Charge readout analysis in liquid argon Time Projection Chambers for neutrino and astro-particle physics

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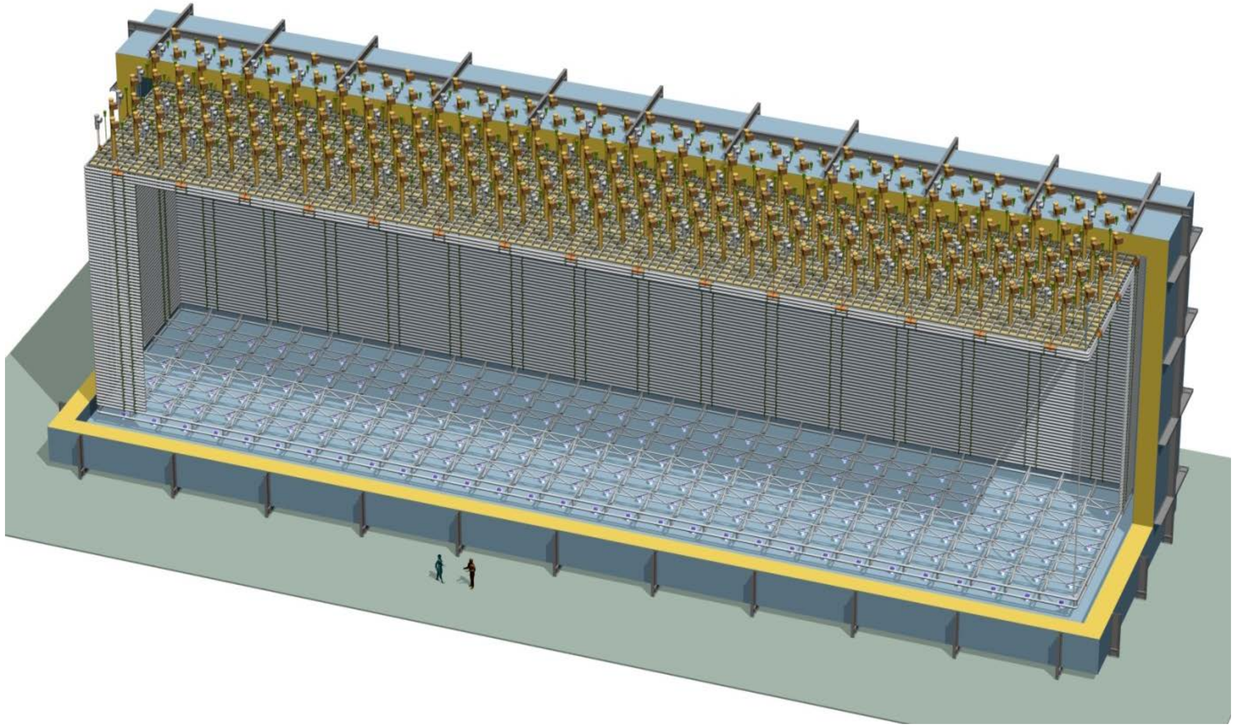


Outline

- CP violation measurement
- Liquid Argon Time Projection Chamber
- Charge reconstruction and its physics impact
- Conclusions

Standard 3 neutrinos framework

Three neutrino flavors mixing: favorite parametrization of U: in terms of 3 mixing angles θ_{12} θ_{23} θ_{13} and one Dirac-like CP phase δ:

$$|\nu_\alpha\rangle = U_{\alpha i}|\nu_i\rangle$$

α : e, μ, τ (flavor index)
i : 1, 2, 3 (mass index)
$U_{\alpha i}$: unitary mixing matrix

In the case of two flavors α and β the oscillation probability is

$$\mathcal{P}_{\alpha\beta}(L) = \sin^2(2\theta)\sin^2(1.267\Delta m^2 \frac{L}{E})$$

$$\Delta m^2 = m_2^2 - m_1^2$$

$$U \equiv U_{23}U_{13}U_{12} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric oscillations — Solar oscillations

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

where: $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$.

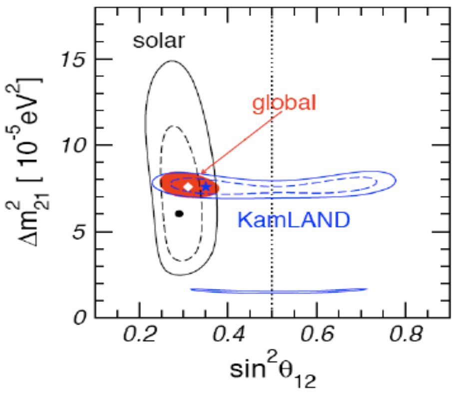
θ_{13}
δ**?**

Solar neutrinos

$$\Delta m_{21}^2 \sim 7.5 \cdot 10^{-5} eV^2$$
$$\sin^2\theta_{12} \sim 0.3$$

Solar neutrinos + Kamland
ν_e, anti-ν_e disappearance

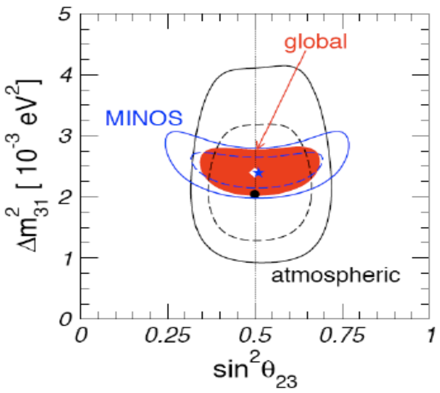
L/E ~ 15 km/GeV



Atmospheric neutrinos

$$|\Delta m_{31}^2| \sim 2.5 \cdot 10^{-3} eV^2$$
$$\sin^2\theta_{23} \sim 0.50$$

L/E ~ 500 km/GeV



Atm neutrinos + accelerators
ν_μ disappearance

How to measure CP-violation

Direct evidence for CP violation must be searched in sub-leading oscillation $\nu_\mu \rightarrow \nu_e$ at the Δm^2 of the atmospheric neutrinos ($\Delta m^2 \sim 10^{-3}$ eV^2)

Matter effect

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta)$$

Leading term

$$+\alpha\frac{8J_{CP}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

CP-terms

$$+\alpha\frac{8I_{CP}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

$$+\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)$$

Solar term

The same oscillation channel provides infos on:

- θ_{13}
- **Matter effects and mass hierarchy**
- **CP violation**

CPV

$$J_{CP} = 1/8 \sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$I_{CP} = 1/8 \cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31},\ \Delta = \Delta m^2_{31} L/4E$$

E_ν dependence

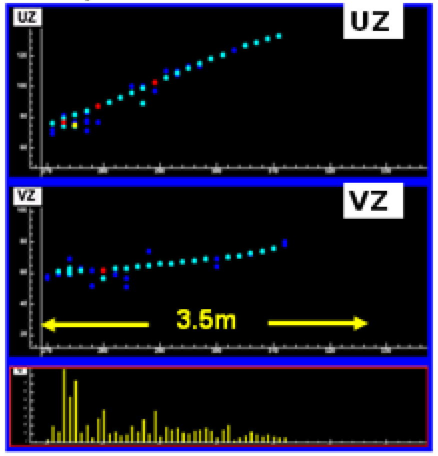
$$\hat{A} = 2VE/\Delta m^2_{31} \approx (E_\nu/GeV)/11 \text{ For Earth's crust.}$$

To study this channel it is crucial to use a detector capable of providing a very good measurement of electrons (electron identification, background rejection and energy resolution)

Typical neutrino interactions events

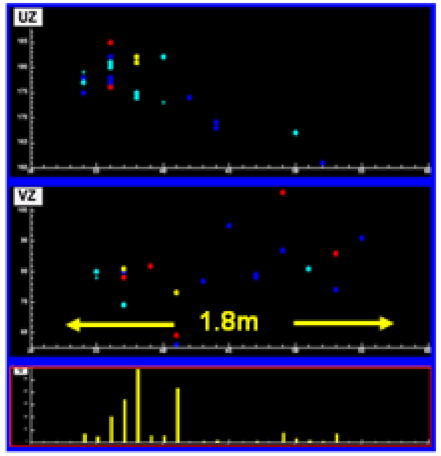
MINOS (sandwich of 2.54 cm magnetized steel and 1 cm scintillator plates)

ν_μ CC Event



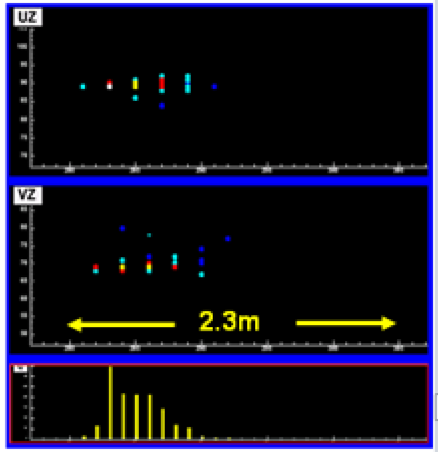
- Long muon track + hadronic activity at vertex

NC Event



- Short showering event, often diffuse

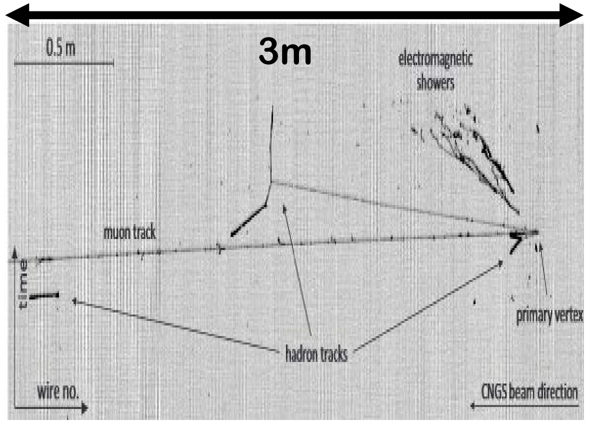
ν_e CC Event



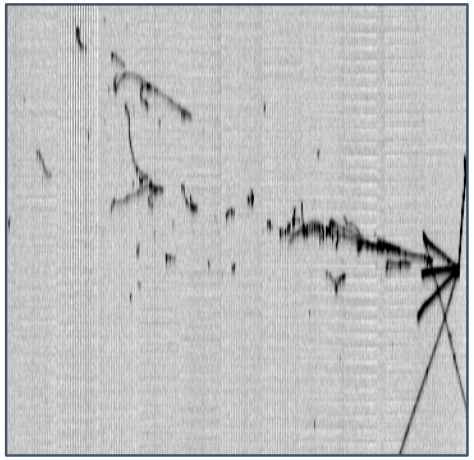
- Short event with typical EM shower profile

ICARUS LAr TPC neutrino interactions from CNGS beam

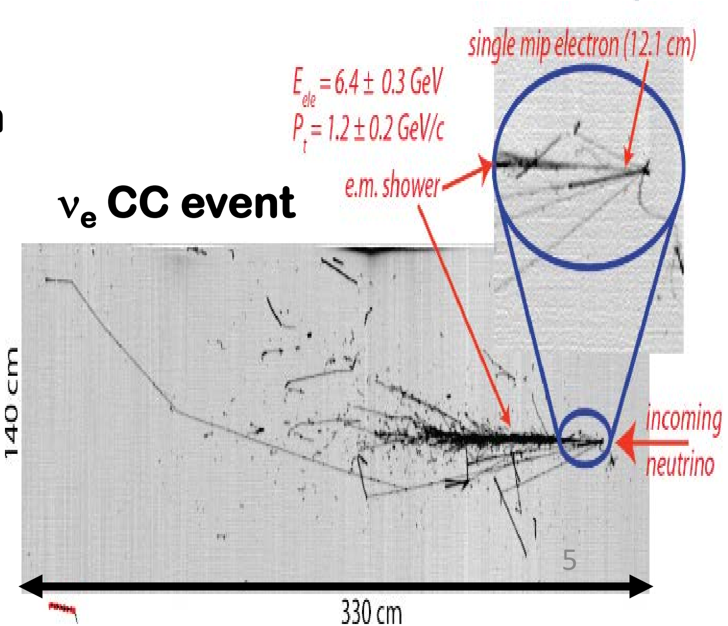
ν_μ **CC event with** π^0 **production**



ν_μ **NC event with** π^0 **production**

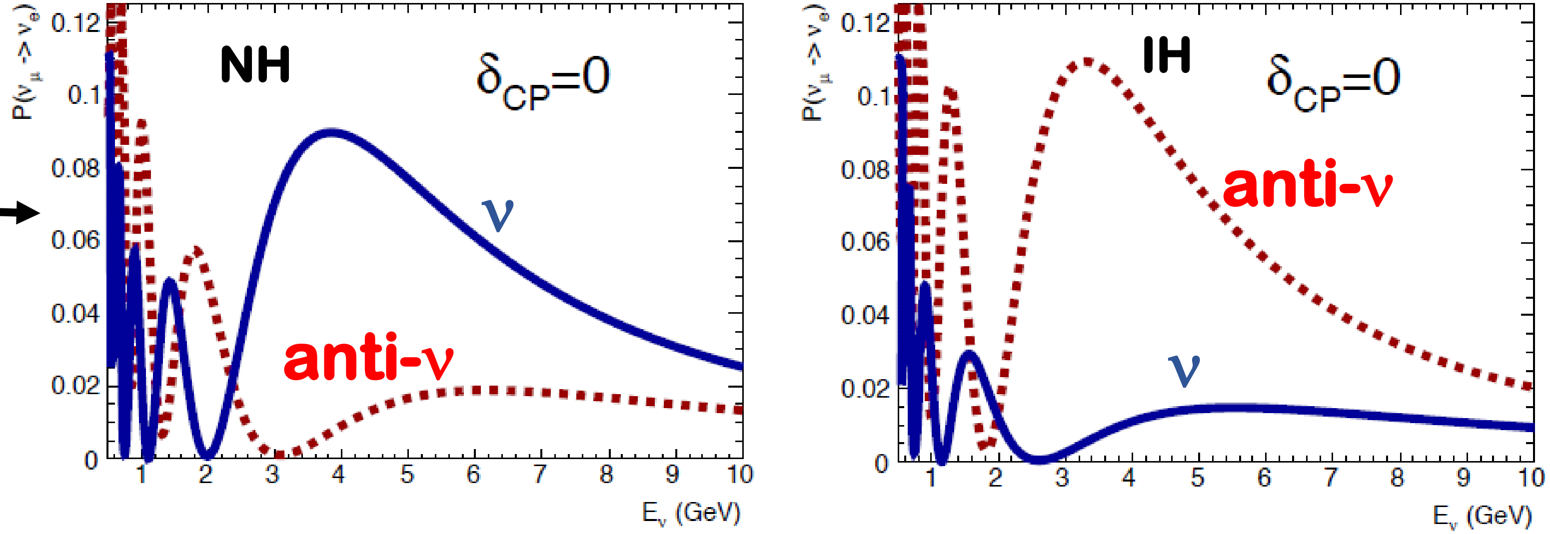


ν_e **CC event**



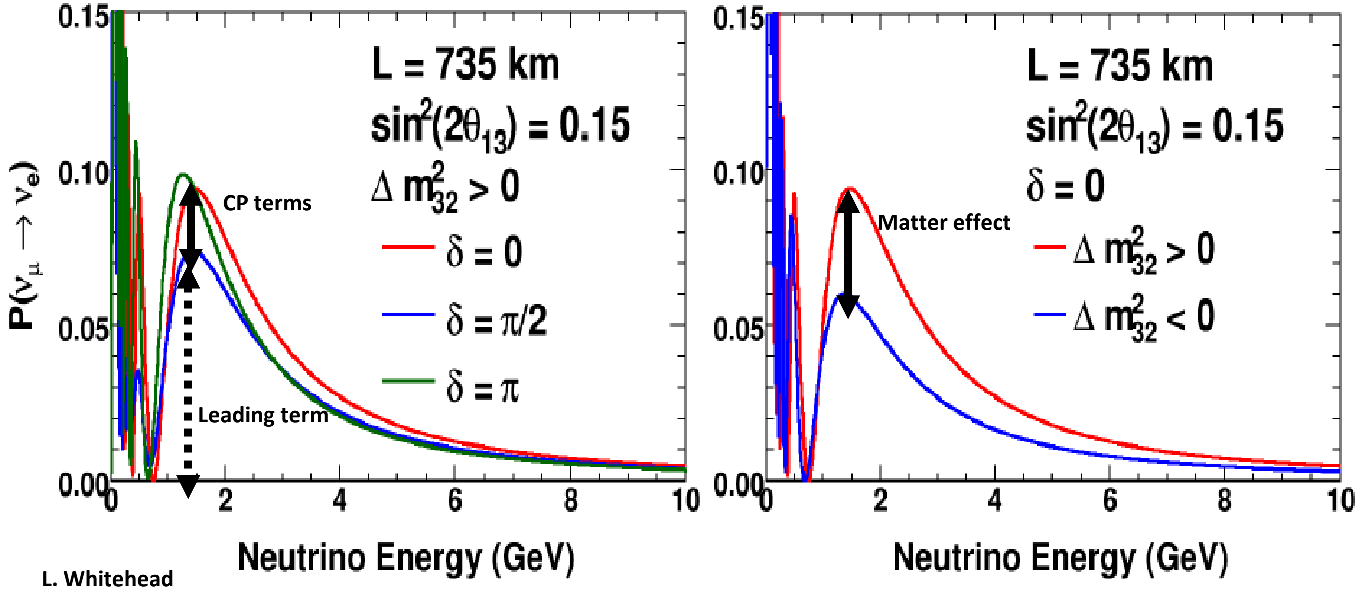
Matter effects and CP violation effects degeneracy

Matter effects on the oscillation probability at L = 2300 km for ν and anti-ν in the case of Normal (NH) or Inverted (IH) hierarchy



Since CP violation is also measured by comparing ν and anti-ν oscillation probabilities matter effects mimic CP violation if the mass hierarchy is not known

- **It need to accurately measure and subtract the matter effects in order to look for CP**
- **Matter effects dominate around the first maximum**



L. Whitehead

Asymmetry as a function of L/E

CP violation is measured by comparing ν and anti-ν oscillation probabilities in an asymmetry variable

$$\mathcal{A} \equiv P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) =$$

$$16\frac{a}{\delta m^2_{31}}\sin^2\frac{\delta m^2_{31}L}{4E}c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

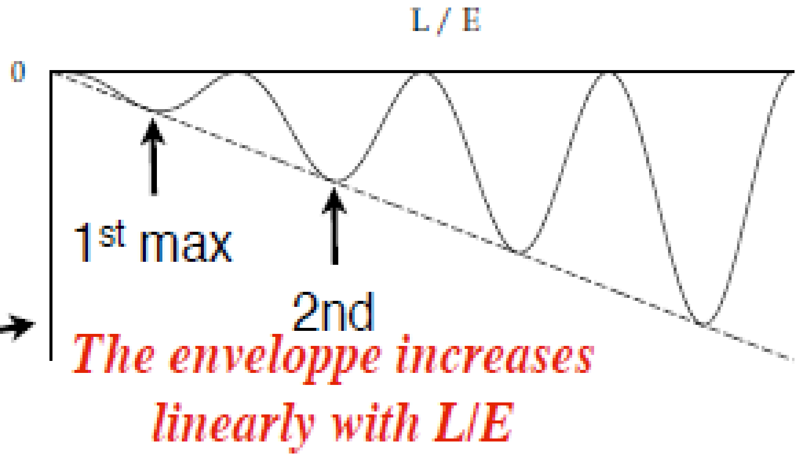
$$-4\frac{aL}{2E}\sin\frac{\delta m^2_{31}L}{2E}c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

$$-8\frac{\delta m^2_{21}L}{2E}\sin^2\frac{\delta m^2_{31}L}{4E}s_\delta c^2_{13}s_{13}c_{23}s_{23}c_{12}s_{12}$$

Matter terms

Pure CP-term

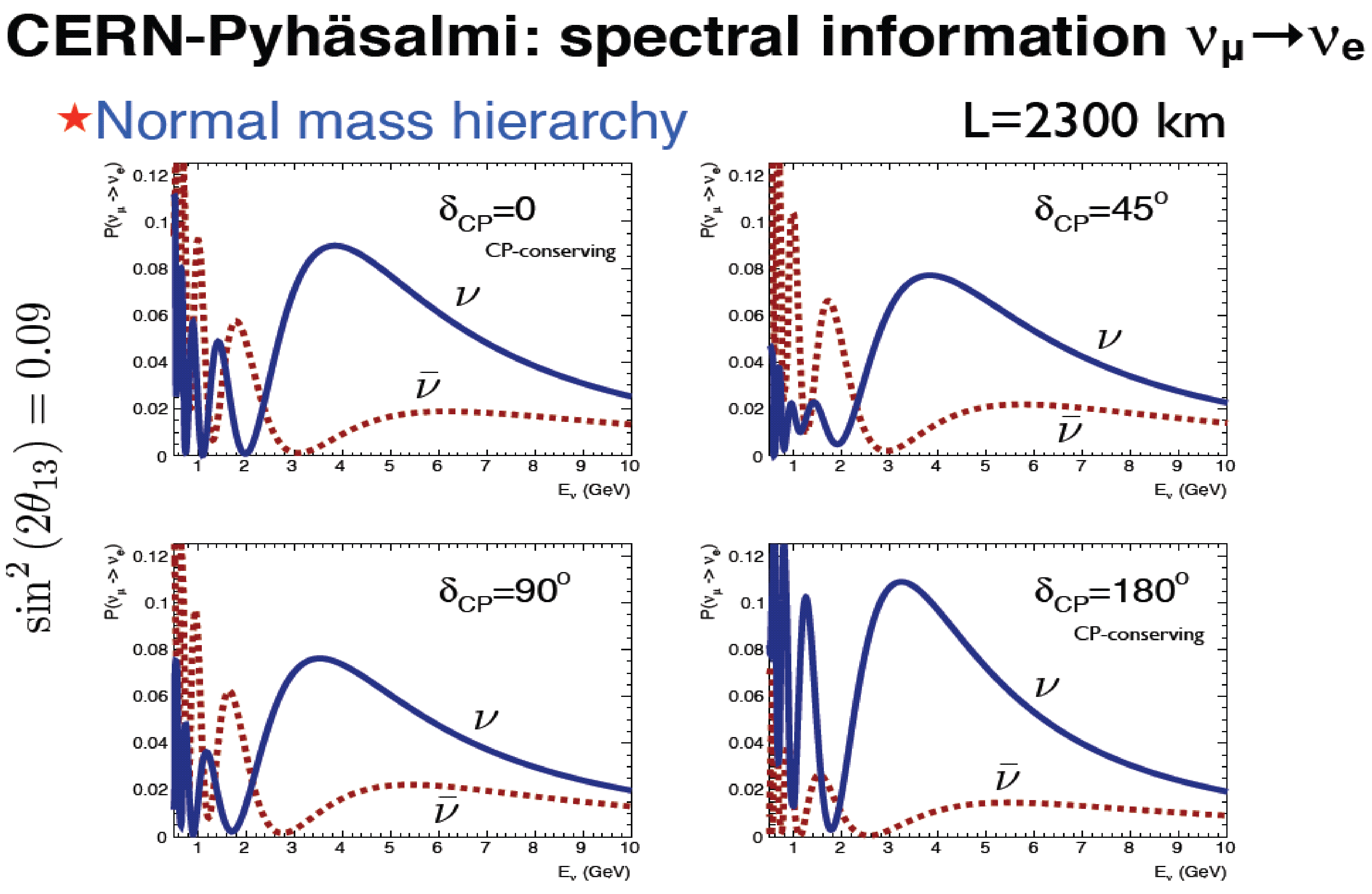
$$\left.\frac{P(\nu)-P(\bar{\nu})}{P(\nu)+P(\bar{\nu})}\right|_{a=0} \approx -\frac{2s_\delta c_{12}s_{12}}{s_{13}}\cot\theta_{23}\frac{\delta m^2_{21}L}{2E}$$



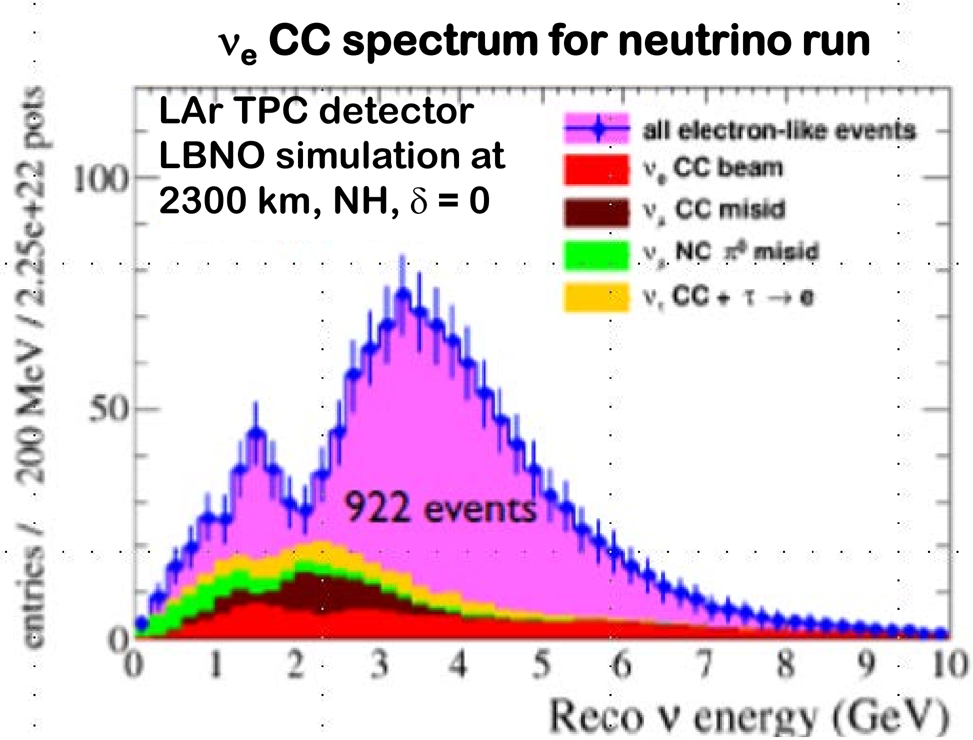
The amplitude of the pure CP term increases with L/E → this effect is stronger at the second oscillation maximum.
The measurement at the second oscillation maximum is very important and it is possible only with a detector with very good energy resolution

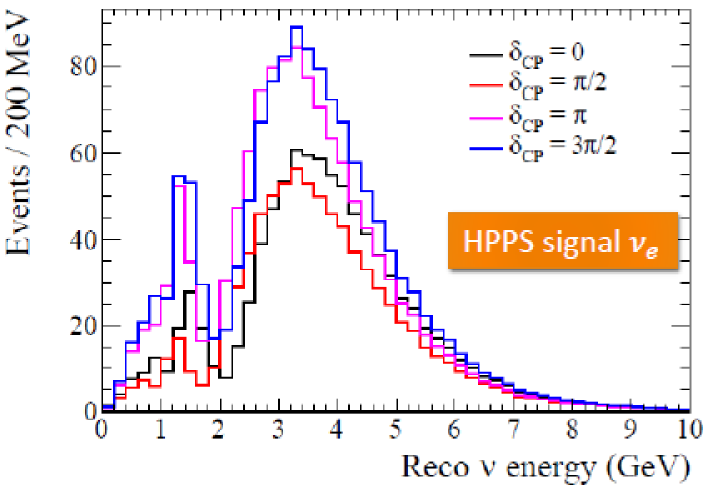
Effects on oscillation probabilities as a function of δ CP

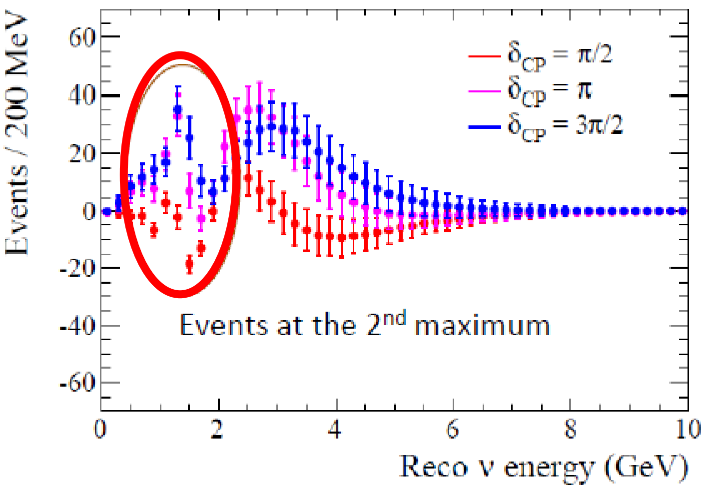
Once the mass hierarchy is determined, it is possible to study the CP-violation and determine the value of δ by measuring the ν and anti-ν oscillation probabilities

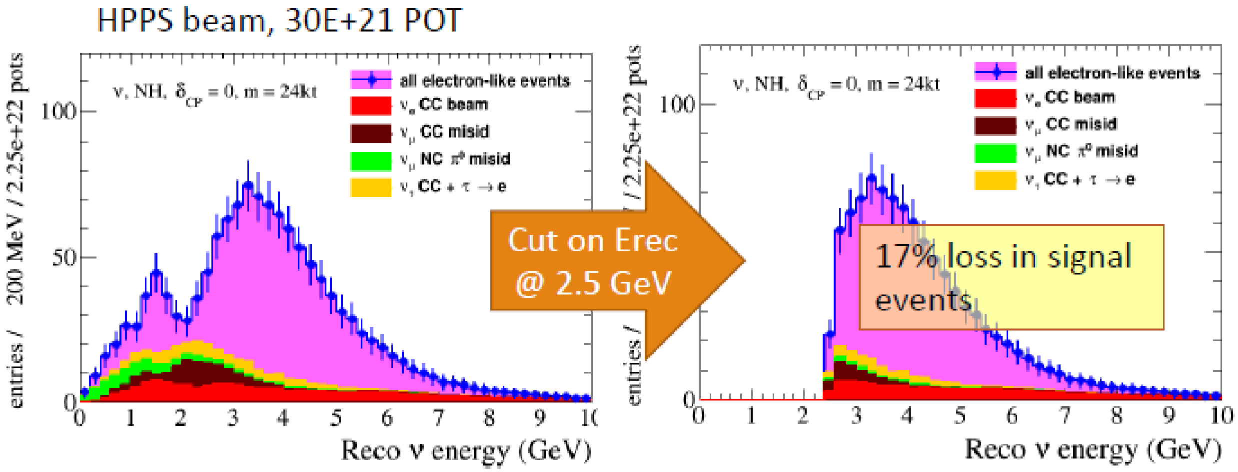


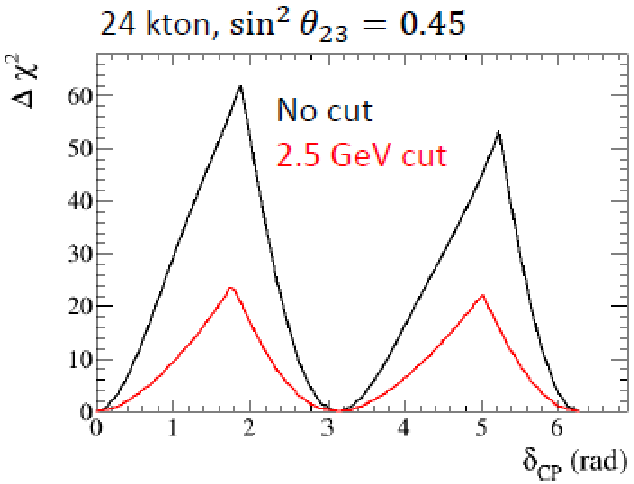
What is observed in the detector, relevance of spectral informations











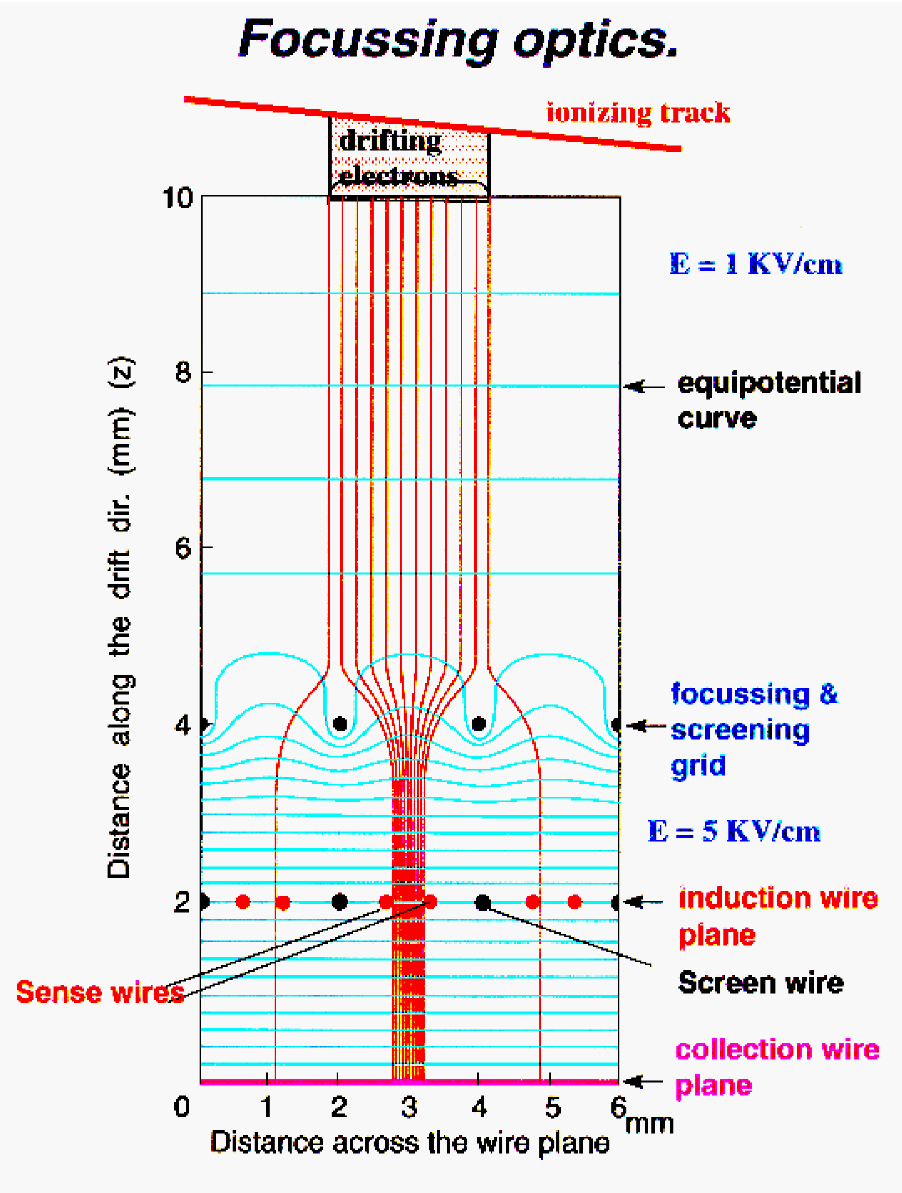
Studying CP at only the first oscillation maximum results in a strong loss of sensitivity!

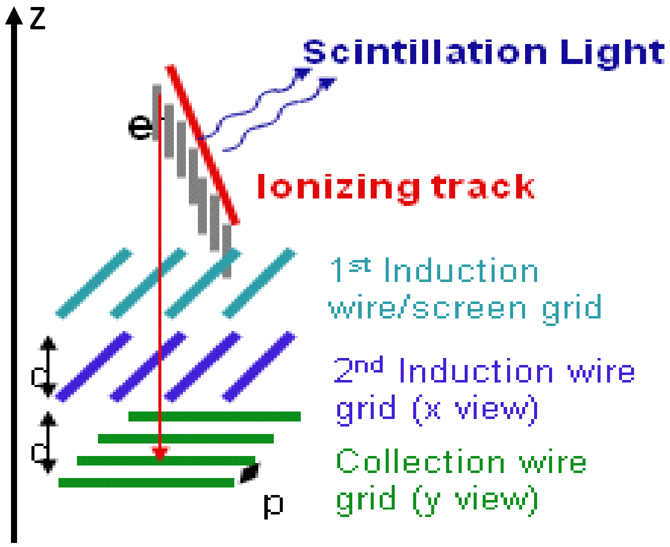
Outline

- CP violation measurement
- **Liquid Argon Time Projection Chamber**
- Charge reconstruction and its physics impact
- Conclusions

The Liquid Argon Time Projection Chamber (C. Rubbia 1977)

- **Homogeneous massive target** and **ionization detector** →electronic bubble chamber
- **3D event reconstruction** with ~1mm resolution, surface readout
- **High resolution calorimetry**
- Ionization in LAr 1m.i.p~20000e^- on 3 mm
- **Detection of UV scintillation light in Argon** (5000 photons/mm @128 nm) to provide t=0 signal for the event





z=drift time

drift field: 0.5-1 kV
drift time: 0.5ms/m @ 1 kV/cm

Drift requiring<0.1ppb O_2 equiv. impurities

Ionization yield

- **Ionization and recombination**

$$q = R\frac{Energy}{W_{ion}}e$$

R is the fraction of the produced ionization charges which do not recombine:

$$R = \frac{A}{1 + \frac{k}{E_{field}}\frac{dE}{dx}}$$

- **Recombined charges → Light production @128 nm (5000 photons/mm)**

- **Drift and impurity losses**

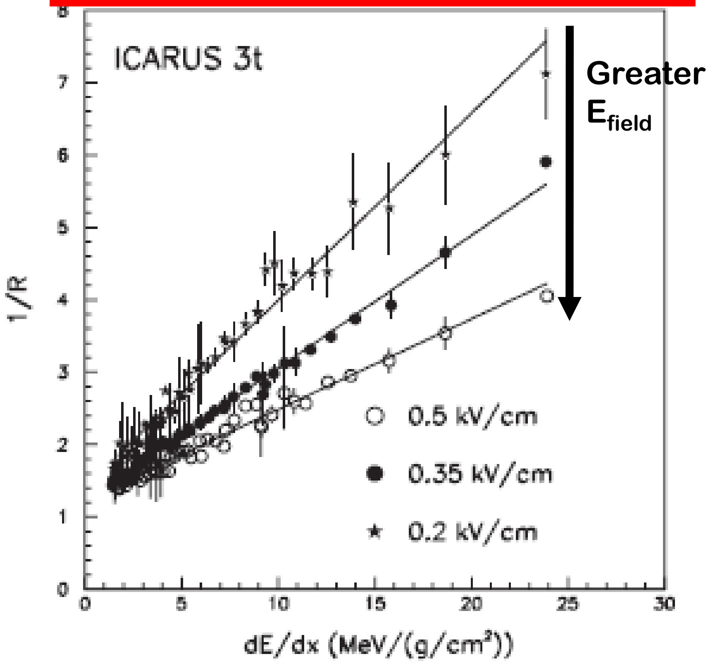
$$q' = q \cdot e^{-\frac{t_d}{\tau}}$$

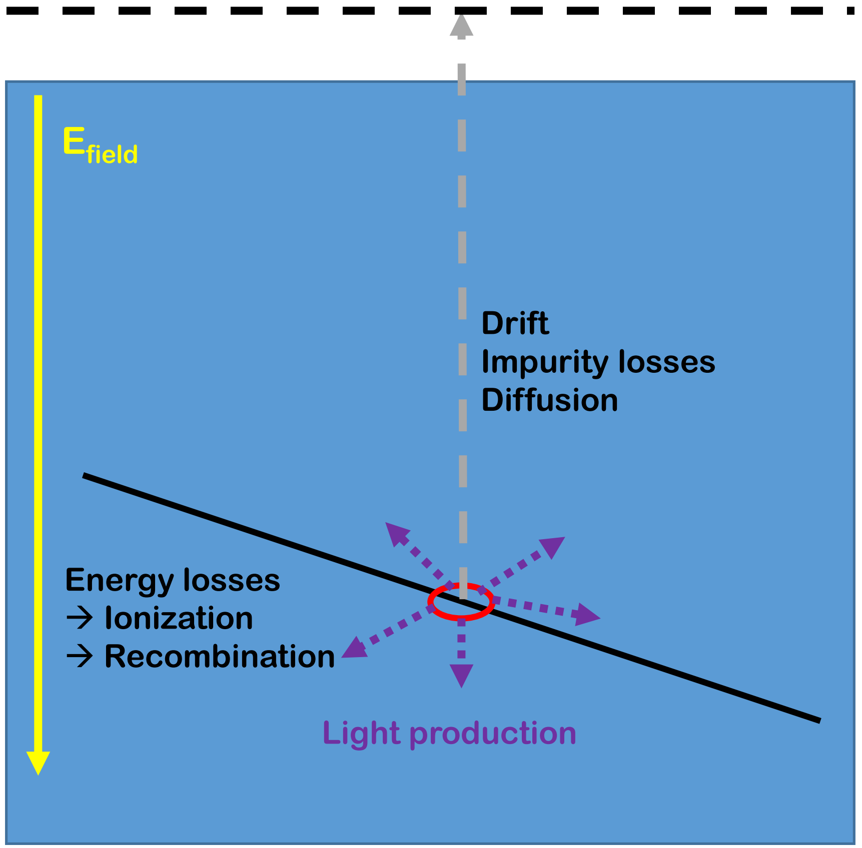
t_d= drift time
typical τ ~ 3 ms for 0.1 ppb

W_{ion} = 23.6 eV
dE/dx = 2.096 MeV/cm for 1 m.i.p
e^- in 3 mm for 1 m.i.p~ 26000

ICARUS results
A = 0.800
k = 0.0486 kV/cm *(g/cm2)/MeV

@ E_{field} = 1 kV/cm, (dE/dx)m.i.p
R = 0.747
e^- after recombination on 3 mm ~ 20000



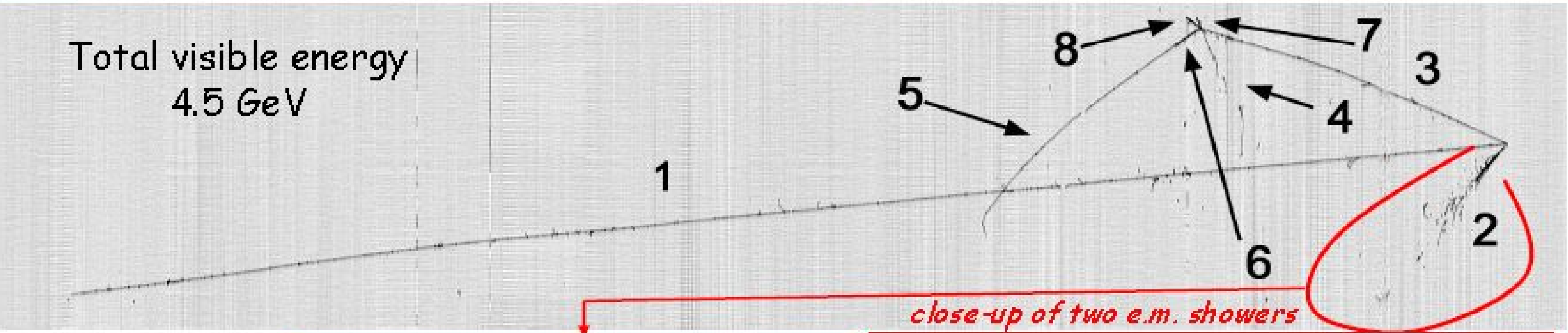


Larger E field → less recombination → increase of R

The LAr TPC as an electronic bubble chamber

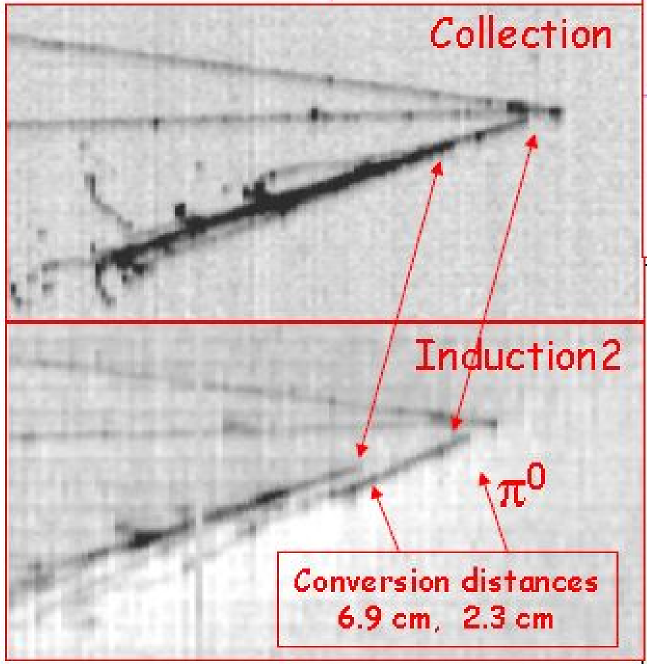
- Large mass, homogeneous detector, low threshold, exclusive final states by particle identification with dE/dx
- Tracking + calorimetry (electromagnetic and hadronic), reconstruction of event kinematics
- Electron identification and energy measurement, π_0 rejection

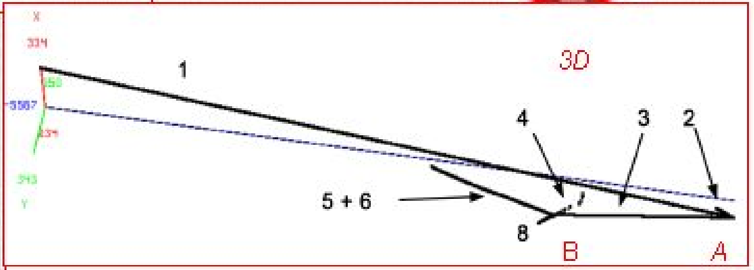
Run 9927 Event 572: ν_μ-CC CNGS event



Primary vertex (A):
very long μ (1), e.m.cascades(2), π (3)

Secondary vertex (B):
the longest track (5) is a μ coming from stopping **k** (6). μ decay is observed





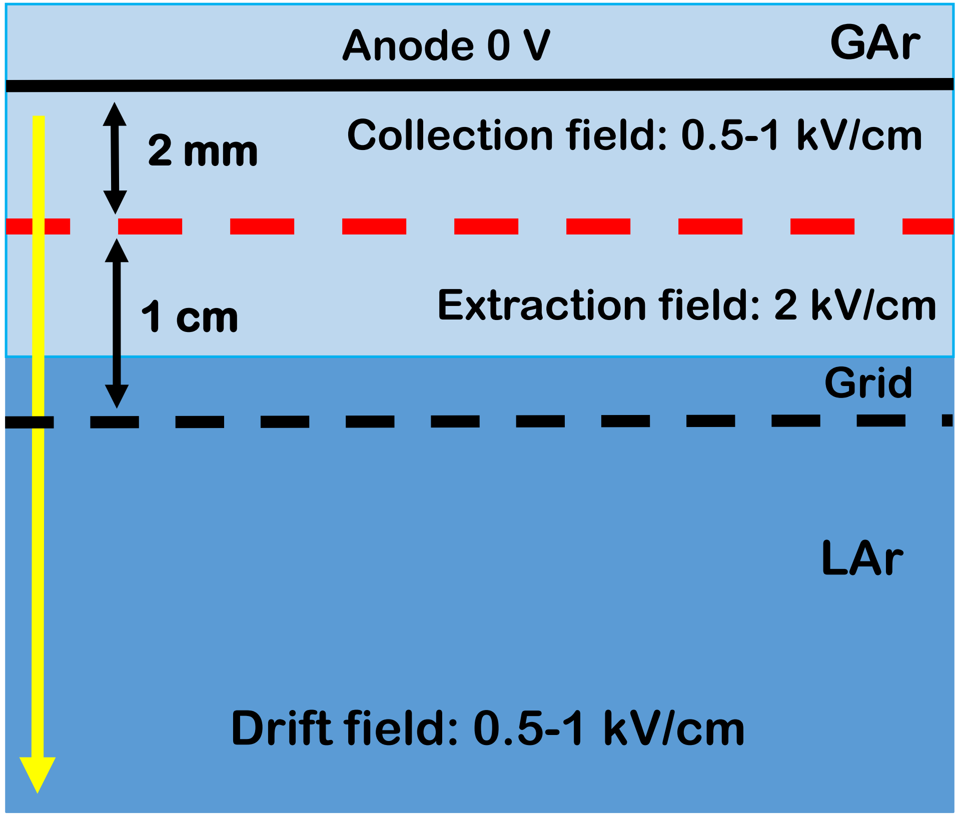
Track	E_{dep}[MeV]	cosx	cosy	cosz
1 (μ)	2701.97	0.069	-0.040	-0.997
2	520.82	0.054	-0.420	-0.906
3 (p)	514.04	-0.001	0.137	-0.991
Sec. vtx.	797			
4	76.99	0.009	-0.649	0.761
5 (μ)	313.9			
6 (K)	86.98	0.000	-0.239	-0.971
7	35.87	0.414	0.793	-0.446
8	283.28	-0.613	0.150	-0.776

Double-phase readout

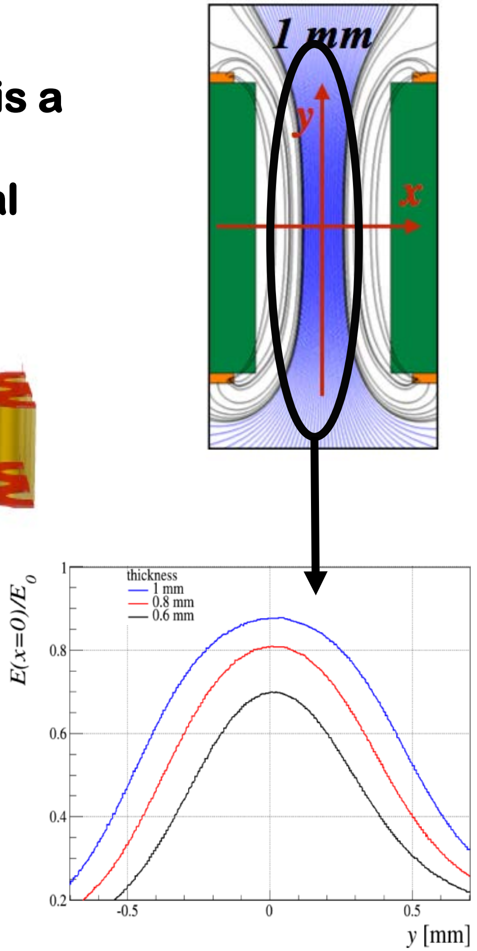
The double-phase readout allows for some gain in the detector which increases the number of collected electrons → longer drifts, bigger detectors

The electrons are extracted from the liquid and drifted in the gas phase

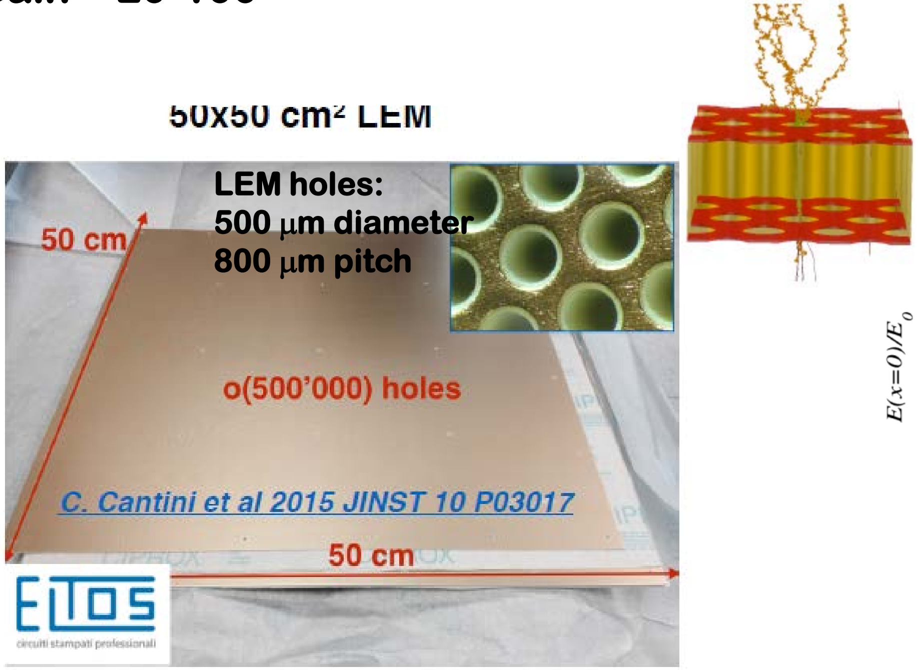
In the LEM (Large Electron Multiplier) there is a strong electric field in order to generate a Townsend avalanche and increase the signal
Gain ~ 20-100

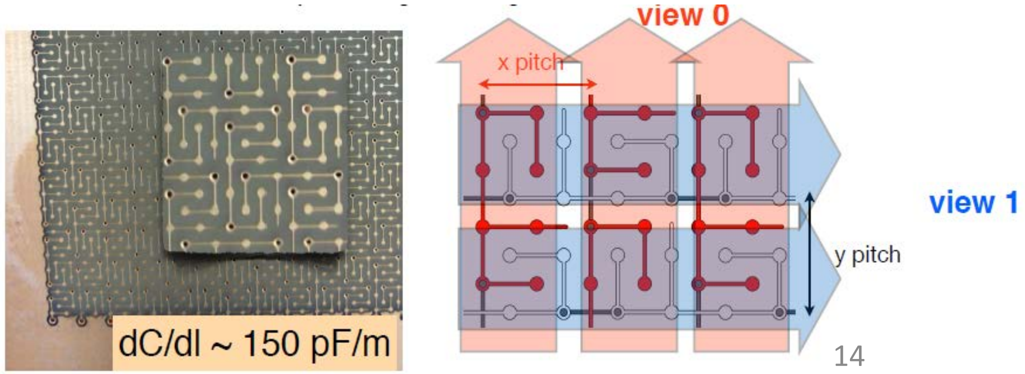


LEM (1mm)
2.5-3.5 kV

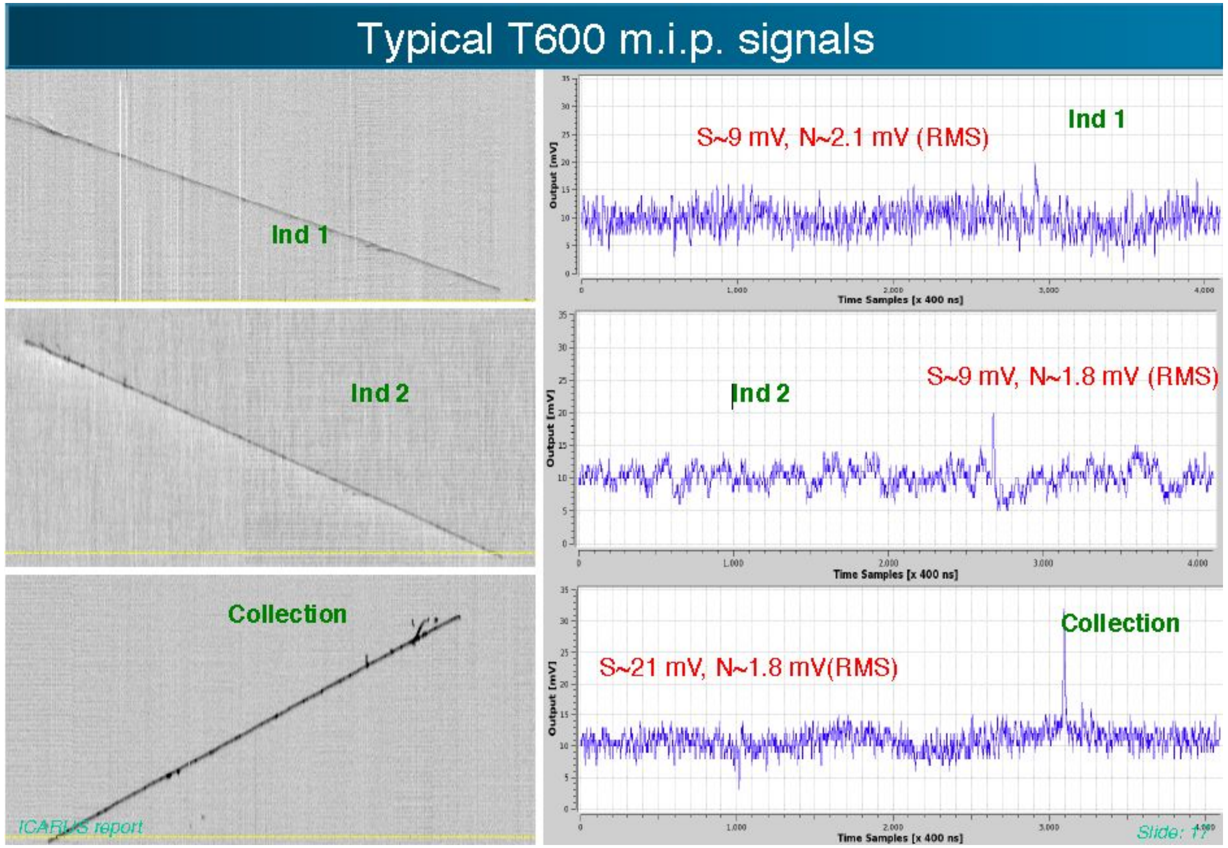


50x50 cm² LEM





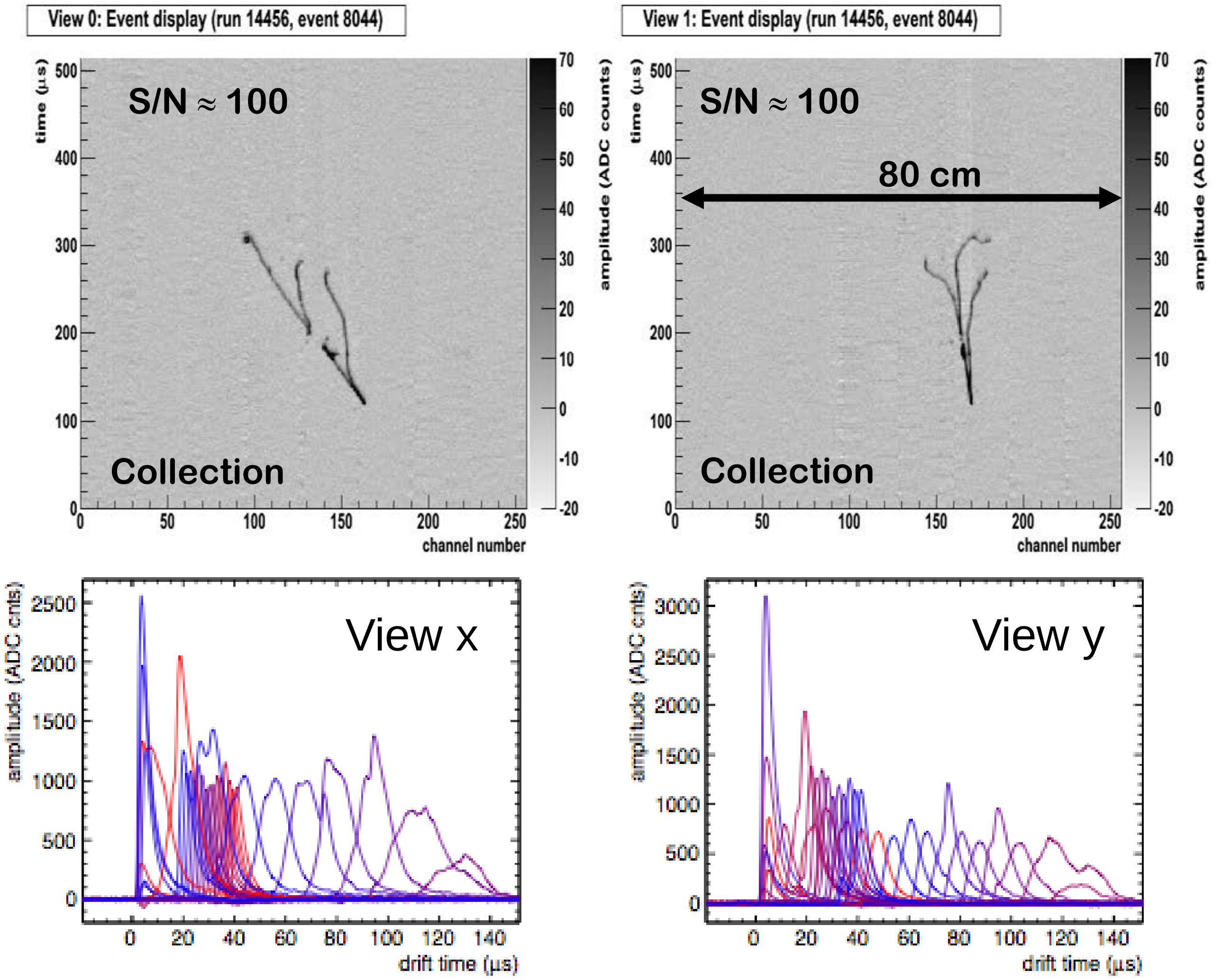
Advantages of double-phase readout



Example of event in single phase LAr TPC (ICARUS)

S/N ~ 10 collection

S/N ~ 5 induction

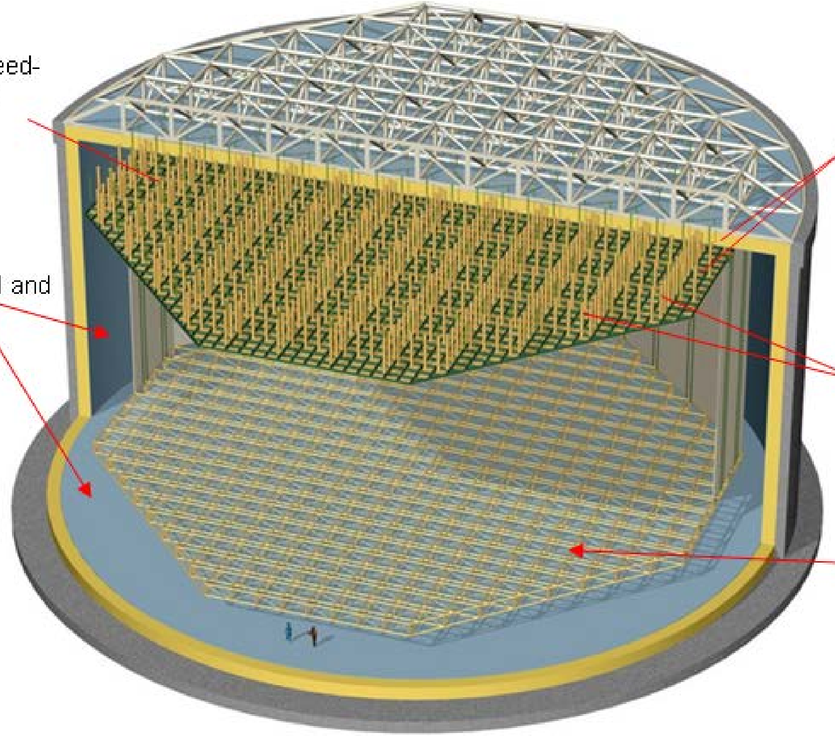


Example of event in double phase LAr TPC

S/N ~ 100

Advantages of double-phase on detector design

- Anode with 2 collection (X, Y) views (no induction views), no ambiguities
- Strips pitch 3 mm, 3 m length
- Tunable gain in gas phase (20-100), high S/N ratio for m.i.p. > 100, <100 KeV threshold, min. purity requirement 3ms electrons lifetime→ operative margins vs purity, noise
- Long drift projective geometry: reduced number of readout channels
- No materials in the active volume
- Accessible and replaceable cryogenic FE electronics

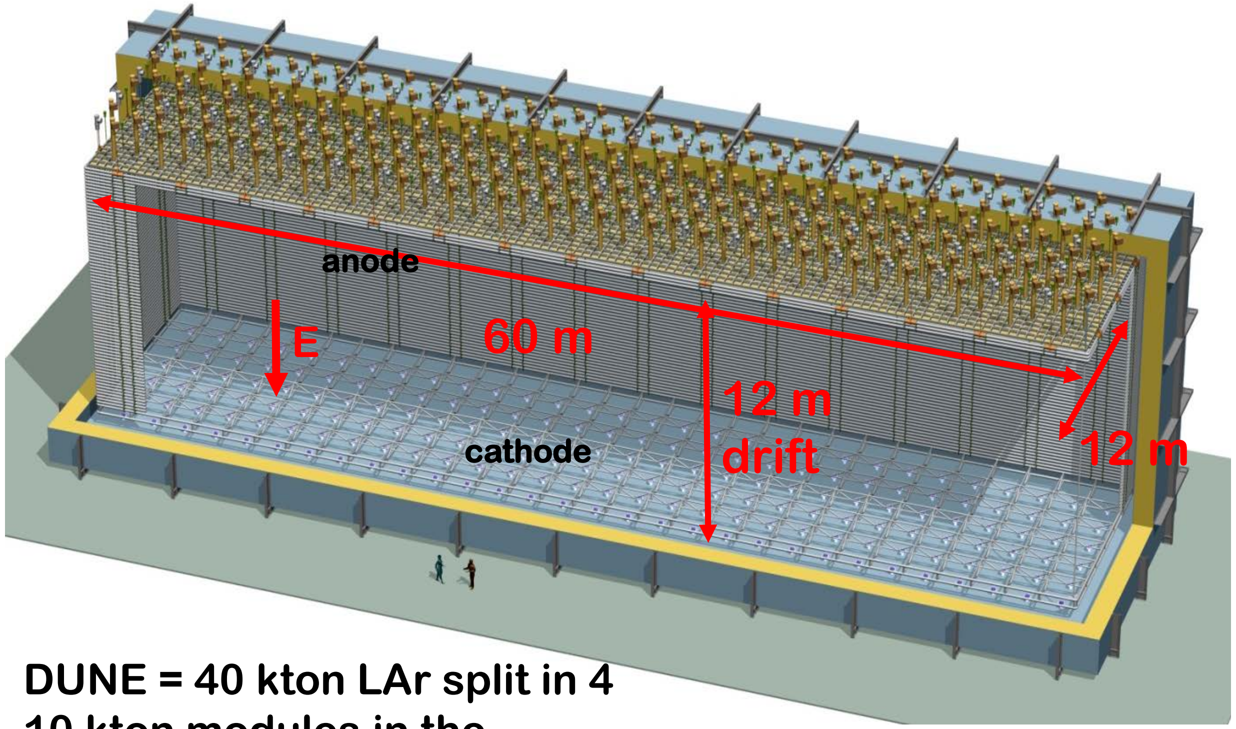


LBNO 50 kton detector developed in the Laguna-LBNO design study

- Drift 20 m
- Cathode span 47 m
- 573444 channels
- Active mass 51.3 kton

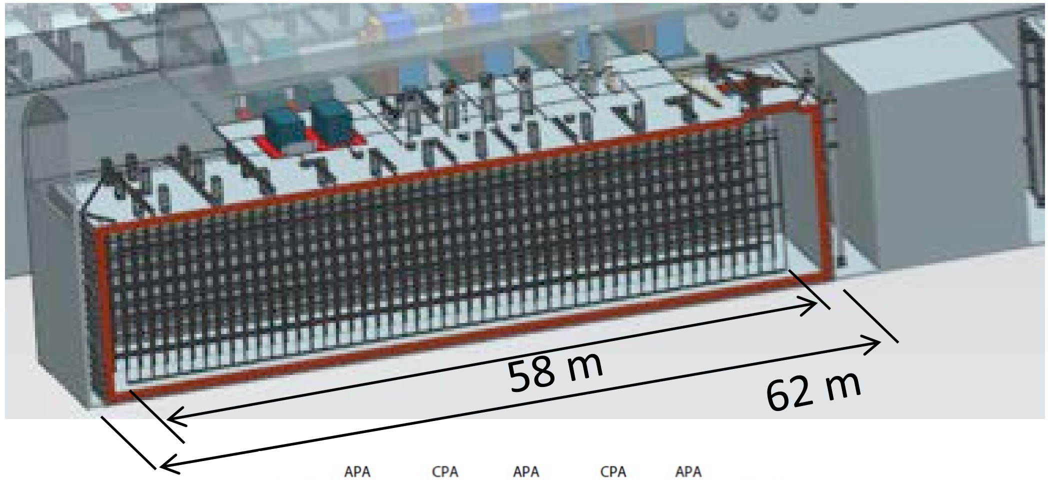
Double-phase and single-phase 10 kton modules for DUNE

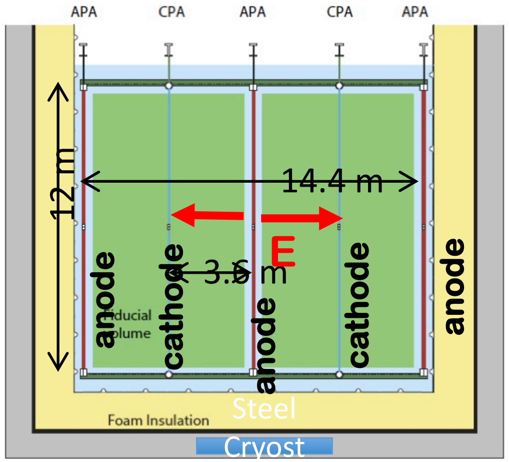
Double-phase 10 kton module



DUNE = 40 kton LAr split in 4 10 kton modules in the Homestake mine at 1300 km from Fermilab

Single-phase 10 kton module

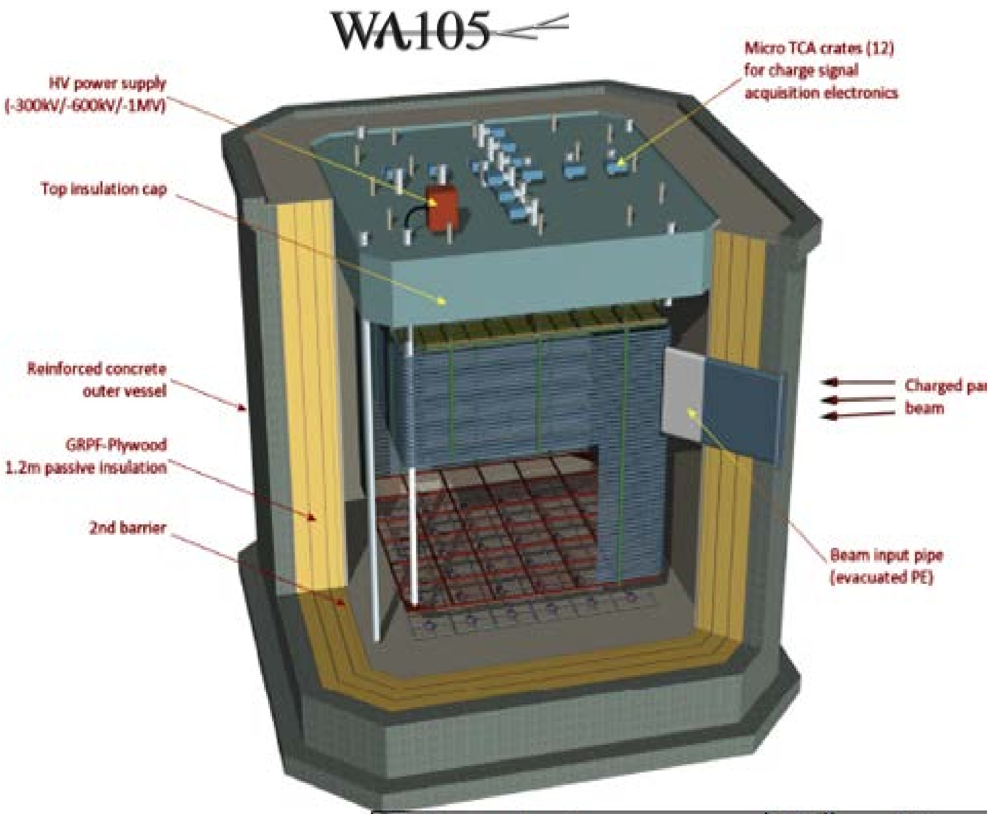




Drift length: 12 m
Number of channels: 153600, pitch: 3 mm
Two collection views

Drift length: 3.6 m, 2 cathodes, 3 anodes
Number of channels: 384000, pitch: 5 mm
One collection view, two induction views (one wrapped view)

The LBNO-DEMO/WA105 experiment at CERN



Liquid argon density	T/m^3	1.38
Liquid argon volume height	m	7.6
Active liquid argon height	m	5.99
Hydrostatic pressure at the bottom	bar	1.03
Inner vessel size (WxLxH)	m^3	8.3 × 8.3 × 8.1
Inner vessel base surface	m^2	67.6
Total liquid argon volume	m^3	509.6
Total liquid argon mass	t	705
Active LAr area	m^2	36
Charge readout module (0.5 x0.5 m^2)		36
N of signal feedthrough		12
N of readout channels		7680
N of PMT		36

Full scale demonstrator for DUNE 10 kton double-phase
6x6x6m^3 active volume, 300 ton , 7680 readout channels, LAr TPC (double phase+2-D collection anode): DLAr
Exposure to charged hadrons, muons and electrons beams (0.5-20(10) GeV/c)

Full-scale demonstrator of all innovative LAGUNA-LBNO technologies for a large LAr detector:

- LNG tank construction technique (with non evacuated vessel)
- Purification system
- Long drift
- HV system 300-600 KV, large hanging field cage
- Large area double-phase charge readout
- Accessible FE and cheap readout electronics
- Long term stability of UV light readout

Assess performance in reconstructing hadronic showers (most demanding task in neutrino interactions):

- Measurements in hadronic and electromagnetic calorimetry and PID performance
- Full-scale software development, simulation and reconstruction to be validated and improved

Installation ongoing in the CERN NA EHN1 extension, data taking in 2018

Outline

- CP violation measurement
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Charge readout

The LAr TPC charge readout is crucial for:

- Neutrino energy reconstruction (electromagnetic and hadronic calorimetry, measurement of total ionization of ranging out particles)
- π^0 rejection, most dangerous background to ν_e CC sample (dE/dx discrimination between single electrons and e^+e^- pairs from photon conversion)
- Particle identification, essential for identification of exclusive final states and search for proton decay (dE/dx measurements for passing through particles and near stopping point for ranging out particles)

The goals of my thesis in WA105 (the 6x6x6 m^3 double phase demonstrator of DUNE at CERN) are:

- Development of a complete charge readout analysis in WA105 integrated in the QSCAN reconstruction program
- Correlated studies of systematic effects in the dE/dx measurement and energy reconstruction (effects related to Birk's law, diffusion, charge attenuation along the drift, electronics response, pitch, δ-rays identification, tracks reconstruction)
- Development of the dE/dx and particle ID algorithms (WA105 will be exposed to a charged particles beam e, μ, π, K, p and collect many millions of interactions on which we can apply particle ID to primary particles and particles from secondary vertices in order to test the particle ID for proton decay etc.)

Neutrino energy reconstruction

It is possible to evaluate the neutrino energy by measuring the kinetic energies of the final state particles after ranging out in LAr

$$E_\nu = K_\nu \approx K_l + \sum K_h$$

where K_l and K_h are the lepton's and hadrons' kinetic energies. Typical E_ν resolution ~10%

In the LAr TPC, there are three methods to measure a particle's kinetic energy

- Electromagnetic calorimetry (electrons, photons)

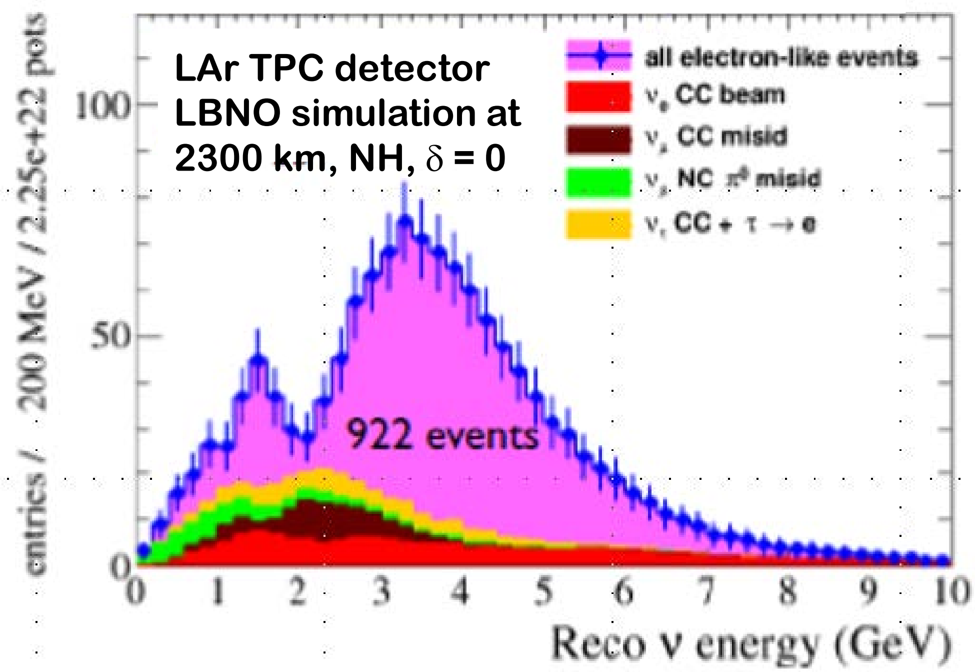
$$\frac{\Delta E}{E} = \frac{0.33}{\sqrt{E(MeV)}} + 0.01$$

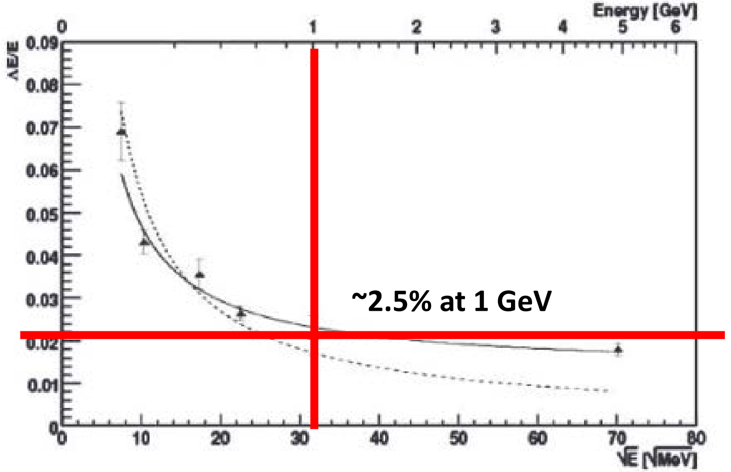
- Hadronic calorimetry (interacting hadrons)

$$\frac{\Delta E}{E} = \frac{30\%}{\sqrt{E(GeV)}}$$

- Track reconstruction (muons, charged hadrons not producing hadronic showers as low energy protons) Resolution 1-3%

Example of neutrino energy reconstruction: ν_e CC spectrum for neutrino run

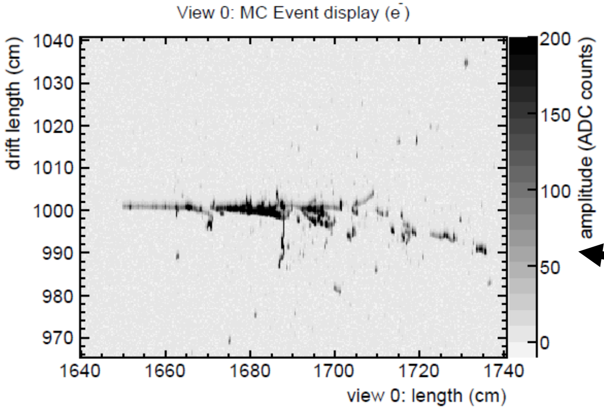


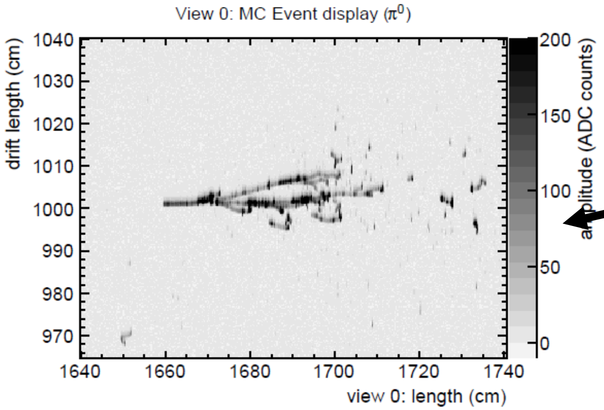


Resolution for em calorimetry

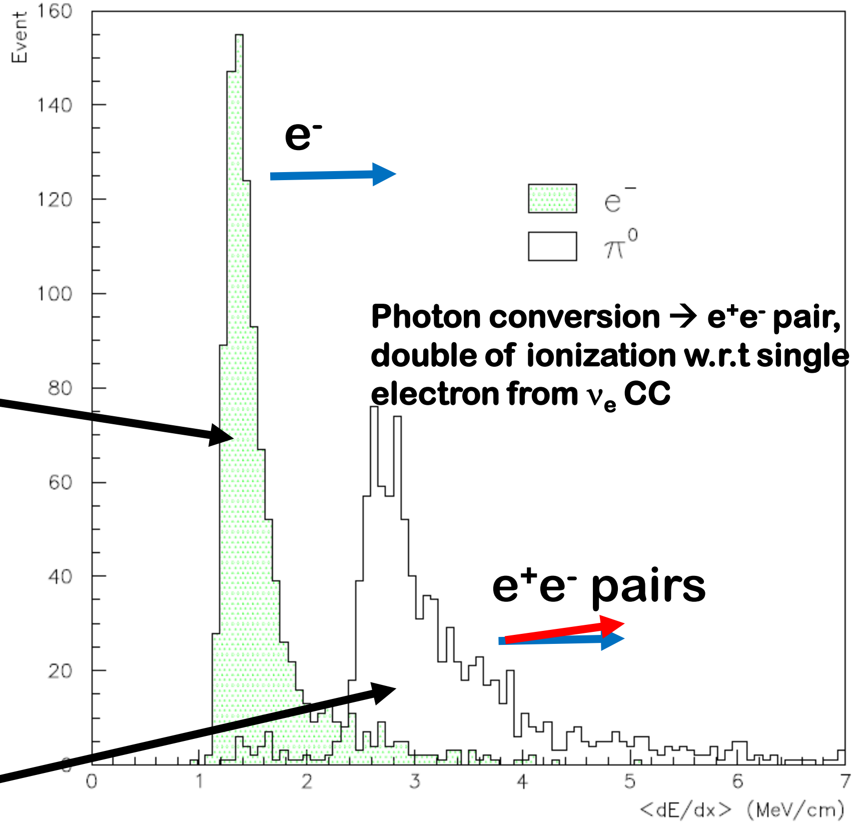
π^0 rejection

e⁻ (top) and γ from π^0 (bottom) showers look very similar



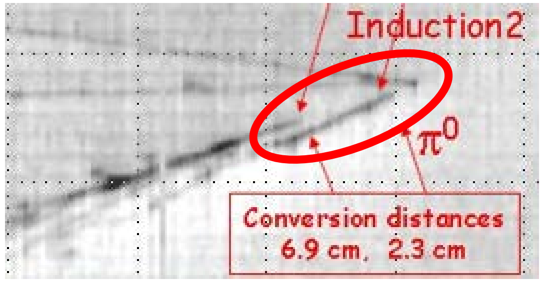


MC showers from ν_e CC electrons and π^0

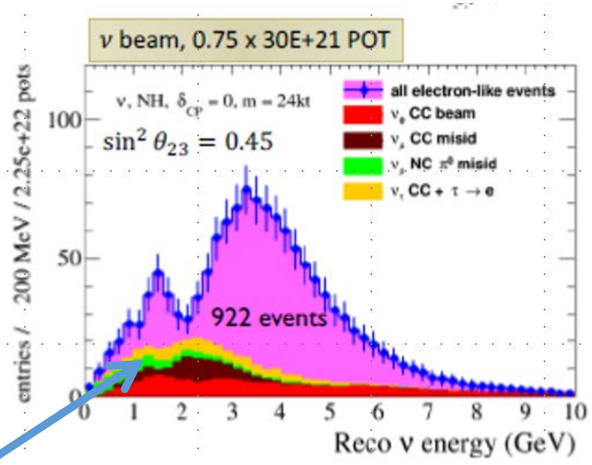


Looking at the energy deposition at the beginning of the track originating the shower it is possible to distinguish a single particle (electron) from a double particle (pair from gamma conversion from π^0 decay)

Tracking resolution provides another way to identify the e.m. shower generated by a photon:

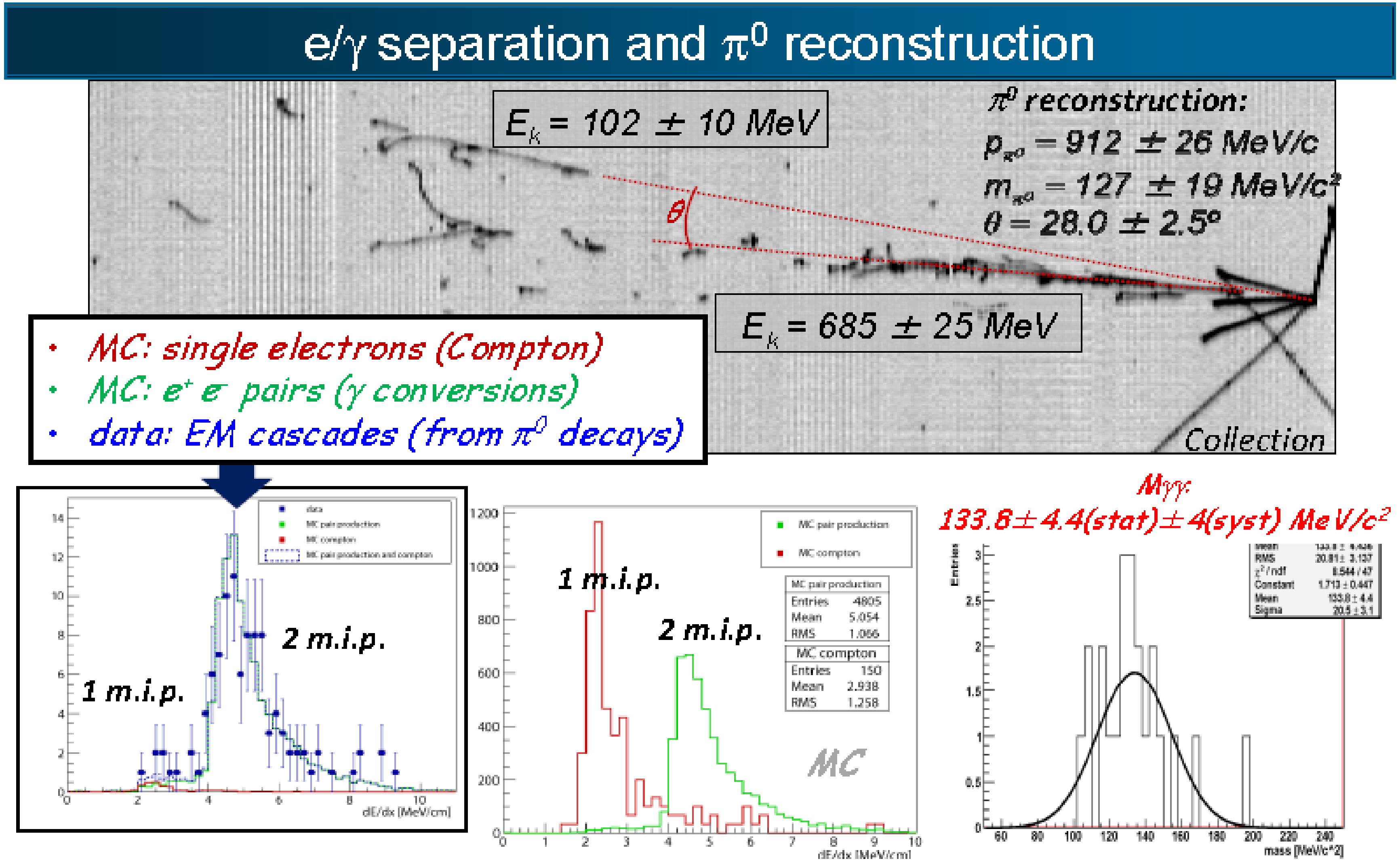


→presence of a gap in between primary and conversion vertices



→ The dE/dx+gap criteria suppress the gamma conversions background by a factor 50 with 90% signal efficiency. Otherwise this background would be as large as the signal from ν_e CC from oscillations.

e/γ separation and π^0 reconstruction (ICARUS data: dE/dx for converted γ)

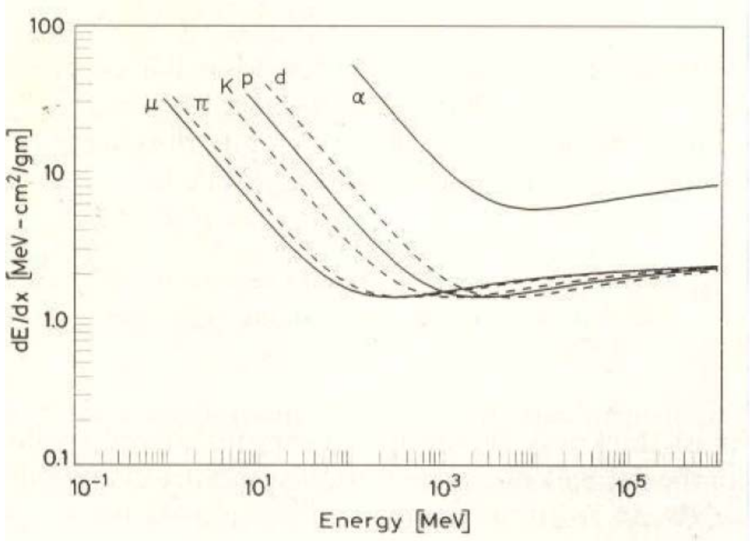


Particles identification

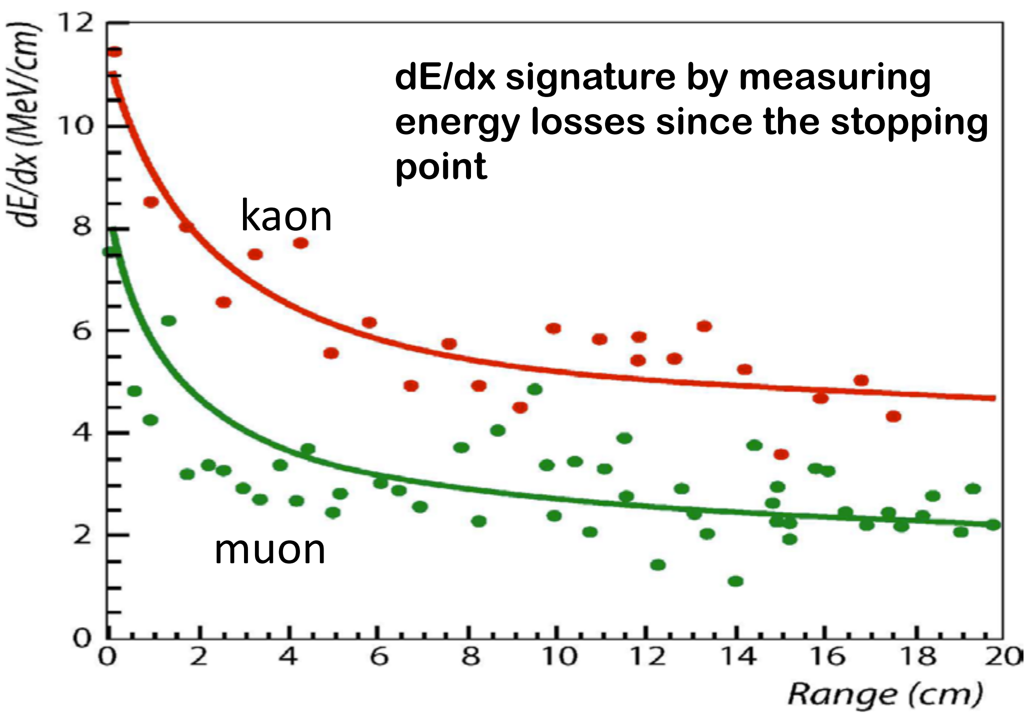
Using the Bethe-Block formula

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

It is possible to identify different particles measuring their dE/dx.
This can be done for passing through particles by sampling their trajectory or for stopping particles by measuring the ionization losses in proximity of the stopping point (this is the mostly used technique for LAr TPC events)



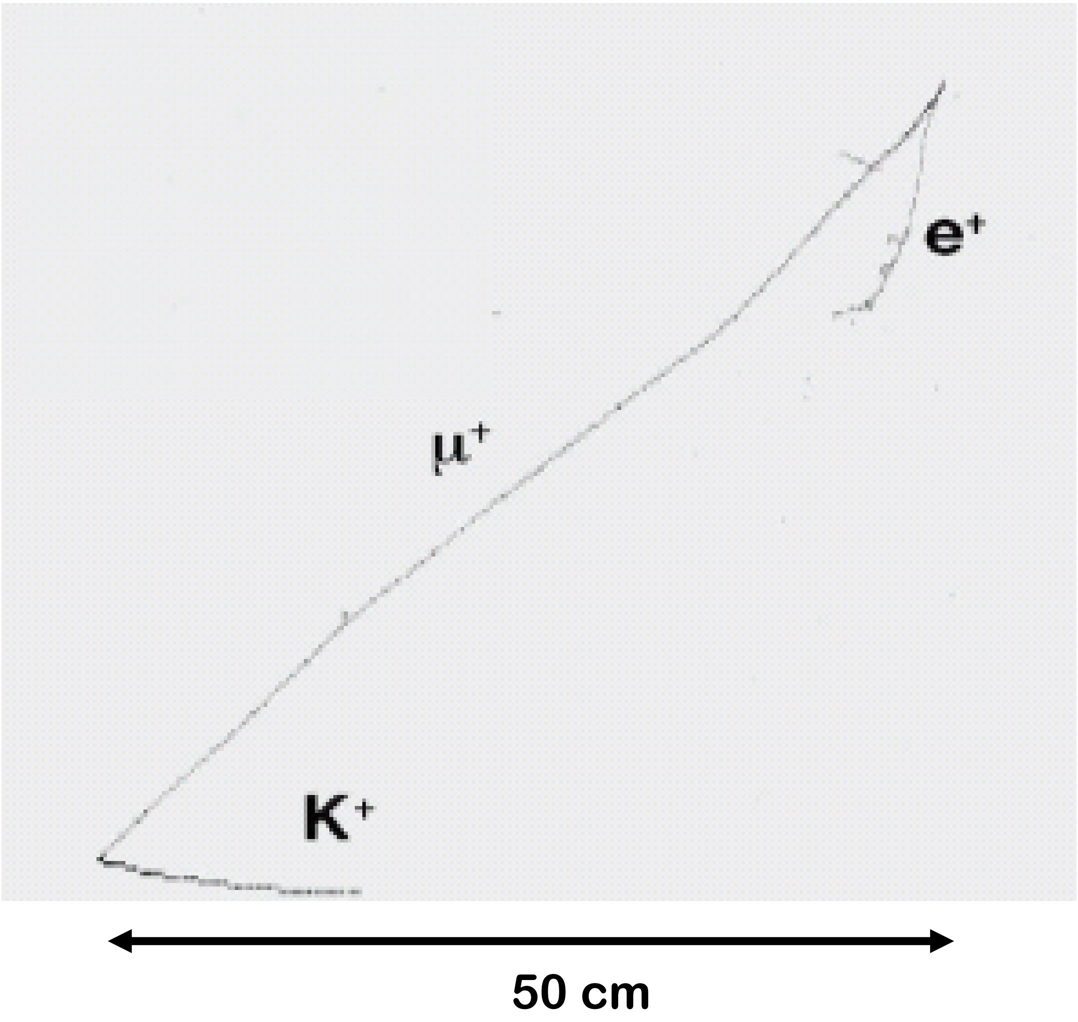
A giant liquid argon TPC, on top of the study of the neutrino oscillations, can naturally search for **proton decay**, in particular in some decay channels such as the p → K + ν decay

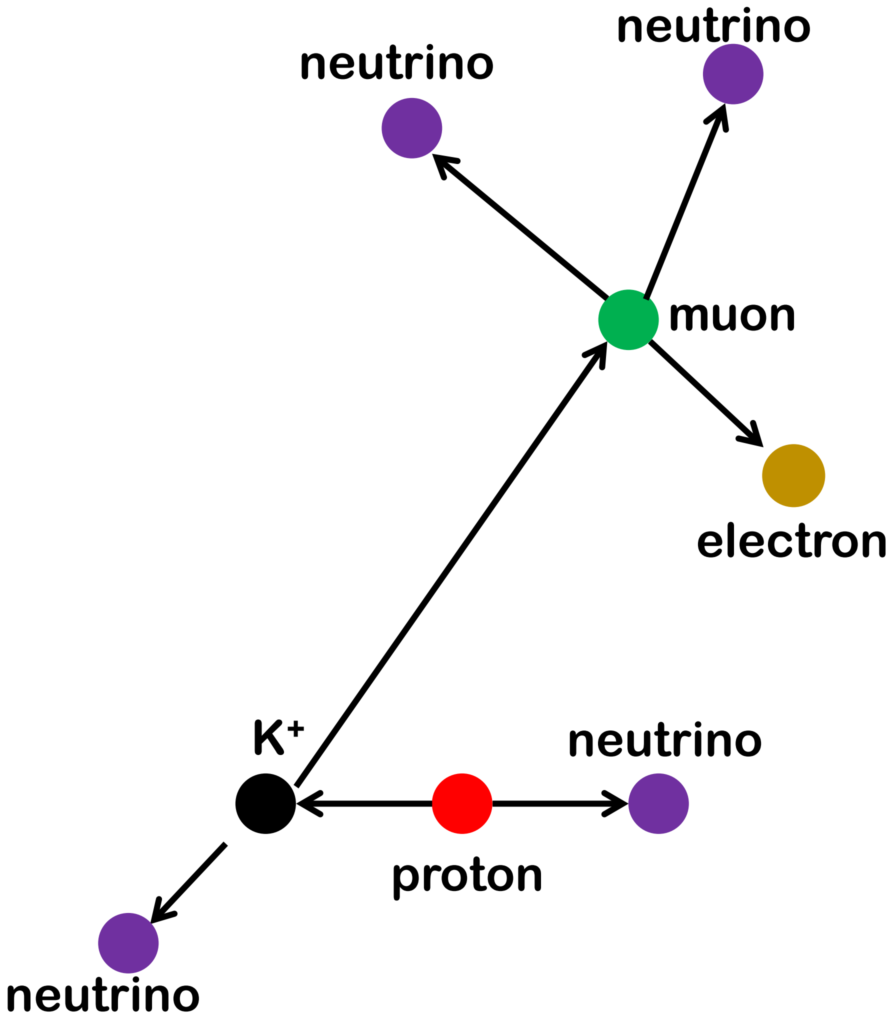


Two bodies decay → monochromatic → K at 340 MeV/c + effect of Fermi momentum smearing
K range in LAr for 340 Mev/c = 14 cm
K → μ → e decay chain observed

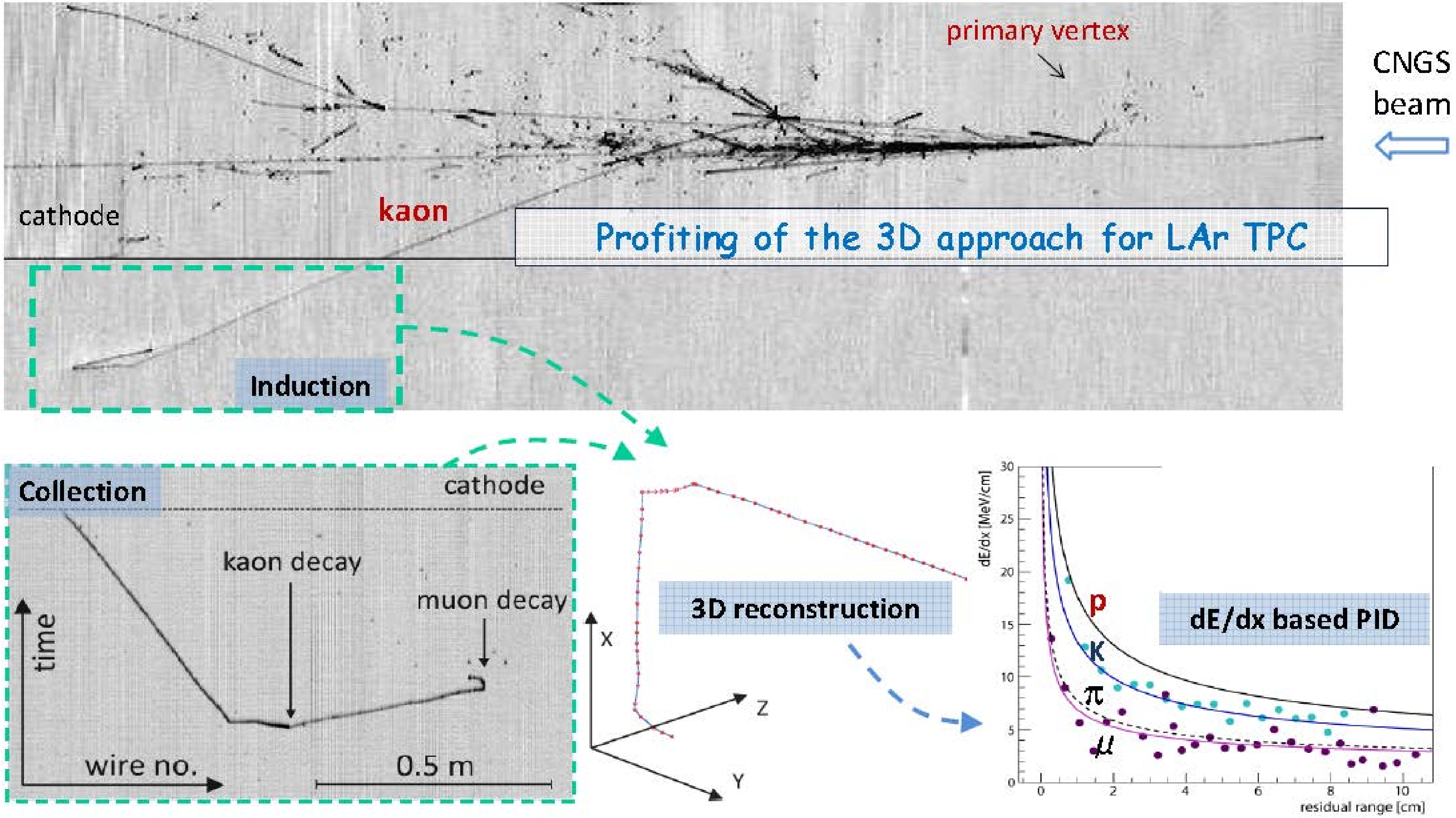
Simulated proton decay event

daughter neutrinos in the final state not detectable





K decay identification in a real neutrino event

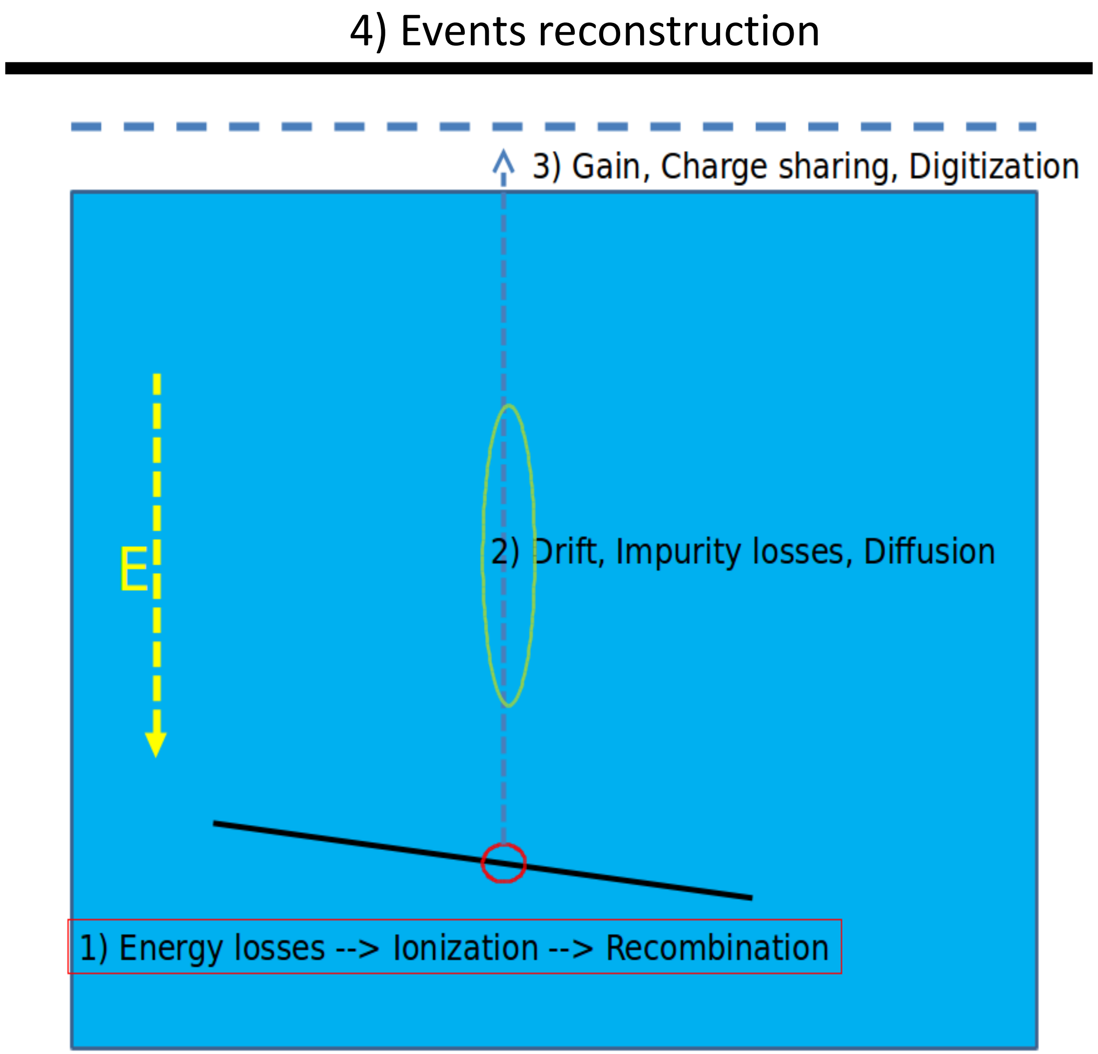


Systematic and reconstruction effects on charge readout

→ **Study of the charge readout and knowledge of the detector response.**

For this study, it is needed a precise knowledge of several basic aspects:

- **How the simulation software (GEANT3,4) handles the energy losses and their fluctuations**
- **The recombination effects (Birk's law)**
- **The effects related to electrons drift (diffusion, impurity losses)**
- **The simulation of the detector response and analog and digital readout electronics**
- **Reconstruction effects related to hits and tracks reconstructions (angles w.r.t. the strips), identification of δ-rays**



Work in progress and perspectives

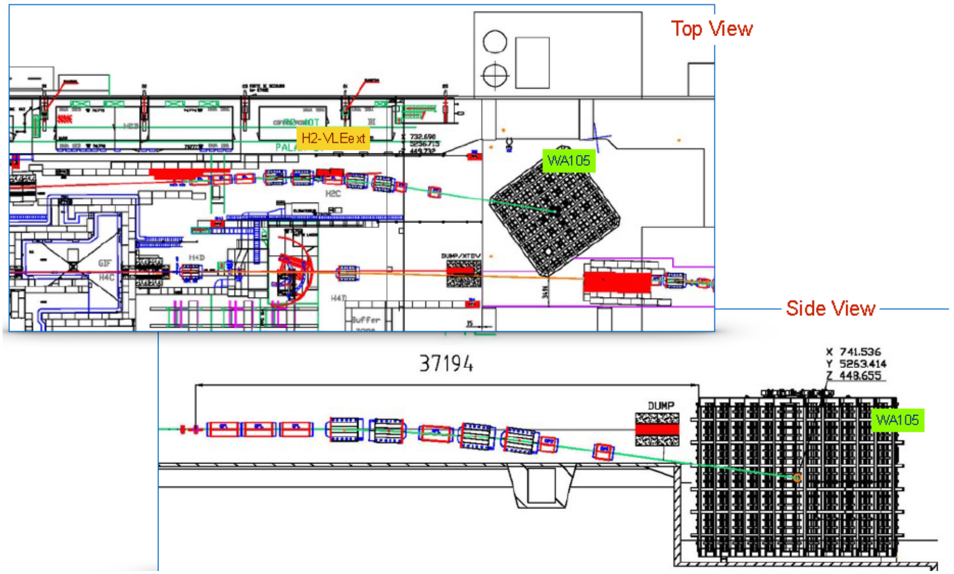
- Complete for my thesis the charge readout analysis, systematic studies and writing of related tools (algorithms for dE/dx measurement, particles ID at end of range)

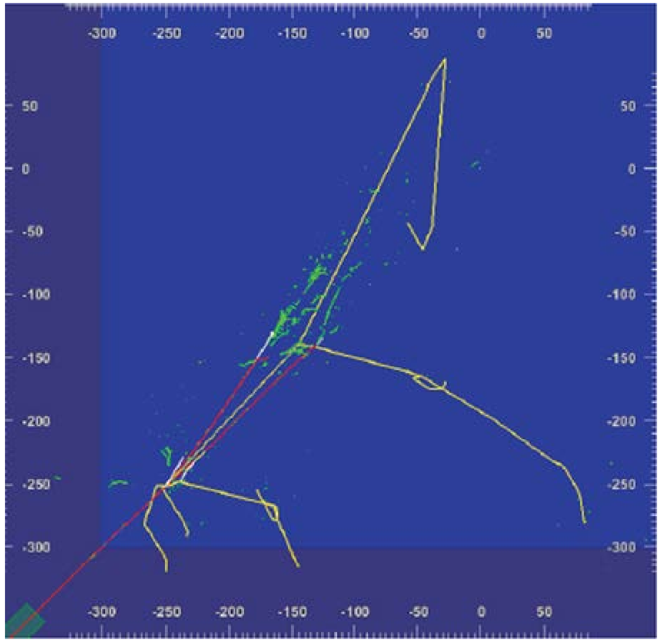
- Evaluate performance for π^0 rejection and proton decay, evaluate enhancements of performances related to double-phase detector (S/N, pitch, two collection views)

- Preparation of analysis tools for WA105 which will collect a few millions of hadrons/muons/electrons with particles pre-tagged on the beam line with TOF and Cerenkov counters (0.5-12 GeV/c)

→ ideal environment to apply dE/dx measurements and particle ID for hadrons from beam and secondary vertices of hadronic interactions (check particles ID and π^0 rejection)

Beam layout - H2-VLEext





Conclusions

- **Neutrino oscillations provide hints of new physics beyond Standard Model, we entered in a new era of precision measurements and search for CP violation**

- **Giant Liquid Argon TPCs are ideal detectors for these studies (excellent electron identification and reconstruction, 3D tracking/imaging, high resolution calorimetry, particles identification)**

- **Double phase Liquid Argon TPCs allow to extend this concept in a convenient way on very large target masses (many 10ktons needed for CP search): signal amplification, long drift, better S/N~100, lower thresholds, less readout channels**

- **Charge readout analysis is crucial for neutrino energy reconstruction, π^0 rejection, particle identification**

- **The knowledge of the charge readout and the detector response needs a precise knowledge of several basic aspects (how the simulation software handles the energy losses, the recombination effects, the effects related to electrons drift, the simulation of the detector response and analog and digital readout electronics and reconstruction effects related to hits and tracks reconstructions (angles w.r.t. the strips), identification of δ-rays)**

- **The developments on the dE/dx reconstruction and particle identification for WA105 will be used to analyze a few millions of hadronic interaction events which will allow to get to a very precise understanding of this matter**