Precision oscillation neutrino experiments, nuclear physics and the need for near detectors

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ν oscillation

- The neutrino oscillation models assume that:
  - neutrinos have mass, albeit a very small one.
  - neutrinos interacts as ν_e or ν_μ (neutrino flavour).
  - the eigenstates of flavour and mass (Lorentz) are not the same.
  - The are related via a rotation between the two bases.

Flavour states: $|\nu_e>$ & $|\nu_\mu>$ Mass states: $|\nu_1>$ & $|\nu_2>$

$$|\nu_e> \;=\; \cos\theta|\nu_1> + \sin\theta|\nu_2>$$
$$|\nu_\mu> \;=\; -\sin\theta|\nu_1> + \cos\theta|\nu_2>$$

ν Oscillation

- Neutrinos are transported in vacuum following the Schrödinger equation in vacuum:

$$i\hbar\frac{\partial\nu}{\partial t} = H\,\nu = E\,\nu = \sqrt{m_\nu^2 + p^2}\,\nu$$

- When we produce electron neutrino:

$$|\nu_e> \;=\; \cos\theta|\nu_1> + \sin\theta|\nu_2>$$

- $m_\nu << p$:

This condition prevents to get similar effects in quarks.

$$i\hbar\frac{\partial\nu}{\partial t} = (p + \frac{m_\nu^2}{2p})\nu$$

$$\nu(t) = e^{i(p+\frac{m_\nu^2}{2p\hbar})t}\nu(0)$$

ν Oscillation

- If we produce a ν_e, after some time the state is:

$$|\nu_e;t>=\cos\theta e^{i(p+\frac{m_1^2}{2p})\frac{t}{\hbar}}|\nu_1;0>+\sin\theta e^{i(p+\frac{m_2^2}{2p})\frac{t}{\hbar}}|\nu_2;0>=$$
$$e^{i(p+\frac{m_1^2}{2p})}(\cos\theta|\nu_1;0>+\sin\theta e^{i\frac{m_2^2-m_1^2}{2p}\frac{t}{\hbar}}|\nu_2;0>)$$

- The probability of getting a ν_μ at the interaction is then:

It depends on the mass difference not the absolute mass.

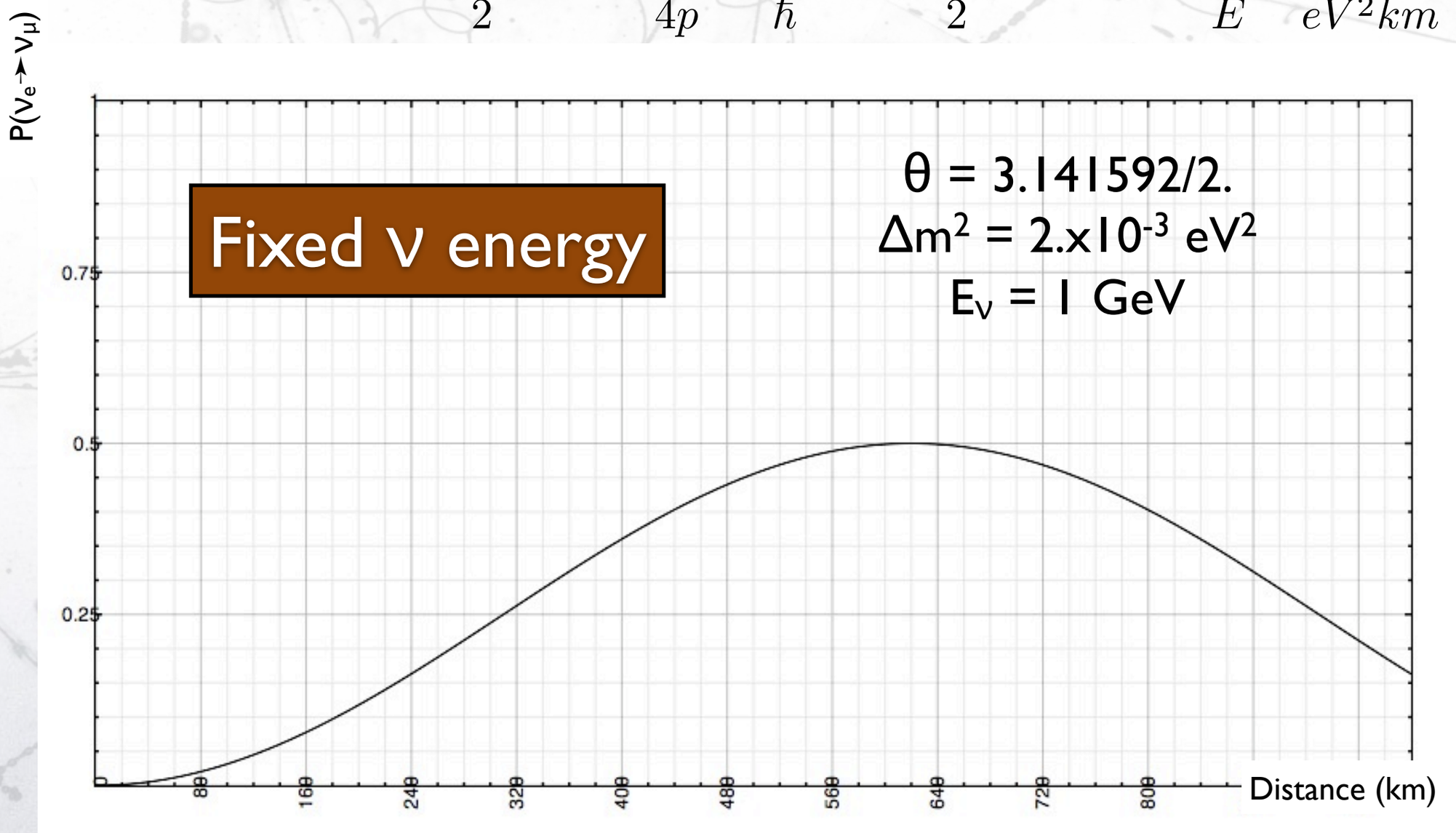
$$\begin{aligned}|<\nu_\mu|\nu_e;t>|^2 &= |-\cos\theta\sin\theta<\nu_1|\nu_1;0>+\sin\theta\cos\theta e^{i\frac{m_2^2-m_1^2}{2p}\frac{t}{\hbar}}<\nu_2|\nu_2;0>|^2\\ &= \sin^2\frac{\theta}{2}\sin^2\frac{m_2^2-m_1^2}{4p}\frac{t}{\hbar}=\sin^2\frac{\theta}{2}\sin^2 1.267\frac{\Delta m^2 L}{E}\frac{GeV}{eV^2 km}\end{aligned}$$

- Flavour-lepton number is not conserved!.
- Opens the possibility for flavour violation in lepton decay & production.

ν Oscillation

$$|<\nu_\mu|\nu_e;t>|^2 = |-\cos\theta\sin\theta<\nu_1|\nu_1;0>+\sin\theta\cos\theta e^{i\frac{m_2^2-m_1^2}{2p}\frac{t}{\hbar}}<\nu_2|\nu_2;0>|^2$$

$$= \sin^2\frac{\theta}{2}\sin^2\frac{m_2^2-m_1^2}{4p}\frac{t}{\hbar} = \sin^2\frac{\theta}{2}\sin^2 1.267\frac{\Delta m^2 L}{E}\frac{GeV}{eV^2 km}$$



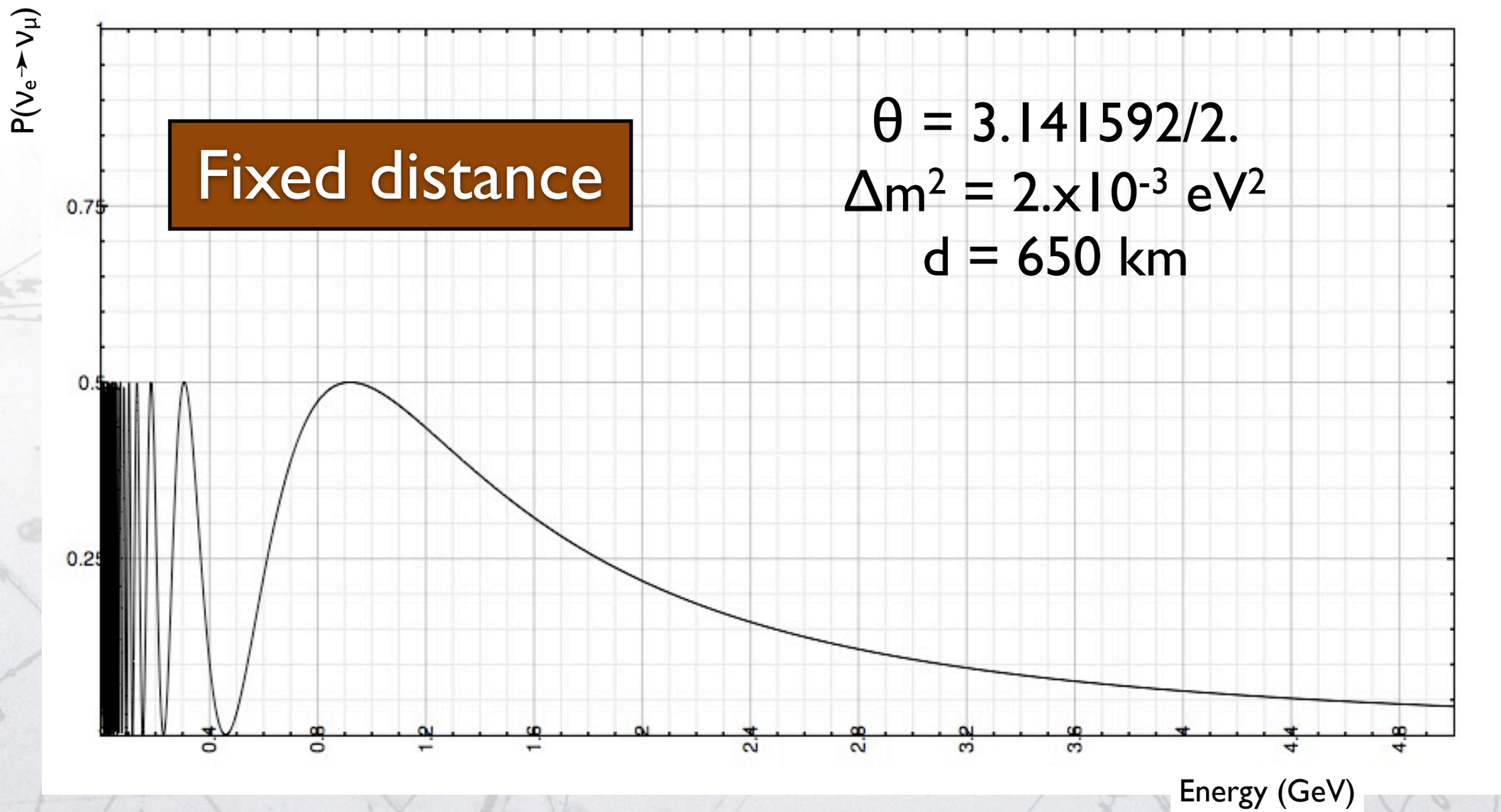
Fixed ν energy

θ = 3.141592/2.
$\Delta m^2 = 2.\times10^{-3}$ eV^2
E_ν = 1 GeV

ν Oscillation

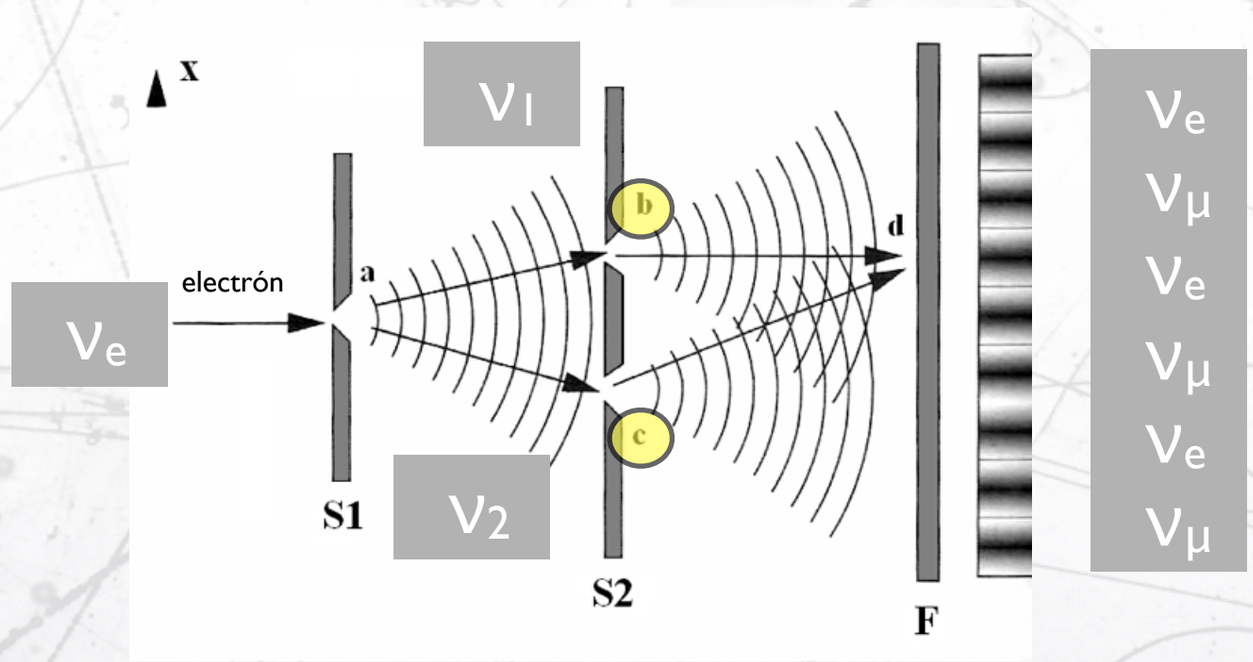
$$|<\nu_\mu|\nu_e;t>|^2 = |-\cos\theta\sin\theta<\nu_1|\nu_1;0>+\sin\theta\cos\theta e^{i\frac{m_2^2-m_1^2}{2p}\frac{t}{\hbar}}<\nu_2|\nu_2;0>|^2$$

$$= \sin^2\frac{\theta}{2}\sin^2\frac{m_2^2-m_1^2}{4p}\frac{t}{\hbar} = \sin^2\frac{\theta}{2}\sin^2 1.267\frac{\Delta m^2 L}{E}\frac{GeV}{eV^2 km}$$



ν oscillation

Neutrino oscillations are a quantum interference phenomena similar to the two slit experiment:



analogy

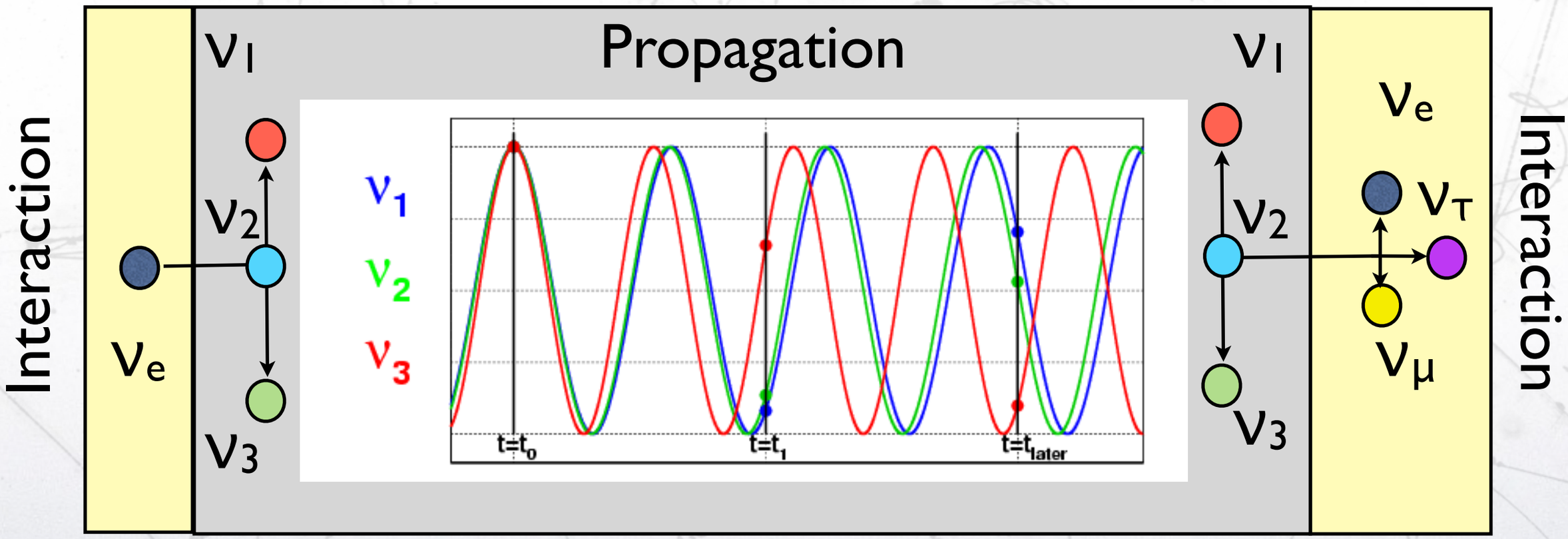
The path is defined by the neutrino mass over the transport time and the interference provides the pattern of electron and muon neutrinos.

ν oscillation

- With 3 neutrino families (one per massive lepton):

Flavour states: $|\nu_e\rangle$ $|\nu_\mu\rangle$ $|\nu_\tau\rangle$

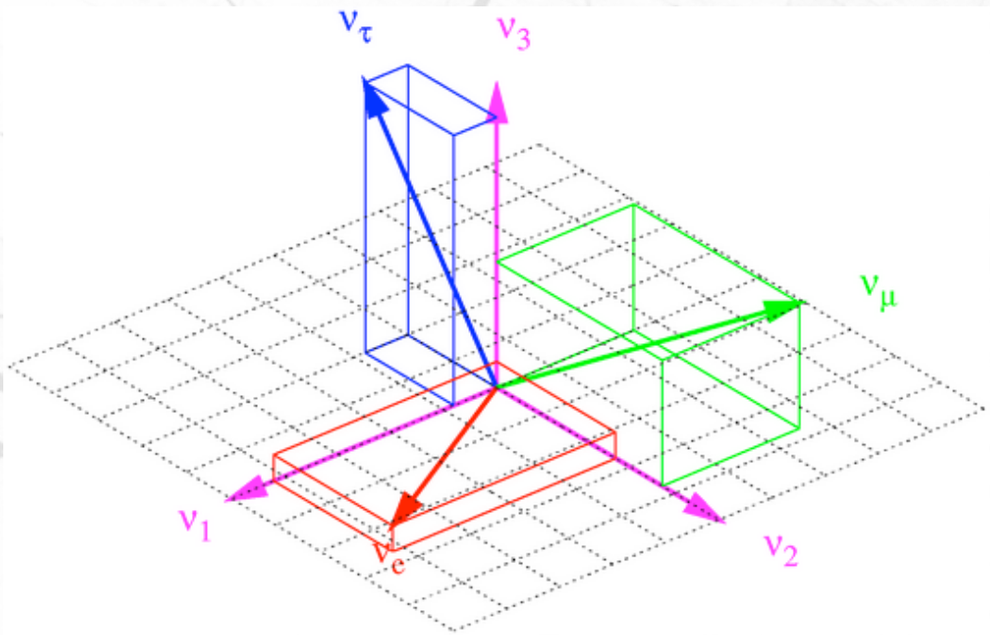
Mass states: $|\nu_1\rangle$ $|\nu_2\rangle$ $|\nu_3\rangle$



ν oscillation

Pontecorvo–Maki–Nakagawa–Sakata matrix

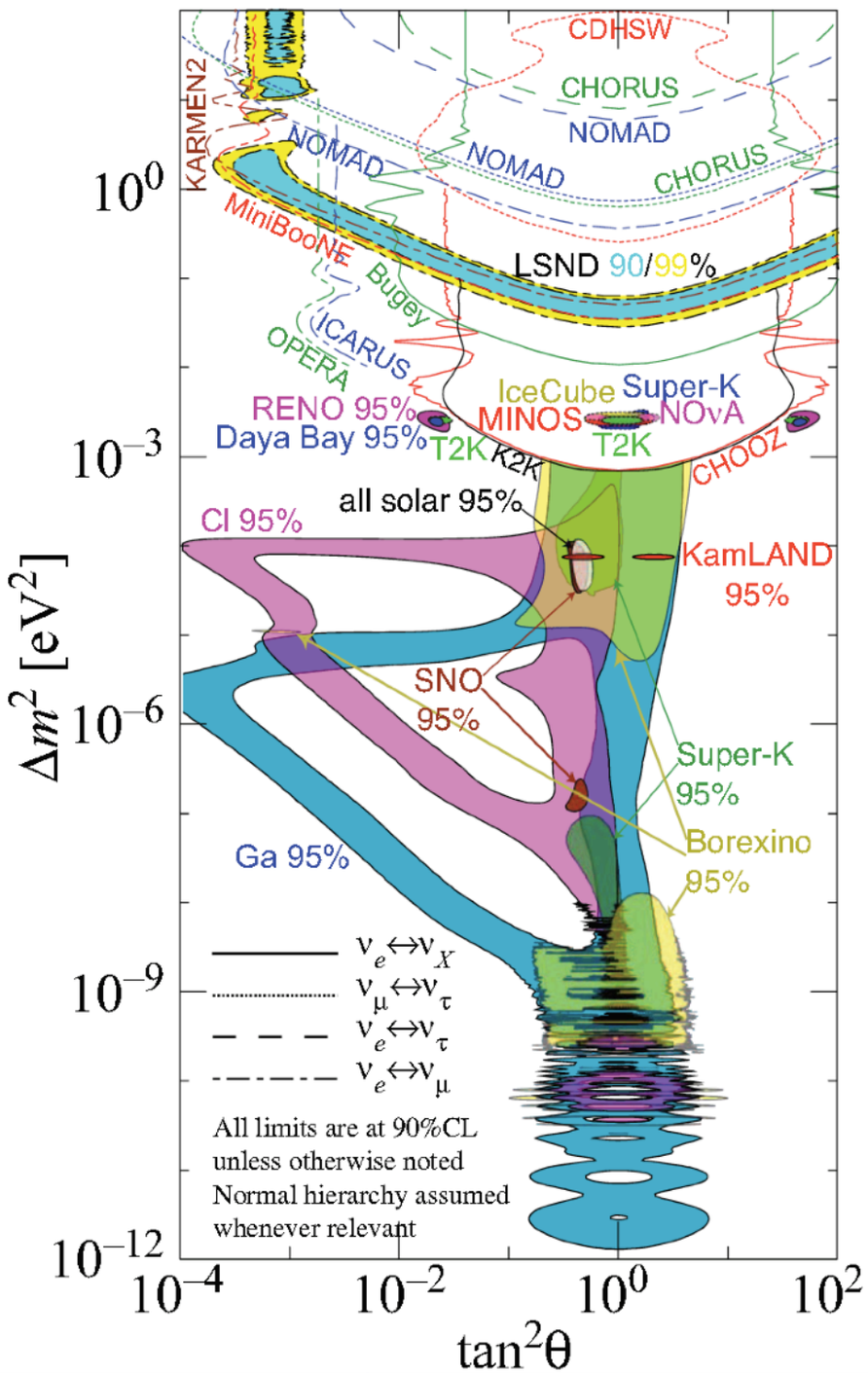
$$\begin{pmatrix}\nu_e & \nu_\mu & \nu_\tau\end{pmatrix} = U_{PNMS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



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

- With 3ν: there are 3 angles and 1 imaginary phase δ_{CP} (complex 3x3 matrix).
  - The phase allows for CP violation similar to the quark sector (CKM)
- There are also 2 values of Δm^2, traditionally Δm^2_{12} & Δm^2_{31}.

ν oscillation



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

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

	Parameter	best-fit	3σ
	Δm^2_{21} [10^{-5} eV ^{2}]	7.37	6.93 – 7.97
Hierarchy	$\lvert\Delta m^2\rvert$ [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
CP violation	δ/π	1.35 (1.32)	(0.92 – 1.99) ((0.83 – 1.99))

Missing measurements

- Two remaining parameters to measure

Hierarchy : is $m_3 > m_1$?

Neutrinos interacting with matter alter the oscillation angles and Δm!

It requires ***long base line*** experiments through earth (matter effects)

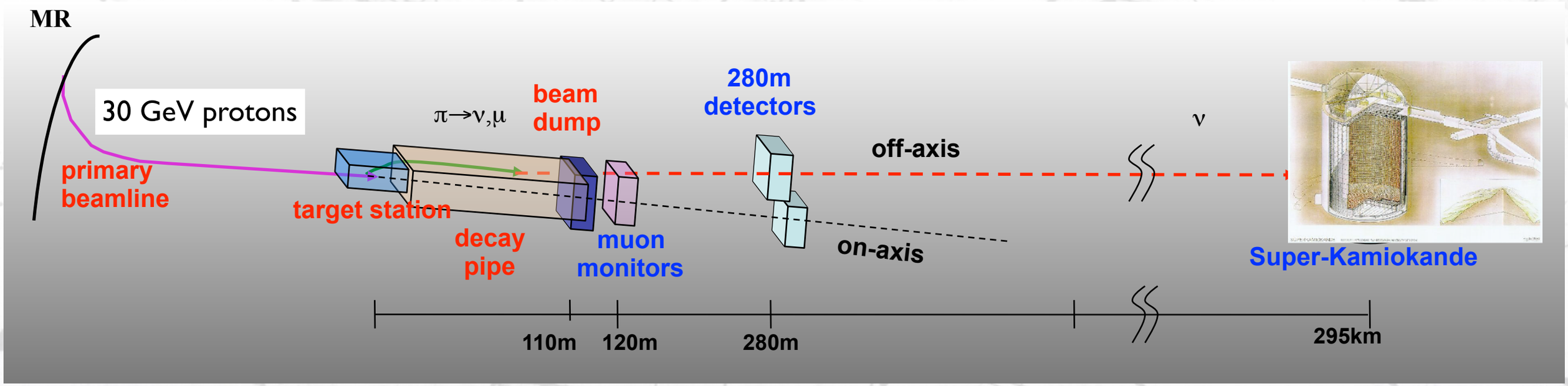
CP violation : Matter = Antimatter?

The probabilities:

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

Measured with ***long base line*** oscillations of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Typical Long Base Line experiment layout



Neutrinos produced in a particle accelerators:

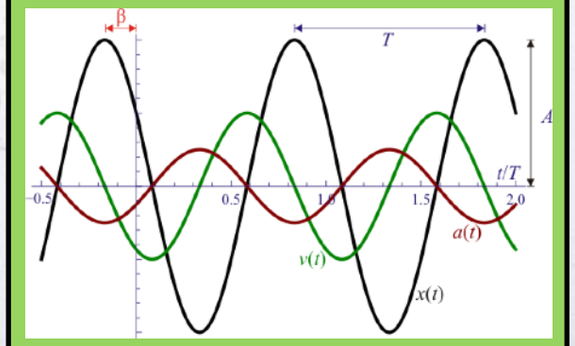
$pA \rightarrow \pi^+ \pi^+ \pi^- \ldots$

$\pi^+ \rightarrow \mu^+ \nu$

$\pi^- \rightarrow \mu^- \bar{\nu}$

Neutrino flux meas

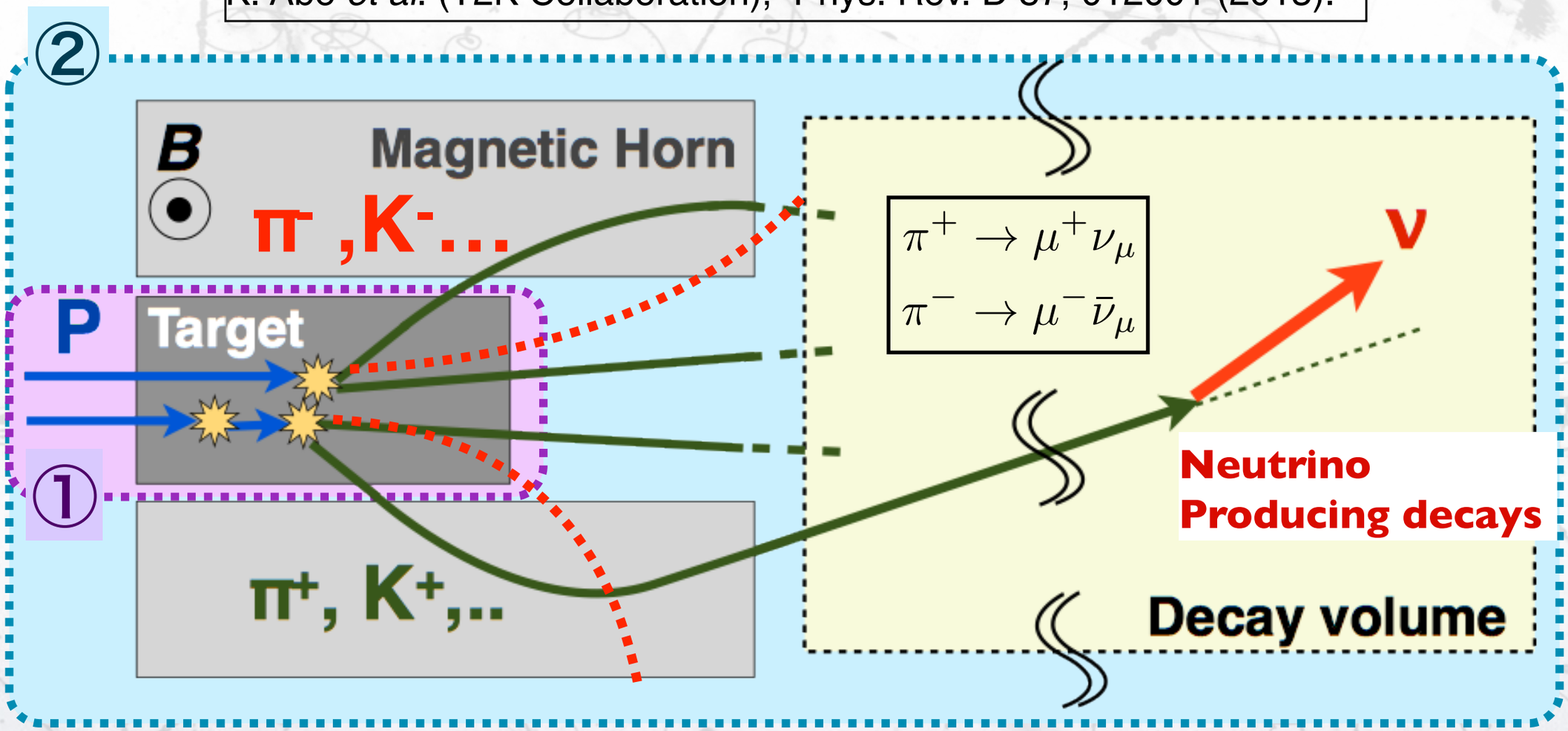
Oscillations



Neutrino flux meas

Neutrino production

K. Abe *et al.* (T2K Collaboration), Phys. Rev. D 87, 012001 (2013).

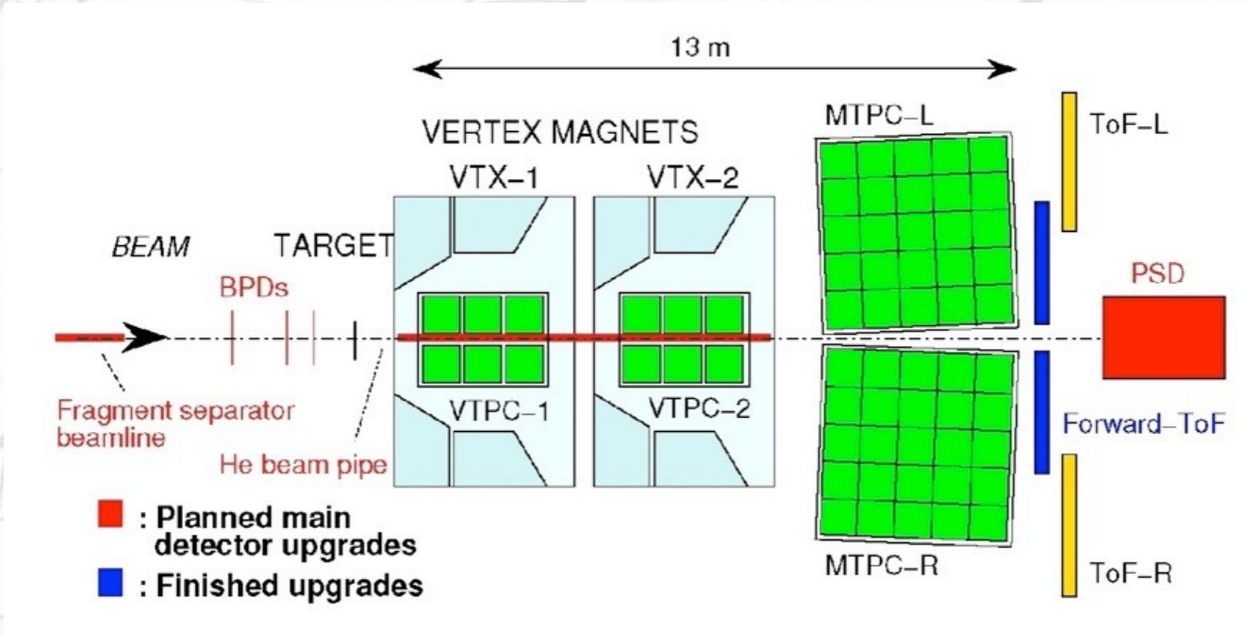


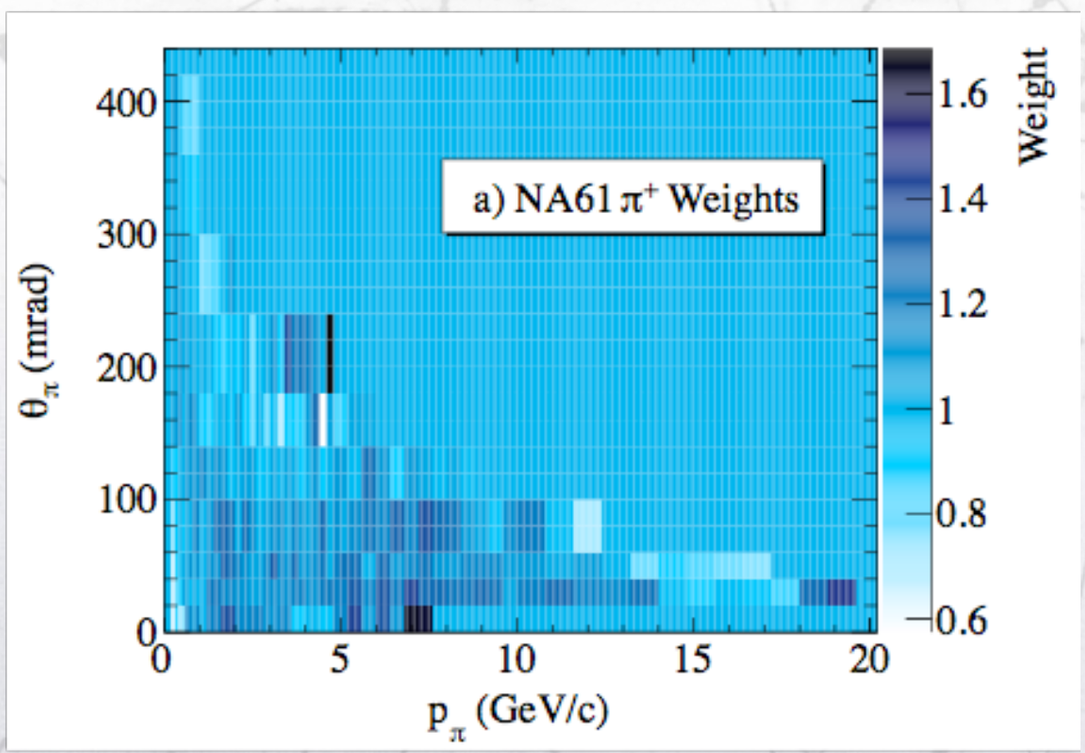
Other source of neutrinos is the low energy electron antineutrinos from nuclear reactors.

Flux prediction: Shine

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

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

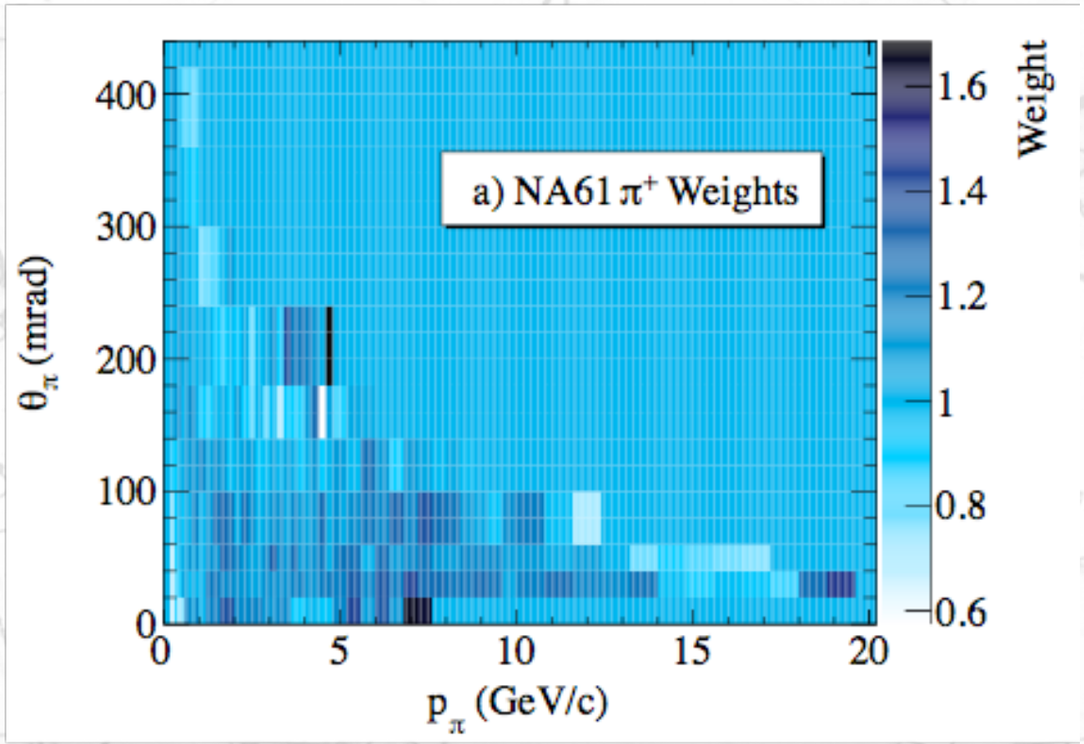




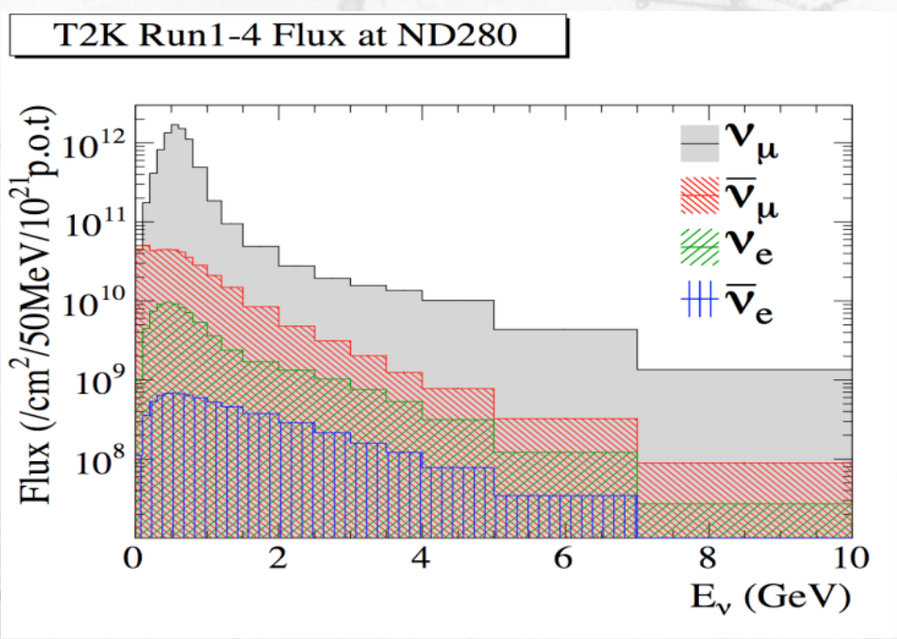
NA61/Shine measures a thin target for absolute production and thick target that is a copy of the ν target and provides also the reinteractions of particles.

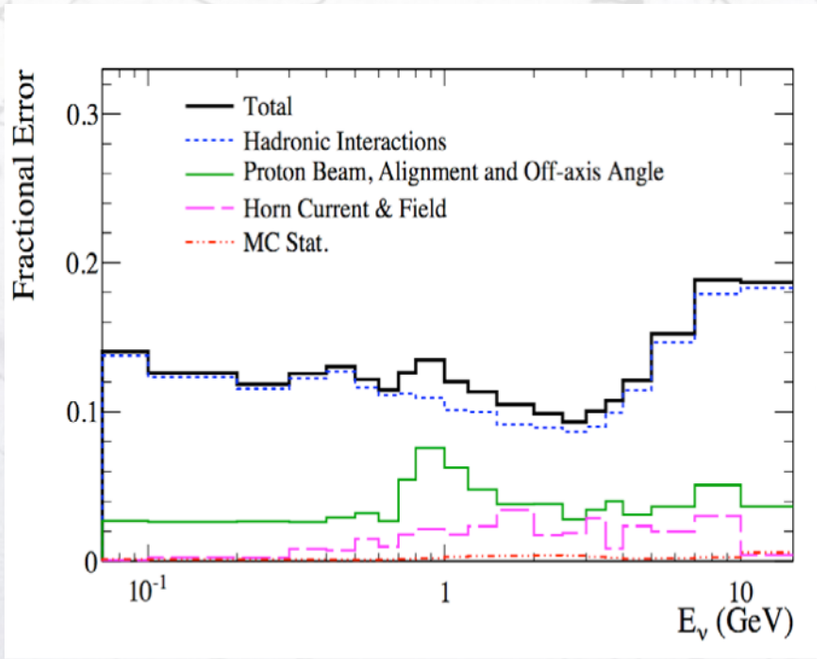
Flux prediction

pion and kaon production



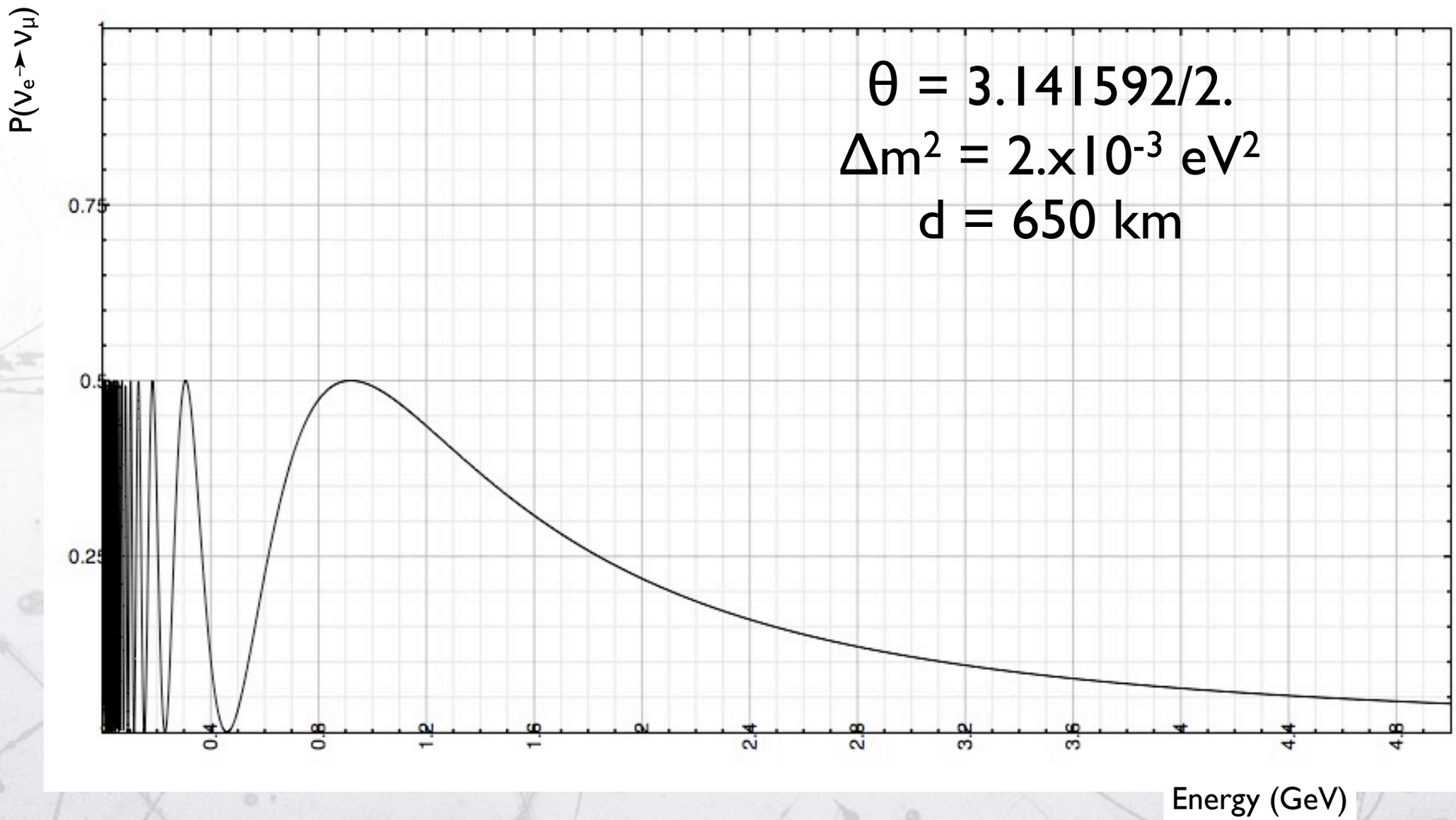
"A priori" flux error: ~15% below @ 1 GeV.





ν Oscillation

For a fixed distance we need to measure the Energy



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 & flux:

$$N_{events}(E_\nu) = \sigma_\nu(E_\nu)\Phi(E_\nu)$$

  - at the far detector

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

- The ratio cancels flux and cross-section:
- $$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = P_{osc}(E_\nu)$$

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.

Neutrino oscillations

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

Oscillation experiments require to know:

Neutrino flux:	$\Phi(E_\nu)$
Neutrino cross-section	$\sigma(E_\nu)$
True neutrino energy	$P(E_\nu\|E'_\nu)$

$P(E_\nu|E'_\nu)$ is not only caused by detector smearing
Neutrino interaction channels are critical.

Neutrino interactions

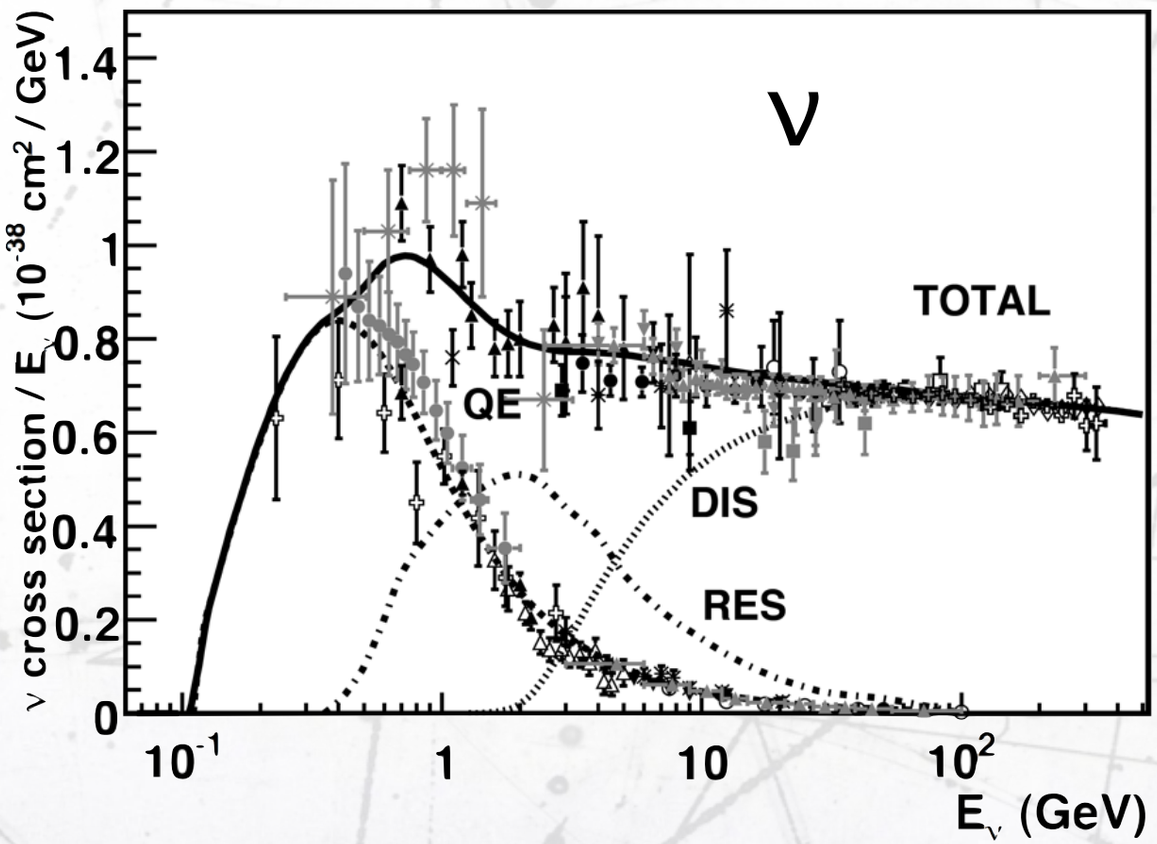
Neutrino interations @ the nucleon level !

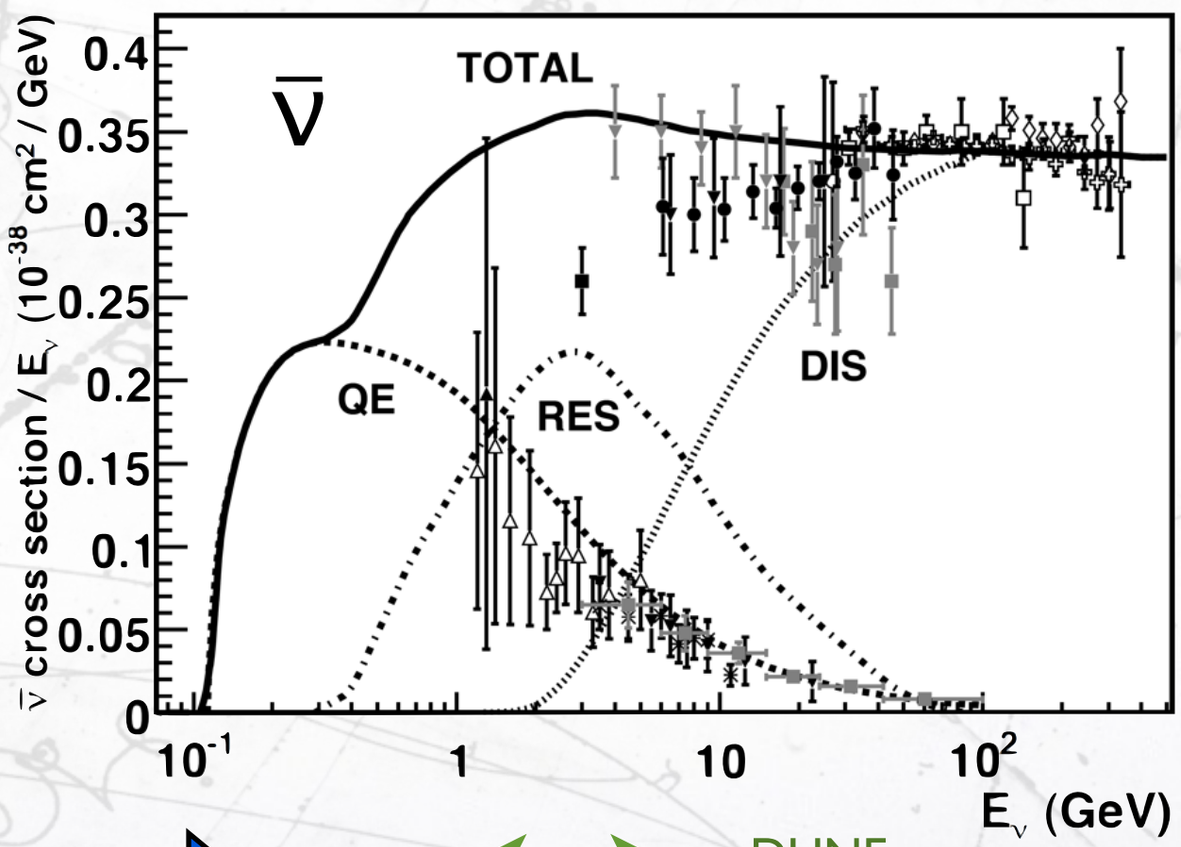
$CCQE$	$\nu_\mu n \to \mu^- p$
$CC1\pi$	$\nu_\mu p \to \mu^- \Delta^{++} \to \mu^- \pi^+ p$
	$\nu_\mu n \to \mu^- \Delta^{+} \to \mu^- \pi^+ n$
	$\nu_\mu n \to \mu^- \Delta^{+} \to \mu^- \pi^0 p$
$CCN\pi$	$\nu_\mu N \to \mu^- \Delta^{+,++} \to \mu^- N' \pi\pi ...$
$CCDis$	$\nu_\mu N \to \mu^- N' \pi,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

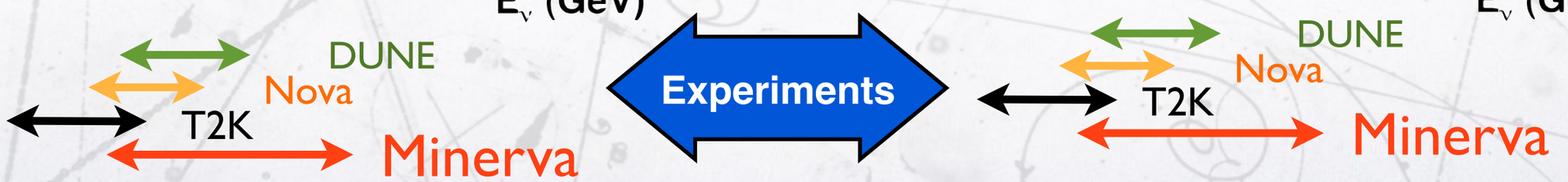
Complementary for antineutrinos.

X-sections

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

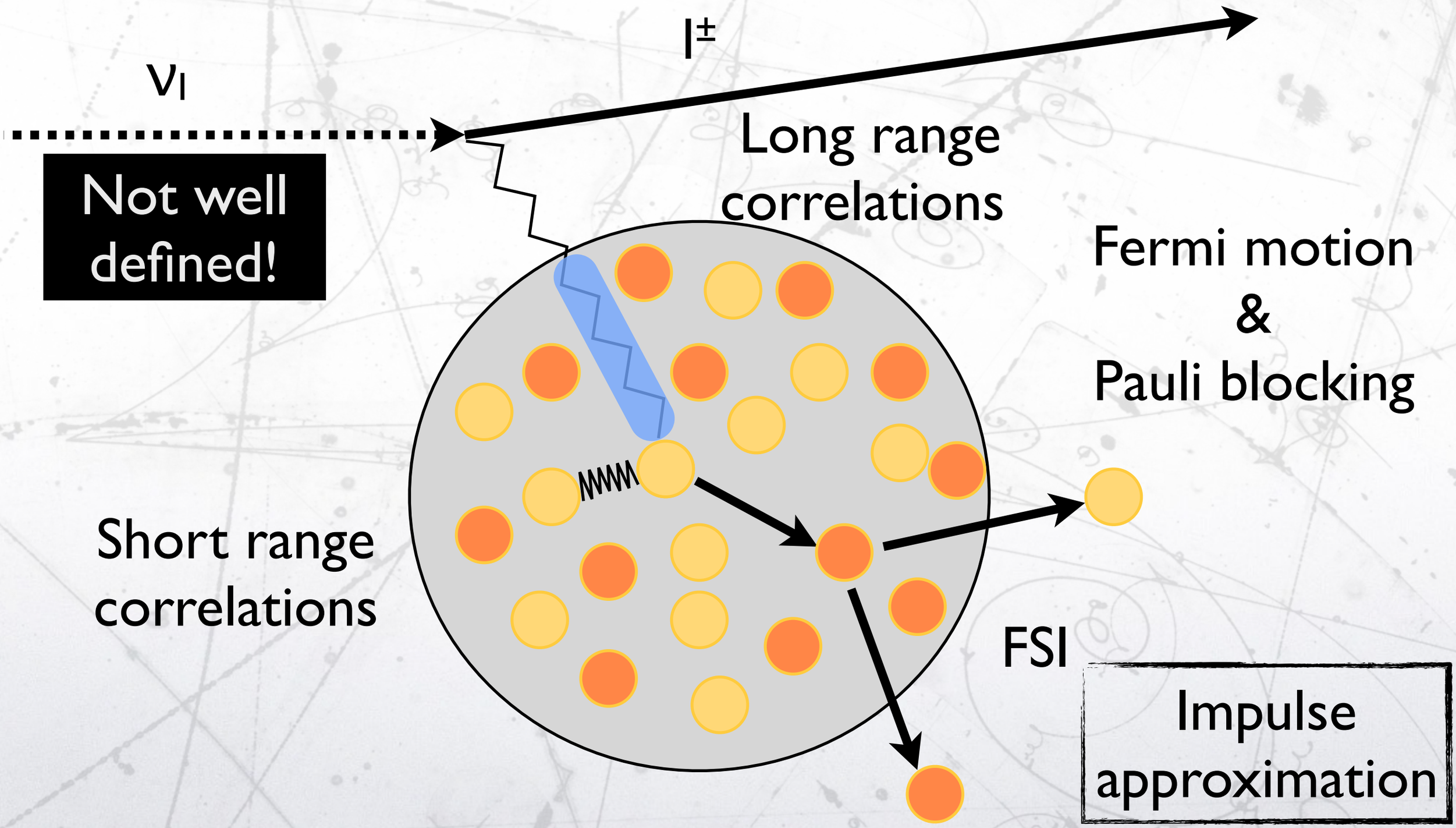




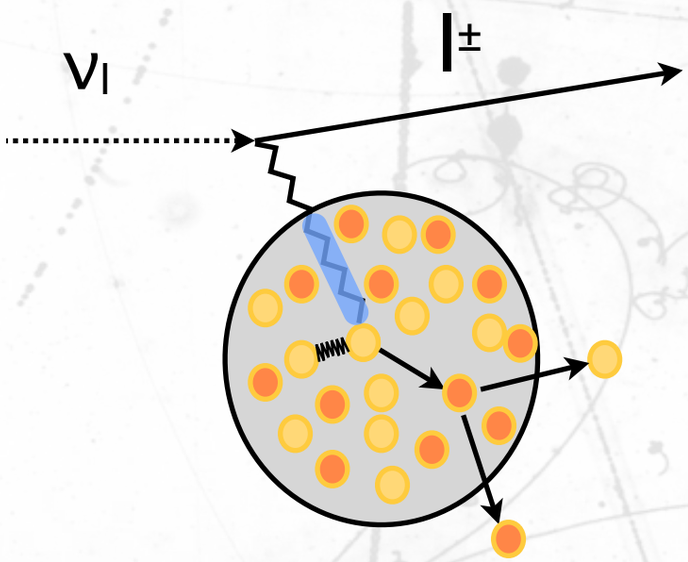


Present and future oscillation experiments cover a complex region full of reaction thresholds and sparse data.

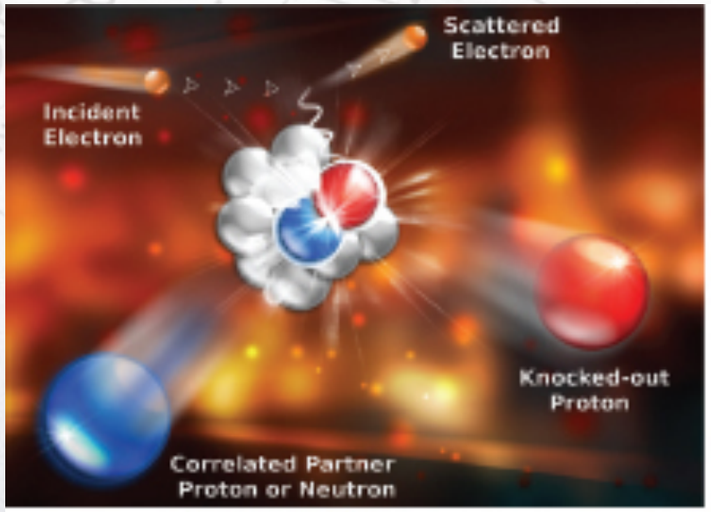
Neutrino interactions

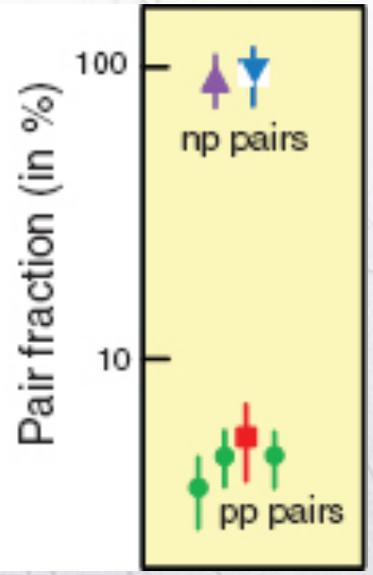


Modelling interactions



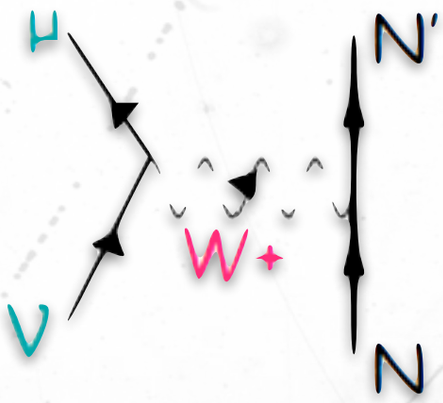
- Normally considered the "impulse approximation" or factorisation:
  - nucleon **assumed** free in nuclear media !
  - nucleon free in nuclear potential: no nucleon correlations!.
- Nuclear effects added on the top:
  - Fermi momentum.
  - Pauli blocking.
  - Short and long range nuclear correlations.



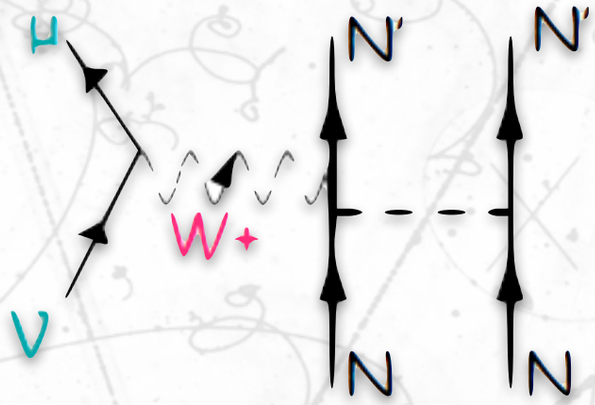


Modelling interactions

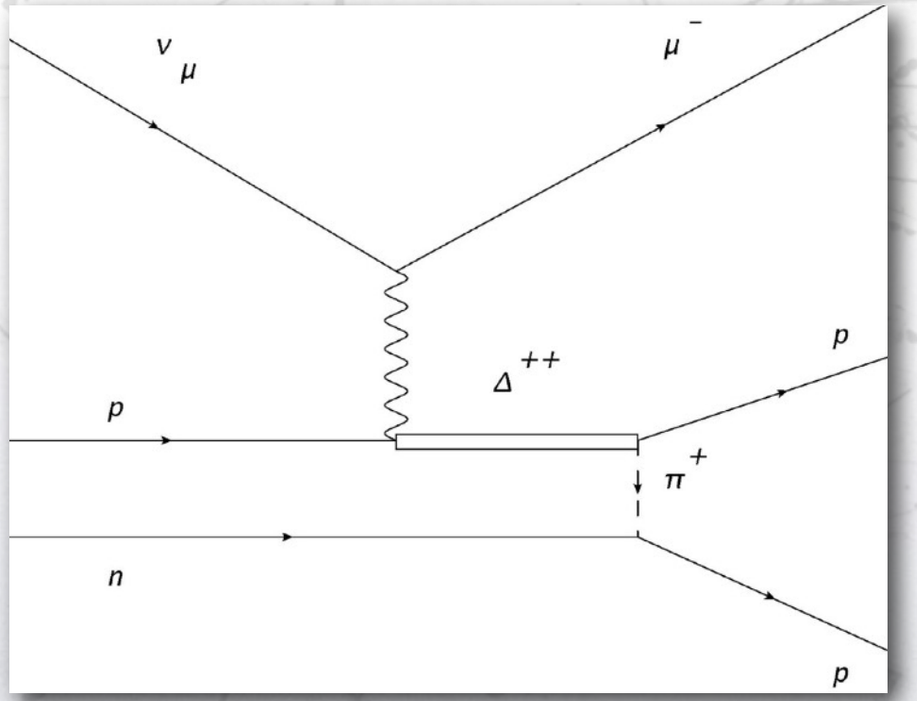
CCQE

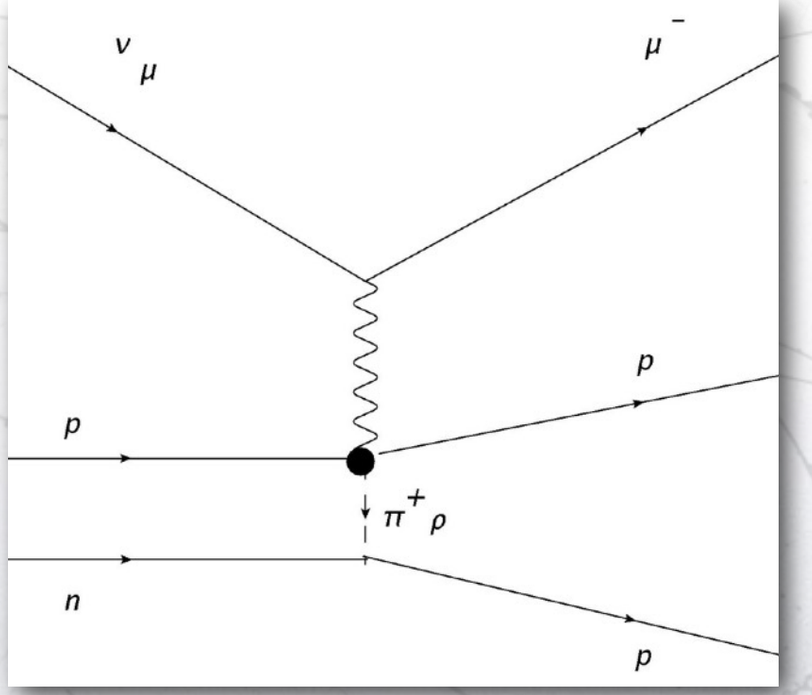


CC-2p2h



- Charge current without pions are made of several interactions
- 2p2h is basically the exchange of a meson between two close by nucleons in the nucleons with the emission of 2 nucleons.

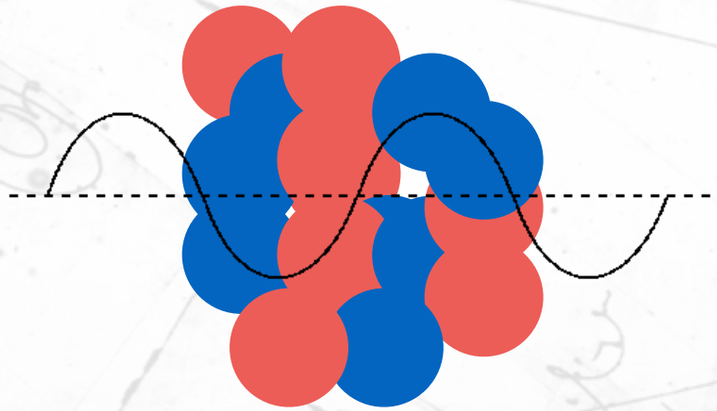




- The pion can be produced in a contact point or virtual Δ^{++}.

Long range correlations

- The typical wavelength of the particles in ν interactions are the size of the nucleus.
- Particles see the nucleus as whole.
- Long range correlations modify the W self-energy in the presence of high density nuclear media.
- Long Range Correlations alter the cross-section dependency on virtual energy of the W



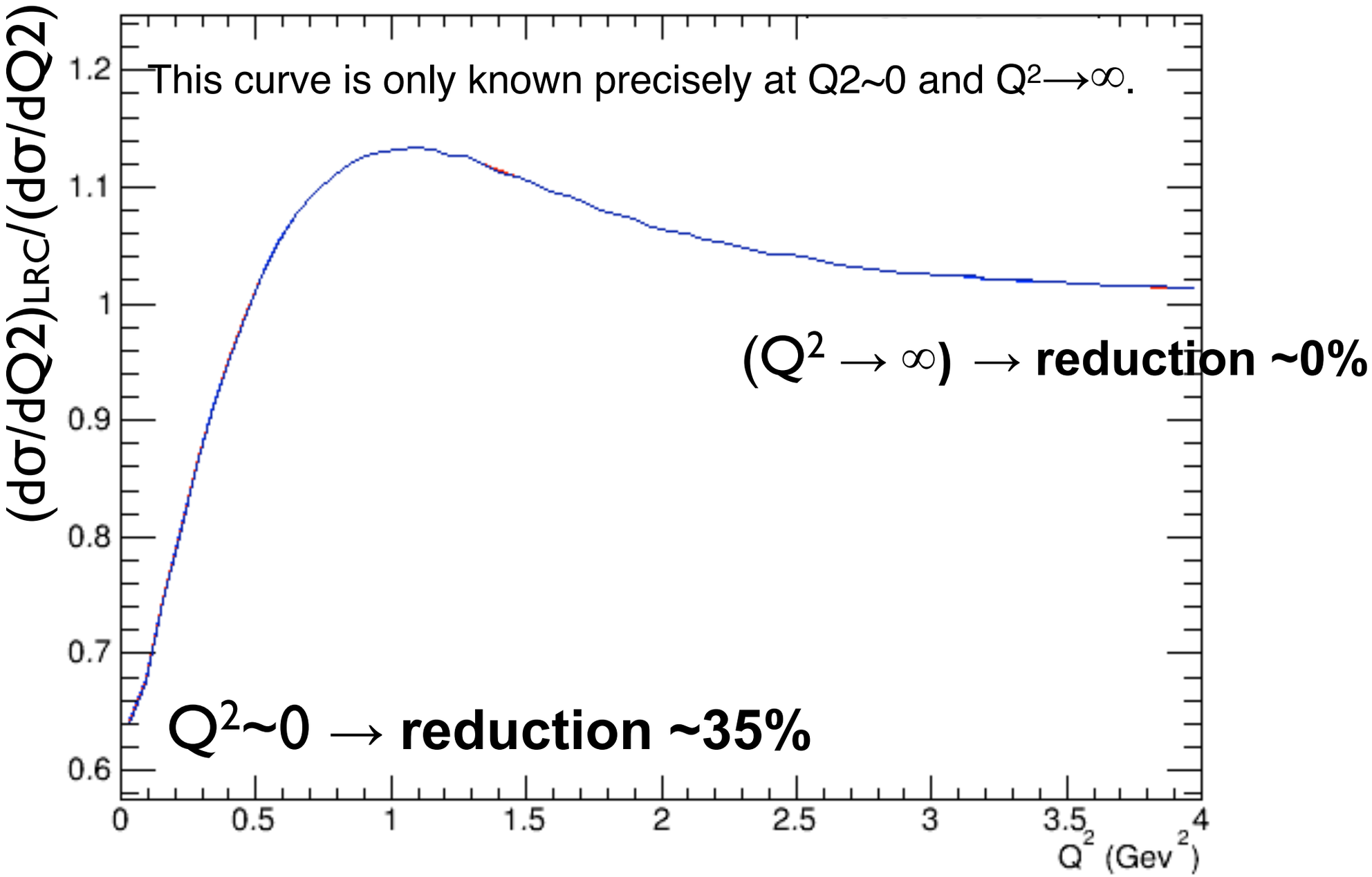
De Broglie particle wavelength

$$\lambda = \frac{\hbar}{E} = \frac{197.3nm}{E(eV)}$$

$$\lambda_{100MeV} = 1.97fm$$

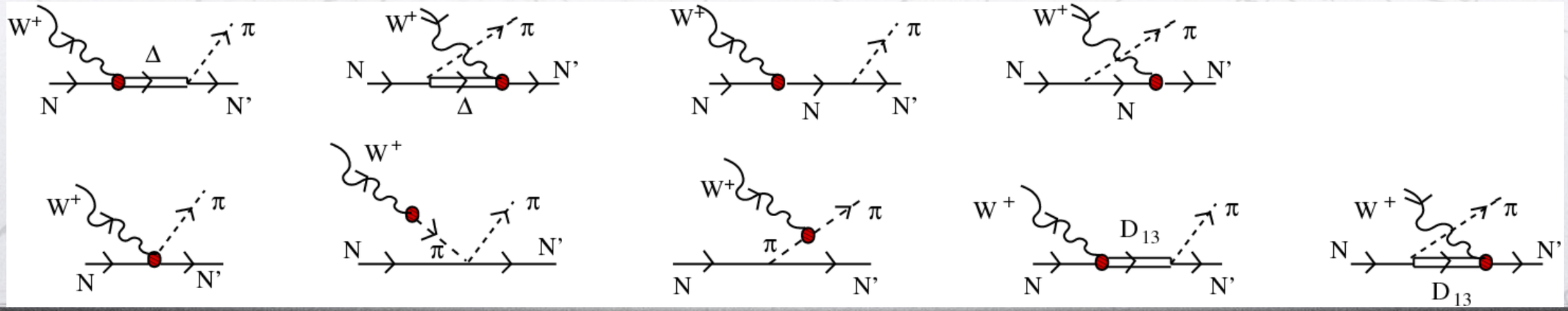
$$R_{Carbon} \approx 2.7fm$$

Modelling interactions



Single pion production

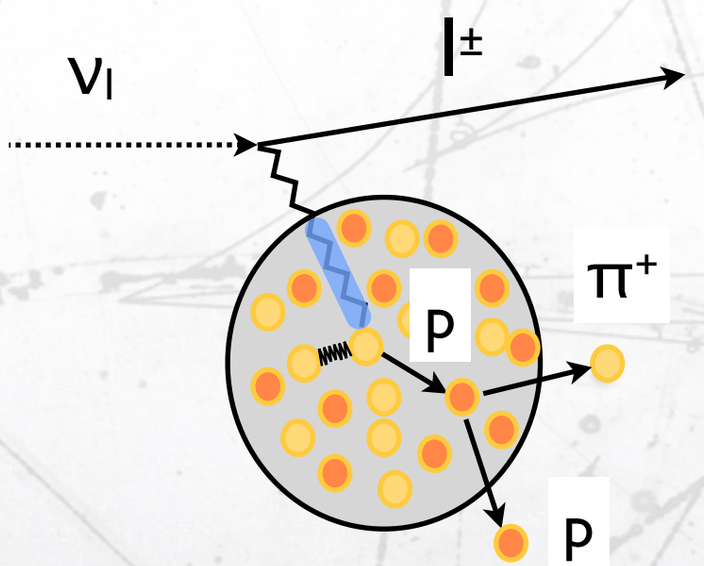
- CCπ Second most relevant cross-section in oscillation experiments.
- Cross-section unknown @ the nucleon level.
  - Complex modelling with many intermediate resonances and non-resonant contributions.
- All set of long and short rage correlation effects in CC1π are ignored in actual pion production models.

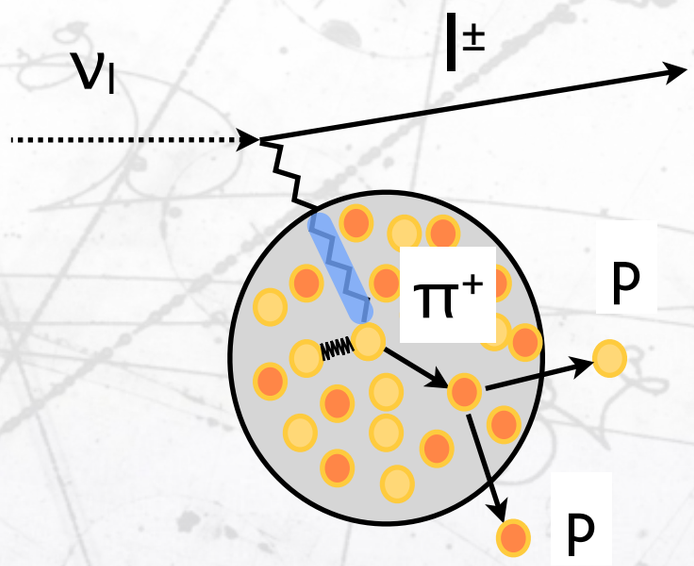


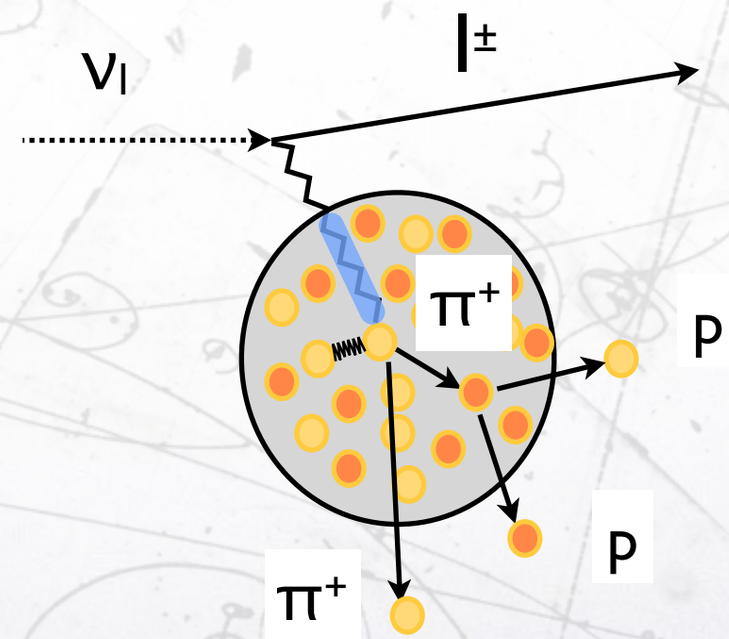
Final state interactions

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

FSI alters the definition of the event







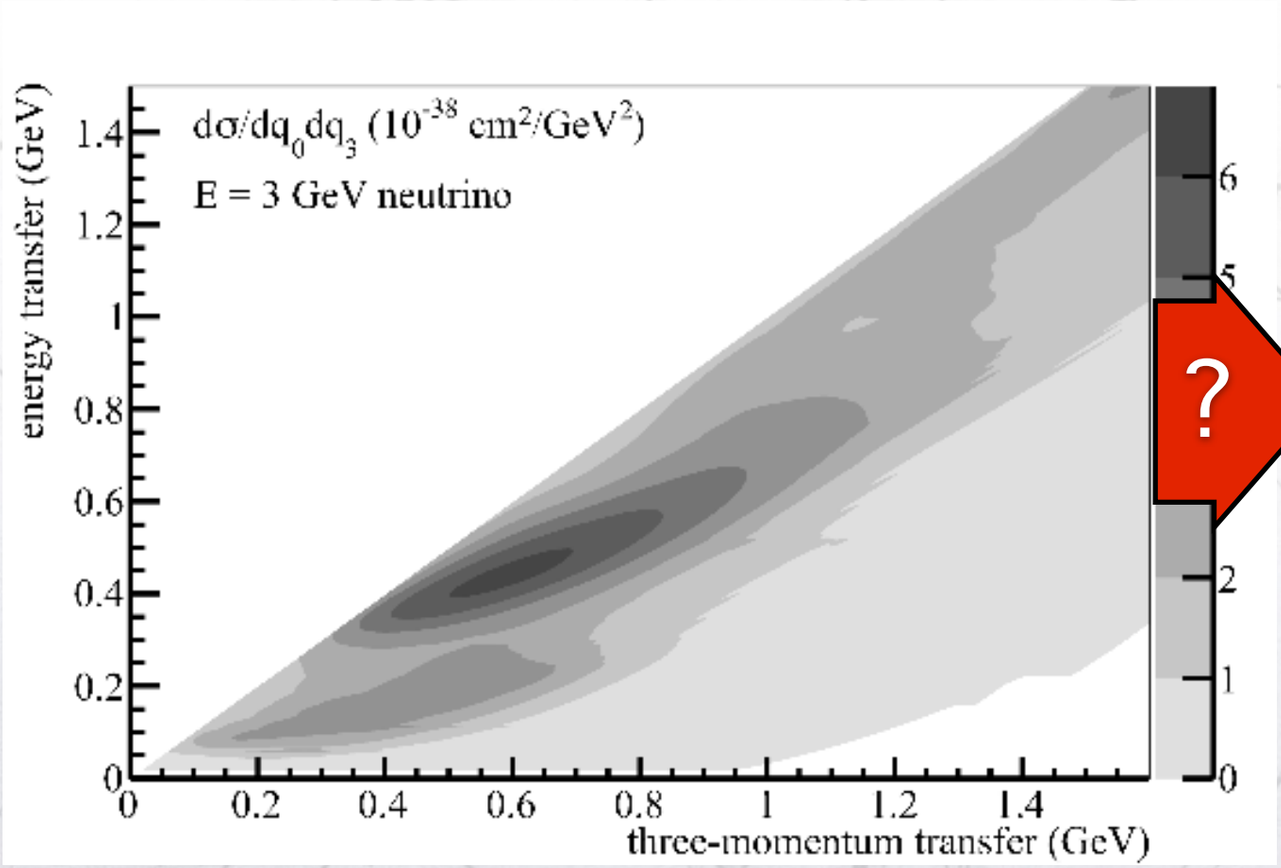
1. CCQE
2. proton in final state
3. p p -> p π^+

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

1. CC $2\pi^+$
2. $2\pi^+$ in final state
3. π^+ p -> p p

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 vs. non-relativistic, etc...).
- Agreement with experiments might vary with experiment energy range.



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

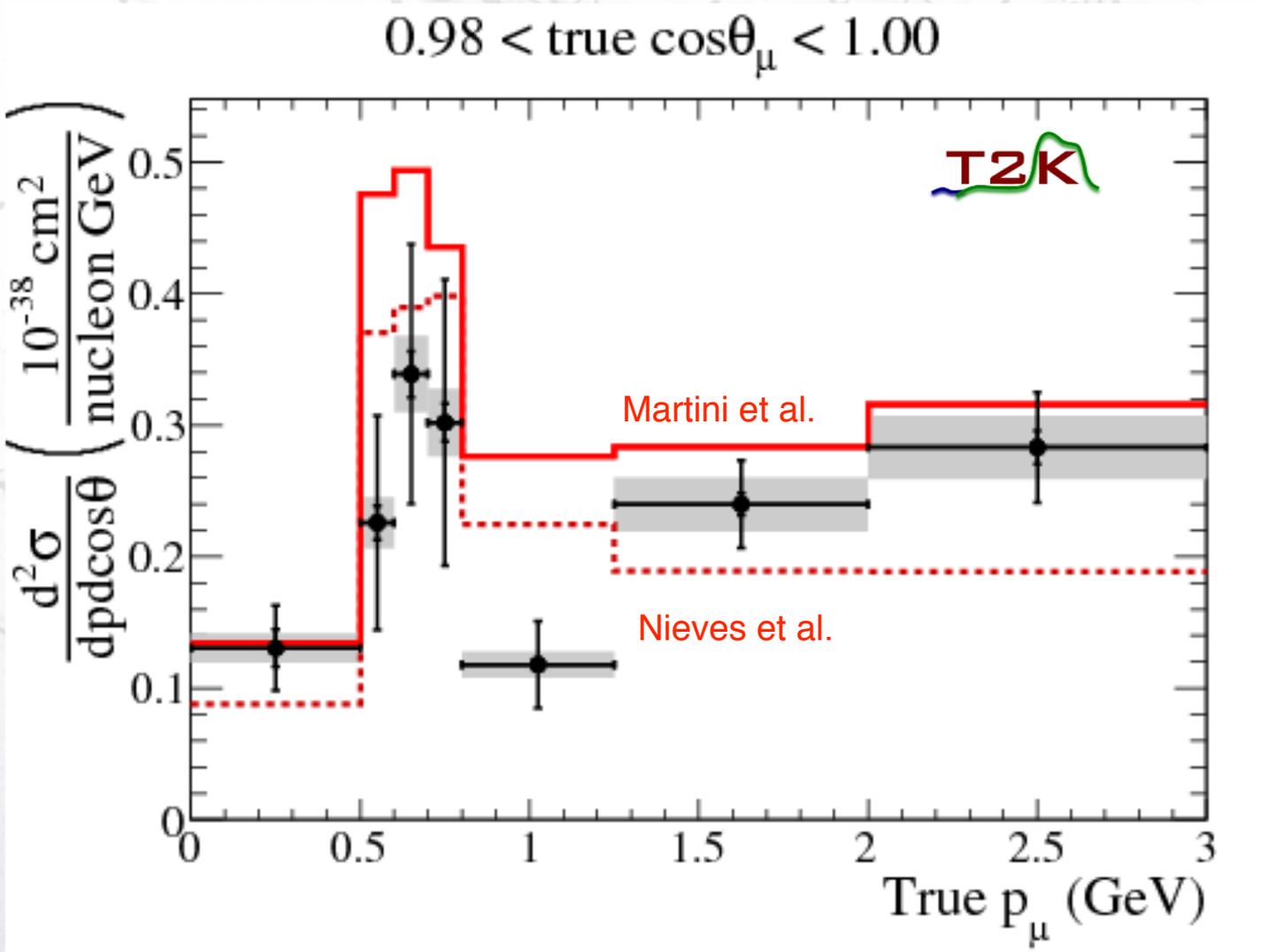
?

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

Theorists are needed!

How bad is bad ?

μ momentum distribution in the forward direction



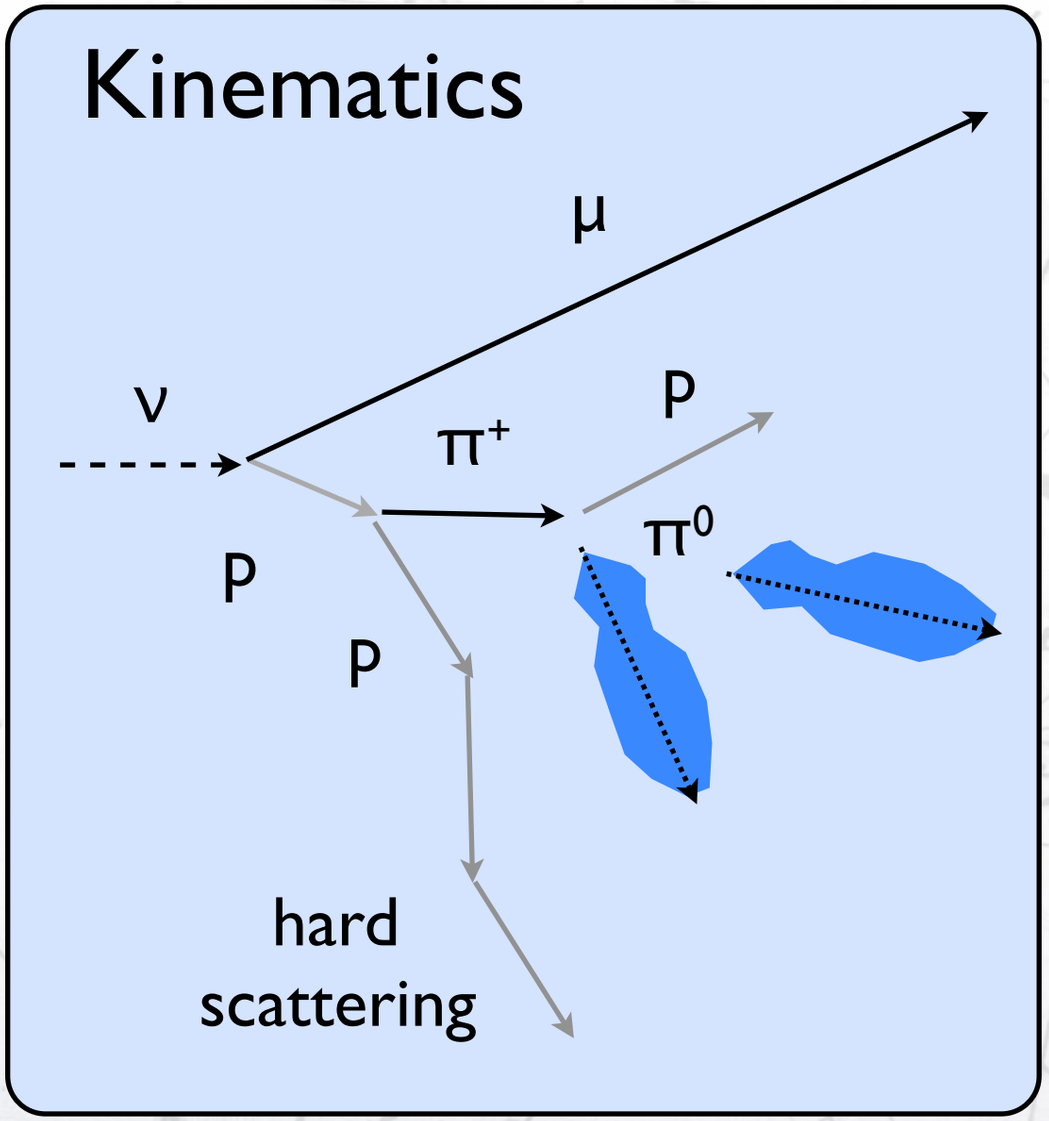
$$Q^2 = -q^2 = 2(E_\nu E_\mu - p_\nu p_\mu \cos\theta_m u) - m_\mu^2$$

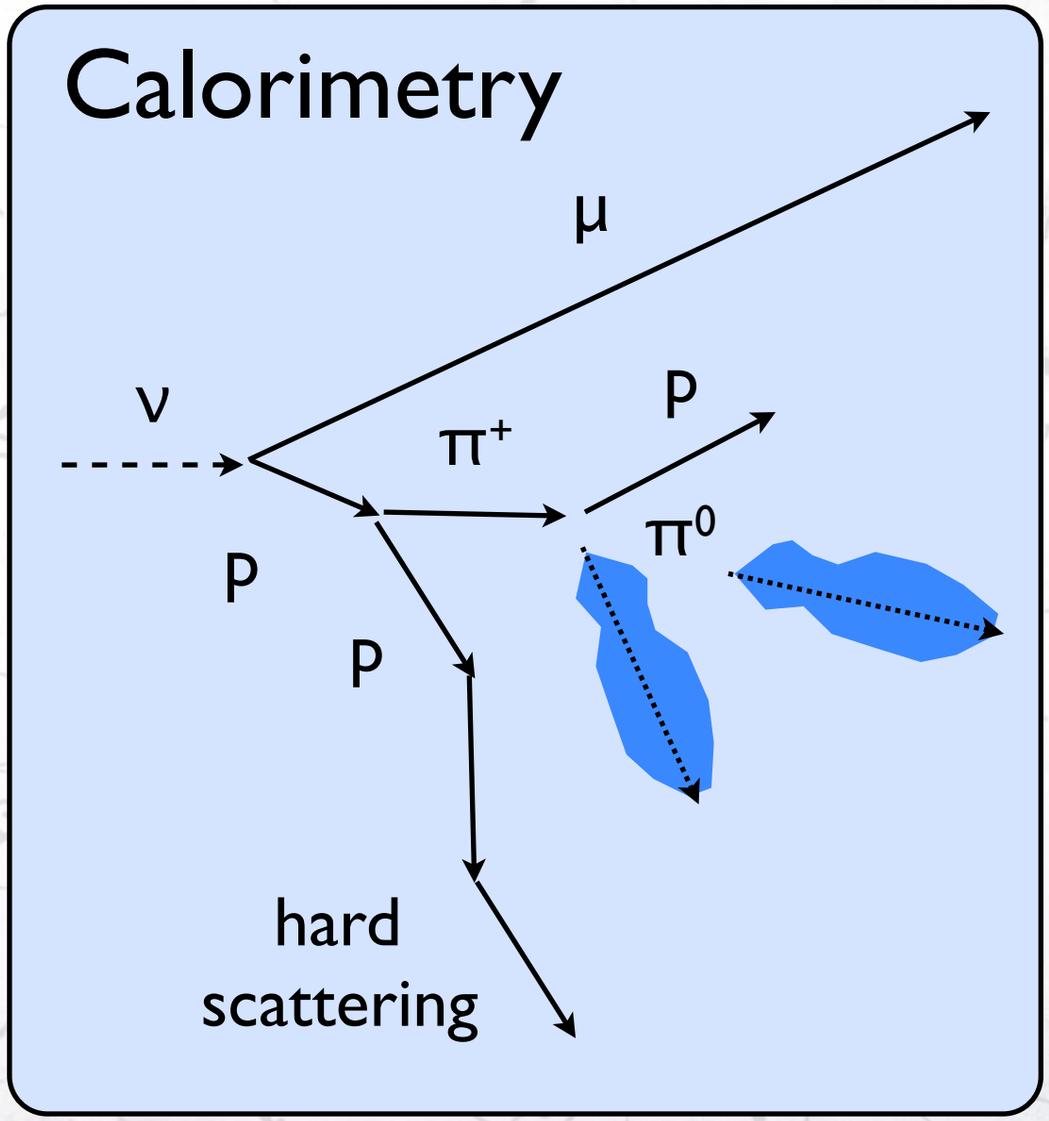
- In one bin we get different E_ν (flux) & Q^2 (x-section) contributions.
- The flux is constrained from the hadro-production.
- Adjusting the model to the flux will migrate problems from flux to cross-section and viceversa.

Low and High Q2 contains different level of uncertainties at the nucleon level (form factors) and nuclear level (short and long range correlations)

Nieves et al. and Martini et al. are the best two models in the market. Same physics but two implementations !

ν Energy reconstruction

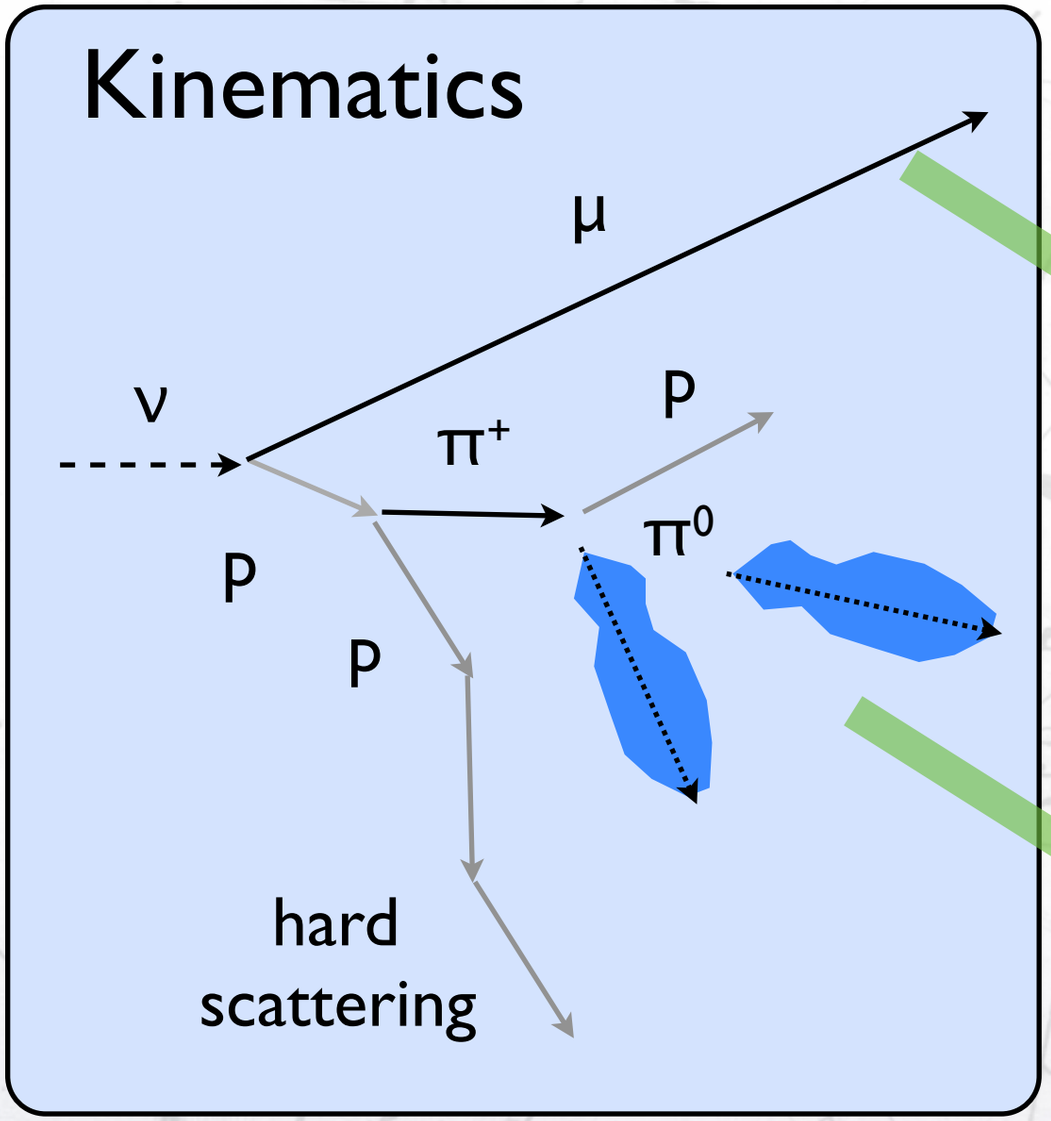




- Only a fraction of the energy is visible.
- Rely on channel interaction id.

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

ν Energy reconstruction



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

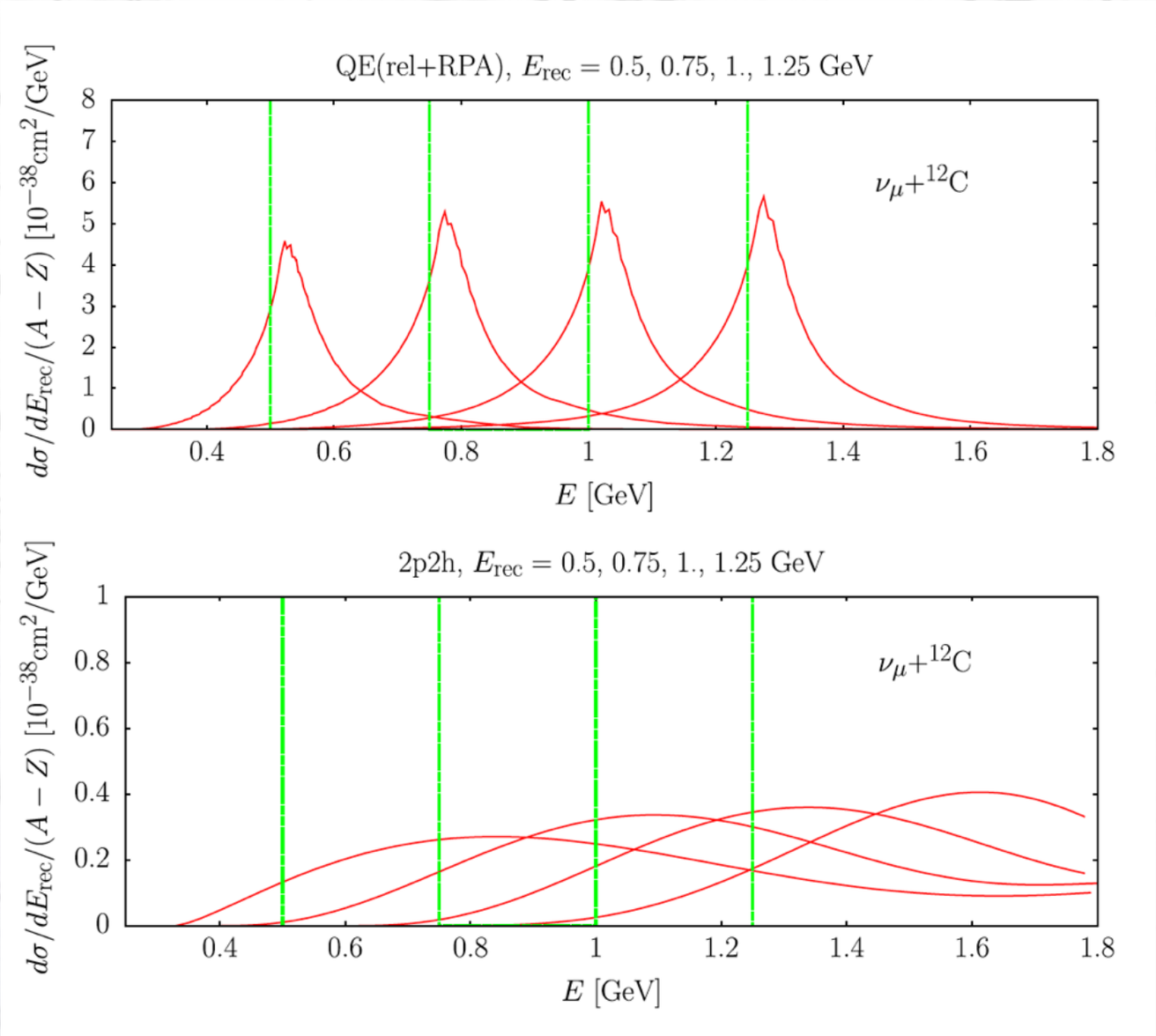
- From conservation of momentum and energy:

$$E_{reco} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

- Assumptions:
  - We know the reaction channel: CCQE, CCΔ, etc…
    - Normally identified with presence of pions in the event.
  - The target nucleon is at rest (no fermi momentum).

Kinematic Approach

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



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ν Energy reconstruction

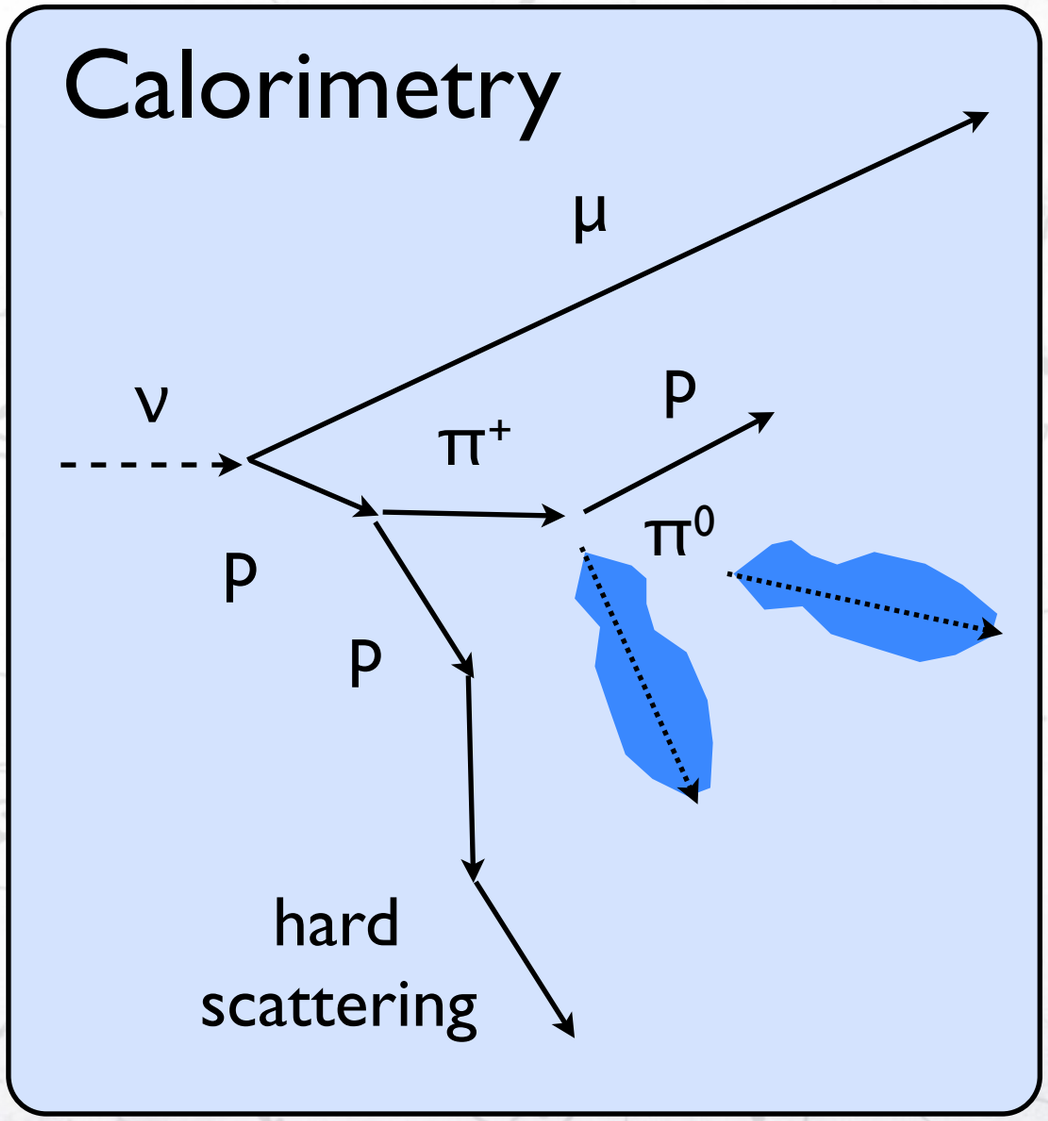
- The energy is reconstructed by summing all detected energy:

$$E_{reco} = E_{\mu} + \sum_{hadron} E_{hadron}$$

- The deposited energy is only the kinetic energy. The total energy requires the identification of particles:

$$E = E_{kin} + mass$$

- This approach requieres:
  - fully sensitive detector.
  - Understanding of the energy deposition by different particles.

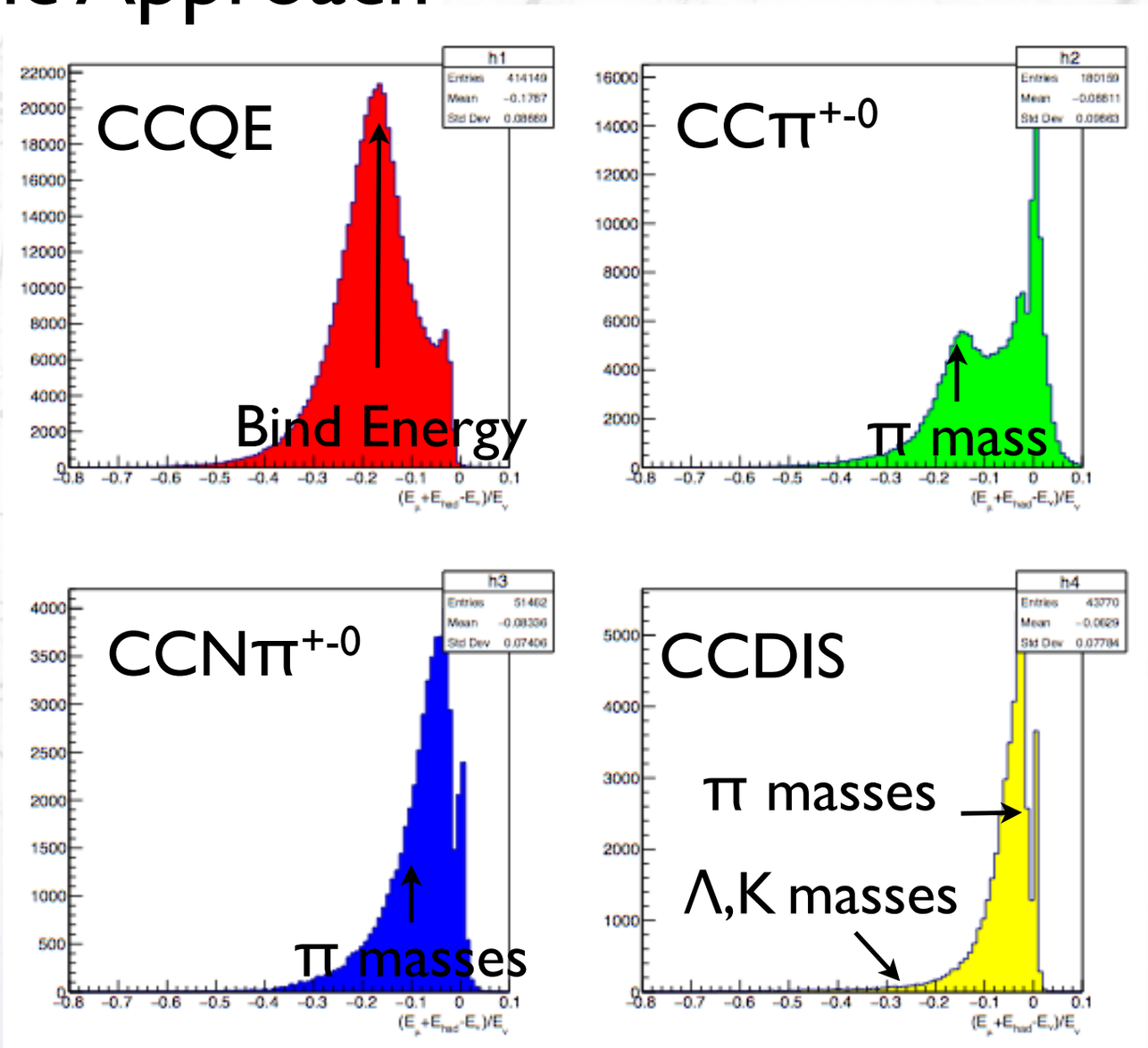


- The visible energy is altered by the hadronic interactions and it depends on hadron nature.

ν Energy reconstruction

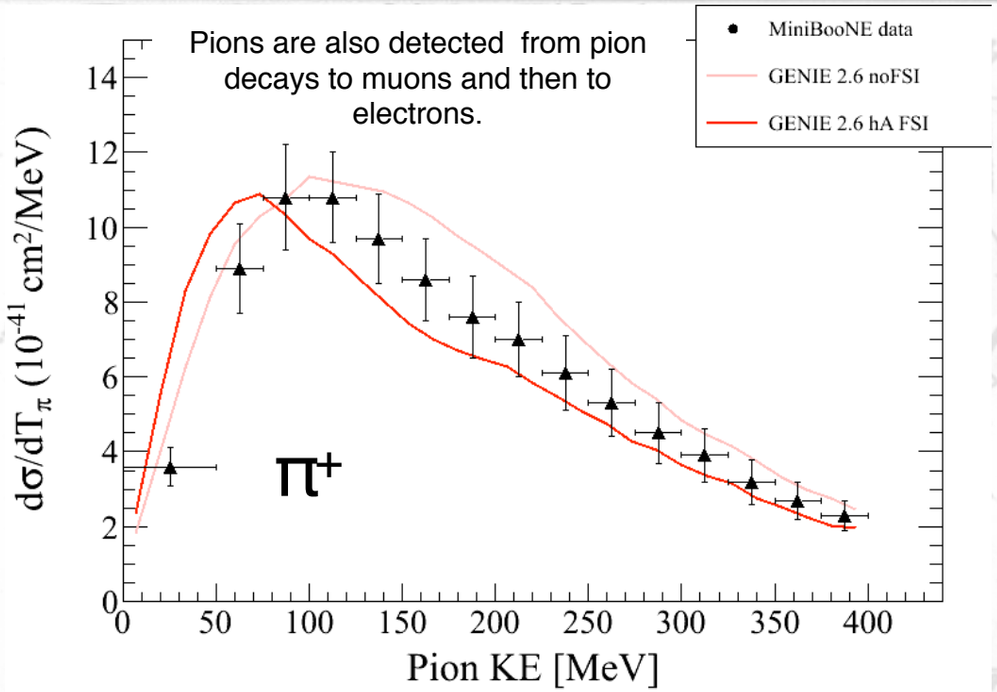
Calorimetric Approach

- Simple exercise (Simulations):
  - 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.
  - The energy to change nuclear state (bind energy) needs to be considered.
- Part of the pion and kaon mass can be recovered through its decay chain.

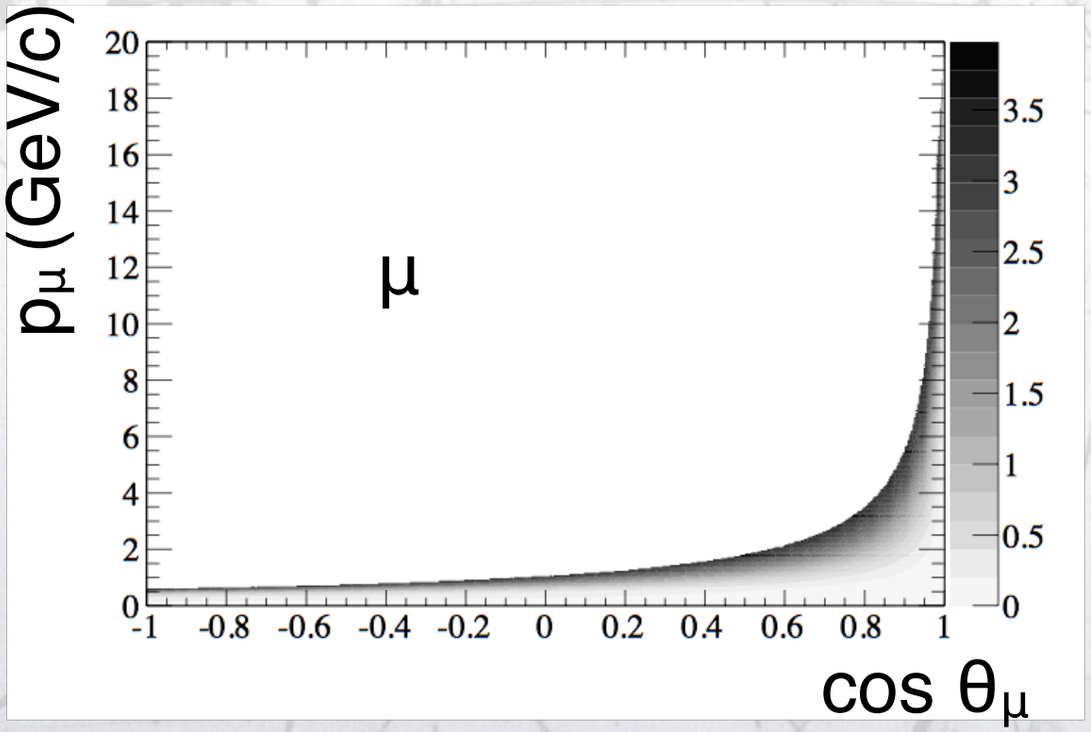


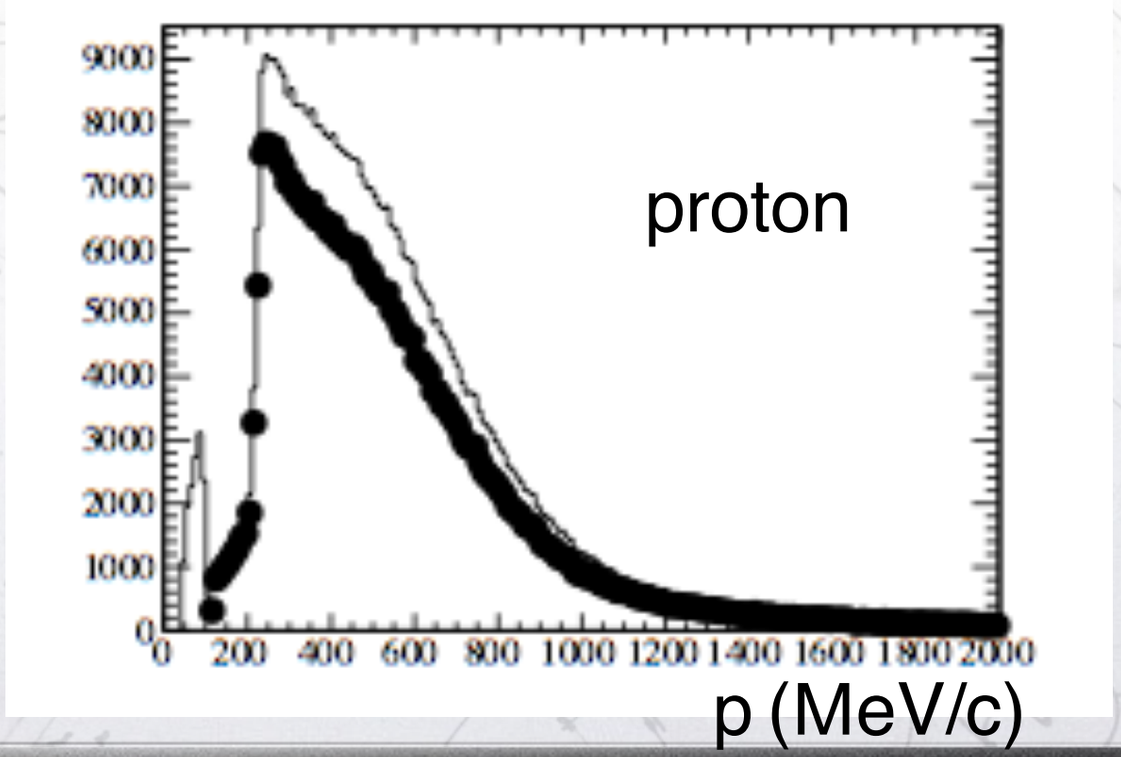
Calorimetric energy reconstruction requires x-section knowledge!

Momentum and angle



- Neutrino beams are relative low energy (0.5 to 3 GeV)
- Particle produced are low energy and spreading over all angles.
- Main challenge is to detect very low pions and protons (~100 MeV/c)





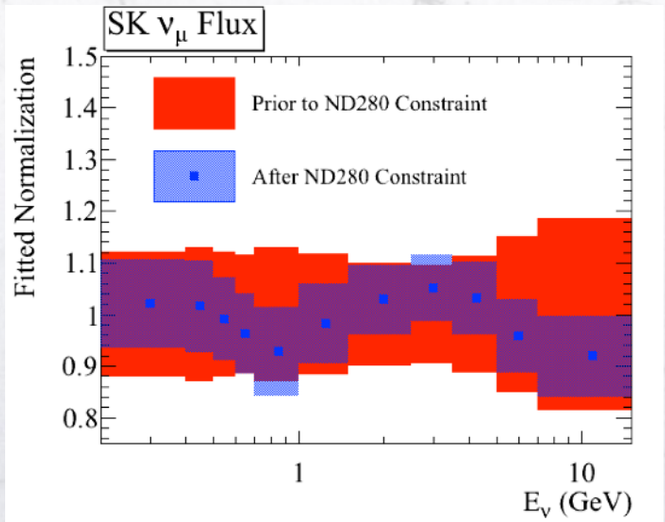
Near detector

Near detector data improves the flux prediction at the cost of introducing undesired correlations with cross-section (theoretical) uncertainties.

Improvements in neutrino models and independent measurements are mandatory.

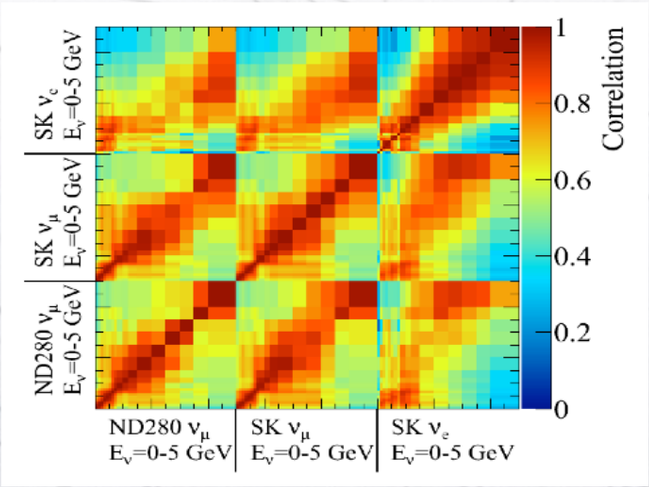
=

Corrected flux and cross-section model



&

correlation

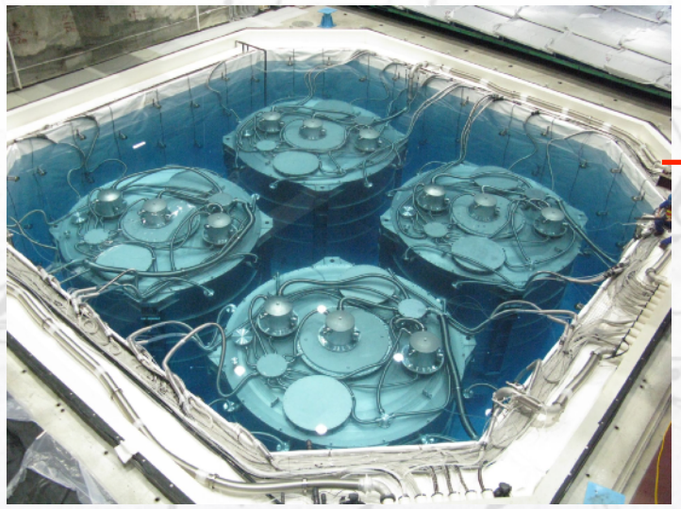


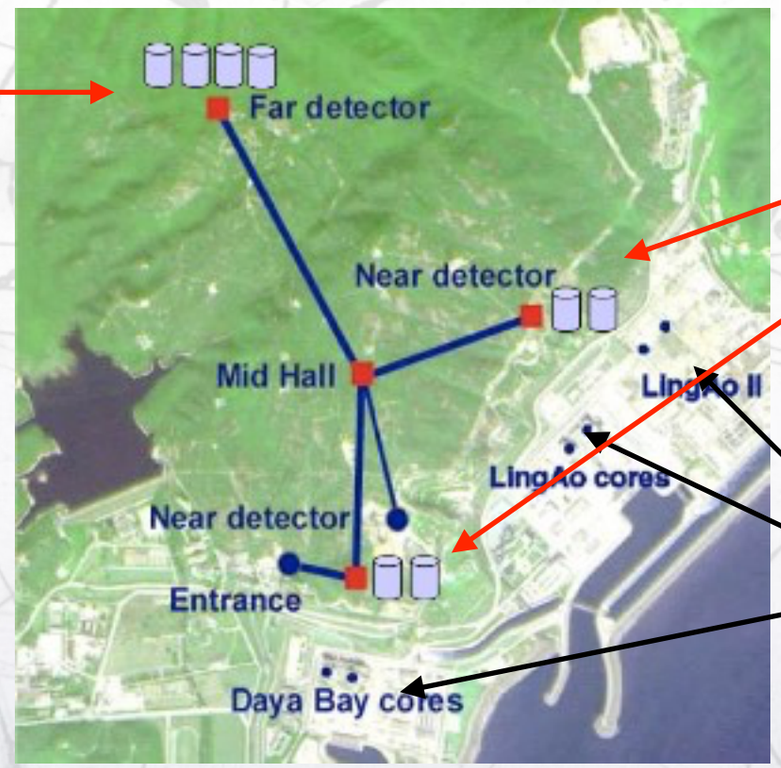
Near detectors

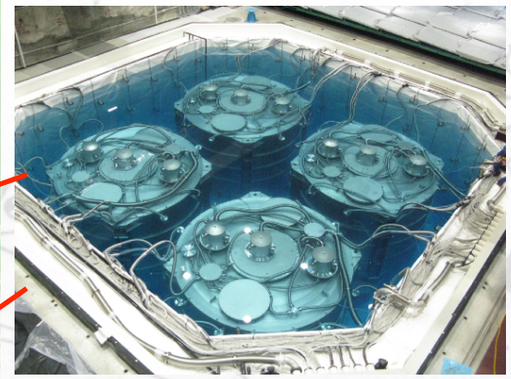
- Near detector is also used in reactor neutrino experiments **to normalise the neutrino flux**.
  - Cross-section is very well known theoretically : **inverse beta decay !**

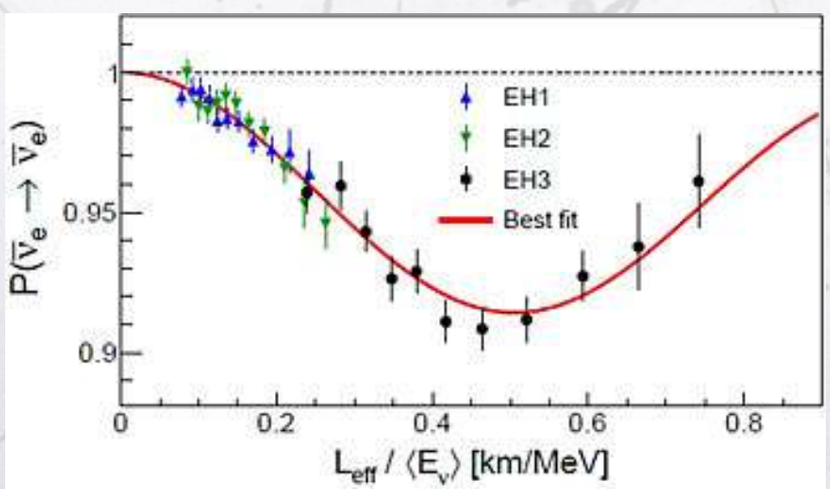
$$\bar{\nu}_e p \rightarrow e^+ n$$

- Near and far detectors are almost identical in this case.





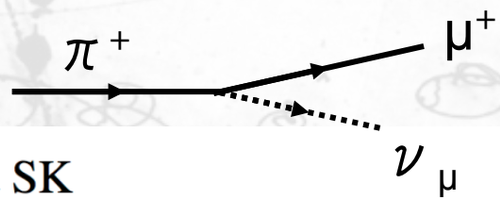


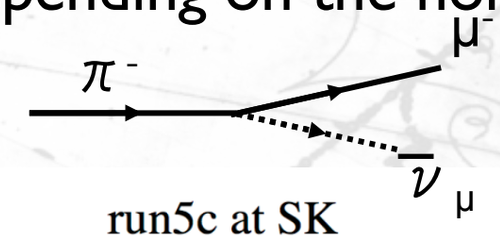


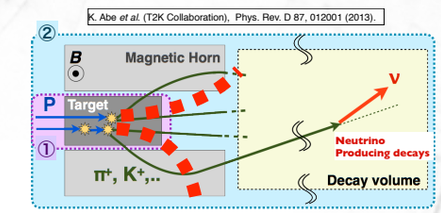
Side Detour

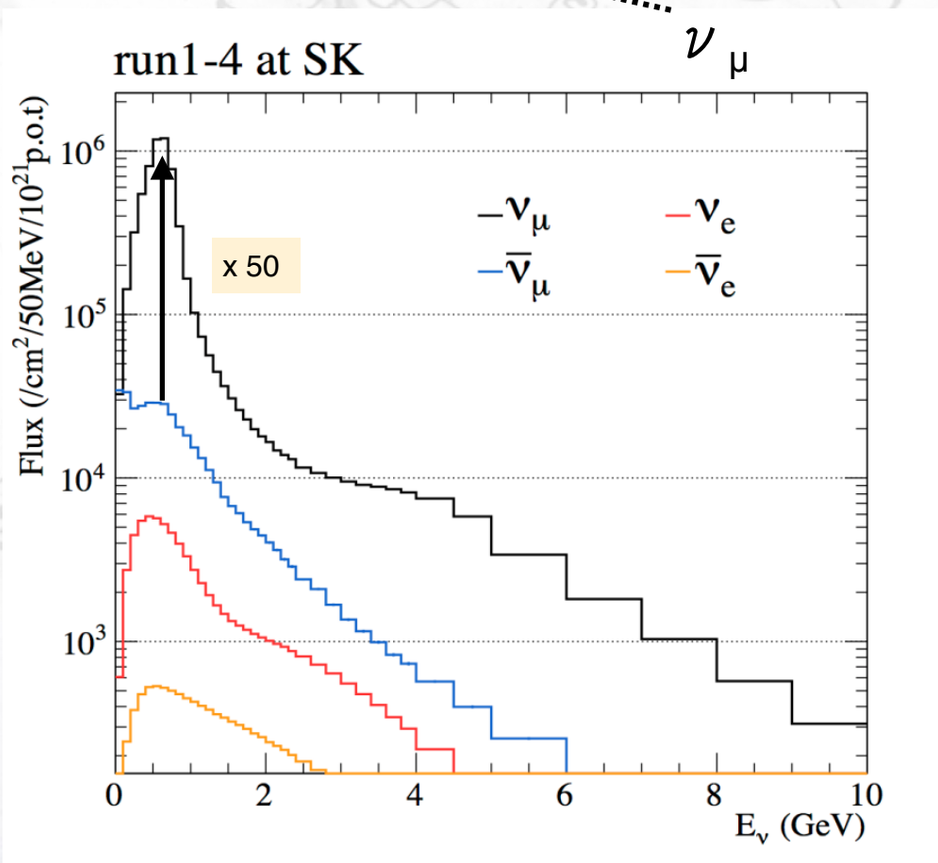
Neutrinos & Antineutrinos

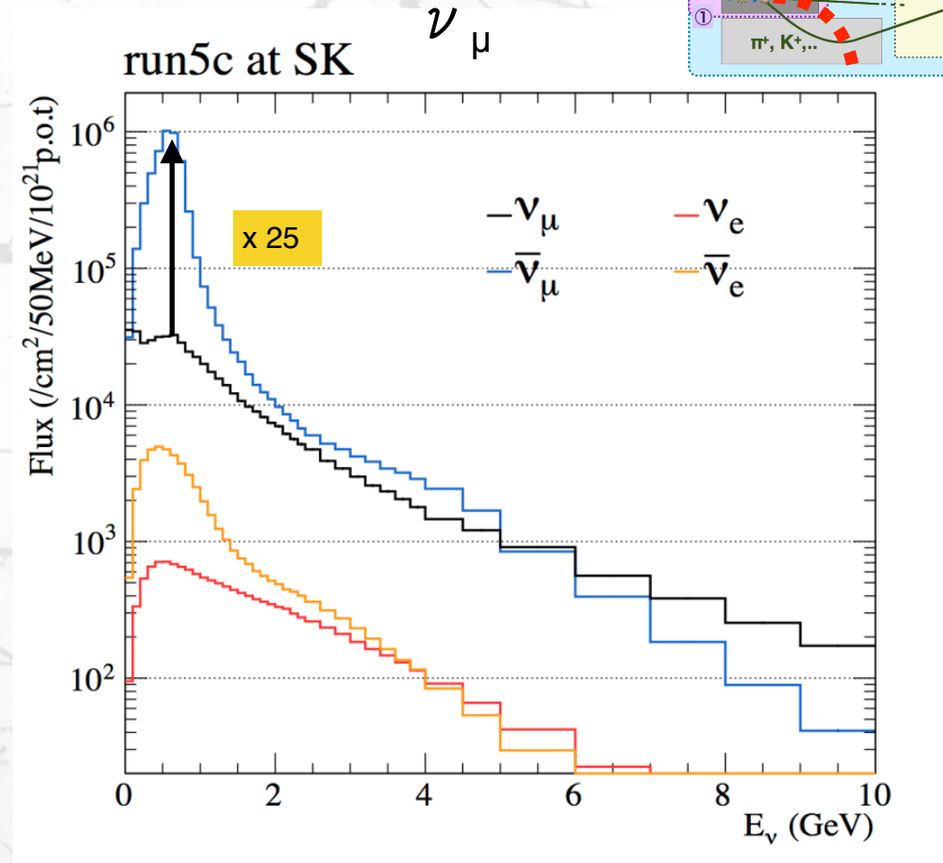
- Neutrinos and antineutrinos are selected depending on the horn current polarity.









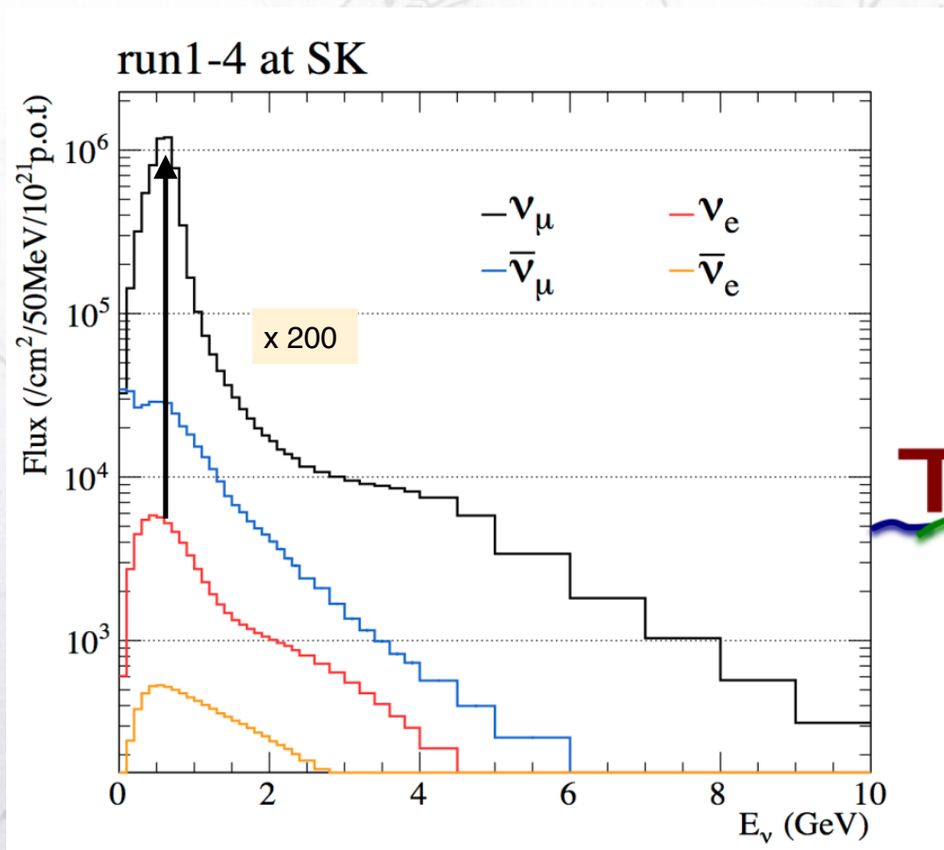


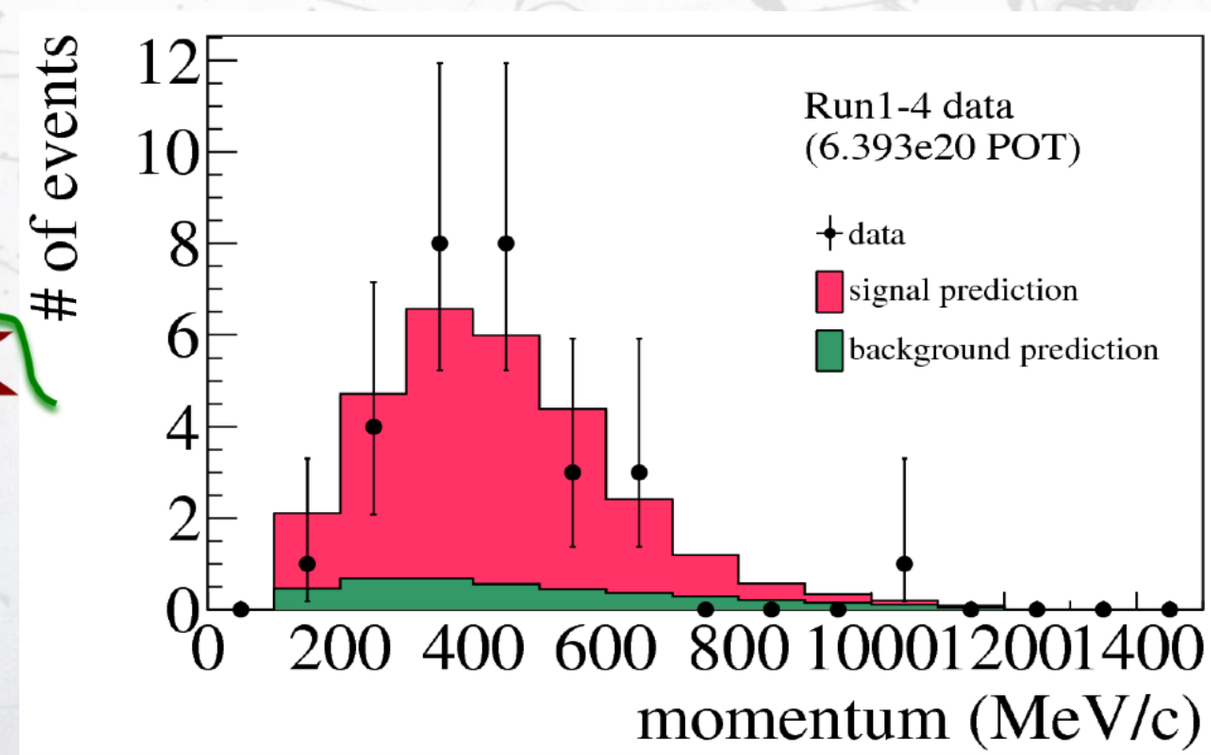
- Neutrino cross-section is **x3 larger** than antineutrinos one.
- Neutrino sample i**s x2 more "pure"** than the antineutrino one.

Far detectors barely distinguish them so
we need to control the sample contamination @ near detector.

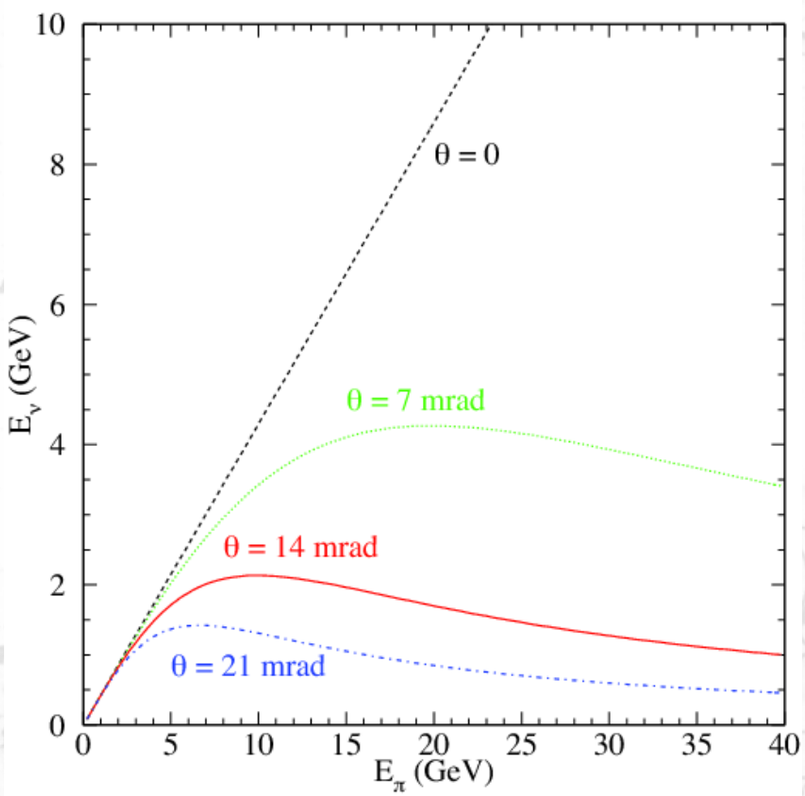
ν_e vs. ν_μ

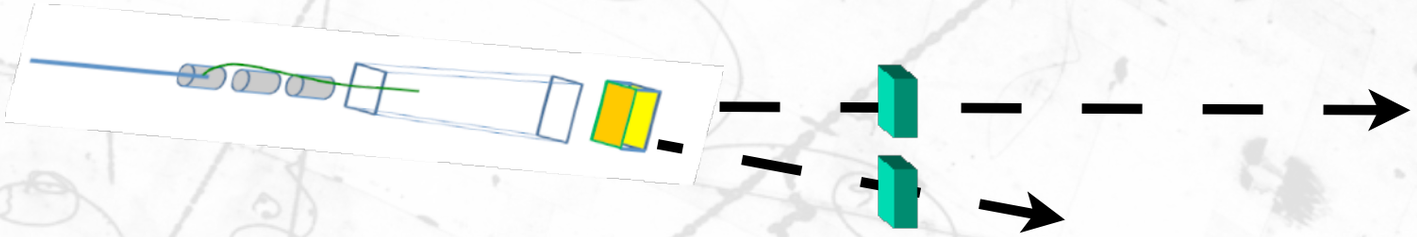
- Electron neutrinos is a key background for the $\nu_\mu \rightarrow \nu_e$ search.
- The un-oscillated flux contains ~200 times less ν_e than ν_μ (T2K).
- The oscillated flux contains ~5 times less ν_e (background) than oscillated ν_e (signal).
- **The near detector is the only place to control this background.**



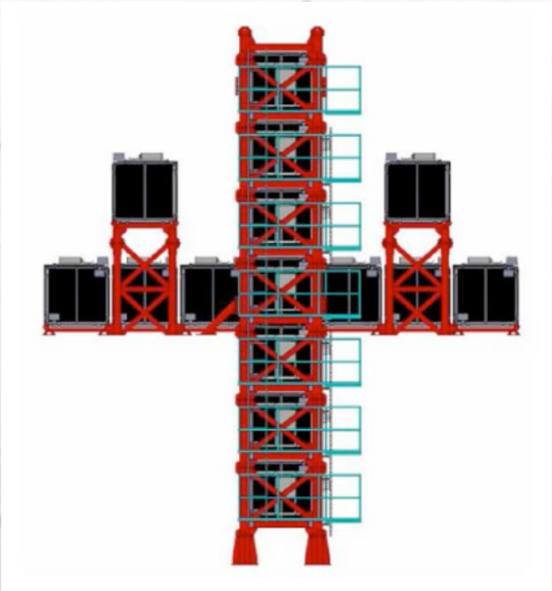


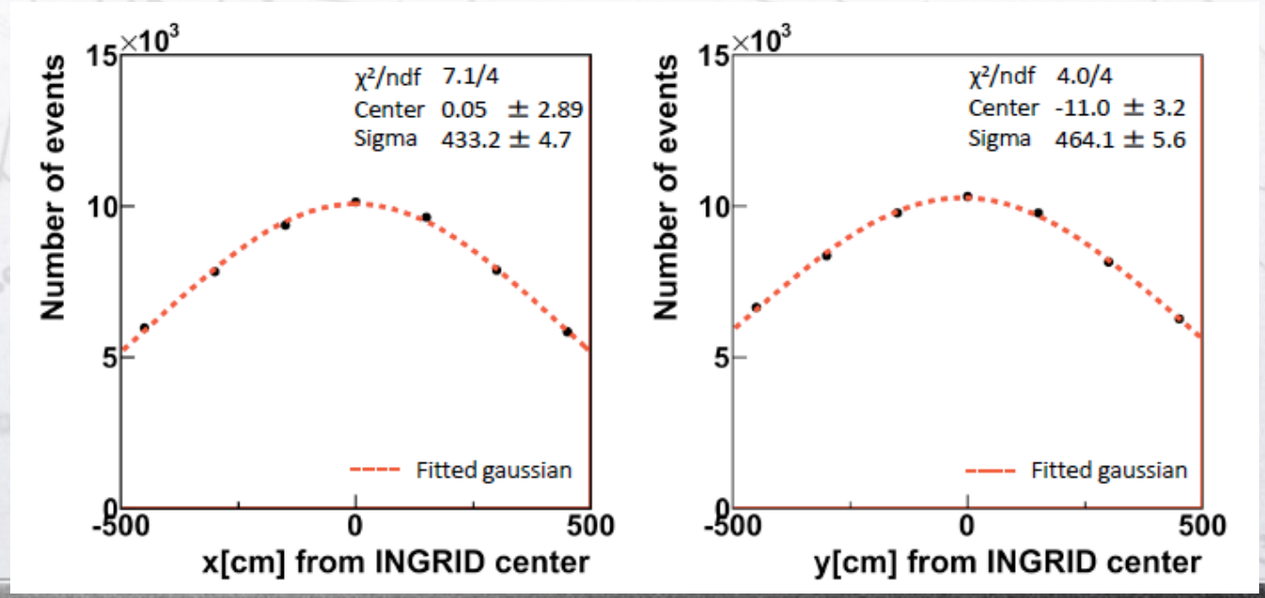
Beam stability monitor





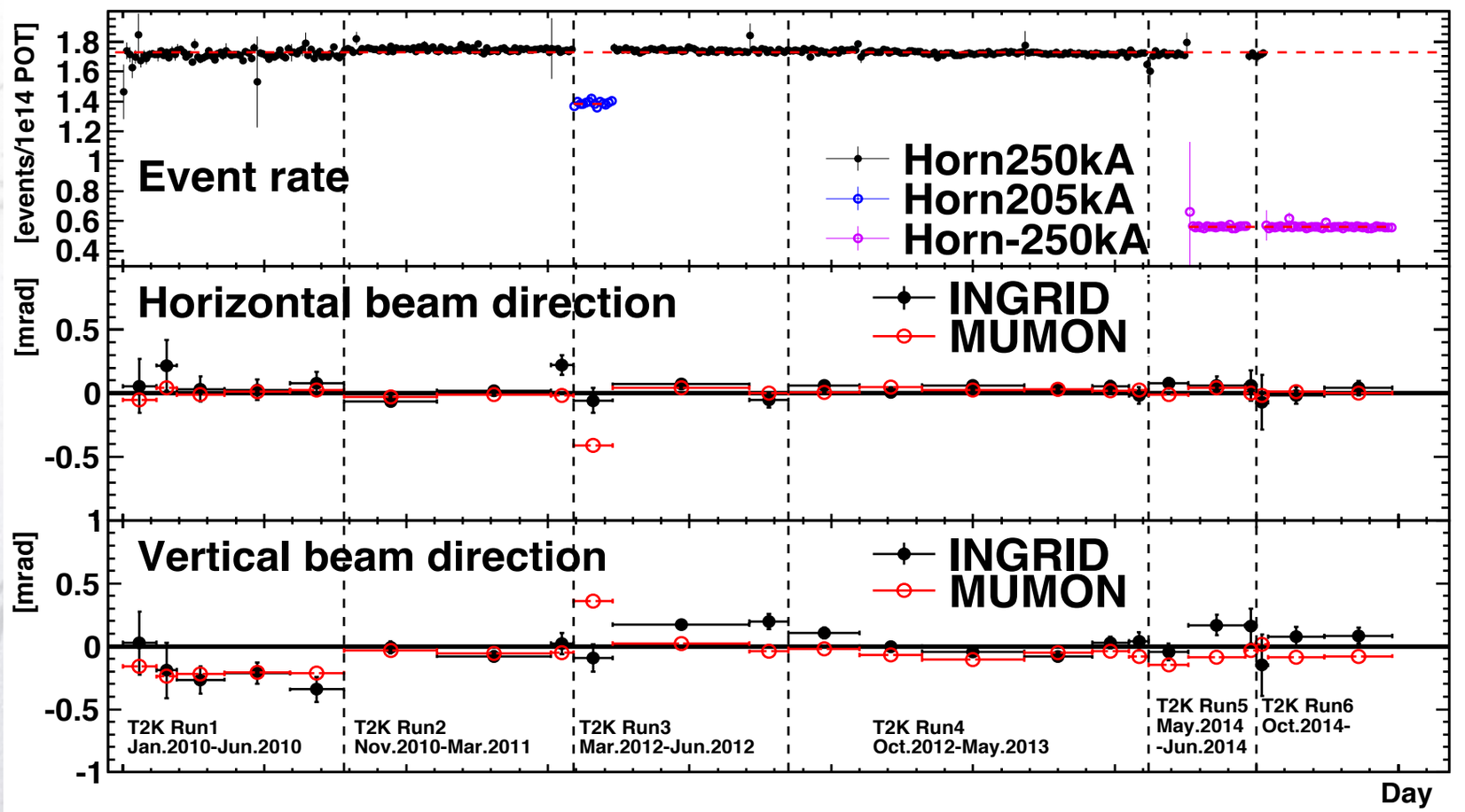
- In an standard beam the neutrino energy depends on the angle.
- The ν energy depends on the angle.
- **The angle, energy and intensity might vary over time due to accelerator alignment & calibration.**





Beam stability monitor

- The neutrino flux needs to be measured also !
- We do not rely on accelerator proton current fluctuations and its monitors but in true ν flux.



Near detector mandate

- Further constrain the **neutrino flux:**
  - reduce uncertainty from hadroproduction experiments.
  - account for horn and decay volume systematics.
- Improve the **cross-section** knowledge:
  - constrain theoretical models.
- Determine the fraction of **neutrinos in antineutrino** beam configuration (and viceversa)
- Measure the **intrinsic ν_e** contamination in the beam.
- Monitor **beam stability** along running period.

Most of the physics efforts in LBL experiments go to the near detectors.
Near detectors are responsible of controlling the majority of systematic errors.

Design parameters

Mass

- With actual beam intensities (~2.0 10^{21} protons on target/ year) and 1 Ton detector ⇒ 150000 events/year.

Mass for beam monitor

- 100 Ton detector provides ⇒ 1.7 events/10^{14} pot ⇒ 5000 events/hour in T2K.

Muon vs electron

- Excellent muon/electron separation to overcome the 1/200 ratio.

Neutrino vs Antineutrinos

- Better with magnetic field to measure wrong "polarity" neutrinos.

Cross-sections

- Excellent detector acceptance & sensitivity to high and low momentum particles.
- Same nucleus in near and far detector to reduce uncertainties.

Approximative numbers !

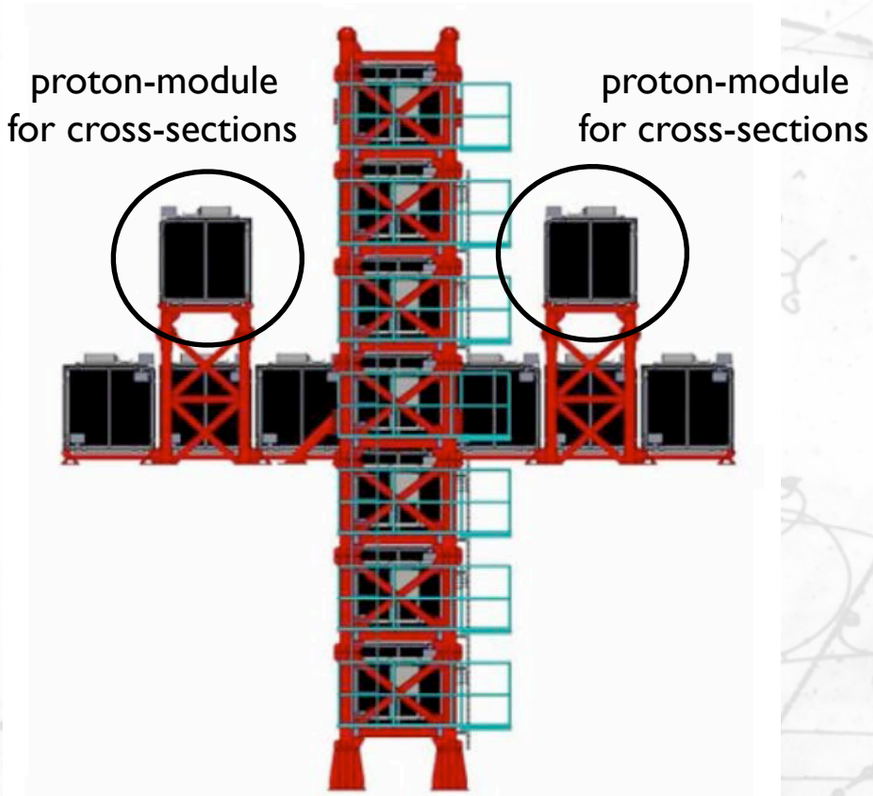
Design parameters

Large mass and high precision ($\lesssim 1\,mm^3$) are difficult to reconcile

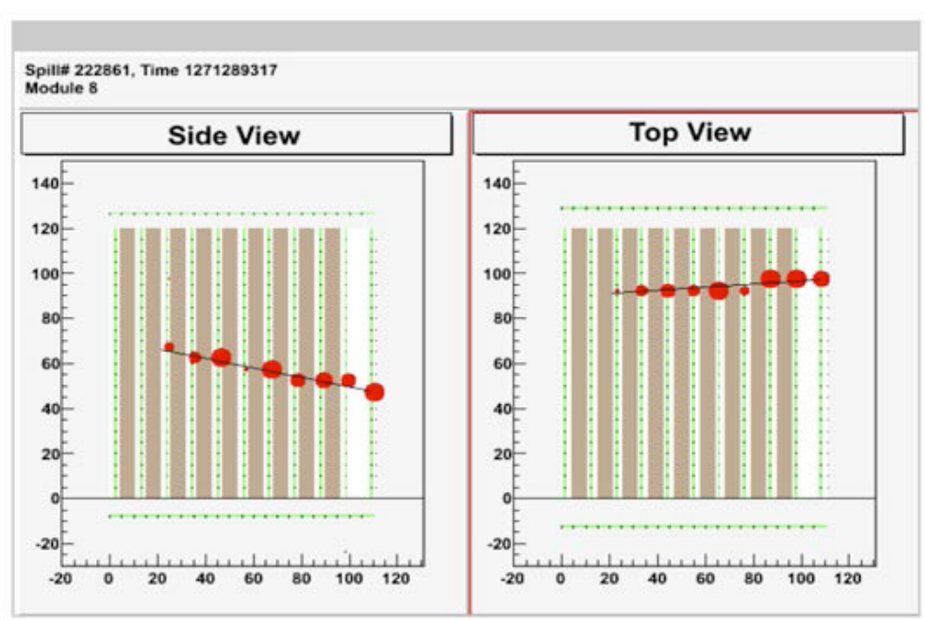
- Tracks emerging from the interaction do not have a preferred direction → almost same segmentation in all directions.
- Contrary to experiments like LHC experiments the interaction happens uniformly in detector volumes of ~m^3.
  - We cannot concentrate segmentation in narrow areas like LHC experiments!!!.
- High segmentation in large volumes:
  - 1 Ton of $1 g/cm^3$ material = $1 m^3$ → **10^9 $1 mm^3$ 3D cells**
  - Projected in one plane → **~10^6 $1 mm^2$ 2D cells**

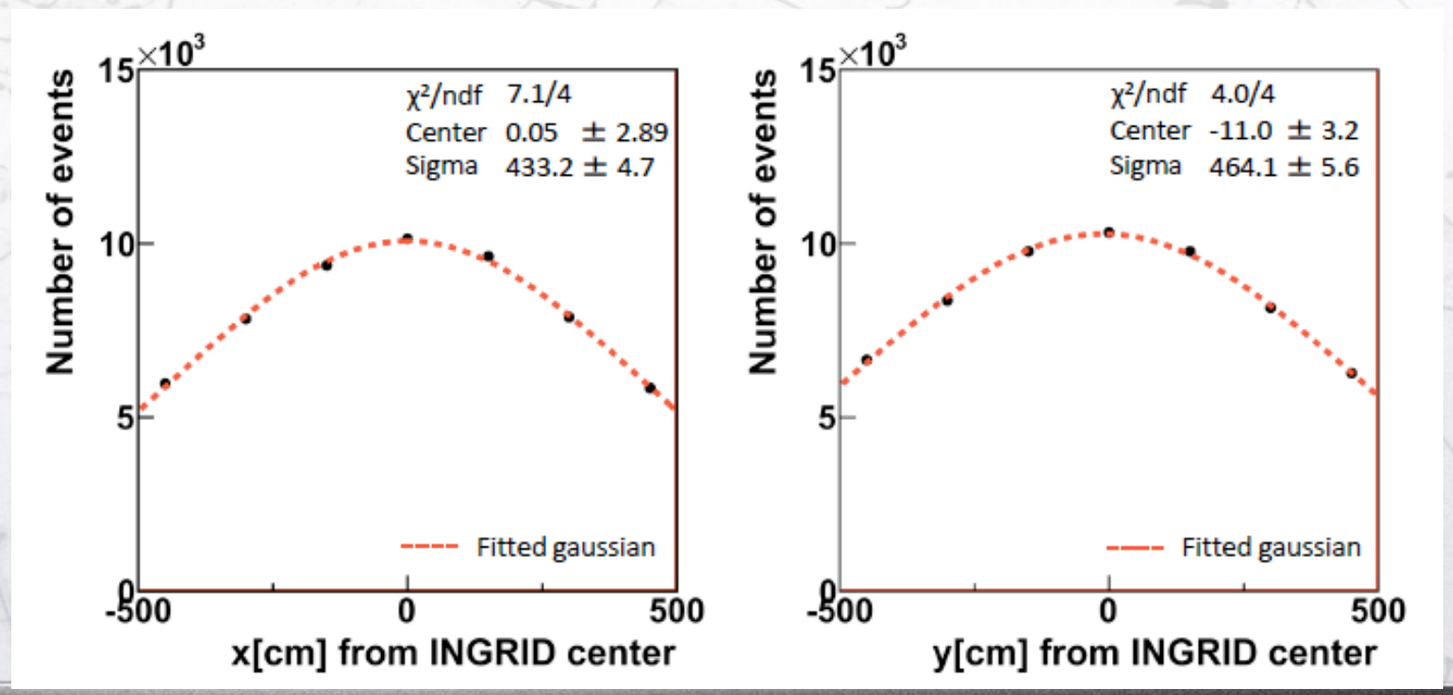
We can do better ! Just an example.

T2K: INGRID



- INGRID counts ν CC events in a cross of 13 identical detectors (~100 Tons):
  - **Normalisation:** total rate monitors beam intensity stability with respect to proton on target counting.
  - **Spectrum:** relative event counts between modules monitor the beam direction stability.



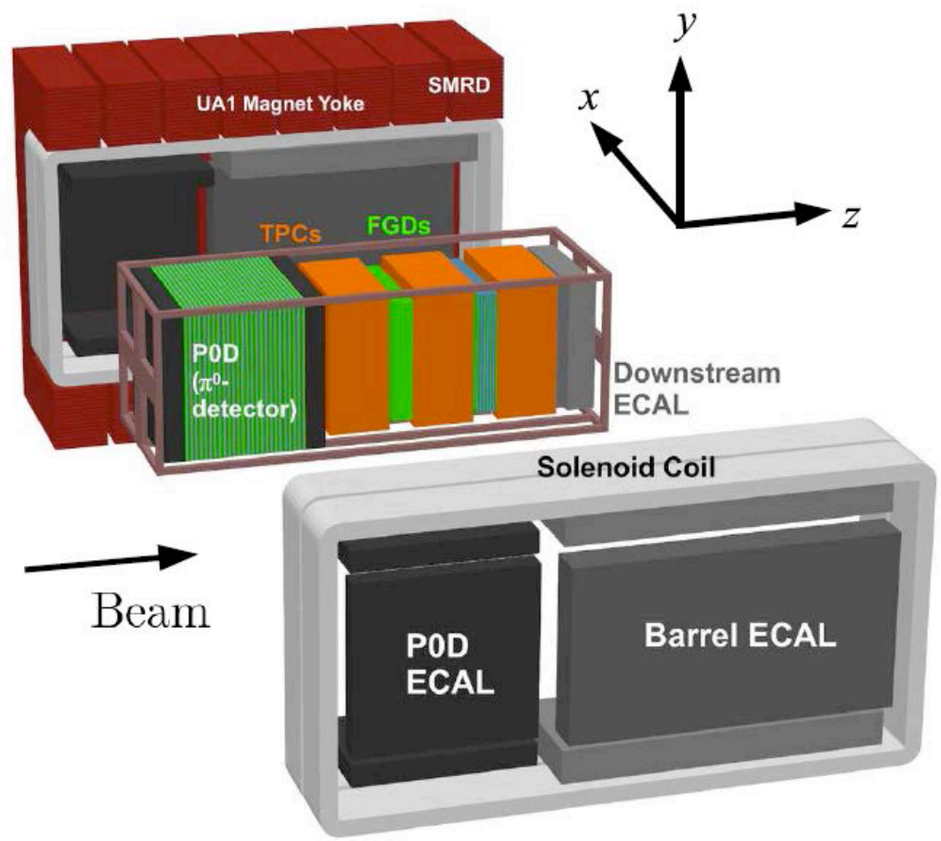


T2K: ND280

T2K far detector is a 40 kTon water (mainly oxygen target) Cerenkov detector.

- Off-axis ND280 is a detector complex with tracking calorimeters, time projection chambers and Electromagnetic calorimeters in the **UA1 0.2T magnet**.
  - **ν interaction target polystyrene (CH) and water** (to measure with same far detector target).
    - 1x1cm^2 → proton track threshold around 500 MeV/c
  - **Particle ID by dE/dx and calorimetry for electrons.**
  - **Charge sign by curvature.**
- **Kinetic reconstruction** approach.

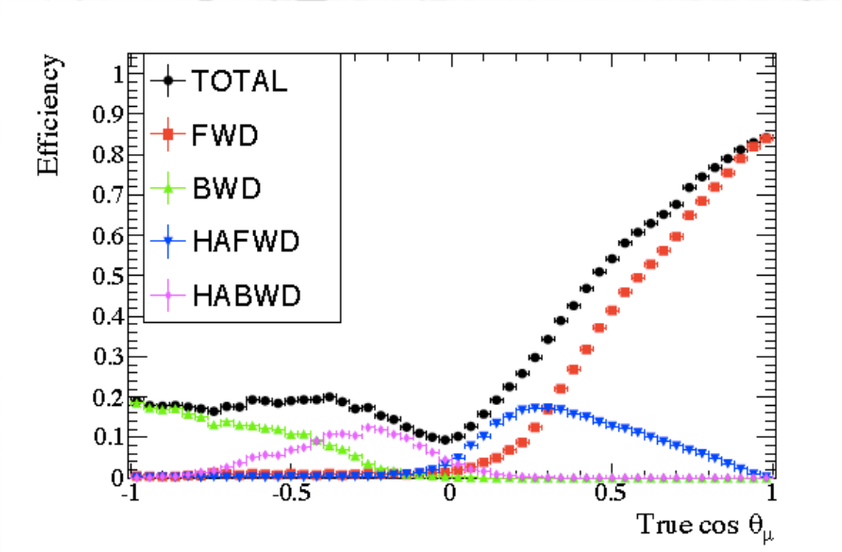
Magnet was granted by CERN

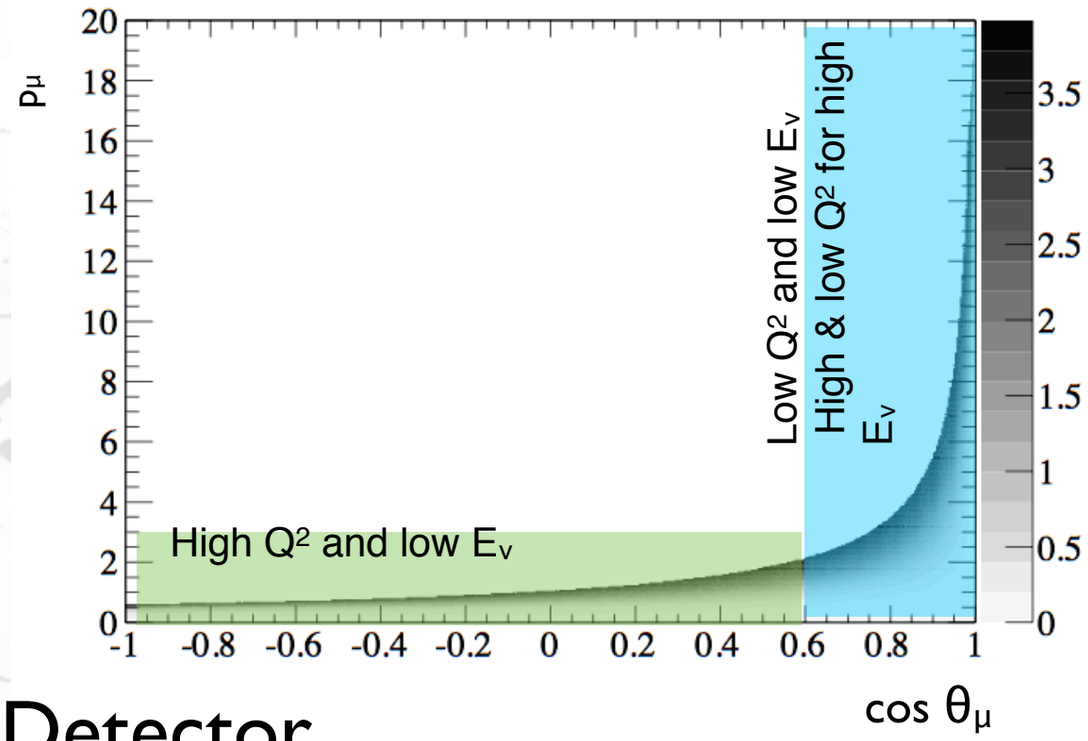



Magnet @ CERN Prévessin

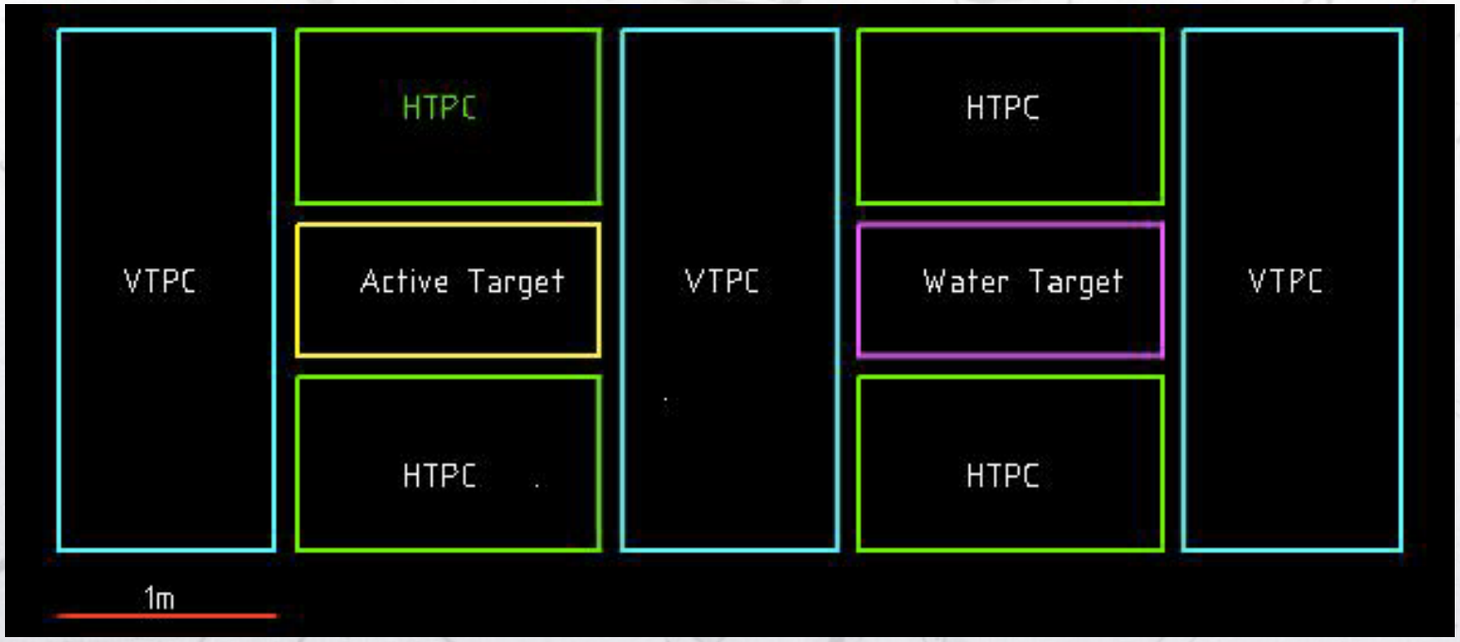
T2K Upgrade

- Actual angular acceptance:





- Proposed modification of the Near Detector.

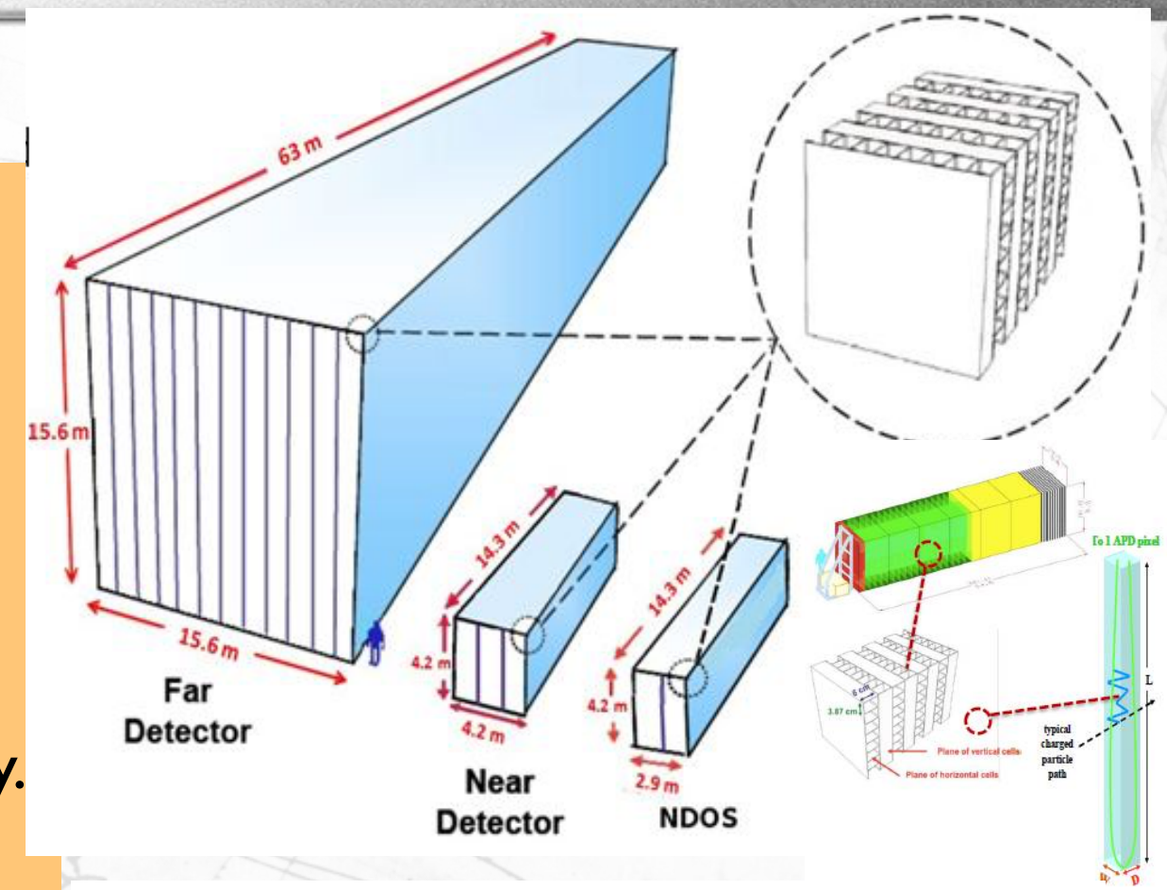


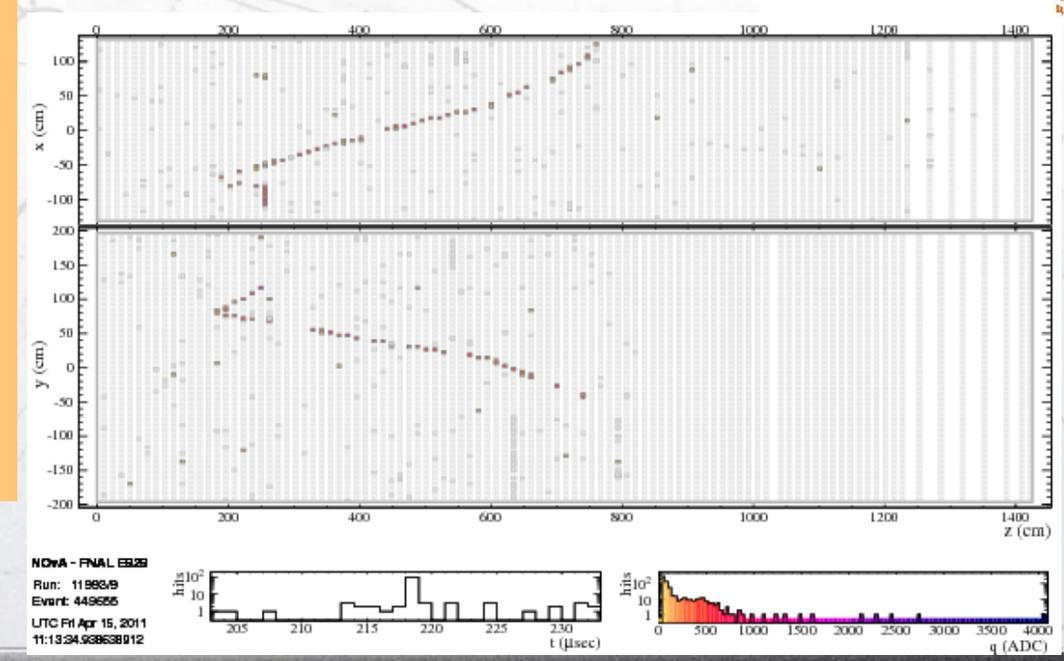
There are large theoretical uncertainties connecting forward (low Q^2) with backward (high Q^2) regions: nuclear form-factors, long and short range correlations,…

https://indico.cern.ch/event/568177/

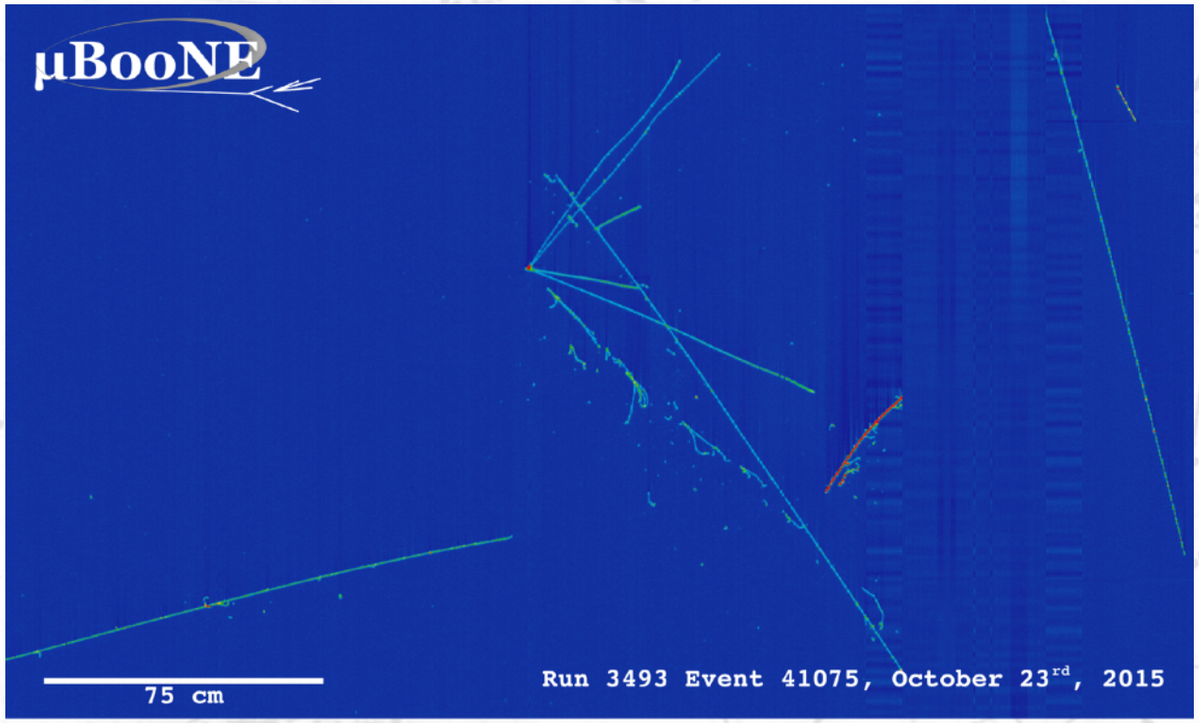
Nova

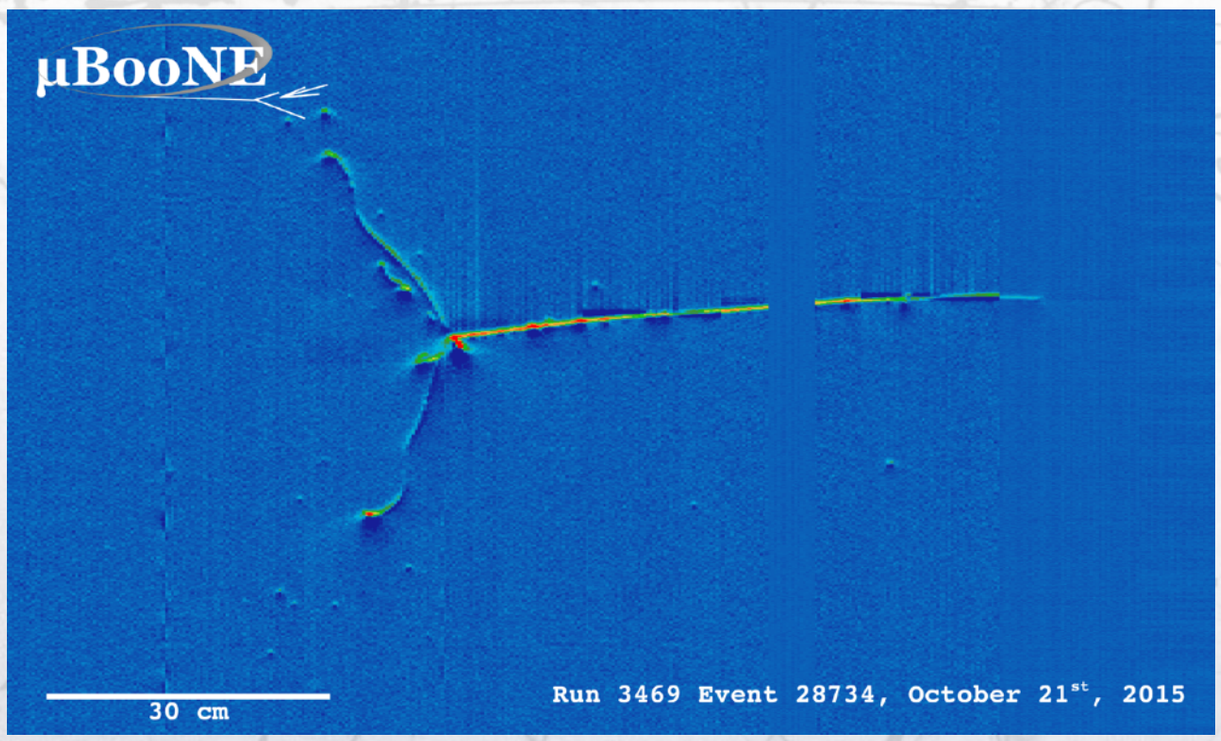
- **Scaled copy of the far detector**.
  - Liquid scintillator poured in extruded plastic bars.
- **~200 Tons** of target mass.
  - Monitor and normalisation functionality.
- **Coarse cell** (3.8x5.9cm^2), proton track threshold around 1GeV/c.
- **No charge sign** determination.
- Calorimetric approach!.





Future: LiqAr TPC

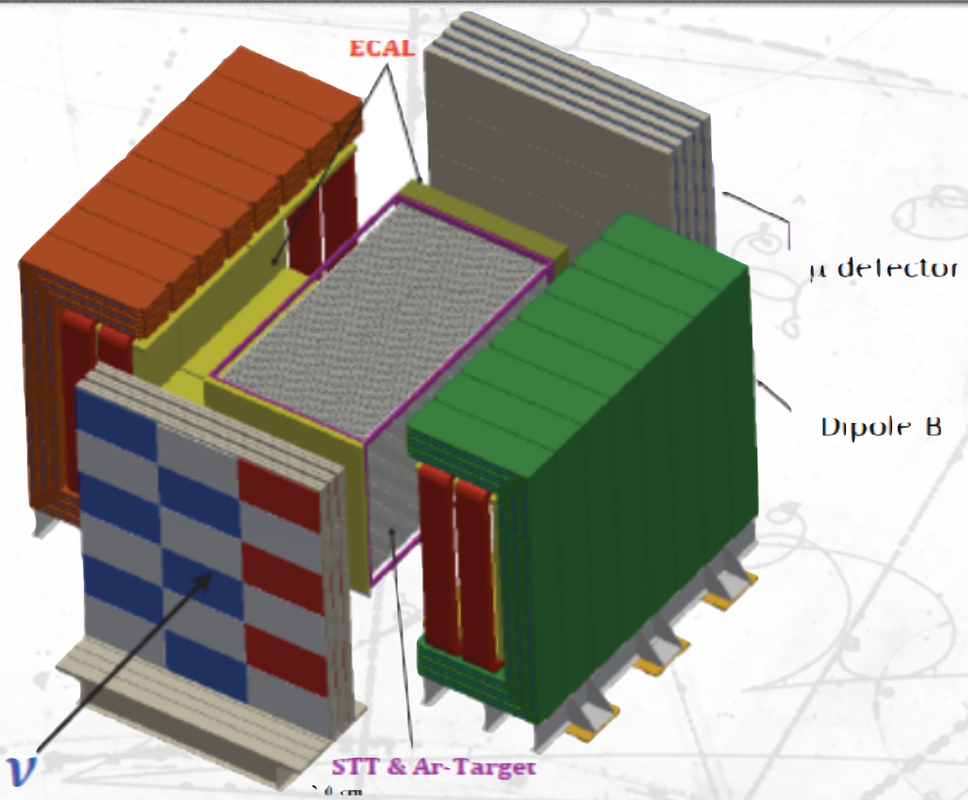


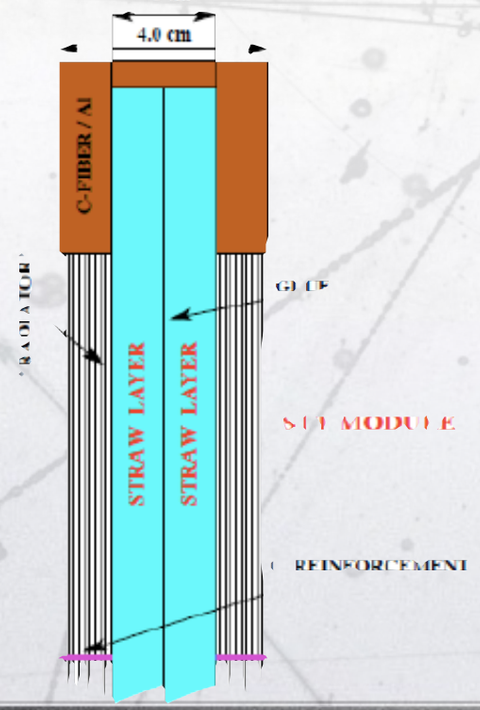


DUNE far detector is made of 4 gigantic LiqArgon detectors 10 kTon fiducial each!.

- **Magnetised (?)** LiqAr detector.
- Potentially **same technology as Far Detector.**
- **Large mass & slow detectors** (~ms) → event pileup!.
- Balance **pile-up vs. particle range.**
- ECAL and muon range.
- **Low proton threshold:** ~150 Mev/c.
- **Calorimetric** approach.

Future: DUNE I

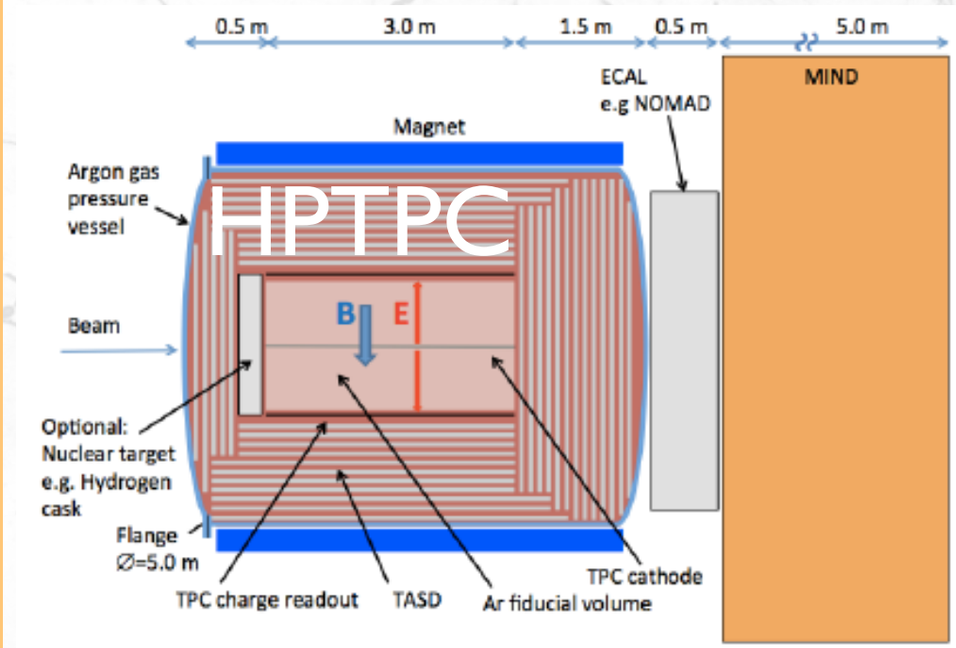


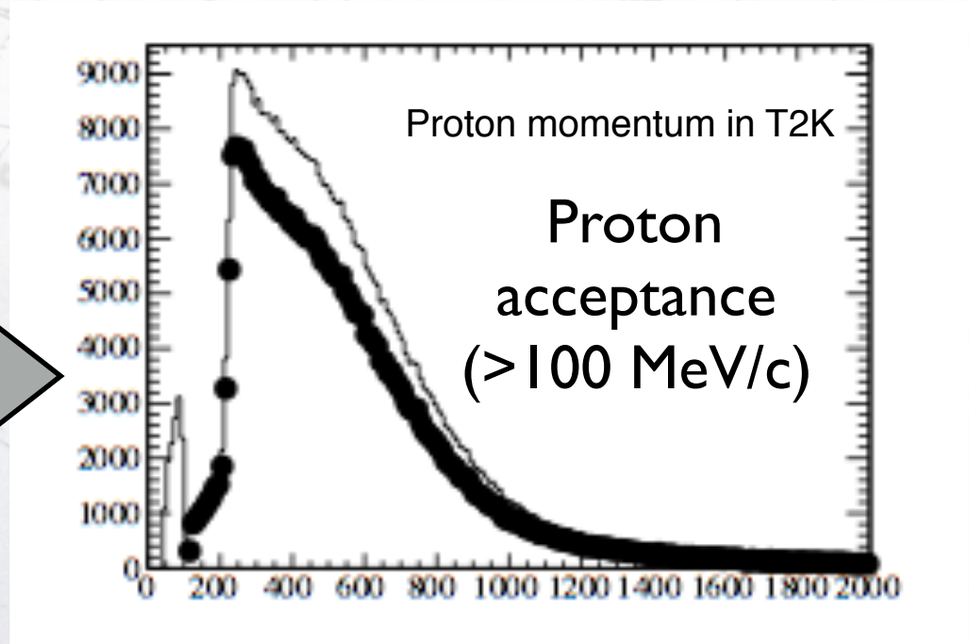


- **Magnetised (0.4T)** high resolution straw tube design with planar geometry (like T2K but finer segmentation).
- **Mixed target (gas and container):** Target/Nucleus selection by track vertexing.
- **Low average density** for low E particle detection.
- **ECAL gamma catcher** and muon range detector.
- **Calorimetric/kinematic** approach.

Future: HPTPC

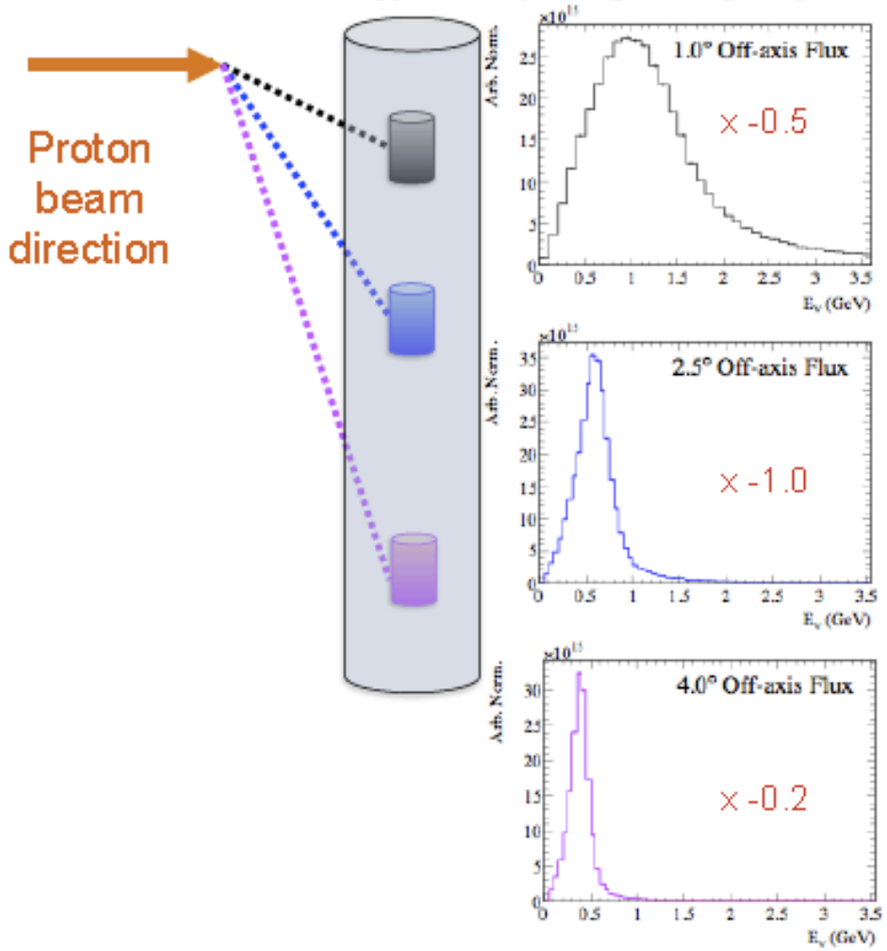
- **Magnetised gas detector** → excellent momentum reconstruction.
- **Same nuclear target as Far Detector,** different technology.
- **Low mass** (~ 100 kg), moderately fast detector (~100 μs)
  - **No pileup** but **large external background** (magnet,…)
- ECAL for π^0 detection and particle Id.
- **Calorimetric** approach.
- **Lowest proton threshold: ~100 Mev/c.**



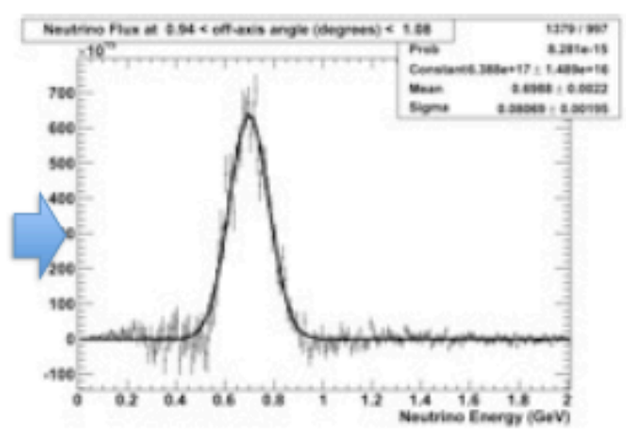


New ideas: NuPrism

- Profit from the **dependency of E_ν with beam angle**.
- Take linear combination of events in angular slices to build a monochromatic beam.
- Technique **only valid with off-axis** beam like T2K. (True beam is one slice!).
- **Big detector (10 m x 50 m deep !)**



$$\Phi(E_\nu) = \sum_{i=0^\circ}^{\theta_{max}} C_i \, \phi_i(E_\nu)$$



For a Gaussian beam peaked at 700 MeV, use linear combination of 30 offaxis angles:

- 0°– 6° corresponds to 1.2 GeV -0.25 GeV
- Cancels HE tail

Reduces the dependency on cross-section models.

$$P(E_\nu|p_\mu,\theta_\mu) = \sum_{i=0^o}^{\theta_{max}} C_i P(p_\mu,\theta_\mu|\theta_i)$$

Final remarks

- Next generation of neutrino experiments faces many challenges:
  - Neutrino flux precision.
  - Neutrino nucleus interaction modelling (P(Eν | Observables)?)
  - Electron neutrino cross-sections.
  - Determining fraction of neutrinos and antineutrinos.
- Near detectors are the place to address all these issues.
  - But not the only one, theory development is also mandatory.
- Near detector design is **as fundamental as the far detector** is to achieve the level of **precision** required in present and future experiments.


ONLY THOSE WHO SEE THE INVISIBLE
CAN DO THE IMPOSSIBLE
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