Measurement of $\bar{\nu}_\mu$ interactions with the ND280 detector of the T2K experiment

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Outlook:

- **Neutrino Oscillation (PMNS Matrix)**
- **T2K experiment and main results obtained in 2013-2014**
  - Physics goals and description of experimental setup
  - Results of ν_e appearance and ν_μ disappearance
- **$\bar{\nu}_\mu$ analysis motivations**
- **$\bar{\nu}_\mu$ analysis in neutrino beam mode**
  - $\bar{\nu}_\mu$ selection criteria
  - Signal extraction with likelihood ratio fit
  - Evaluation of systematics uncertainties
- **$\bar{\nu}_\mu$ analysis in anti-neutrino beam mode**
  - $\bar{\nu}_\mu$ selection criteria
  - Performance and data/MC ratios of selected $\bar{\nu}_\mu$ samples
  - Evaluation of the impact of systematic uncertainties on the selected samples
- **Final results and future plans**

T2K one of the biggest international collaboration of neutrino LBL

Canada
TRIUMF
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

~350 physicists, 58 institutions, 11 nations, 3 countries

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U.Warsaw
Warsaw U.T.
Wroklaw U.

Russia
INR

Germany
Aachen U.

United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
STFC/RAL/Daresbury
U. Liverpool
U. Sheffield
U.Warwick

Spain
IFAE, Barcelona
IFIC,Valencia

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
Okayama U.
Tokyo Metropolitan U.
U.Tokyo

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U.Washington

ITALY
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Switzerland
ETH Zurich
U. Bern
U. Geneva

Neutrino mixing (PMNS*)

Flavor eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"atmospheric ν"
(Super-K, K2K, T2K, MINOS)
$\sin^2 2\vartheta_{23} > 0.95$ (90% C.L.)

"ν from accelerators and reactors"
(T2K, MINOS
Daya Bay RENO, Double Chooz)
$\sin^2 2\vartheta_{13} = 0.098 \pm 0.013$

"solar ν"
(SNO, Super-K, KamLAND)
$\sin^2 2\vartheta_{12} = 0.857 \pm 0.024$

$c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$

$\delta_{cp} = ?$

accessible only from **accelerators neutrinos**

* Pontecorvo-Maki-Nakagawa-Sakata

T2K: Goal di fisica

T2K is sensitive to:

- θ_{13} e δ_{cp} in the ν_e **appearance** channel

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \frac{\Delta m^2_{13} L}{4E} + (\text{termine CPV}) + (\text{termine MSW}) + \ldots$$

- θ_{23} e Δm^2_{23} in the ν_μ **disappearance** channel

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{13} L}{4E} + (\text{termini sub-leading})$$

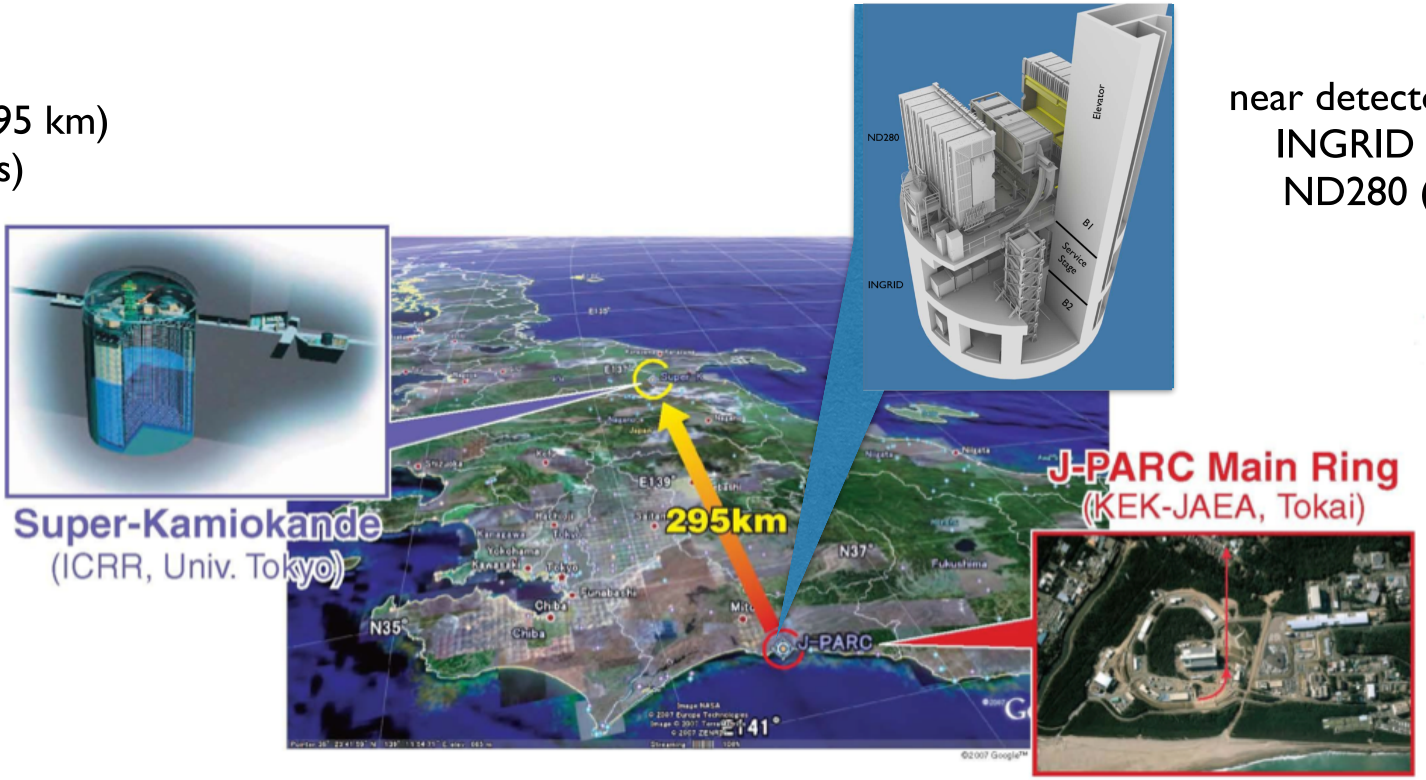
- **Measurement of θ_{13} ($\bar{\theta}_{13}$)**
  - Direct measurement of $\nu_\mu \to \nu_e$ appearance (and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance)
  - up to 3σ level of significance can be achieved for $\bar{\nu}_e$ appearance
- **Precise measurement of atmospheric parameters θ_{23}, Δm^2_{23}**
  - $\theta_{23} = 45° \pm 5°$ (T2K can distinguish the octant)
- **Initial measurement of δ_{cp}**
  - up to 2.5σ level of significance can be achieved
- **X-section measurement in the GeV region @ ND280**
- **Exotics: sterile neutrinos and sub-leading effects**

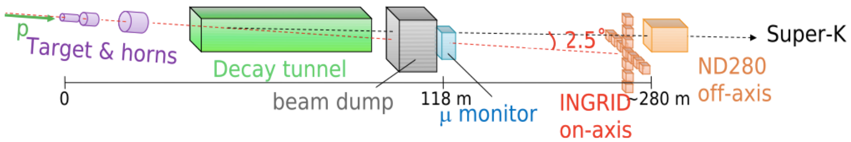
The T2K experiment

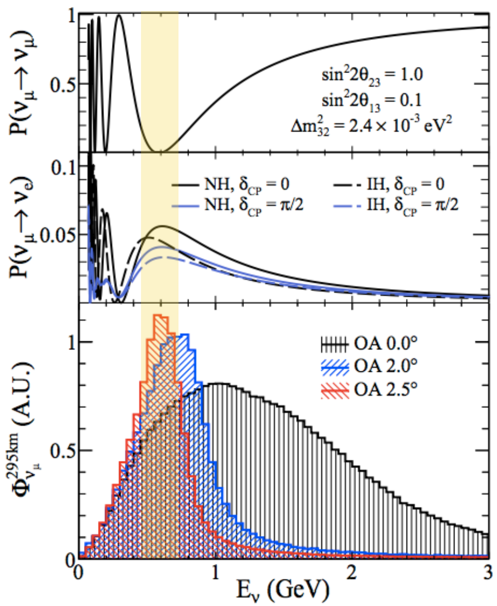
T2K is a LBL experiment able to measure the neutrino oscillation in a high purity ν_μ beam

Far detector (295 km)
SK (off-axis)

near detectors (280 m)
INGRID (on-axis)
ND280 (off-axis)







E_ν ~0.6 GeV

T2K is the first experiment which uses an off-axis neutrino beam

Advantages of the off-axis beam:

- The effect of neutrino oscillation is maximized
- High background reduction (small tail at high energy)

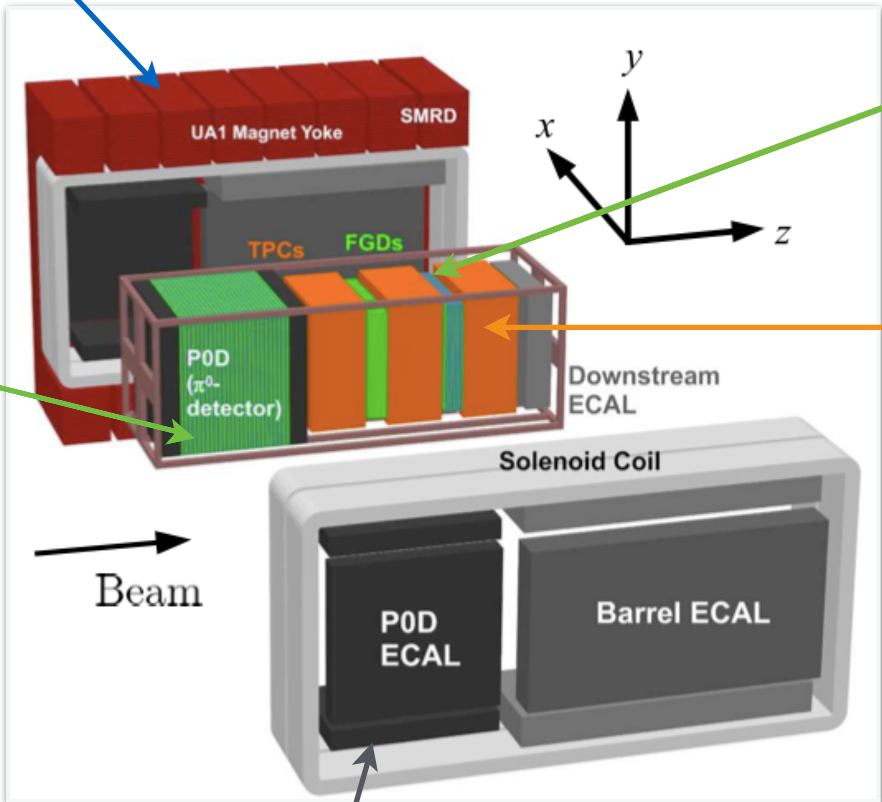
ND280 (off-axis)

ND280 (Off-axis Near Detector @ 280 m from the target)

- Measure of the un-oscillated neutrino spectrum
- Measure of intrinsic beam contamination
- Study of π^0 production in NC events
- Exclusive x-section measurements below 1GeV
- Constraint x-section and flux systematic uncertainties at SK

The UA1/NOMAD magnet produce a magnetic field of 0.2 T.
The SMRD (installed in the magnet joke): modules of plastic scintillators able to reconstruct high angle μ, cosmic rays and "sand muons" events.

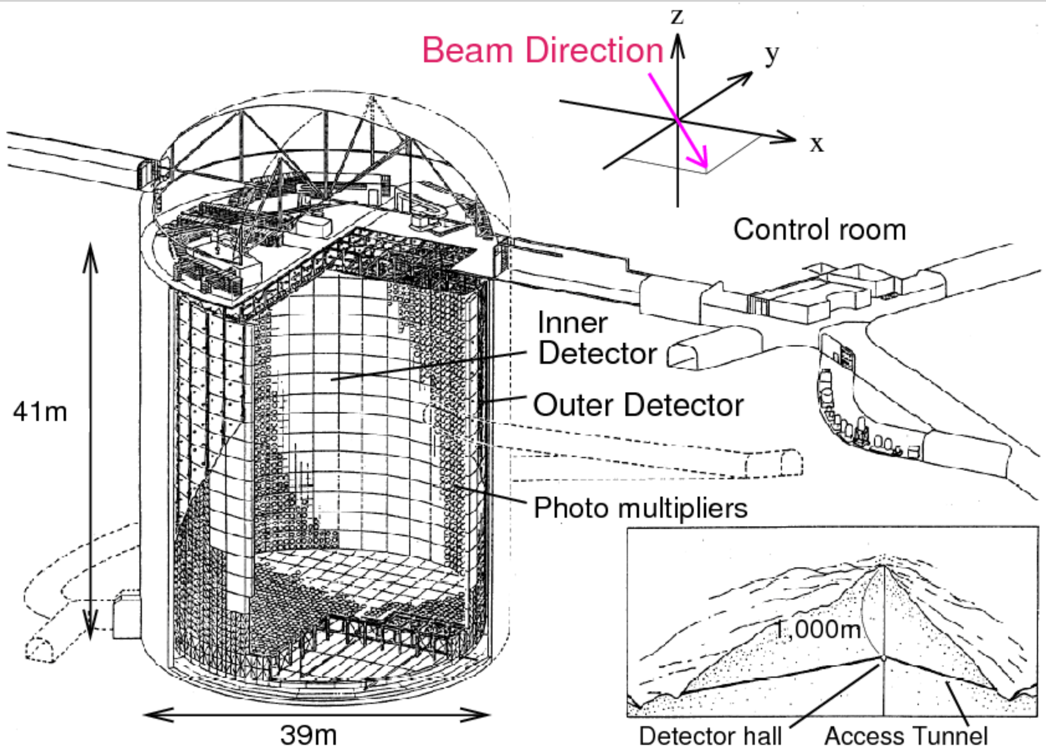
P0D:
scintillator planes interleaved by layers made of lead/brass and water. It is used as an active target to measure photons coming from NC e $CC\pi^0$ interactions



Tracker:
2 FGD: X-Y planes of scintillator bars used as a target for ν interactions and able to track charged particles.
3 TPC: able to perform 3D tracking, measure of charge, momentum and dE/dx of charged particles.

ECal: it surrounds all the internal detectors and it has the capability to distinguish γ/e/μ. It is a sampling ECal made of 13 independent modules of X-Y planes of plastic scintillator/lead.

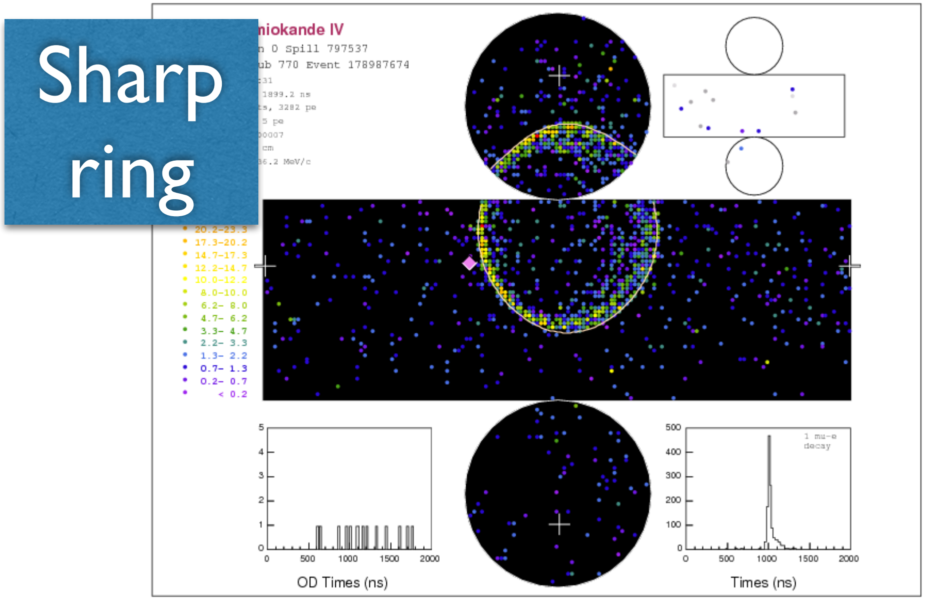
Super-Kamiokande (“off-axis”)

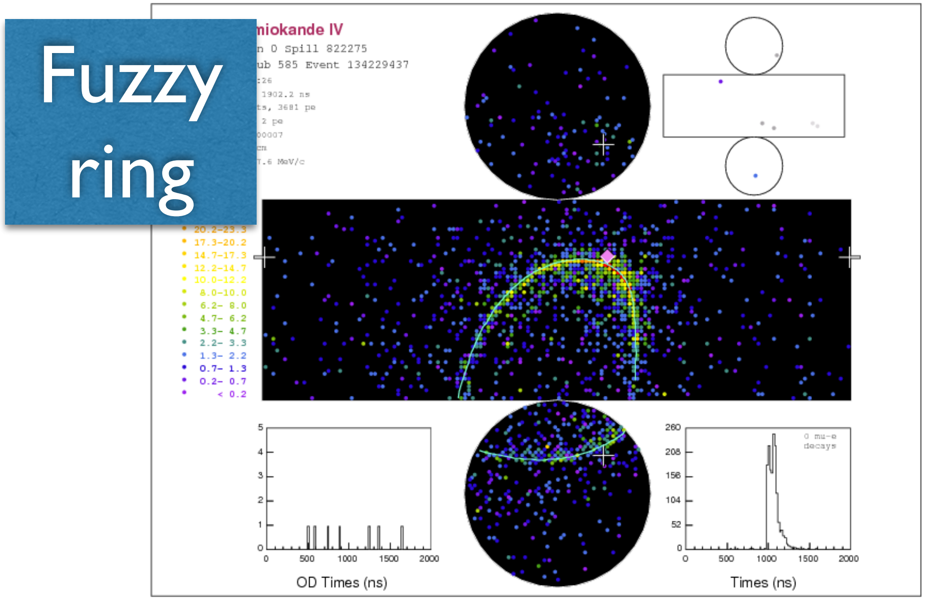


Super-Kamiokande

- 50 kton water Cherenkov detector (25 kton Fiducial volume)
- Detection of μ
  - Low scattering ⇒ “sharp rings”
- Detection of e
  - High scattering ⇒ “fuzzy rings”
- Detection of π^0
  - 2 e-like rings ($\pi^0 \rightarrow 2\gamma$)
  - A π^0 event can be identified ONLY if two e-like rings are detected

~99% capability in the μ/e separation

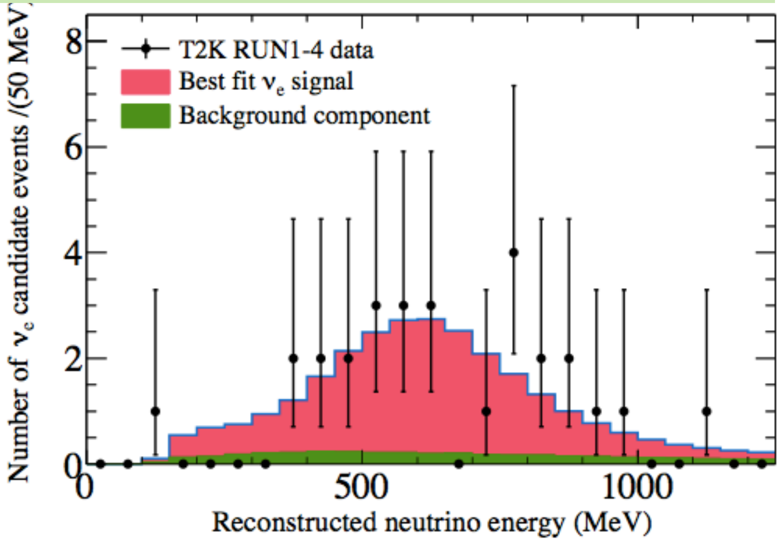


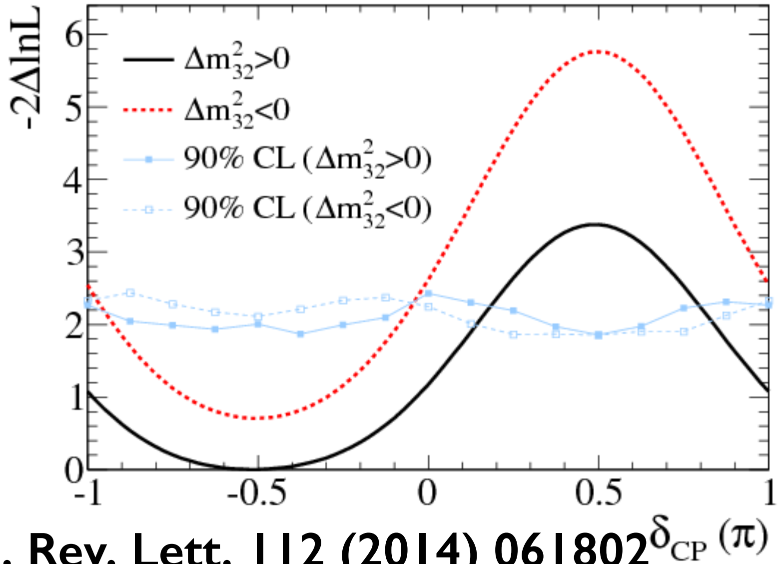


T2K highlights 2014

ν_e appearance

7.3σ significance for $\vartheta_{13} \neq 0$





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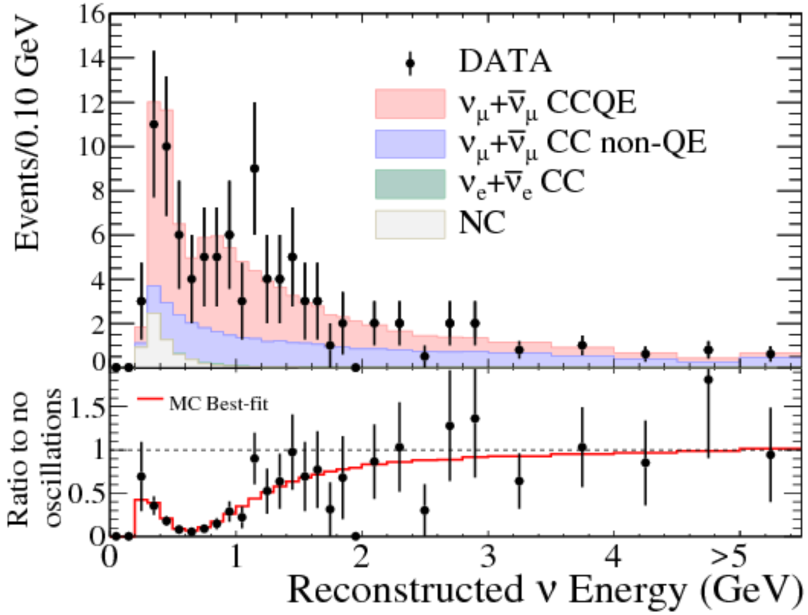
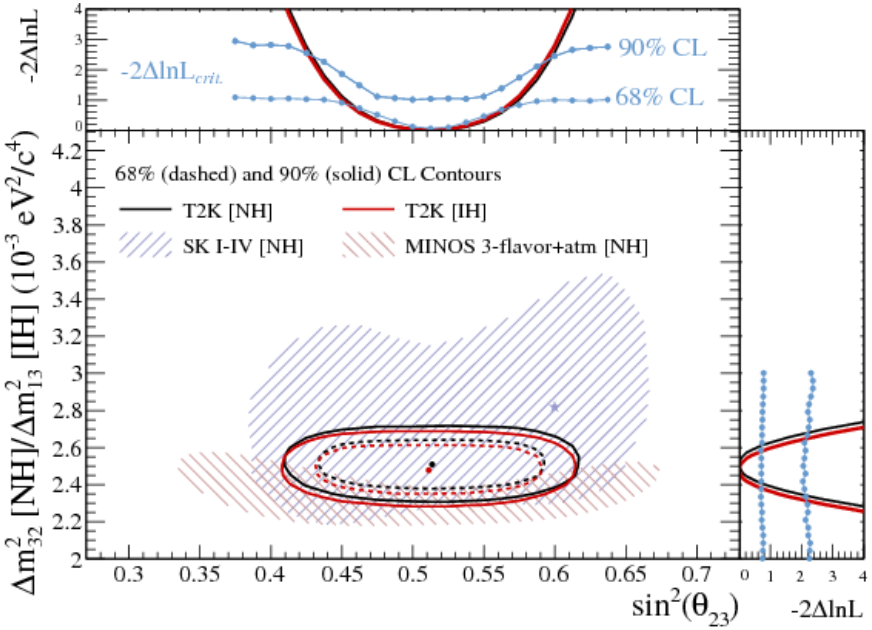
- For the first time the ν_e appearance is observed in a high purity ν_μ beam
- $\vartheta_{13} \neq 0$ opens the door to the measurement of δ_{cp}
- T2K is the first experiment able to reject some values of δ_{cp} with 90% C.L.

ν_μ disappearance





Phys. Rev. Lett. 112 (2014) 181801

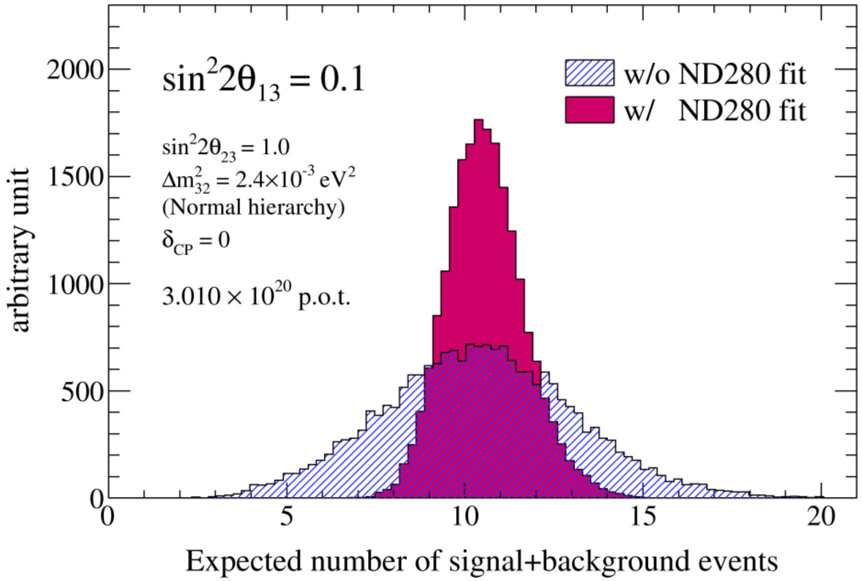
The best worldwide measurement of θ_{23} !

$\overline{\nu}_{\mu}$ analysis motivations

- To achieve a precise measurement of the oscillation parameters, the systematic uncertainties must be reduced as much as possible
- The main systematic uncertainties on the oscillation analyses are:
  - flux uncertainty at SK
  - neutrino x-section models

These systematic uncertainties are reduced by ND280 (ND280 constraint)

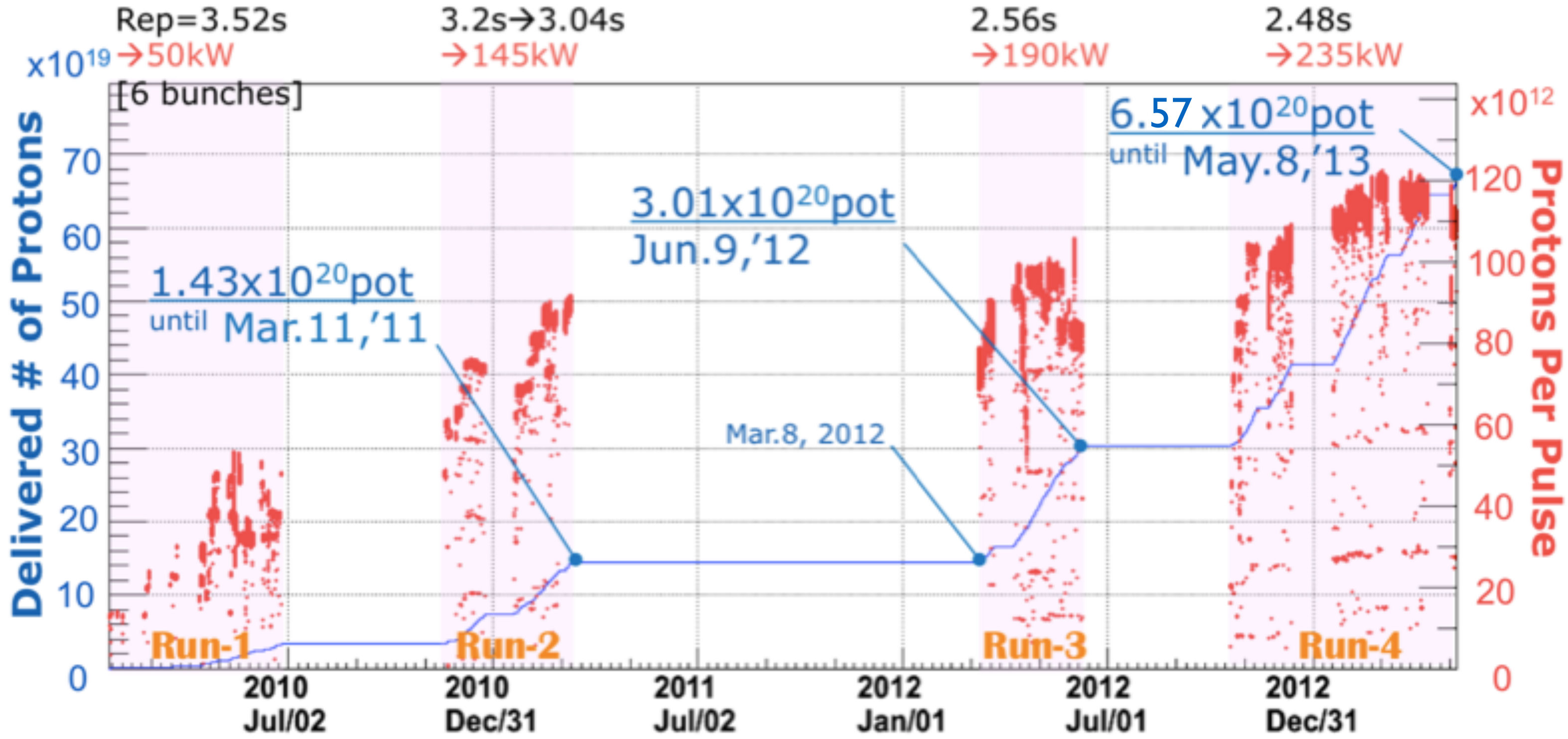
Beam **A**nd **N**d280 **F**lux measurement task **F**orce **(BANFF) Fit**



- The **BANFF fit** currently uses only the **ν_{μ}** sample
- As a consequence, some systematic errors like the anti-NuMu flux uncertainty and $\sigma_{\bar{\nu}}/\sigma_{\nu}$ are slightly or not reduced.
- The measurement of anti-nu is useful to reduce these systematic uncertainties ⇒ **analysis used in the BANFF fit since 2014**
- Main analysis at ND280 in anti-neutrino beam mode data taking to measure **δ_{CP} (since 2014)**
- **Run 5 in anti-nu beam mode: 4-24 June 2014. Accumulated statistic: ~5 ×10^{19} POT**
- **Run 6 data taking in anti-nu beam mode since 26 October 2014**

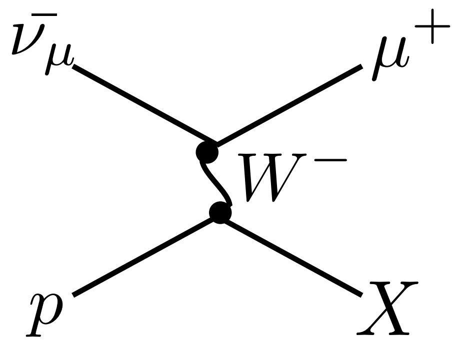
$\bar{\nu}_\mu$ analysis in neutrino beam mode

Data and MC samples



- In this analysis I used the official T2K Monte Carlo production and the whole amount of data collected in the period 2010-2013 (Run1+Run2+Run3+Run4)
- Whole statistic used: 6.57×10^{20} POT.

$\overline{\nu}_\mu$ selection criteria



At the T2K energy (0.6GeV), in 95% of cases, the most energetic positive particle produced in a anti-NuMu CC interaction is the μ^+ => μ^+ MUST BE SELECTED TO STUDY THE ANTI-NUMU (~4% beam component)

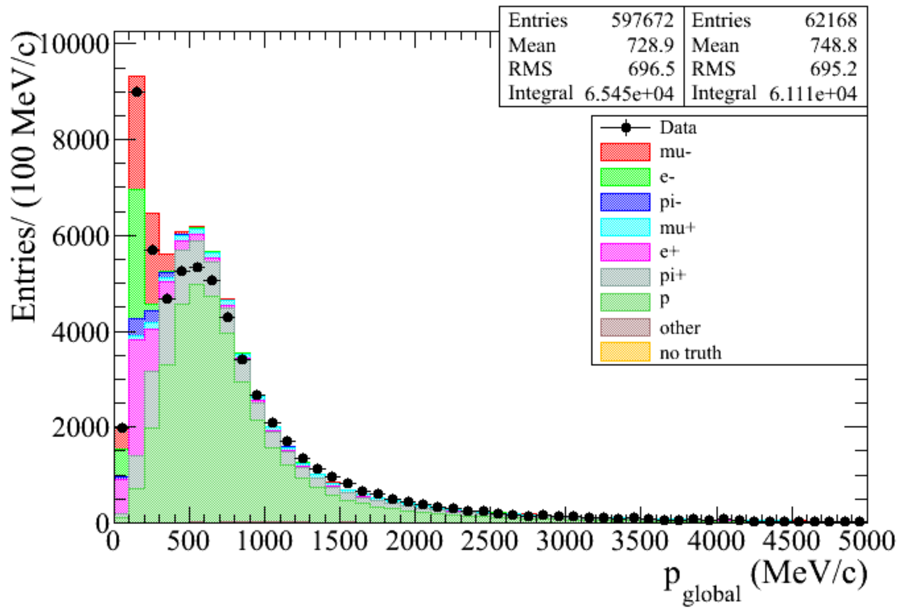
	# Cut	Cut Name	Cut Description
Preselection	1	Bunch Cut	In defined Bunch
	2	FGD FV	Origin of the track selected in FV
	3	TPC track quality	Tracks with the first TPC segment with more than 18 nodes
	4	Positive tracks	The selected track must be positive
	5	TPC veto	Veto on backwards events or coming from P0D or Magnet
μ^+ selection	6	TPC PID	μ^+ selection: $0.1 < L_\mu < 0.7$ (if $p < 500$MeV => $L_{MIP} > 0.9$)
	7	1 track events	1 FGD-TPC matching in the event
	8	Has ECAL info	Selection of events with the selected track in ECAL
	9	ECAL PID	MIP-EM LLR < -10 && MIP-PION LLR < -5

Cuts 1–5: Selection of the Highest Momentum Positive Track (HMPT)

Cuts 6–9: μ^+ identification

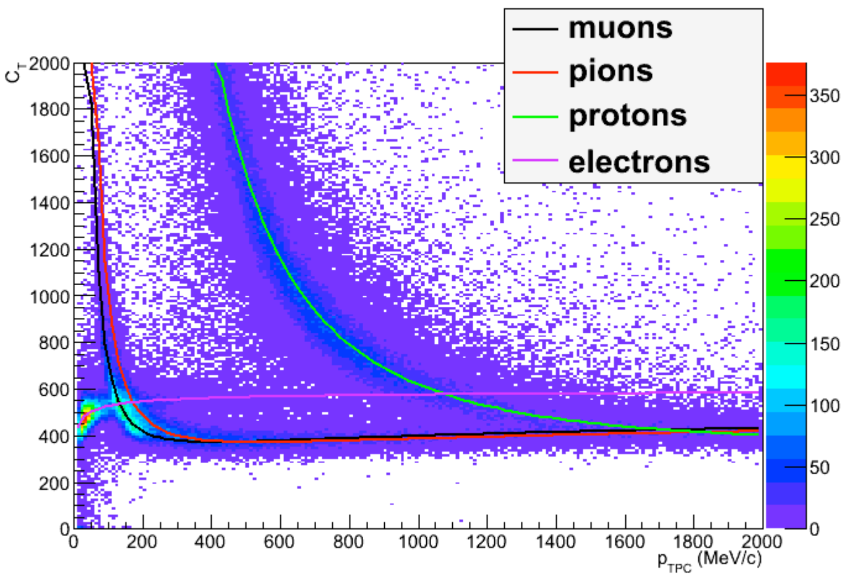
Selection of $\overline{\nu}_\mu$ CC interactions using the tracker

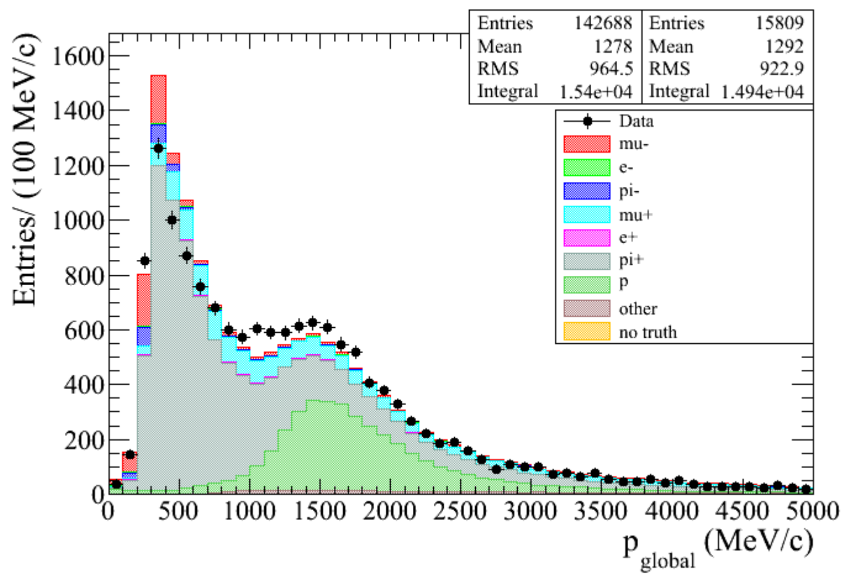
Result after the pre-selection:



μ^+ signal

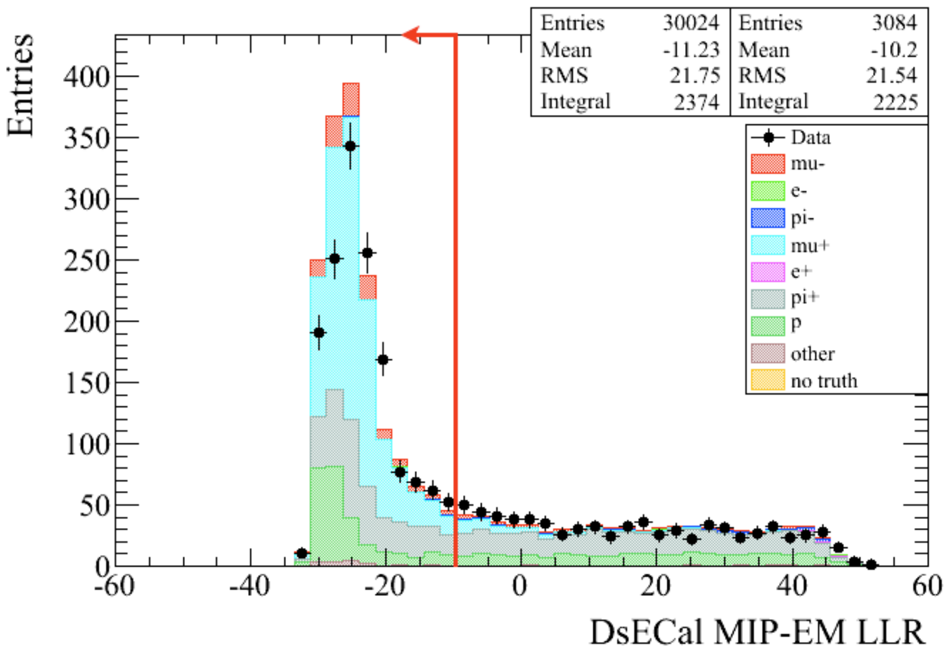
The selected sample is dominated by ν_μ interactions and moreover the TPC PID alone cannot select μ^+ with an acceptable purity.

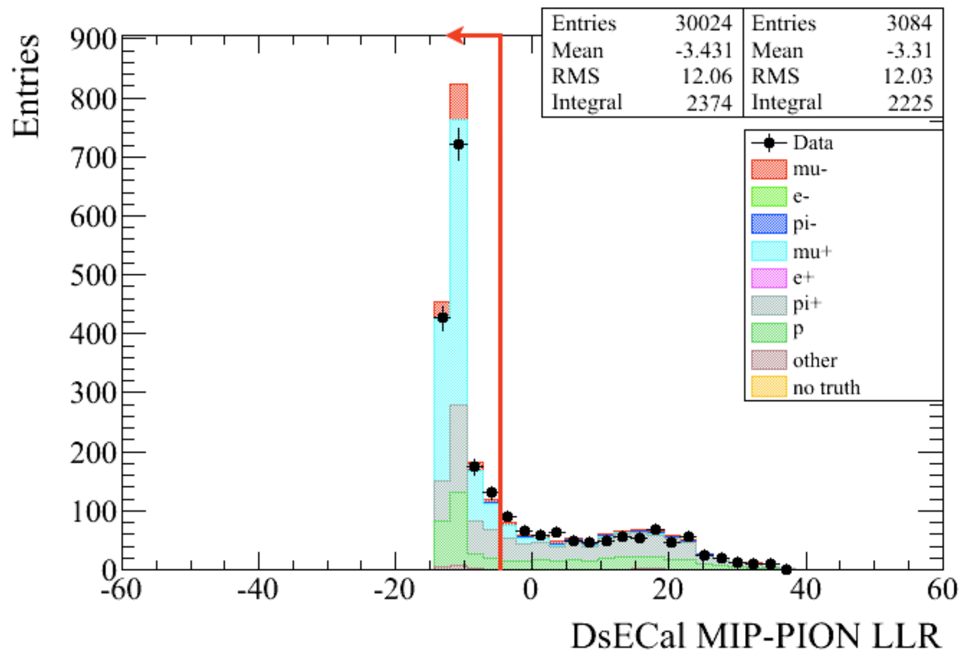




Selection of $\overline{\nu}_\mu$ CC interactions using the ECal

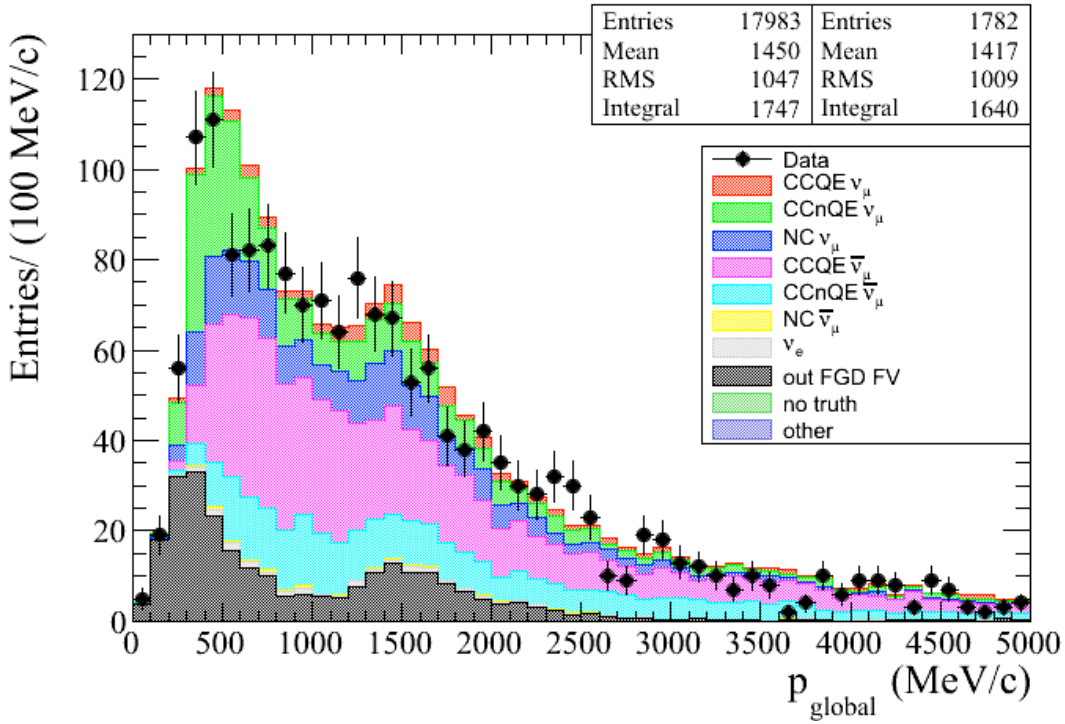
- In order to select μ+ with a higher purity than the one obtained using the TPC PID alone, the ECal PID must be used. The ND280 ECal corresponds to ~10.6 X_0 and ~1λ_I. Thus it is possible to identify and reject the amount of showering protons and pions in the ECal.

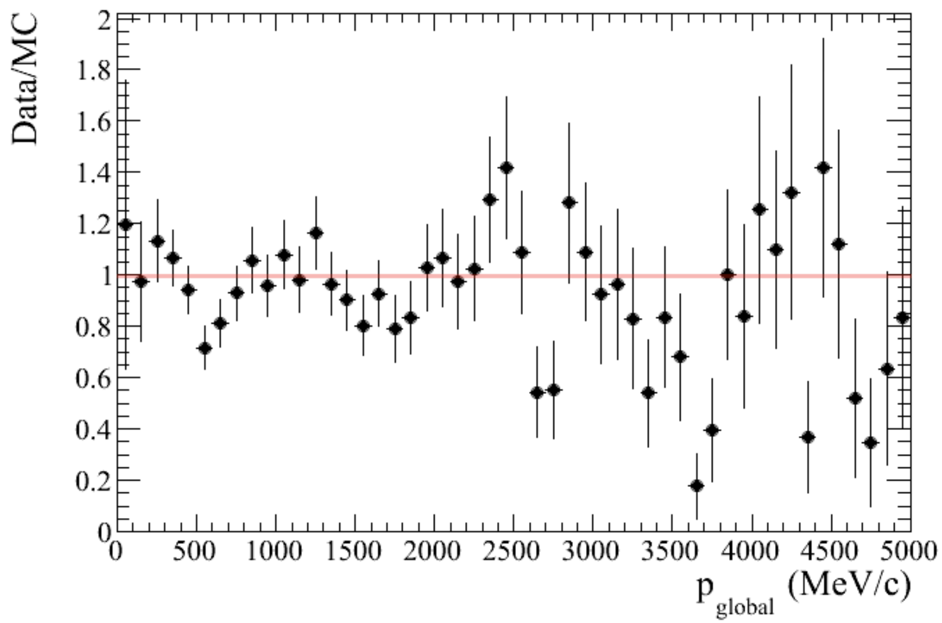




Final result

<data/MC>$_{0<p<5GeV}$ = 0.95

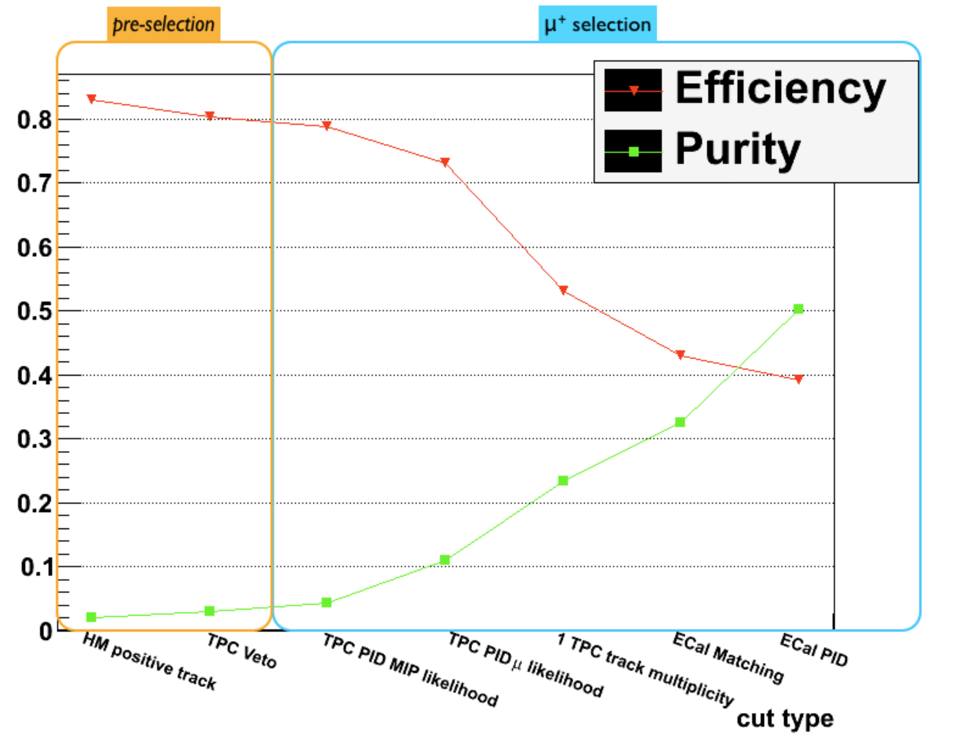




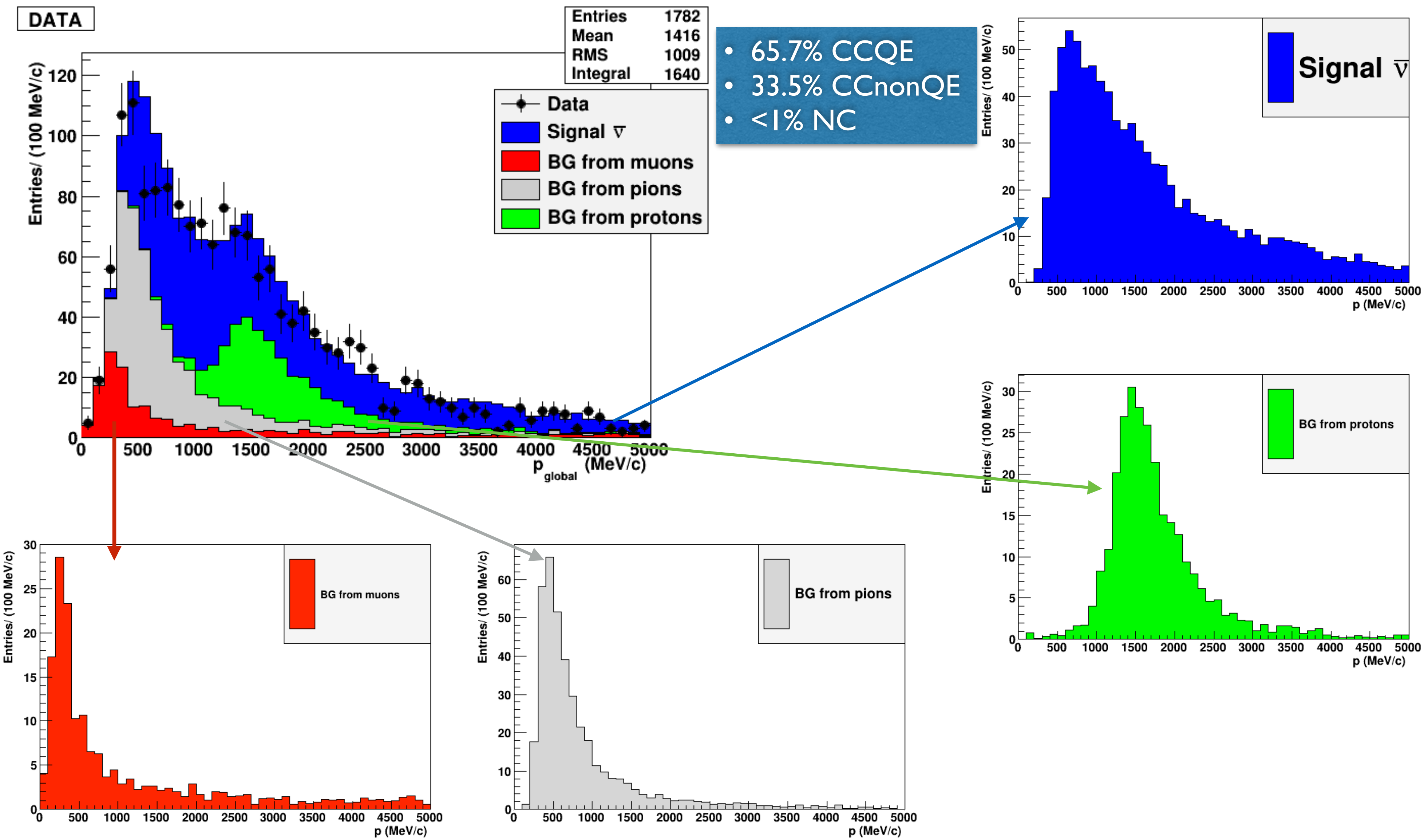
NuMu CCQE	5,5%
NuMu CCnQE	17%
NuMu NC	11,4%
anti-NuMu CCQE	33,2%
anti-NuMu CCnQE	17%
OOFV	14,4%

CC Inclusive ~50%

More than 98% of background rejected



Final result: signal and background



- 65.7% CCQE
- 33.5% CCnonQE
- <1% NC

The background is divided depending on the particle type

Increase fit performance

Likelihood ratio fit for signal and backfround in p-cos(ϑ) space

FIT STRATEGY:

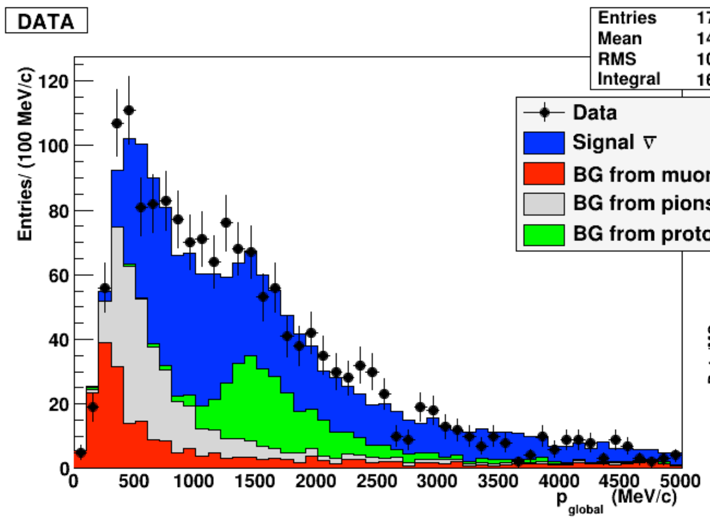
MC fitted on data in 0<p<30GeV (10 bins) and -1<cos(ϑ)<1 (4 bins)

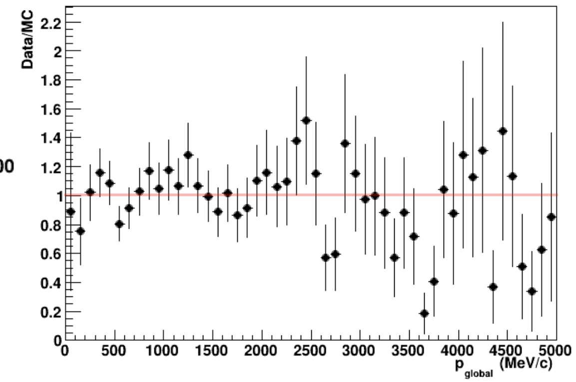
$$F(p, \cos\theta) = f(\bar{\nu}_\mu) g_{\bar{\nu}_\mu}(p, \cos\theta) + \sum_i f(BG_i) g_{BG_i}(p, \cos\theta) \qquad (i = \mu, \pi, p)$$

$$-2 \log \mathcal{L}_{\bar{\nu}_\mu} = 2 \times \sum_{i=1}^{10} \sum_{j=1}^{4} F_{i,j} - n_{i,j}^{data} + n_{i,j}^{data} \times \log \frac{n_{i,j}^{data}}{F_{i,j}}$$

Binning:

- ***xbins edge***={0,400,500,600,700,800,1000,1250,1500,2000,30000}, ***ybins edge***={-1,0.8,0.9,0.95,1}
- Finer binning around 0.6 GeV
- ≥10 entries per bin to avoid Poissonian fluctuations in the toy MC studies





f(anti-nu) = 0.94 +/- 0.06 (stat.)

N_{events} = 908.5 +/- 62.1

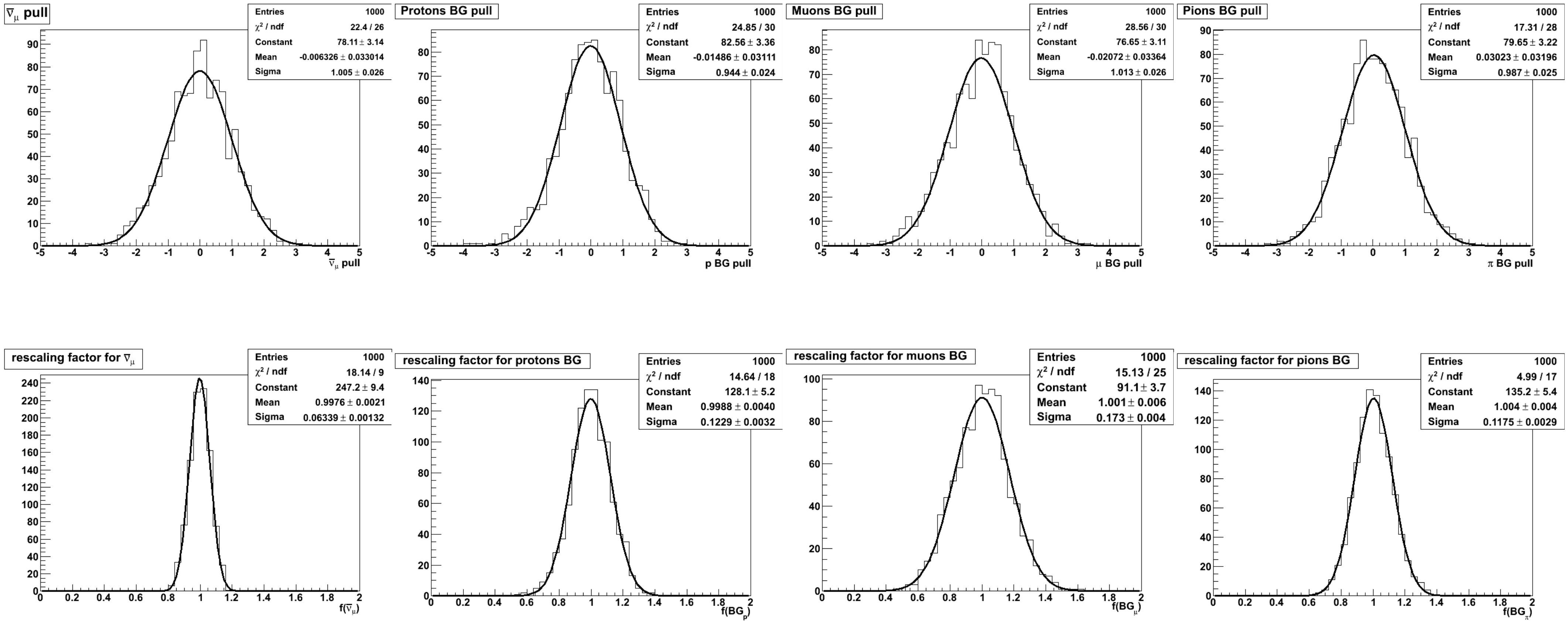
f(anti-nu) = ratio data/MC

Fit Stability

1000 toy-MC with a fixed rescaling factor ***f***

$$\text{pull} = \frac{f_{\text{fitted}} - f_{\text{set}}}{\sigma_{\text{fit}}}$$

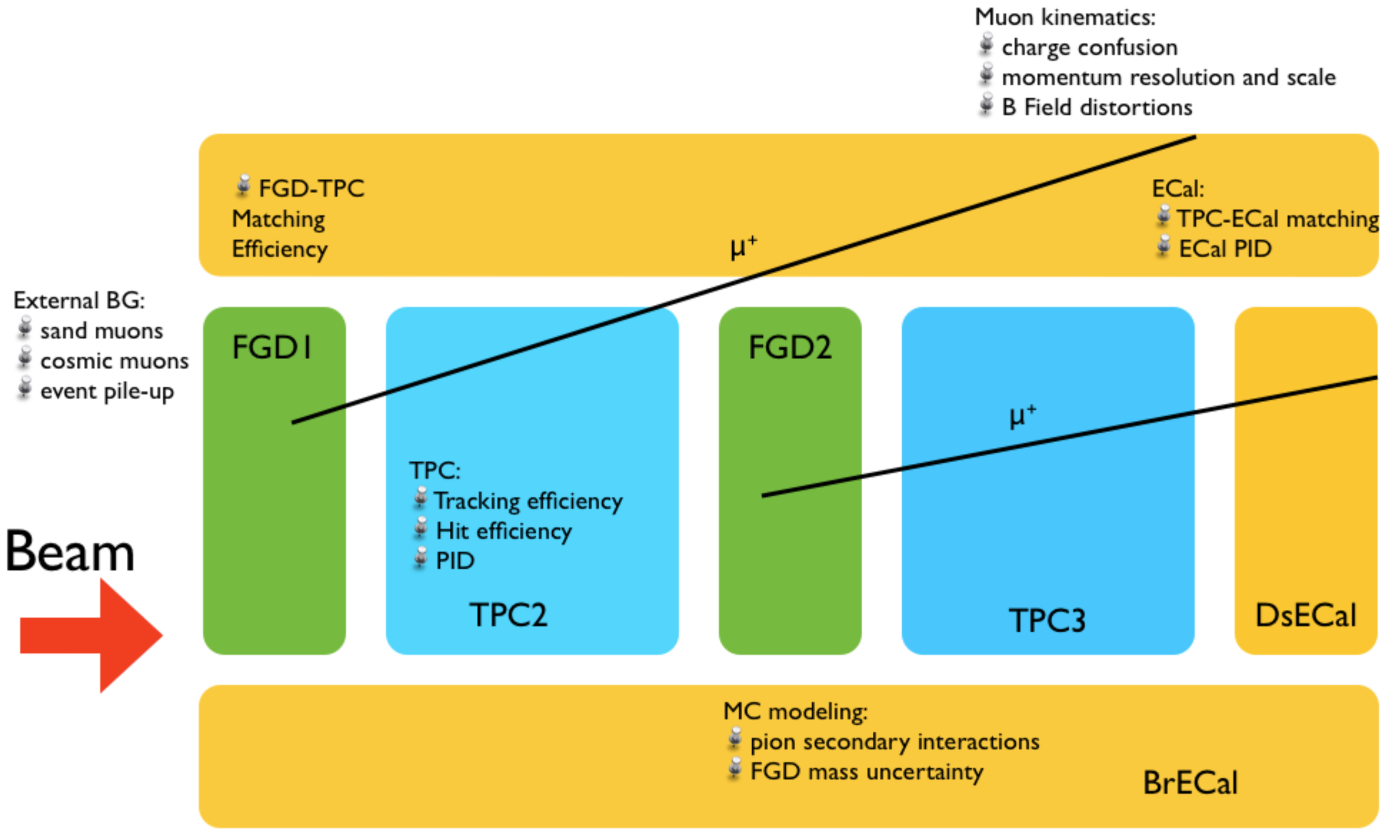
No bias found in the fit!



Systematic uncertainties

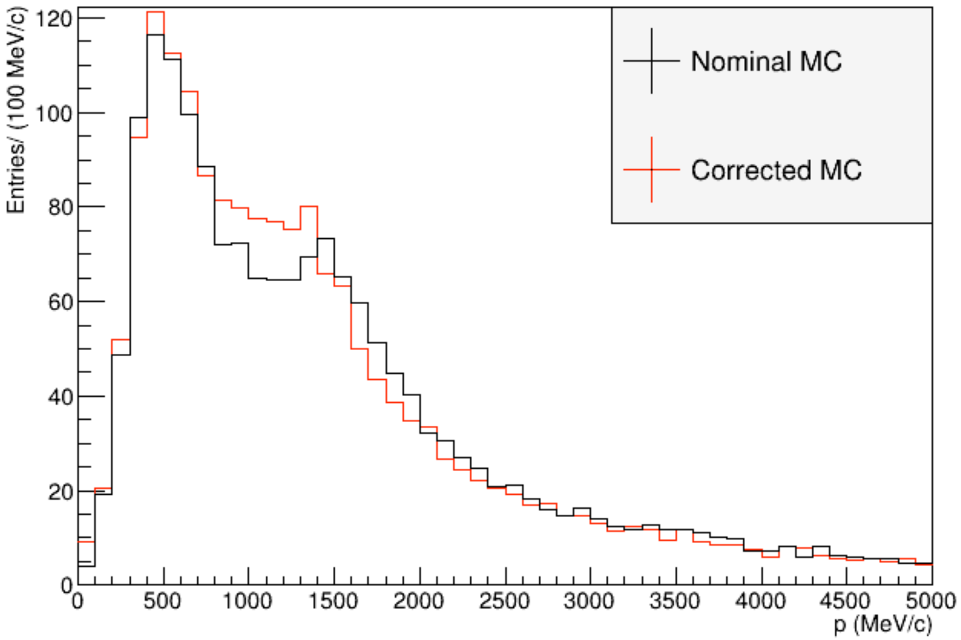
3 systematic error sources:

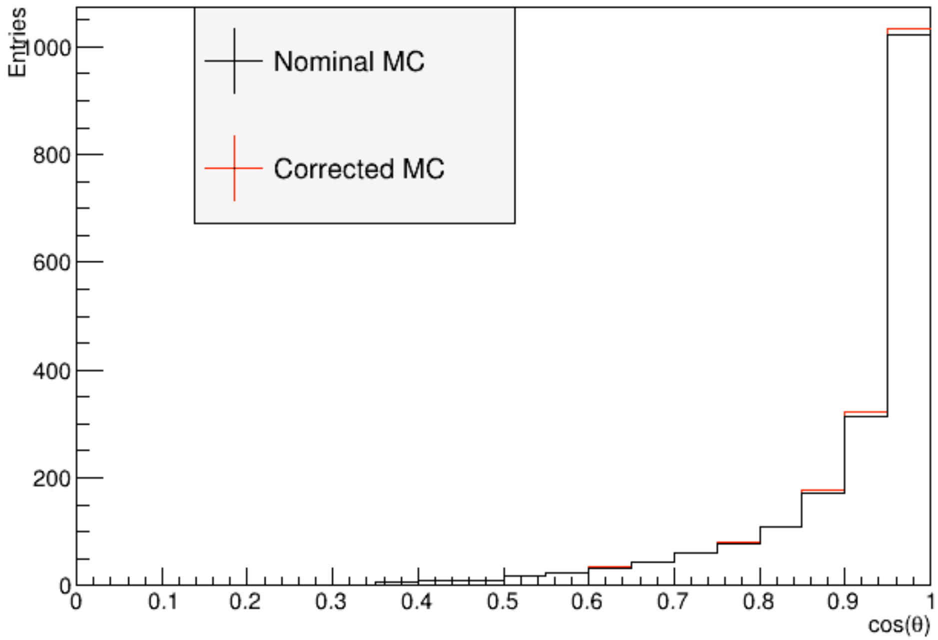
- detector systematic (data-MC discrepancies due to event reconstruction)
- Flux systematics (MC)
- X-section parameter systematics (MC)

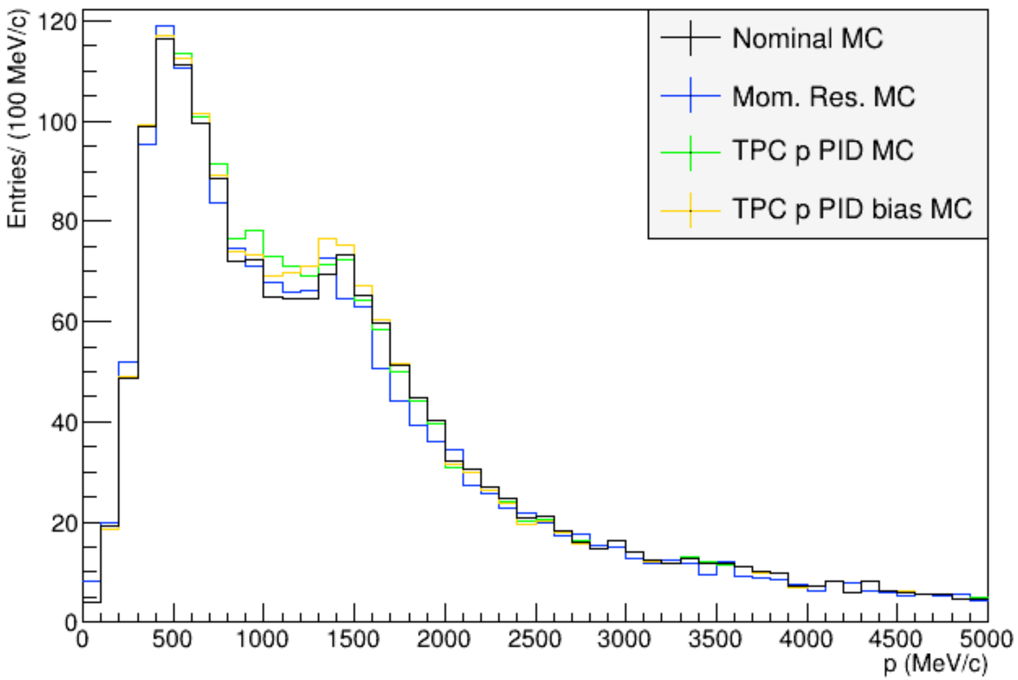


TPC PID for protons is the main systematic uncertainty in this analysis

Detector systematics: Corrected Monte Carlo







Il MC is "corrected" with the prior values of detector systematics

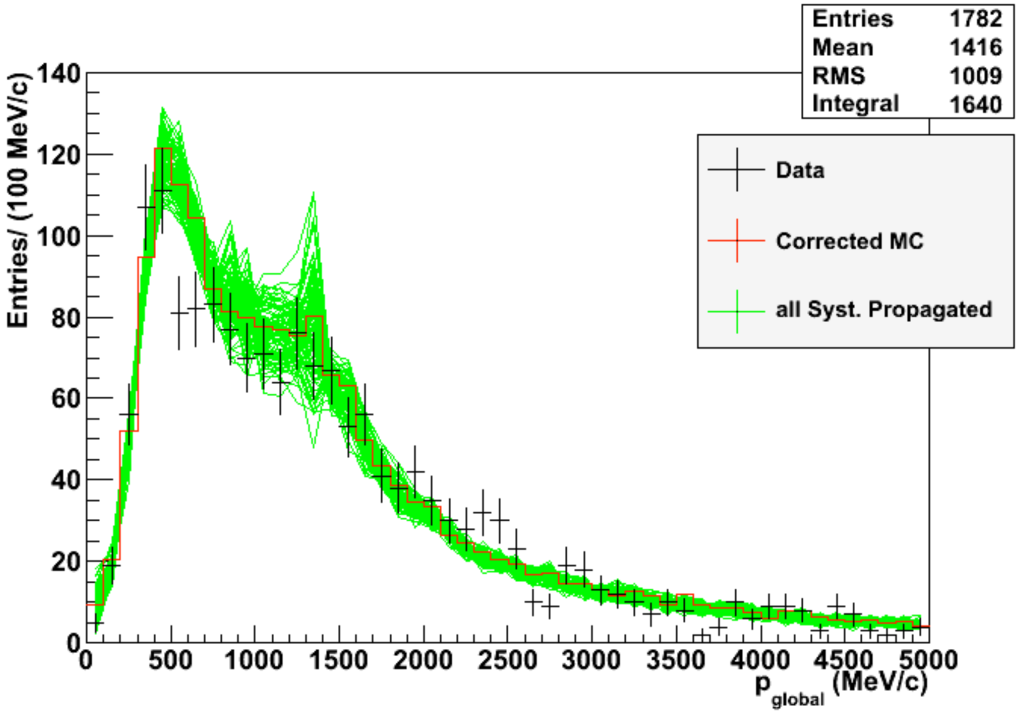
Goal: build a simulation that takes into account the dati-MC differences observed .

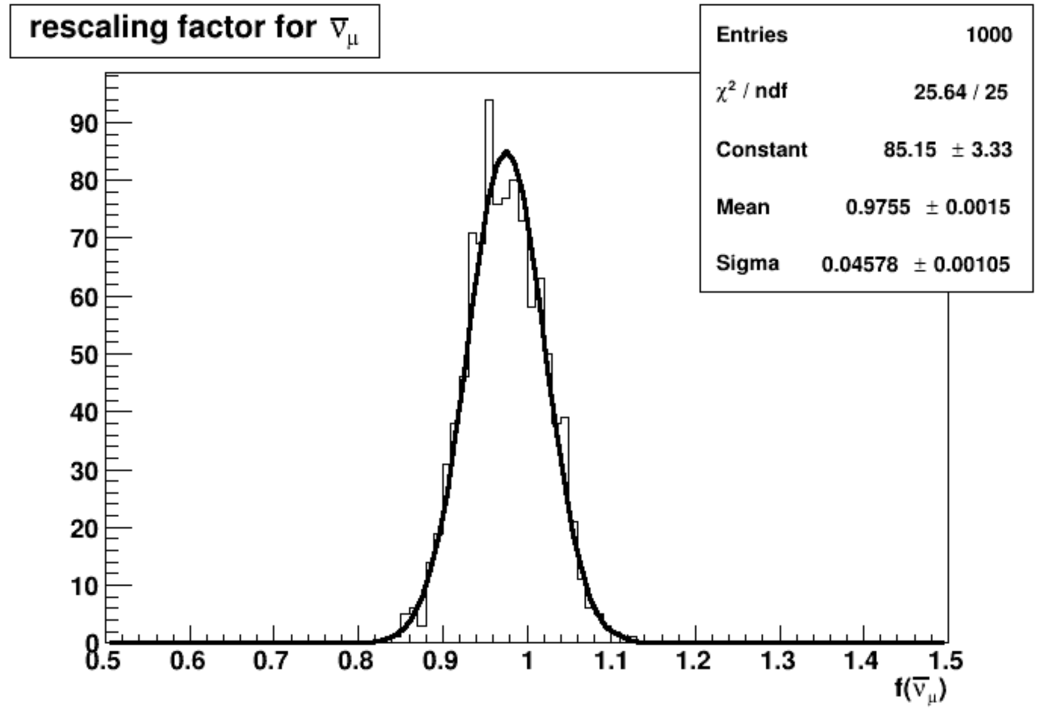
Main corrections:

- TPC proton PID
- Mom. Res.

Detector systematic error propagation

I produced **1000 MC toys** varying simultaneously the effect of all detector uncertainties.
The effect of the systematic error propagation is than evaluated in the Likelihood fit





Systematic source	detector syst. err. on $f_{\bar{\nu}_\mu}$
width of syst. throws	0.045
difference from corrected MC	0.025

FINAL RESULT INCLUDING THE DETECTOR SYSTEMATIC UNCERTAINTIES:

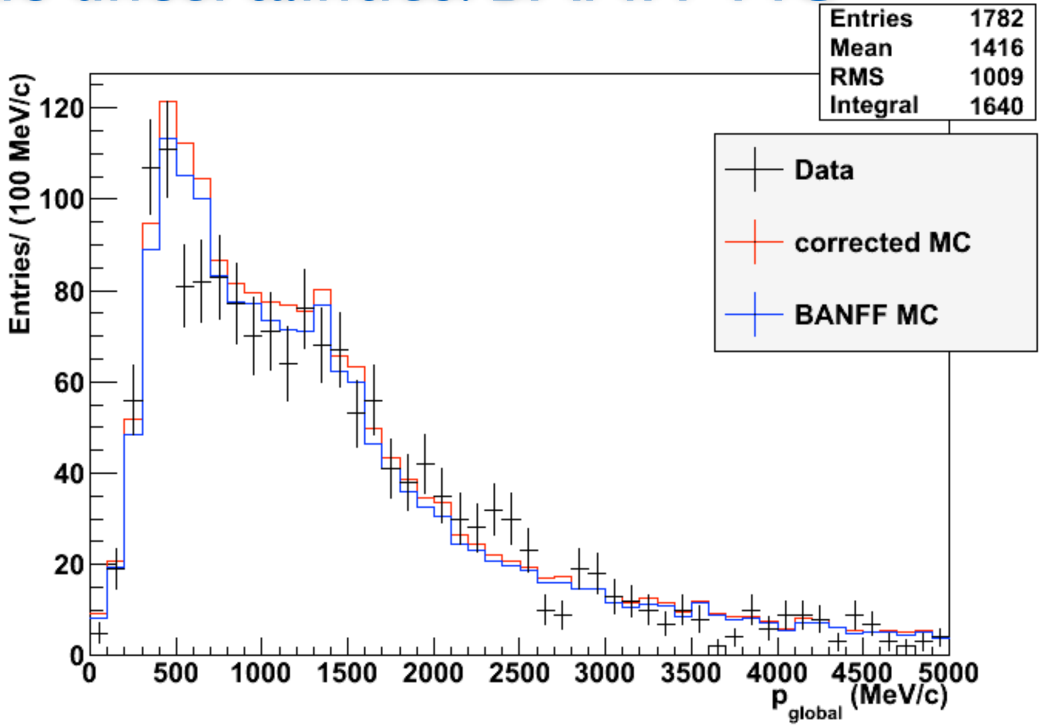
f(anti-nu) = 0.97 +/- 0.07 (stat.) +/- 0.05 (det. syst.)

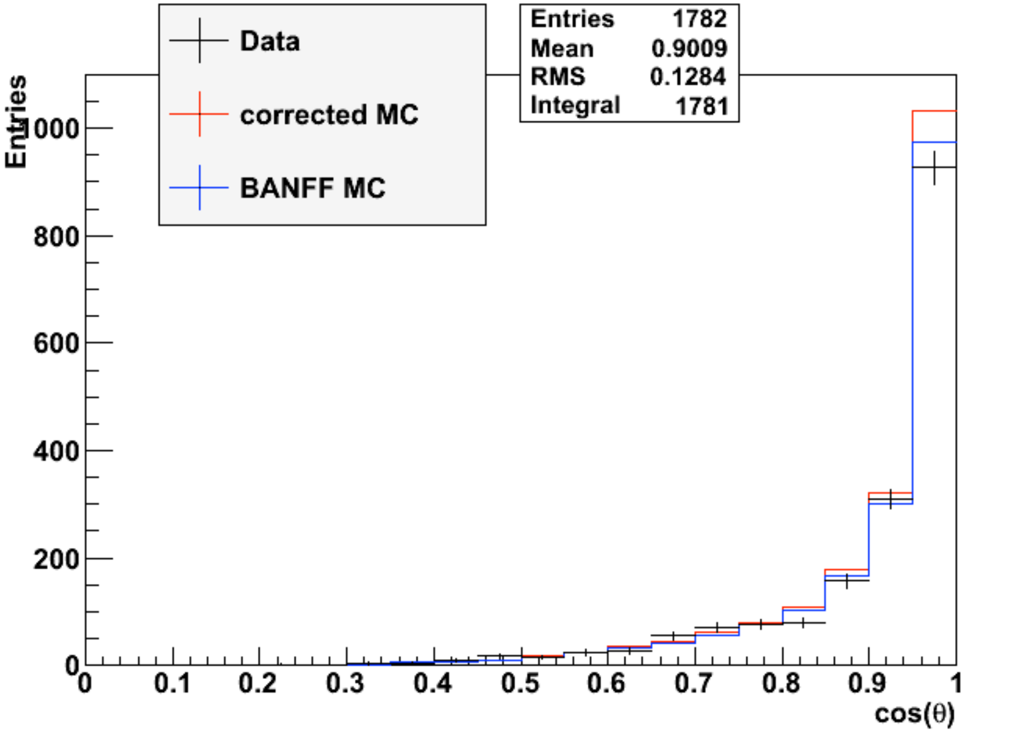
Flux and x-section systematic uncertainties: BANFF MC

The goal of the BANFF fit is the reduction of **flux** and **x-section** systematics in the oscillation analyses. The best fit values obtained from the 2013 BANFF fit are listed in the Table

Systematic	BANFF central values	parameters
ν_μ flux	$\sim$ 0.9-1.00	11
$\bar{\nu}_\mu$ flux	$\sim$ 0.98-1.01	5
ν_e flux	$\sim$ 0.9-1.01	7
$\bar{\nu}_e$ flux	$\sim$ 0.9-1.0	2
FSI	~ -0.52-0.38	6
M_A^{QE} [GeV]	1.22	1
M_A^{RES} [GeV]	0.96	1
CC Other Shape [GeV]	0.3	1
Spectral Function (^{12}C & ^{16}O)	0.28	1
E_b (^{12}C & ^{16}O) [MeV/c]	28.885	1
P_F (^{12}C & ^{16}O) [MeV/c]	269.37	1
π-less Δ decay	0.17	1
CCQE norm.	0.96, 0.90, 0.87	3
CC1π norm.	1.20, 1.07	2
CC Coh. norm.	0.47	1
NC Other norm.	1.32	1
NC1π^0 norm.	1.08	1

The MC must be re-weighted using the BANFF best fit values to be consistent with the oscillation analyses

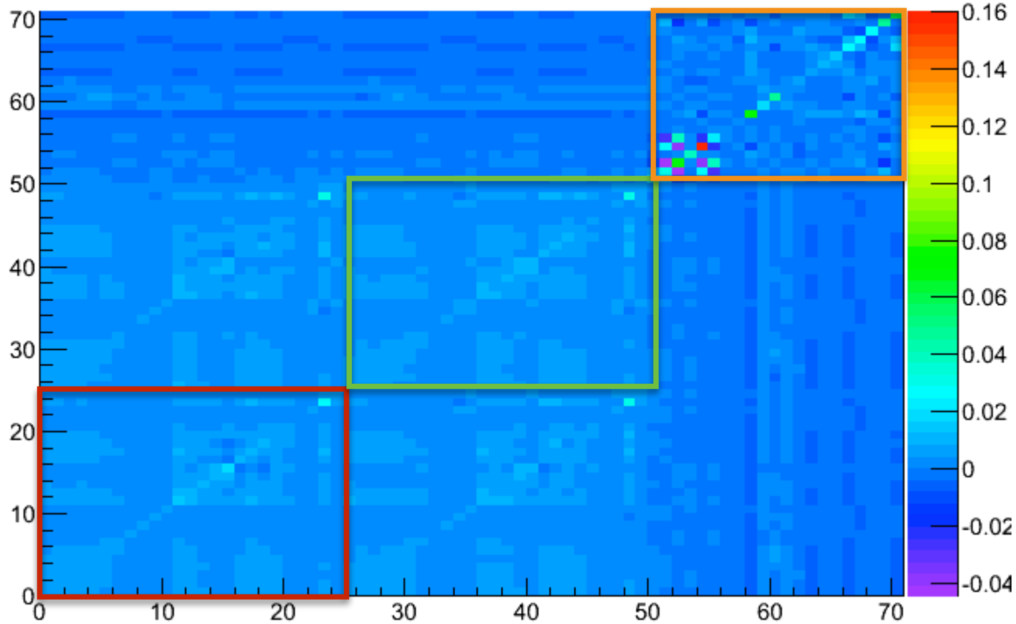


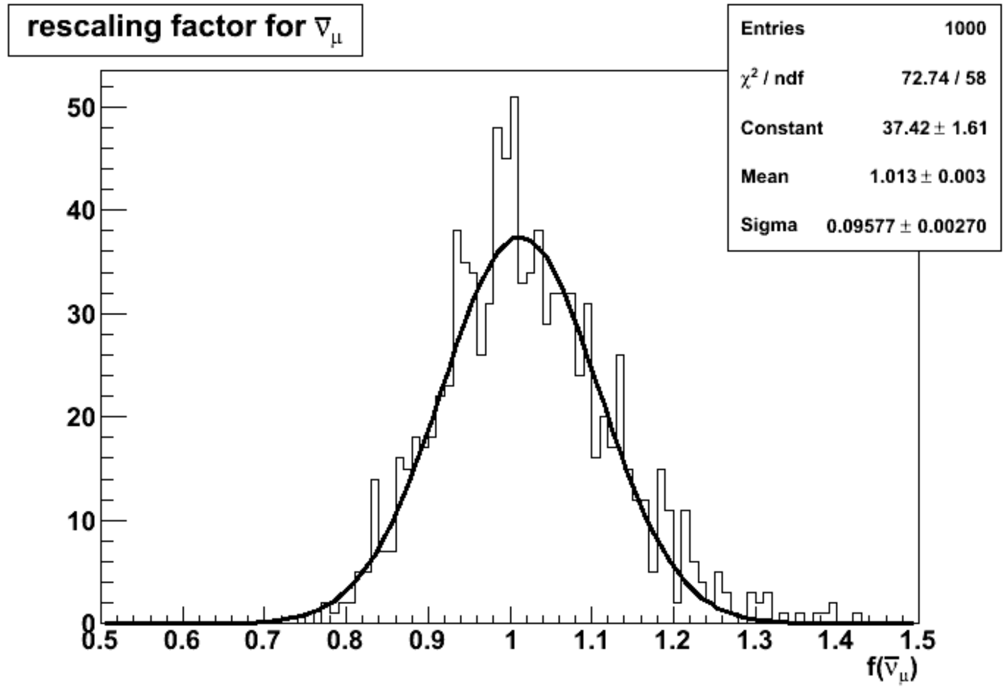


Flux and x-section systematic errors propagation

I produced **1000 throws** in the 2013 BANFF covariance matrix,.

The effect of the systematic error propagation is than evaluated in the Likelihood fit





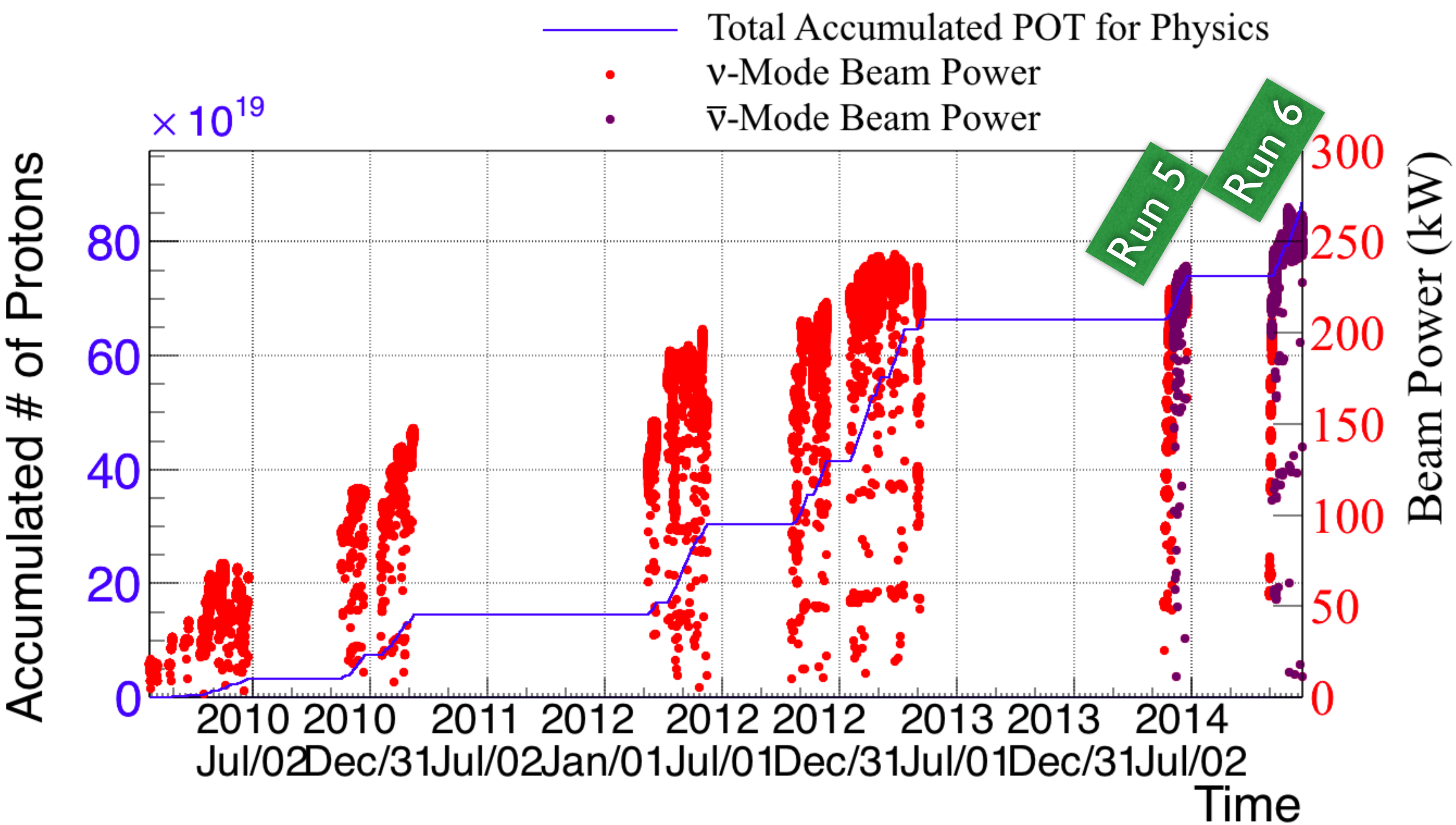
FINAL RESULT INCLUDING FLUX AND X-SEC SYSTEMATIC UNCERTAINTIES:

f(anti-nu) = 1.01 +/- 0.08 (stat.) +/- 0.05 (det. syst.) +/- 0.09 (flux x-sec syst.)

- The obtained results is in agreement with the MC expectation and it confirms a very good prediction of $\bar{\nu}_\mu$ background in the oscillation analyses.
- It is already possible to quantify how much this analysis can helps in the reduction of the anti-NuMu related systematic errors in the oscillation analyses:
  - Reduction of the systematic uncertainty related to the anti-NuMu flux component up to 9% on the whole energy spectrum
  - Reduction from 40% to 13% of the $\sigma_{\bar{\nu}}/\sigma_{\nu}$ uncertainty.

$\bar{\nu}_\mu$ analysis in anti-neutrino beam mode

Data and MC samples

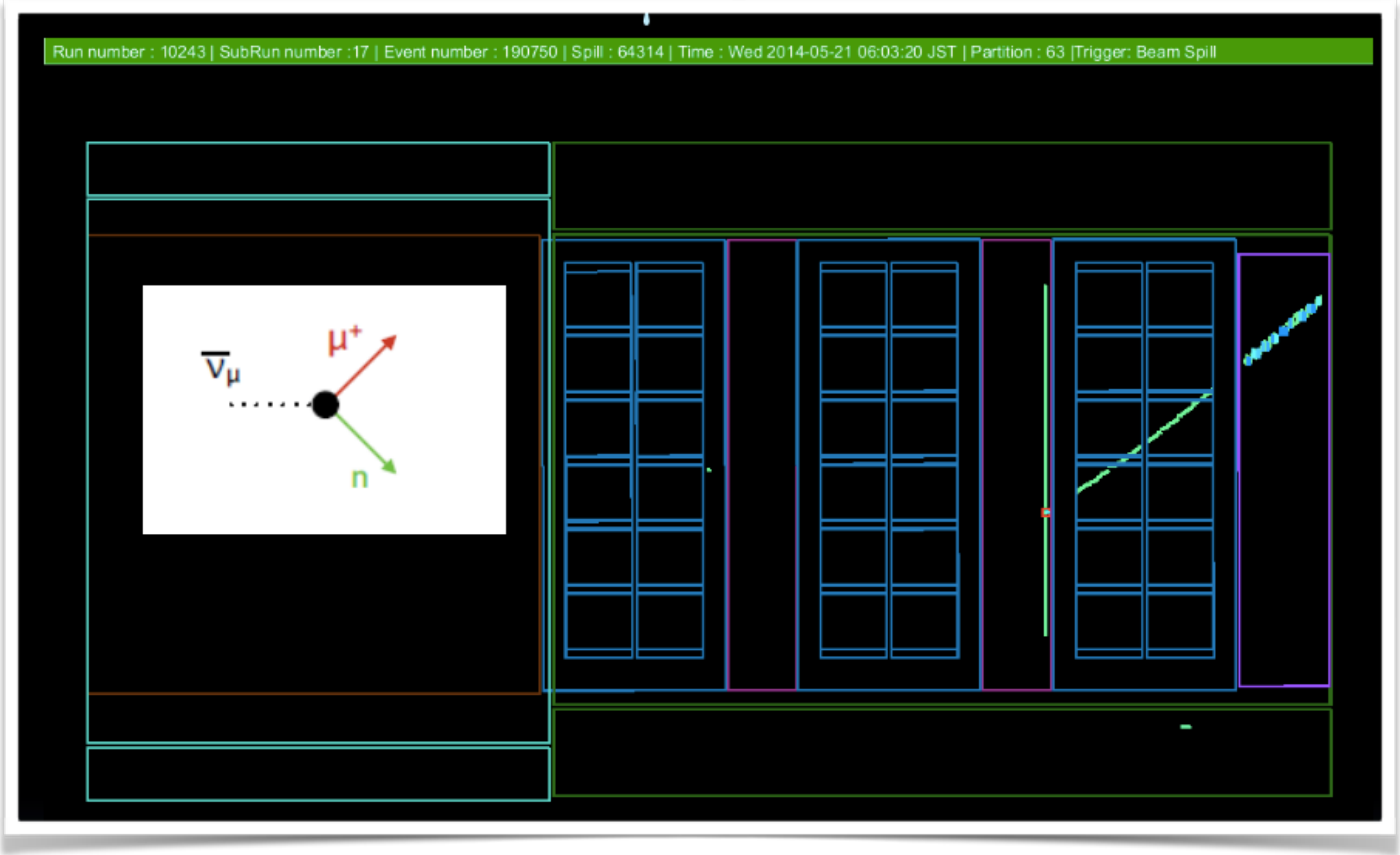


- anti-nu beam mode data collected up to now: 1.808 $\times 10^{20}$ POT

In the next slides:

- run5 anti-nu data: ~5 $\times 10^{19}$ POT
- MC sample used: ~2 $\times 10^{21}$ POT

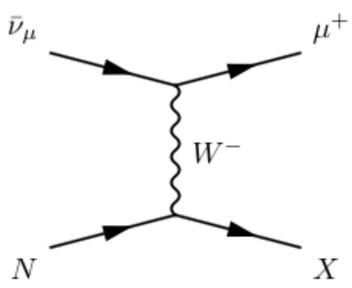
First $\bar{\nu}_\mu$ event in the anti-nu beam



The first $\bar{\nu}_\mu$ at ND280 was analyzed using the software developed by me during the PhD and the analysis was performed in Bari!

- Single positive track reconstructed in TPC and ECal
- Momentum: 572 ± 39 MeV/c
- Probability to be a μ^+: 99.3%
- Vertex in the FGD2 Fiducial Volume
- Purity (MC) > 95%

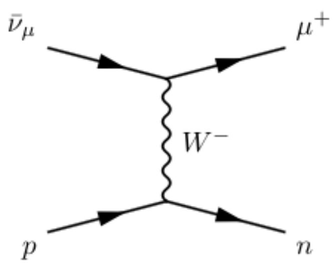
$\overline{\nu}_\mu$ selection criteria



CC Inclusive

	# Cut	Cut Name	Cut Description
Preselection of the HMPT	0	Event quality	The event must occur in defined Bunch
	1	Total multiplicity	In the selected event, at least one track must cross the TPC
	2	Quality & Fiducial	The HMPT in the event must have its origin in FGD1 FV and more than 18 TPC nodes
	3	Positive multiplicity	The HMPT must be the HMT in the event
	4	TPC veto	Veto on backwards events or coming from P0D or Magnet
	5	External FGD1	Rejection of external BKG from the last two layers of FGD1
μ^+ selection	6	TPC PID	μ^+ selection: $0.1 < L_\mu < 0.7$ (if $p < 500$MeV => $L_{MIP} > 0.9$)

Samples provided to the oscillation analyses

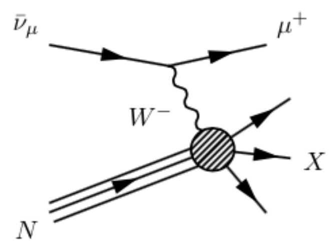


"CC-1trk sample"

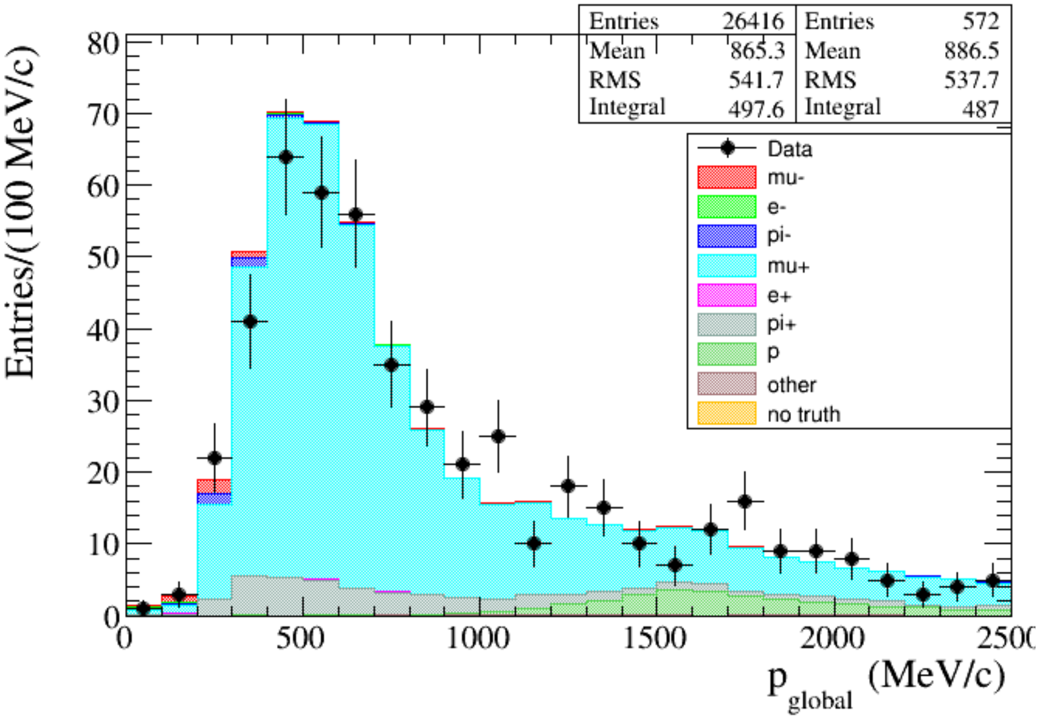
1 TPC-FGD track

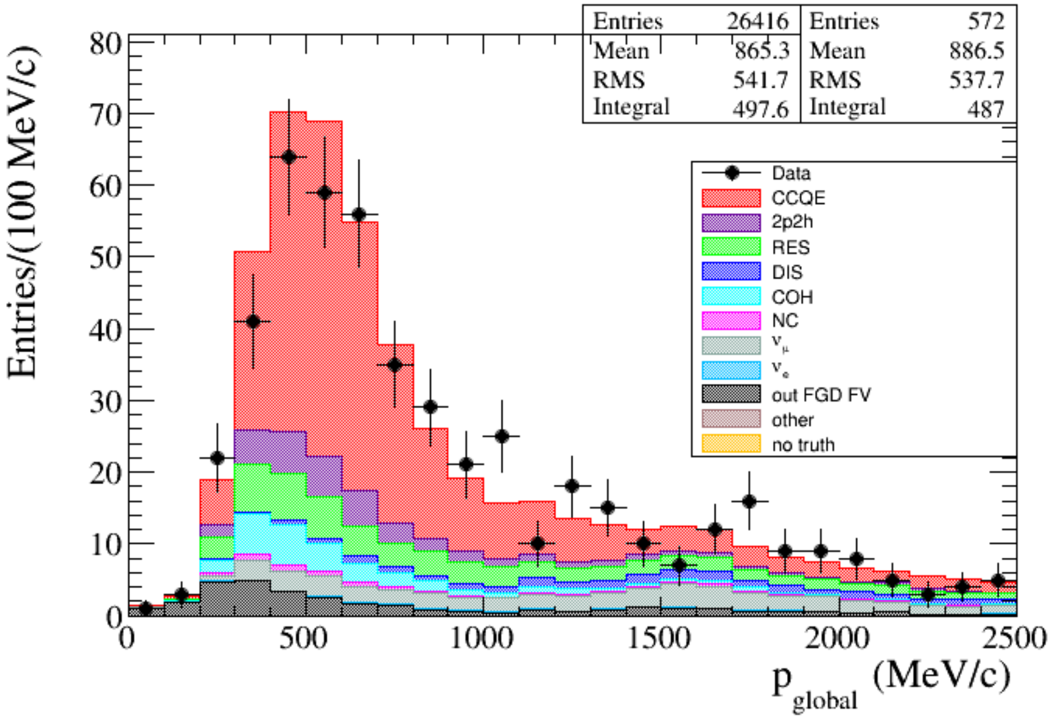
"CC-Ntrk sample"

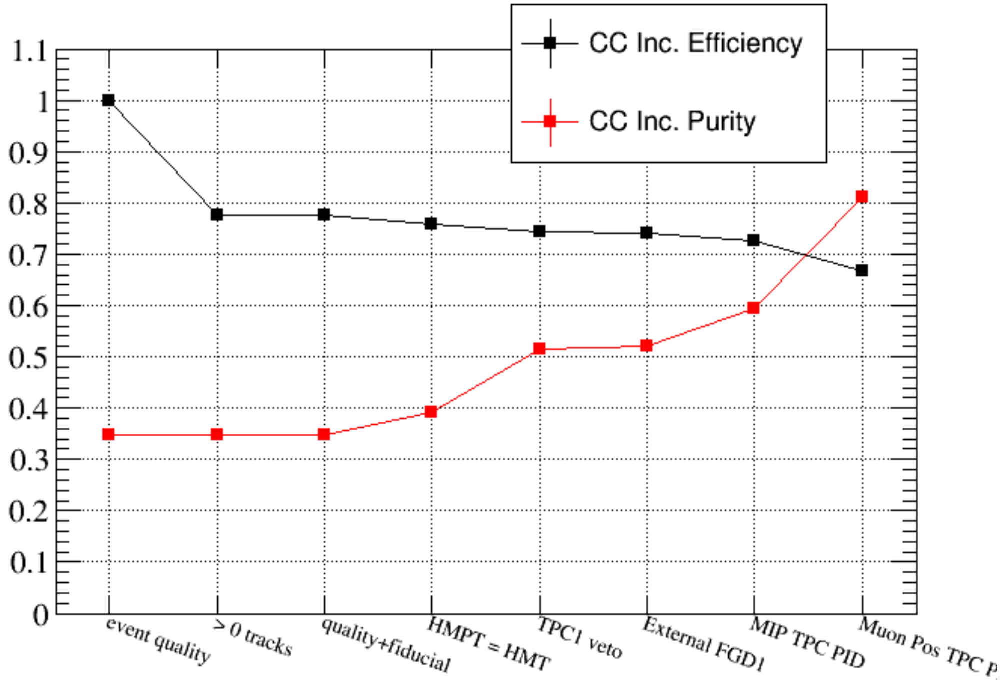
>1 TPC-FGD track

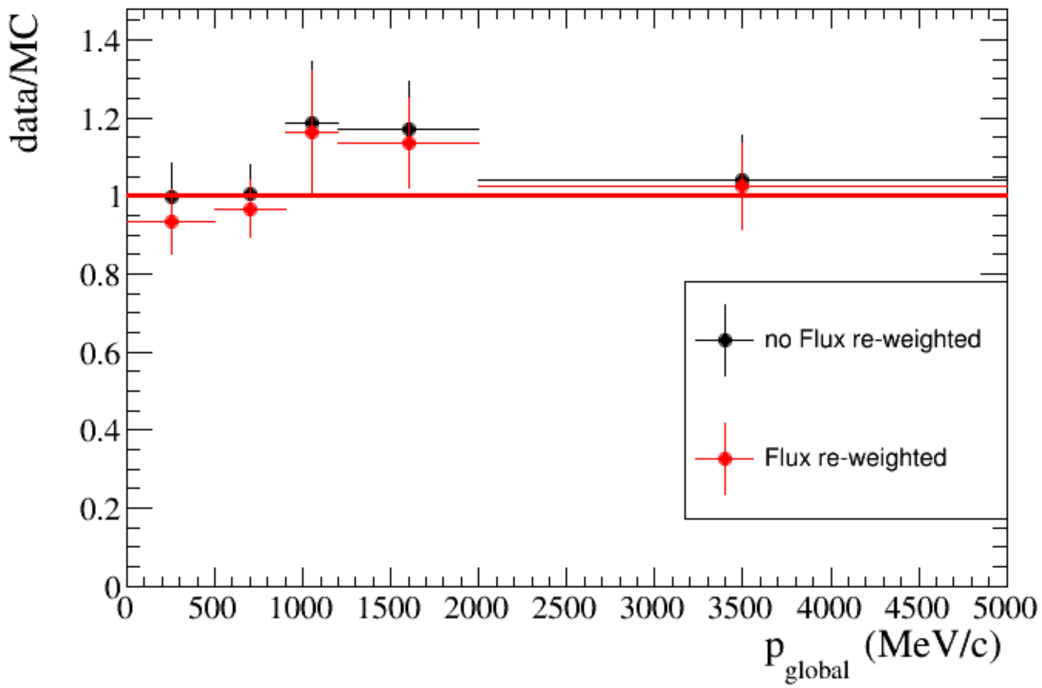


CC Inclusive sample

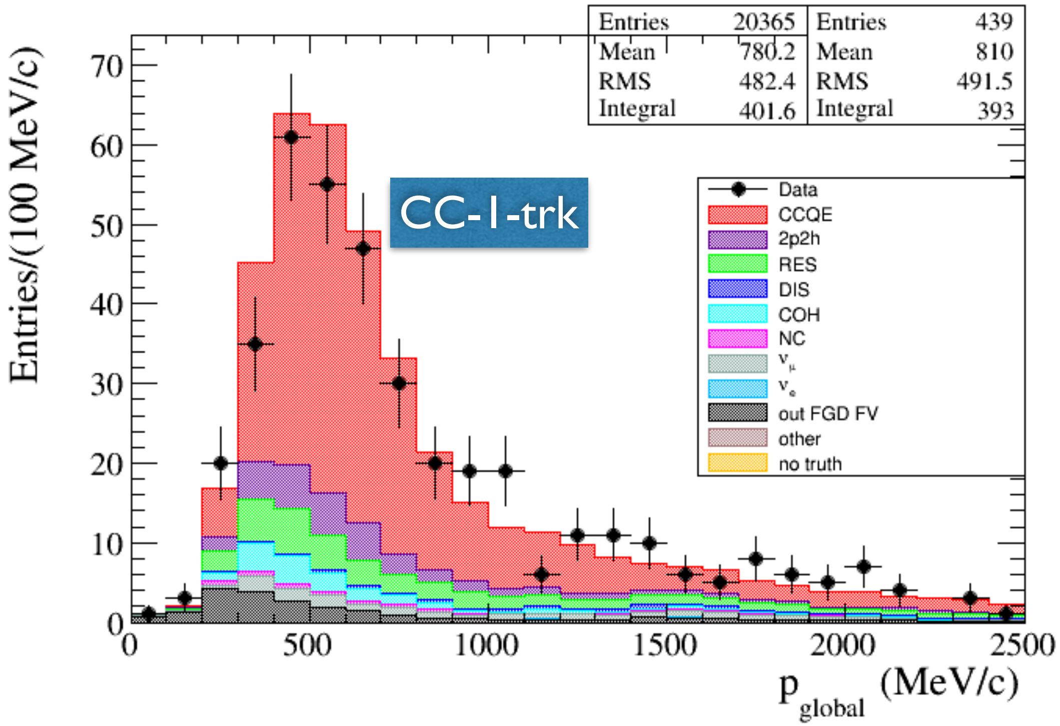








CC-1-track (CCQE like) and CC-N-tracks (CCnQE like) samples

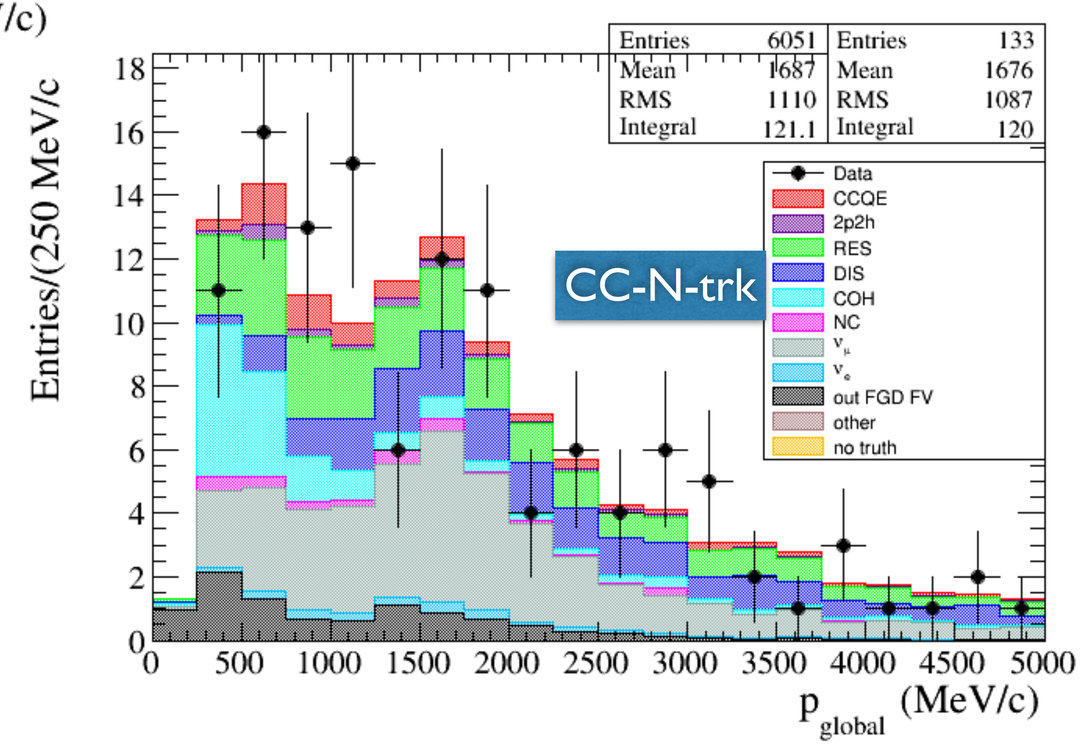


Purity: 73%
Efficiency: 66%

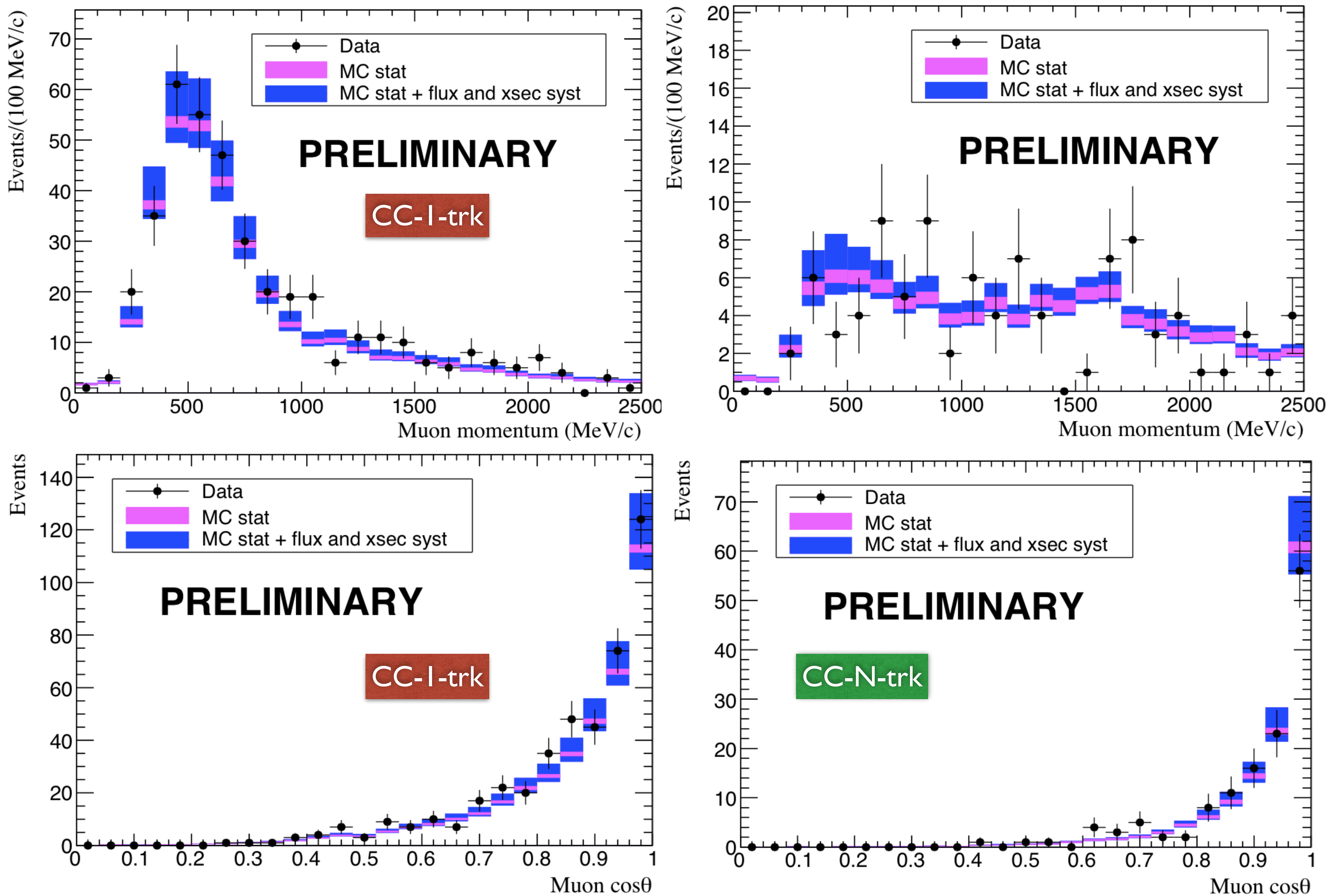
<data/MC>$_{0<p<5\ \mathrm{GeV}}$ = 0.99 ± 0.06

Purity: 47%
Efficiency: 29%

<data/MC>$_{0<p<5\ \mathrm{GeV}}$ = 1.08 ± 0.13



Official T2K plots showed at Moriond 2015



Conclusions and future plans

The $\bar{\nu}_\mu$ component in the neutrino beam has been measured using the ND280 detector of the T2K experiment. The data/MC ratio obtained is:

f(anti-nu) = 1.01 +/- 0.08 (stat.) +/- 0.1 (syst.) = 1.01 +/- 0.13 (total)

- The obtained results is in agreement with the MC expectation and it confirms a very good prediction of $\bar{\nu}_\mu$ background in the oscillation analyses.
- It is already possible to quantify how much this analysis can helps in the reduction of the anti-NuMu related systematic errors in the oscillation analyses:
  - Reduction of the systematic uncertainty related to the anti-NuMu flux component up to 9% on the whole energy spectrum
  - Reduction from 40% to 13% of the $\sigma_{\bar{\nu}}/\sigma_{\nu}$ uncertainty.

The $\bar{\nu}_\mu$ flux at ND280 in anti-neutrino beam mode has been measured

- The selection criteria developed yield $\bar{\nu}_\mu$ CC inclusive sample with a purity of ~81% and an efficiency of ~67%
- This analysis is used to reduce the systematic uncertainties at Super-Kamiokande in the anti-nu beam mode oscillation analyses (summer conferences)

Next publications:

- Precise measurement of $\bar{\nu}_\mu$ σ_{CC} e σ_{CCQE} on Carbon below 1 GeV with ~4×10^{20} POT
- Precise measurement of the $\sigma_{\bar{\nu}}/\sigma_{\nu}$ ratio below 1 GeV

Backup slides