Neutrino energy reconstruction from final state particles and effects related to the simulation of the physics of neutrino interactions in DUNE

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PhD days - 16.04.2024

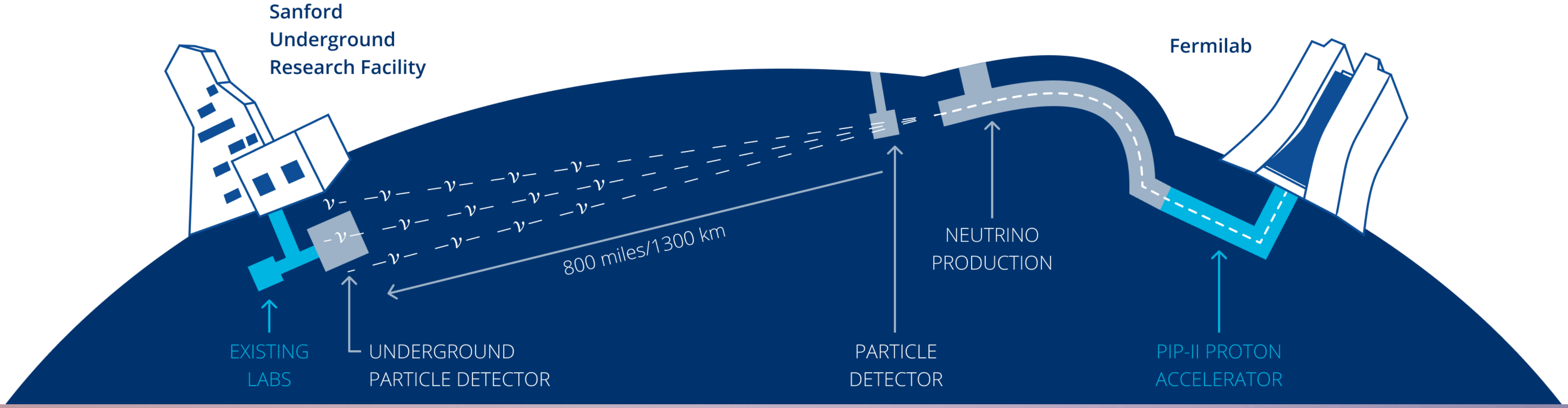
DUNE (Deep Underground Neutrino Experiment)

Main goals :

- Precision neutrino oscillation measurements
- CP violation in the neutrino sector
- Neutrino mass hierarchy

Based on $\nu_\mu \rightarrow \nu_e$ oscillation for neutrinos and antineutrinos (subleading atmospheric oscillation)

Long baseline neutrino experiment



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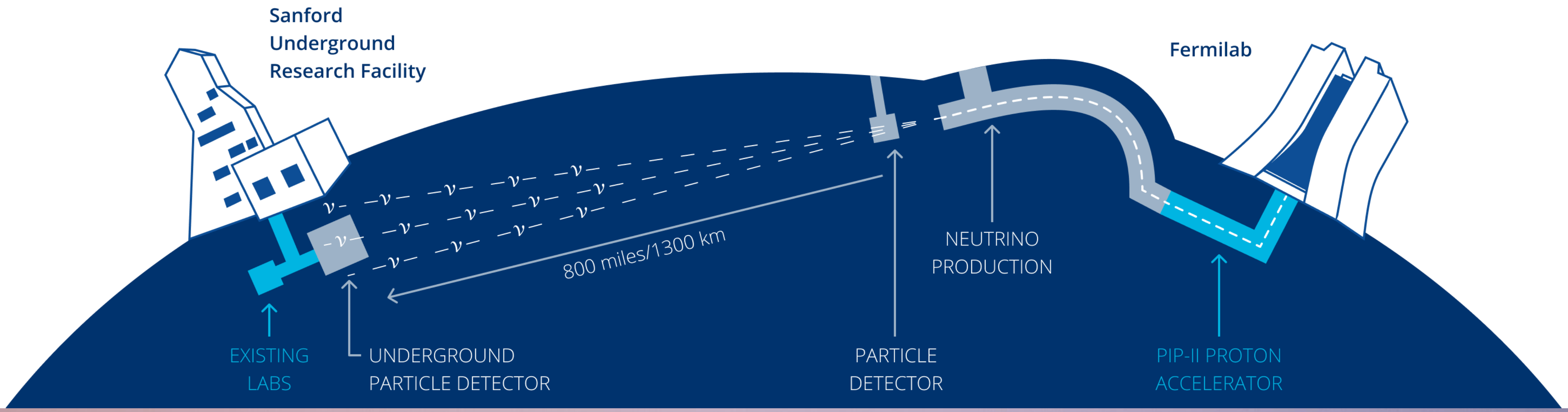
Long baseline neutrino experiment

A muonic neutrino beam is produced at Fermilab

Neutrinos propagate for 1300 km

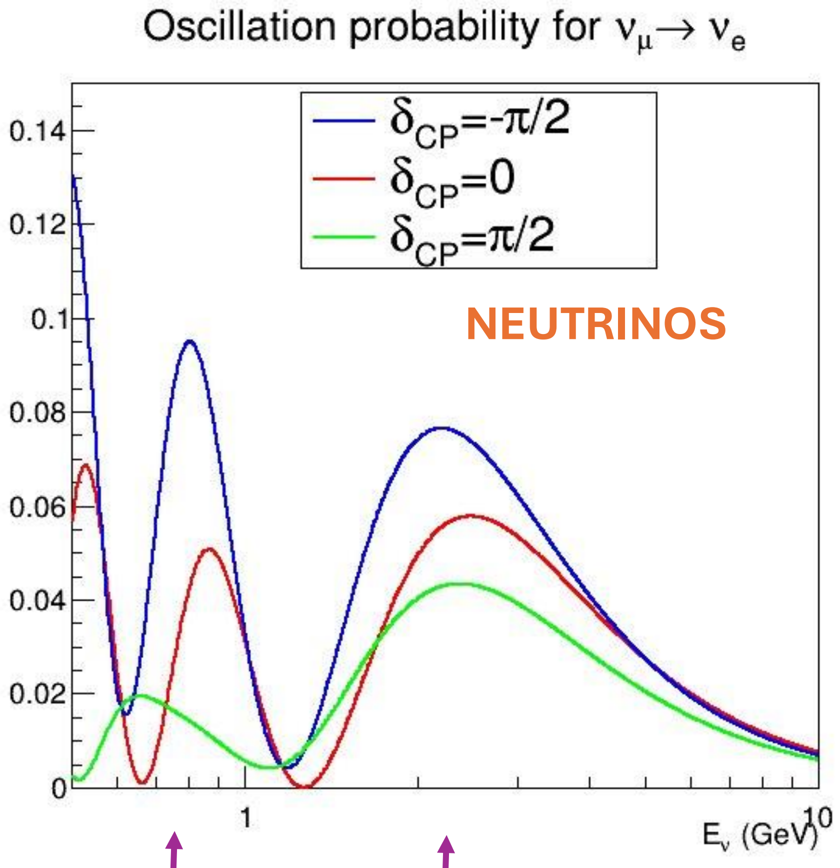
Neutrinos can oscillate to different neutrino flavours

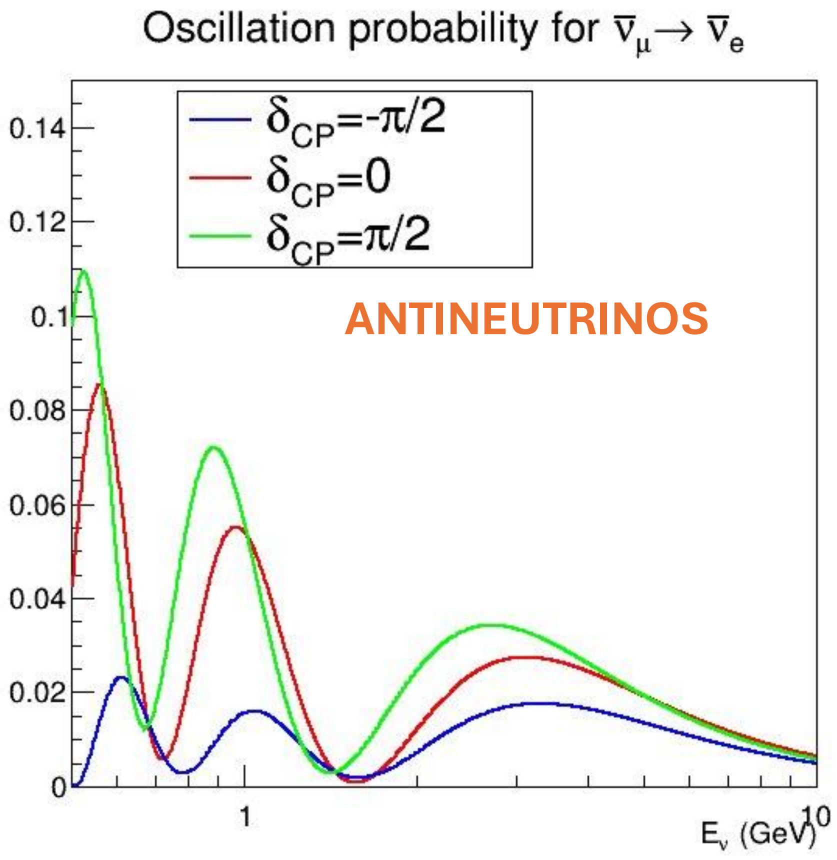
They are then detected at the far site at SURF



Oscillation probability

NORMAL ORDERING

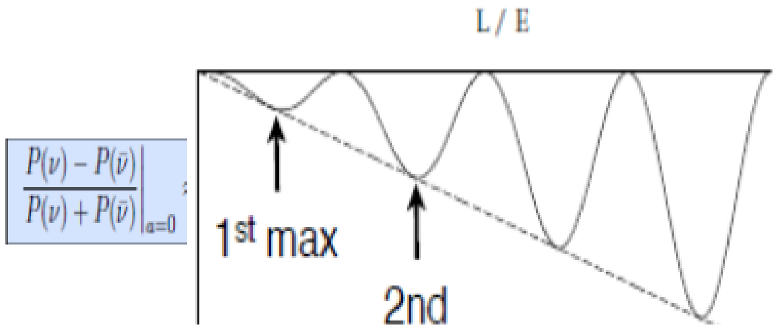




2nd   1st   oscillation maxima

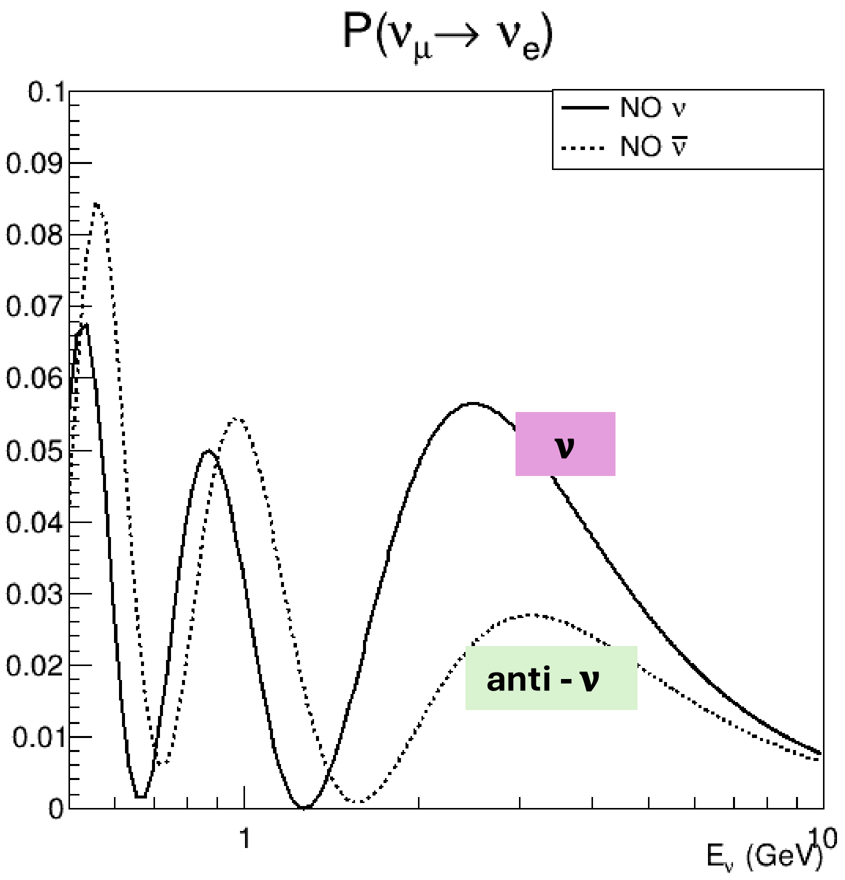
Neutrino (antineutrino) oscillation probabilities depend on

- L/E
- Mass ordering
- **CP phase (δ_{CP})**



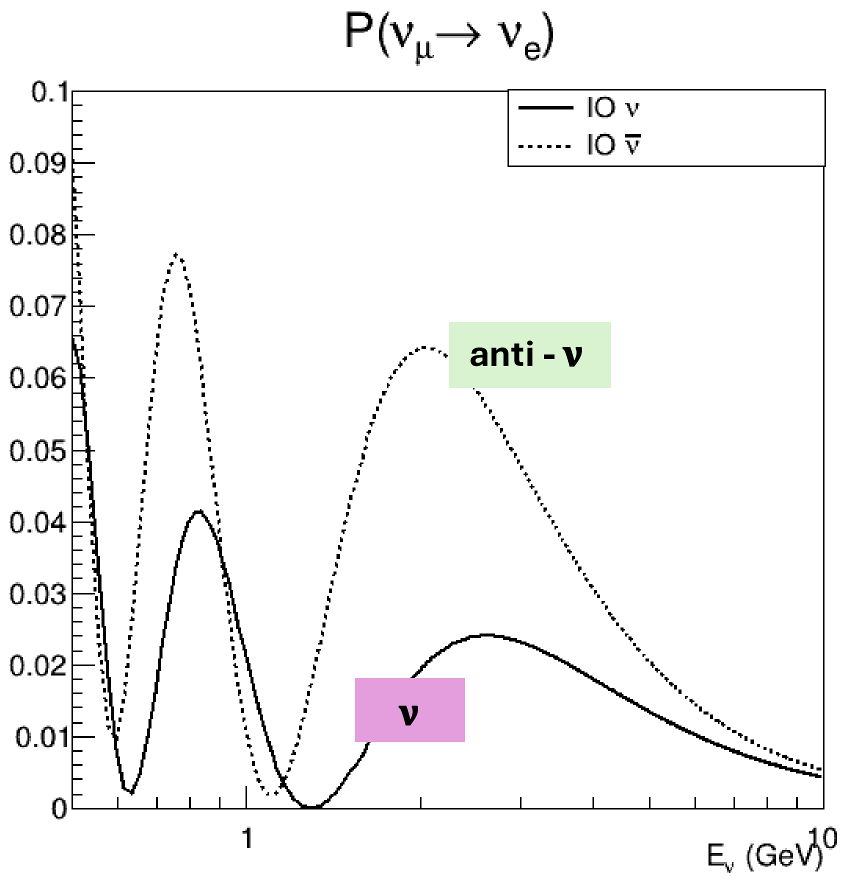
Oscillation probability

NORMAL ORDERING



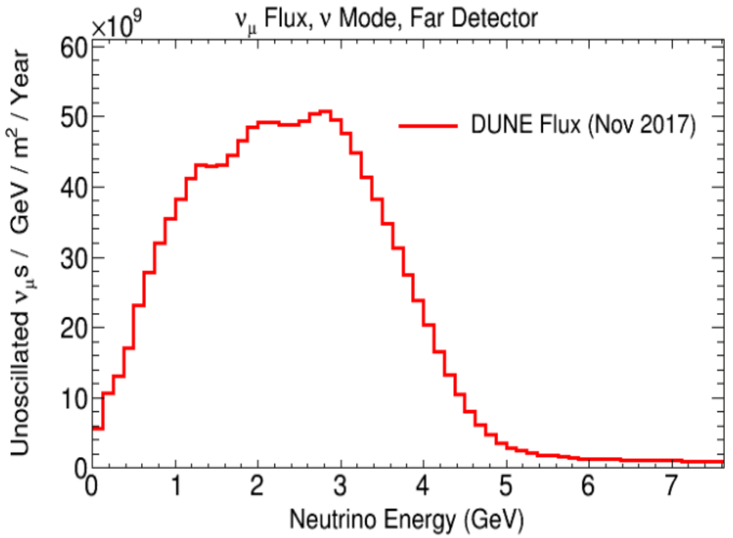
computed for $\boldsymbol{\delta}_{CP} = 0$

INVERTED ORDERING



Neutrino (antineutrino) oscillation probabilities depend on

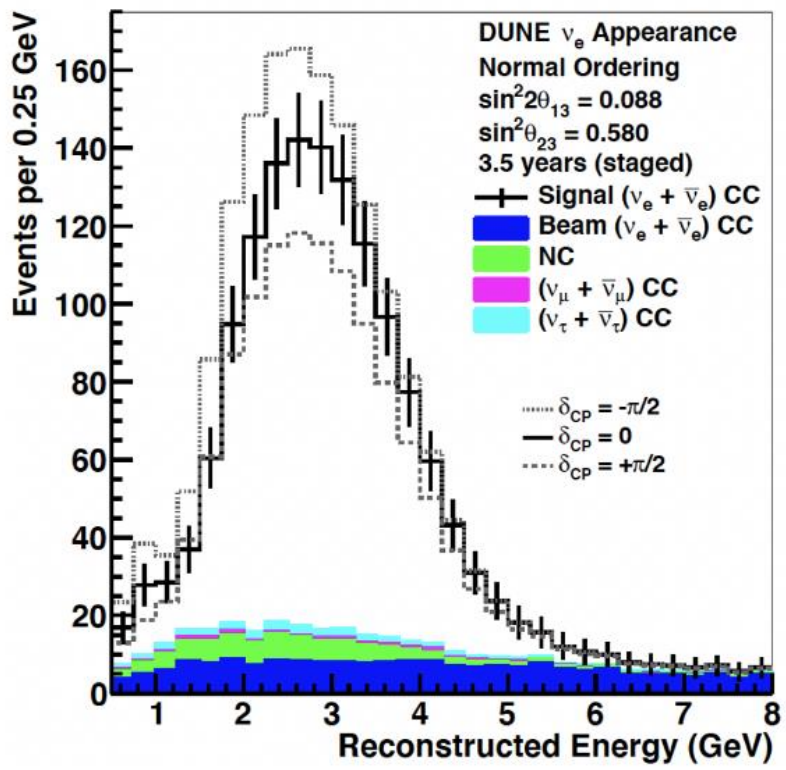
- L/E
- **Mass ordering**
- CP phase ($\boldsymbol{\delta}_{CP}$)

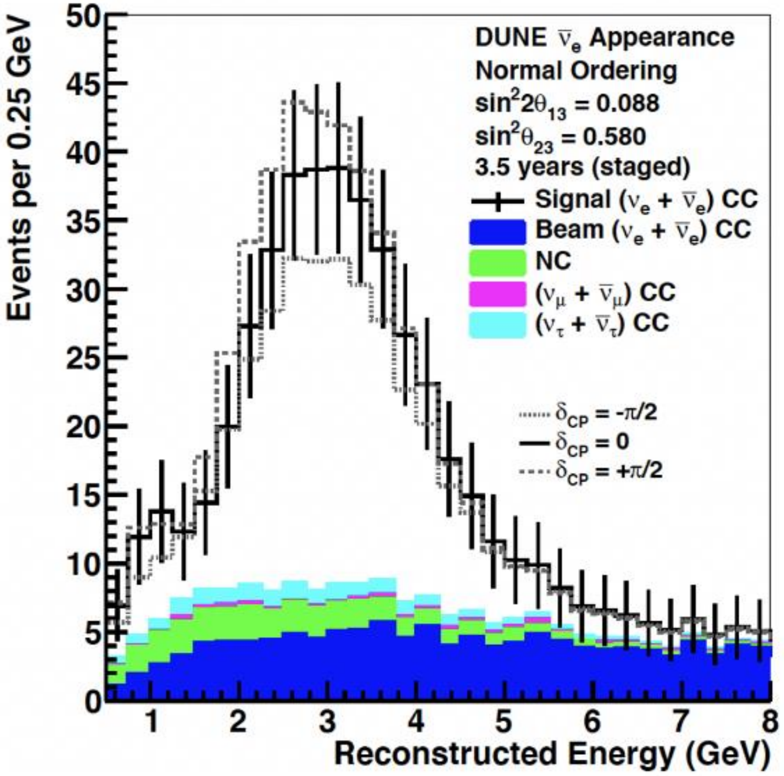


beam flux covering
1st and 2nd maxima

Appearance spectrum

- What is experimentally measured is the appearance spectrum of the ν_e coming from the oscillated ν_μ





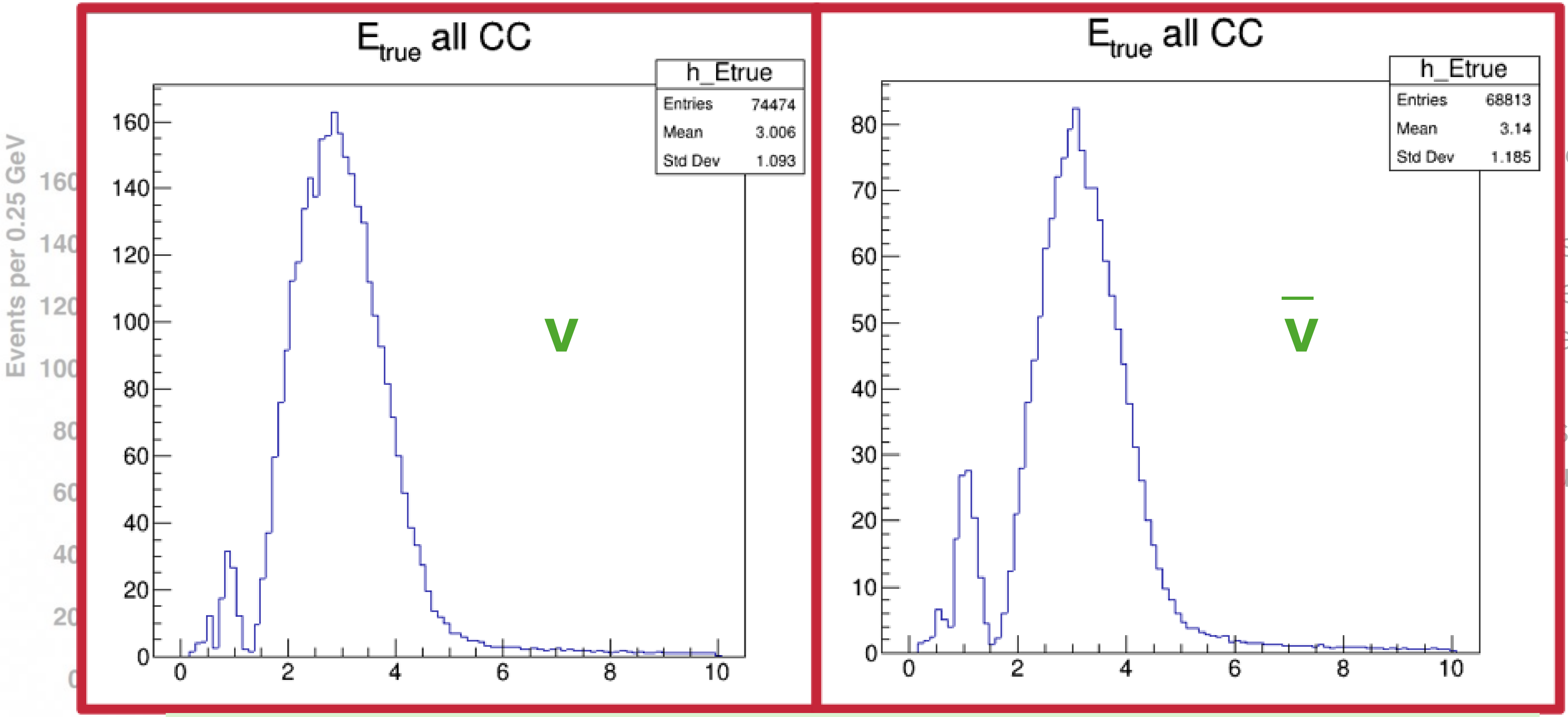
This is a convolution of:

- incoming neutrino flux
- oscillation probability
- neutrino-nucleus cross section
- detector resolution

The X axis is not the *true* neutrino energy but it is **reconstructed**

Appearance spectrum

- What is experimentally measured is the appearance



olution of:
coming neutrino flux
scillation probability
eutrino-nucleus cross
ection

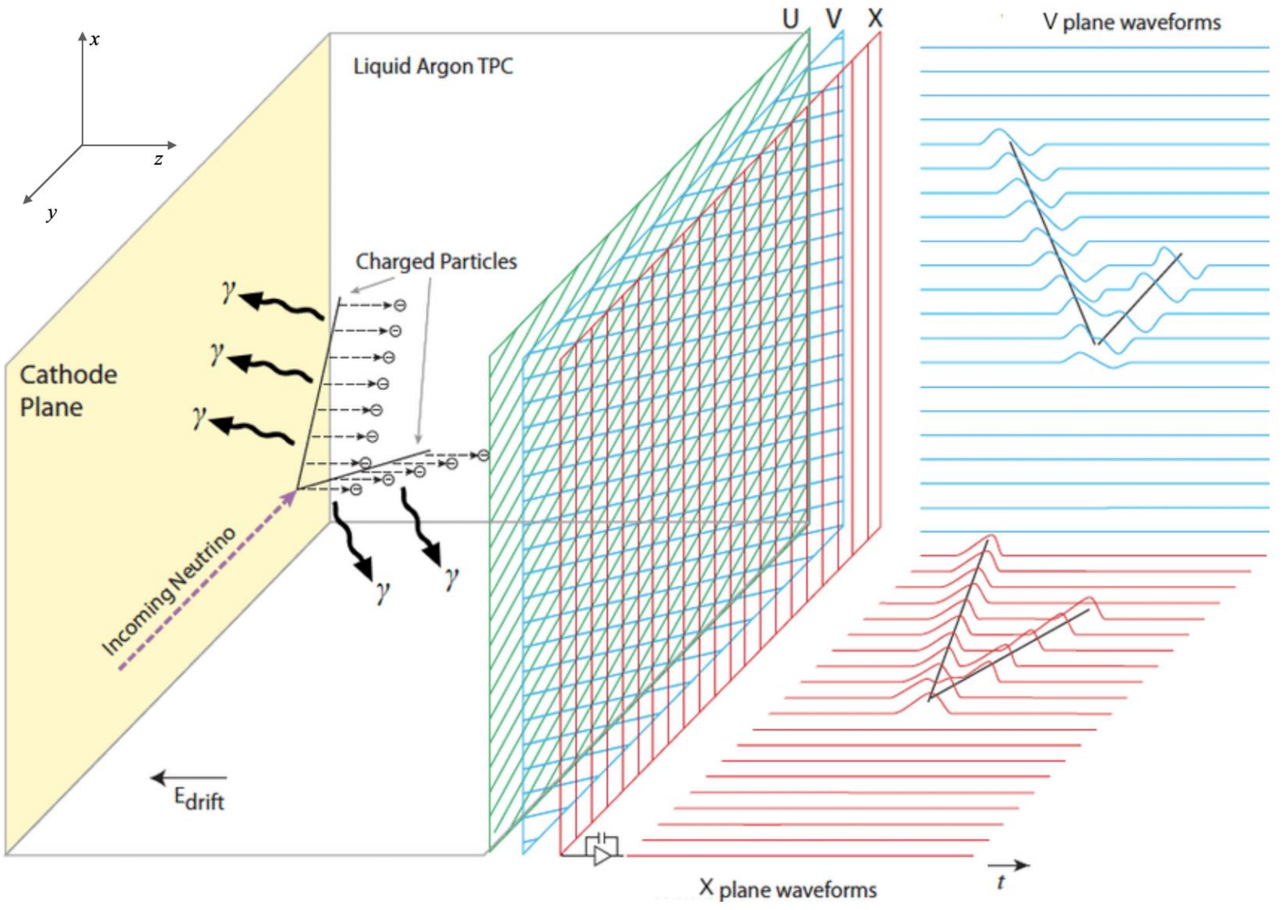
is not the *true* neutrino
t it is **reconstructed**

This is what it would happen if it was the **true energy**!

Detection principle

+ Neutrinos interact with the nuclei of the LAr producing other particles
+ The neutrino properties (energy, flavor) can be reconstructed from the final state particles of the interaction via ionization in LAr
+ The knowledge of the neutrino-nucleus cross sections is crucial!

LAr TPC: very good energy and space resolution
- charged particles at ionization minimum deposit ~10k electrons/mm of path
- space resolution ~1.5 mm

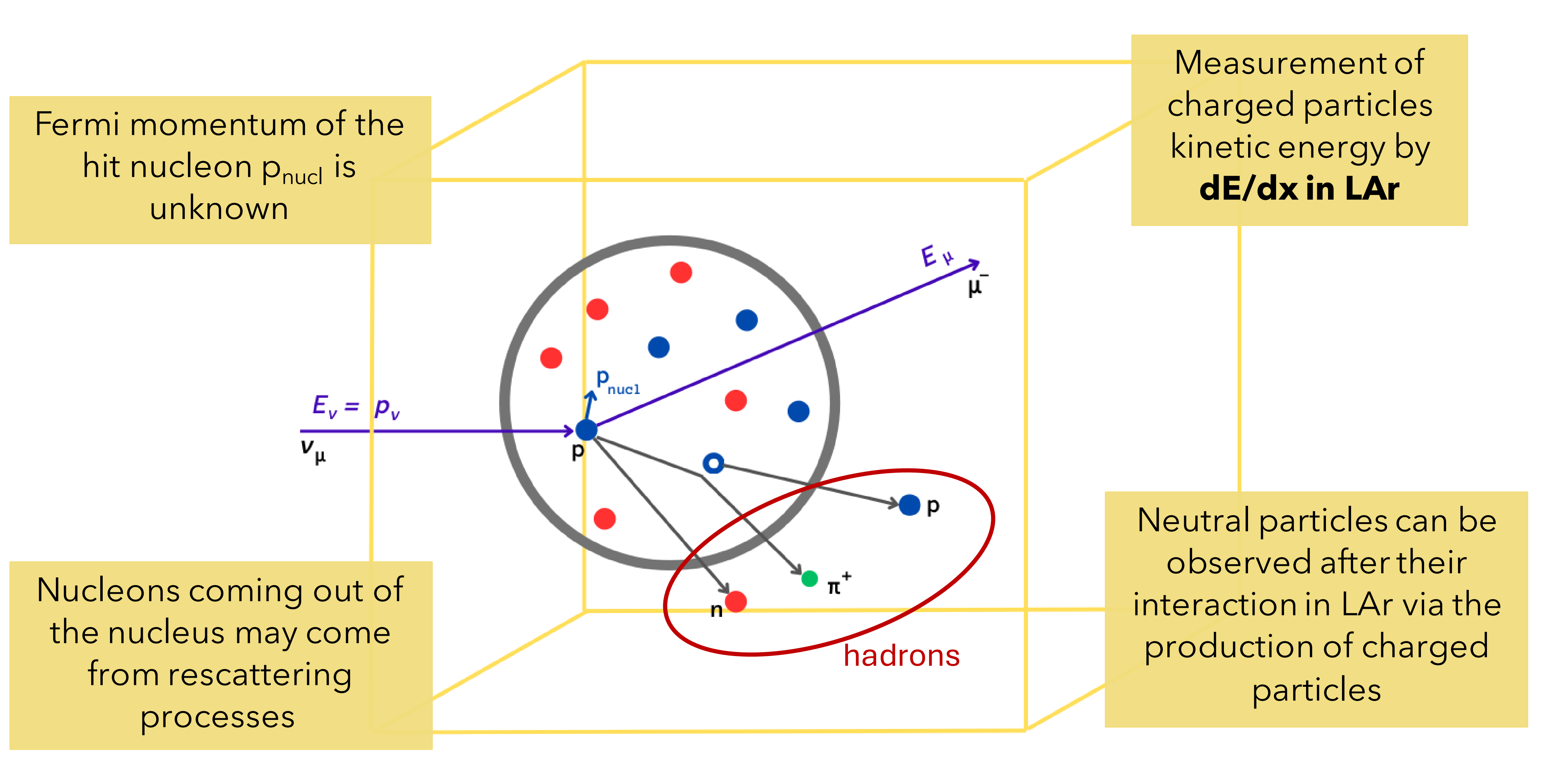


Questions addressed in my thesis work

DUNE is a wide band beam experiment with a detector with very good energy resolution and the potentiality to extract a large amount of information on the oscillation pattern from the energy spectrum of detected neutrinos.

1. How to measure the neutrino energy from final state particles?
2. Which is the ultimate neutrino energy resolution limited by the physics of neutrino interactions and how is it affected by nuclear effects?
3. How does the neutrino energy resolution change as a function of energy and the different processes involved and which is the associated model dependency?
4. How the interaction processes and nuclear effects affect the populations of final state particles and which is the impact on the neutrino energy resolution and on the detector measurements ? Which are the associated uncertainties ? What is the best use of the detector in measuring final state particles at different energies ?
5. Is there a class of events/energy region where we can maximize the neutrino energy resolution and the CP sensitivity?

Neutrino interaction with a nucleon in the Ar nucleus



Neutrino energy reconstruction methods

1. Total energy: $E_\nu = E_{lepton} + sum(E_{hadrons})$ → Bias due to presence of nucleons masses from nuclear rescattering not created by the neutrino energy
2. Attributing charged pion mass to the hadrons : → To reduce the bias due to nuclear rescattering
3. Real momenta vectors: $p_\nu \sim E_\nu = |sum(P_i)|$ → Possible in magnetic spectrometer Biased by the Fermi momentum
4. Like (3.) but assuming charged pion mass for hadrons $E_\nu = sum(P_i)$ → Experimental version of (3) for a detector without a magnetic field
5. Kinetic energies: $E_\nu = E_{lepton} + sum(E_k)$ → where E_k are the kinetic energies of the hadronic tracks (neglect hadron masses)

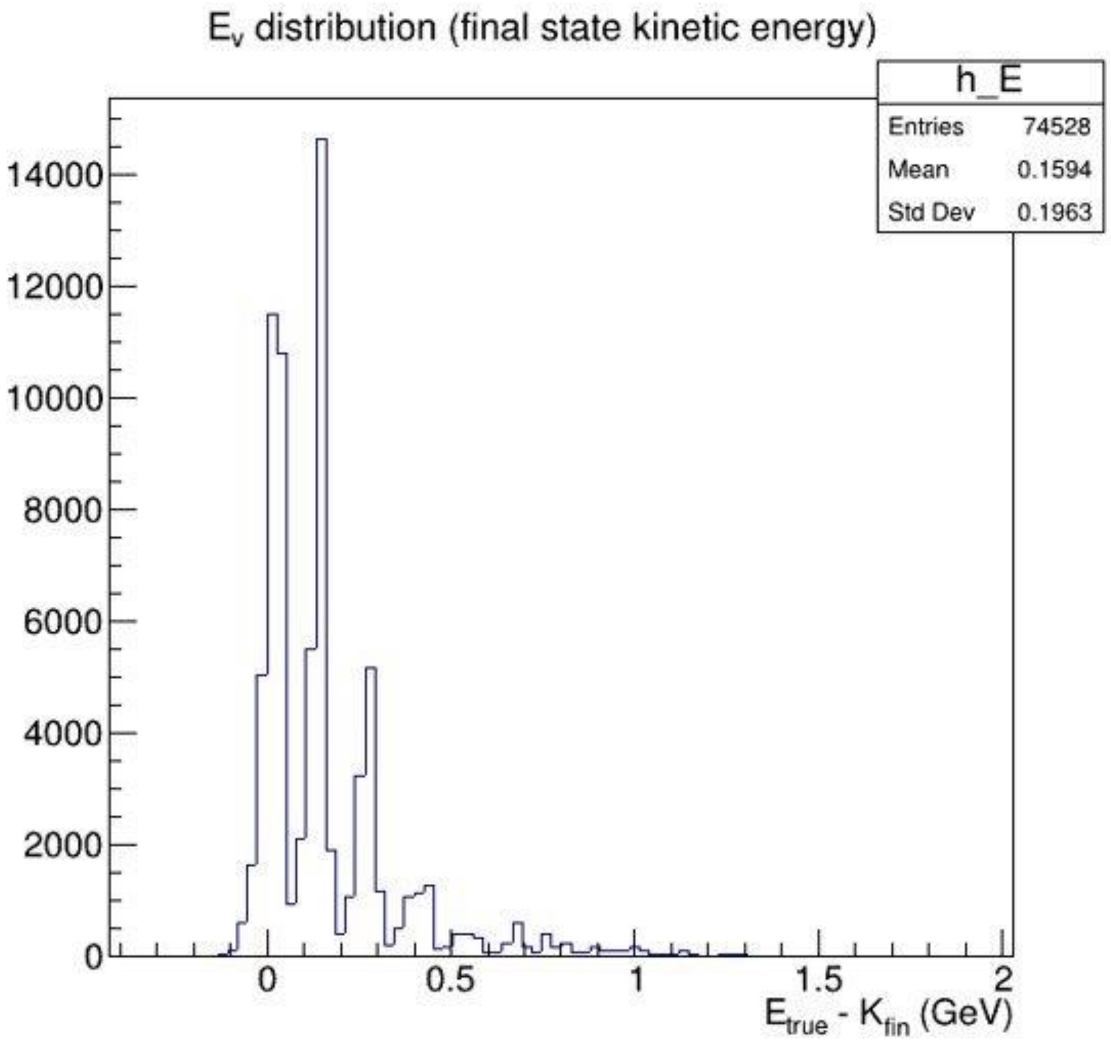
Energy resolutions

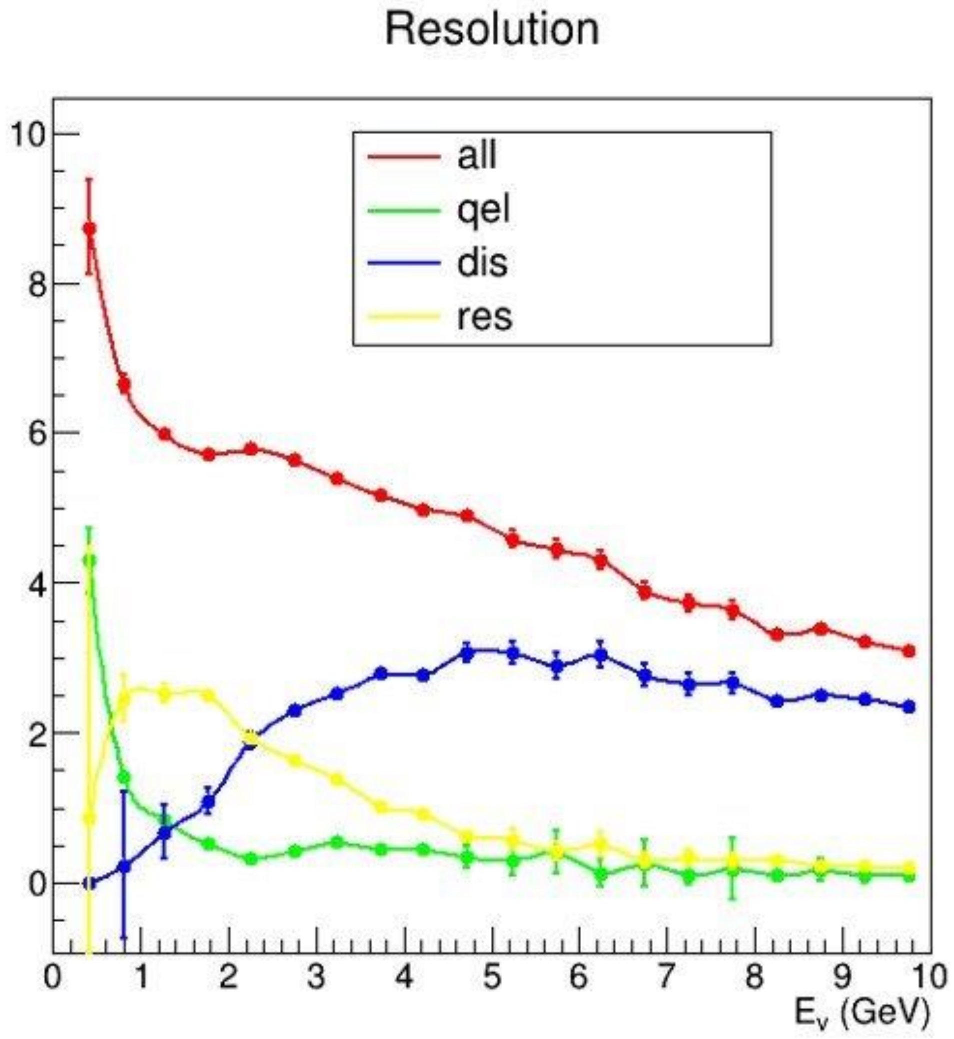
	GENIE		GiBUU	
Method	Resolution (%)	Bias(%)	Resolution(%)	Bias(%)
1: total energy	>87	<-103	>110.5	-144
2: pion masses	36.2	-20	36.5	-35
3: total momentum	12.6	-0.05	32.1	-8
4: total momentum (no B field)	19.2	14	27.2	18
5: neglect hadron masses	**5.5**	4	**6.2**	5

Resolution = $(E_{true} - E_{reco})/E_{true}$

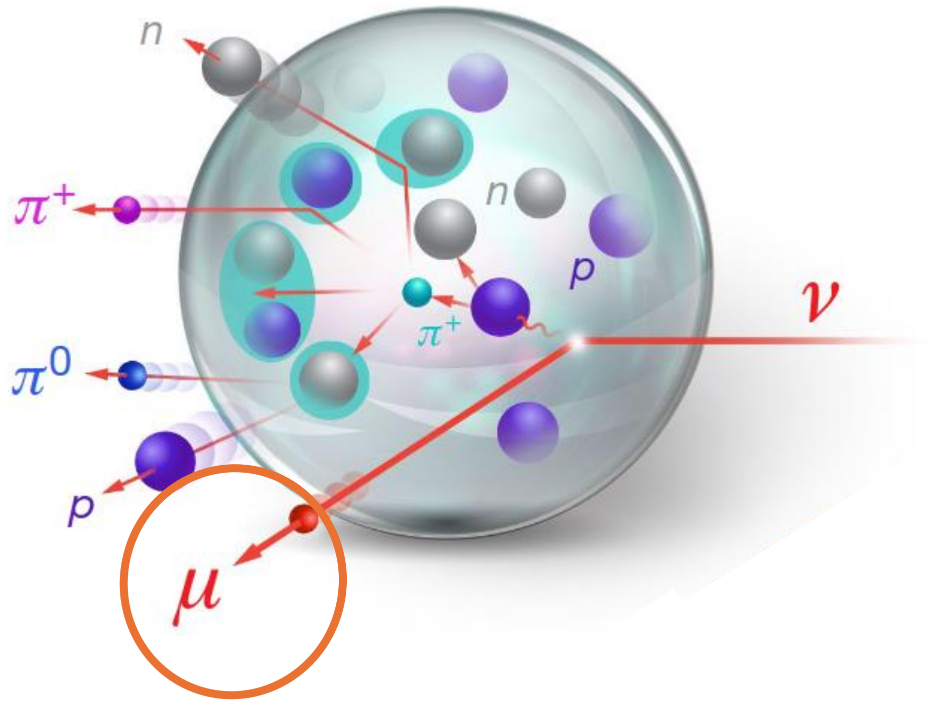
At the best the resolution is intrisically limited at a ~5-6% level by the physics of neutrino interactions

Energy resolutions





Neutrino interactions final state



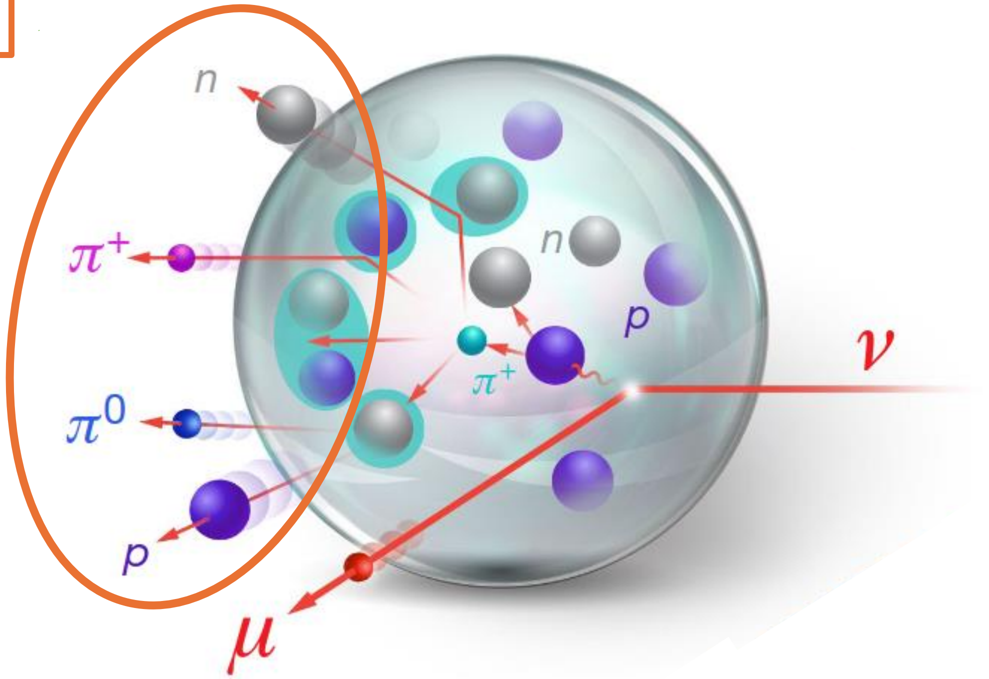
Lepton of the corresponding neutrino flavour

Neutrino interactions final state

Hadronic intranuclear cascade

Extraction of neutrons and protons already present in the nucleus

- Nuclear rescattering
- Elastic scattering
- Absorption
- Charge exchange



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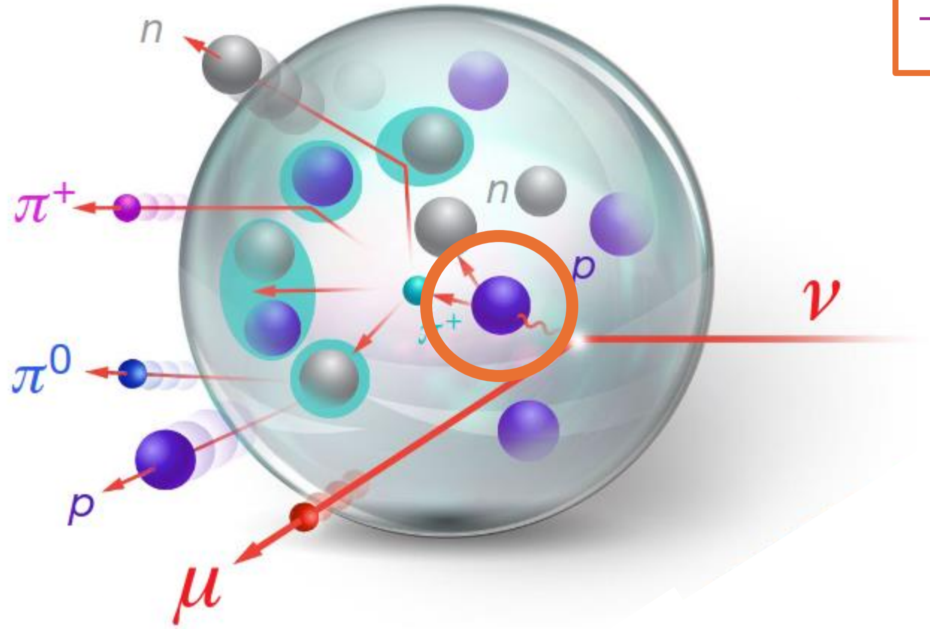
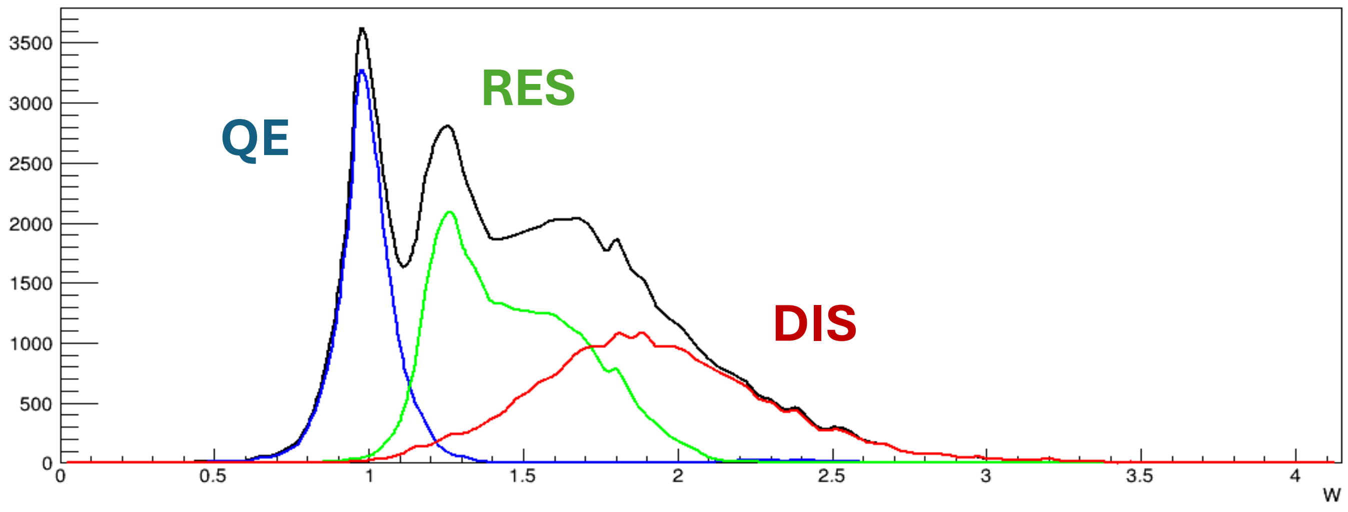


- Fermi momentum of struck nucleon
- Binding energy

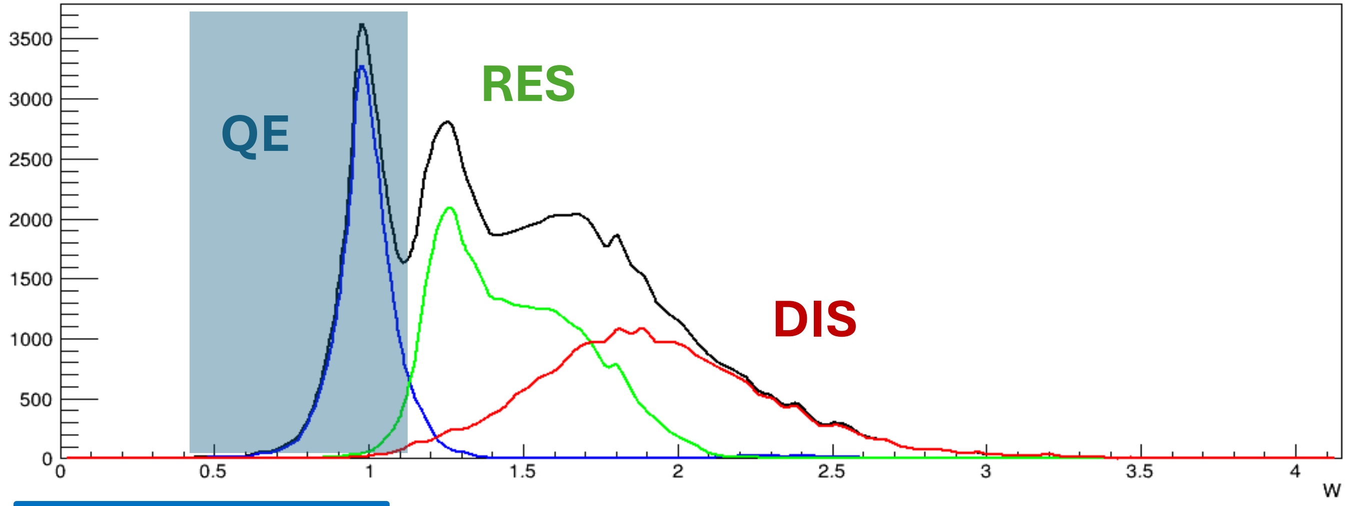
Lepton of the corresponding neutrino flavour

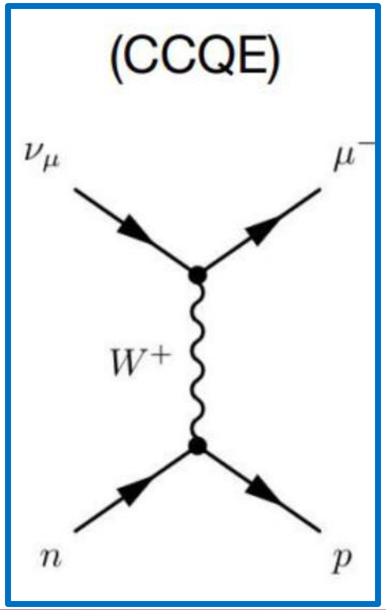
Reaction mechanisms



Different reaction mechanisms contribute!

Reaction mechanisms





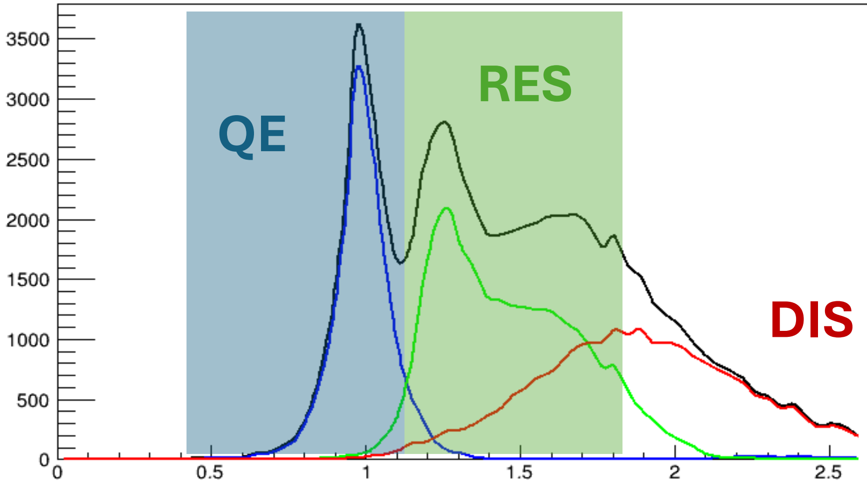
Different reaction mechanisms contribute!

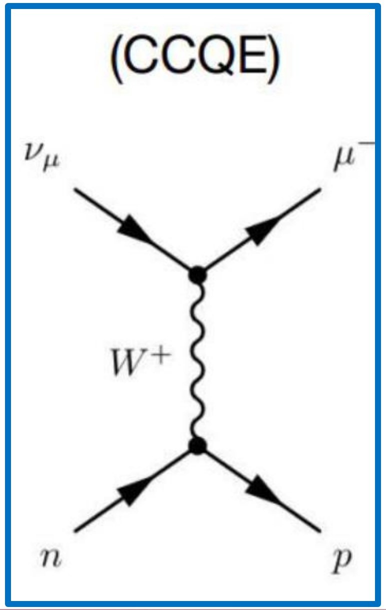
+ Quasielastic (QEL)

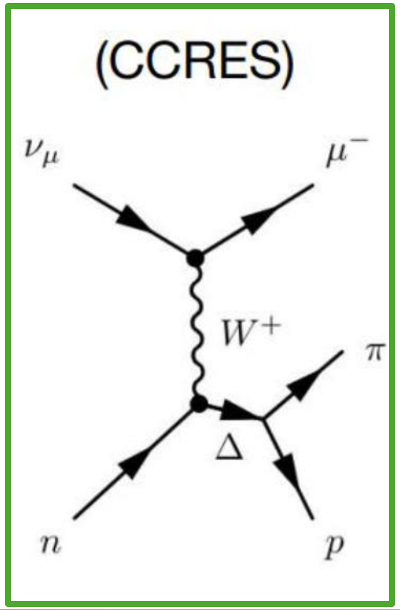
$$\nu_l + n \rightarrow l^- + p$$

$$\bar{\nu}_l + p \rightarrow l^+ + n$$

Reaction mechanisms



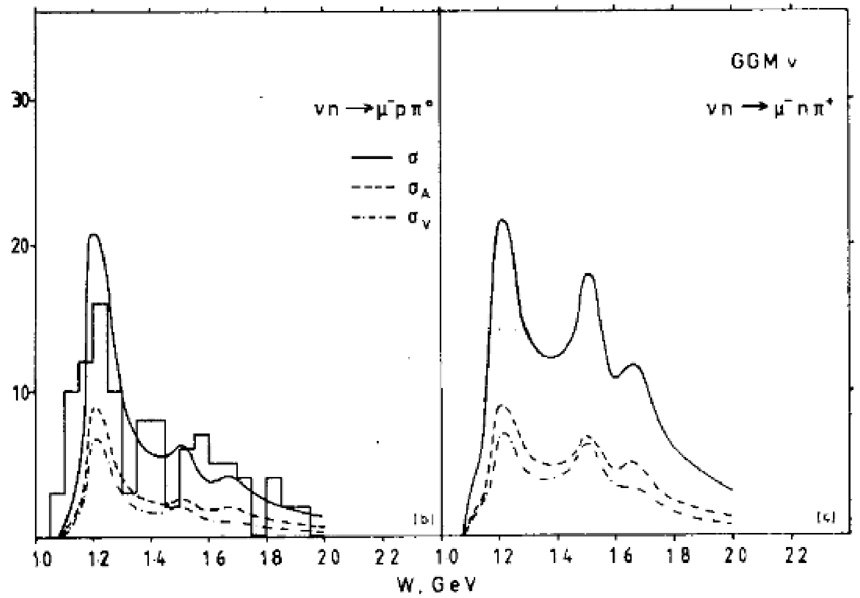




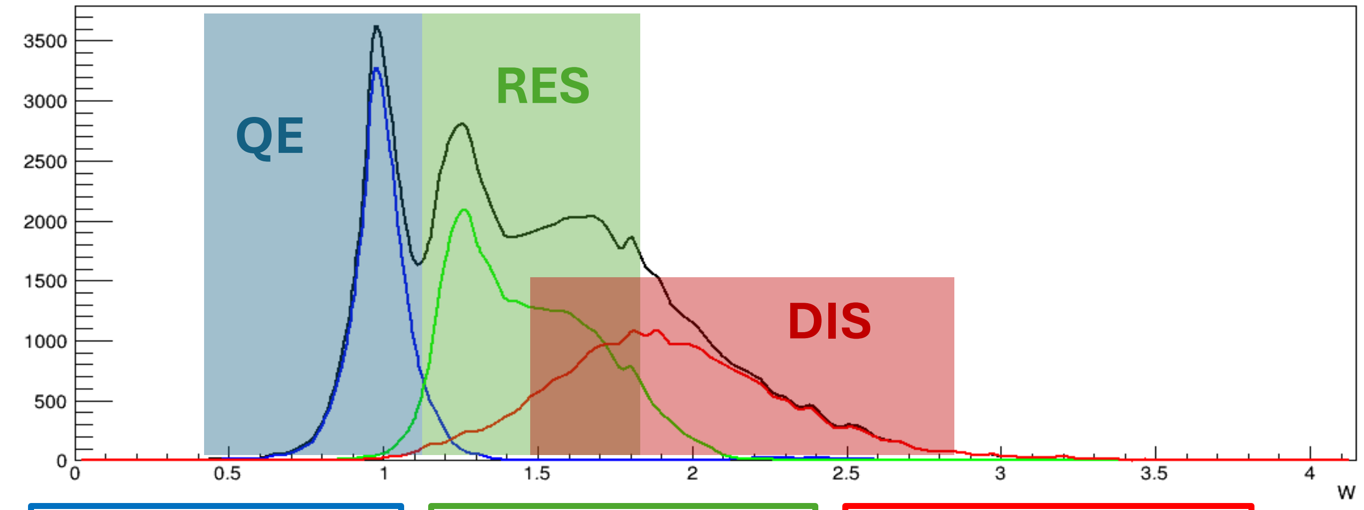
Resonance	M_R	Γ_0	χ_E
$P_{33}(1232)$	1232	117	1
$P_{11}(1440)$	1430	350	0.65
$D_{13}(1520)$	1515	115	0.60
$S_{11}(1535)$	1535	150	0.45
$P_{33}(1600)$	1600	320	0.18
$S_{31}(1620)$	1630	140	0.25
$S_{11}(1650)$	1655	140	0.70
$D_{15}(1675)$	1675	150	0.40
$F_{15}(1680)$	1685	130	0.67
$D_{13}(1700)$	1700	150	0.12
$D_{33}(1700)$	1700	300	0.15
$P_{11}(1710)$	1710	100	0.12
$P_{13}(1720)$	1720	250	0.11
$F_{35}(1905)$	1880	330	0.12
$P_{31}(1910)$	1890	280	0.22
$P_{33}(1920)$	1920	260	0.12
$F_{37}(1950)$	1930	285	0.40

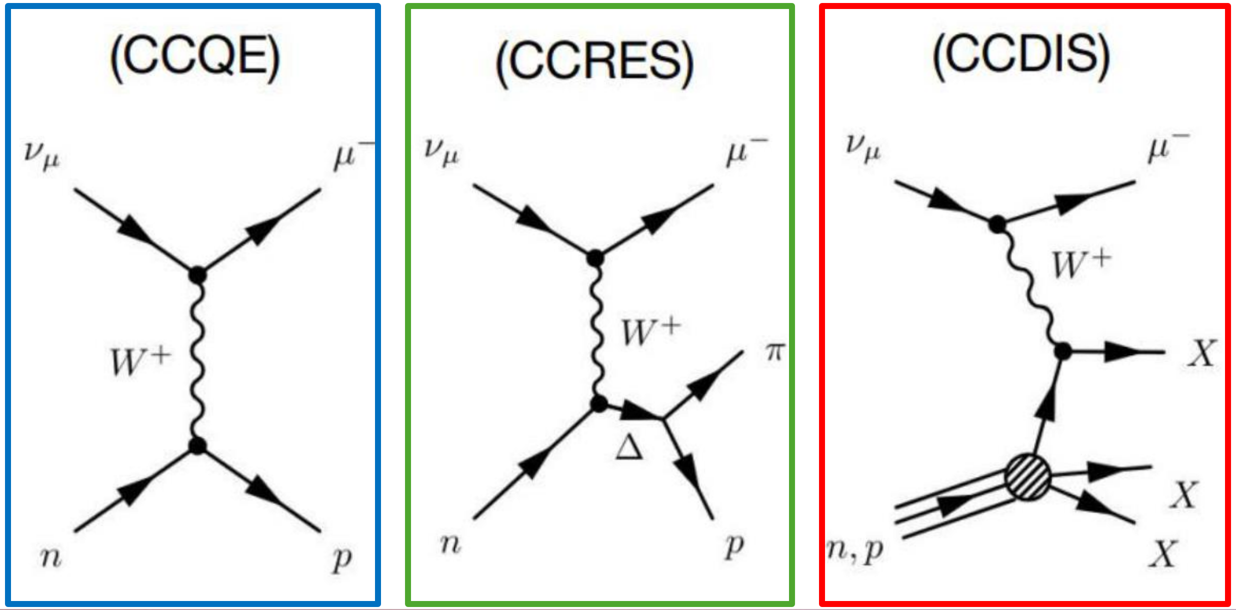
Different reaction mechanisms contribute!

- Quasielastic (QEL)
- Resonances (RES) → single pion production



Reaction mechanisms





Different reaction mechanisms contribute!

- Quasielastic (QEL)
- Resonances (RES) → single pion production
- Deep Inelastic Scattering (DIS)

↓

Neutrino probes the nucleon structure interacting with quarks, multi-particles hadronic final state

Event generators

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

GENIE

GENIE (Generates Events for Neutrino Interaction Experiments) is a neutrino event generator largely used by many neutrino experiments and it is **DUNE official Montecarlo**

GiBUU

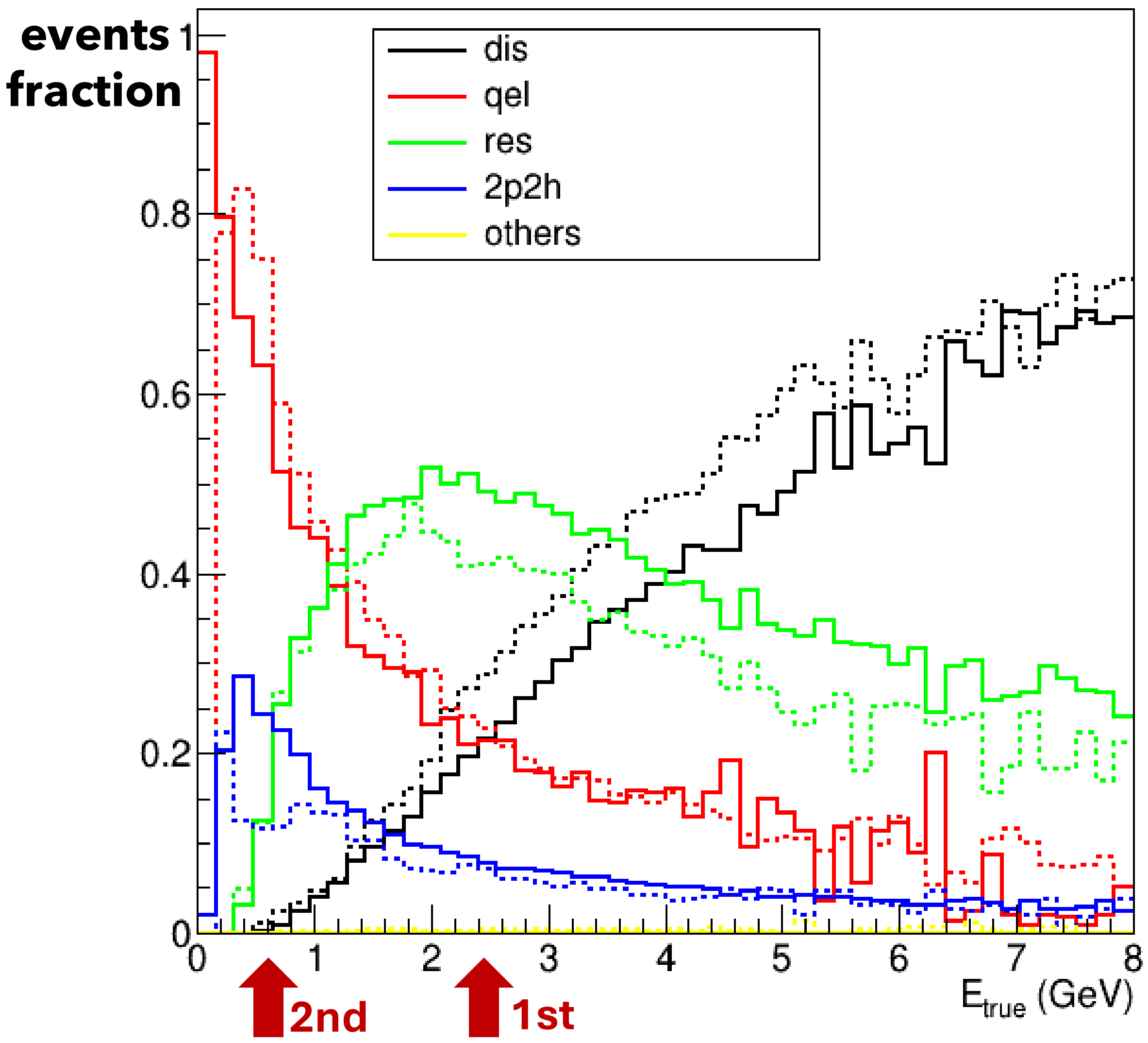
GIBUU

GiBUU (Giessen Boltzmann-Uehling-Uhlenbeck) is a transport model applied to nuclear interactions. Its aim is to provide a unified theory and transport framework for a wide range of reactions using the same physics input and code This code has a **more precise and detailed description of nuclear effects**.

Neutrinos different interaction processes

- The continuous line correspond to GiBUU, the dashed one to GENIE simulation
- At low energy (2nd oscillation maximum) the spectrum is dominated by QEL processes
- At the 1st oscillation maximum RES and DIS contributions are relevant

	GENIE		GiBUU	
Process	%	E_{mean}(GeV)	%	E_{mean}(GeV)
		3.01		2.92
QE	22.07	2.50	21.53	2.43
DIS	34.09	3.57	26.43	4.22
RES	37.24	2.86	43.85	2.85
2p2h	6.26	2.58	8.19	2.41
Others	0.32	3.14	0	0



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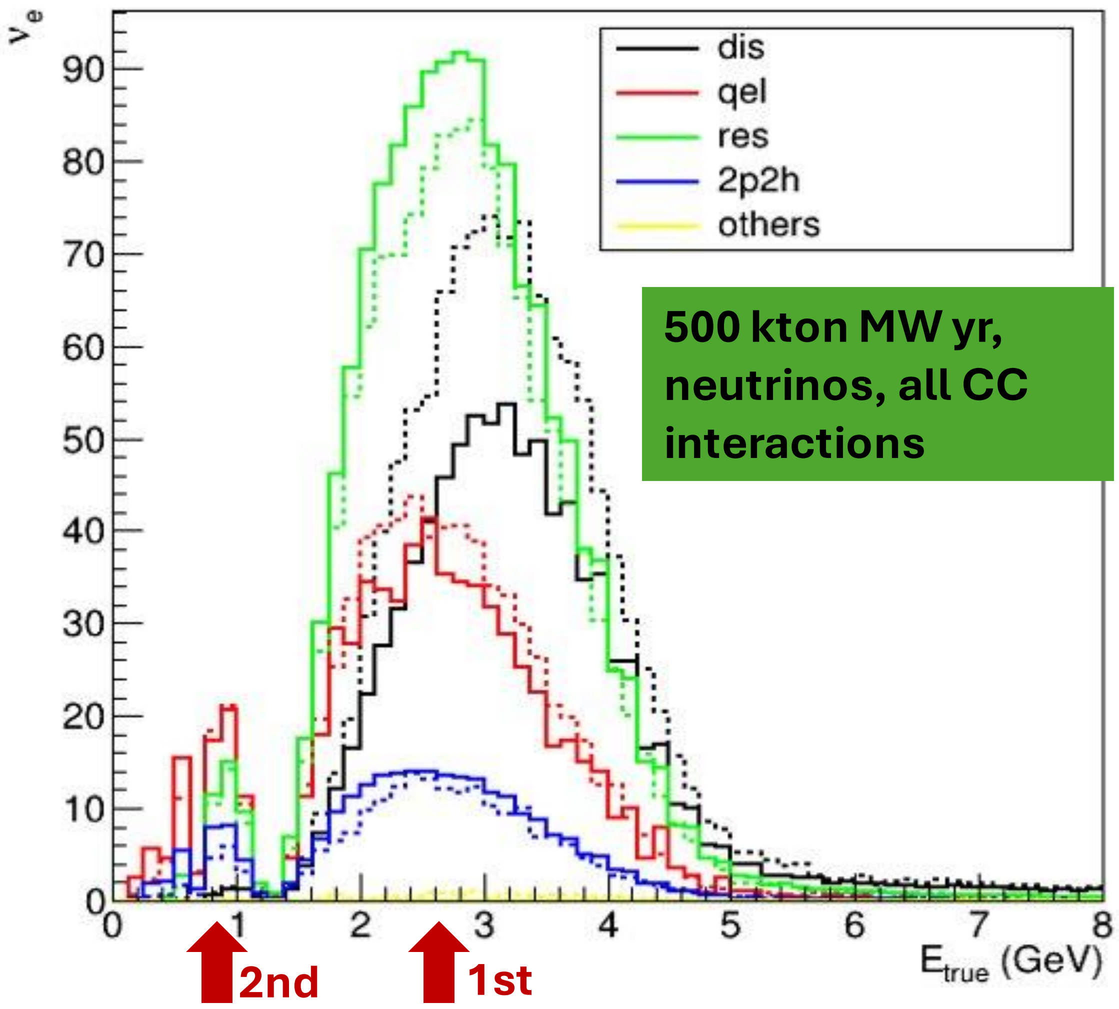
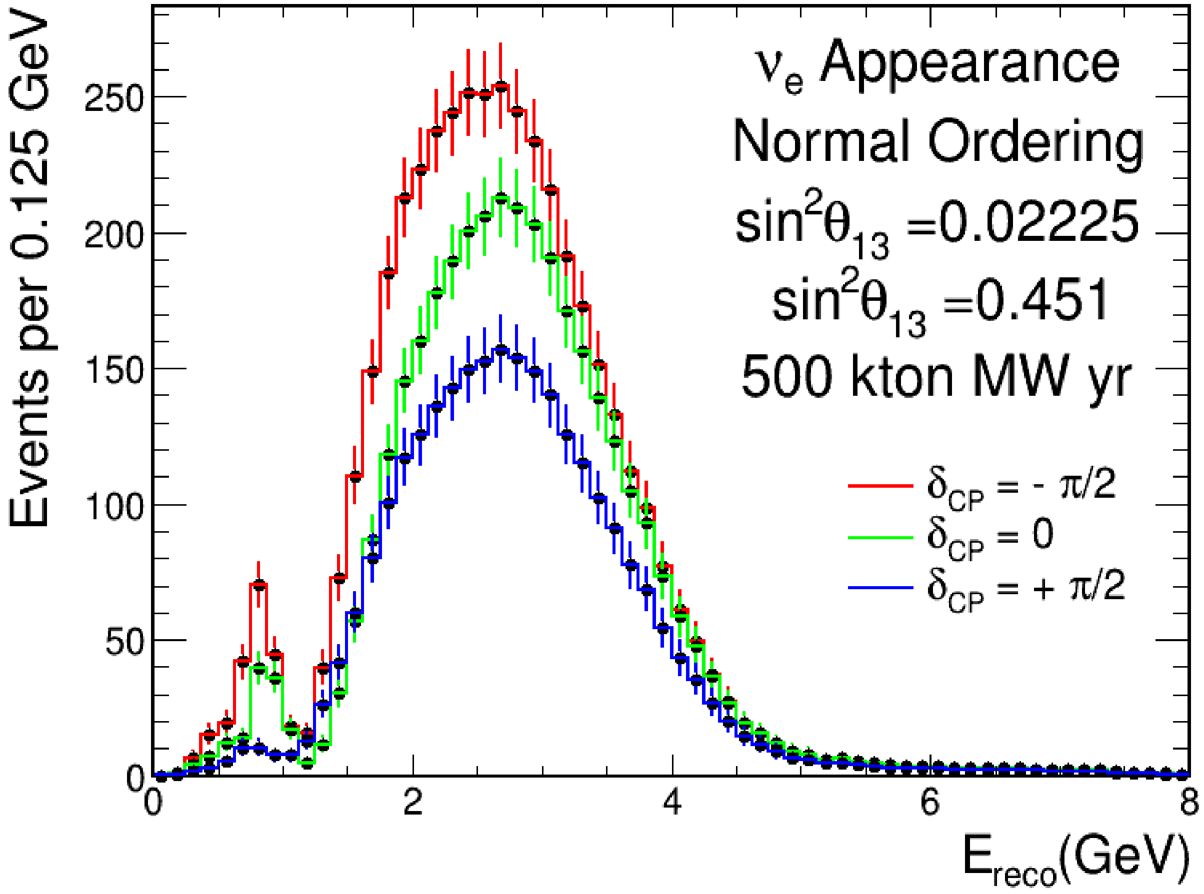
Spectrum of interacted neutrinos

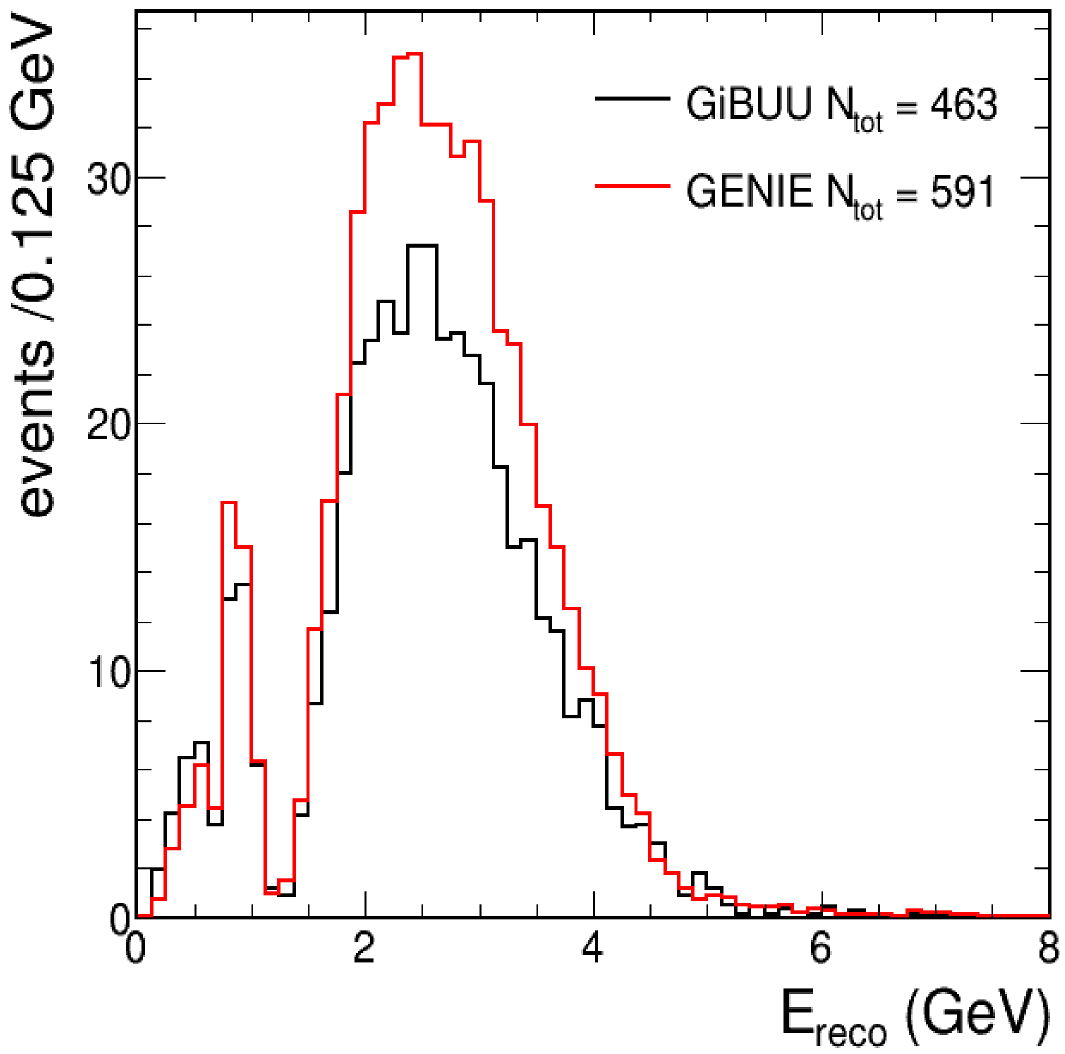


Best energy reconstruction method

- 500 kton/MW/yr in neutrino mode
- All the CC events are included
- Energy is reconstructed with the kinetic energy method
- This plot does not yet include the detector resolution however these don't change the result
- I expect to have between the 350 and 630 neutrino CC interactions per year



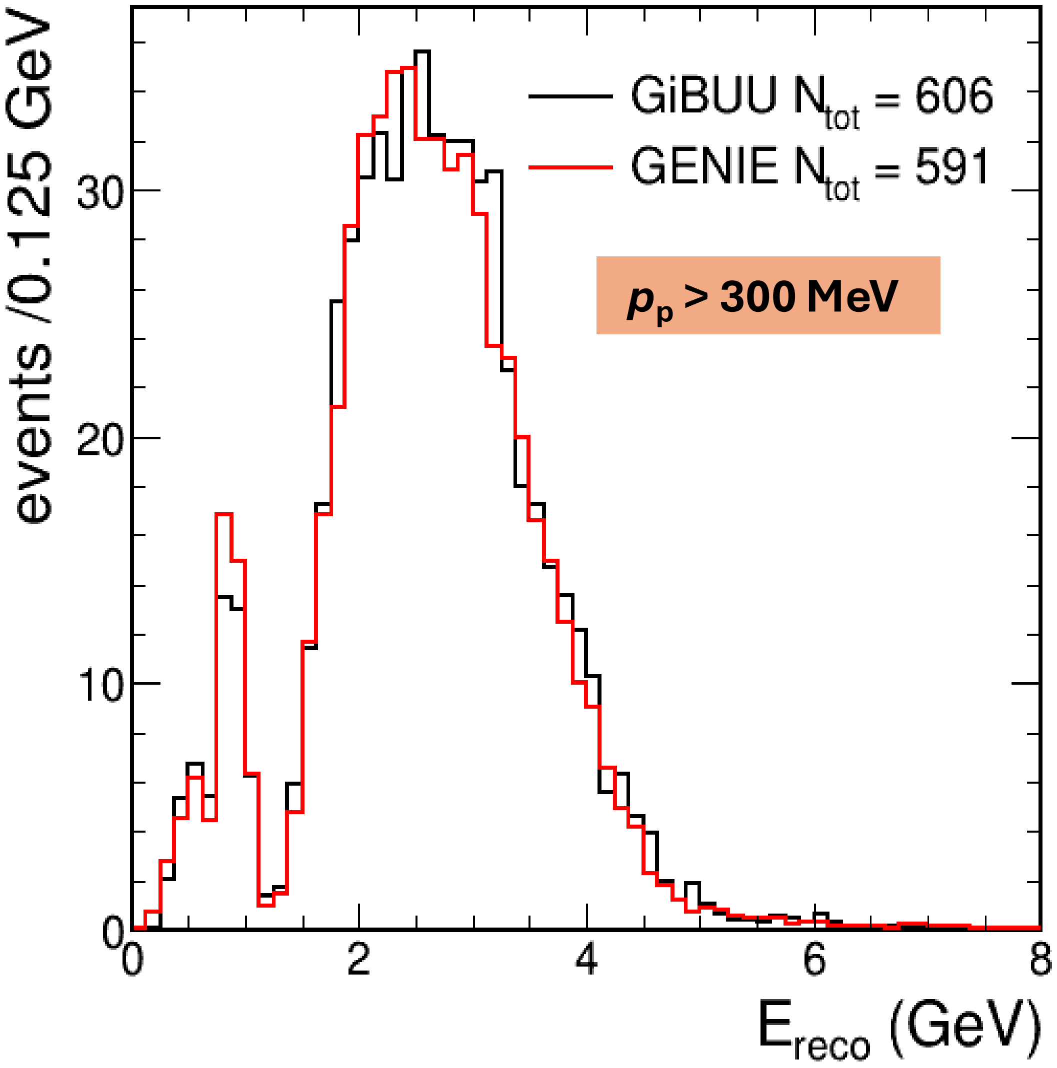
Restrict to 1p0π interactions: CCQE-like



- Among the many interaction topologies, we can do a selection
- Simpler interaction channel with 1p and 0π
- Can be more easily identified and reconstructed
- Lower statistic but the oscillation peak is well visible
- GiBUU and GENIE seem to disagree when doing an event cut based on the topology

???

Restrict to 1p0π interactions: CCQE-like



- If I neglect all the low energy protons with low momentum (< 300 MeV/c, Ek <47 MeV) the two models agree
- Low energy protons are hard to detect and more model dependent, neglecting them stabilizes the results

The second oscillation maximum is still well visible

Minimized model dependency

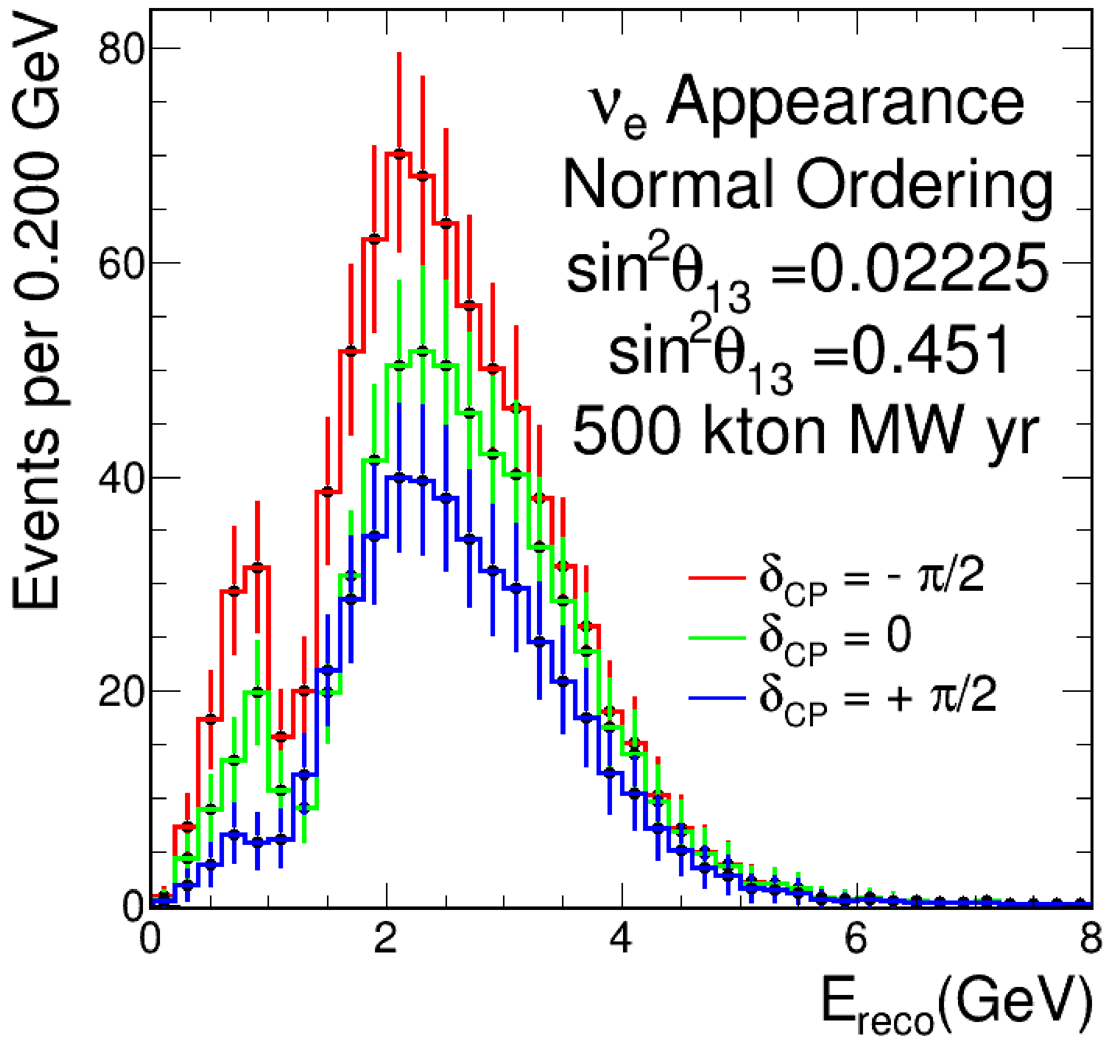
Restrict to 1p0π interactions: CCQE-like

Enhanced sensitivity at the second maximum

Statistical impact of restriction of 1p0π sample (500 kton/MW/yr)

δ_{CP}	N_{tot}	$N_{1p0\pi}$
-π/2	4398	794
0	3494	591
+π/2	2651	446

Detector resolution included as a 10% effect



Conclusions and outlook

- Very good energy resolution of the detector must be handled properly with respect to neutrino interaction physics
- Studying the best energy reconstruction method and assessing the physics systematics is crucial to extract the largest amount of information from the detector
- Strong impact on the CP violation sensitivity
- Assessment of model dependency systematics
- Ways to check the models from specific observables in the data (backward going protons)

- Next steps:
  - complete assessment of differences bias neutrinos/antineutrino interactions
  - implement the detector energy flow in a more sophisticated way
  - conclude assessment on CP violation sensitivity and systematics

Thanks for your attention!

Oscillation probability

Probability of muon neutrino going into electronic neutrino in a three flavour scenario:

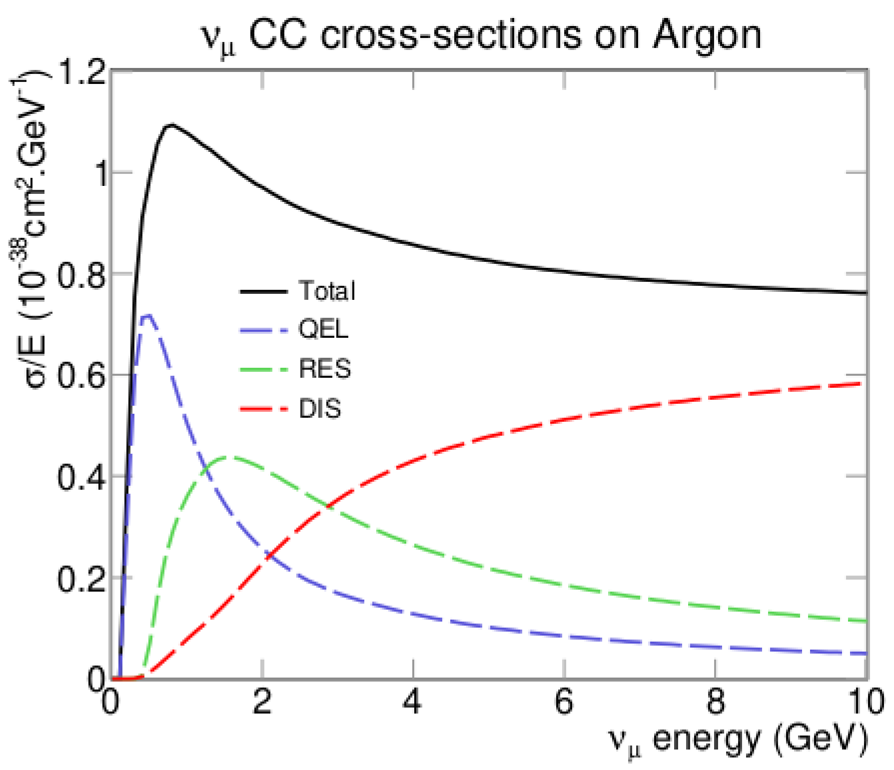
$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 +$$

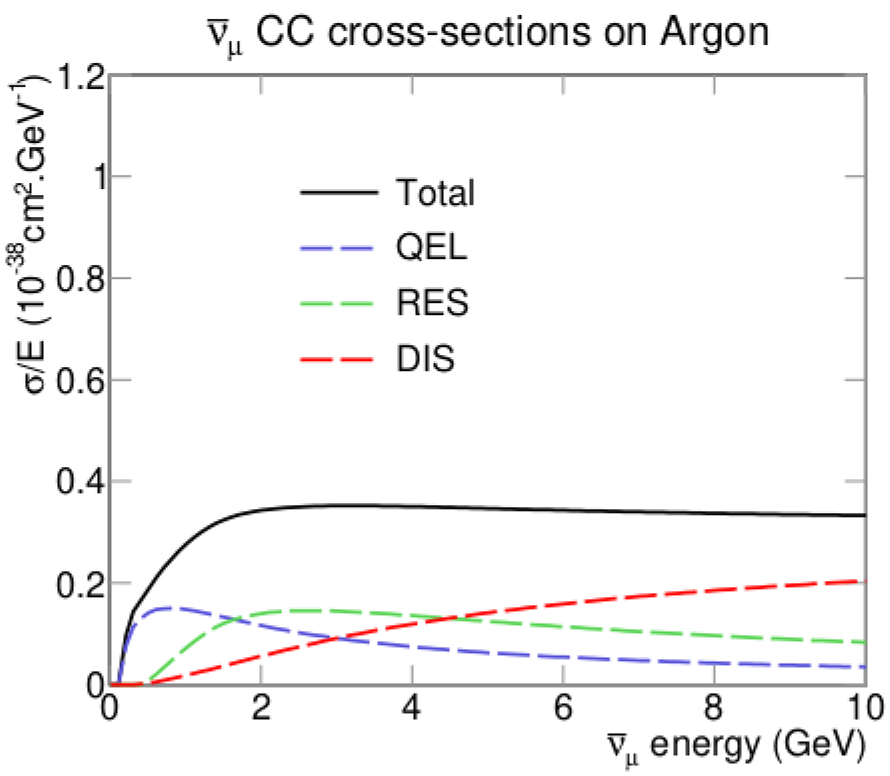
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31}+\delta_{CP})+$$

$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

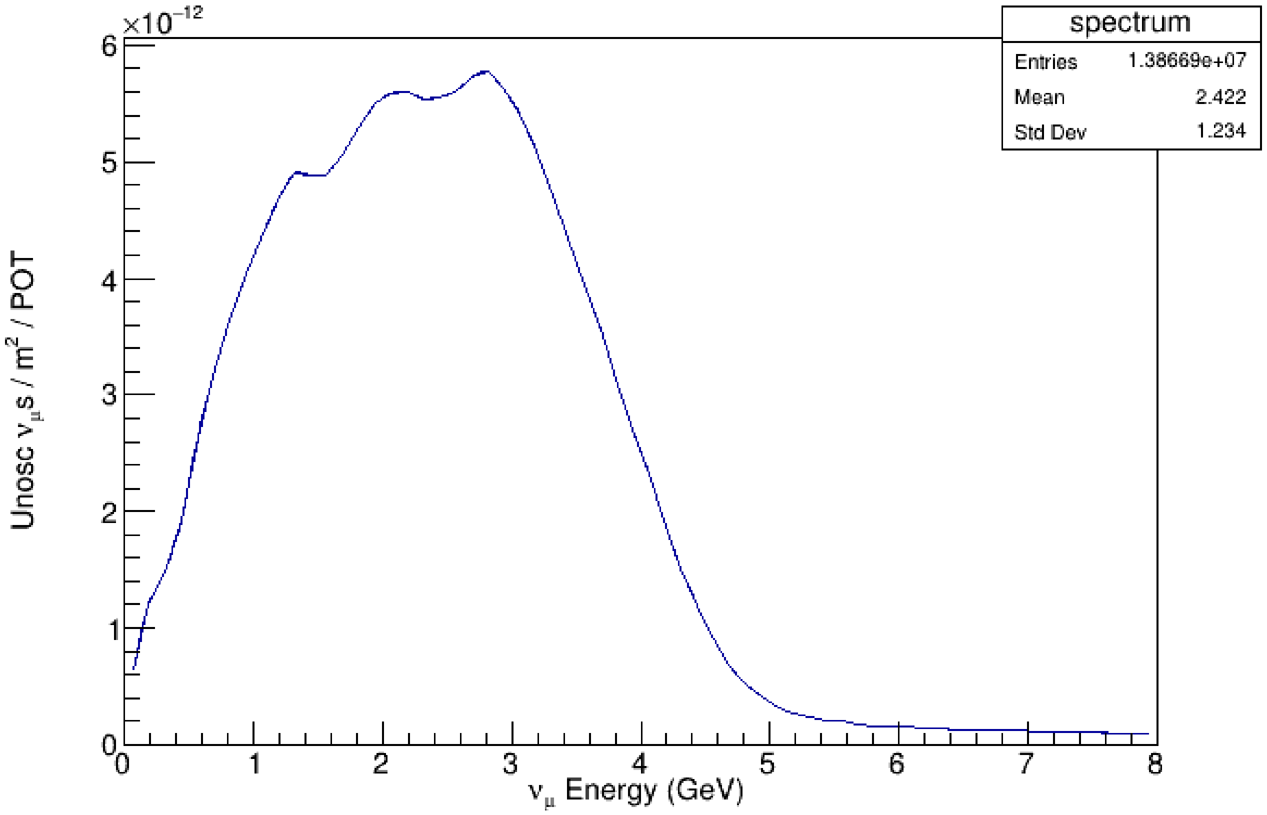
Where: $\Delta_{ij} = \Delta m_{ij}^2 L/4E_\nu$ $\quad a = G_F N_e/\sqrt{2}$

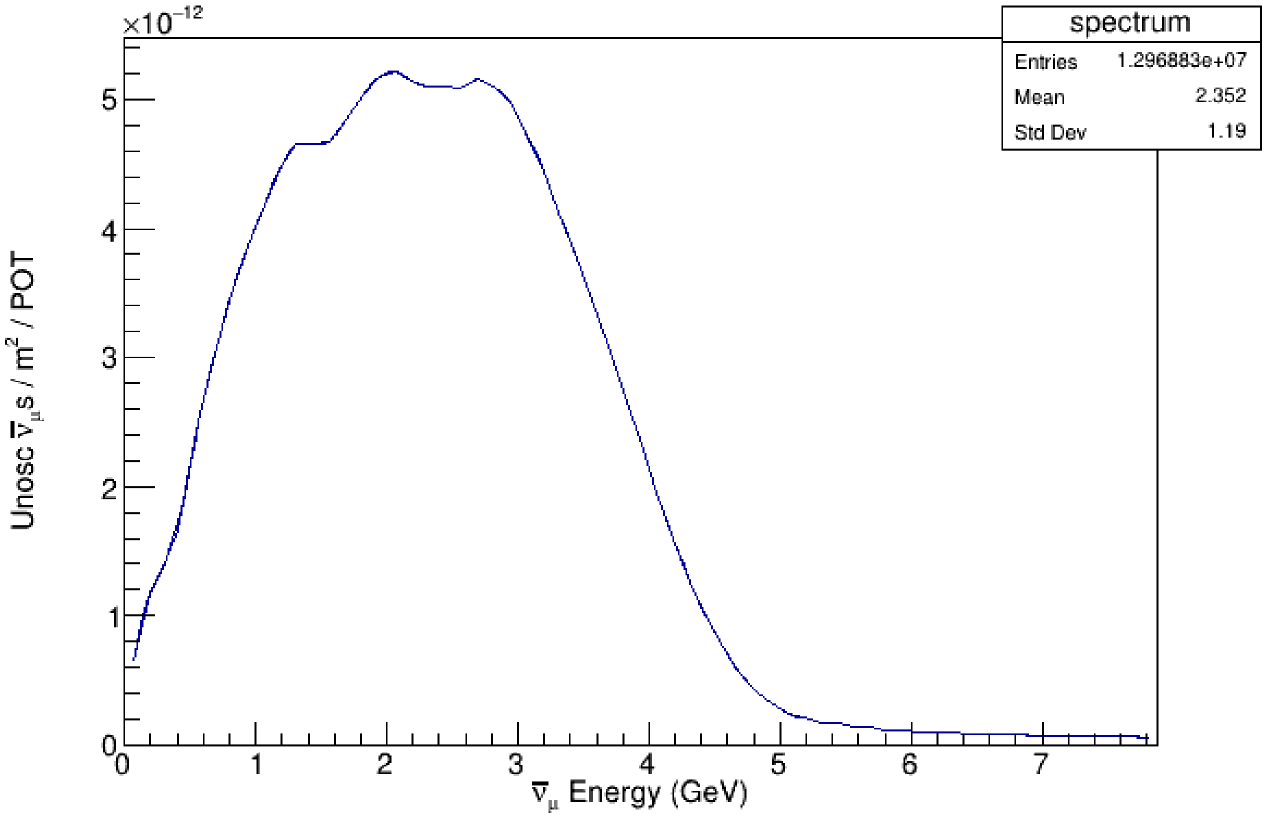
Cross sections





Incoming flux at FD

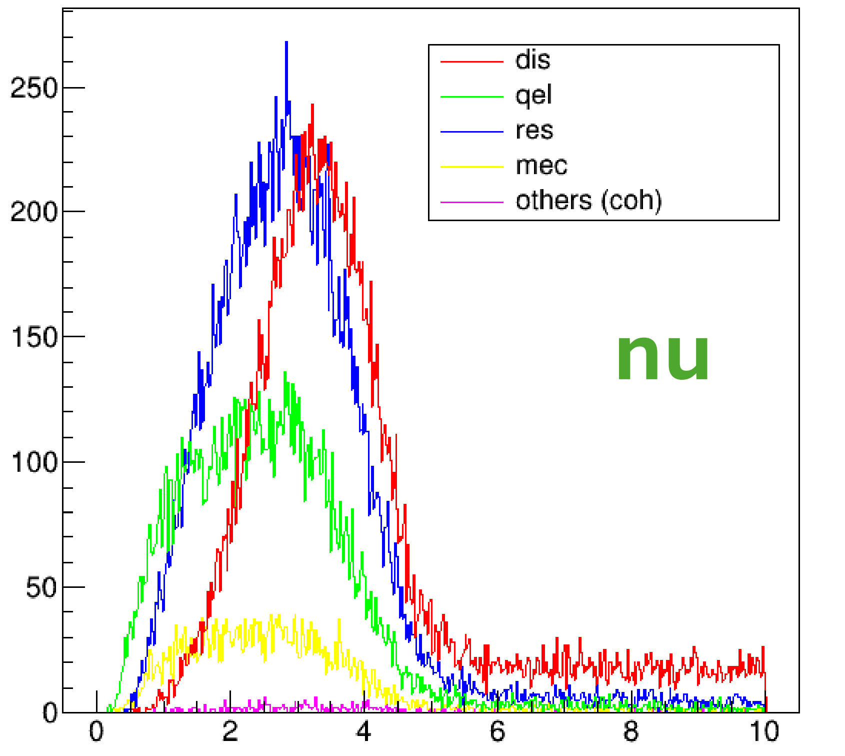


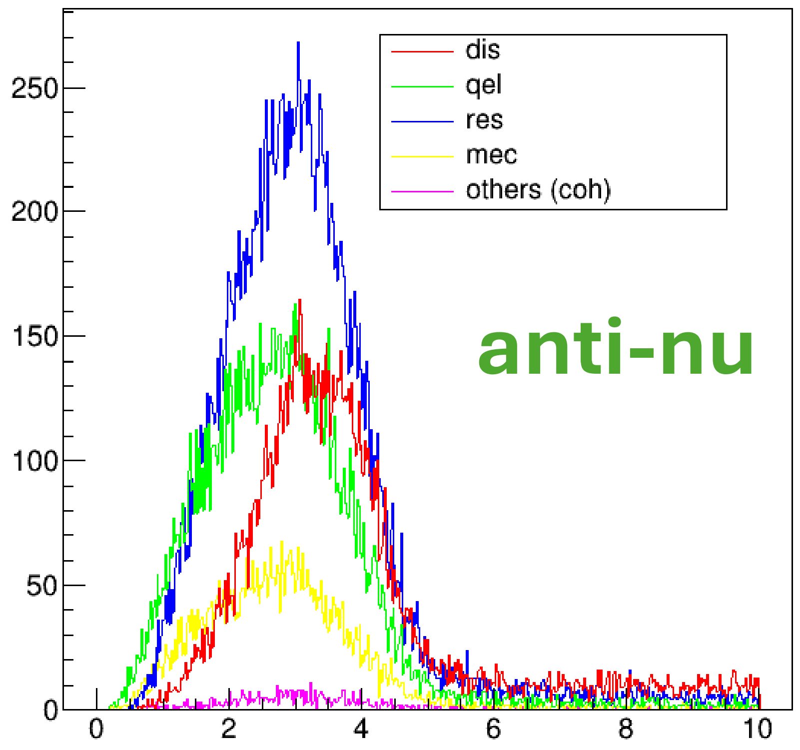


Neutrinos/antineutrinos interactions

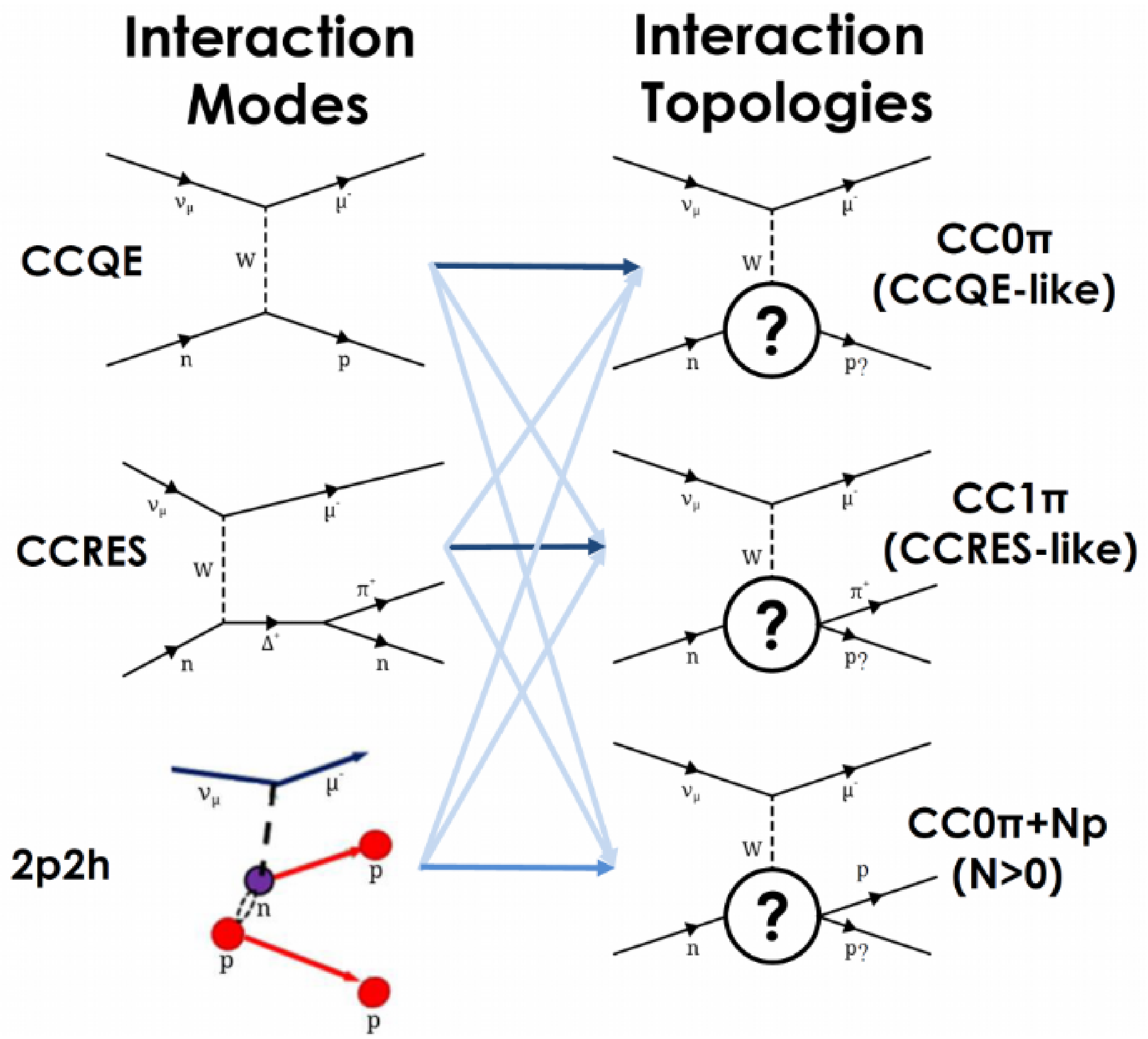
	Entries	Perc (%)	Mean (GeV)	RMS (GeV)
All CC	74474		3.19	1.61
QEL	16587	22.27	2.58	1.35
DIS	25761	34.59	3.91	1.80
RES	27389	36.78	2.97	1.33
Others	47085	6.36	2.68	1.38

	Entries	Perc (%)	Mean (GeV)	RMS (GeV)
All CC	68813		3.18	1.48
QEL	18102	26.31	2.80	1.27
DIS	15964	23.20	3.84	1.74
RES	27407	39.82	3.14	1.34
Others	7340	10.67	2.83	1.26





What do we actually measure?



Many modes contribute to any measurement

Integrated over broad ω region

Difficult to tune theory models!

Graphic from S. Dolan