Neutrino physics at low energy (0,2 – 5,0 GeV)

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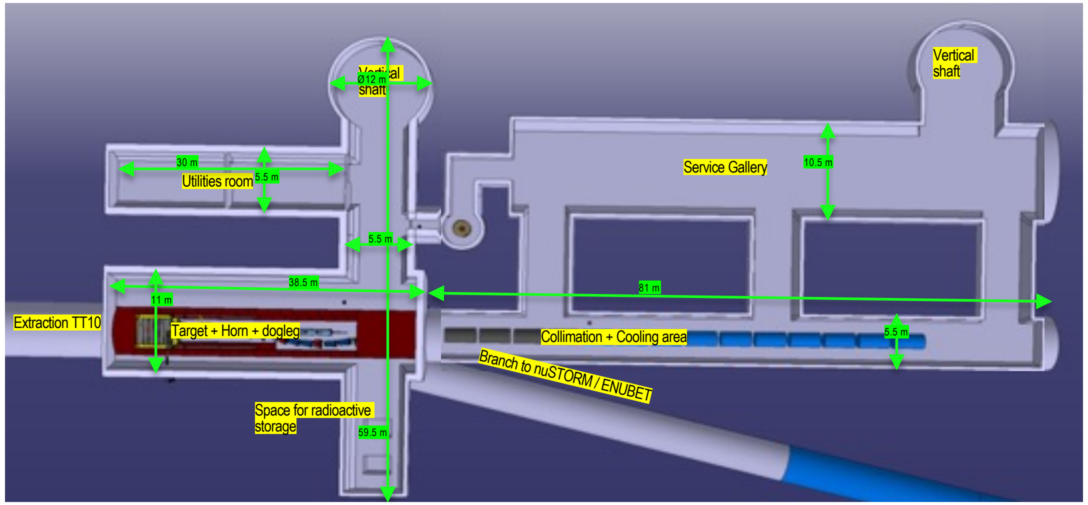
RD_MUCOL , 5 Dicembre 2024

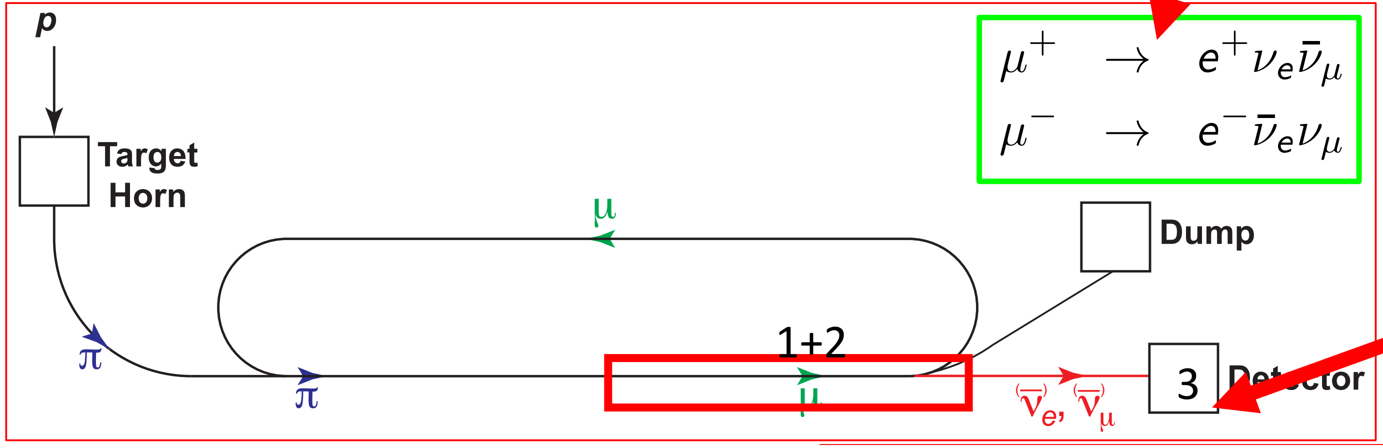
The Demonstrator will produce a large number of muons/neutrinos of 200 MeV or less



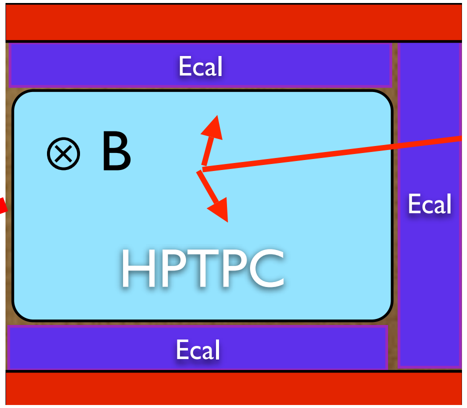
Great advantage respect to a traditional neutrino beam but to match the physics goal it requires:

1) Muons from 200 MeV => 1 -1,5 GeV (acceleration phase (linear ?)
2) A decay tunnel (100 m)
3) A limited space to host the detector (compact design)
4) Location :An existing tunnel can be used at CERN ? (< 1km tunnel)

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

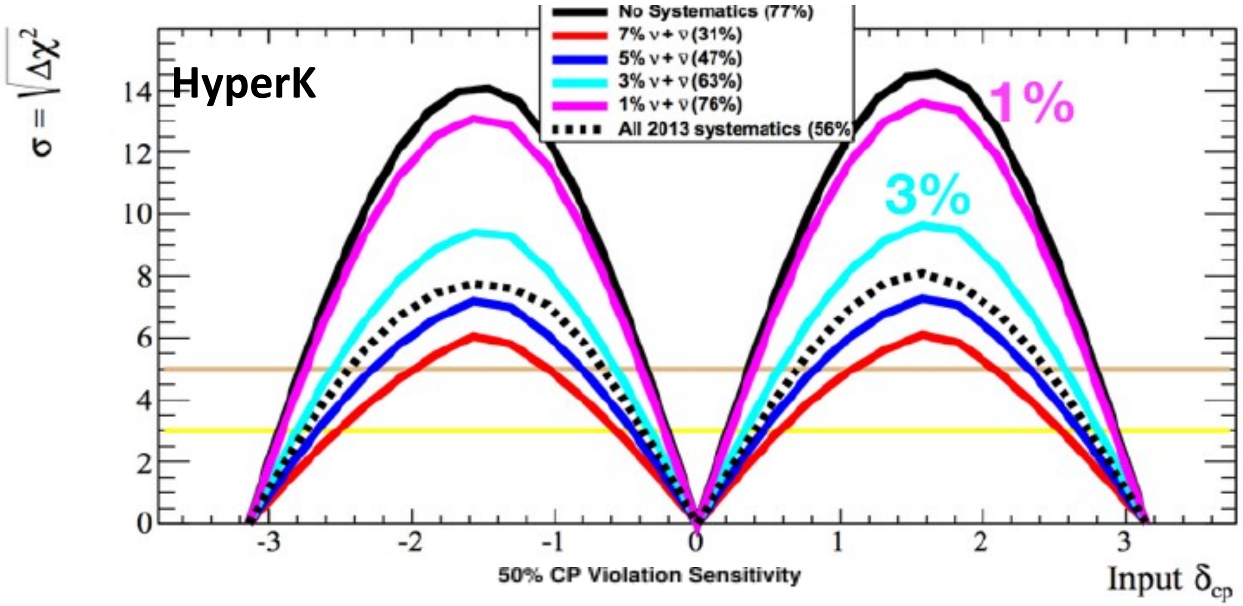


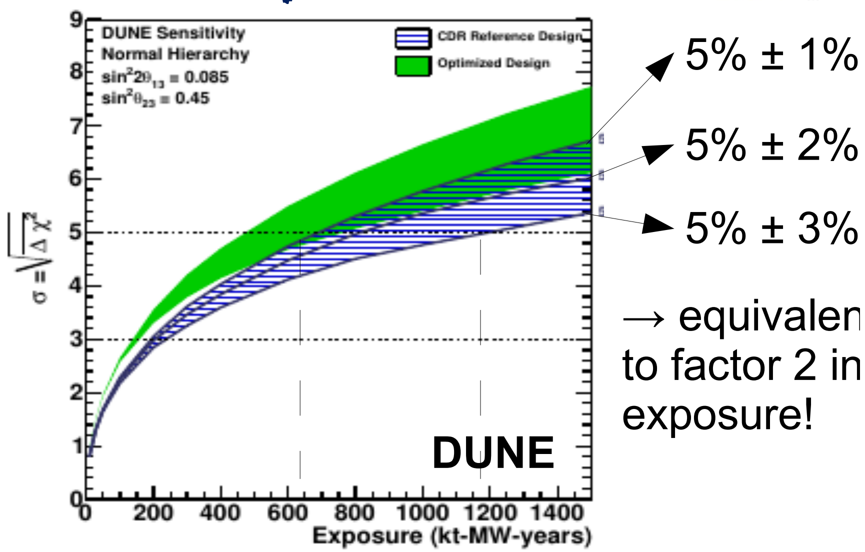
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$



Concept for a neutrino X-sec measurement

Future Neutrino Oscillation Experiments

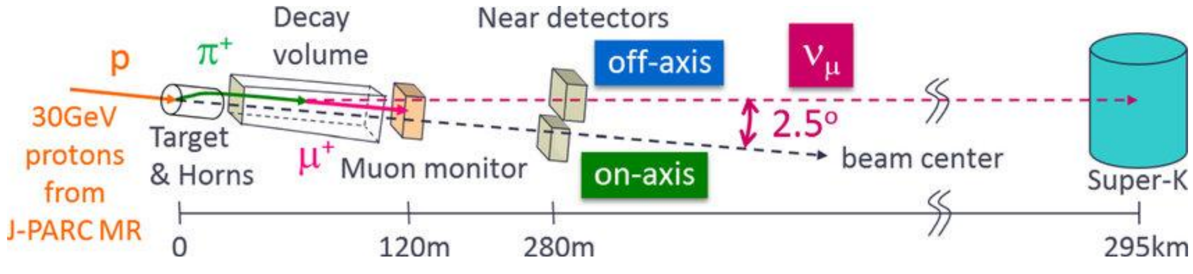


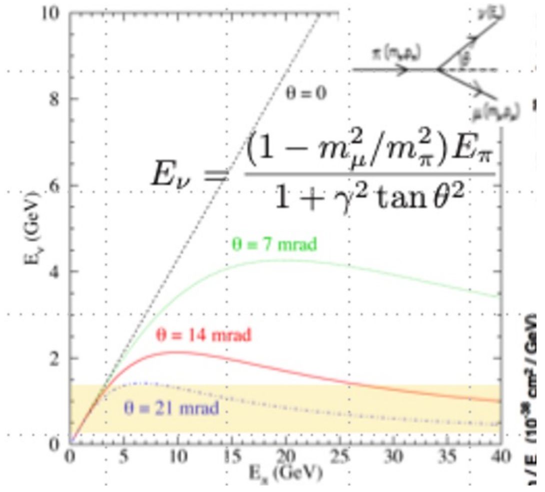


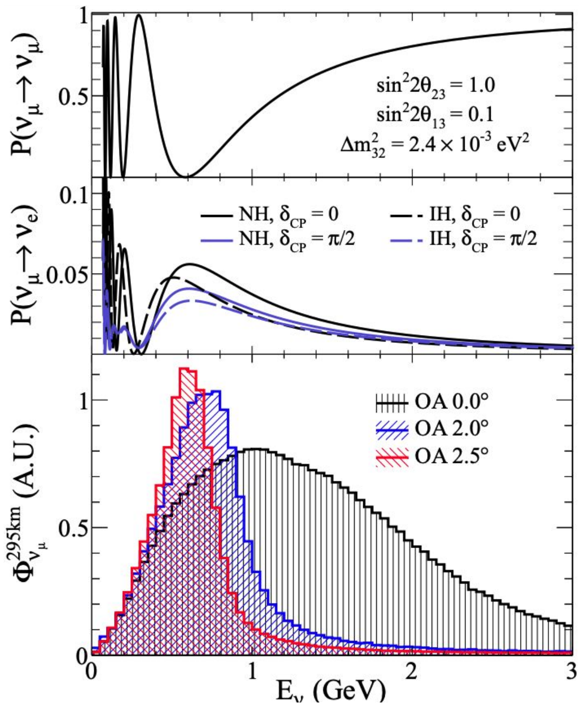
- La sensibilita' dei futuri esperimenti di oscillazione di neutrino dipende fortemente dalla capacita' di ridurre l'impatto degli errori sistematici nell'ordine del %.
- Le incertezze nelle *misure delle sezioni d'urto a bassa energia (0.2-5 GeV/c)* e nei *modelli montecarlo* incidono nell'estrapolazione dei flussi dai Near Detector (ND) ai Far Detector (FD) , limitandone la precisione dei risultati

Neutrino Beams (0.2-5.0 GeV)

T2K/Hyper-K

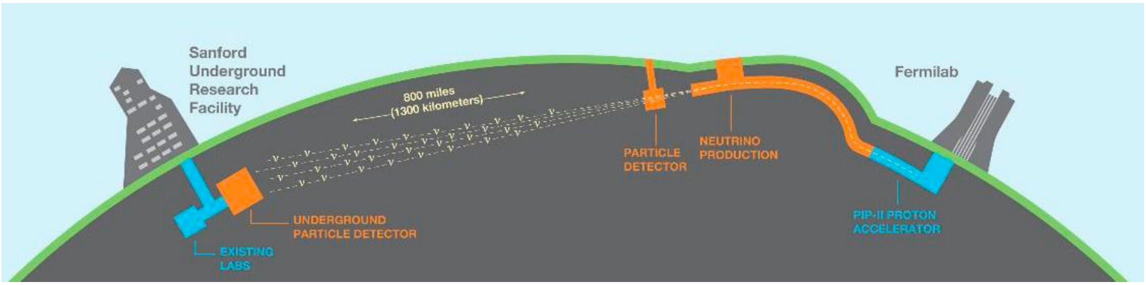




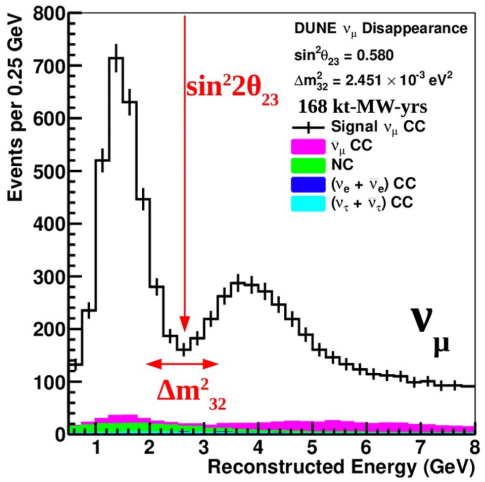


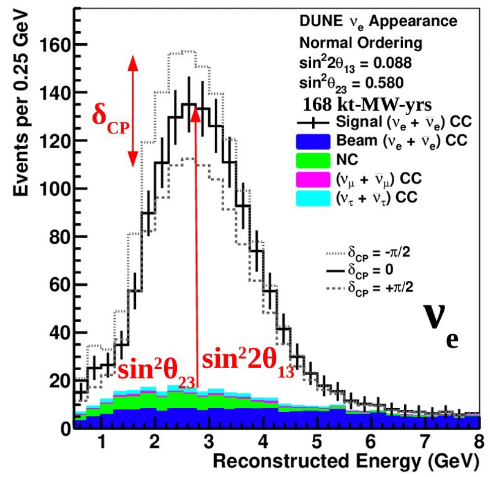
30 GeV protons
L=300 Km
E_{peak} = 600 MeV/c
Off-axis

Dune

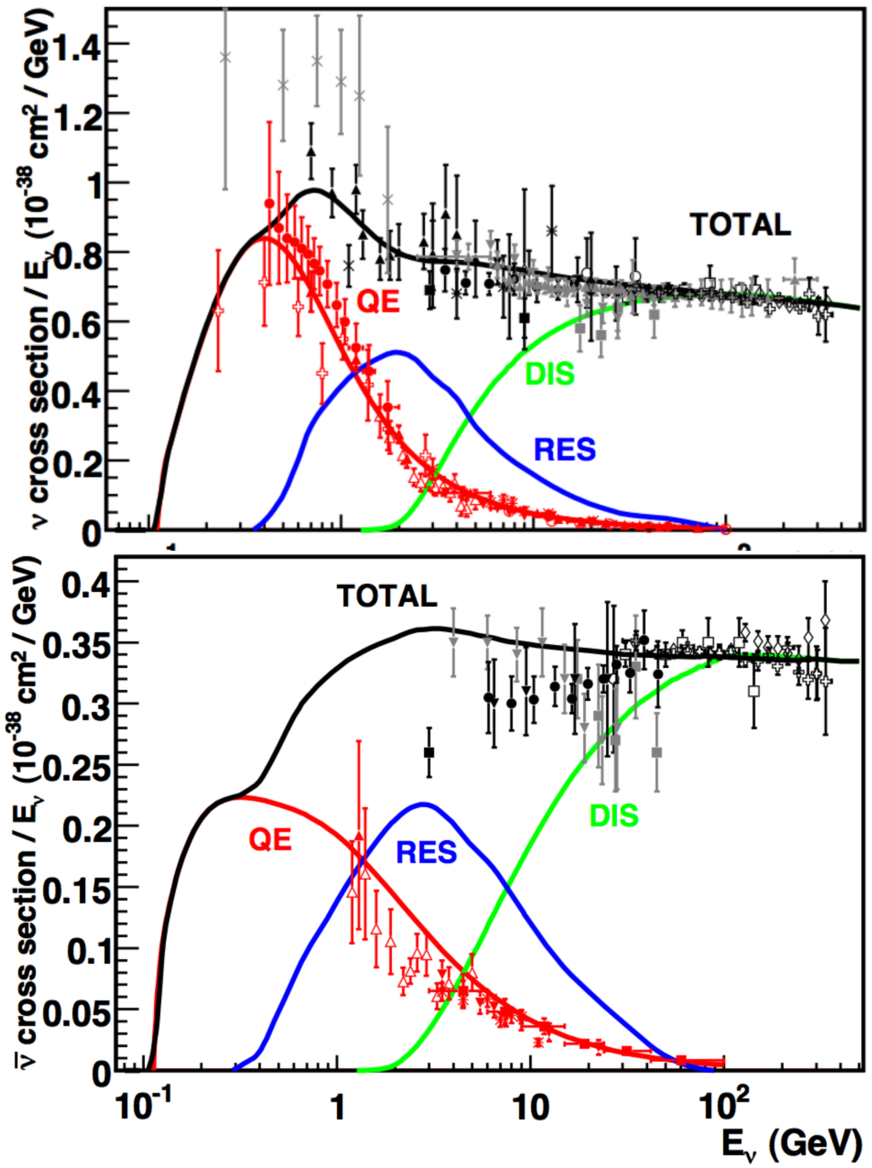


60-120 GeV protons
L=1300 Km
E_{peak} = 2-4 GeV/c
Wide on Axis

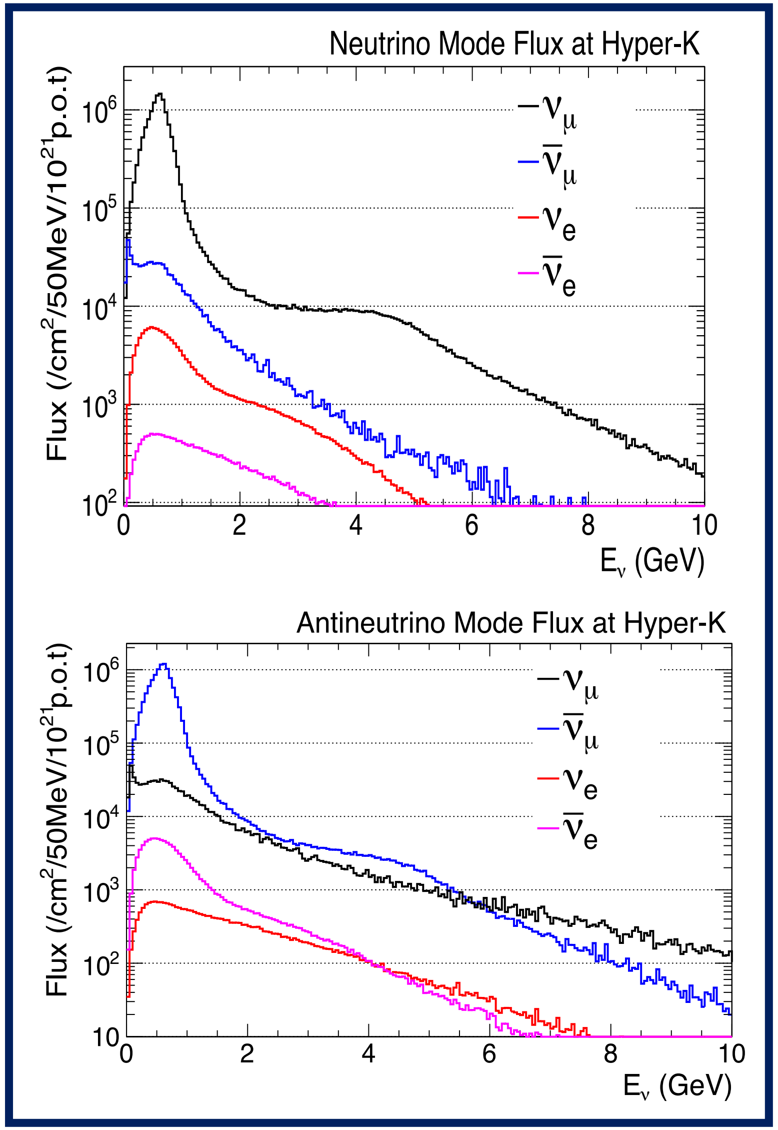




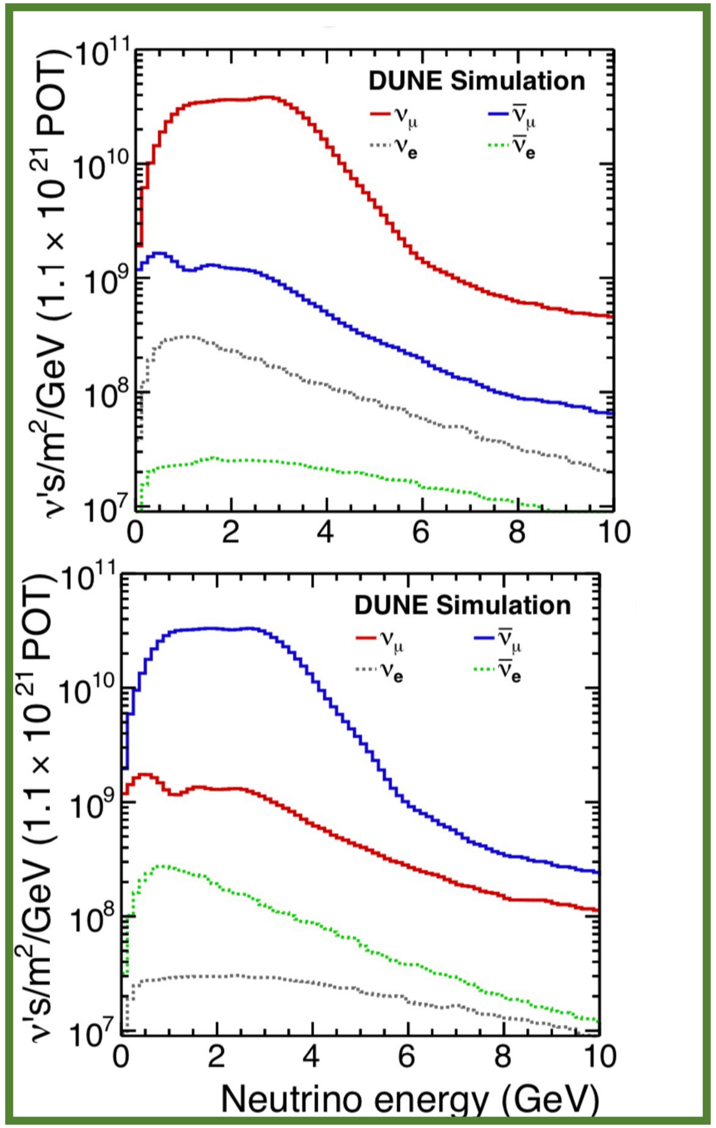
X-Sections



Hyper-K



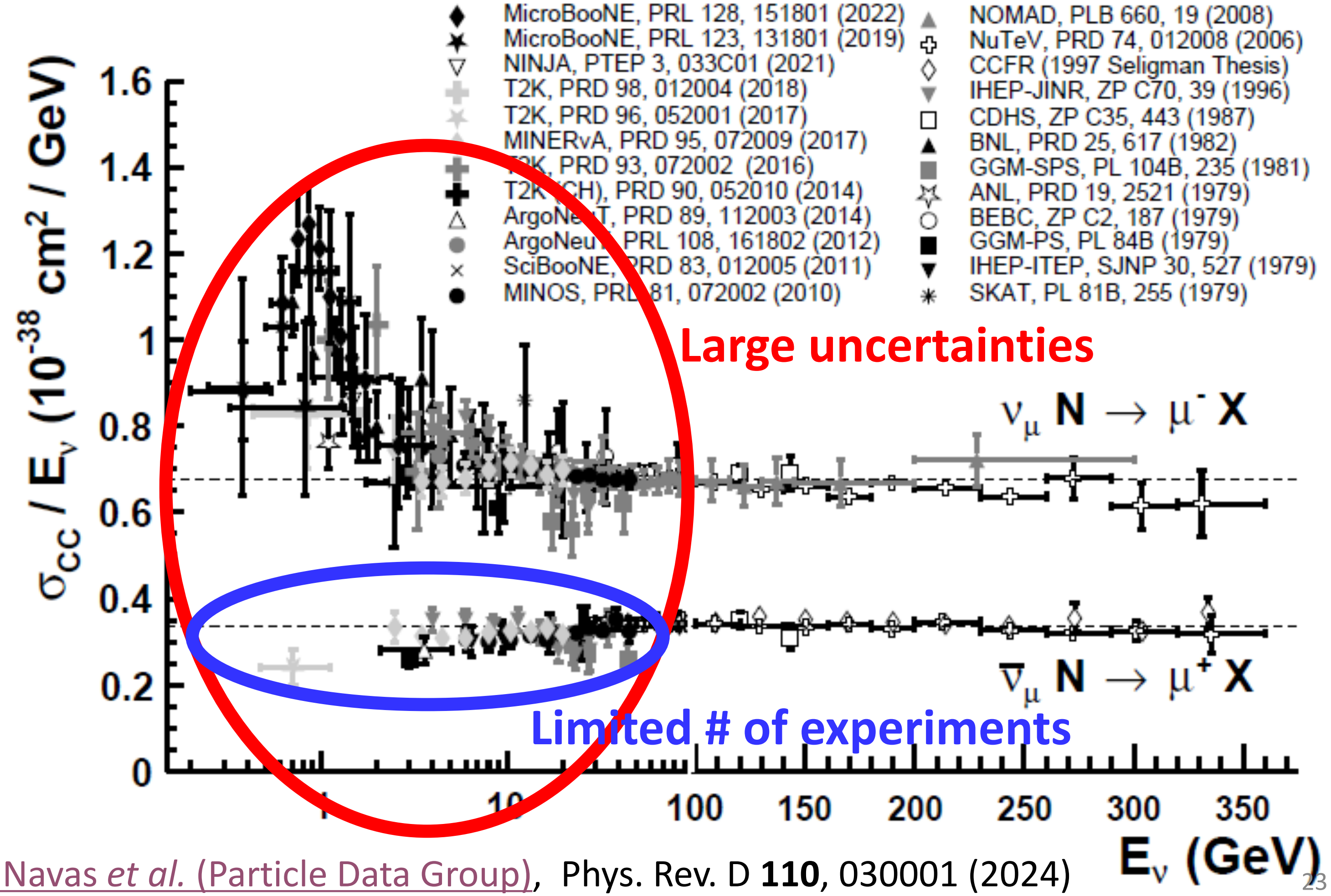
DUNE



Current status of “neutrino cross-section” measurements

Inclusive charged current total cross-section

(G.P. Zeller’s review)

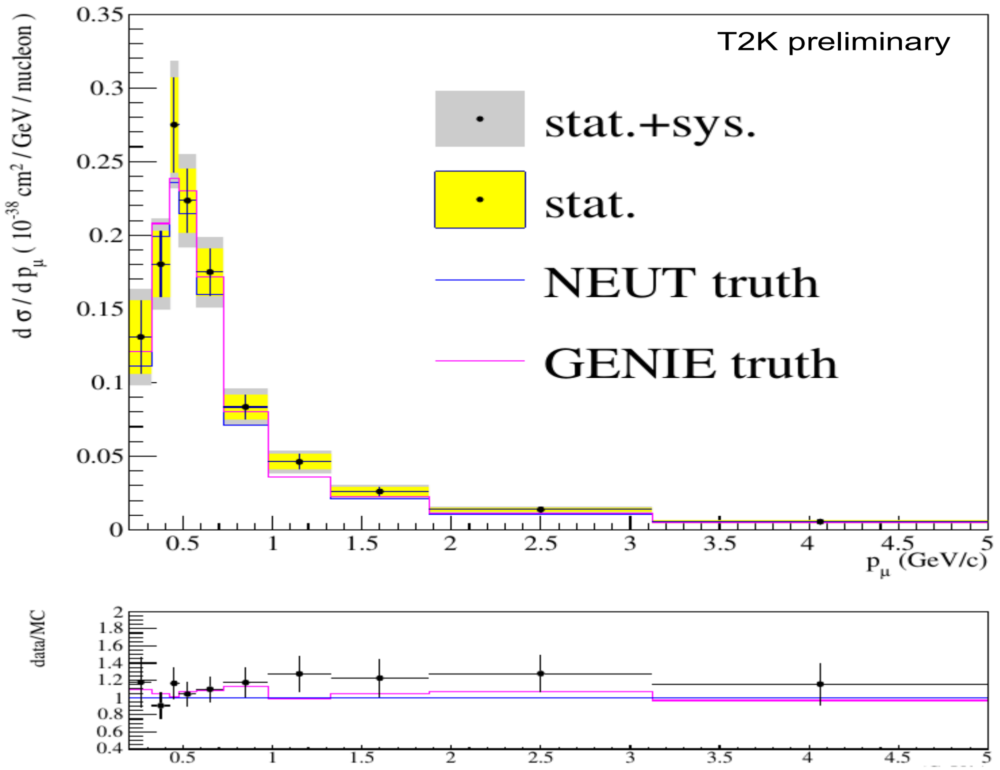


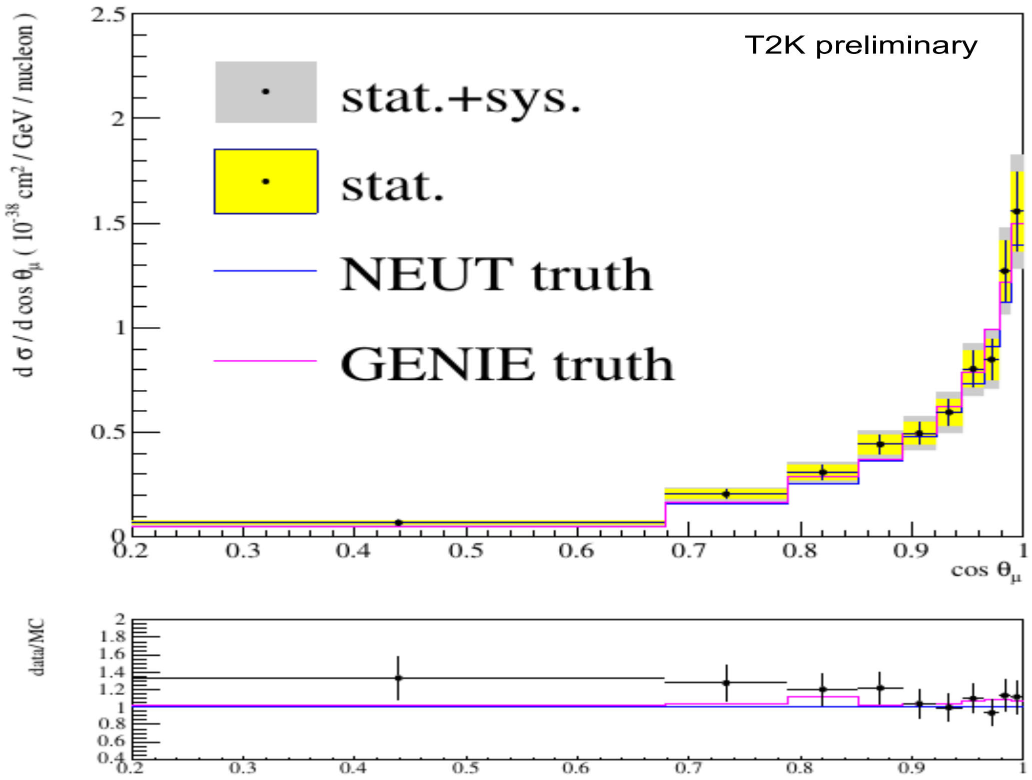
S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110**, 030001 (2024)

$\bar{\nu}$ cross section measurement

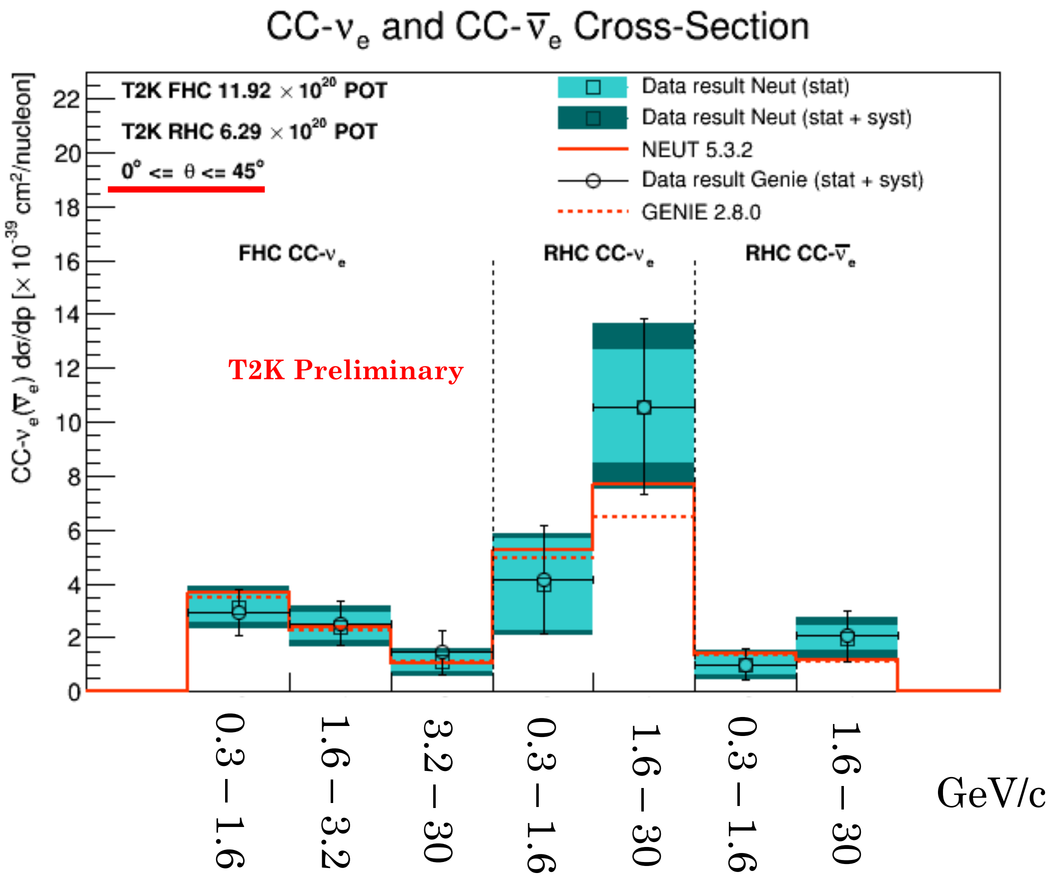
The measurement of δ_{CP} crucially depends on the comparison of ν vs $\bar{\nu}$ oscillation

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





ν_e X-section

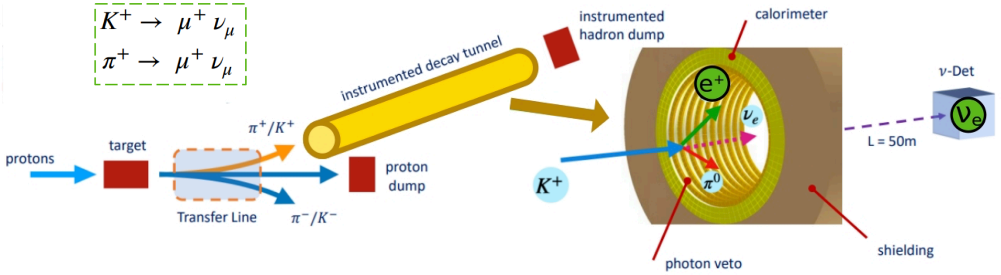


- CERN Neutrino Platform: NP06/ENUBET (2022-present), part of the Physics Beyond Colliders initiative

  Aim: Extend measurement to anti-muons from $K_{\mu 2}$ (in tunnel) and $\pi_{\mu\nu}$ (in dump) decays to determine the ν_μ flux

$K^+ \to \mu^+ \nu_\mu$

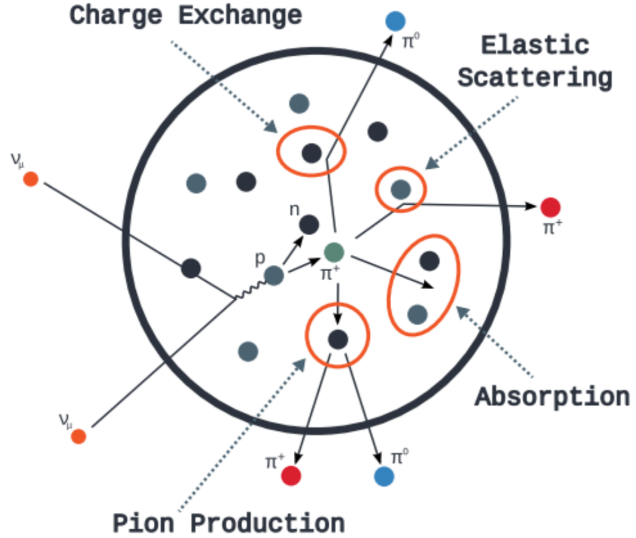
$\pi^+ \to \mu^+ \nu_\mu$



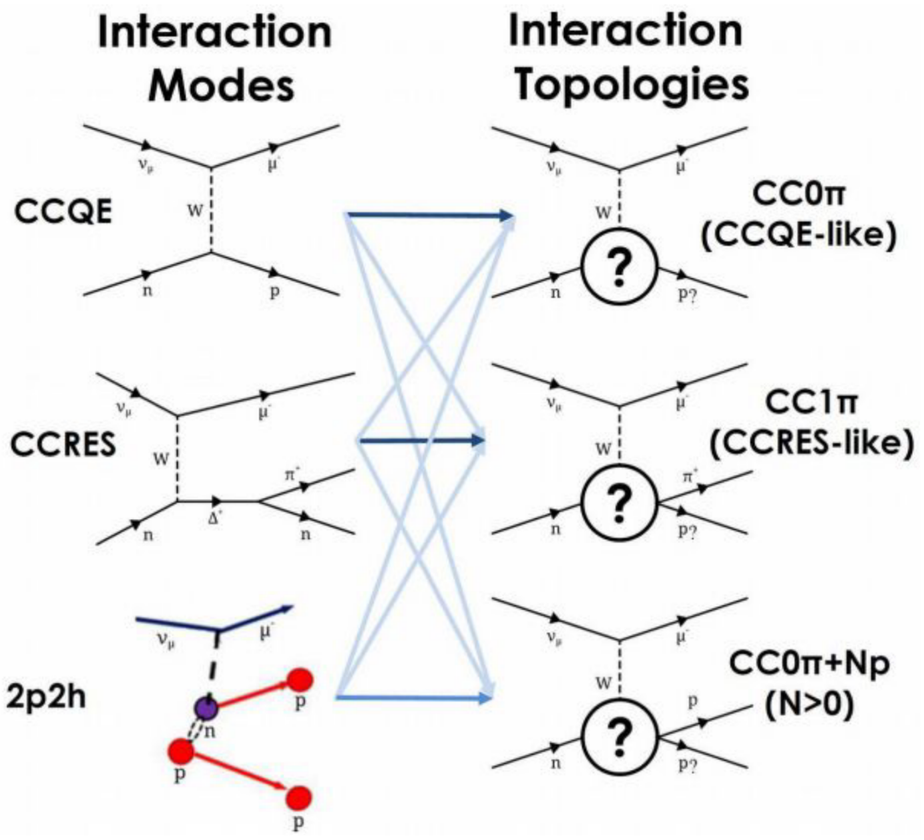
ν_e Tag (E> 2GeV)

Cosa bisogna misurare?

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



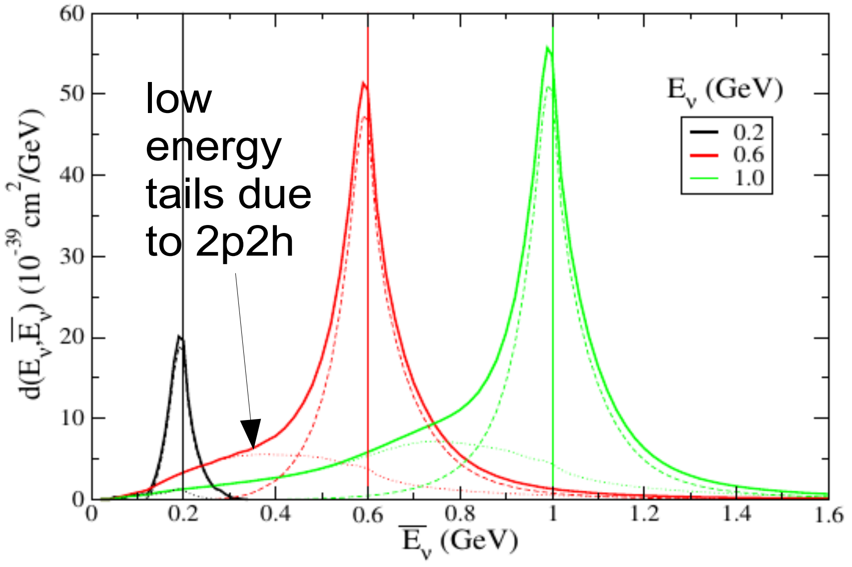
T. Golan, What is inside MC generators and why it is wrong. NuSTEC 2015



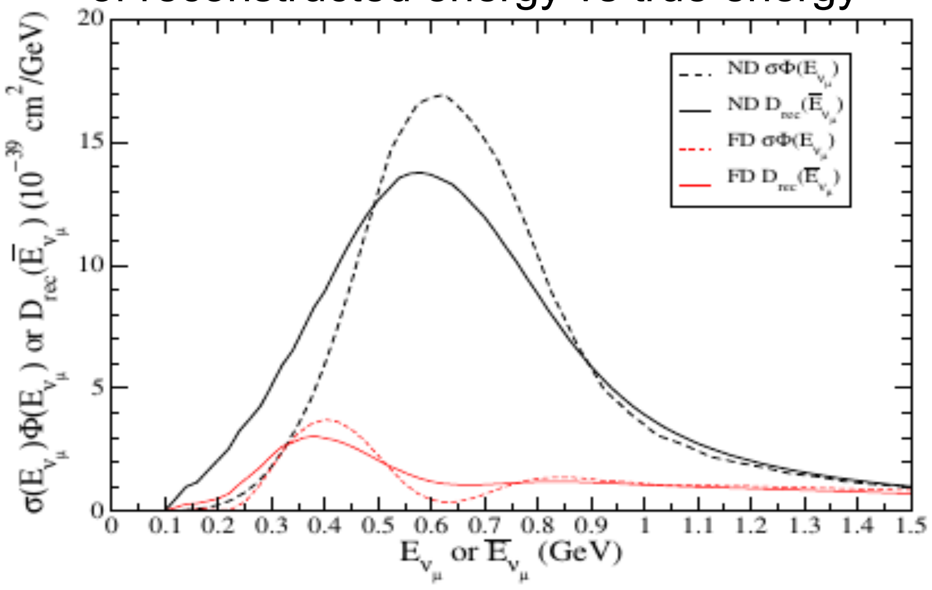
Why we need good models ?

Neutrino oscillation goes like ~L/E_ν but we do not measure E_ν ! 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**

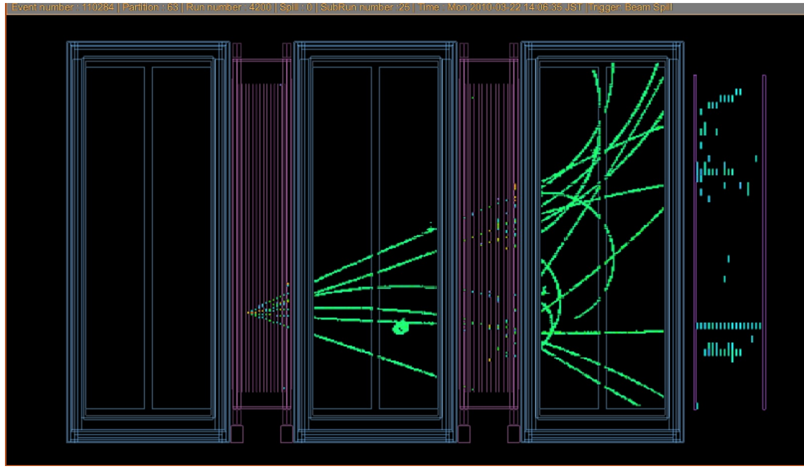
S. Bolognesi –Jennifer Meeting

What do we need to measure?

Uncertainties in ND→FD extrapolation :

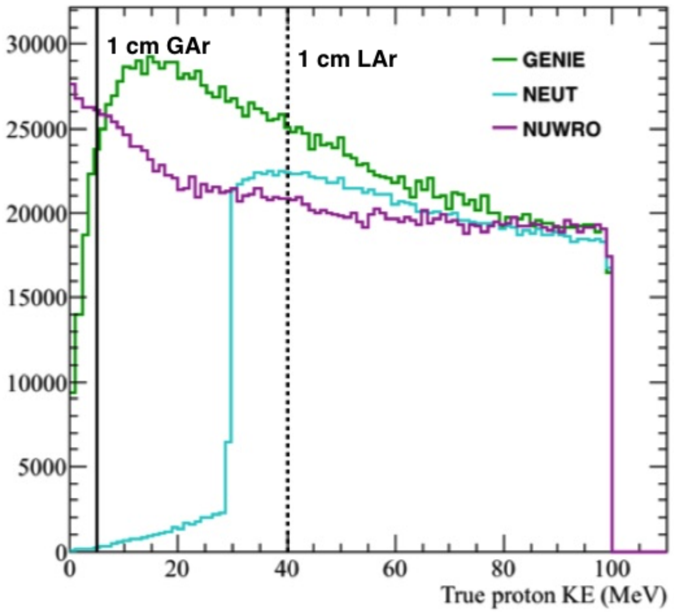
✔	• different E_ν distribution (because of oscillation)	⇨ need to reconstruct the neutrino energy from the final state particles
✔	• different target	⇨ A-scaling: measure cross-sections on different targets (and/or on the same target of FD)
➔	• different acceptance	⇨ measurement of cross-section in the 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 HP-TPC with optical readout as neutrino detector at low energy (below 1GeV)

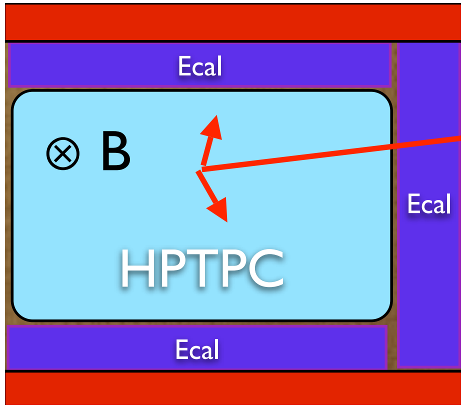


A neutrino interaction in the T2K near detector

- 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
- Very large volumes require low cost per readout channel (pixel)

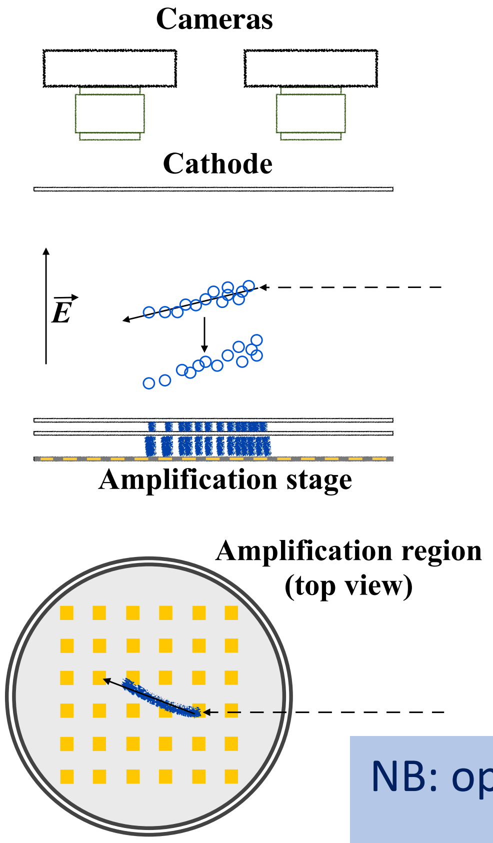


The flow of neutrinos at low energy produced by a demonstrator at CERN can fit very well the requirements for a neutrino's X-sec experiments



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

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



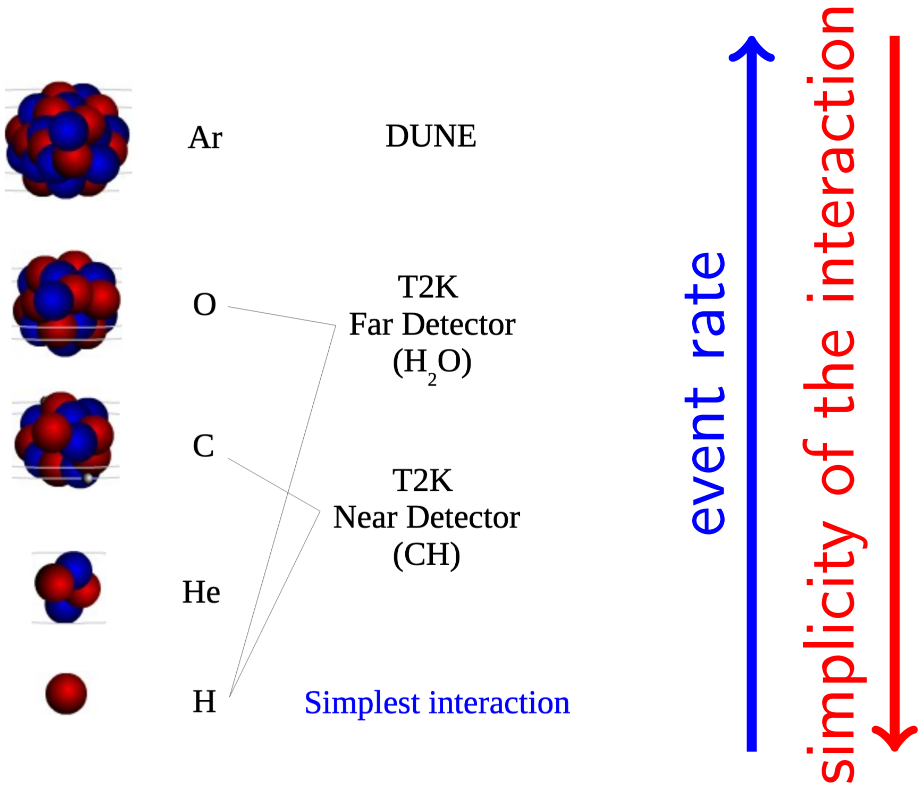
- Primary ionisations in the drift region are guided to the amplification region by an electric field
- Amplification produces electrons and photons
- Cameras image the amplification region and record a 2D projection of the electroluminescence photon
- Highly segmented readout (~ 100 × 100 μm^2) at low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

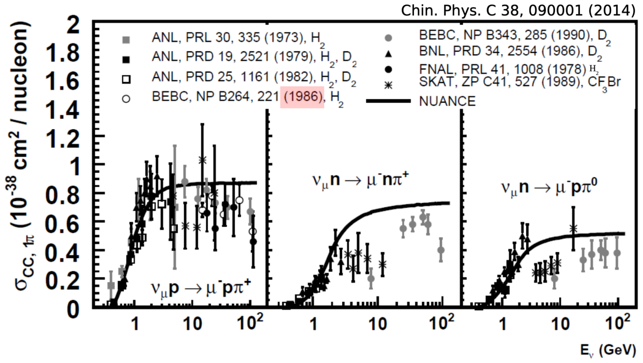
NB: optical readout is also of great interest for for the beam instrumentation case:

1) reduction of the budget material along the beam line
2) readout optimization ➔ low gas amplification factor ➔ high density of tracks

Different Gas mixtures for neutrino scattering experiments

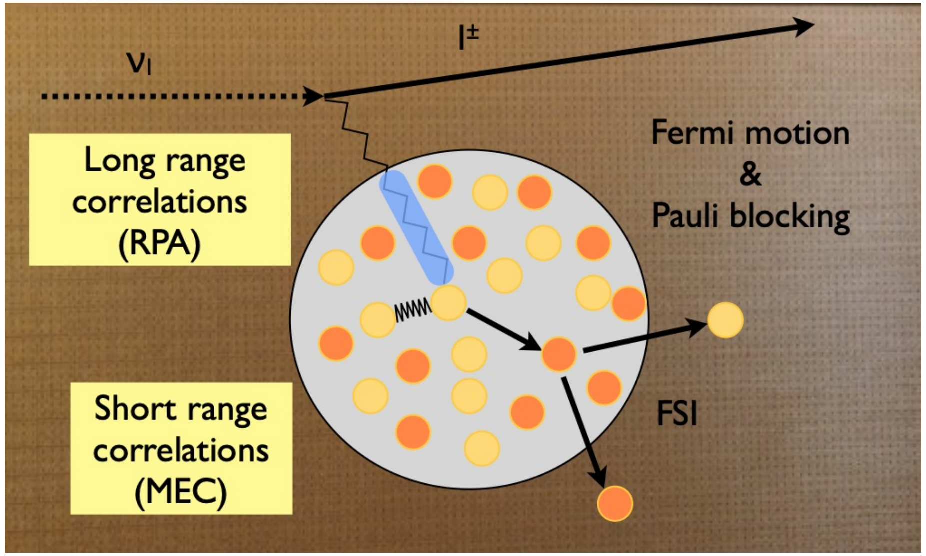


- New ν-hydrogen scattering measurements are much desired for flux constraints and nucleon cross section (input for Oscillation Analysis)
- Hydrogen rich gas mixtures in a high pressure TPC could provide new data of ν-H scattering
- T2K experience + MC simulations tell us that in a HP-TPC 95 % purity 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

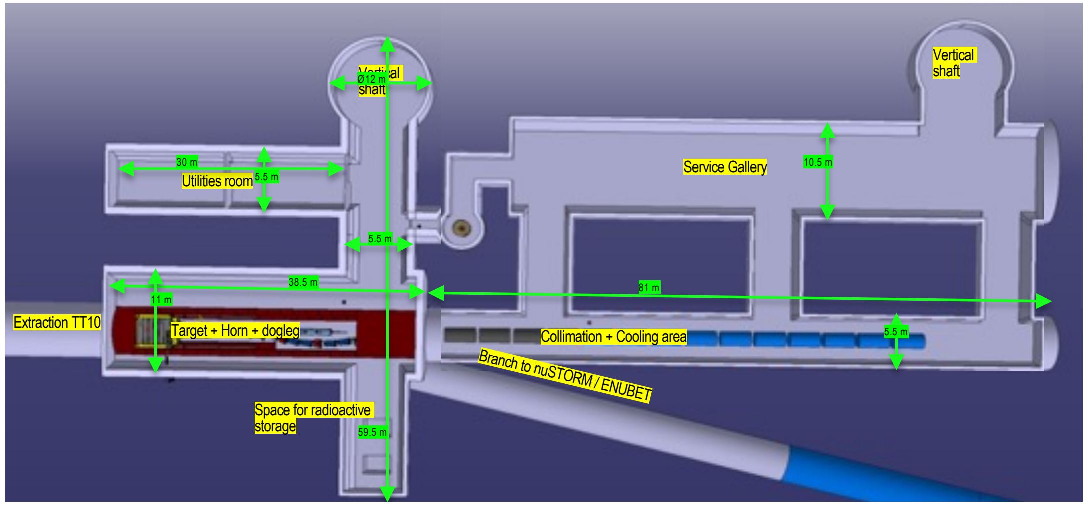
Number of events (example)



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.

The Demonstrator will produce a large number of muons/neutrinos of 200 MeV or less



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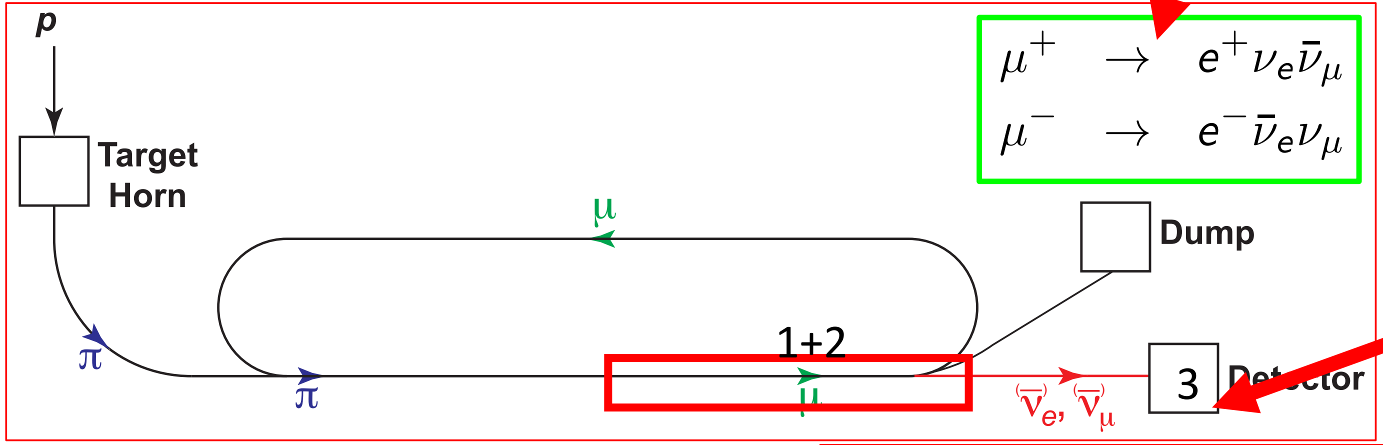

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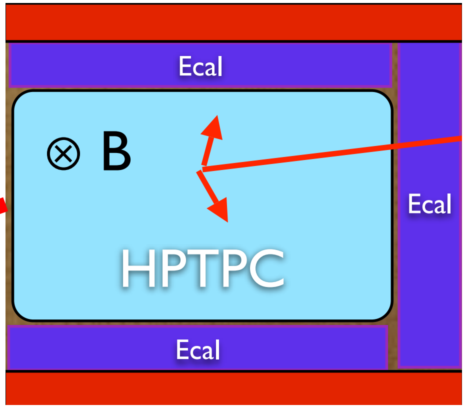

Concept for a neutrino X-sec measurement

Prototipo di HP-TPC

Conclusioni

- *La realizzazione del dimostratore apre per la prima volta la possibilita' di misurare eventi di neutrino generati dal decadimento di muoni focalizzati (il sogno di tutti i fisici del neutrino)*
- *Gia solo la misura di alcuni di questi eventi rappresenterebbe una novita' importante*
- *Se fosse possibile aumentare anche solo di un fattore 2 o 3 l'energia dei muoni prodotti dal dimostratore sarebbe possibile ottenere dei risultati di fisica dei neutrini di tutto rispetto, utilizzando un detector relativamente compatto.*
- *Se fosse possibile trovare una "location" al CERN per ospitare una linea di fascio che contenesse oltre il dimostratore , un piccolo acceleratore lineare e il tunnel di decadimento dei muoni) sarebbe un plus.*
- *A questo punto se vogliamo provare a studiare seriamente questa ipotesi e' importante passare a una fase piu quantitativa che ci permetta di ottimizzare caratteristiche del fascio e del detector. La collaborazione con i colleghi della macchina e' fondamentale*
- *Il 23-24 gennaio 2025 e' previsto un workshop al CERN su futuri esperimenti neutrino al CERN. https://indico.cern.ch/event/1460367/overview che riguarda proposte per fasci di neutrino al CERN . Al momento (a parte Nustorm) non c'e' nulla di collegato al muon collider*