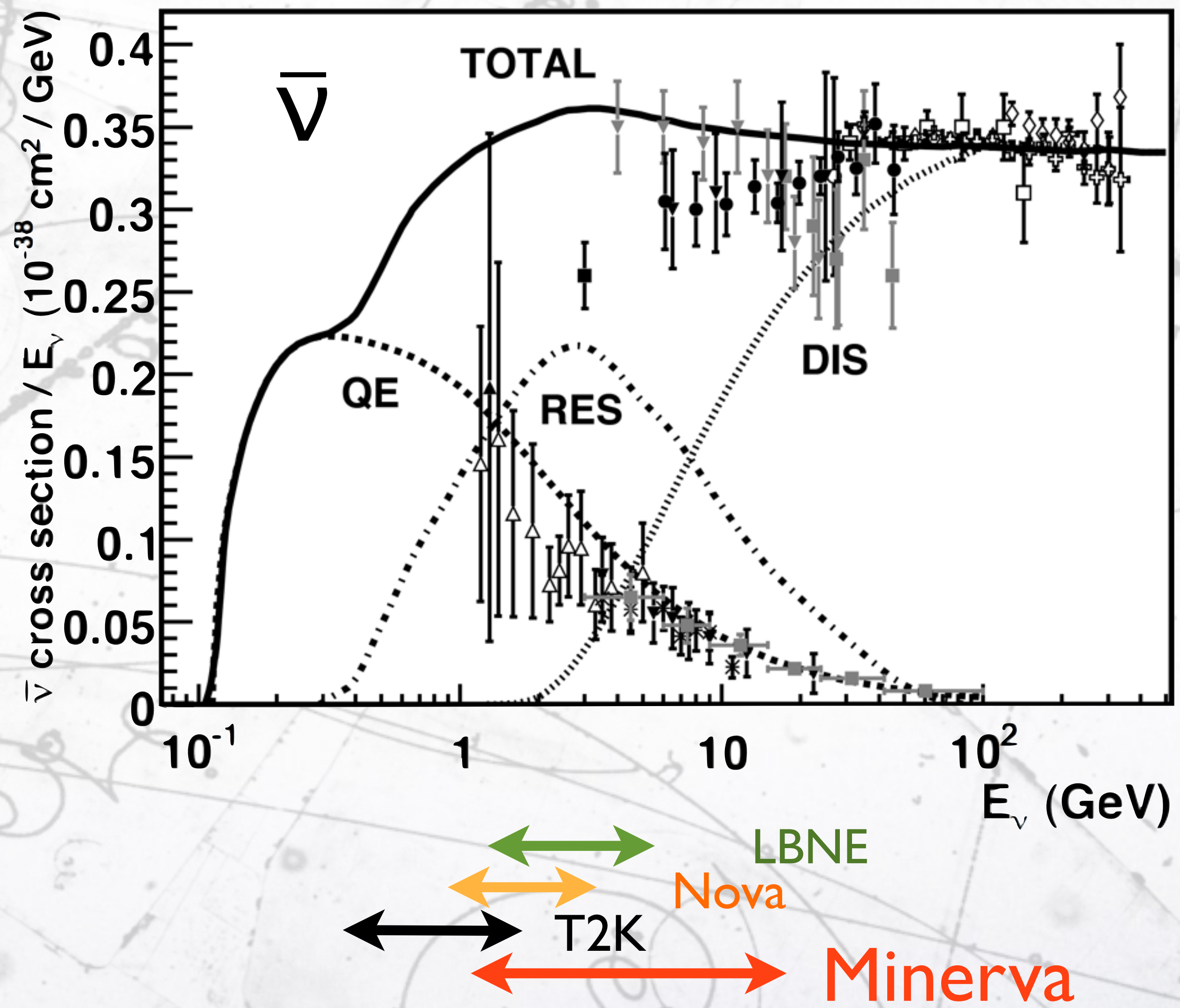
@ the nucleon level !

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

The xsec problem

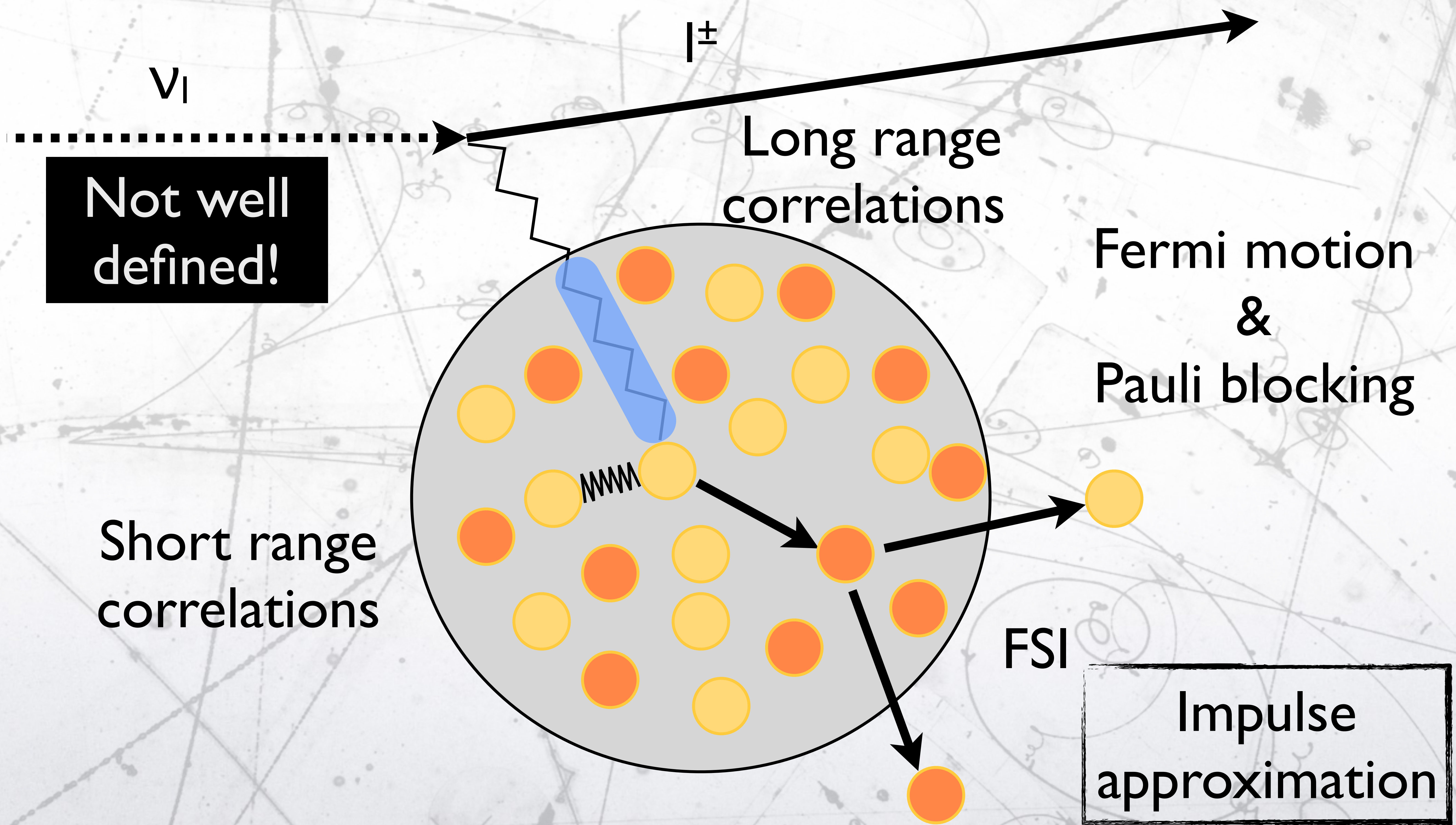
J.A.Formaggio, G.P.Zeller, Rev.Mod.Phys. 84 (2012) 1307





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

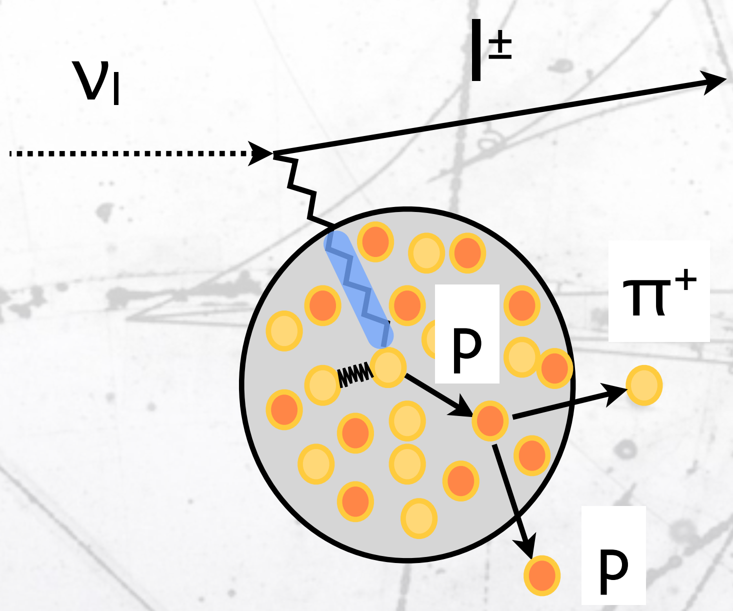
Neutrino interactions

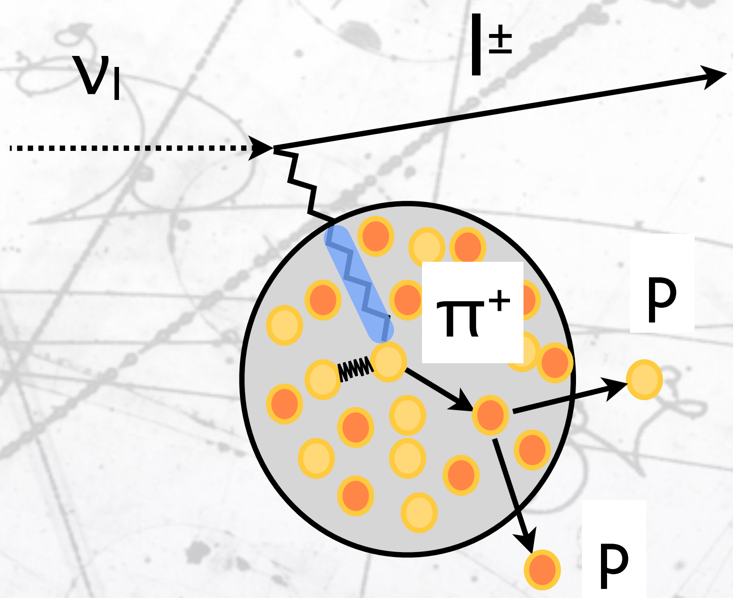


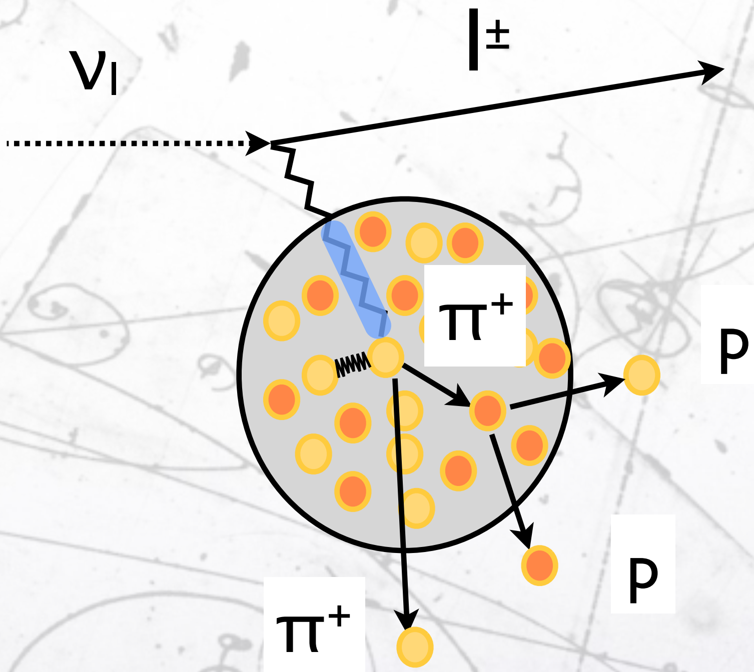
Problem factorisation

- 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 2π^{+}
2. 2π^{+} in final state
3. π^{+} p -> p p

ND for oscillations

How to measure the neutrino energy ?

$P(E_\nu|E'_\nu)$

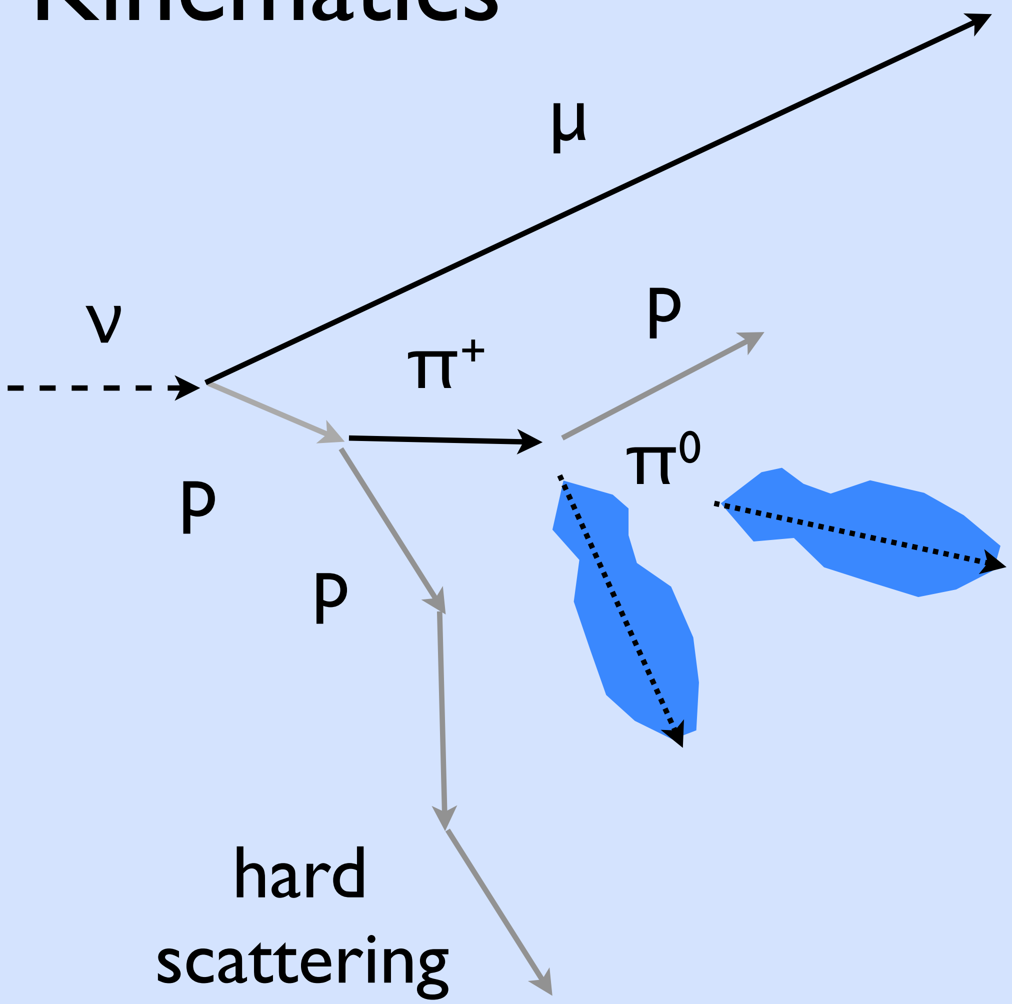
Kinematics

- 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.

Calorimetry

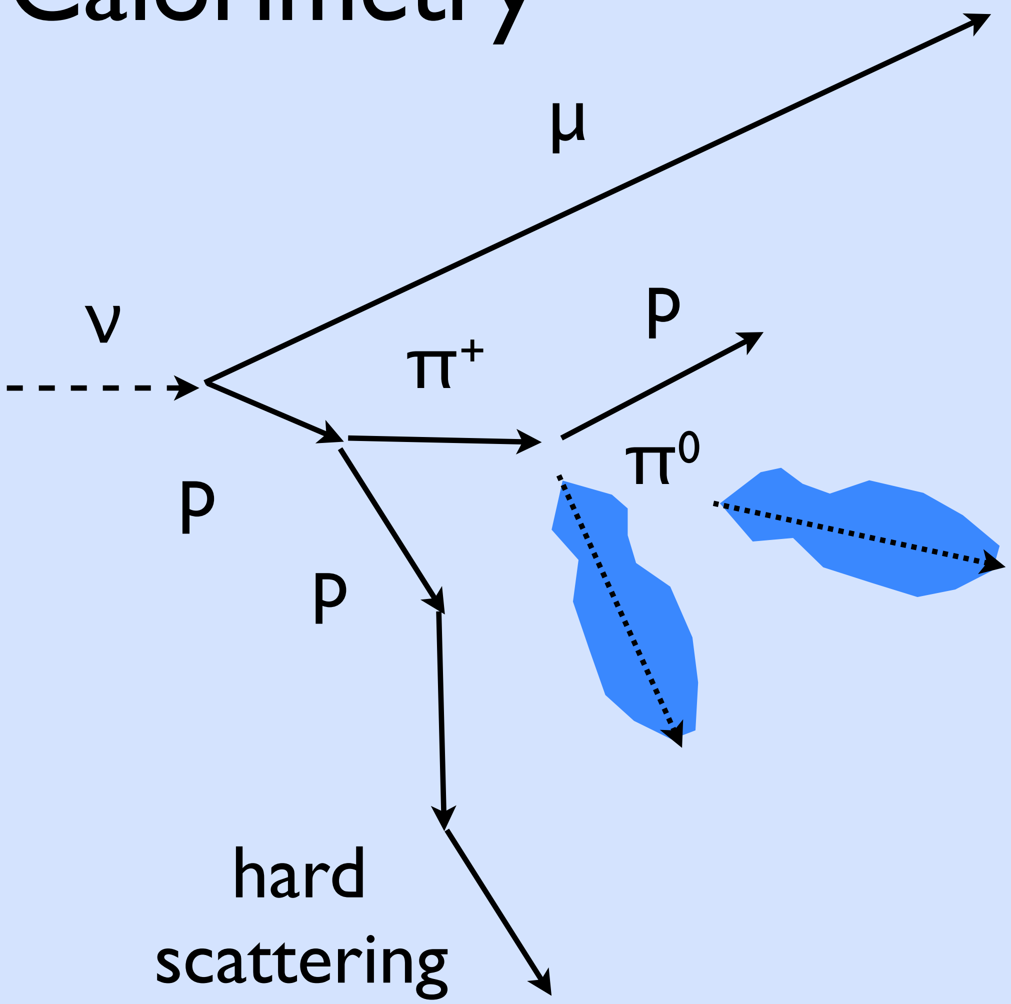
- $E_\nu = E_l + E_{hadrons}$ with $E_{hadrons} << E_l$
- Hadronic energy depends on modelling of DIS and high mass resonances.
- Hadronic energy depends on Final State Interactions and detector response.

Kinematics



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

Calorimetry

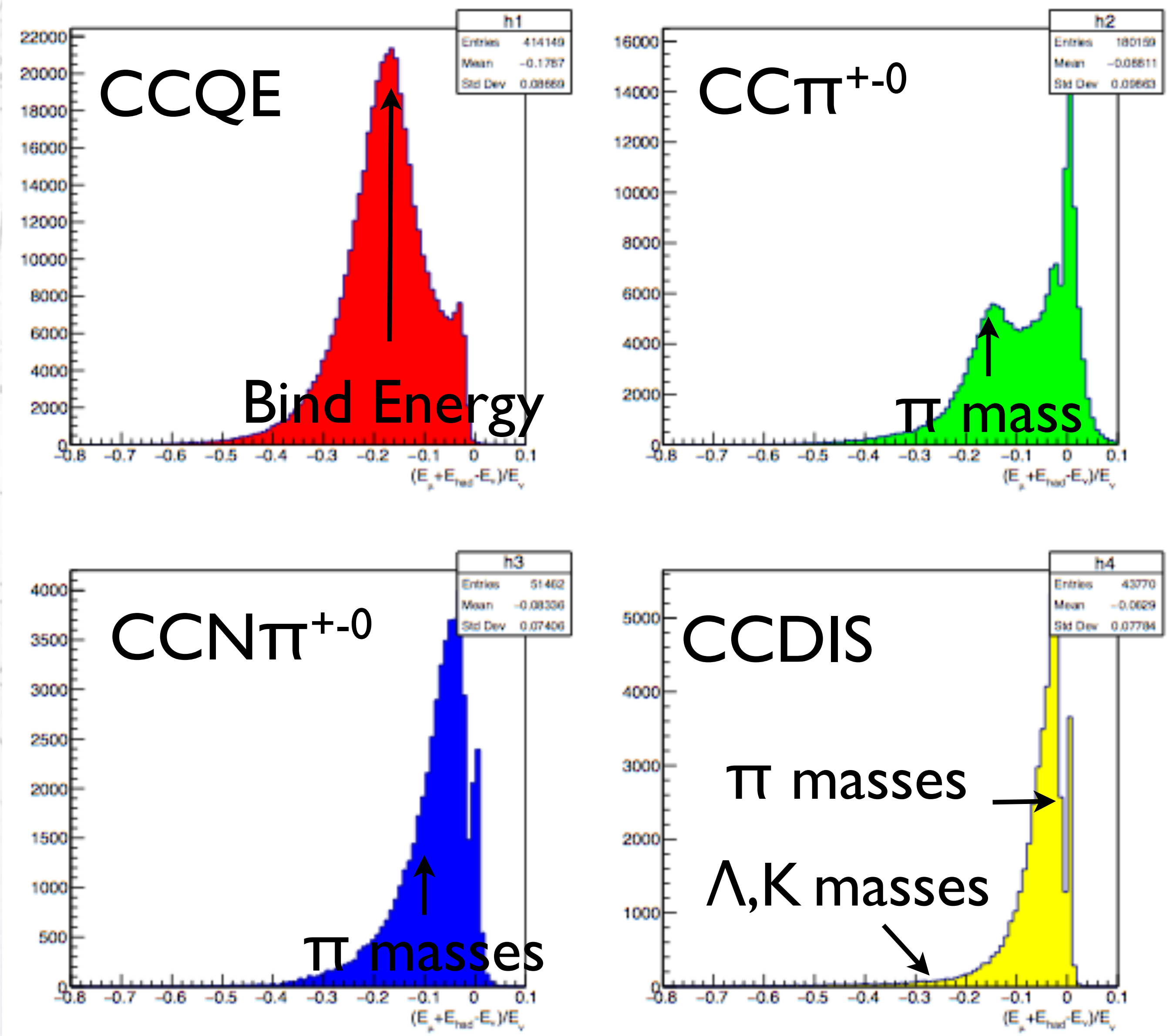


- The visible energy is altered by the hadronic interactions and it depends on hadron nature.

ND for oscillations

Calorimetric Approach

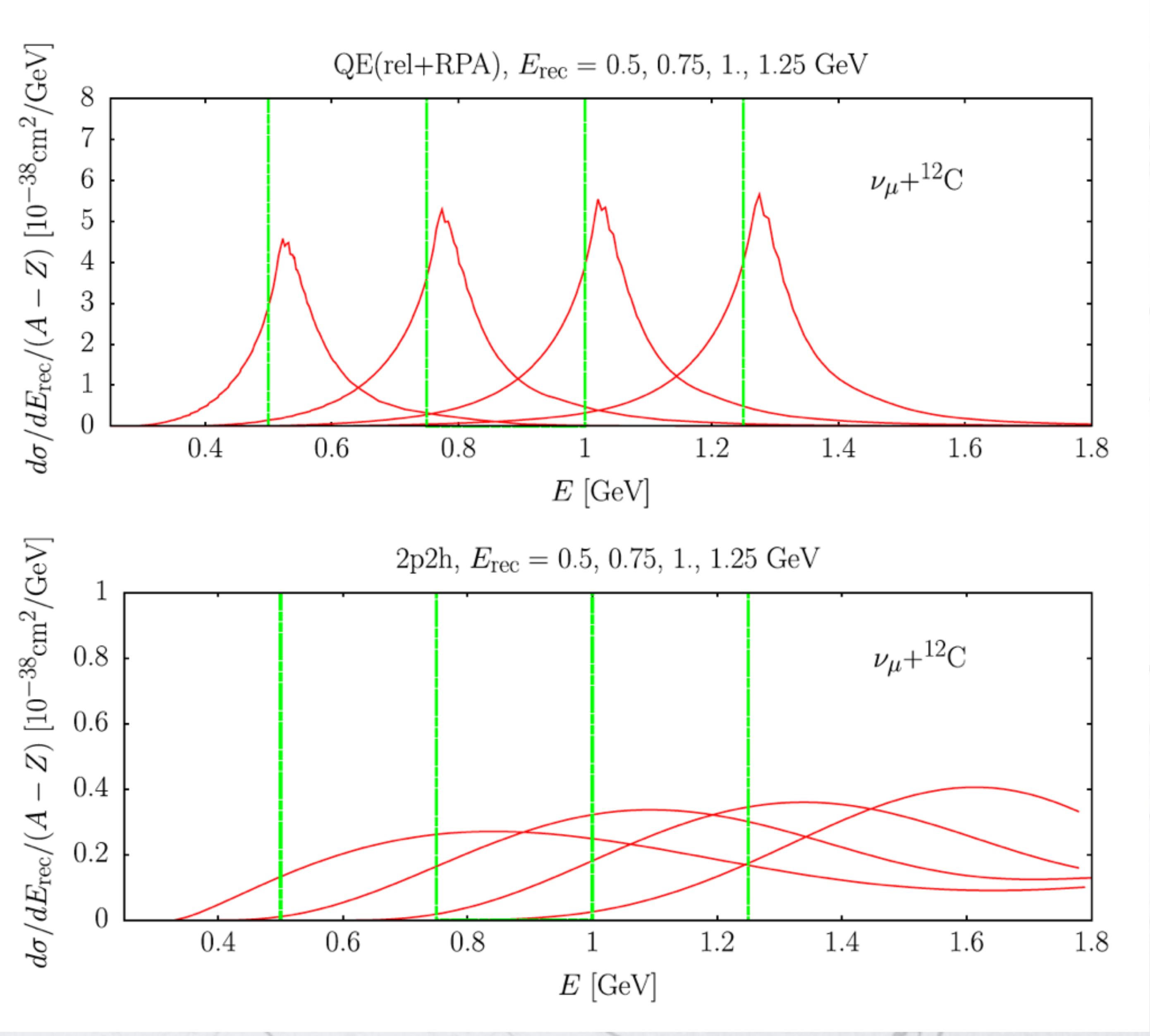
- Simple exercise:
  - Take all particles predicted by Neut MC outside the nucleus and sum the kinetic energy (including neutrons!).
  - Plot the relative energy deviation (E_μ+E_{had}-E_ν)/E_ν for different channels.
  - The response depends on the channel and the topology of events outside the nucleus.
- This is too simple because it is not clear that Neut includes all possible energy balances in the equation.
- Part of the pion and kaon mass can be recovered through its decay chain.



- Are the neutrino interaction models ready for this type of analysis?

Kinematic Approach

- The kinematic approach relies on the knowledge of the reaction channel.
- Experimentally we can confuse the channel because:
  - nuclear effects (absorption).
  - detector effects (thresholds).
- If two reactions are confused the energy is wrongly reconstructed.



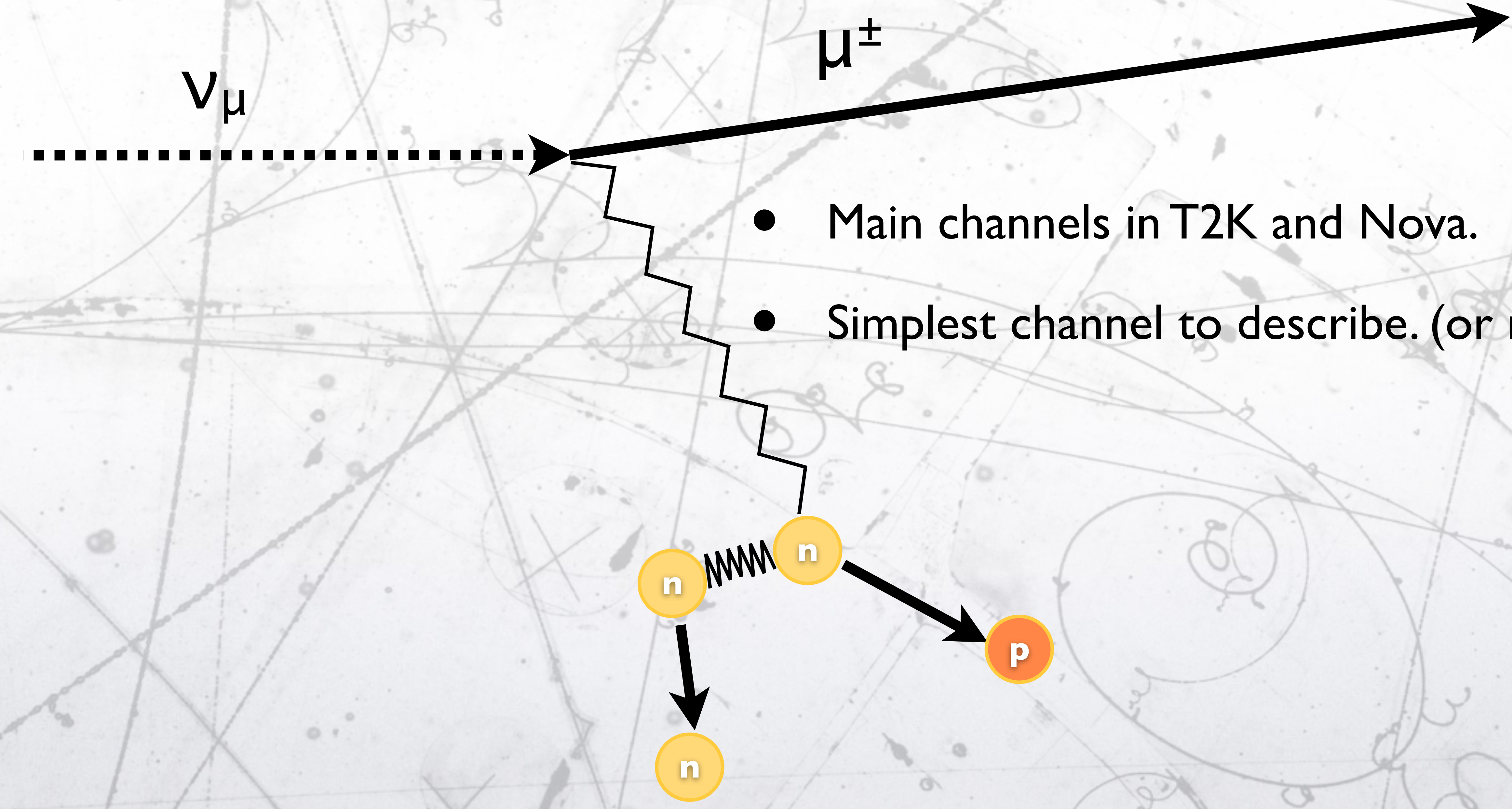
PHYSICAL REVIEW D **85,** 113008 (2012)

ND for oscillations

- $P(E_\nu|E'_\nu)$ is the critical point on the above formula.
- This reconstruction depends on:
  - BIAS: The validity of the reconstruction assumption for the right topology of the event.
  - BACKGROUND: The error when the formula is applied to the wrong event.
  - ENERGY SCALE AND EXPERIMENTAL BIAS: Difference between the near and the far detector and absolute calibration scale.

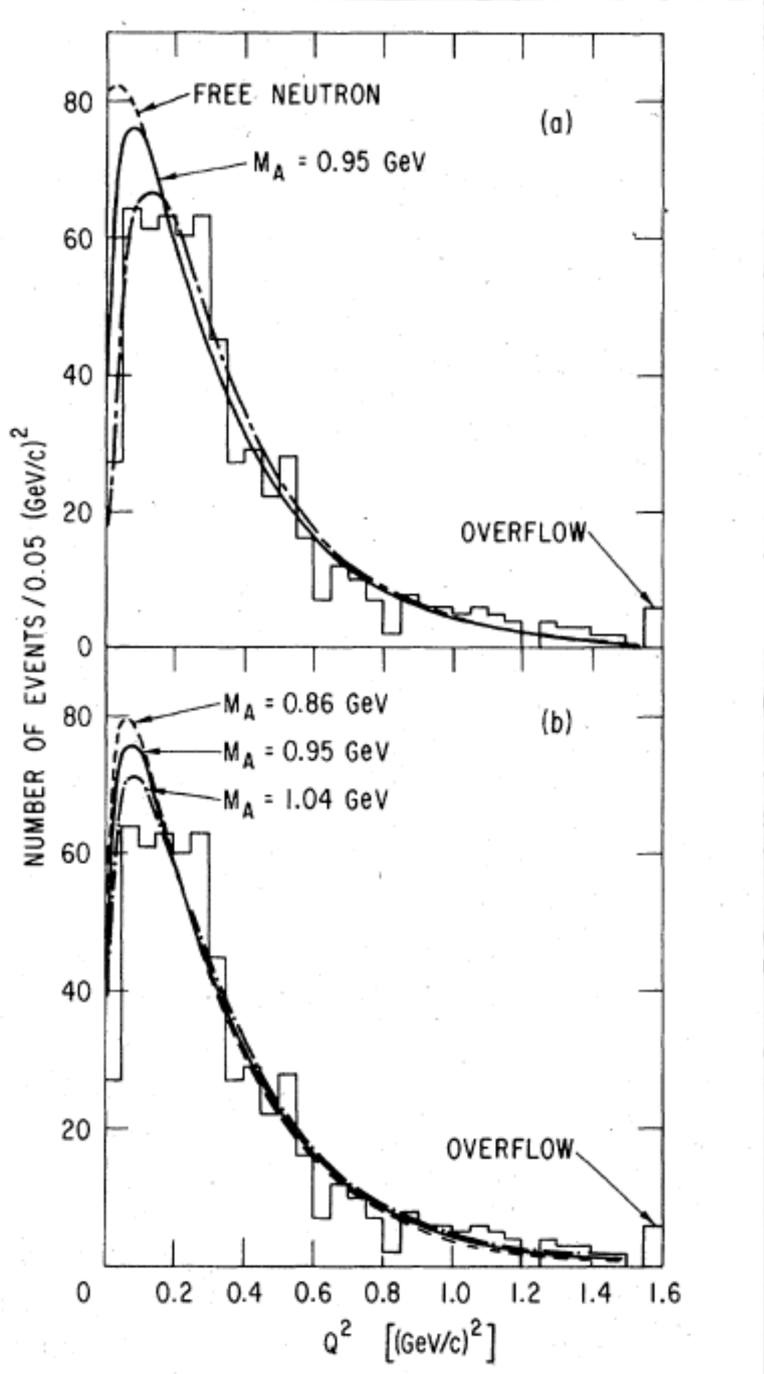
Similar near and far detector technology is a plus but it is not always the right solution.

CC 1p1h + 2p2h



- Main channels in T2K and Nova.
- Simplest channel to describe. (or not?)

Single nucleon

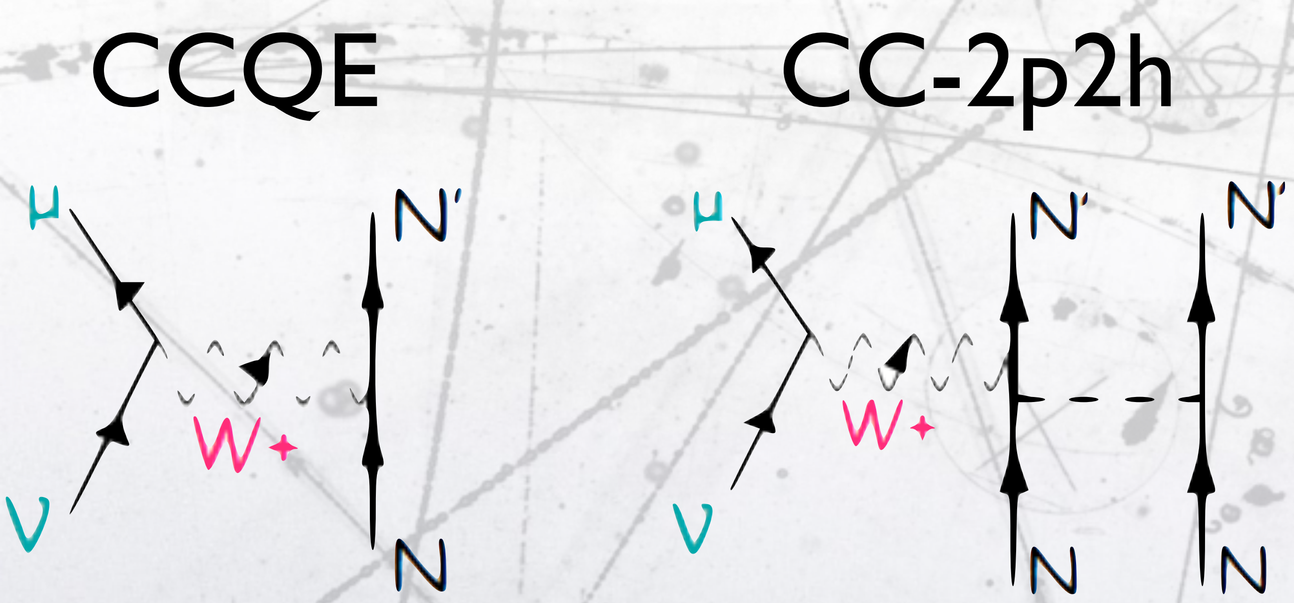


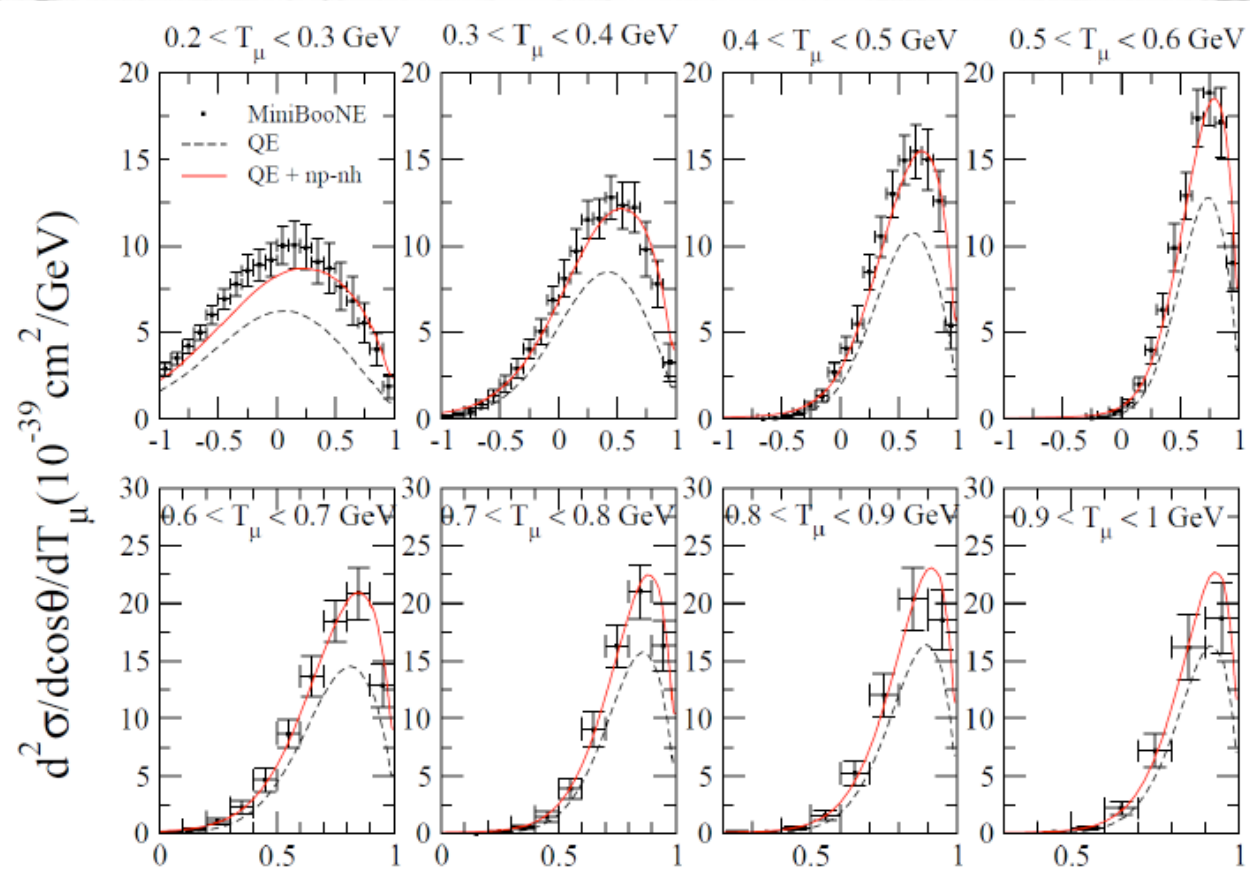
PHYSICAL REVIEW D
VOLUME 16, NUMBER 11
1 DECEMBER 1977

- Free nucleon (H and D) data is very limited.
- Many of the assumptions of the basic cross-section can't be accurately tested with nuclei:
  - Conserved Vector Current
  - Partially Conserved Axial Current.
  - Dipole form factor
  - Vanished scalar and tensor form factors.
- …

1p1h vs 2p2h

- Recently the community has realised the presence of short range correlations, so called 2p2h.
- They are basically interactions with 2 nucleons at the time.
- They alter the energy balance and the neutrino energy reconstructions.





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

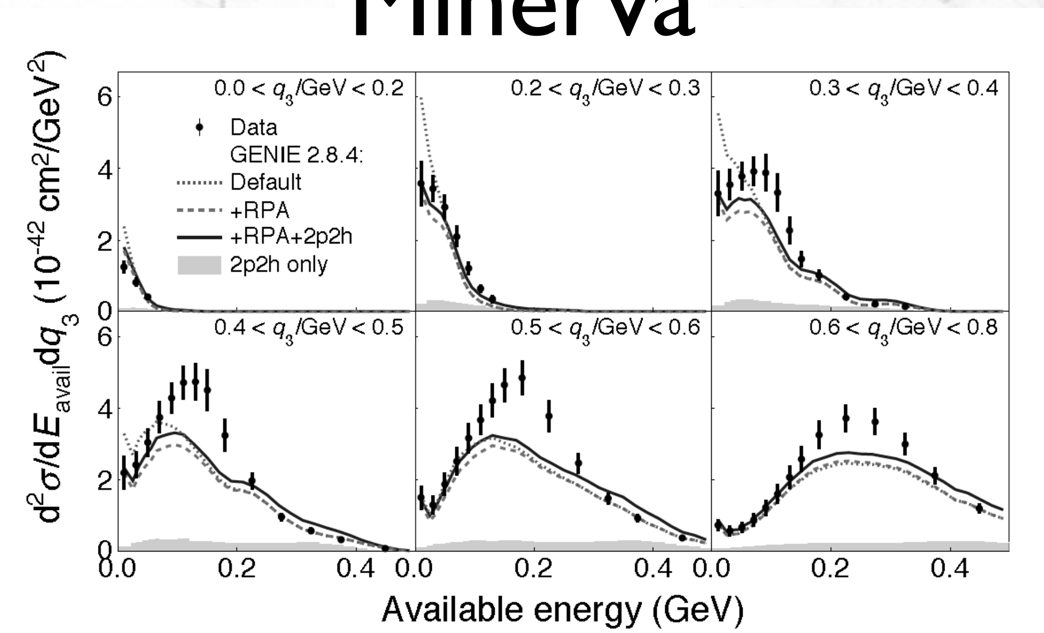
Martini et al. PRC 84 055502 (2011)

1p1h vs 2p2h

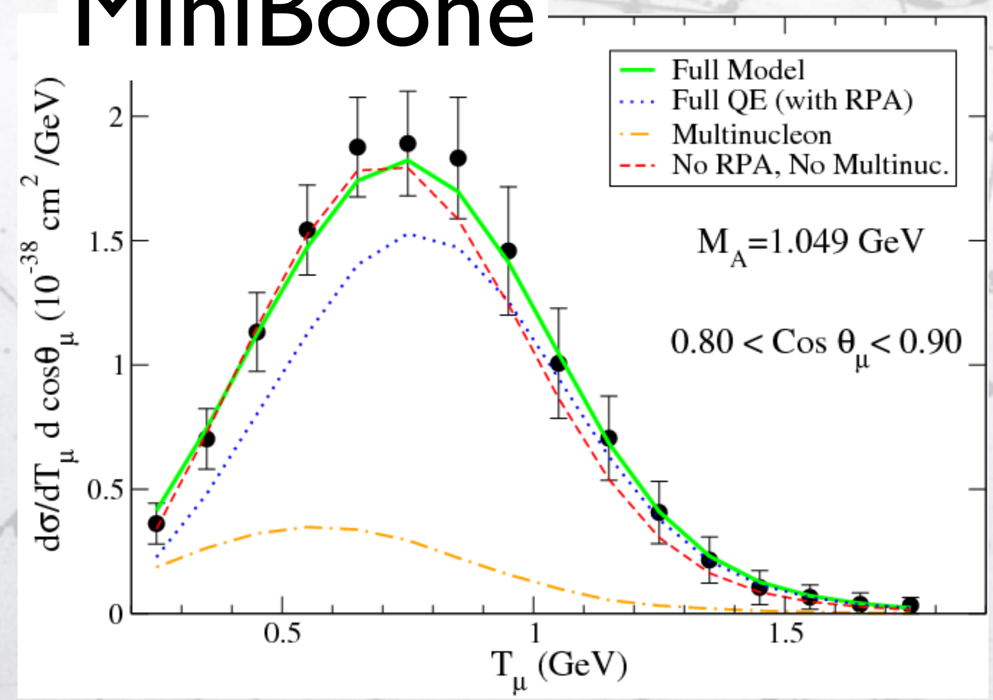
- Models agree with MiniBoone but not with other experiments: Minerva and T2K.
- Models based on same principles do not agree.

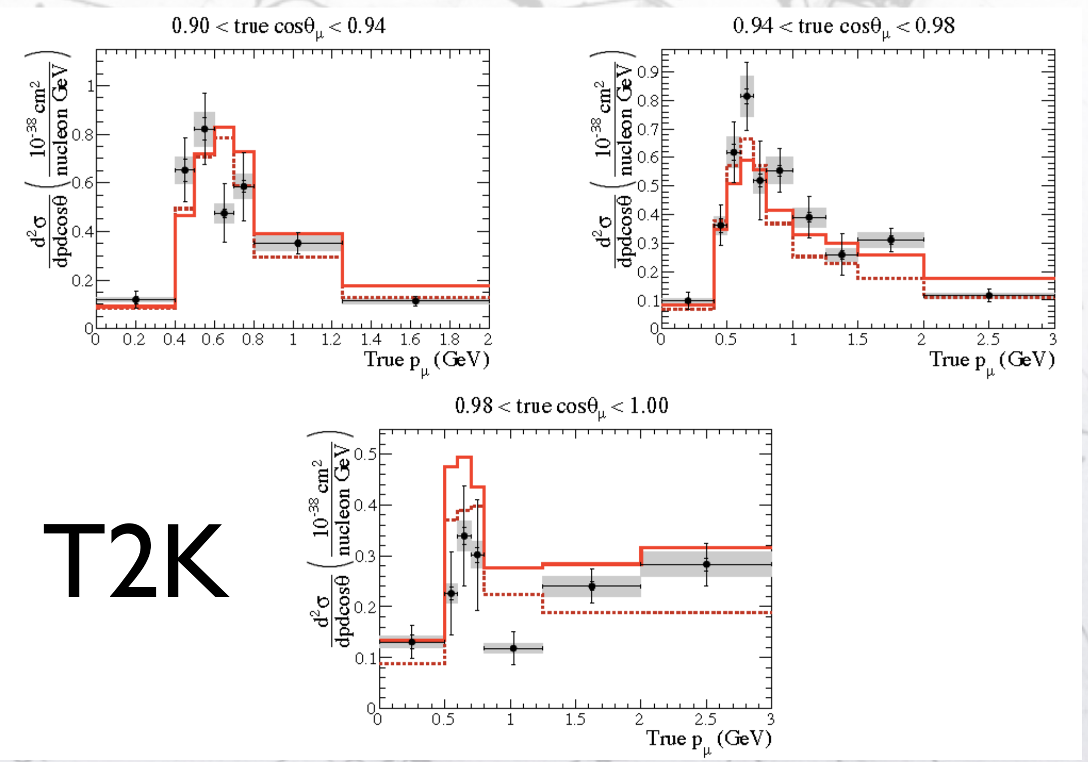
This is a large systematic error in T2K & Nova

Minerva

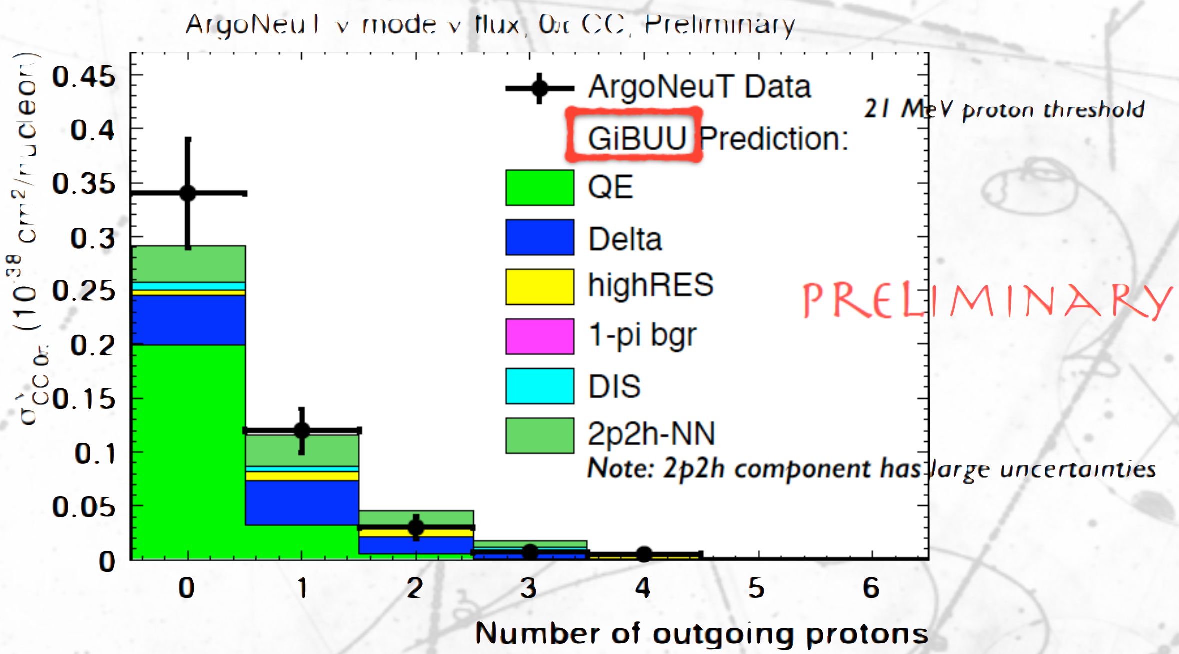


MiniBoone

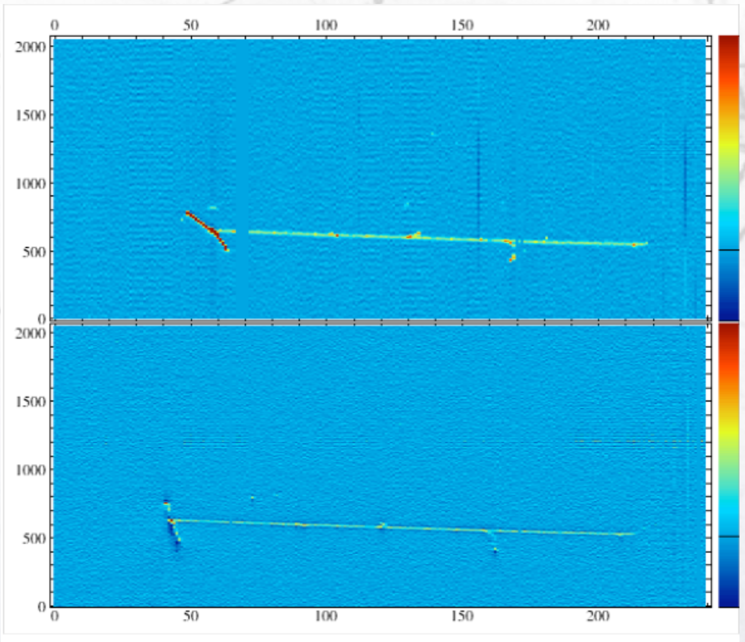


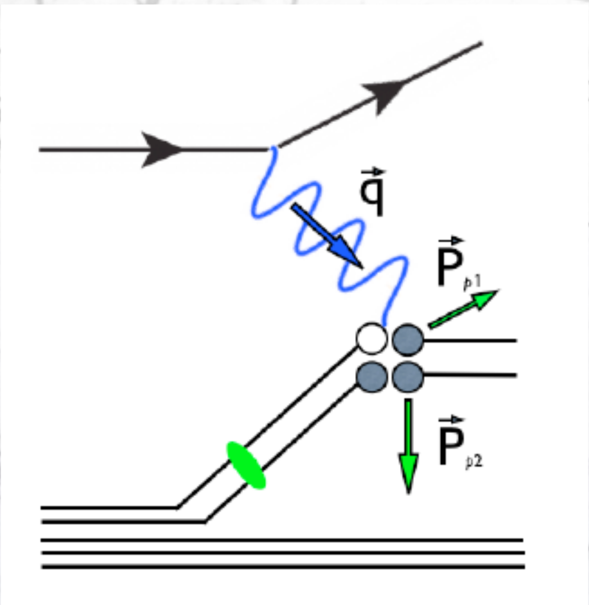


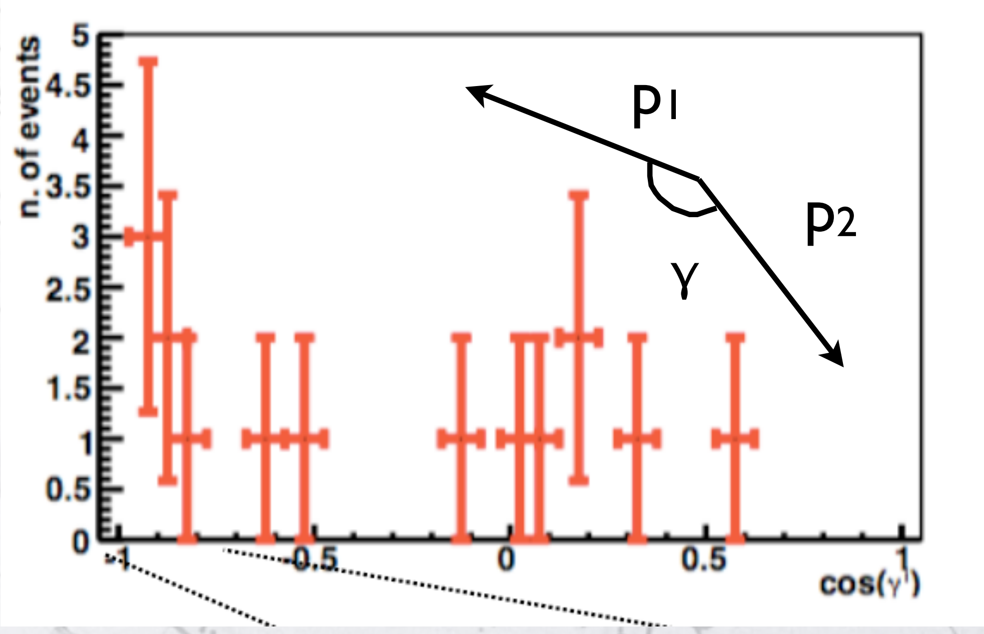
Search for 2p2h



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



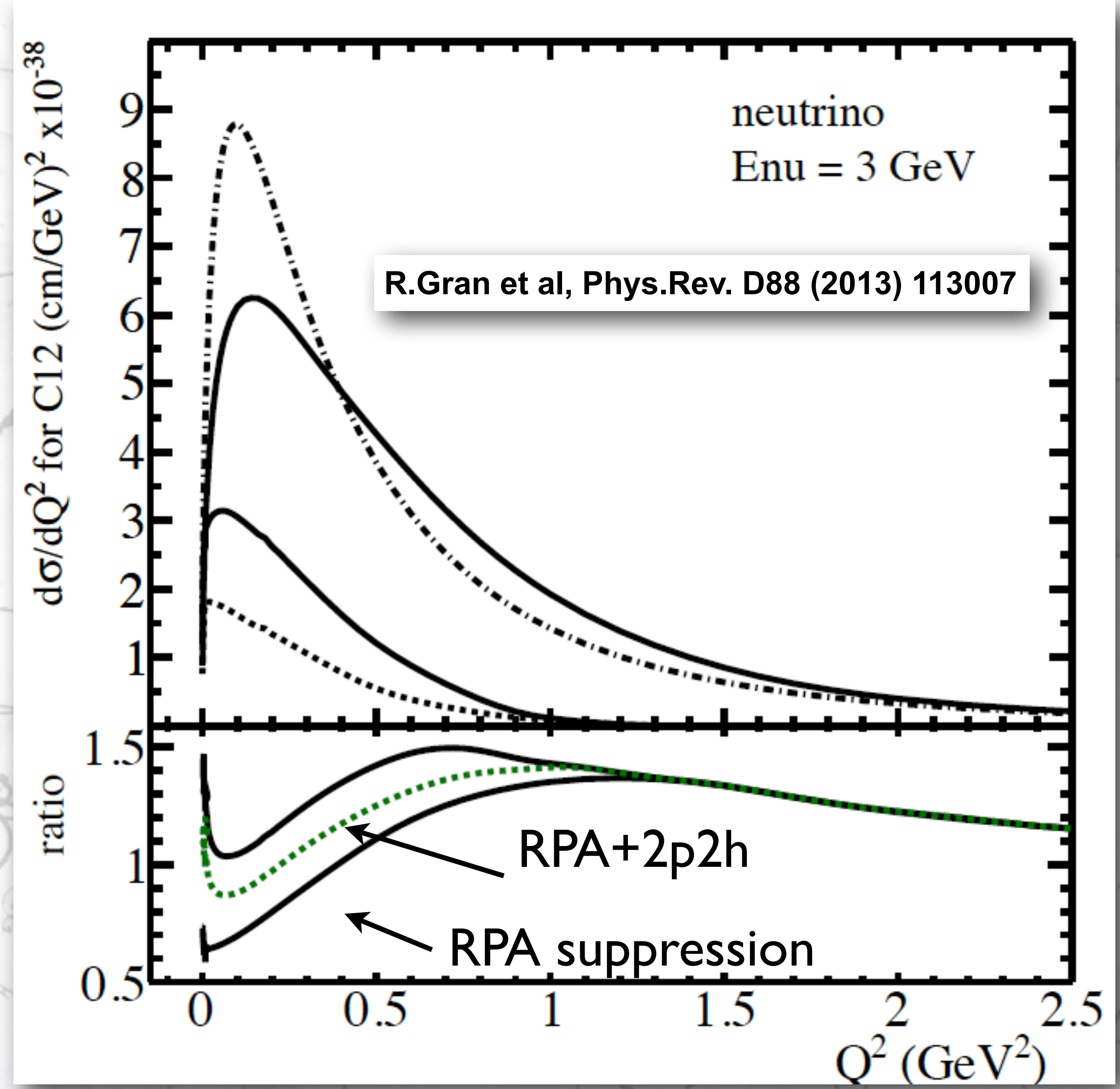




Strength of new generation of low threshold detectors

1p1h

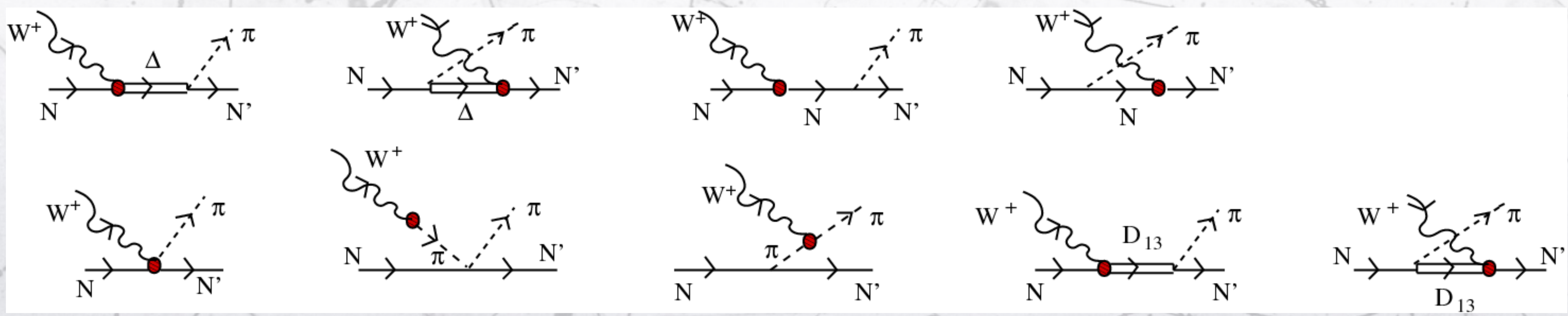
- Actually one of the problems is that the basic nucleus is probably not well described:
  - bind energy !
  - Fermi momentum description: RFG, LFG, Spectral functions.
  - Final State interactions.
  - Large Range correlation appearing as low q^2 quench of the reaction.



Sometimes the different models are degenerate and it is difficult to resolve them. Need different experimental conditions.

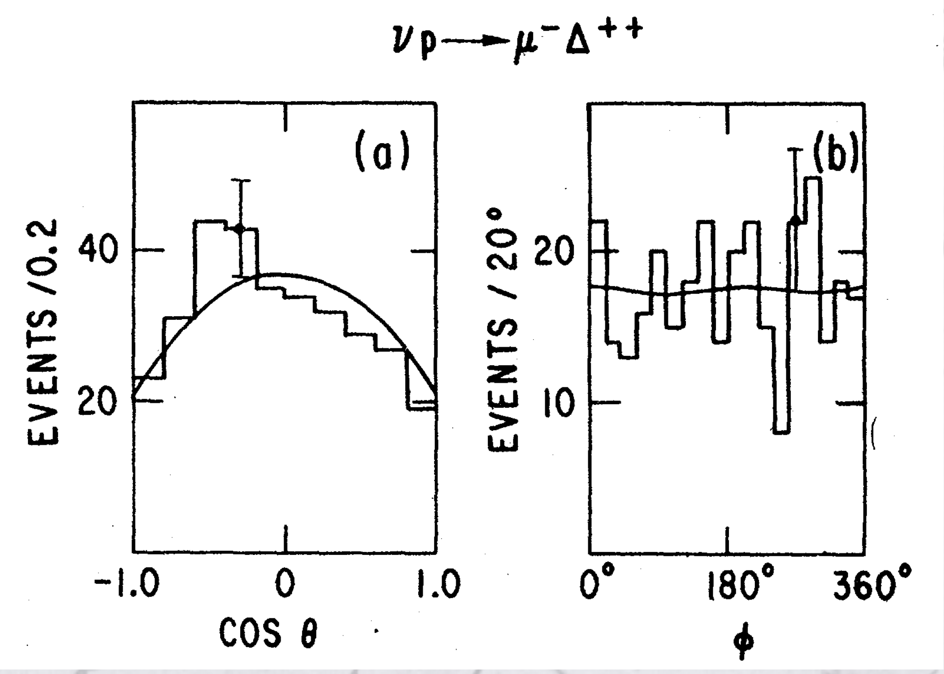
Single pion production

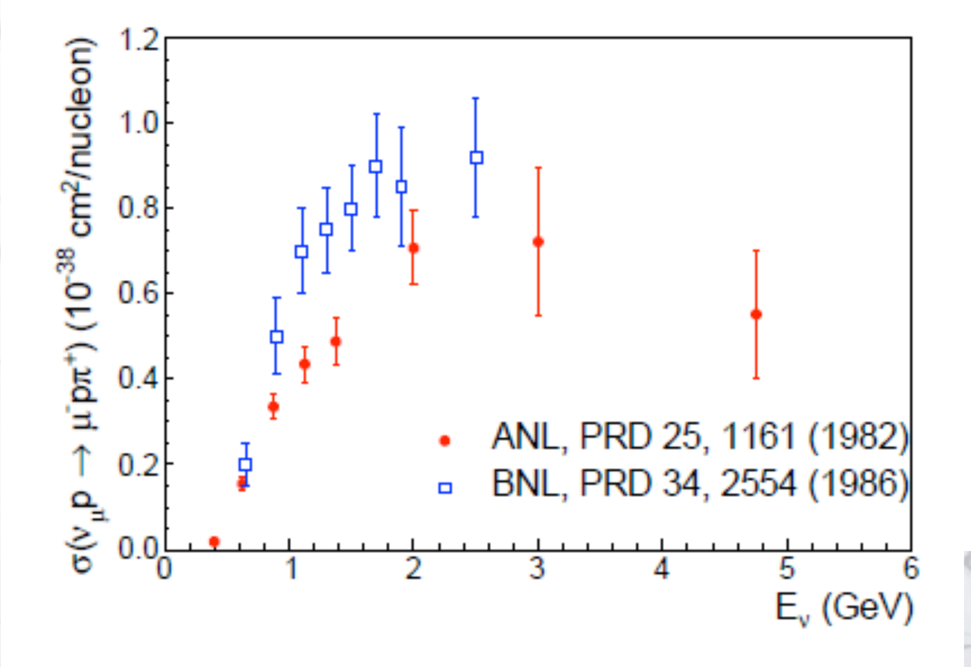
- Second most relevant cross-section in oscillation experiments.
- All set of long and short rage correlation effects in CC1π are ignored in actual pion production models.
  - models are still uncertain on its implementation to CCQE.
- Complex modelling with many intermediate resonances and non-resonant contributions.

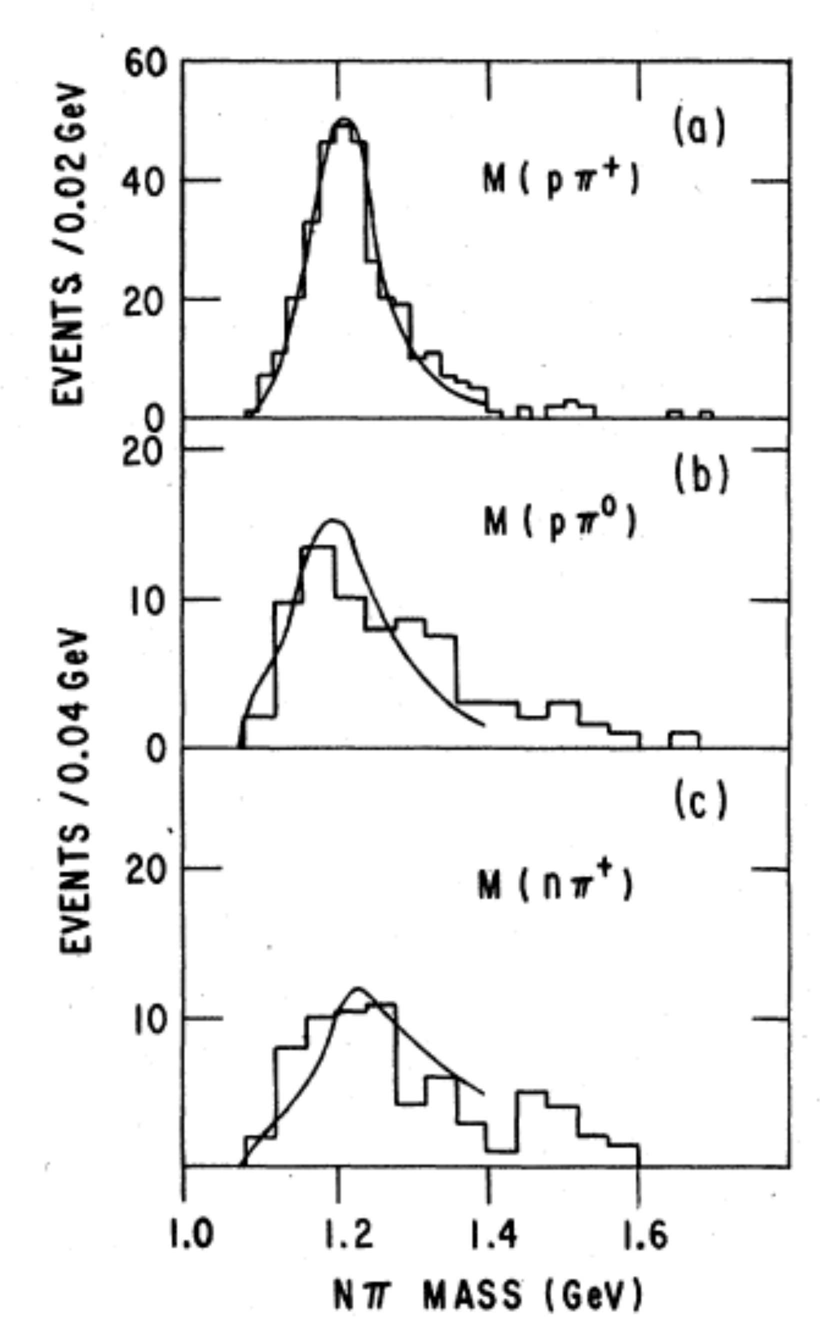


Single pion production

- Poor knowledge at nucleon level both theory and experiment:
  - Mixture between resonant and non-resonant interactions.
  - many resonances and spin amplitudes.
  - poor data.

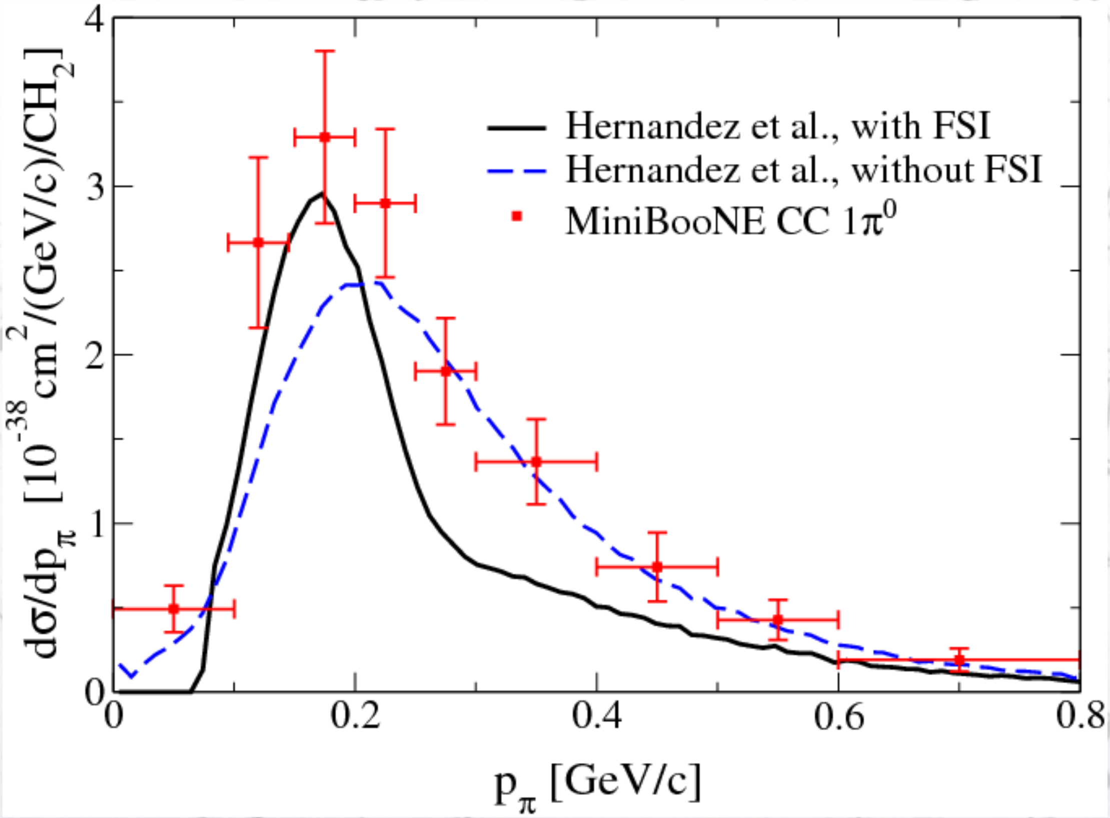


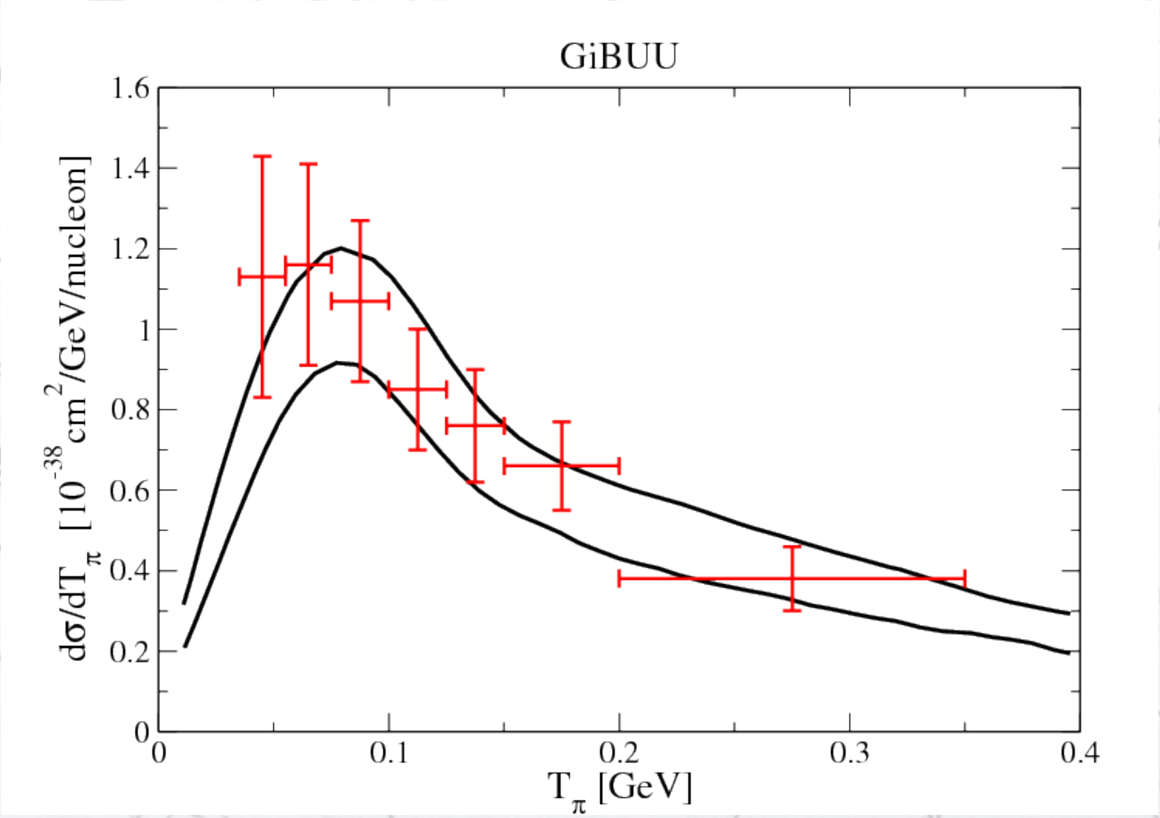




π modern data

- The nucleus distorts severely the distributions.
- Experiments normally define “topological” signal based on the particles emitted by the nucleus and not at the nucleon level.

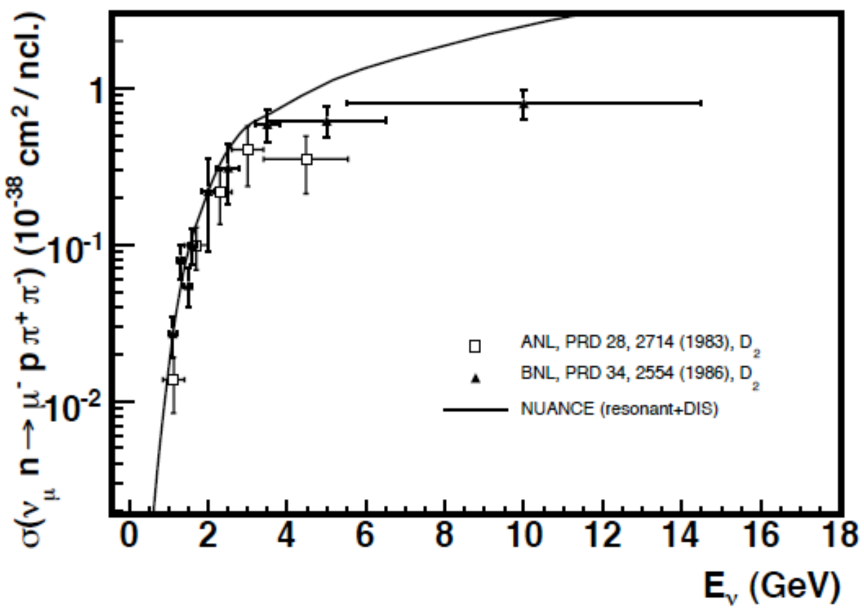


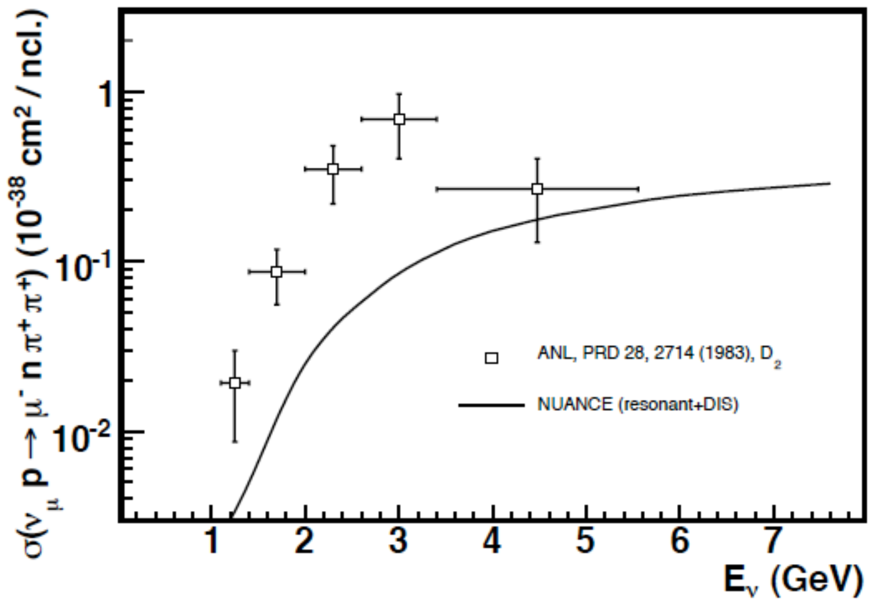


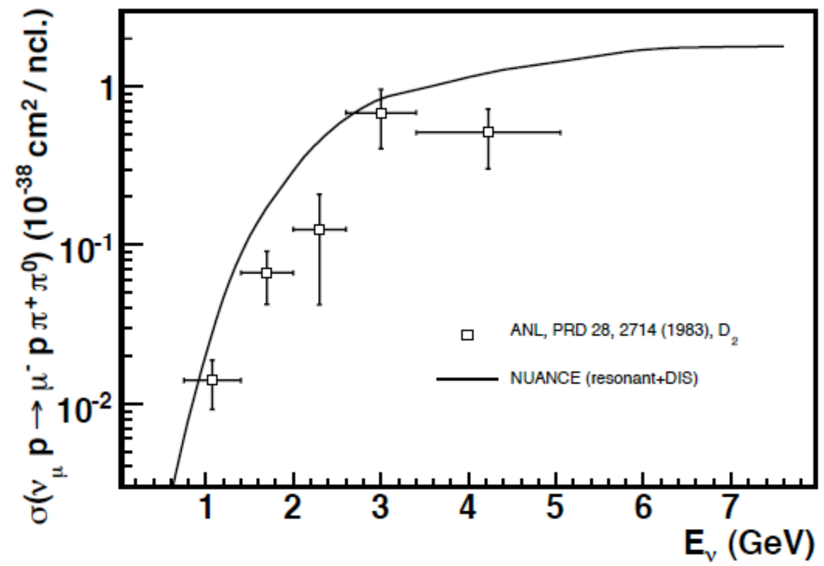
- Experimental errors or faulty models ?

Nπ to DIS

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





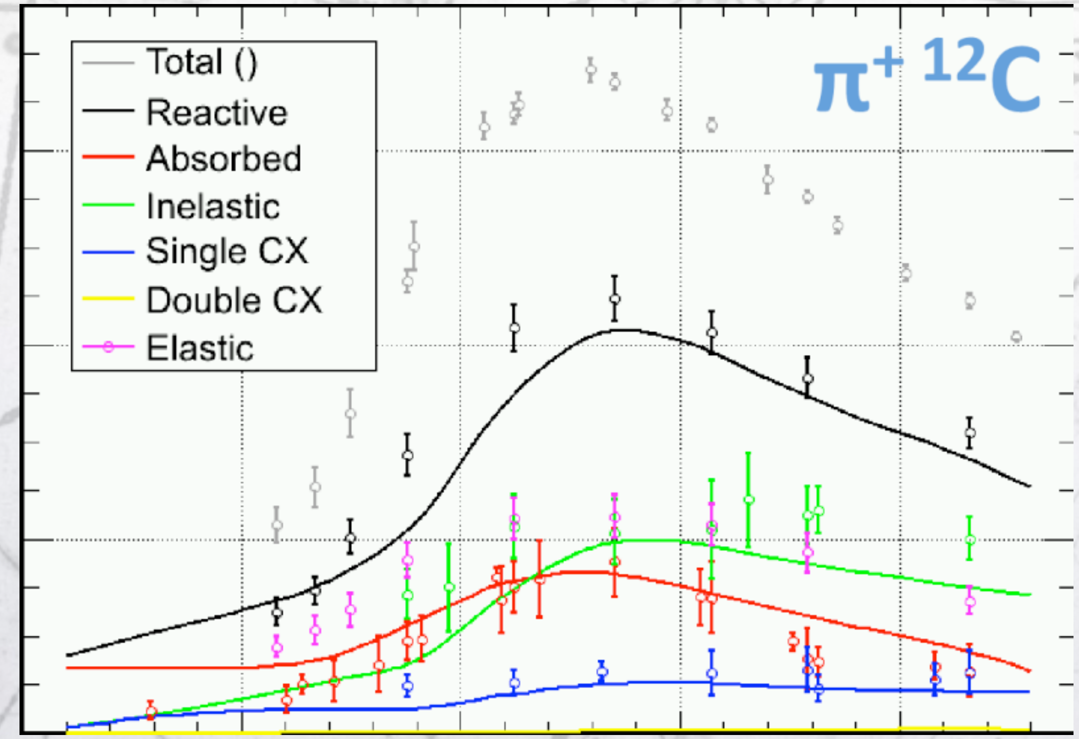


- Complex region with contributions from high mass Δ resonances and low ω DIS. Mixture of models from Pythia to add-hoc pion production.
- There is no new data since ANL and BNL back to the 80's.
- No data in nuclei: difficult measurement due to FSI.
- No detailed pion kinematics available.
- Critical for Dune!.

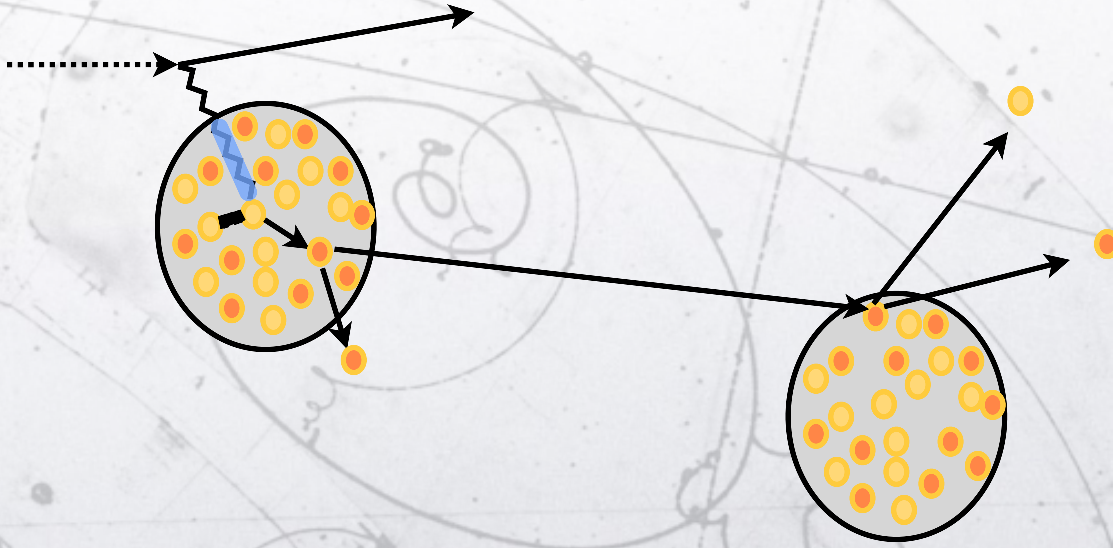
No data for NC potential background

Secondary interactions

- Interactions outside ther nucleus are also critical:
  - Hadronic particles leaving the nucleus are affected by hadronic interactions similar to the FSI.
  - Those cross-sections are not well known for low energy (< GeV) pions and nucleons.
  - Data is even more sparse in Argon.



➜ Test beams like the ones at the CERN neutrino platform.

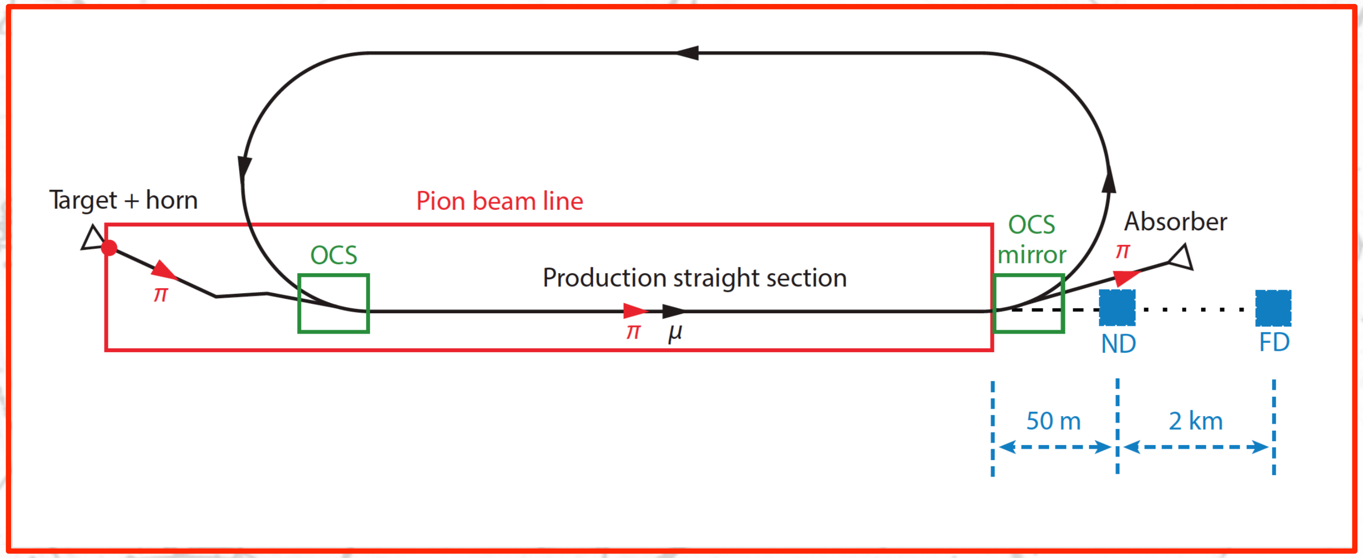


How to ?

- Near detectors perform most of the cross-section studies.
- This does not be to be ideal since many parameters are static:
  - target nuclei
  - flux
- How to address the problem ?

- New experiments ? : NuStorm, dedicated cross-section experiments…
- New detectors with low detection threshold: modern bubble chambers.
- New ideas? : electron scattering, NuPrism, …
- We are accumulating a lot of data but we struggle with THEORY !

NuStorm

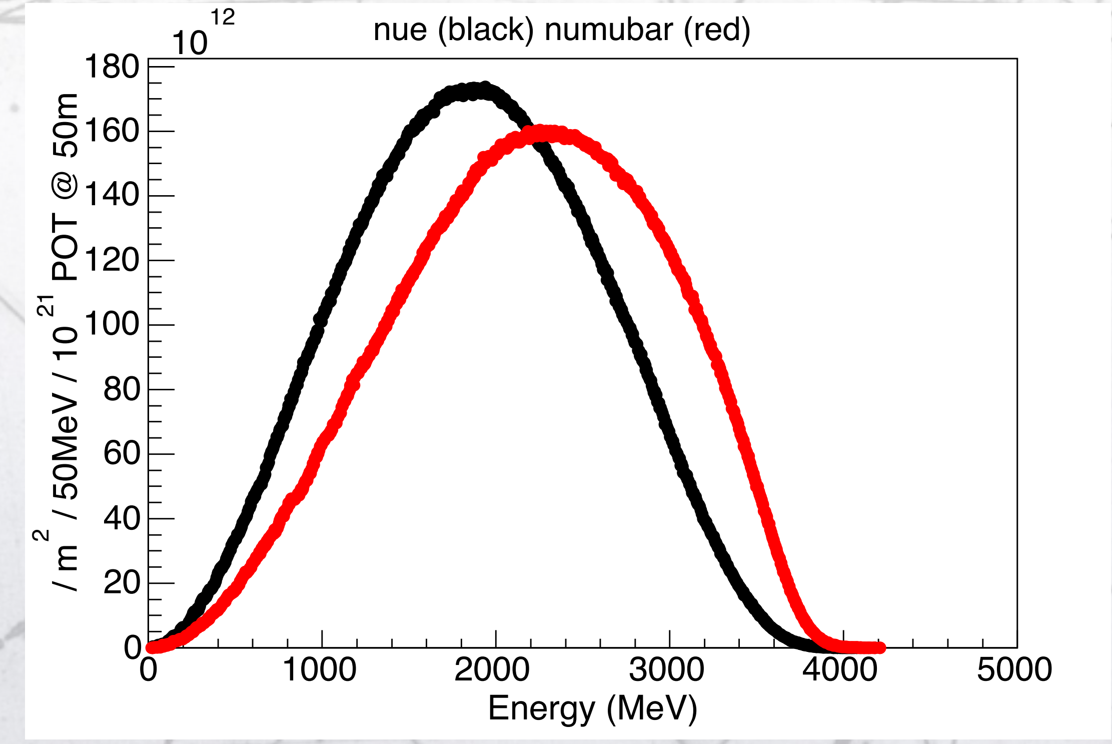


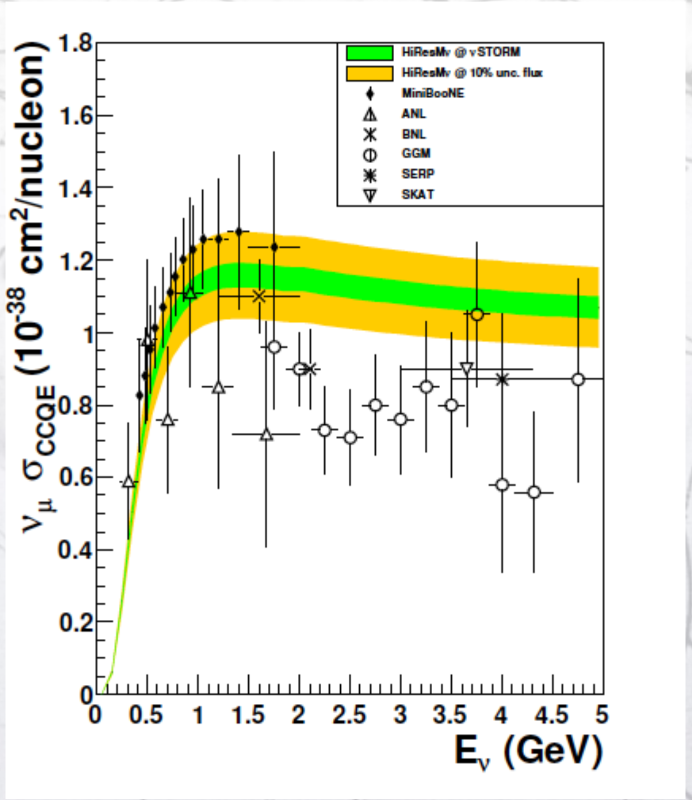
- A ~4GeV muon storage ring NuStorm is probably the best facility to study cross-sections.
- The number of events is sufficient with a 100 Ton LiqAr @ 50 m.

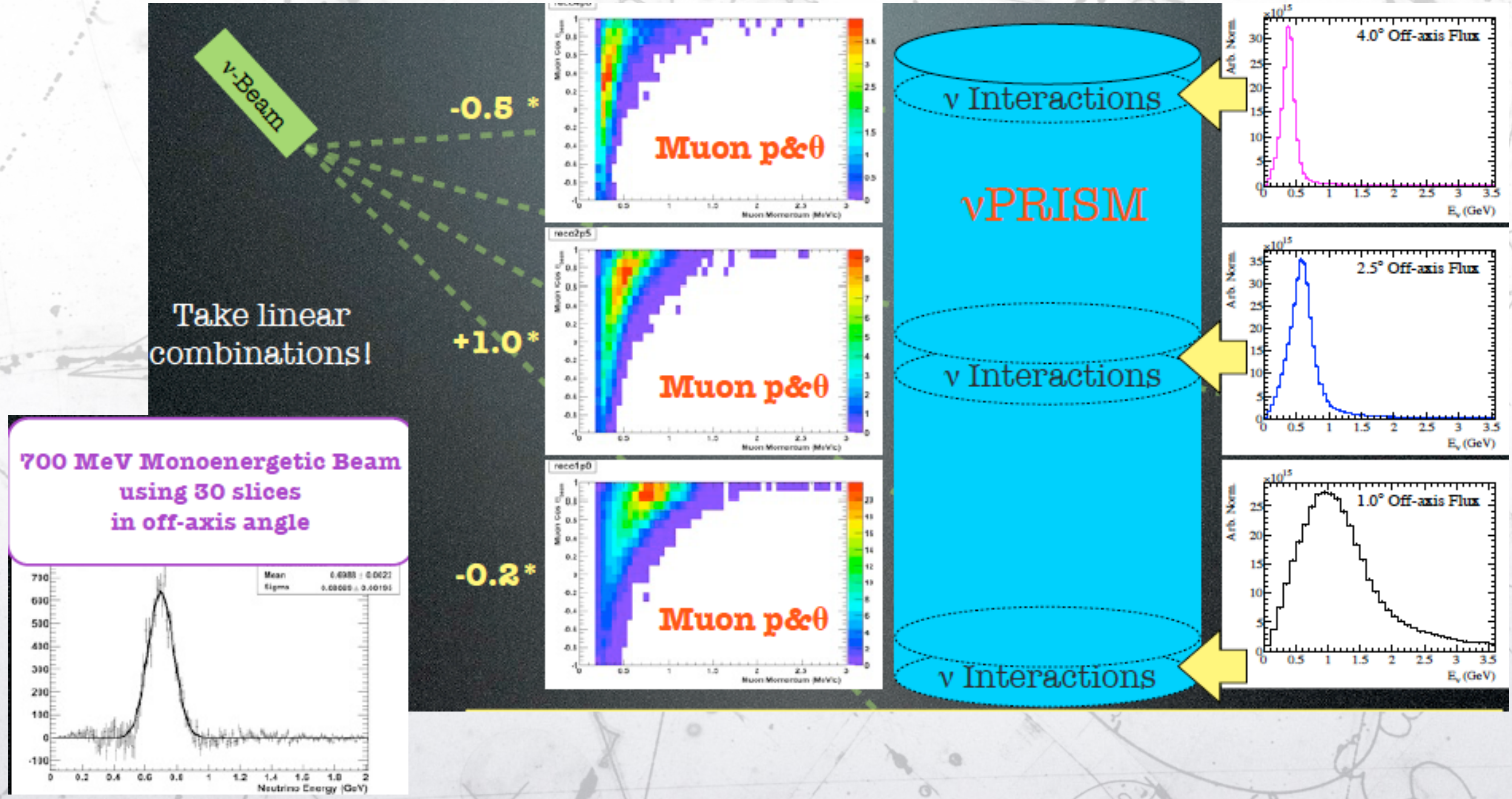
μ^+ Channel	N_{evts}	μ^- Channel	N_{evts}
$\overline{\nu}_\mu$ NC	1,174,710	$\overline{\nu}_e$ NC	1,002,240
ν_e NC	1,817,810	ν_μ NC	2,074,930
$\overline{\nu}_\mu$ CC	3,030,510	$\overline{\nu}_e$ CC	2,519,840
ν_e CC	5,188,050	$\overline{\nu}_\mu$ CC	6,060,580
π^+ Channel	N_{evts}	π^- Channel	N_{evts}
ν_μ NC	14,384,192	$\overline{\nu}_\mu$ NC	6,986,343
ν_μ CC	41,053,300	$\overline{\nu}_\mu$ CC	19,939,704

NuStorm

- NuStorm has two main potential contributions to neutrino-nucleus scattering:
  - large ν_e fraction even below 1 GeV.
  - Precise flux prediction for precise ν_μ cross-section.
- NuStorm can provide the equivalent errors in ν_e and ν_μ cross-sections.



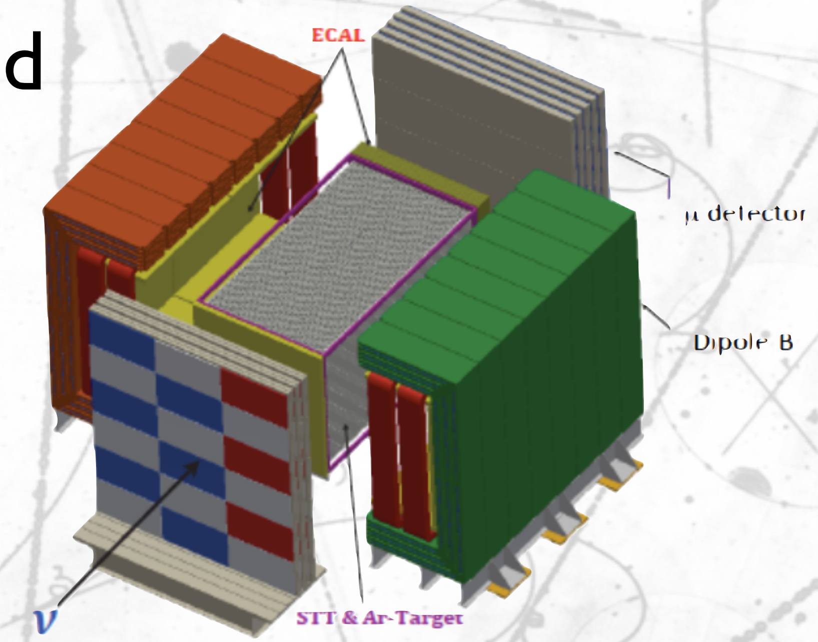


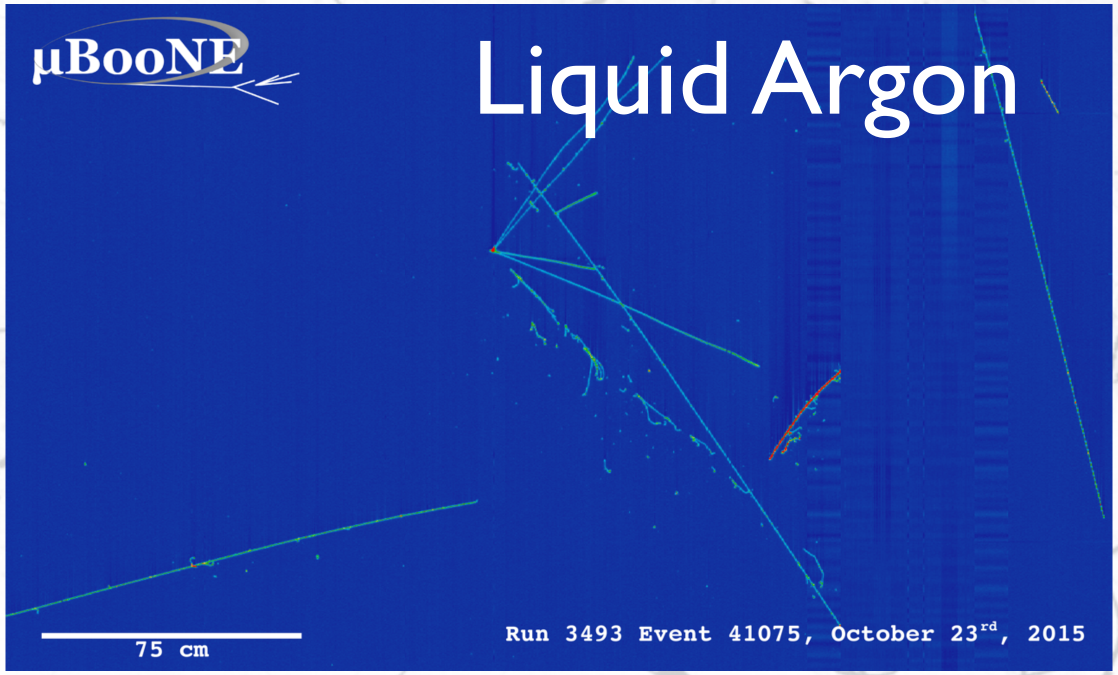


ν-Beam
-0.5 *
+1.0 *
-0.2 *
Take linear combinations!
Muon p&θ
Muon p&θ
Muon p&θ
ν Interactions
νPRISM
ν Interactions
ν Interactions
4.0° Off-axis Flux
2.5° Off-axis Flux
1.0° Off-axis Flux
700 MeV Monoenergetic Beam using 30 slices in off-axis angle
Neutrino Energy (GeV)

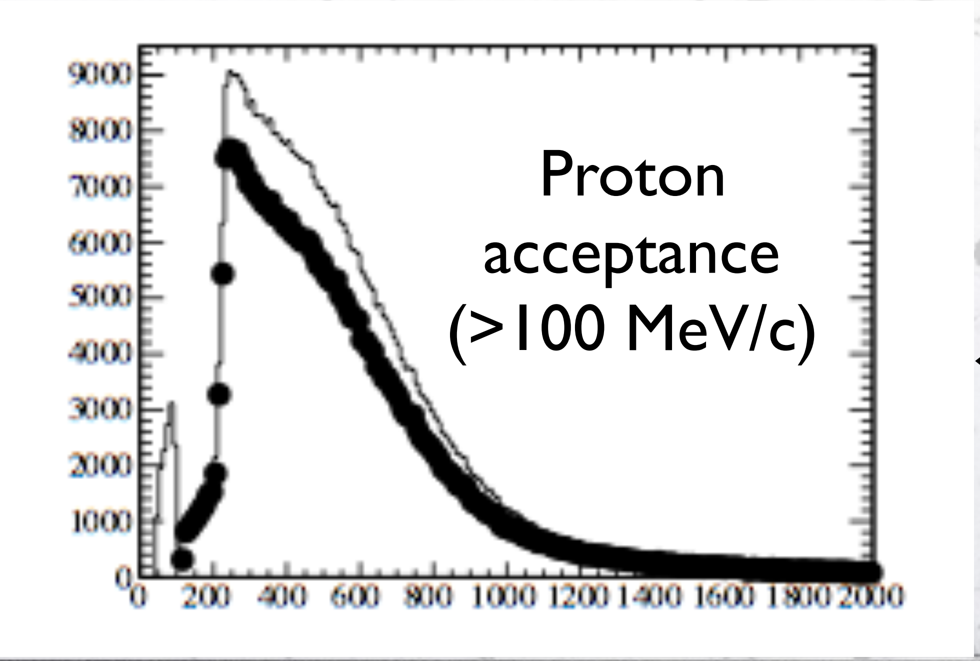
New detectors

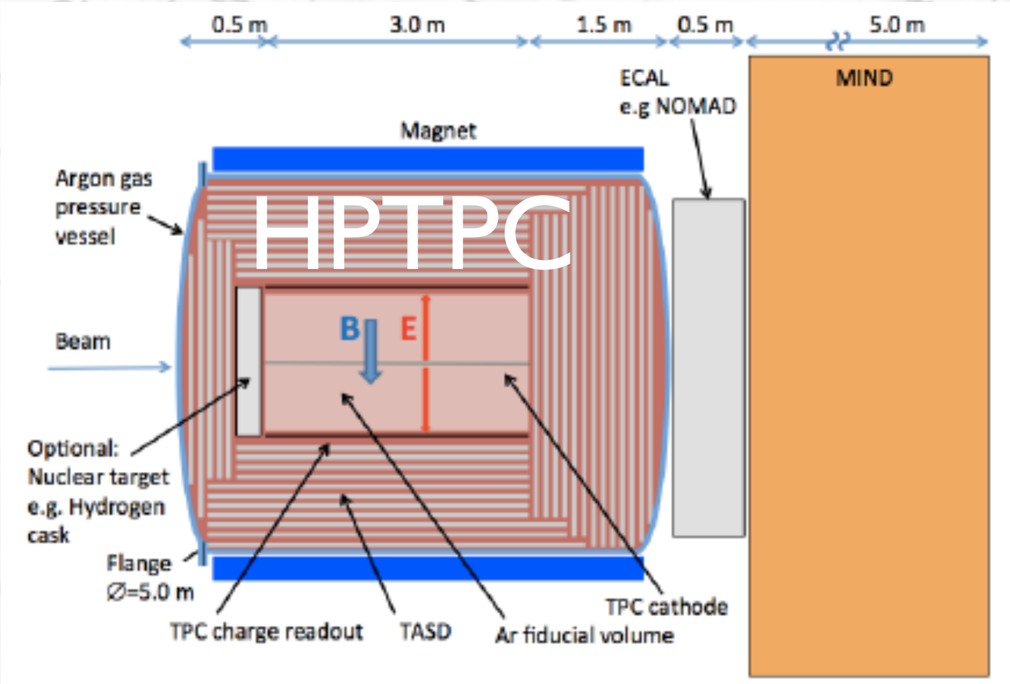
Segmented tracker





Highly segmented low density detectors





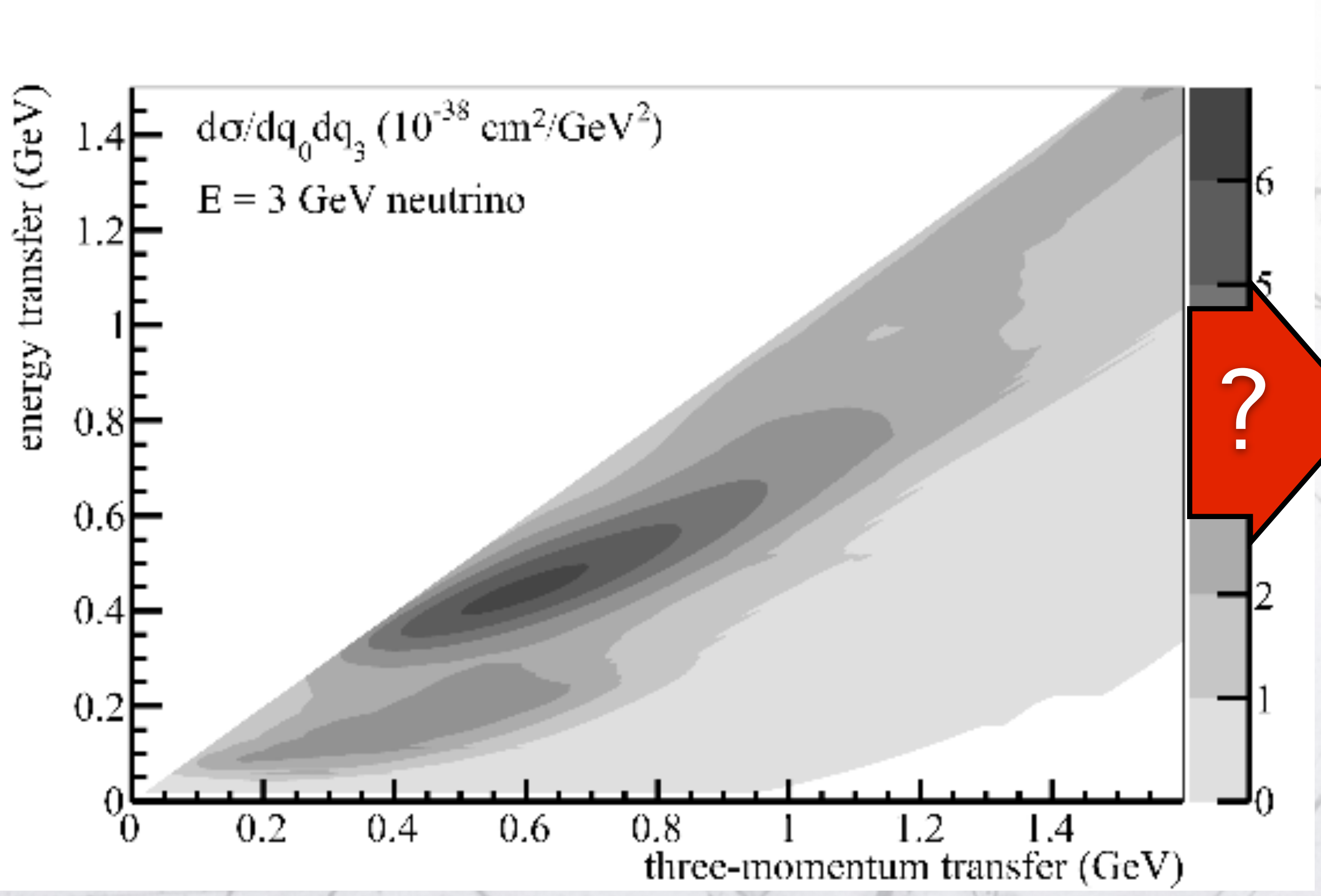
Theory

- One of the key point is the lack of a consistent theory able to describe all interactions at several nuclei and over a large range of energies (0.5 to 10 GeV).
  - This is a tough region with many transitions from non-relativistic to relativistic nuclear descriptions.
- Very little number of theorists around the world. This is normally not the main focus of their research.
- Some phenomenology activity to extract sensitive variables based on transverse observables.

We can't advance without the help of the theory.

Limits of models

- The main problem with 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 experiment energy range.



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

?

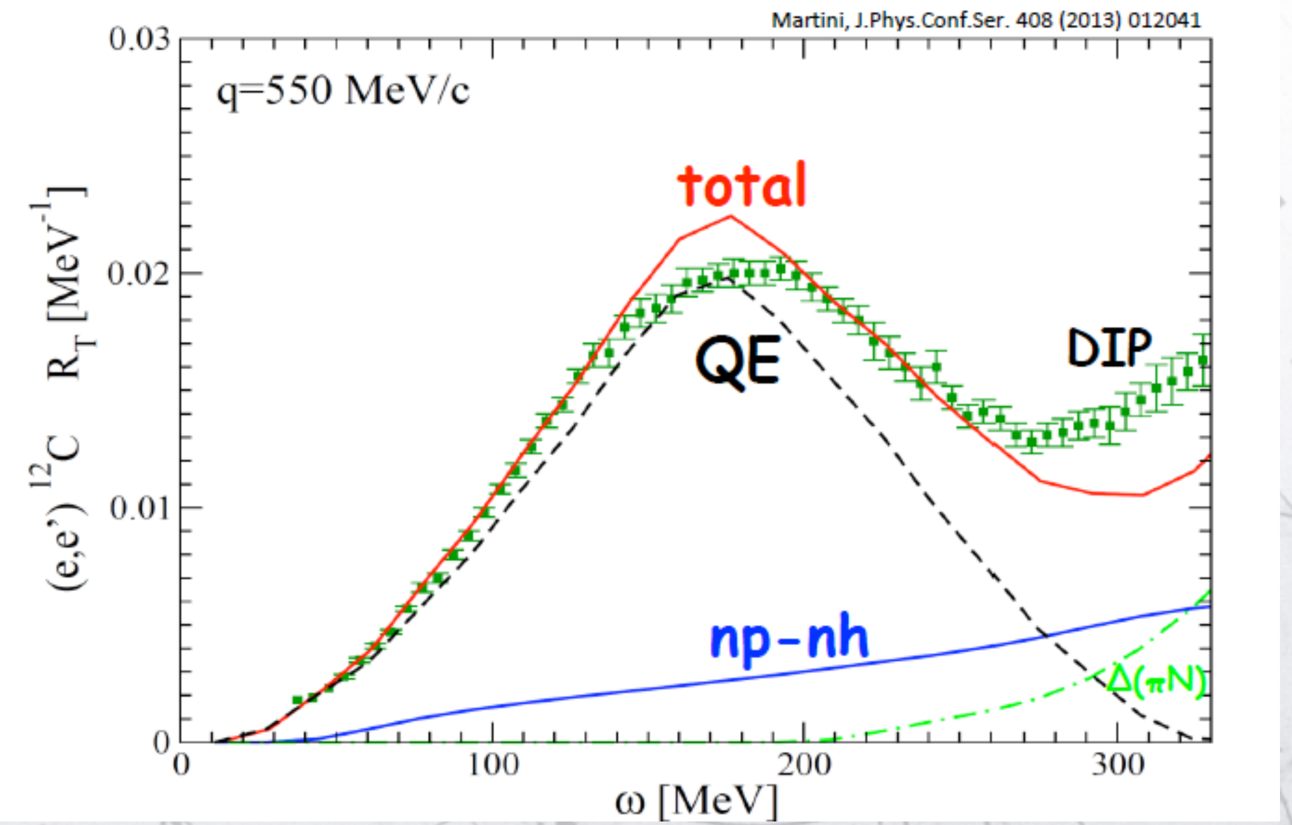
Proposed to use the momentum transfer to the nucleus as a reference cut and not neutrino energy.

Theorists are needed!

Electron Scattering

- Many of the theories can be checked on electron scattering data.
  - Effort started to produce interaction MC able to predict electron data.
- Some times the electron scattering experiments do not cover the "uninteresting" kinematical region of neutrino experiments.
- Most electron scattering experiments ignore the hadron production that is critical for neutrinos.

New and existing electron scattering data is a must to improve our knowledge and systematic control of the neutrino-nucleus interaction models.



As conclusions

- Cross-section knowledge is one of the critical items for future oscillation experiments:
    - Nuclear effects make predictions very delicate.
    - Broad beams and coarse resolution experiments make experiments difficult.
- Several experiments show the weakness of the model but it is not obvious they will provide the level of precision required by future experiments.

As conclusions

- Near Detectors might not be the best place to develop a complete and exhaustive cross-section program.
  - fixed ν flux and target nuclei.
  - minimal ν_e sample.
- Development of a parallel program to address x-section problem is mandatory:
  - theory, mainly nuclear physics component.
  - neutrino scattering experiments. (JPARC, FNAL, NuStorm?)
  - electron scattering experiments.
  - pion/proton scattering experiments.

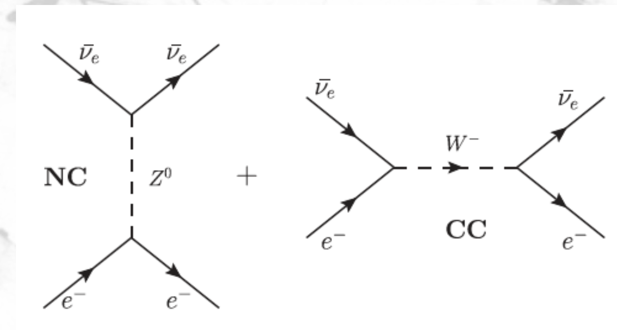

ONLY THOSE WHO SEE THE INVISIBLE
CAN DO THE IMPOSSIBLE
MAMALLAPURAM SPECIAL GRADE TOWN PANCHAYAT

Backup slides

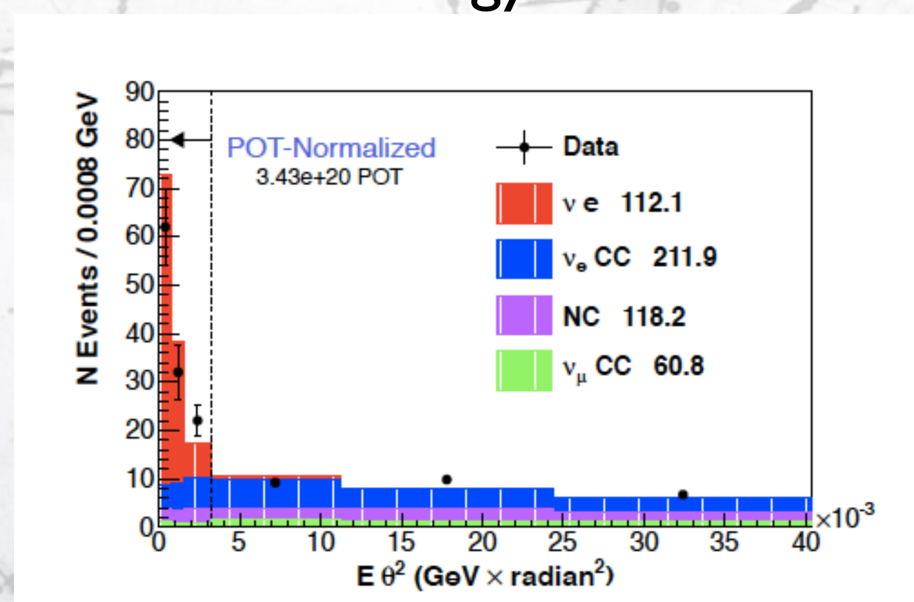
Neutrino flux

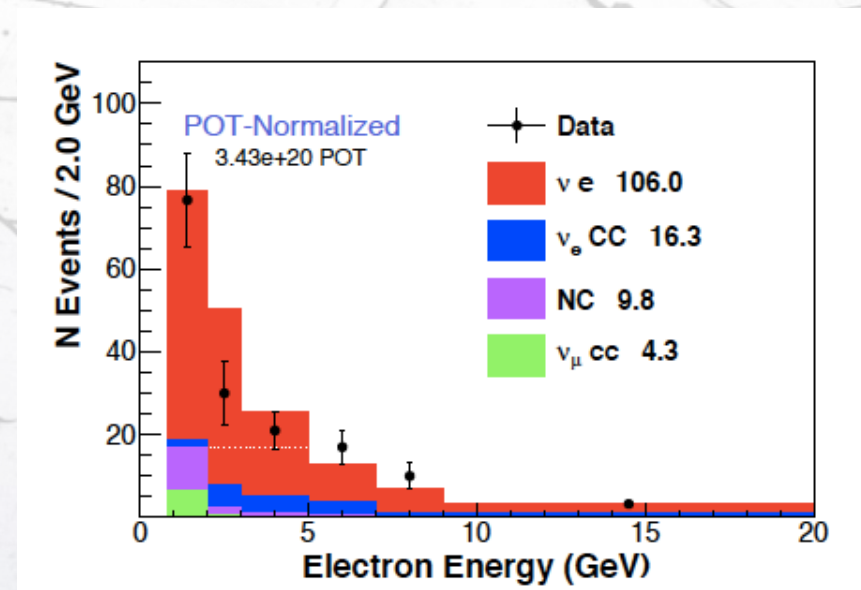
- Constrain the flux using the neutrino-electron scattering:
  - $\overset{(-)}{\nu}_\mu e^- \rightarrow \overset{(-)}{\nu}_\mu e^-$
  - The cross-section is well known:

$$\left[\frac{d\sigma}{dT}(\overset{(-)}{\nu}_\mu e)\right]_{SM} = \frac{G_F^2 m_e}{2\pi}\cdot\left[(g_V \pm g_A)^2 + (g_V \mp g_A)^2 \times \left(1-\frac{T}{E_\nu}\right)^2 - (g_V^2 - g_A^2)\frac{m_e T}{E_\nu^2}\right],$$



- The electron energy can constrain both absolute flux and the energy dependency.





It requires large mass and good discrimination against ν_e backgrounds

No direct distinction between neutrinos and antineutrinos.

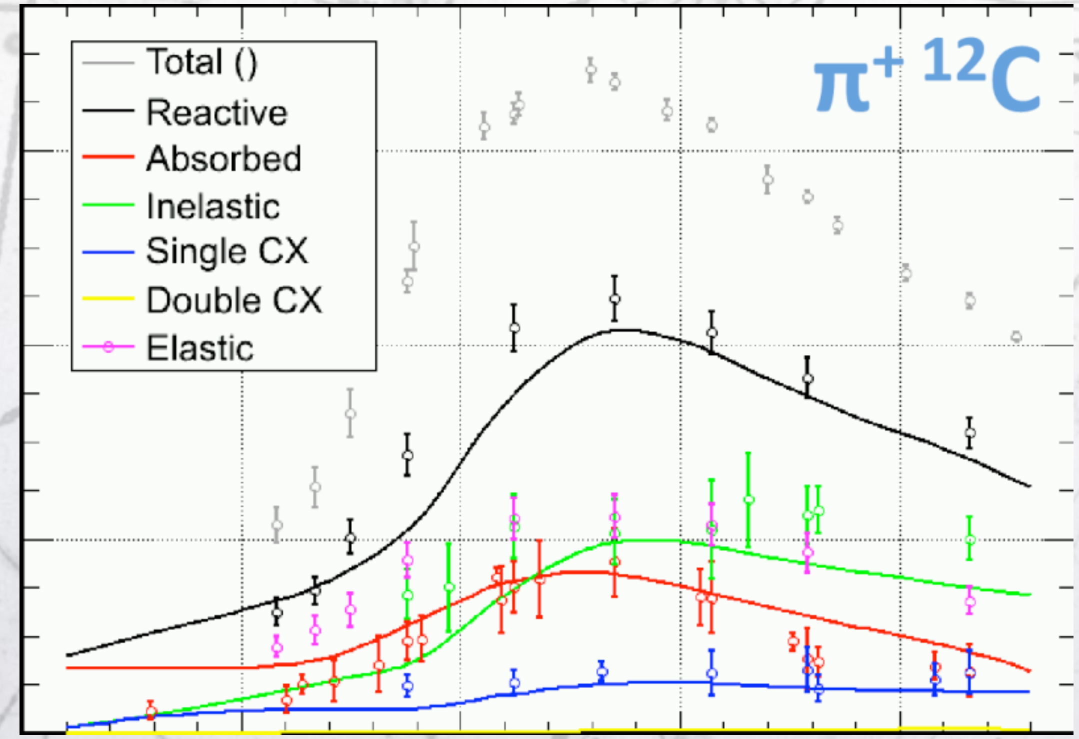
ND for oscillations

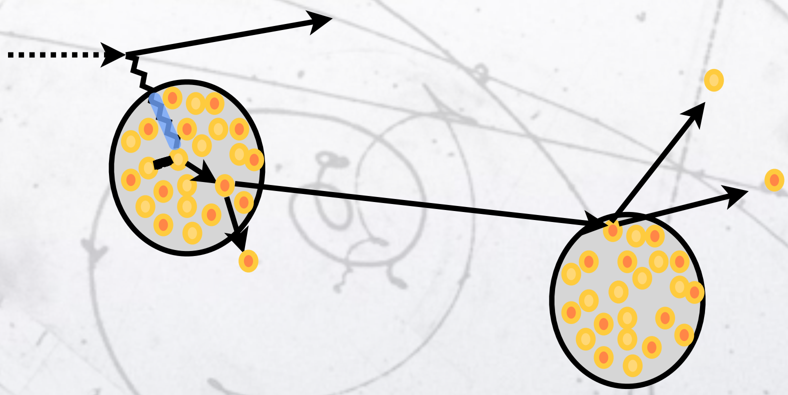
- Obviously, we can't make the ND the same size as the far detector:
  - The hermeticity of the detector will be different for neutrons electrons and gammas.
    - Low energy gamma's from π^0 critical!
  - The momentum of long range particles need to be estimated in different ways:
    - FD: range for muons/pions and energy for electromagnetic energy.
    - ND: range/curvature/energy depending on the particle and the range.
- This will affect the reconstruction criteria and energy reconstruction depending in hadronic secondary interactions.

ND for oscillations

- Secondary interactions are also critical:
  - Hadronic particles leaving the nucleus are affected by hadronic interactions similar to the FSI.
  - Those cross-sections are not well known for low energy (< GeV) pions and nucleons.
  - Data is even more sparse in Argon.

→ ProtoDune





ND for oscillations

- The nuclear target alters the cross-section:
  - Number of nuclei (~A)
  - Fermi momentum change probabilities close to reaction thresholds.
  - Pauli blocking inhibits interactions.
  - Final State Interactions does not have a simple dependency with A.

Model dependent

It is recommended that near and far detector are made of the same nuclei.

Difficult for water (T2K/HK) easy for argon (DUNE)

ND for oscillations

- If ($Acc_{FD} \subseteq Acc_{ND}$), the acceptance is not a problem.
- If ($Acc_{FD} \supseteq Acc_{ND}$), there are two potential issues:
  - The total cross-section extrapolation from the accepted events in the near detector to the far detector is model dependent.
    - And models are poor!!!!
  - For the same topologies, P(E|E´) might depend on the event properties:
    - Large vs small hadronic energy (E_{had})
    - …

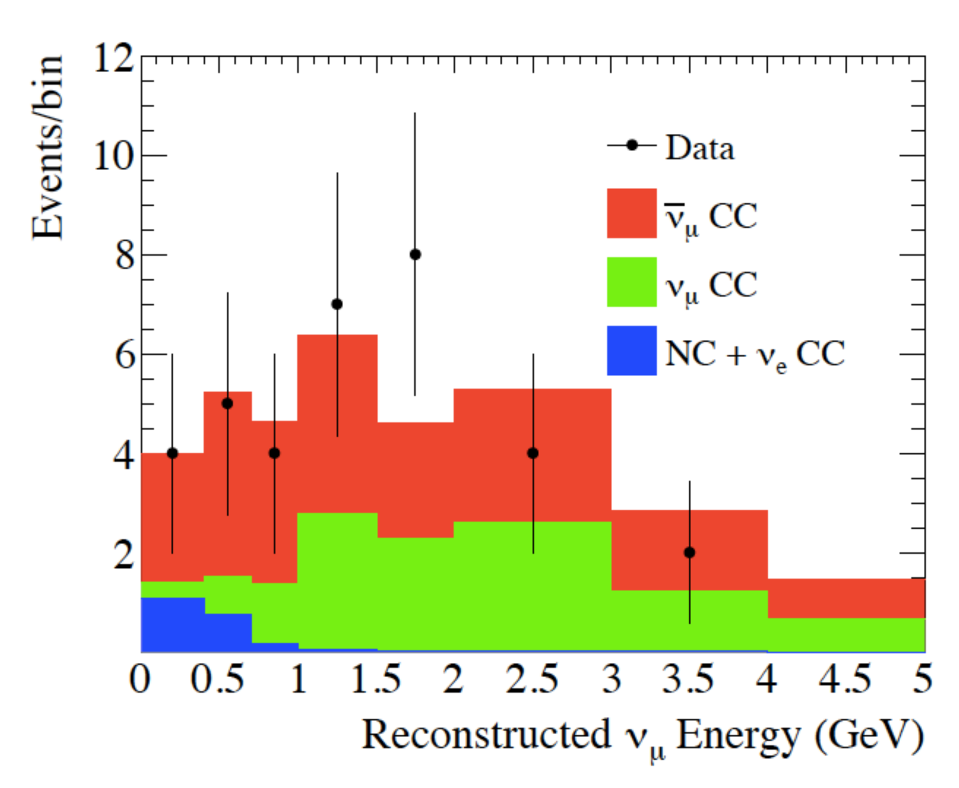
ND for oscillations

- The ν_e appearance has two additional issues:
  - Near $\Phi(E_\nu)x\sigma(E_\nu)$ is computed for ν_μ but far detector is for ν_e. This implies that we need to compute or model:
    - $\sigma_e(E_\nu)/\sigma_\mu(E_\nu)$ for neutrinos and anti-neutrinos.
    - Additional model of $P(E_\nu|E'_\nu)$ and energy scale.
    - Control the π^0 background in the electron sample.
  - There is also the intrinsic beam ν_e background to be constrained.

Excellent $e/\mu/\pi^0$ separation.
Large statistics: masive near detector / large flux !
Enhanced electron sample (off-axis ?)

ND for oscillations

- CP violation also requires the separation of neutrinos and antineutrinos.
  - neutrino beam is normally very pure.
  - anti-neutrino beam has large contribution of neutrinos:
    - antineutrino cross-section and production yield is low.
- FD has some capability to distinguish neutrinos from antineutrinos (i.e. neutron production in CCQE).
- ND has to be able to measure the neutrino background in the antineutrino beam → Magnetised detector.



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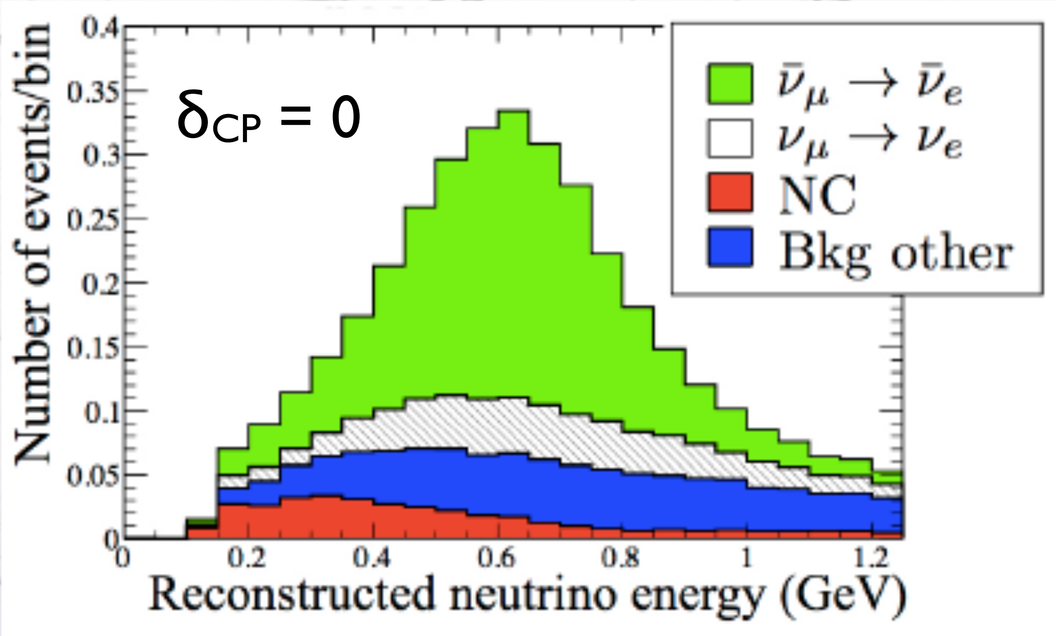
T2K



Cross-section and flux

- Resolving the three components in $\Phi(E_\nu) x \sigma(E_\nu) x\ P(E_\nu|E'_\nu)$ is complex:
  - Need to improve on cross-section models:
    - dedicated experiment?
    - electron scattering?
    - but also strong theoretical support.
  - Have the possibility of change $\Phi(E_\nu)$ in the experiment or with other experiments.
  - Start with an excellent prediction for $\Phi(E_\nu)$ (external pA experiments like Shine)

Physics requirements

- The perfect ND detector has:

Same/better acceptance as far detector

Same/Similar technology

Same nuclear target

Excellent $e/\mu/\pi^0$ discrimination

Large mass

Good control on external backgrounds

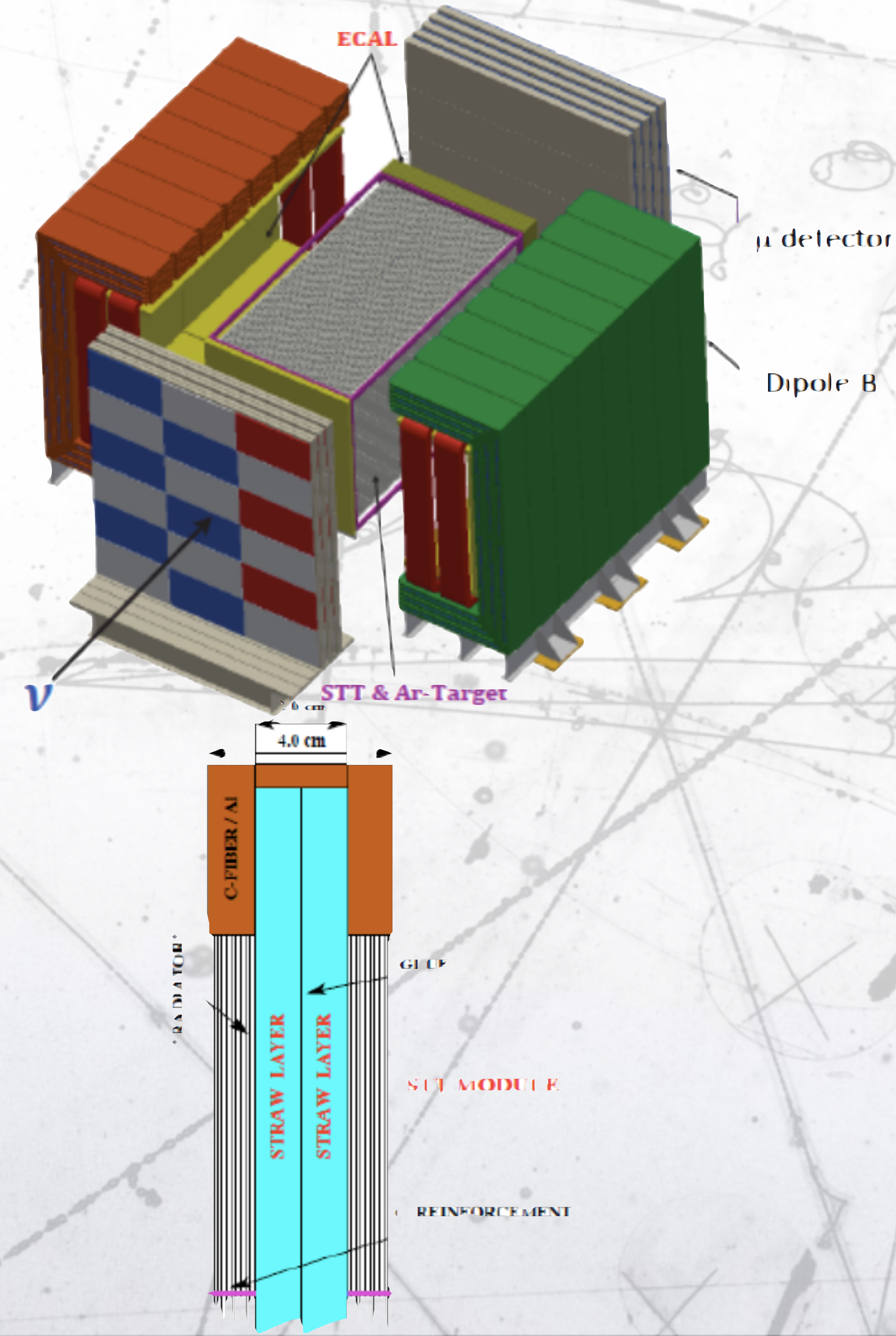
Excellent purity for ν_μ e^- scattering samples

Excellent charge separation for neutrino vs antineutrino

Options

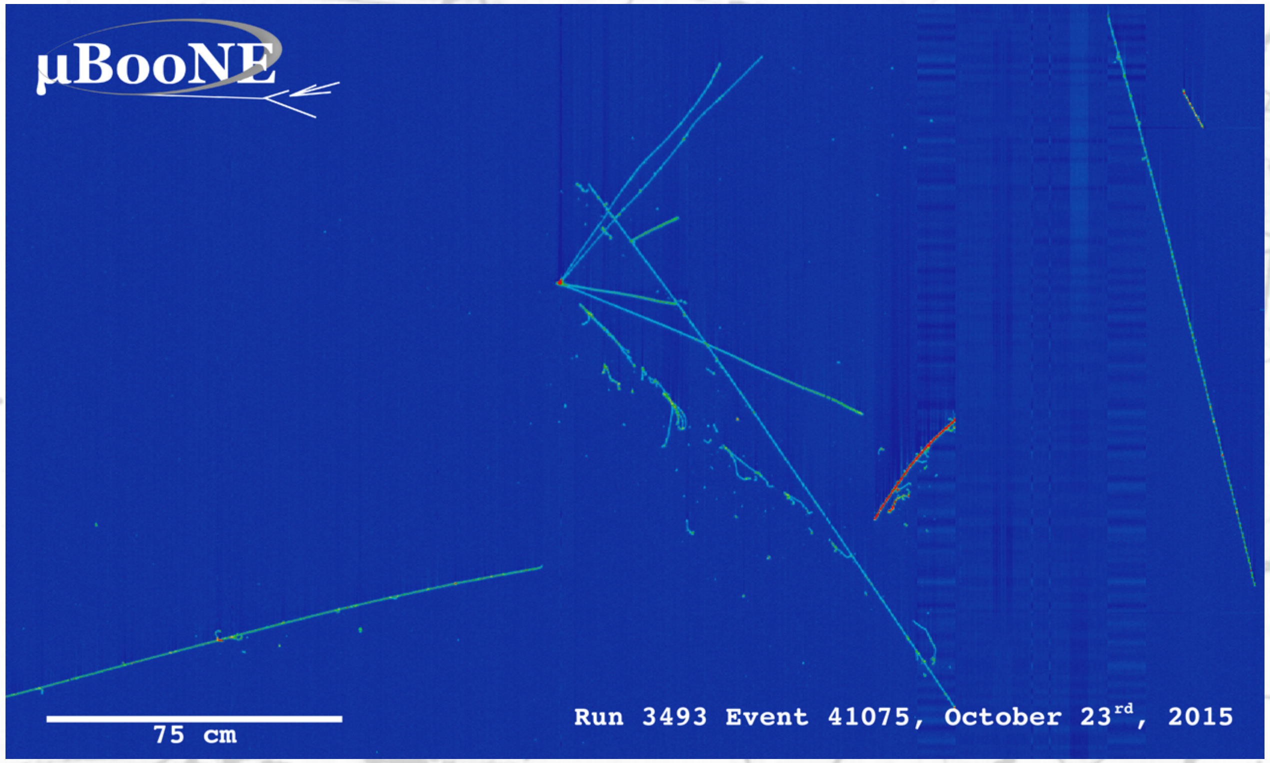
- There are three options for ND:
  - Segmented tracker.
  - LiqAr TPC.
  - HPTPC
- But, there is no reason why there should be only one detector. Neutrino beams are very "democratic".

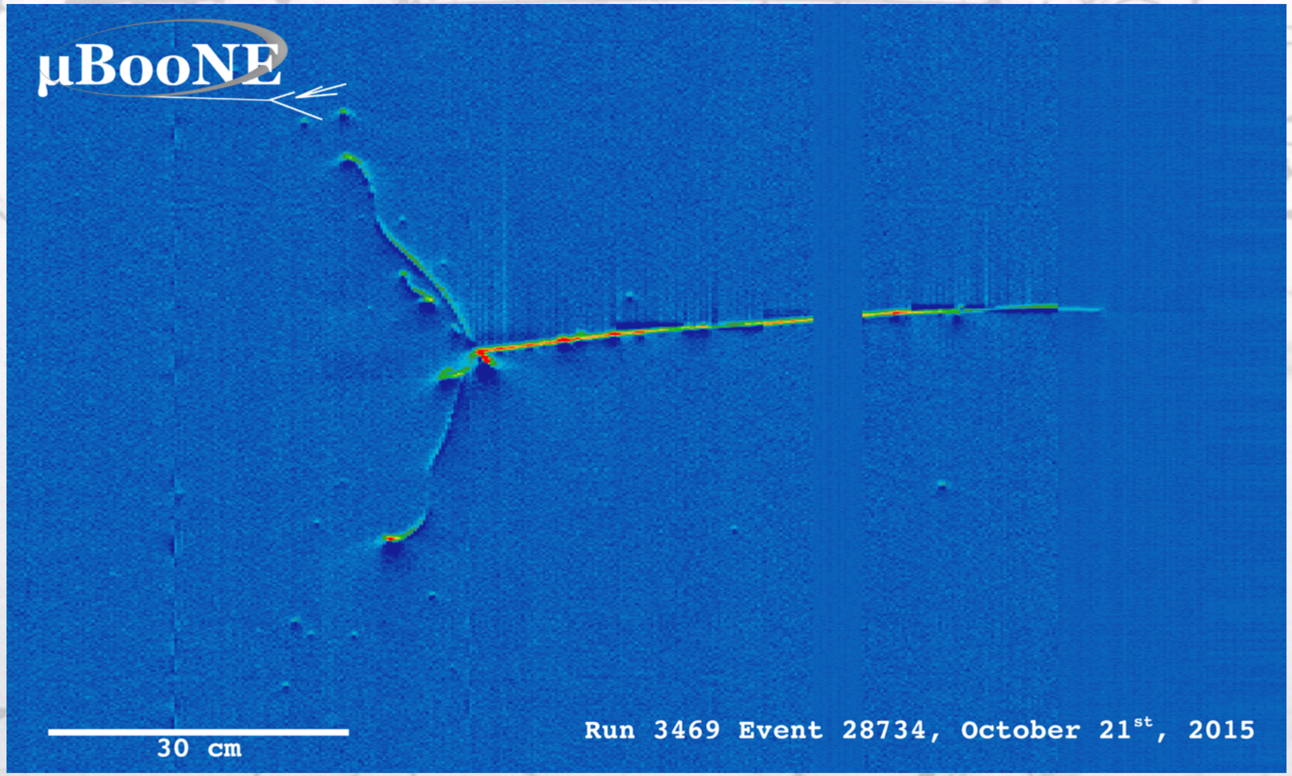
Segmented tracker



- Magnetised (0.4T) high resolution straw tube design “a la” Nomad with plannar geometry.
- Target/Nucleus selection by track vertexing.
- Low density for low E particle detection.
- ECAL gamma catcher and muon range detector.

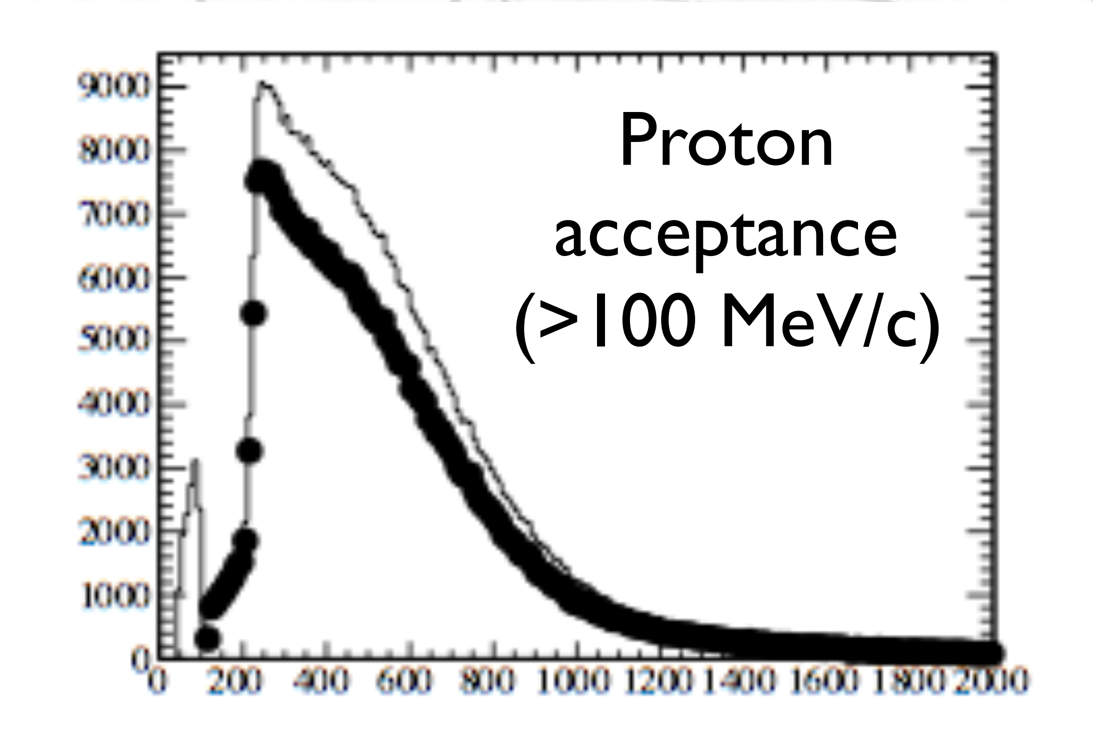
LiqAr TPC

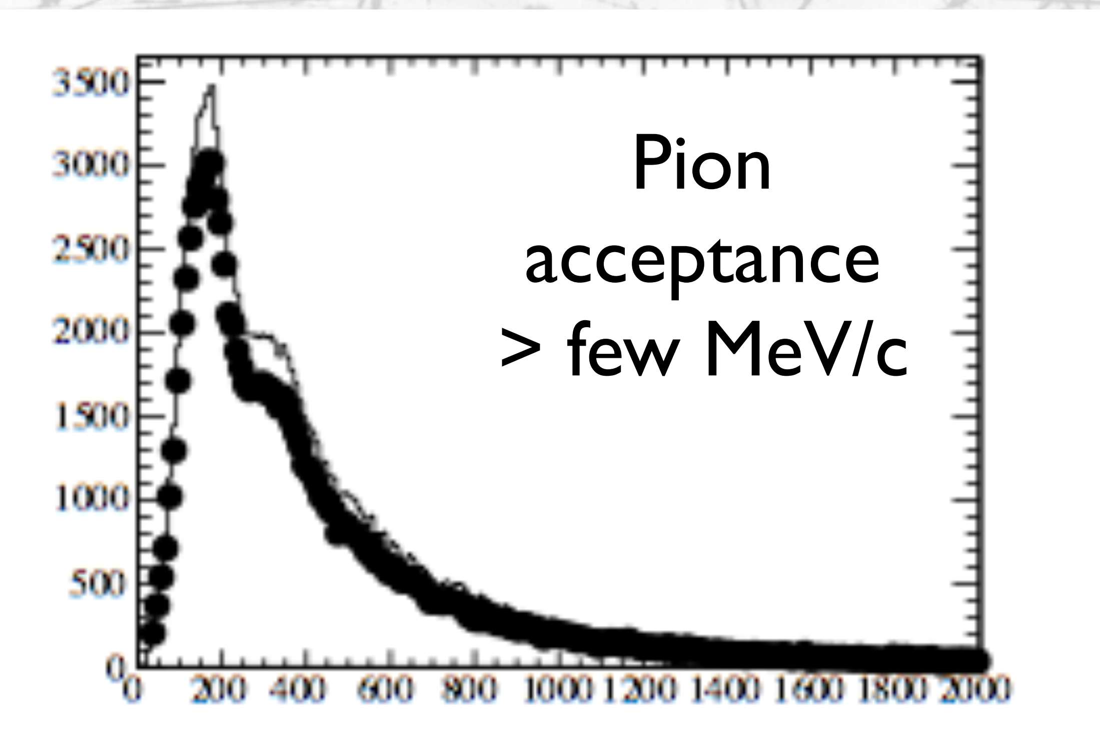




- Magnetised (?) LiqAr detector.
- Same technology as FD.
- Large mass.
- Balance pile-up / range.
- ECAL and muon range.

HPTPC





- Magnetised High Pressure TPC.
- Low mass.
- Very low momentum threshold.
- Same target as far detector / similar technology.
- Inner/Outer mass balance.
- ECAL and muon range.

Conclusions

- The dominant errors in the oscillation analysis depends on the knowledge of the flux and neutrino conclusions.
- ND has a broad program of physics beyond oscillation physics related to neutrino-nucleus cross-sections.
- The ND is the place to reduce these systematics to the minimum:
  - the "battle" of precision will take place at ND if mass and power is available.
- The requirements on the ND design are very stringent.
  - Proper degin of the ND is clue for the success of the DUNE program.

Conclusions

- The language to describe the ND to FD flux extrapolation and analyse the FD data is neutrino interactions. We need to speak it properly not be “lost in translation”.
- It is likely that the ND program needs to be complemented by external experiments (electron scattering, hadroproduction,dedicated cross-sections), test-beams and giving strong support to the nuclear theory community.
- The three proposed options have pros and cons (I did not enter into the discussion) but we need to keep in mind that the right answer might be to have two detectors and not only one.