Results in T2K

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For the T2K collaboration

XXIV Rencontres de Blois, May 27th - June 1st 2012

neutrino oscillations as of early 2011

- flavor oscillation described by PNMS matrix
- parametrized by 3 mixing angles and CP-violating phase δ_{CP}

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"atmospheric sector"

θ_{23}

ν_μ disappearance

(SuperK, K2K, MINOS)

ν_τ appearance

(OPERA, SuperK)

$0.92 < \sin^2 2\theta_{23} < 1.0$

$2.3 \cdot 10^{-3} < \Delta m^2_{23}(eV^2) < 2.56 \cdot 10^{-3}$

"solar sector"

θ_{12}

ν_e disappearance

(SNO, KamLAND, SuperK and others)

$0.84 < \sin^2 2\theta_{12} < 0.89$

$7.38 \cdot 10^{-5} < \Delta m^2_{12}(eV^2) < 7.80 \cdot 10^{-5}$

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θ_{13}

only upper limit known

$\sin^2 2\theta_{13} < 0.13$ @ 90% CL (2010)

(CHOOZ, MINOS)

Mass Hierarchy: ?

$\Delta m^2_{23} > 0$

$\Delta m^2_{23} < 0$

θ_{13}

reactor experiment

$\bar{\nu}_e \rightarrow \bar{\nu}_e$ oscillation

($\bar{\nu}_e$ disappearance)

δ_{CP} unknown

accelerator experiment

θ_{13}

observation of $\nu_\mu \rightarrow \nu_e$ oscillation

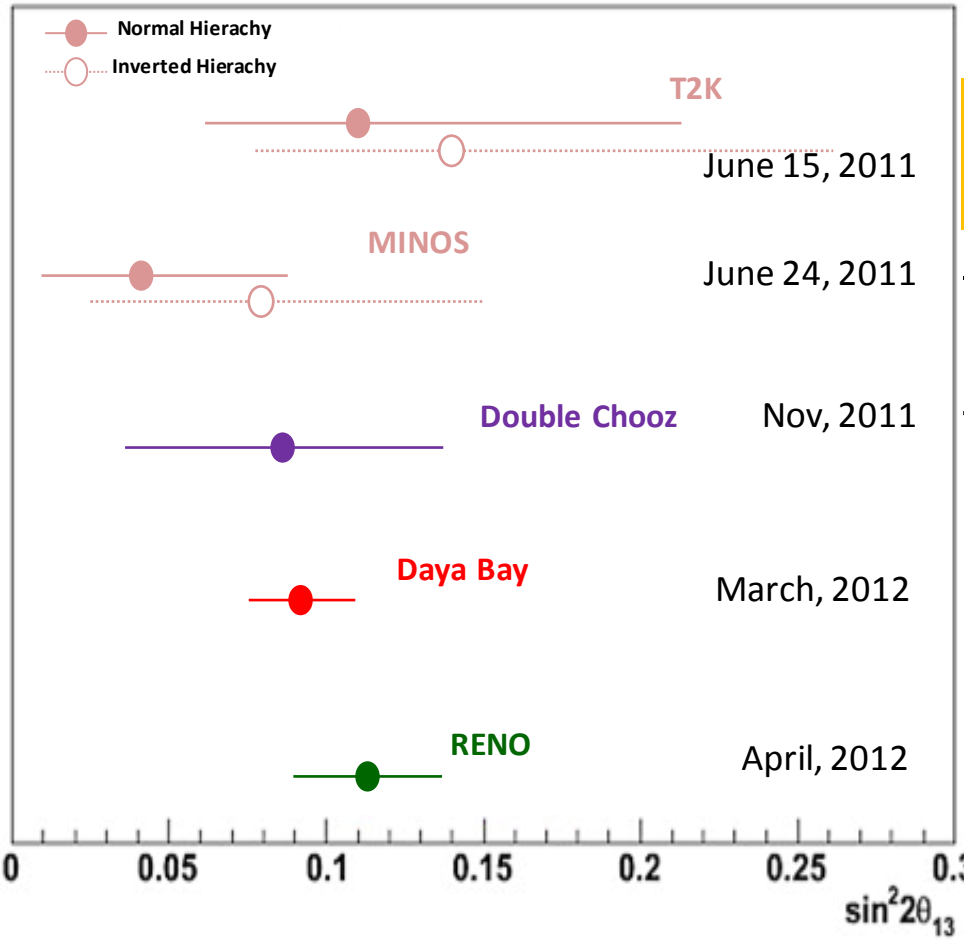
(ν_e appearance)

δ_{CP}

visible if $\theta_{13} \neq 0$

neutrino oscillations: a year after

- θ_{13} has been well measured by different experiments
- Interest now focused to the *Mass Hierarchy* determination & measurement of the *CP phase*



T2K $\nu_\mu \to \nu_e$

first indication of $\theta_{13} \neq 0$ with 2.5 σ significance

MINOS $\nu_\mu \to \nu_e$

$\theta_{13} = 0$ *disfavored @1.7 σ*

Double Chooz $\bar{\nu}_e \to \bar{\nu}_e$

$\theta_{13} \neq 0$ *@3σ combined with T2K and MINOS*

Daya Bay $\bar{\nu}_e \to \bar{\nu}_e$

$\sin^2 2\vartheta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

5.2σ significance

RENO $\bar{\nu}_e \to \bar{\nu}_e$

$\sin^2 2\vartheta_{13} = 0.113 \pm 0.013(\text{stat}) \pm 0.019(\text{syst})$

4.9σ significance


T2K
500 members, 59 Institutes, 12 countries

T2K: a Long Baseline neutrino experiment

➢ **Key Measurement**: observation of $\nu_\mu \rightarrow \nu_e$ oscillation (ν_e appearance)

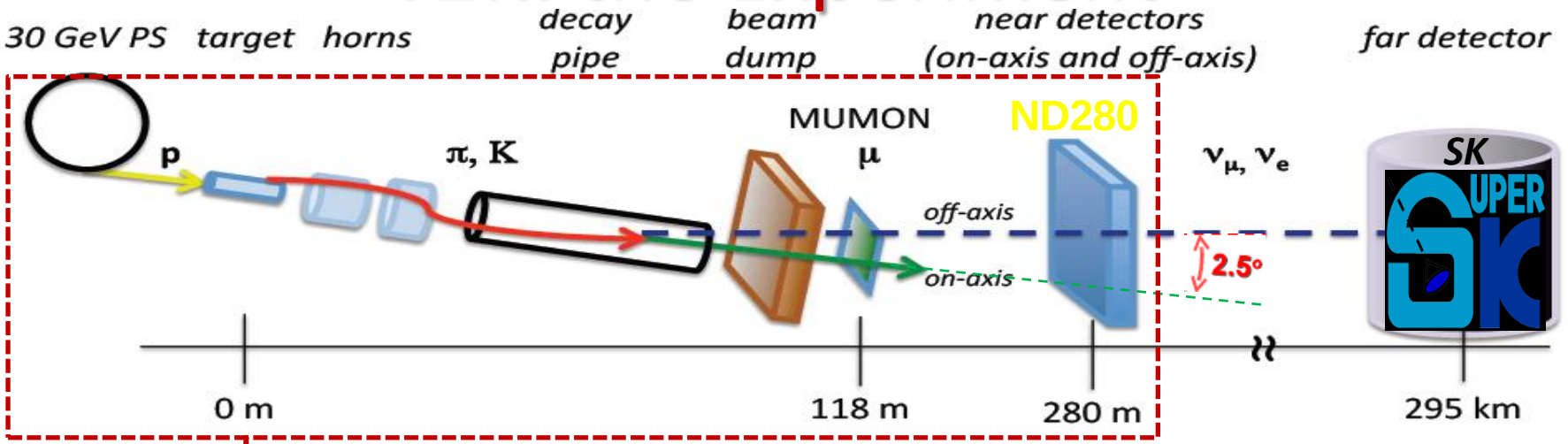
$$P(\nu_\mu \rightarrow \nu_e) \propto \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{23} L}{4E_\nu}$$

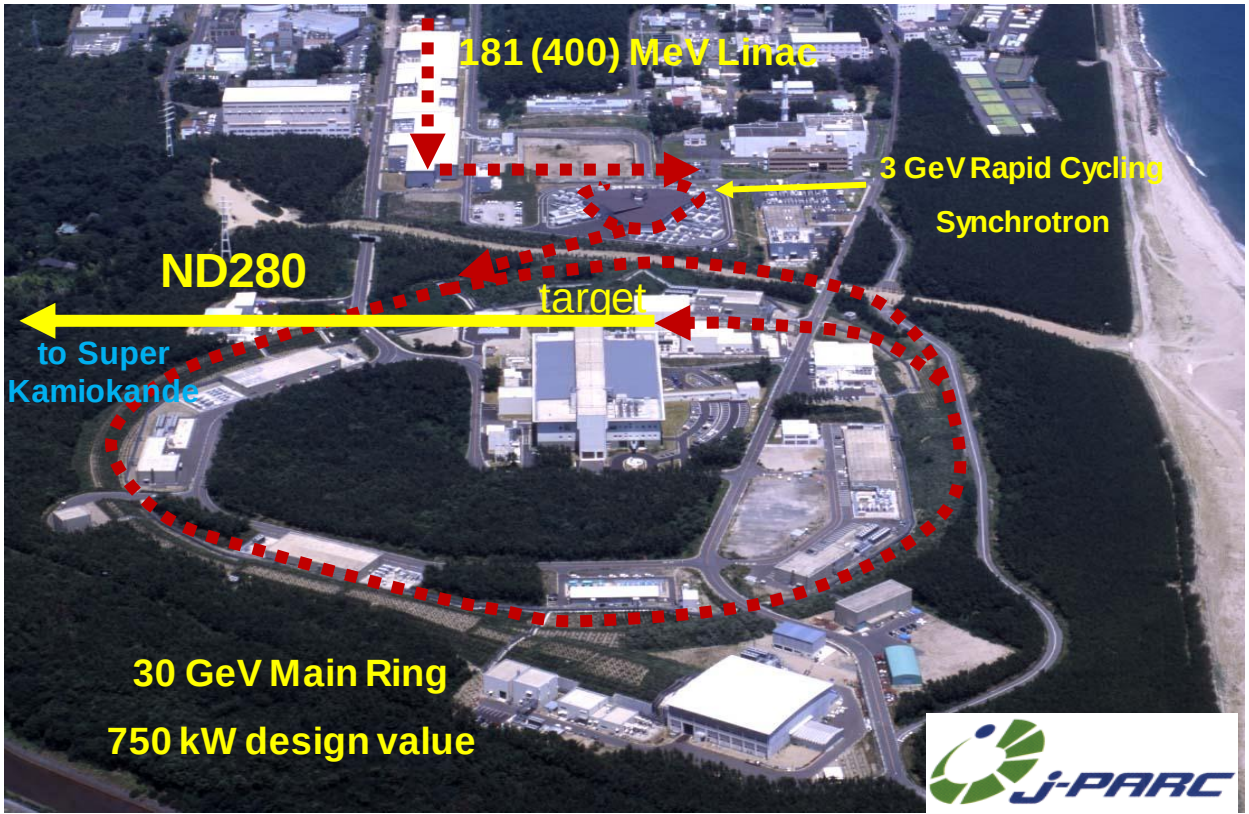
$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu - \bar{\nu}_e) \propto \sin\theta_{12} \sin\theta_{13} \sin\theta_{23} \sin\delta_{CP}$$

➢ Precise measurement of the ν_μ disappearance:

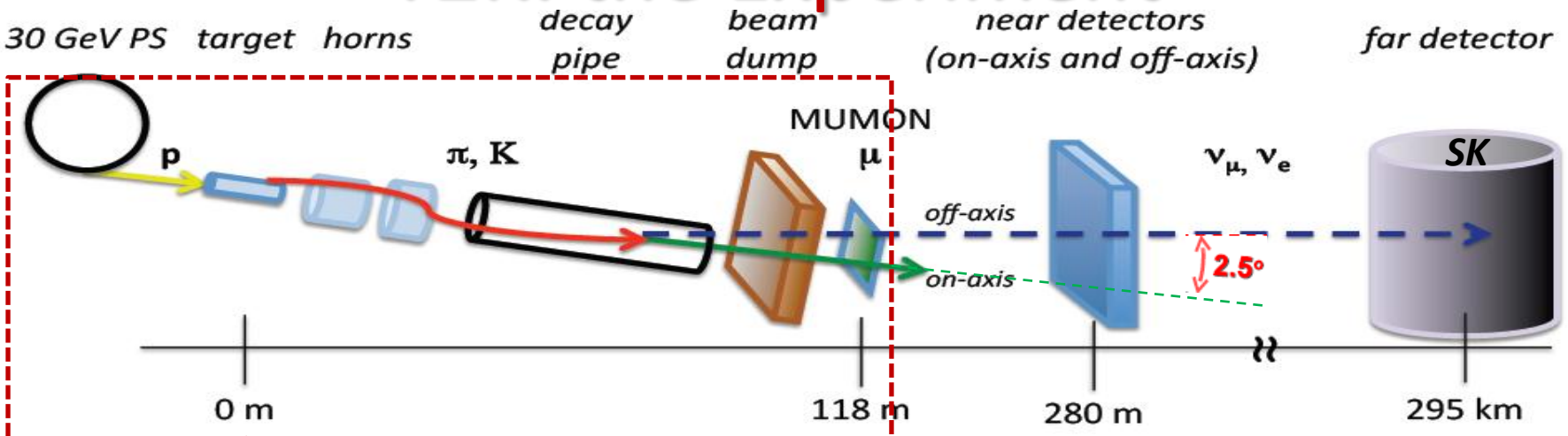
$$P(\nu_\mu \rightarrow \nu_\mu) \propto 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{23} L}{4E_\nu}$$

T2K: the Experiment

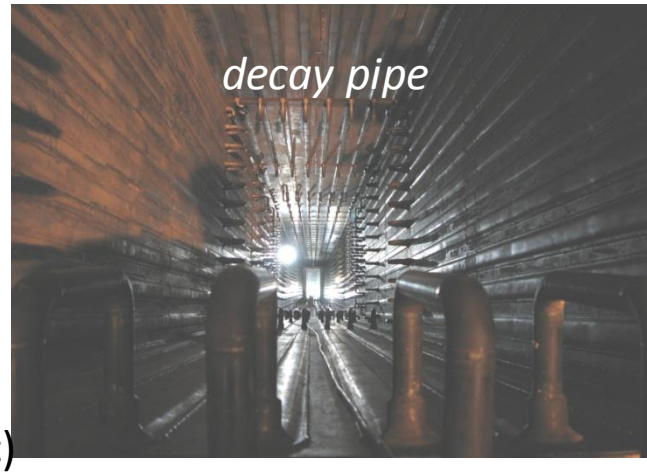




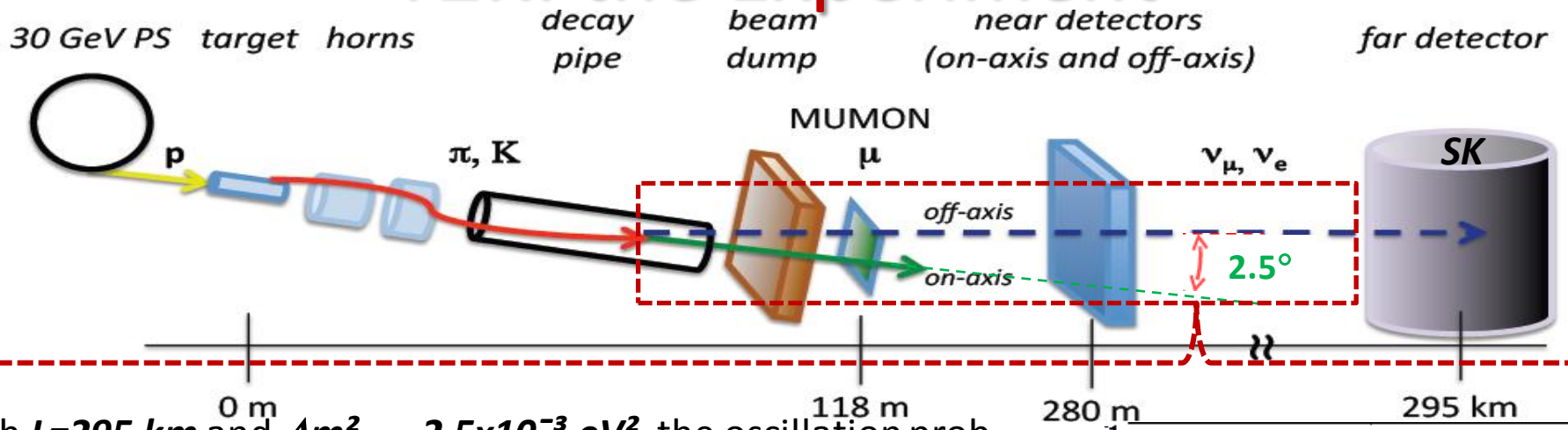
T2K: the Experiment



- 30 GeV **proton beam**
- Design power: 750 kW
- **Target: graphite**, 90 cm long
- 3 horns to focus positive π/K
- ~96 m decay pipe
- Beam Dump to stop *h*'s/μ's
- Beam profile measured with punch through μ's (> 5 GeV/c) (MUMON)



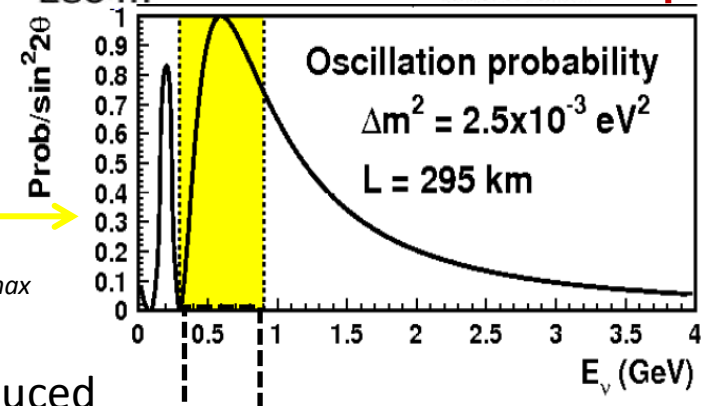
T2K: the Experiment



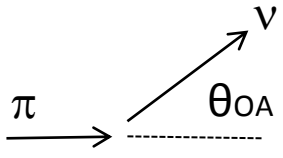
With ***L=295 km*** and ***$\Delta m^2_{23} \sim 2.5\times10^{-3}$ eV²*** the oscillation prob.

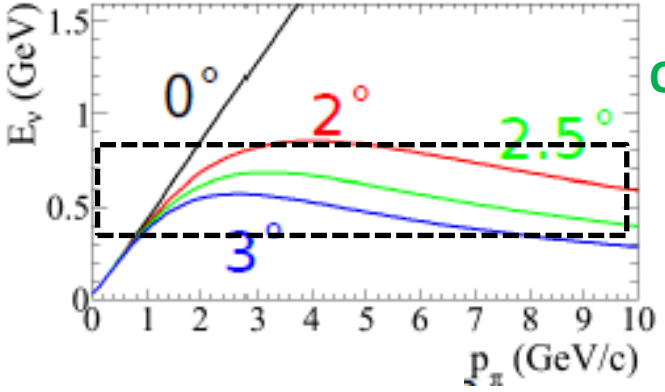
$$P(\nu_\mu \to \nu_e) \propto \sin^2(1.27\Delta m^2_{23}[eV^2]\frac{L[km]}{E_{\nu_\mu}[GeV]})$$

is maximal for $E_{\nu_\mu} = E_{max} \sim$ **0.6 GeV**

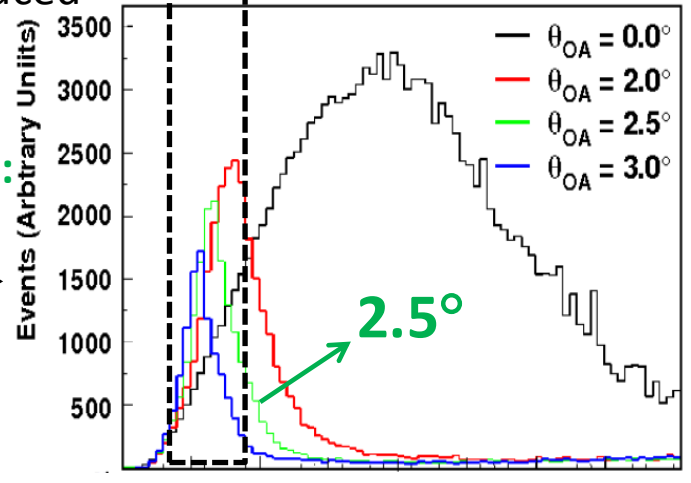


- Spectrum of detected neutrinos can be peaked around E_{max} by adjusting the off-axis angle
- High energy ν tail reduced -> BKG from π^0 production reduced

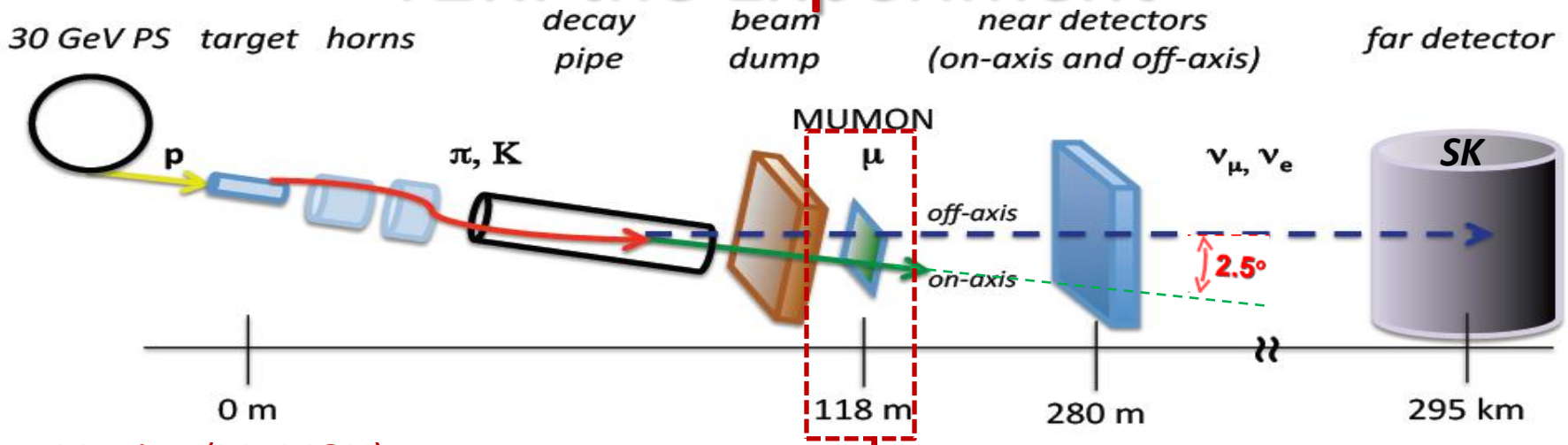




Chosen Off-Axis angle: θOA= 2.5°

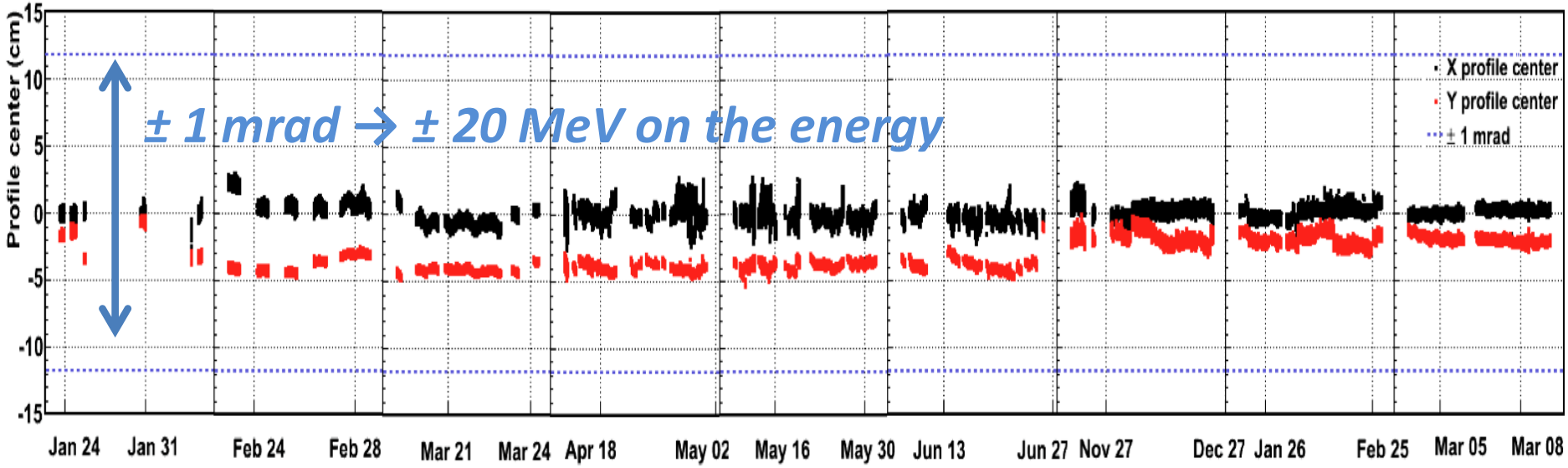


T2K: the Experiment

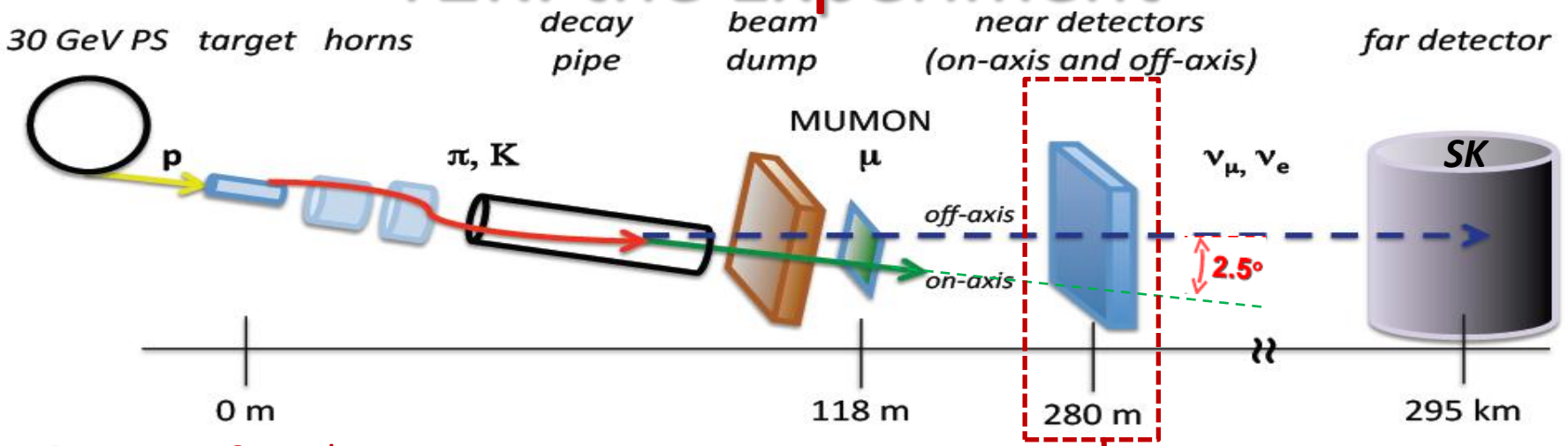


MuonMonitor (MUMON)

Pulse-by-Pulse Muon Direction Measurements



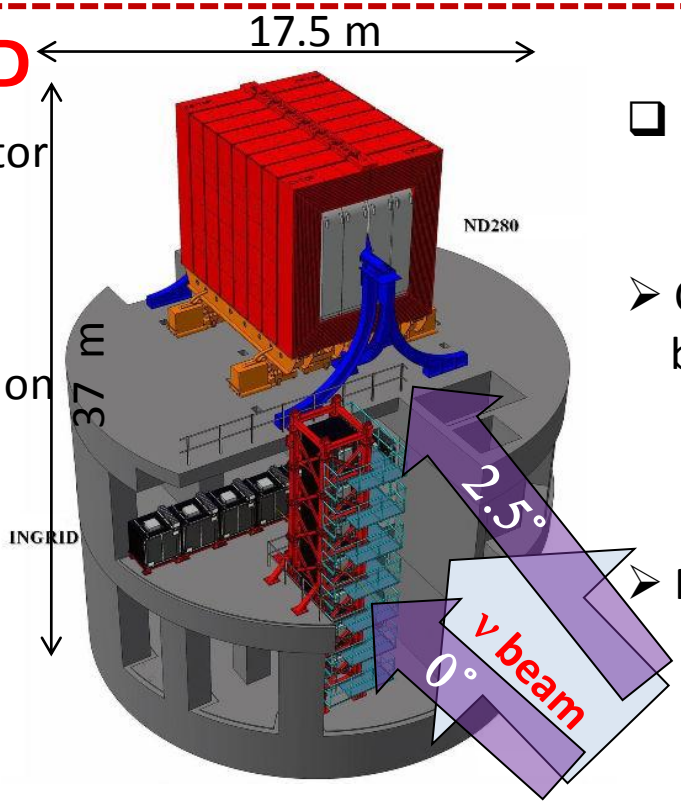
T2K: the Experiment



Near Detectors Complex

On-axis: INGRID

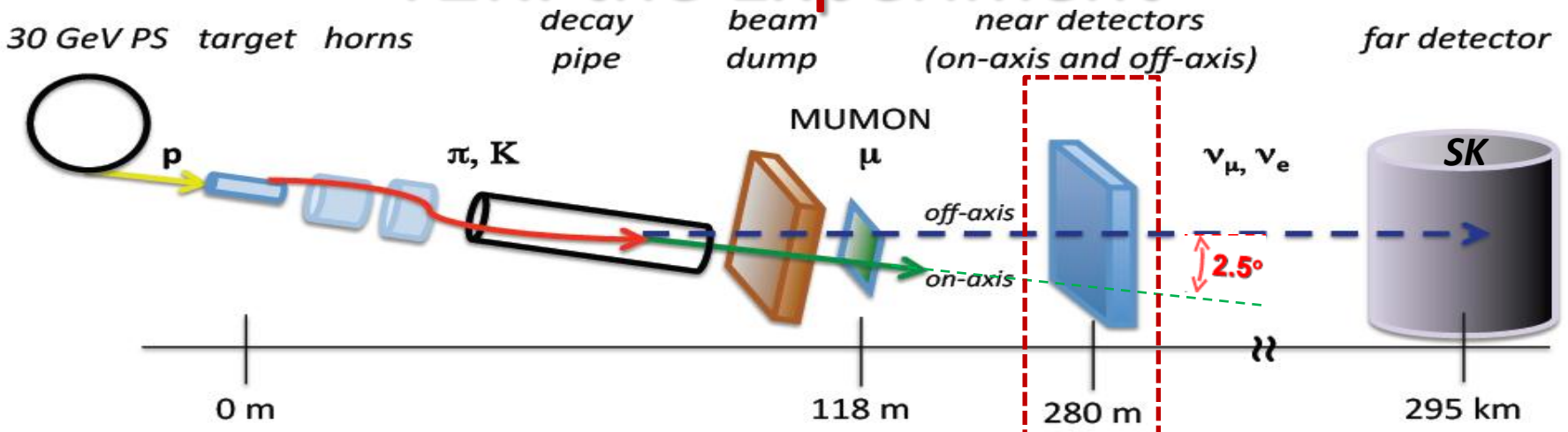
- Array of Fe/Scintillator tracking detectors
- Monitor the ν's beam profile, direction and intensity



Off-axis: ND280

- Fine grained detector complex in 0.2 T magnetic field
- Characterization of the ν beam before oscillations
  - ν_μ flux/Energy Spectrum
  - ν_e contamination
    → bkg to ν_e appearance
- Measurement of ν_μ interactions
  - ν_μ induced π° production
    → bkg to ν_e appearance

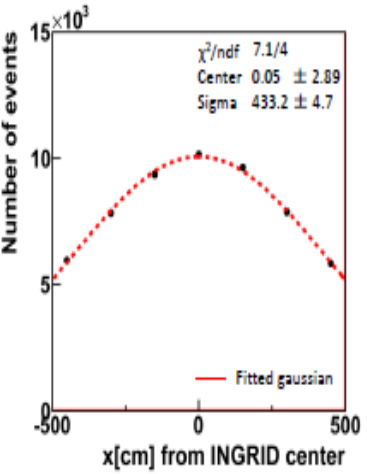
T2K: the Experiment

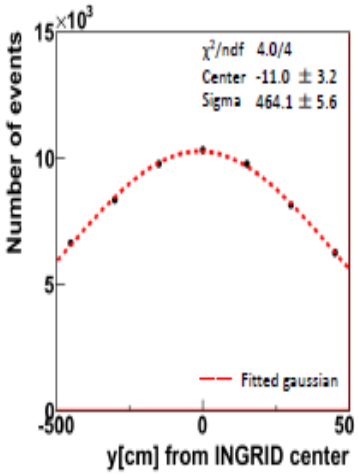


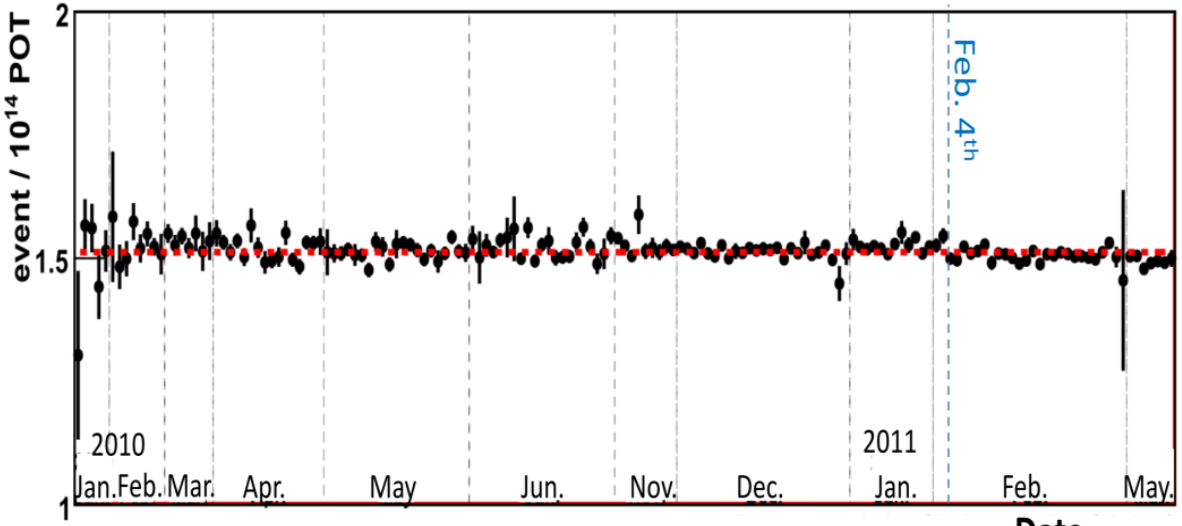
INGRID

Neutrino Beam Properties Measurements with INGRID

arXiv:1111.3119 (2011) to be published in Nucl. Instr. Meth.







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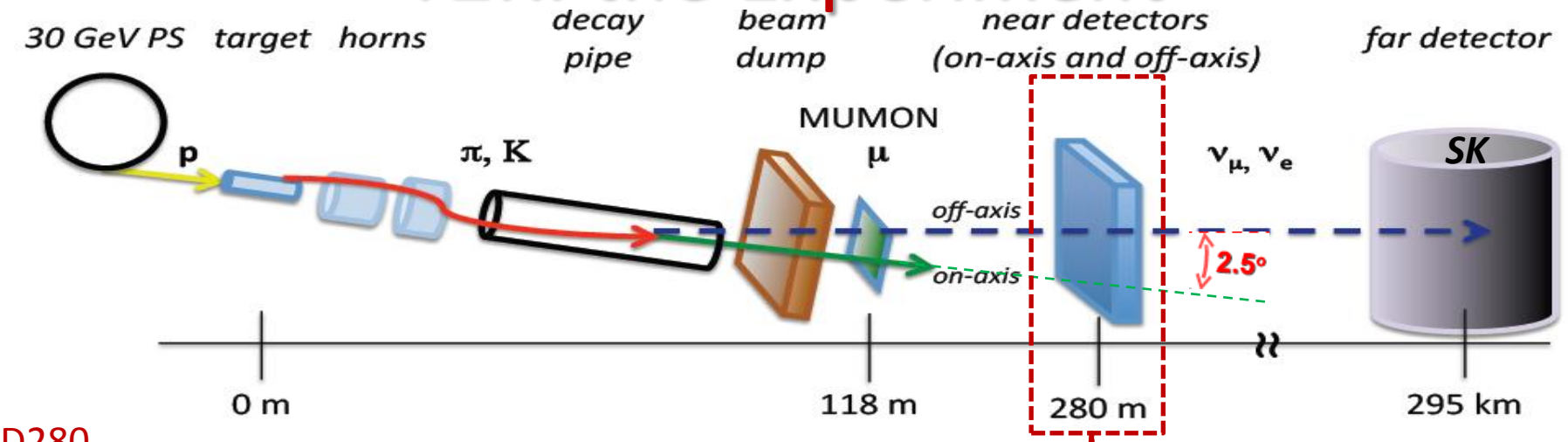


ND280

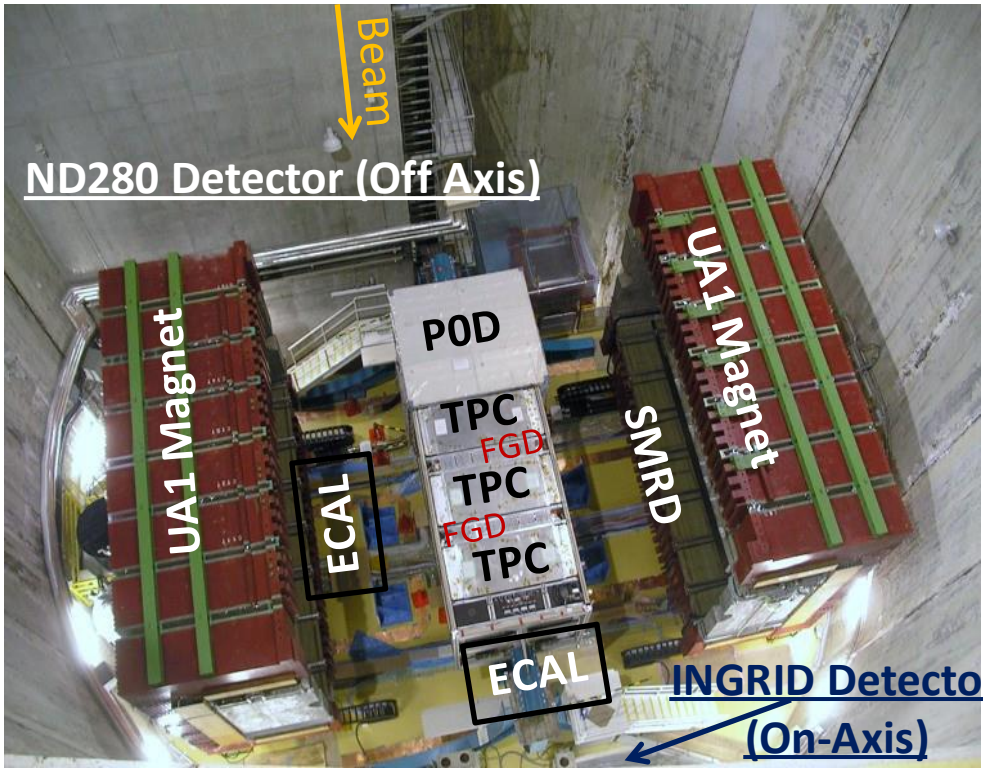
Magnet: fully refurbished from **Cern/UA1**
Water cooled Al coils.
0.2 T dipole field

Used in current analysis

- **F**ine **G**rain **D**etectors (x2) :
  2.2 tons ν scintillator bars target
- Time Projection Chambers **TPC**'s (x3):
  < 10 % dE/dx resolution
  < 10% δp/p @ 1 GeV/c

Important for future analysis

- H_2O water target in the FGD
- **P0D** π° detector
- Barrel and Downstream **EM** **CAL**orimeters
- **SMRD** muon detectors in the magnet yoke



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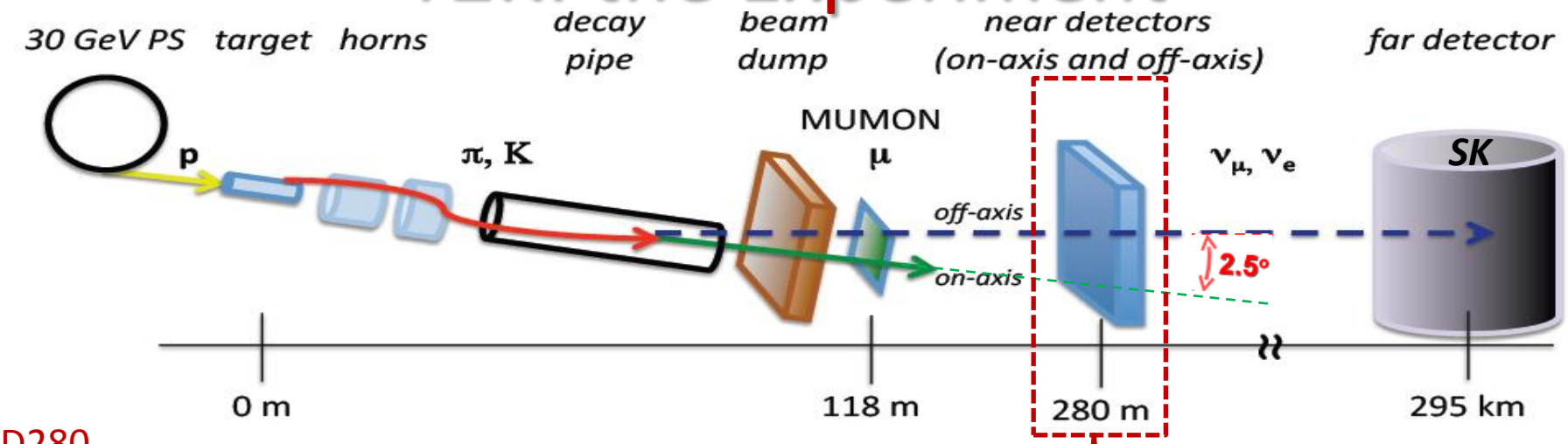

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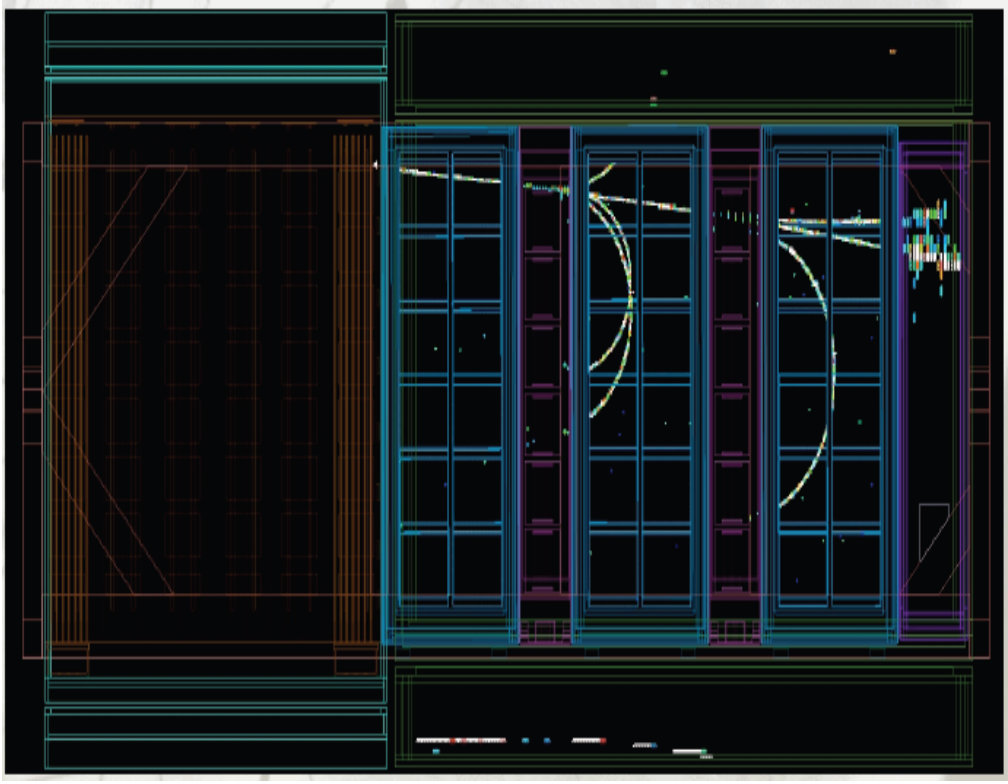

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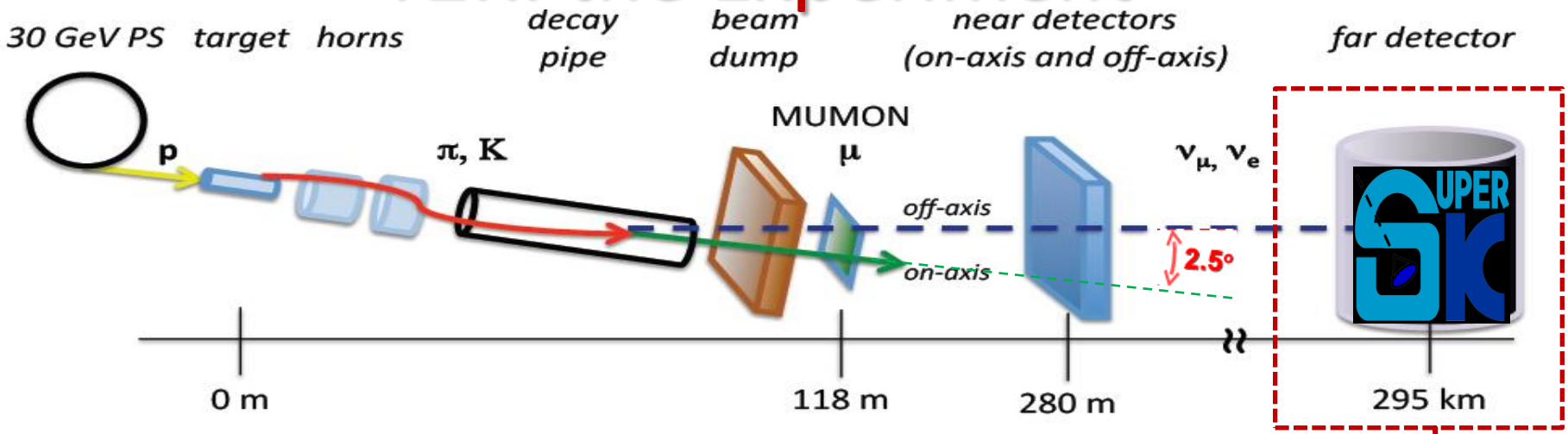
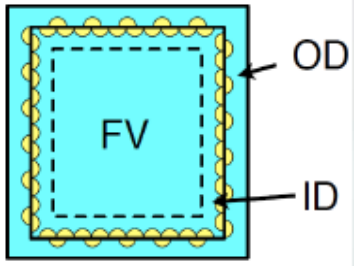
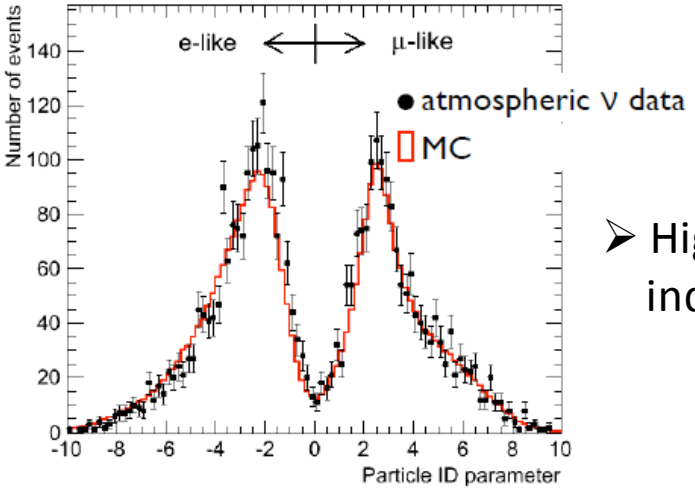


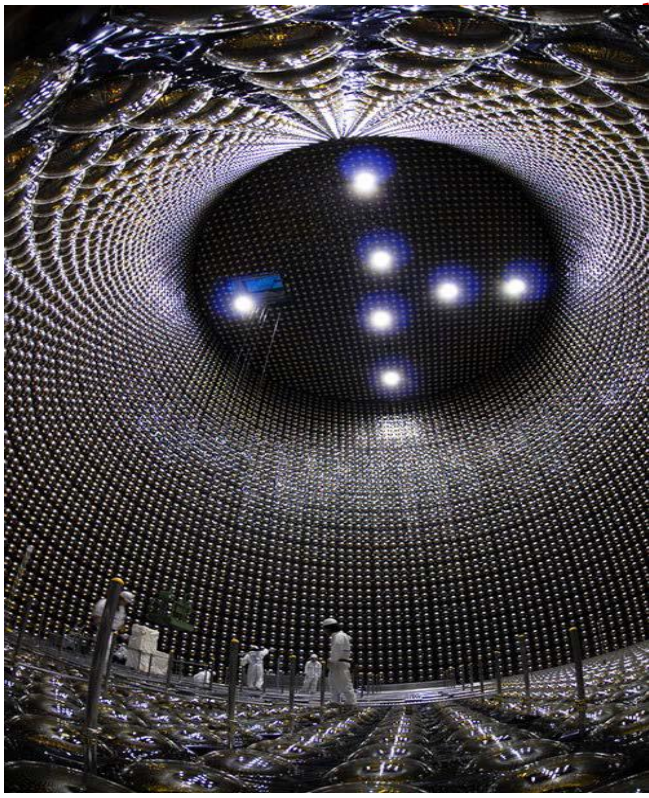
Super Kamiokande (SK)



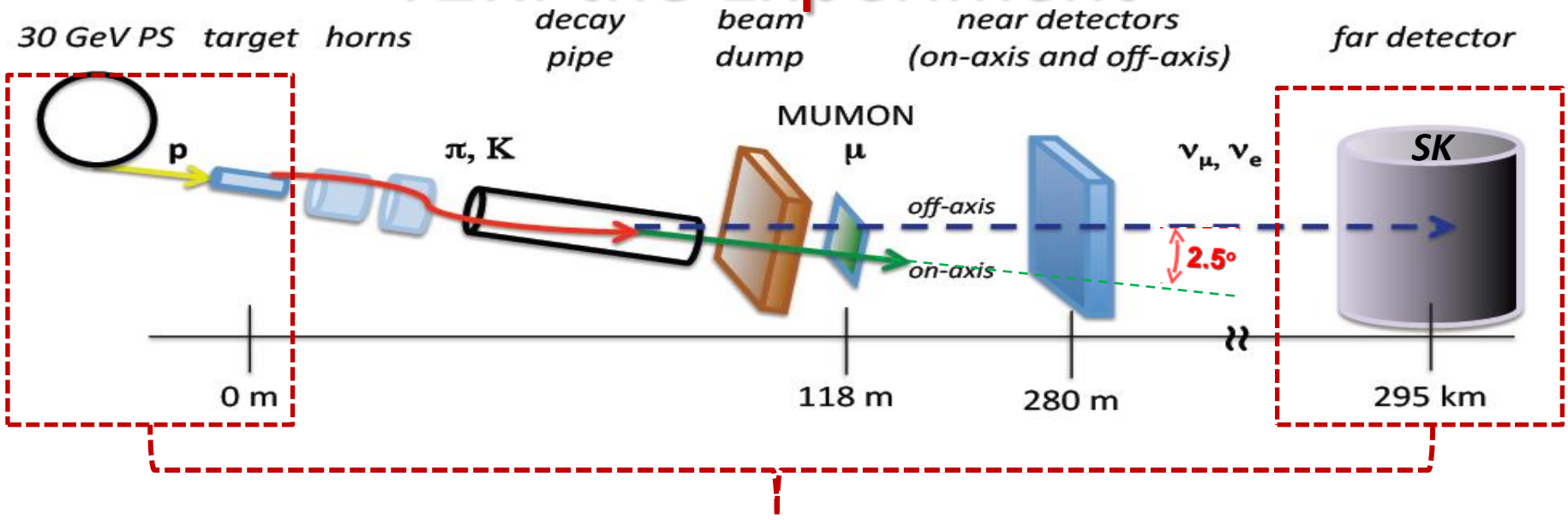
- ***Water Cherenkov detector***
  - Total Mass: 50 kton.
    - In the Fiducial Volume: 22.5 kton
  - ~12k PMTs facing inward (ID)
  - ~2k PMTs facing outward (OD): veto for cosmics and bkg



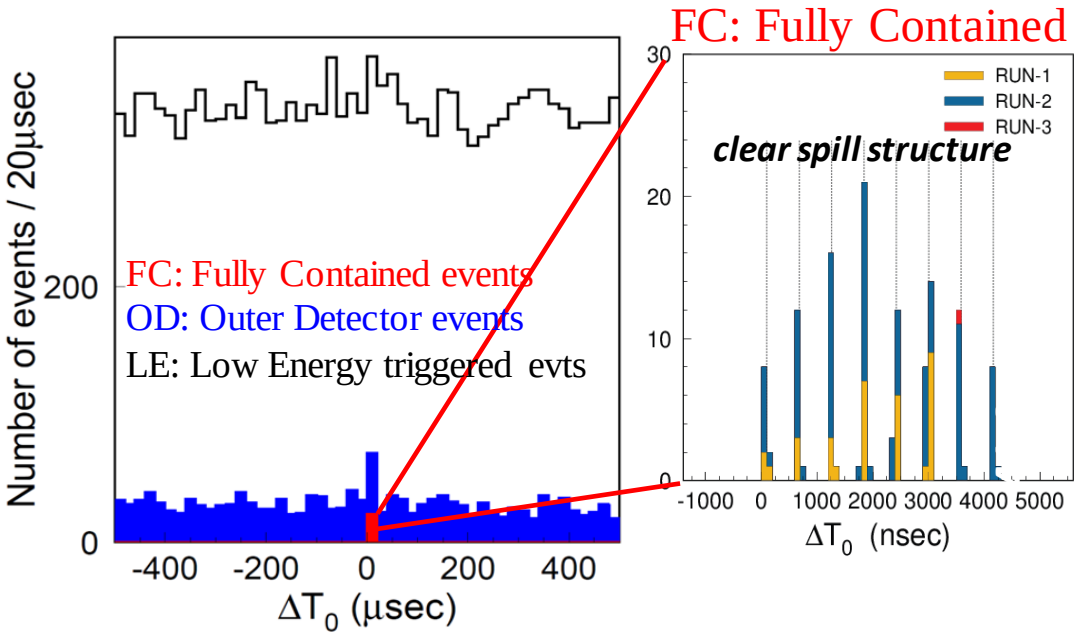
- High Separation of ν_e/ν_μ induced interactions: ~99%



T2K: the Experiment

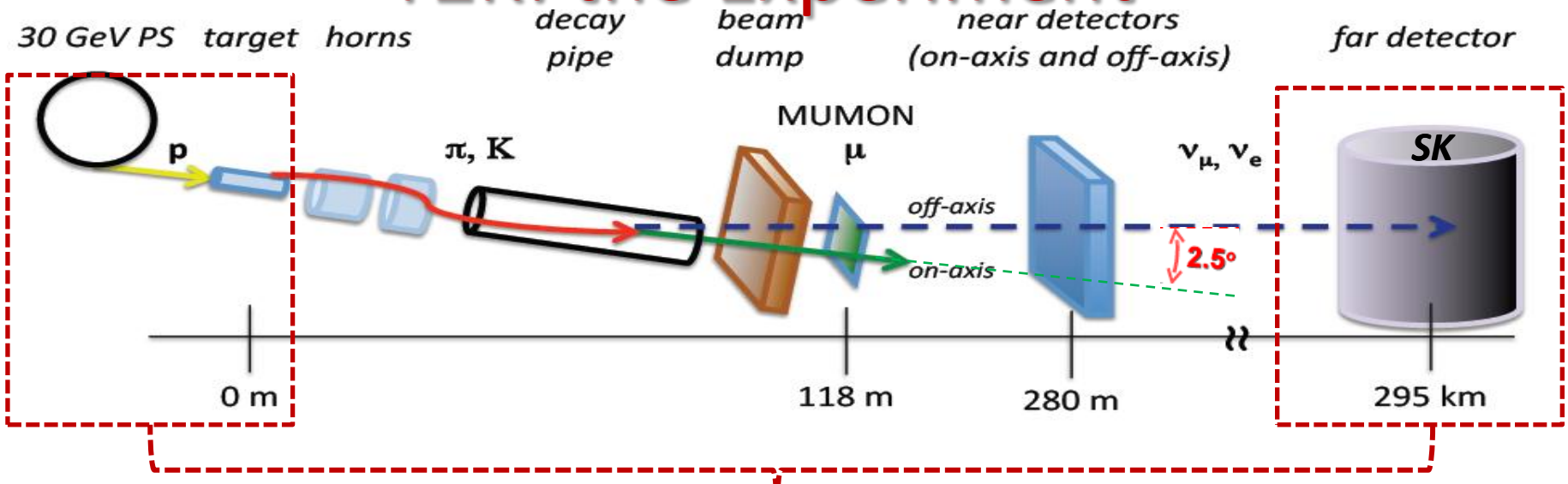


- SK synchronized to the accelerator spill timing via GPS : ~20 ns accuracy
  - Events Fully Contained in the ID show clear beam time structure (8 bunch/pulse). No out-of-time
  - Background: no time structure



$$\Delta T_0 = T_{GPS}@\mathrm{SK} - T_{GPS}@\mathrm{J\text{-}PARC} - \mathrm{TOF}(\approx 985\,\mu s)$$

T2K: the Experiment

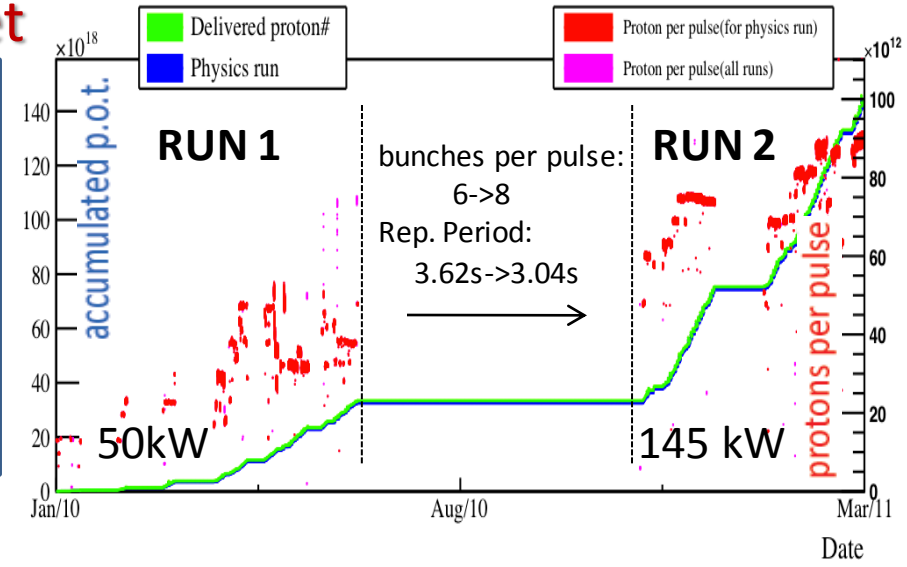


Collected Data

p.o.t.: proton on target

RUN 1 (Jan 2010-Jun 2010)
50kW
RUN 2 (Nov 2010-Mar 2011)
up to 145 kW

Total p.o.t: 1.43×10^{20}
~2% of T2K final goal



RUN 3
(Jan 2012-Jun 2012)
Up to 190 kW
Rep. Period 2.56 s

ν_e appearance & ν_μ disappearance results published in 2011

- double the statistics by summer 2012
- analysis ongoing

Oscillation Analysis Technique

Flux predictions
- proton beam measurements
- horn current monitoring
- hadron production data (NA61+others)

ND280 Measurement
- inclusive ν_μ CC measurement

output: $R_{ND}^{\mu,Data} \Big/ R_{ND}^{\mu,MC}$

- measure ν_e rate as cross-check

Neutrino Cross Sections
- interaction models
- external cross section data

T2K Far Detector Measurement

develop ν_e & $\nu\mu$ CCQE candidate selection

- predict # events using ND280 normalization:

$$N_{SK}^{\exp} = R_{ND}^{\mu,Data} \times N_{SK}^{MC} \Big/ R_{ND}^{\mu,MC}$$

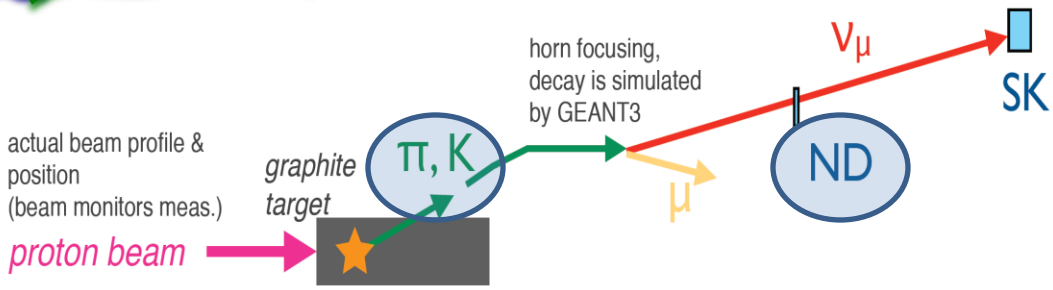
- Evaluate systematics

evaluate confidence intervals for data sample

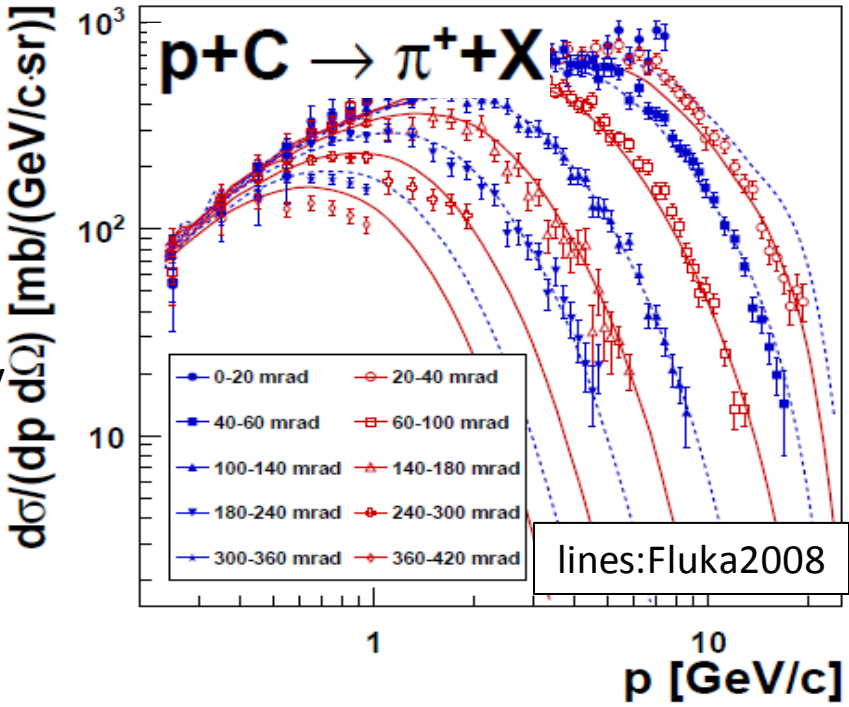
$\nu_\mu \rightarrow \nu_e$
$\sin^2 2\vartheta_{13}$ single bin measurement (counting)

$\nu_\mu \rightarrow \nu_\mu$
($\sin^2 2\vartheta_{23}, \Delta m^2_{23}$) fit to data

ν flux prediction



NA61 Phys.Rev.C 84:034604 (2011)

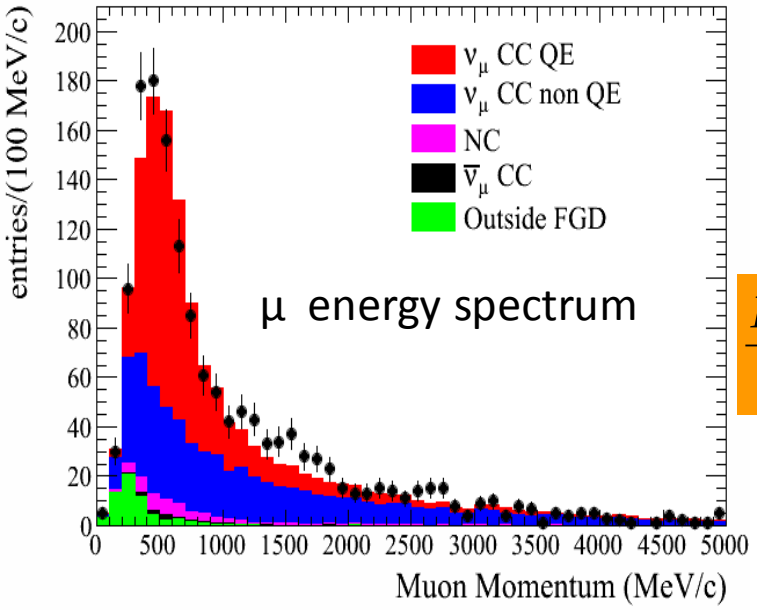


Use CERN NA61 $\pi^{\pm}$ cross section meas. in p+C @30GeV

Kinematic acceptance > 95%

Errors: 5-10% stat⊕sys

ND280 measurements



Data and MC prediction for 2.88×10^{19} p.o.t. (RUN 1)

Comparison to p.o.t. normalized MC

- Flux: NA61+FLUKA
- Rates: NEUT MC

$$\frac{R_{ND}^{\mu,DATA}}{R_{ND}^{\mu,MC}} = 1.036 \pm 0.028^{+0.044}_{-0.037}(\text{det.sys}) \pm 0.038(\text{phys.model})$$

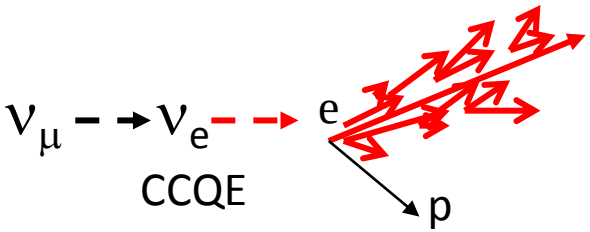
↓

Dominant contribution: dE/dx and FGD/TPC matching

ν_e/ν_μ event selection in T2K

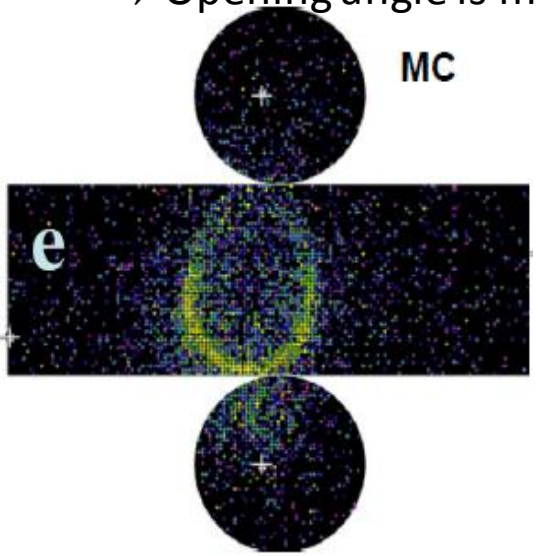
Characterization of Signal and Background final states

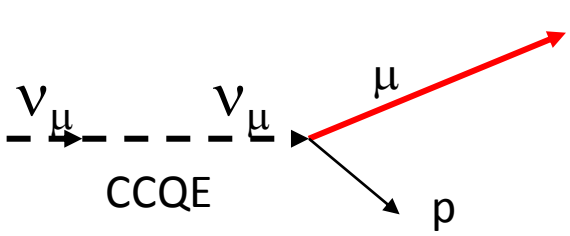
SIGNALS



electrons

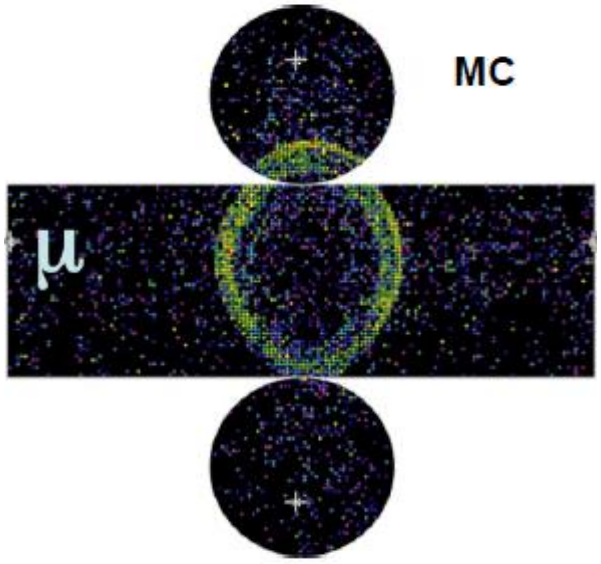
EM shower
Multiple Scattering
→ Ring has "fuzzy" edge
electron is relativistic
→ Opening angle is maximal





muons

Low Scattering
→ Ring has sharp edge

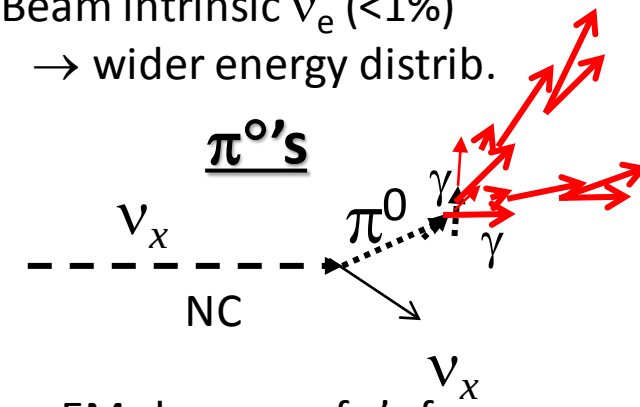


BKG

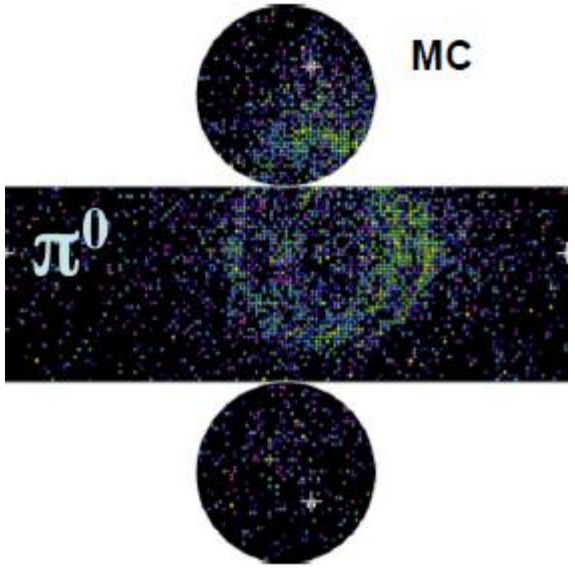
electrons

Beam intrinsic ν_e (<1%)
→ wider energy distrib.

π^0's



EM showers of γ's from π^0 can fake an electron



Oscillation Analysis: systematic errors

	$\nu_\mu \rightarrow \nu_e$			$\nu_\mu \rightarrow \nu_\mu$	
Error source	[%]			[%]	
ν Beam	+8.5	-8.5		+4.8	-4.8
ν cross section	+9.7	-9.7		+4.9	-4.5
Final state interaction	+10.1	-10.1		+5.9	-5.9
Super-K	+14.7	-14.7		+10.3	-10.3
ND280 measurements	+6.2	-5.9		+6.1	-5.9
Total	+22.8	-22.7		+15.1	-14.8

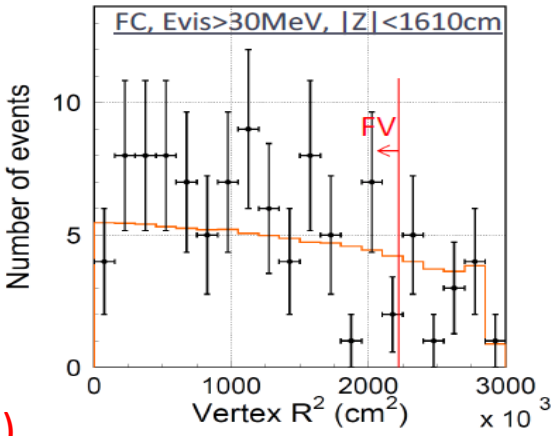
for expected # of BKG ν_e events $\sin^2 2\vartheta_{13}=0$

for expected # of ν_μ events $\sin^2 2\vartheta_{23}=1$, $\Delta m^2_{23}=2.4\times10^{-3}$ eV²

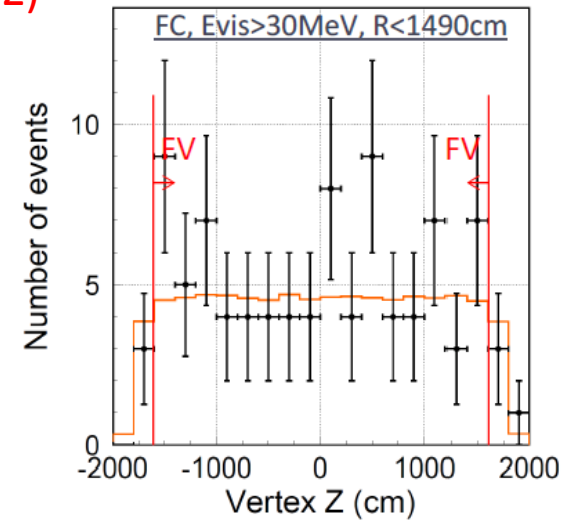
Indication of νe appearance: νe event selection in T2K

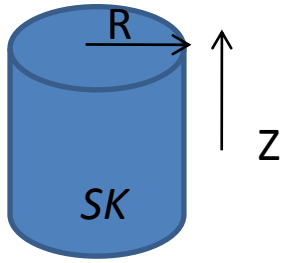
selection criteria fixed before the analysis. Unbiased

1) In the beam timing window.
   fully-contained in the inner detector (ID)
   no activity in the outer detector (OD) — 121 events
2) Fiducial Volume cut — 88 events
3) Single e-like ring — 8 events
4) Visible Energy > 100 MeV — 7 events
5) No decay electrons — 6 events
6) π^0 mass cut $M_{inv} < 105$ MeV/c^2 — 6 events
7) Reconstructed ν energy < 1250 MeV — 6 events

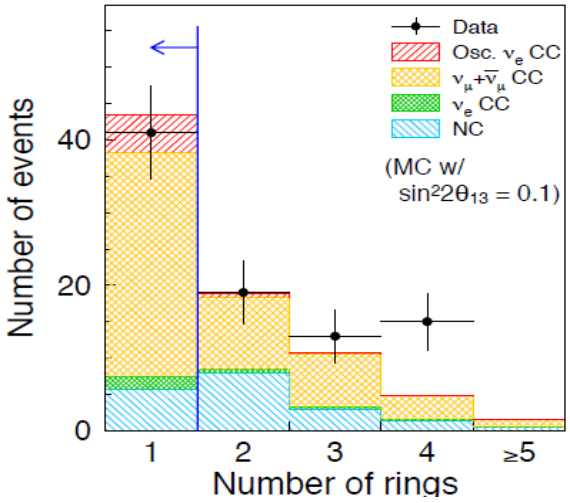


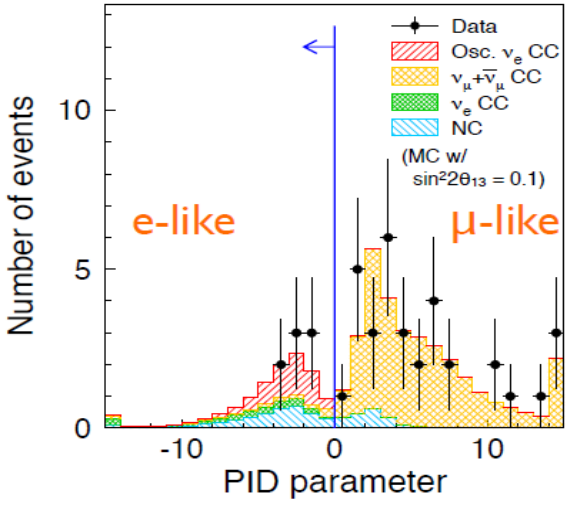
2)





3)





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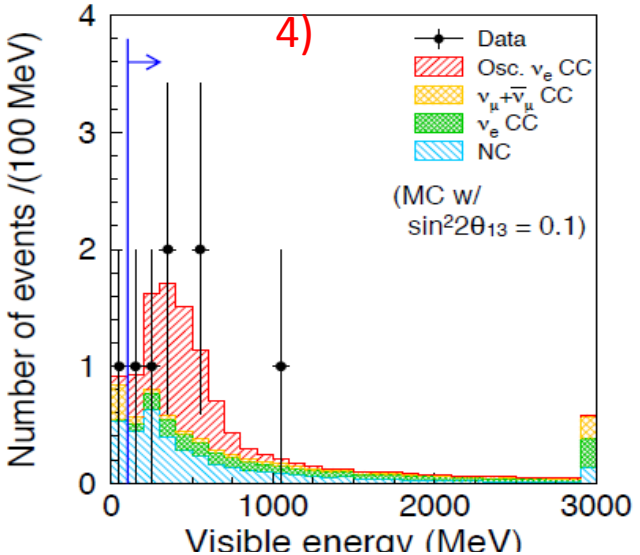

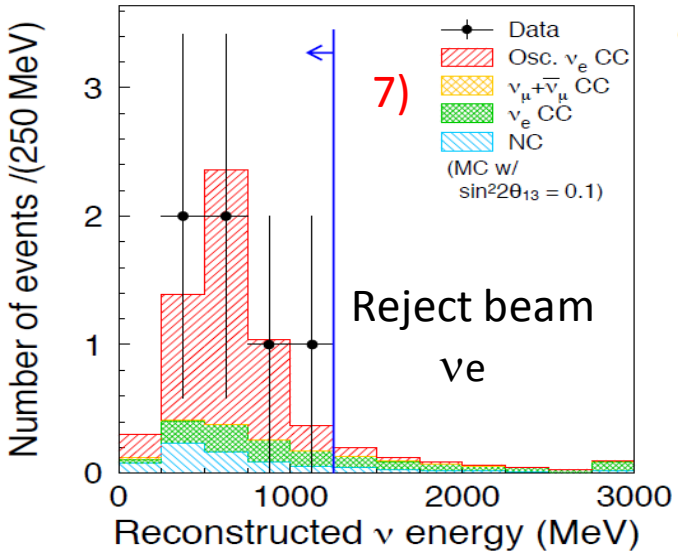

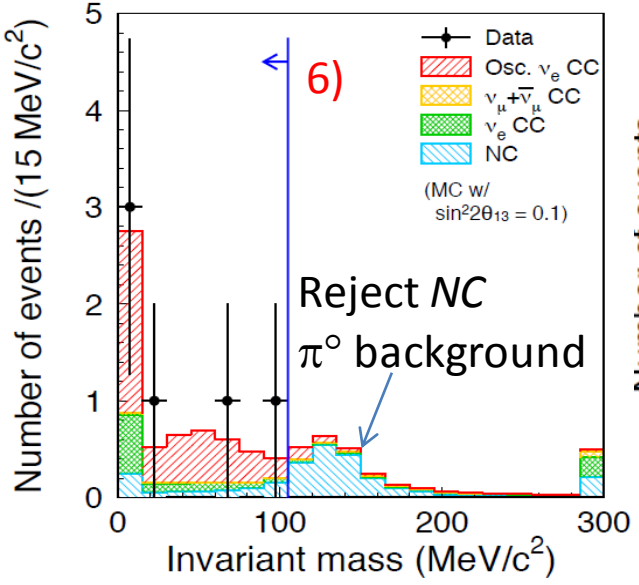

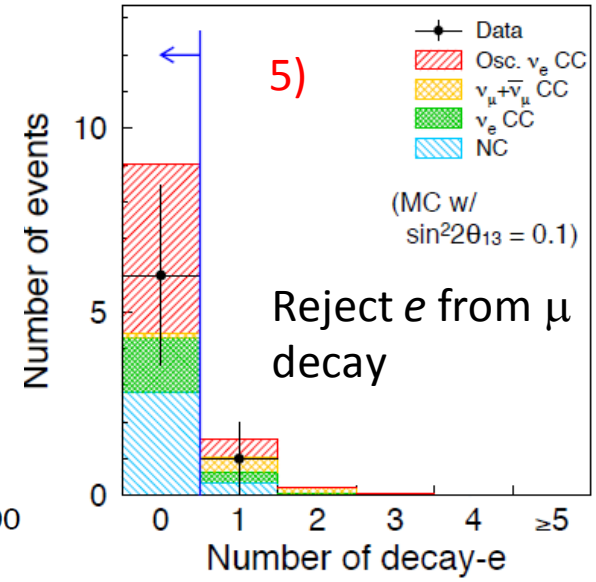

Indication of νe appearance: νe event selection in T2K

selection criteria fixed before the analysis. Unbiased

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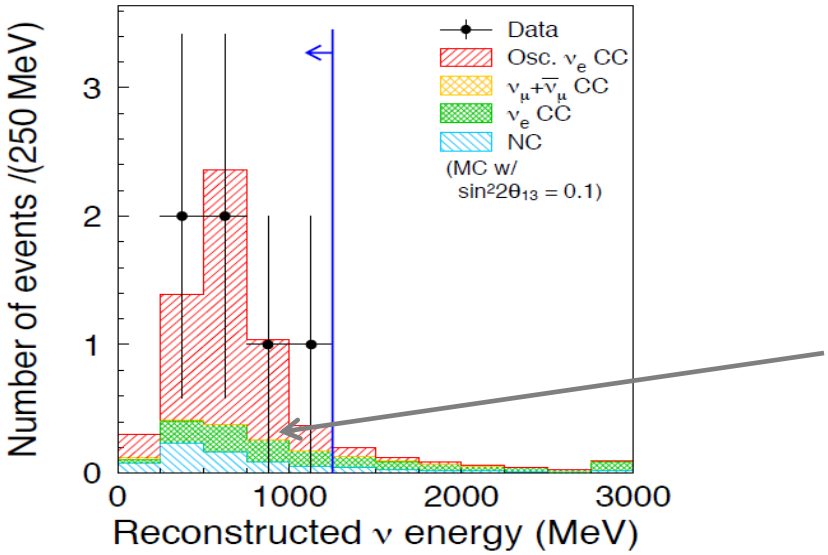
3) Single e-like ring — 8 events
4) Visible Energy > 100 MeV — 7 events
5) No decay electrons — 6 events
6) π^0 mass cut Minv < 105 MeV/c² — 6 events
7) Reconstructed ν energy < 1250 MeV — 6 events

1.43×10^{20} p.o.t.



Observed ν_e events: 6

Expected Background events:

$$N_{SK}^{exp} = 1.5 \pm 0.3$$

$$N_{SK}^{exp} = N_{SK\nu eSIG}^{exp}(\theta_{13}, \Delta m_{13}^2) + N_{SK\nu eBEAM}^{exp} + N_{SK(\nu\mu+NC)}^{exp} + N_{SK(\nu_e solar)}^{exp}$$

1.5 = 0 + 0.8 + 0.6 + 0.1

Indication of ν_e appearance

Phys.Rev.Lett. 107:041801, 2011

if $\sin^2 2\theta_{13} = 0$, the probability to observe six or more candidate events is 0.7% for an expected background of 1.5±0.3 events (equivalent to 2.5σ significance)

$\Rightarrow$ The best fit to $\sin^2 2\vartheta_{13}$:

$\Delta m^2_{23} > 0$

Best fit: $\sin^2 2\vartheta_{13} = 0.11$

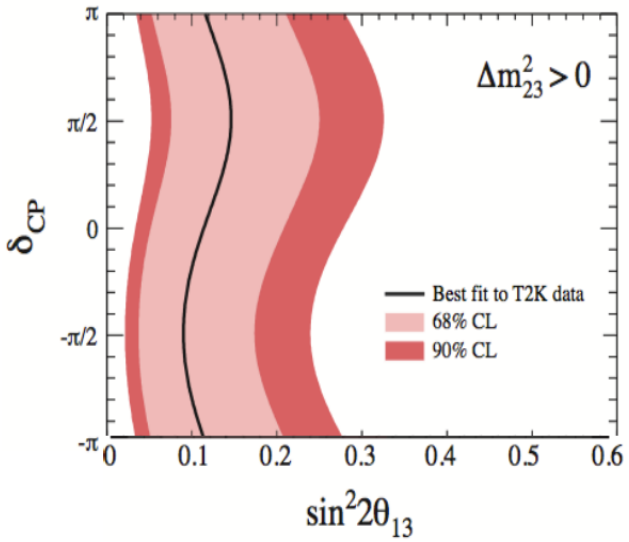
$0.03 < \sin^2 2\vartheta_{13} < 0.28$ @ 90% C.L.

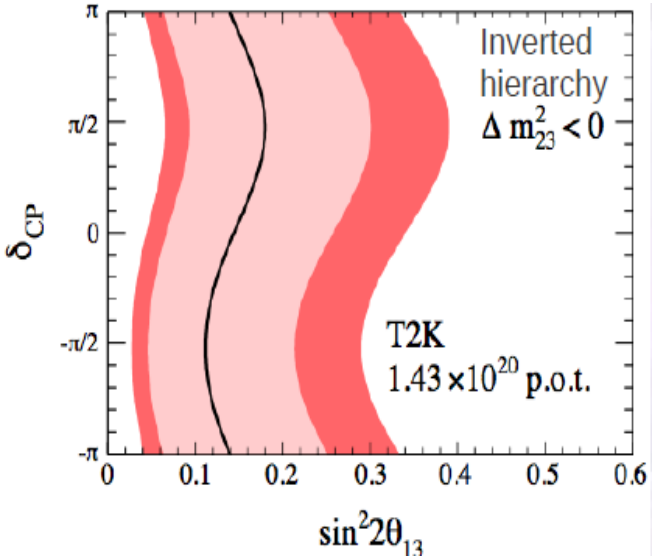
$\Delta m^2_{23} < 0$

Best fit: $\sin^2 2\vartheta_{13} = 0.14$

$0.04 < \sin^2 2\vartheta_{13} < 0.34$ @ 90% C.L.

$\sin^2 2\theta_{23}=1$, $\Delta m^2_{23}=2.4\times10^{-3}$, $\delta_{CP}=0$

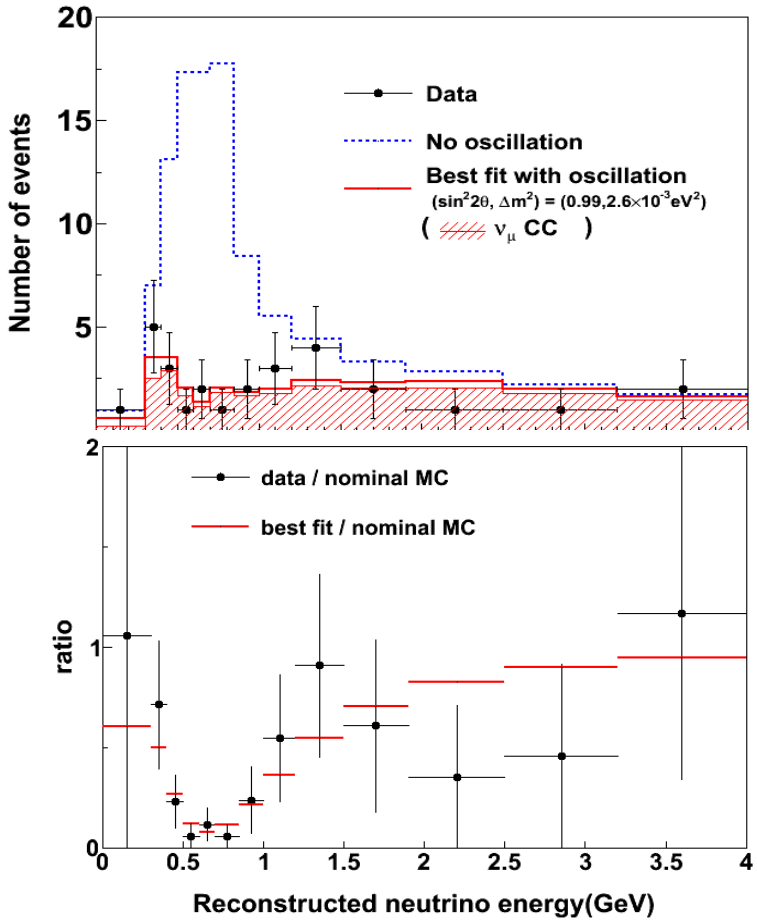




ν_μ disappearance results

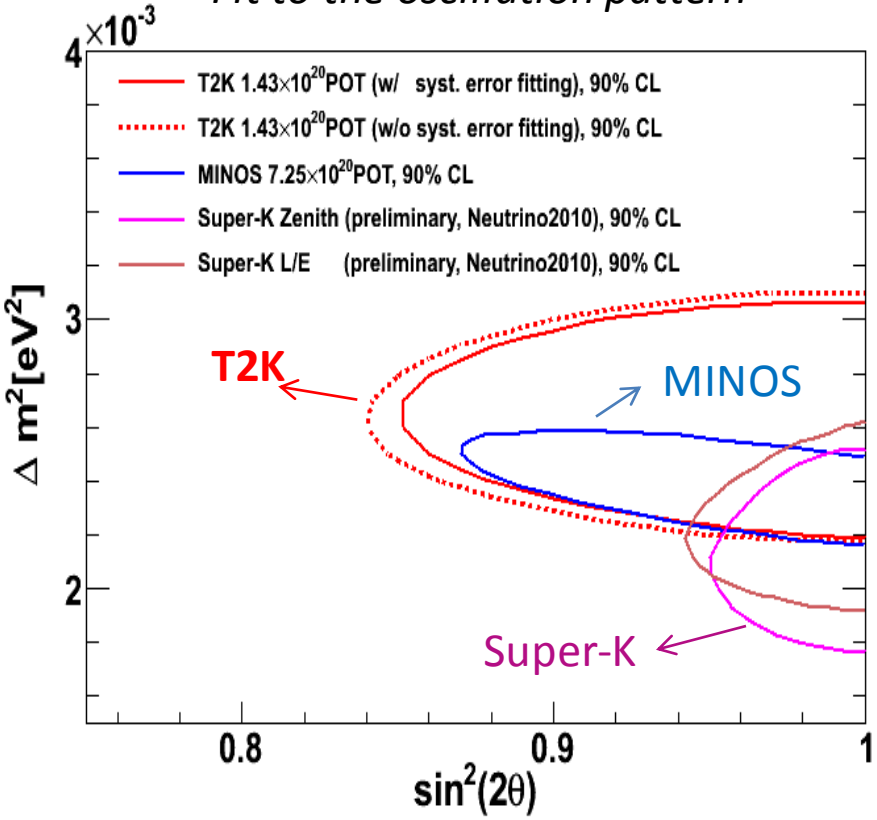
Phys.Rev.D 85 (2012) 03183

➢ 104 events **expected** w/o oscillation. 31 **observed** ν_μ candidates (4.5 σ signficance)



$(\sin^2 2\vartheta_{23}, \Delta m^2_{23})$

Fit to the oscillation pattern

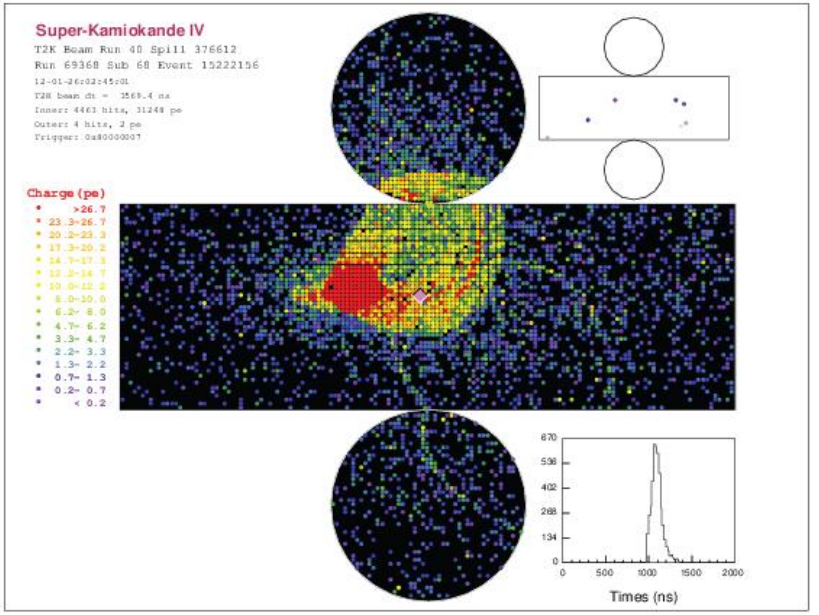


➢ **First observatio of ν_μ disappearance with off-axis beam**

➢ **Good agreement with existing measurements**

Conclusions

- The experiment accumulated 2% of the planned data until the earthquake of March 2011
- We obtained
  - the first indication of $\nu_\mu \rightarrow \nu_e$ appearance
  - first measurement of $\nu_\mu \rightarrow \nu_\mu$ disappearance using off-axis ν beam
- Data taking restarted in January 2012
  <u>double the statistics by summer 2012</u>
- Thanks to the new knowledge of θ_{13} focus is moving to the Mass Hierarchy determination & CPV measurement with long baseline accelerator experiments

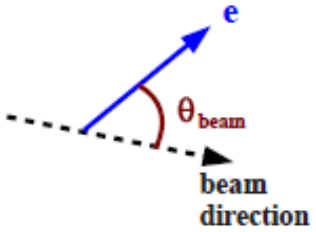


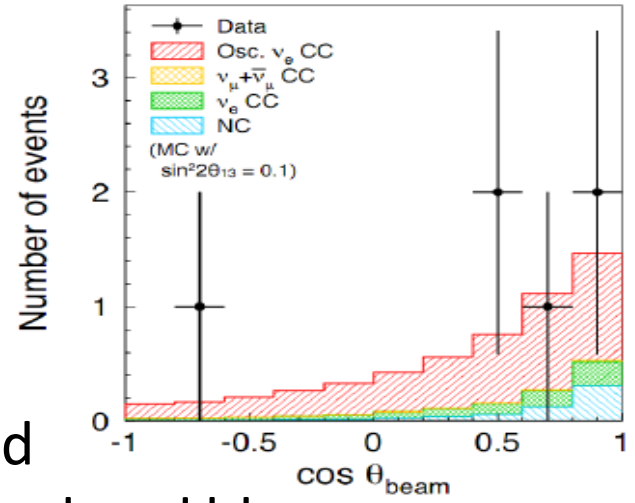
Jan 2012. First T2K event since earthquake

Backup

ν_e Candidate Events: Further Checks

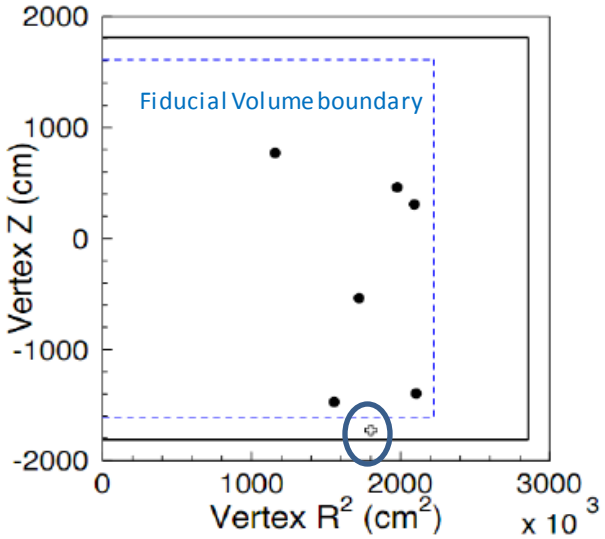
- Angular distribution w.r.t. to the beam direction

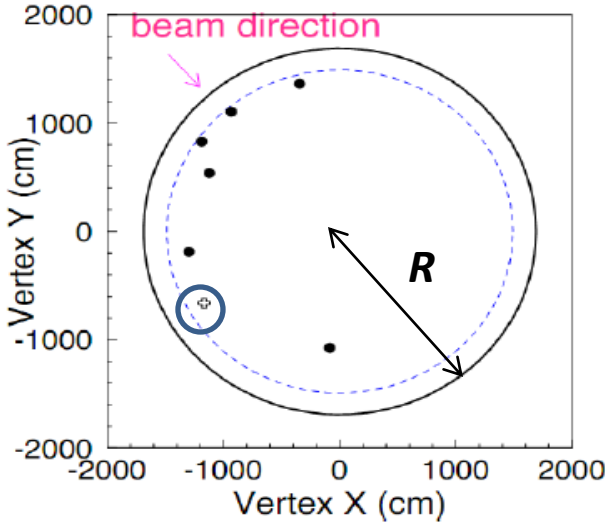


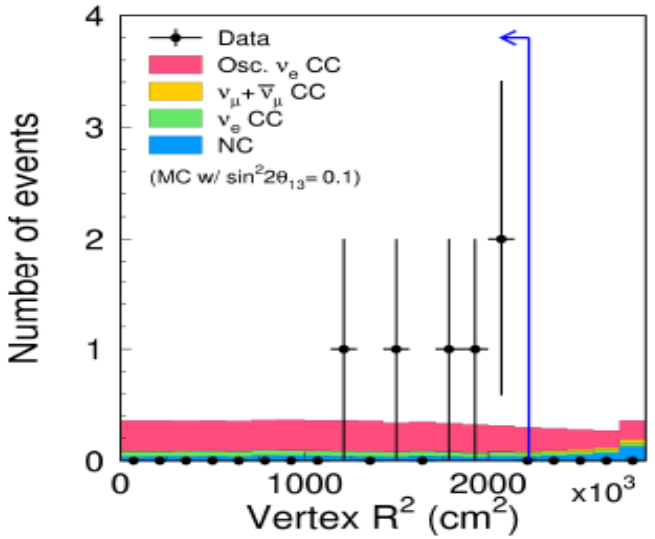


- Vertex Distribution

  Events are clustered at large R
  - Only one event outside the FV which passed all the other cuts: in the presence of beam related bkg from outside the FV more events are expected in this region
  - Kolmogorov-Smirnov test on the R^2 distrib.: p-value is 0.03

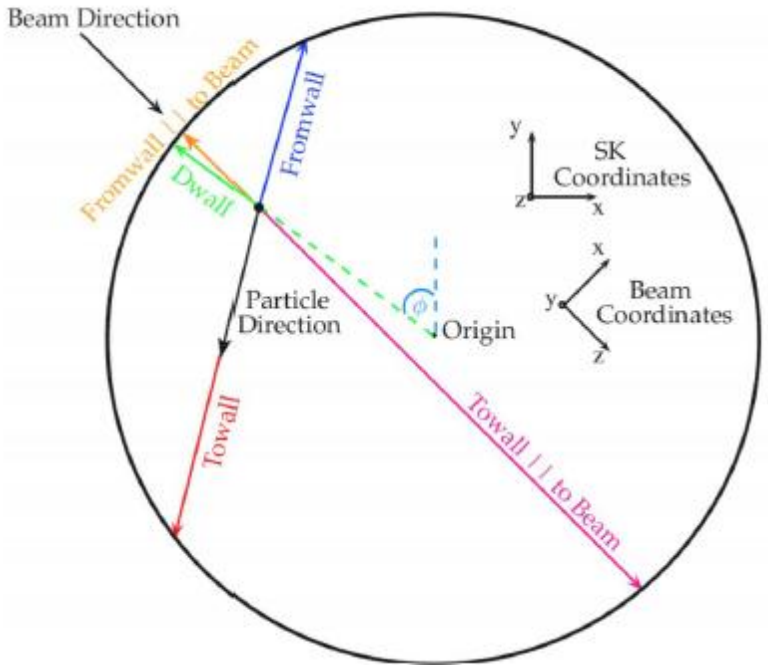


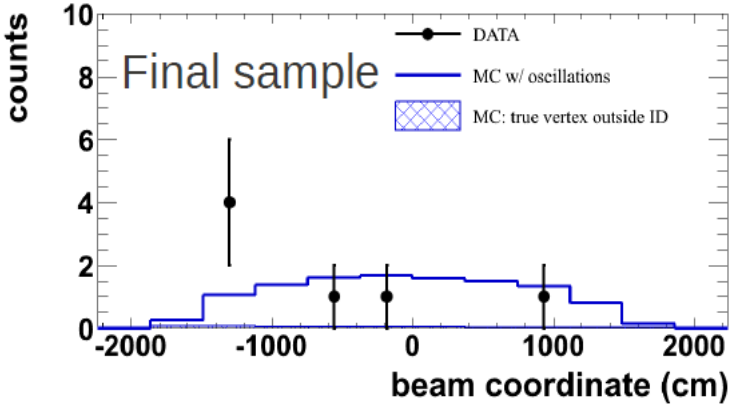


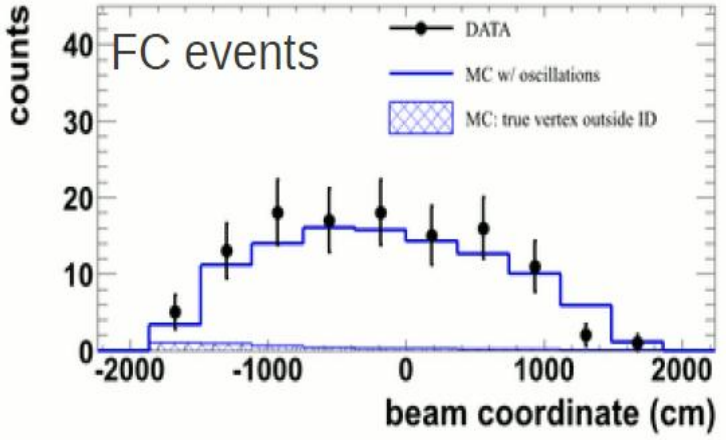


ν_e Candidate Events: Further Checks

- Vertex Distribution
  - distributions along the beam direction are consistent with the MC

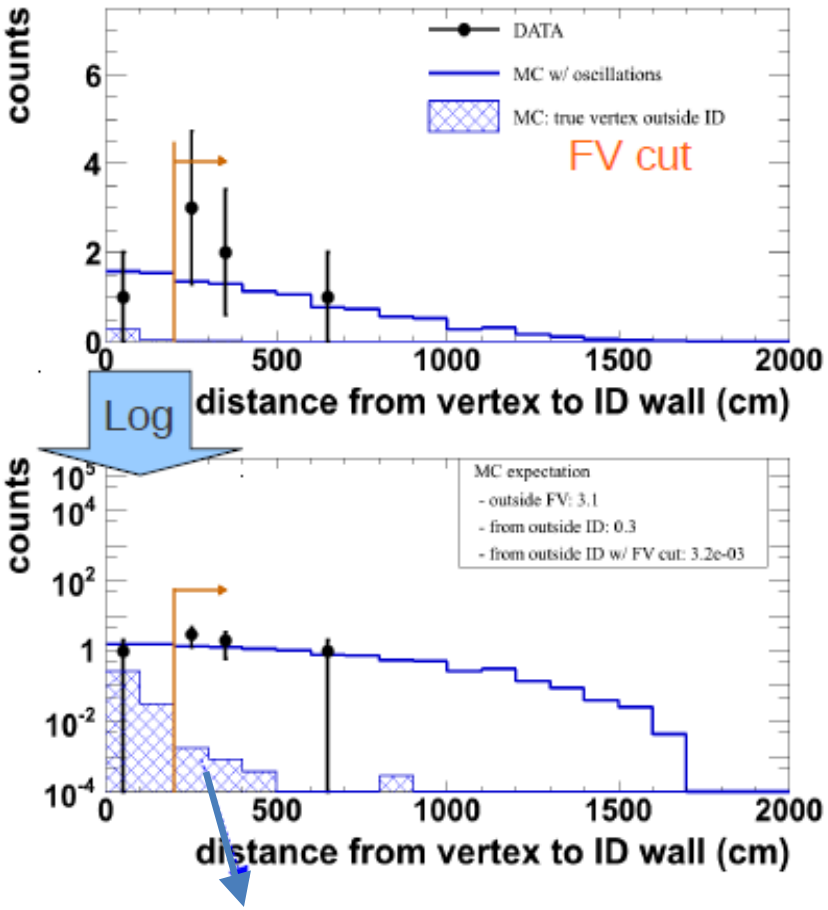




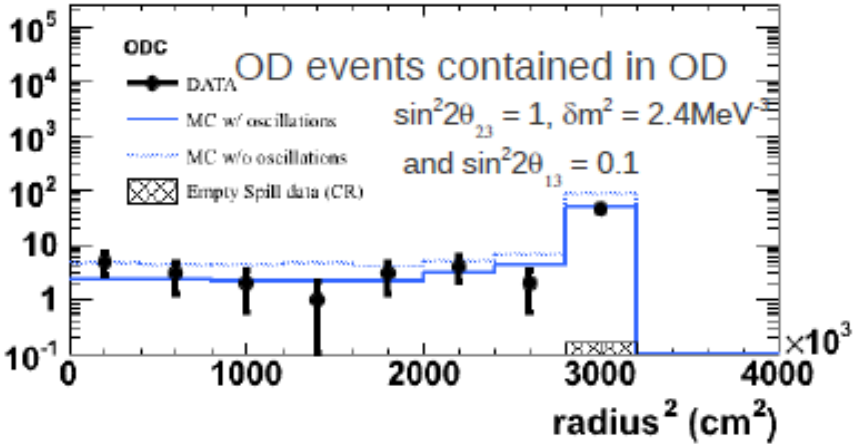


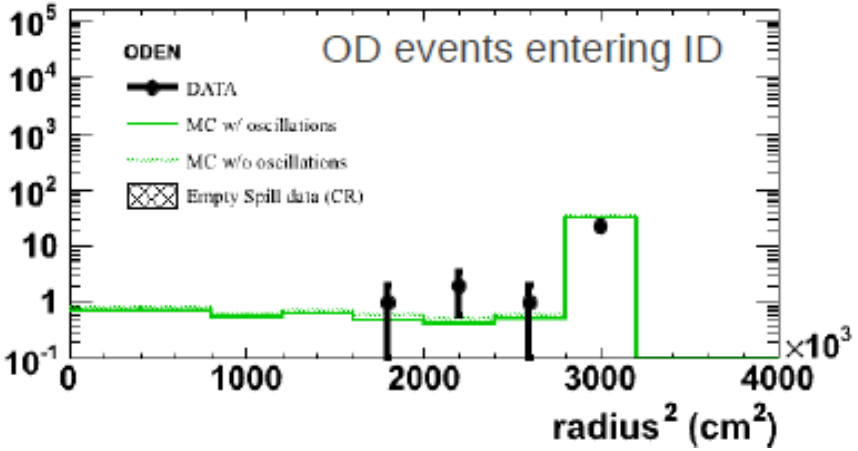
ν_e Candidate Events: Further Checks

- Vertex Distribution
  - Outer Detector events show no indication of contamination from outside Inner Detector



3.2×10^{-3} expected events from outside ID with FV cut





No significant excess of events in the OD

Indication of νe appearance: expected νe events

$$N_{SK}^{\exp} = N_{SK\nu e\mathrm{SIG}}^{\exp}\left(\theta_{13}, \Delta m_{13}^2\right) + \underbrace{N_{SK\nu e\mathrm{BEAM}}^{\exp} + N_{SK(\nu\mu+\mathrm{NC})}^{\exp} + N_{SK(\nu_e solar)}^{\exp}}_{\text{BKG}}$$

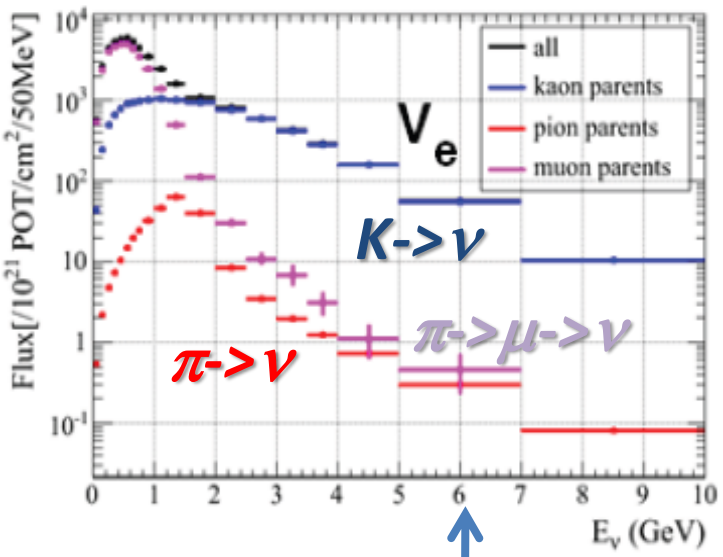
P(νμ→νe) Sub-Leading term not related to θ13

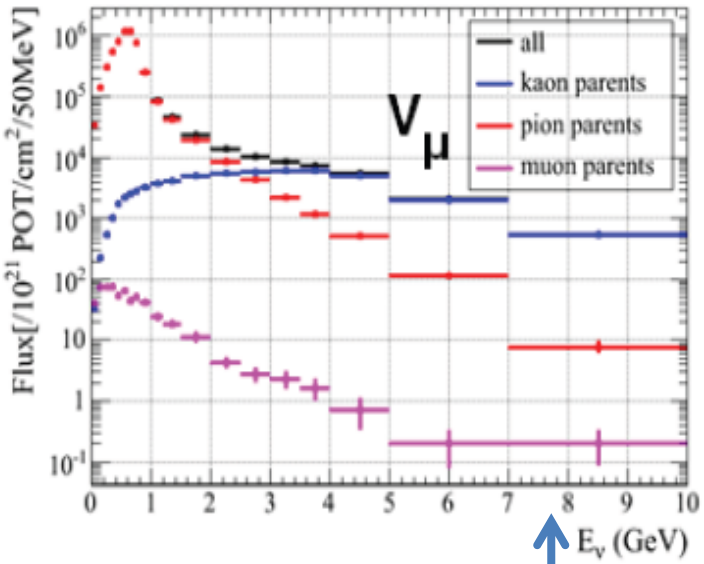
$$N_{SK}^{\exp} = R_{ND}^{\mu,Data} \times N_{SK}^{MC} / R_{ND}^{\mu,MC}$$

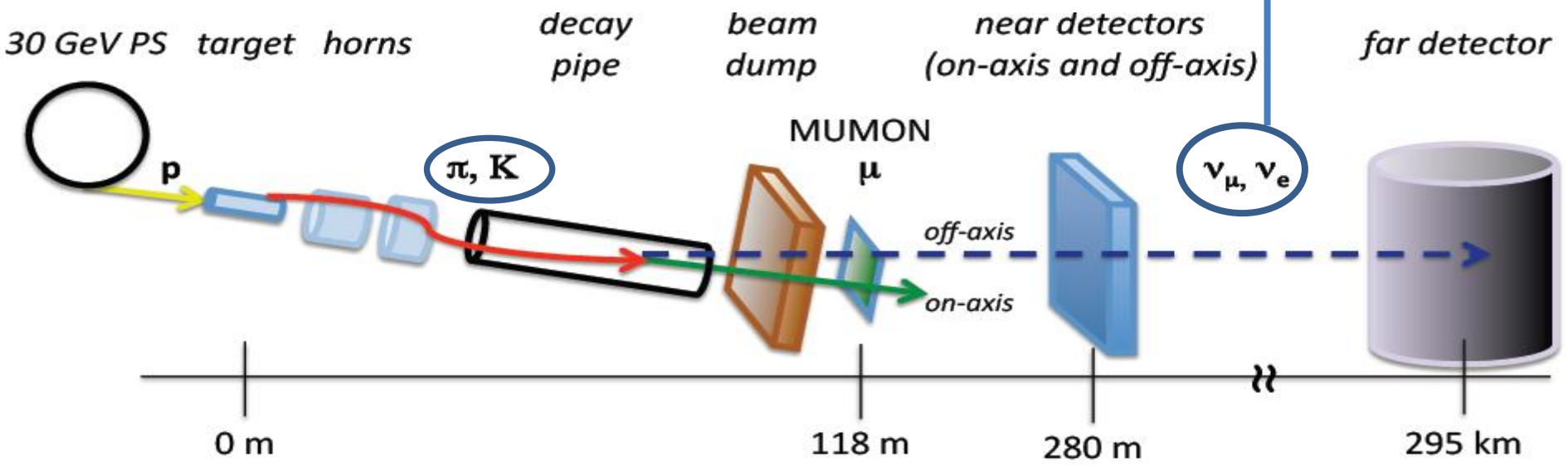
$$\frac{\int \Phi_{\nu_\mu(\nu_e)}^{SK}(E_\nu)\cdot P_{osc}(E_\nu)\cdot\sigma(E_\nu)\cdot\epsilon_{SK}(E_\nu)\,dE_\nu}{\int \Phi_{\nu_\mu}^{ND}(E_\nu)\cdot\sigma(E_\nu)\cdot\epsilon_{ND}(E_\nu)\,dE_\nu}\,\frac{M_{SK}}{M_{ND}}\cdot POT_{SK}$$

- ND280 statistical uncertainty
- Flux uncertainty → expect cancellation in ratio
- Neutrino interaction cross section uncertainties
- SK reconstruction, selection uncertainties
- ND280 reconstruction, selection uncertainties

Importance of the NA61 Measurements: Pion/Kaon Contribution to the ν flux in T2K

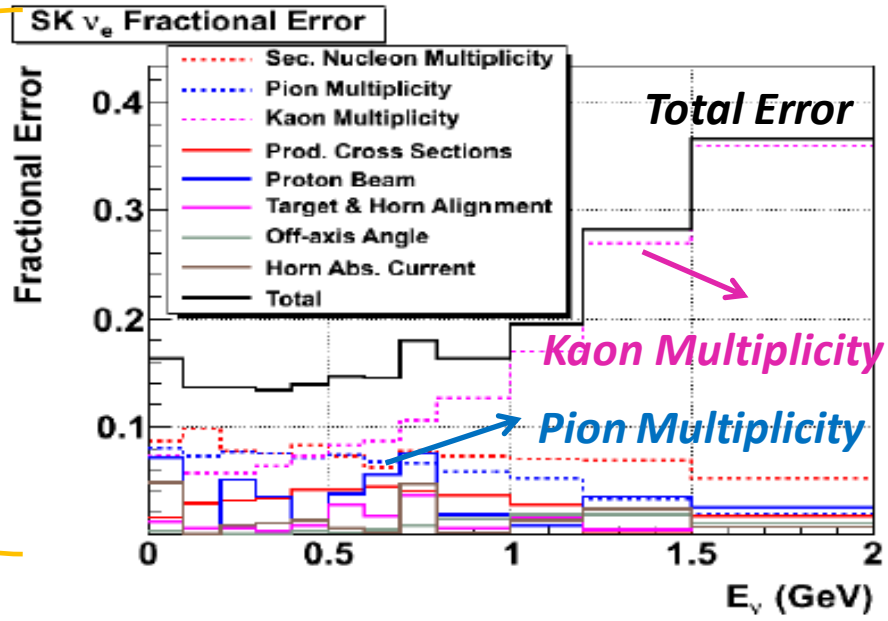






Indication of νe appearance: expected νe events

Error Source	$\sin^2(2\theta_{13})=0$	$\sin^2(2\theta_{13})=0.1$
Beam flux	8.5%	8.5%
ν cross sections	14.0%	10.5%
ND280 detector	$^{+5.6}_{-5.2}$ %	$^{+5.6}_{-5.2}$ %
SK detector	14.7%	9.4%
ND280 statistics	2.7%	2.7%
Total	$^{+22.8}_{-22.7}$ %	$^{+17.6}_{-17.5}$ %



- $sin^2 2\vartheta_{13}=0$
- After νe selection Criteria in SK (shown further)

$$N_{SK} = 1.5 \pm 0.3$$

$$N_{SK}^{\exp} = N_{SK\nu e\mathrm{SIG}}^{\exp}\left(\theta_{13}, \Delta m_{13}^2\right) + N_{SK\nu e\mathrm{BEAM}}^{\exp} + N_{SK(\nu\mu+\mathrm{NC})}^{\exp} + N_{SK(\nu_e solar)}^{\exp}$$

1.5 = 0 0.8 0.6 0.1

Summary of ν x-section Uncertainties on N^{exp}_{SK} for $\sin^2 2\theta_{13} = 0$

Error source	syst. error on N^{exp}_{SK}
CC QE shape	3.1%
CC 1π	2.2%
CC Coherentπ	3.1%
CC Other	4.4%
NC $1\pi^0$	5.3%
NC Coherentπ	2.3%
NC Other	2.3%
$\sigma(\nu_e)$	3.4%
FSI	10.1%
Total	14.0%

Pion final state interactions dominate

The total uncertainty on N^{exp}_{SK} due to the ν x-section uncertainty is **14%** ($\sin^2 2\theta_{13} = 0$)

$\nu_\mu \rightarrow \nu_e$ appearance

$$P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\left(1 - 2S_{13}^2\right)\right)$$

θ_{13}

$$+8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23}) \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E}$$

CPC

$$-8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta \sin\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E}$$

CPV

$$+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta\right\} \sin^2\frac{\Delta m_{21}^2 L}{4E}$$

Solar

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E}\left(1 - 2S_{13}^2\right)$$

Matter effect (small in T2K)

$a \rightarrow -a$, $\delta \rightarrow -\delta$ for $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

L=295km, $\langle E_\nu \rangle$ ~0.6GeV

$$a = 7.56\times10^{-5}[\mathrm{eV}^2]\cdot\left(\frac{\rho}{[\mathrm{g/cm}^3]}\right)\cdot\left(\frac{E}{[\mathrm{GeV}]}\right)$$