Recent results from T2K

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(for the T2K collaboration)

LPNHE PARIS

Outline

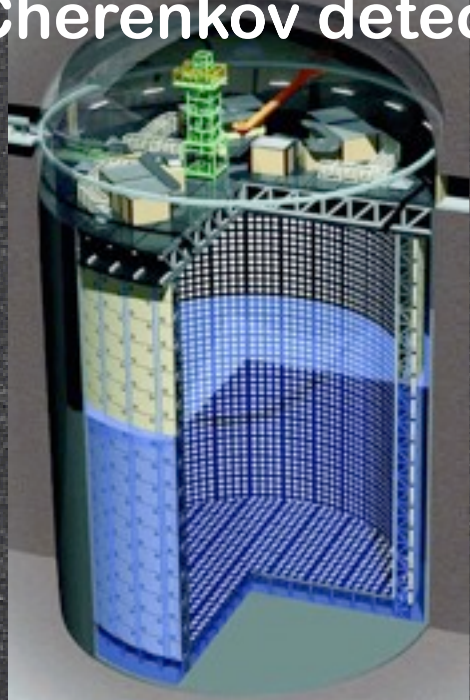
- T2K experiment
- T2K oscillation results
  - ν_e appearance
  - ν_μ disappearance
  - joint ν_μ/ν_e analysis
- ND280 ν_e analyses
  - Measurement of the beam ν_e component
  - Inclusive ν_e CC cross section
  - Sterile analysis: search for ν_e disappearance at ND280

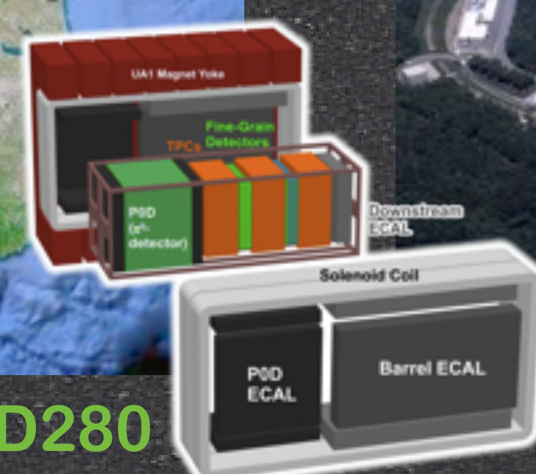
- I don't have time to show INGRID and ND280 ν_μ cross section results → many results were presented at NuINT

T2K experiment

- High intensity ~700 MeV ν_μ beam produced at J-PARC (Tokai, Japan)
- Neutrinos detected at the Near Detector (ND280) and at the Far Detector (Super-Kamiokande) 295 km from J-PARC
- Main physics goals:
  - Observation of ν_e appearance → determine θ_{13} and δ_{CP}
  - Precise measurement of ν_μ disappearance → θ_{23} and Δm^2_{23}

Super-Kamiokande: 22.5 kt fiducial volume water Cherenkov detector



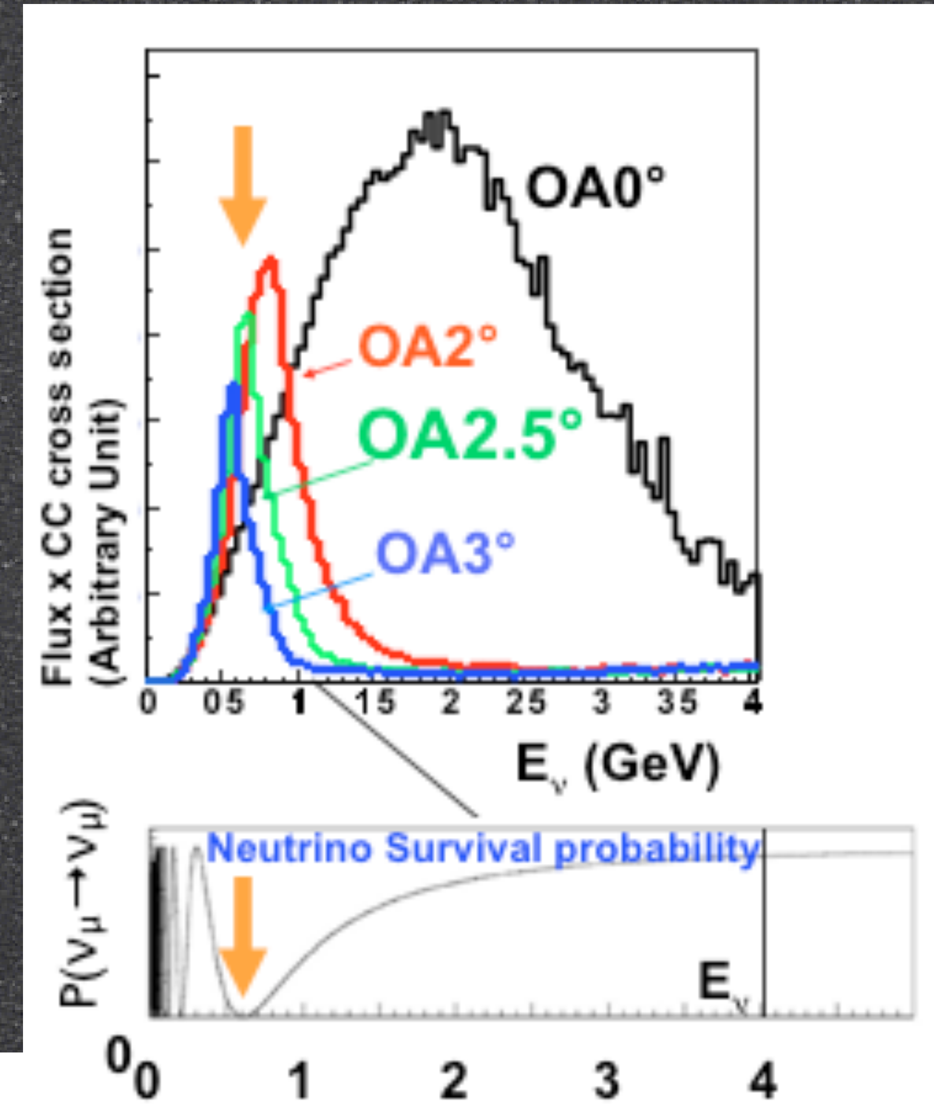


ND280

JPARC accelerator:
Design power: 750 kW

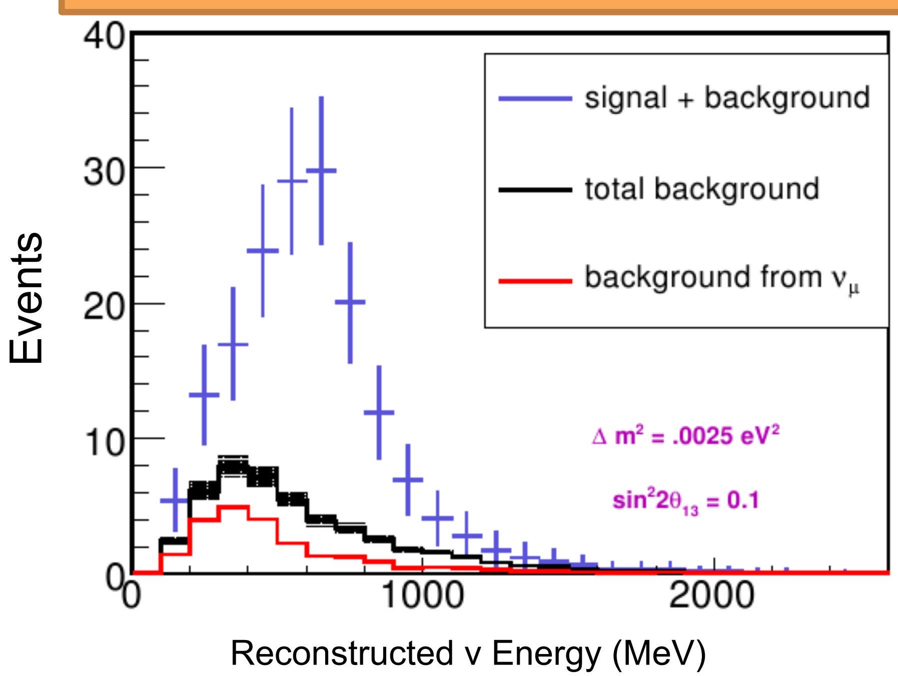
Physics goals

- Off-axis beam centered at the oscillation maximum
- Ideal place to look for ν_e appearance (driven by θ_{13} and δ_{CP}) and ν_μ disappearance (θ_{23} and Δm^2_{32})



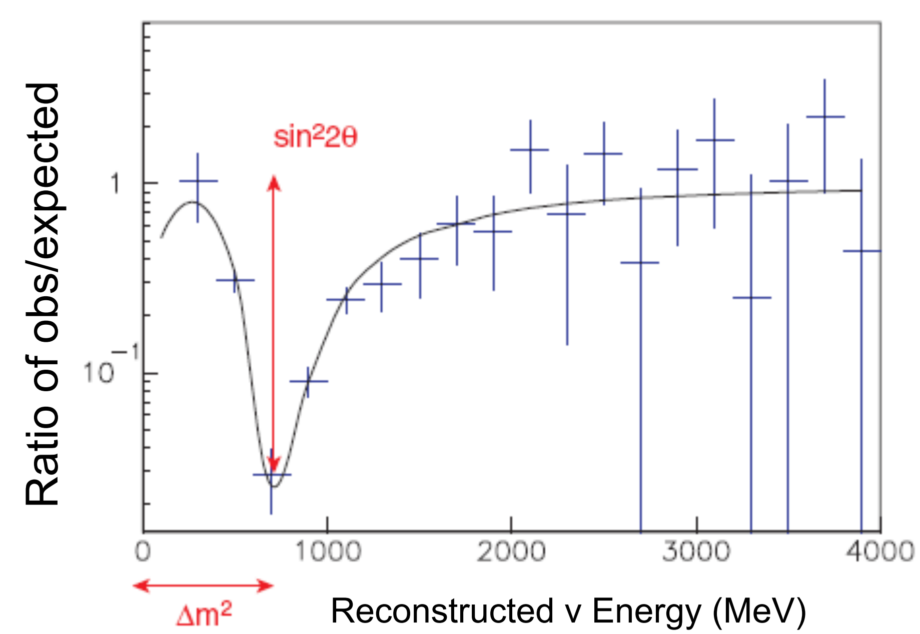
Appearance

ν_e appearance: determine θ_{13} constrain δ_{CP}

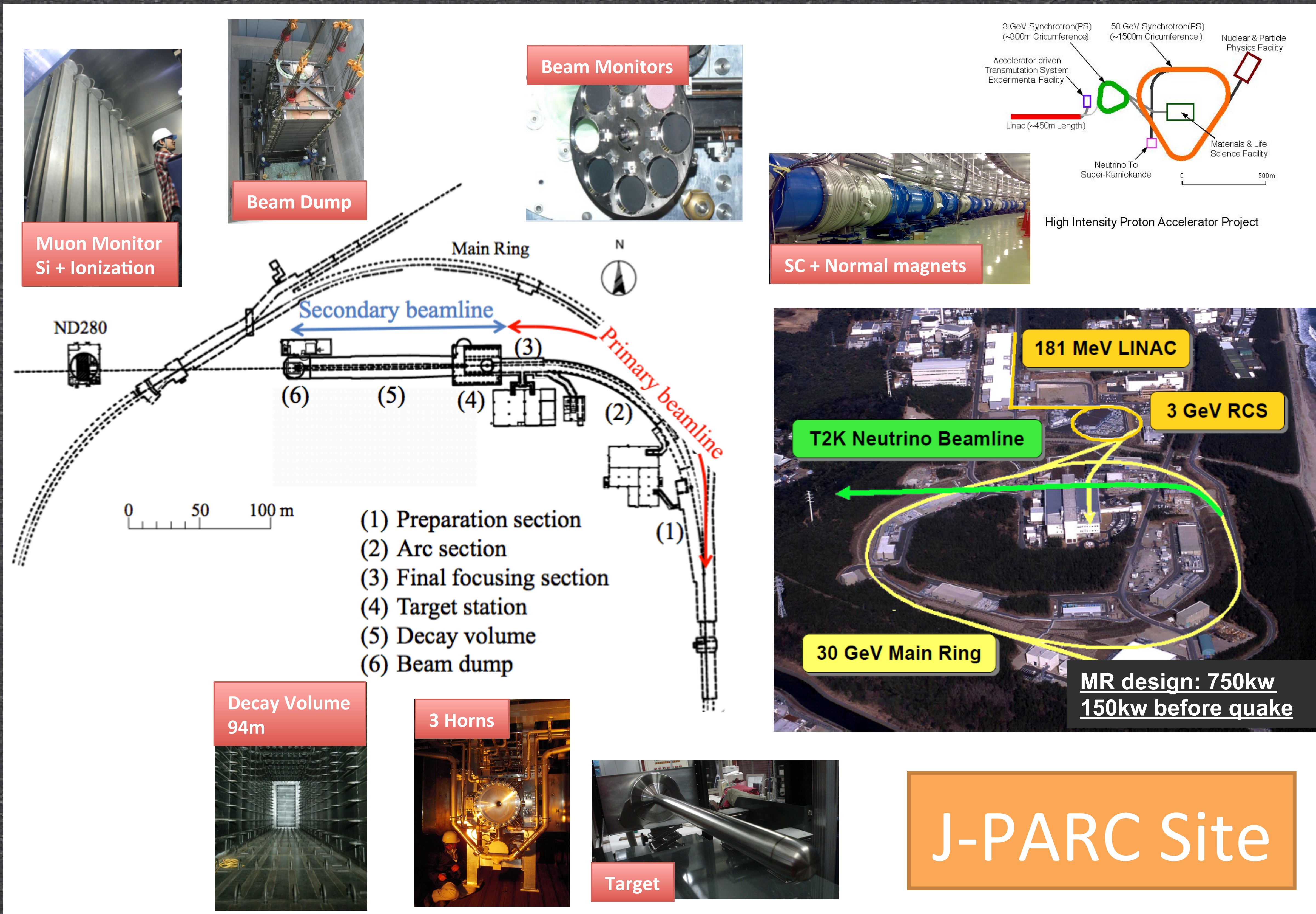


Disappearance:

ν_μ disappearance: determine θ_{23} and Δm^2_{32}

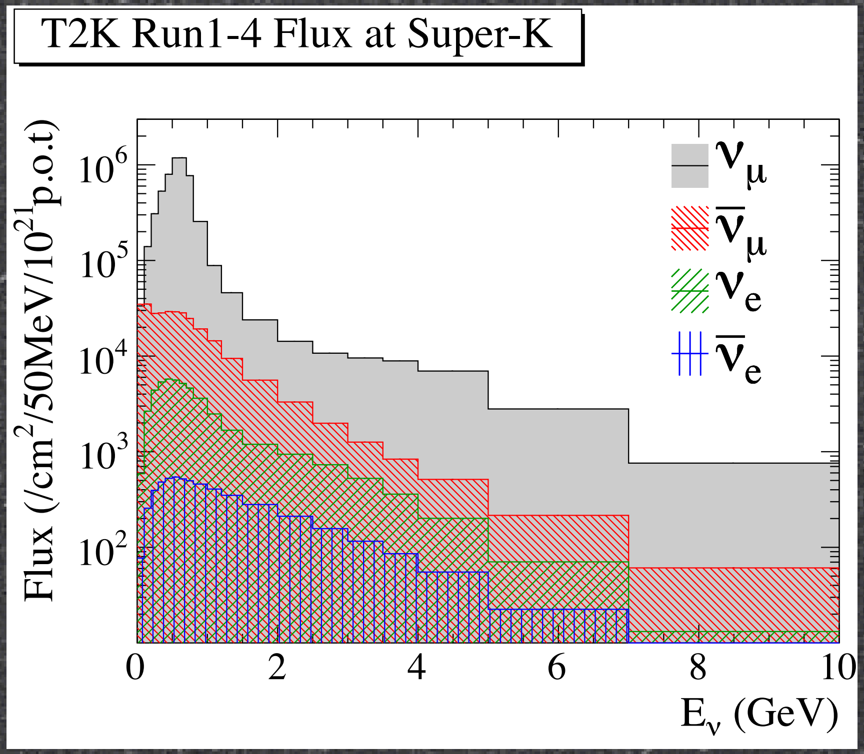


J-PARC neutrino beamline

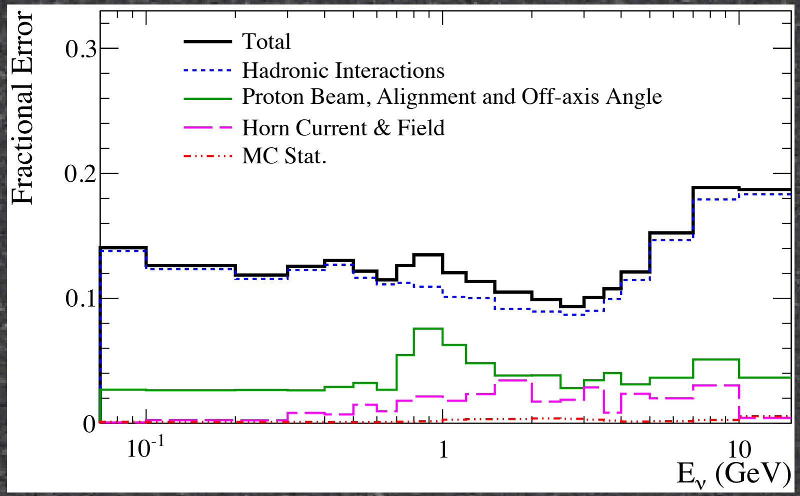


Flux predictions

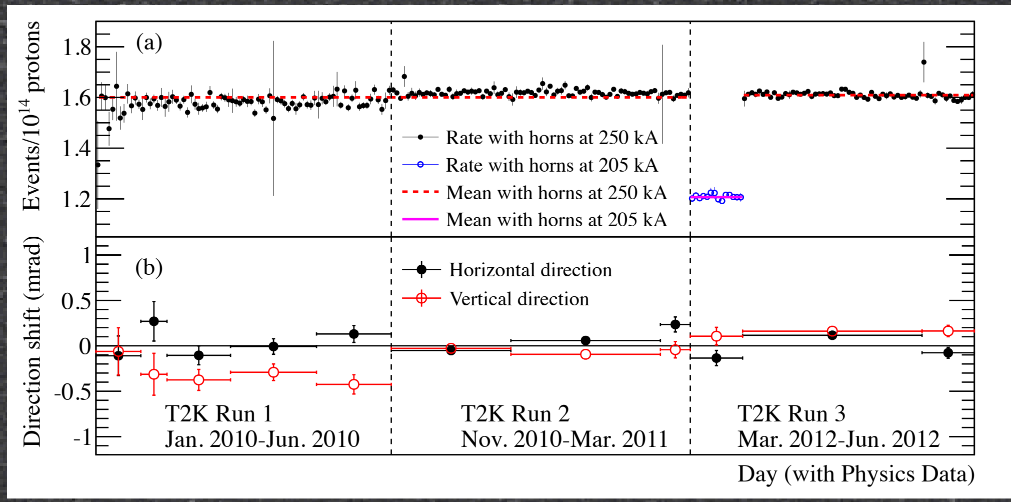
- 30 GeV proton beam → produce a ν_μ beam with <Eν>~700 MeV
  - Small intrinsic ν_e component (~1.2%)
- Neutrino fluxes predicted with NA61/SHINE hadronproduction data ~10-15% uncertainties
- Beam stability controlled day-by-day with INGRID



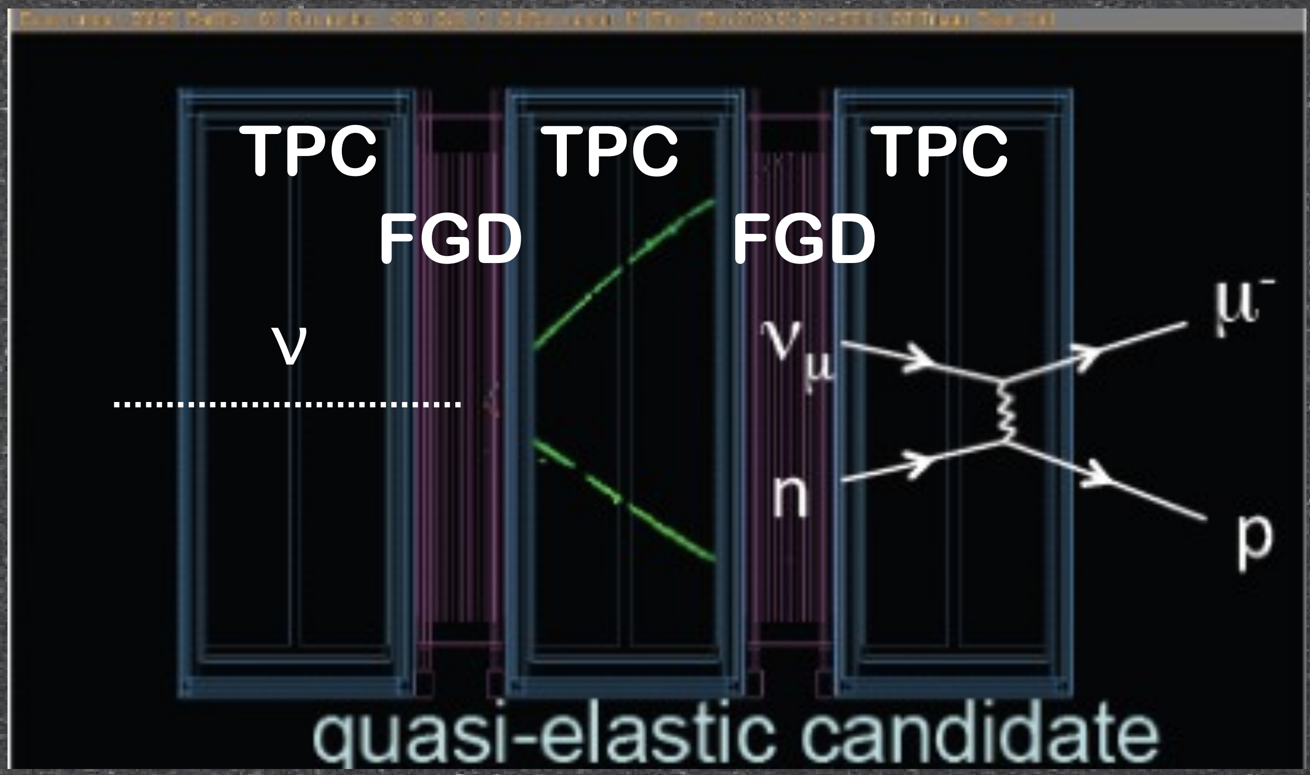
ν_μ flux uncertainties

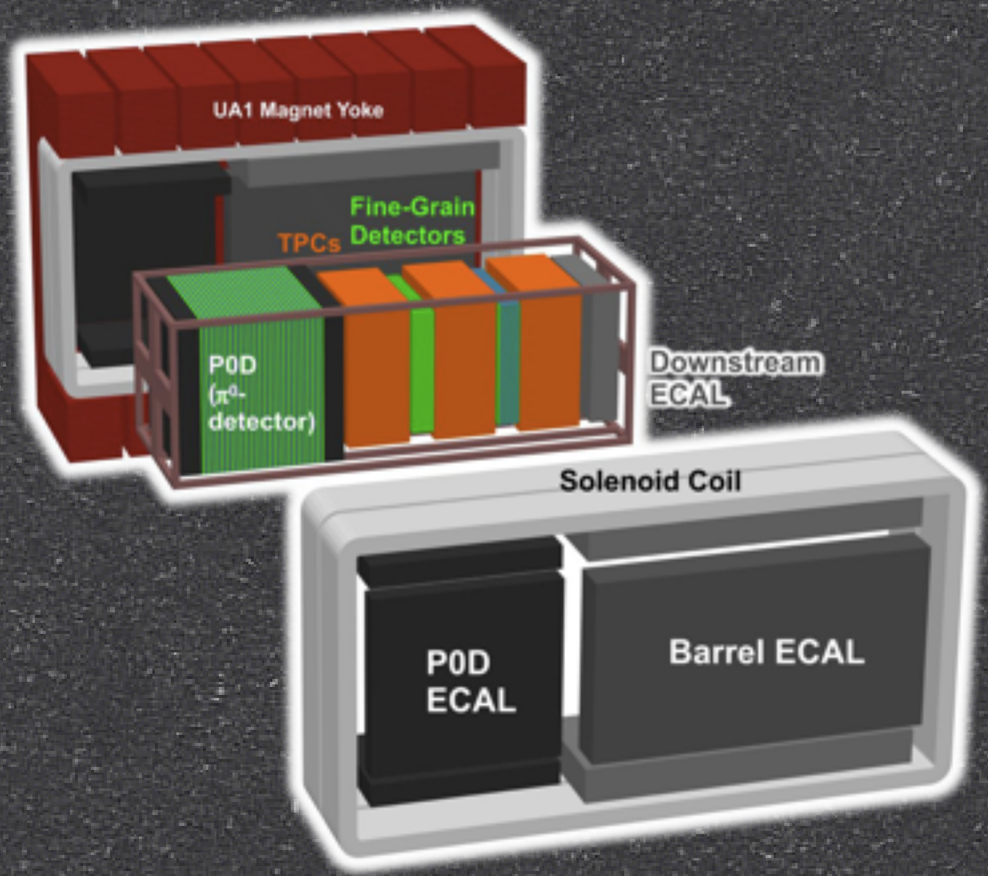


ν beam stability → INGRID



ND280 off-axis

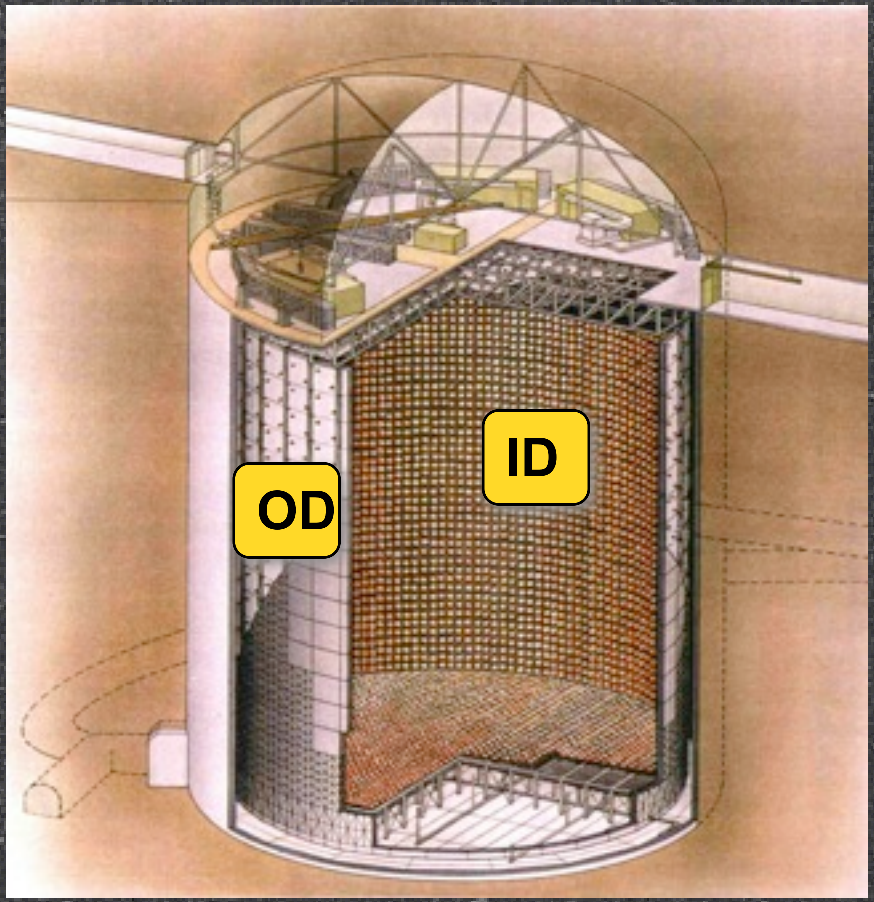


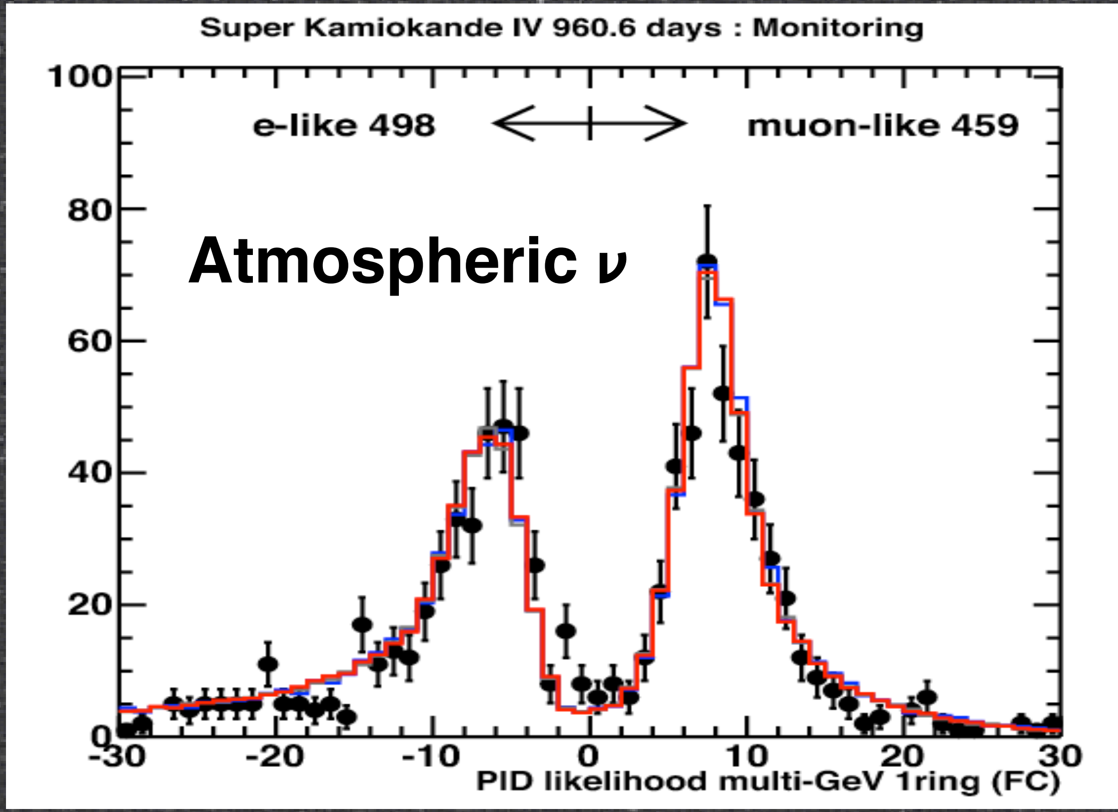


- Detectors installed inside the UA1/NOMAD magnet (0.2 T magnetic field)
  - Allow to select the charge of the particles from their curvature
- In the analysis described today we use the ND280 tracker:
  - 2 Fine Grained Detectors (target for neutrino interactions)
  - 3 Time Projection Chambers: reconstruct momentum and charge of the particles produced in ν interactions, PID based on ionization
  - Electromagnetic Calorimeter do distinguish tracks from showers

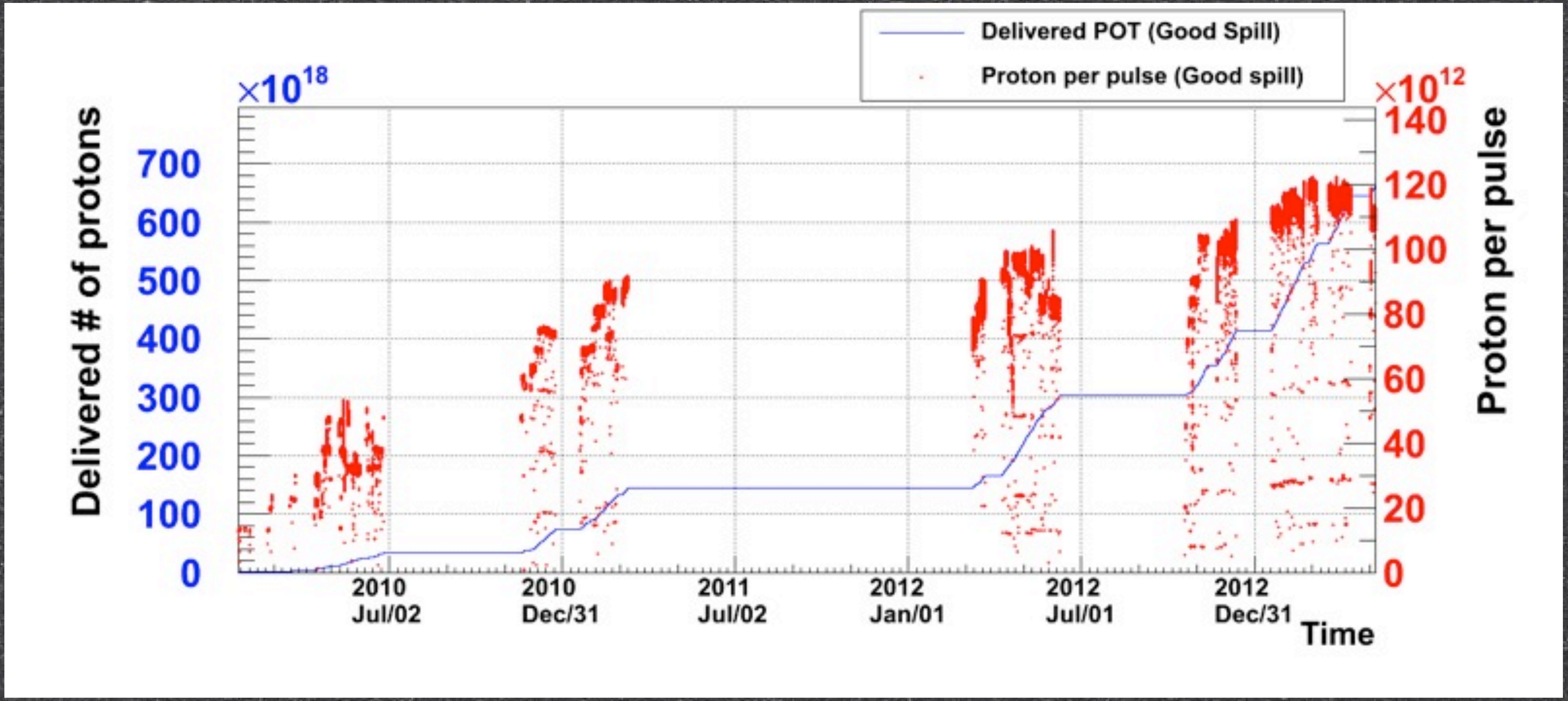
Super-Kamiokande

- 50 kton water Cherenkov detector (22.5 kton FV)
  - ~11000 20'' PMT inner detector (~2000 8'' PMT outer detector used as veto)
- ~1000 meters underground in the Kamioka mine
- Operated since 1996 (upgraded for T2K)
- Very good PID capabilities to distinguish electrons from muons





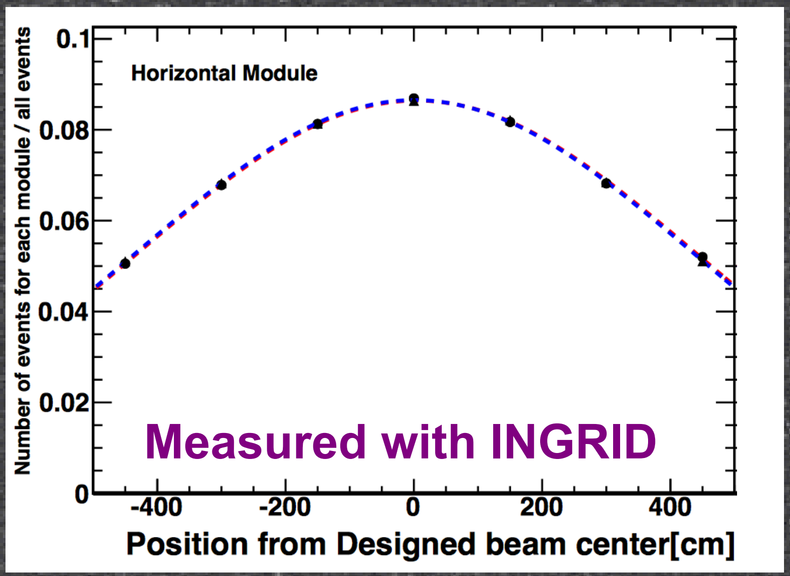
Data taking



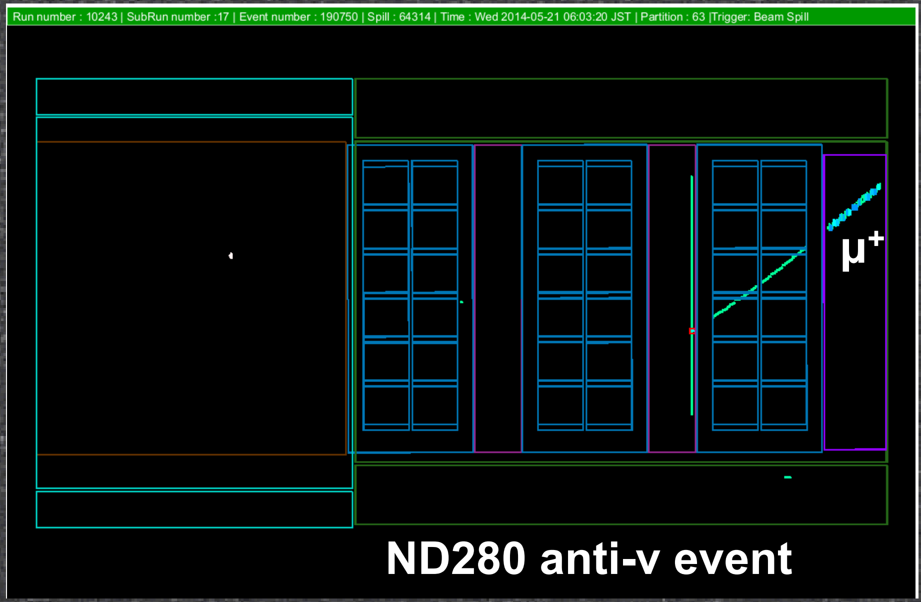
- Delivered 6.57 x 10^{20} proton on target (<10% of the final design goal)
  - ~97% of the POT used for physics analyses
- Reached stable beam power 235 kW
- Recentely restarted with anti-neutrinos

Run status

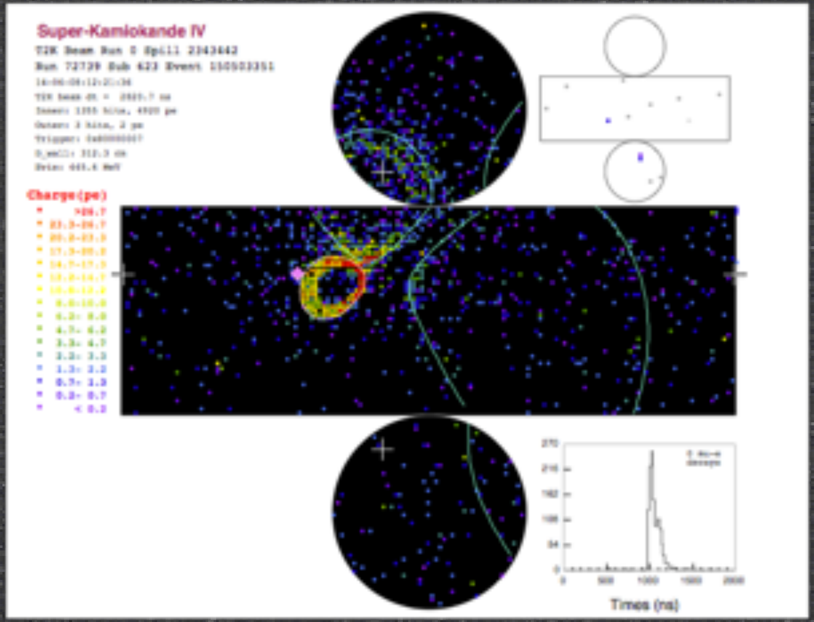
beam profile at INGRID



anti-νμ CC at ND280



Fully contained event at SK



- All the detectors working well
- Steadily taking data focusing negative hadrons → anti-neutrinos beam
- Plan is to collect >5x10^{20} POT by Summer 2015 in anti-neutrino mode to perform:
  - Best measurement of anti-ν_μ disappearance
  - Start searching for anti-ν_e appearance
- Then run 50% ν - 50% anti-ν to have best sensitivity to δ_{CP}

T2K oscillation analyses

Flux prediction:
- ✓ Proton beam stability
- ✓ Hadron production (NA61 and others external data)

ND280 measurements:
- ✓ ν_μ selection to constrain flux and cross-sections
- ✓ Measure ν_e beam component

Neutrino interactions:
- ✓ Interaction models
- ✓ External cross-section data

Prediction at the Far Detector:
- ✓ Combine flux, x-section and ND280 to predict the expected events at SK

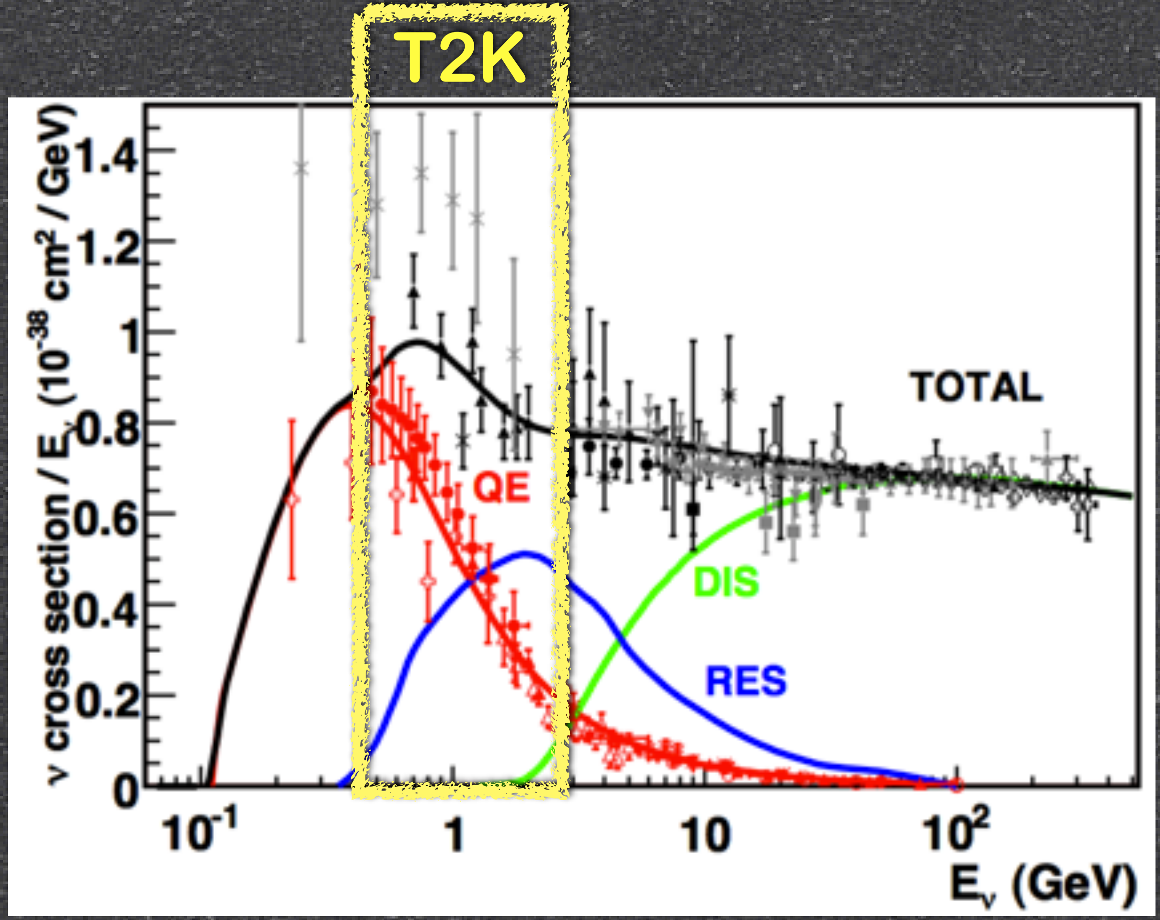
Extract oscillation parameters!!!

Super-Kamiokande measurements:
- ✓ Select CC ν_μ and ν_e candidates after the oscillations

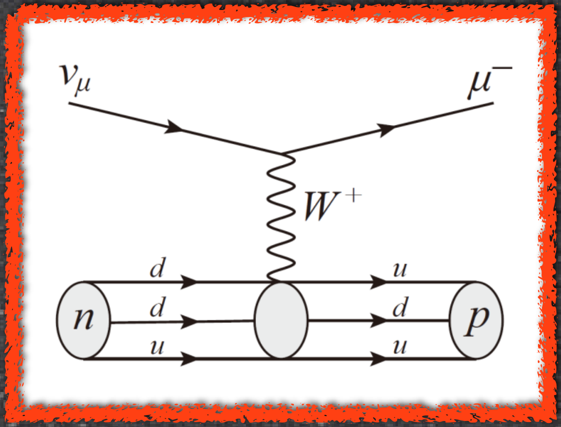
Neutrino interactions

- At T2K energies neutrino interactions occurs through many different processes (CCQE, CC1π, NC1π, DIS) each with large model uncertainties
- Model the parameters for each interaction type by selecting neutrino interactions at ND280

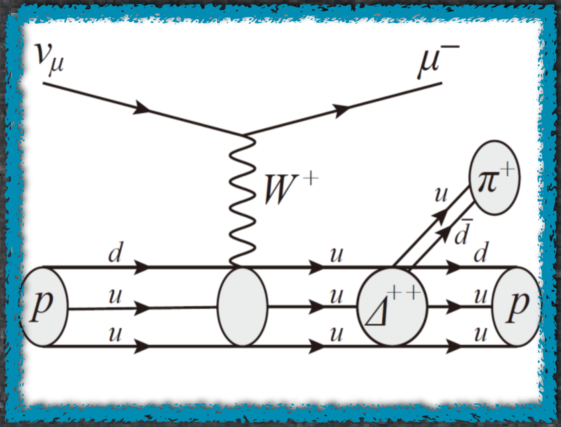
T2K



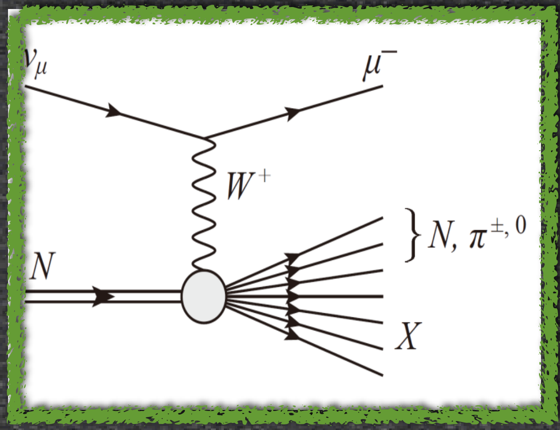
CCQE



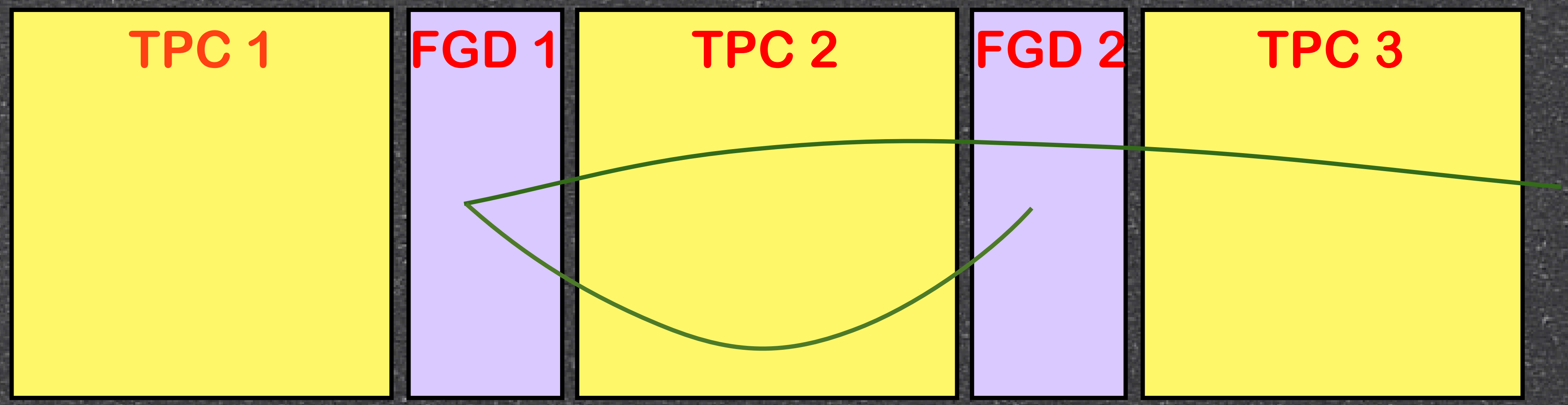
CCRES



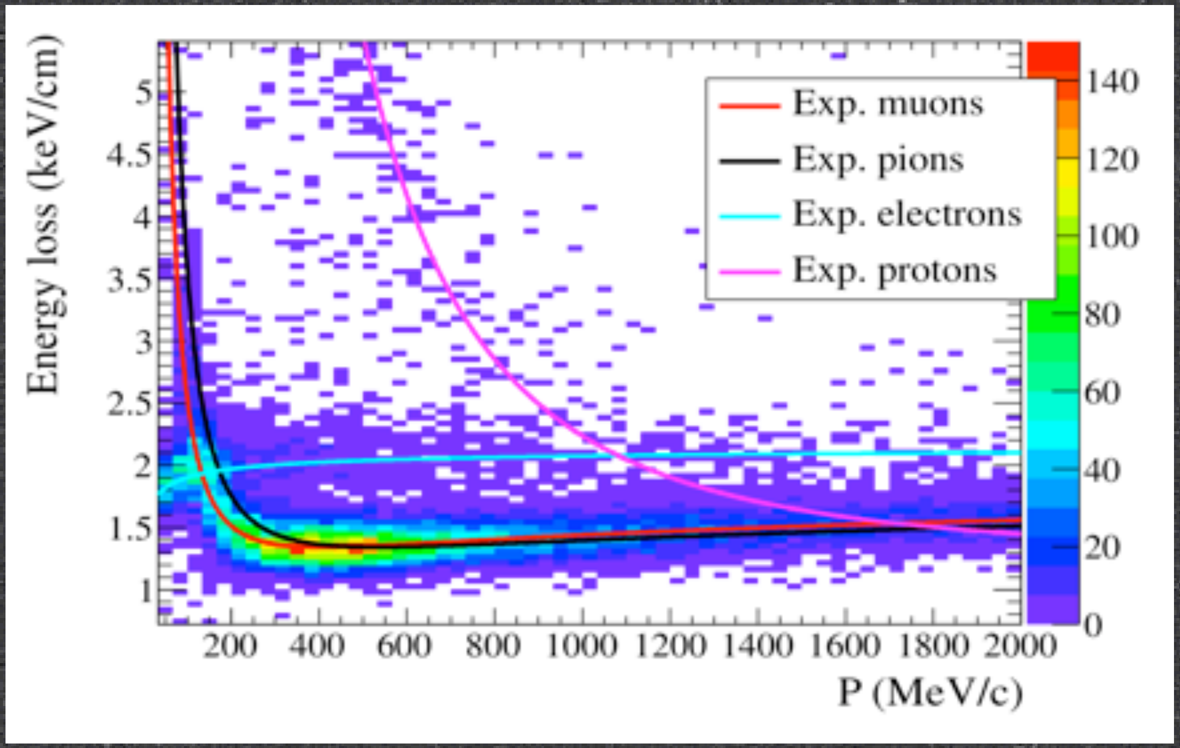
CCDIS



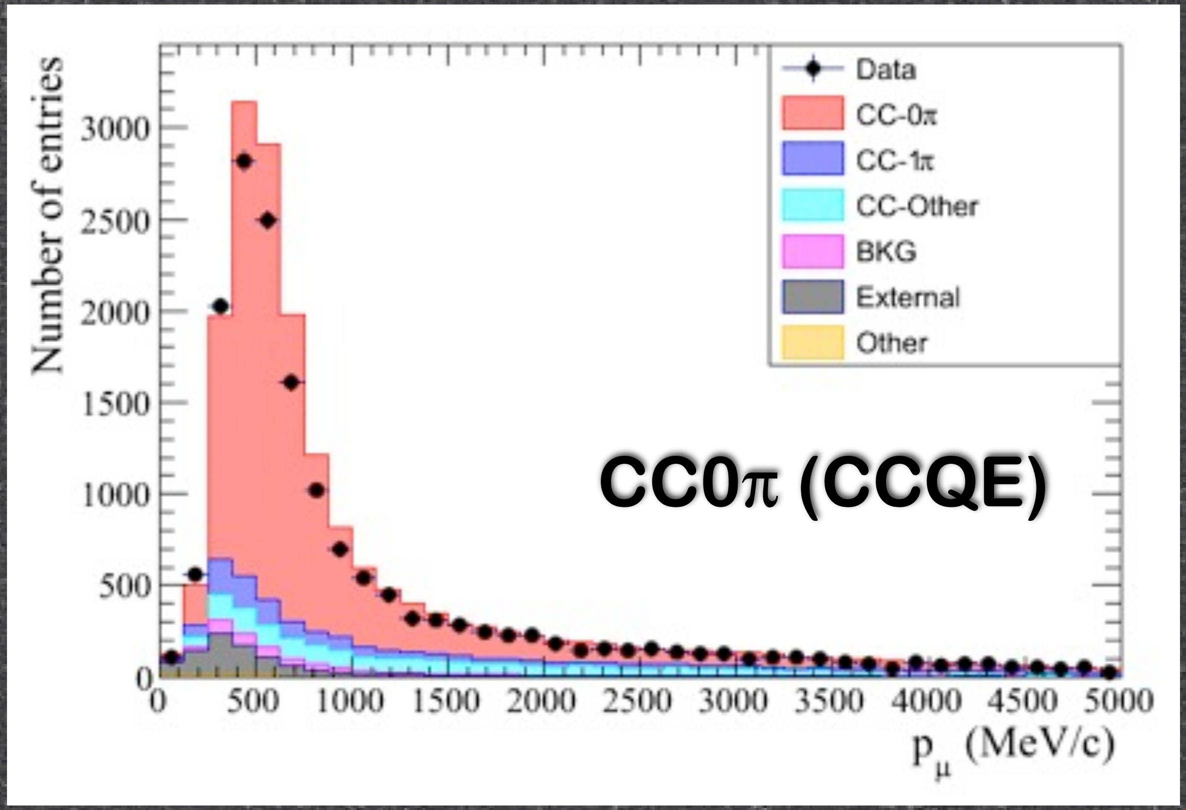
ND280 ν_μ CC analysis

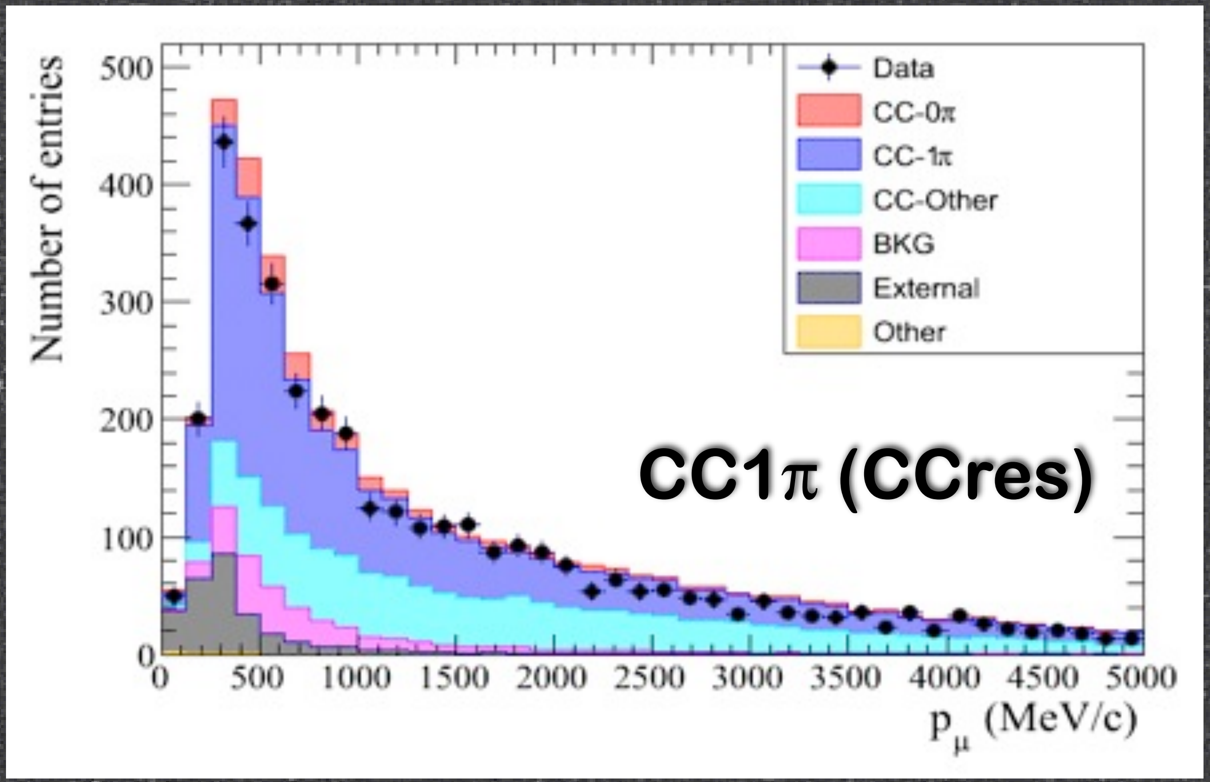


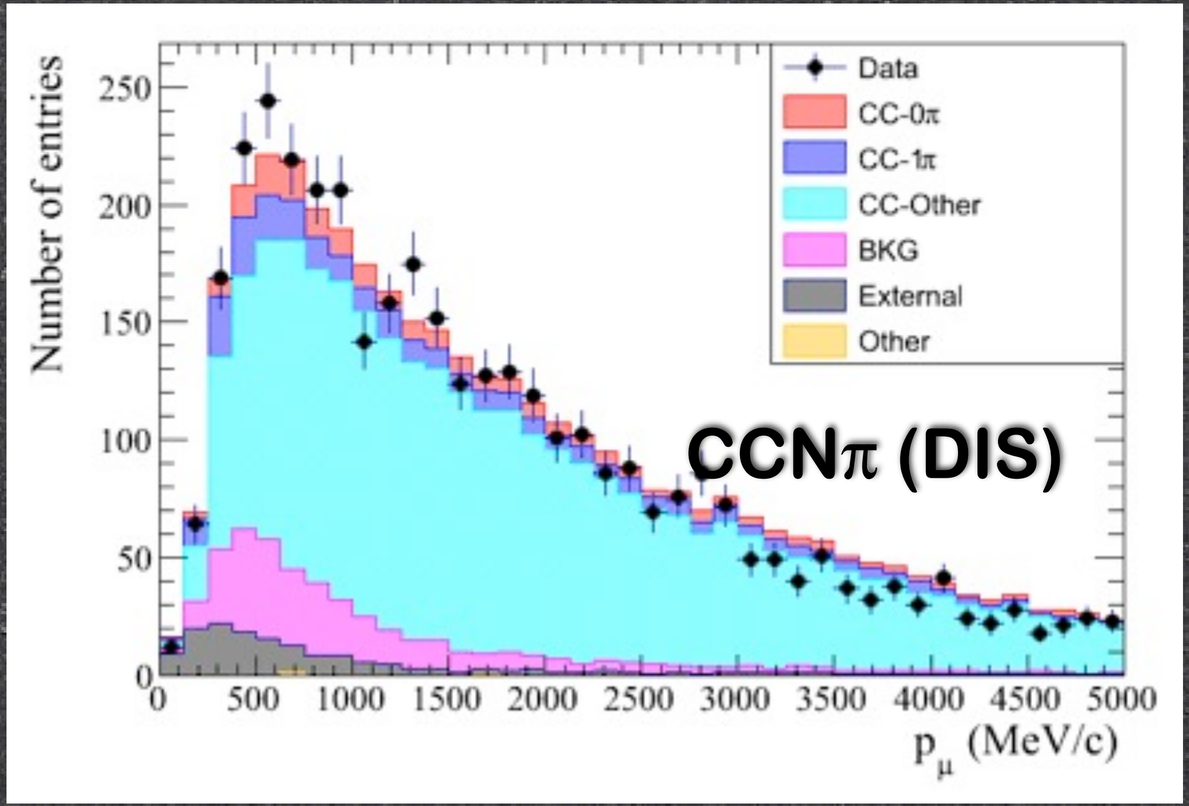
- Select neutrino interactions in the FGD FV with tracks entering the TPC
- Identify the lepton as the most energetic negative track → require the TPC PID compatible with a μ
- Distinguish 3 samples according to the topology of the other tracks
  - 0 π, 1 π^+, others



ND280 ν_μ CC analysis

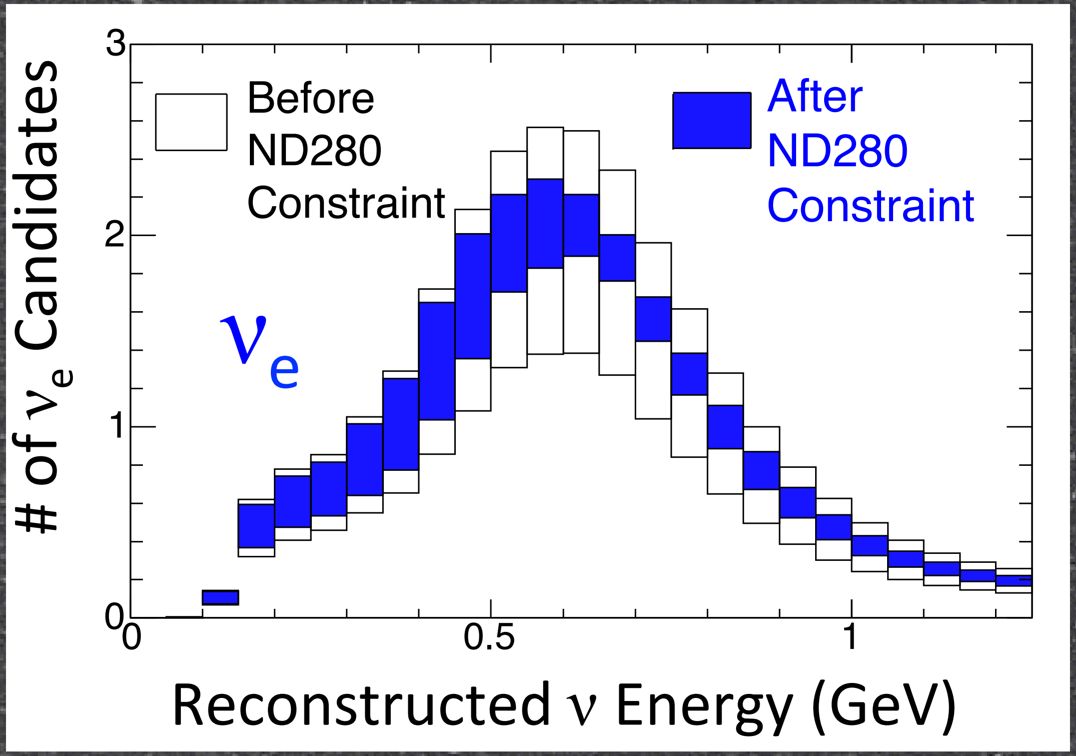


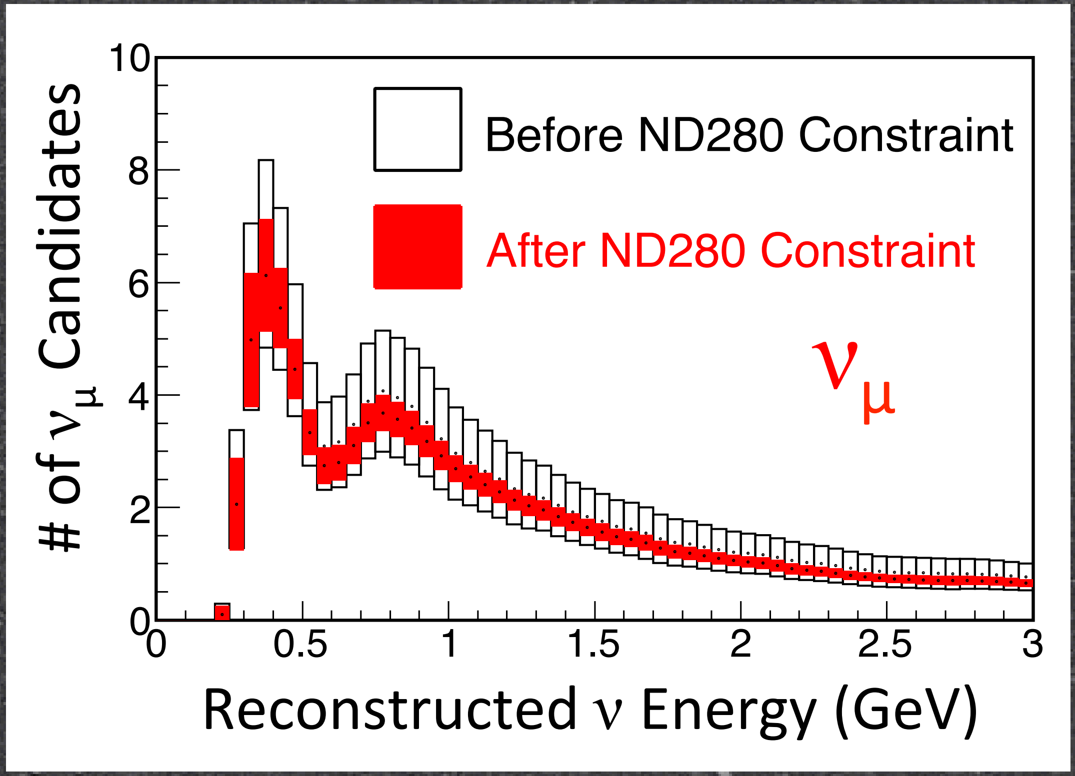




- Fit the three distributions to jointly constrain flux and cross-section parameters

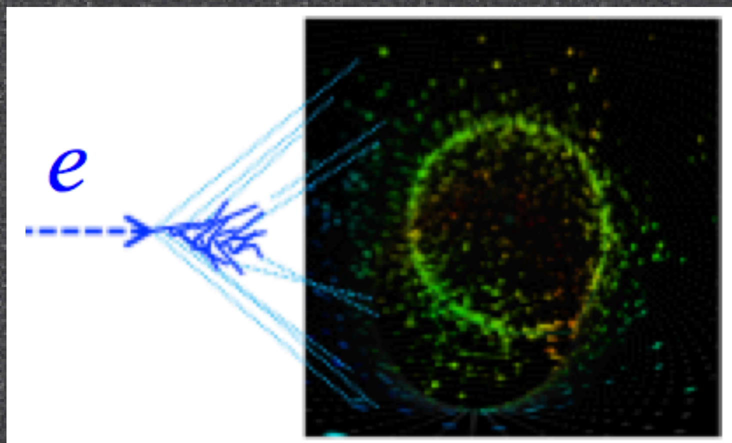
Systematic errors

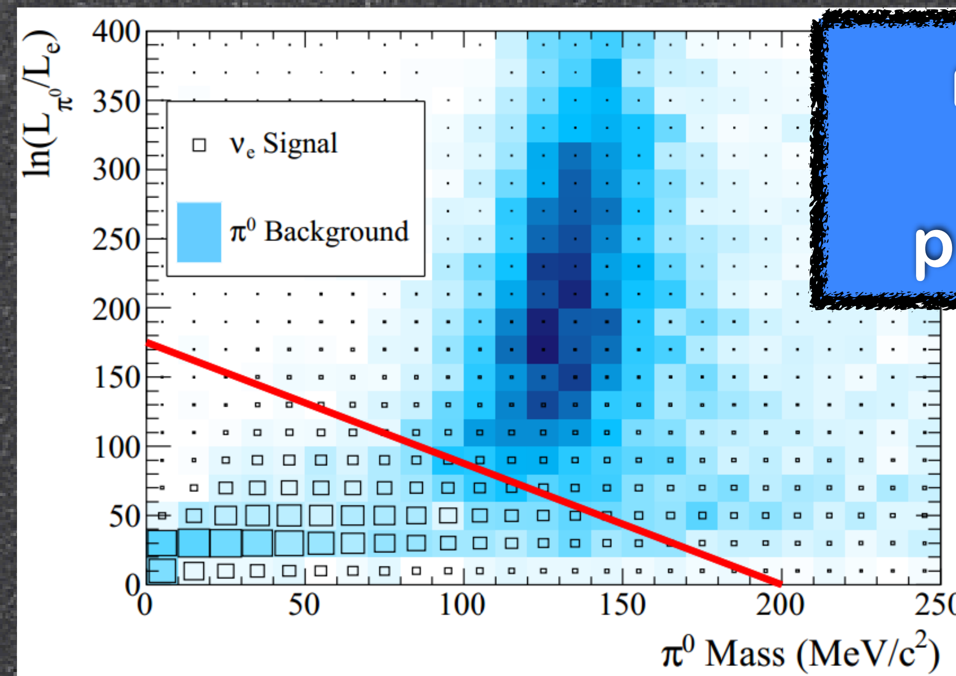




Systematic Source	Relative Uncertainty in # of ν_e Candidates (%)	Relative Uncertainty in # of ν_μ Candidates (%)
Flux + cross section (ND280 constrained)	3.1	2.7
Cross section (ND280-independent)	4.7	5.0
π Hadronic Interactions	2.3	3.5
SK Detector	2.9	3.6
Total	**6.8**	**7.6**

SK ν_e event selection

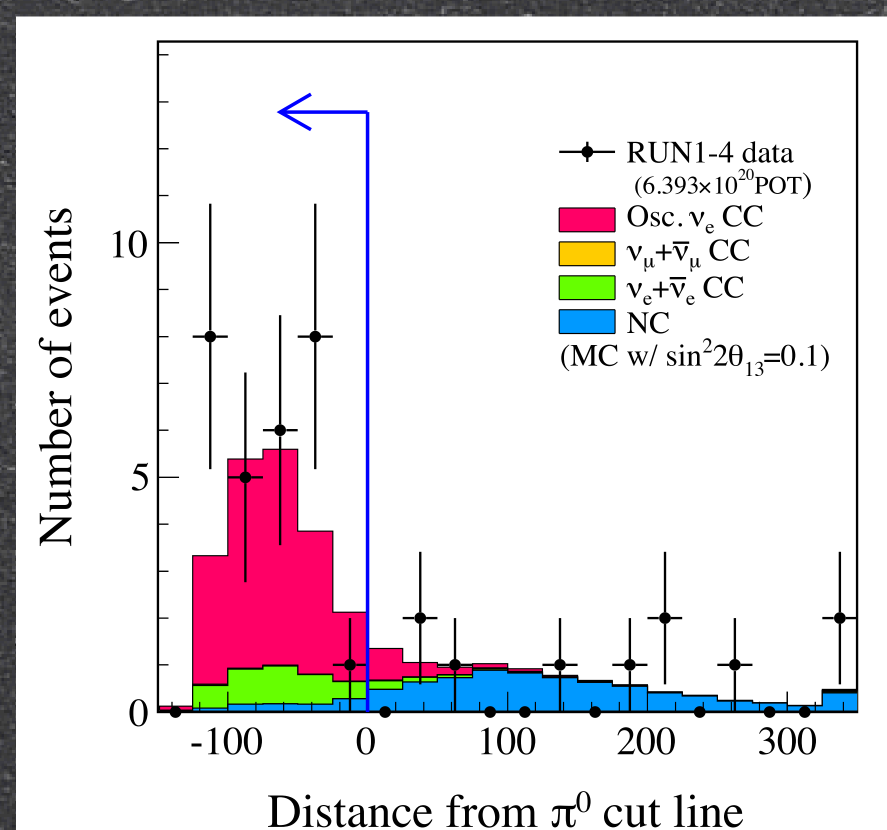




reject > 80% NCπ0 more than the previously used cuts

ν_e Selection Cuts

- Fully Contained FV events
- # of rings = 1
- Ring is e-like
- $E_{visible}$ > 100 MeV
- no Michel electrons
- 0 < E_ν < 1250 MeV
- fiTQun π^0 cut

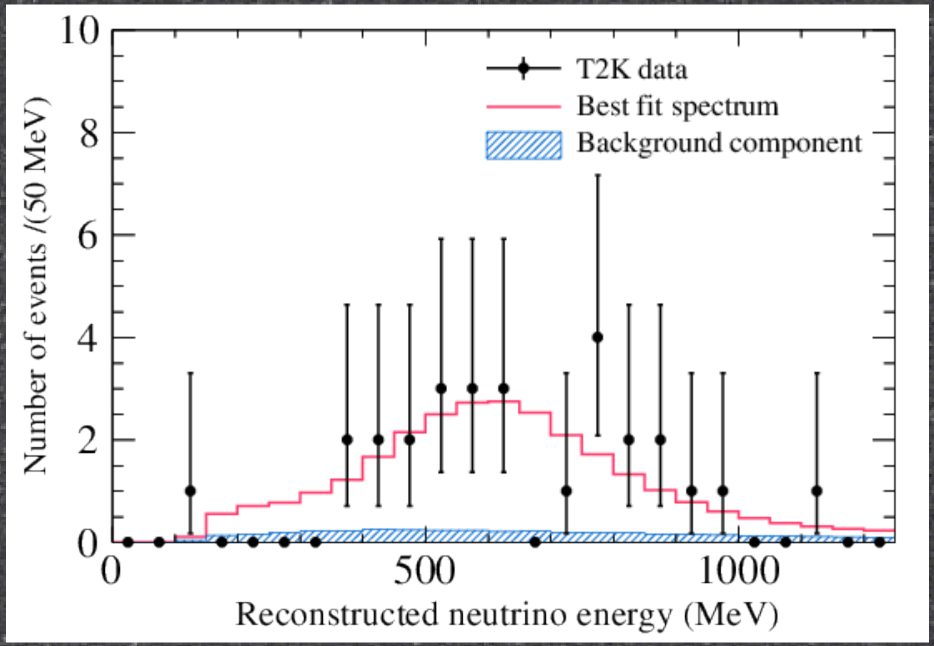


28 ν_e candidates are selected

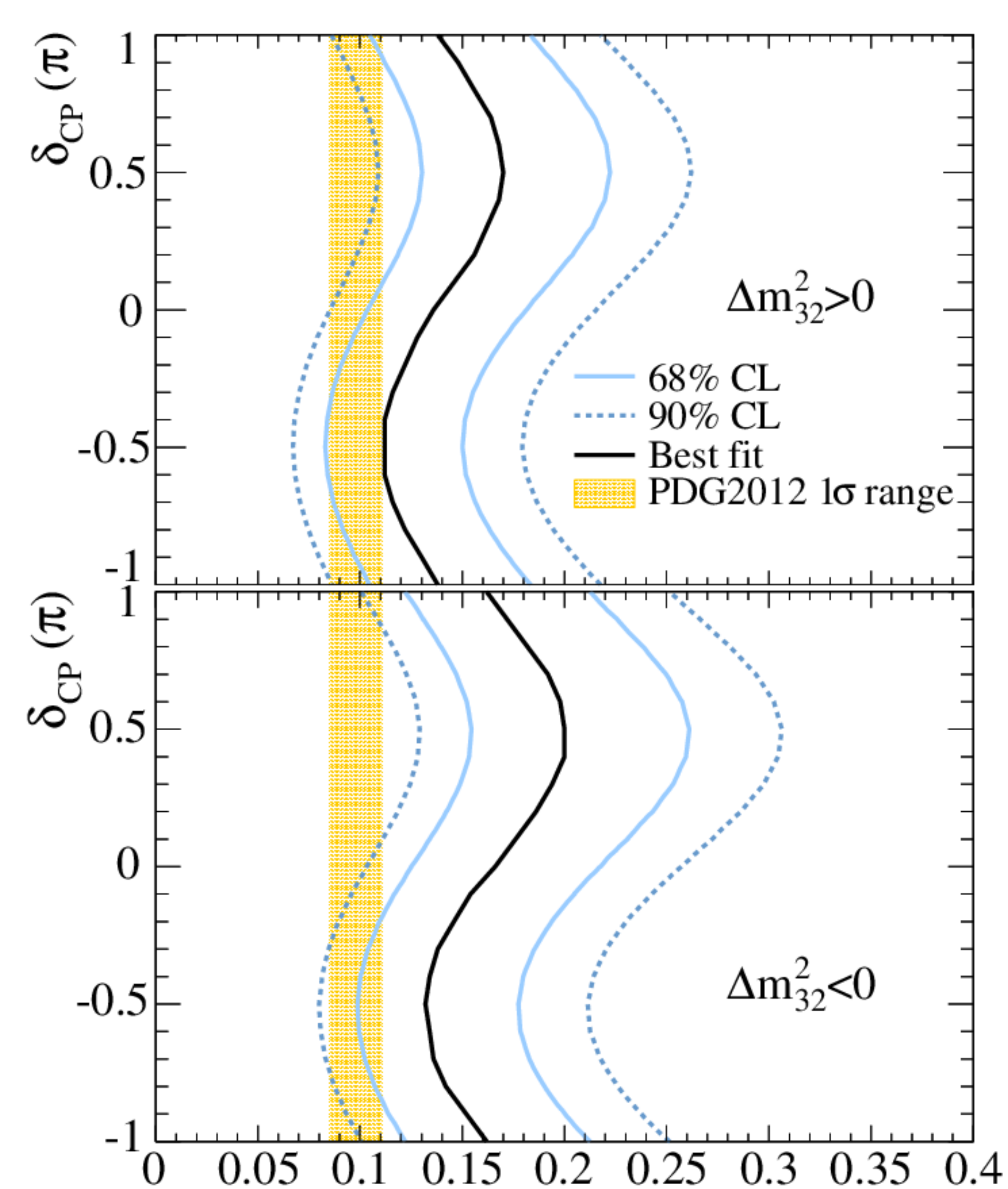
Exp. Bcg 4.92±0.55 events

(mainly from beam ν_e)

ν_e appearance analysis



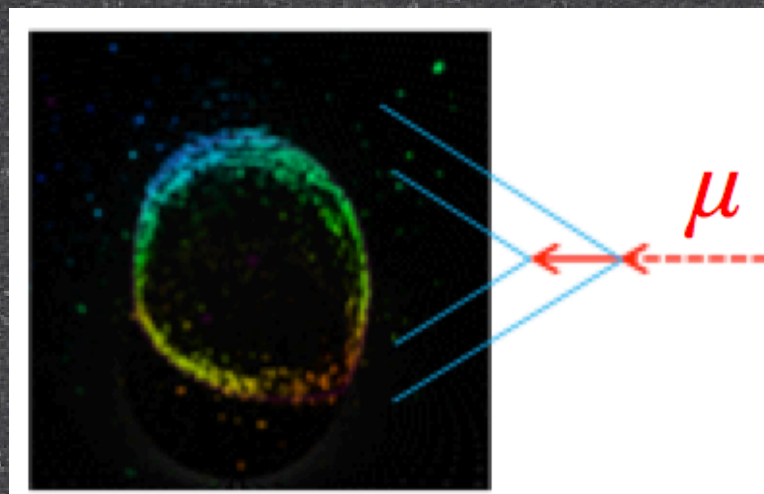
PRL 112, 061802 (2014)



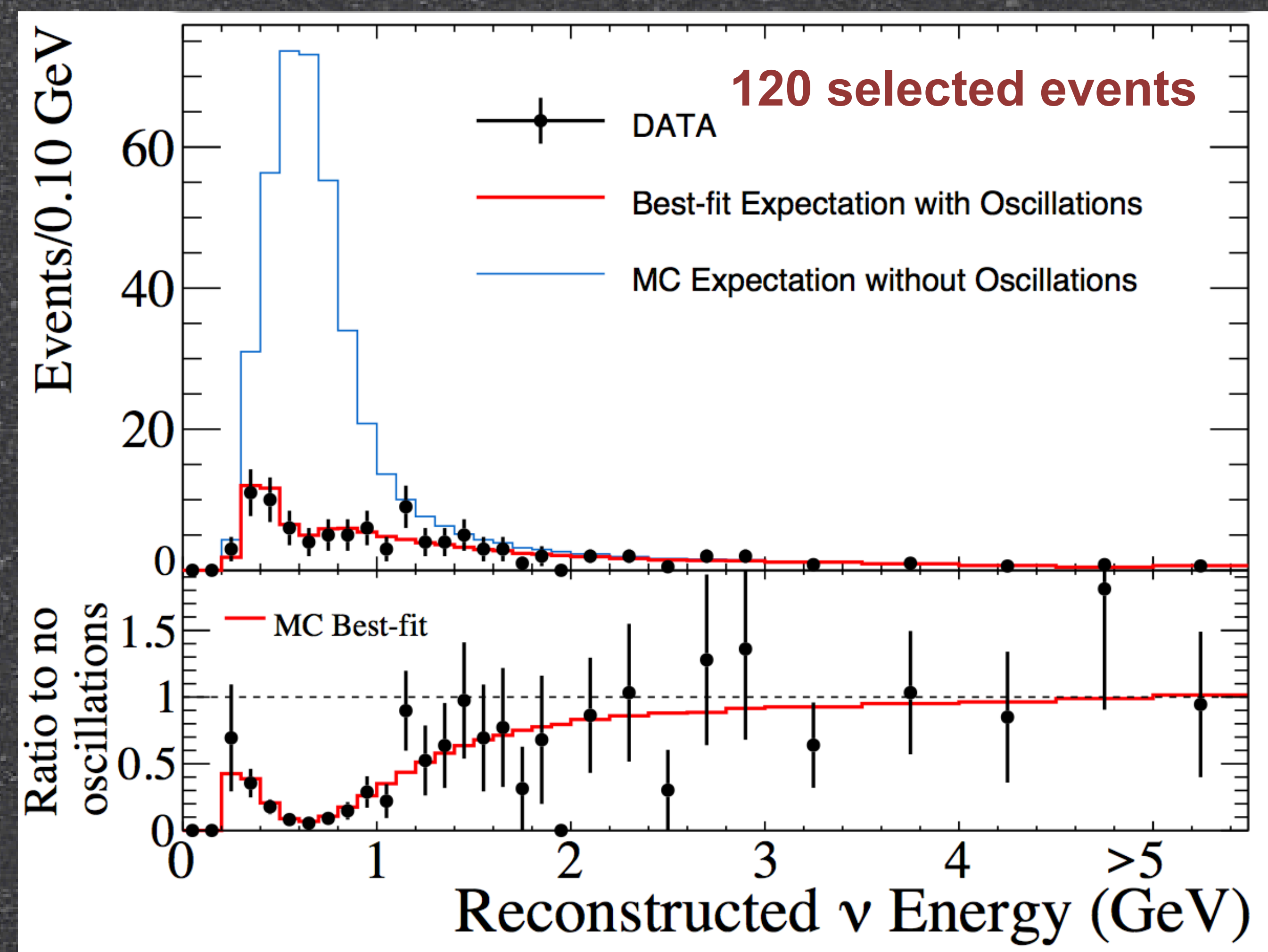
Note: Marginalized over θ_{23} and Δm^2_{32}

- 28 observed events → 7.3σ significance for non-zero θ_{13}
- First ever observation of an explicit ν appearance channel!!
- Combination with the reactor results for θ_{13} → put constraints on δ_{CP}
- Also depends on θ_{23} → need to do a joint fit

SK ν_μ event selection



120 selected events
(450 expected without oscillation)
→ power of off-axis technique

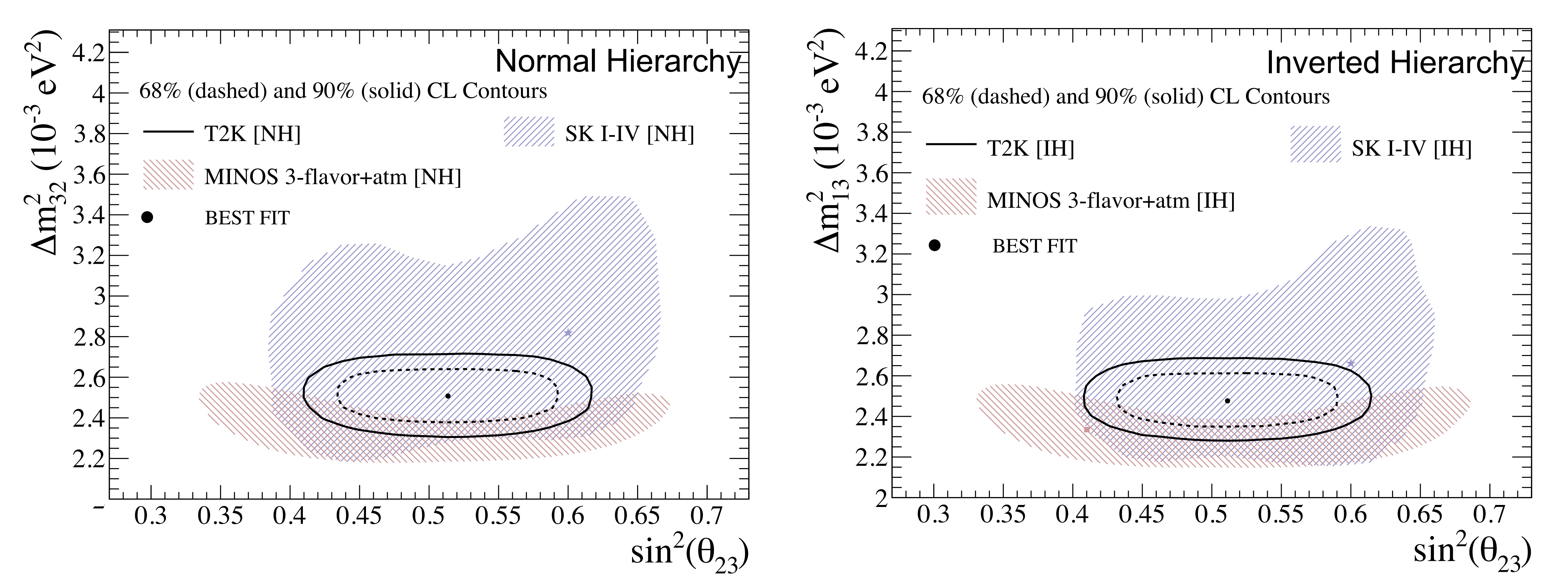


<u>ν_μ Selection Cuts</u>

- Fully Contained FV events
- # of rings = 1
- Ring is μ-like
- P_μ > 200 MeV
- Less than 2 Michel electrons

ν_μ disappearance analysis

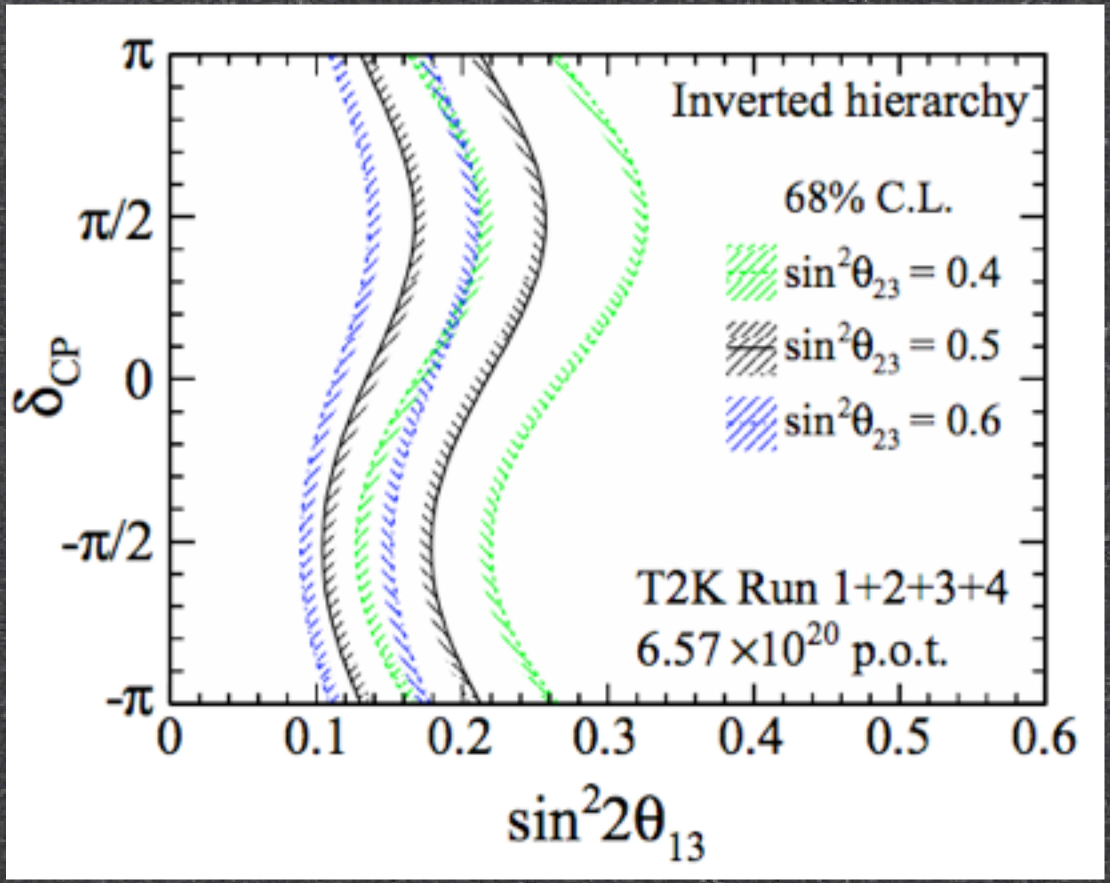
PRL. 112, 181801 (2014)



- For the first time the mixing angle θ_{23} is better constrained by an accelerator experiment than by atmospheric neutrinos
- $\sin^2(\theta_{23}) = 0.514 \pm 0.055$ (NH) → 10% uncertainty corresponding to an uncertainty of 3° on the angle

Joint fit analysis

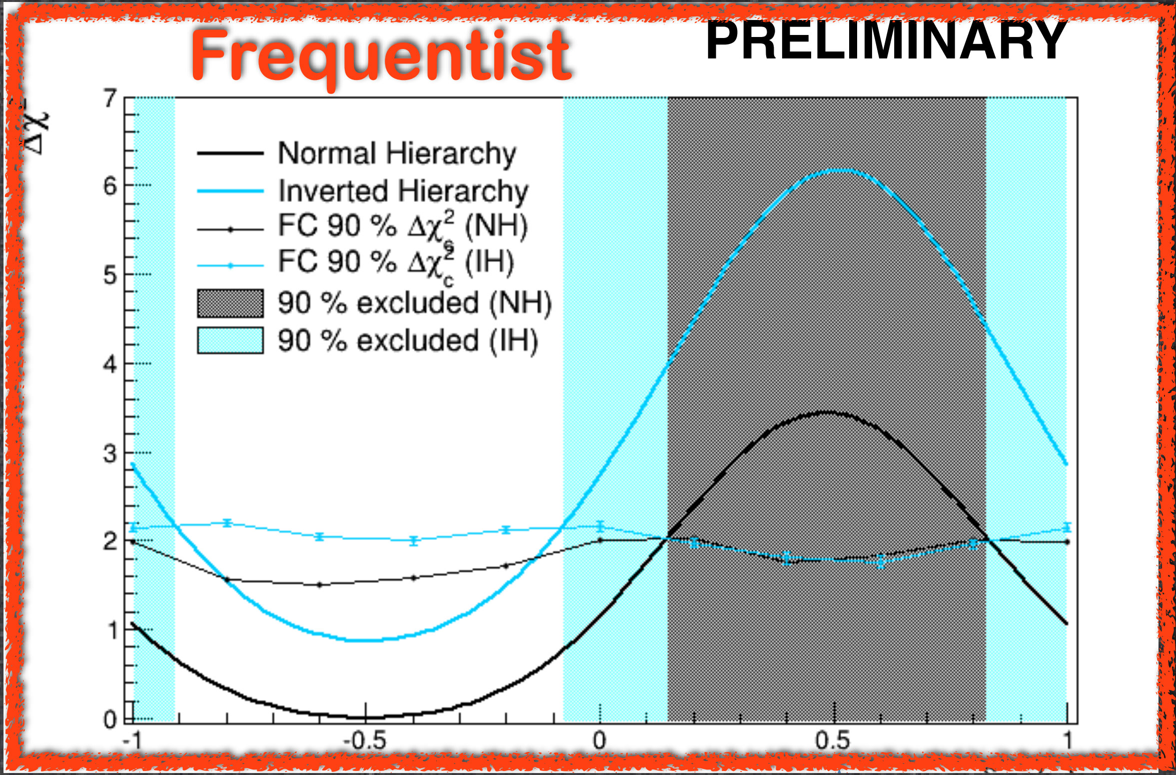
- A joint fit is needed because of the correlations between the mixing parameters → θ_{23}, θ_{13}, δ_{CP} ...
- ν_e appearance only analysis → marginalize over θ_{23} and Δm_{32}
- A better procedure is to jointly fit ν_e and ν_μ samples
- Including reactor measurement of θ_{13} → put constraints on δ_{CP}

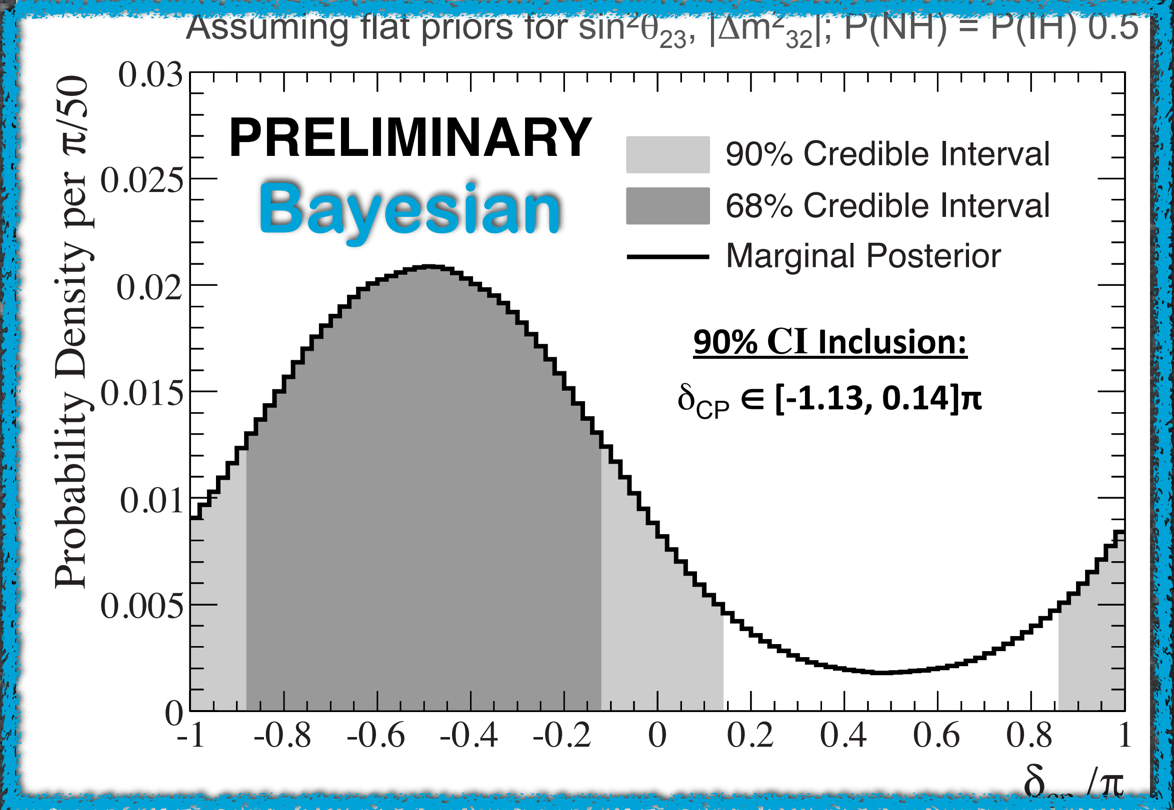


2 different analyses:
- Frequentist based on Feldman-Cousin
- Bayesian based on Markov Chain MC

Joint fit analysis

- Both analyses give similar results
  - Although they seem completely reversed
- Best fit value of $\delta_{CP} \sim -\pi/2$
- Values of $\sim 0.2 < \delta_{CP} < \sim 0.8$ excluded at more than 90% CL
- Bayesian analysis can compare probabilities for hierarchy and for octant of θ_{23} → both weak preferences

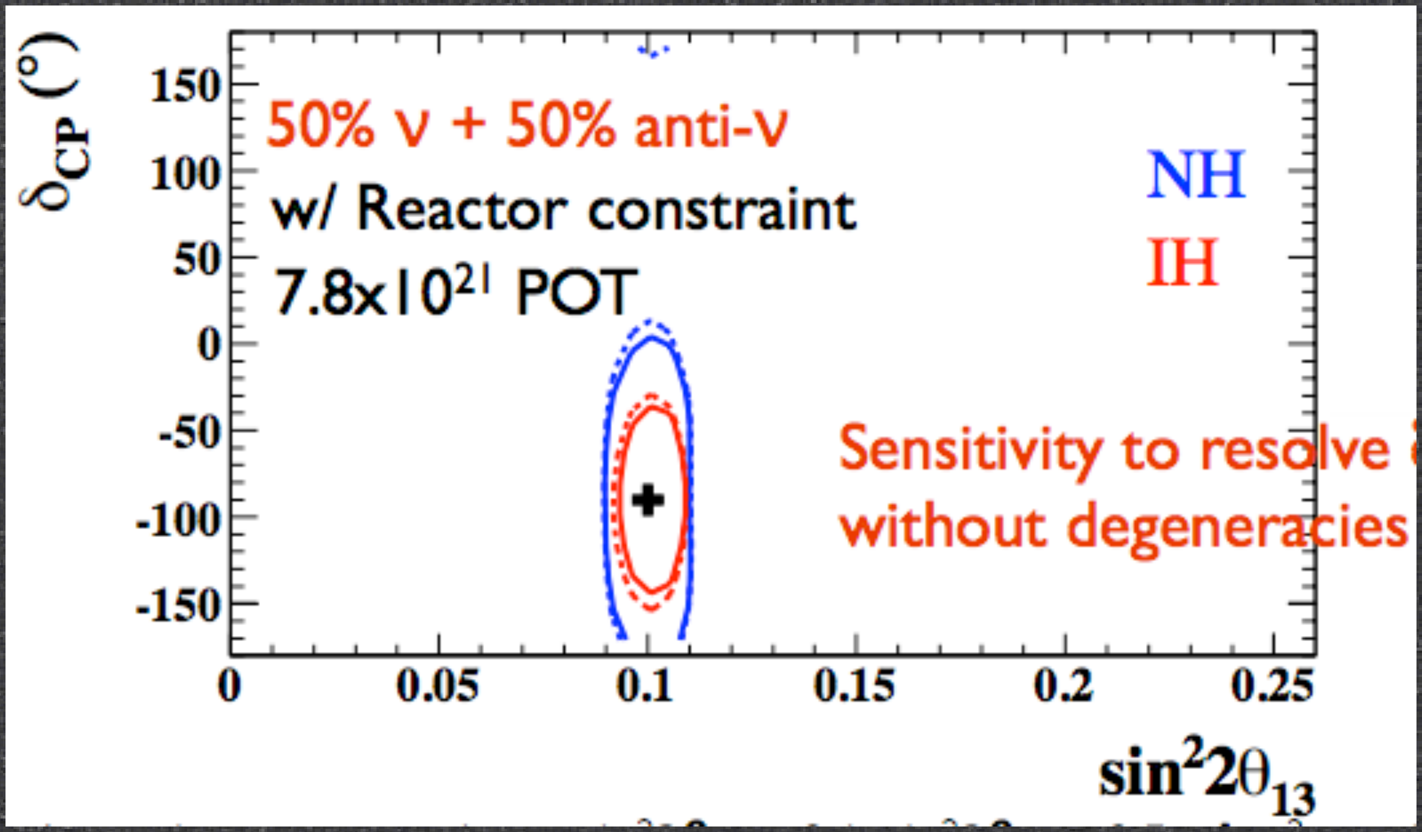




(%)	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	18	8	26%
$\sin^2\theta_{23} > 0.5$	50	24	74%
Sum	68%	32%	

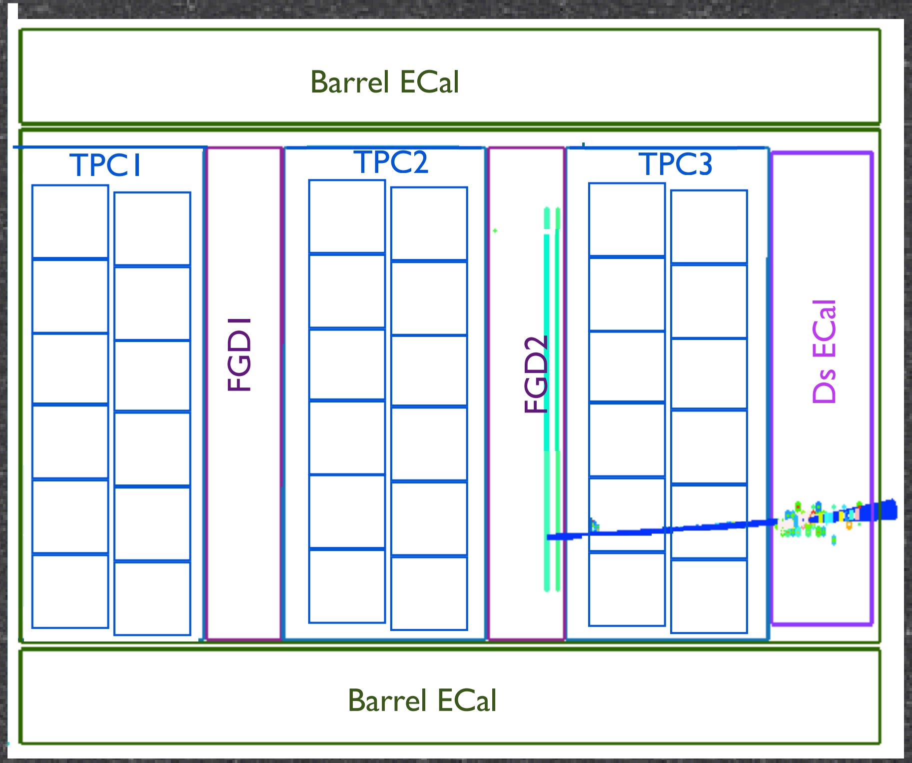
Future of T2K

- T2K collected so far <10% of the expected POT
- Thanks to the large values of θ13 and to the good control of the systematics errors (already smaller than 10%) we already observed νe appearance
- But we also started to put some constraints on δCP
- More data will allow to put better constraints and if we are lucky have hints (2-3 σ level) of CP violation in the leptonic sector!

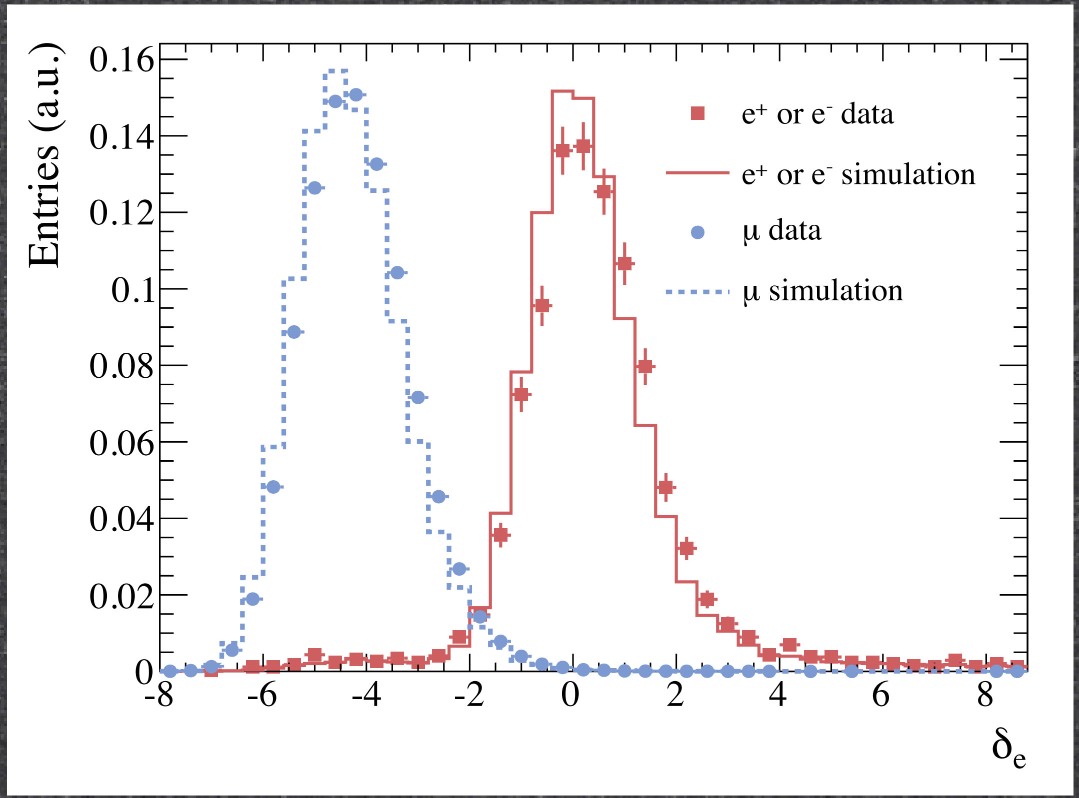


ND280 ν_e analyses

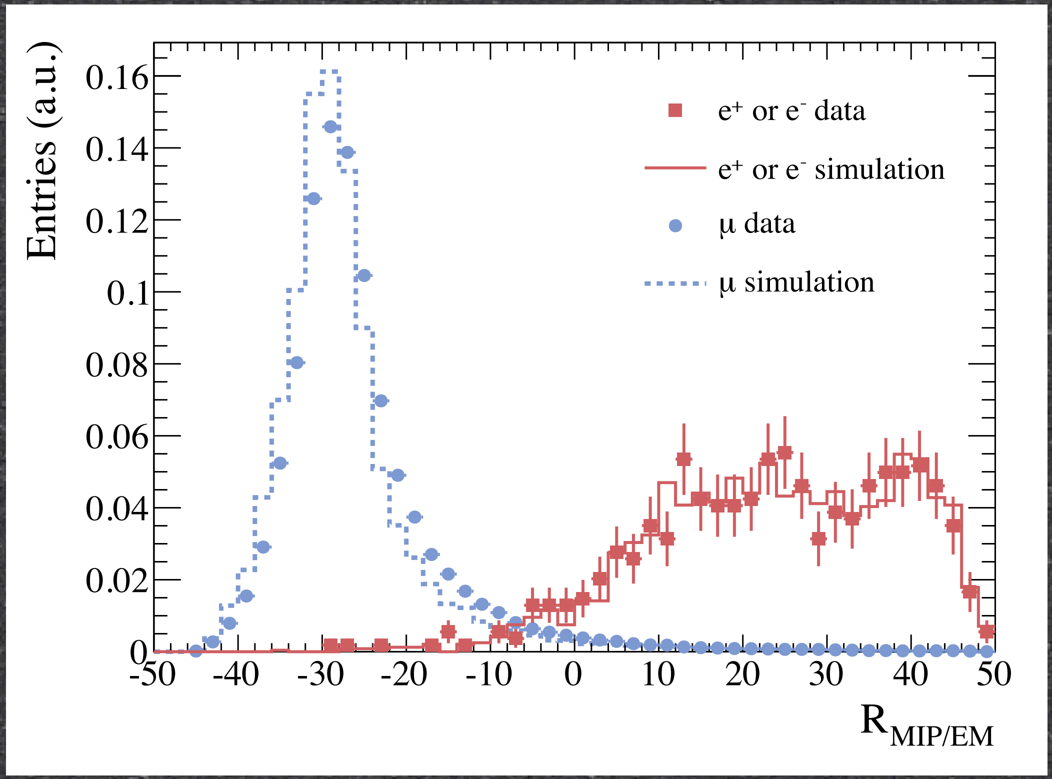
- The main background to appearance analysis is the beam ν_e component
- ND280 can measure this component
  - Difficult since only 1% of the flux is composed by ν_e
  - Combine TPC and ECAL PID to select electrons and reject muons



TPC PID



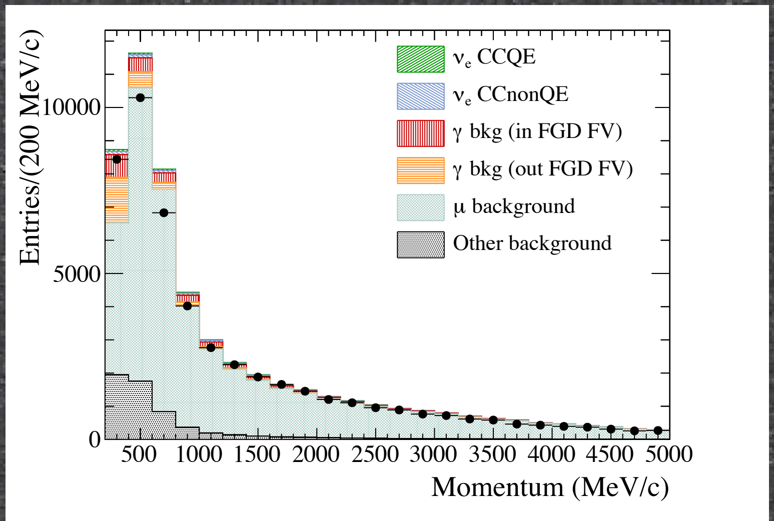
ECAL PID



ν_e selection at ND280

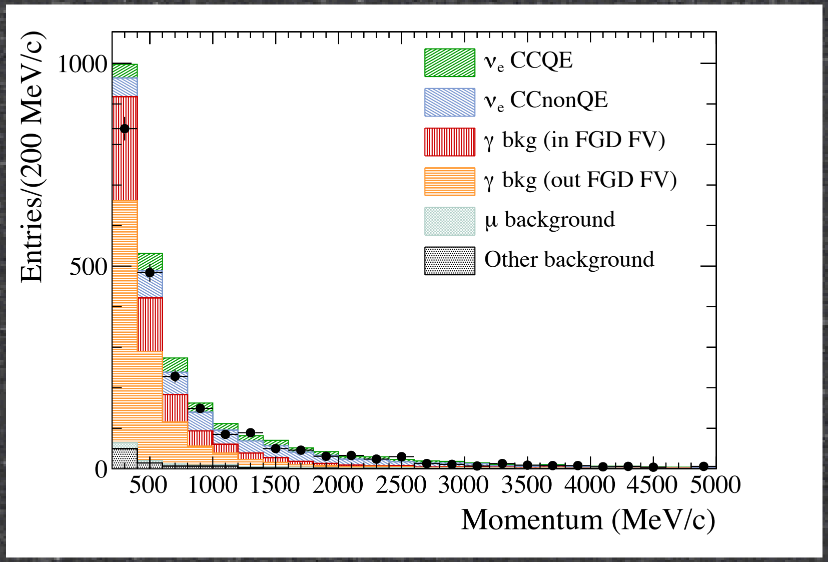
- Combining TPC and ECAL PID → reject > 99.8% of the muons
- Separate the selected sample in CC0π and CCNπ (N>=1)
- Purity of the ν_e sample ~65%
- Large background from γ conversions from π^0

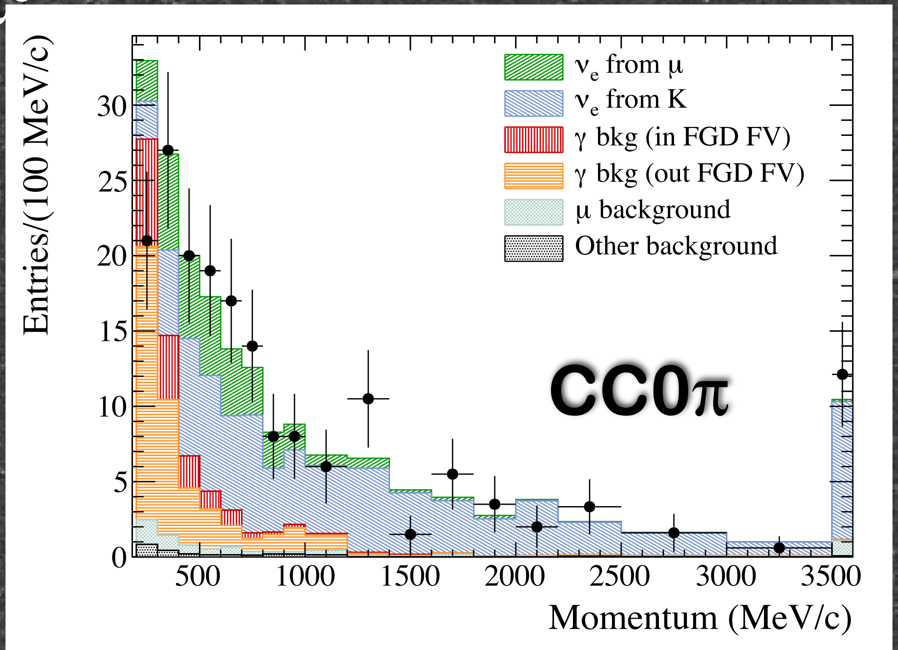
Additional cuts → 65% ν_e purity

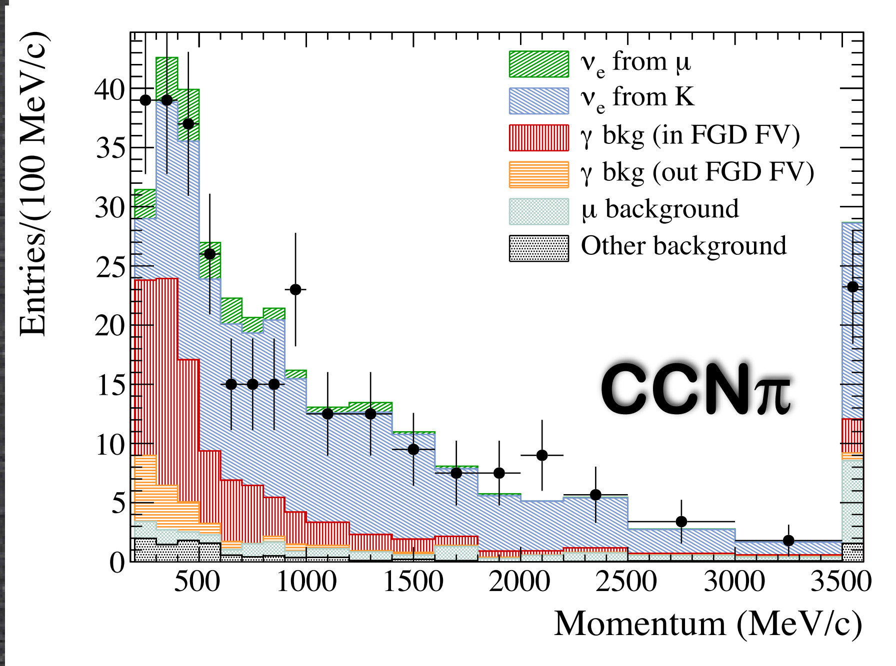


Before PID → dominated by muons

After PID → 92% of e-, only 26% from ν_e





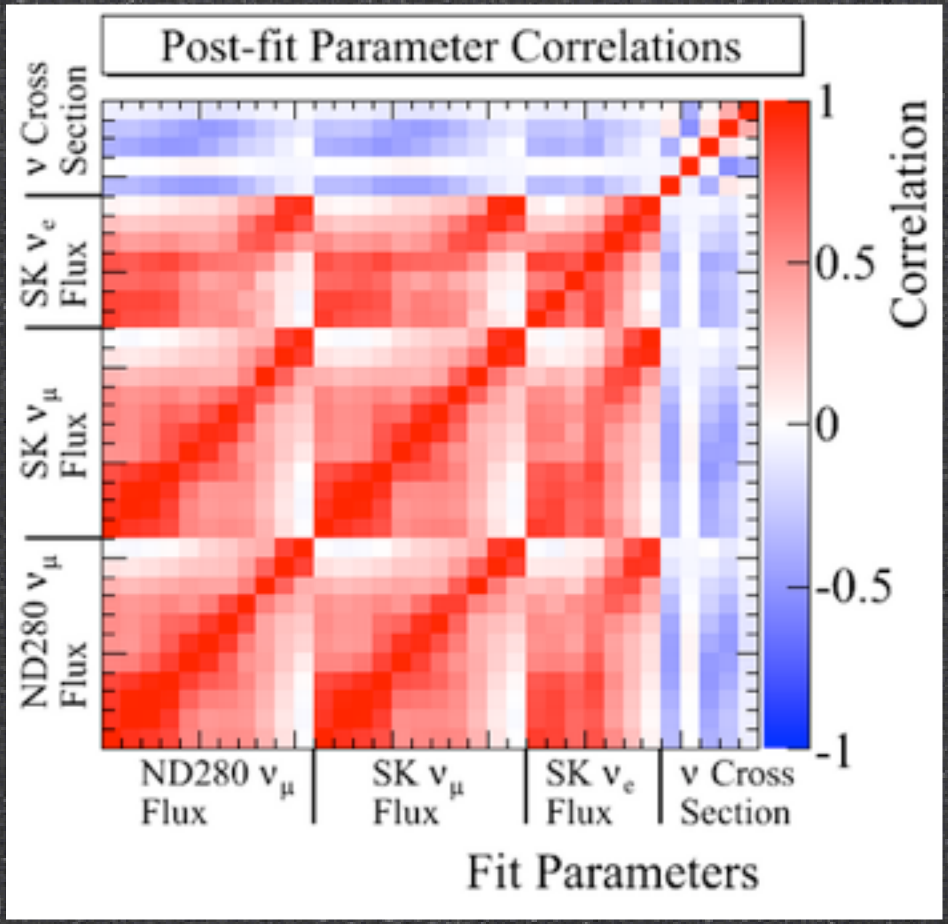


Why it's important

- Beam ν_e component is the main background to appearance analysis
- T2K oscillation analyses are done constraining flux and cross section systematics using ND280 ν_μ data
  - Strong correlations between ν_μ and ν_e fluxes
  - No differences are expected between ν_μ and ν_e x-sections

a. Build a model to include flux and x-section systematics
b. Fit ND280 ν_μ data
c. Reduce errors on ν_μ and ν_e fluxes and x-section from ~20% to ~3%

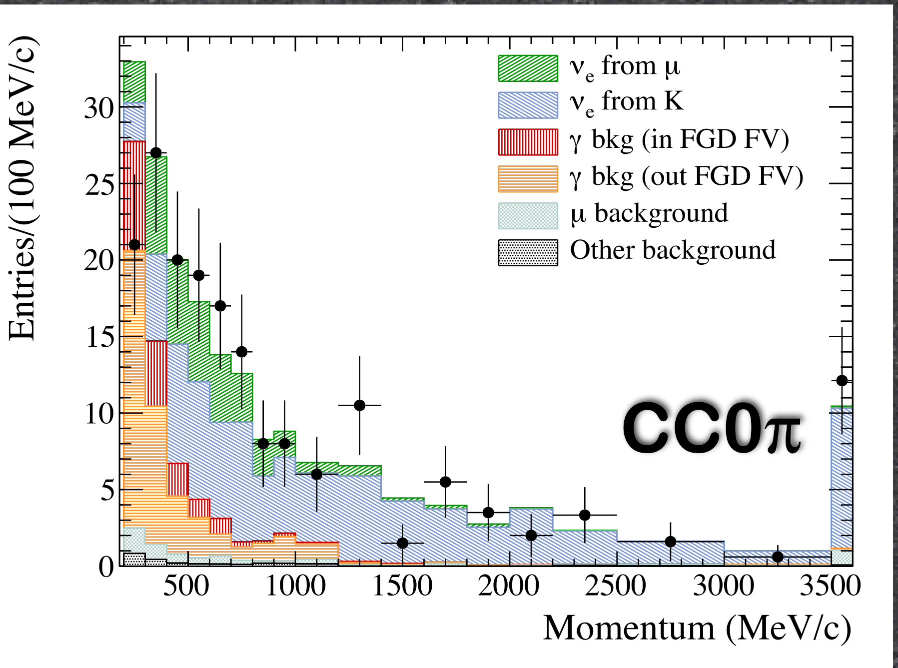
- The model used cannot be checked at SK → impossible to disentangle from oscillations
- The only cross-check is to use ND280 ν_e selection and compare data with the expectations (after ND280 ν_μ fit)

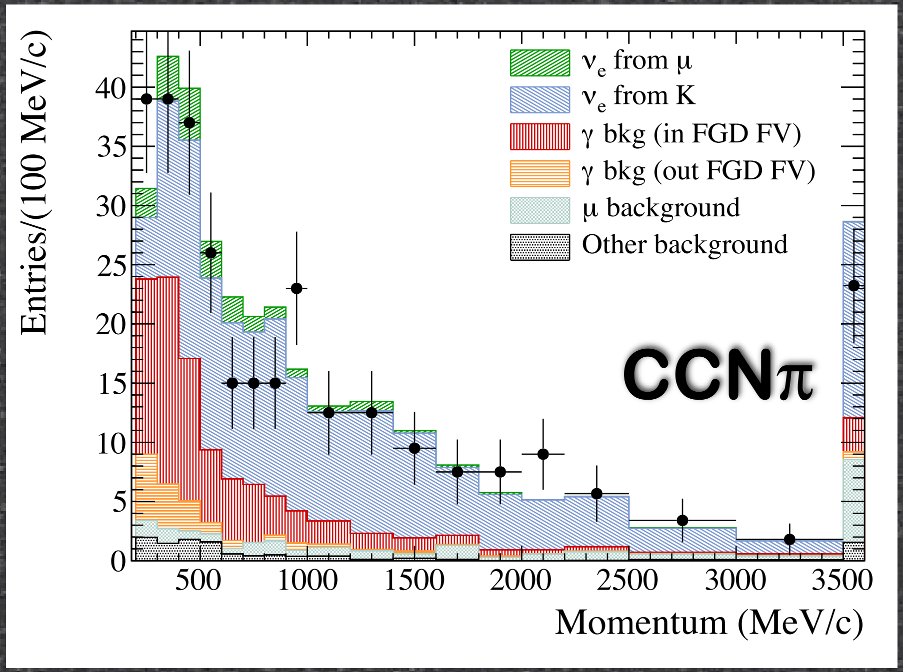


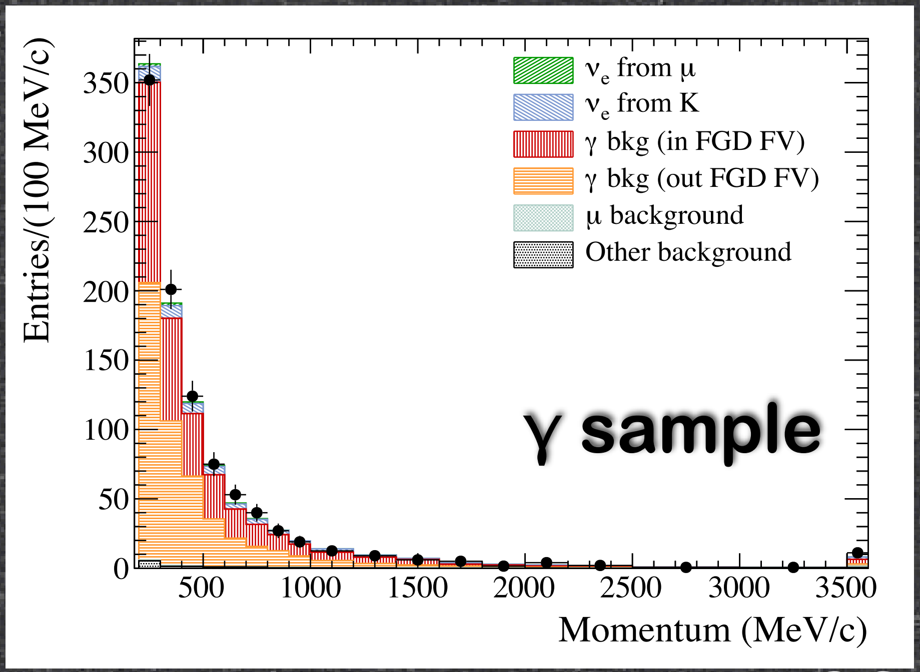
Measurement of beam νe

- Log-likelihood ratio to measure the data/MC ratio for ν_e
- γ→e+e- sample is used to constrain the background
- Inclusive beam νe component
  - $R(\nu_e)$ = 1.01 ± 0.06 (stat.) ± 0.06 (flux + x-sec) ± 0.05 (detector) → 1.01 ± 0.10
- Separate ν_e from μ and from K decays
  - $R(\nu_e$ from $\mu)$ = 0.68 ± 0.30
  - $R(\nu_e$ from $K)$ = 1.10 ± 0.14

PRD **89**, 092003 (2014)

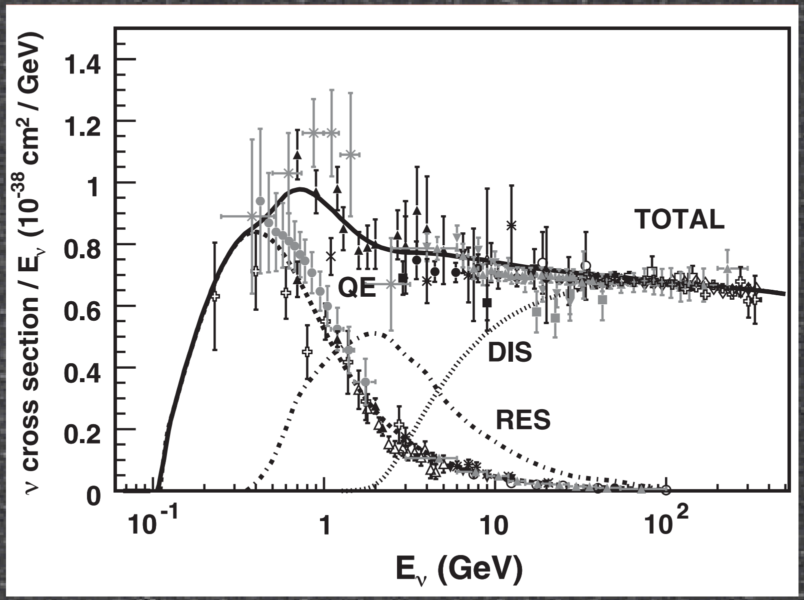




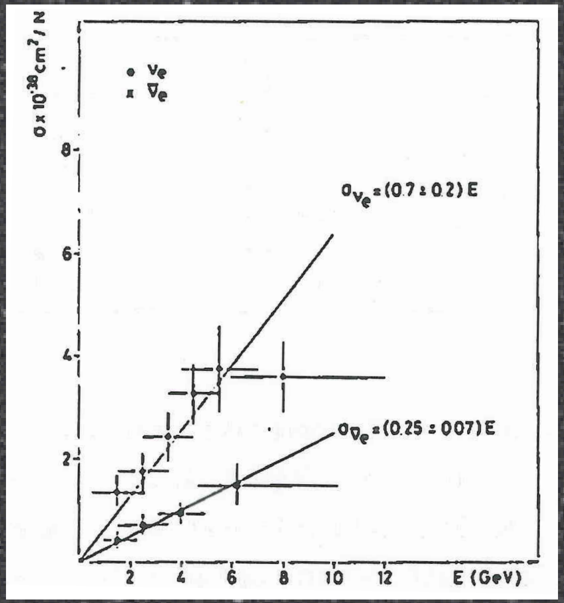


ν_e cross sections

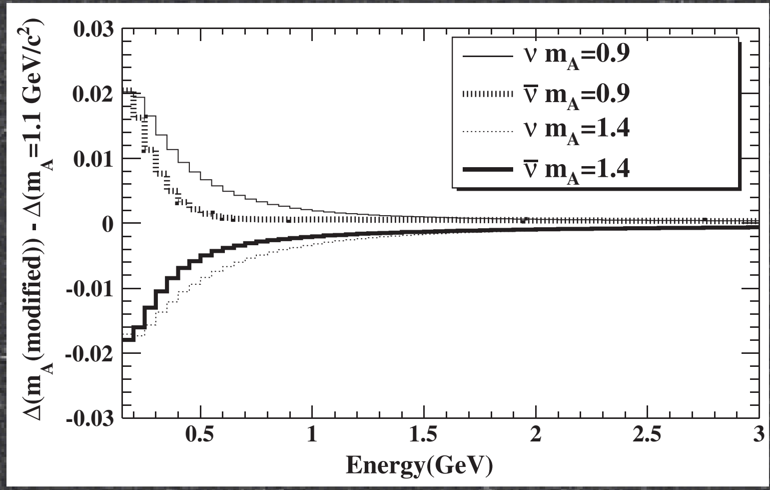
Many ν_μ measurements



Only ν_e x-sec from 1978



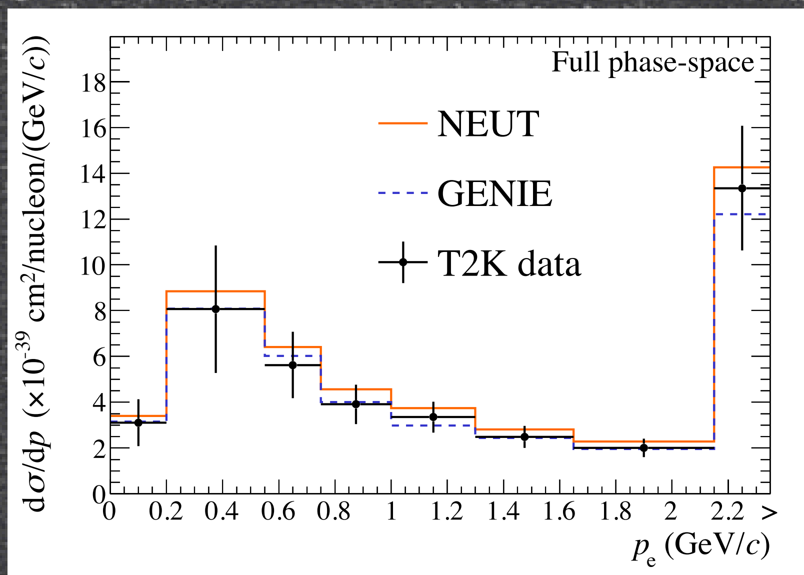
Theoretical models predict ν_e/ν_μ x-sec differences → need to check with data!



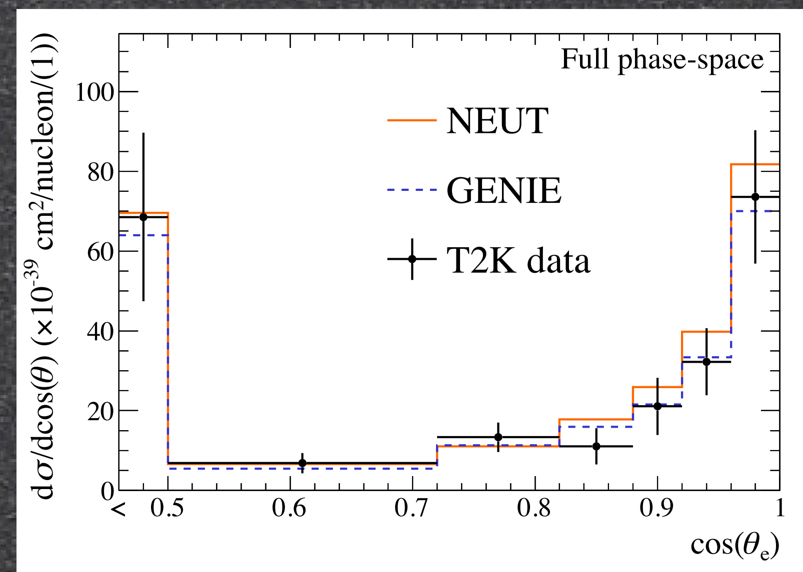
- ν_e appearance → depends on ν_e cross-section → need to measure them!
- We performed a first measurement of νe cross-section on carbon
  - First ν_e cross-section measurement since Gargamelle (1978)
  - First differential measurement of ν_e cross-section

Inclusive ν_e CC cross-section

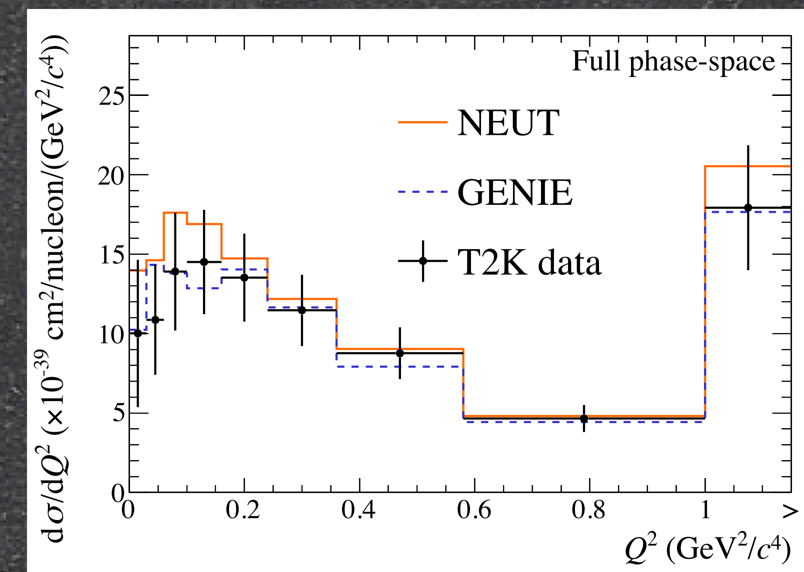
$d\sigma/dp$



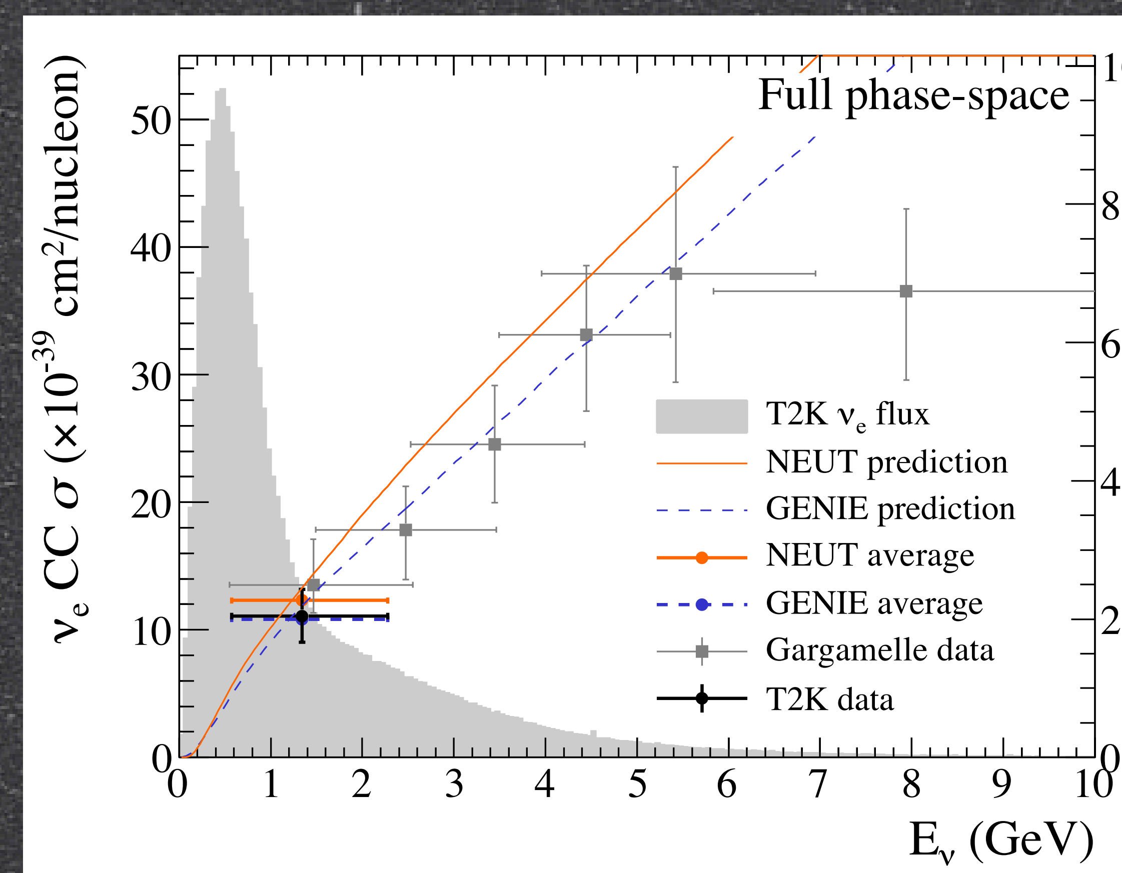
$d\sigma/d(\cos\theta)$



$d\sigma/dQ^2$



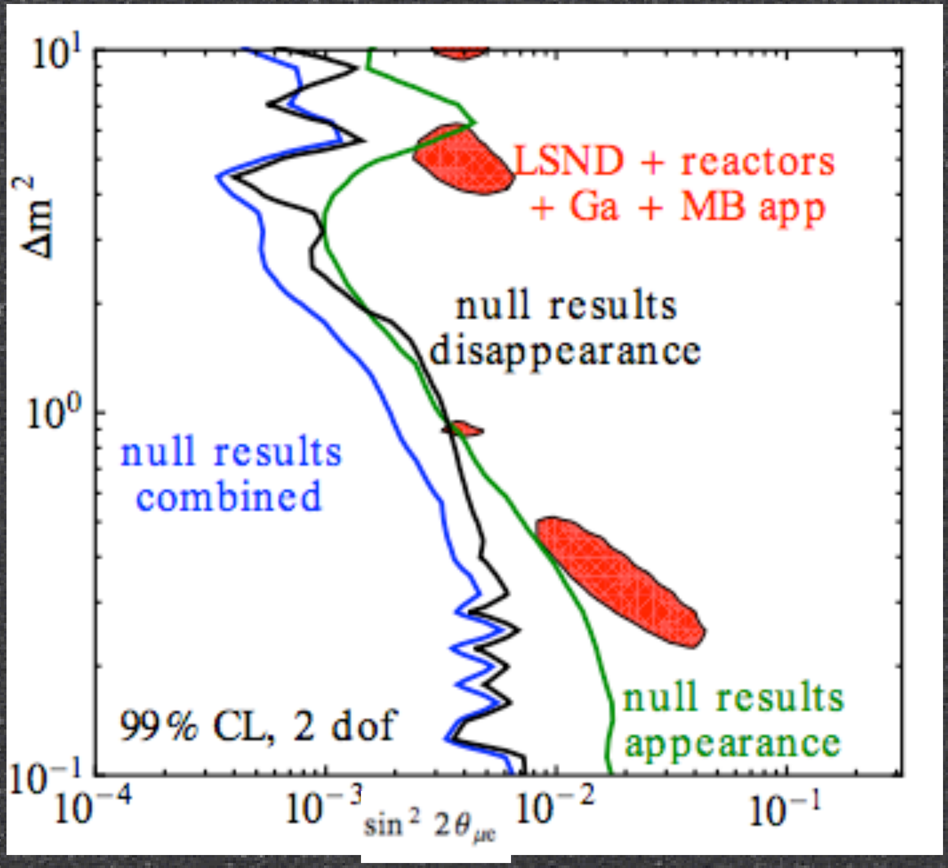
- Good agreement between data and MC
- Good agreement with Gargamelle data
- Some discrepancies at low Q^2 → most interesting region for ν_e/ν_μ differences
- In the future many more ν_e cross-section measurements will be needed if we want to measure CPV using ν_e appearance channels!



Search for sterile neutrinos

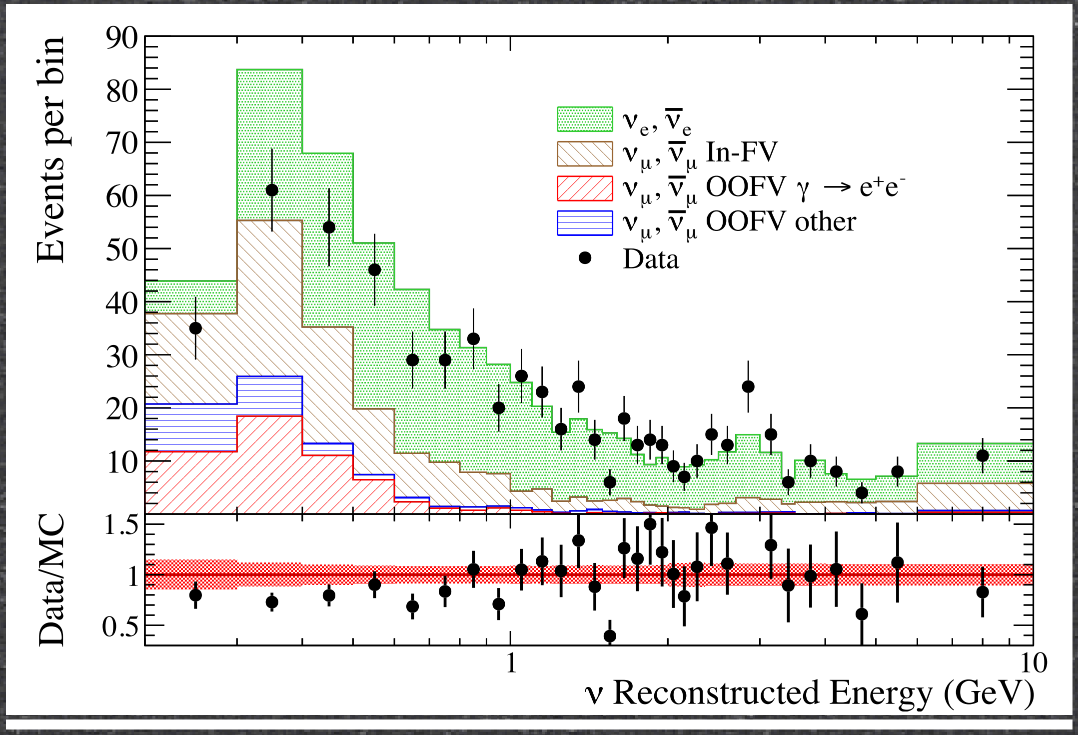
- Several "anomalies" exist in the neutrino sector
  - ν_e appearance ($P_{\mu e}$) → LSND, MiniBooNE
  - ν_e disappearance (P_{ee}) → reactor and gallium anomalies
  - No sign of ν_μ disappearance ($P_{\mu\mu}$)→ limits from MINOS and MiniBooNE
  - All the three channels are related:
    - $2P_{\mu e} \sim (1-P_{ee})(1-P_{\mu\mu})$

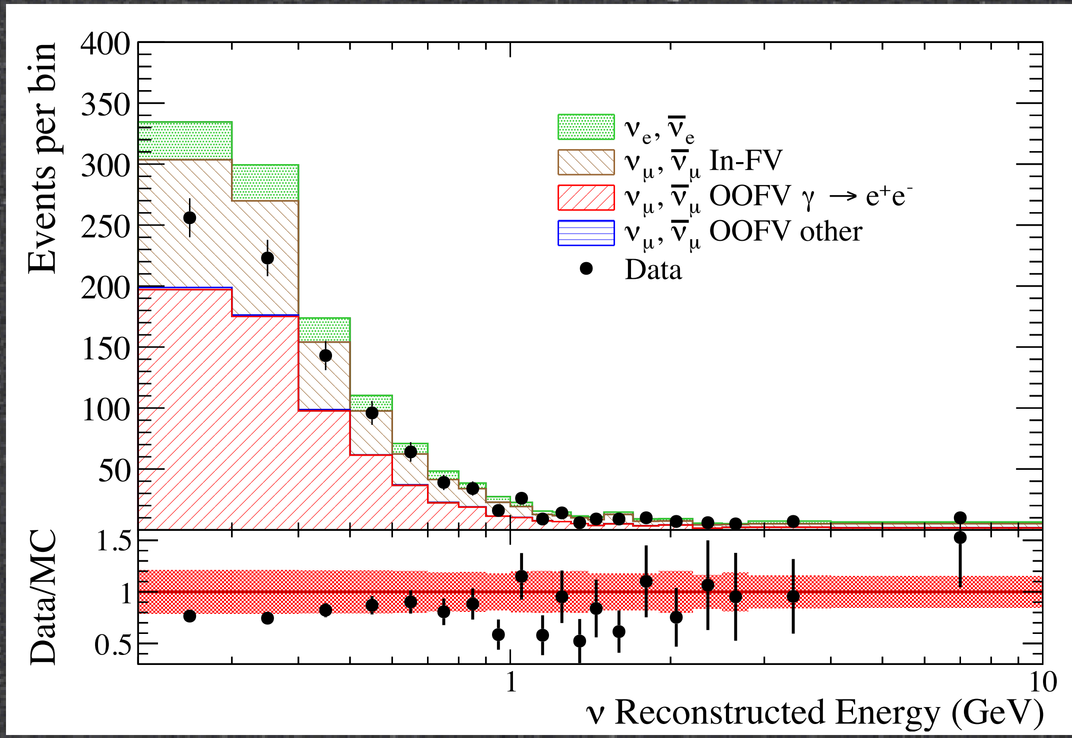
Tensions when all the channels are combined together → some of them has to be wrong?
We decided to concentrate on the ν_e disappearance channel (reactor anomaly)
use ND280 ν_μ data to constrain the systematics (no ν_μ disappearance)



Sterile neutrino analysis

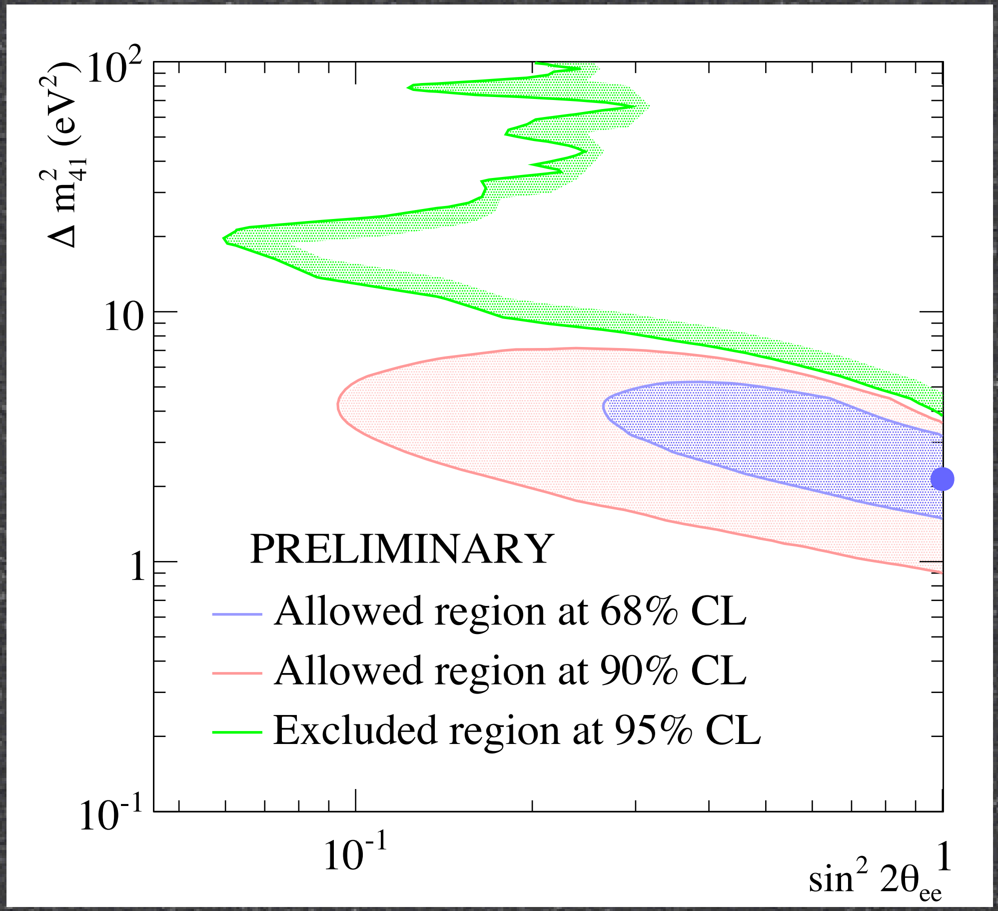
- 3+1 model: $P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta_{ee} \cdot \sin^2 \left(\frac{1.267 \Delta m_{41}^2 L_\nu}{E} \frac{\text{GeV}}{\text{eV}^2\text{km}} \right)$
- No hints of ν_μ disappearance exist → $\sin^2(2\theta_{\mu\mu})=0$
- Look for ν_e disappearance in $(\sin^2(2\theta_{ee}), \Delta m^2_{41})$ plane
  - Study gallium and reactor anomaly
- Use ND280 ν_e and γ selections and fit E_{rec} distributions
- Constrain flux and x-sec systematics using ND280 ν_μ sample

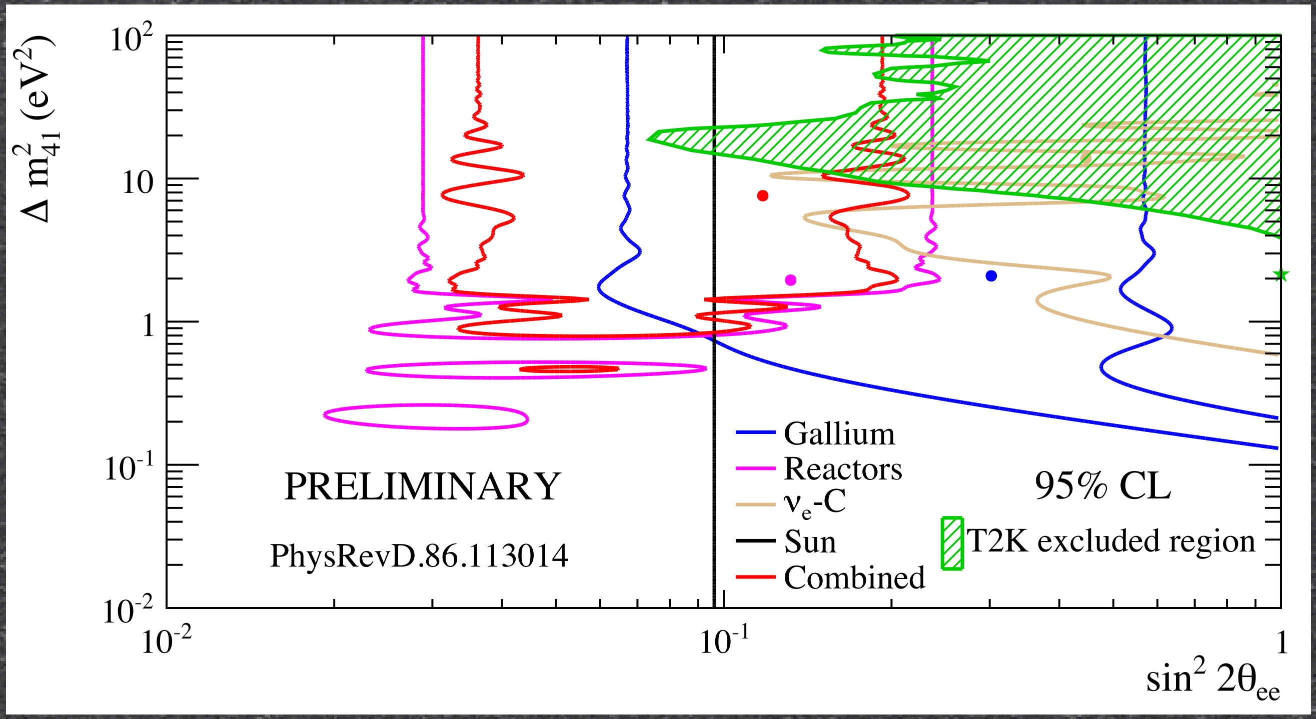




Results

- Frequentist method for confidence intervals (FC)
- Out of fiducial volume reduced of ~30% → compatible with systematics uncertainties
- Best fit values: $\sin^2 2\theta_{ee}=1$ and $\Delta m^2_{41}=2.14\ eV^2$



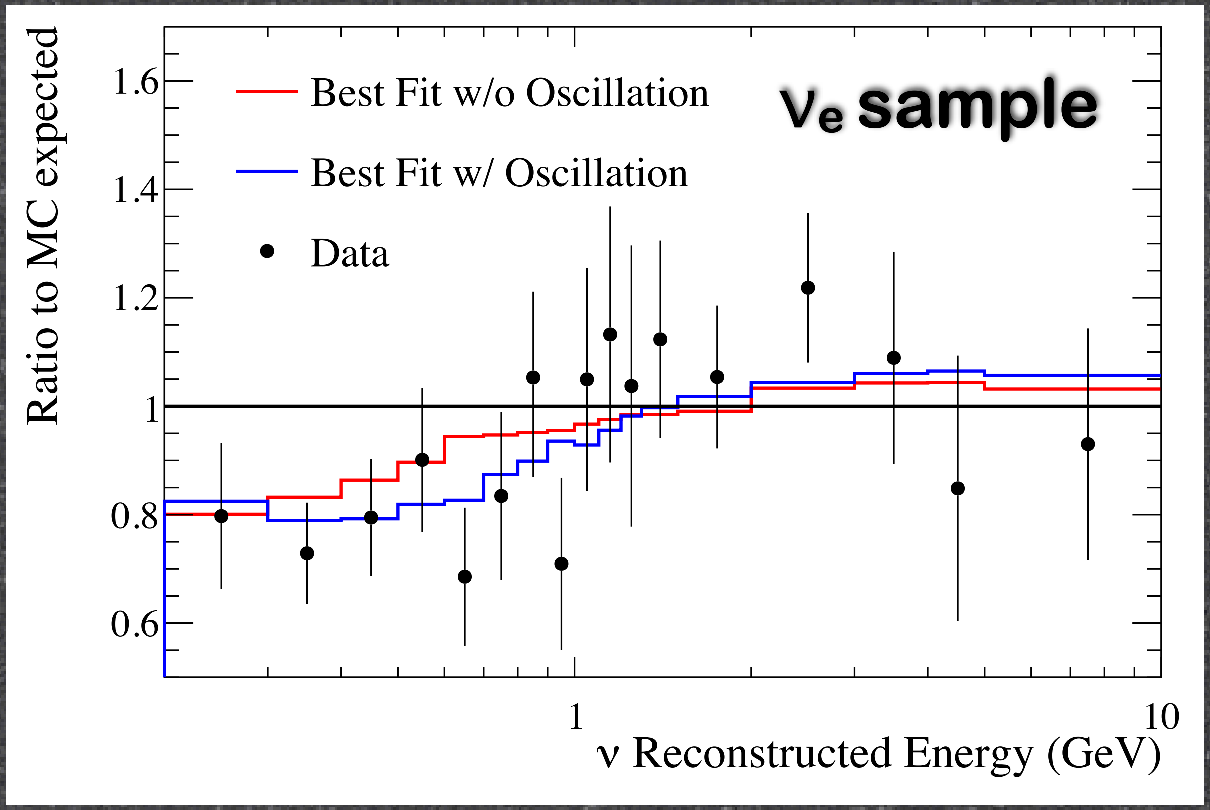


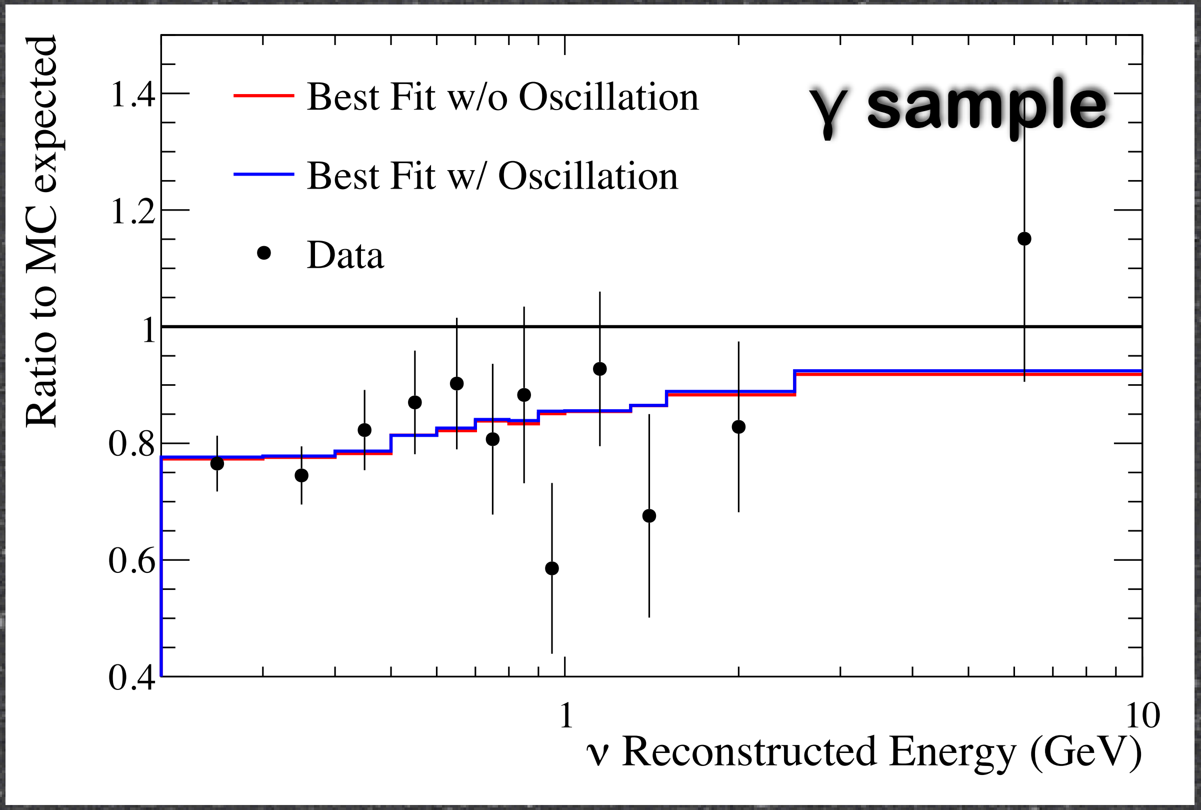
p-value with respect to null oscillation hypothesis: 6.1%

95% CL excluded intervals: $\sin^2 2\theta_{ee}>0.2$ and $\Delta m^2_{41}>8\ eV^2$

need to repeat this analysis when more data will be available!

With and without oscillations





- γ sample is reduced to fit the data
- That's not enough for the ν_e sample in the low energy part
- Mild preference to include oscillations → p-value no oscillations ~6%
- Interesting to see what happen when more statistics is collected!

Conclusions

- T2K has performed world leading results by taking only 8% of the total expected statistics
  - First observation of ν (ν_e) appearance at 7.3 σ
  - Best measurement of θ_{23} through ν_μ disappearance → 3° error
  - Joint appearance and disappearance analysis, combined with reactor constraints allow to have hints for $\delta_{CP}=-\pi/2$
- A lot of interesting physics is also done at the Near Detectors
  - ν_μ and ν_e cross sections
  - Searches for sterile neutrinos
- We recently started the first anti-neutrino run
  - Measure anti-ν_μ disappearance and anti-ν_e appearance
  - Running 50% anti-ν allow to optimize the δ_{CP} sensitivity