Joint Analysis of the Double Chooz and T2K Experiments

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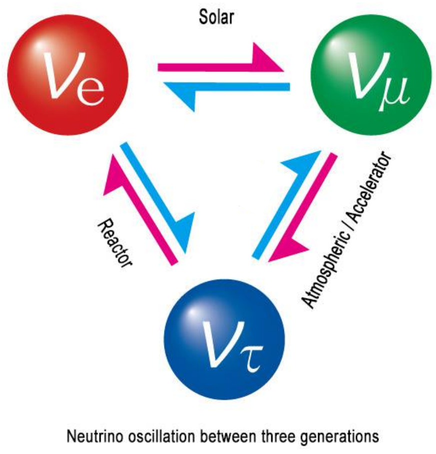
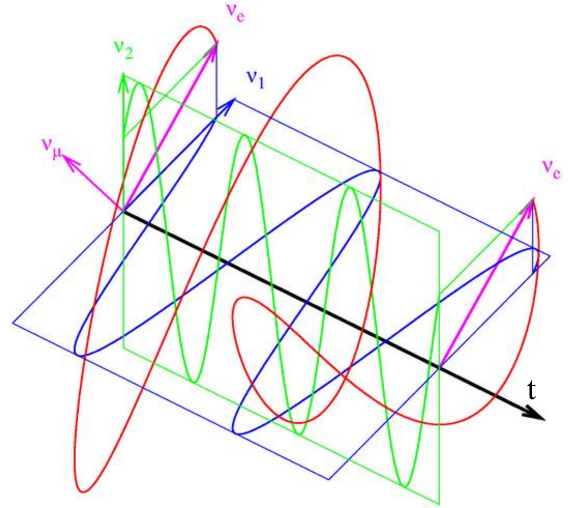
- Motivation and Idea
- The Experiments
  - Double Chooz
    - Setup
    - Final Fit
  - T2K
    - Setup
    - Final Fit
- A Joint Analysis Framework
- Summary and Outlook



Neutrino Oscillation:



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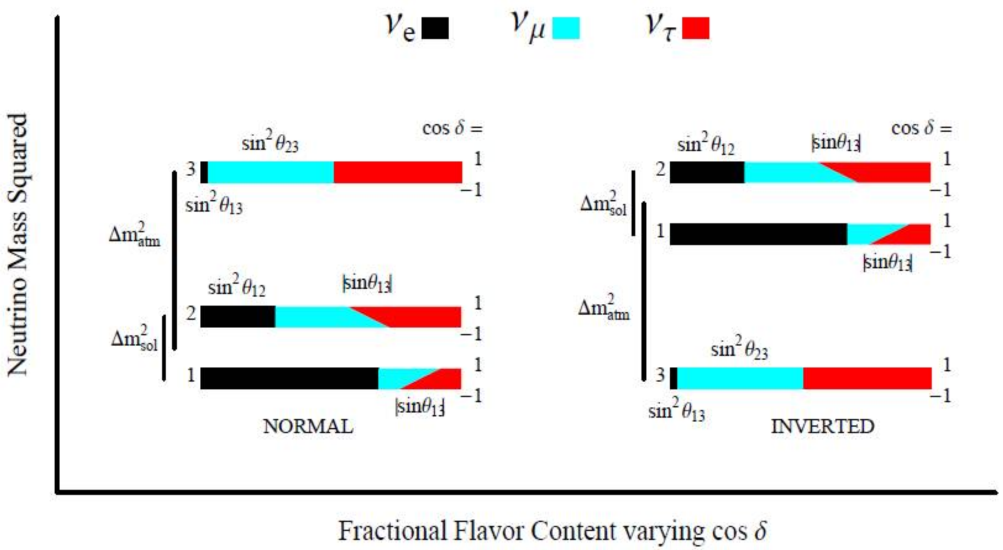
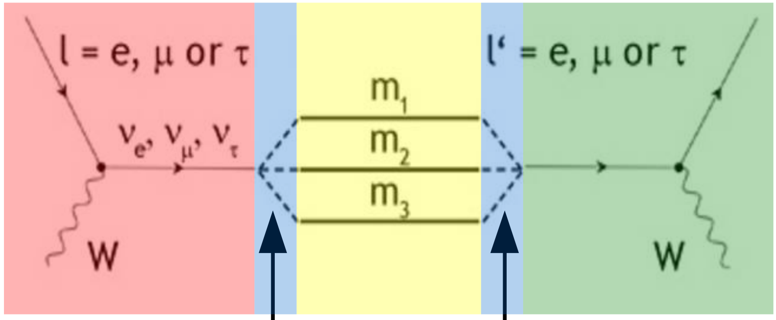
Neutrino oscillations

Neutrino mixing: Flavour eigenstates and mass eigenstates do not map bijectively onto each other



$$|\nu_\alpha\rangle = \sum_{j=1}^{3} U_{\alpha j} |\nu_j\rangle, \qquad \alpha = e, \mu, \tau.$$

Neutrino propagation:



$$|\nu_\alpha(L)\rangle = \sum_{j=1}^{3} U^*_{\alpha j} |\nu_j(0)\rangle e^{-i m_j^2 L/(2E)}$$

Creation: flavour eigenstate

Mixing

Propagation: mass eigenstates

Mixing

Detection: flavour eigenstate

Unknown or recently measured parameters:

$\sin^2(2\theta_{13})$	mixing between e and 3
δ_{CP}	CP violating phase
sgn(Δm^2_{31})	mass hierarchy $m_1<m_2<m_3$ (normal) versus $m_3<m_1<m_2$ (inverted)

Motivation and Idea

III. Physikalisches Institut B

RWTH AACHEN UNIVERSITY

Reactor experiments:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

Sensitive only to

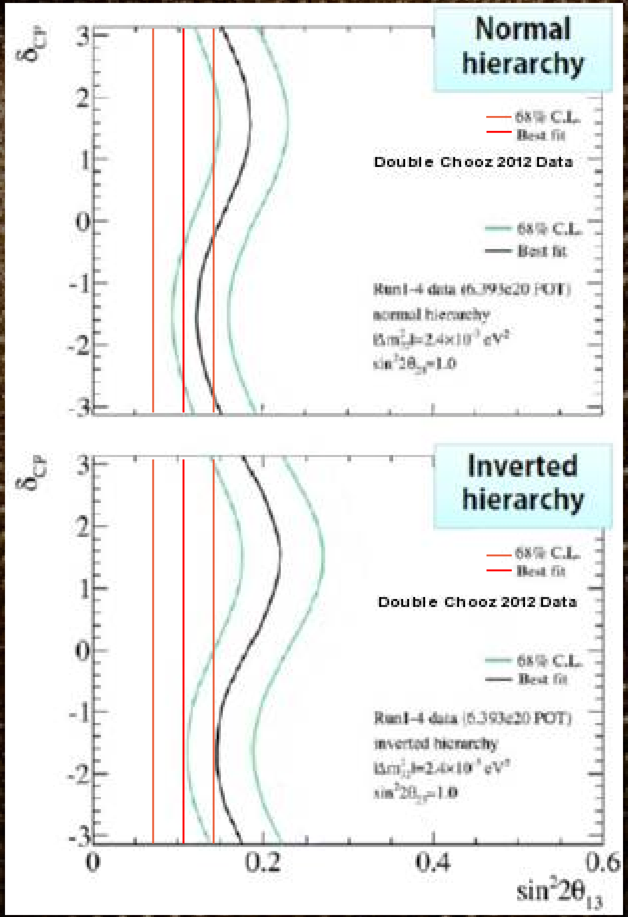
$\sin^2(2\theta_{13})$

Long baseline beam experiments:

$$\begin{aligned}P(\nu_\mu \rightarrow \nu_e) = {} & \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) \\ & + 2\sin(\theta_{23}) \sin(2\theta_{13}) \sin(2\theta_{12}) \cos(\theta_{23}) \cos(\theta_{13}) \\ & \cdot \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{21}^2 L}{4E}\right) \cos\left(\frac{\Delta m_{31}^2 L}{4E} + \delta_{CP}\right) \\ & + \cos^2(\theta_{23}) \cos^2(\theta_{13}) \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)\end{aligned}$$

Sensitive to combination of

$\sin^2(2\theta_{13})$ and δ_{CP} (with two scenarios w.r.t. Δm_{31}^2)



Remark to all equations:

- $\Delta m_{jk}^2 := m_j^2 - m_k^2$
- matter effects and higher orders omitted
- further parameters or dependencies already determined or negligible

Using both experiments:

Sensitive to δ_{CP} (with two scenarios w.r.t. Δm_{31}^2)

Outline

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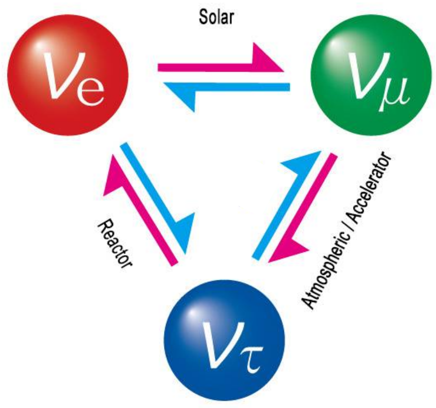
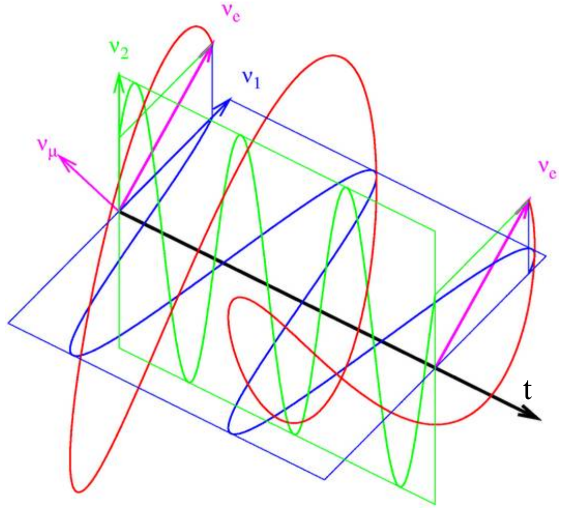


Neutrino oscillation between three generations

Neutrino Oscillation:



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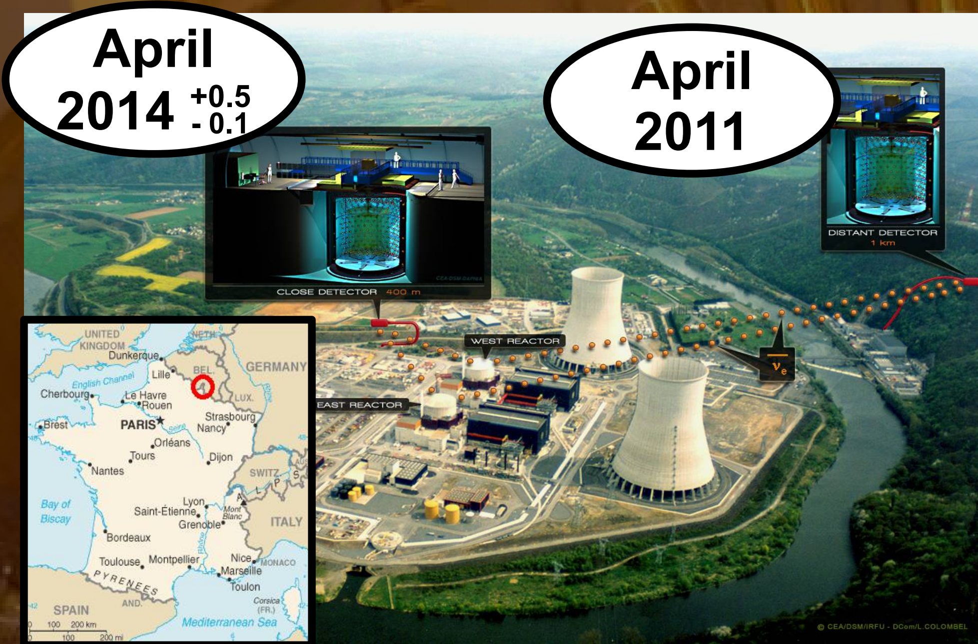
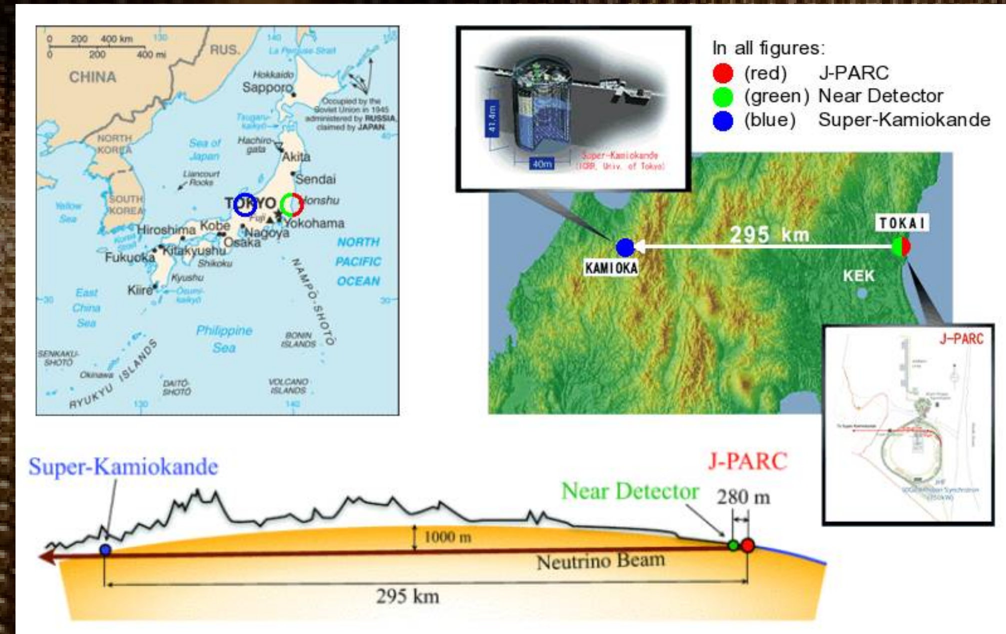
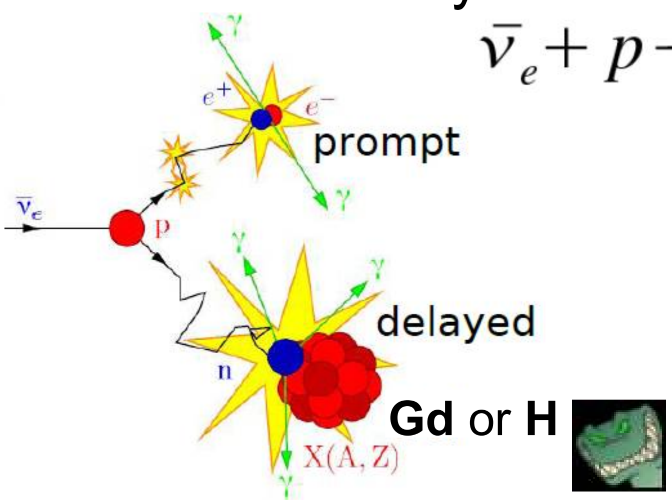
Experiment Setups



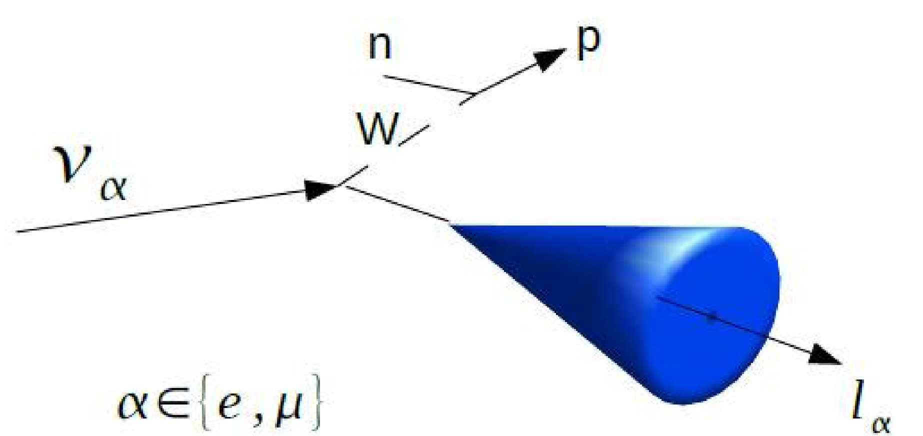


Inverse beta-decay of the neutrino:

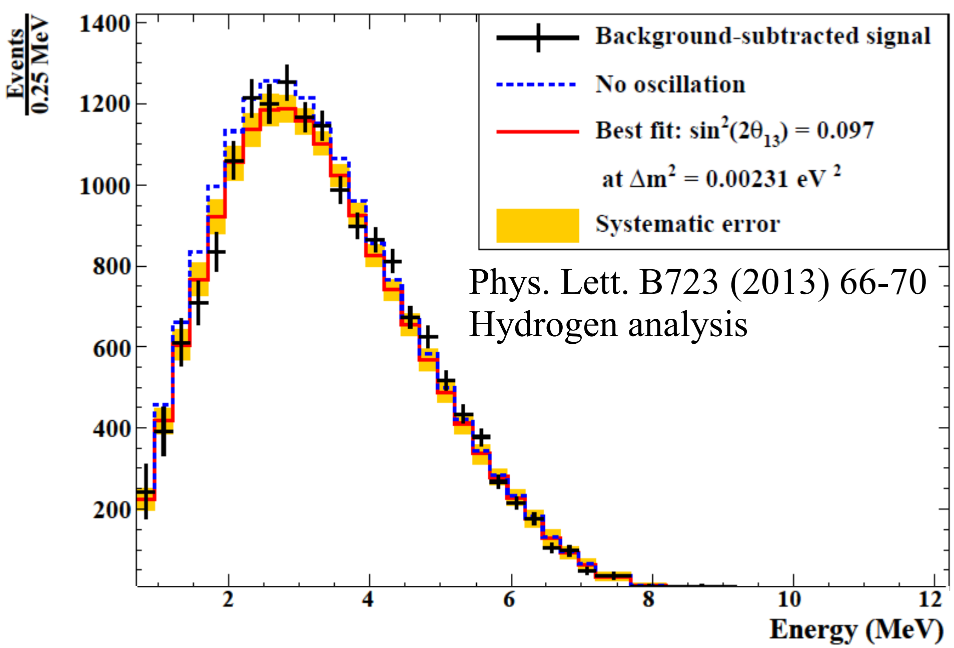
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



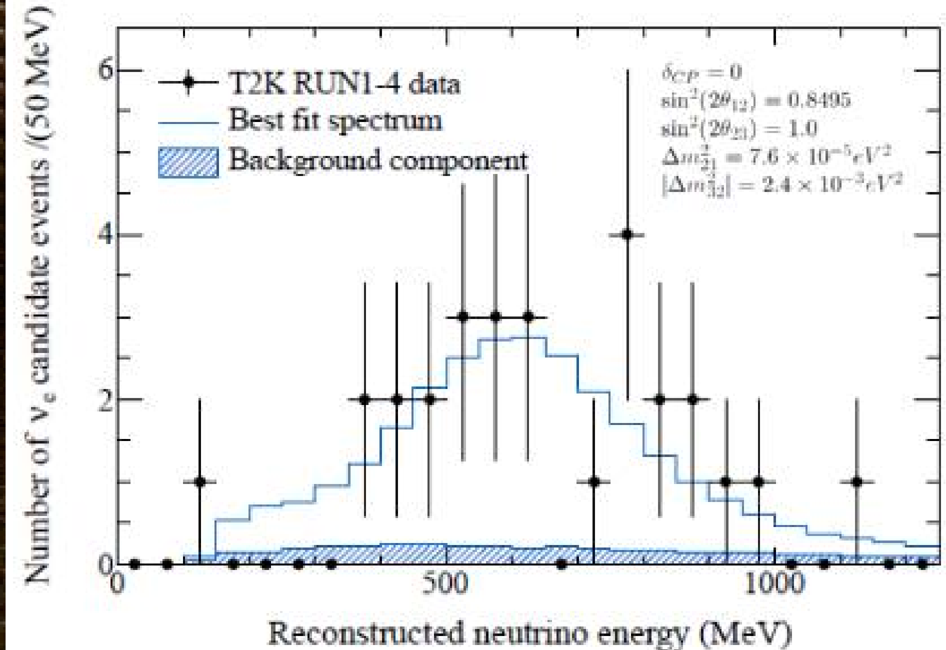
Cherenkov light of charged lepton:



Idea Double Chooz:
- χ^2 fit to observed neutrino events
- Use spectral rate + shape info (49 variable sized energy bins)
- Two correlated samples: Hydrogen (31 bins) and Gadolinium (18 bins)
- Additional data for background estimation from both reactors off data
- Systematics parameters are constrained by pull parameters



Idea T2K:
- Maximum likelihood fit of observed events
- Use spectral rate + shape info (25 bins)
- systematics parameters are constrained by pull parameters
- Perform series of $\sin^2(2\theta_{13})$ fit with variable, but fixed pairs of (δ_{CP} , Δm^2_{31})



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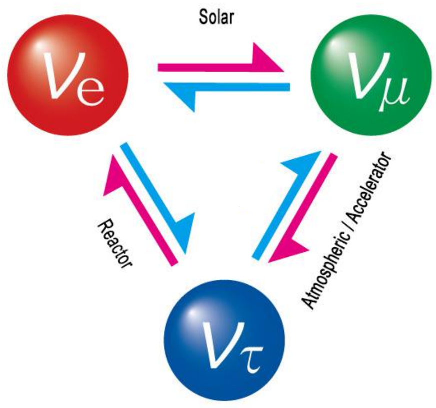
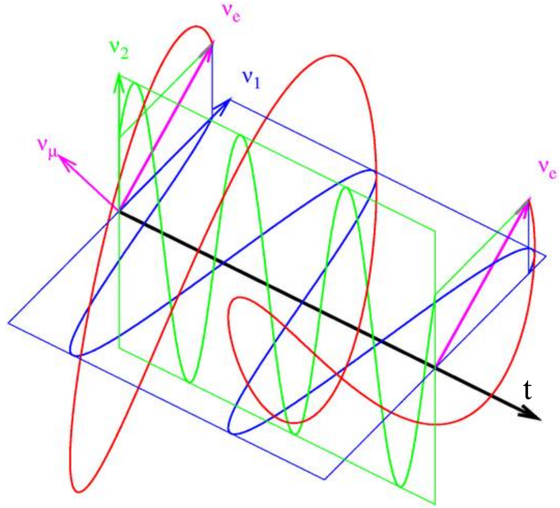


Neutrino oscillation between three generations

Neutrino Oscillation:



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A Joint Analysis

Joint analysis idea:

- Adapt analysis methods of DC/T2K, but now with a "large DC-T2K" experiment
- Add up DC analysis bins and T2K analysis bins and consider correlations
- Now possible: inference on δ_{CP}
- Use detailed systematics information of experiments
- Merge common systematics
- Some modifications to original analysis approaches required

Modification list:

1) T2K and DC analyses have to be switched to a common approach

2) DC analysis has to be switch from mixed χ^2 / $\sin^2(2\theta_{13})$ to χ^2 discriminant ✔

3) original T2K analysis was not sensitive on δ_{CP} thus fixed in fit
→ additional free parameter

4) identify / compute correlations between experiments (cross sections / assumed additional oscillations parameters / ...) and recompute covariance matrix

5) what ever additionally shows up...

Summary

- Final fit strategies of the Double Chooz and T2K experiments were investigated

- Joint analysis framework is currently under implementation
    - Will use detailed systematics
    - Necessary modifications to the original final fit analyses of the two experiments were identified
    - Modifications partly implemented

- Next steps:
    - Finish implementation
    - Reproduce single experiment results
    - Do joint analysis
    - Measure δ_{CP}

References:

Double Chooz:
Phys. Rev. Lett. 86, 052008
Phys. Rev. D 87, 011102
Phys. Lett. B 723 (2013) 66-70

T2K:
Phys. Rev. D 88, 032002 (2013)

The Double Chooz Collaboration

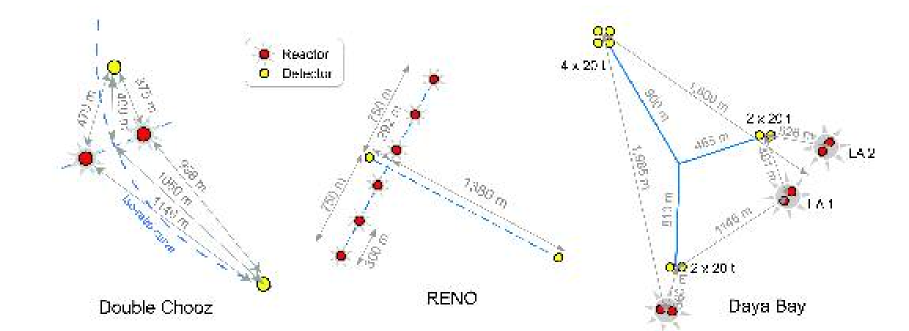
The T2K Collaboration

Appendix

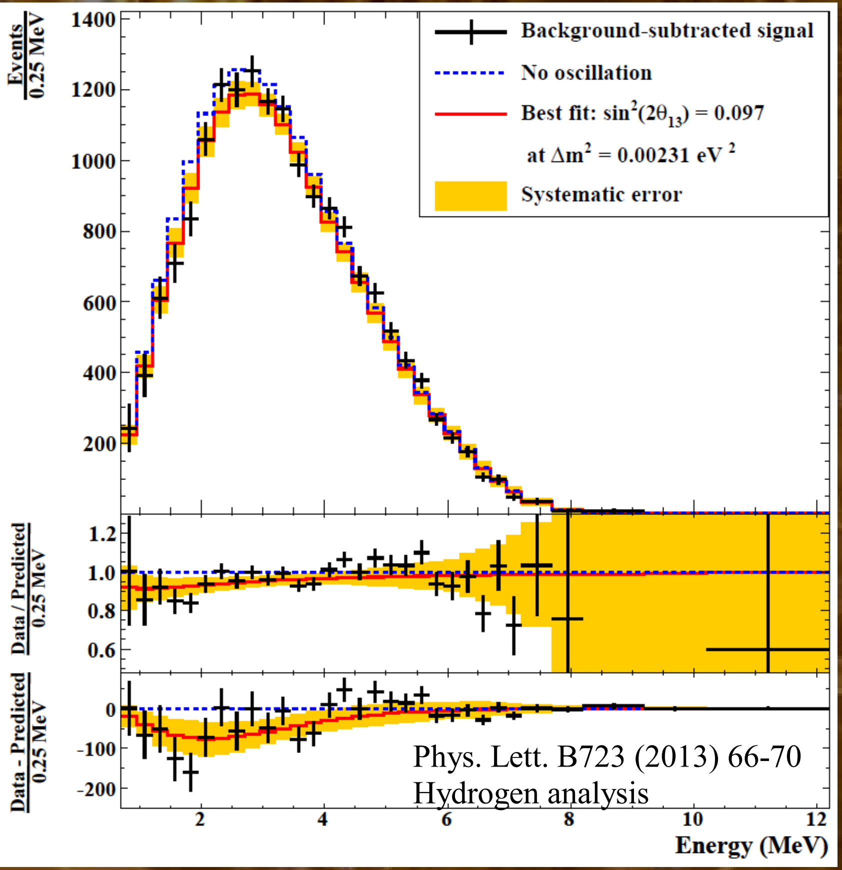
DCs uniqueness

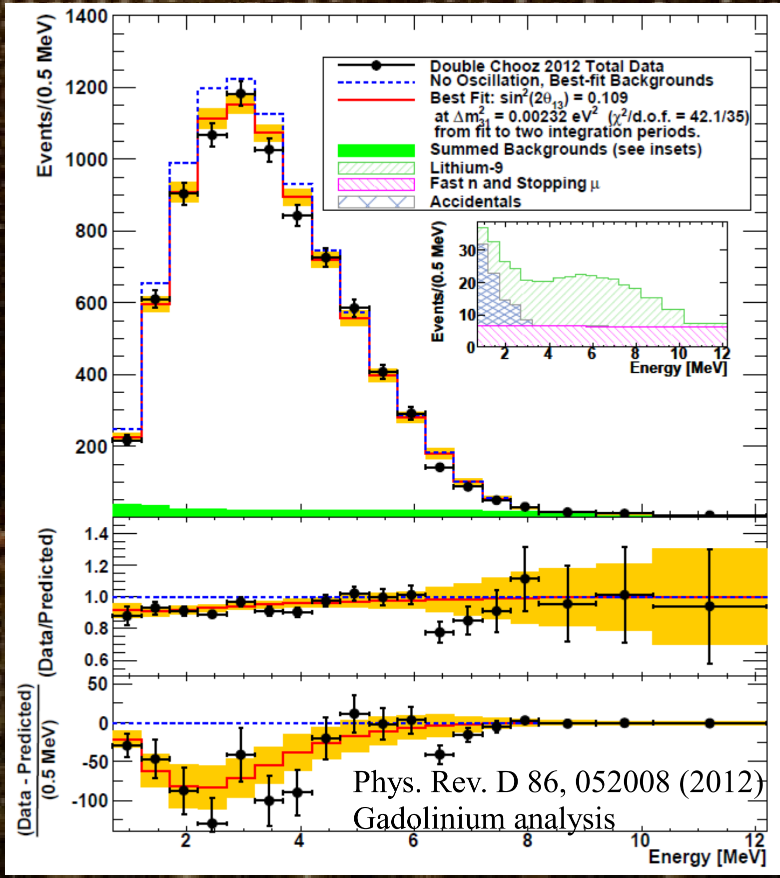
Double Chooz

- Published rate + shape analysis
- Uses reactor off-off data
- Has additional analysis with Hydrogen



J.Phys. G37 (2010) 103001





Final Fit (Details)

Double Chooz

(1) (sample) covariance matrix incorporating correlated uncertainties between energy bins

$$\chi^2 = \sum_i^B \sum_j^B (N_i^{pred} - N_i^{obs})\, M_{ij}^{-1}\, (N_j^{pred} - N_j^{obs})$$

$$+ \frac{(\Delta m^2 - \Delta m^2_{MINOS})^2}{\sigma^2_{MINOS}}$$

(2) global pull parameter for mass difference

$$+ \left[(\alpha_{li}^{Gd}-1),\,(\alpha_{fn}^{Gd}-1),\,(\alpha_{e}^{Gd}-1),\,(\alpha_{li}^{H}-1),\,(\alpha_{fn}^{H}-1),\,(\alpha_{e}^{H}-1)\right]$$

$$\times \begin{bmatrix} (\sigma_{li}^{Gd})^2 & 0 & 0 & \rho_{li}\sigma_{li}^{Gd}\sigma_{li}^{H} & 0 & 0 \\ 0 & (\sigma_{fn}^{Gd})^2 & 0 & 0 & \rho_{fn}\sigma_{fn}^{Gd}\sigma_{fn}^{H} & 0 \\ 0 & 0 & (\sigma_{e}^{Gd})^2 & 0 & 0 & \rho_{e}\sigma_{e}^{Gd}\sigma_{e}^{H} \\ \rho_{li}\sigma_{li}^{H}\sigma_{li}^{Gd} & 0 & 0 & (\sigma_{li}^{H})^2 & 0 & 0 \\ 0 & \rho_{fn}\sigma_{fn}^{H}\sigma_{fn}^{Gd} & 0 & 0 & (\sigma_{fn}^{H})^2 & 0 \\ 0 & 0 & \rho_{e}\sigma_{e}^{H}\sigma_{e}^{Gd} & 0 & 0 & (\sigma_{e}^{H})^2 \end{bmatrix}^{-1}$$

$$+ \left[(\alpha_{li}^{Gd}-1),\,(\alpha_{fn}^{Gd}-1),\,(\alpha_{e}^{Gd}-1),\,(\alpha_{li}^{H}-1),\,(\alpha_{fn}^{H}-1),\,(\alpha_{e}^{H}-1)\right]^T$$

(3) individual (correlated) pull parameters (Gd or H)

$$+ \left[(\alpha_{li}^{Gd} R_{li}^{Gd,pred} + \alpha_{fn}^{Gd} R_{fn}^{Gd,pred} - R_{off}^{Gd}),\,(\alpha_{li}^{H} R_{li}^{H,pred} + \alpha_{fn}^{H} R_{fn}^{H,pred} - R_{off}^{H})\right]$$

$$\times \begin{bmatrix} (\sigma_{off}^{Gd})^2 & \rho_{off}\sigma_{off}^{Gd}\sigma_{off}^{H} \\ \rho_{off}\sigma_{off}^{H}\sigma_{off}^{Gd} & (\sigma_{off}^{H})^2 \end{bmatrix}^{-1} \times \begin{bmatrix} (\alpha_{li}^{Gd} R_{li}^{Gd,pred} + \alpha_{fn}^{Gd} R_{fn}^{Gd,pred} - R_{off}^{Gd}) \\ (\alpha_{li}^{H} R_{li}^{H,pred} + \alpha_{fn}^{H} R_{fn}^{H,pred} - R_{off}^{H}) \end{bmatrix}$$

(4) reactor off-off data inclusion

T2K

$$\mathcal{L}(N_{obs}, \boldsymbol{E}_{obs}^{rec}; \boldsymbol{\theta}, \boldsymbol{f}) = \mathcal{L}_{norm}(N_{obs}; \boldsymbol{\theta}, \boldsymbol{f}) \times \mathcal{L}_{shape}(\boldsymbol{E}_{obs}^{rec}; \boldsymbol{\theta}, \boldsymbol{f}) \times \mathcal{L}_{syst}(\boldsymbol{f})$$

$$\mathcal{L}_{norm}(N_{obs}; \boldsymbol{\theta}, \boldsymbol{f}) = \frac{e^{-N_{exp}(\boldsymbol{\theta}, \boldsymbol{f})}[N_{exp}(\boldsymbol{\theta}, \boldsymbol{f})]^{N_{obs}}}{N_{obs}!}$$

$$\mathcal{L}_{shape}(\boldsymbol{E}_{obs}^{rec}; \boldsymbol{\theta}, \boldsymbol{f}) = \prod_{i=1}^{N_{obs}} \rho(E_{obs,i}^{rec}; E^{rec}, \boldsymbol{\theta}, \boldsymbol{f})$$

$$\mathcal{L}_{syst}(\boldsymbol{f}) = \frac{1}{(2\pi)^{k/2}\sqrt{|V|}} \exp\left(-\frac{1}{2}\Delta\boldsymbol{f}^T V^{-1} \Delta\boldsymbol{f}\right)$$

(1) far detector expectation uses near detector flux
(2) ρ denotes the likelihood that the individual neutrinos were observed at precisely the reconstructed energy
(3) V represents the (sample) covariance matrix of nuisances / systematics $\boldsymbol{f}$

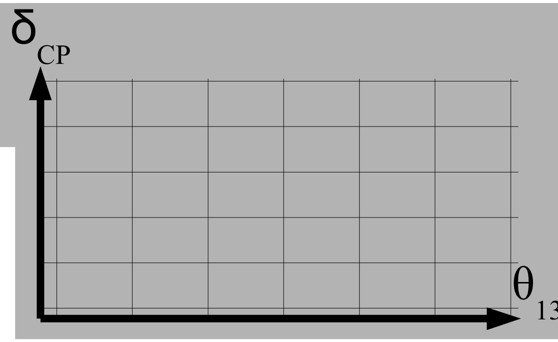
Finding Confidence Sets

One needs:
- All parameters used in neutrino expectation
- Their uncertainties

a + [Gaussian], **b** + [Gaussian], **c** + [Gaussian], : + :

$N_{exp}=f(a,b,\ldots)$

→ set up a lattice in the oscillation parameter space



↓ choose a (new) lattice point

↓ i=0

Perform random draw for each parameter (if needed correlated)

a_i = [dice] (a, [Gaussian])
b_i = [dice] (b, [Gaussian])
c_i = [dice] (c, [Gaussian])
:
:

→ i++

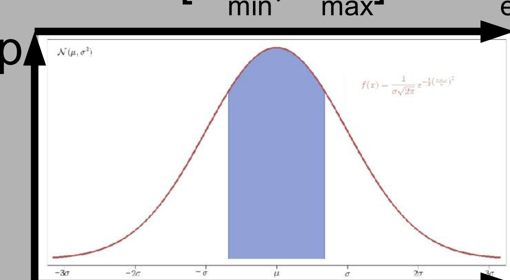
Compute new number of expected neutrinos with these new parameters
→ this is called a **pseudo experiment**

$N^{(i)}_{exp}=f(a_i,b_i,\ldots) \hat{=}$ [dice] (N_{exp})

↺ repeat

→ if i big

Look at all numbers of expected neutrinos and find the region in which 68% (90%,...) of the outcomes are



↑ (back to: choose a (new) lattice point)

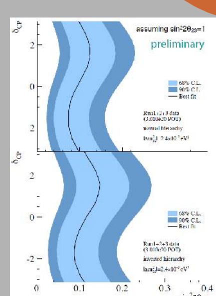
← if lattice done

take all the parameter tuples for which $[N_{min},N_{max}]$ includes N_{meas}
or
$[\chi^2_{min},\chi^2_{max}]$ includes χ^2_{meas}

←

mark these points in blue

they define the 68% (90%,...) confidence set



Confidence / Exclusion Levels

Double Chooz

Confidence levels:

1) Generate toy MC experiments N_i for different assumed $\sin^2(2\theta_{13})$=:$\sin^2(2\theta_{MC})$
2) Determine $\Delta\chi^2(N_i|\theta_{MC}) := \chi^2(N_i|\theta_{MC})-\chi^2(N_i|\theta_{best})$ of these toy MCs
3) determine for each $\sin^2(2\theta_{MC})$ the region where the minimal α% of all $\Delta\chi^2$ is located
4) look if $\Delta\chi^2(N_{DATA})$ is in this regions
5) the $\sin^2(2\theta_{MC})$, for which $\Delta\chi^2(N_{DATA})$ is in the region, build up the α% C.L.

No-oscillation hypothesis rejection:

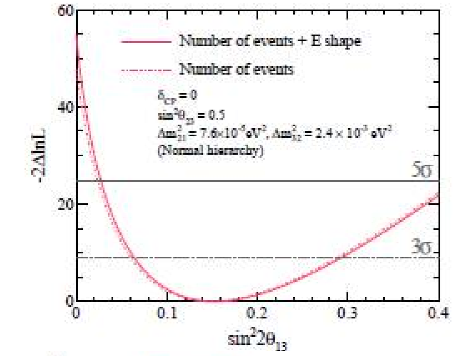
1) Generate toy MC experiments N_i for $\sin^2(2\theta_{13})=0$
2) Determine $\Delta\chi^2(N_i|\theta=0) := \chi^2(N_i|\theta=0)-\chi^2(N_i|\theta_{best})$ of these toy MCs
3) determine the exclusion level as

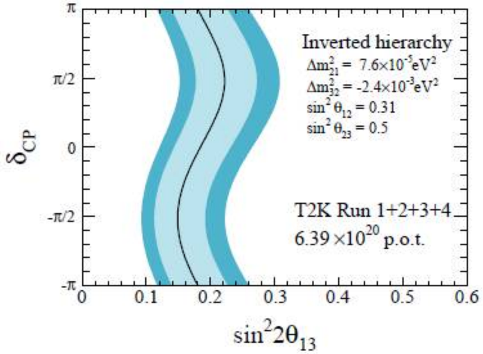
$$\beta := \#\{N_i \mid \Delta\chi^2(N_i|\theta=0)<\Delta\chi^2(N_{DATA}|\theta=0)\} \,/\, \#\text{ of toy MC}$$

T2K

Confidence levels:

1) Generate toy MC experiments N_i for different assumed $(\sin^2(2\theta_{13}), \delta_{CP}, \mathrm{sgn}(\Delta m^2_{32}))$ =: $(\sin^2(2\theta_{MC}), \delta_{MC}, \mathrm{sgn}_{MC}(\Delta m^2_{32}))$
2) Determine $-2\Delta\ln\mathcal{L}(N_i|\theta_{MC})$ $:= -2\ln\mathcal{L}(N_i|\theta_{MC}) + 2\ln\mathcal{L}(N_i|\theta_{best})$
3) α% C.L. is determined by fixed value method for each $(\delta_{MC}, \mathrm{sgn}_{MC}(\Delta m^2_{32}))$
4) union of all α% C.L. give the global confidence set





No-oscillation hypothesis rejection:

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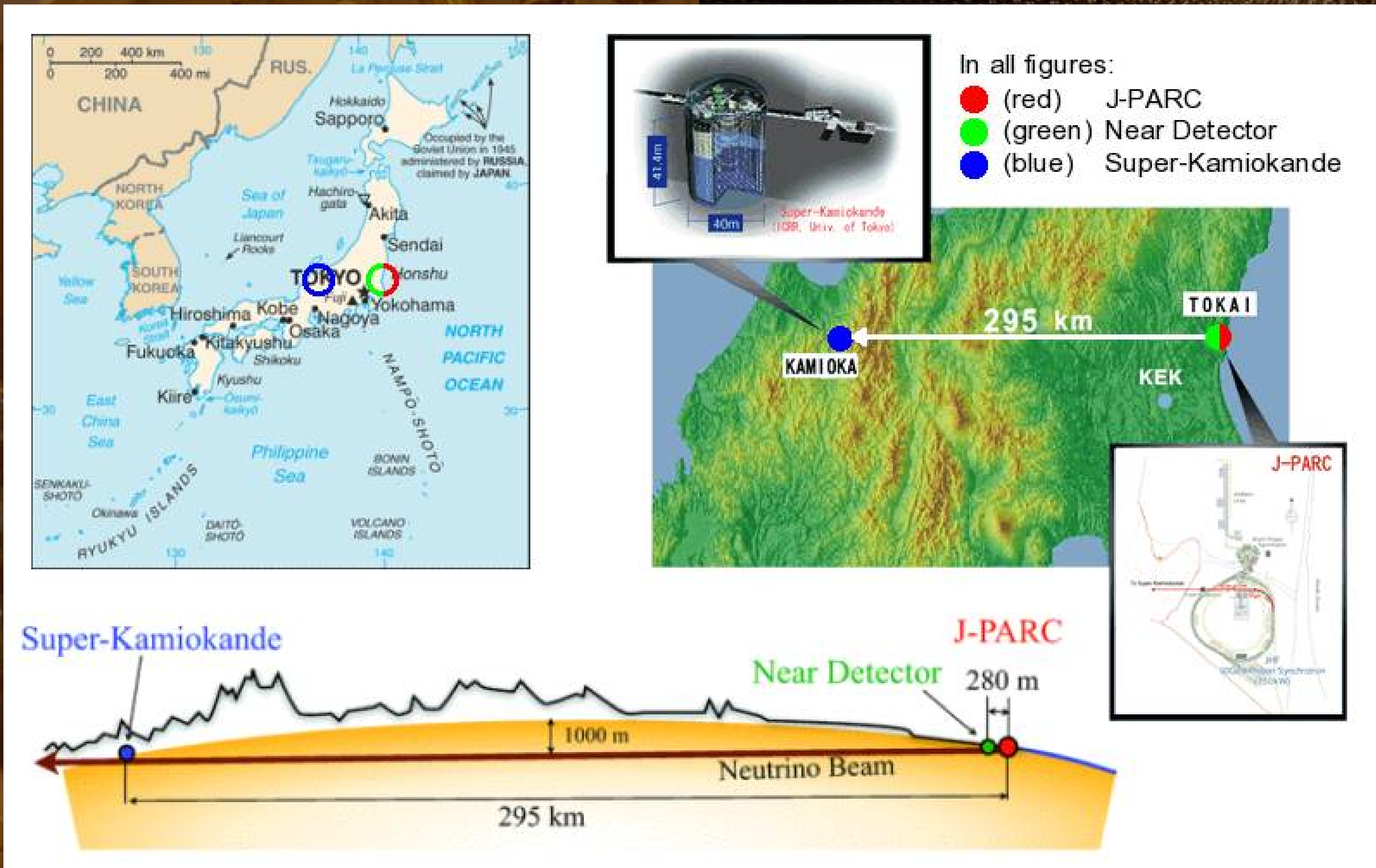
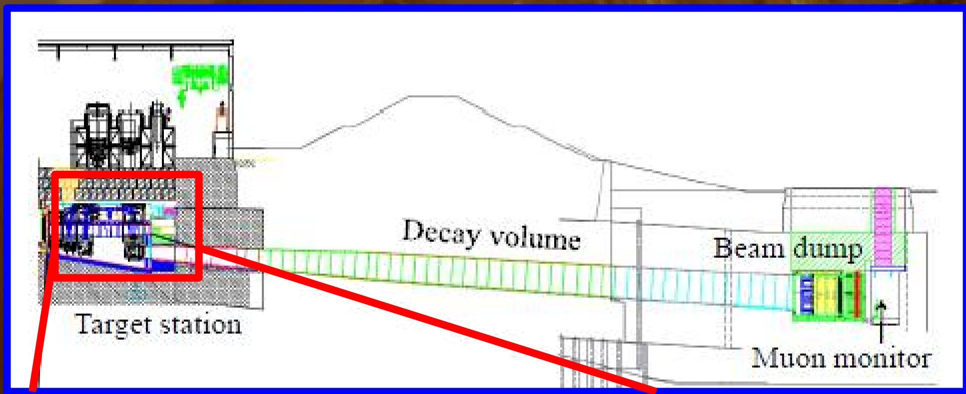
2) Determine $-2\Delta\ln\mathcal{L}(N_i|\theta=0) := -2\ln\mathcal{L}(N_i|\theta=0) + 2\ln\mathcal{L}(N_i|\theta_{best})$ of these toy MCs
3) determine the exclusion level as

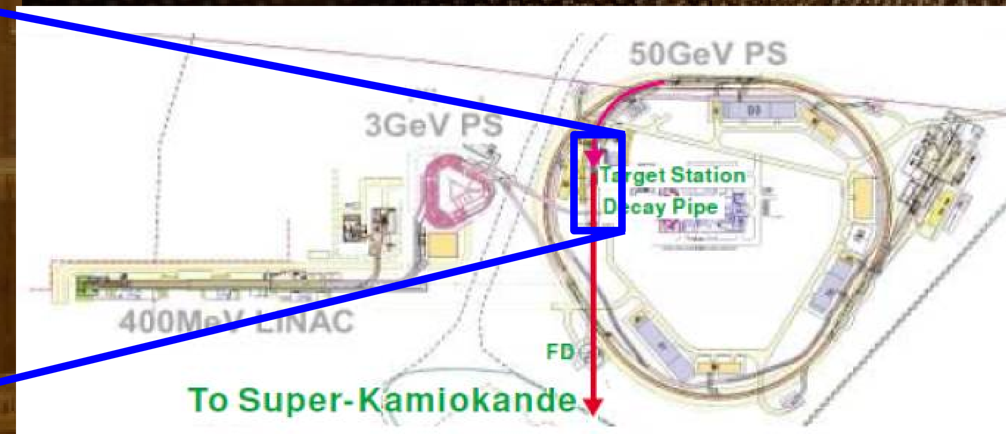
$$\beta := \#\{N_i \mid -2\Delta\ln\mathcal{L}(N_i|\theta=0) < -2\Delta\ln\mathcal{L}(N_{DATA}|\theta=0)\} \,/\, \#\text{ of toy MC}$$

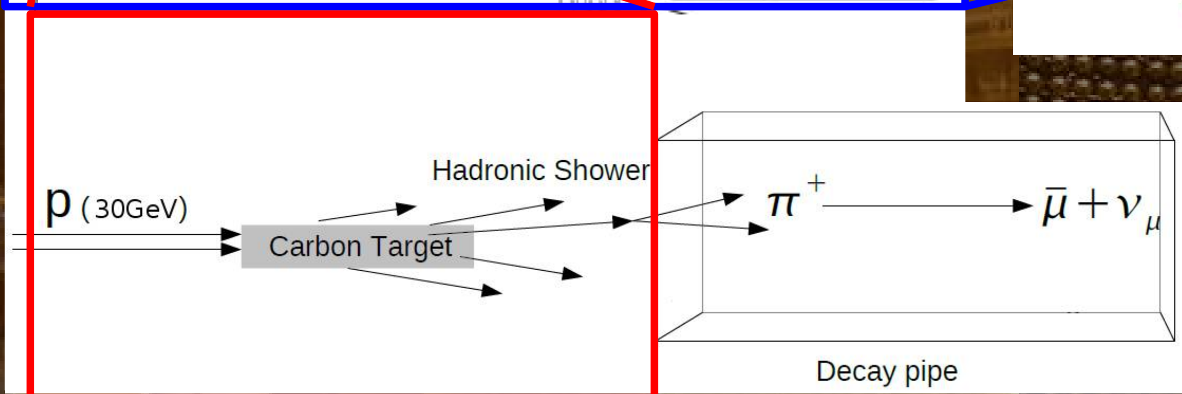
T2K Setup


In all figures:
(red) J-PARC
(green) Near Detector
(blue) Super-Kamiokande
CHINA
RUS.
NORTH KOREA
SOUTH KOREA
Sea of Japan
Yellow Sea
East China Sea
Philippine Sea
NORTH PACIFIC OCEAN
Hokkaido
Sapporo
Akita
Sendai
TOKYO
Honshu
Yokohama
Nagoya
Kobe
Osaka
Hiroshima
Kitakyushu
Fukuoka
Shikoku
Kyushu
Kiire
Okinawa
RYUKYU ISLANDS
NAMPO-SHOTO
BONIN ISLANDS
VOLCANO ISLANDS
DAITO-SHOTO
SENKAKU-SHOTO
0 200 400 km
0 200 400 mi
41.4m
40m
Super-Kamiokande
TOKAI
295 km
KAMIOKA
KEK
J-PARC
Super-Kamiokande
J-PARC
Near Detector
280 m
1000 m
Neutrino Beam
295 km

Beam

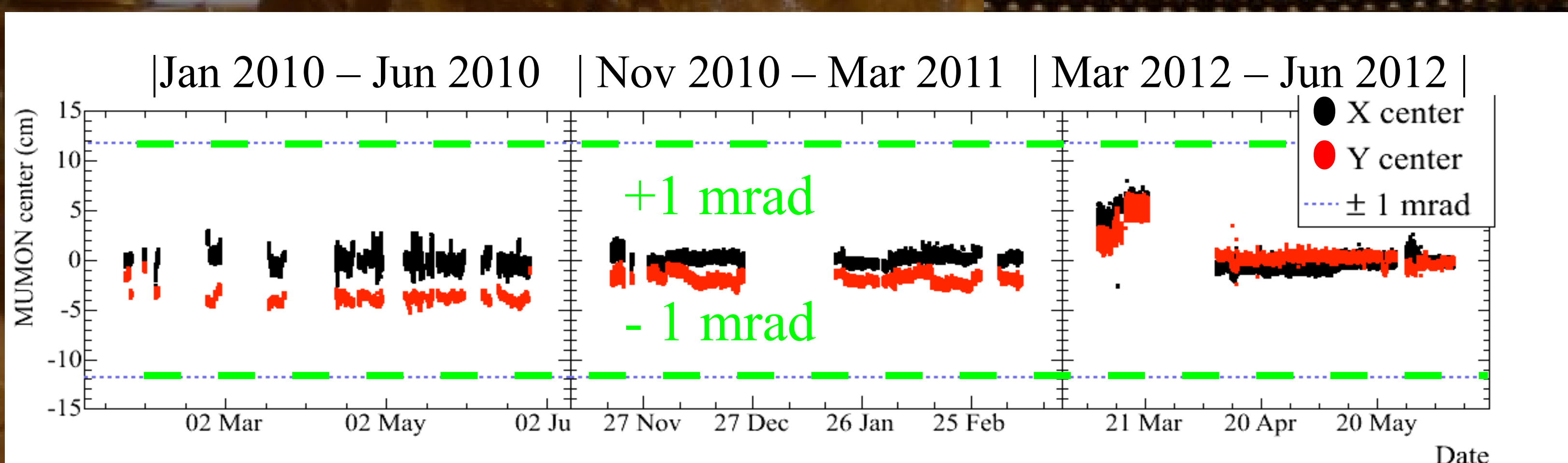




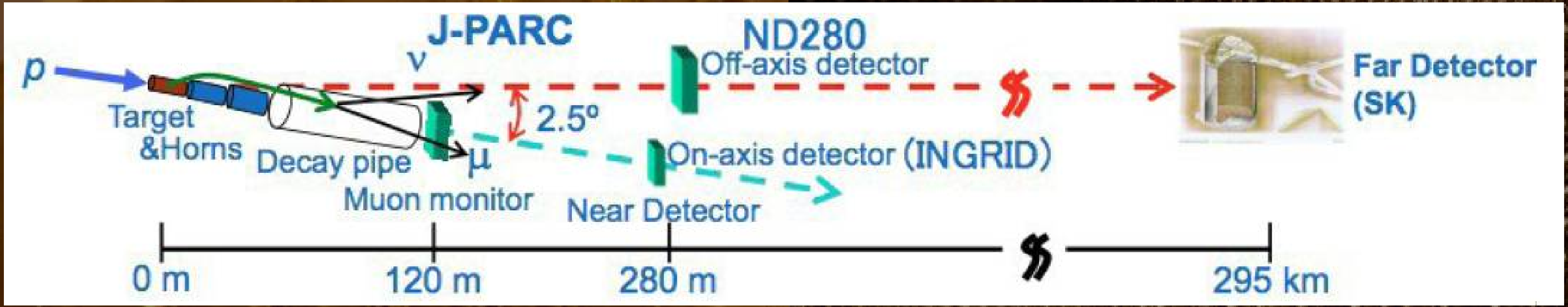


J-PARC:

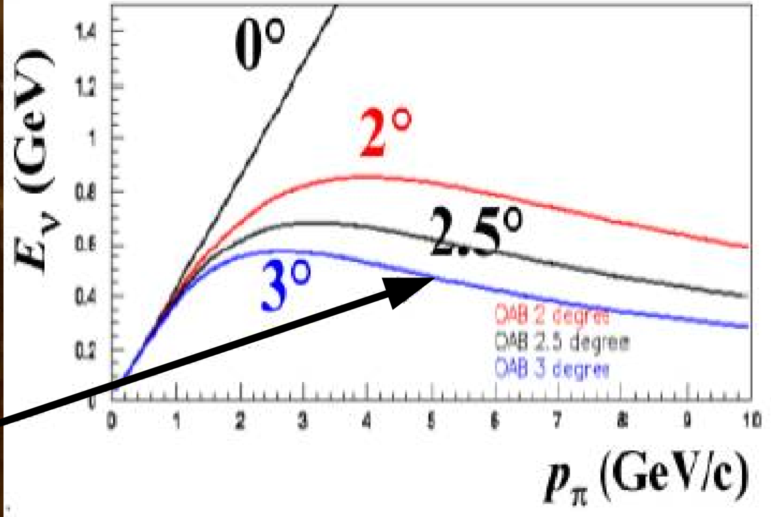
- 30 GeV proton beam
- carbon target
- 0.6 GeV ν_μ beam



- 2.5° off-axis beam
- stable within 1mrad = 0.057°

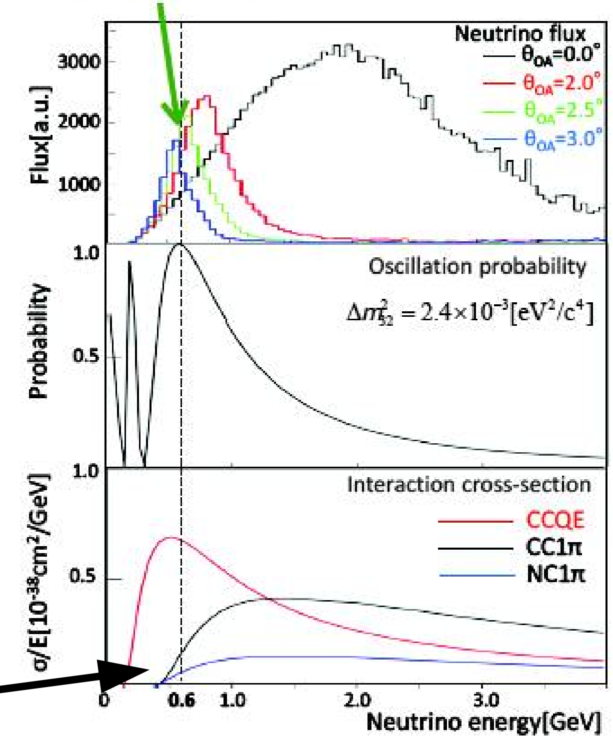


- Tuned to maximal oscillation probability @ T2K baseline
- Weaker dependence on pion momentum → narrow peak in energy



Dominating at 0.6 GeV:
CCQE (ν_μ + p → μ + n)
only few pions

T2K off-axis angle is 2.5°

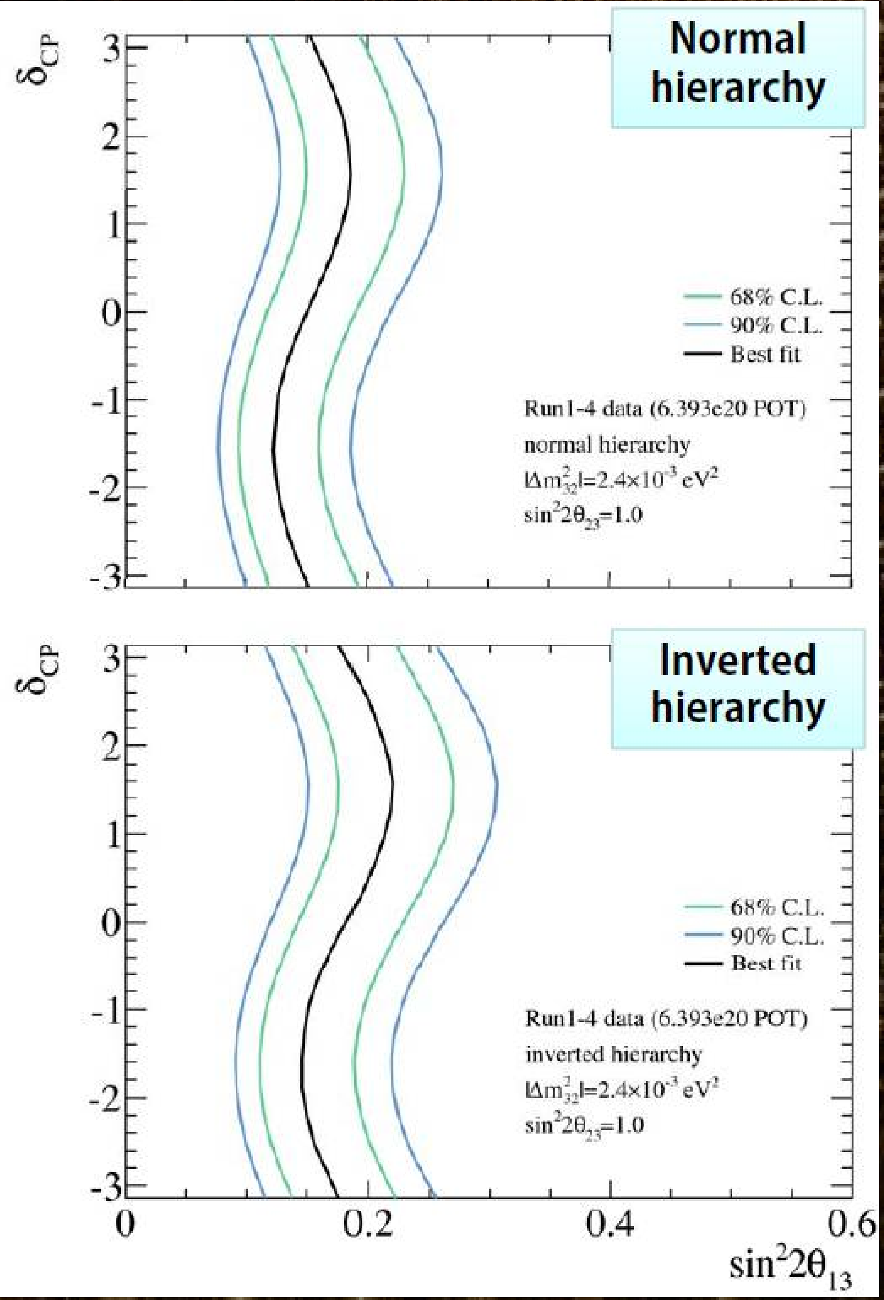


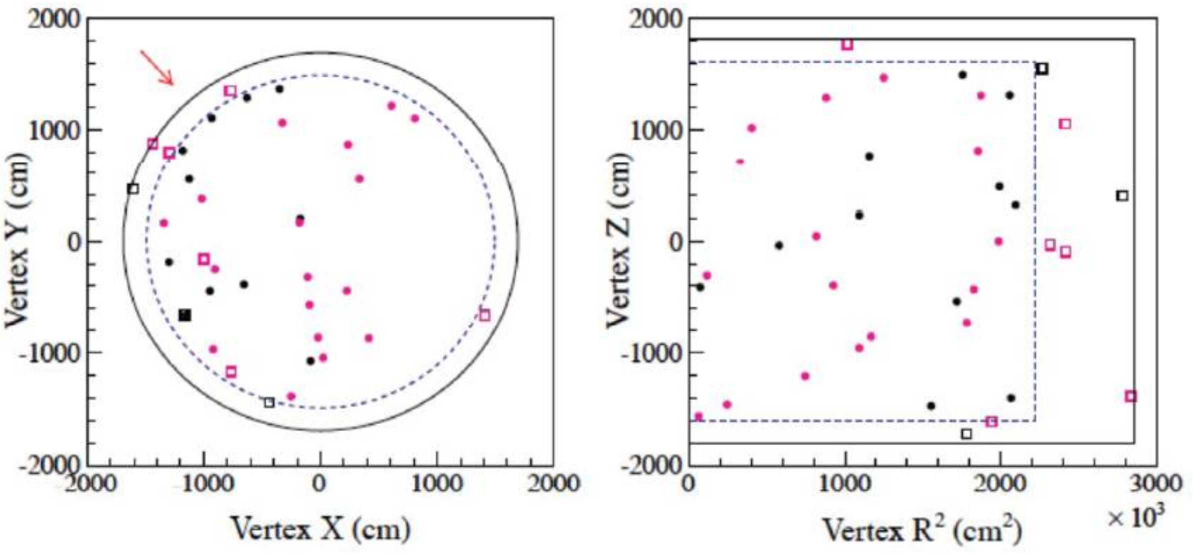
Data	28	
MC	$\sin^2 2\theta_{13}=0$	$\sin^2 2\theta_{13}=0.1$
Osci. $\nu_\mu \to \nu_e$	0.38	16.42
ν_e BG (Beam)	3.17	2.93
ν_μ BG(NCπ0etc)	0.89	0.89
$\overline{\nu}_e + \overline{\nu}_\mu$ BG	0.20	0.19
MC Total	4.64	20.44
Sys.Err(%)	(11.1%)	(8.8%)
Sys.Err(#)	±0.52	±1.80
Sys.Err(%)-2012	(13.0%)	(9.9%)

Observation: 28 events
→ null hypothesis exclusion at 7.5σ
→ discovery of ν_e appearance in a ν_μ beam

→ normal hierarchy: $\sin^2(2\theta_{13}) = 0.150$
$0.116 < \sin^2(2\theta_{13}) < 0.189$
→ inverted hierarchy: $\sin^2(2\theta_{13}) = 0.182$
$0.142 < \sin^2(2\theta_{13}) < 0.228$

→ for $\delta_{CP}=0$, $|\Delta m_{32}^2|=10^{-3}$ eV², $\sin^2(2\theta_{23})=1.0$ and 68% C.L.

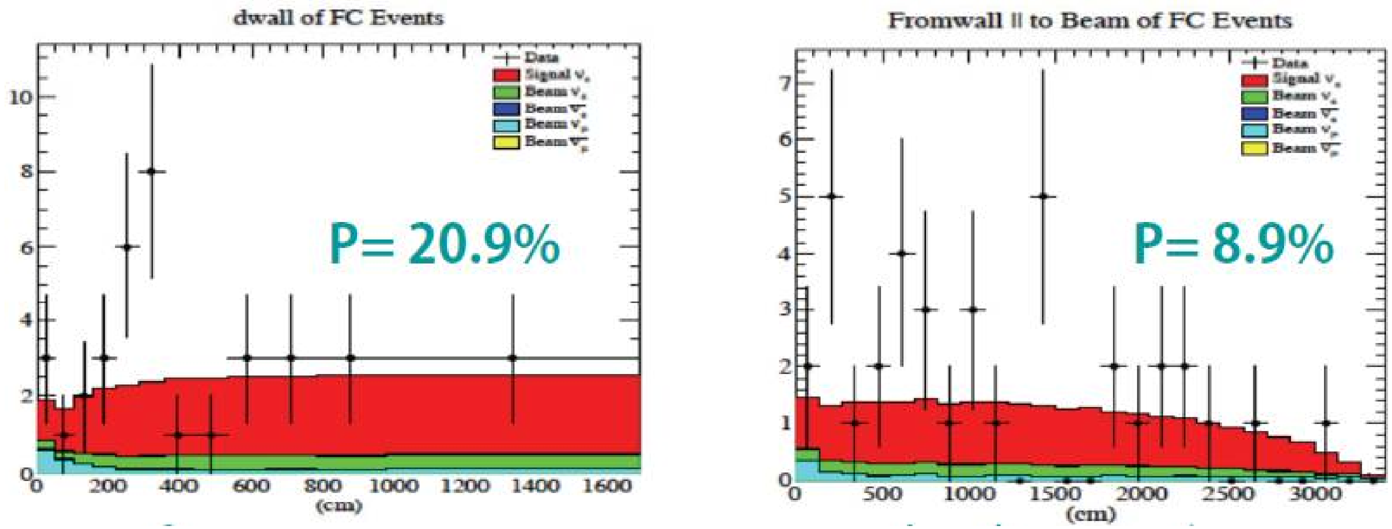




→ p-value of vertex distribution investigated

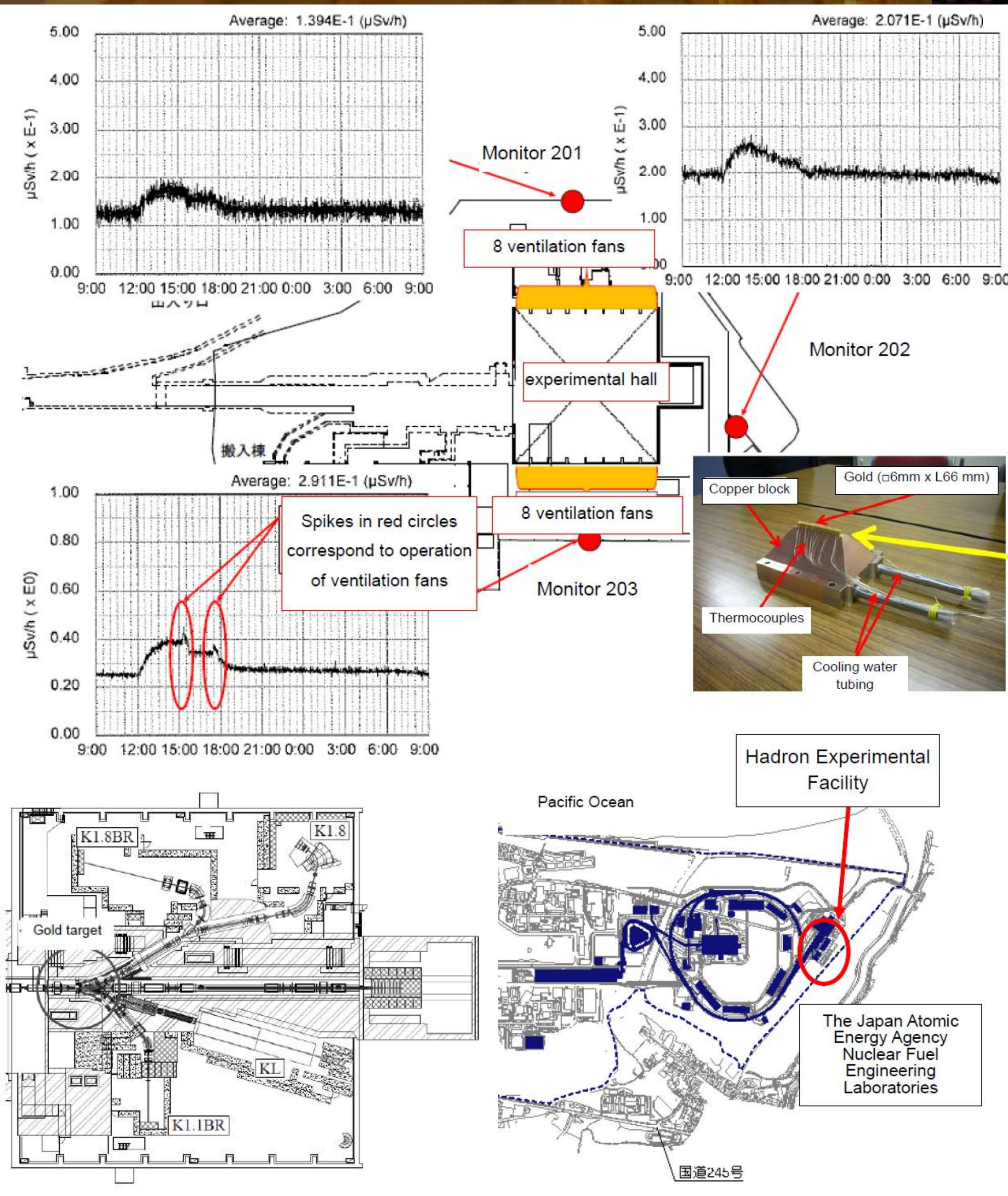
→ the in Aachen strongly favoured "binomial-2-half-view" of the problem
p-value = 0.17

→ all p-values below 2 σ



→ for now no evidence for second source found

→ more data to come in future: 6.39×10^{20} p.o.t. done ↔ 7.5×10^{21} p.o.t. to do



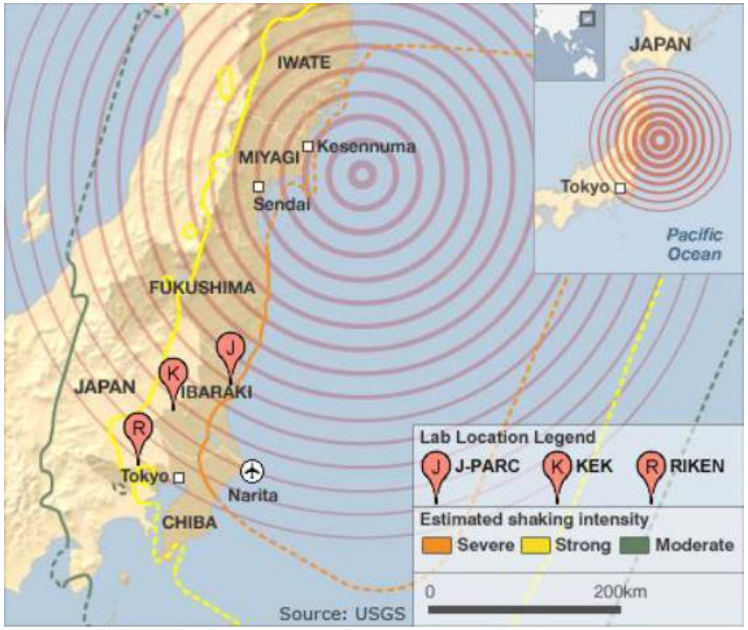
Radiation accident in “Hadron Experiment” (neighbour experiment of T2K in Tokai)

Extract from offical report:
23rd May 11h55 beam extraction malfunction caused damage of gold target / elevated radiation levels in hall.
12h08 run coordinators were unable to detect damage and seriousness of radiation levels and decided on continuing beam
15h15 ventilation fans were turned on / radiation ventilated to environment
16h15 beam stopp due to high radiation
17h30 evacuation of experiment hall / second ventilation performed
23h30 facility sealed off
24th May 17h30 Inquiry of JAEA NFEL concerning high radiation levels recorded
18h00 examination of J-PARC ray monitors yield contamination of environment
21h10 emergency procedures were activated / notification of authorities

Results:
- 34 workers received doses up to 1.7 mSv
- maximum integrated dose outside hall: 0.29 µSv
- Total shut down of all activities in J-PARC (including T2K) for an indefinite periode
- Further investigations carried out by authorities

Official report: http://j-parc.jp/index-e.html

Earthquake

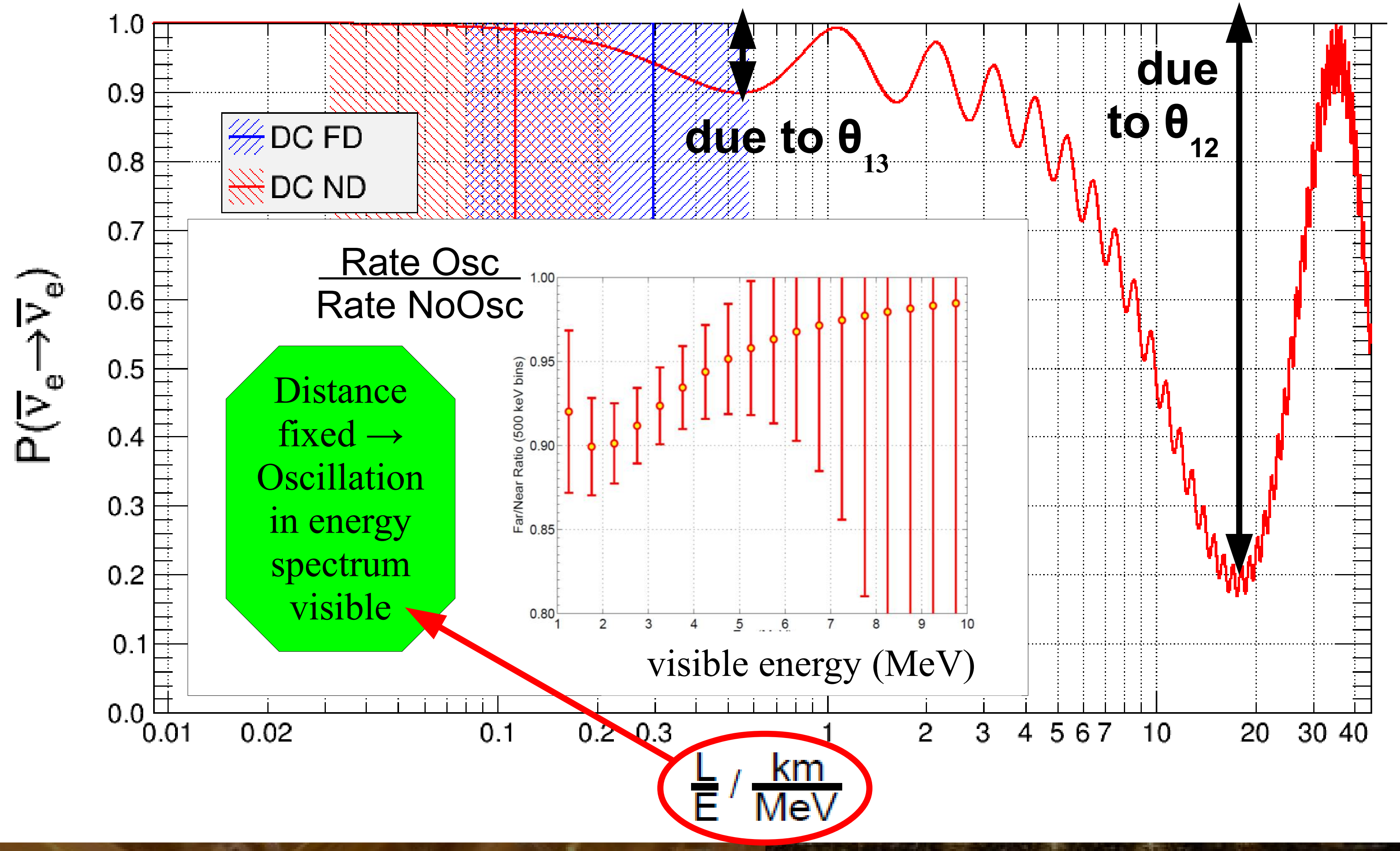

IWATE
MIYAGI
Kesennuma
Sendai
FUKUSHIMA
JAPAN
IBARAKI
Tokyo
Narita
CHIBA
Source: USGS
JAPAN
Tokyo
Pacific Ocean
Lab Location Legend
J-PARC
KEK
RIKEN
Estimated shaking intensity
Severe
Strong
Moderate
0
200km

III. Physikalisches Institut B

RWTH AACHEN UNIVERSITY

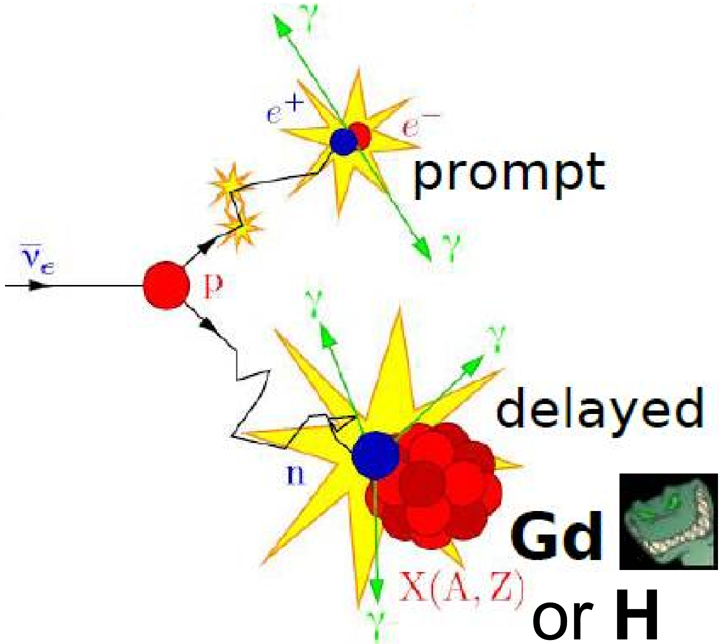
DC

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \alpha^2\left(\frac{\Delta m^2_{31} L}{4E}\right)^2 \cos^4(\theta_{13})\sin^2(2\theta_{12}).$$

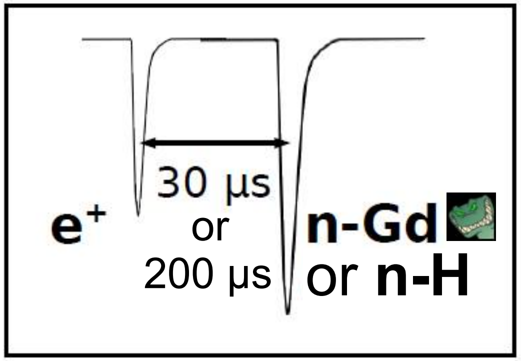


Inverse beta-decay of the neutrino:

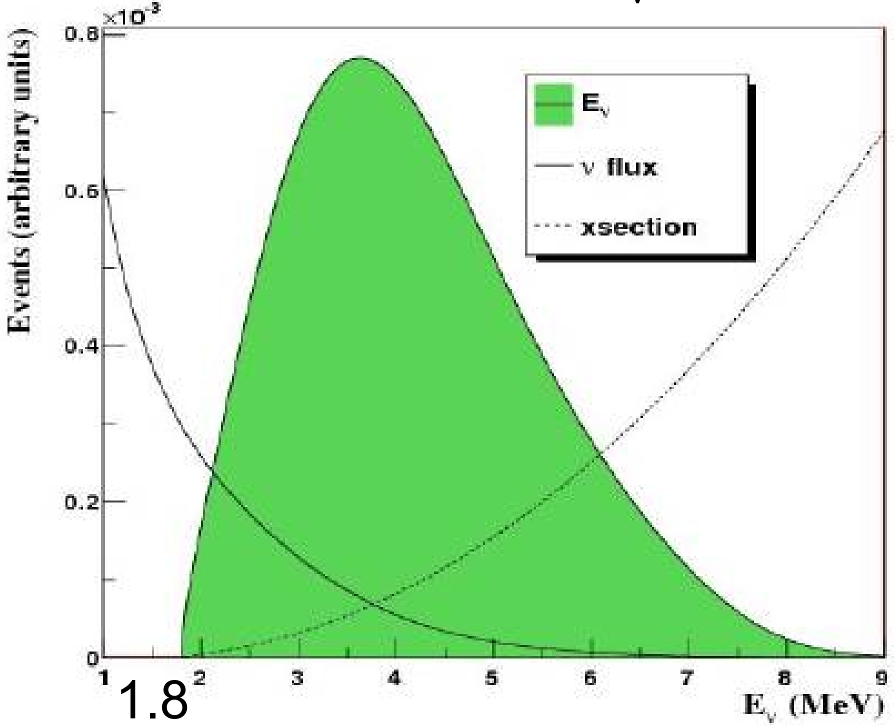
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



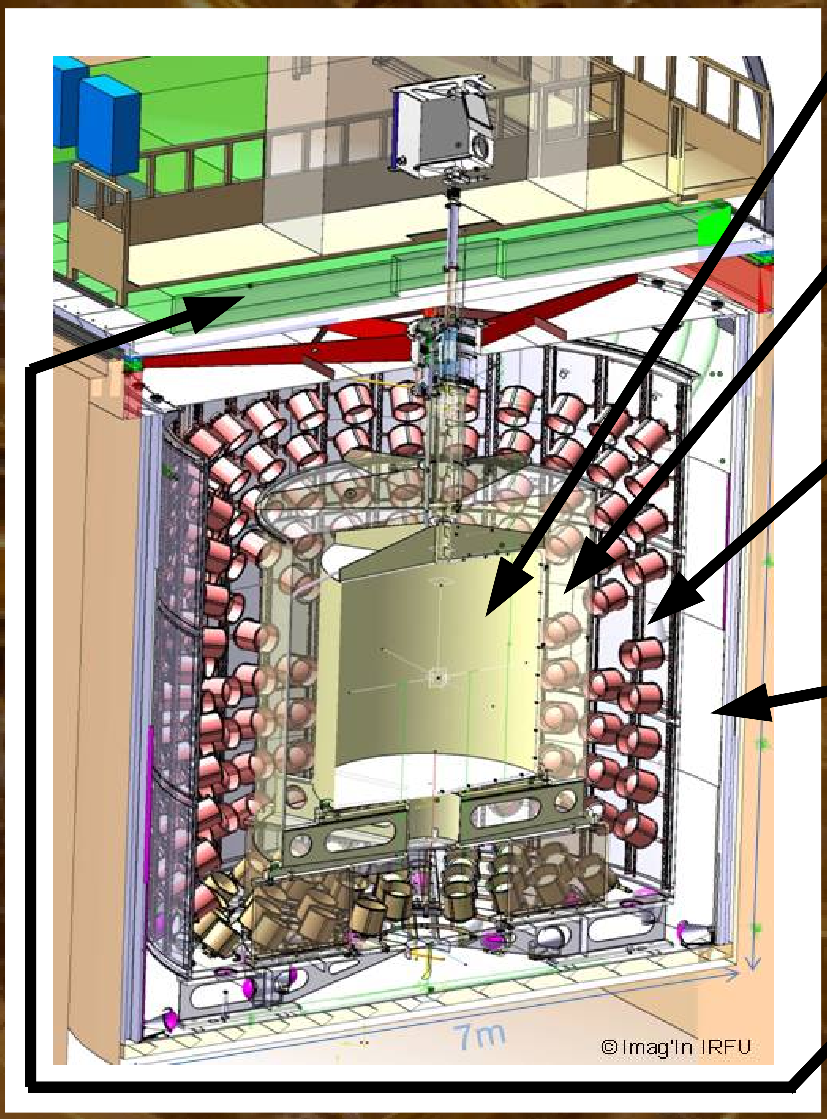
Delay due to thermalisation of neutron before capture



IBD: Energy threshold at E_ν = 1.8 MeV



Backgrounds:
→ beta-decays by spallation products of carbon nuclei induced by atmospheric muons
→ neutrons from the same source
→ intrinsic radioactivity

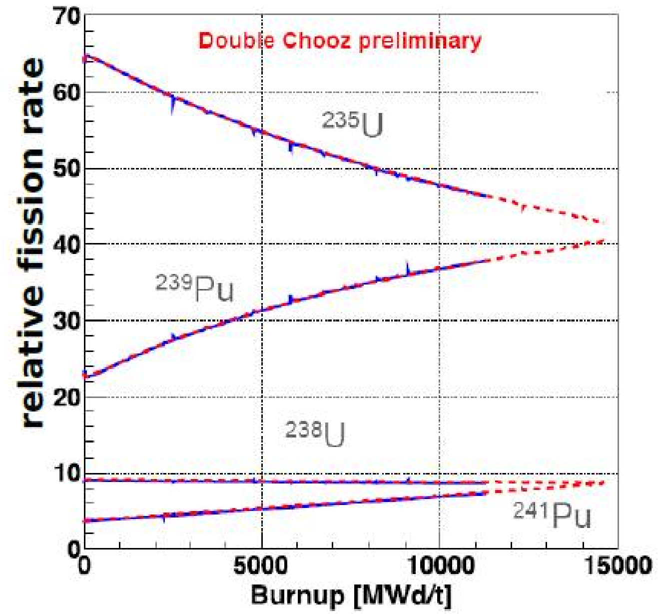


- Target
  12 m³ liquid scintillator + Gd
- γ-Catcher
  28 m³ liquid scintillator w/o Gd
- Buffer
  100 m³ non-scintillating mineral oil
- ~~Inner Veto~~
  110 m³ liquid scintillator
- ~~Outer Veto~~
  plastic scintillator stripes

The Reactors

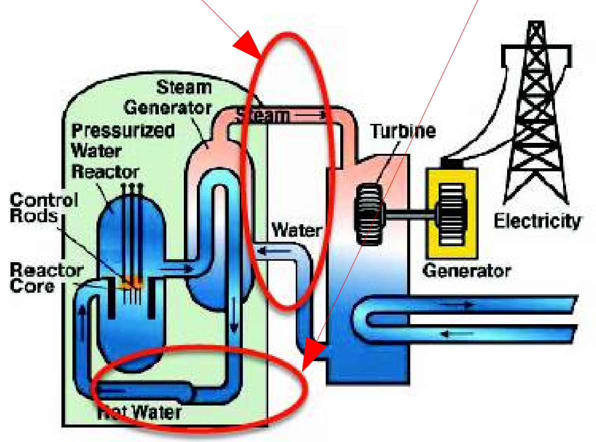
2 pressurised water reactors (Type N4)
electrical power: 2 * 1.5 GW
thermal power: 2 * 4.27 GW
neutrino flux: 1.7 * 10^{21} 1/s

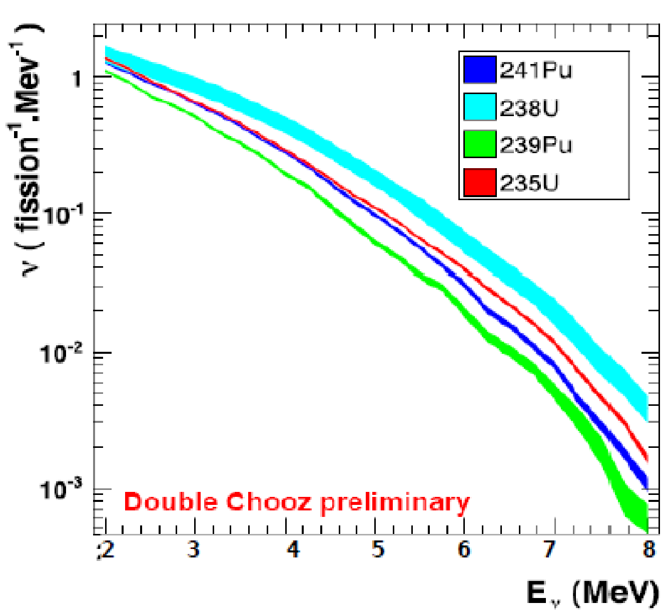
Conversation of power in flux includes spectra and burnup of fuel components

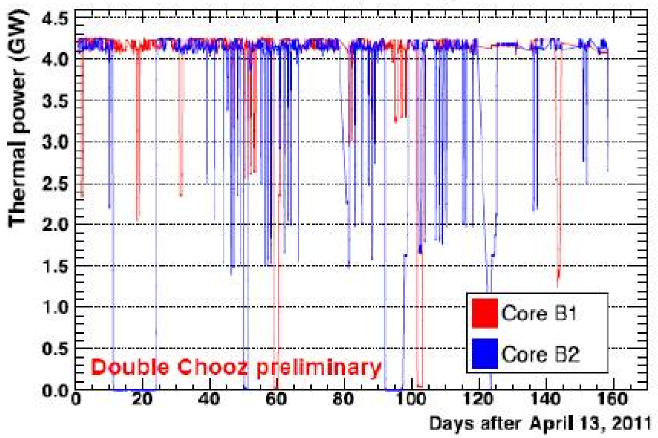


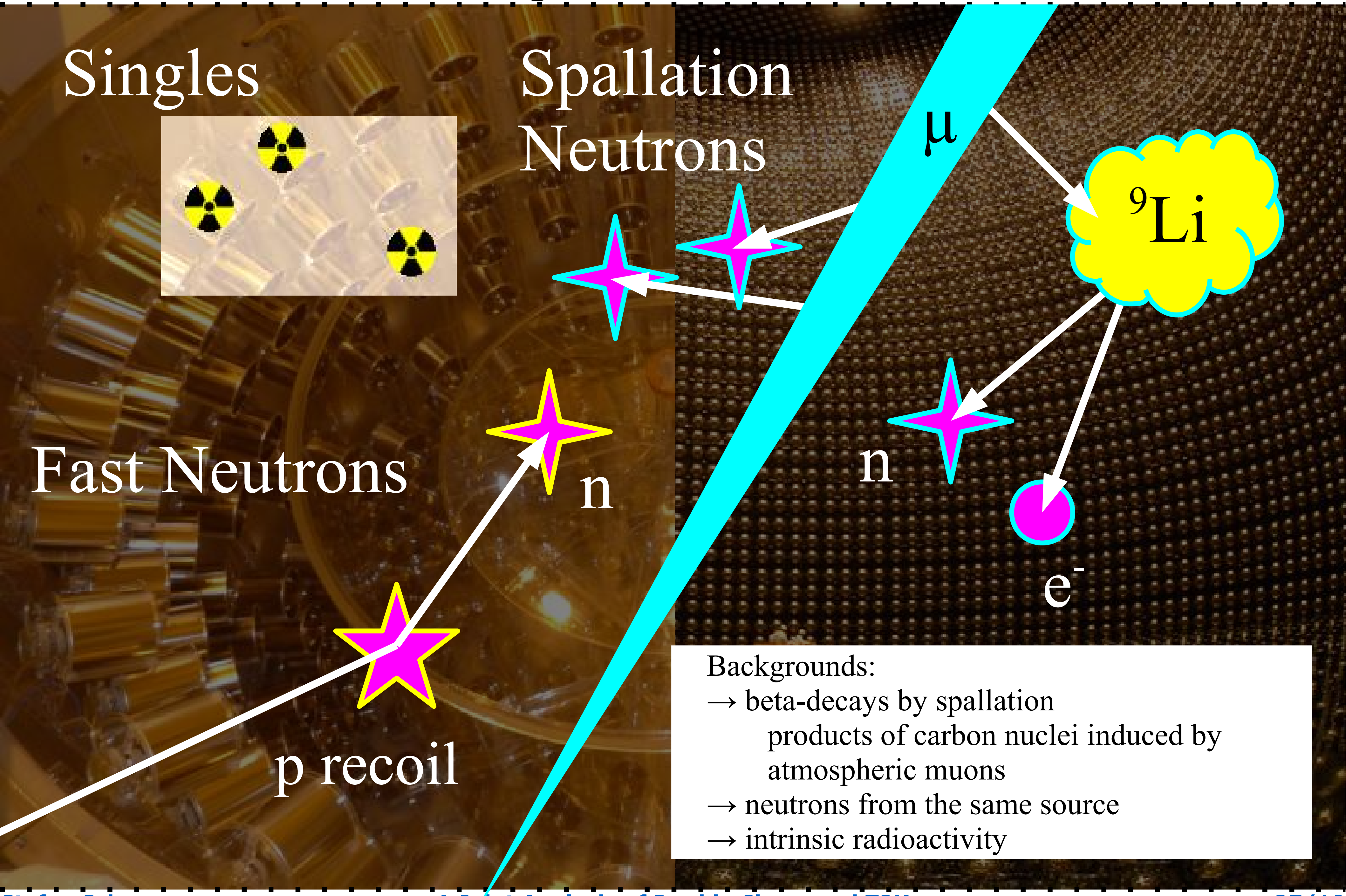
check of flux:
→ weekly via enthalpy at steam generator
→ every minute via temperature in primary loop

steam generator
primary loop



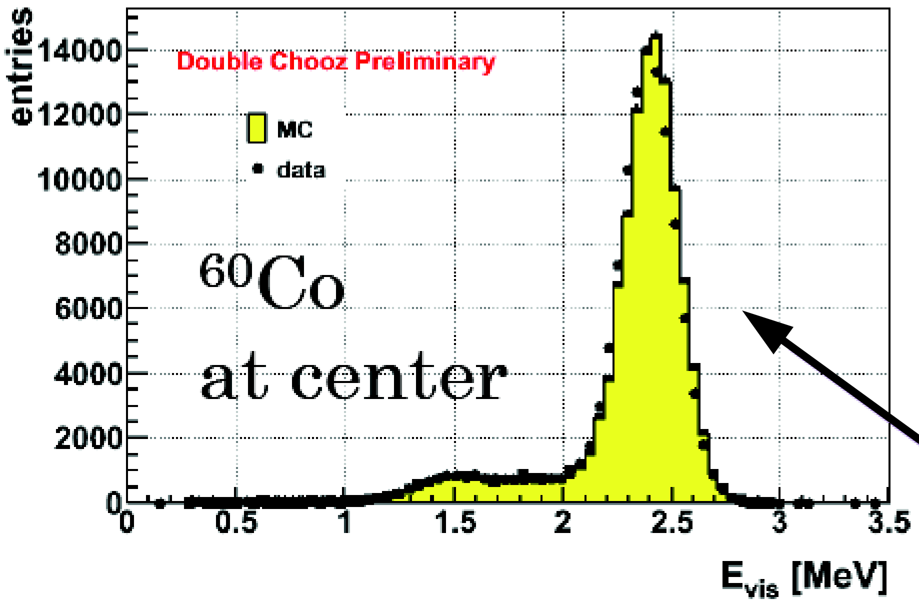


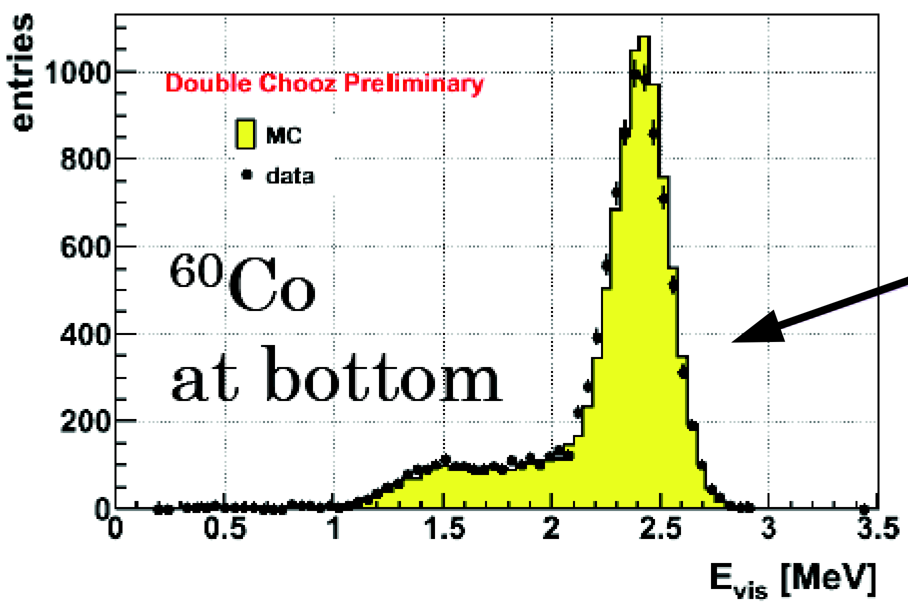




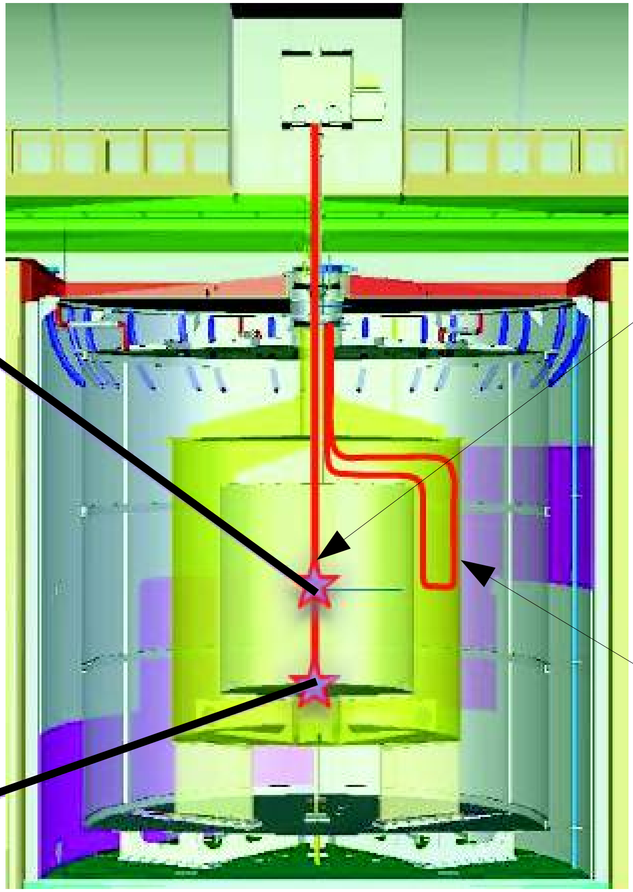
Backgrounds:
→ beta-decays by spallation products of carbon nuclei induced by atmospheric muons
→ neutrons from the same source
→ intrinsic radioactivity

Calibration





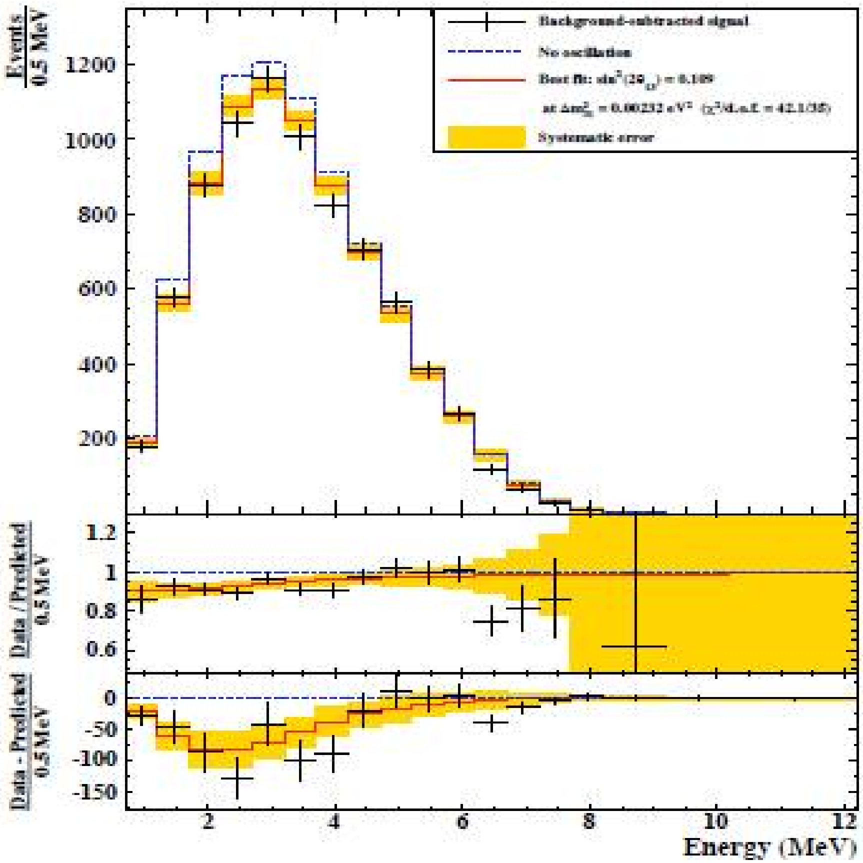
Insertion of radioactive probes with known energy spectrum



→ map of energy vs position

→ map of energy vs particle type (positron vs neutron &c)

Latest results



Latest Gd Analysis Result (Summer 2012)

$\sin^2 2\theta_{13} = 0.109 \pm 0.030$ (stat.) ± 0.025 (syst.)

See PRD.86.052008 for detail

$\sin^2(2\theta_{13})=0$ excluded at 99.9% (3.1 σ) by a frequentist methode

Source	Uncertainty [%]
Reactor Flux	1.67%
Detector Response	0.32%
Statistics	1.06%
Efficiency	0.95%
Cosmogenic Isotope Background	1.38%
FN/SM	0.51%
Accidental Background	0.01%
Total	2.66%

* Normalized to total prediction (signal + BG)