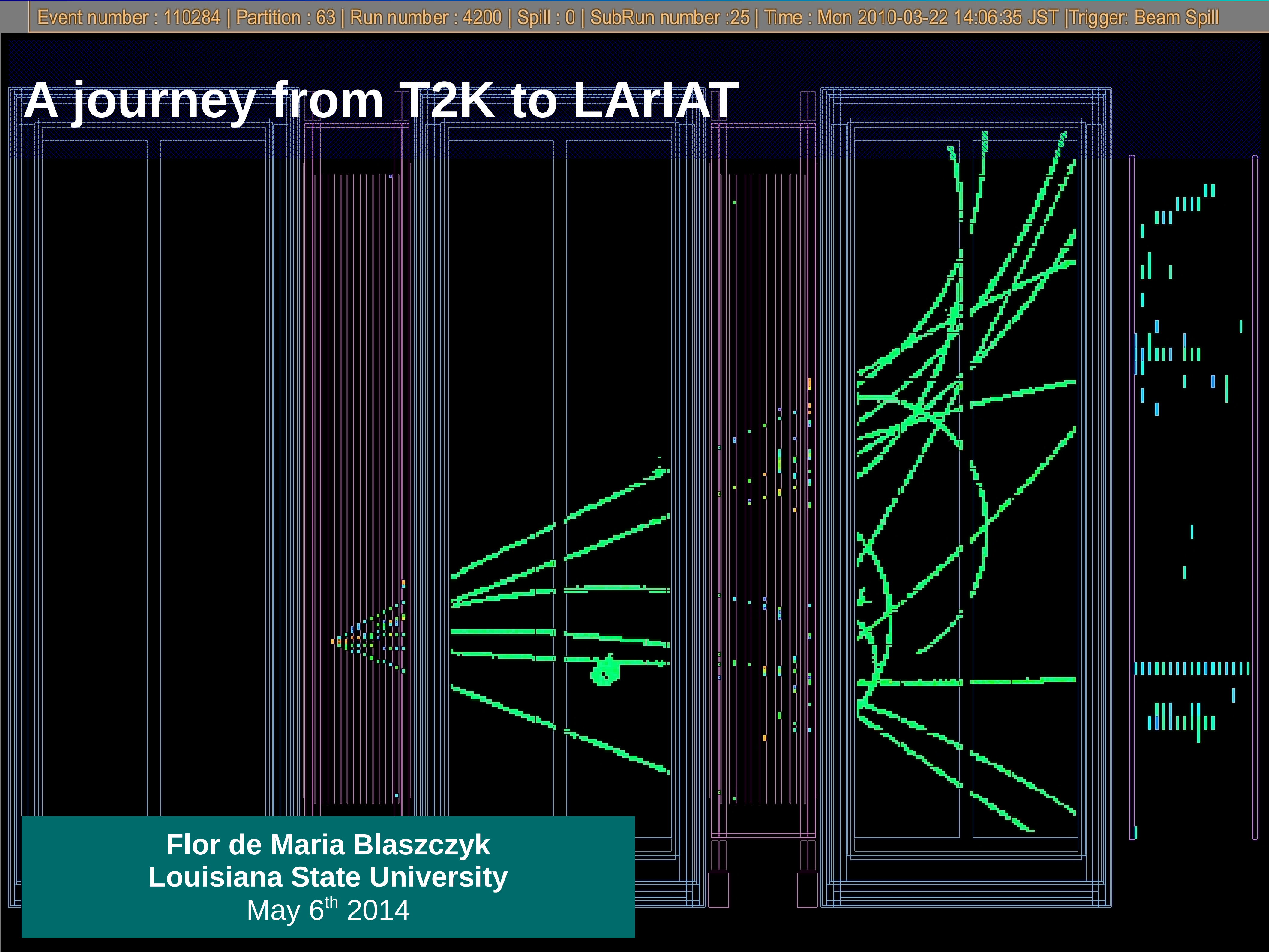


A journey from T2K to LArIAT

Flor de Maria Blaszczyk
Louisiana State University
May 6th 2014

Outline

- Introduction: neutrino physics
- T2K
  - The T2K experiment and the off-axis near detector
  - ν_μ flux and spectrum measurement in the near detector
  - Neutral current single pion cross-section
  - Other work
- LArIAT
  - Liquid argon TPCs goals and the LArIAT experiment
  - Online monitoring / slow control for LArIAT
- Conclusion

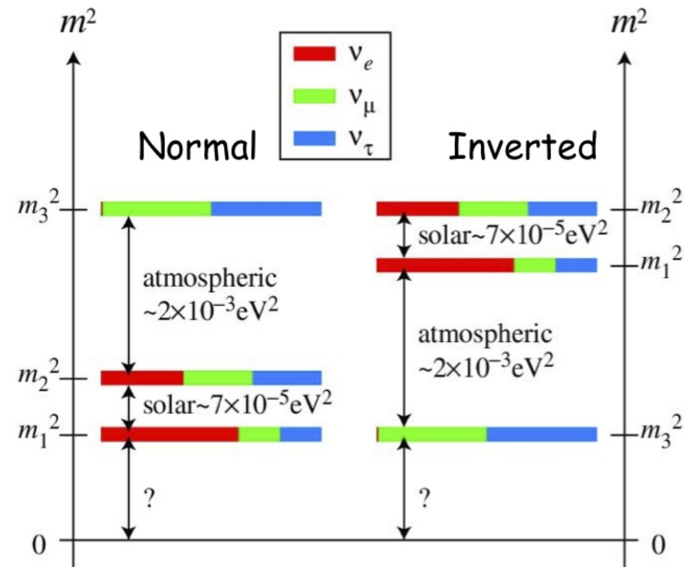
Neutrino physics

Neutrino physics challenges

- Neutrino nature: Majorana or Dirac? → neutrino = anti-neutrino?
- Neutrino oscillations :
  - 3 flavor eigenstates ≠ 3 mass eigenstates → PMNS matrix
  - Oscillation parameters: **2 Δm^2_{ij}** ($\Delta m^2_{ij} = m^2_i - m^2_j$), **3 mixing angles θ_{ij} and 1 phase.**
  - All parameters have been measured **except δ, the CP-violation phase**.

    → if $\delta \neq 0$, then CP violation in leptonic sector, hint for leptogenesis
  - Mass hierarchy normal or inverted?
- Neutrino masses?

  → From cosmological limits $\Sigma\, m_\nu < 0.3$ eV
- Sterile / right handed neutrinos?
- Relic neutrinos, supernovae neutrinos, geo-neutrinos ...



Neutrino physics is a rich and exciting field!

ν_μ osc. probabilities

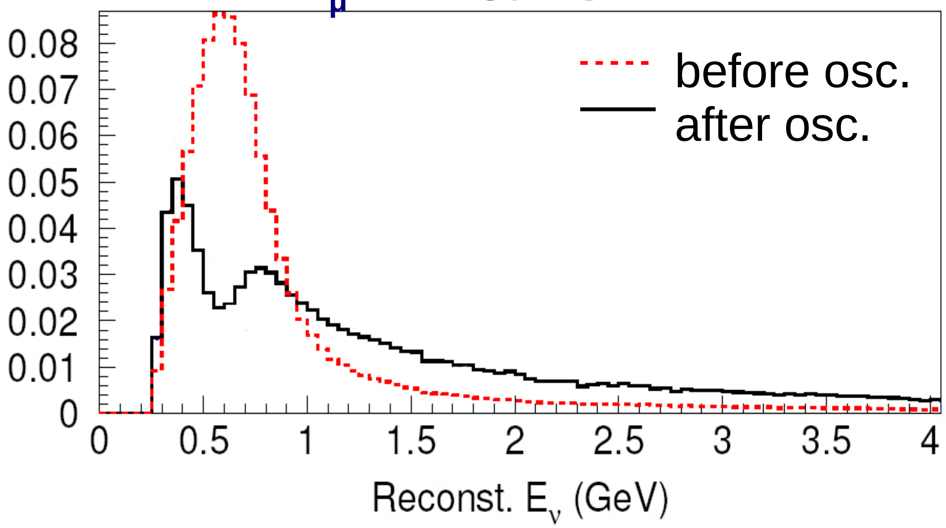
- Neutrino oscillation probability (simplified):

$$P(\nu_\mu \rightarrow \nu_e) \approx sin^2(2\theta_{13}) sin^2\left(1.27\Delta m^2_{13}\frac{L}{E_\nu}\right)$$

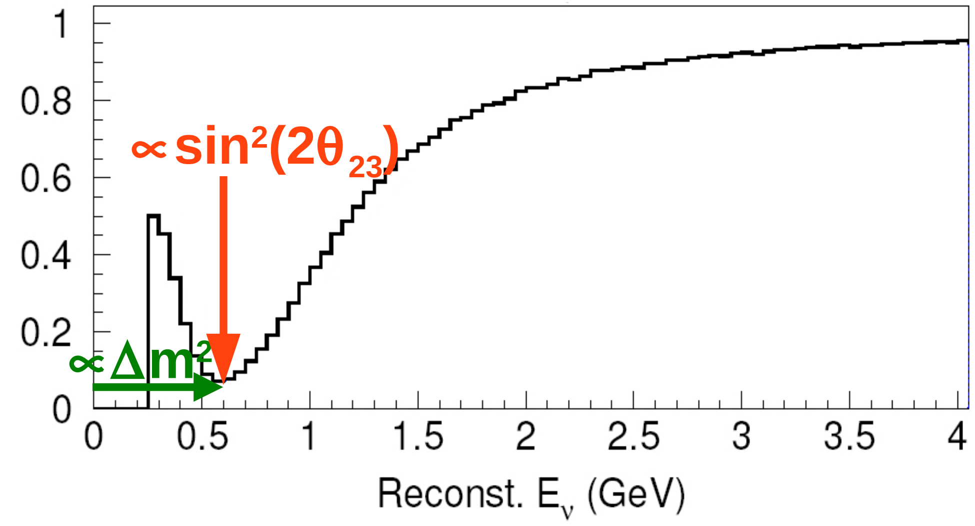
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - cos^4\theta_{13} sin^2(2\theta_{23}) sin^2\left(1.27\Delta m^2_{32}\frac{L}{E_\nu}\right)$$

→ where L = propagation distance (km), E_ν = neutrino energy (GeV).

ν_μ energy spectra



Ratio osc./unosc.

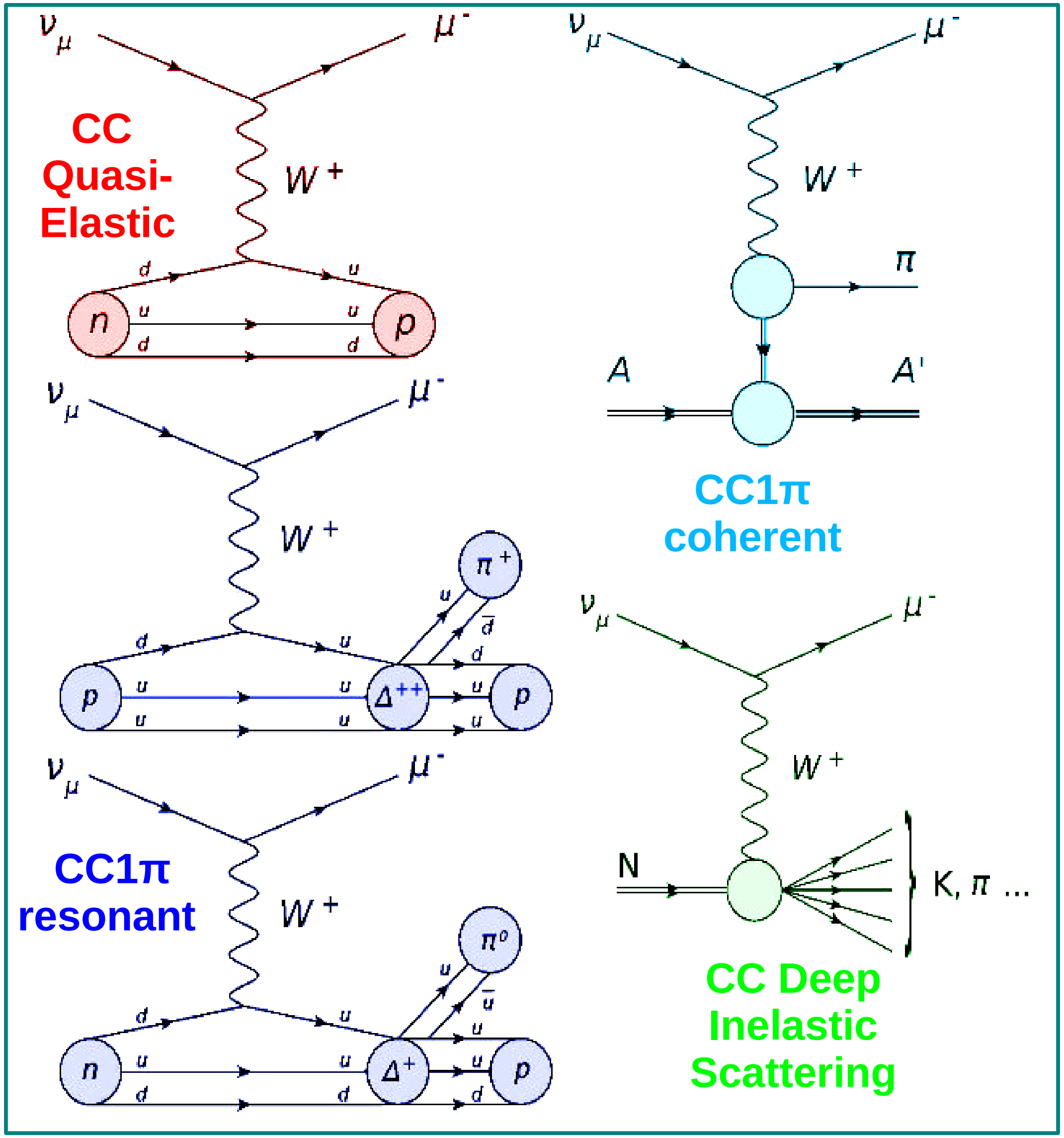


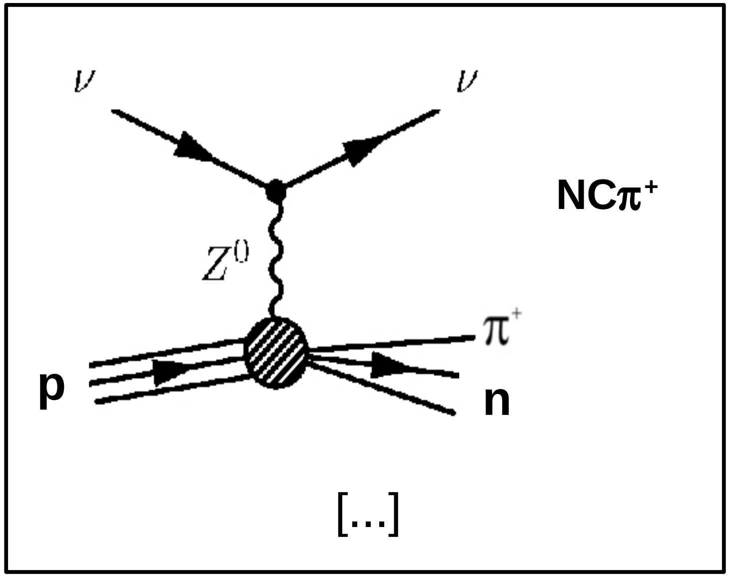
- Need to **reconstruct ν_μ energy**, measure the **ν_μ energy spectra** before and after oscillation, and **calibrate the energy scale.**

Neutrino-nucleus interactions

- Neutrino interact through weak interaction only, either through the exchange of a **W$^{\pm}$ boson (charged current)** or a **Z⁰ boson (neutral current)** with a nucleon or nucleus.

CHARGED CURRENT





NEUTRAL CURRENT

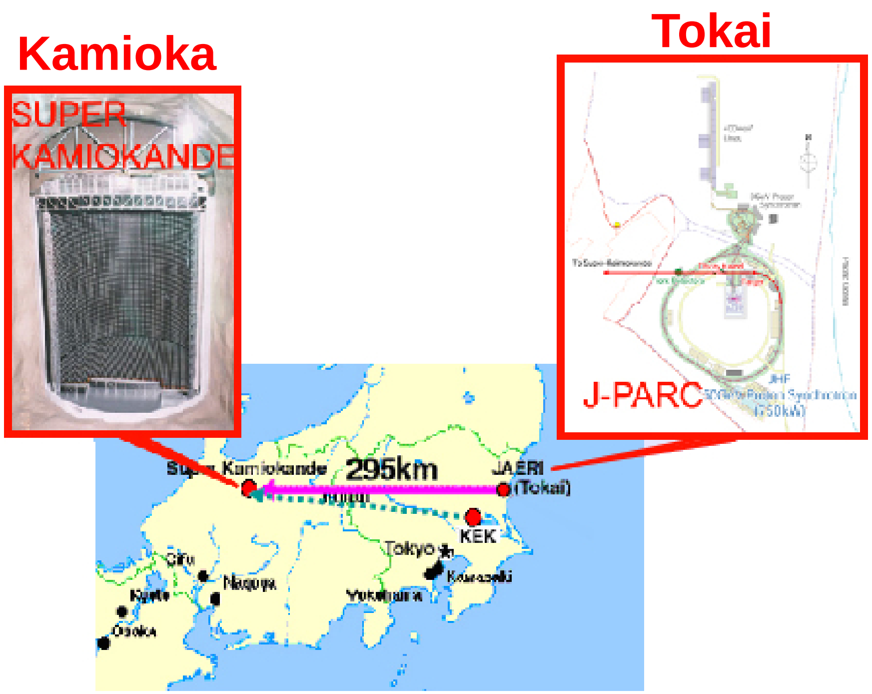
Used for ν_μ flux & energy spectrum measurement

n = neutron
p = proton
A = nucleus
N = nucleon

The Tokai to Kamioka experiment (T2K)

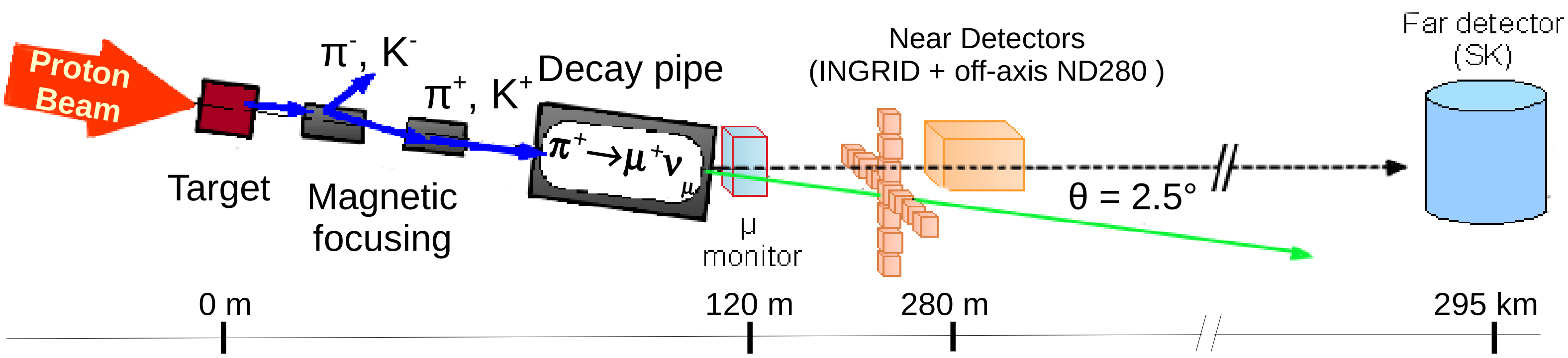
Tokai to Kamioka (T2K)

- **Goals**
  - $\nu_\mu \rightarrow \nu_e$ **:** Measure or improve limit on θ_{13} by at least an order of magnitude;
  - ν_μ **disappearance:** Precise measurement of Δm^2_{32} and θ_{23}.



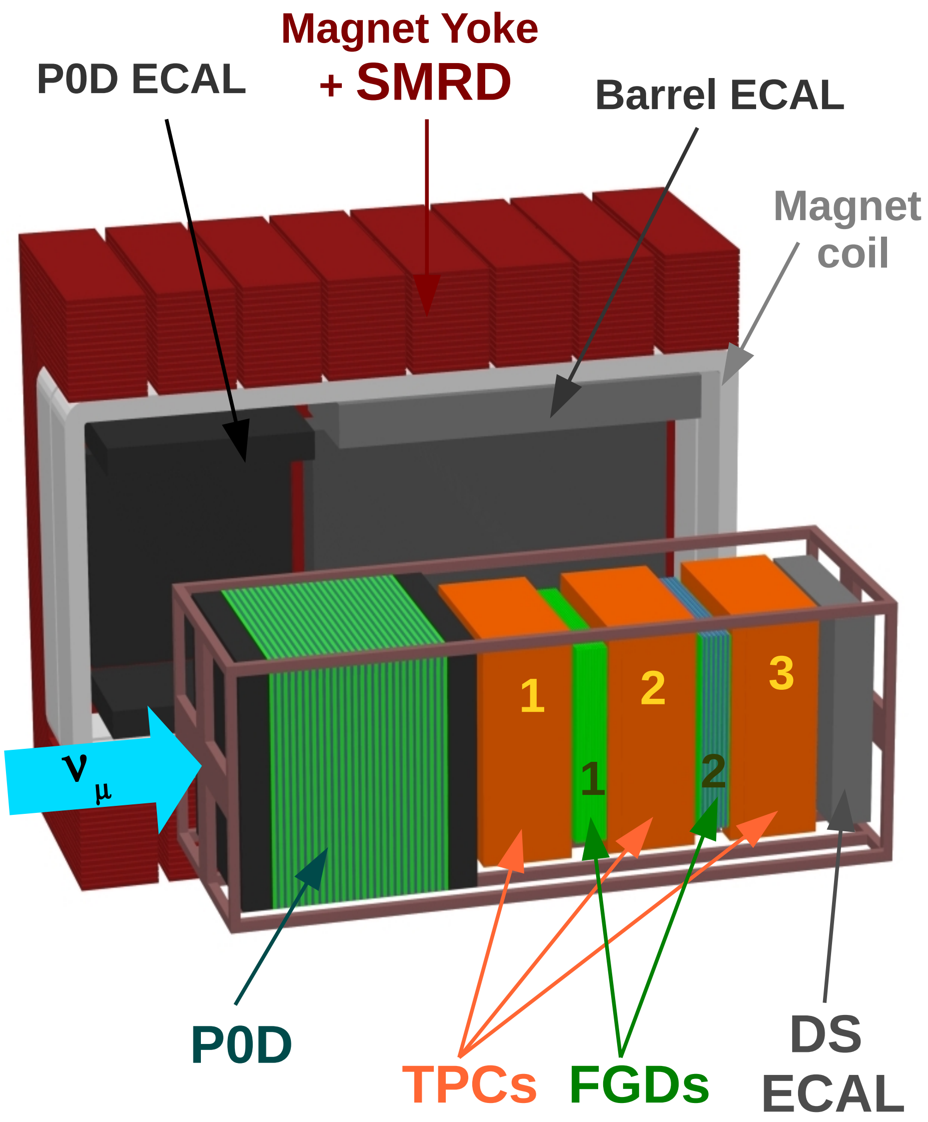
- **Off-axis ν oscillation long baseline experiment (Japan)**
  - ν_μ **beam (~600 MeV)** produced at **J-PARC** (Tokai) by a **30 GeV proton beam** ;
  - **Near** detectors: **ND280** at **280m**;
  - **Off-axis far** detector: **Super Kamiokande** at **295km**.

- Data taking started in January 2010.
- T2K will be delivered 5.10^{21} POT (protons on target).



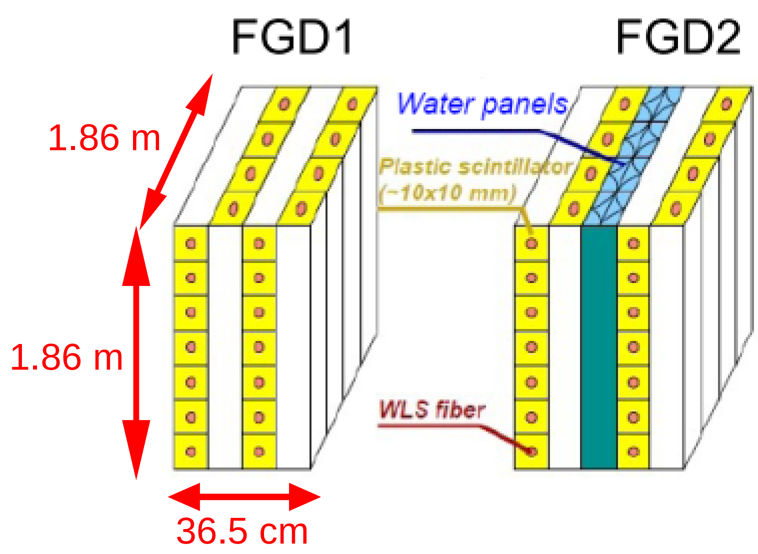
Off-axis near detector (ND280)

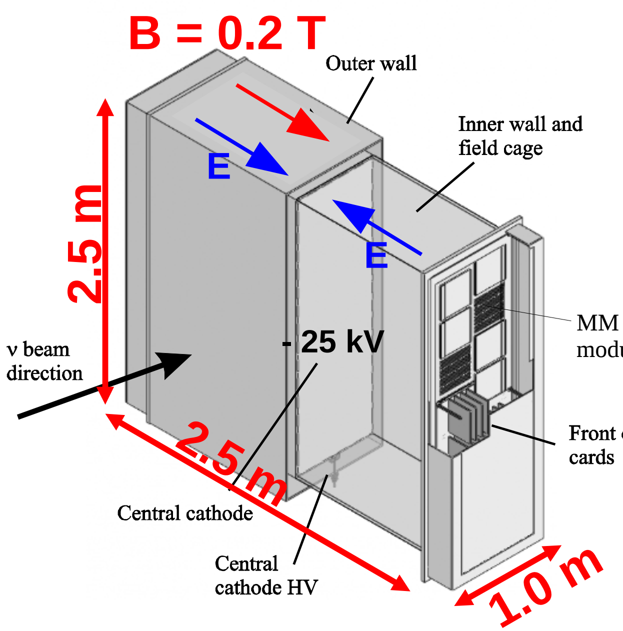
- Located at **280m** from the proton target, off-axis angle of **2.5°**.
- **Goals:**
  - **characterize** neutrino beam before oscillation
    → flux, ν energy spectra, beam composition and direction, ν interaction cross-section measurements.
- Uses **UA1 magnet: 0.188 T** magnetic field.
- **Different detector types:**
  - **P0D (π^0 detector) ;**
  - **Tracker**: **3 Time Projection Chambers (TPCs) + 2 Fine Grained Detectors (FGDs)** ;
  - **ECAL** (Electromagnetic calorimeter) ;
  - **SMRD** (Side Muon Range Detector) embedded in the magnet yoke.



ν_μ flux measurement in the off-axis near detector tracker

Near detector tracker





Fine grained detectors (FGDs)

- Provide **target mass** for neutrino interactions (~1 ton per FGD).
- Measure **neutrino cross sections** in carbon and water (oxygen).
- **Track and vertex reconstruction.**

- **FGD design:**
  - **Thin scintillator bars** organized in X-Y layers
  - Additional **passive water panels** in FGD2

Time projection chambers (TPCs)

- **Reconstruct charged particle's tracks**
- **Particle identification** (dE/dX resolution < 10%) → distinguish μ / e and protons / π.
- **Momentum measurement** (resolution < 10% @1 GeV) → measure track curvature.

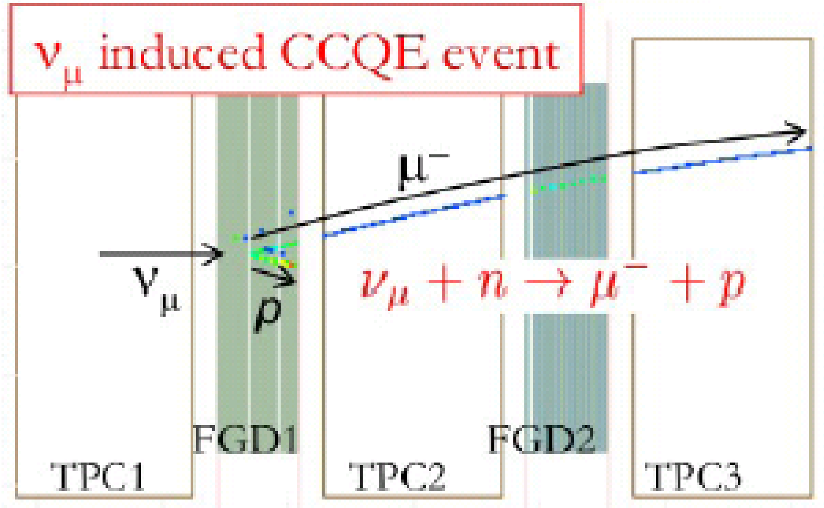
- **TPC design :**
  - Gaseous detector instrumented with **bulk MICROMEGAS** on the readout plane.

Motivations and goal

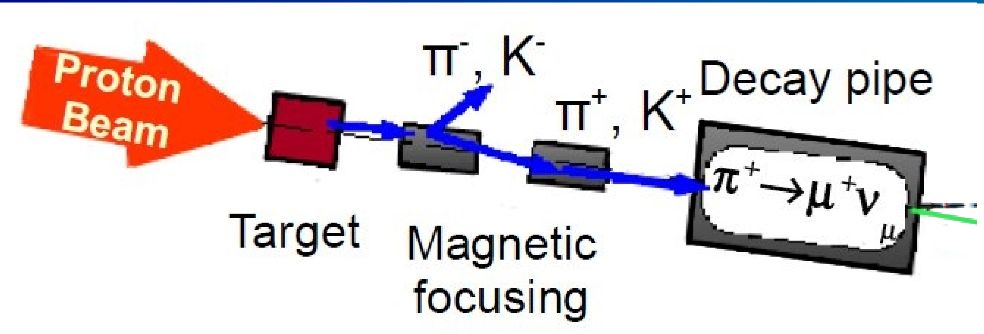
- ***Motivation:*** Δm^2_{32} and θ_{23} measurement require both the oscillated and the **unoscillated ν_μ flux and energy spectrum**.

- ***Goal:*** **first measure of the ν_μ energy spectrum** at the near detector for future oscillation analyses and **validation of the 1st T2K oscillation analyses**.

- ***What are we looking for ?***
  - ν_μ flux and spectrum can be measured using an **inclusive charged current sample**.
    → simple and robust, good for 1st data sample
    → charged current events tagged with the **outgoing muon track**.



Flux prediction

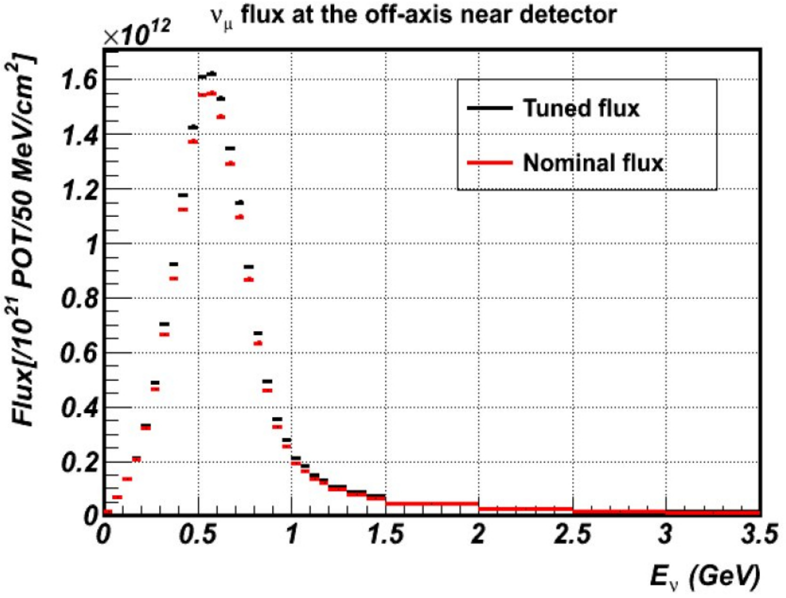


- The **flux prediction** will be compared to the measured flux per energy bin.
- Simulation is divided into 2 main steps:
  - **Hadroproduction** (GCALOR or FLUKA2008).
    → tuned with SHINE data (CERN hadroproduction experiment).
  - **Beam propagation** (JNUBEAM, GEANT3).

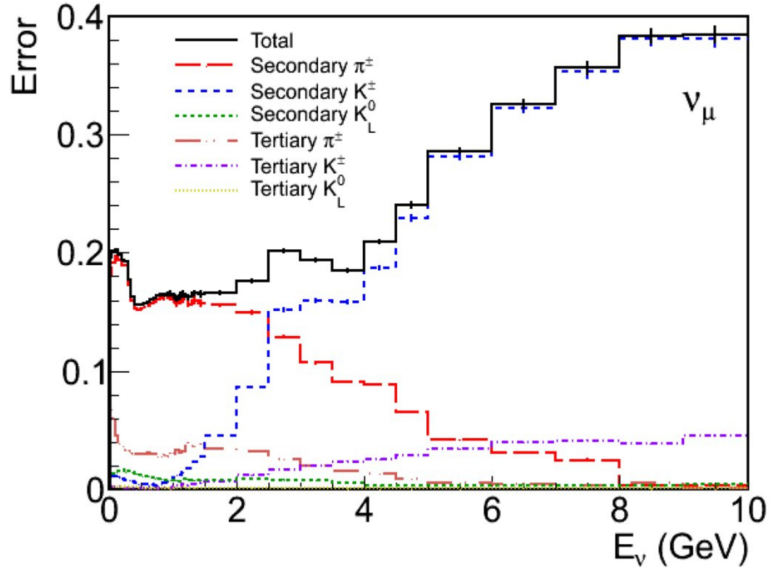
- Uncertainty up to 15% for $E_\nu < 1$ GeV and up to 30% for $E_\nu > 1$ GeV.

→ **limited by hadroproduction understanding** (π + K multiplicity and production cross-sections).

ν_μ flux prediction at ND280



Uncertainty on flux prediction



Data / MC samples

- **Data set:** Full 1st T2K data set (2010, January - June runs)

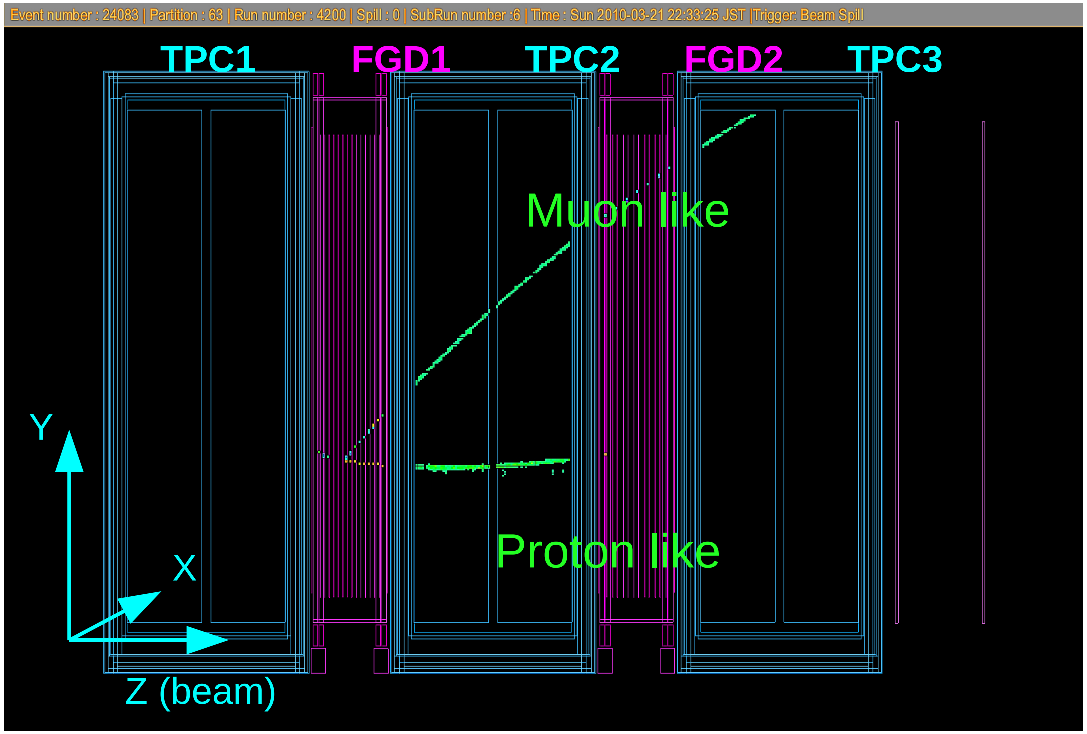
  → **2.91×10^{19} POT (protons on target)** .

Currently T2K has been delivered ~ 10^{21} POT!

- **Monte Carlo sample:**

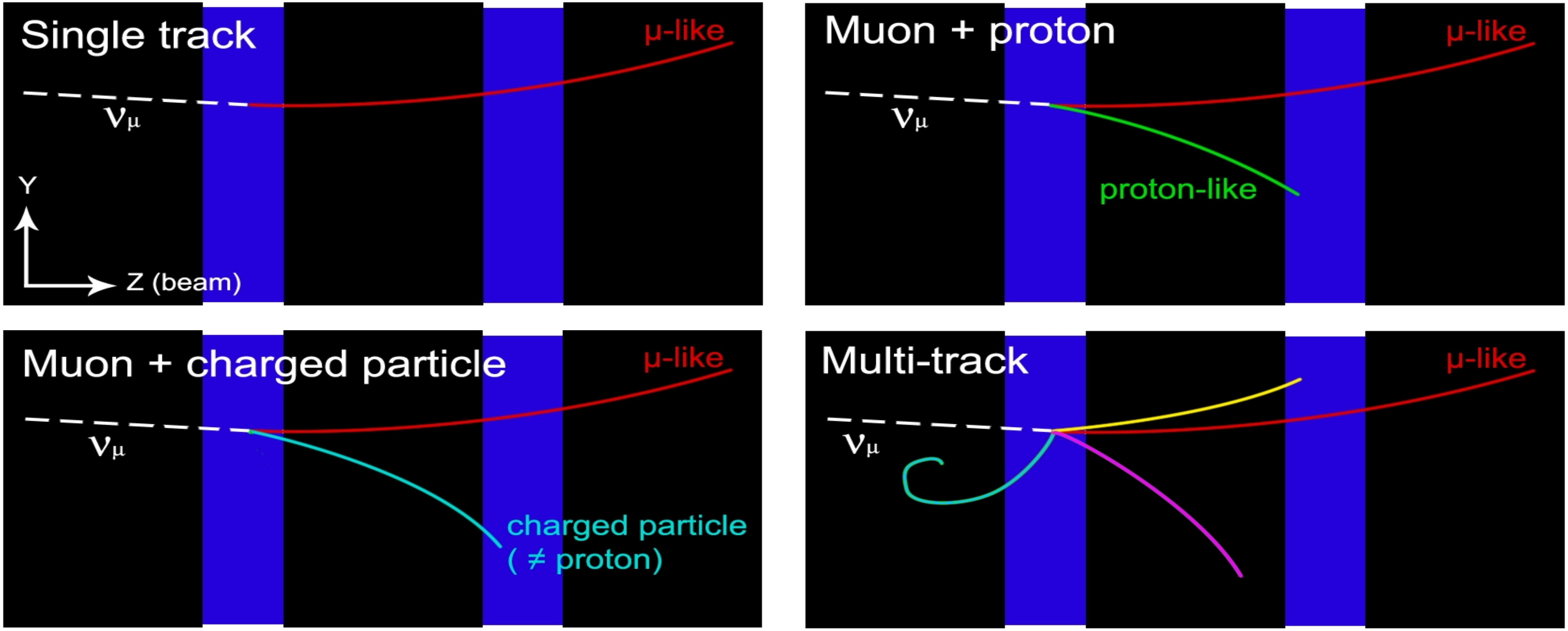
Neutrino interaction generator NEUT, full off-axis detector with magnet geometry simulated by GEANT 4.

- Normalization: **POT_{MC} / POT_{Data} = 33.7**



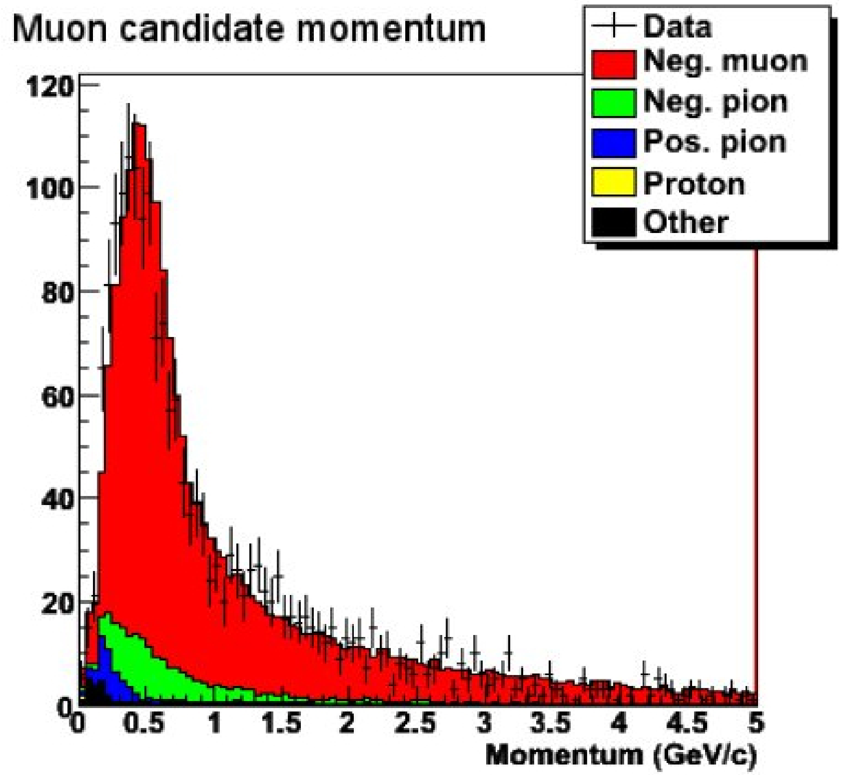
CCQE candidate event observed in the near detector tracker

Event selection



- **All tracks must cross at least ¼ of the TPC** (18 pts) and be within 10 cm radius of the muon track starting point
- Muon candidate cuts:
  - **Negative track with highest momentum**
  - **Must start in either FGD1 or FGD2** (fiducial volume ~ 78% of the total volume)
  - PID cuts: Compatible with **μ hypothesis at < 2.5 σ** and incompatible with **e hypothesis at > 2 σ**
- Proton-like track must be consistent with the proton hypothesis (momentum and dE/dx cuts).

Selected sample



- Good agreement between normalized MC and data after selection.
- **μ purity of the sample: 84%**
- **Charged current purity (CCQE): 84.35% (42.71%)**
- **Charged current in fiducial volume efficiency: 46.04%**

Flux fit method (1)

- **CCQE hypothesis to reconstruct ν_μ energy**, spectrum binned in 9 energy bins up to 5 GeV.

$$E_\nu^{CCQE} = \frac{m_P^2 - m_\mu^2 - m_{Neff}^2 + 2m_{Neff}E_\mu}{2(m_{Neff} - E_\mu + p_\mu \cos\theta)}$$

Bin e^ν_{meas}	e^ν_{meas} range (GeV)
1	0 - 0.2
2	0.2 - 0.4
3	0.4 - 0.6
4	0.6 - 0.8
5	0.8 - 1
6	1 - 1.5
7	1.5 - 2
8	2 - 3
9	3 - 5

- Minimize -log likelihood (Poisson distribution probability)

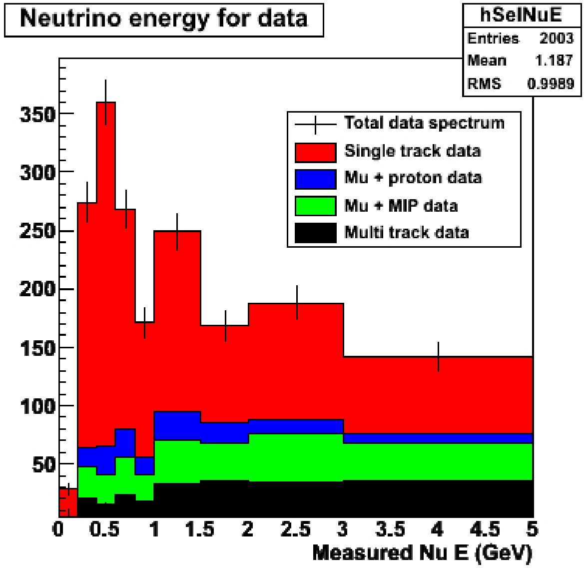
$$-ln(\mathcal{L}_{full}) = \sum_{e_{meas}=1}^{9} n_{exp}(e_{meas}) - n_{obs}(e_{meas}) \times ln(n_{exp}(e_{meas}))$$

- Expected number of events for a measured energy bin

$$n_{exp}(e_{meas}) = \underbrace{\int_0^\infty n_{exp}(e_{true})de_{true} \times P(e_{meas}|e_{true})}_{\text{flux dependent}} + \underbrace{n_{exp}^{bgd}(e_{meas})}_{\text{fixed}}$$

→ Energy resolution $P(e_{meas}|e_{true})$

→ Backgrounds: NC, out-of-FV, anti ν_μ, ν_e and anti ν_e.



Flux fit method (2)

- **Expected number of events for a true energy bin**

$$n_{exp}(e_{true}) = f(e_{true})\Phi(e_{true}) \times \sum_{j_{atom}=C,H,O} N_{j_{atom}} \sum_{k_{proc}=1}^{4} \sigma_{j_{atom},k_{proc}} \times \epsilon_{k_{proc}}(e_{true})$$

Flux factors we fit
(expected to be close to 1)

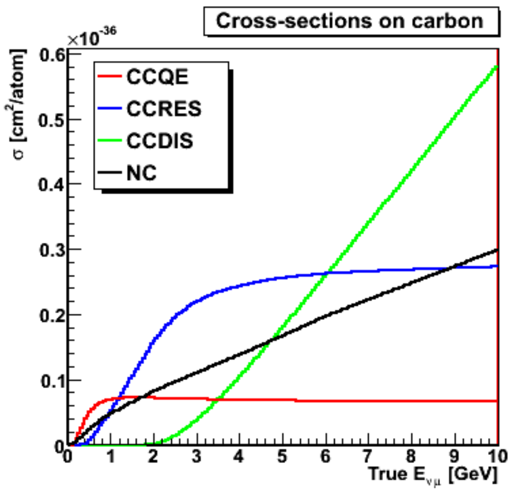
Predicted fluxes $\Phi(e_{true})$
(from slide 13)

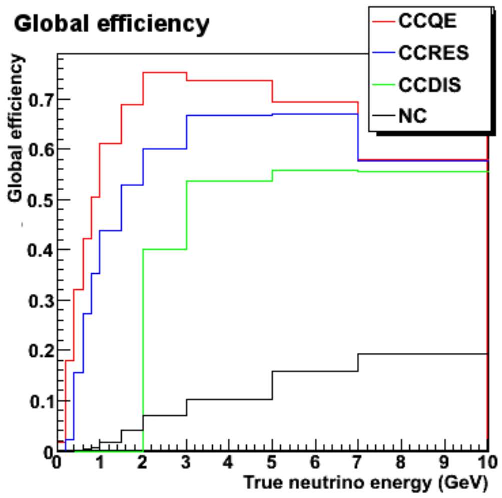
Number of each atom type N
(C, H, O) in the fid. vol.

Cross-sections σ on C, H, O
per interaction type

Global efficiencies ε
nb of selected evts / generated evts

- Interaction types k_{proc}: CCQE, CCRES (all CC - CCQE - CCDIS), CCDIS, and NC (background)



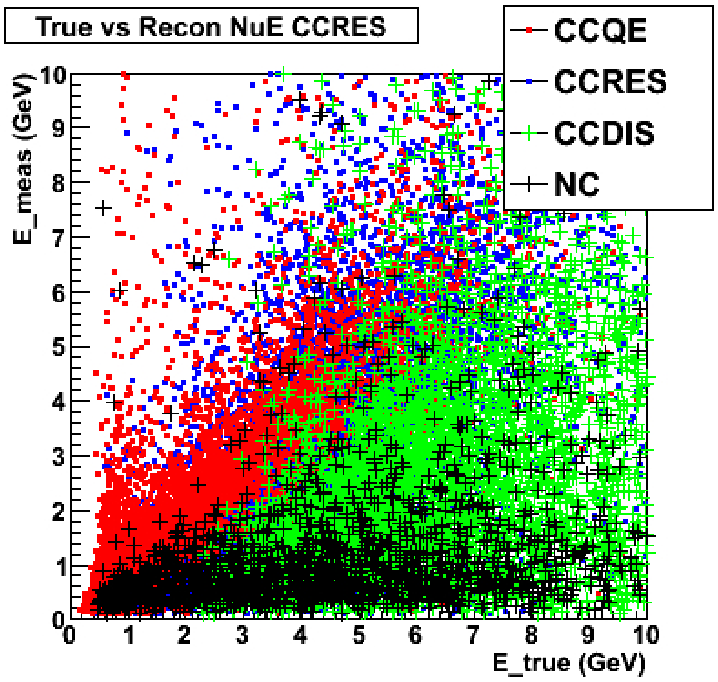


Energy resolution

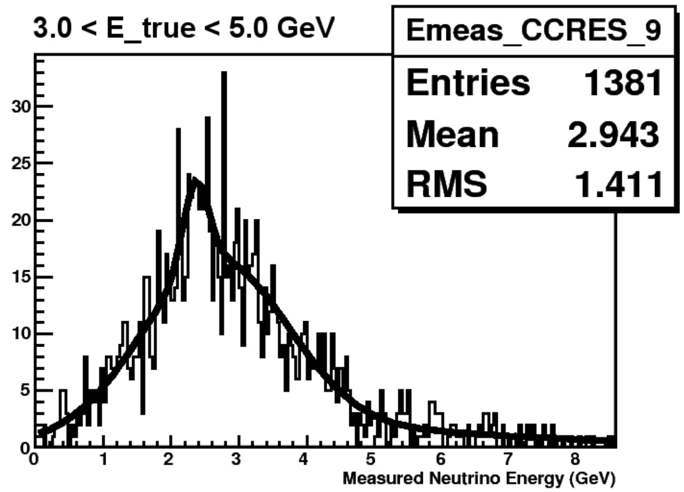
- Represents the probability to reconstruct E_{meas} knowing E_{true}, and **depends on the interaction type** and to a lesser extent of the topology.

- CCQE resolution matrix is mainly diagonal, CCRES/CCDIS/NC matrices have important **off-diagonal contributions** → **strong correlation** between energy bins → **large errors** in the fit.

- E_{true} > 10 GeV contribute to E_{meas} < 5 GeV → correction applied for E_{true} > 10 GeV.



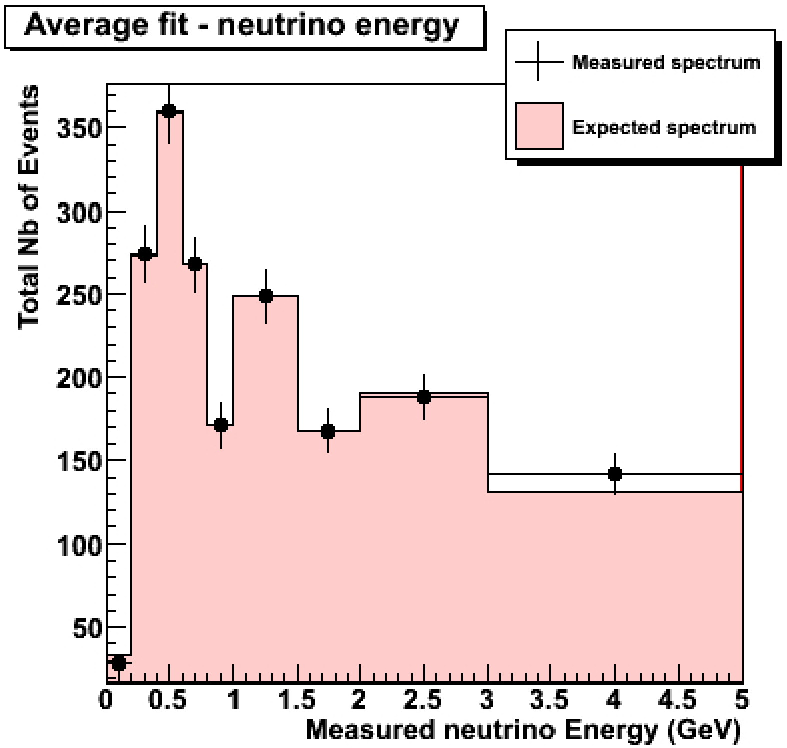
Fit example for CCRES category 9th true energy bin, 2 track topo combined



Data fit results

Correlation with low bin → f_2

f_1	1 (fixed)
f_2	3.813 ± 0.825
f_3	1.101 ± 0.160
f_4	0.627 ± 0.141
f_5	0.893 ± 0.305
f_6	0.789 ± 0.365
f_7	1.333 ± 0.686
f_8	1.524 ± 0.453
f_9	0.712 ± 0.191



- Prior to fitting data, the procedure was validated with Monte Carlo using 2 different approaches.

- Good agreeement between expected spectrum after fit and measured spectrum.

Systematics

Several sources of systematic uncertainties were studied:

- Cross-section related uncertainties (see next slide)
- Out-of-fiducial volume contamination

  → cannot be predicted by calculation but can study how the variation of the fraction of out-of-fv events changes the flux factors.
- Final state interactions (theoretical models)

  → comparison between GENIE and NEUT, which have different approaches on FSI.
- Other sources of error:
  - Number of atoms in the fiducial volume
  - Contributions from true energies higher than 5 GeV
  - PID related errors

Systematics: Cross-sections

- Cross-section related systematics computed by applying ± 1 σ variations on each process cross-section independently.

Int. Category	< 2 GeV	> 2 GeV
CCQE	25%	
CCRES	46%	30%
CCDIS	30%	25%
NC	36%	

- Fit the flux factors and compute difference with the non-modified results.

f_2	-0.894	+1.049
f_3	-0.202	+0.281
f_4	-0.113	+0.170
f_5	-0.159	+0.257
f_6	-0.151	+0.237
f_7	-0.328	+0.377
f_8	-0.169	+0.225
f_9	-0.228	+0.314

Correlation with low populated neighboring bin (f_2)

≈ uncertainty on cross-sections (f_3–f_9)

→ **Our flux measurement is limited by the uncertainties on cross-sections.**

Flux fit summary

- **Data fit results with fit errors and detailed systematic errors**

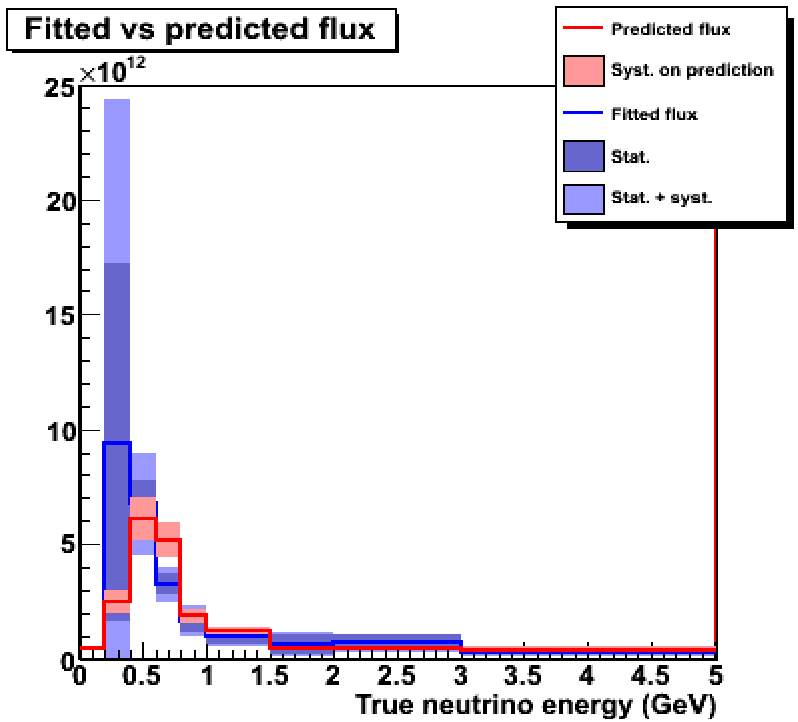
	Average fit	Xsec	Out-of-FV	Th. Model	E > 5 GeV	N_{atom}	$Pull_{\mu}$
f_2	3.813 ± 0.825	$^{+1.049}_{-0.894}$	$^{+0.850}_{-0.767}$	± 0.097	± 0.007	± 0.016	± 0.020
f_3	1.101 ± 0.160	$^{+0.281}_{-0.202}$	$^{+0.043}_{-0.046}$	± 0.005	< 0.001	± 0.016	± 0.020
f_4	0.627 ± 0.141	$^{+0.170}_{-0.113}$	$^{+0.026}_{-0.026}$	± 0.010	± 0.003	± 0.016	± 0.020
f_5	0.893 ± 0.305	$^{+0.257}_{-0.159}$	$^{+0.022}_{-0.027}$	± 0.019	± 0.002	± 0.016	± 0.020
f_6	0.789 ± 0.365	$^{+0.237}_{-0.151}$	$^{+0.031}_{-0.037}$	± 0.035	± 0.013	± 0.016	± 0.020
f_7	1.333 ± 0.686	$^{+0.377}_{-0.328}$	$^{+0.042}_{-0.032}$	± 0.178	± 0.126	± 0.016	± 0.020
f_8	1.524 ± 0.453	$^{+0.225}_{-0.169}$	$^{+0.014}_{-0.026}$	± 0.151	± 0.156	± 0.016	± 0.020
f_9	0.712 ± 0.191	$^{+0.314}_{-0.228}$	$^{+0.094}_{-0.057}$	± 0.005	± 0.231	± 0.016	± 0.020

- Our measurement is **limited by the knowledge on neutrino interaction cross-sections**.
- Improvements possible: **more statistics** (both data and MC) and **fit measured energies up to 10 GeV**

Flux fit conclusions

- **First measurement of the ν_μ energy spectrum successful!**
- **The initial flux prediction and the fitted flux are in good agreement** within the errors.
  - → flux prediction is validated as well as the oscillation analyses!

	Average ± stat. ± syst.
f_2	$3.813 \pm 0.825 ^{+1.354}_{-1.182}$
f_3	$1.101 \pm 0.160 ^{+0.285}_{-0.209}$
f_4	$0.627 \pm 0.141 ^{+0.174}_{-0.119}$
f_5	$0.893 \pm 0.305 ^{+0.260}_{-0.164}$
f_6	$0.789 \pm 0.365 ^{+0.243}_{-0.162}$
f_7	$1.333 \pm 0.686 ^{+0.438}_{-0.396}$
f_8	$1.524 \pm 0.453 ^{+0.314}_{-0.278}$
f_9	$0.712 \pm 0.191 ^{+0.402}_{-0.331}$

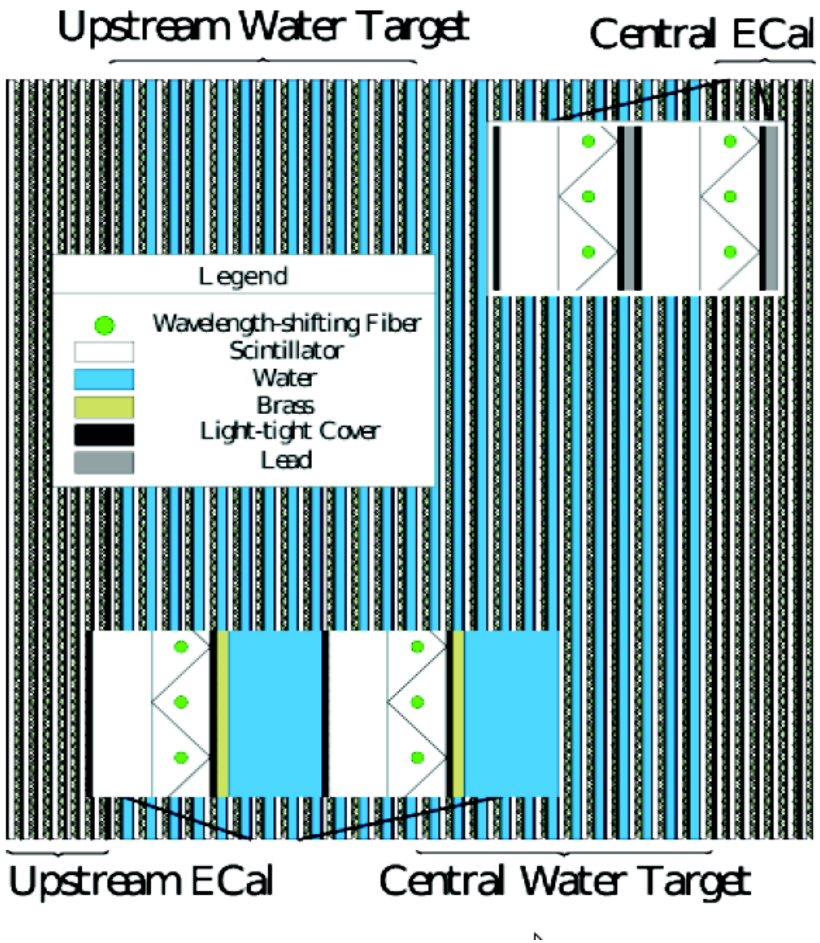


Neutral current single π^+ cross-section measurement in the P0D (feasibility study)

Near π^0 detector (P0D)

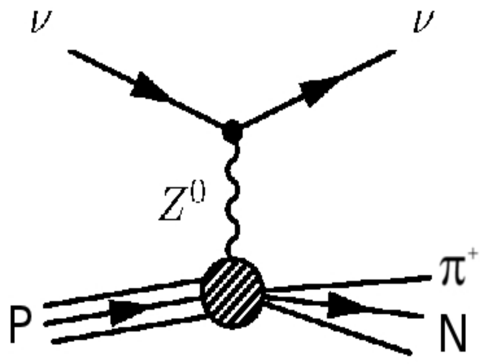
- **Purpose:**
  - Provide **target mass** for neutrino interactions (~13-16 tons).
  - Measure **neutrino cross sections** in carbon and water (oxygen), in particular the ones with **π^0 in the final state**.
  - **Track and vertex reconstruction.**

- **P0D design:**
  - **Thin triangular scintillator bars** organized in X-Y layers alternating with brass or lead sheets
  - Cental volume: **water bags** between each scintillator + brass sheet group
  - Fibers read with **multi-pixel photon counters** (MPPC)



Goals and motivation

- Measuring the NC1π^+ xsec with the P0D
  → single measurement done by Gargamelle
  → in T2K, tracker analysis (C. Liccardi thesis)
- Can shed some light on final state interactions



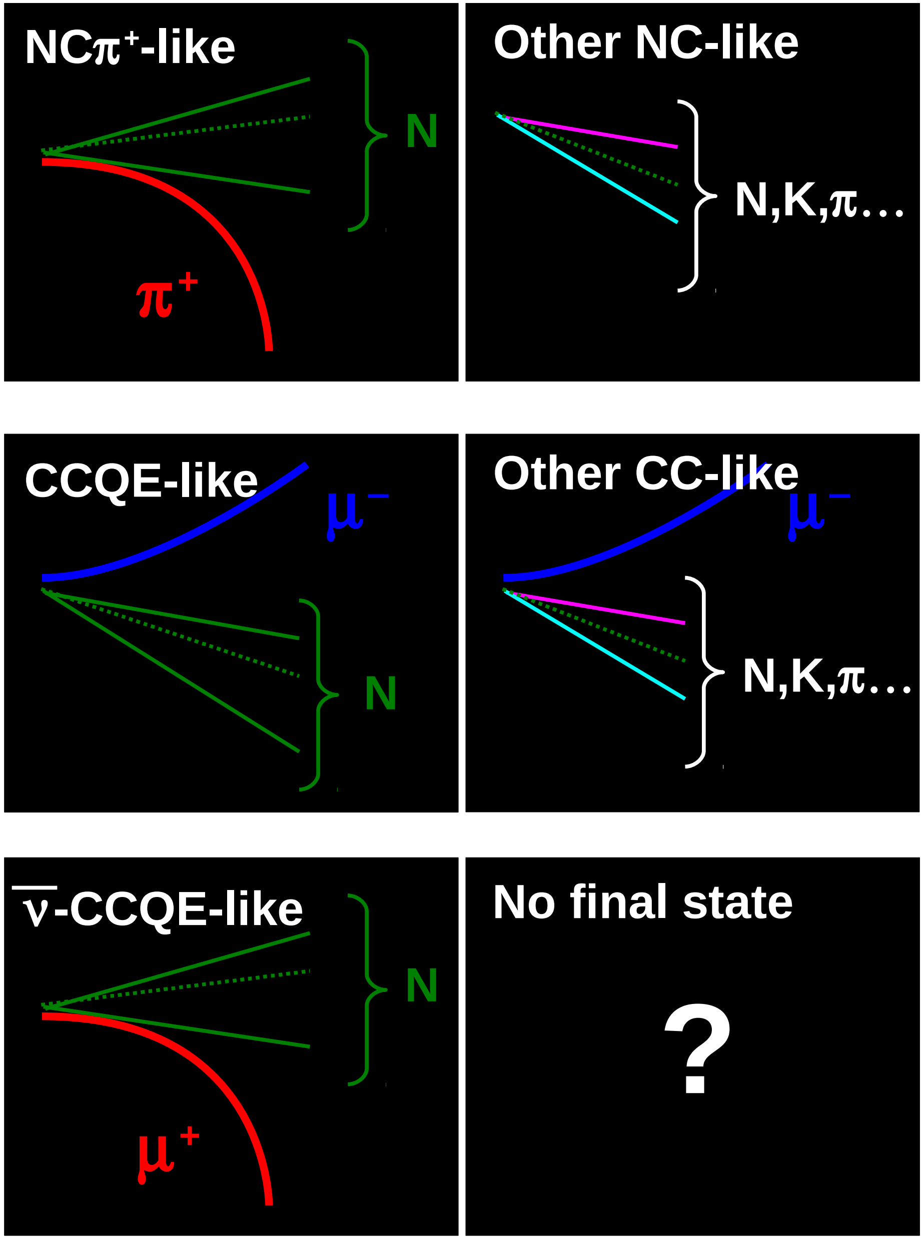
- **Signal: Single positive track (consistent with a π^+)**

  → *no charged leptons, no other mesons, N baryons (because of final state interactions).*

- Expected main background: muons (μ^+ from anti-ν CCQE and from μ^- CCQE).

This is a Monte Carlo-simulation-only analysis

Truth: generated in P0D FV



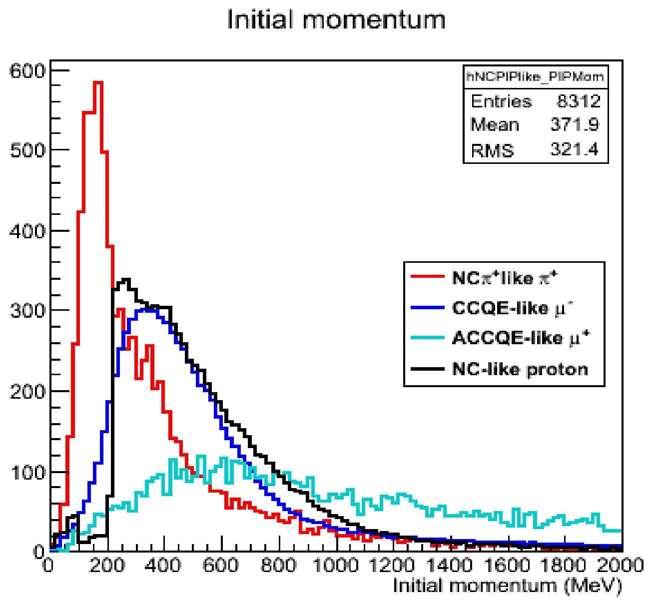
Before FSI

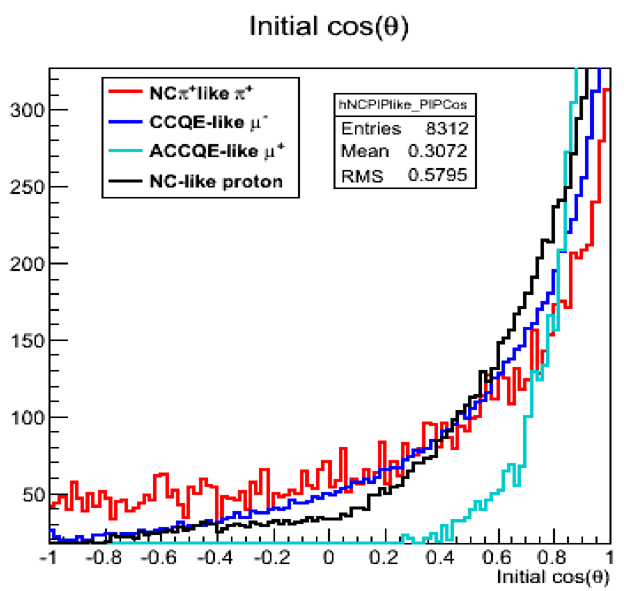
	NEUT channel	
Total	581 872	100 %
NCπ+	**9 059**	**1.6 %**
CCQE	219 681	37.8 %
CCπ+	100 953	17.3 %
CC-other	89 548	15.4 %
Anti-ν CCQE	5 557	0.9 %
NCE	94 048	16.2 %
NC-other	63 026	10.8 %

After FSI

	Final state	
NCπ+ like	**8 312**	**1.4 %**
CCQE-like	250 107	43 %
Other CC-like	146 928	25.2 %
ACCQE-like	6 424	1.1 %
Other NC-like	163 353	28.1 %
No final state	6 748	1.2 %

Expectations from truth





- π+ from NCπ+ have:
  → more scattering (nuclear interactions) → more kinks (broken tracks?)
  → lower momentum

- Rejection of:

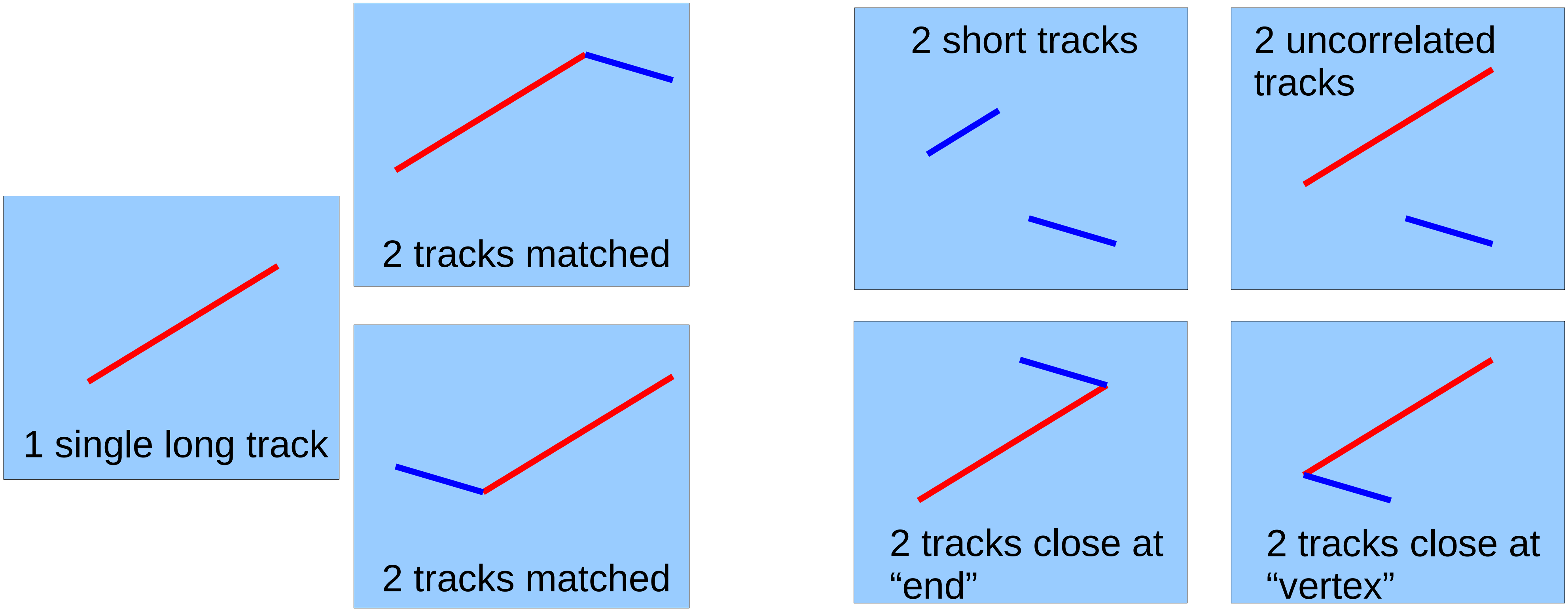
- anti-ν CCQE: apply cut on momentum
  → requires momentum reconstruction

- CCQE / CC in general:
  → μ- identification: good charge (negative or positive track) reconstruction

  →vertex activity cut (for CCQE in particular, when the proton is not reconstructed)

- Other NC, NCE in particular:
  →proton identification: use PID defined in neutral current elastic analysis (D. Ruterbories).

Event selection



SELECTED **REJECTED**

1) 1 reconstructed track > 15 cm, starting in P0D fiducial volume
2) "Kinked" track proximity cut < 10 cm
3) Tracks must be contained and Kalman filter fitted
4) **Longest track must be positive**
5) Initial charge < 120 peu (sum of 1st 2 hit clusters of the most upstream track)
6) Proton/muon PID cut at the end of most upstream track < 20

Event rates per topology

	All events	
Total	**269 403**	**100 %**
2 short	**106 478**	**39.5 %**
Single long	**135 186**	**50.2 %**
2 tracks	**27 739**	**10.3 %**
Uncorrelated	11 453	4.3 %
Close at vtx	14 954	5.5 %
Close at end	251	0.1 %
Matched	1 081	0.4 %

(1 short, 1 long = 2350)

	NCπ+ like	
Total	**2 291**	**100 %**
2 short	**599**	**26.1 %**
Single long	**1 459**	**63.7 %**
2 tracks	**233**	**10.2 %**
Uncorrelated	170	7.4 %
Close at vtx	38	1.7 %
Close at end	11	0.5 %
Matched	14	0.6 %

(1 short, 1 long = 45, 2 long 232)

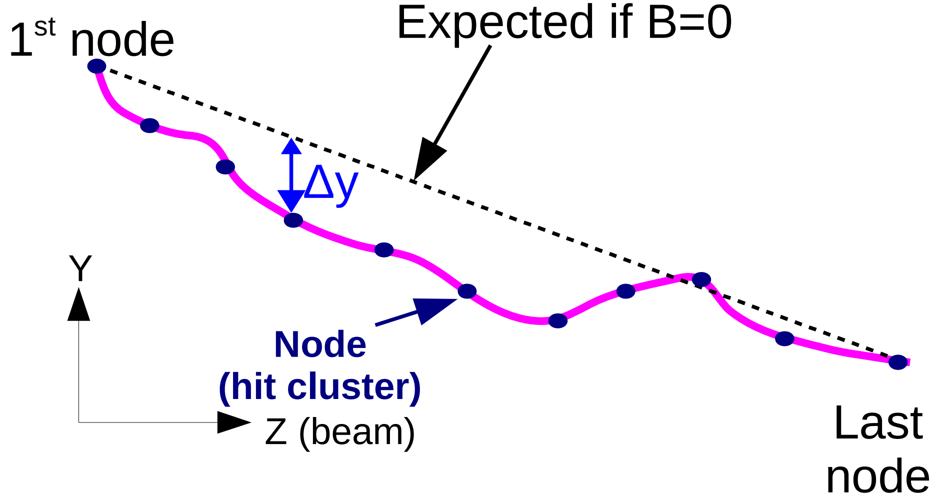
Almost 40% of the total events have 2 tracks shorter than 15cm
→ Reconstruction issue or real short tracks?

→ **Leads to rejecting 26 % of the signal!!!**
→ **Constrained by PID charge reconstruction**

PID Charge reconstruction

- No charge reconstruction algorithm available and because of scattering in P0D, difficult to compute track curvature.
- Principle:
  - Compute “expected” track if B = 0
  - Compare node position to expected position, y-wise.
  - Sum the differences

    → $\sum \Delta y > 0$ = negative particle



- **Tracks must be at least 15cm** to compute properly the charge.
- P0D has 2 algorithms for track reconstruction → **only using Kalman fitted** tracks, the others are too short / not curved enough.
- **To study efficiency, particle guns samples generated:**

  → 20k events each, 0 – 2 GeV uniform, 30°cone along z direction (neutrino beam direction), uniformly generated in P0D (**π^+**, **μ^-** , and **proton)**

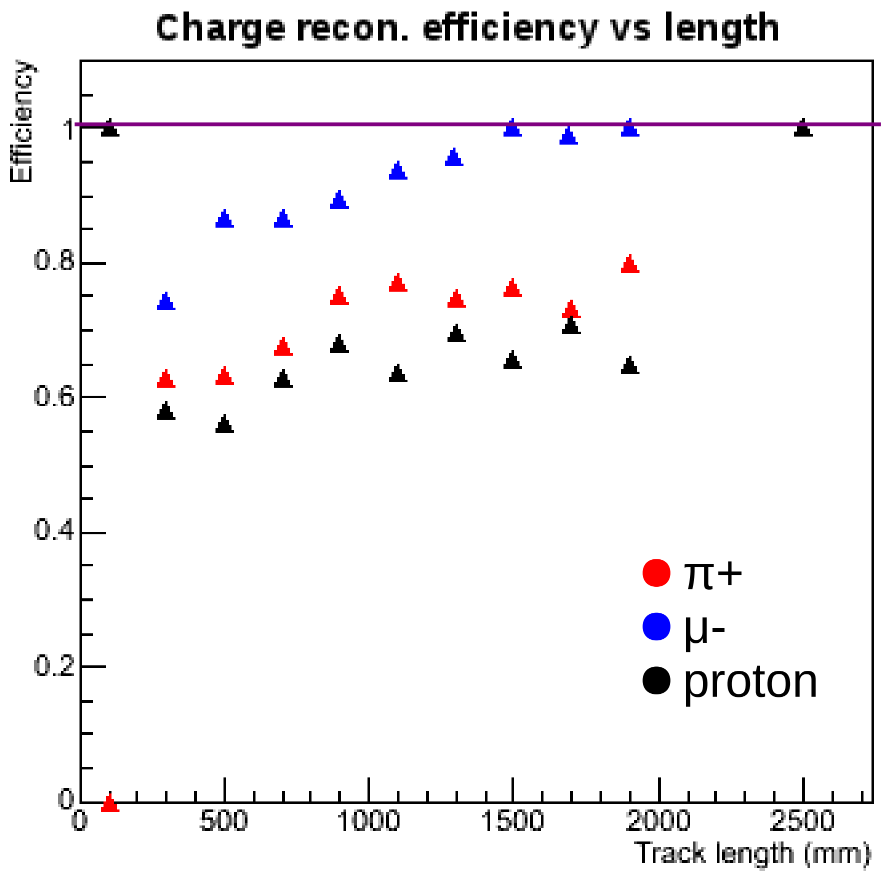
Charge reconstruction (2)

Expected track method

Efficiencies obtained after topologies, P0D containment, and Kalman cuts

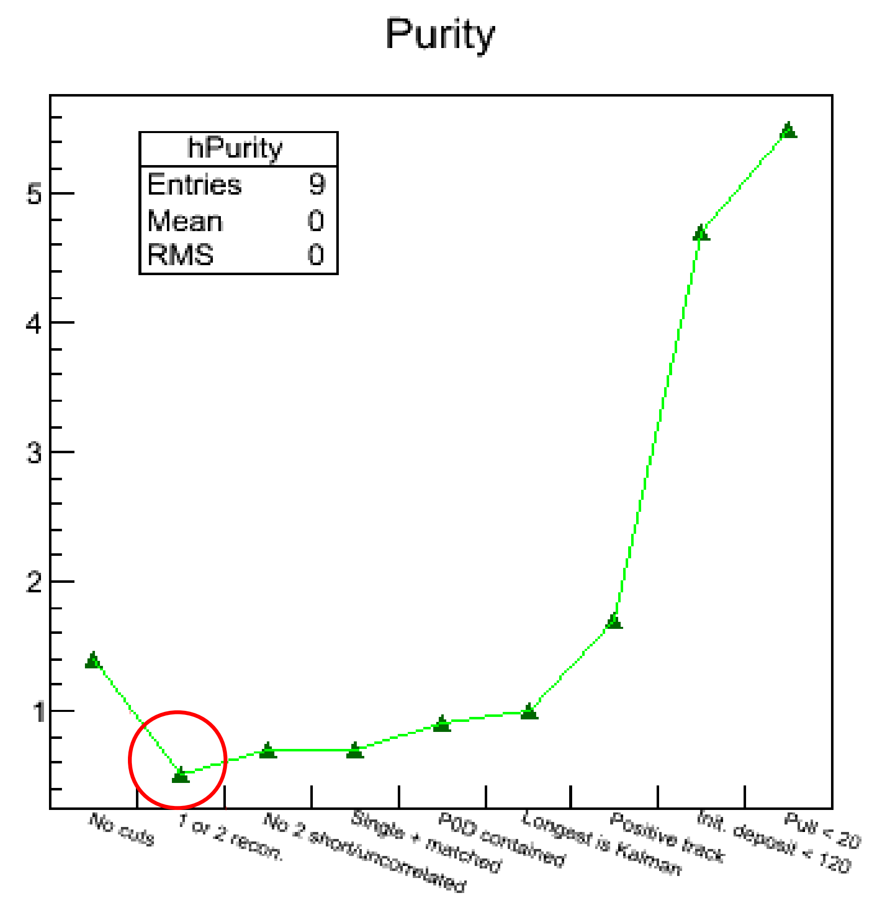
Particle gun files					
	Q ok	Mis-ID	Fail	Total	Efficiency
π+	583	263	0	846	**68.9 %**
μ-	1 170	114	0	1 284	**91.1 %**
Proton	912	555	0	1 467	**62.2 %**

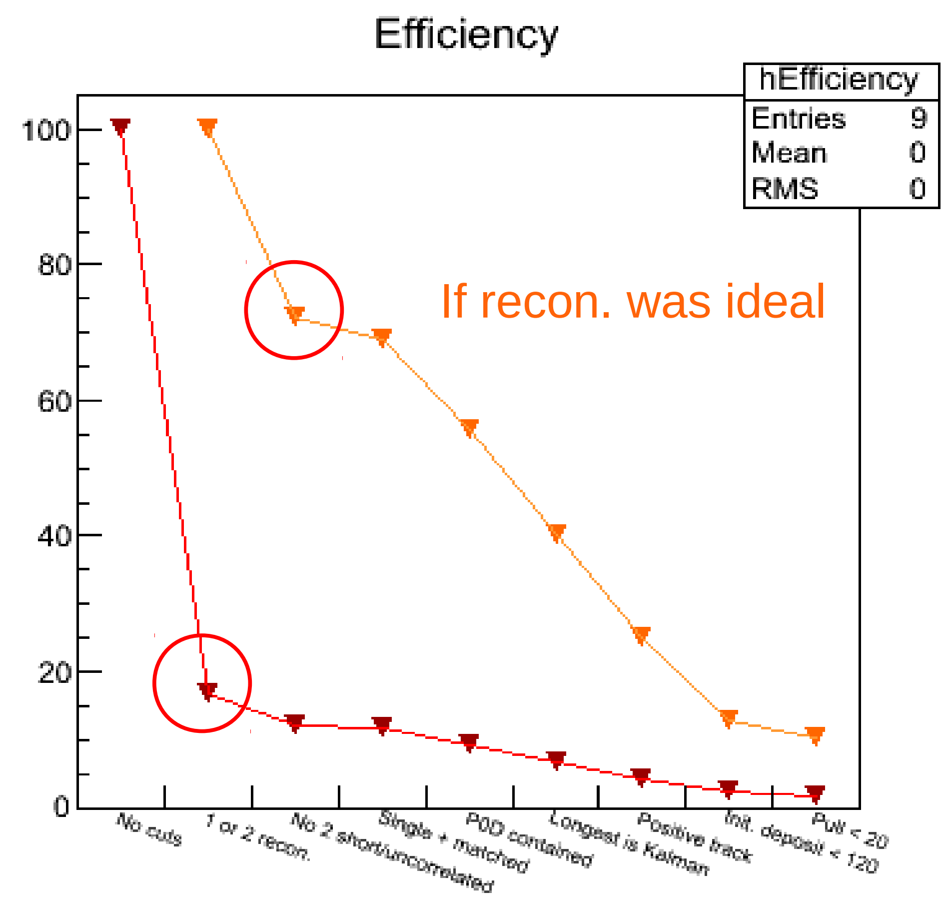
- Pions, muons and protons have with energies between 0 and 2 GeV.
- If 2 tracks “matched” into 1, charge cut applied on the longest track
- Lower efficiencies for protons and pions because more scattering.



Efficiency and purity

	Total	NCπ+ like	CCQE like	ACCQE like	CC like	NC like	No FS	Out of FV
After cuts	2 612	144	1 173	277	266	145	87	520





$$\text{Purity}_i = \frac{\text{Nb. of NC}\pi^+\text{-like after cut i}}{\text{Total nb. of events after cut i}}$$

$$\text{Efficiency}_i = \frac{\text{Nb. of NC}\pi^+\text{-like after cut i}}{\text{Generated nb. of NC}\pi^+\text{like in FV}}$$

NCπ^+ conclusion

- **Efficiency needs to be increased:**
  - Recover events with short tracks or uncorrelated tracks
  - Include parametric fitted tracks
  - Improve track reconstruction, in particular for kinked tracks

  → *Better reconstruction algorithm under study.*

- **To increase purity**:
  - Optimize selection cuts / change cut order
  - Add unused hits to the initial charge deposition cut to improve CC-like rejection

Measurement feasible once reconstruction becomes more efficient
On stand-by for now

Other work for T2K

- Feasibility study: calibration of the absolute momentum scale of the tracker by reconstructing the invariant mass of K^0

  → feasible if good control of backgrounds

- Micromegas-bulk module cross-talk measurements.

  → measured the cross-talk between 2 neighbouring pads with a ^{55}Fe source.

- Participated in the production and testing of the Micromegas modules at CERN

  → gain and uniformity mapping, supervision of detector baking.

- Participated in the installation of the TPCs in Japan and tested the front-end electronics.

- Pion formation zone reweighting implementation to study impact of formation zone on cross-section measurements / oscillation analyses.

Liquid Argon TPC in a Test-beam (LArIAT)

Liquid argon TPCs

	Water	He	Ne	Ar	Kr	Xe
Boiling Point [K] @ 1atm	373	4.2	27.1	87.3	120.0	165.0
Density [g/cm^3]	1	0.125	1.2	1.4	2.4	3.0
Radiation Length [cm]	36.1	755.2	24.0	14.0	4.9	2.8
Scintillation [γ /MeV]	-	19,000	30,000	40,000	25,000	42,000
dE/dx [MeV/cm]	1.9		1.4	2.1	3.0	3.8
Scintillation λ [nm]		80	78	128	150	175

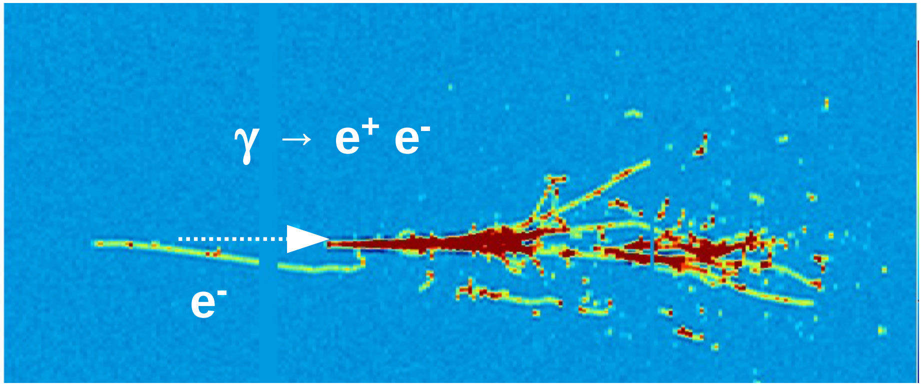
- Small neutrino cross-sections → massive detectors needed
- Better than 80% signal (CC ν_e) efficiency (T2K efficiency ~ 66%)
- ν_e appearance background rejection (π^0) → photon / electron discrimination possible
- Detection through ionization (3D tracking) and scintillation (trigger)
- Ionization electrons can be drifted over long distances → large detectors possible
- Good dielectric properties → high-voltages possible
- Liquid argon is cheap and easy to obtain

LArIAT Goals

“How well known are the energy resolution and particle identification capabilities of LArTPCs?”

→ Place a LArTPC in a charged particle test beam = LArIAT is born!

ArgoNeut



- Goals:
  - Electron / photon shower separation
  - Optimization of particle identification :

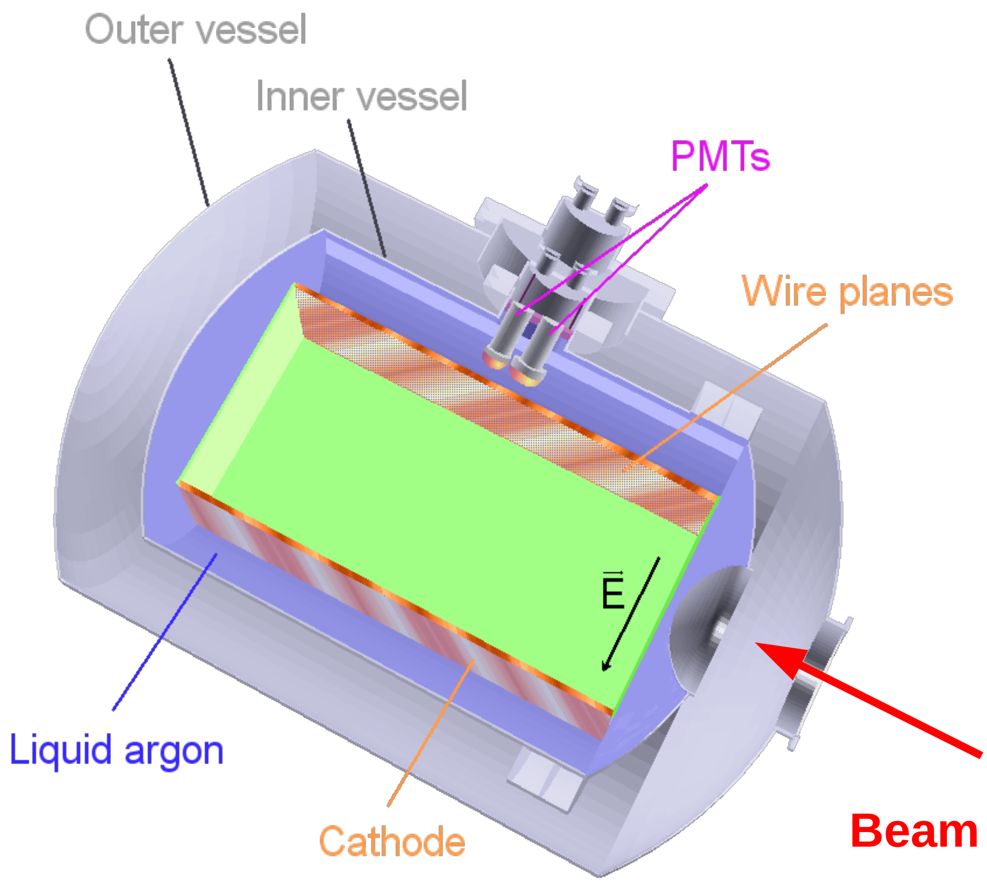
    → Proton ID, proton / K separation

    → Kaon ID, K / π / μ separation
  - Muon and pion sign determination without magnetic field → efficiency, purity
  - Cross-section measurements

Modified ArgoNeut cryostat for LArIAT

LArIAT Design

- Refurbished ArgoNeut TPC and cryostat.
- Features:
  - Active volume: 175 L (550 L cryostat)
  - 90 cm x 40 cm x 47.5 cm TPC
  - 3 wire planes: 1 induction, 1 collection plane, 1 shield
  - Scintillation light collection: 2 standard PMTs (+ 2 SiPM)
  - New cryogenic system
  - Cold readout electronics
  - New DAQ



LArIAT sliced top view

What do we want to monitor?

- The experiment will be in a beam enclosure area so it is important to be able to control the devices remotely and if possible place them outside...

- “Basic” items :
  - **Beam:** beam triggers, power
  - **Cryo:** temperature, pressure, levels
  - **TPC wire planes:** voltages, currents
  - **TPC and veto PMTs:** voltages, currents

Responsible for this part

- A bit more sophisticated:
  - **Beam:** particle type, particle momentum
  - **Cryo:** purity, filters
  - **Wire planes:** pedestals, hit occupancy, pulse shape
  - **PMTs:** noise level / pedestals
  - **Electronics:** nb. of crates / cards / channels

How do we want to monitor?

- Which framework?
  - Re-use old system? Not possible, ArgoNeut did not have an OM framework.
  - Needed quickly, cannot start from scratch...

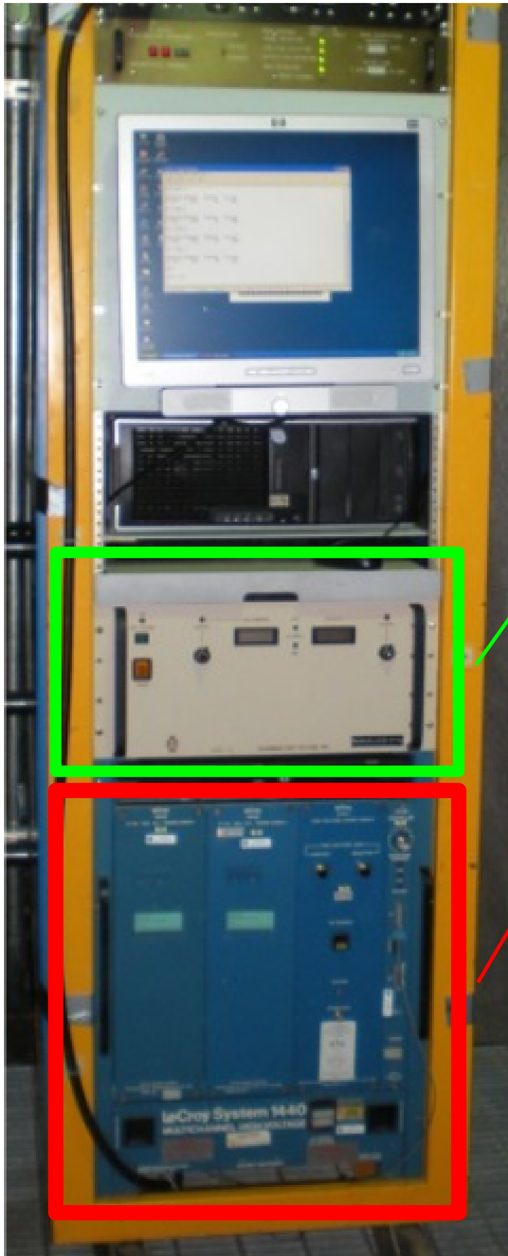
    → Accelerator control based framework, ACNET
  - Needs to be easy to use

    → Java based GUI Synoptic.

- Is it compatible with the equipment we have?

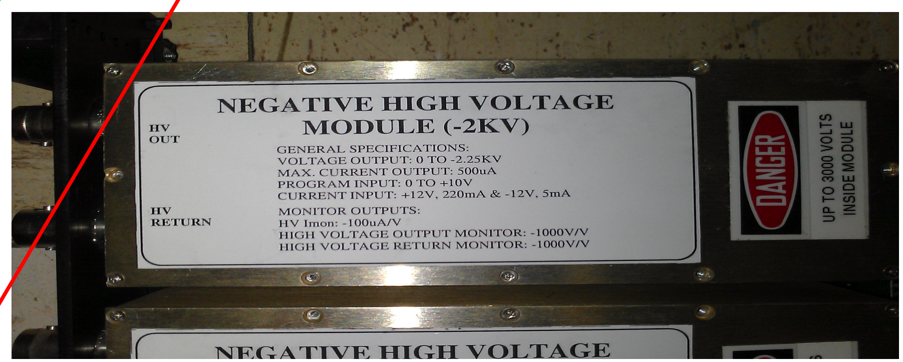
  → no, ArgoNeut did not have remote control so when possible, we need to upgrade to “ACNET friendly” devices.

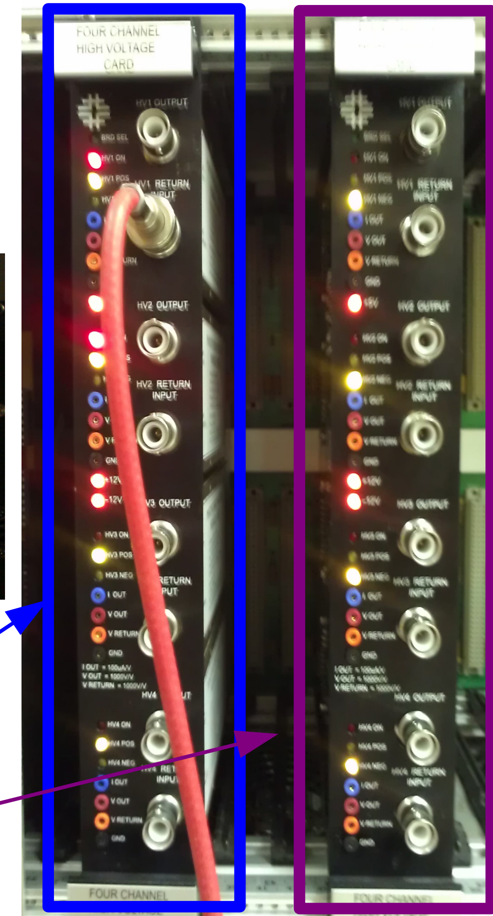
HV supplies: old and new



Glassman LX-125: for cathode HV
Exists in ACNET, but with RS232 protocol, C. Briegel (AD) has built an HRM as interface... currently working on installing it.

LeCroy 1440: for TPC wire planes bias and PMTs
Replaced by AD cards. (provided by B. Fellenz)





Positive voltage

Negative voltage

Online monitoring status

- Display and controls ready for most HV supplies

→ some are still on waiting list to be added to ACNet

- Cryogenic system will have iFix controls

→ implementation is quite straightforward since used for NOνA: only need to provide a list of device tags.

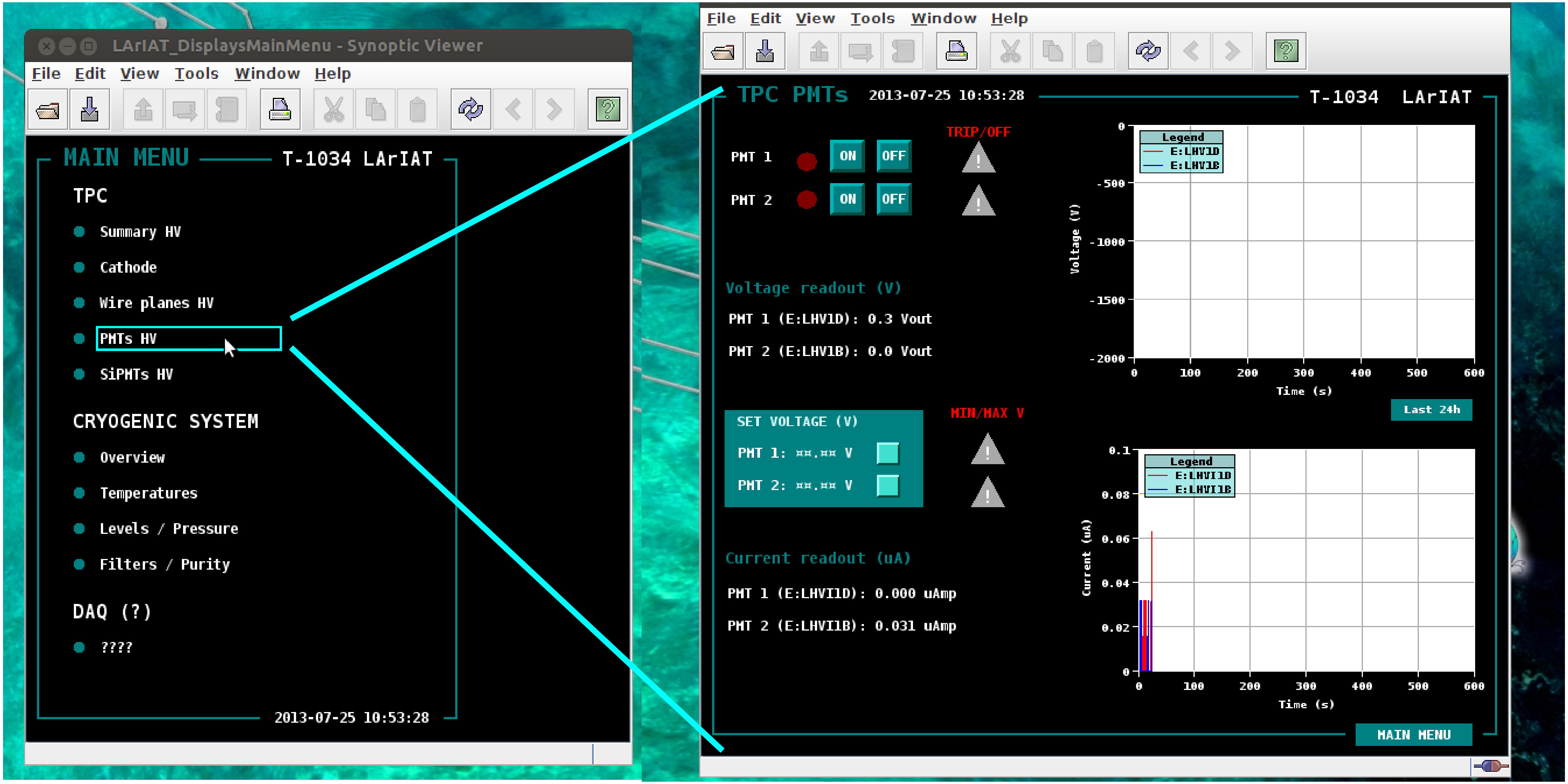
- Looking for beam information: should be in ACNet already...
- Waiting for DAQ to define data to be monitored

→ DAQ currently working on converting raw data into a user friendly format

→ Possibility to use “fake” ACNET devices as input and the use Synoptic for the displays.

- Will request IFBeam and Lumberjack logging as soon as the number of devices is defined.

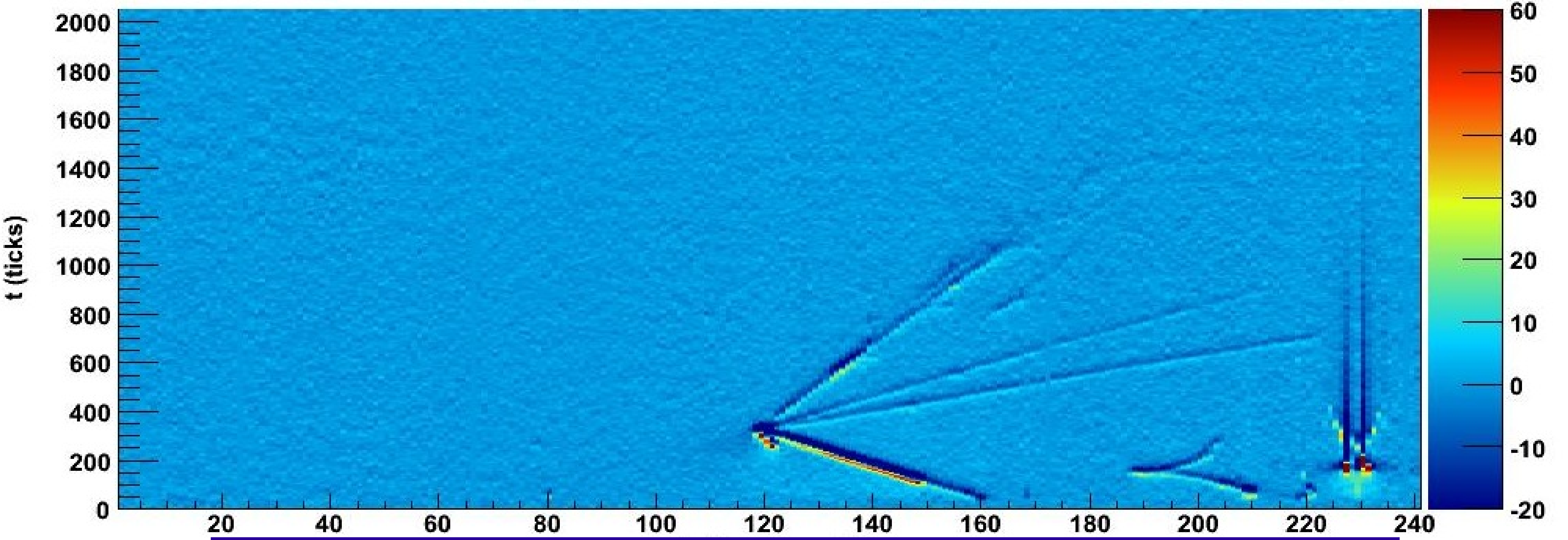
So... what does it look like?



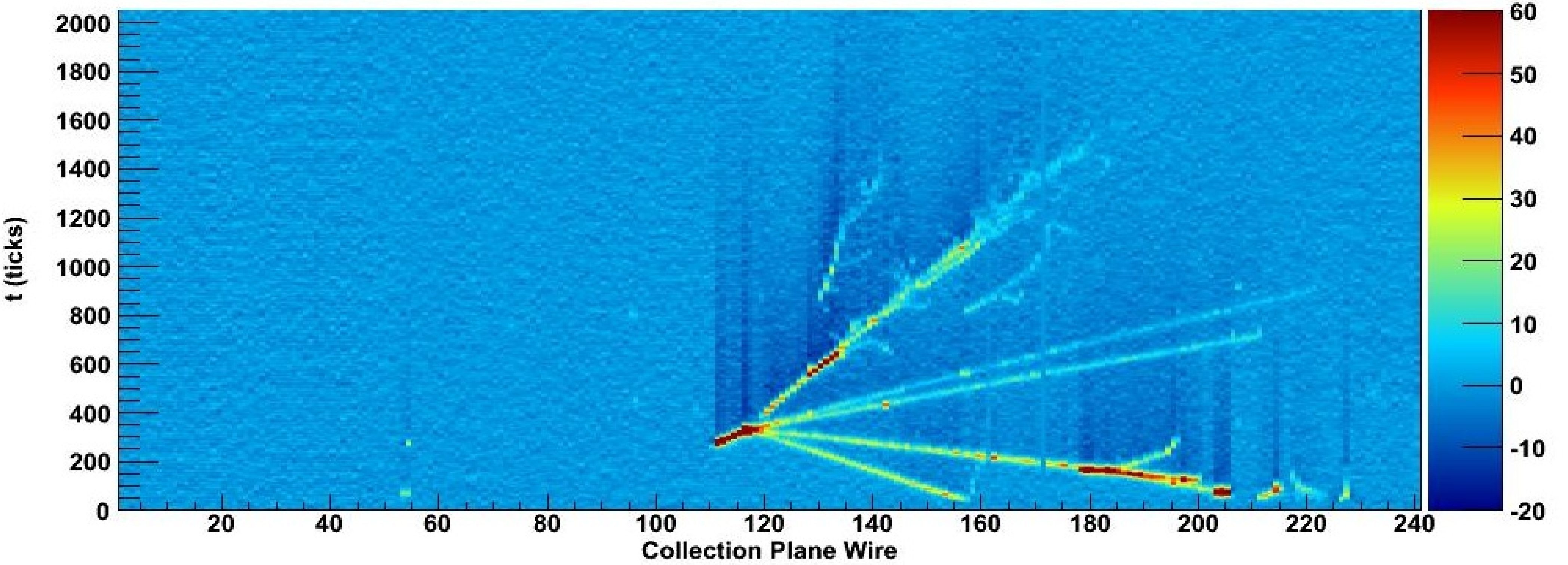
Conclusions

- To study neutrino oscillations, the energy and flux spectra of the neutrinos are needed, both before and after oscillation, therefore a good understanding of the neutrino beam is needed.
- To properly measure the flux, cross-sections need to be measured as precisely as possible.
- To measure cross-sections, reconstruction must be efficient.
- Since neutrino oscillation physics is switching to liquid argon technology, it is essential to understand how the neutrino interaction outgoing particles behave in argon.

- In general, because of the small neutrino interaction cross-sections, more intense and more pure neutrino beams are required so we need to improve the neutrino beam production.



Thank you for your attention!



Back up

ν oscillations mechanism

- Flavour (interaction) eigenstates ≠ Mass (propagation) eigenstates, linked by the

PMNS mixing matrix:

$$\underbrace{\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}}_{\textbf{FLAVOR}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\textbf{PMNS matrix}} \underbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}}_{\textbf{MASS}}$$

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$, δ = CP violation phase

→ oscillation parameters: **2 Δm^2_{ij}** ($\Delta m^2_{ij} = m^2_i - m^2_j$), **3 mixing angles θ_{ij} and 1 phase.**

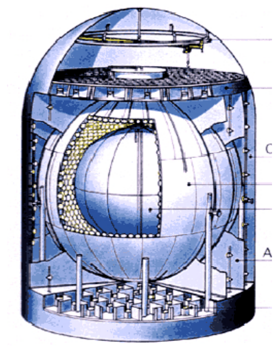
- All parameters have been measured **except δ**.

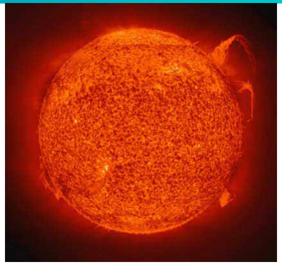
- Oscillations important because:
  - First (and only) experimental proof that **neutrinos are massive**.
  - If **δ ≠ 0 then CP violation in leptonic sector** → hint for leptogenesis.

ν osc. state-of-the-art

- **Solar neutrinos** (ν_e disappearance) + **KamLAND** (reactor $\bar{\nu}_e$ disappearance)
  - ➔ **$\sin^2(2\theta_{12}) = 0.857 \pm 0.024$**
  - ➔ **$\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5}\ eV^2$**

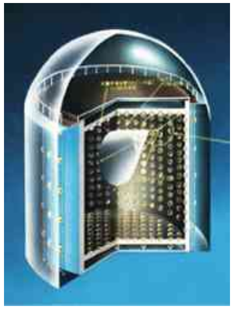
KamLAND



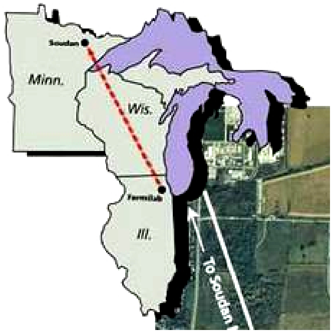


Homestake, SAGE, GALLEX, SNO, Borexino

- **Atmospheric neutrinos** + **long baseline** (ν_μ disappearance)
  - ➔ **$\sin^2(2\theta_{23}) > 0.95$** (C.L. 90%)
  - ➔ **$\Delta m_{32}^2 = (2.32 \pm 0.12) \times 10^{-3}\ eV^2$**



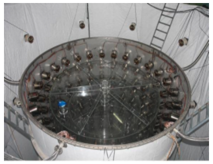
Super Kamiokande



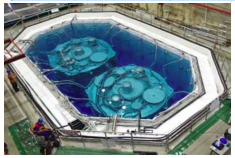
MINOS

- **Reactor $\bar{\nu}_e$** (disappearance) + **long baseline** (ν_e appearance)
  - ➔ **$\sin^2(2\theta_{13}) = 0.095 \pm 0.010$**

T2K

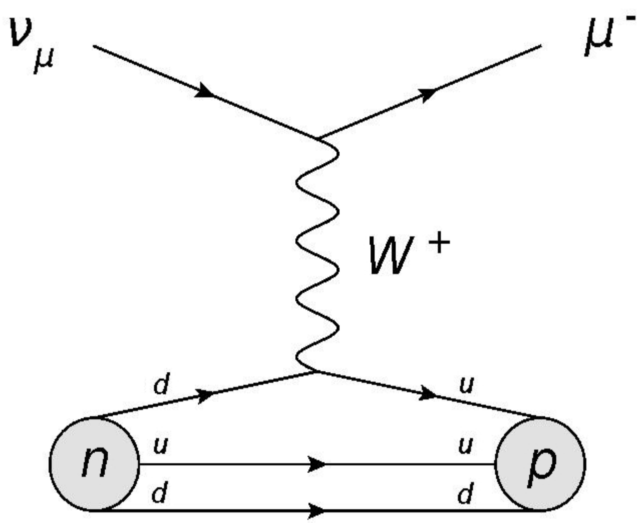


RENO
Daya Bay



Neutrino energy

- All **charged current** processes can be tagged with the corresponding **outgoing lepton**, such as the **μ -** for an incoming ν_μ .
- **CCQE** are important because the **neutrino energy** can be reconstructed using only the **muon momentum** p_μ and its **angle** θ with respect to the incoming neutrino:



$$E_\nu^{CCQE} = \frac{m_P^2 - m_\mu^2 - m_{Neff}^2 + 2m_{Neff}E_\mu}{2(m_{Neff} - E_\mu + p_\mu \cos\theta)}$$

→ neutron not free so must take into account its binding to the nucleus through the **binding energy** ε (set to 25 MeV)

→ $m_{Neff} = m_N - \varepsilon$.

Leptogenesis

- Matter excess observed in the Universe:

$$\eta = \frac{n_B - n_{\overline{B}}}{n_\gamma} = (6.21 \pm 0.16) \times 10^{-10}$$

→ where n_B is the number of baryons, n_γ is the number of photons.

- Sakharov conditions verified only qualitatively, not quantitatively:

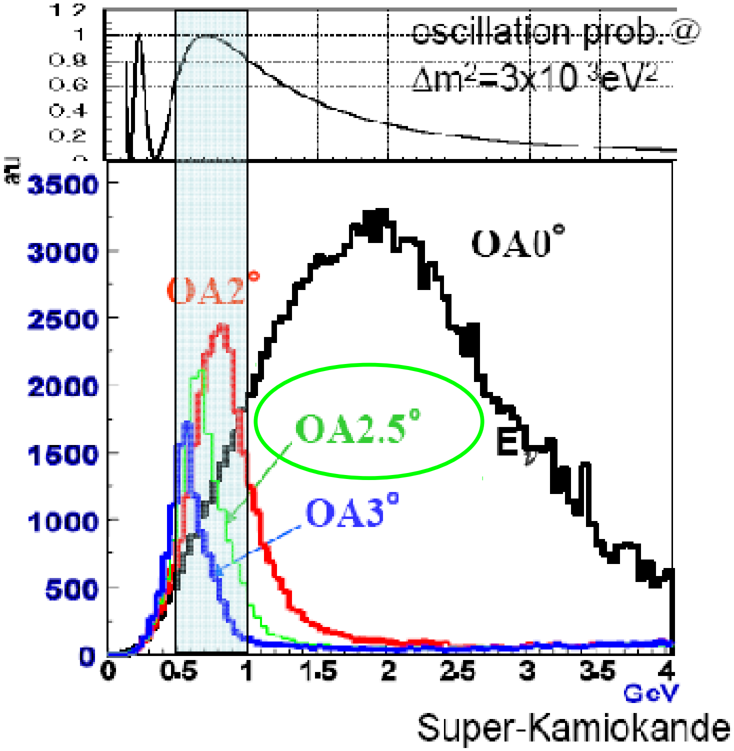
→ CP violation in the quark sector due to the complex phase in the CKM matrix is 10 orders of magnitude below the observed asymmetry.

- Leptogenesis theory: explains how leptonic CP violation can contribute to the matter-antimatter asymmetry, by propagating a lepton-antilepton asymmetry to the baryon-antibaryon asymmetry.

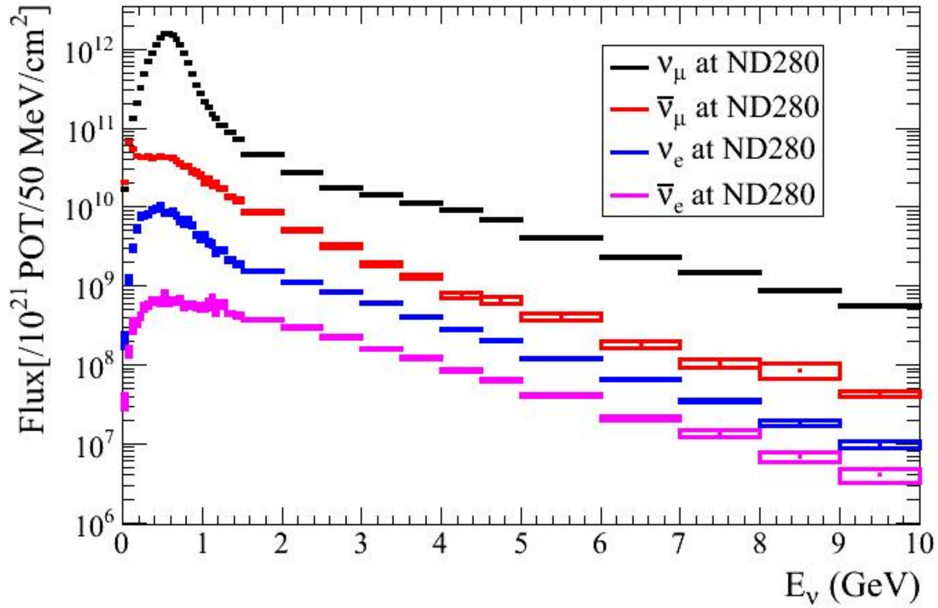
→ requires Majorana neutrinos, and a heavy right-handed neutrino singlet.

T2K neutrino beam

Why off-axis?



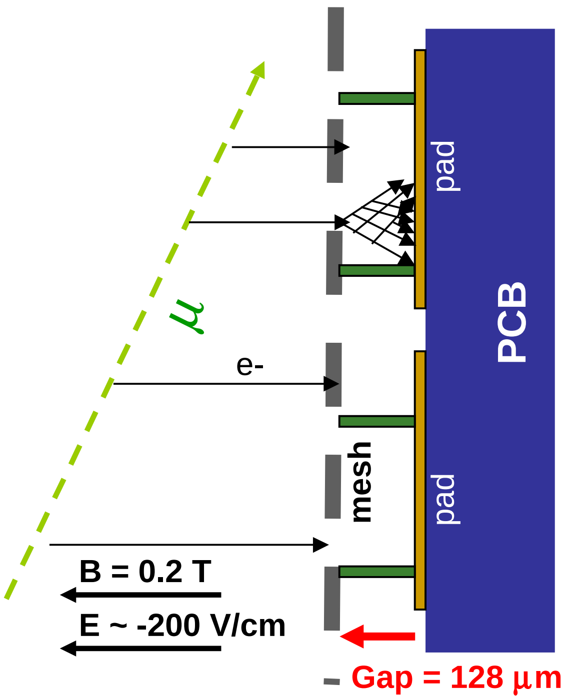
Neutrino flux simulation at ND280



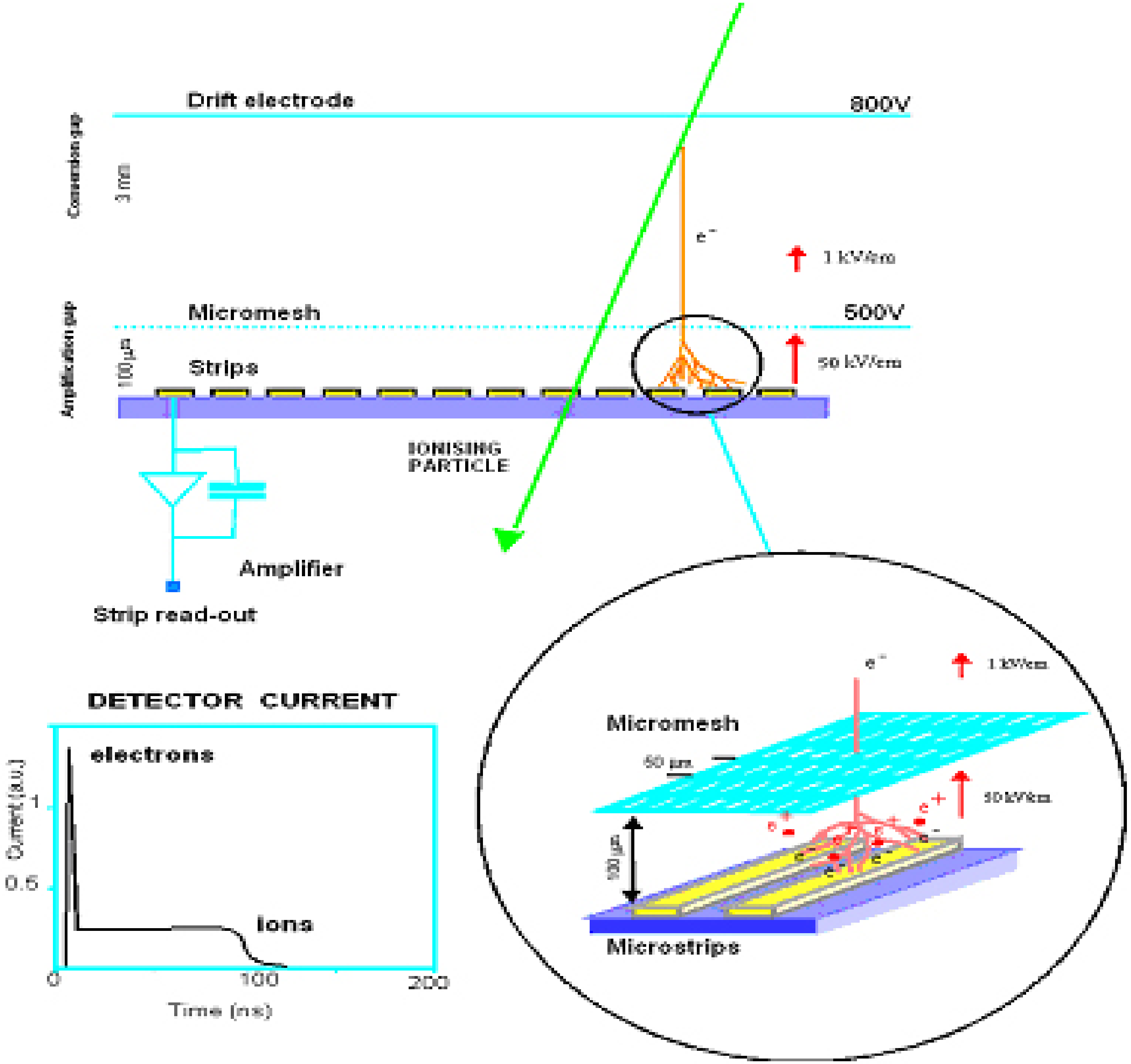
- 1st long baseline experiment **using off-axis**.
- **Quasi-monochromatic beam** → tuned at expected oscillation maximum
- Reduce high energy neutrinos which create NC background

- Beam is mainly ν_μ
- ν_e contamination ~ 1% of total flux

MICROMEGAS



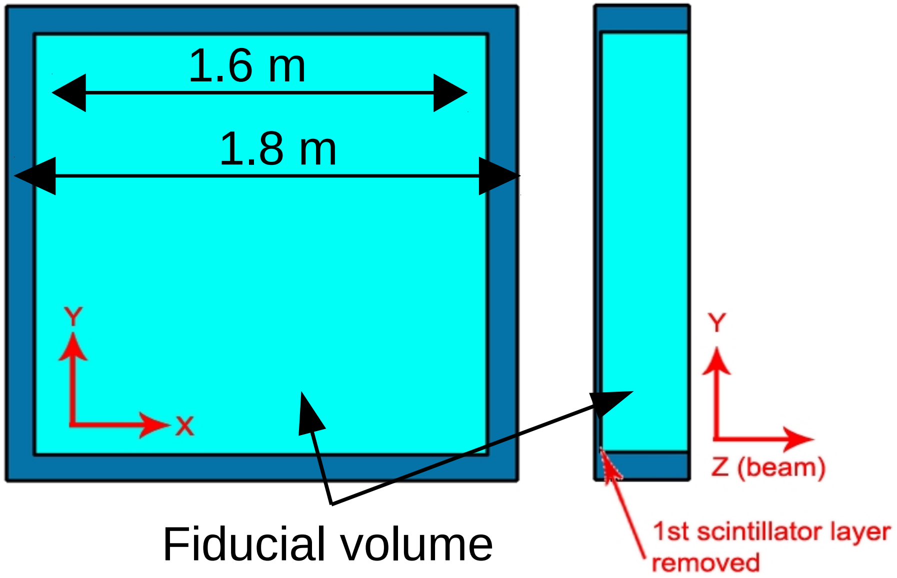
μ
e-
mesh
pad
pad
PCB
B = 0.2 T
E ~ -200 V/cm
Gap = 128 μm



Drift electrode
800V
Micromesh
500V
Strips
IONISING PARTICLE
Amplifier
Strip read-out
DETECTOR CURRENT
electrons
ions
Time (ns)
Micromesh
Microstrips

Flux fit event selection

- **Cuts applied to select the muon candidates (in order):**
  - 1) μ candidate tracks must have **at least 1 TPC segment** that crosses **¼ TPC length**
    → momentum and dE/dx reconstructed correctly.
  - 2) Select **negative tracks**, then select the one with **highest momentum** per event
    → muon carries most of the momentum.
  - 3) **Track must start in either FGD1 or FGD2** (fiducial volume cut: 78% of the total volume) → ν don't leave tracks, must be sure the interaction is in the FGD.
  - 4) Particle identification cuts:
    - Compatible with **μ hypothesis at < 2.5 σ**
    - Incompatible with **e hypothesis at > 2 σ**



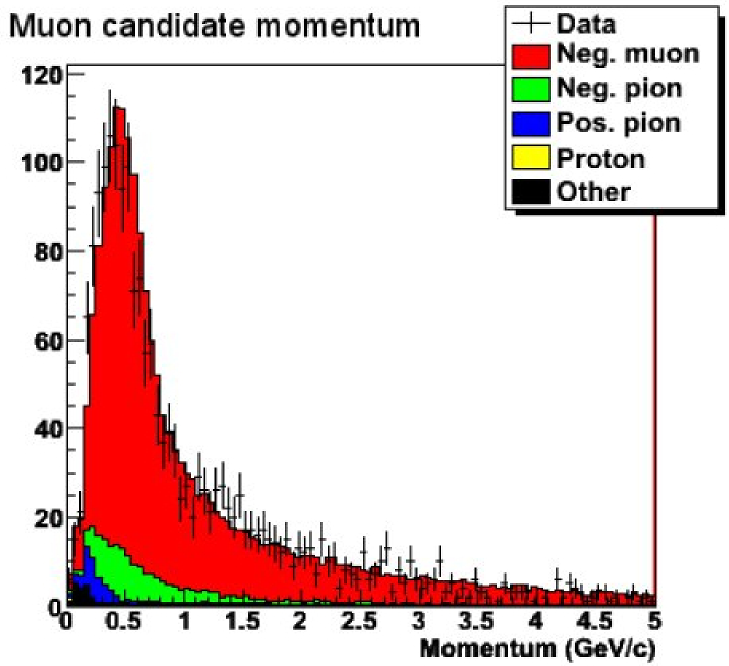
CC purity (CCQE): 84.35% (42.71%)

CC in fid. vol. efficiency: 46.04%

After selection: 2003 data events

Selected sample

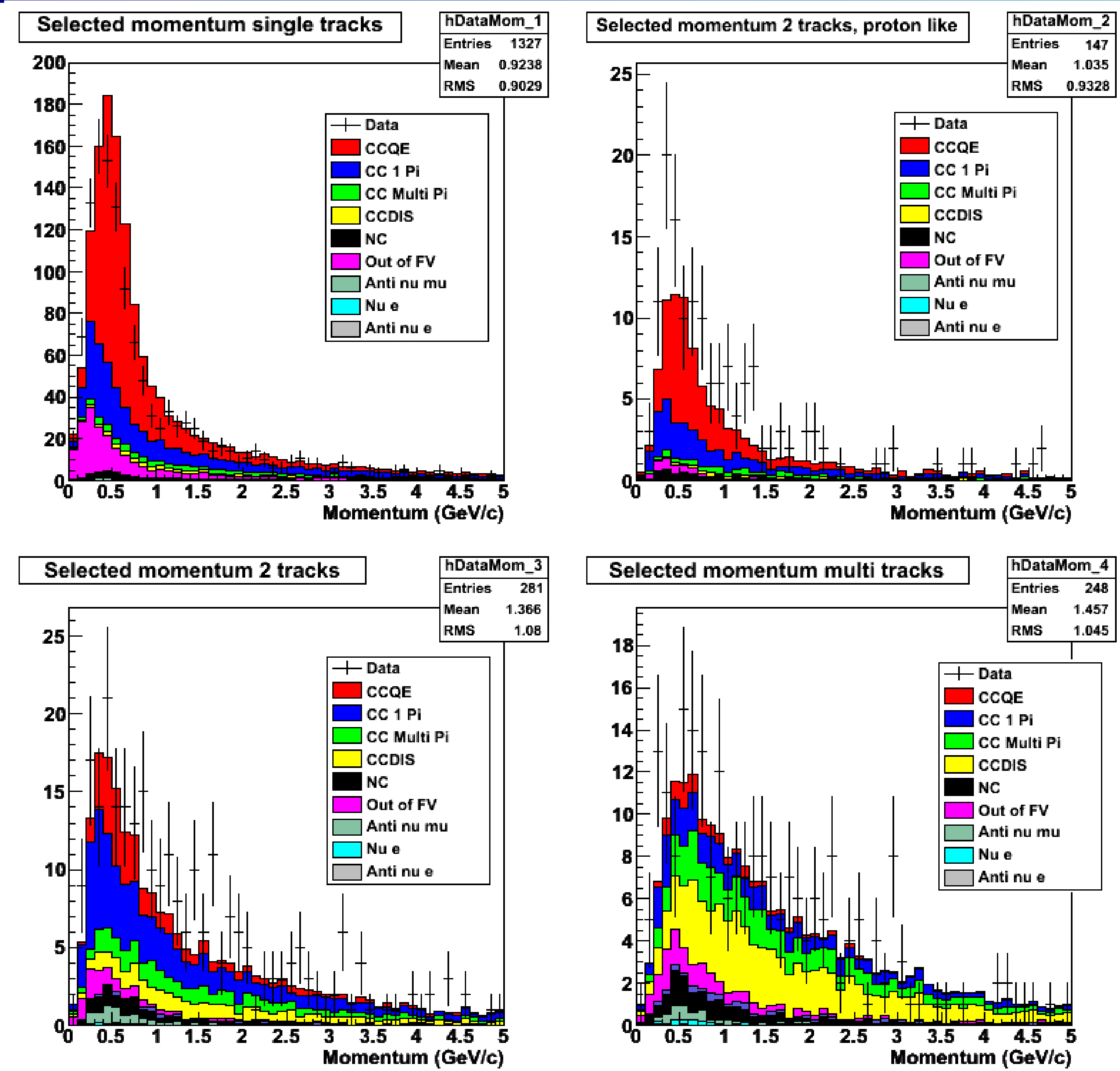
Cuts	Data	Data efficiency	MC normalized	MC efficiency
Nb spills	891 328	-	388 757.8	-
1 neg. TPC track	58 596	6.6%	32 916.7	8.5%
Fiducial volume	3 114	5.3%	3 147.6	9.6%
FGD1	1 504	-	1 535.4	-
FGD2	1 610	-	1 612.2	-
Muon PID cut	2163	69.5%	2 251.8	71.5%
FGD1	1 083	72%	1 107.4	72.1%
FGD2	1 080	67.1%	1 144.4	71%
Electron PID cut	2003	90.8%	2105.9	93.5%
FGD1	1 001	92.4%	1 038.8	93.8%
FGD2	1 002	92.8%	1 067.1	93.3%



→ **μ purity of the sample: 84%**

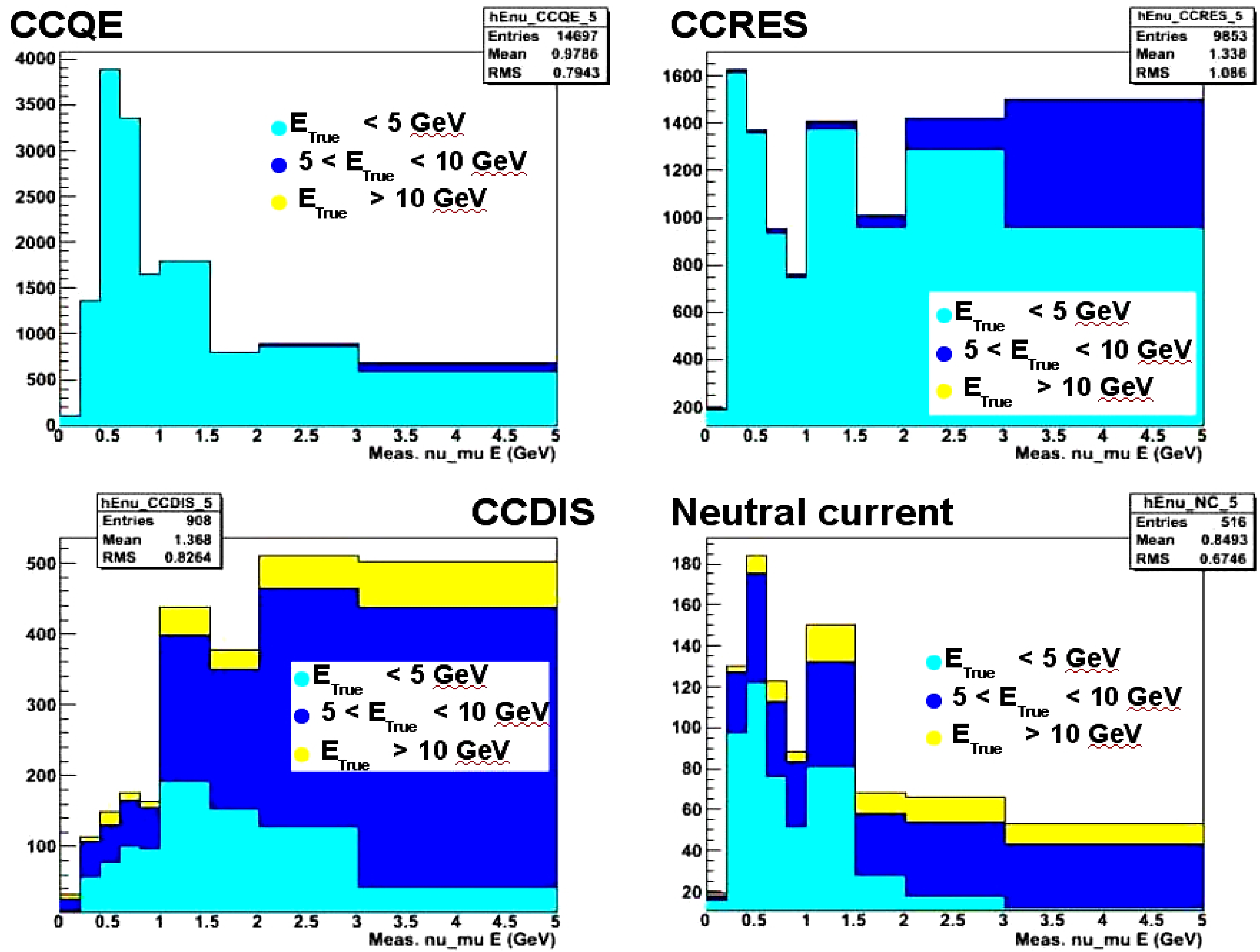
- Data-MC difference after selecting highest momentum negative TPC track → sand muons not simulated in the MC.
- Ratio data/MC = 95.1% good, **4% difference after the muon PID cut**.
- Calibration issue on the dE/dx which leads to a difference between data and MC, and between the different TPCs → a correction must be applied on the expected number of events → **systematic related to the correction**.

Flux fit: μ candidate momentum plots



- Each topology **enhances the expected interaction type**.
- Better understanding of backgrounds → **out-of-FV** events are the **main source of background**.
- Data / MC differences:
  - MC excess in single track
  - MC deficit in all other topos.
- Results **consistent with previous CC selections**.

True energy contributions to E_{meas}



- Correction factor: ratio of the total histogram to the sum of E_{true} < 10 GeV histograms, same for all topologies.

Validation with full MC

- **Good agreement** between the calculated expected nb. of evts. and the measured nb. of evts. when fixing flux factors to 1.
- Fit the full MC sample, **quality of the fit** measured by 2 types of χ^2
  - **Spectrum χ^2 → characterizes shape of the energy spectrum**

$$\chi^2_{spectrum} = \sum_{i=1}^{9} \frac{(N_{obs} - N_{exp})^2}{\sigma^2_{obs}} \quad \text{with } \sigma_{obs} = \sqrt{N_{obs}}$$

$$\chi^2_{spectrum} = \sum_{i_{topo}=1}^{4} \chi^2_{spectrum}(i_{topo})$$

  - **Flux χ^2 → how far from predicted flux?** (8 dof)

$$\chi^2_{flux} = \overrightarrow{F}^T \times \mathrm{COV}^{-1} \times \overrightarrow{F}$$

→ correlation up to 75% (neighboring f_i)

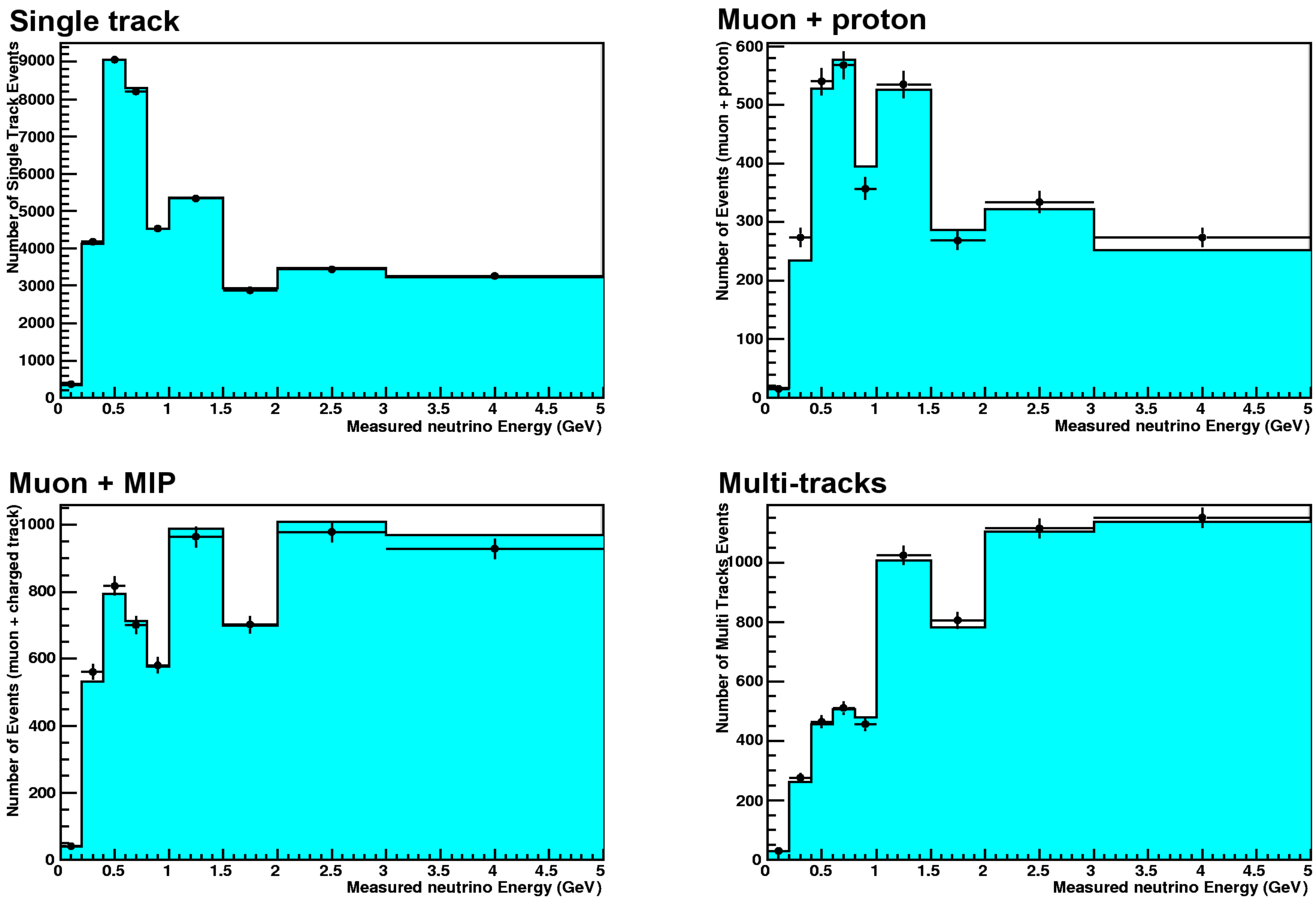
Fitted flux factors for both fit configurations

	Average fit	4-topology fit
f_1	1 (fixed)	1 (fixed)
f_2	1.087 ± 0.138	1.097 ± 0.128
f_3	1.024 ± 0.031	1.020 ± 0.029
f_4	0.984 ± 0.028	0.987 ± 0.027
f_5	1.003 ± 0.053	0.986 ± 0.049
f_6	1.002 ± 0.059	1.032 ± 0.051
f_7	0.966 ± 0.115	0.936 ± 0.093
f_8	0.985 ± 0.081	0.982 ± 0.064
f_9	1.053 ± 0.034	1.014 ± 0.028
Spectrum χ^2	1.9 (1 dof)	22.2 (28 dof)
Flux χ^2	6.02	3.33

- Fit each topology separately → flux χ^2 consistent with 8 dof χ^2 and f_i consistent with 1.

Validation full MC (2)

Comparison measured vs expected (blue) event number per measured energy bin for each topology.



→ Good agreement for all topologies.

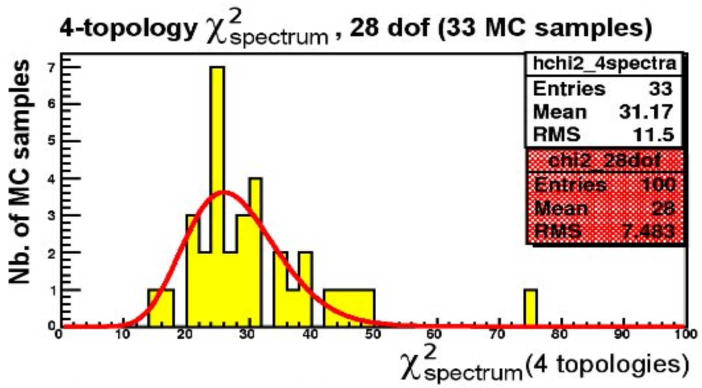
Validation with 33 MC samples

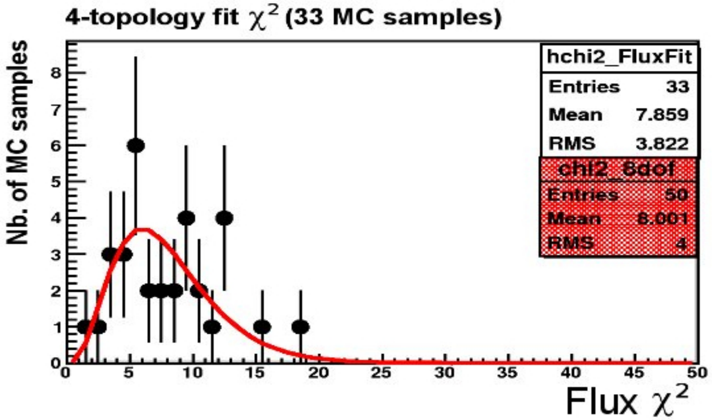
- Divide the MC sample into POT_{DATA} equivalent sub-samples

→ **33 MC samples**.

- Fit each sample individually and fit each flux factor distribution with a Gaussian → **no bias**.
- **Pulls** for each flux factor **are good** (means consistent with 0 and sigmas consistent with 1) → **errors are well computed**.
- Flux and spectrum χ^2 consistent with expected χ^2 distributions.

4-topology fit χ^2





Mean and σ of the Gaussians fitting the flux factor distributions

	Average fit		4-topologies fit	
	Mean	σ	Mean	σ
f_2	1.114 ± 0.146	0.831 ± 0.105	1.135 ± 0.142	0.782 ± 0.116
f_3	1.027 ± 0.029	0.169 ± 0.021	1.008 ± 0.032	0.181 ± 0.022
f_4	0.989 ± 0.032	0.181 ± 0.022	0.989 ± 0.030	0.170 ± 0.021
f_5	0.997 ± 0.048	0.275 ± 0.034	0.992 ± 0.053	0.302 ± 0.038
f_6	0.997 ± 0.062	0.359 ± 0.044	1.026 ± 0.058	0.331 ± 0.044
f_7	0.932 ± 0.148	0.849 ± 0.106	0.936 ± 0.106	0.608 ± 0.078
f_8	0.979 ± 0.107	0.611 ± 0.078	0.955 ± 0.078	0.424 ± 0.060
f_9	1.073 ± 0.046	0.265 ± 0.033	1.014 ± 0.033	0.190 ± 0.023

Systematics (2): FSI – Genie vs NEUT

- Genie and NEUT are 2 different ν interaction generators.
- Efficiency for each topology = Global ε x relative ε with

$$\mathrm{Eff}_{rel} = \frac{\text{nb. of selected } k_{proc} \text{ in } i_{topo}}{\text{nb. of selected } k_{proc}}$$

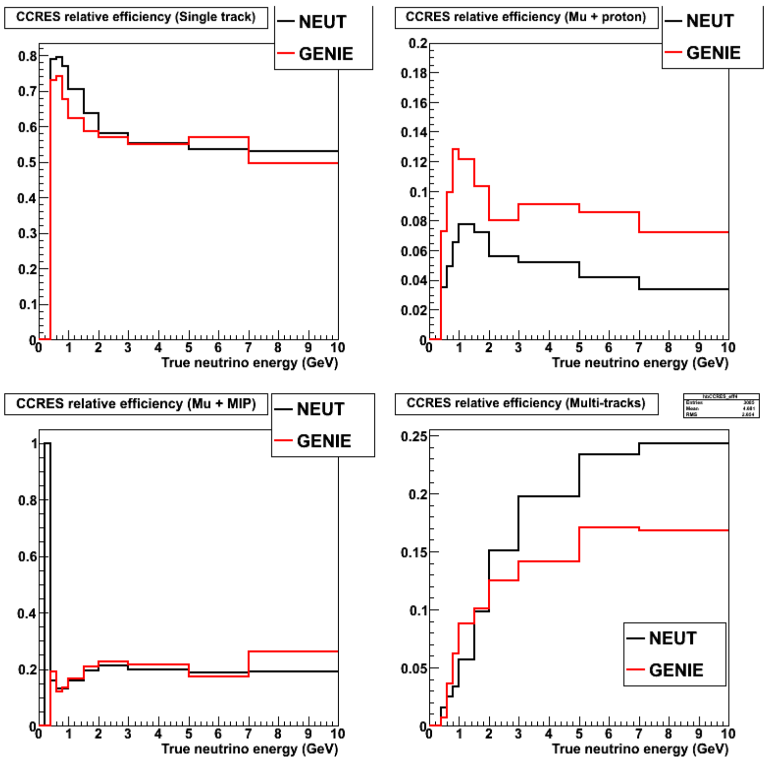
- With GENIE, **spectrum χ^2 better, in particular for topologies mu + proton and mu + MIP**

- Event migration between topologies can be due to final state interactions (FSI).

Fitted flux factors (4-topology fit)

	NEUT	GENIE	Diff. GENIE - NEUT	σ_{stat}
f_2	2.821	2.724	-0.097	$\pm$ 0.756
f_3	1.167	1.162	-0.005	$\pm$ 0.153
f_4	0.577	0.567	-0.010	$\pm$ 0.134
f_5	0.725	0.707	-0.019	$\pm$ 0.287
f_6	1.175	1.140	-0.035	$\pm$ 0.328
f_7	0.810	0.632	-0.178	$\pm$ 0.587
f_8	1.423	1.574	+0.151	$\pm$ 0.396
f_9	0.920	0.915	-0.005	$\pm$ 0.178

CCRES relative efficiency



Spectrum χ^2 and contribution from each topology

	NEUT	GENIE
$\chi^2_{spectrum}$	77.9	71.2
$\chi^2_{spectrum}$(single track)	27.5	25.9
$\chi^2_{spectrum}(\mu^-$ + Proton)	19.7	8.9
$\chi^2_{spectrum}(\mu^-$ + MIP)	15.8	13.0
$\chi^2_{spectrum}$(Multi-tracks)	14.9	23.4

Systematics (3): Out-of-FV

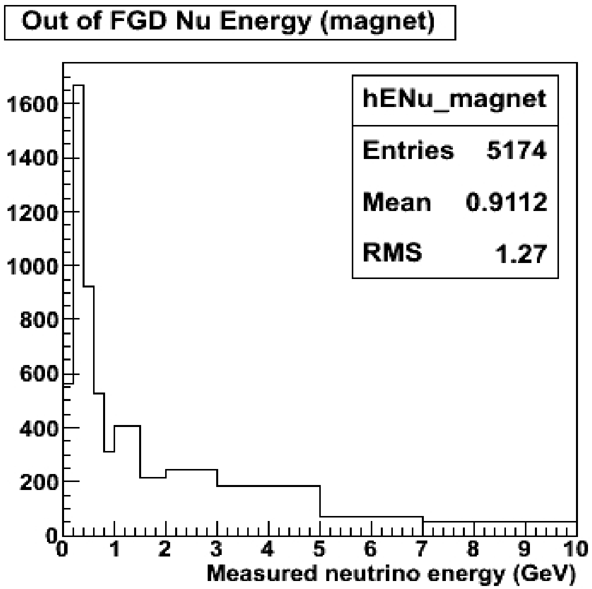
- Main source of background, not modeled.
- Fitting simultaneously the out-of-FV fraction
  → **"normalization" error**

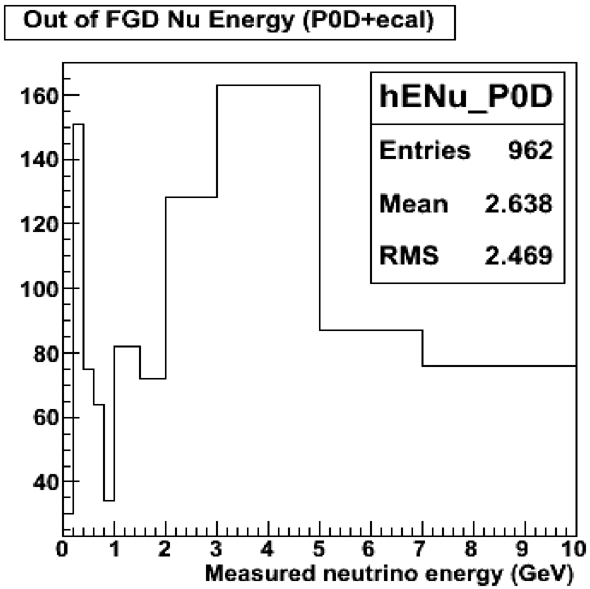
$$f_{out}^{average} = 0.705 \pm 0.303 \quad \text{and} \quad f_{out}^{4-topology} = 0.506 \pm 0.239.$$

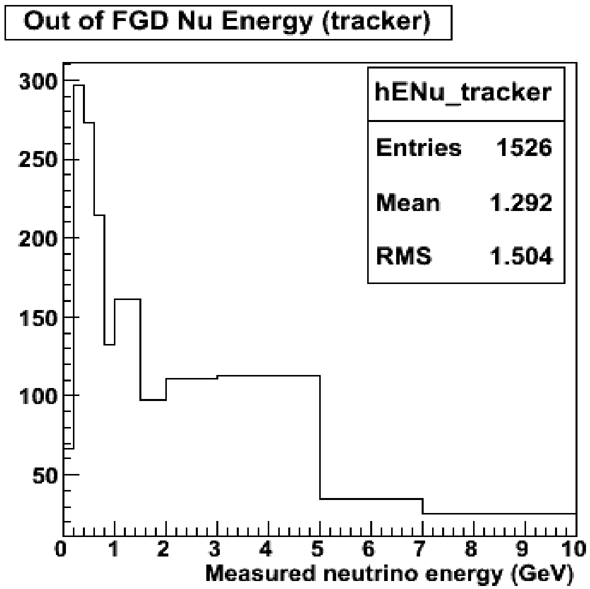
- Divided the out-of-FV contribution according to true vertex position: magnet, P0D + ecal, or tracker.
- Applied ± 50% variation on the P0D-ecal or tracker relative fraction , keeping the total fraction constant
  → **"shape" error**.

Flux factors variations (combined shape + norm.)

	Average		4-topology	
f_2	-0.767	+0.850	-1.786	+1.712
f_3	-0.046	+0.043	-0.072	+0.061
f_4	-0.026	+0.026	-0.044	+0.039
f_5	-0.027	+0.022	-0.055	+0.025
f_6	-0.037	+0.031	-0.064	+0.061
f_7	-0.032	+0.042	-0.061	+0.042
f_8	-0.026	+0.014	-0.039	+0.043
f_9	-0.057	+0.094	-0.067	+0.066







Systematics (4): other

- -3.2% correction because of prediction excess (due to nb of atoms) → **± 1.6 % systematic**

- Data presented an overall deficit of 4% with respect to MC because of muon PID cut → **± 2 % systematic**

- Measured energies up to 5 GeV but the contribution from true energies > 5 GeV not fitted
→ ± 30 % variations on the flux factors for E_{true} > 5 GeV (normally fixed to 1)
→ **Error increases with true energy** since contribution from E_{true} > 5 GeV is more important for the last measured bins (slide 12)

- Detector systematics still need to be computed.

Flux factors variations when E_{true} > 5GeV flux factors variate

	Average	4-topology
f_2	± 0.007	± 0.001
f_3	-	± 0.001
f_4	± 0.003	± 0.001
f_5	± 0.002	± 0.001
f_6	± 0.013	± 0.010
f_7	± 0.126	± 0.119
f_8	± 0.156	± 0.184
f_9	± 0.231	± 0.269

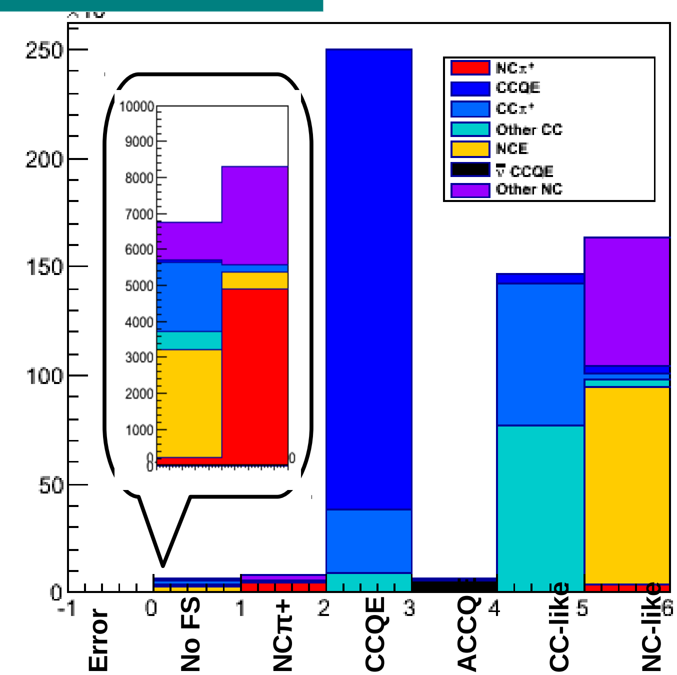
Expectations from truth

Events generated with a primary vertex in the P0D fiducial volume:

	NEUT channel	
Total	581 872	100 %
NCπ+	**9 059**	**1.6 %**
CCQE	219 681	37.8 %
CCπ+	100 953	17.3 %
CC-other	89 548	15.4 %
Anti-ν CCQE	5 557	0.9 %
NCE	94 048	16.2 %
NC-other	63 026	10.8 %

FSI

	Final state	
NCπ+ like	**8 312**	**1.4 %**
CCQE-like	250 107	43 %
Other CC-like	146 928	25.2 %
ACCQE-like	6 424	1.1 %
Other NC-like	163 353	28.1 %
No final state	6 748	1.2 %

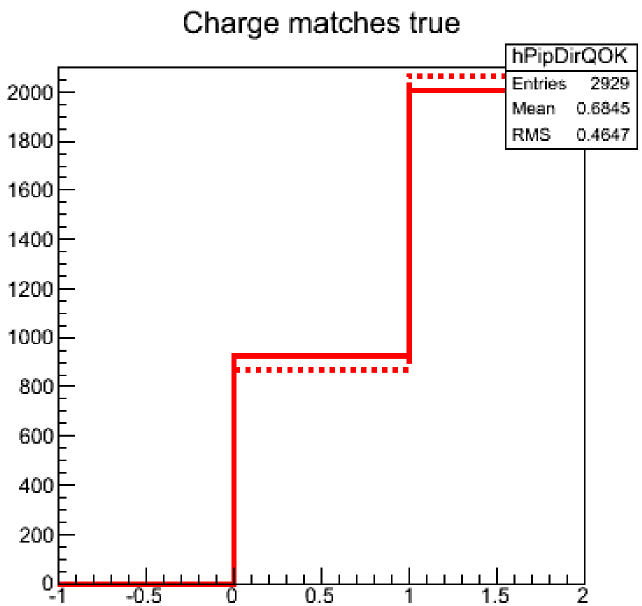


→ **Main background is CCQE-like**

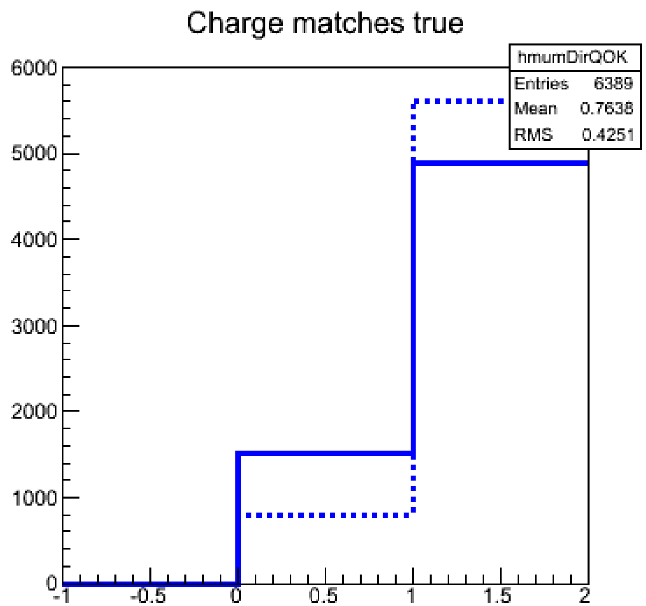
Charge reconstruction

Expected track vs initial direction methods

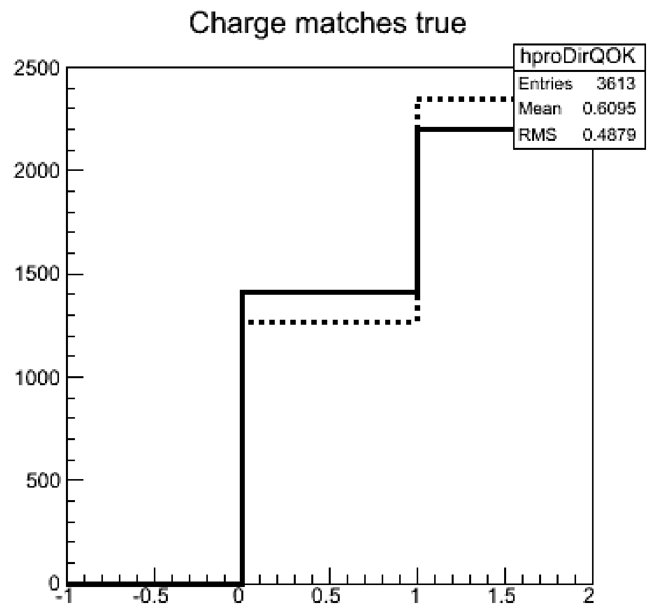
Pi+



Mu-



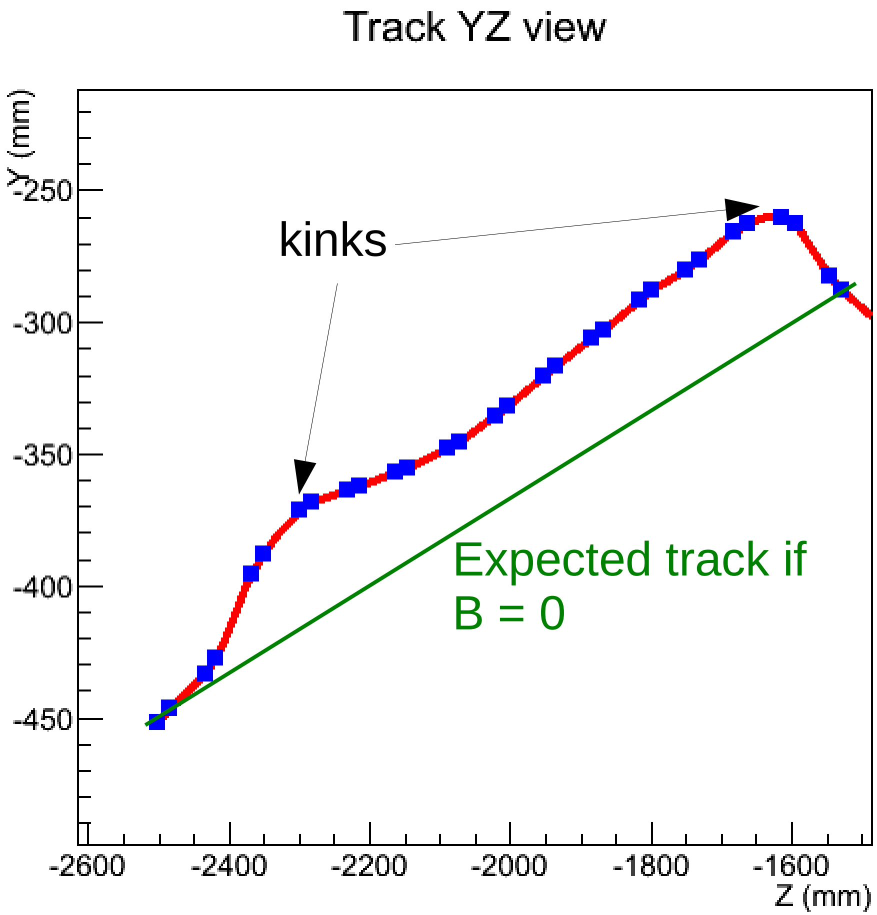
Proton



Continuous line = charge computed using initial direction
Dashed line = charge computed using expected track if B = 0

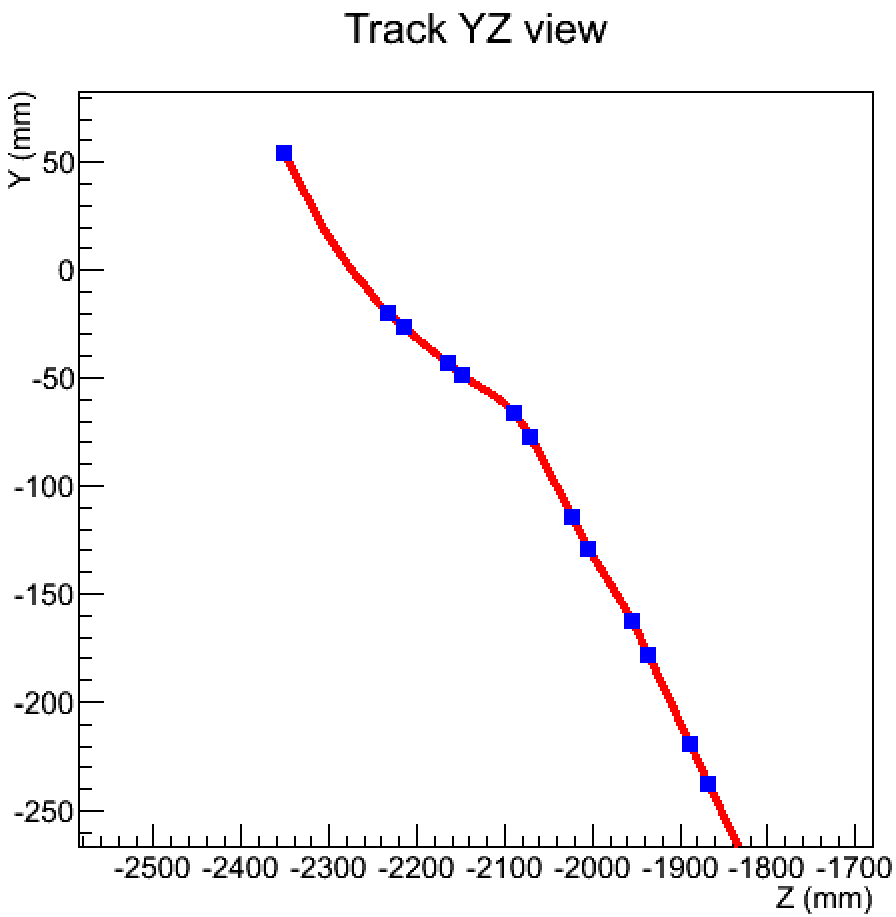
→ **Will only use the expected track method for now.**

Misidentified tracks



Kinks can change the expected track

Sum of ΔY > 0 = negative particle
Sum of ΔY < 0 = positive particle



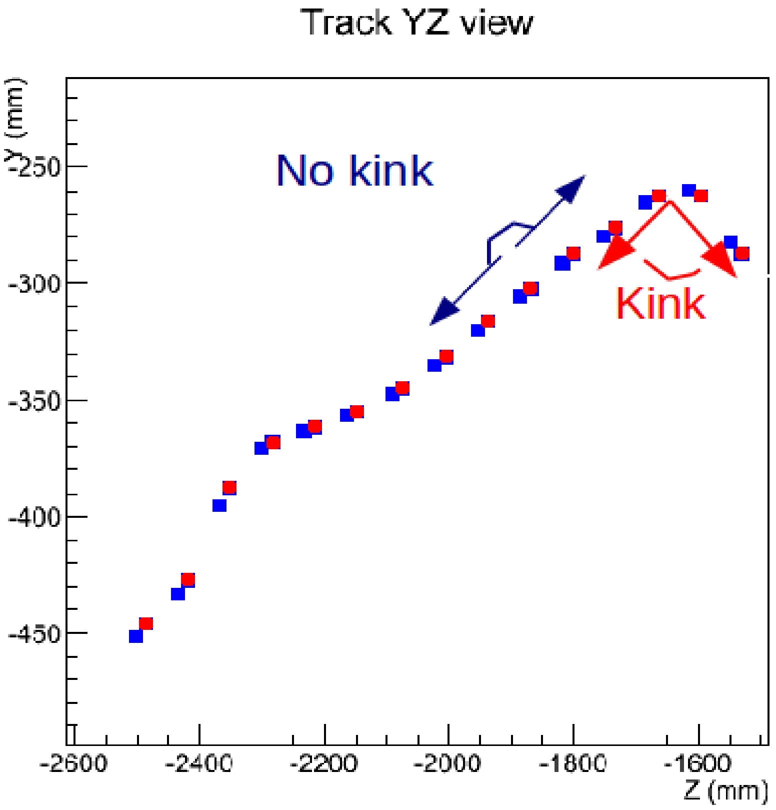
Tracks not curved enough

Improvements

- Angles re-defined: between neighbouring nodes in X or Y layer, defined with respect to the central node every 3 nodes (1 node per XY layer → either blue or red dot).

- Compute angle between “neighbour” nodes to localize kinks
  - re-compute expected track for the longest segment before/after kink.
  - re-compute sign of curvature
  - if more kinks for pions than muons, might be used to discriminate pions from muons if significant difference.
  - compute a likelihood based on this angle distribution

- **Kink = small angle!**



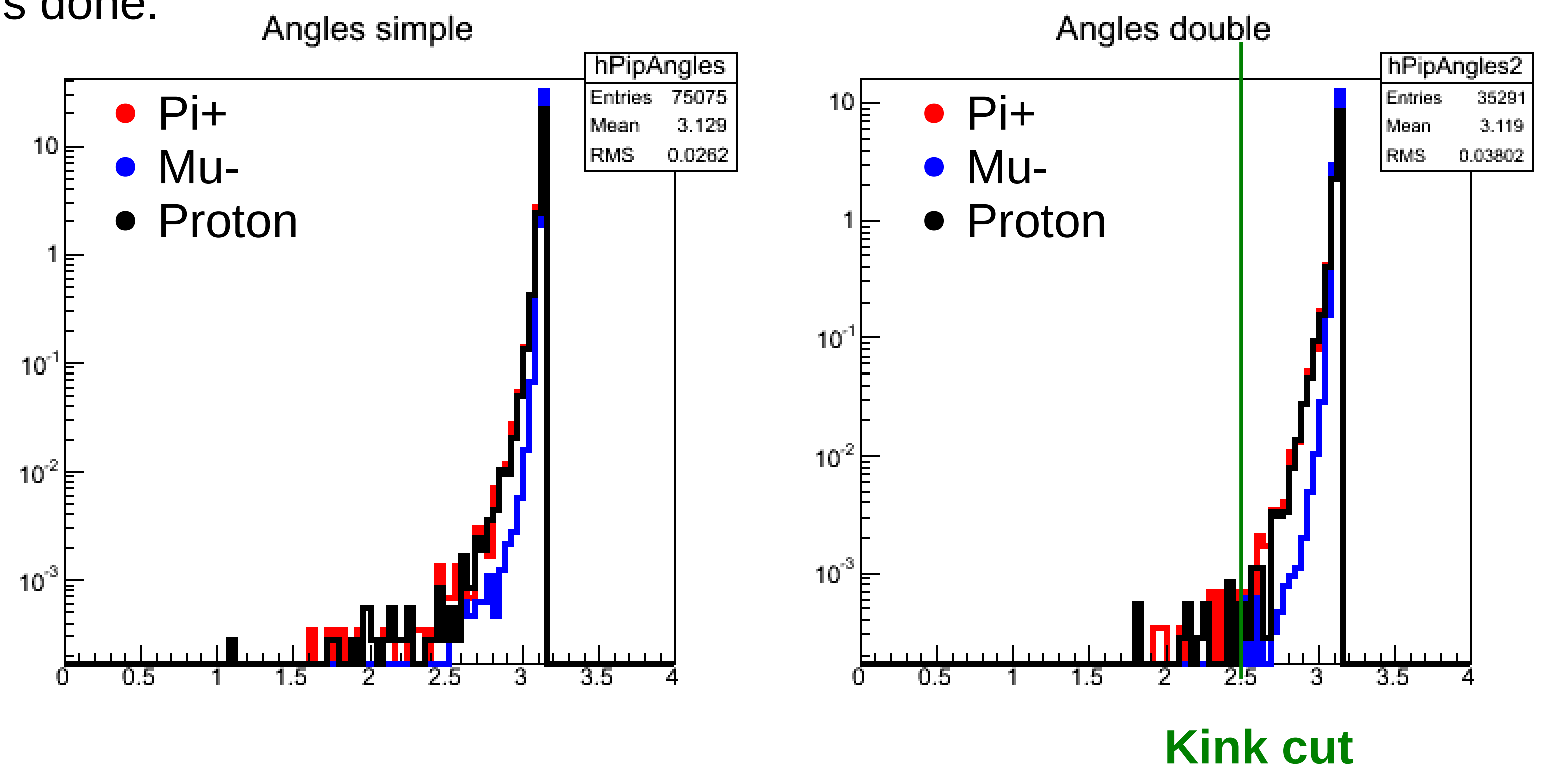
Improvements

- Computed angles between neighbor nodes to localize kinks.
- There is a difference between muon and proton/pion angle distribution:

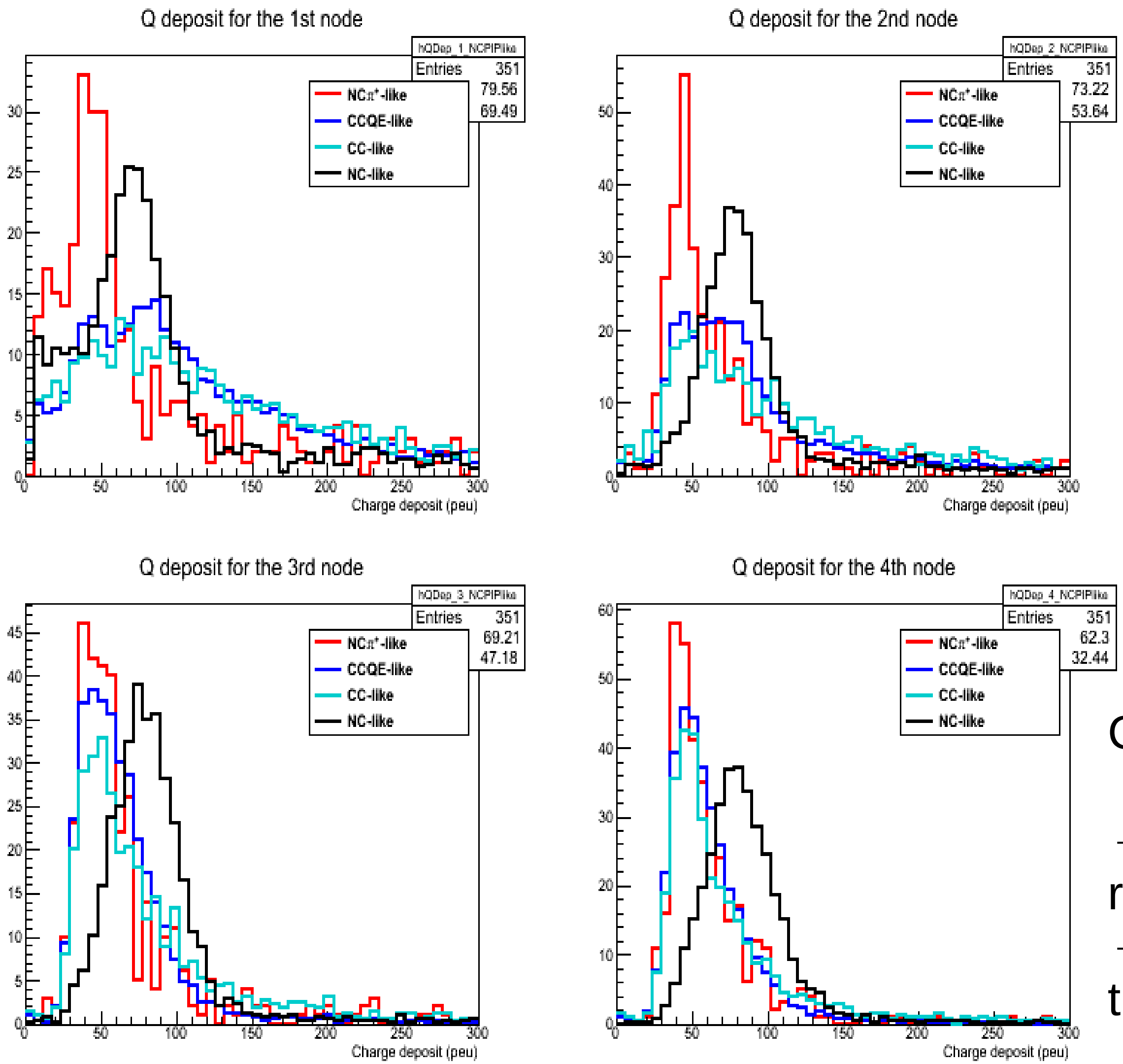
→ muon scatter less than pions / protons, might be able to use this to discriminate pions from muons

- Kink if angle < 2.5 rad.

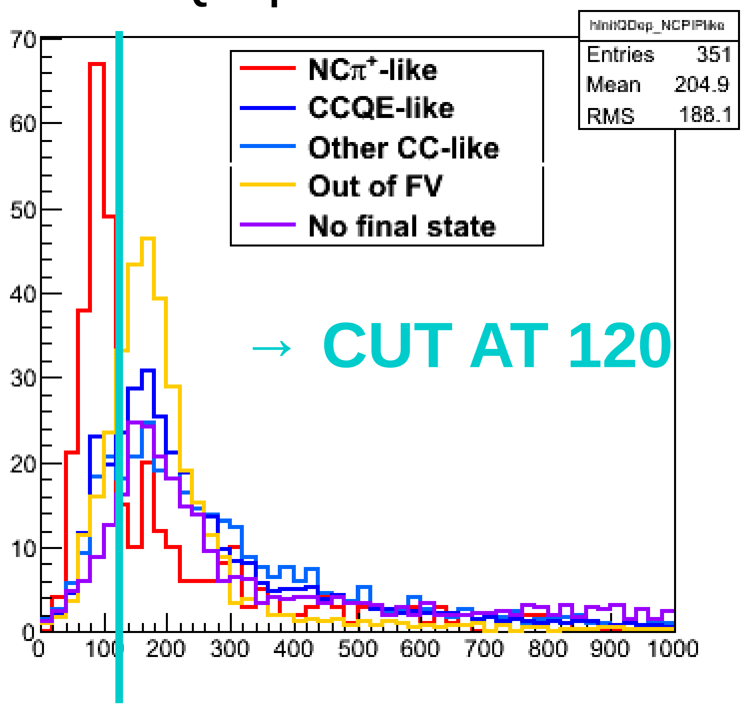
→ no improvement observed in charge reconstruction still, will conclude when kinked tracks matching is done.



Charge deposit, 1st 4 hit clusters



Sum of Q deposit for 1st 2 nodes

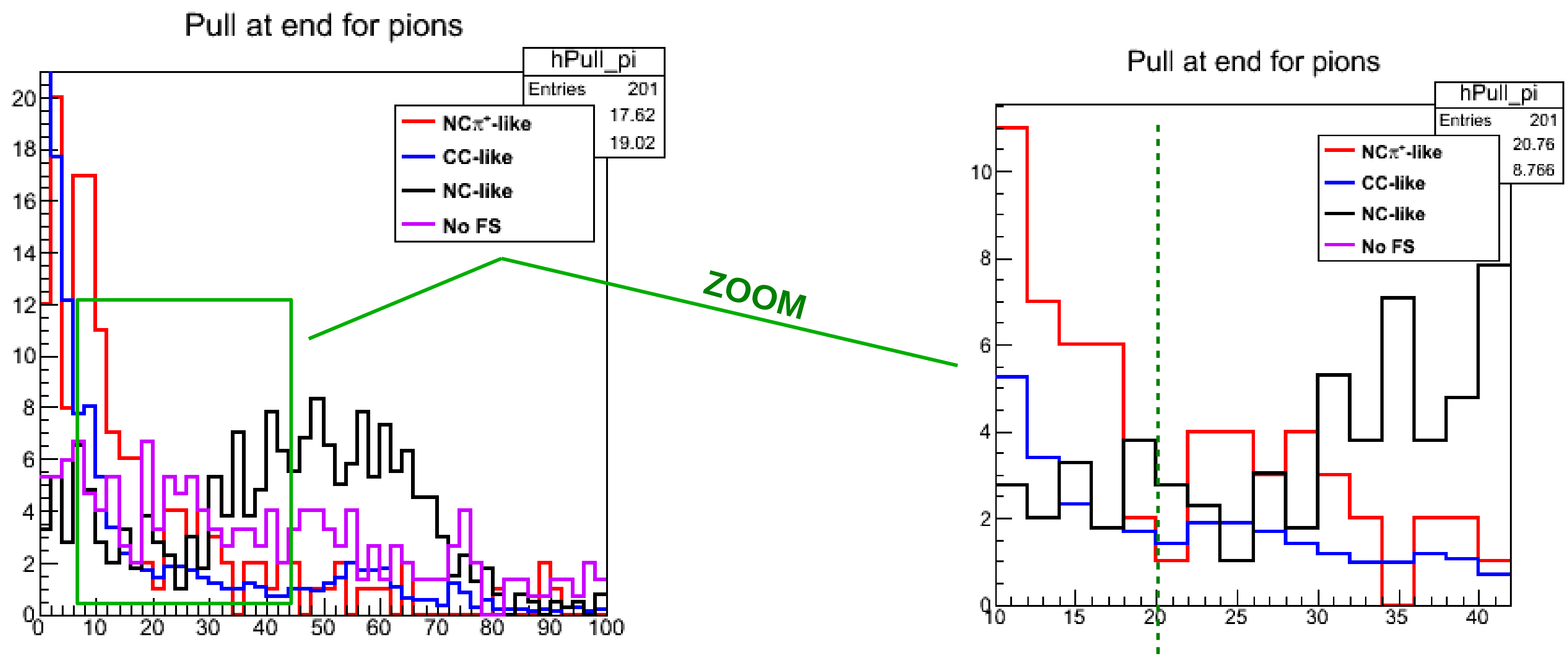


CC and other NC deposit more in 1st clusters:

→ for CCQE: when the proton is not reconstructed.

→ for NCE: because protons deposit more than pions.

Muon-like pull



CUT AT 20

Muon-like pull definition (P0D NCE analysis, D. Ruterbories)

$$\text{Pull} = \sum^{\text{Track nodes}} \frac{Q_{meas} - Q_{expected}}{\sigma_{expected}}$$

Pions are similar to muons so this pull cut rejects proton-like tracks.

Muon-like pull cut to discriminate NC-like events = pull < 20

Reduction table per final state

CUTS	Total	NCπ+ like	CCQE like	ACCQE like	CC like	NC like	No FS	Out of FV
Generated in FV	581 872	8 312	250 107	6 424	146 928	163 353	6 748	-
1-2 recon. tracks	269 403	1 395	83 313	2 706	23 770	12 802	73 725	71 692
1 or 2 long tracks	151 472	1 006	77 704	2 569	18 875	9 040	11 154	31 124
Tracks matched	136 267	961	69 818	2 492	14 084	8 714	9 730	30 468
P0D contained	83 078	775	35 266	515	6 939	7 873	6 135	25 575
Kalman only	56 538	561	33 146	489	5 572	5 080	4 108	7 582
Positive track	20 137	351	7 925	425	1 913	3 042	2 015	4 466
Charge < 120	3 839	179	1 424	280	341	630	218	767
Pull < 20	**2 612**	**144**	**1 173**	**277**	**266**	**145**	**87**	**520**

Absolute momentum scale calibration

- ***Goal:***
  - Uncertainty $\Delta p/p < 2\%$ so the systematic error on Δm^2_{32} measurement is smaller than the statistical error for 5.10^{21} POT → 5.10^{-5} eV^2 expected for Δm^2_{32}.

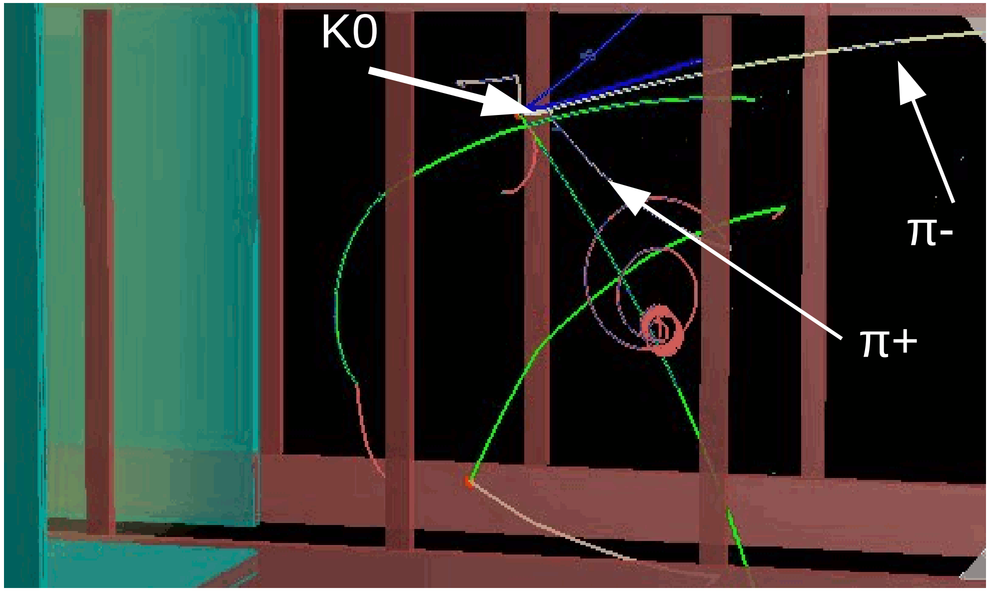
- ***How?***
  - Use the DIS events, look for $K^0_s \rightarrow \pi^+\pi^-$ ($\Gamma_i / \Gamma = 69.2\%$)

    → < 400 events per year per ton expected.
  - K^0_s mass is given by:

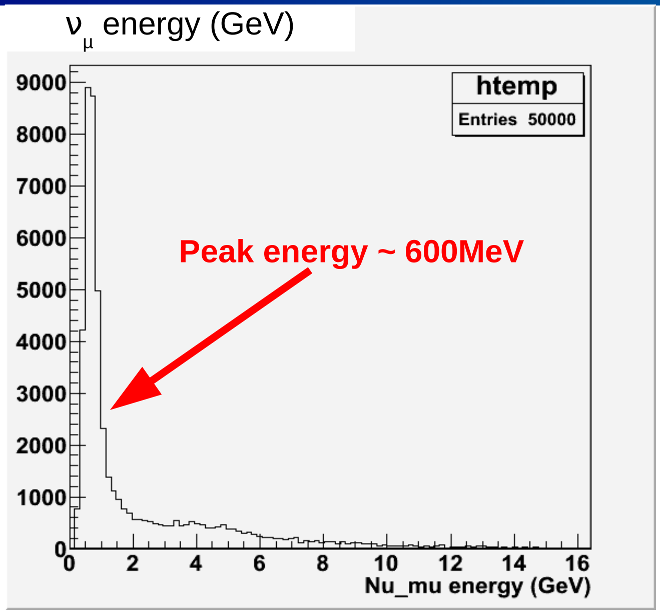
$$M_K^2 = 2\{m_\pi^2 + \sqrt{m_\pi^4 + m_\pi^2(p_+^2 + p_-^2) + p_+^2 p_-^2} - p_+ p_- cos\theta\}$$

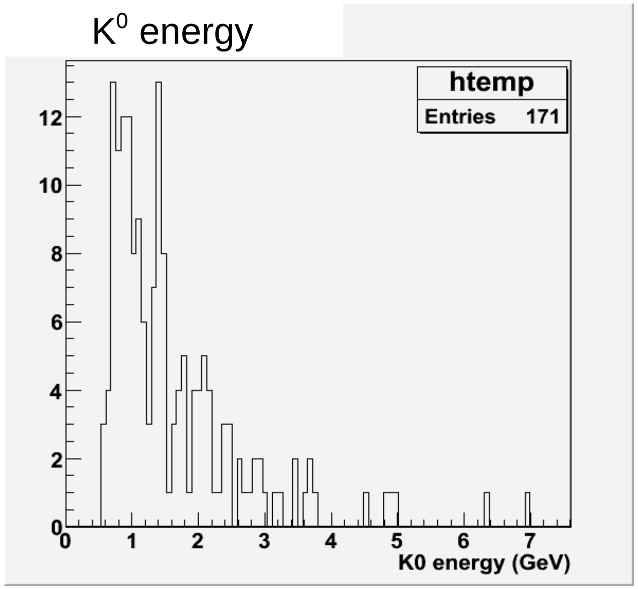
    → depends only on pion momenta and angle at vertex.

- ***3 main steps:***
  - Selection of K^0_s events: few events with **complex topology**.
  - Reconstruct the K^0_s invariant mass, expected at **497.6 MeV/c^2**.
  - Determine momentum scale uncertainty.



Physics related difficulties





(GENIE output, using J-PARC neutrino flux @750kW, 5.10^4 events)

K0 production:

- Few K^0_s produced: **340 expected** per year per ton for **10^5 neutrino interactions** (@750 kW – 10^{21} POT).

Why so few?

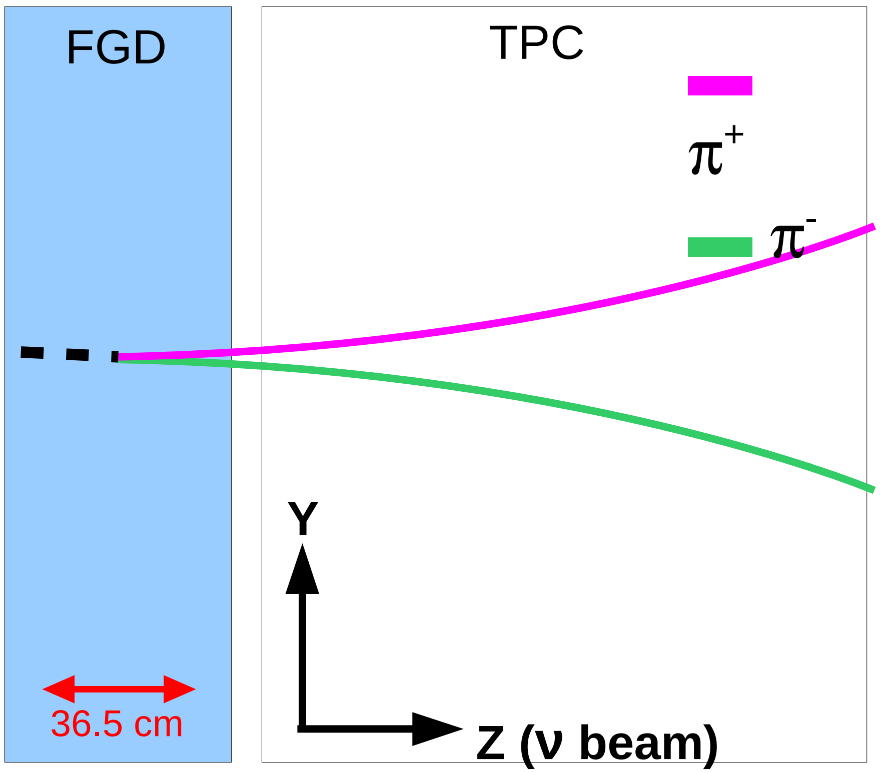
- Produced through **deep inelastic scattering only**:

  $\nu_\mu + n \rightarrow \mu^- +$ mesons (+p)
- ν_μ energy > 1 GeV required to produce them → tail of the ν energy spectrum.
- **Background must be well understood**.
- Main background reducing cut:

  → K^0_s flight distance

Calibration procedure

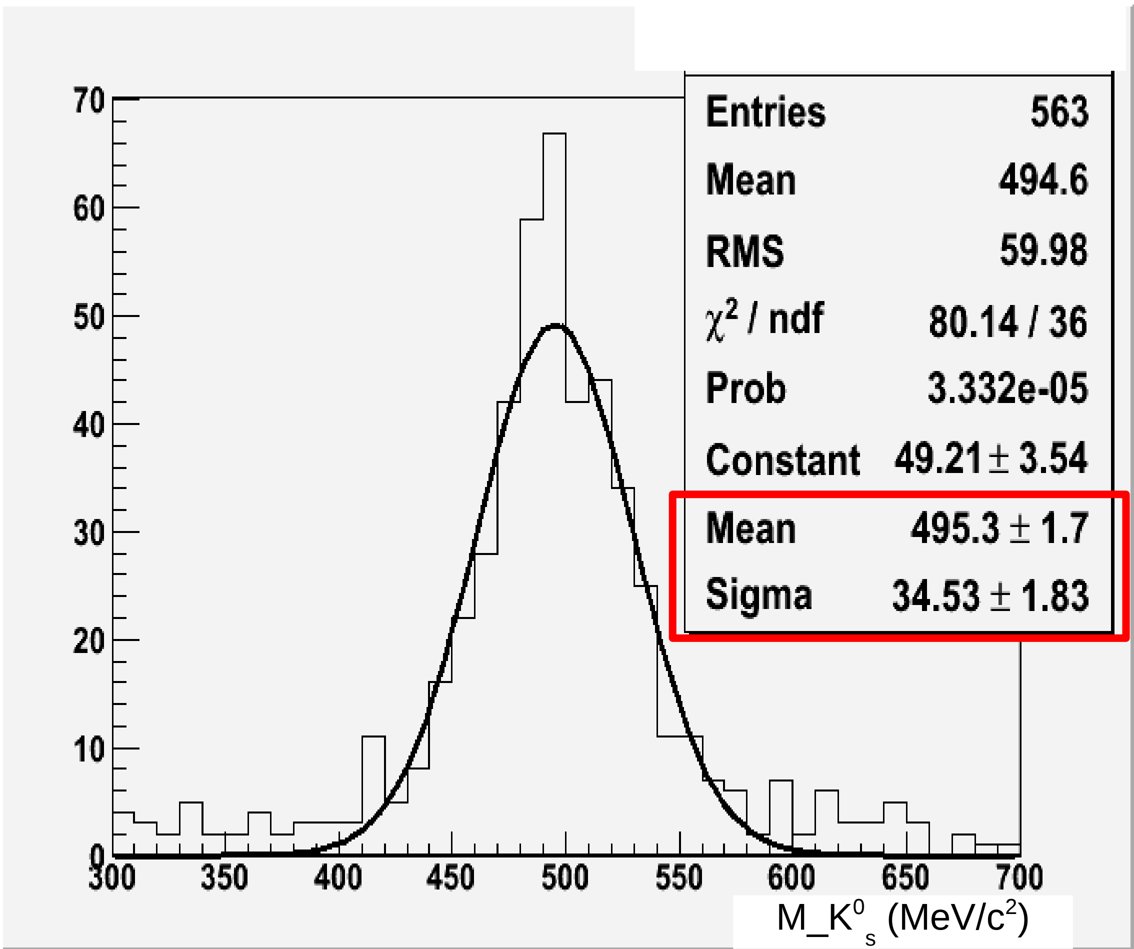
Typical event (side view):

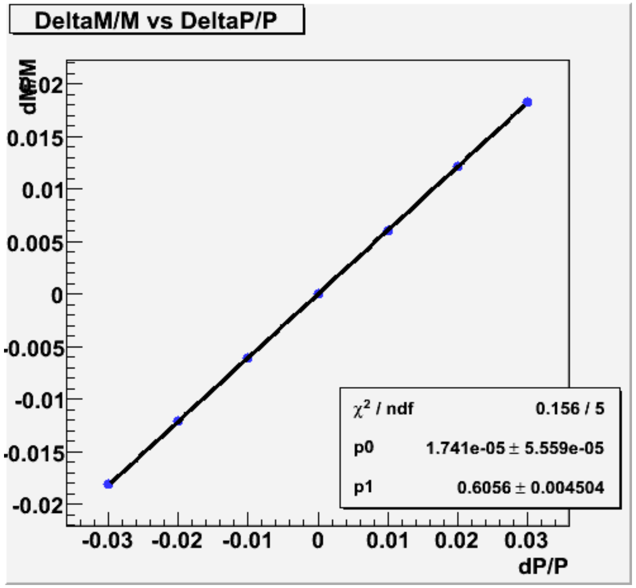


- Done only with Monte Carlo (MC).
- **Pure K^0_s MC**, 500 MeV kinetic energy in FGD1 volume, **10 000 events**
- **K^0_s decays in the FGD ($\beta\gamma c\tau \sim 5$cm).**
- Procedure:
  - 2 tracks required at least
  - opposite sign curvatures + cut on curvature error ($\sigma < 2.10^{-5}$ mm^{-1})
  - vertex reconstruction: extrapolation of TPC tracks into the FGD
  - π^+ and π^- energy loss correction.
  - K^0_S mass computed with reconstructed angles and momenta.

Absolute momentum scale

Reconstructed K^0_s invariant mass





- Is it enough to reach the required precision?

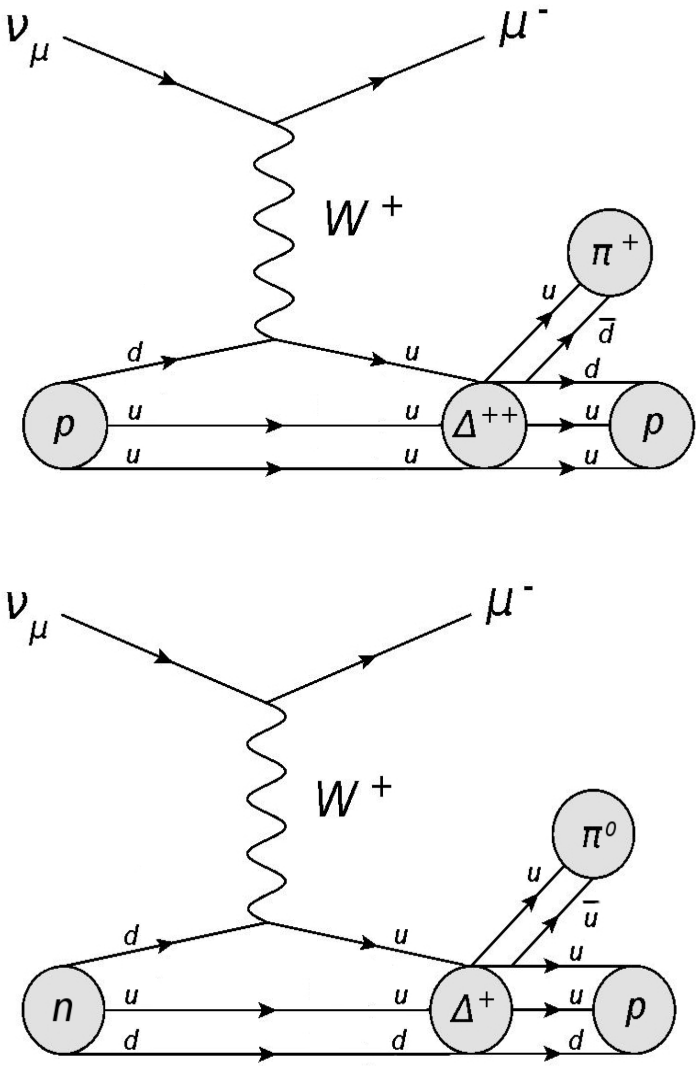
→ $\Delta p_\pi/p_\pi < 2\ \%$ → $\Delta m_K/m_K < 1.2\ \%$

- Normalised to expected number of K^0_s for 10^{21} POT :

→ **$\Delta m_K/m_K = 1.3\%$**

Calibration of the absolute momentum scale with K^0_s decays is feasible if backgrounds are under control.

Formation zone: motivation



CHARGED CURRENT

- Δ decay is not immediate and at interaction point → decay time + distance = π formation zone
- Pions are produced in the nuclear medium, which has a variable density.

→ Final state interactions depend on π initial position.

- If the formation zone changes, so does the probability of π absorption, escape or charge exchange.
- Final state distributions change

→ **cross-section measurements are affected.**

Formation zone in NEUT

- NEUT uses the SCAT parametrisation for lab framework (Baranov et. al.) :

$L_{fstd} = p / \mu^2 \rightarrow$ "typical" formation length

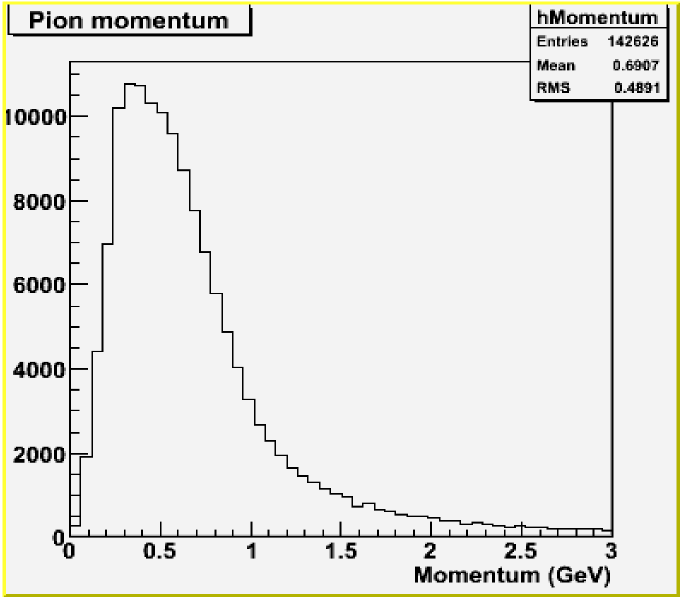
$$L_f = - L_{fstd} \ln(\text{random nb.} < 1)$$

- where μ is a "characteristic hadron mass", unpredicted by theory and measured to be

$$\mu^2 = 0.08^{+0.05}_{-0.04} \text{ GeV}^2$$

→ this is the formation zone parameter implemented in T2KReWeight

A large μ² means a small formation zone and vice-versa.



"Typical" formation length for pions