Neutrino physics at low energy

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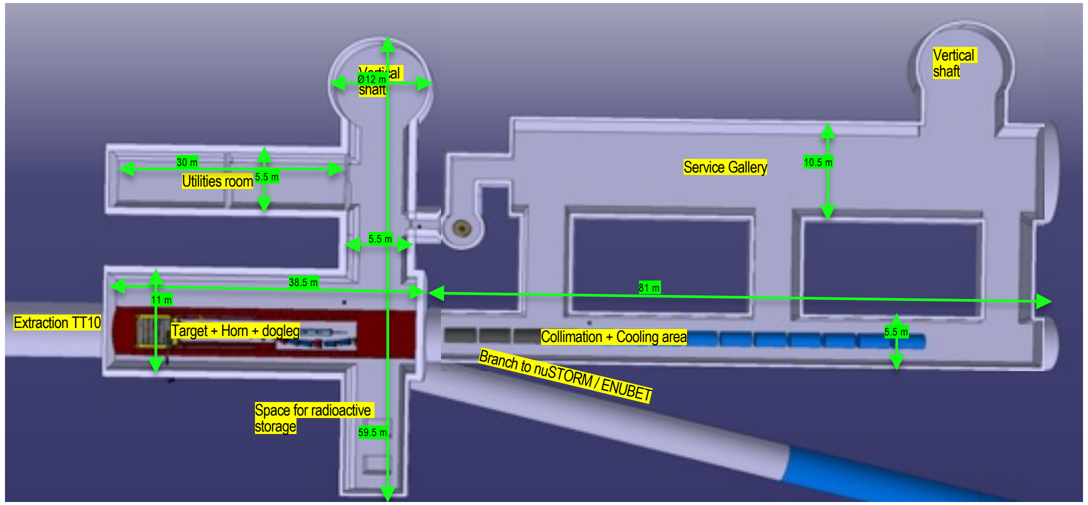
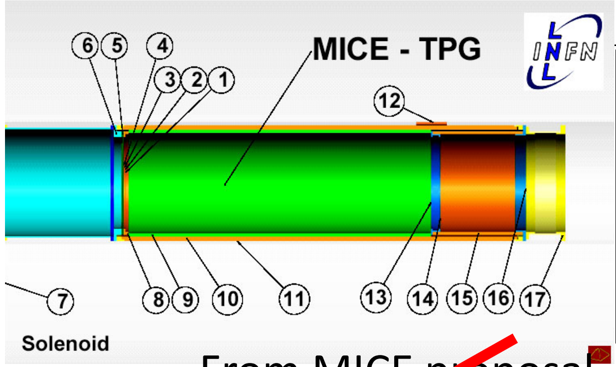
The Demonstrator will produce a large number of muons/neutrinos of few hundred MeV or less

A TPC can be used as tracker for the detection of muons in the cooling sector and/or as active target to detect neutrinos.





From MICE proposal

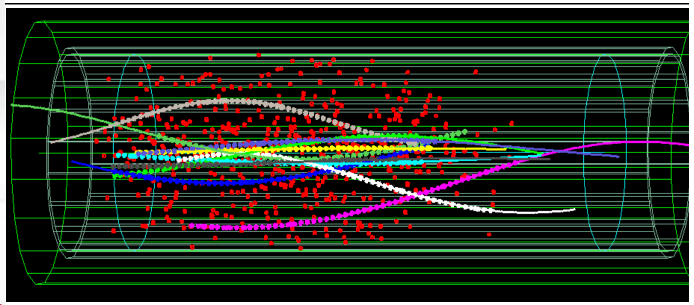
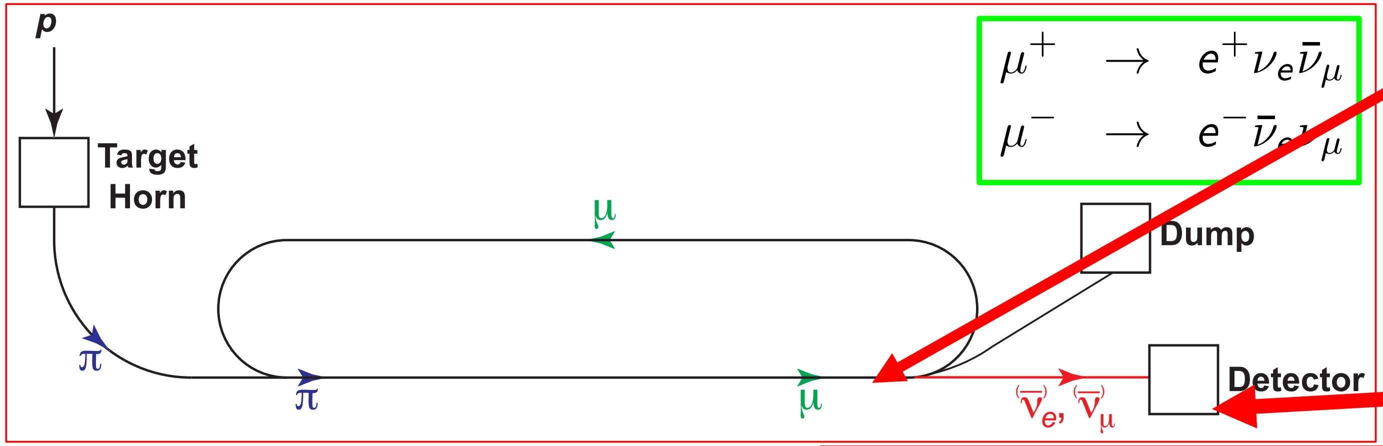
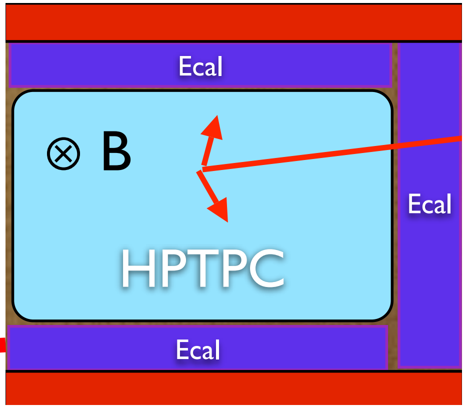


Figure 8.7: top: simulated track and noise hits in the TPG; middle: highlighted hits are those assigned by the pattern recognition to belong to the same track; bottom: track fitted on the selected hits.

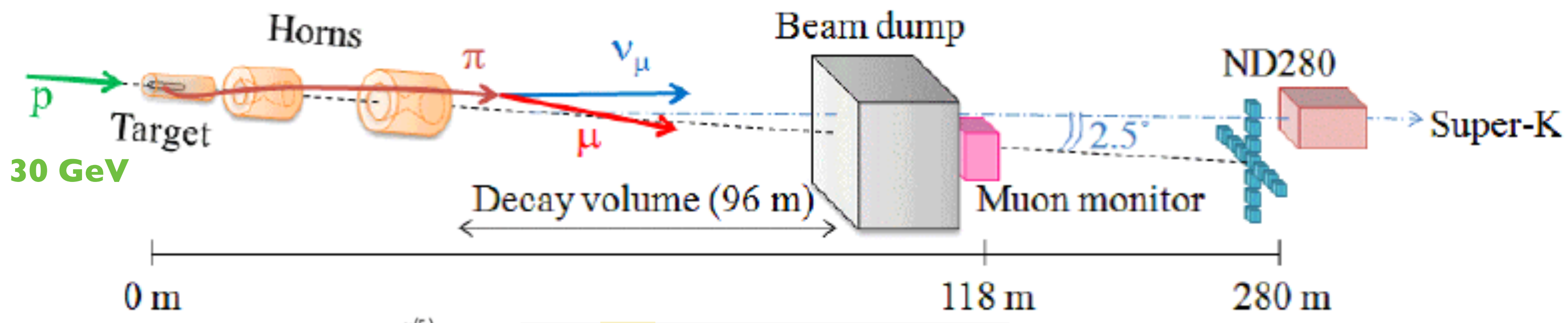
a unique facility for neutrino physics and muon-collider test bed

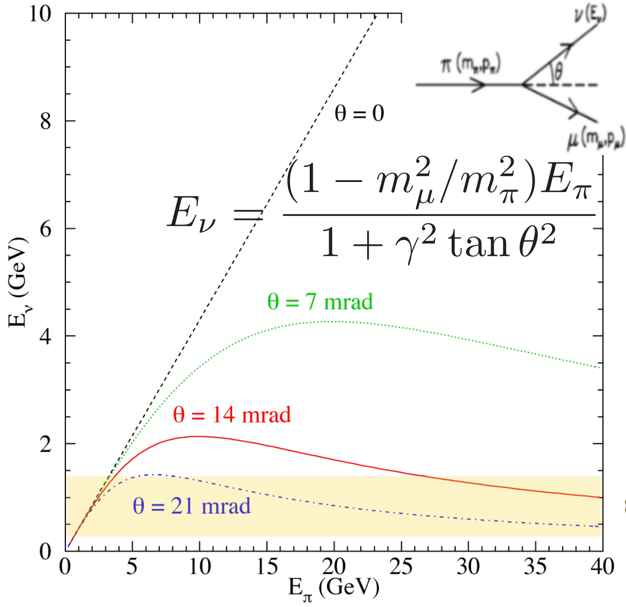


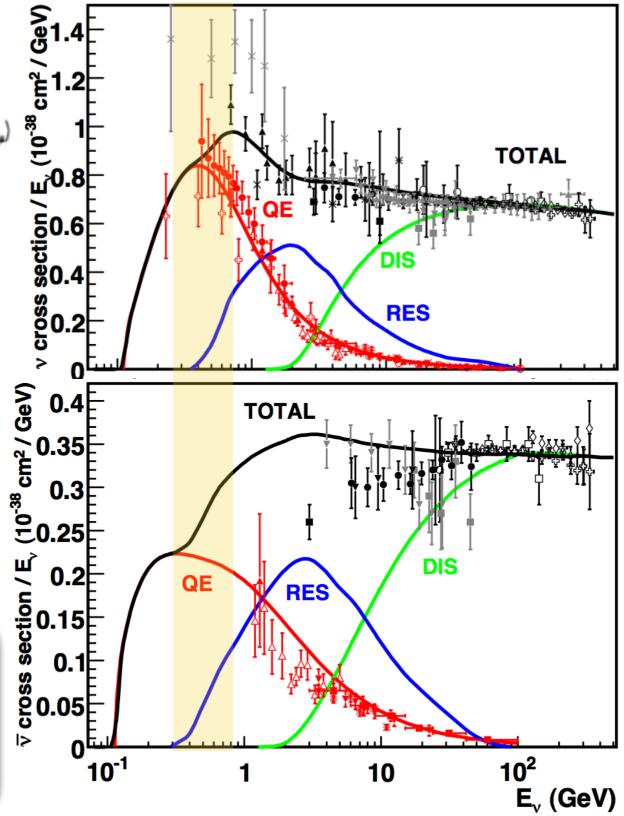


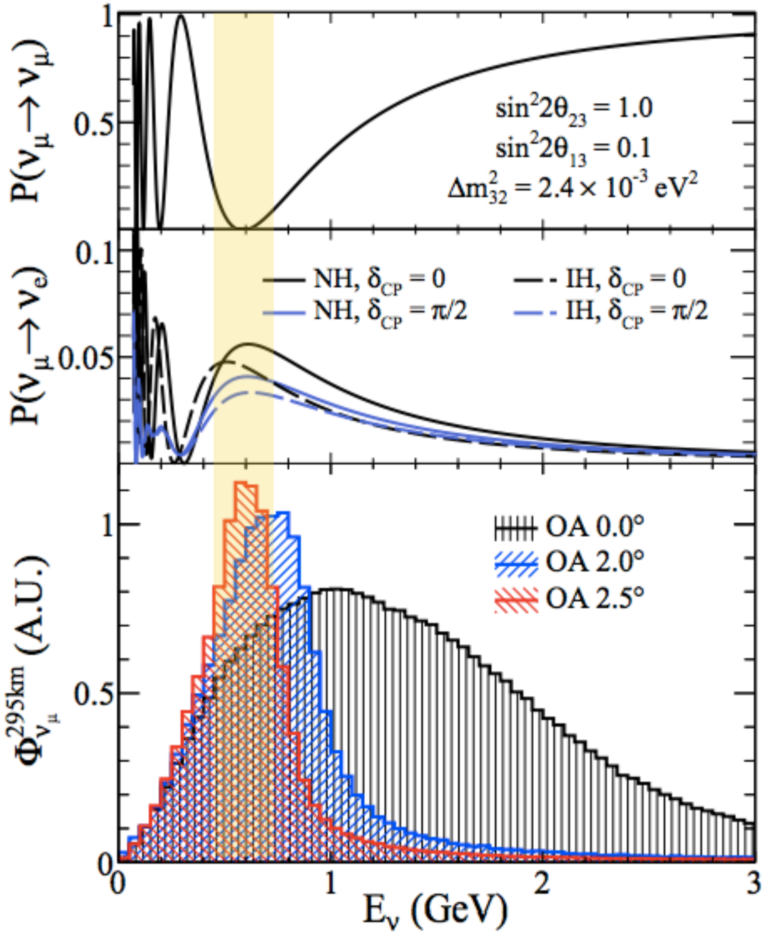
Concept for a neutrino X-sec measurement

The off-axis neutrino beam







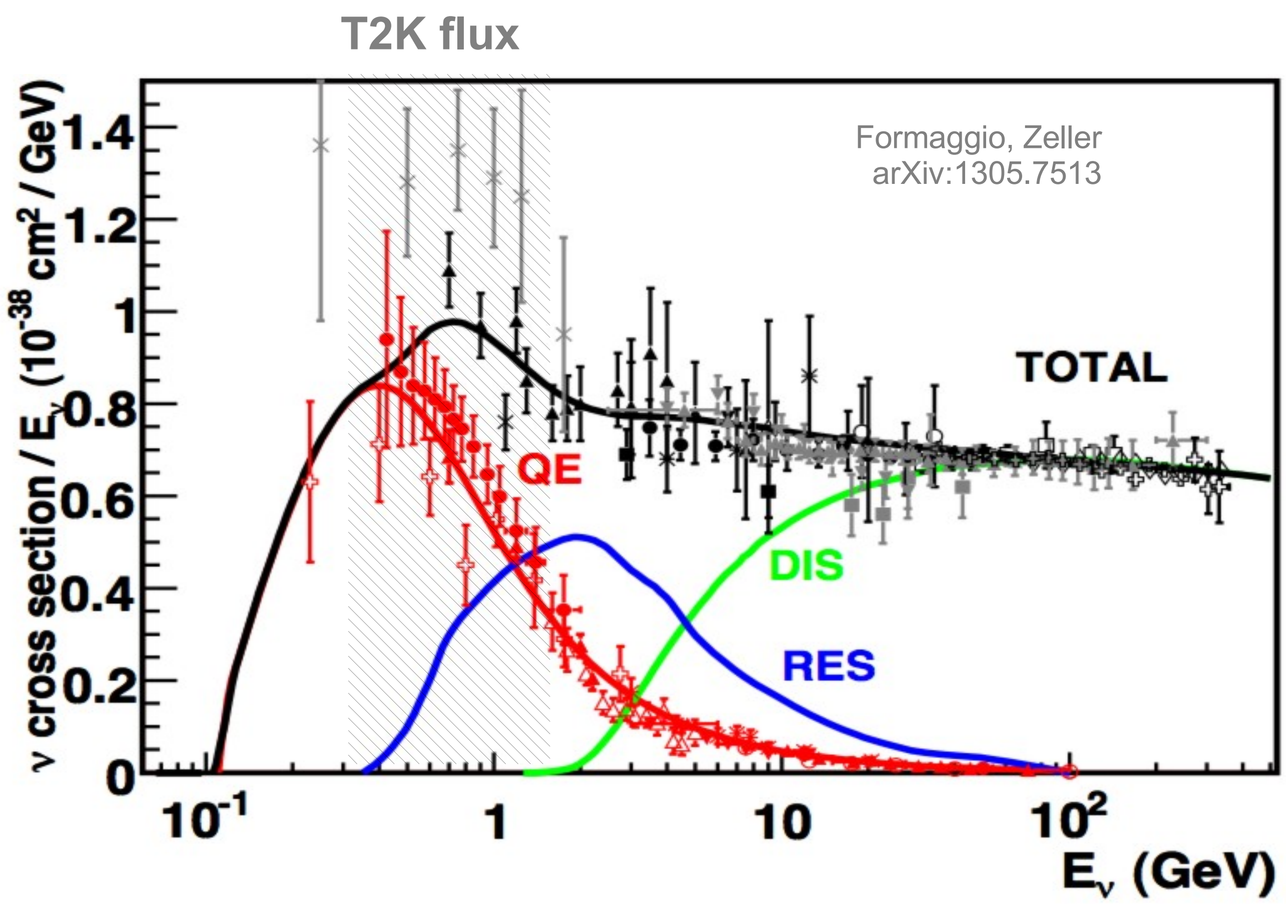


Charged Current Quasi-Elastic (CCQE)

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

- Enhance neutrino oscillation effects
- Enhance CCQE-like interactions (signal at Super-Kamiokande)
- Reduce background from π^0 interactions

- Neutrino xsec as a <u>nuclear physics</u> problem



- **CC0π dominant at T2K**

  → from the detector measurement (muon+proton) to the incoming neutrino energy

- **CC1π (+ DIS)**

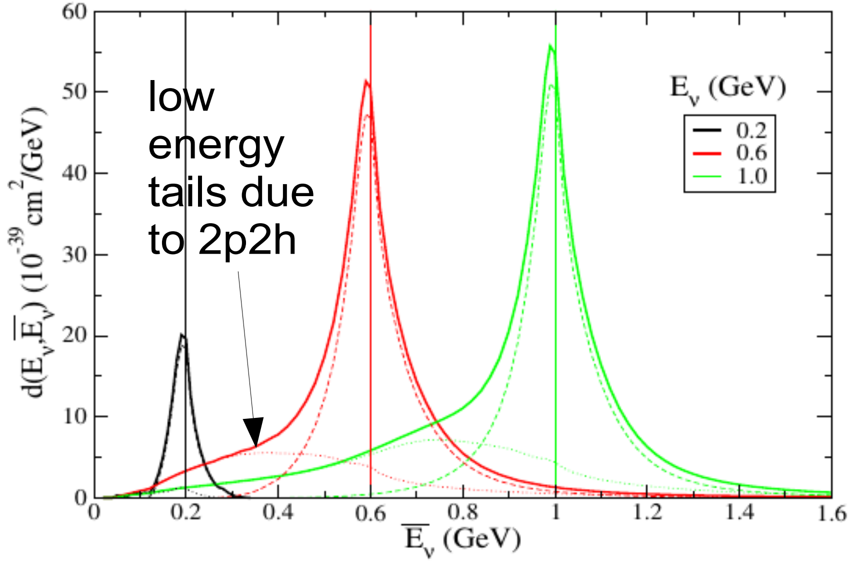
  → how to disentangle Final State Interaction effects

- **Impact on present and future oscillation measurements (δ_{CP}) : $\bar{\nu}_\mu$**

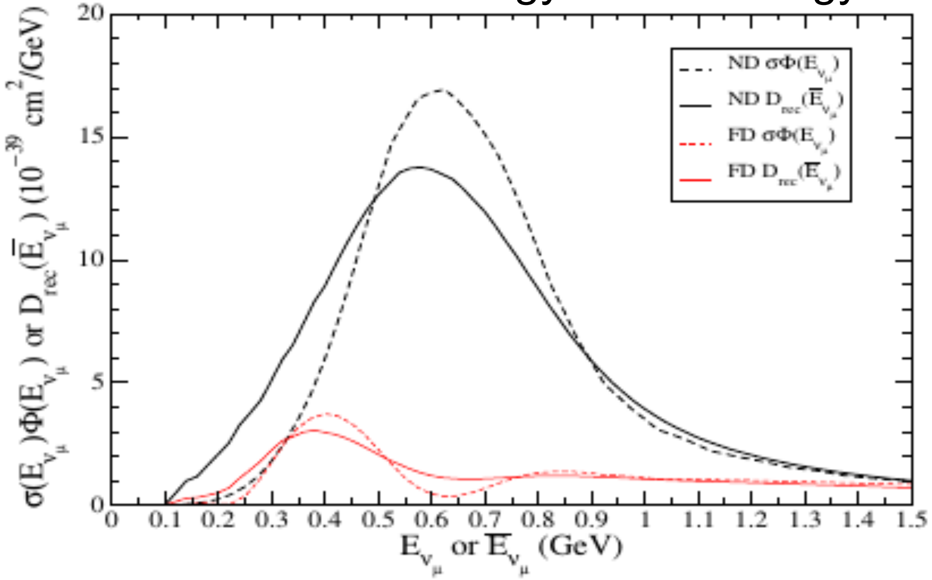
Why we need good models ?

Neutrino oscillation goes like ~L/E$_\nu$ but we do not measure E$_\nu$! We measure the outgoing muon at SuperKamiokande and we infer the neutrino energy on the base of available models

Distribution of true energy for a given reconstructed energy



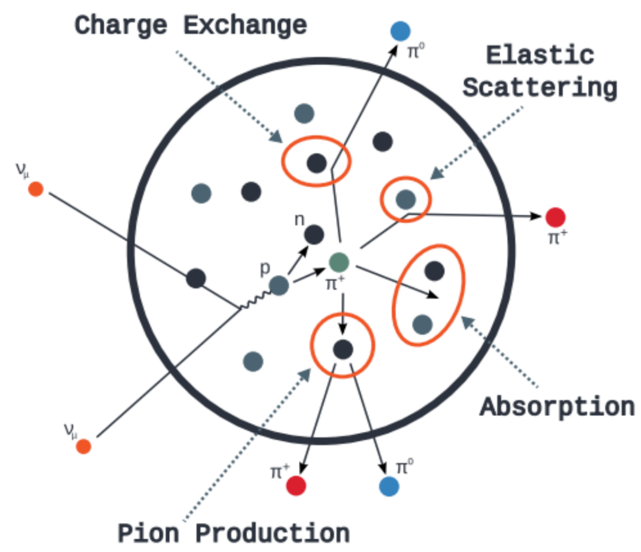
Near Detector and Far Detector spectra of reconstructed energy vs true energy



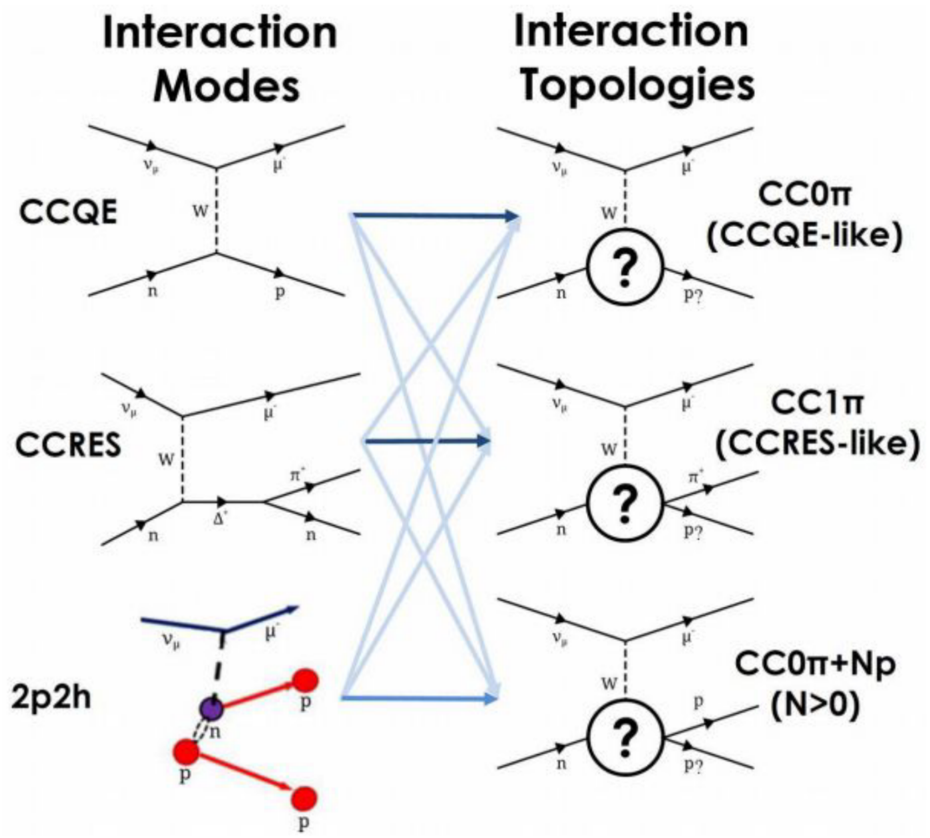
2p2h events fill the “dip” region sensitive to neutrino oscillation → **wrong modelling would cause bias on oscillation parameters**

Measuring Neutrino Interactions

- Define signal by 'topology' (final state)
- Generally split by
  - ν flavour
  - interaction mode ($W^{\pm}/Z^0$)
  - π, proton multiplicity



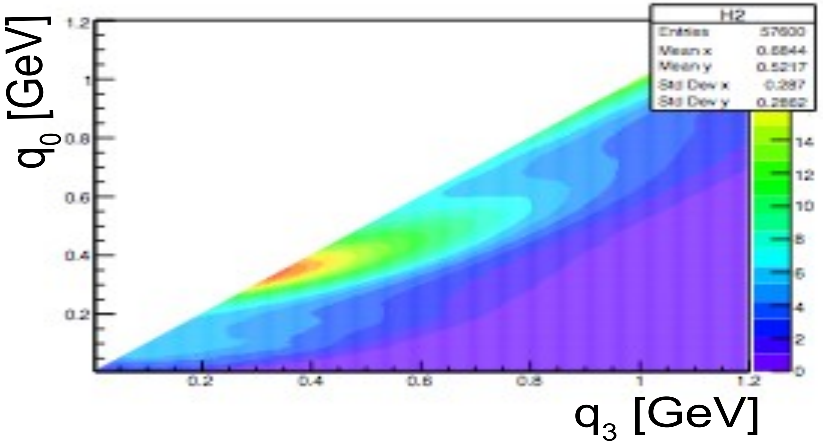
T. Golan, What is inside MC generators and why it is wrong. NuSTEC 2015

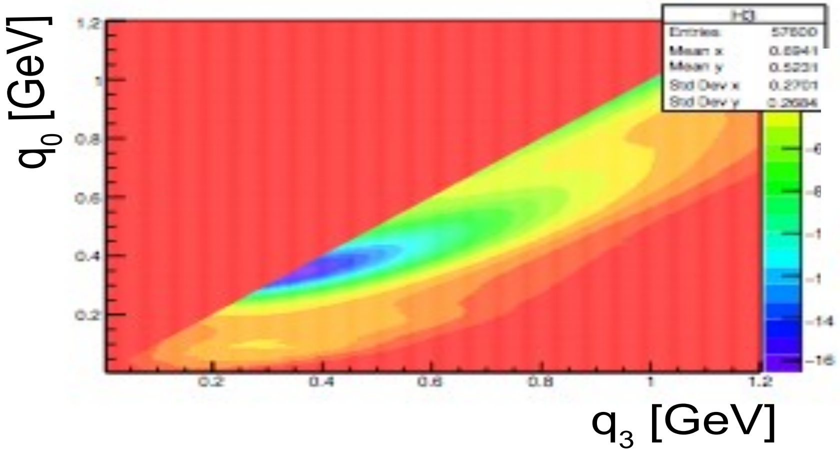


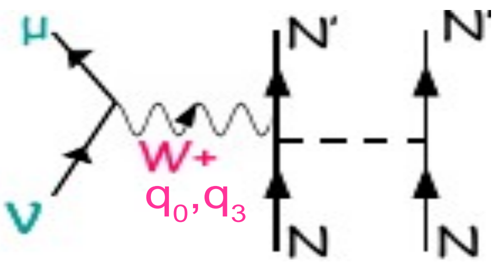
From models to Monte Carlo

- **Various 2p2h models available → completely generic mechanism to include any model in MC simulation: Hadron Tensors**

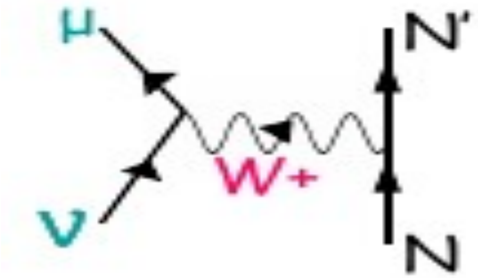
  Lookup tables encoding the nuclear physics as a function of transferred quadrimomentum to the nucleus

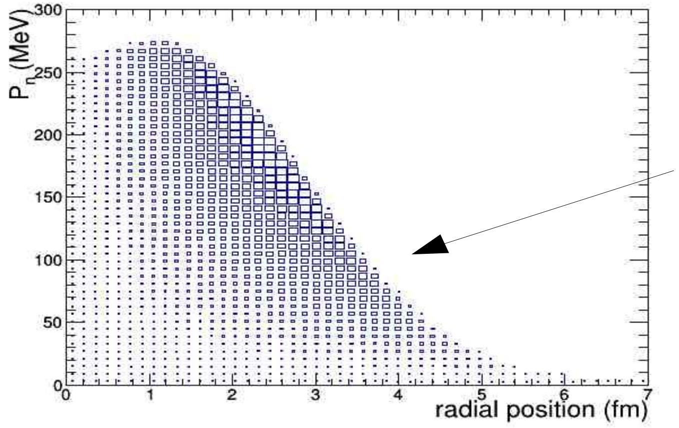






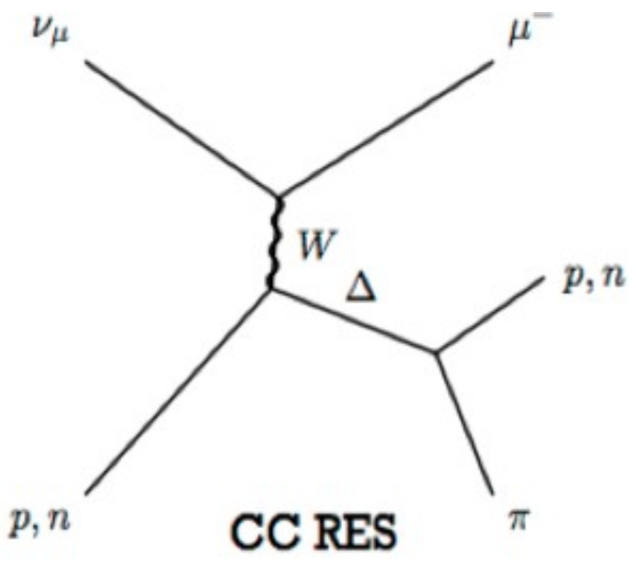
- **Nuclear effects important also on single nucleon scattering** (screening, binding energy, ...)

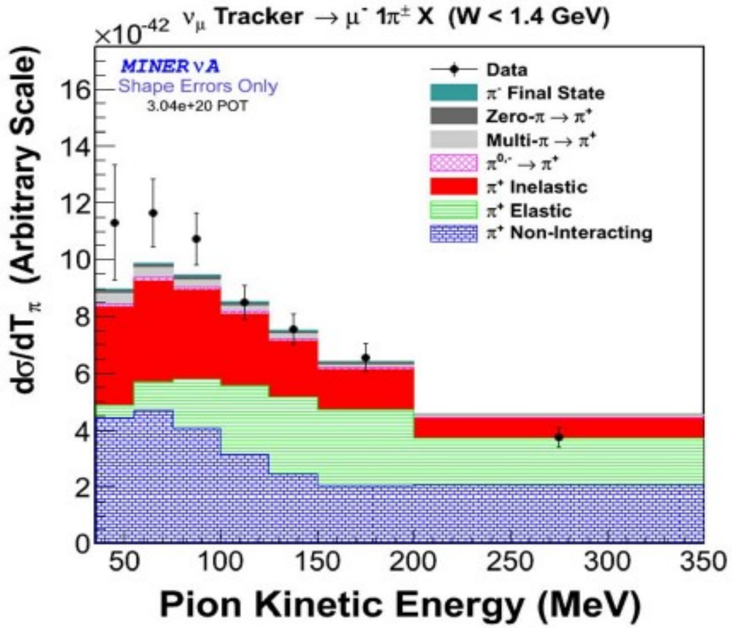




Nucleus modeled as a Fermi gas of nucleons: **nucleon momentum as a function of its radial position in the nucleus**

CC1π





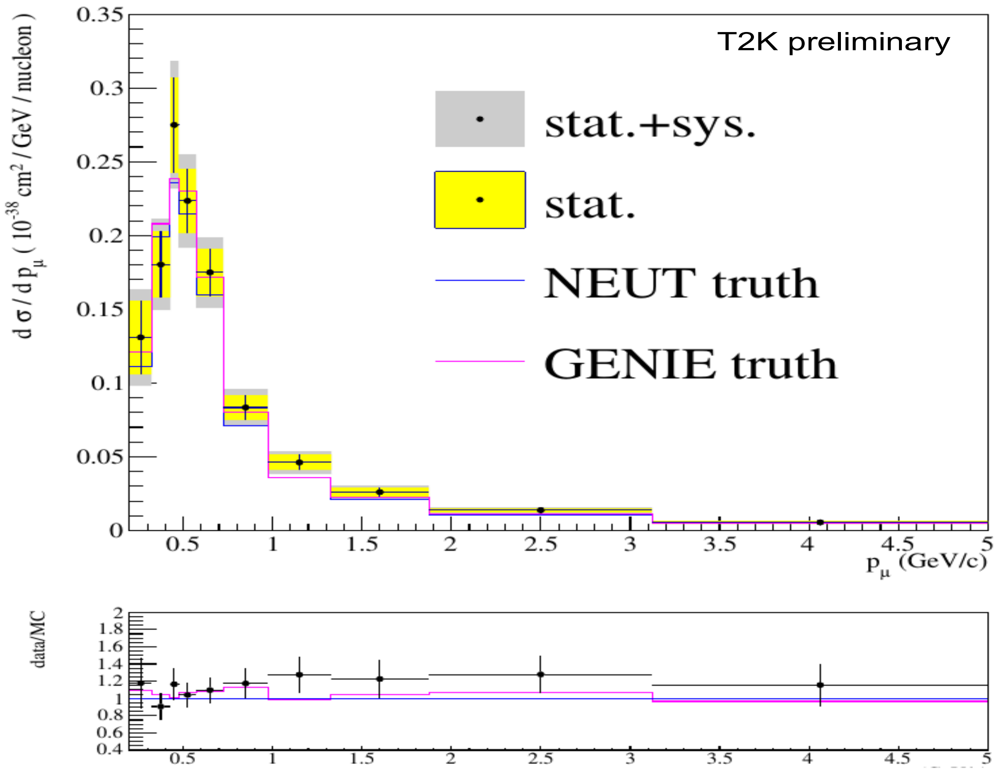
Large effects from Final State Interaction: re-scattering of the π inside the nucleus (nuclear physics again!)

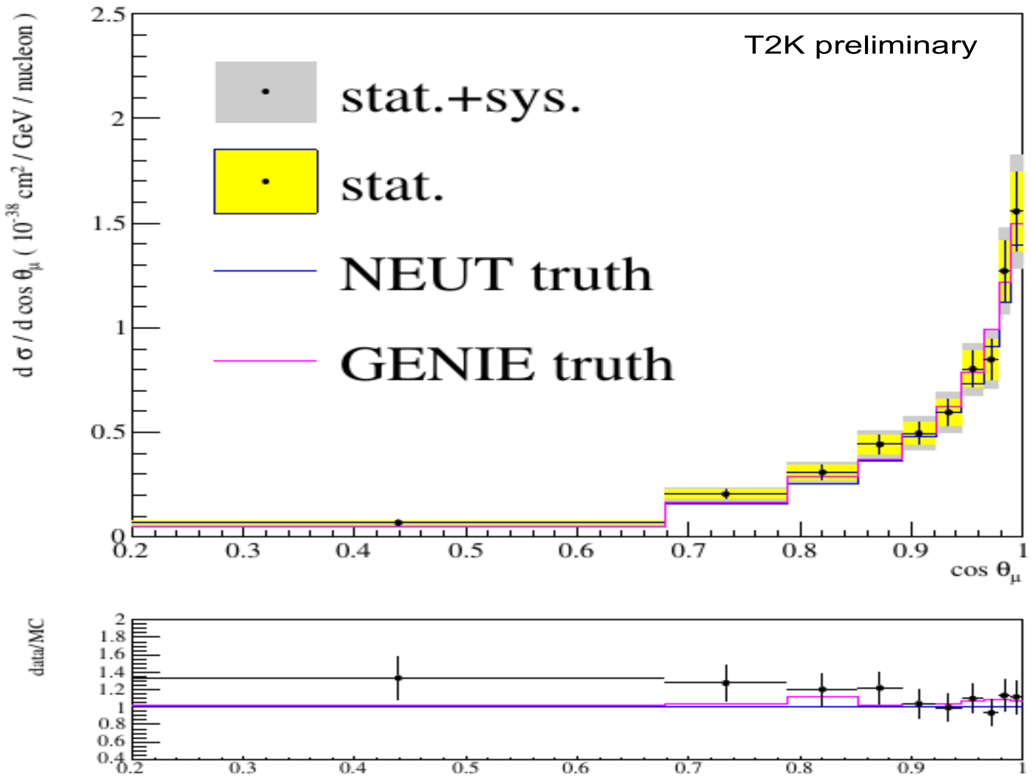
Cross-section and FSI have different A-dependence → important effect when extrapolation from ND and FD with different material

$\bar{\nu}$ cross section measurement

The measurement of δ_{CP} crucially depends on the comparison of ν vs $\bar{\nu}$ oscillation

$\rightarrow$ **bias on ν vs $\bar{\nu}$ cross section direct reflect in bias on δ_{CP} measurement**



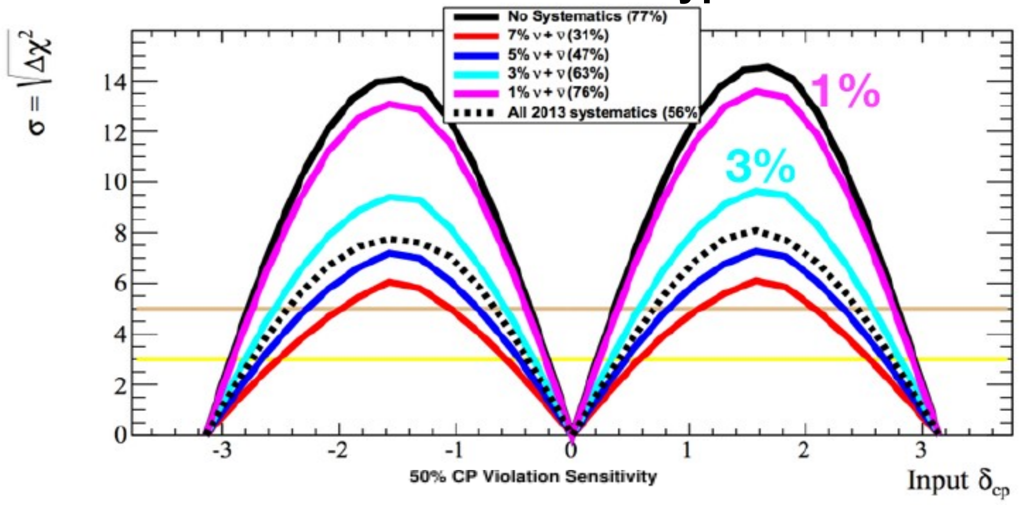


Future experiments: ν_e

- We are interested to **ν_e appeareance and δ_{CP} from $\nu - \bar{\nu}$ comparison** but in ND we mostly measure ν_μ cross-sections.

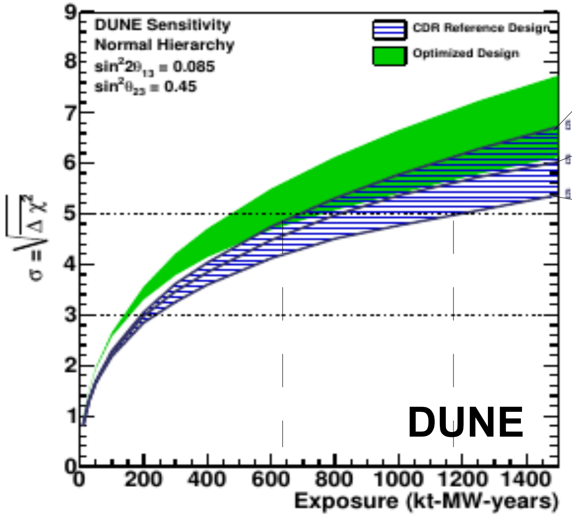
  T2K uncertainty today 5-6%
  → ν_e/ν_μ uncorrelated 2.5%
  → $\bar{\nu}/\nu$ uncorrelated 2%

HyperKamiokande



- In future (HK, DUNE) large samples of 4 ν species → the uncorrelated uncertainties are relevant
  - **HK** needed uncertainty to have negligible impact on δ_{CP}:
    ν_e-$\bar{\nu}_e$ uncorrelated 1%
  - For **DUNE** assumed: **uncorrelated ν_μ - $\bar{\nu}_\mu$ 5%** and **ν_e - $\bar{\nu}_e$ 2%**

  (shape of ν_μ itself may be more important for DUNE: shape analysis and spanning over different xsec)



5% ± 1%
5% ± 2%
5% ± 3%

→ equivalen to factor 2 in exposure!

What do we need to measure?

Uncertainties in ND→FD extrapolation :

✔ • different E_ν distribution (because of oscillation) ⇨ need to reconstruct the neutrino energy from the final state particles

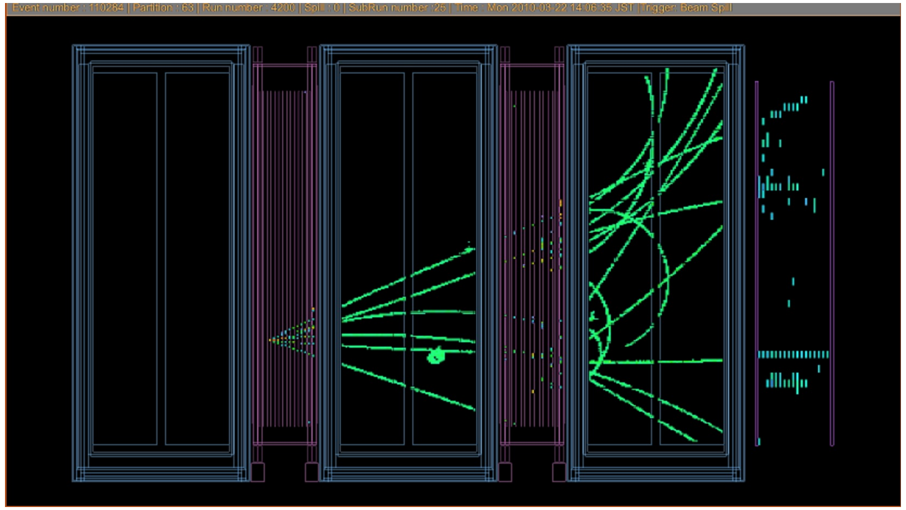
✔ • different target ⇨ A-scaling: measure cross-sections on different targets (and/or on the same target of FD)

➔ • different acceptance ⇨ measurement of cross-section in the larger possible phase-space: increase angular acceptance of ND

➔ • different neutrino flavor (because of oscillation) ν ($\bar{\nu}$) flux has typically a wrong sign component ⇨ measure cross-section asymmetries between different neutrino species (eg ν vs $\bar{\nu}$ important for for δ_{CP})

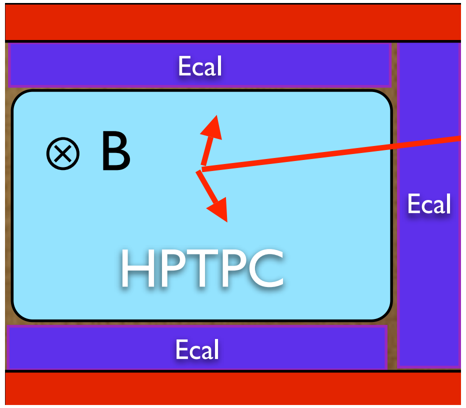
Why a TPC as neutrino detector at a demonstrator

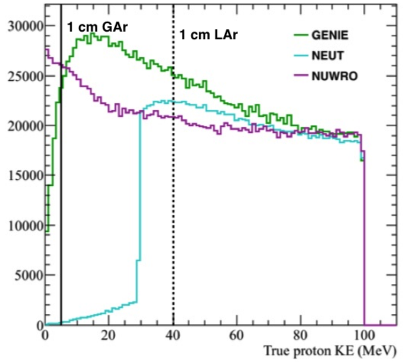
- Neutrino beams from muon decays are "clean" with perfectly know characteristics → high value of data from collected interaction data
- Target = detector
- 3D reconstruction capabilities.
- Possibility to exchange targets changing gas
- low density → low thresholds
- excellent PID capabilities.
- Almost uniform 4π acceptance.
- low number of interactions → requires high pressure and large volume.
- requires in addition a magnet to measure momentum and to distinguish between neutrinos and anti-neutrinos



A neutrino interaction in the T2K near detector

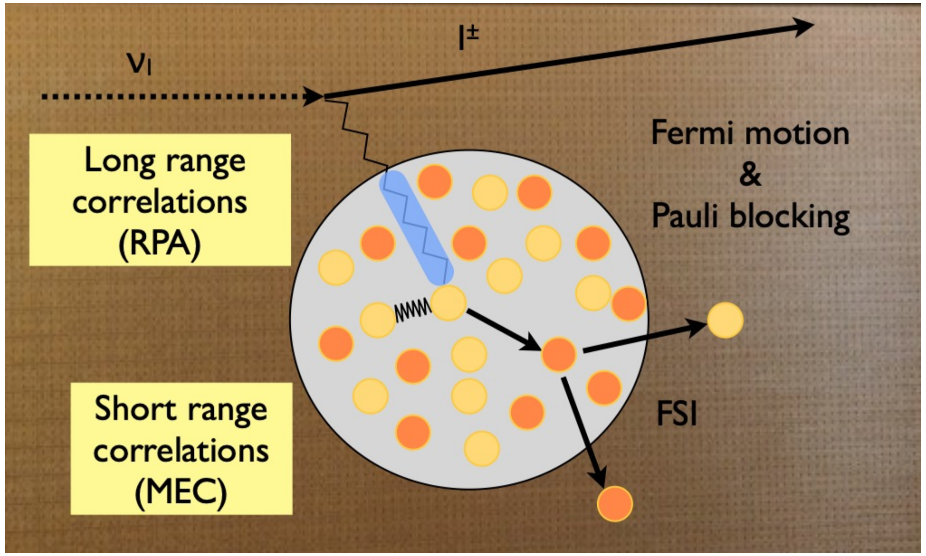
The flow of neutrinos at low energy produced by the demonstrator fit very well the requirements for a neutrino's X-sec experiments





Differences within models are at low KE and are below the threshold of a liquid argon device

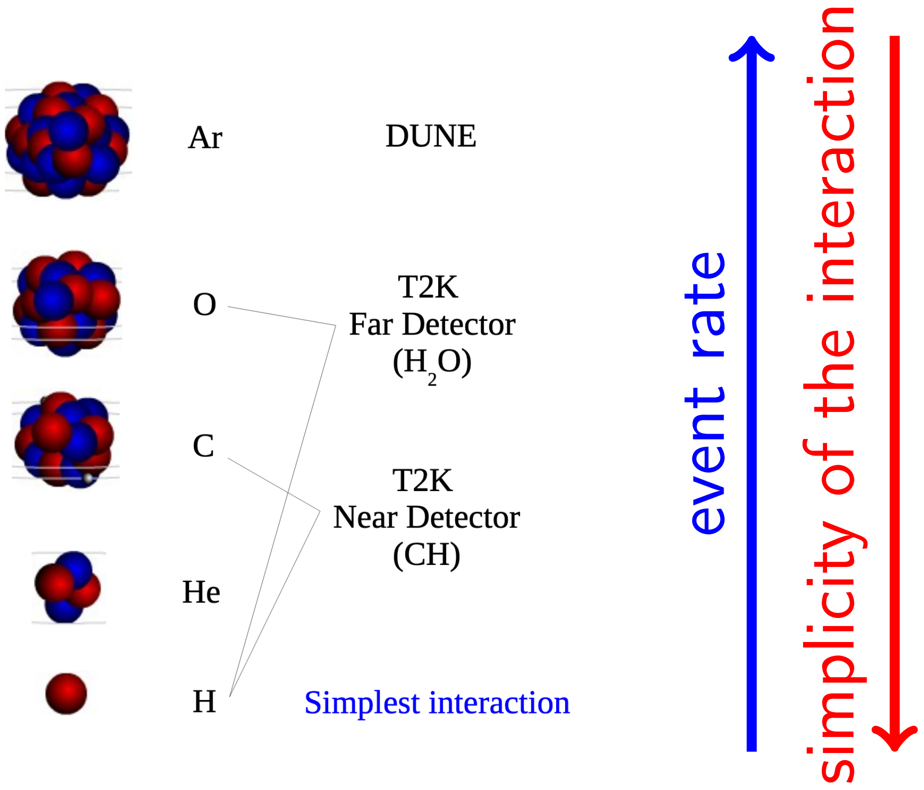
Number of events (example)



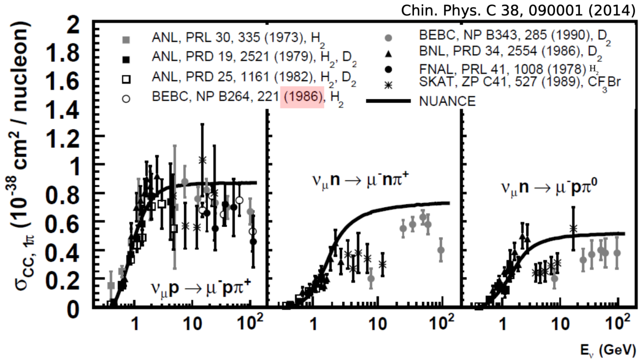
2x2x2 m^3 20°C	5 bars	10 bars
He	6.65 kg	13.3 kg
	520 evt/10^{21}pot	1040 evt/10^{21}pot
Ne	32.5 kg	67.1 kg
	2543 evt/10^{21}pot	5086 evt/10^{21}pot
Ar	66.5 kg	133 kg
	5203 evt/10^{21}pot	10406 evt/10^{21}pot
CF_4	146.3 kg	293 kg
	11450 evt/10^{21}pot	22893 evt/10^{21}pot

- As a cross-section experiment, HP-TPC allows to change the nuclear target addressing nuclear uncertainties systematics.

Different Gas mixtures for neutrino scattering experiments

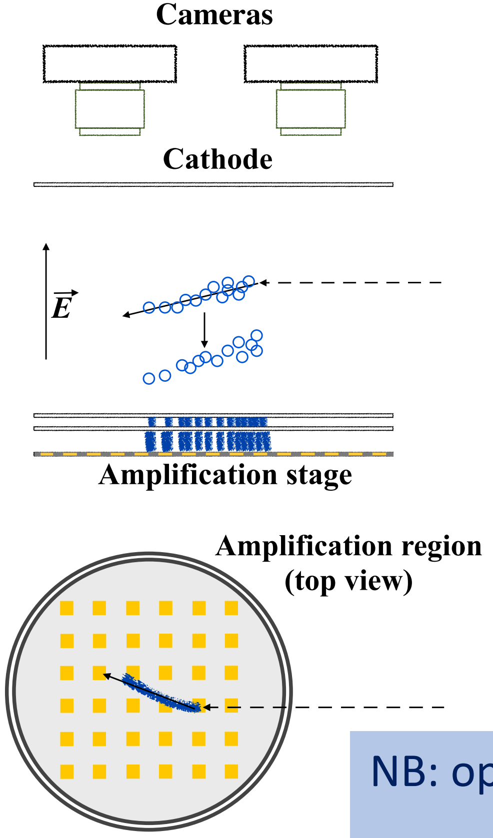


- New ν-hydrogen scattering measurements are much desired for flux constraints and nucleon cross section (input for Oscillation Analysis)
- Hydrogen rich gas mixtures in a high pressure TPC could provide new data of ν-H scattering
- T2K experience + MC simulations tell us that in a HP-TPC 95 % purity for the extraction of ν-H interactions could be achieved with He-CH4 (50-50)or He-C2H6 (50-50)
- Research needed to find the ideal mixture, which still allows for safe and stable operation of a TPC



Bubbles chambers data

HPTPC with optical readout
(a possible "great" improvement)



- Primary ionisations in the drift region are guided to the amplification region by an electric field
- Amplification produces electrons and photons
- Cameras image the amplification region and record a 2D projection of the electroluminescence photon
- Highly segmented readout (~ 100 × 100 μm^2) at low cost per pixel possible

Current CCD cameras do not allow to access the longitudinal coordinate due to their slow readout speed
The goal is to combine optical and charge readout ➔Full 3D tracking information (since the longitudinal coordinate can be reconstructed from charge signals) ➔ (TimePix or SIPM array)

NB: optical readout is also of great interest for for the beam instrumentation case:
1) reduction of the budget material along the beam line
2) readout optimization ➔ low gas amplification factor ➔ high density of tracks