The DUNE near detector

(reference design, options and scientific goals)

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Outlook

- Near detector for oscillations
  - Cross-sections
  - ν_e & ν_μ fluxes
- Physics requirements
- Options:
  - segmented tracker
  - HPTPC
  - Liquid Argon

ND for oscillations

- 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:

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

The 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, 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 $\Phi(E_\nu)$, $\sigma(E_\nu)$ & $P(E_\nu|E'_\nu)$

The oscillations

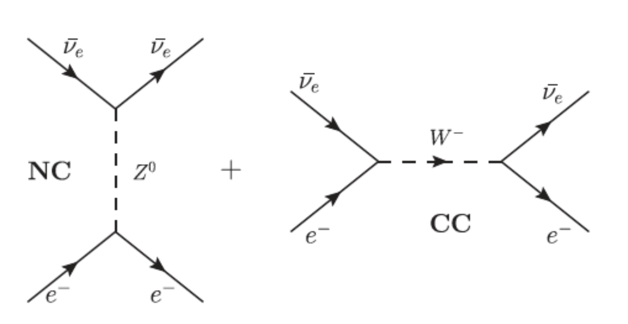
- Far detector also have several sources of backgrounds:
  - wrong sign backgrounds (neutrinos vs. antineutrinos).
  - NC interactions populating low energy bins.
- We need to control both backgrounds using a near detector.

ND for oscillations

- The only tool we have to calibrate all these parameters is with a near detector using neutrino interactions.
  - Cross-sections are the key to this problem.
  - But, also the source of most of our problems.
- Other alternatives are possible to complement the measurement (ν e^- scattering).

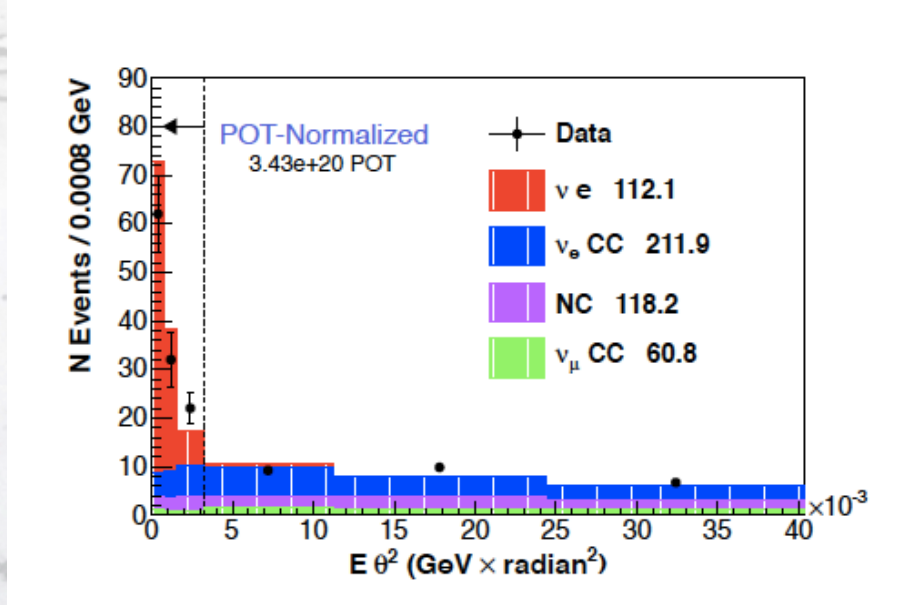
Cross-section and flux

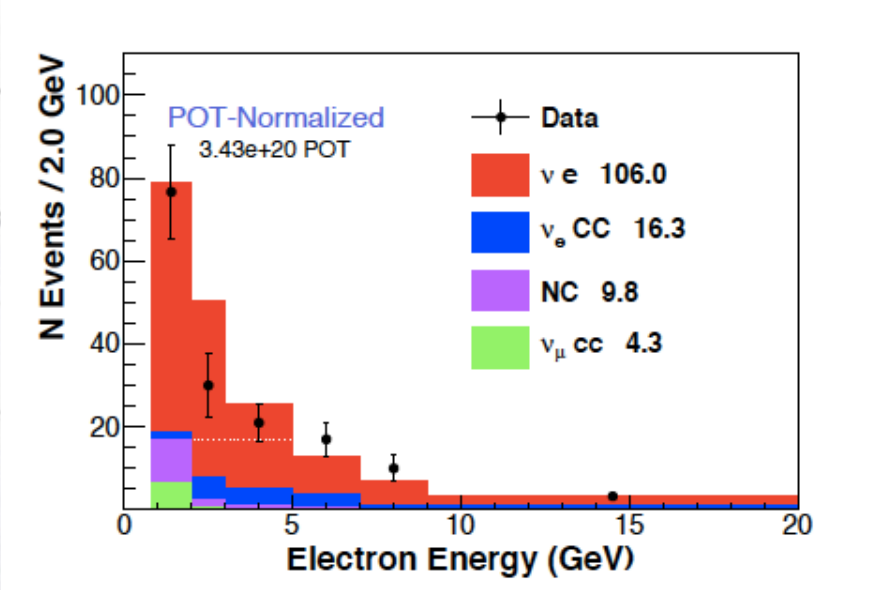
- Constrain the flux using the neutrino-electron scattering:
  - $\overset{(-)}{\nu}_\mu e^- \rightarrow \overset{(-)}{\nu}_\mu e^-$
  - The cross-section is well known:



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

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



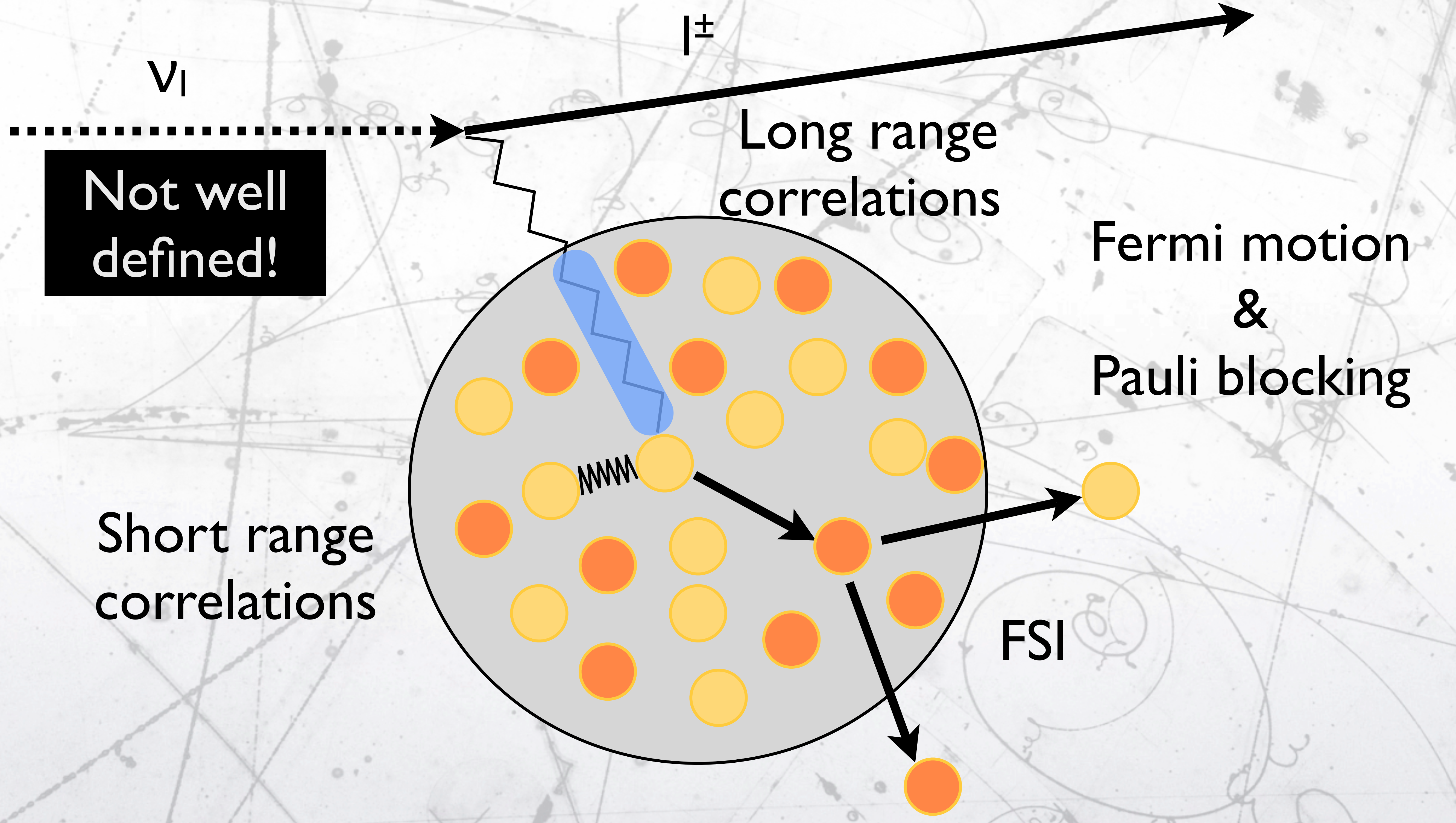


arXiv:1512.07699v2

It requires large mass and good discrimination against ν_e backgrounds

No direct distinction between neutrinos and antineutrinos.

Neutrino interactions



Neutrino interactions

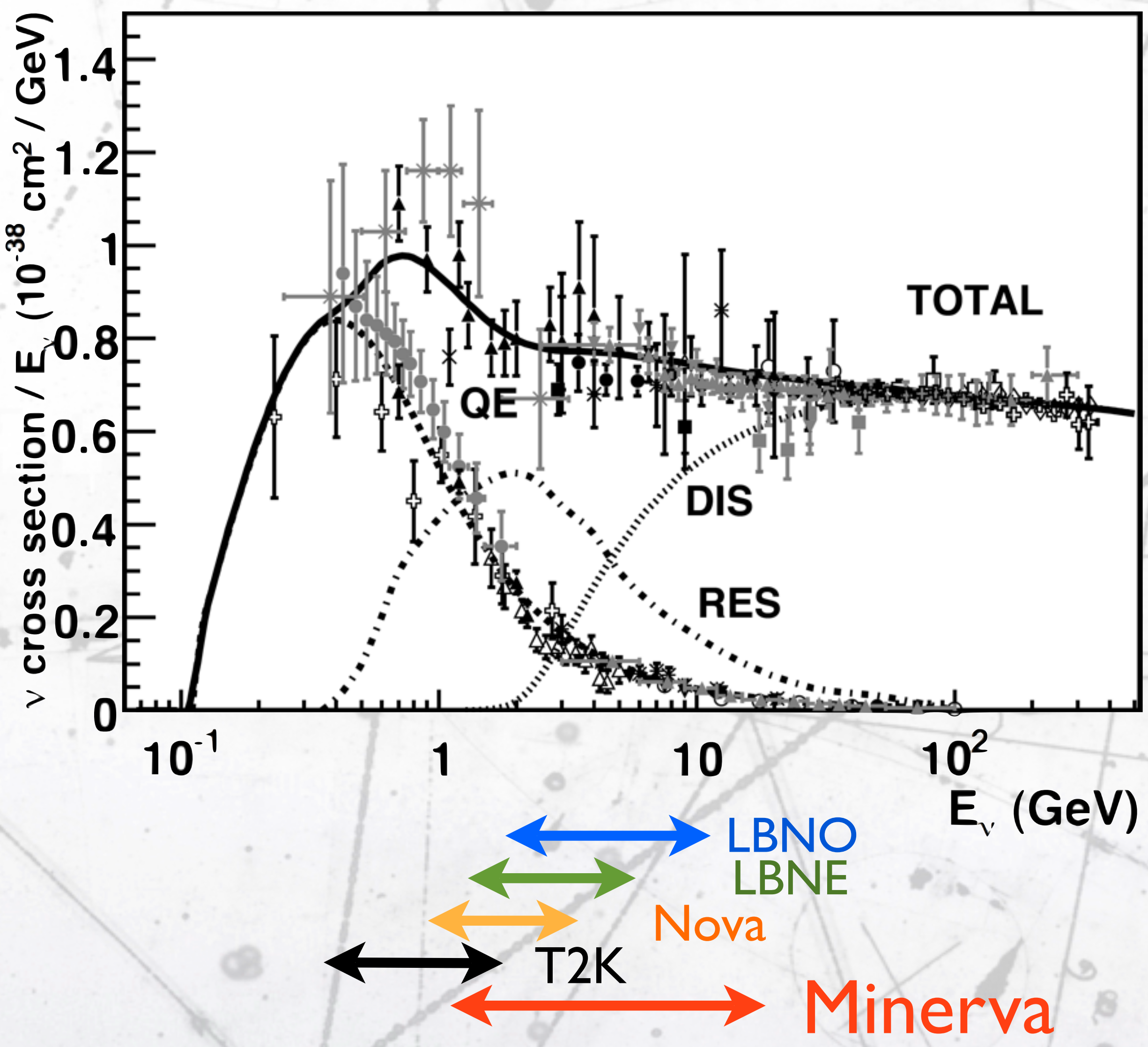
at the nucleon level !

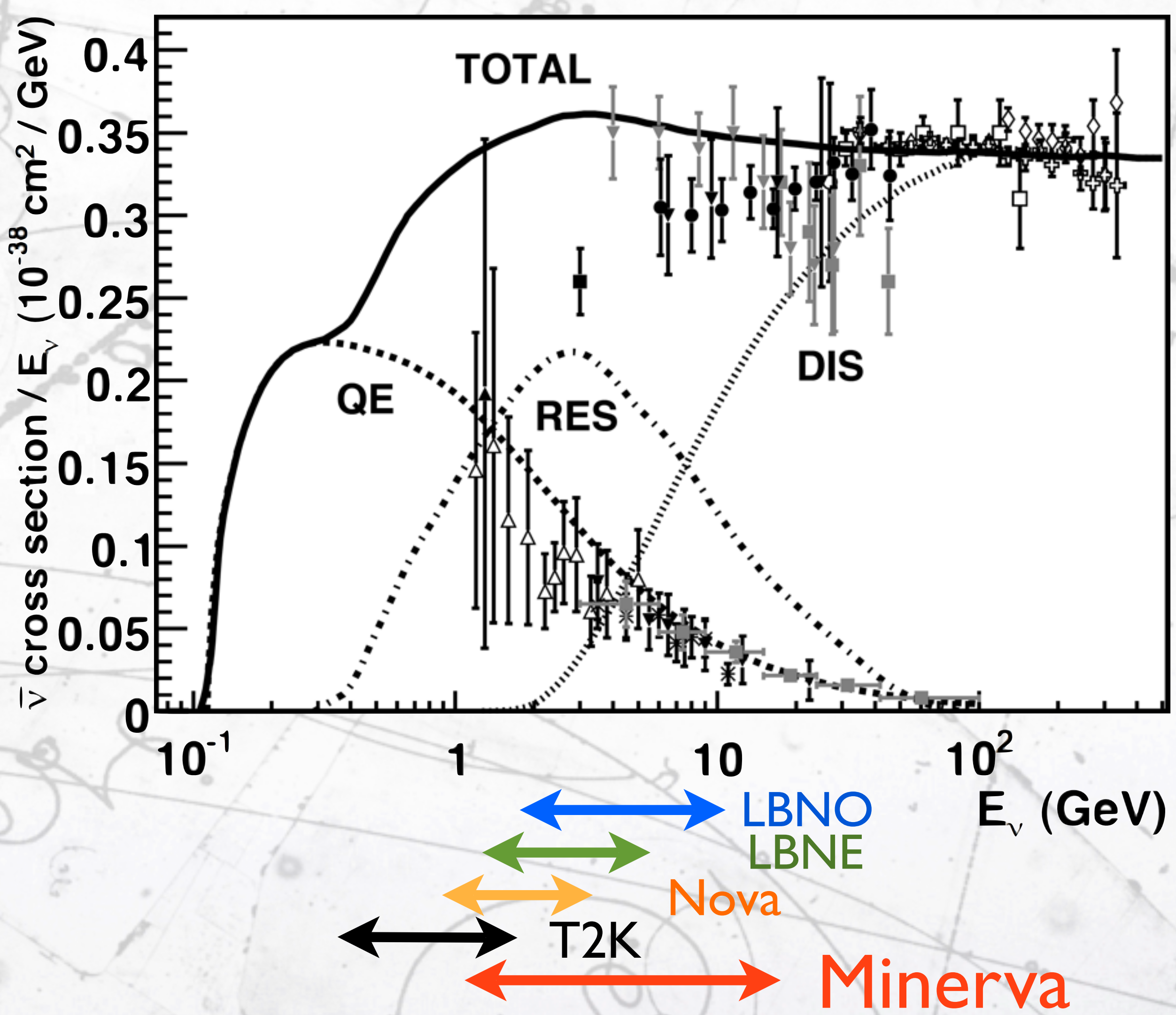
$CCQE$	$\nu_\mu n \rightarrow \mu^- p$
$CC1\pi$	$\nu_\mu p \rightarrow \mu^- \Delta^{++} \rightarrow \mu^- \pi^+ p$ $\nu_\mu n \rightarrow \mu^- \Delta^{+} \rightarrow \mu^- \pi^+ n$ $\nu_\mu n \rightarrow \mu^- \Delta^{+} \rightarrow \mu^- \pi^0 p$
$CCN\pi$	$\nu_\mu N \rightarrow \mu^- \Delta^{+,++}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

FSI adds/removes π and nucleons mixing the interaction channels

The xsec problem

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





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

ND for oscillations

How to measure the neutrino energy ?

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

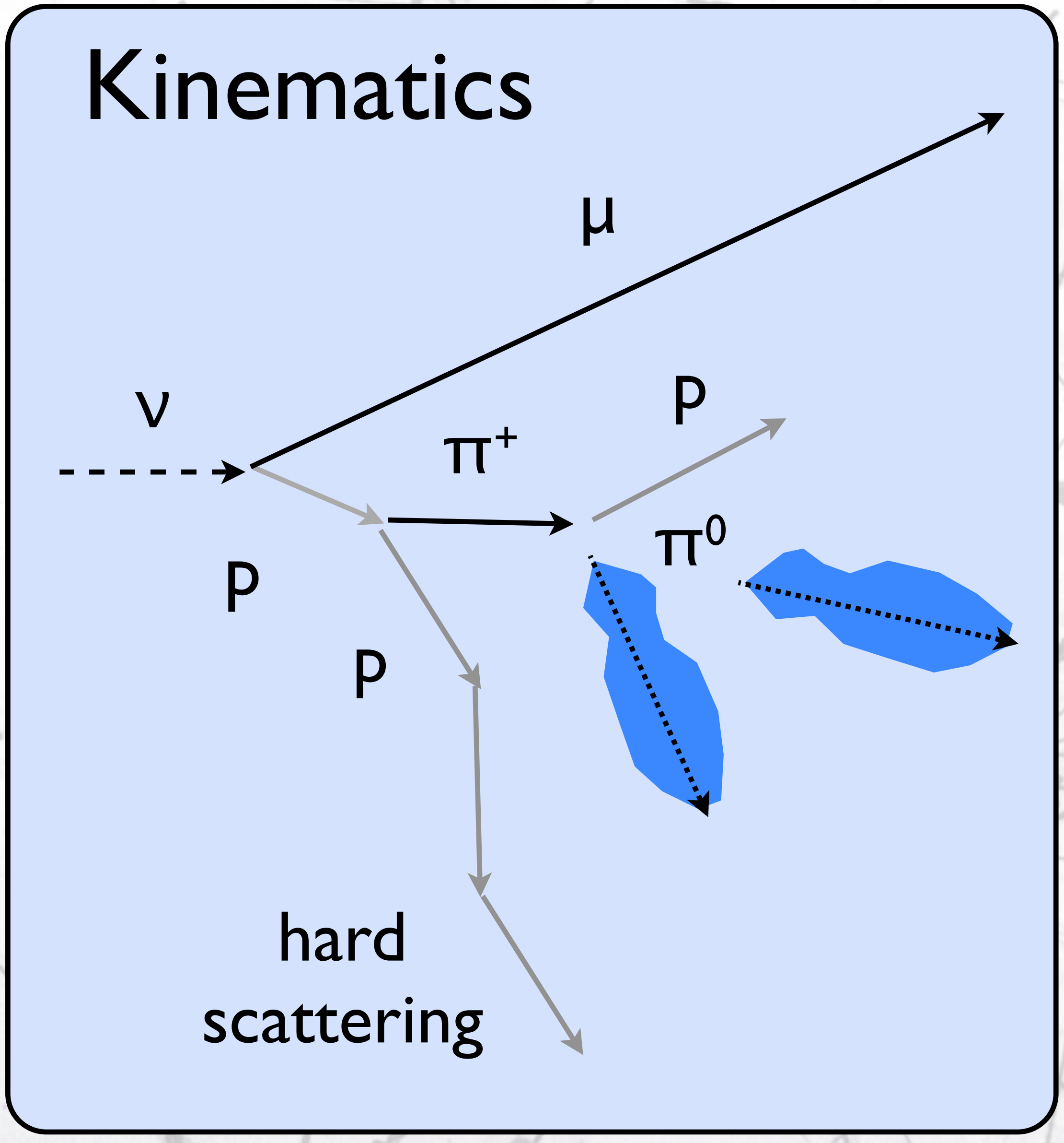
Low Energy ν's (≲2GeV)

- 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.

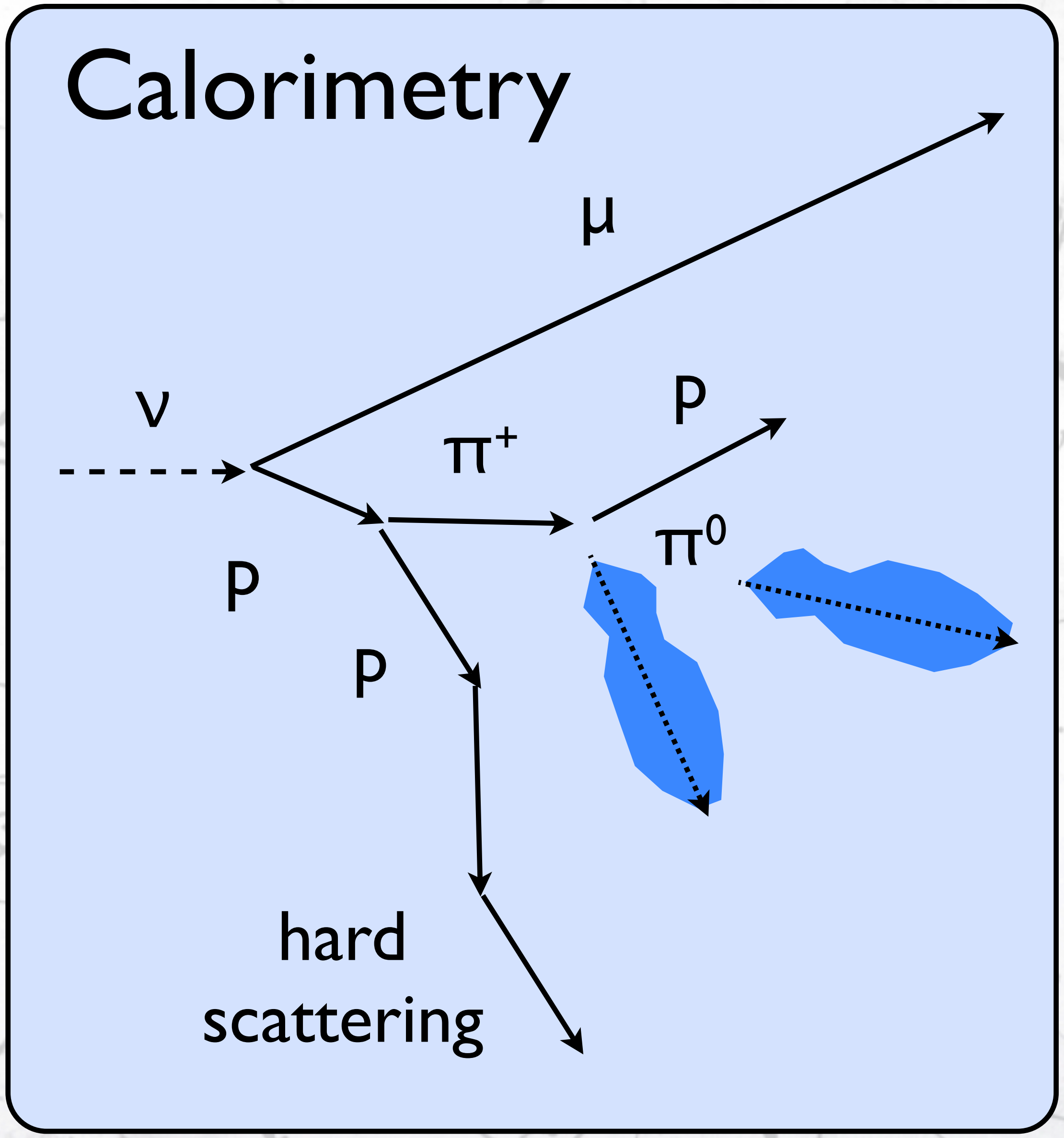
Medium-high Energy ν's (≳ 3GeV)

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

ND for oscillations



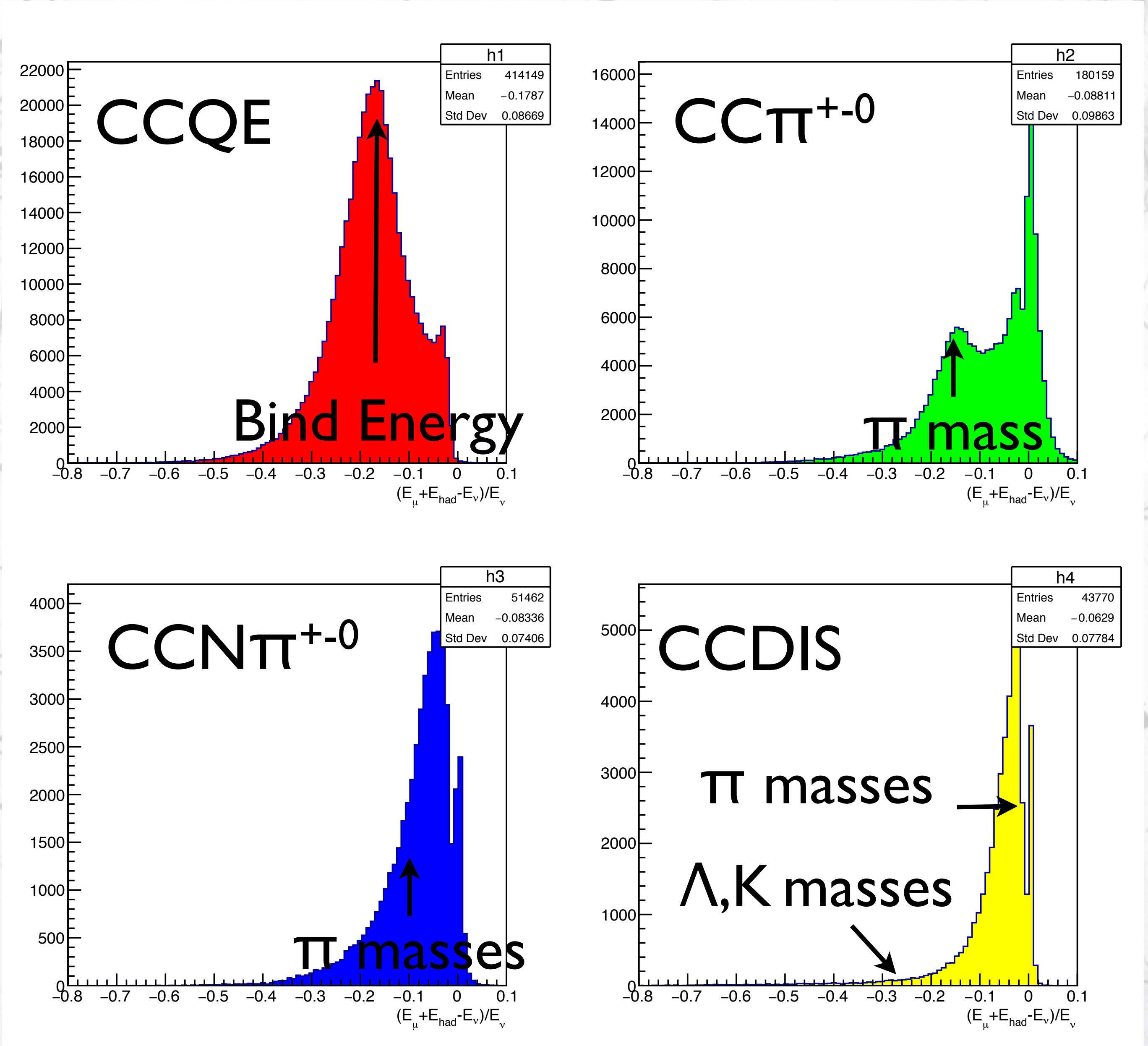
- Only a fraction of the energy is visible.
- Rely on channel interaction id.



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

ND for oscillations

- Simple exercise:
  - Take all particles predicted by Neut outside the nucleus and sum the kinetic energy (including neutrons!).
  - Plot the relative energy deviation ($(E_\mu + E_{had} - E_\nu)/E_\nu$ 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 mass can be recovered through its decay.



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

ND for oscillations

- $P(E_\nu|E'_\nu)$ is the critical point on the above formula. It implies several issues:
  - 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 scale.

Similar near and far detector technology is a plus.

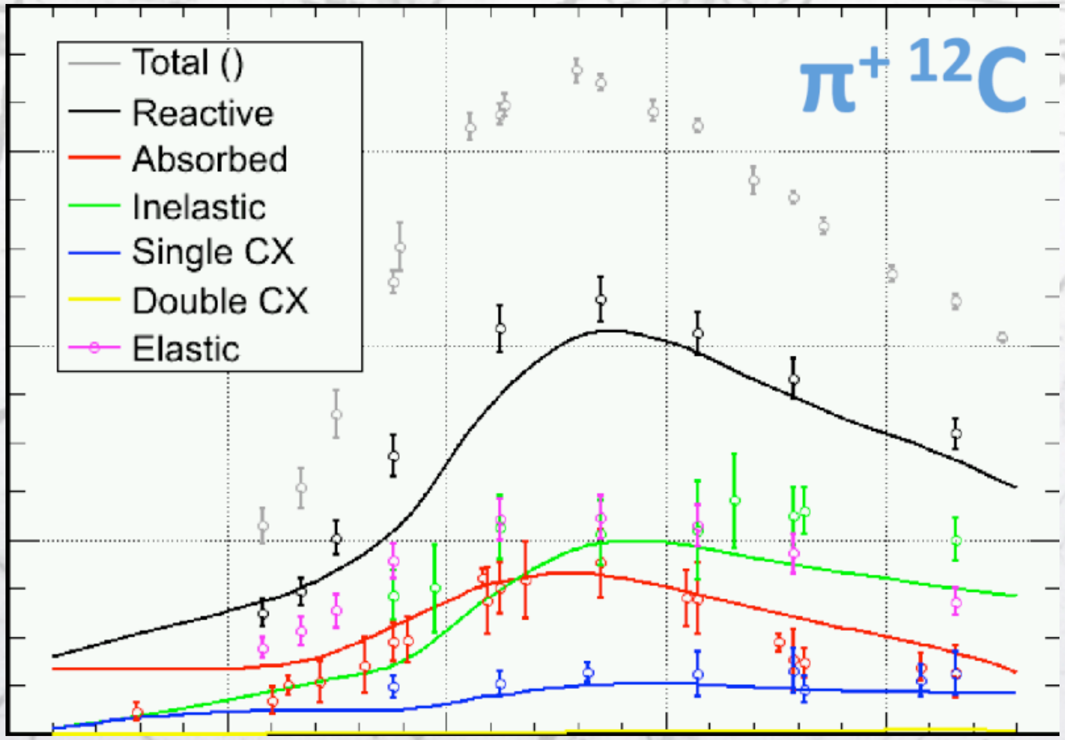
ND for oscillations

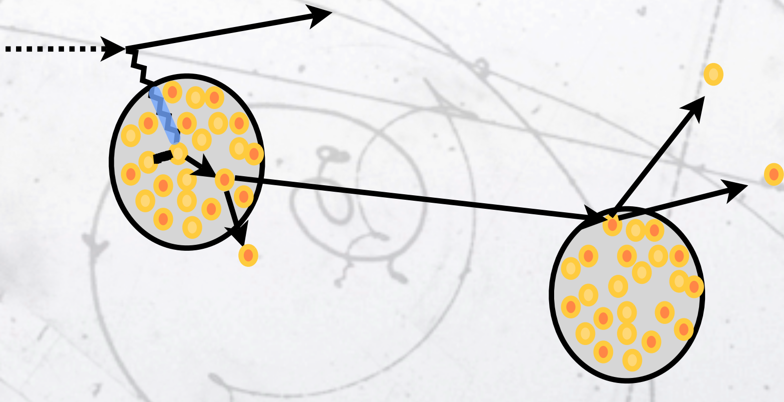
- Obviously, we can't make the ND the same size as the far detector:
  - The hermeticity of the detector will be different for neutrons electrons and gammas.
    - Low energy gamma's from π^0 critical!
  - The momentum of long range particles need to be estimated in different ways:
    - FD: range for 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})
    - …

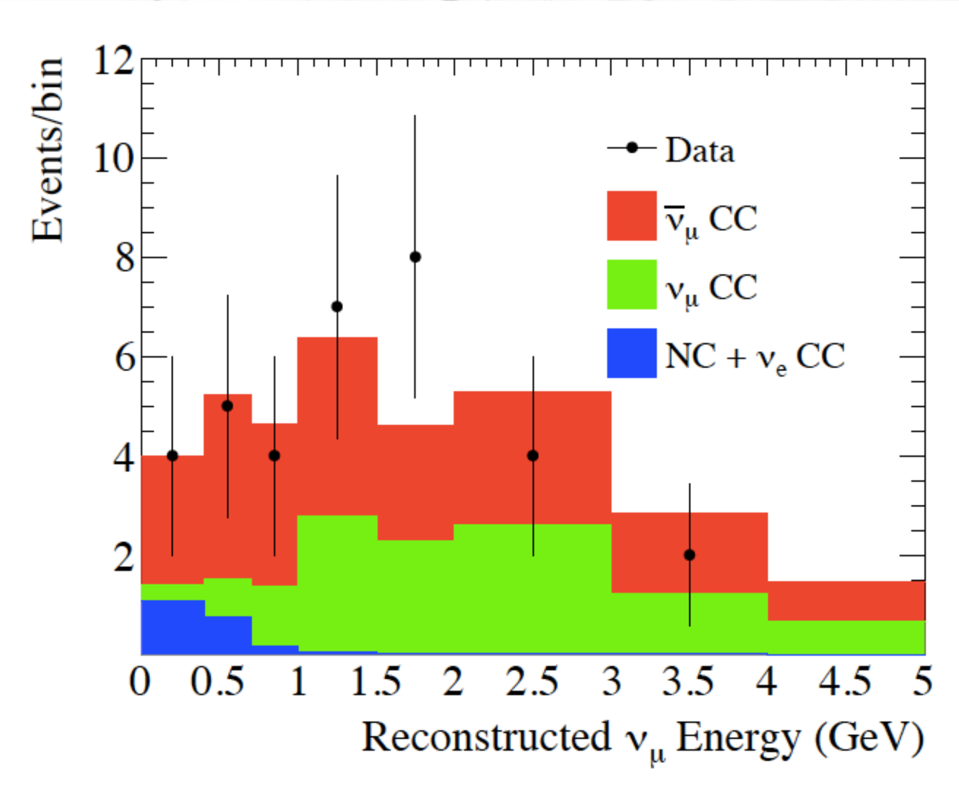
ND for oscillations

- 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 ?)

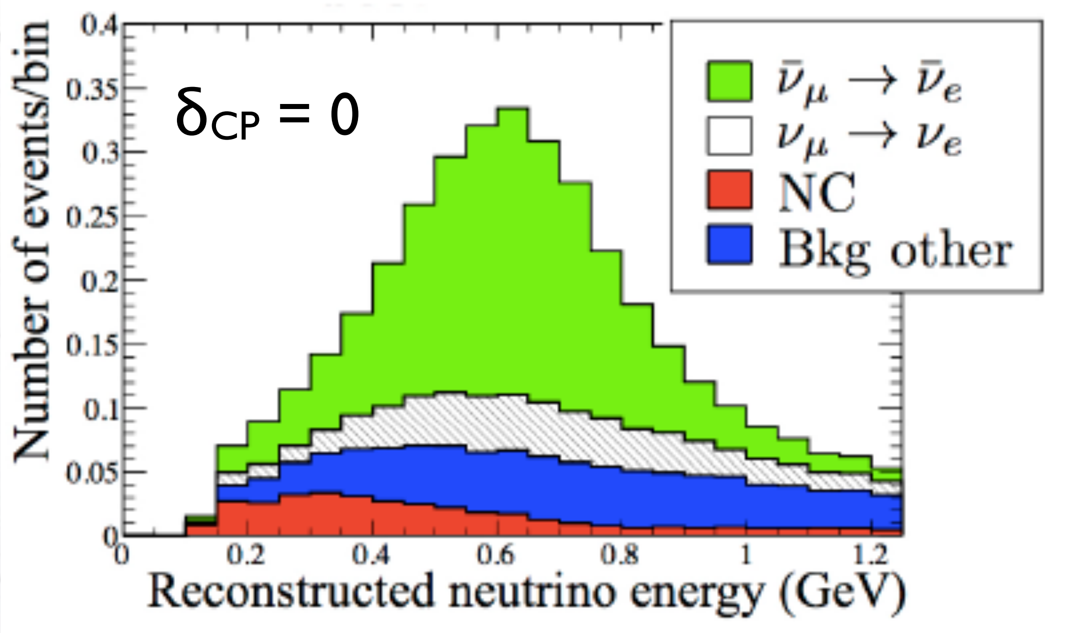
ND for oscillations

- 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.



PoS EPS-HEP2015 (2015) 047

T2K



Cross-section and flux

- Resolving the three components in $\Phi(E_\nu) \times \sigma(E_\nu) \times P(E_\nu|E'_\nu)$ 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

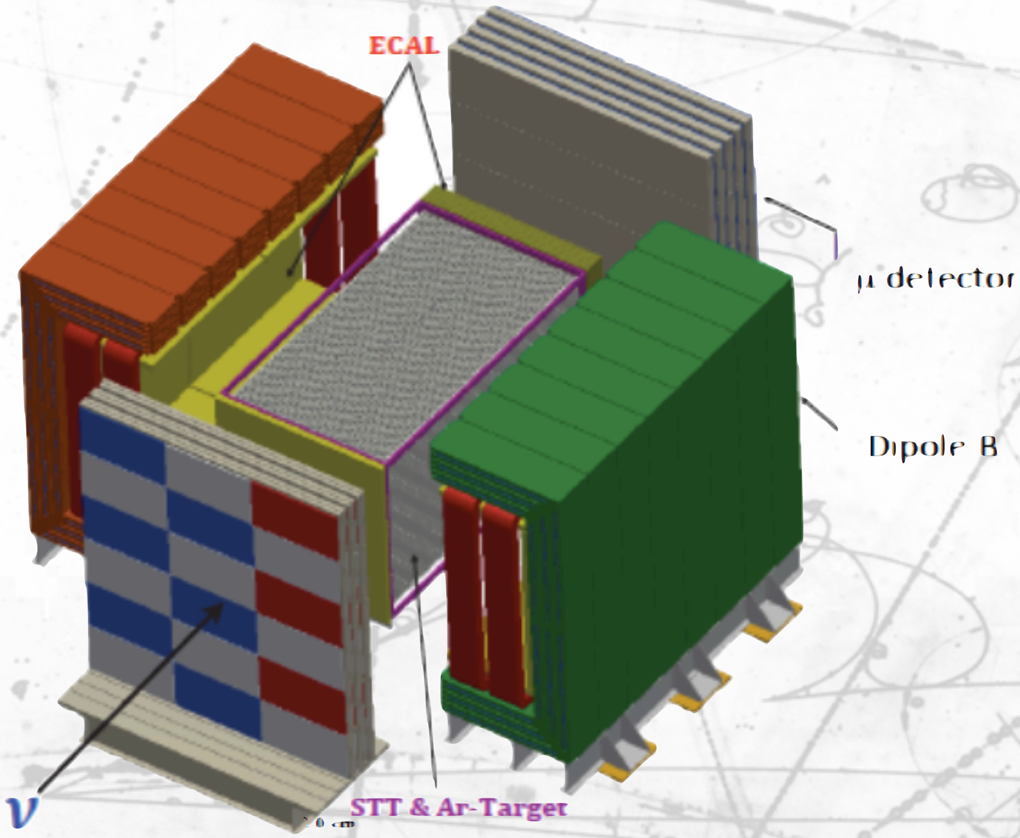
Excellent purity for ν_μ e^- scattering samples

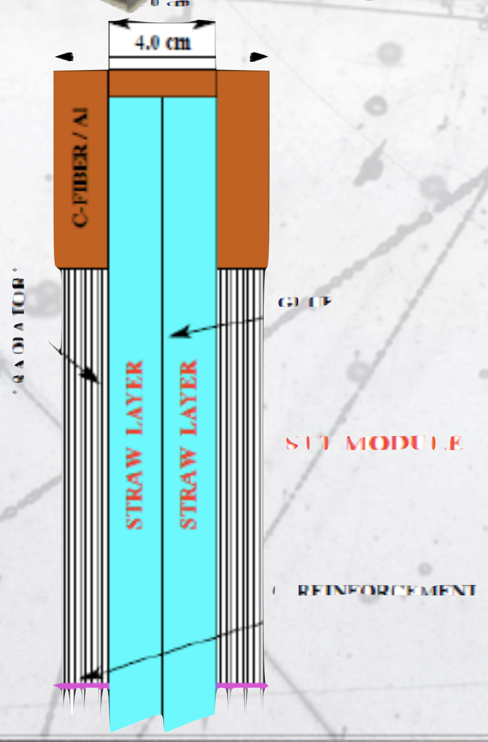
Excellent charge separation for neutrino vs antineutrino

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”.

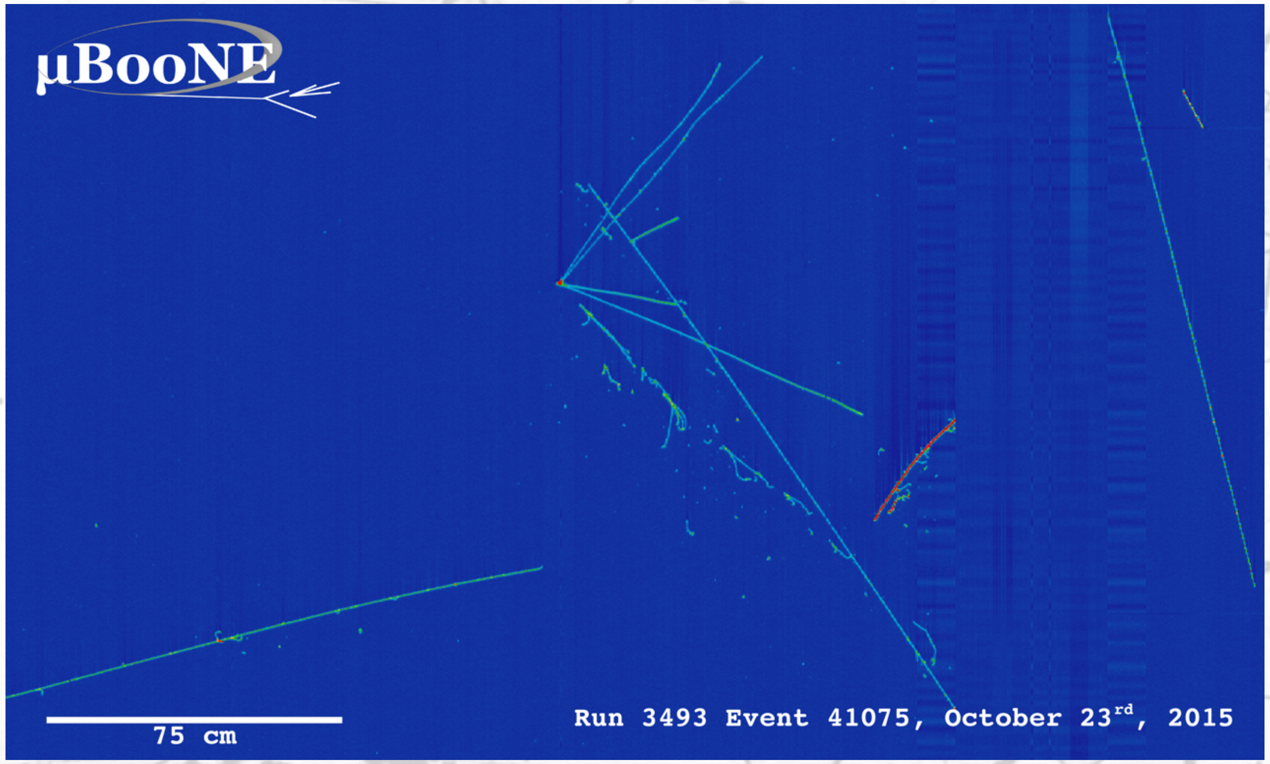
Segmented tracker

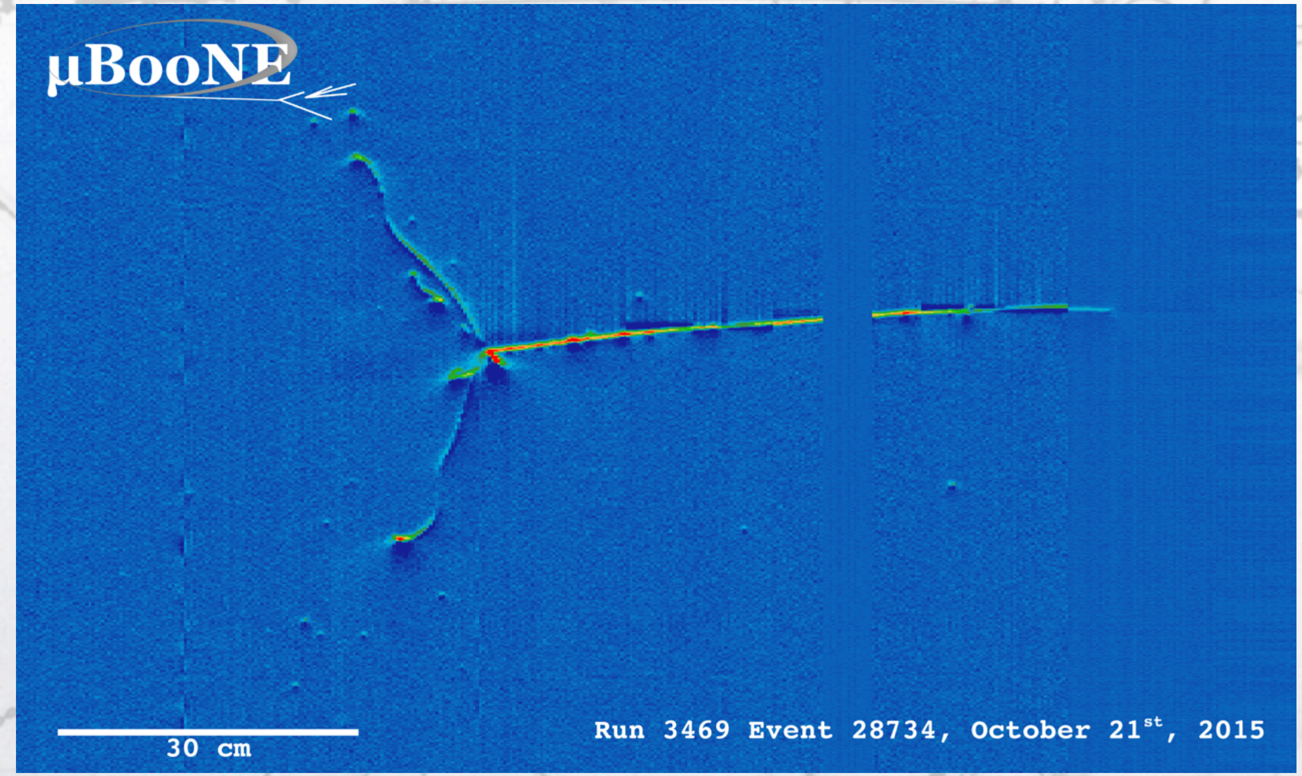




- Magnetised (0.4T) high resolution straw tube design “a la” Nomad with plannar geometry.
- Target/Nucleus selection by track vertexing.
- Low density for low E particle detection.
- ECAL gamma catcher and muon range detector.

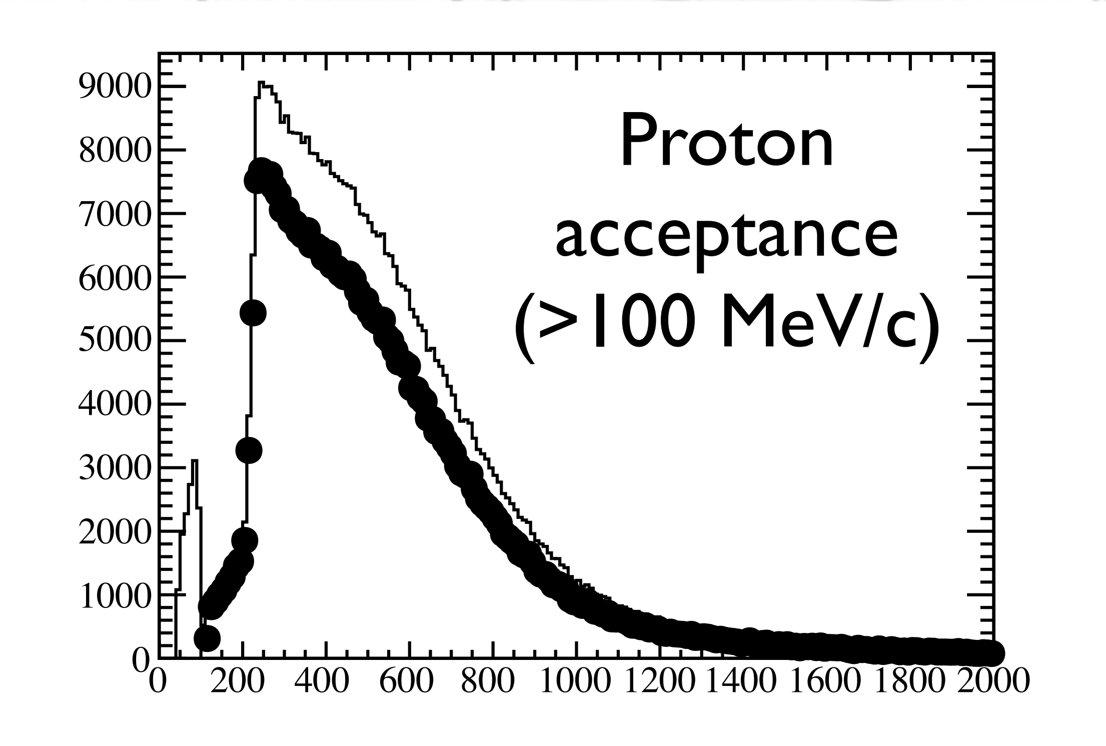
LiqAr TPC

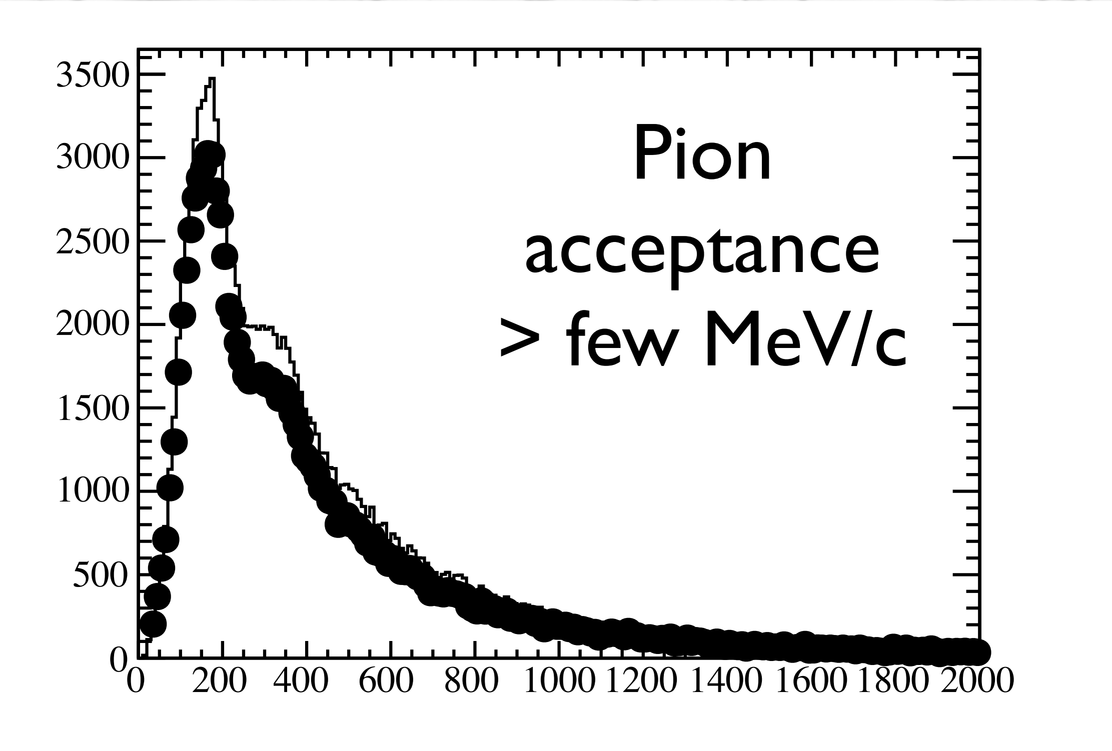




- Magnetised (?) LiqAr detector.
- Same technology as FD.
- Large mass.
- Balance pile-up / range.
- ECAL and muon range.

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.