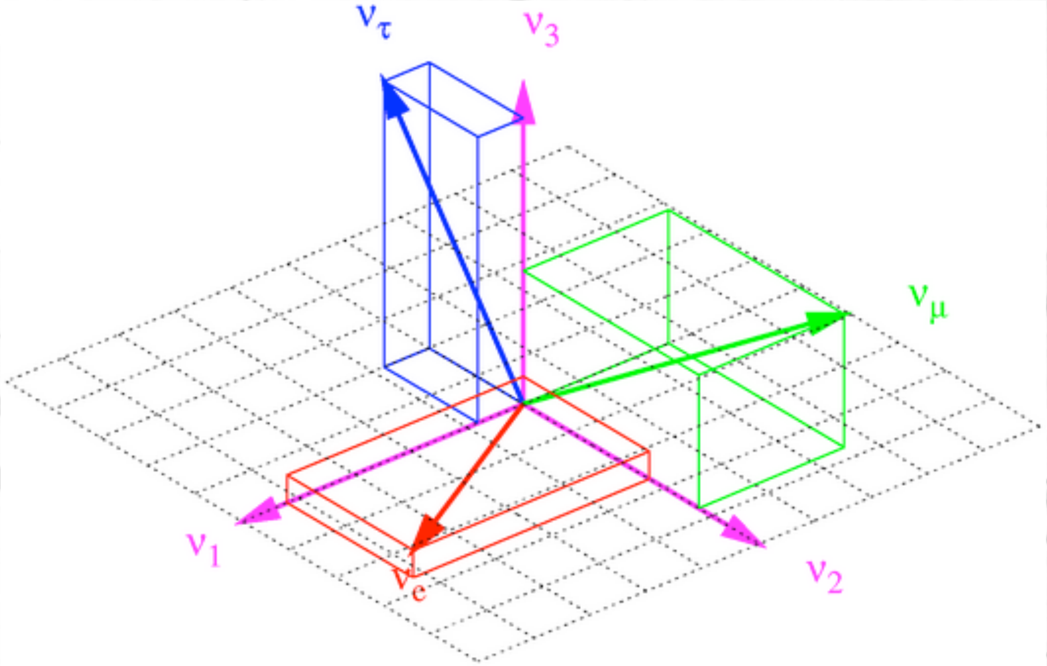
(Future) Long Baseline Experiments

F.Sánchez
Barcelona

ν oscillations

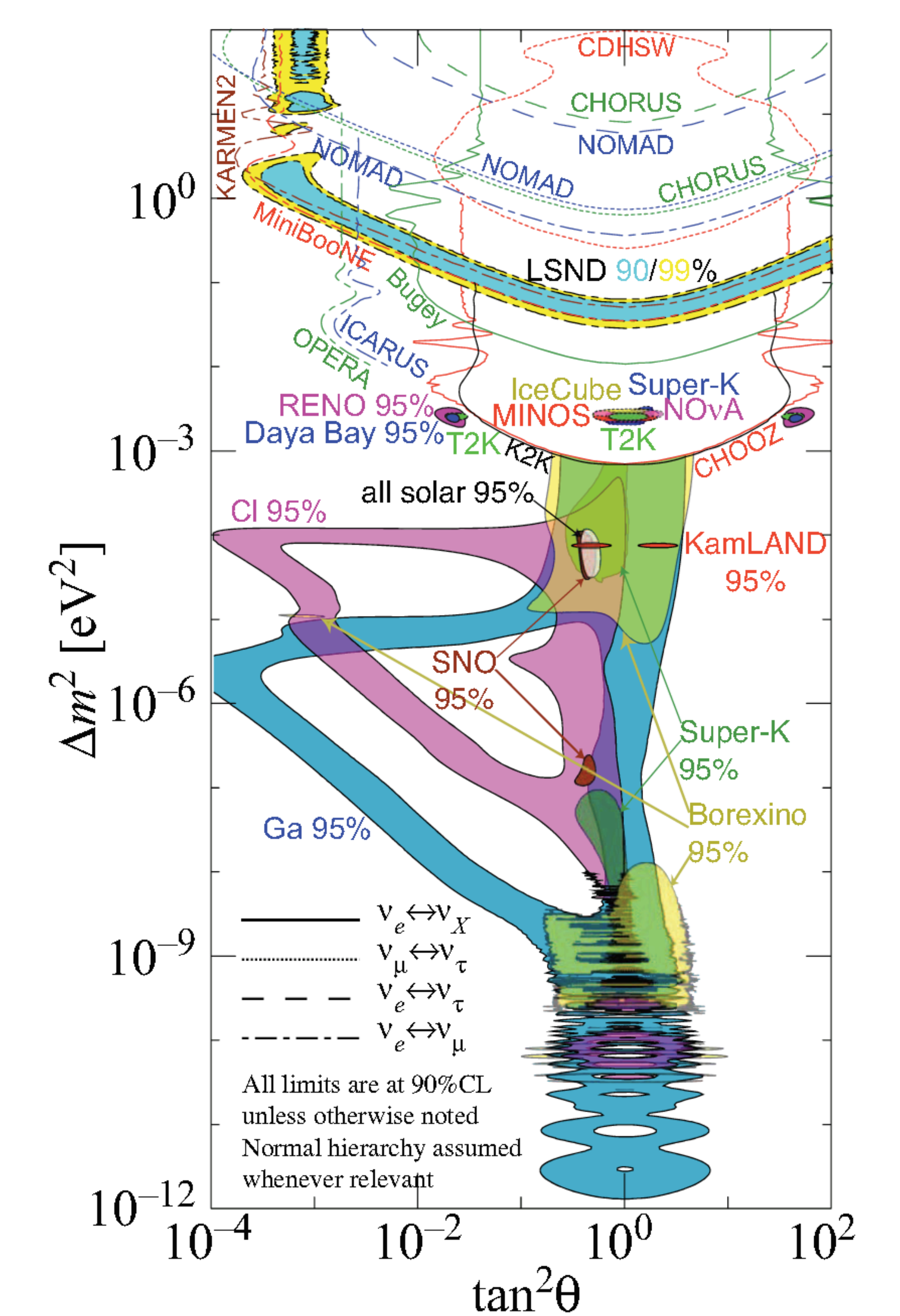
$$\begin{pmatrix}\nu_e & \nu_\mu & \nu_\tau\end{pmatrix} = U_{PNMS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



$$U_{PNMS} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & e^{-\delta_{CP}}\sin\theta_{13}\\ 0 & 1 & 0\\ -e^{\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

- With 3ν, there are 3 angles and 1 imaginary phase:
- The phase allows for CP violation similar to the quark sector.
- There are also 2 values of Δm^2, traditionally Δm^2_{12} &Δm^2_{31}.

ν oscillations



$$U_{PNMS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Many parameters measured the last 15 years!
- But not all!

3 angles and 1 imaginary phase:

or CP viola

Hierarchy

Precision!

CP violation

Parameter	best-fit	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	7.37	6.93 – 7.97
$\lvert\Delta m^2\rvert$ [10^{-3} eV ^{2}]	2.50 (2.46)	2.37 – 2.63 (2.33 – 2.60)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	0.379 – 0.616
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	0.383 – 0.637
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	0.0185 – 0.0246
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	0.0186 – 0.0248
δ/π	1.35 (1.32)	(0.92 – 1.99) ((0.83 – 1.99))

ν oscillations

$P(\nu_\mu \to \nu_\mu)$ & $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$
K2K, T2K, MINOS, NOVA, SK, ICECUBE
θ_{23} & Δm^2_{23}

$P(\nu_e \to \nu_e)$ & $P(\bar{\nu}_e \to \bar{\nu}_e)$
SNO, SK, Daya Bay, RENO, Double Chooz, KAMLAND, BOREXINO
θ_{12} θ_{13} Δm^2_{12} Δm^2_{23}

$P(\nu_\mu \to \nu_e)$ & $P(\bar{\nu}_\mu \to \bar{\nu}_e)$
T2K, Nova, MINOS
θ_{13} $\sin \delta_{CP}$

$P(\nu_\mu \to \nu_\tau)$
OPERA
θ_{23} & Δm^2_{23}

θ_{23} & Δm^2_{23}
from atmospheric and acc. neutrinos.

θ_{12} & Δm^2_{12}
from solar and reactor neutrinos

θ_{13} & $\sin \delta_{CP}$
from manmade neutrinos.

Future projects:
- accelerator: T2HK, DUNE
- reactors: RENO, SK/HK
- atmospheric: ORCA/ARCA, ICECUBE, INO

None of them includes (efficient) ν_τ production or detection.

$\nu_\mu \rightarrow \nu_\mu$

$$P(\nu_\mu \rightarrow \nu_\mu) =$$

$$1 - \sin^2 2\theta_{23} \sin^2 \theta_{m,13} \sin^2\left(\frac{\Delta m^2_{12}}{4E}\right)$$

$$- \sin^4 \theta_{23} \sin^2 2\theta_{m,13} \sin^2\left(\frac{\Delta m^2_{31}}{4E}\sqrt{(\frac{a}{\Delta m^2_{31}} \mp \cos 2\theta_{31})^2 \pm \sin^2 2\theta_{31}}\right)$$

$$- \sin^2 2\theta_{23} \cos^2 2\theta_{m,13} \sin^2\left(\frac{\Delta m^2_{31}}{4E}\sqrt{(\frac{a}{\Delta m^2_{31}} \mp \cos 2\theta_{31})^2 \pm \sin^2 2\theta_{31}} + \frac{\Delta m^2_{12}}{4E}\Delta\right)$$

$$\sin^2 2\theta_{m,13} = \frac{\sin^2 2\theta_{13}}{(\frac{a}{\Delta m^2_{13}} \mp \cos 2\theta_{13})^2 \pm \sin^2 2\theta_{13}}$$

- This oscillation allows to measure the atmospheric mixing angle (θ_{23}) and mass splitting (Δm^2_{31}) and the hierarchy.

$\nu_\mu \to \nu_e$

$$P(\nu_\mu \to \nu_e) \approx$$

leading $$4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \left(1 \pm \frac{2a}{\Delta m_{13}^2}(1-2s_{13}^2)\right)$$

CPC $$+ 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12}c_{23} \cos\delta - s_{12}s_{23}s_{13}) \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E}$$

CPV $$\mp 8c_{13}^2 C_{12} C_{s3} s_{12} s_{13} s_{23} \sin\delta \sin\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E}$$

Solar $$+ 4s_{12}c_{13}(c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13} \cos\delta) \sin\frac{\Delta m_{21}^2 L}{4E}$$

Matter $$\mp 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{21}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E}(1-2s_{13}^2)$$

- Comparison between neutrinos and antineutrinos allows to derive δ_{CP} and hierarchy through matter effects.
- The probability depends on all mixing parameters.

$\bar{\nu}_e \rightarrow \bar{\nu}_e$

$$P(\bar{\nu}_e \to \bar{\nu}_e) =$$

$$1 - 4c_{13}^4 s_{12}^2 c_{12}^2 \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$

$$- 2s_{13}^2 c_{13}^2 \left(1 - \sqrt{1 - 4s_1^2 2c_{12}^2 \sin^2 \frac{\Delta m_{21}^2 L}{4E}} \cos(2|\Delta_{ee}| \pm \phi)\right)$$

$$\Delta_{ee} = \frac{c_{12}^2 \Delta m_{31}^2 + s_{12}^2 \Delta m_{32}^2}{4E}$$

$$sin\phi = \frac{c_{12}^2 \sin(2s_{12}^2 \frac{\Delta m_{21}^2}{4E}) - s_{12}^2 \sin(2c_{12}^2 \frac{\Delta m_{21}^2}{4E})}{\sqrt{1 - 4s_1^2 2c_{12}^2 \sin^2 \frac{\Delta m_{21}^2 L}{4E}}}$$

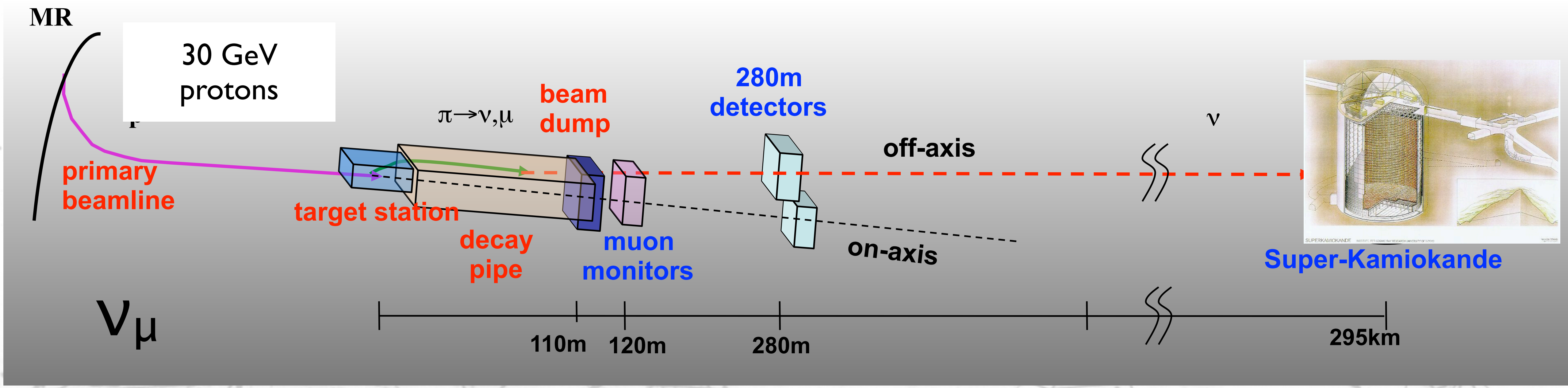
$$cos\phi = \frac{c_{12}^2 \sin(2s_{12}^2 \frac{\Delta m_{21}^2}{4E}) + s_{12}^2 \sin(2c_{12}^2 \frac{\Delta m_{21}^2}{4E})}{\sqrt{1 - 4s_1^2 2c_{12}^2 \sin^2 \frac{\Delta m_{21}^2 L}{4E}}}$$

- The neutrino oscillation in vacuum also contains information about the hierarchy through a phase!.

- Precise measurement of solar term (θ_{12}) and mass split (Δm^2_{12})

Oscillation experiments

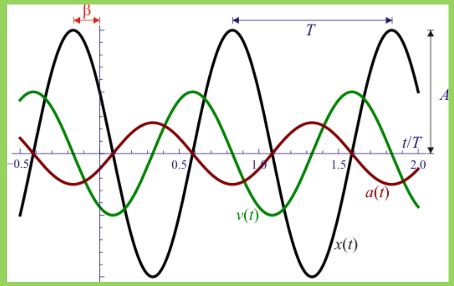
Typical Long Base Line experiment layout



Neutrinos produced in a particle accelerators or nuclear reactors.

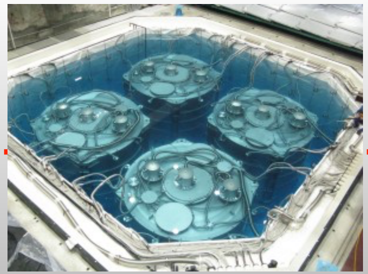
Neutrino flux meas

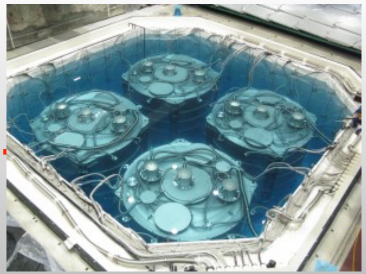
Oscillations



Neutrino flux meas

ν_e





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

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

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

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

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 simple detector smearing.

Reactor experiments

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

- The flux is determined by the near detector:
  - Near and far flux are identical. $\Phi_{near}(E_\nu) = \Phi_{far}(E_\nu)$
  - Uncertainty in fuel composition is relevant.
  - Near and far detectors are similar in technology.
- Inverse beta decay cross-section well known theoretically, $\sigma(E_\nu)$
- Main technological challenge is the energy resolution of the neutrino reconstruction: $P(E_\nu|E'_\nu)$

Near and far neutrino species are the same!

LBL experiments

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

- The flux is determined by the near detector:
  - Near and far flux are not identical. $\Phi_{near}(E_\nu)$!= $\Phi_{far}(E_\nu)$
  - Near and far detectors are normally dissimilar in technology.
- Cross-section are not well known. $\sigma(E_\nu)$
- Many challenges is the energy resolution of the neutrino reconstruction: $P(E_\nu|E'_\nu)$, $\sigma(E_\nu)$ and flux determination.

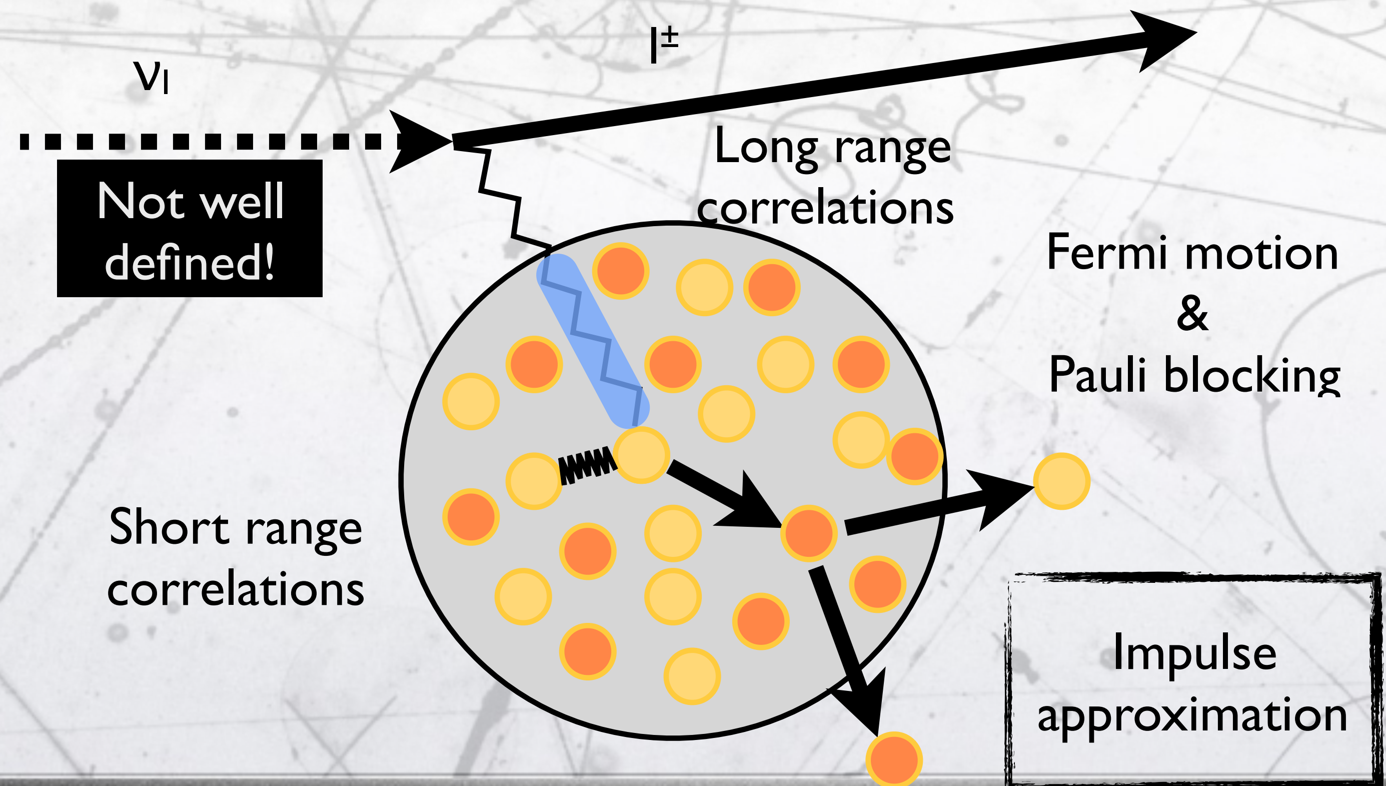
Near and far neutrino specie are **not** the same!

Neutrino interactions

@ the nucleon level !

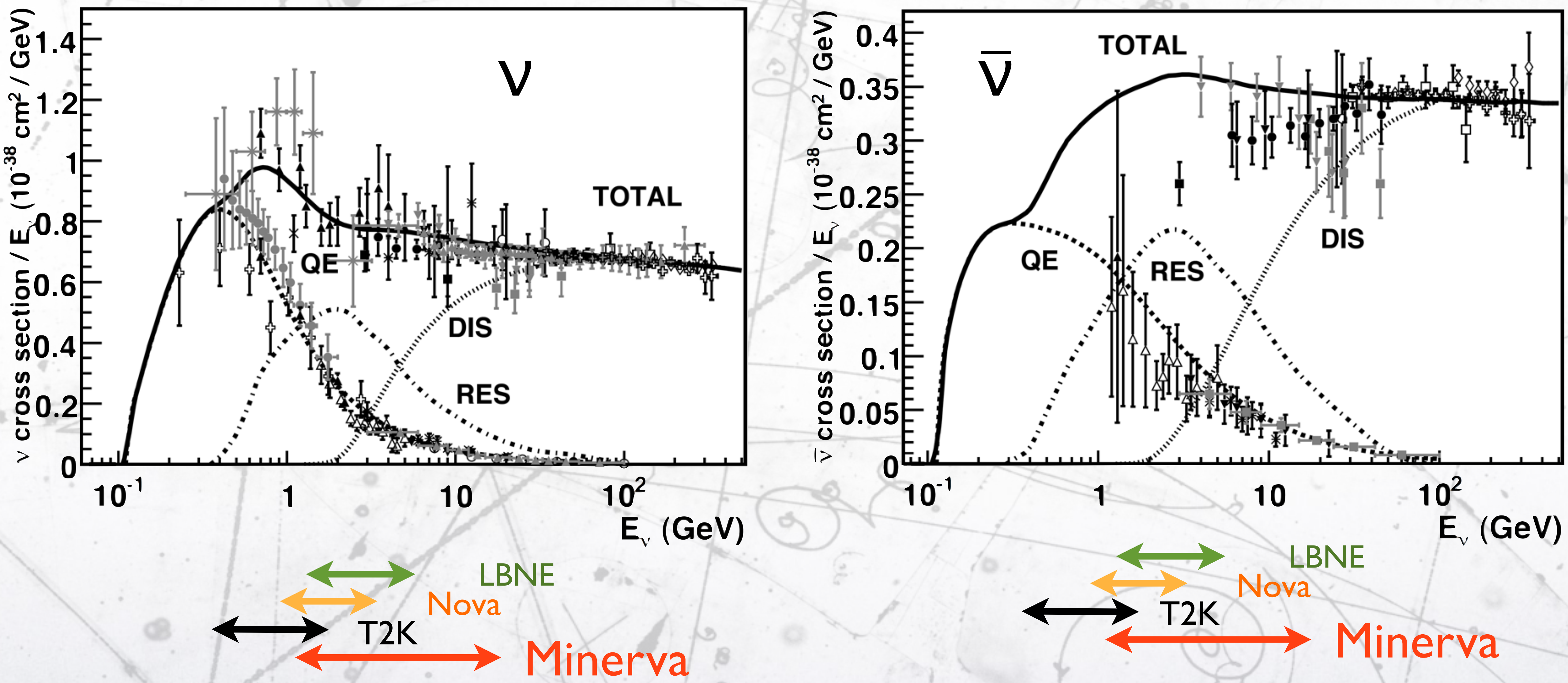
$CCQE$	$\nu_\mu n \to \mu^- p$
$CC1\pi$	$\nu_\mu p \to \mu^- \Delta^{++} \to \mu^- \pi^+ p$
	$\nu_\mu n \to \mu^- \Delta^{+} \to \mu^- \pi^+ n$
	$\nu_\mu n \to \mu^- \Delta^{+} \to \mu^- \pi^0 p$
$CCN\pi$	$\nu_\mu N \to \mu^- \Delta^{+,++} \to \mu^- N' \pi\pi ...$
$CCDis$	$\nu_\mu N \to \mu^- N' \pi,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

@ the nucleus level !



The σ problem

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



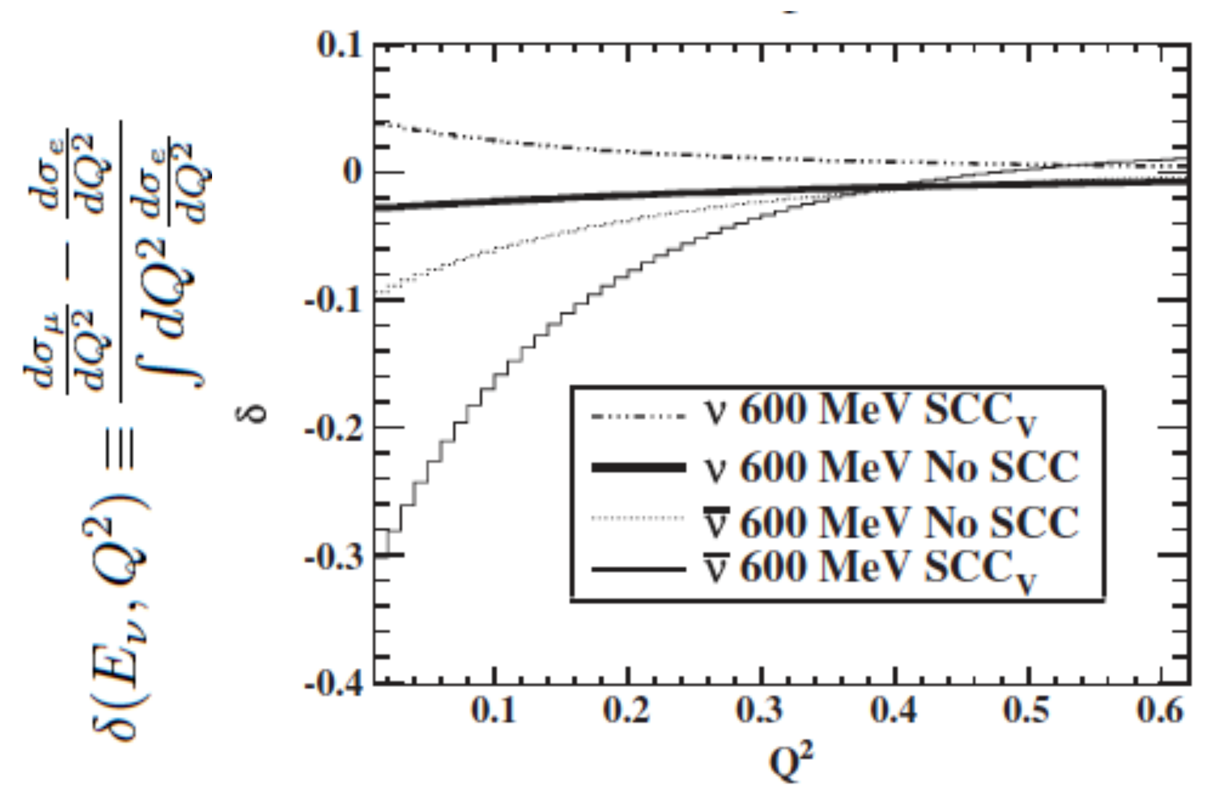
Present and future oscillation experiments cover a complex region full of reaction thresholds and sparse data.

[Review of the problem @ arXiv:1706.03621]

Neutrino Electron

- CP violation requires in addition the knowledge of the ratio $\sigma(\nu_\mu)/\sigma(\nu_e)$ for neutrinos and anti-neutrinos.

$$\sin\delta \propto \frac{N_{\nu_e} - N_{\bar{\nu}_e}}{N_{\nu_e} + N_{\bar{\nu}_e}} = \frac{\phi_{\nu_\mu} P(\nu_\mu \to \nu_e)\sigma_{\nu_e} - \phi_{\nu_{\bar{\mu}}} P(\nu_{\bar{\mu}} \to \bar{\nu}_e)\sigma_{\bar{\nu}_e}}{\phi_{\nu_\mu} P(\nu_\mu \to \nu_e)\sigma_{\nu_e} + \phi_{\nu_{\bar{\mu}}} P(\nu_{\bar{\mu}} \to \bar{\nu}_e)\sigma_{\bar{\nu}_e}}$$



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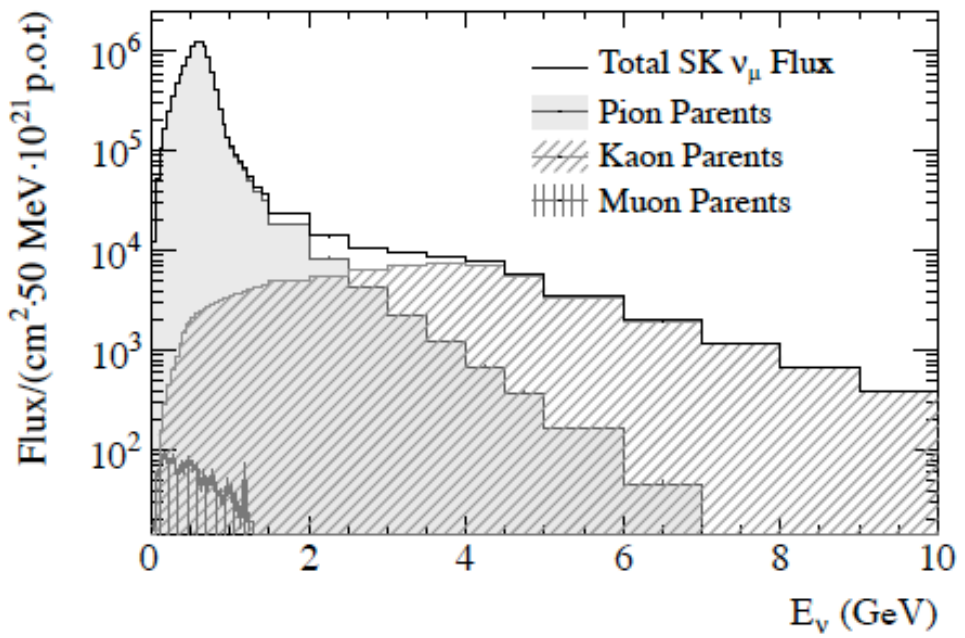
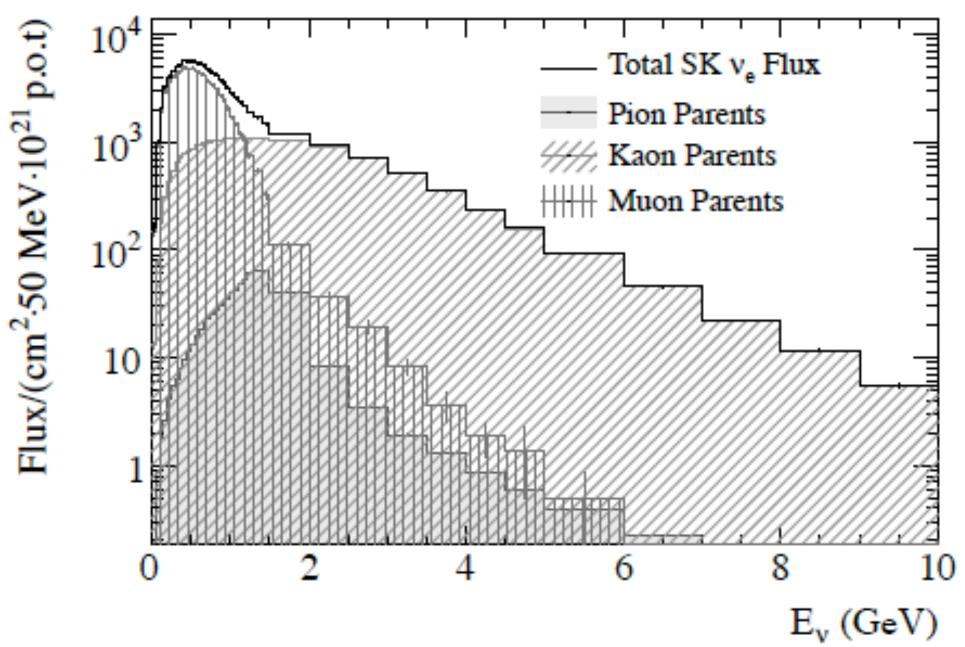
- Neutrino and antineutrino flux is very different.
  - anti-nenutrino beam has large neutrino background.
- Near detector measures $\sigma(\nu_\mu)\times\Phi$:
  - $\sigma(\nu_e)/\sigma(\nu_\mu)$ is critical !!!!
- Very little knowledge (th. & Exp.) is available.

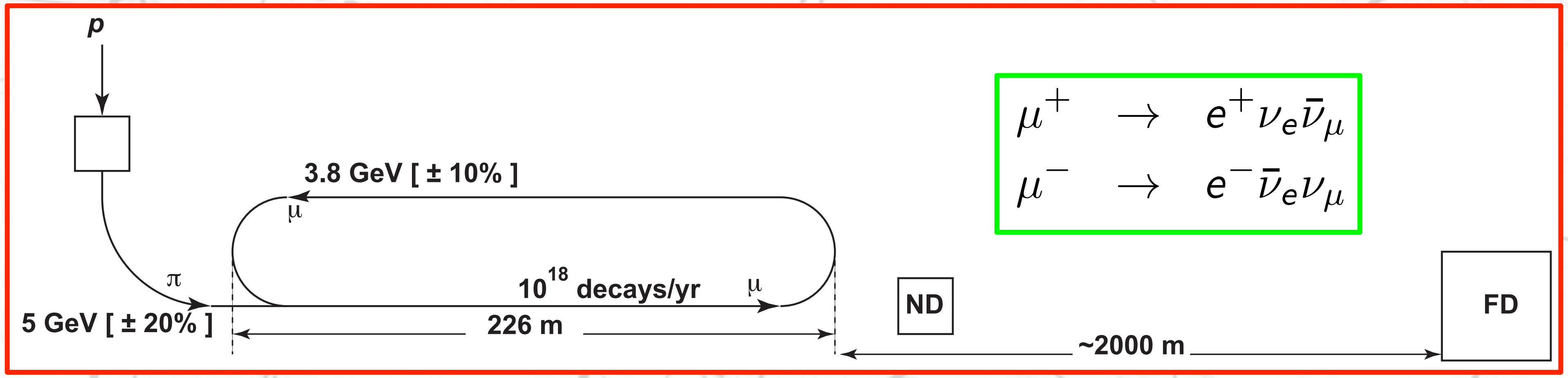
Neutrino Electron





- 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.

NuStorm

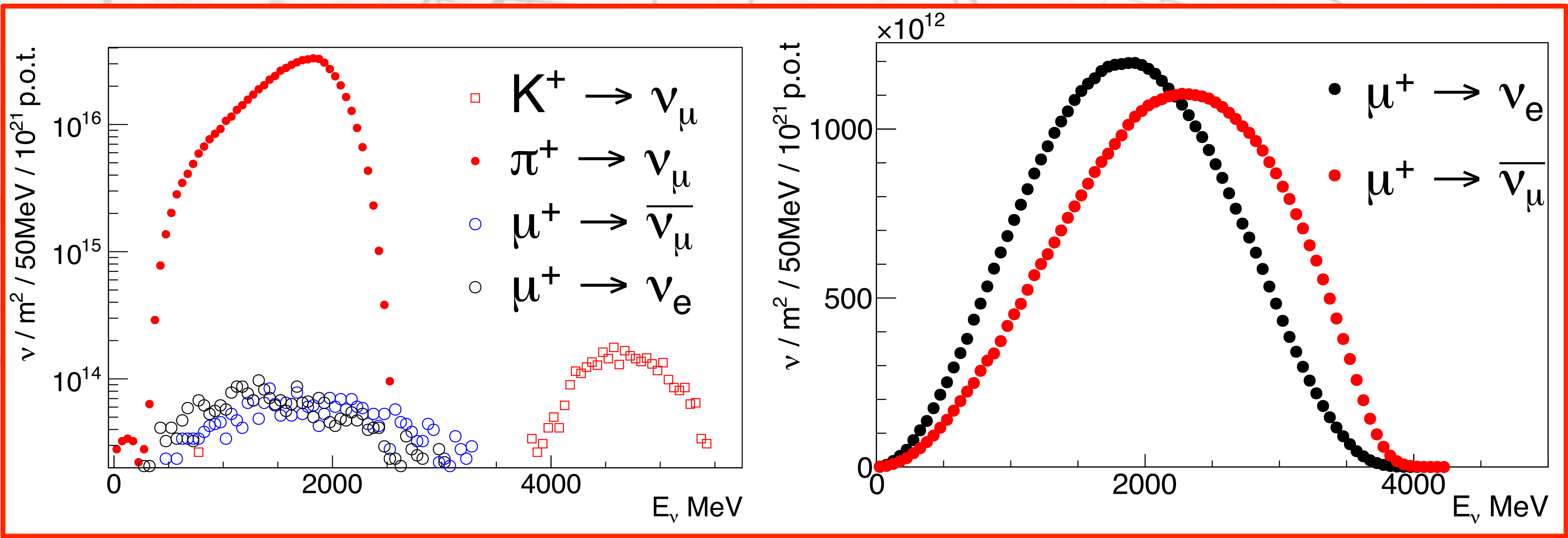


$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

Precise neutrino flux: Normalisation & shape : < 1%

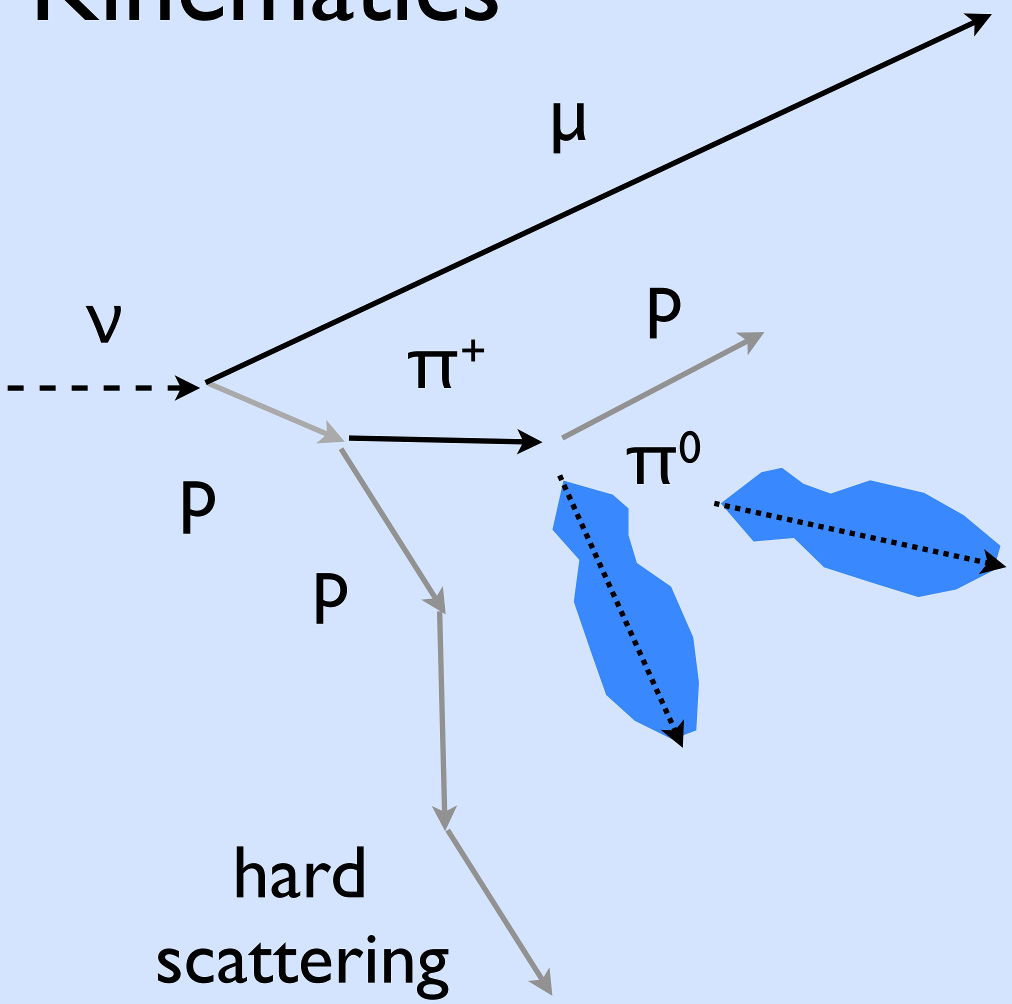
Energy (and flavour) precise $\pi \rightarrow \mu$ injection pass: "Flash" of muon neutrinos

50/50 % of ν_e & ν_μ fluxes



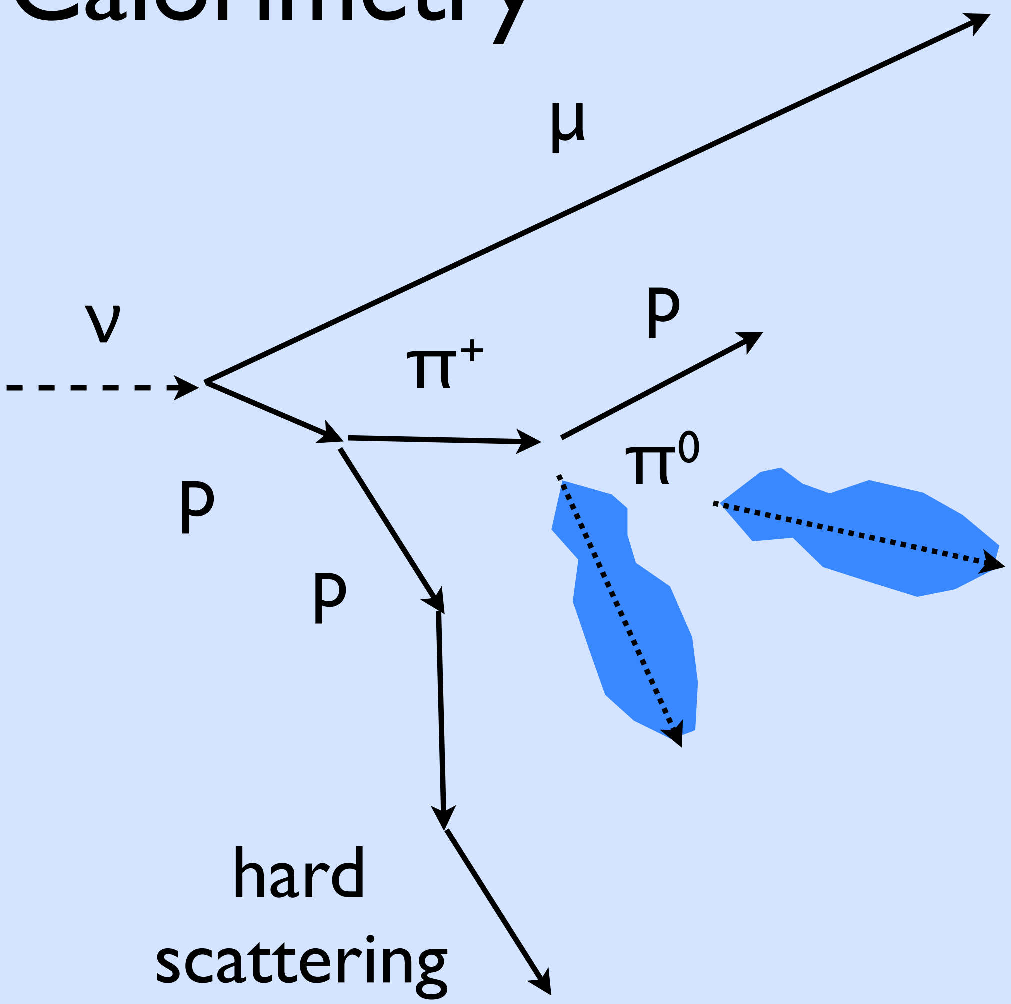
$P(E_\nu|E'_\nu)$

Kinematics



- Only a fraction of the energy is visible.
- Rely on channel interaction id. & cross section model.

Calorimetry



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

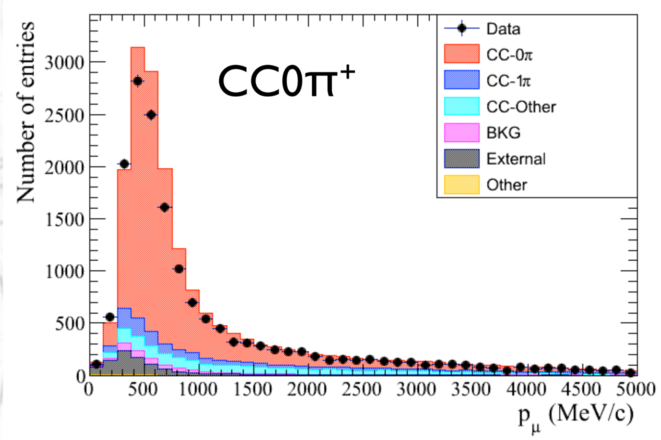
The role of ND

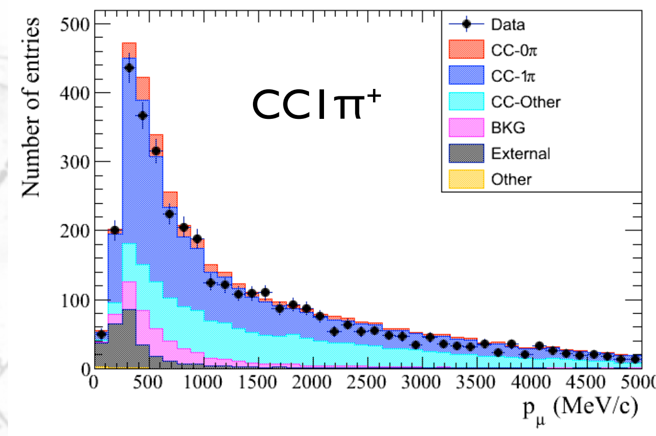
$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

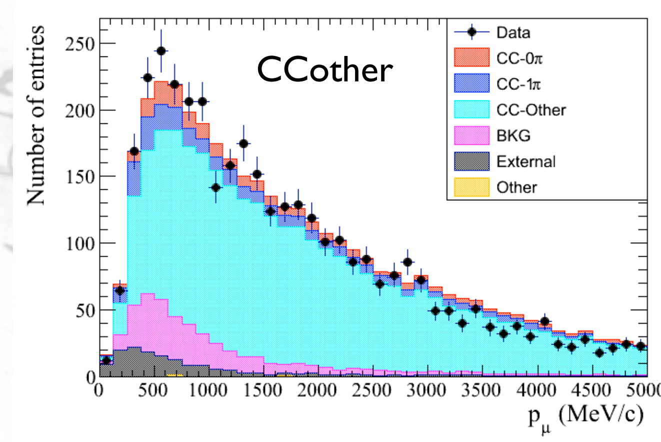
- Near detector is in charge of measuring the denominator.
- Since $\Phi(E_\nu)$, $\sigma(E_\nu)$ & $P(E_\nu|E'_\nu)$ are not well known the ND should also try to factorise the elements.
- A model to describe cross-sections is fundamental during this exercise.

The role of near detector

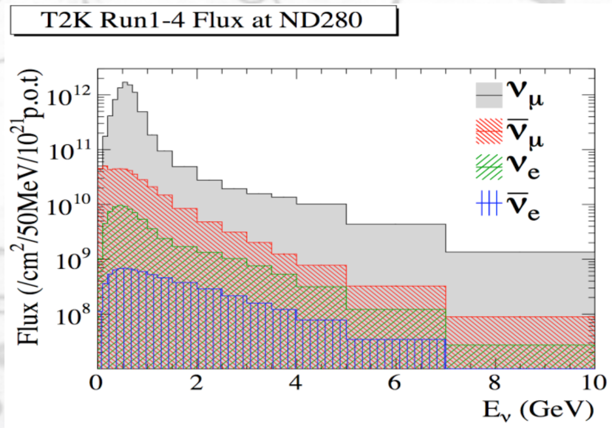
Near detector data



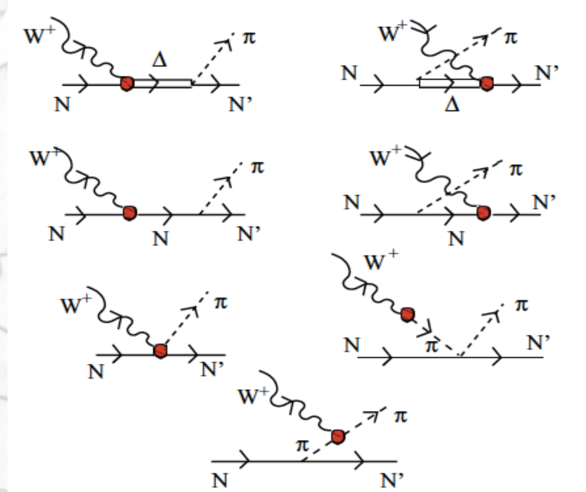




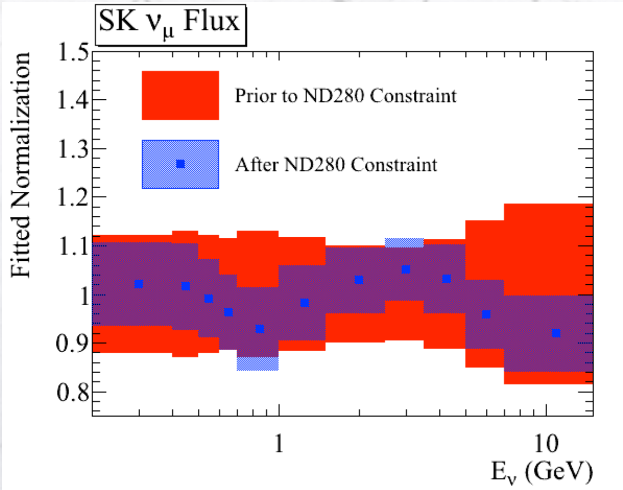
⊕ Hadron production flux prediction



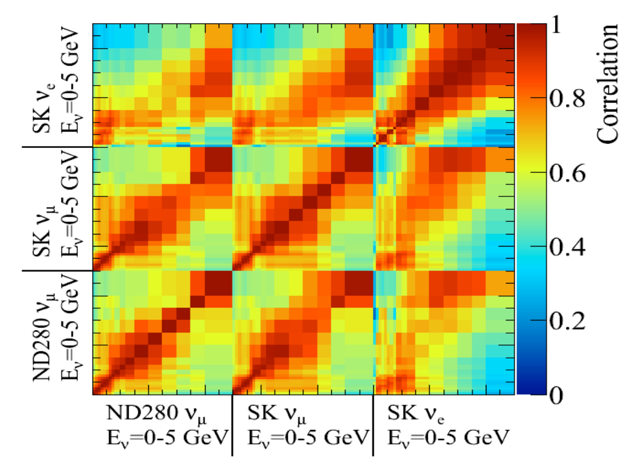
⊕ Cross-section model



= Corrected flux and cross-section model



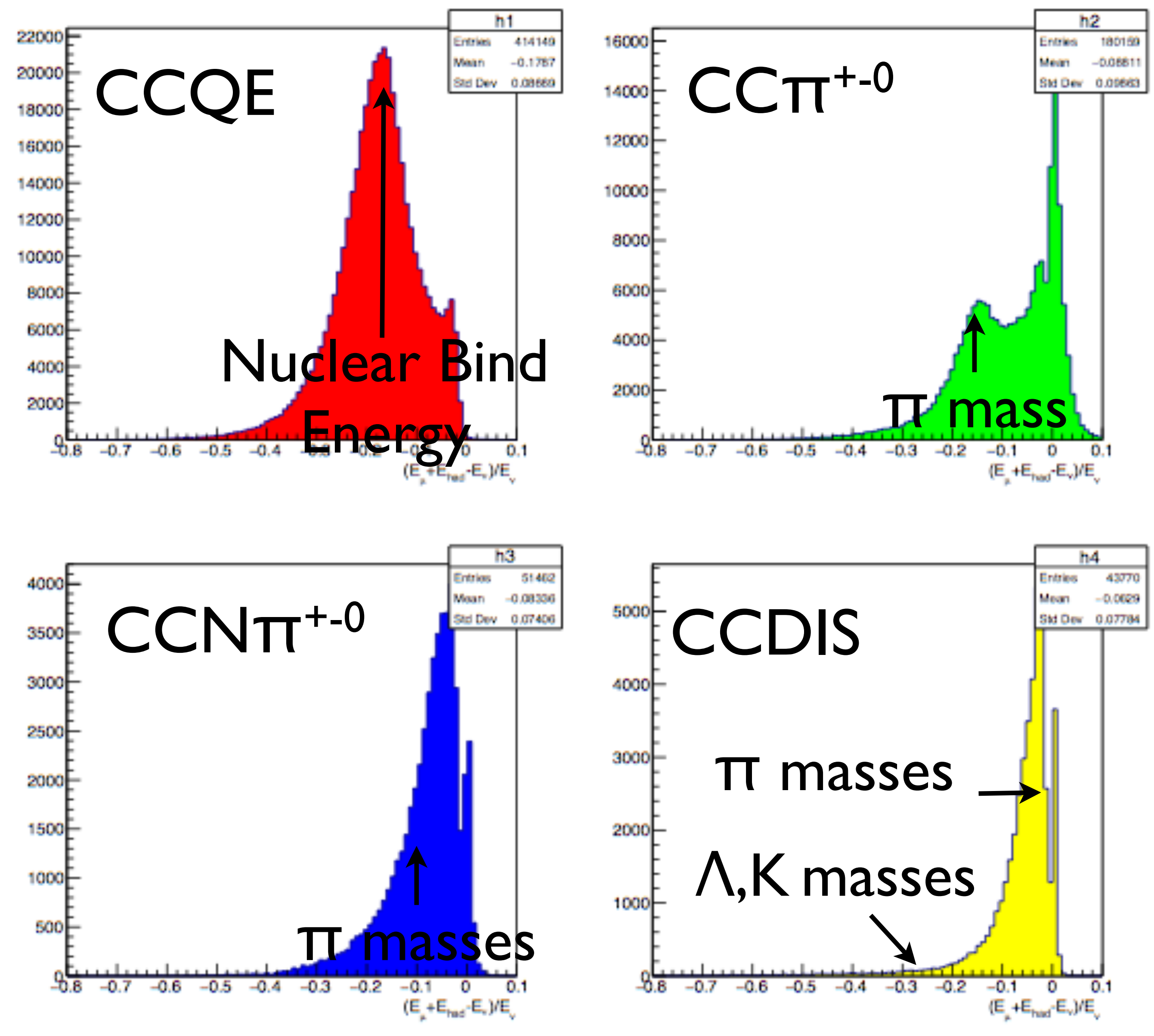
& correlation



@ T2K but similar in Nova.

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 ($E_\mu+E_{had}-E_\nu)/E_\nu$ for different channels.
  - The response depends on the channel and the topology of events outside the nucleus.
- Part of the pion and kaon mass can be recovered through its decay chain.

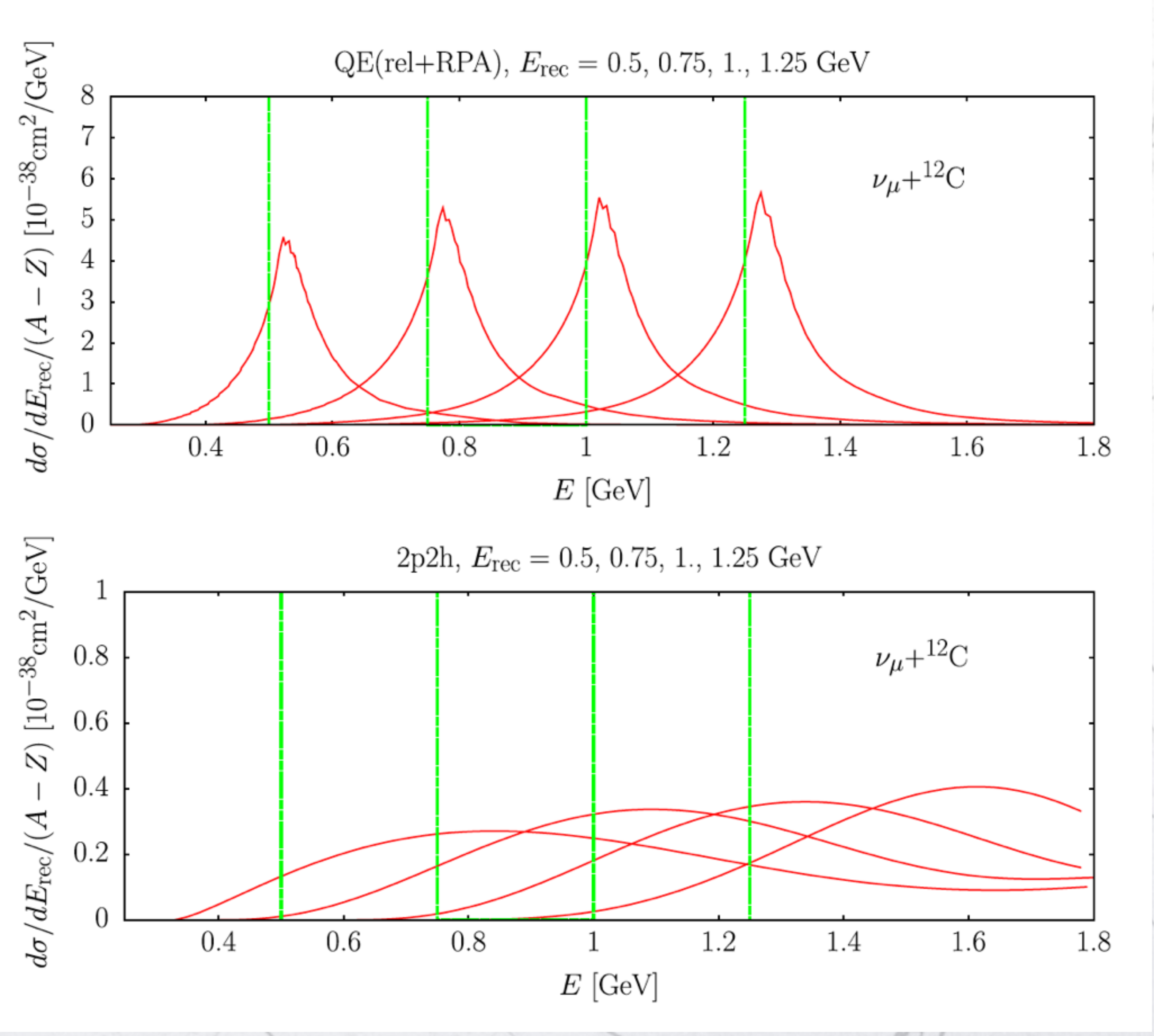


- Are the neutrino interaction models ready for this type of analysis?

ND for oscillations

Kinematic Approach

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



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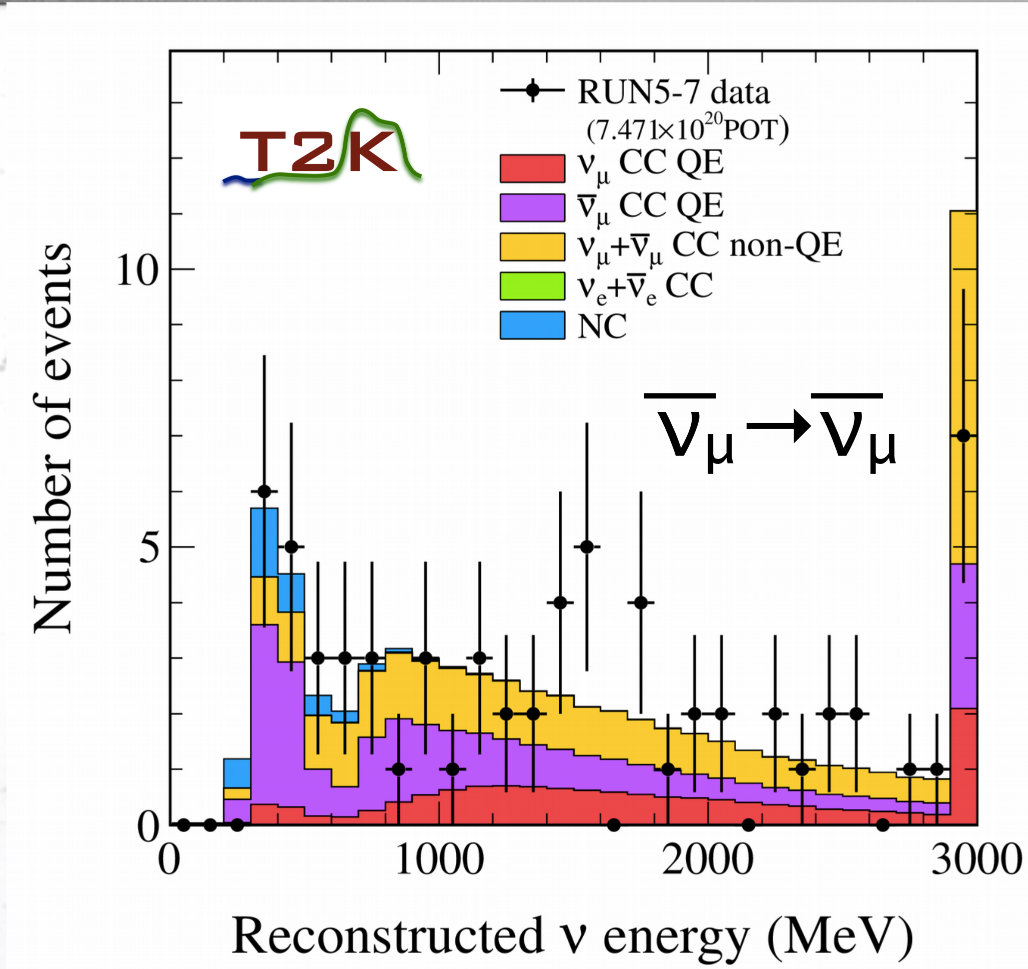
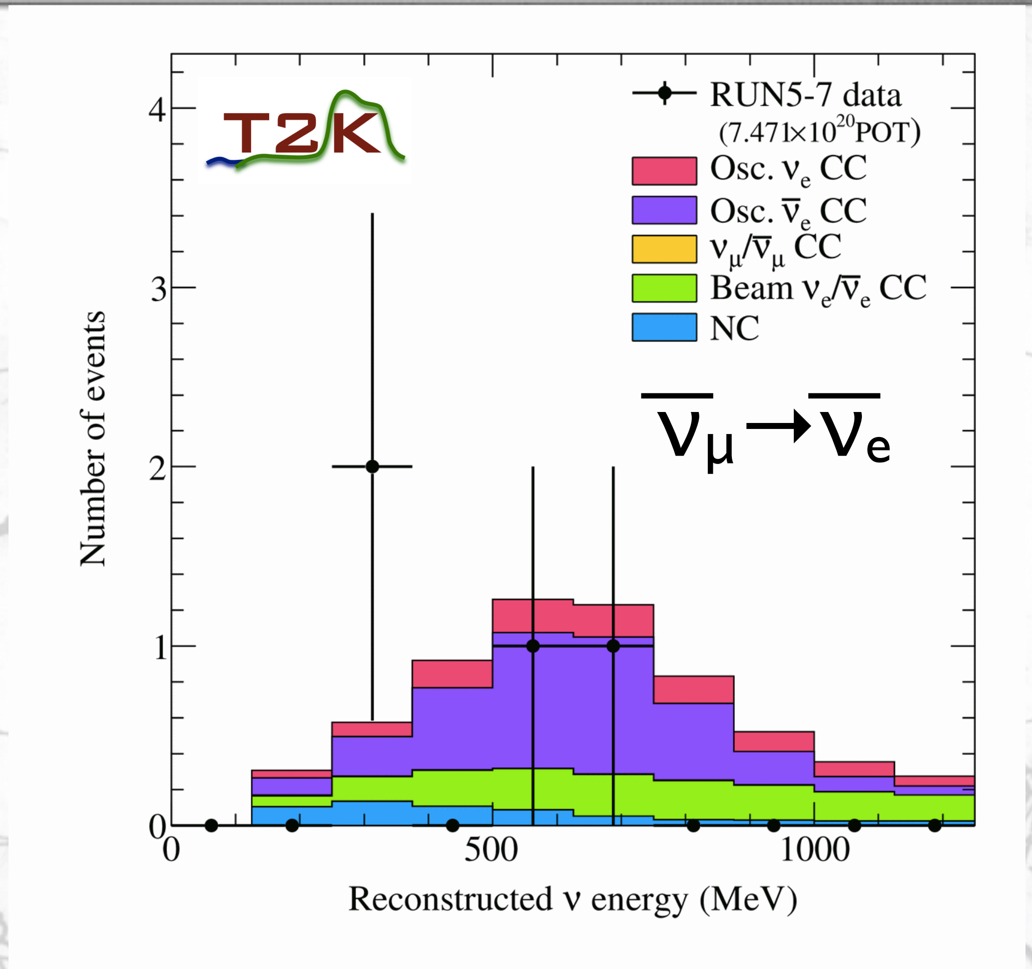
ND and backgrounds





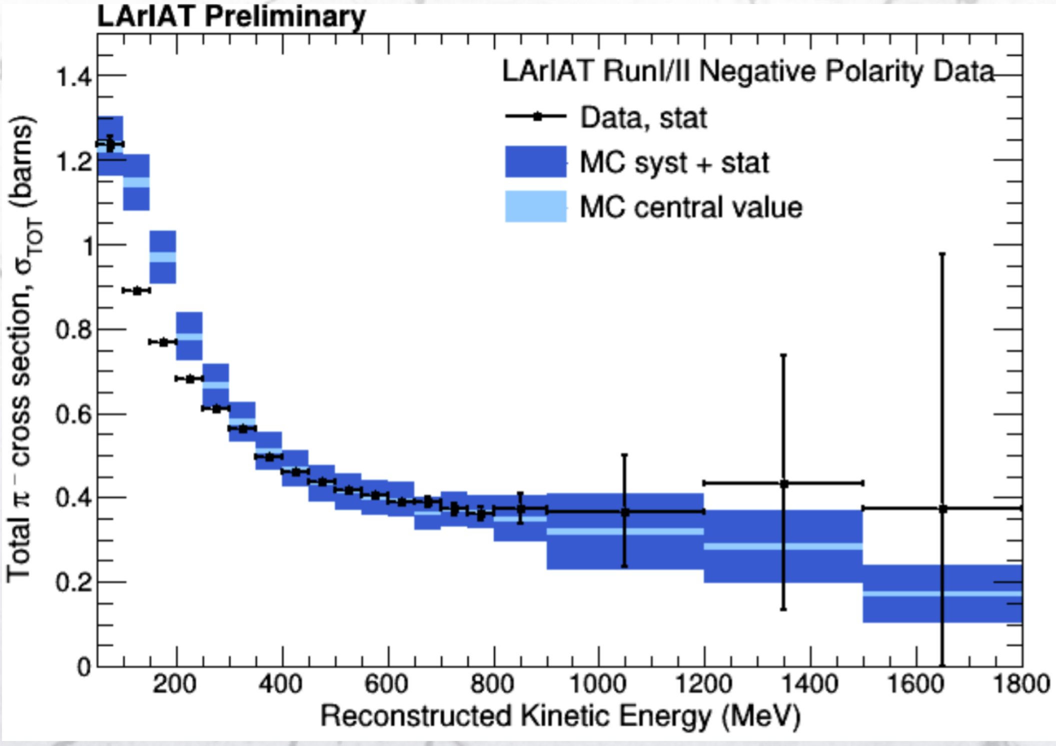
- Far detector also have several sources of backgrounds:
  - wrong sign backgrounds (neutrinos vs. antineutrinos).
  - NC interactions populating low energy bins.
  - Wrong interaction channel leading to biased energies.

Near detector can measure them in "similar" conditions.

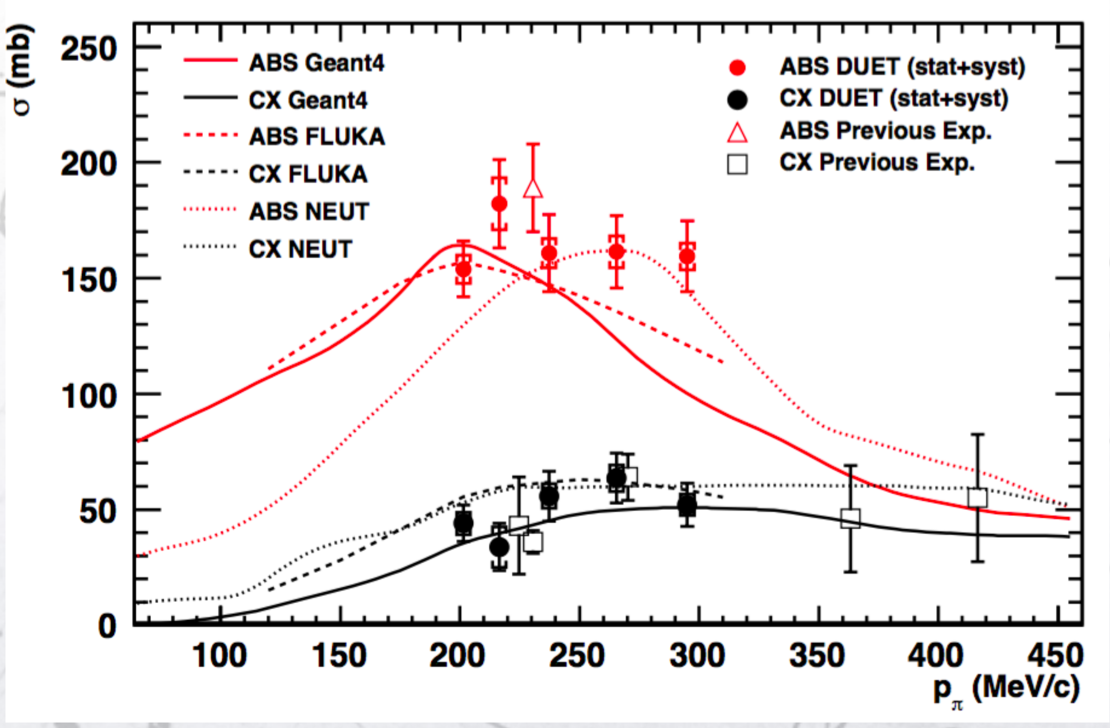
Near & far detector flux is different due to oscillations.

Secondary interactions

- Interactions of pions and protons below 500 MeV/c can change final state identification.
- Poor knowledge of inclusive and exclusive cross-sections:
  - Measurements of pion/nucleus cross/sections in test-beams.
  - Important for detector systematics and FSI. (Most relevant in T2K ND systematics).



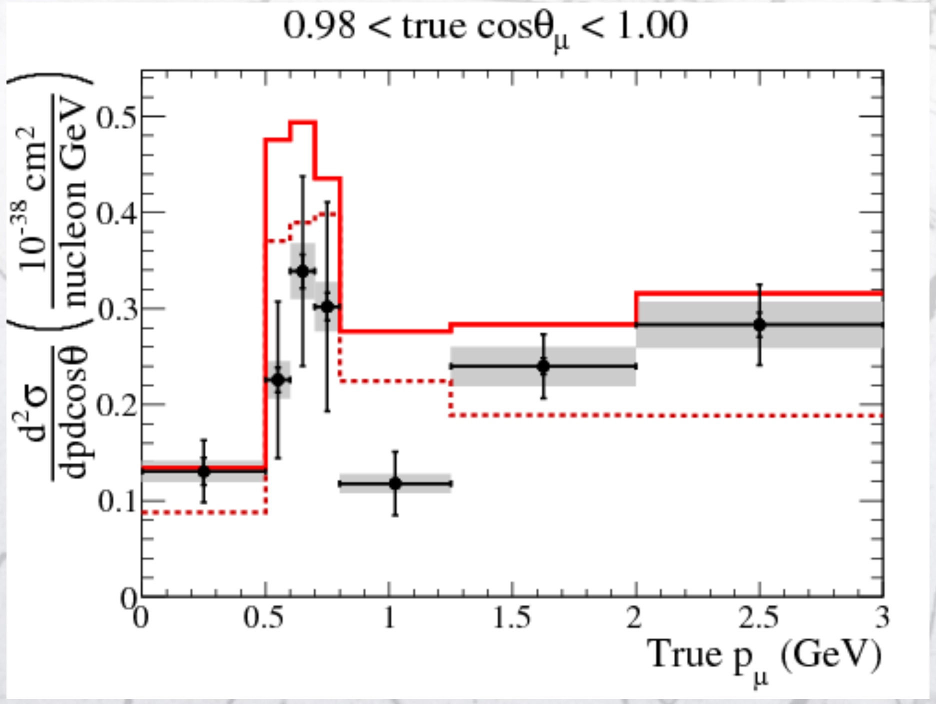
Lariat



DUET

Theory and (e,e')

- Theory is fundamental to improve our understanding of neutrino-nucleus modelling for both kinematic and calorimetric approach.
- Data is sparse and always connected to flux uncertainties and model defects.
    - (e,e') scattering might be of uses regardless the difference in interactions: Vector vs Axial.
- NuStec is an international collaboration of theorists and experimenters (electron scattering and neutrino) to improve on cross-section knowledge.



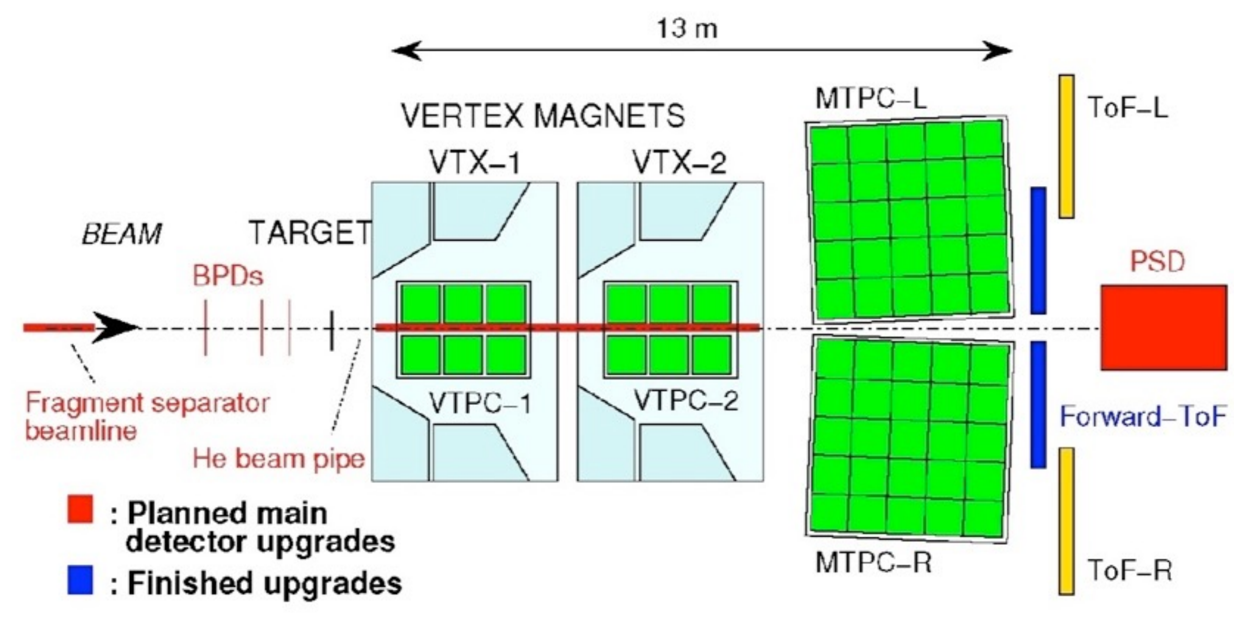
The main problem is a consistent nucleus description in a variety of kinematic regimes from shell model to relativistic approach.

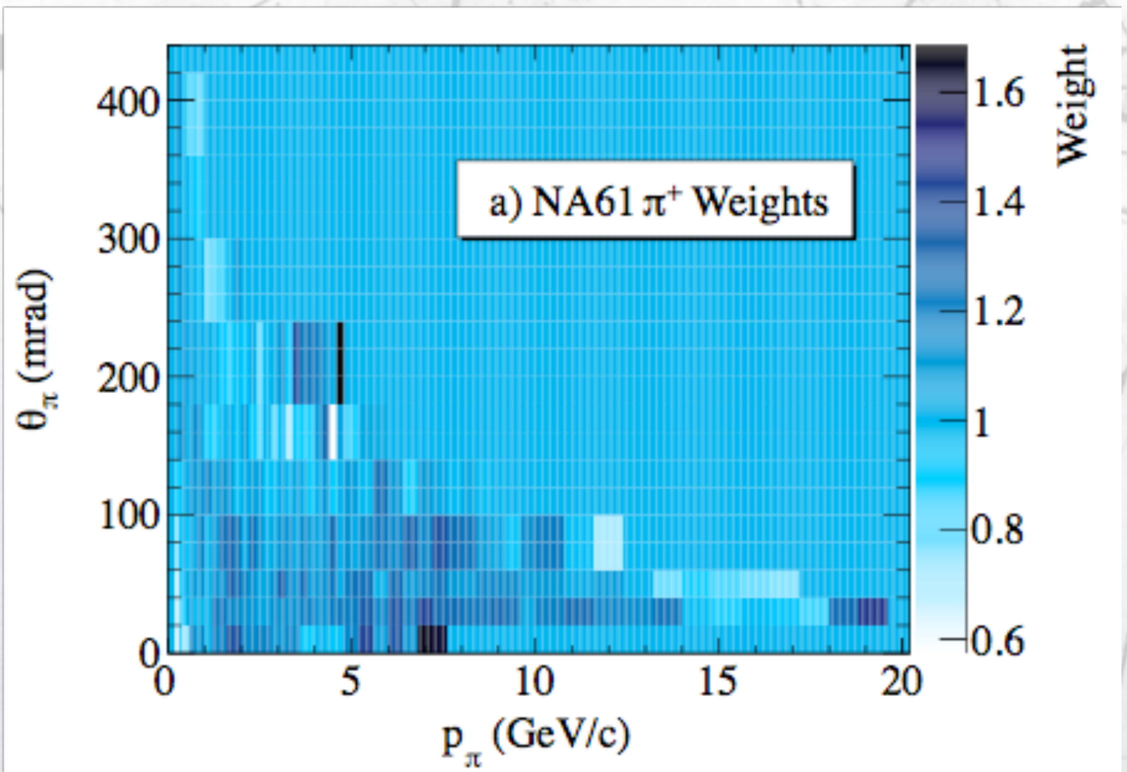
Running ND and SBL experiments will improve. experimental data.
Is this enough ?

Hadro production

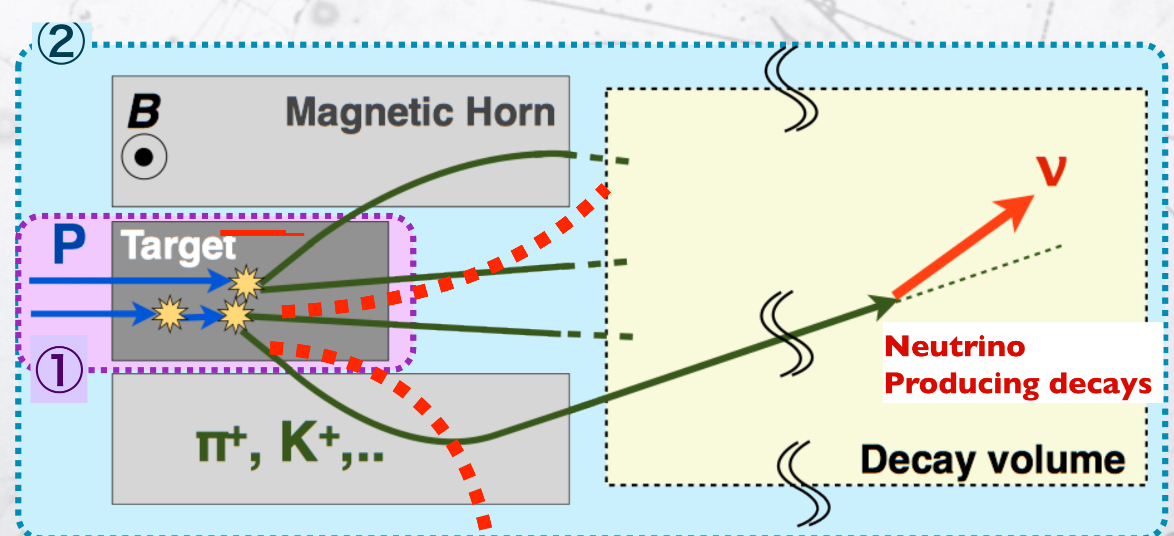
$$\pi^+ \to \mu^+ \nu_\mu$$
$$\pi^- \to \mu^- \bar{\nu}_\mu$$

NA61/Shine measures a thin target for absolute production and thick target that is a copy of the ν target and provides also the re-interactions of particles.



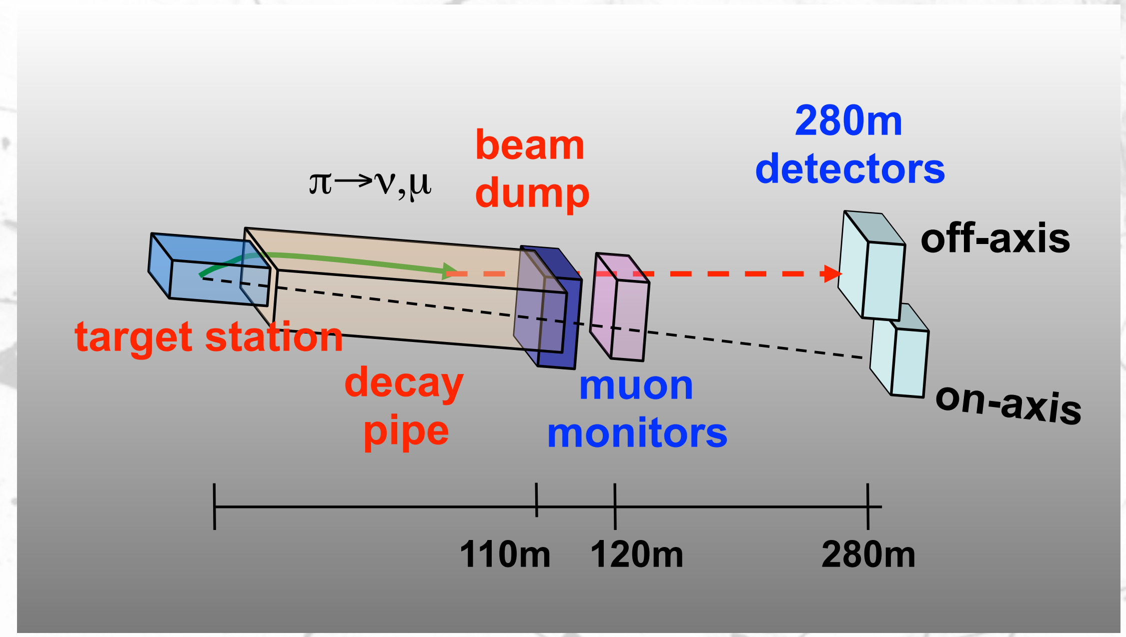


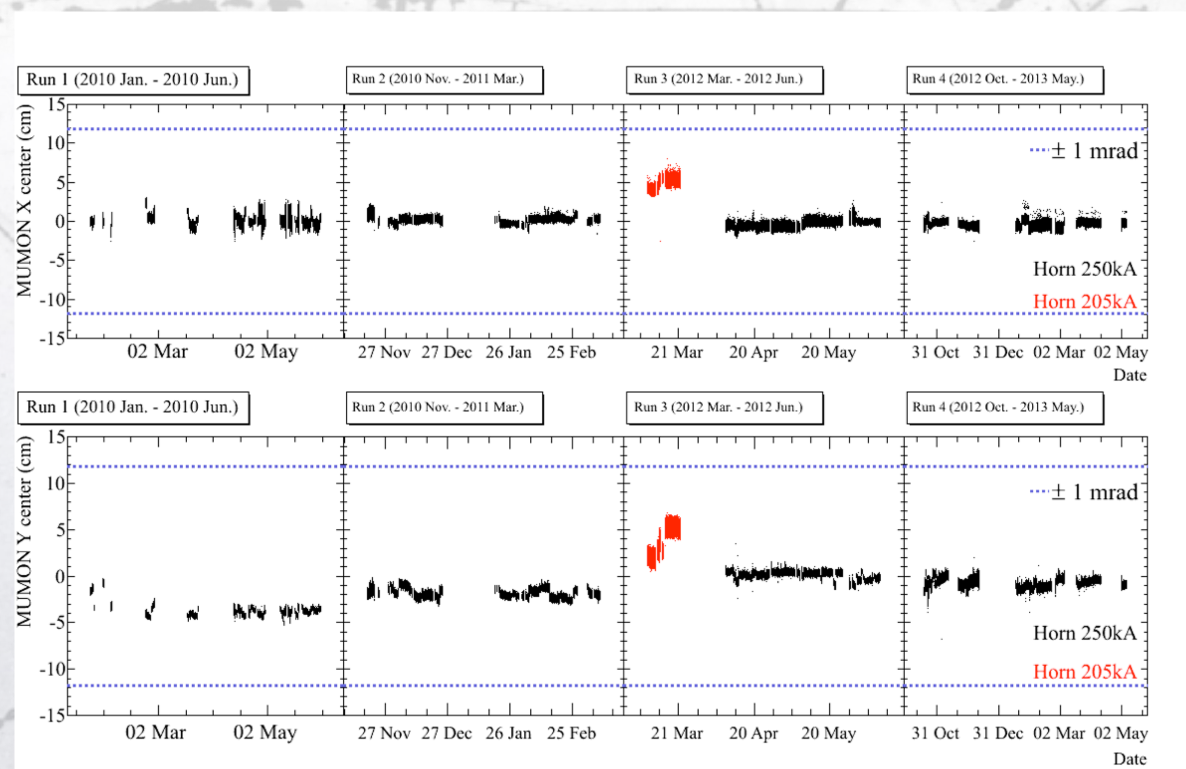
NA61/Shine measures the production of pions and kaons as function of the momentum and angle for protons interacting with carbon.

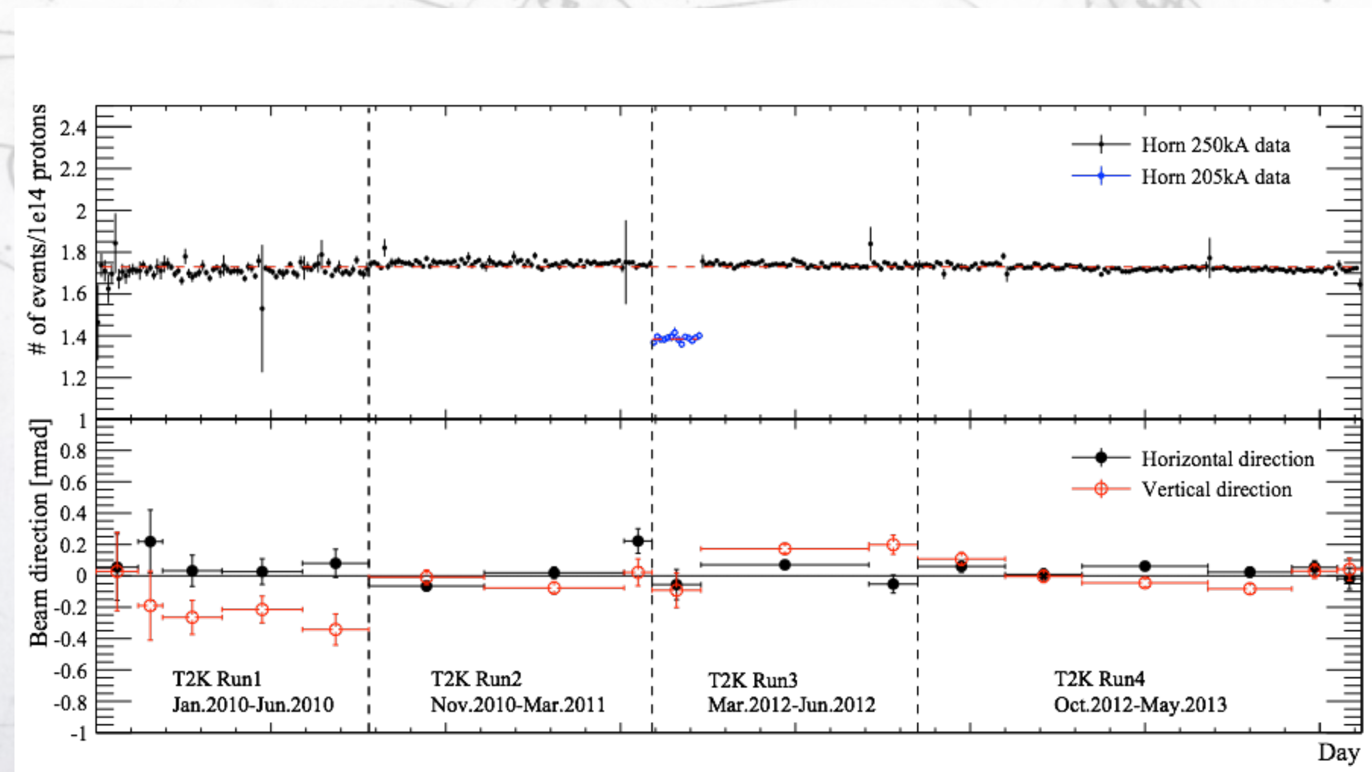


Beam monitoring

- Beam monitor:
  - direction is very critical for off-axis beams and depend on proton beam direction.
  - intensity.
- Monitoring can be done measuring the muons associated to the pion production or by neutrinos themselves.

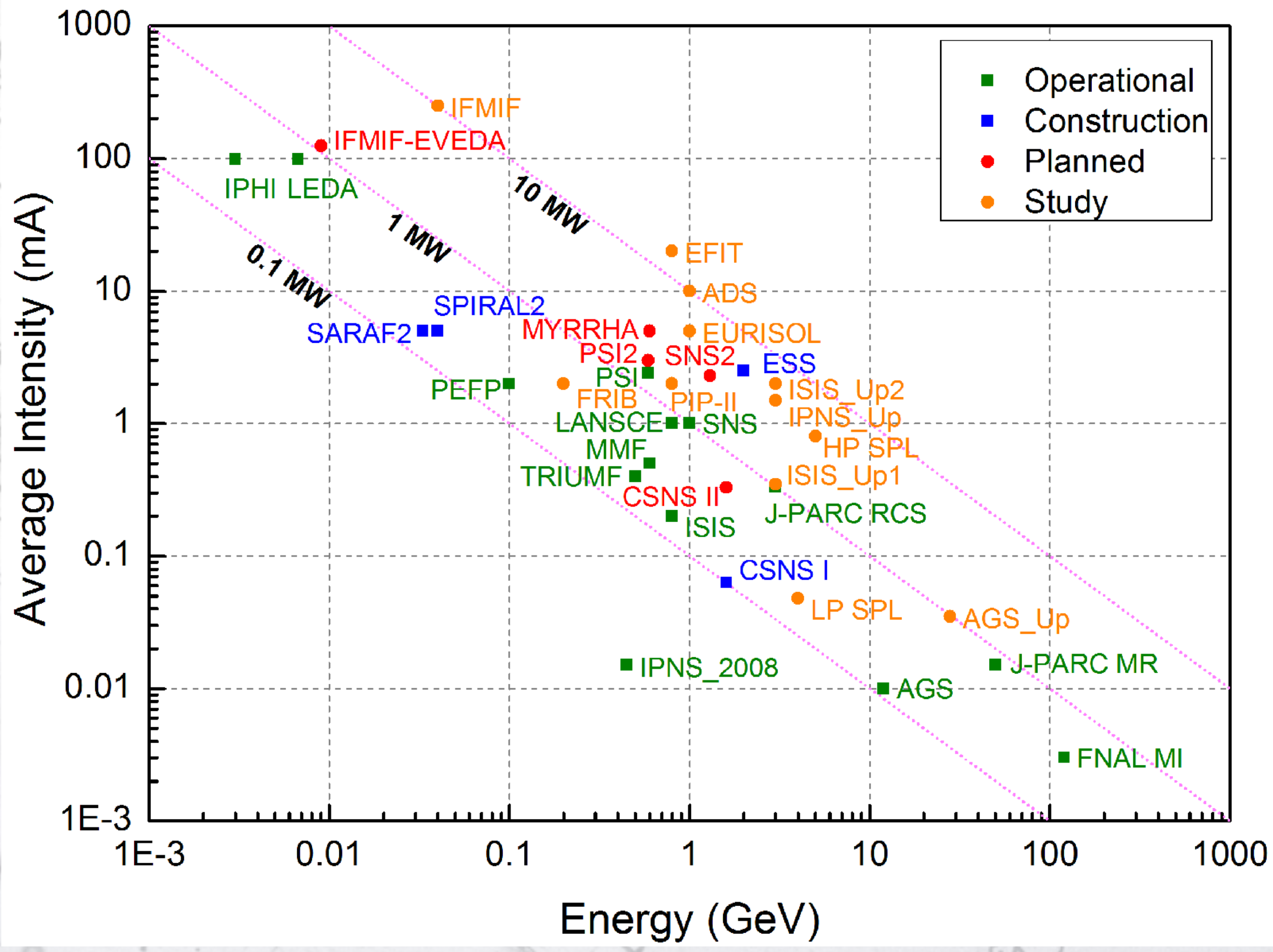




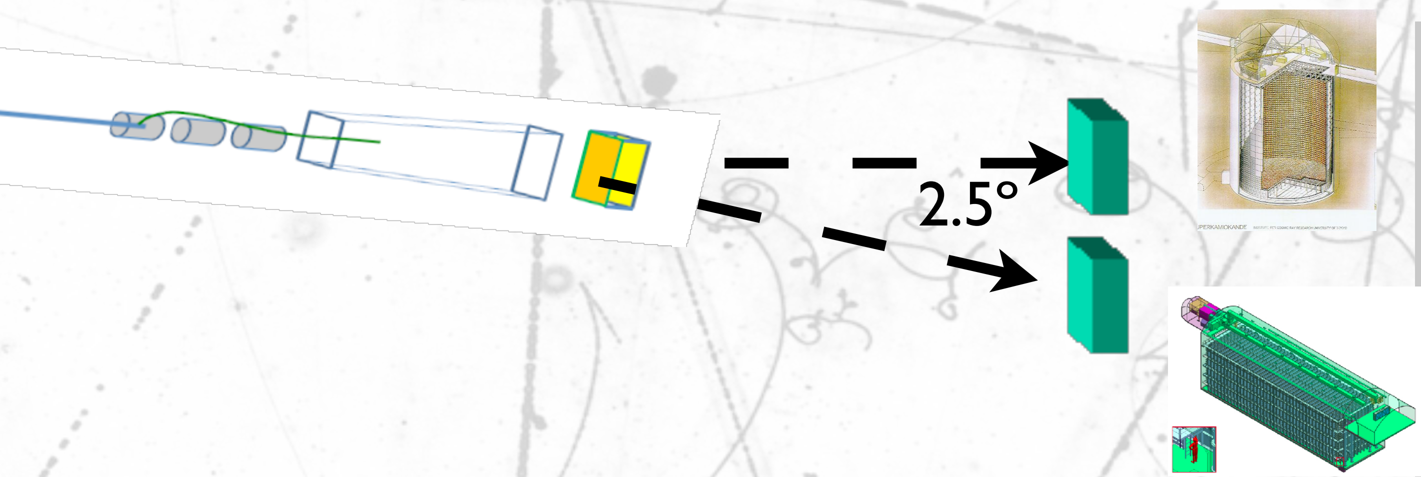


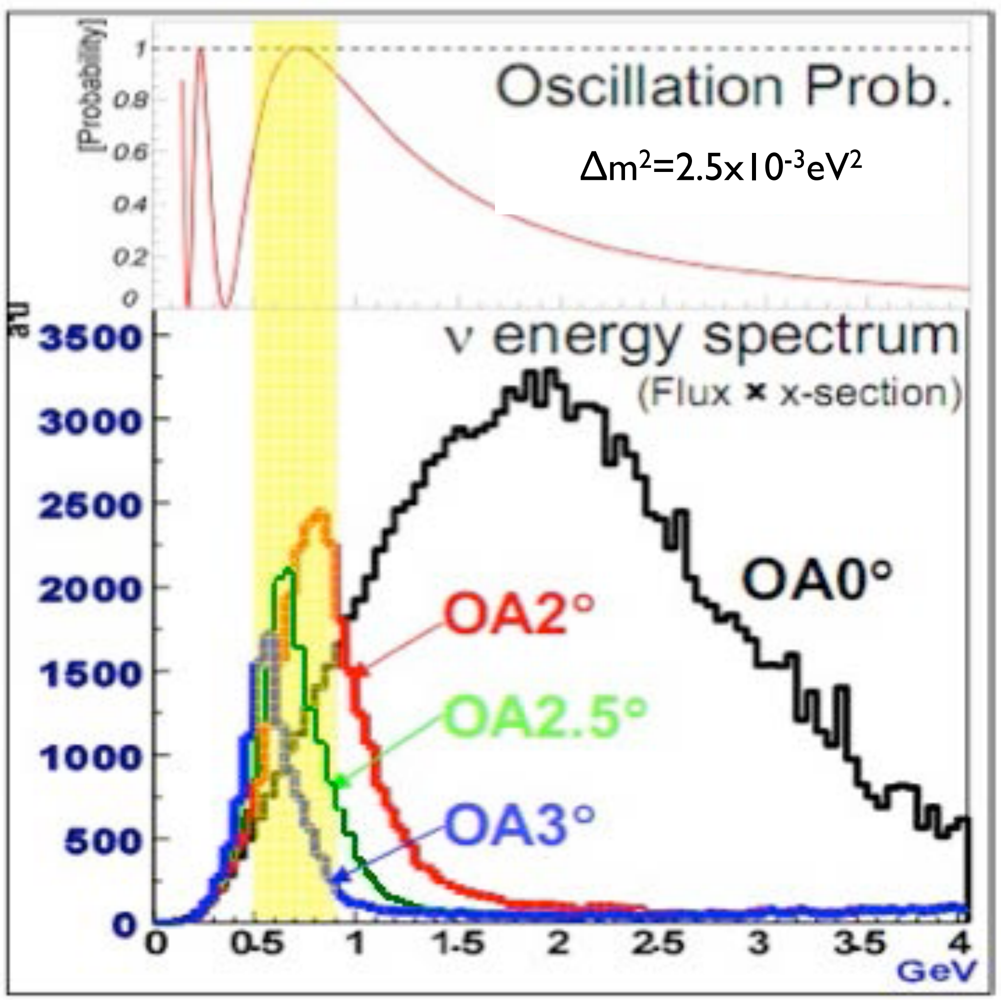
Beam power

- More power = more neutrinos.
- New generation of experiments require beam power of ~MW.



On vs. Off Axis





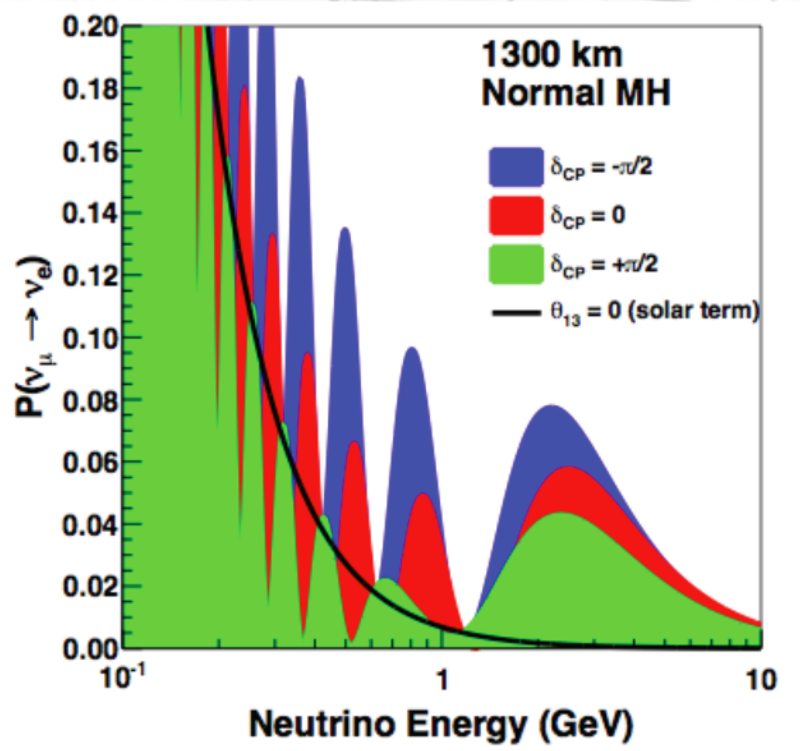
Off-axis

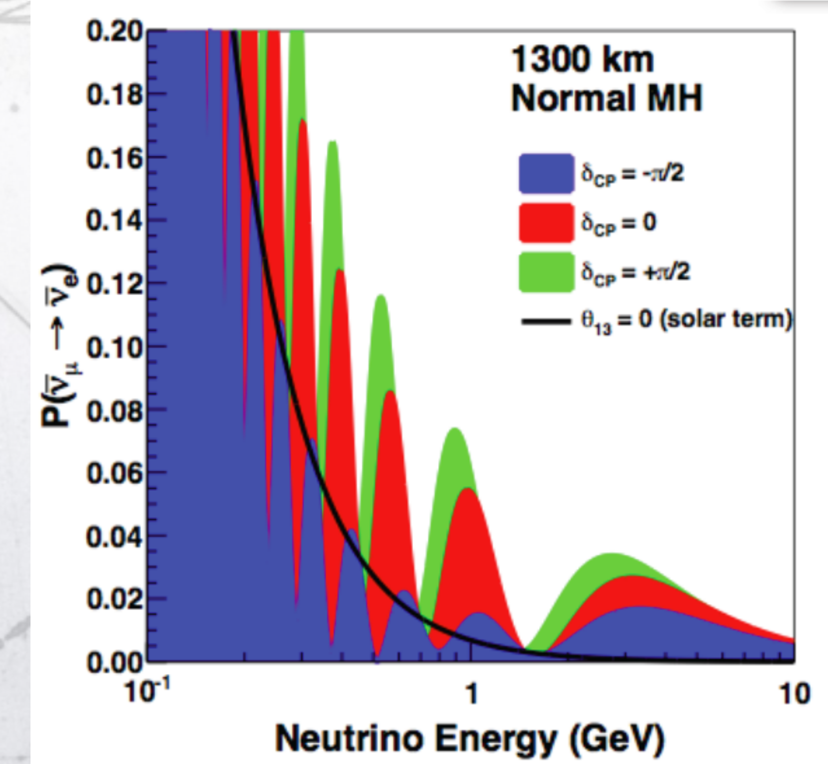
- off-axis optimises the flux at the maximum of the oscillation.
- Only one oscillation maximum can be measured at a fixed distance.
- Narrow beam less dependent on beam uncertainties but more on beam pointing.

On-axis

- on-axis optimises the total flux.
- Has higher neutrino energy.
- Broad beam so more than one oscillation maximum can be measured at a fixed distance.

Beyond 1st oscillation





- Ratio between first and second oscillation maximum changes for different values of hierarchy & δ_{CP}
- Better sensitivity, reduced systematic uncertainties !
- Two ways to get it:
  - Change E or change L.

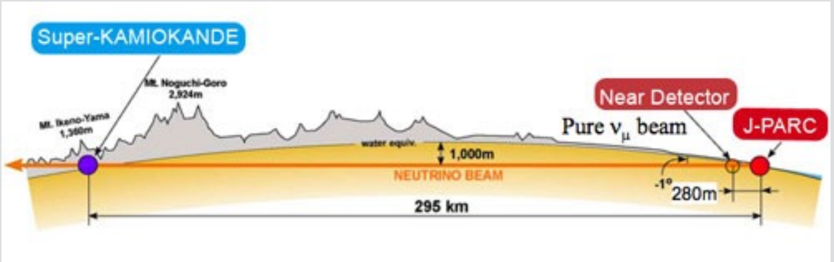
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \approx\ & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E}\left(1 \pm \frac{2a}{\Delta m_{13}^2}(1-2s_{13}^2)\right) \\
& + 8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{23}s_{13}) \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E} \\
& \mp 8c_{13}^2 C_{12} C_{s3} s_{12} s_{13} s_{23} \sin\delta \sin\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E} \\
& + 4s_{12}c_{13}(c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta) \sin\frac{\Delta m_{21}^2 L}{4E} \\
& \mp 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{21}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E}(1-2s_{13}^2)
\end{aligned}
$$

LBL today & near future

@ Japan (since 2009)

baseline : 295 km

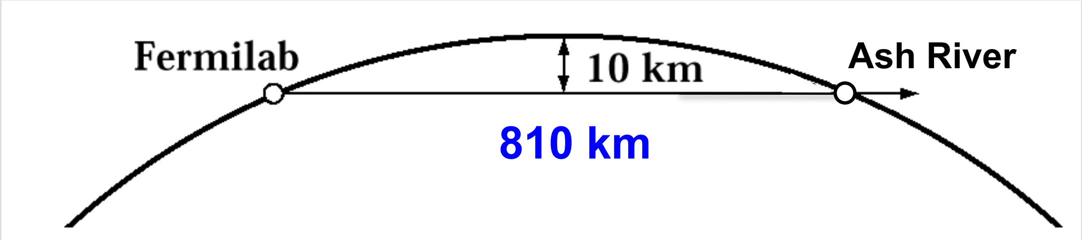
19% of full statistics $(\bar{\nu} : \nu = 1:1)$



@ US (since 2013)

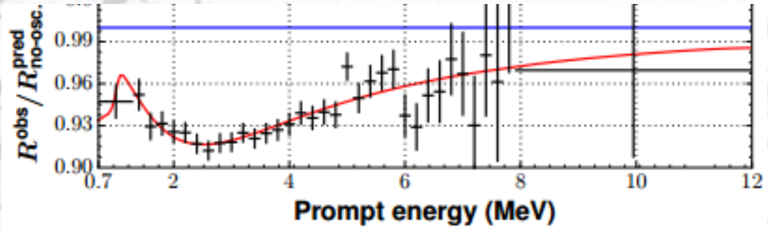
baseline : 810 km

15% of full statistics $(\bar{\nu} : \nu = 1:0)$



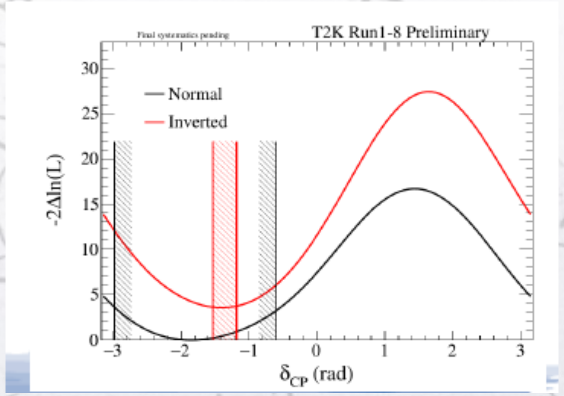
Daya-Bay Double Chooz & RENO

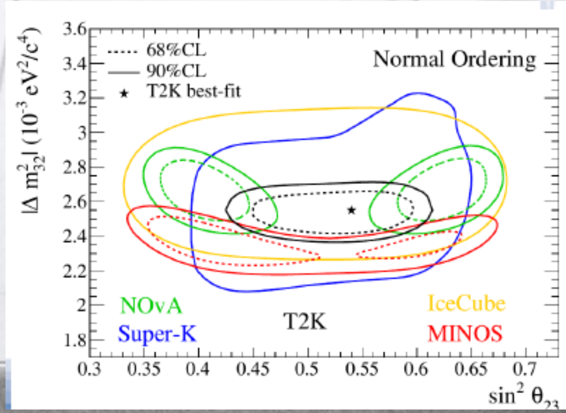
baseline : ~1 km



θ_{13} to 2% precision

δ_{CP} up to 4σ

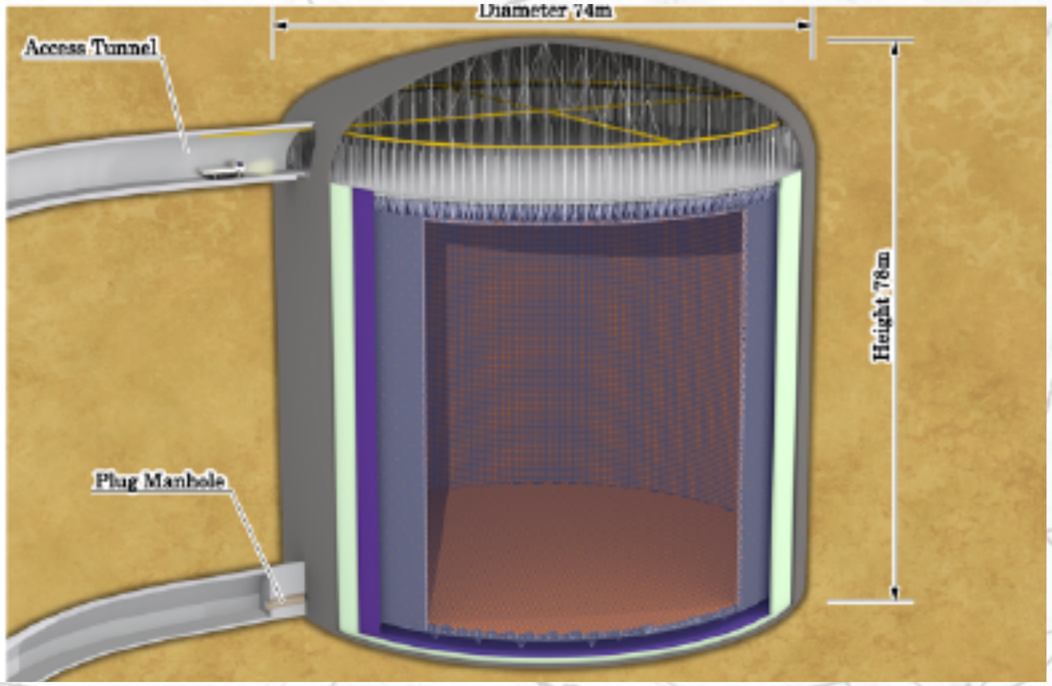


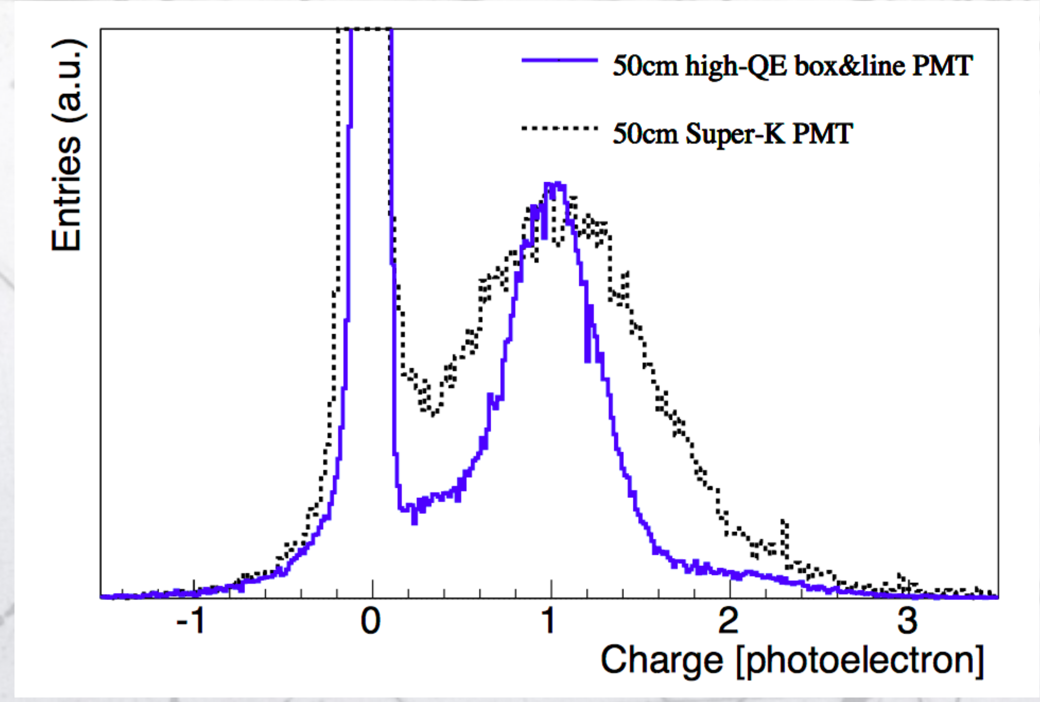


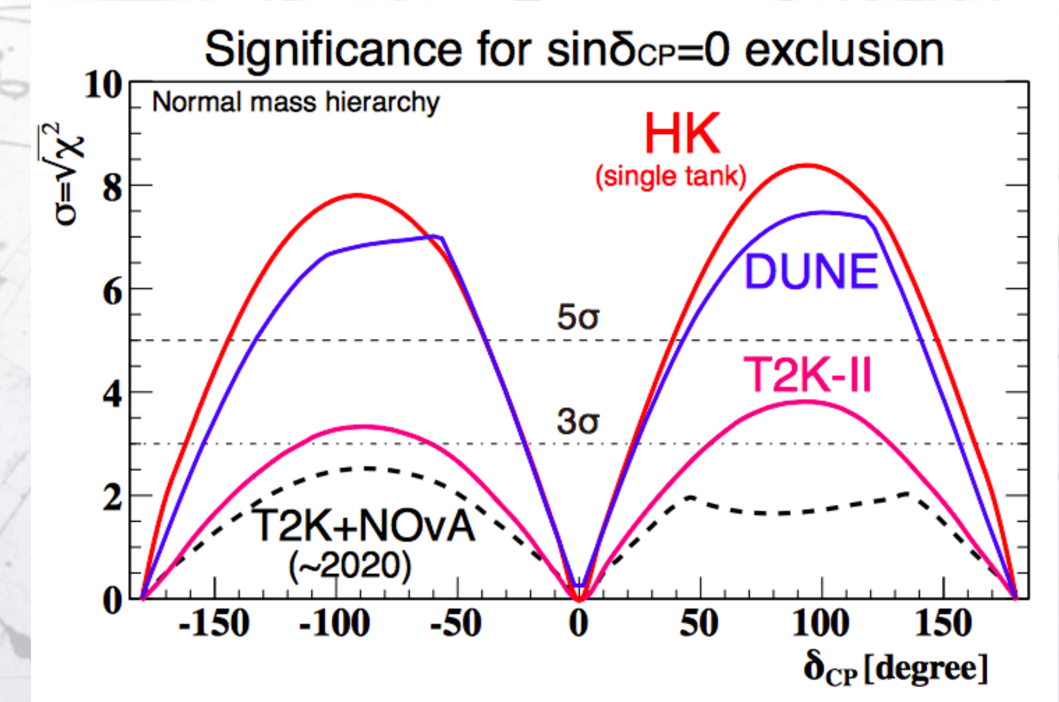
θ_{23} < 10% precision

T2HK(K)

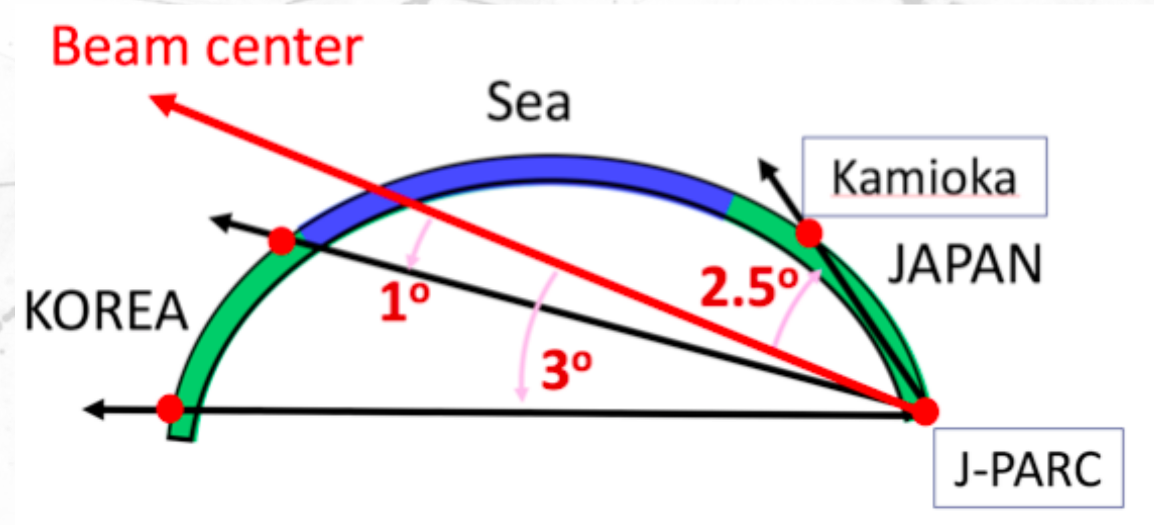
- Off-axis
  - possible 2nd oscillation peak in Korea.
- Kinematic reconstruction.
- Large mass (~1/2 MTon).
- 2-5 σ on Mass Hierarchy depending on θ_{23}

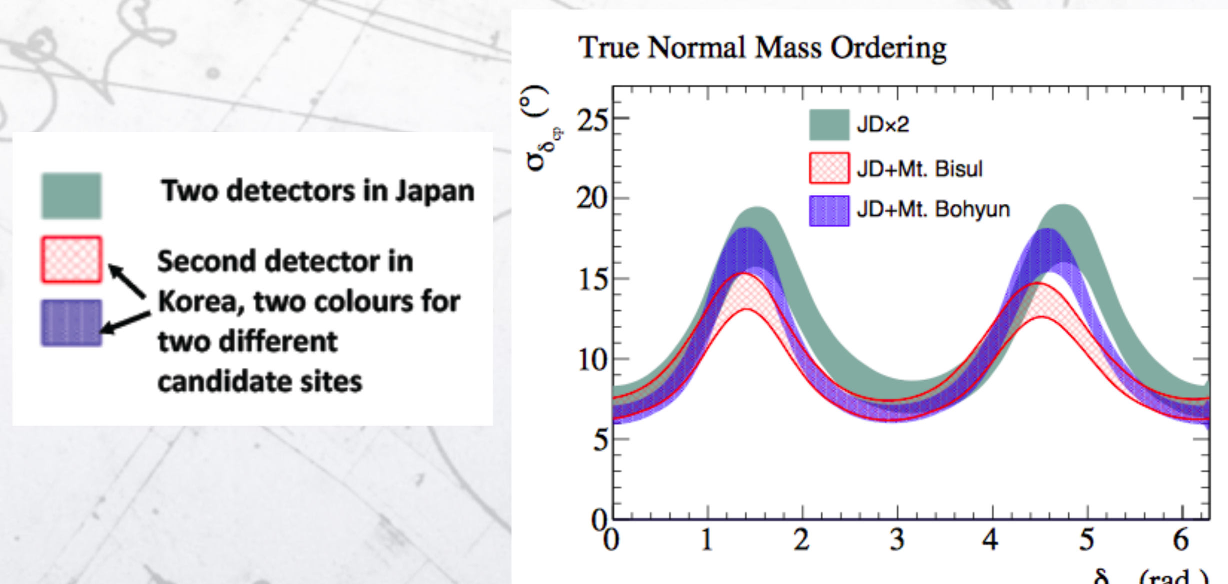




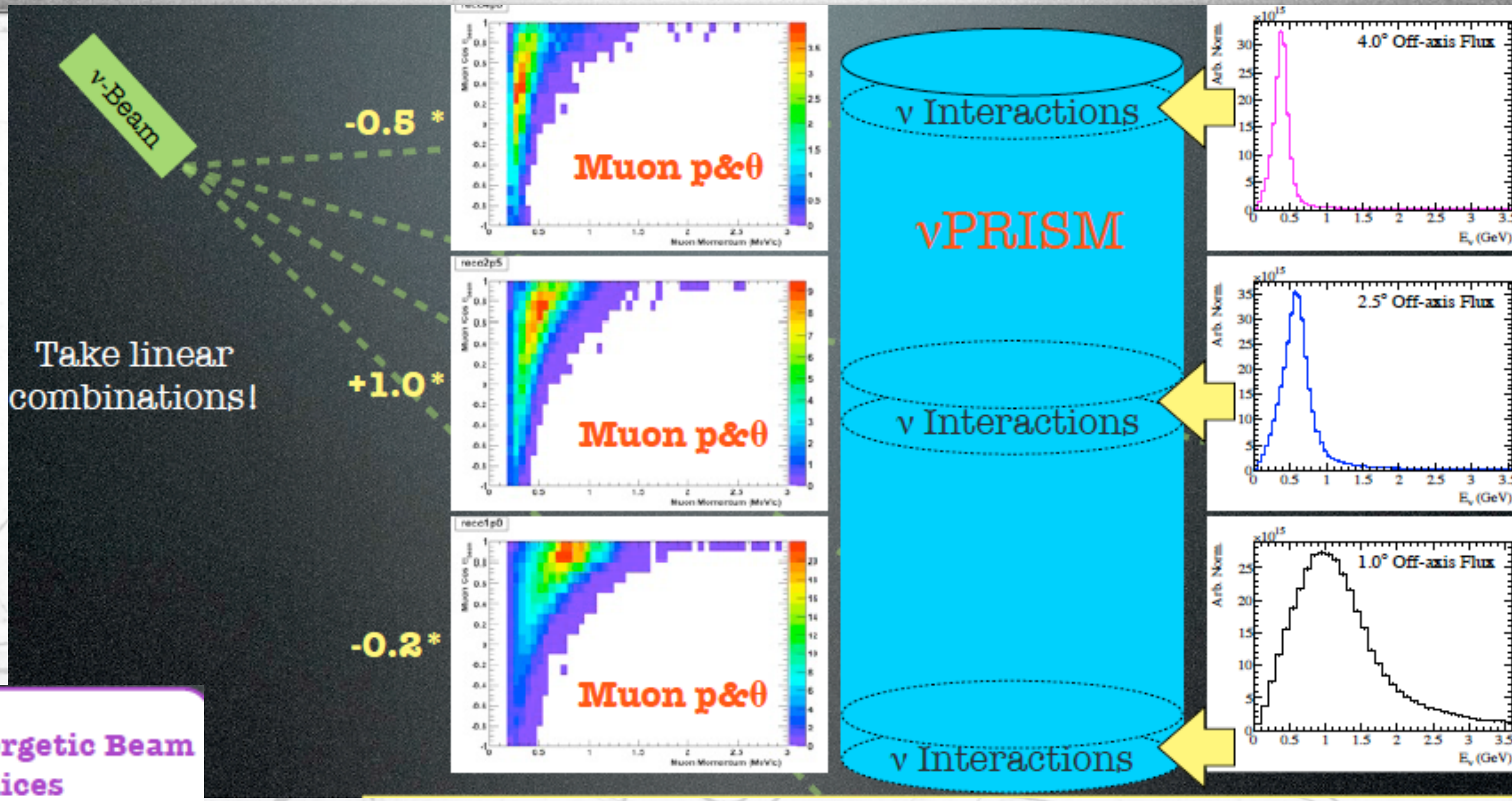


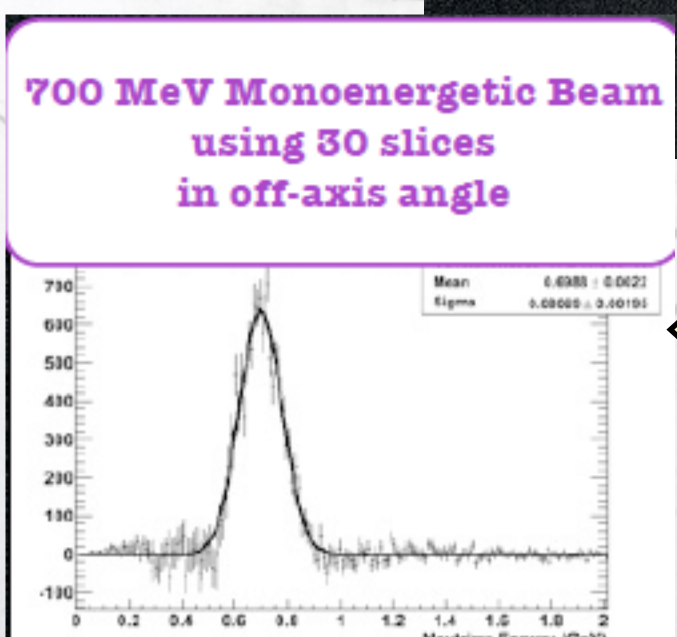
- Second detector in Korea:
  - similar beam shape (2-3º). Reduced systematics.
  - Double the distance : second oscillation.
- Same detector technology for both detectors.
- Increased matter effect for hierarchy measurement.





NuPrism





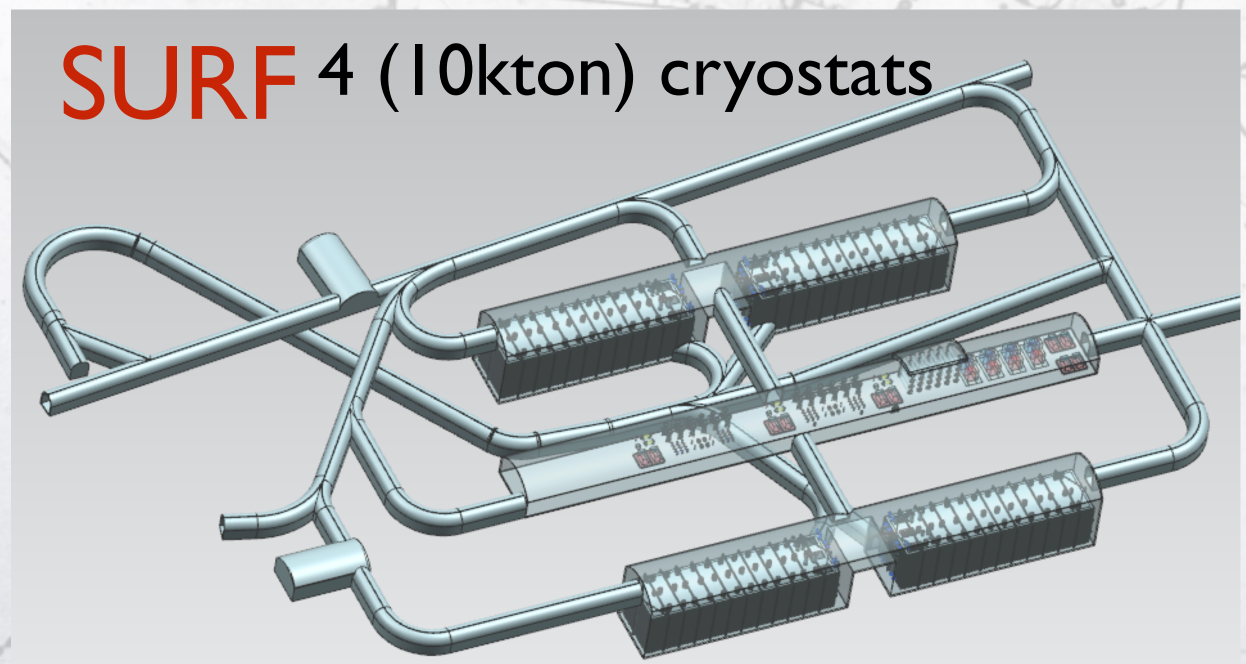
$$N(E_\nu) = \sum_{i=0}^{N_{slices}} C_i \Phi_i(E_\nu)$$

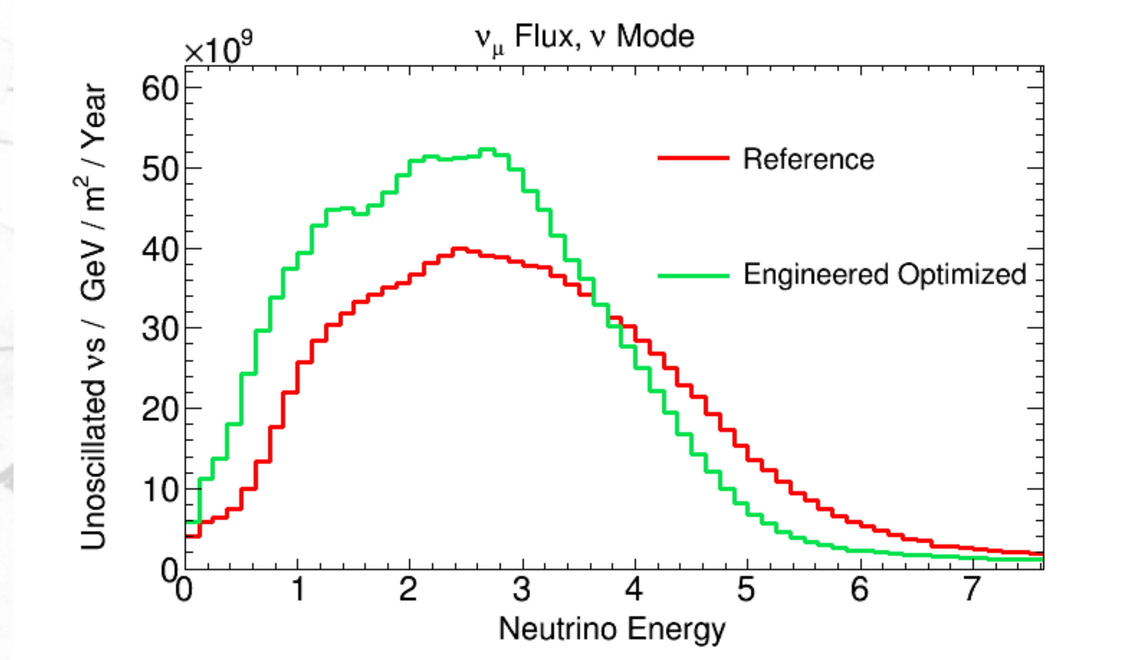
Approach only 100% valid for off-axis beams!

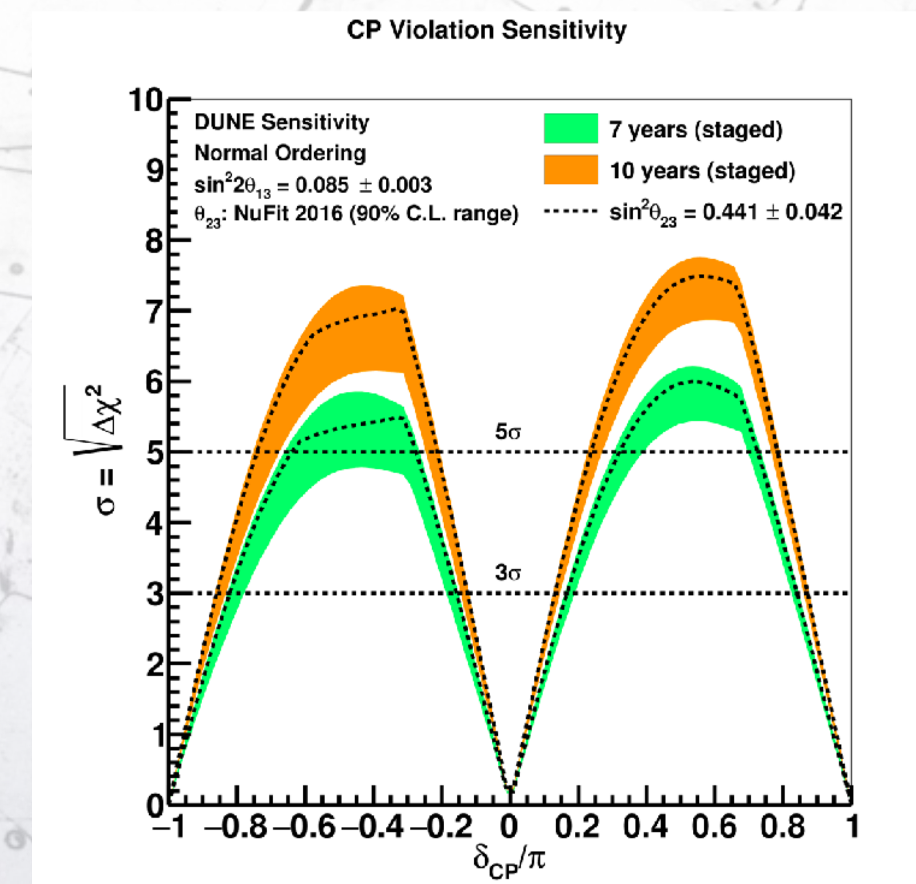
$$P(E_\mu, \theta_\mu | E_\nu) = \sum_{i=0}^{N_{slices}} C_i N_i(E_\mu, \theta_\mu)$$

DUNE

- On-axis
  - 2[nd] oscillation peak by Energy reconstruction.
- Calorimetric reconstruction.
- Moderate mass (40 kTon).
- > 5σ on mass hierarchy.



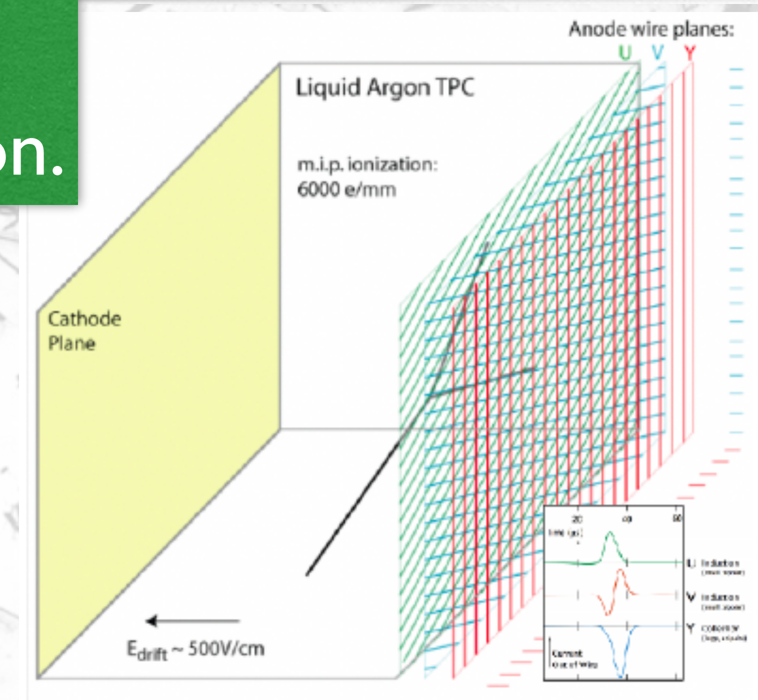




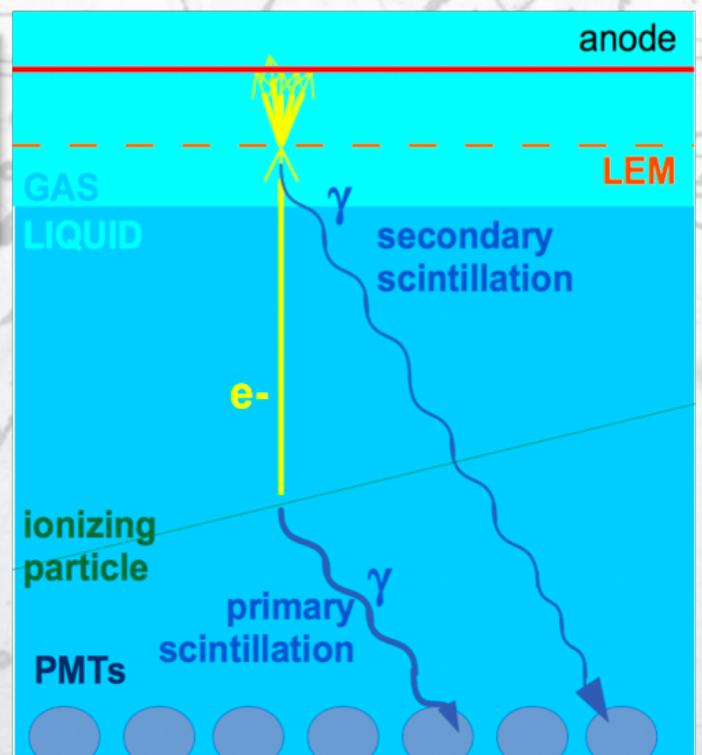
Proto-Dunes

- 2 big (6x6x6 m3) cryostats being build at CERN.
  - prove technologies.
  - Calibrate detector response with beam.

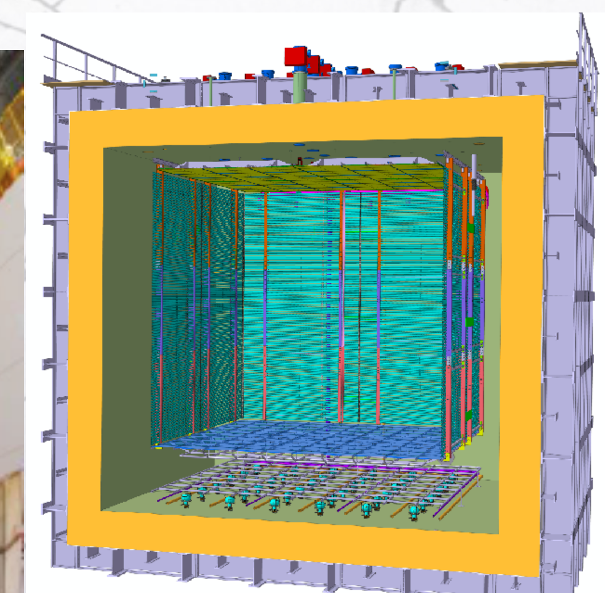
Single phase: no amplification.



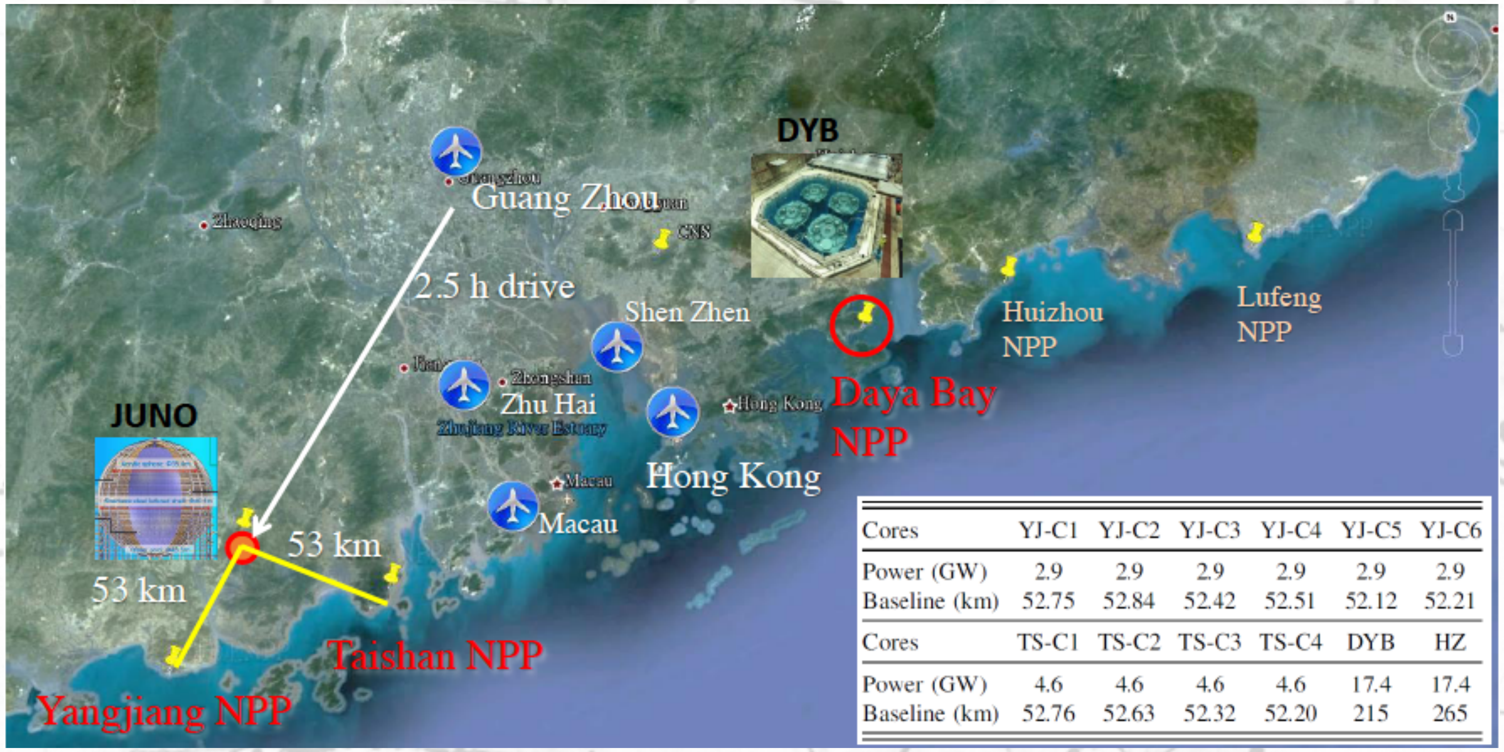
Double phase: amplification in gas



Cryostat construction technology



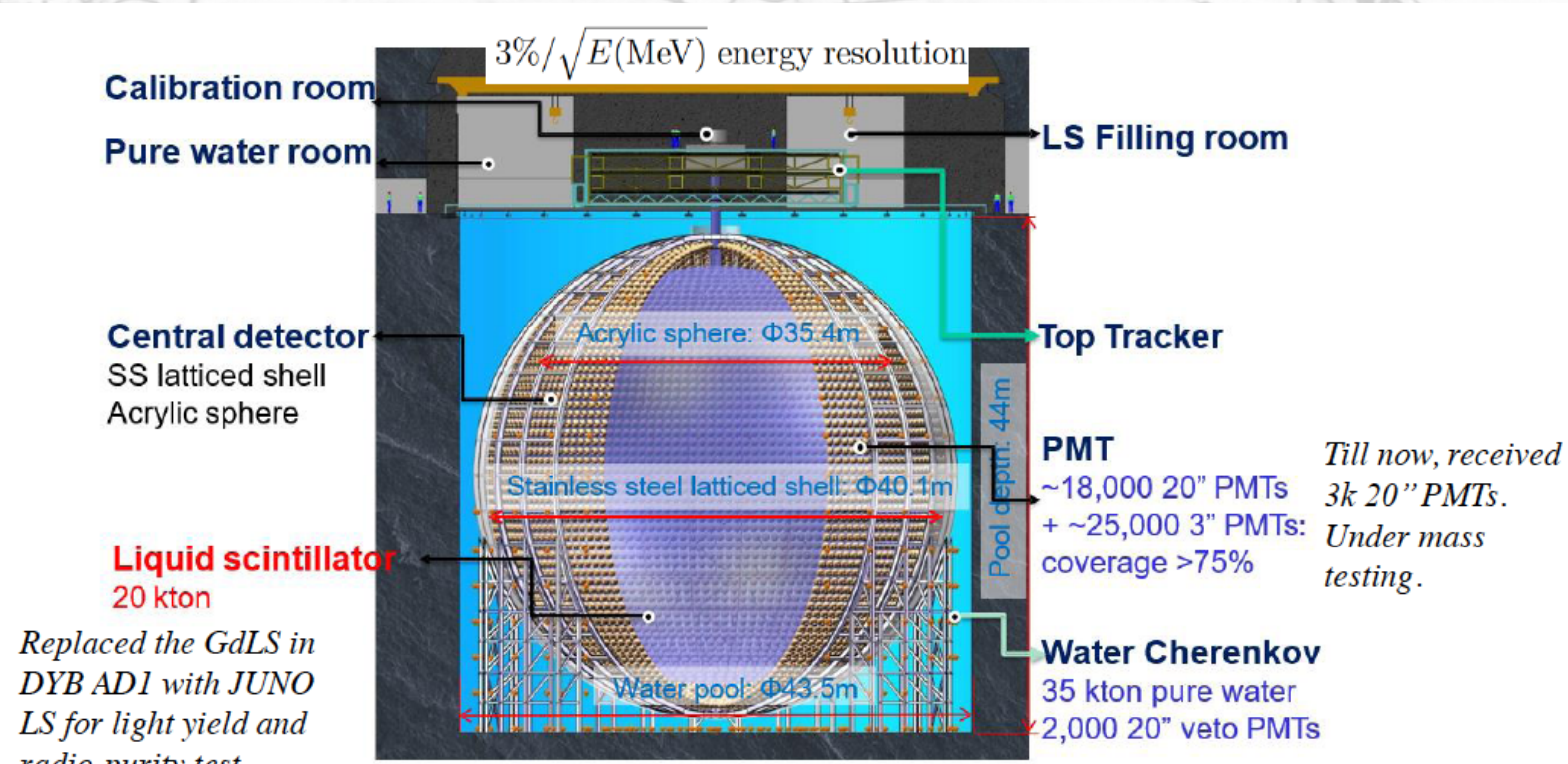
Juno



Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

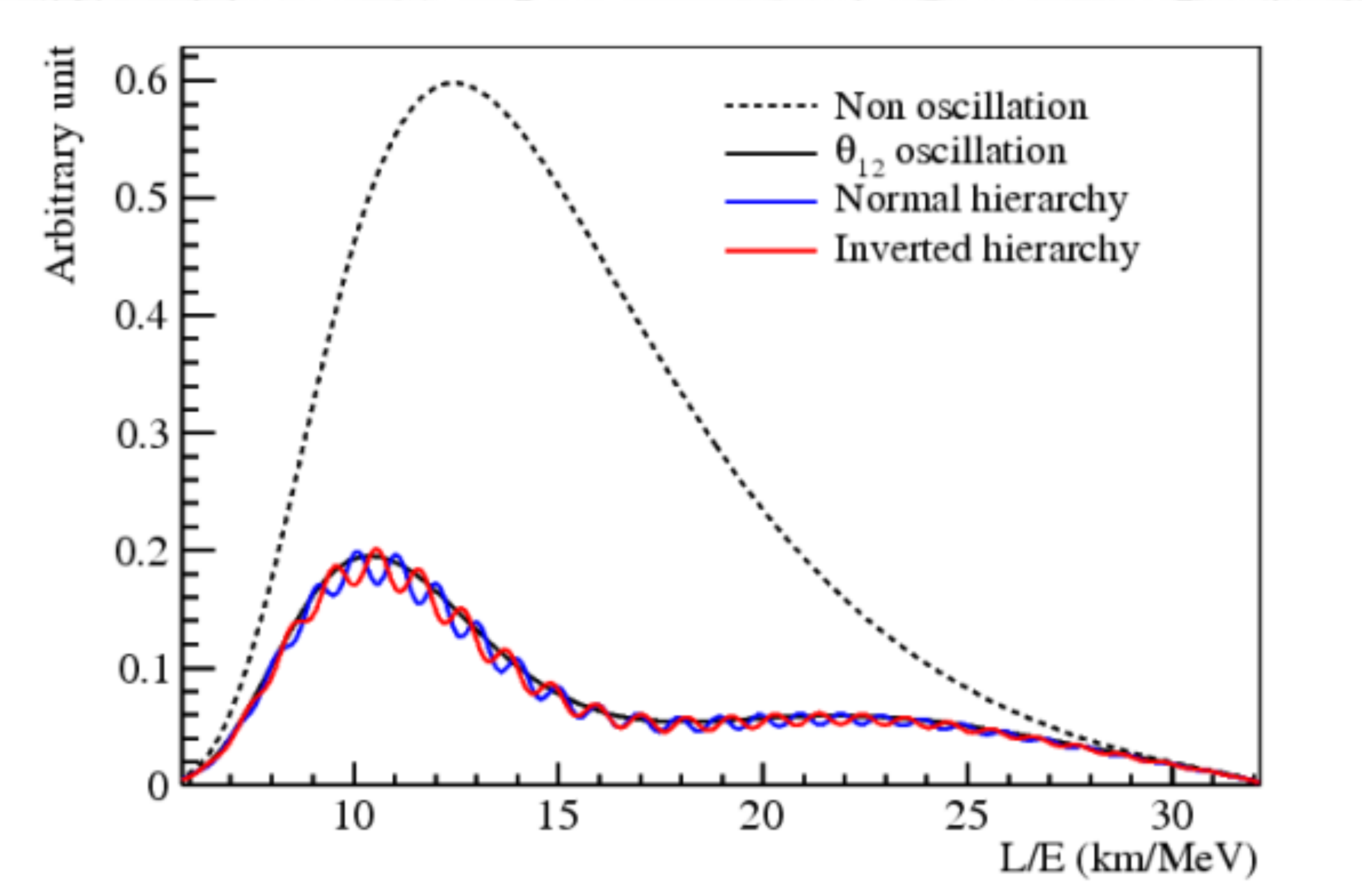
Approx. constant baseline of 52 km.

20 kton detector with $3\% / \sqrt{E}$ resolution.



Juno

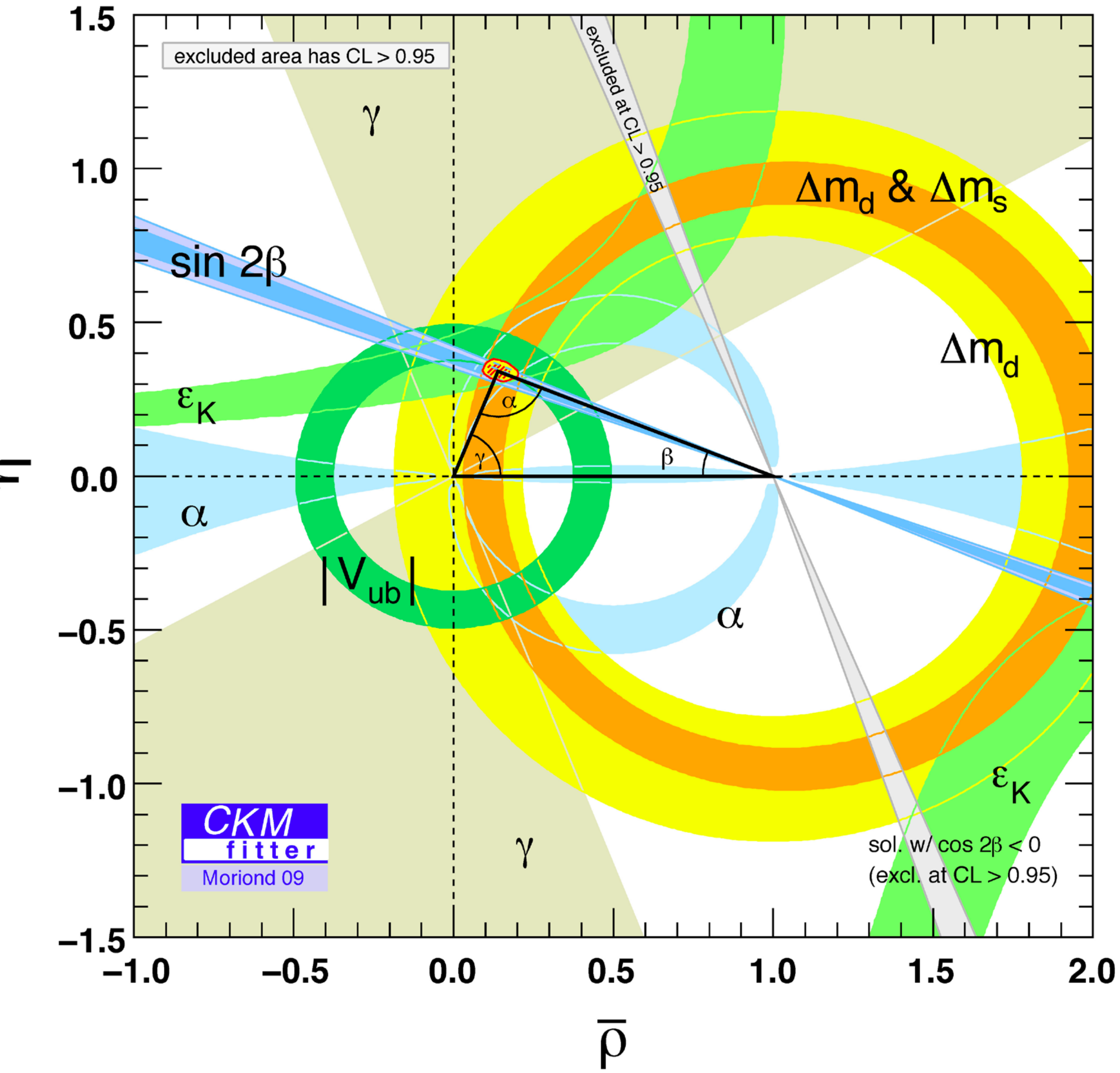
- Precise θ_{12} and Δm^2_{12} measurements.
- 4σ IH/NH determination.
  - σ_E is critical.
- Geo-neutrinos, SN, …



Beyond paradigm

- Testing the model with closure tests:
  - Over-constrain parameter space.

What we ultimately want to achieve:



We need to do this in the lepton sector!

Search for sterile neutrinos is an alternative manner to check unitarity. (see B.Fleming talk)

HOW?

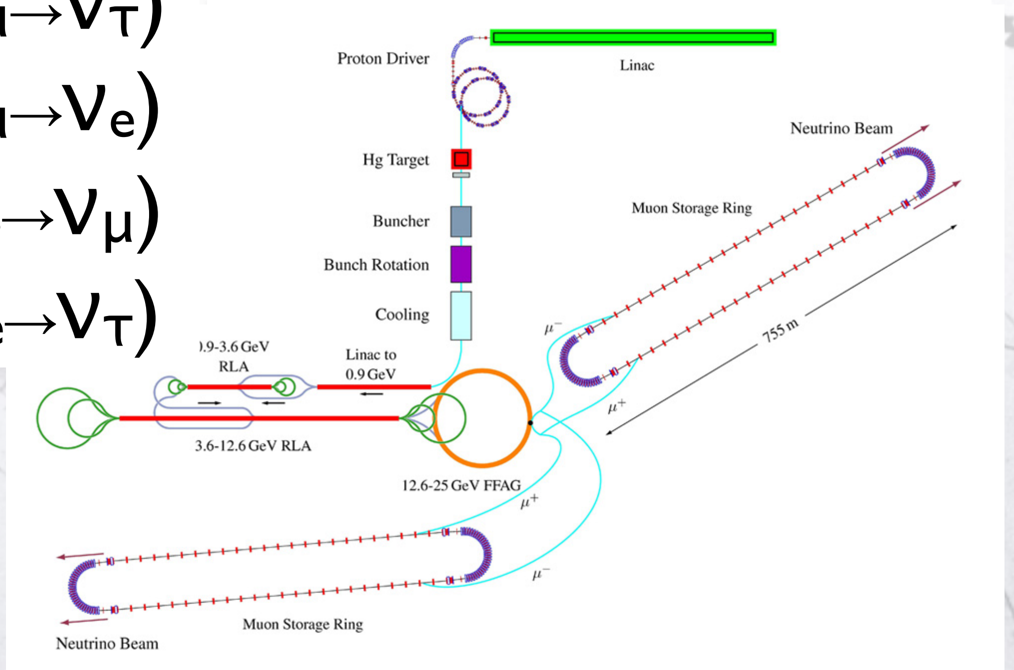
$P(\nu_\mu \rightarrow \nu_\tau)$

$P(\nu_\mu \rightarrow \nu_e)$

$P(\nu_e \rightarrow \nu_\mu)$

$P(\nu_e \rightarrow \nu_\tau)$

Neutrino Factory



Synergies

- Future experiments need each other to get the best result.
- Synergies are provided at two levels:
  - different experimental approaches.
  - Providing precise measurements of oscillation parameters.

Final remarks

- Next generation of experiments aims at a precision that requires an inclusive approach to control many of the systematics:
  - beam, cross-sections and neutrino energy reconstruction.
- This effort requires a global strategy to address all the critical items:
  - Nuclear theorists and experiments (e,e')
  - Ancillary experiments for low energy hadron cross-sections.
  - Beam modelling and measurements.
  - ν cross-section experiments. One of the most critical items is the measurement of $\sigma(\nu e)$
  - Beam power & large detector mass !!!!!
- Different approaches provide very different systematics (HK vs DUNE).

Supporting material

ν oscillations today

@ Japan (since 2009)

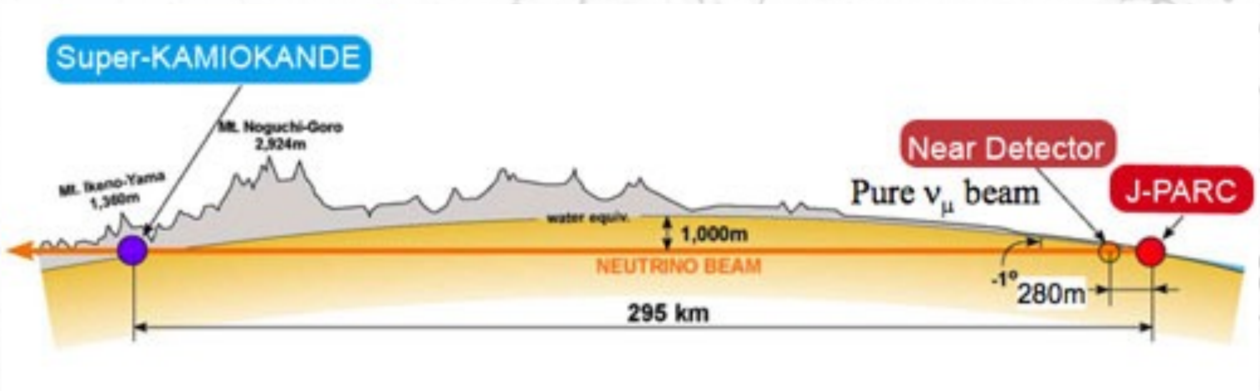
baseline : 295 km

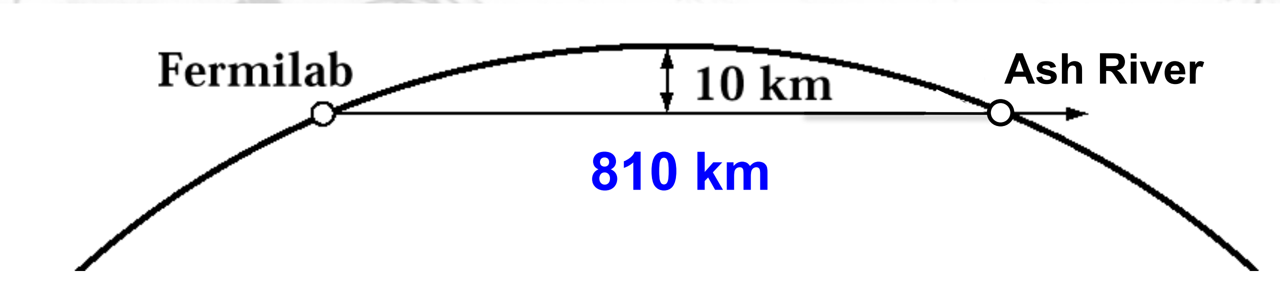
19% of full statistics $(\bar{\nu} : \nu = 1:1)$

@ US (since 2013)

baseline : 810 km

15% of full statistics $(\bar{\nu} : \nu = 1:0)$





- Two leading experiments

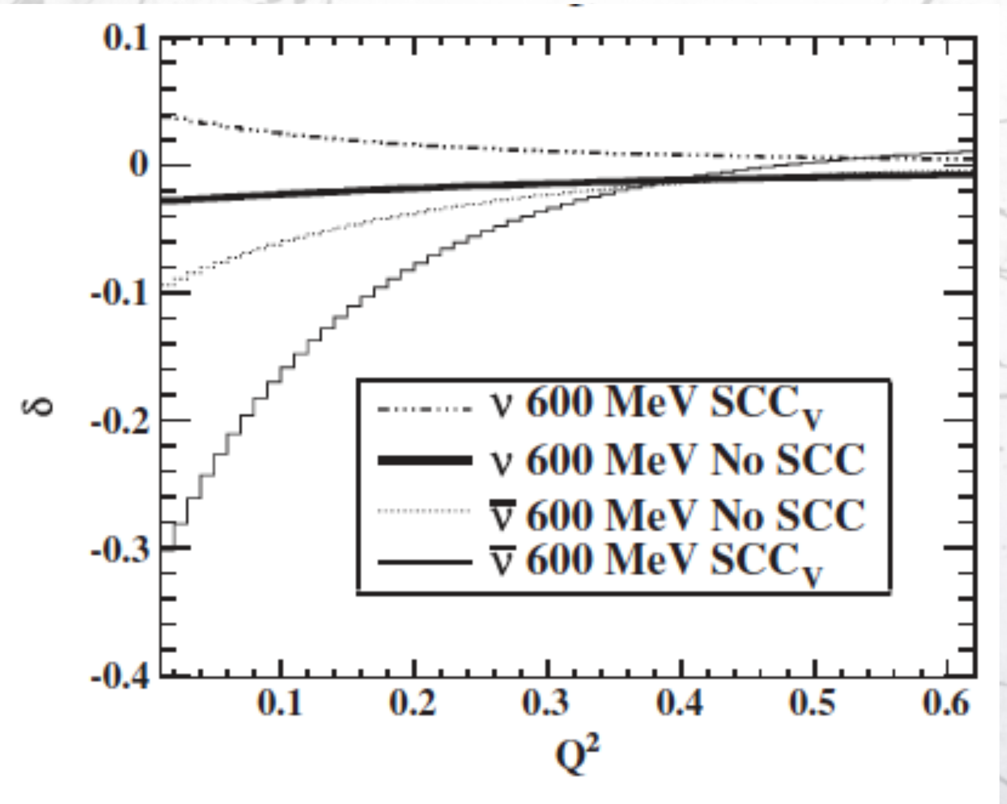
Neutrino Flux

- 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.

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.

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



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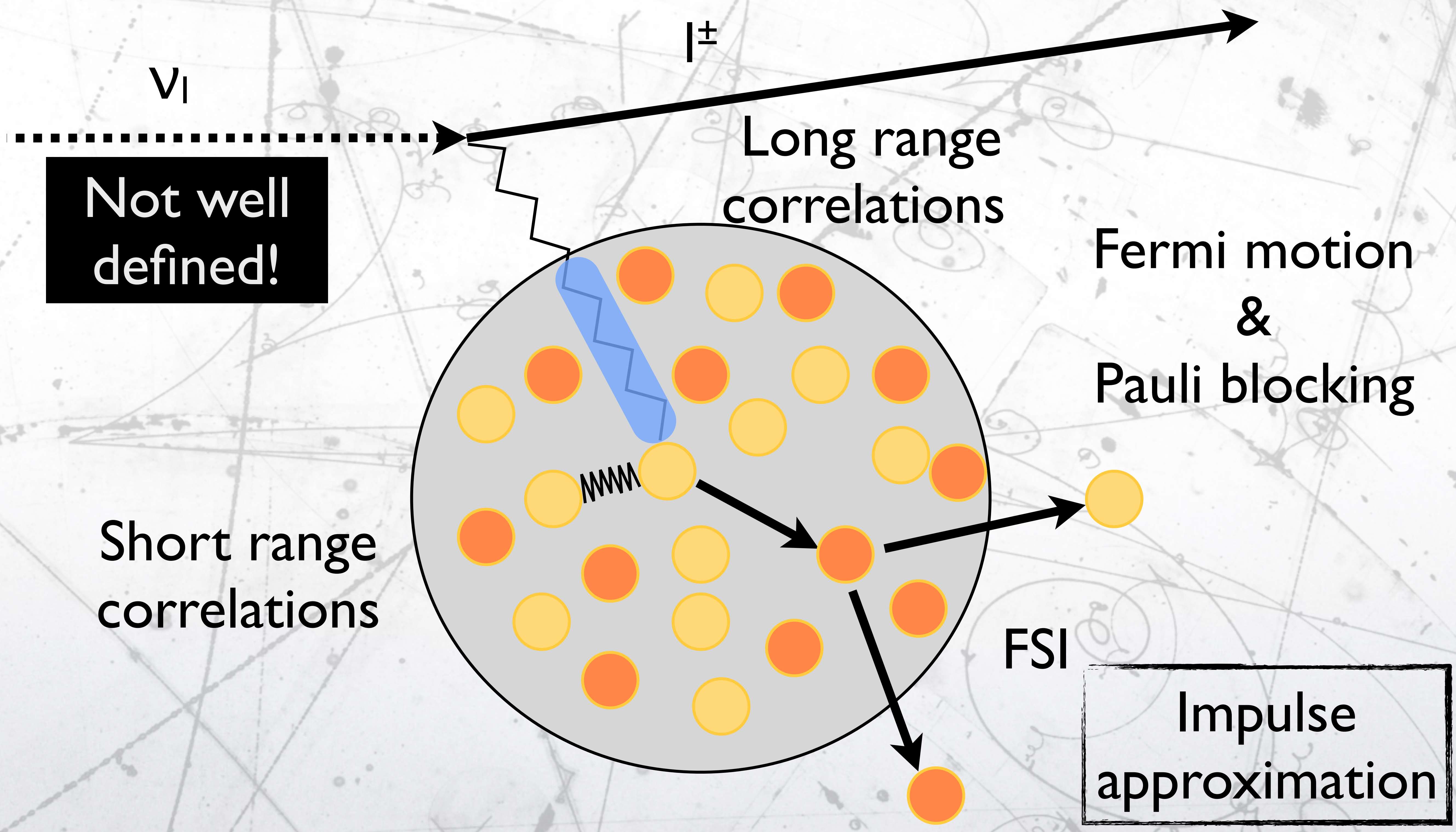
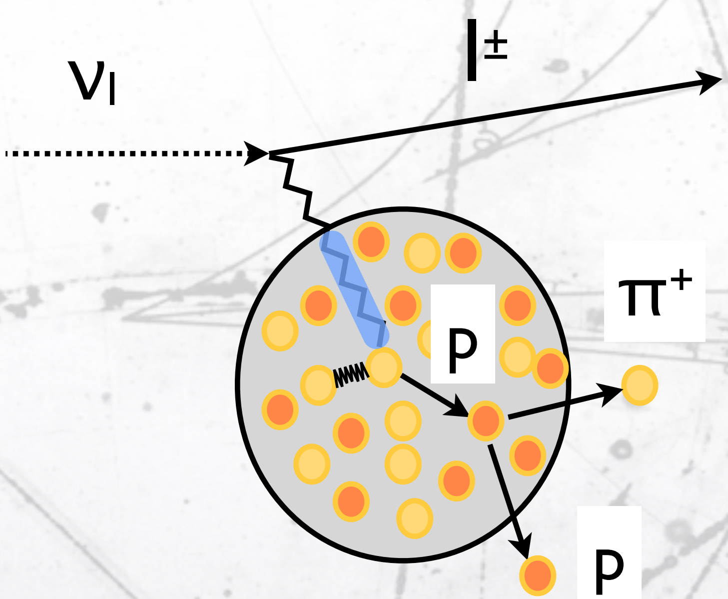
Neutrino interactions



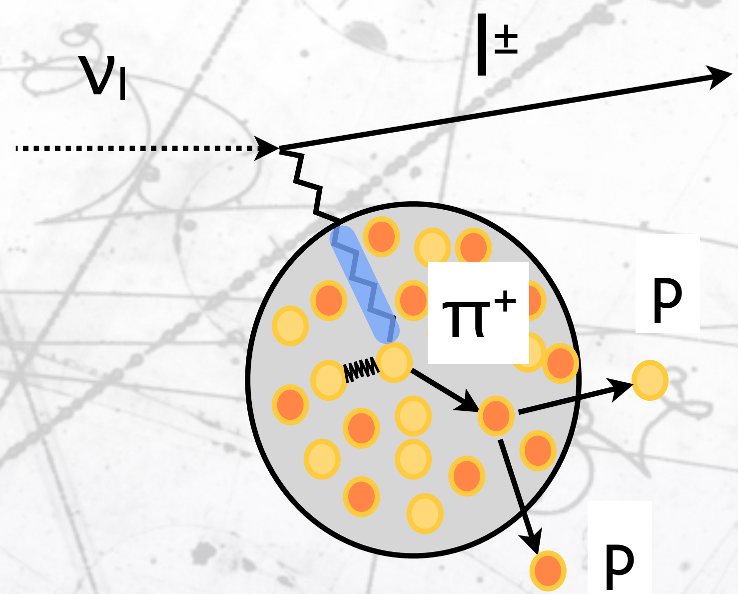
Problem factorisation

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

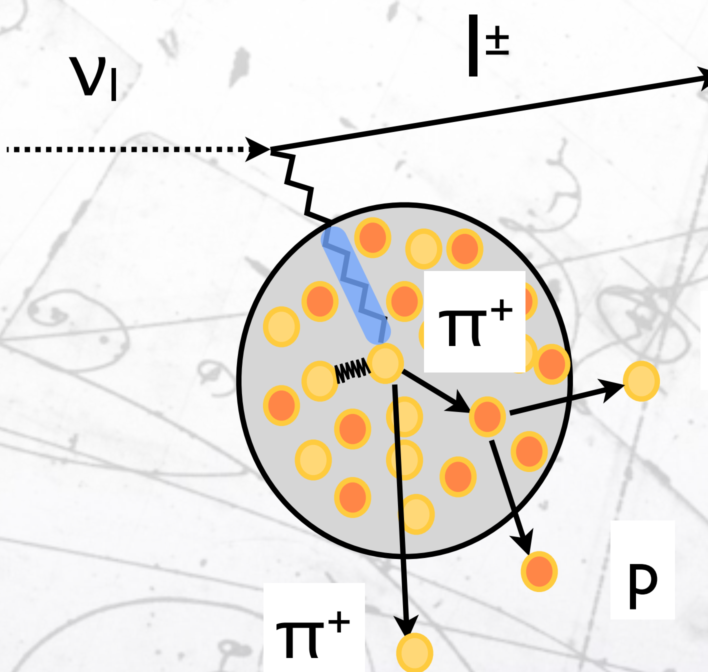
FSI alters the definition of the event



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 ?

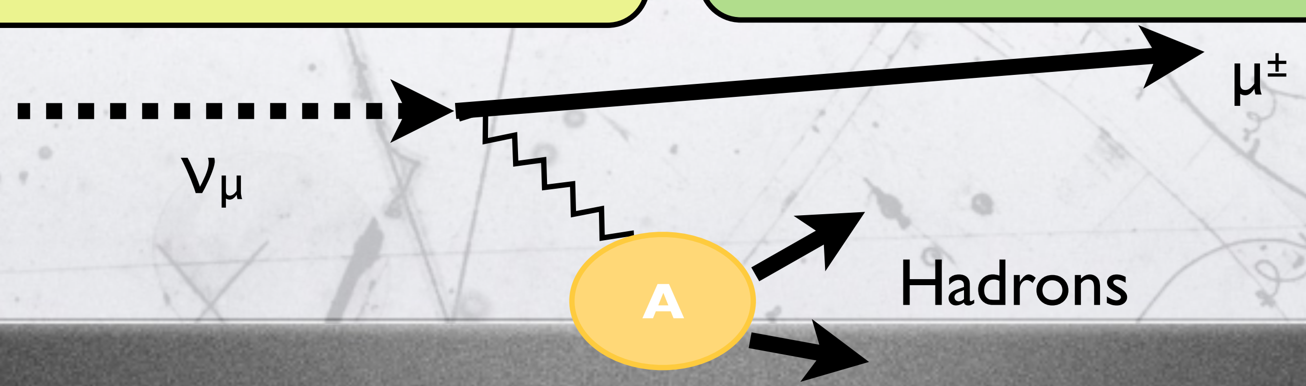
$P(E_\nu|E'_\nu)$

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.

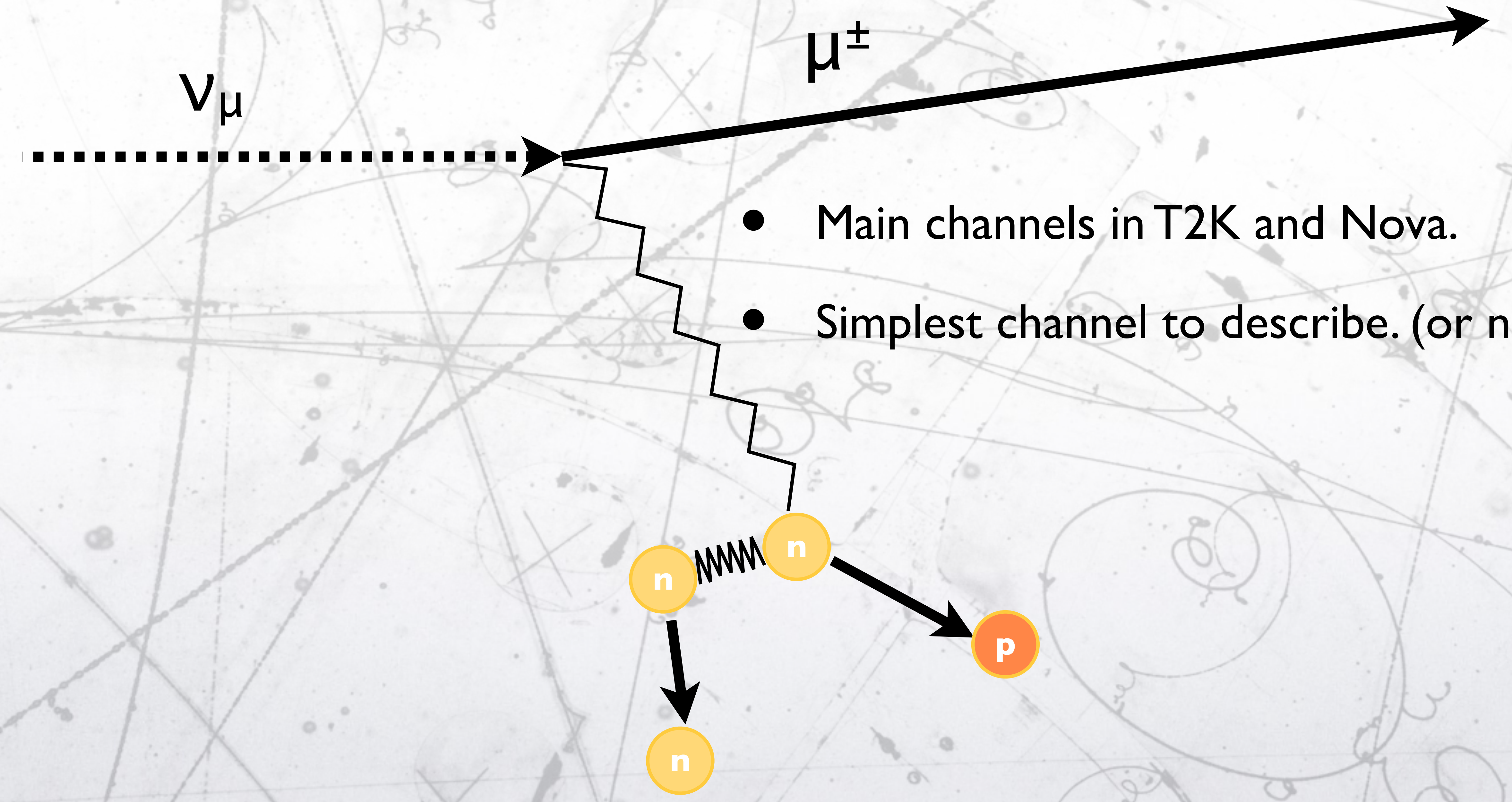


ND for oscillations

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

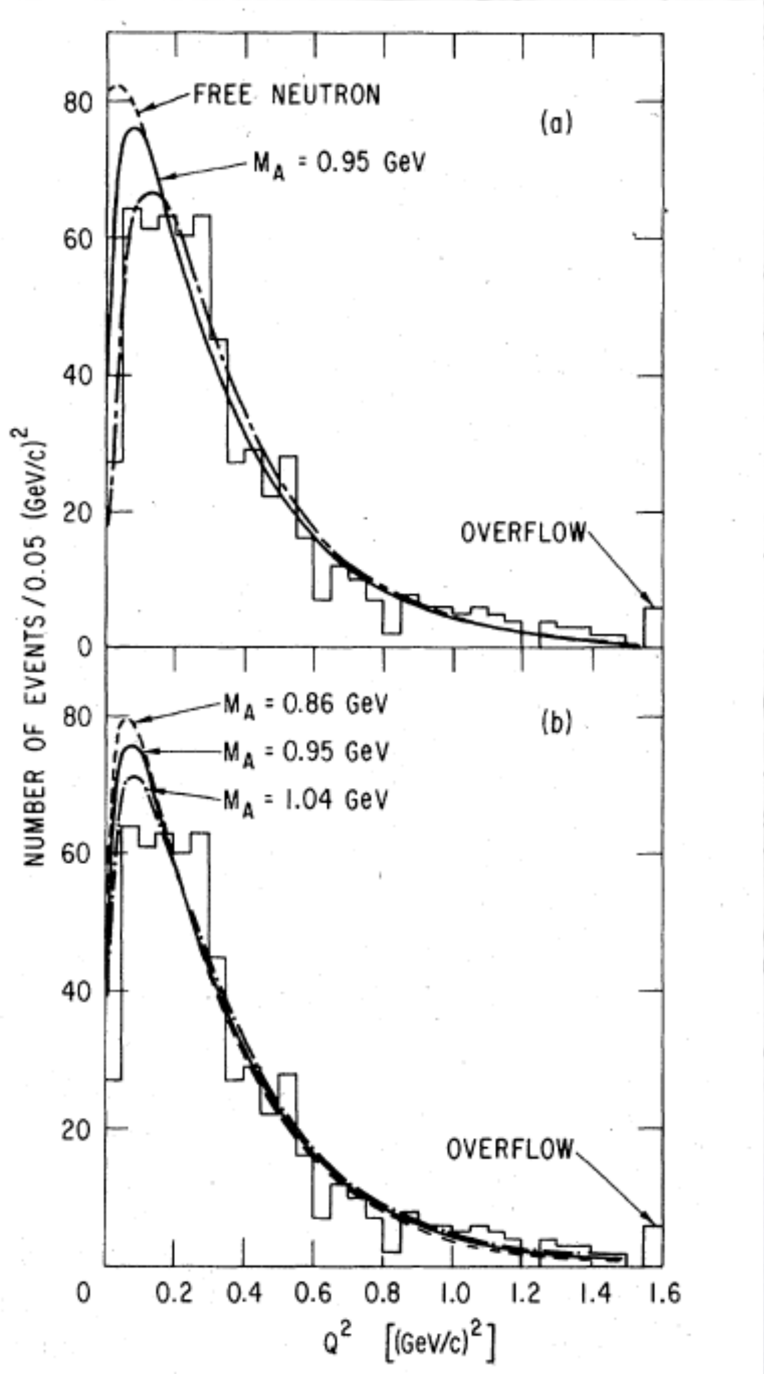
Similar near and far detector technology is a plus but it is not always the right solution.

CC 1p1h + 2p2h



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

Single nucleon



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VOLUME 16, NUMBER 11
1 DECEMBER 1977

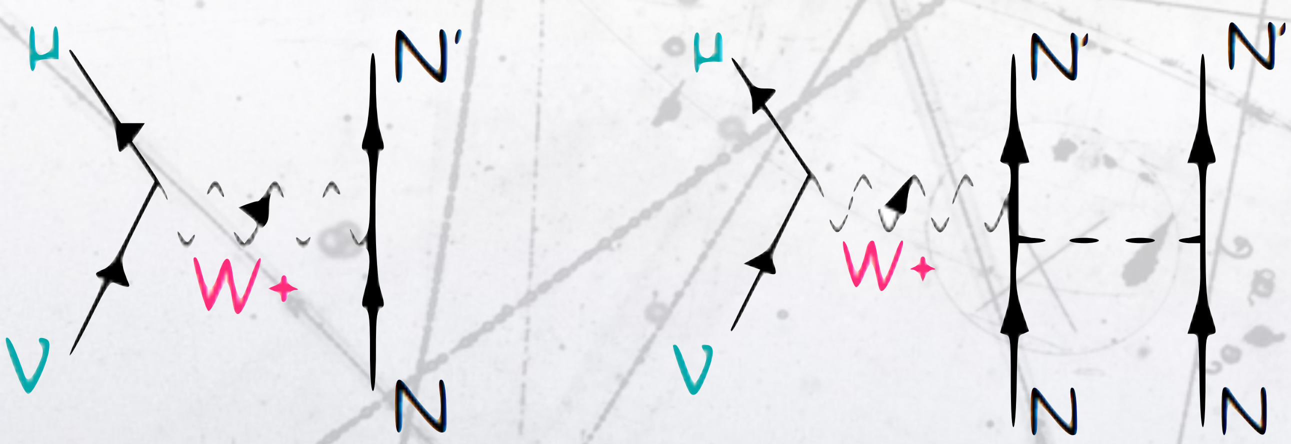
- Free nucleon (H and D) data is very limited.
- Many of the assumptions of the basic cross-section can't be accurately tested with nuclei:
  - Conserved Vector Current
  - Partially Conserved Axial Current.
  - Dipole form factor
  - Vanished scalar and tensor form factors.
- …

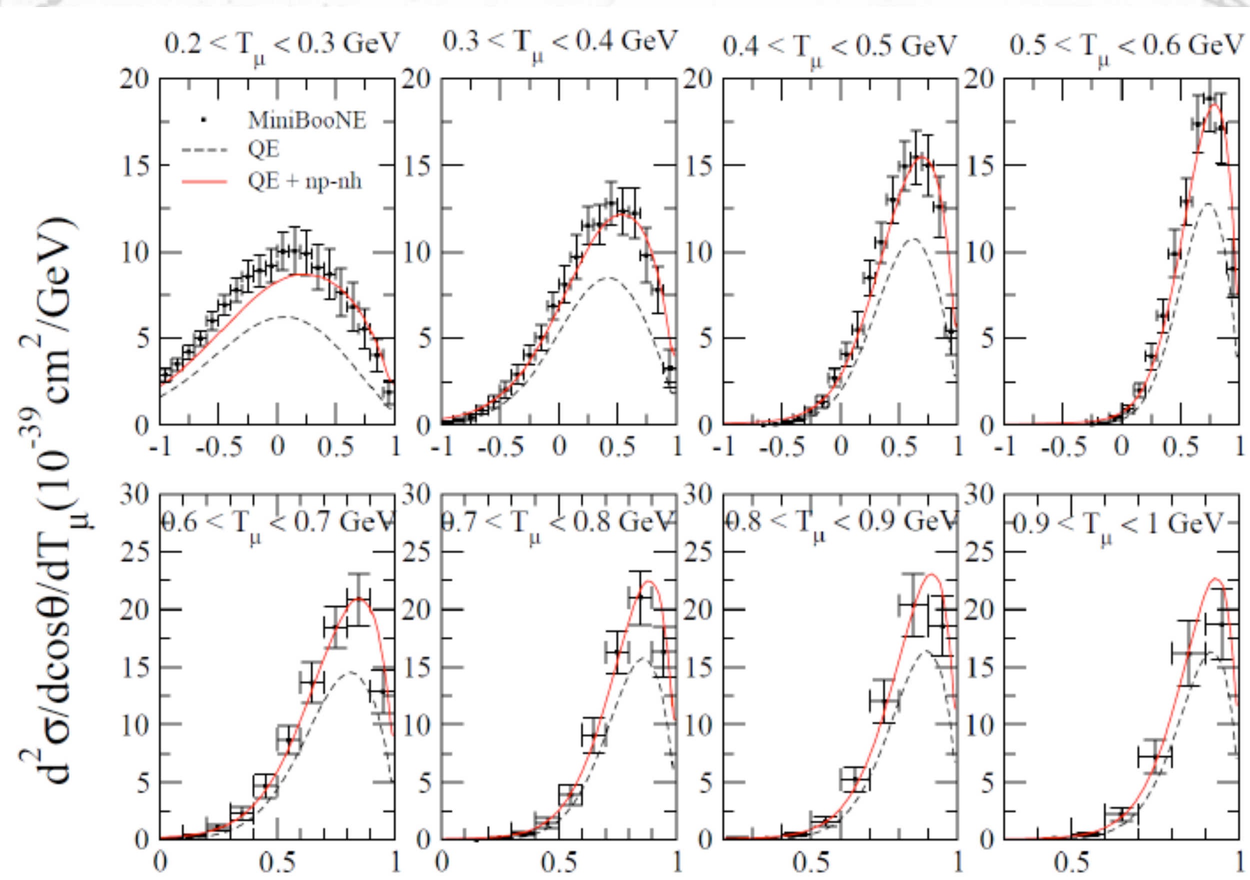
1p1h vs 2p2h

- 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.

CCQE

CC-2p2h





Martini et al. PRC 84 055502 (2011)

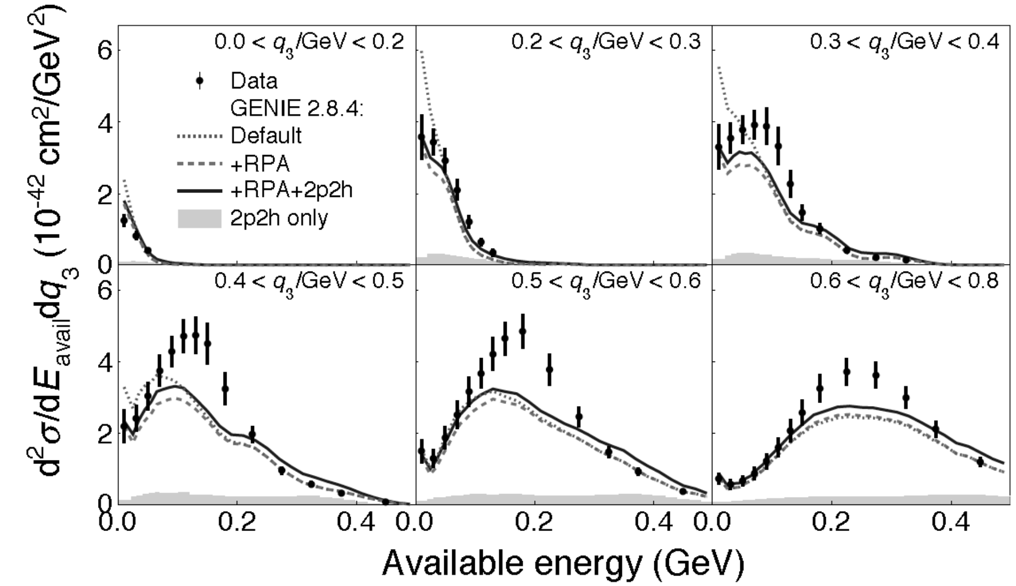
MiniBooNE, Phys. Rev. D 88 (2013) 032001

1p1h vs 2p2h

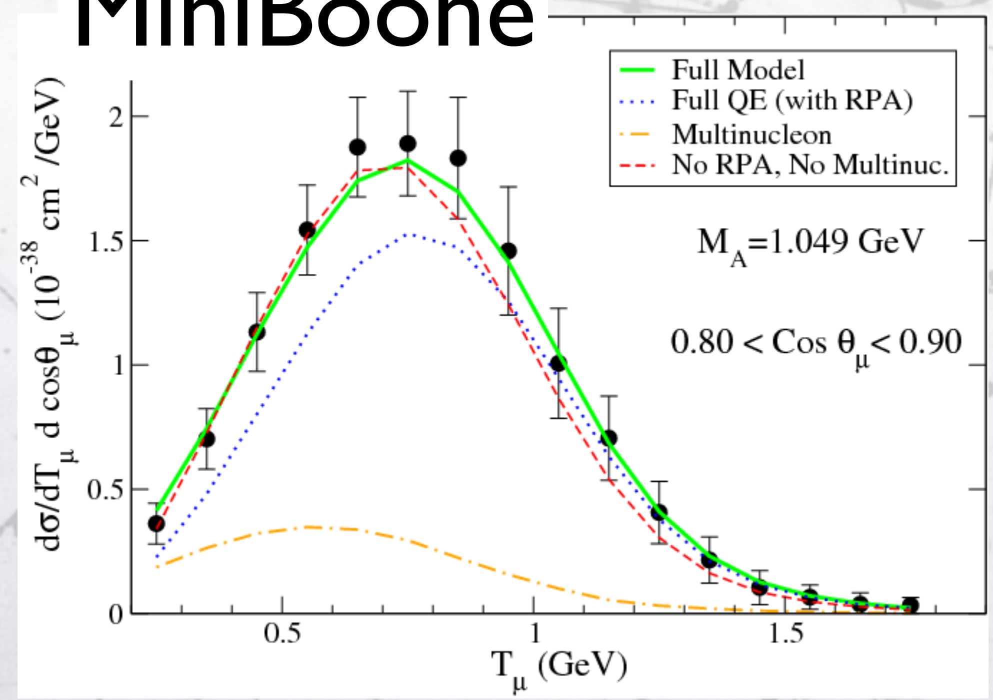
- Models agree with MiniBoone but not with other experiments: Minerva and T2K.
- Models based on same principles do not agree.

This is a large systematic error in T2K & Nova

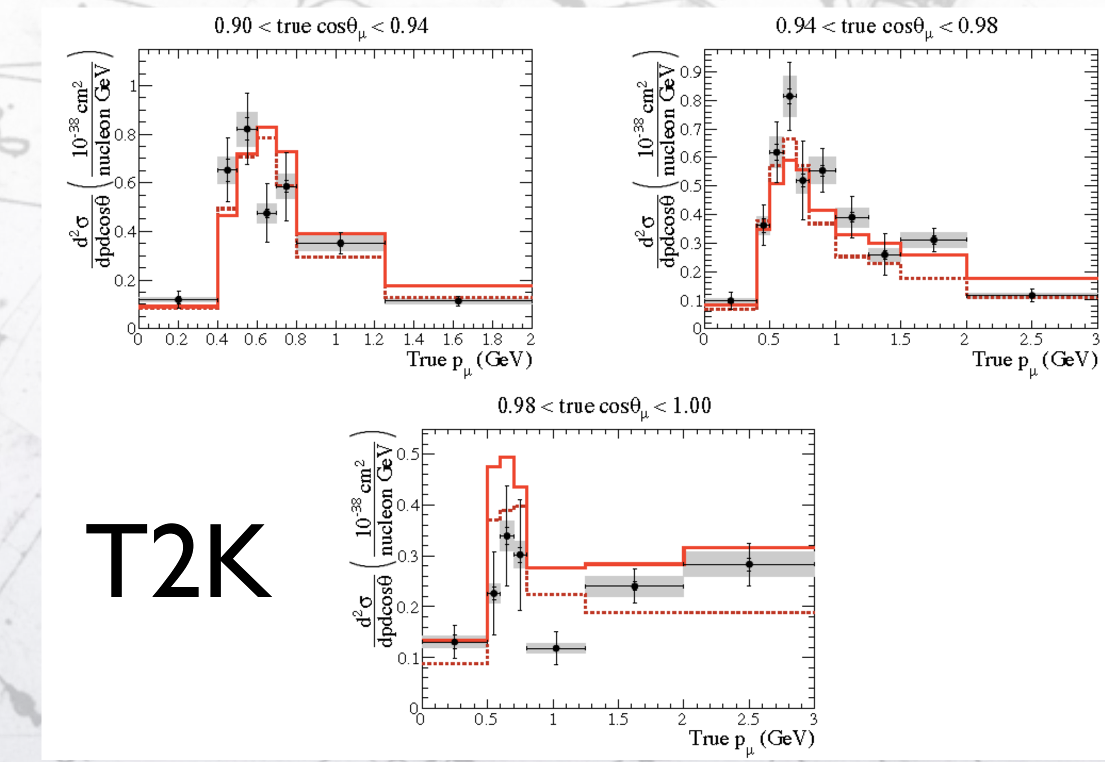
Minerva



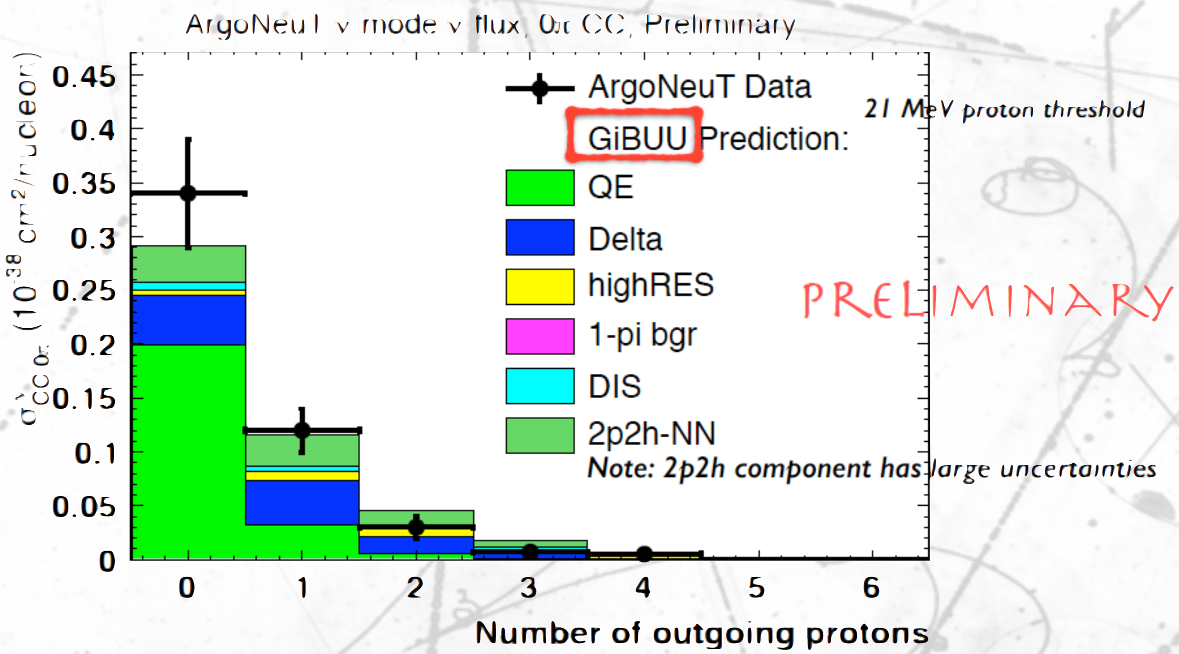
MiniBoone



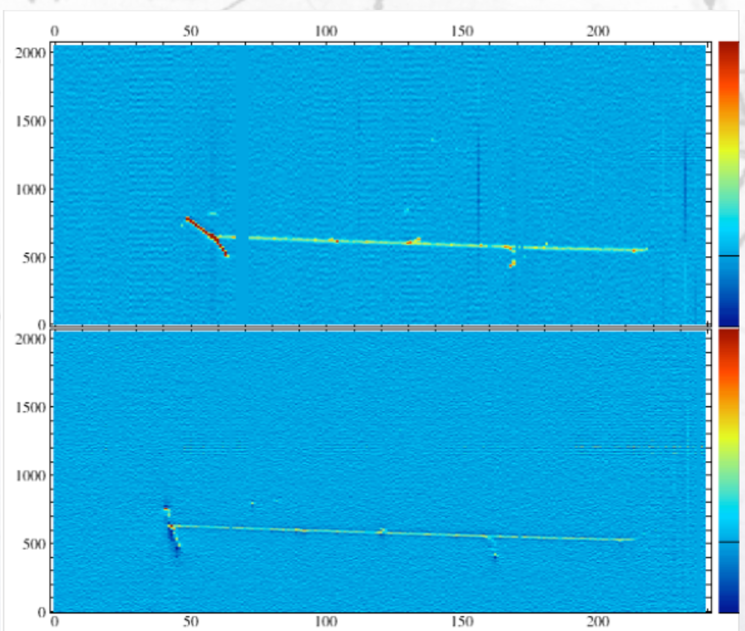
T2K

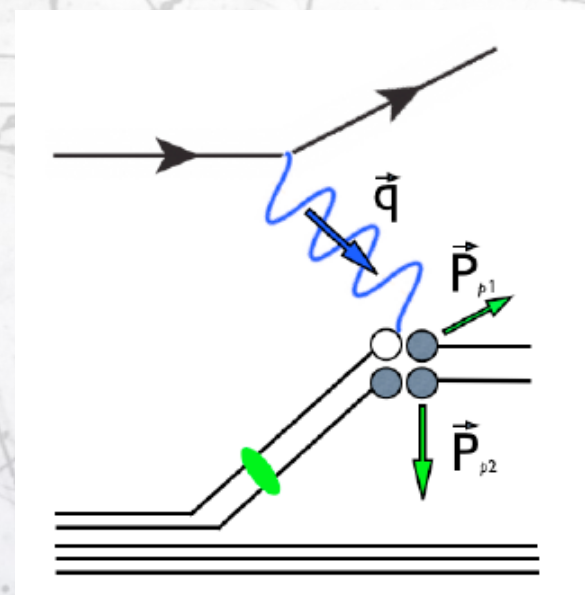


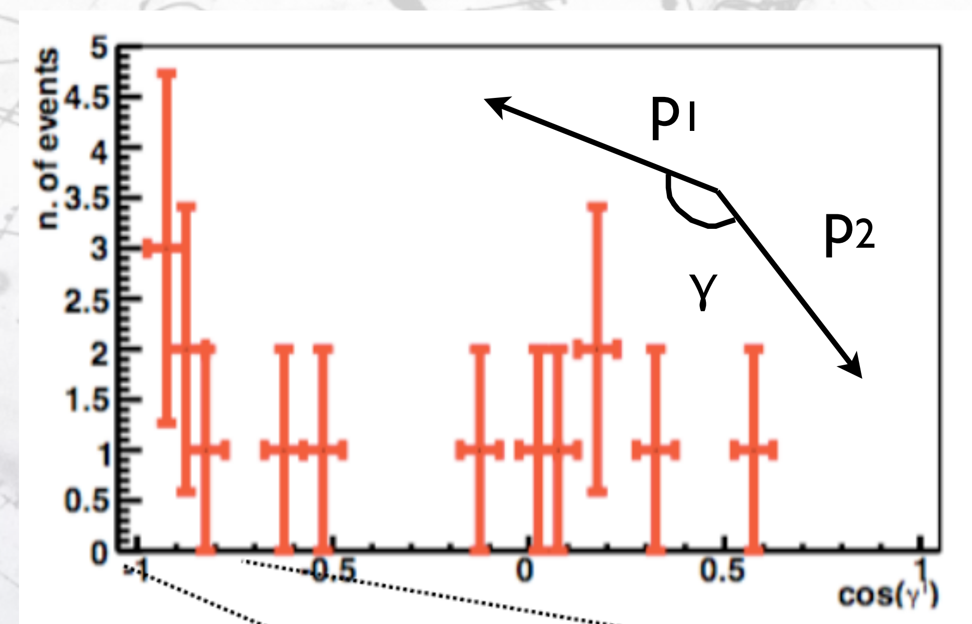
Search for 2p2h



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



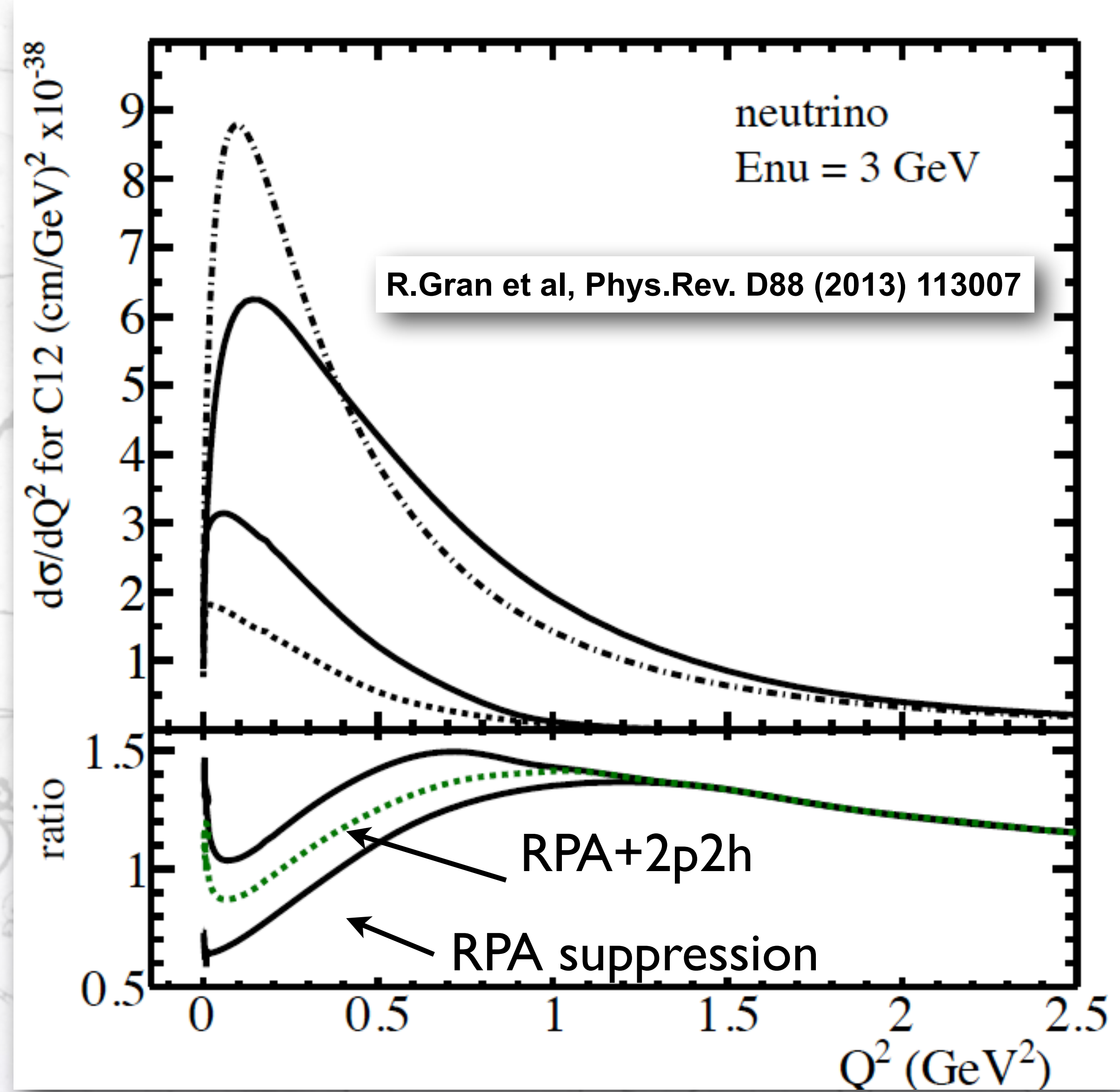




Strength of new generation of low threshold detectors

1p1h

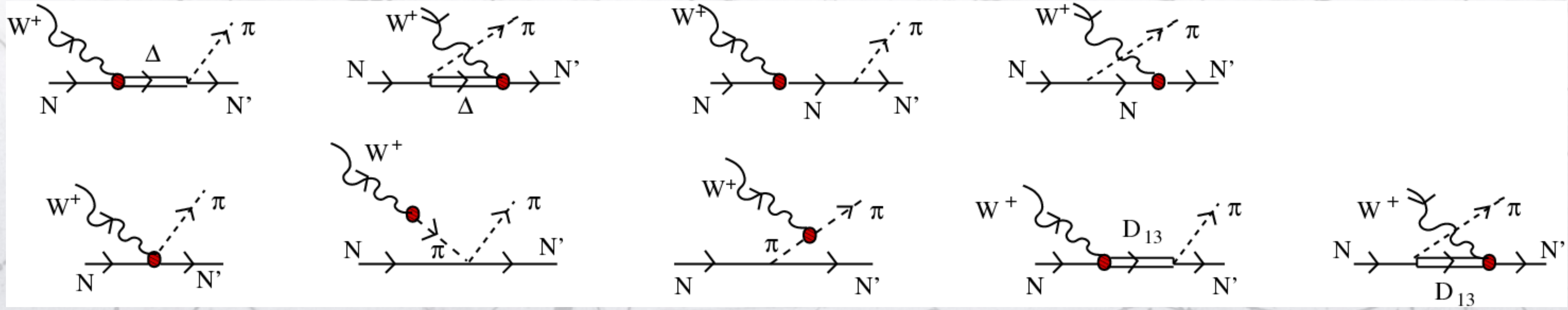
- Actually one of the problems is that the basic nucleus is probably not well described:
  - bind energy !
  - Fermi momentum description: RFG, LFG, Spectral functions.
  - Final State interactions.
  - Large Range correlation appearing as low q^2 quench of the reaction.



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

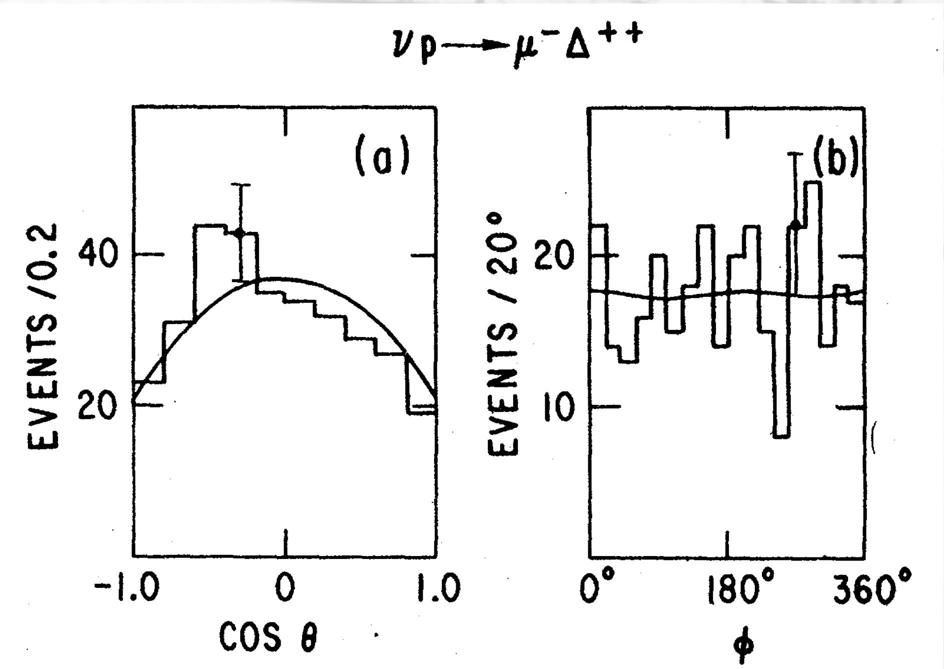
Single pion production

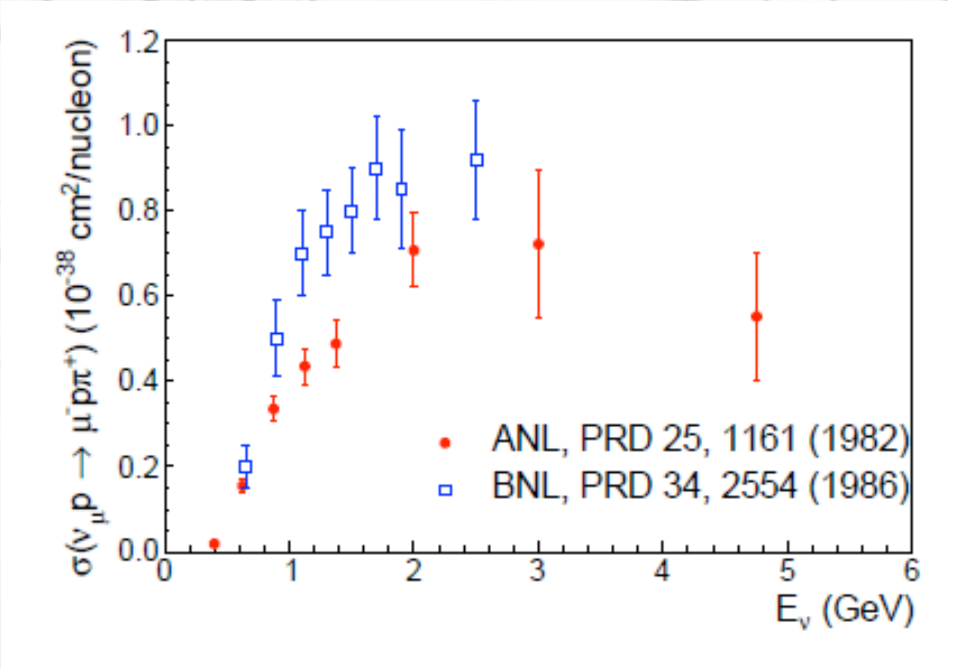
- Second most relevant cross-section in oscillation experiments.
- All set of long and short rage correlation effects in CC1π are ignored in actual pion production models.
    - models are still uncertain on its implementation to CCQE.
- Complex modelling with many intermediate resonances and non-resonant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

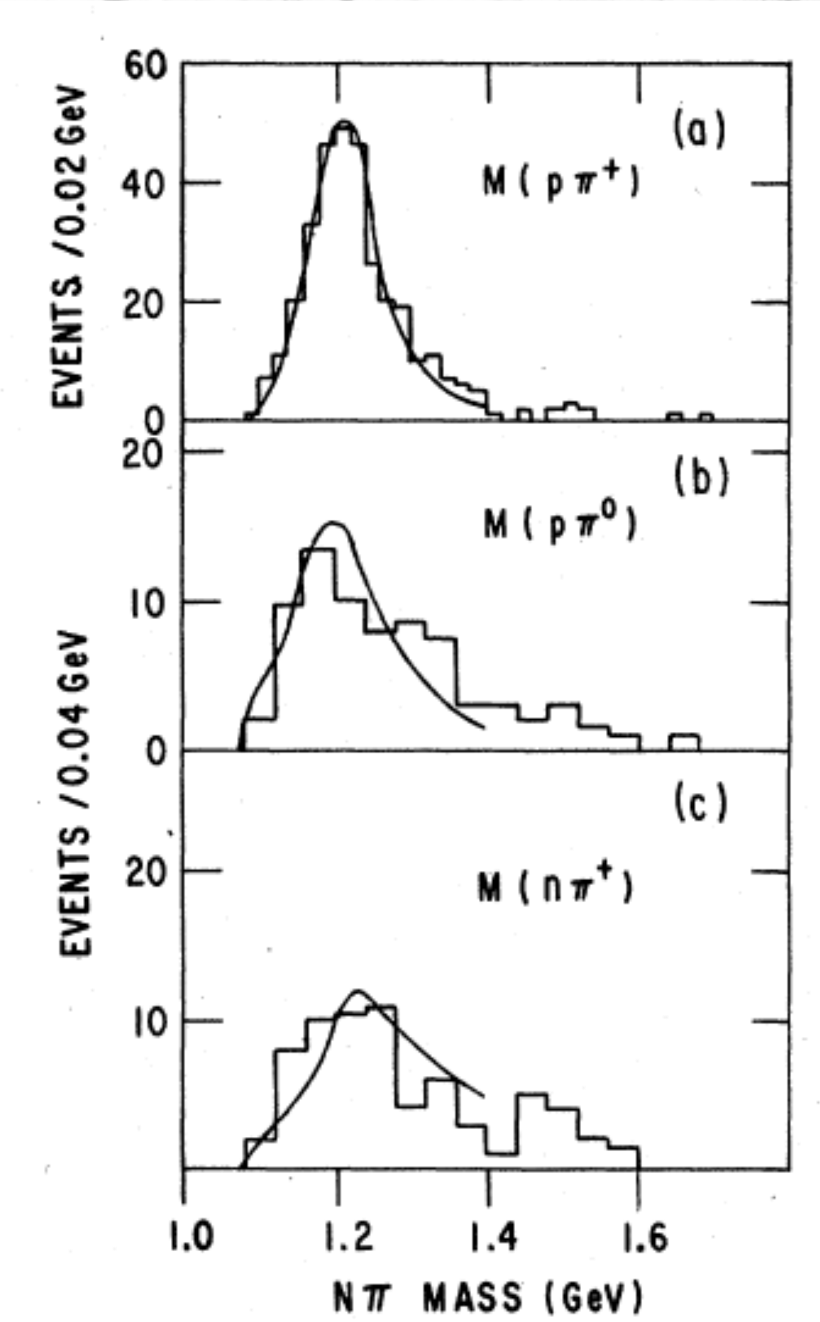


Single pion production

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

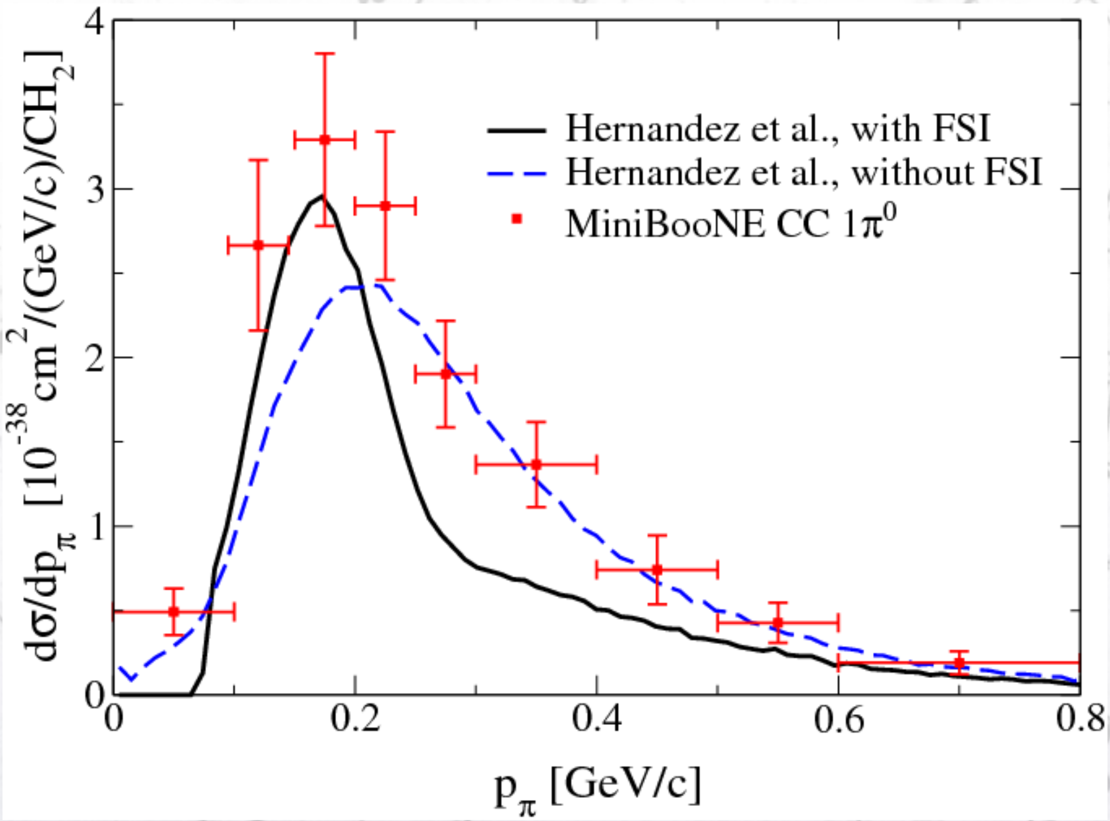


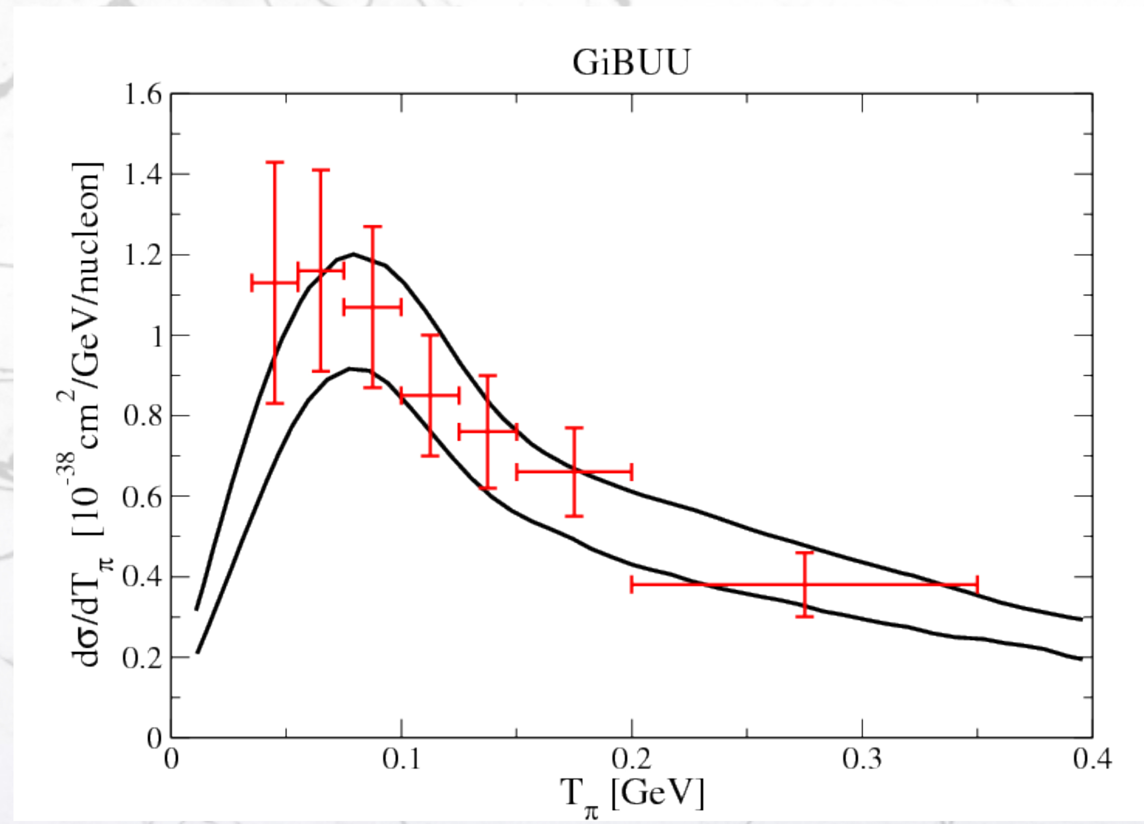




π modern data

- 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.

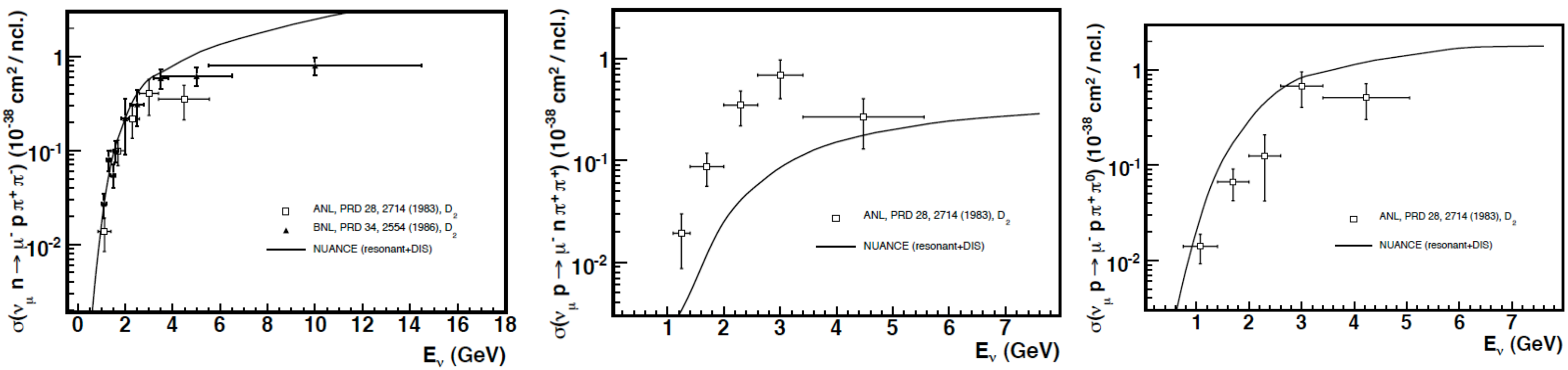




- Experimental errors or faulty models ?

Nπ to DIS

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



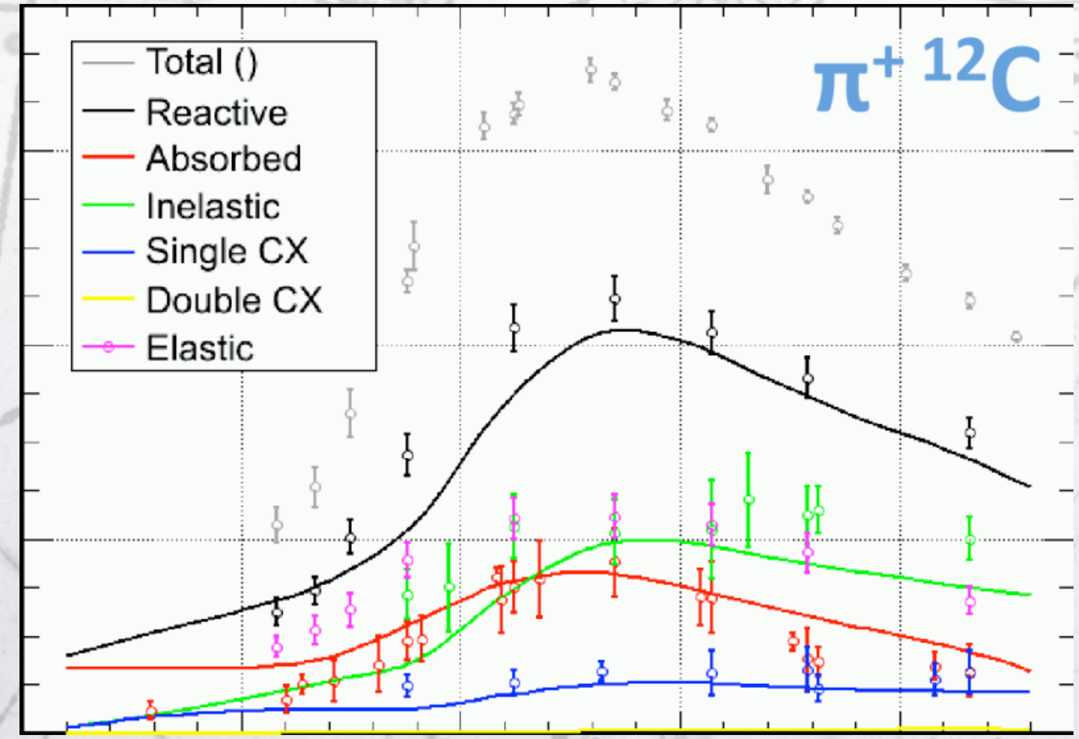
- Complex region with contributions from high mass Δ resonances and low ω DIS. Mixture of models from Pythia to add-hoc pion production.
- There is no new data since ANL and BNL back to the 80's.
- No data in nuclei: difficult measurement due to FSI.
- No detailed pion kinematics available.
- Critical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

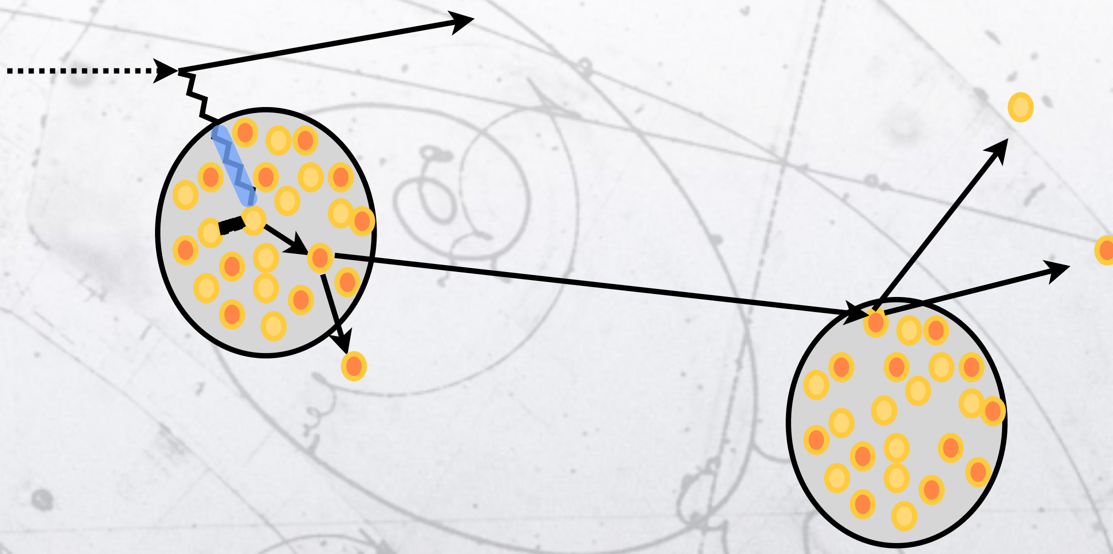
No data for NC potential background

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.





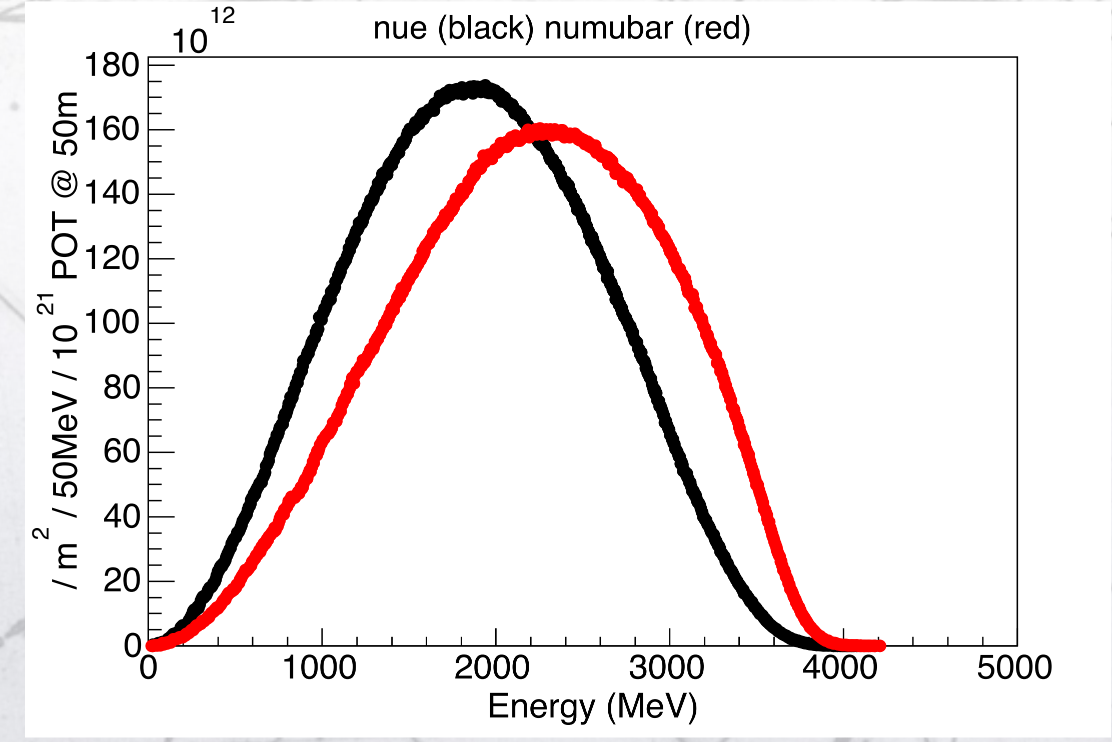
How to ?

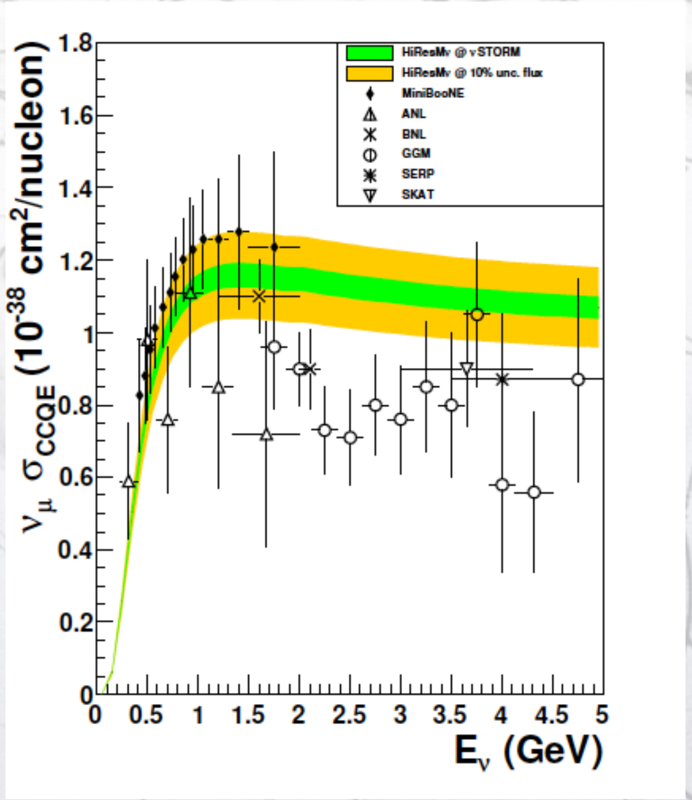
- Near detectors perform most of the cross-section studies.
- This does not be to be ideal since many parameters are static:
  - target nuclei
  - flux
- How to address the problem ?

- 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

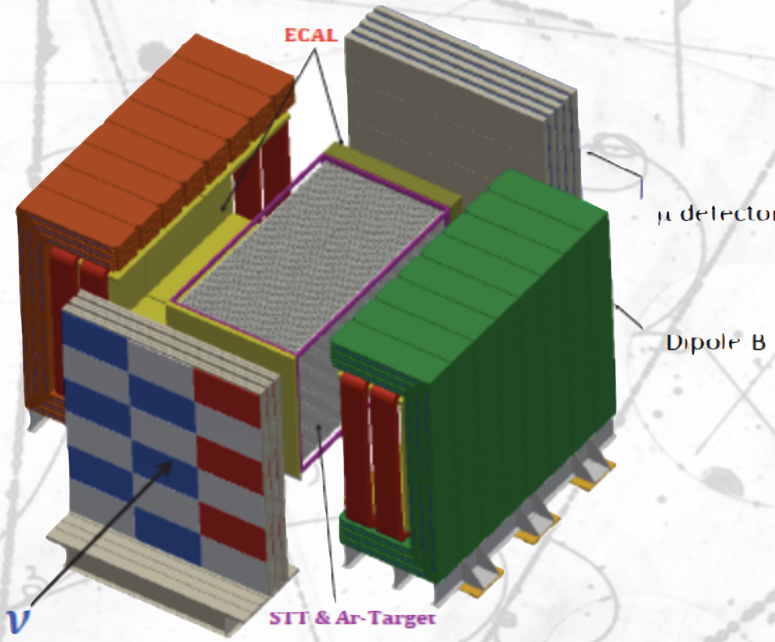
- NuStorm has two main potential contributions to neutrino-nucleus scattering:
  - large ν_e fraction even below 1 GeV.
  - Precise flux prediction for precise ν_μ cross-section.
- NuStorm can provide the equivalent errors in ν_e and ν_μ cross-sections.

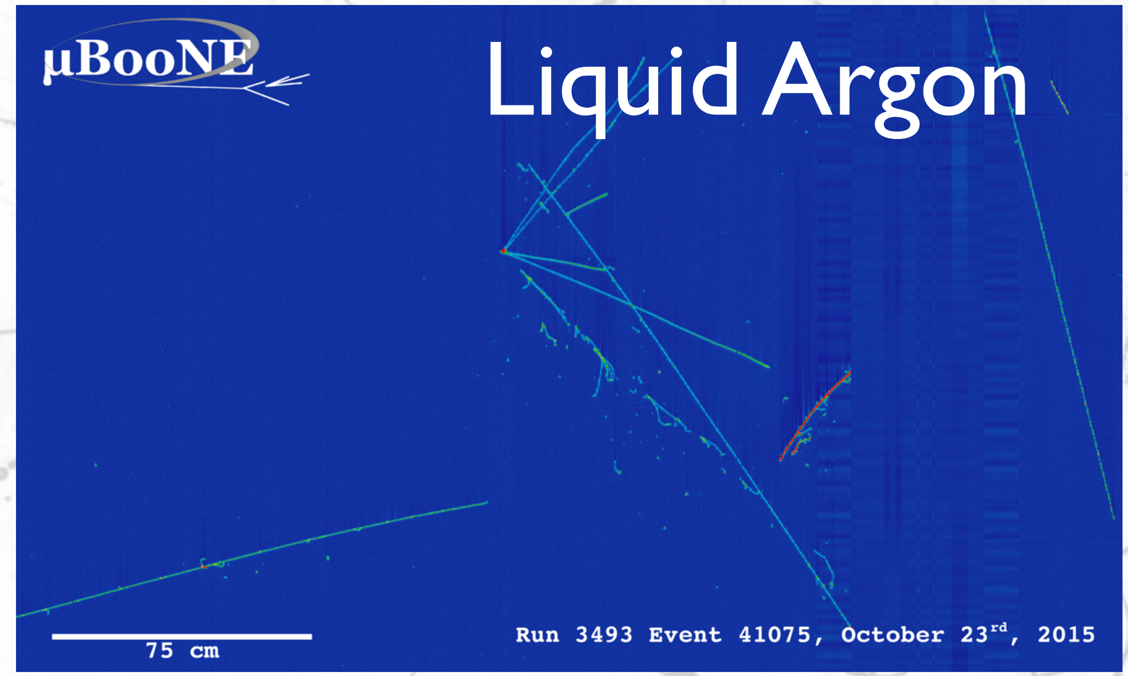




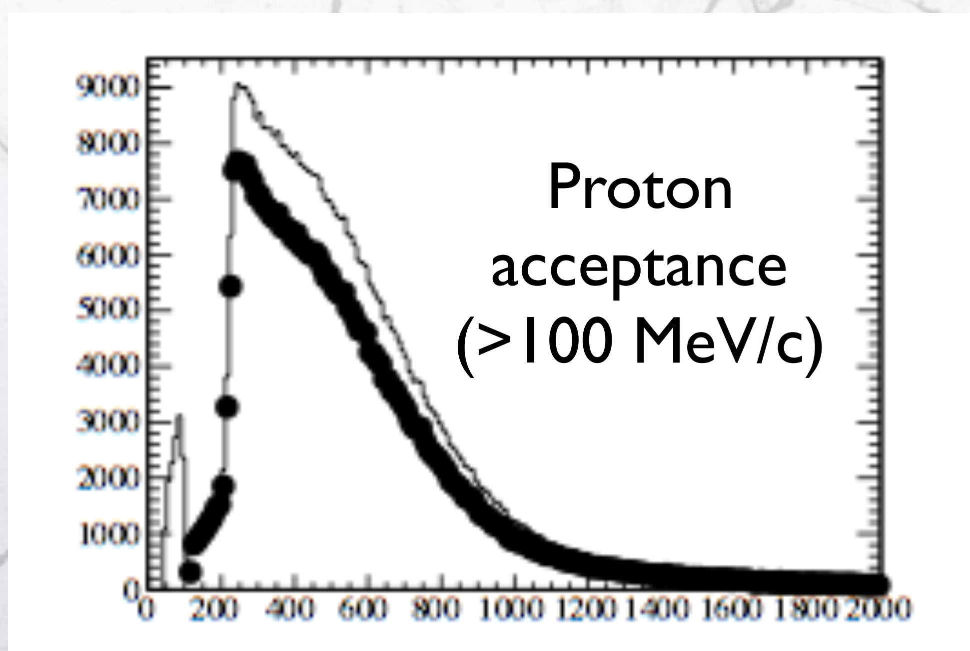
New detectors

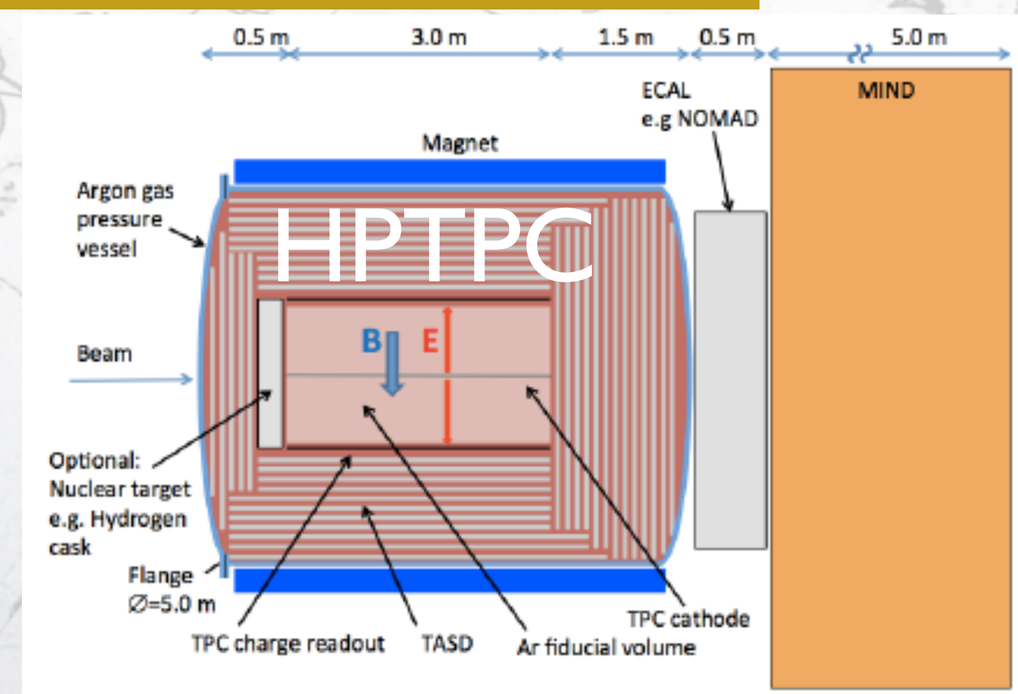
Segmented tracker





Highly segmented low density detectors





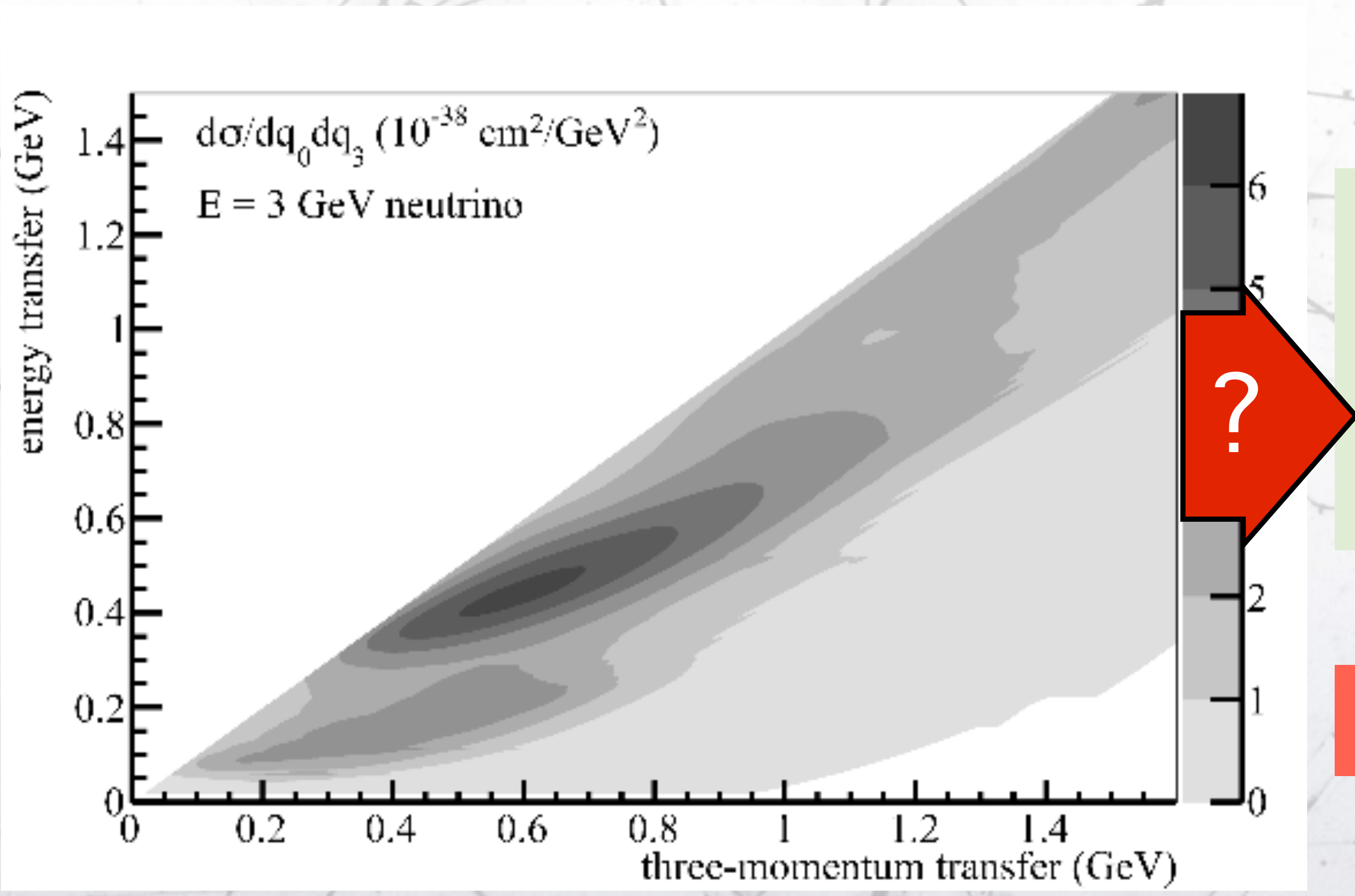
Theory

- 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

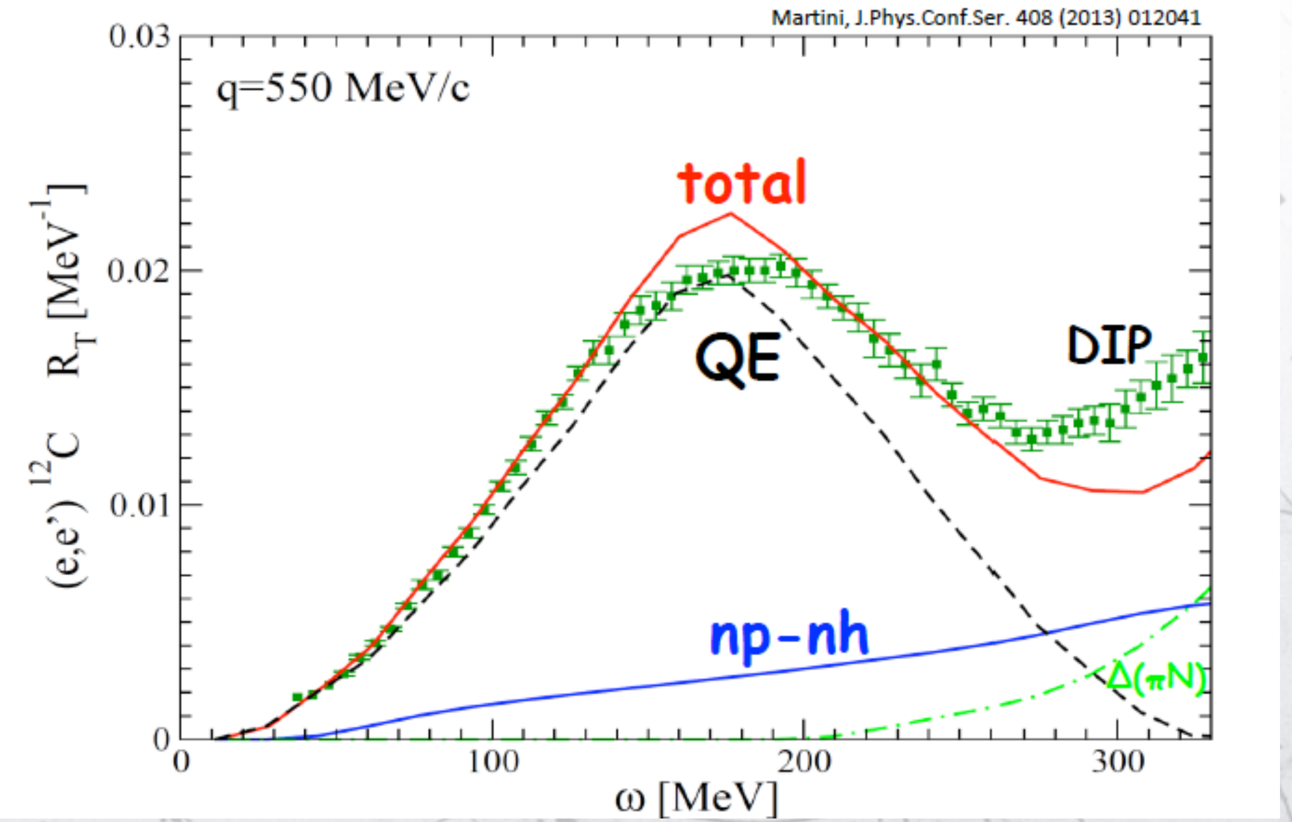
Proposed to use the momentum transfer to the nucleus as a reference cut and not neutrino energy.

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.

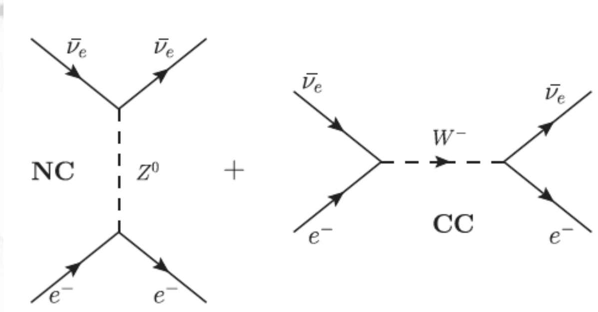
New and existing electron scattering data is a must to improve our knowledge and systematic control of the neutrino-nucleus interaction models.



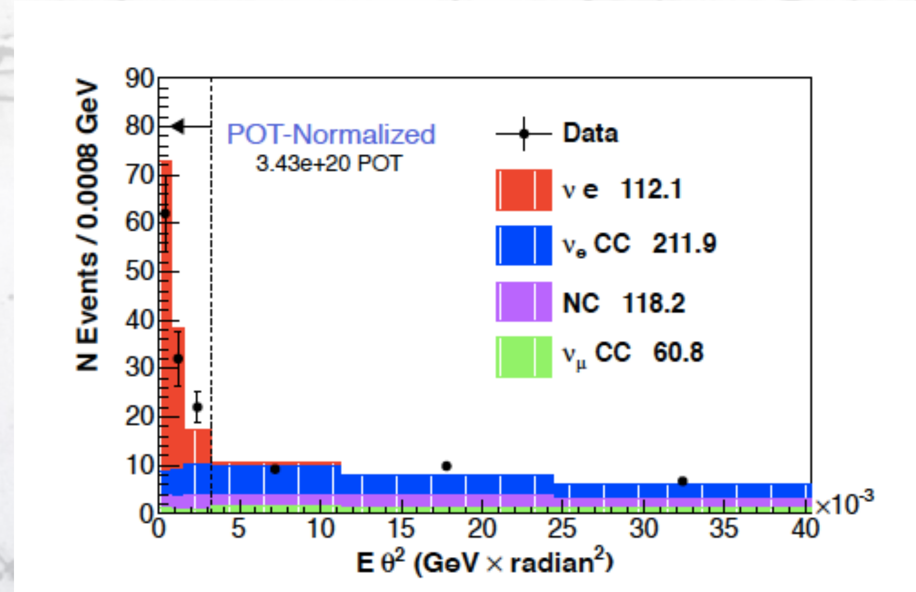
Neutrino flux

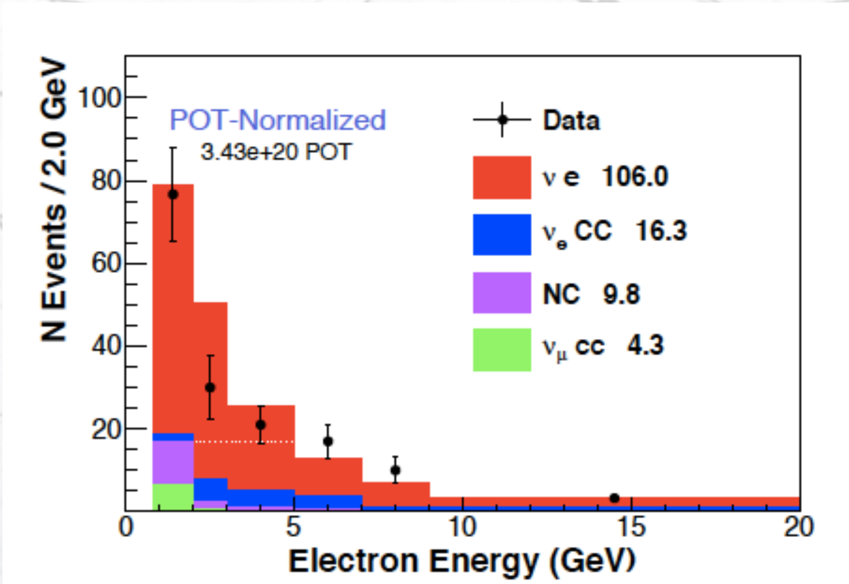
- Constrain the flux using the neutrino-electron scattering:
  - $\overset{(-)}{\nu}_\mu e^- \rightarrow \overset{(-)}{\nu}_\mu e^-$
  - The cross-section is well known:

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



- 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.

arXiv:1512.07699v2

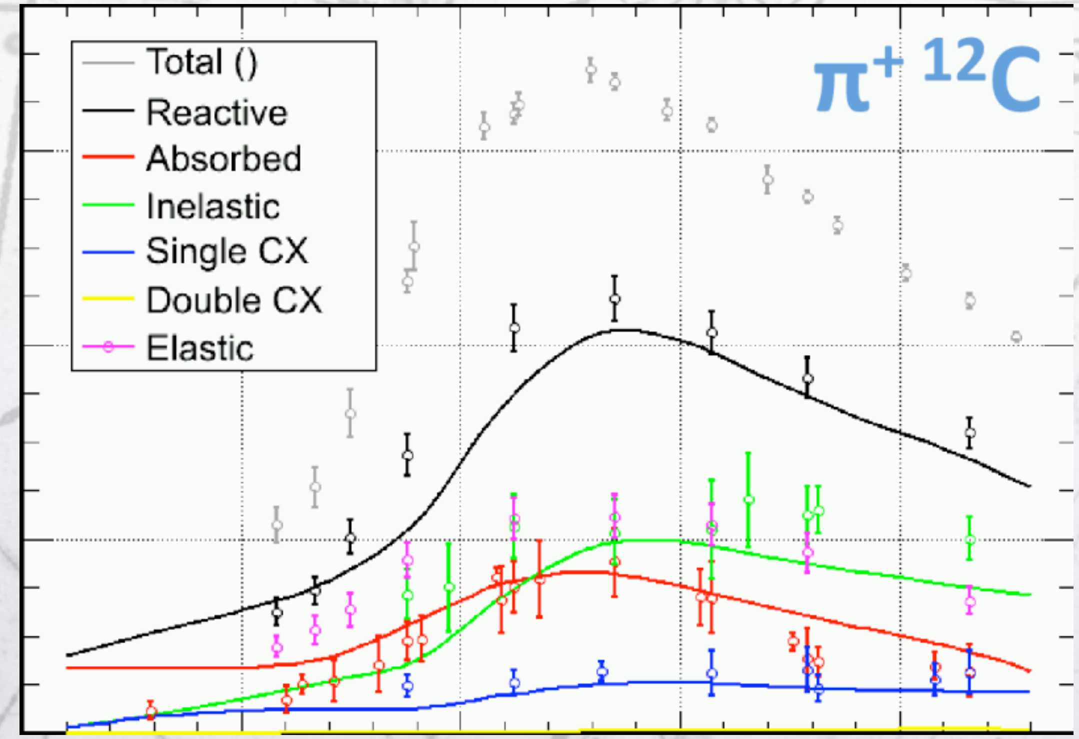
ND for oscillations

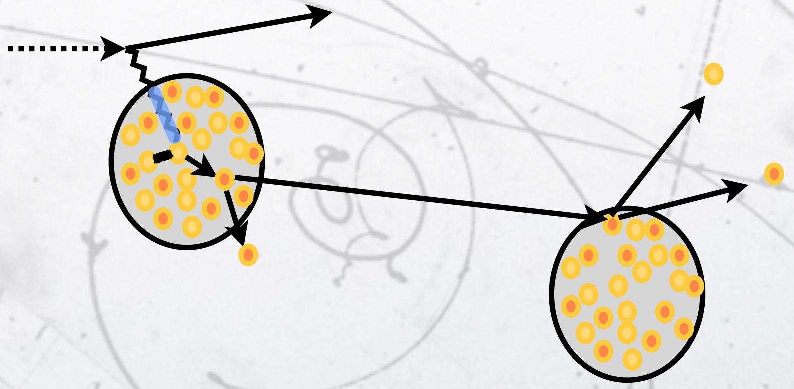
- Obviously, we can't make the ND the same size as the far detector:
  - The hermeticity of the detector will be different for neutrons electrons and gammas.
    - Low energy gamma's from π^0 critical!
  - The momentum of long range particles need to be estimated in different ways:
    - FD: range for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

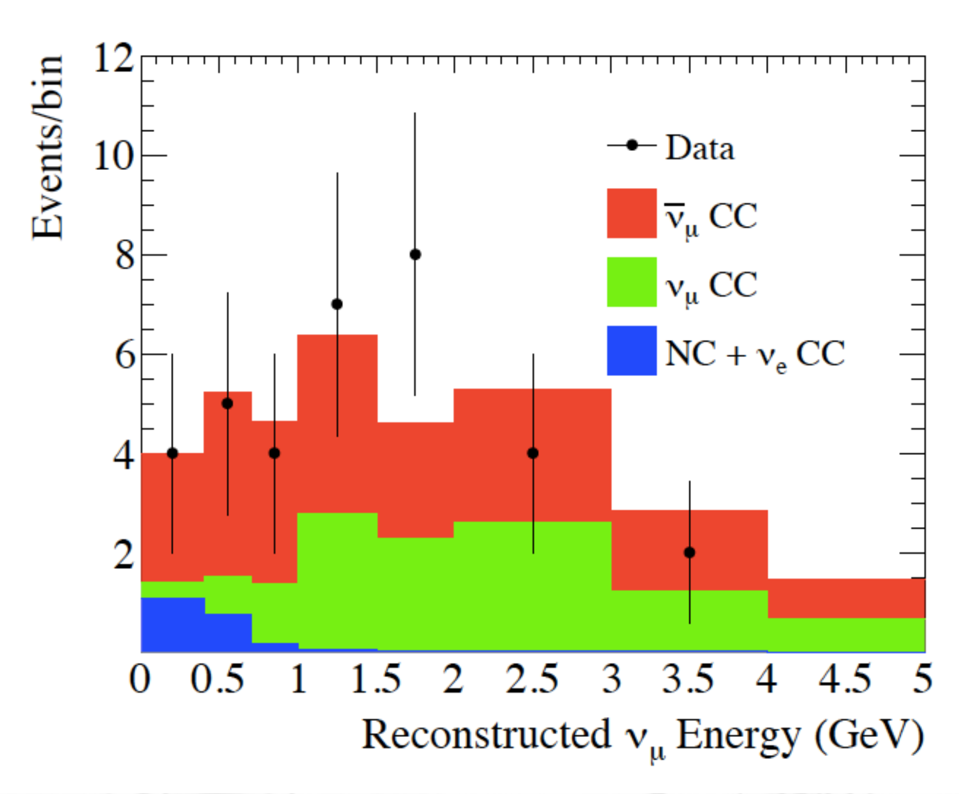
ND for oscillations

- 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.

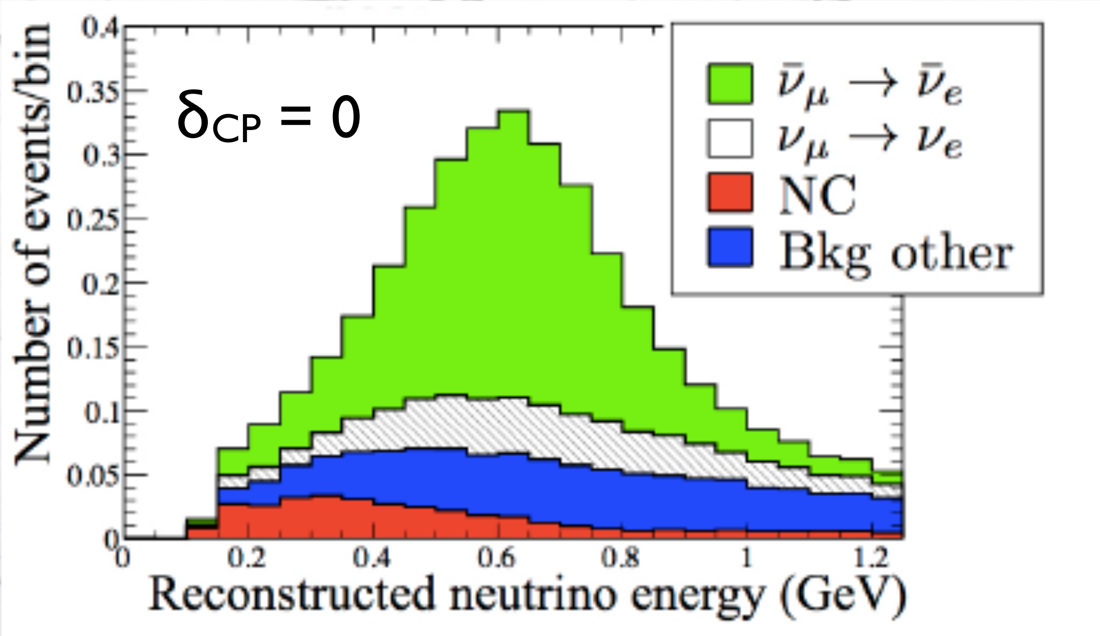
Excellent $e/\mu/\pi^0$ separation.
Large statistics: masive near detector / large flux !
Enhanced electron sample (off-axis ?)

ND for oscillations

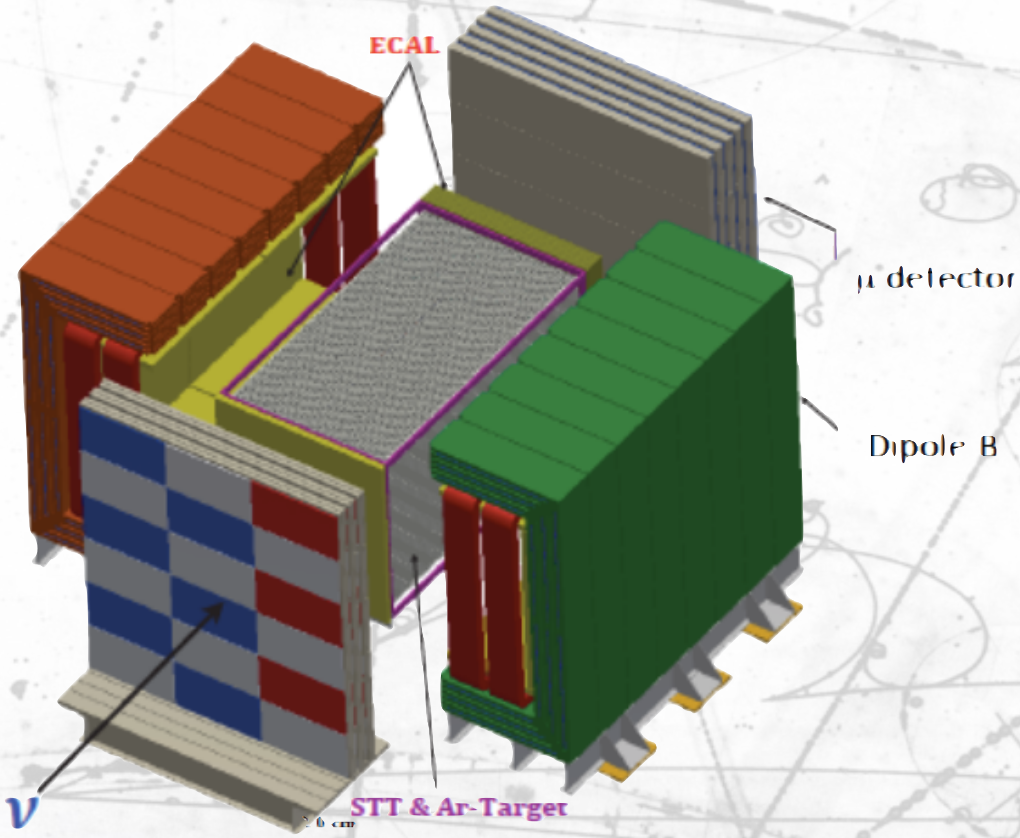
- CP violation also requires the separation of neutrinos and antineutrinos.
  - neutrino beam is normally very pure.
  - anti-neutrino beam has large contribution of neutrinos:
    - antineutrino cross-section and production yield is low.
- FD has some capability to distinguish neutrinos from antineutrinos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

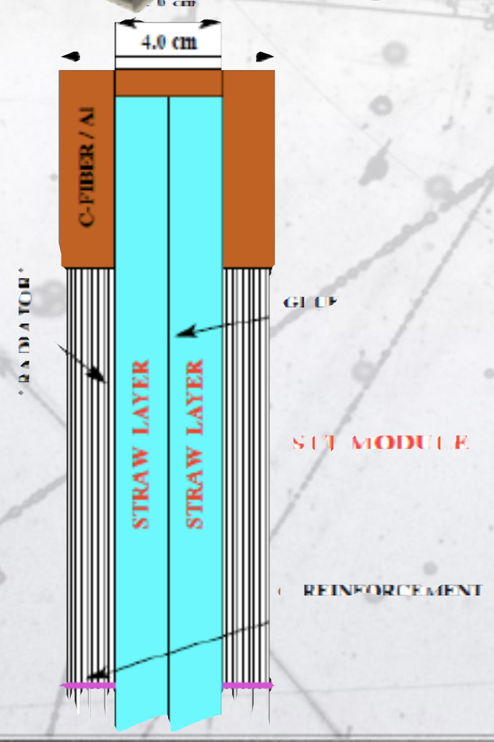


PoS EPS-HEP2015 (2015) 047



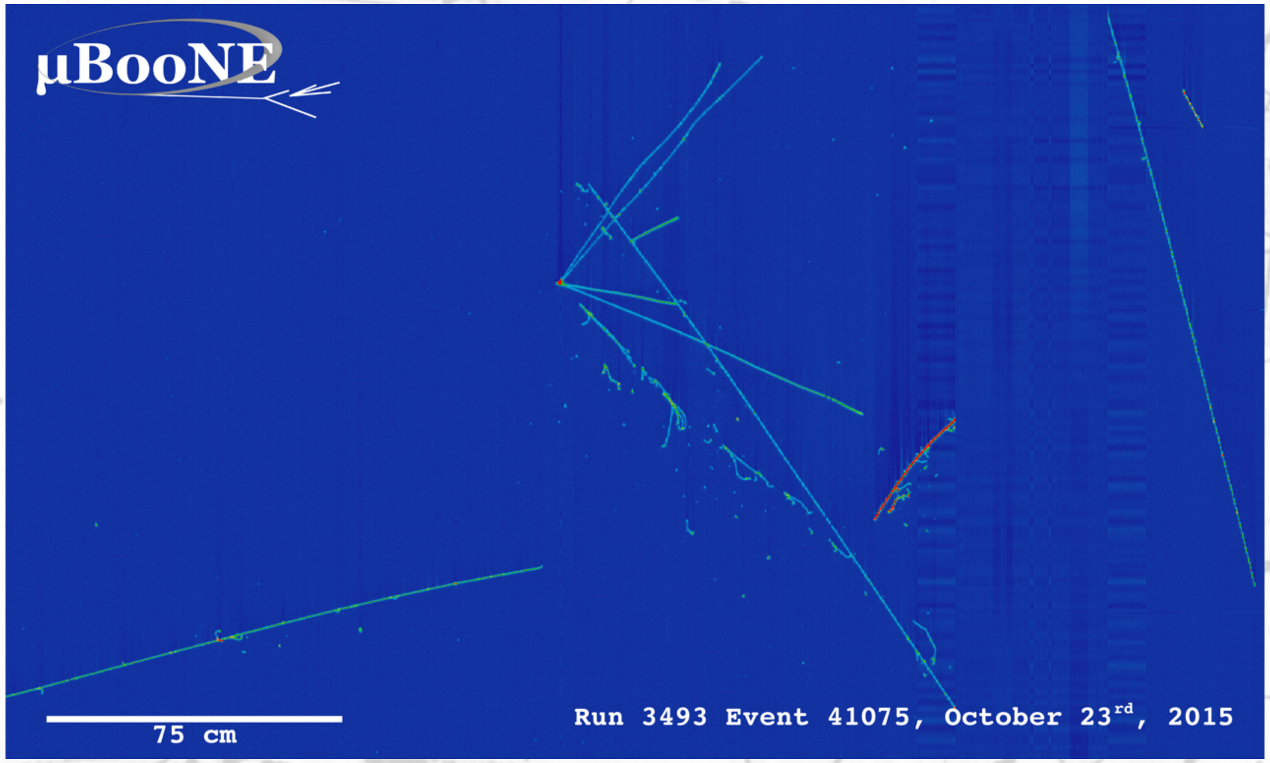
Segmented tracker

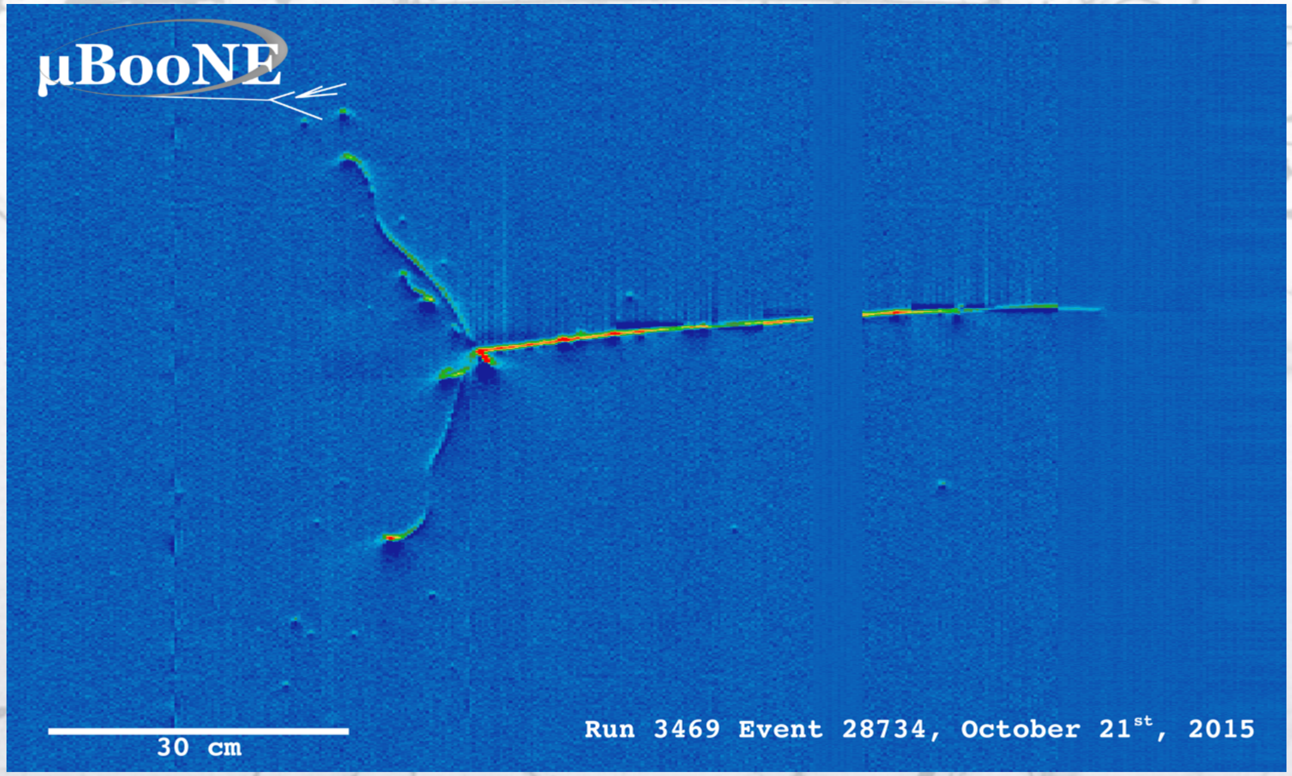




- Magnetised (0.4T) high resolution straw tube design “a la” Nomad with plannar geometry.
- Target/Nucleus selection by track vertexing.
- Low density for low E particle detection.
- ECAL gamma catcher and muon range detector.

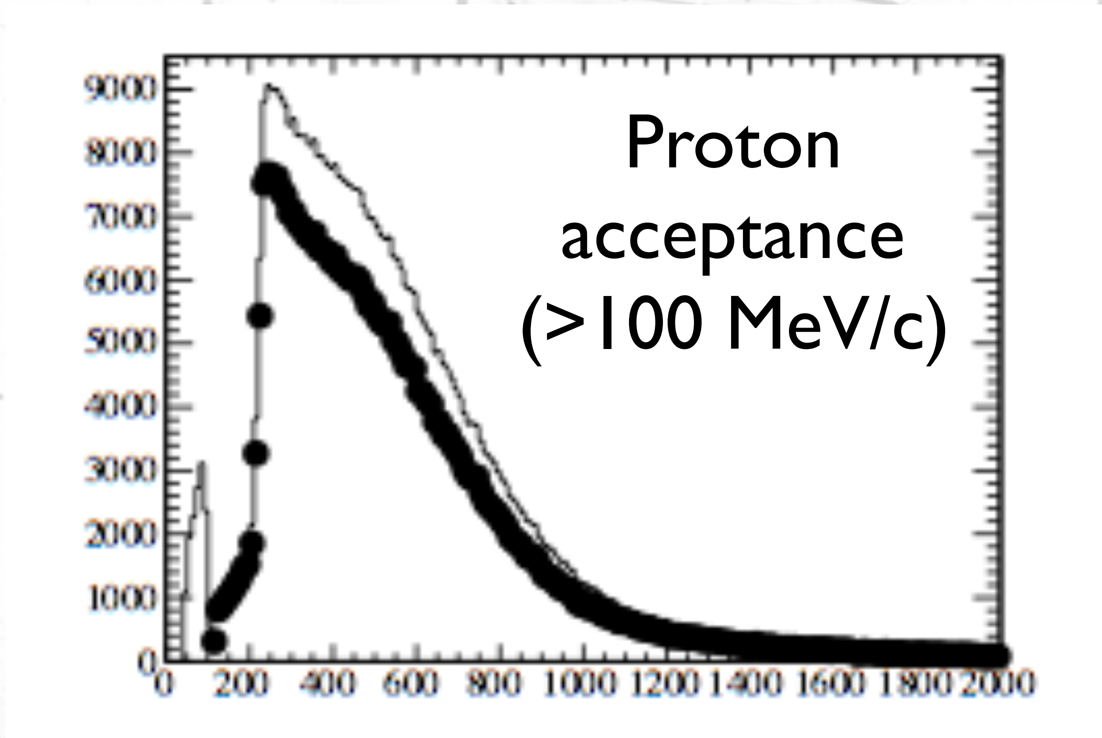
LiqAr TPC

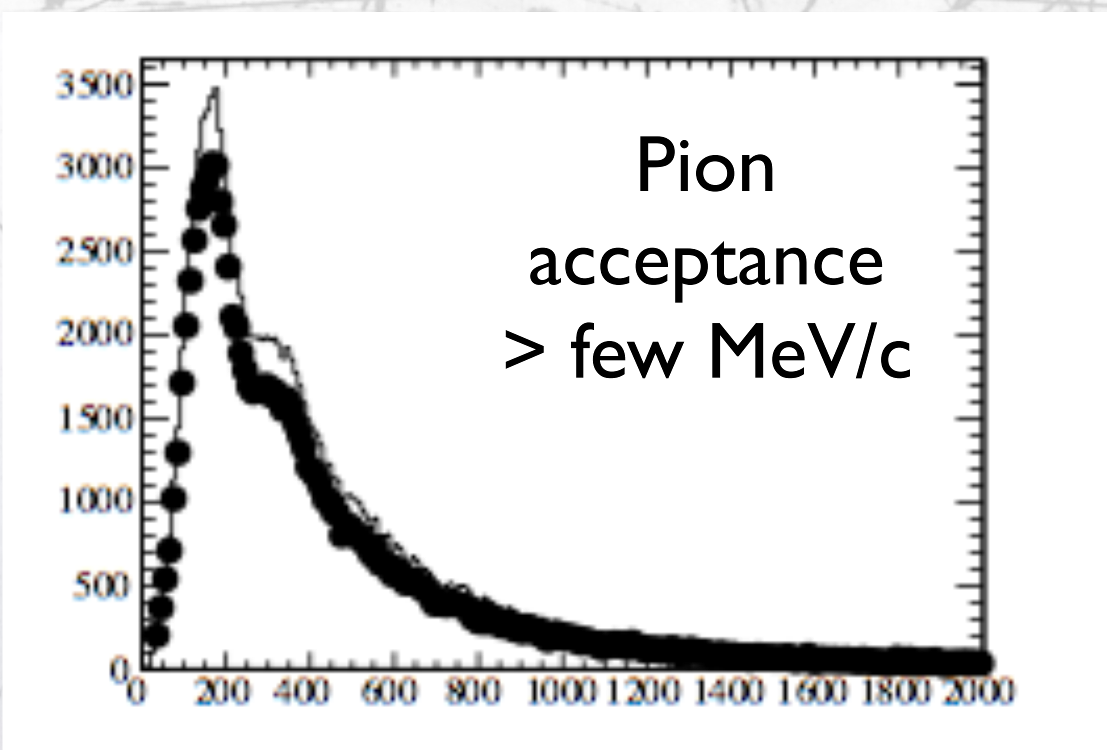




- Magnetised (?) LiqAr detector.
- Same technology as FD.
- Large mass.
- Balance pile-up / range.
- ECAL and muon range.

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.