Reactor neutrino experiments comparison for the measurement of θ_{13}

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Outline

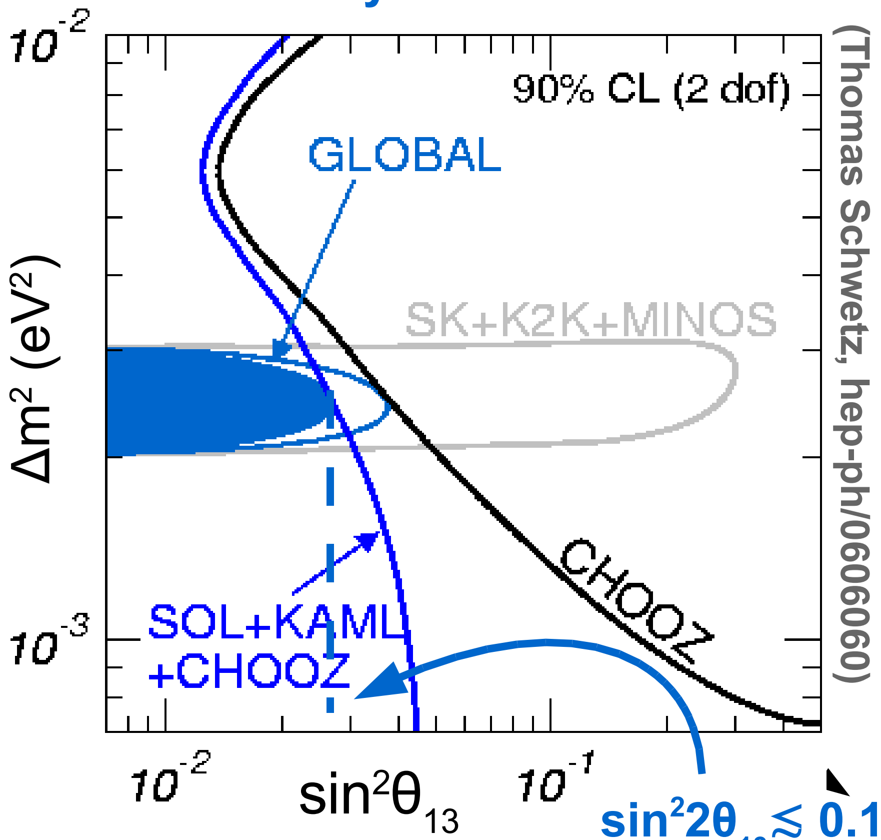
- Neutrino oscillation & the mixings → θ_{13}
- Reactor experiments → ν_e disappearance channel → θ_{13}
- Next to come reactor experiments:
  Daya Bay, Double Chooz, RENO (Angra not included here)

- First comparison of different experiments on a same baseline
  - The statistical method
  - The χ^2 structure
  - Computing θ_{13} sensitivity
  - Inputs: Reactors – Detectors – Backgrounds – Systematics
  - Outputs: sensitivity – robustness w.r.t. systematics

Neutrino oscillations & θ_{13}

$$|\nu_\alpha\rangle = \underbrace{U_{\alpha k}}_{U_{\rm MNSP}} |\nu_k\rangle \qquad U_{\rm MNSP} = U_{\rm atm} \times \begin{pmatrix} \cos\theta_{13} & & \sin\theta_{13}\, e^{-i\delta} \\ & 1 & \\ -\sin\theta_{13}\, e^{i\delta} & & \cos\theta_{13} \end{pmatrix} \times U_{\rm sol} \times U^{\rm diag}_{\rm Maj}$$

Global analysis + best fit Δm^2



$\sin^2 2\theta_{13} \lesssim 0.11$

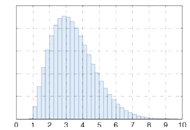
$$P_{\alpha\beta}(L) = \left| \sum_k U_{\beta k}\, U^\star_{\alpha k}\, e^{-i\, m_k^2\, L/2E} \right|^2$$

$\sin^2(2\theta_{13}) < 0.11$ @ 90 % C.L.

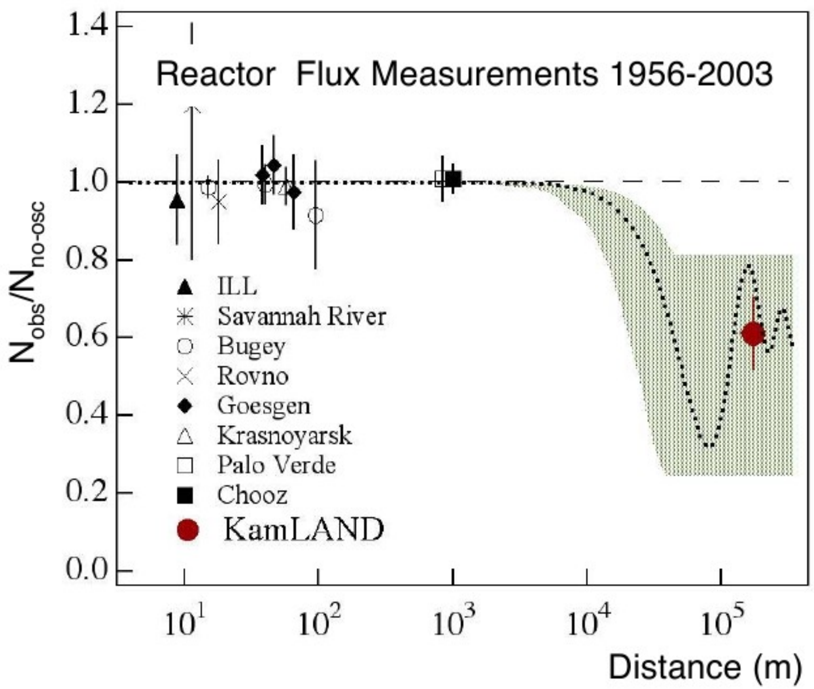
(mainly from reactor experiments)

Reactor experiments & the $\bar{\nu}_e$ channel

Inverse β decay $\bar{\nu}_e + p \rightarrow e^+ + n$ → $E_e \rightarrow E_\nu$

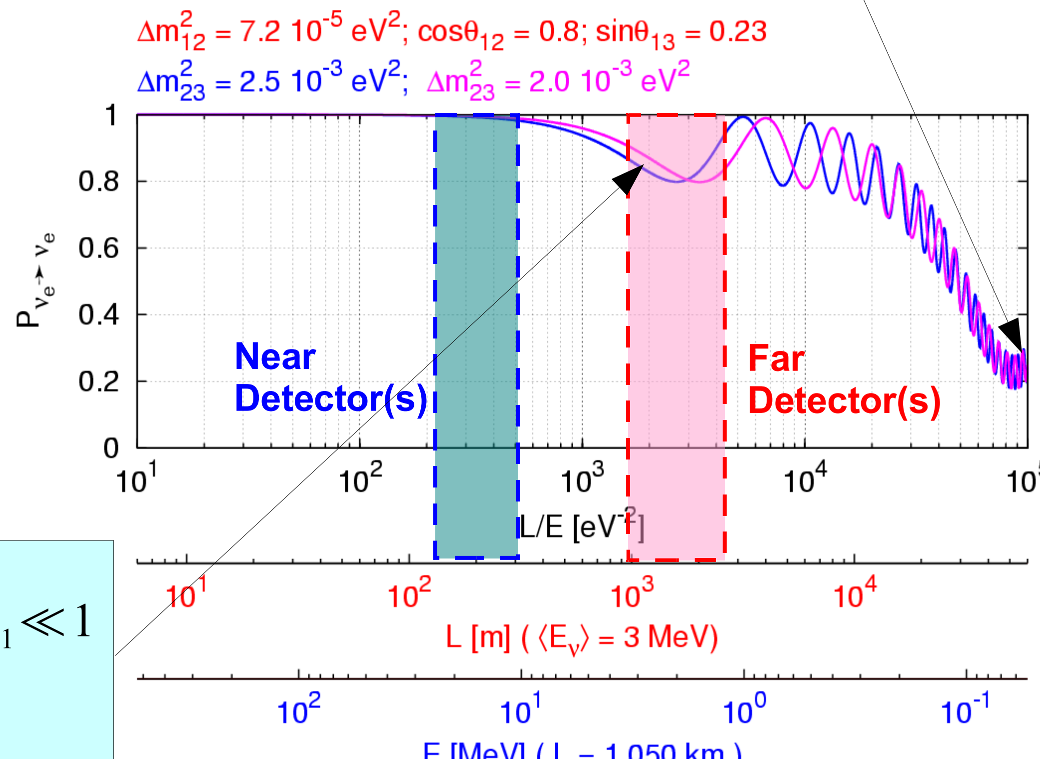


$$P_{ee} \simeq 1 - \sin^2(2\theta_{13})\sin^2\Delta_{31} - \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\Delta_{21} \qquad \Delta_{31} = \frac{\Delta m_{31}^2 L}{4E} \quad \Delta_{21} = \frac{\Delta m_{21}^2 L}{4E} \quad \bar{E} \simeq 4\,MeV$$



KamLAND $\bar{L} \simeq 170\,km \quad \Delta_{21} > 1 \quad \Delta_{31} \gg 1$

$$P_{ee} = 1 - \frac{1}{2}\sin^2(2\theta_{13}) - \cos^4\theta_{13}\sin^{\tilde{2}}(2\theta_{12})\sin^2\Delta_{21}$$

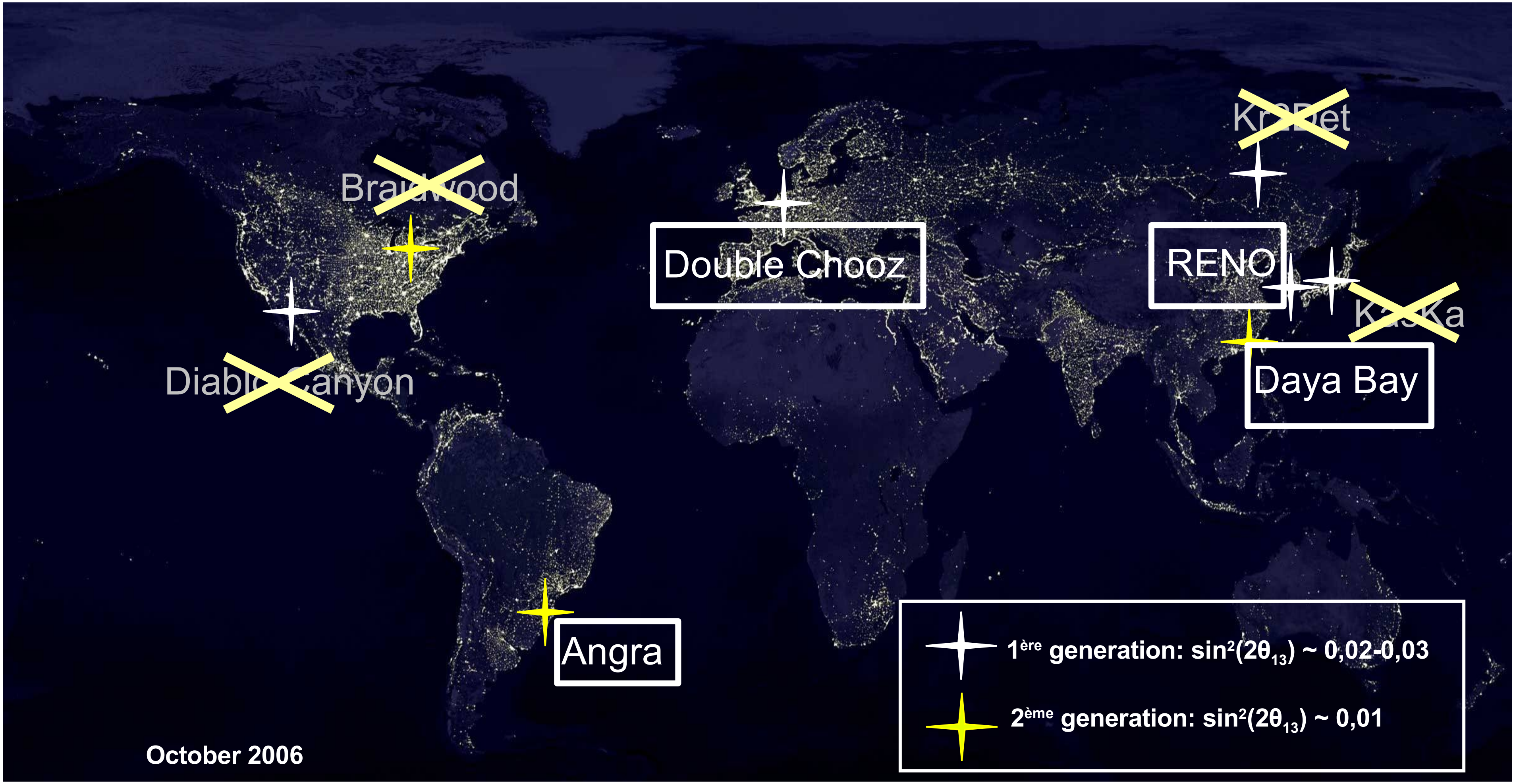


CHOOZ, Palo Verde $\bar{L} \simeq 1\,km \quad \Delta_{31} \simeq 1 \quad \Delta_{21} \ll 1$

$$P_{ee} \simeq 1 - \sin^2(2\theta_{13})\sin^2\Delta_{31}$$

The remaining four

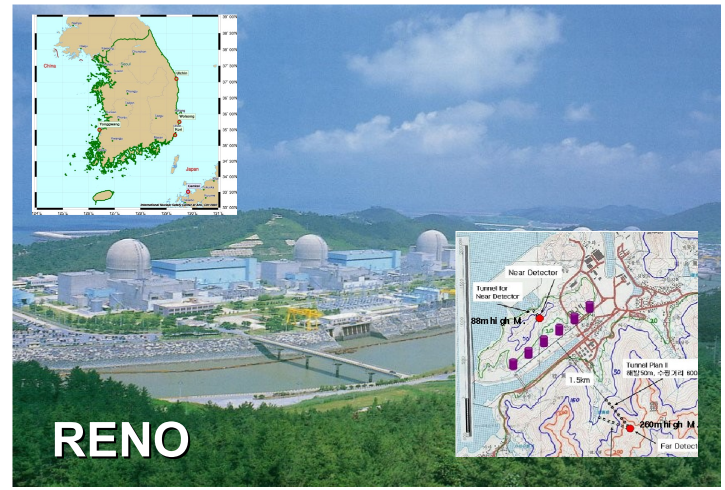
From 2001 to 2007



The remaining four

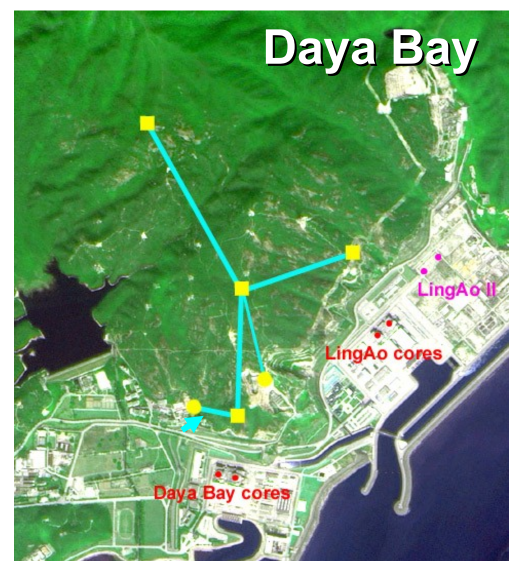
Aim on $\sin^2(2\theta_{13})$

First generation



0.02 - 0.03

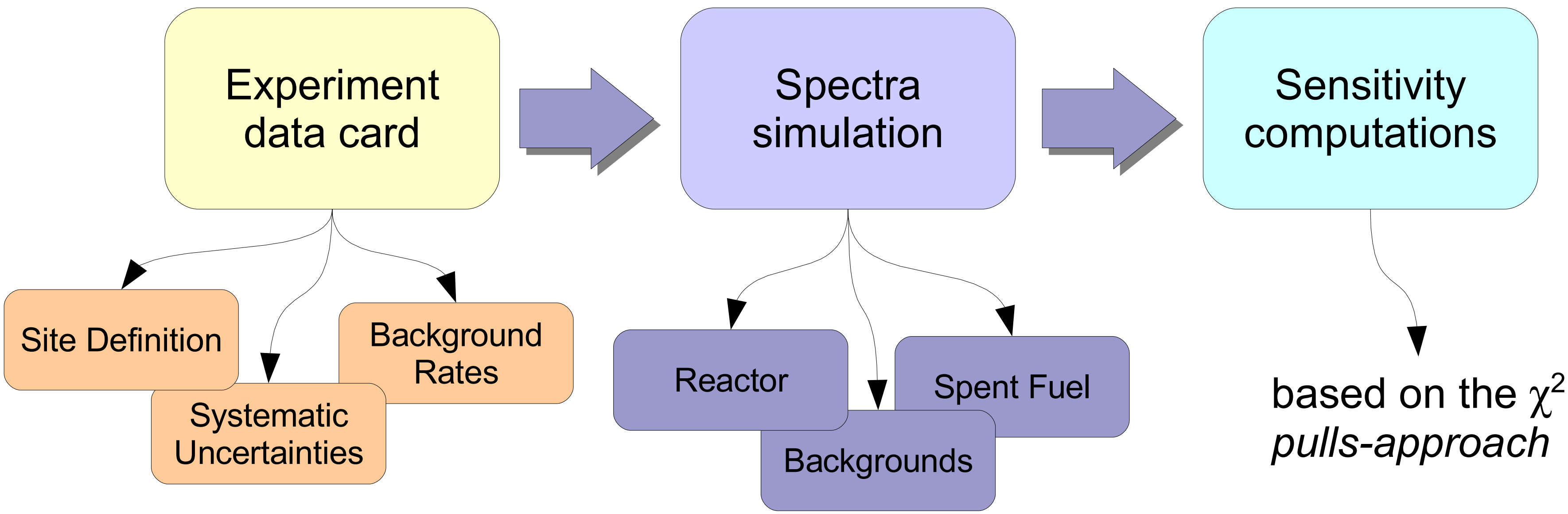
Second generation



< 0.01

=> Statistical and systematical errors → below the percent

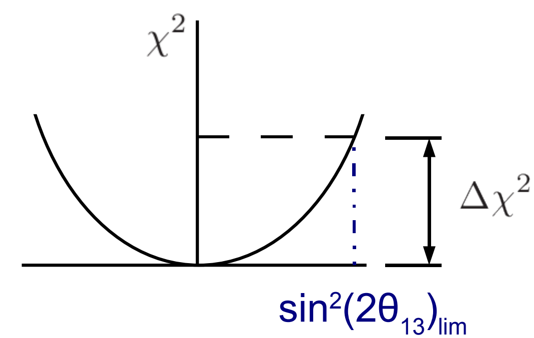
The 1st common comparison – The Method



$\Delta m^2_{31} = 2.5\ 10^{-3}\ \mathrm{eV}^2$ fixed

Set $\sin^2(2\theta_{13})^*$ to 0

Search for $\sin^2(2\theta_{13})$ such that $\Delta\chi^2$ = 2.71 (1 d.o.f., 90 % C.L.)



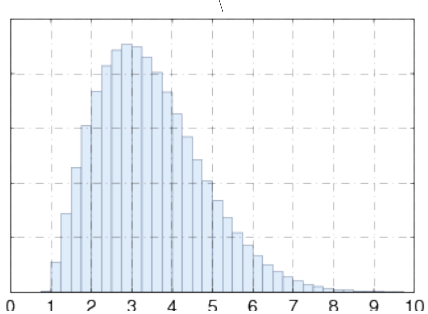
The χ^2

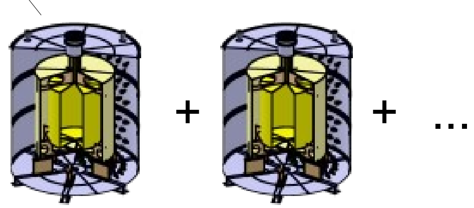
Data-Theory

Systematic shifts

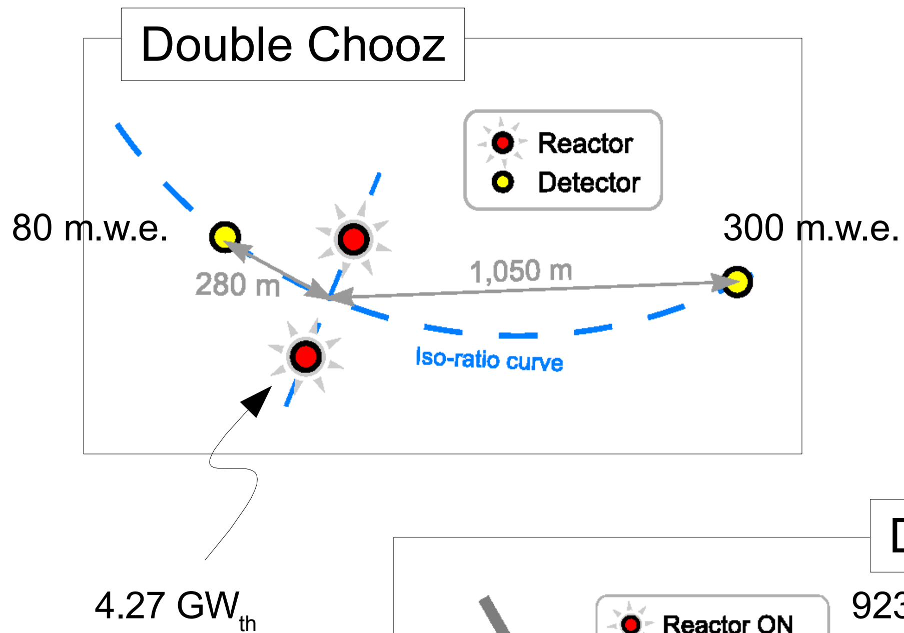
$$\chi^2 = \min_{\{\alpha_k\}} \sum_{\substack{i=1,\dots,N_b \\ D=D_1,\dots,D_{N_d}}} \left(\Delta_i^D - \sum_{k=1}^{K} \alpha_k S_{i,k}^D\right)^2 + \sum_{k,k'=1}^{K} \alpha_k W^{-1}_{k,k'} \alpha_{k'}$$

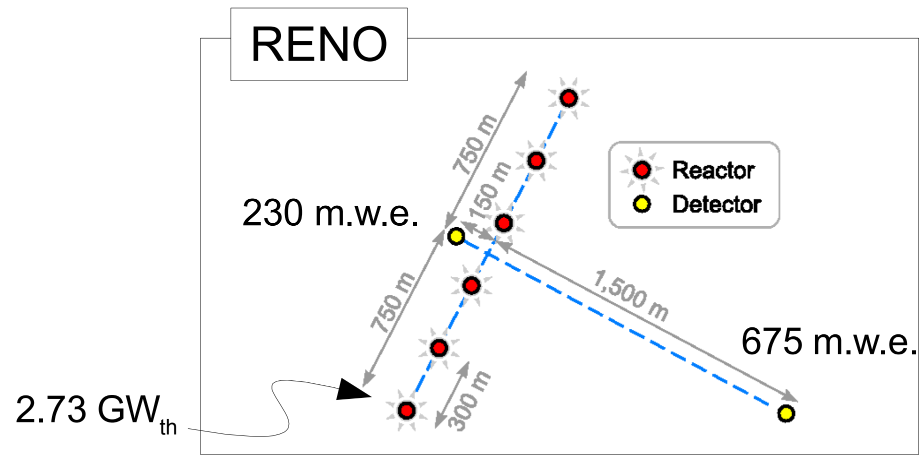
Systematic weights

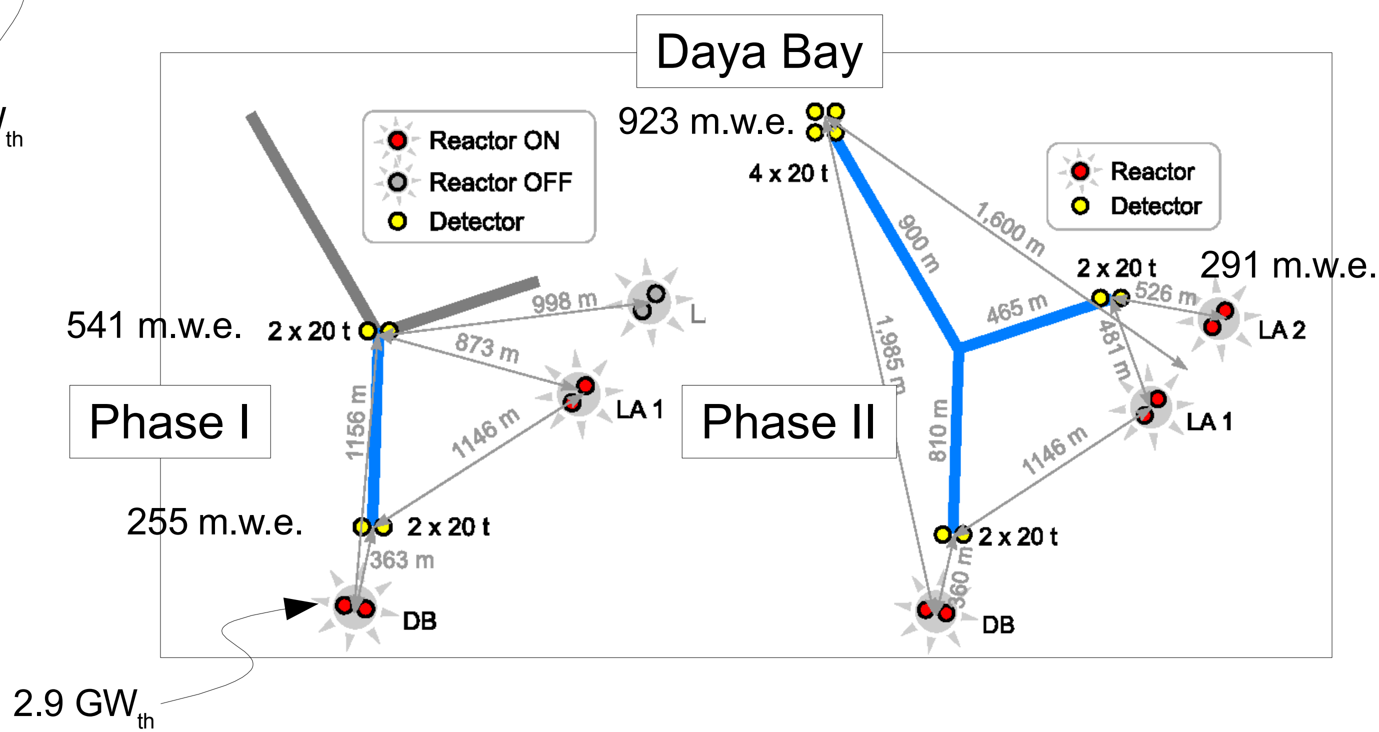




The inputs: *experiment site setups*







The inputs: *Systematics*

Common systematics used for all the experiments

Theoretical knowledge on reactor anti-neutrino spectrum

Detector common calibration (energy scale)

Detector relative calibration (energy scale)

Reactor power and fuel composition

$\sigma_{\rm abs}$	$\sigma_{\rm shp}$	$\sigma_{\rm scl}^{\rm abs}$	$\sigma_{\rm scl}^{\rm rel}$	$\sigma_{\rm pwr}$	$\sigma_{\rm cmp}$
2.0 %	2.0 %	0.5 %	0.5 %	2.0 %	2.3 %

assumed uncorrelated among reactors

Detector correlated systematics

Detector uncorrelated

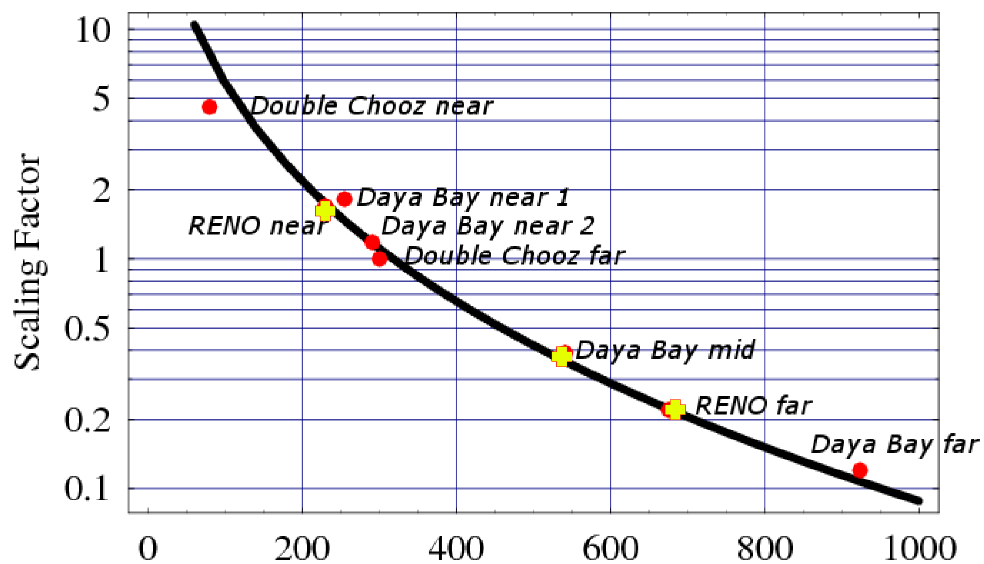
Special systematics

Relative error on $\overline{\nu}_e$ rate between detectors

σ_{rel} from 0.4 % to 0.6 %

The inputs: *Backgrounds rescaling*

Site	depth (m.w.e.), topology	Detailed simulation Φ_μ $m^{-2}\,s^{-1}$	Detailed simulation $\langle E_\mu \rangle$ GeV	Analytical model Φ_μ $m^{-2}\,s^{-1}$	Analytical model $\langle E_\mu \rangle$ GeV	DSF
DC near	80, flat	5.9	22	9.9	17	6.80
RENO near	230, hill	—	—	1.2	40	1.57
DB near 1	255, hill	1.2	55	0.9	44	1.32
DB near 2	291, hill	0.73	60	0.72	49	1.06
DC far	300, hill	0.61	61	0.67	50	1
DB mid	541, hill	0.17	97	0.15	71	0.32
RENO far	675, hill	—	—	0.084	94	0.20
DB far	923, hill	0.04	138	0.035	118	0.10

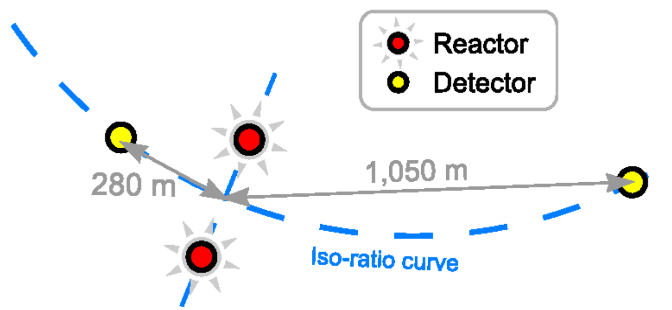


Detector Site	Accidental (d^{-1}) Original	Accidental (d^{-1}) DC ext.	μ-induced fast-n (d^{-1}) Original	μ-induced fast-n (d^{-1}) DC ext.	μ-induced $^9Li/^8He$ (d^{-1}) Original	μ-induced $^9Li/^8He$ (d^{-1}) DC ext.
Double Chooz near		13.60 ± 1.36		1.36 ± 1.36		9.52 ± 4.76
RENO near	—	7.10 ± 0.71	—	0.68 ± 0.68	—	5.40 ± 2.70
Daya Bay DB	1.86 ± 0.19	5.98 ± 0.60	0.50 ± 0.50	0.57 ± 0.57	3.7 ± 1.85	4.55 ± 2.27
Daya Bay LA	1.52 ± 0.15	4.76 ± 0.48	0.35 ± 0.35	0.45 ± 0.45	2.5 ± 1.25	3.63 ± 1.81
Double Chooz far	2.00 ± 0.20	—	0.20 ± 0.20	—	1.40 ± 0.70	—
Daya Bay mid	—	1.45 ± 0.14	—	0.14 ± 0.14	—	1.10 ± 0.57
RENO far	—	0.90 ± 0.09	—	0.09 ± 0.09	—	0.69 ± 0.35
Daya Bay far	0.12 ± 0.01	0.44 ± 0.04	0.03 ± 0.03	0.04 ± 0.04	0.26 ± 0.13	0.33 ± 0.17

Baseline sensitivity

Double Chooz

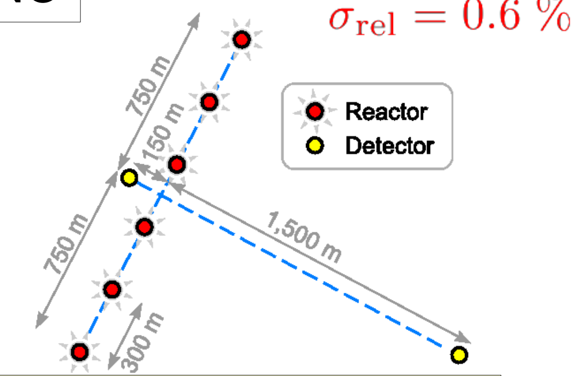
$\sigma_{\rm rel} = 0.6\ \%$



$$\sin^2(2\theta_{13})_{\rm lim} = 0.028$$

RENO

$\sigma_{\rm rel} = 0.6\ \%$

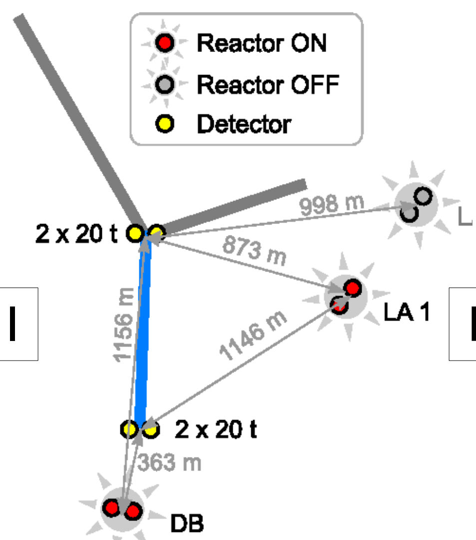


$$\sin^2(2\theta_{13})_{\rm lim} = 0.021$$

("0.02 - 0.03")

Daya Bay

Phase I

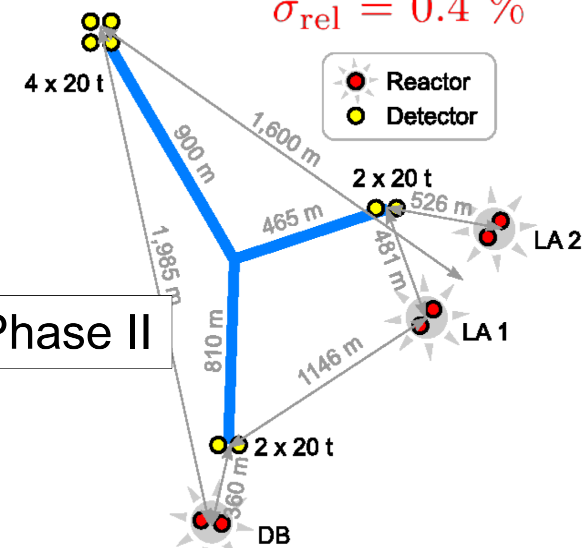


("0.035")

$$\sin^2(2\theta_{13})_{\rm lim} = 0.041$$

Phase II

$\sigma_{\rm rel} = 0.4\ \%$



$$\sin^2(2\theta_{13})_{\rm lim} = 0.011$$

("0.008")

legend

our computations

("quoted sensitivity in publications")

Pulls analysis: Relative contribution to χ^2

$$\chi^2 = \min_{\{\alpha_k\}} \sum_{\substack{i=1,\ldots,N_b \\ D=D_1,\ldots,D_{N_d}}} \left(\Delta_i^D - \sum_{k=1,\ldots,K} \alpha_k S_{i,k}^D \right)^2 + \sum_{k=1,\ldots,K} \alpha_k W_{k,k'}^{-1} \alpha_{k'}$$

	$\delta\chi_i^2$ in %	DC I	DC II	DB Mid	DB Full	RN
residuals	$\delta\chi_{N_1}^2$	—	3.0 %	4.3 %	1.2 %	1.5 %
	$\delta\chi_{N_2}^2$	—	—	—	3.0 %	—
	$\delta\chi_F^2$	29.6 %	37.8 %	23.5 %	30.6 %	34.5 %
pulls	$\delta\chi_{\rm abs}^2$	29.6 %	1.5 %	9.0 %	1.0 %	7.9 %
	$\delta\chi_{\rm shp}^2$	18.6 %	1.3 %	8.3 %	0.6 %	1.0 %
	$\delta\chi_{\rm rel}^2$	—	48.4 %	6.5 %	56.6 %	28.4 %
	$\delta\chi_{\rm scl,abs}^2$	6.8 %	1.2 %	6.1 %	0.1 %	0.1 %
	$\delta\chi_{\rm scl,rel}^2$	—	5.1 %	11.8 %	1.8 %	0.2 %
	$\delta\chi_{\rm bkg}^2$	1.1 %	0.8 %	0.4 %	0.2 %	0.5 %
	$\delta\chi_{\rm pwr}^2$	13.6 %	0.8 %	27.3 %	4.4 %	16.8 %
	$\delta\chi_{\rm cmp}^2$	0.1 %	0.0 %	0.6 %	0.1 %	9.0 %
	$\delta\chi_{\varepsilon}^2$	0.6 %	0.0 %	2.2 %	0.4 %	0.0 %
	$\sin^2(2\theta_{13})_{\rm lim}$	0.0544	0.0278	0.0410	0.0110	0.0213

Contribution of the "weigths" of the systematics to the χ^2

- Allows to stress out systematics which affect the most the θ_{13} sensitivity
  - Reactor power uncertainties
  - Detector relative normalization uncertainties
  - Detector energy scales

Sensitivity robustness w.r.t. systematics Double Chooz

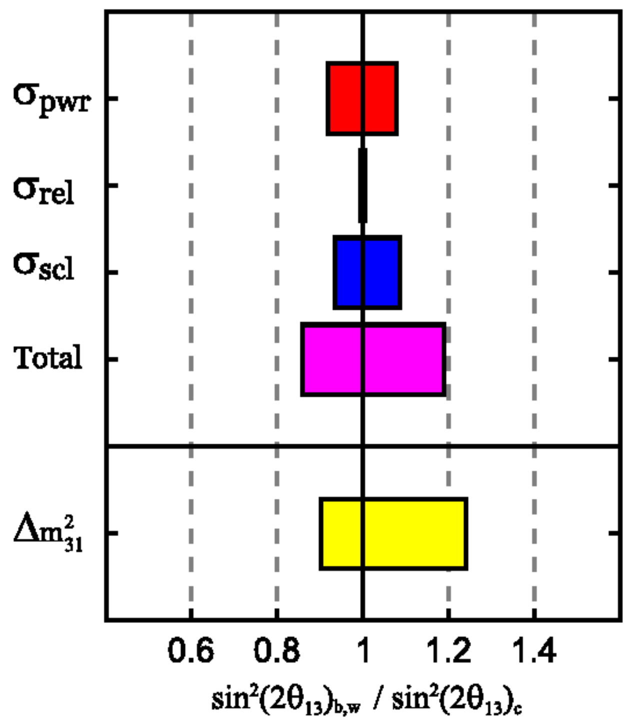
Base line option

σ_{abs}	2.0 %
σ_{shp}	2.0 %
σ_{rel}	0.45 %
σ_{pwr}	2.0 %
σ_{scl}^{abs} σ_{scl}^{rel}	0.5 %
Δm^2_{31}	2.5 10^{-3}

	Best	Worst
σ_{pwr}	0.6 %	3.0 %
σ_{rel}	0.2 %	0.6 %
σ_{scl}^{abs} σ_{scl}^{rel}	0.0 %	1.0 %
Δm^2_{31}	3.0 10^{-3}	2.0 10^{-3}

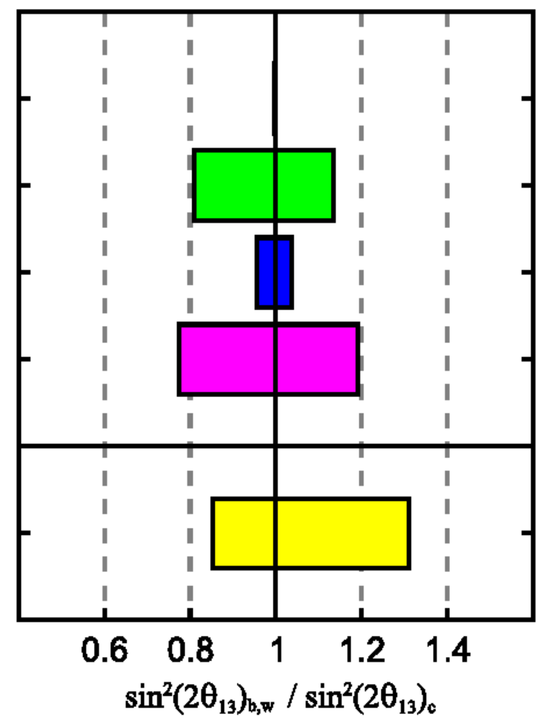
Double Chooz Phase I

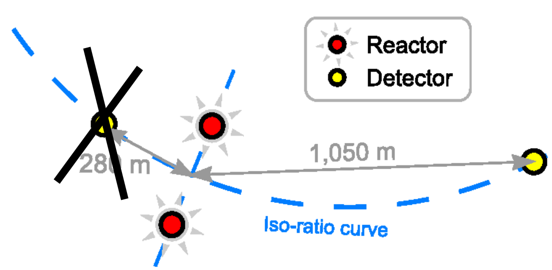
$\sin^2(2\theta_{13})_{lim} = 0.0537$ (90 % CL)

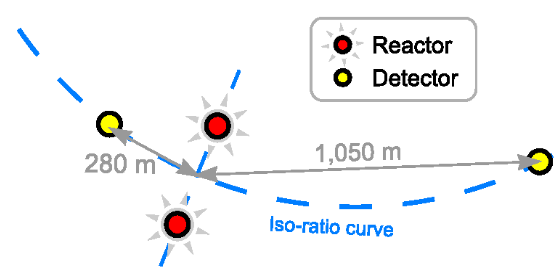


Double Chooz Phase II

$\sin^2(2\theta_{13})_{lim} = 0.0245$ (90 % CL)





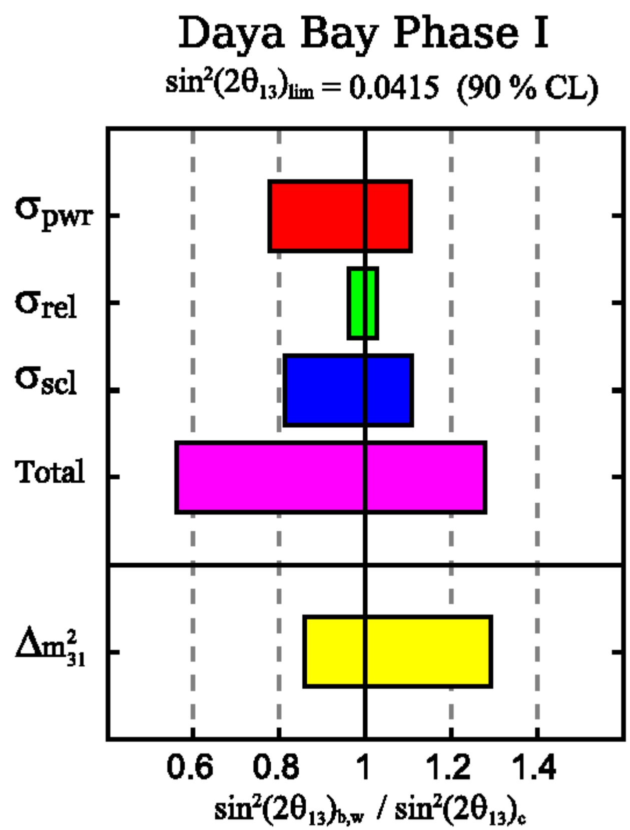


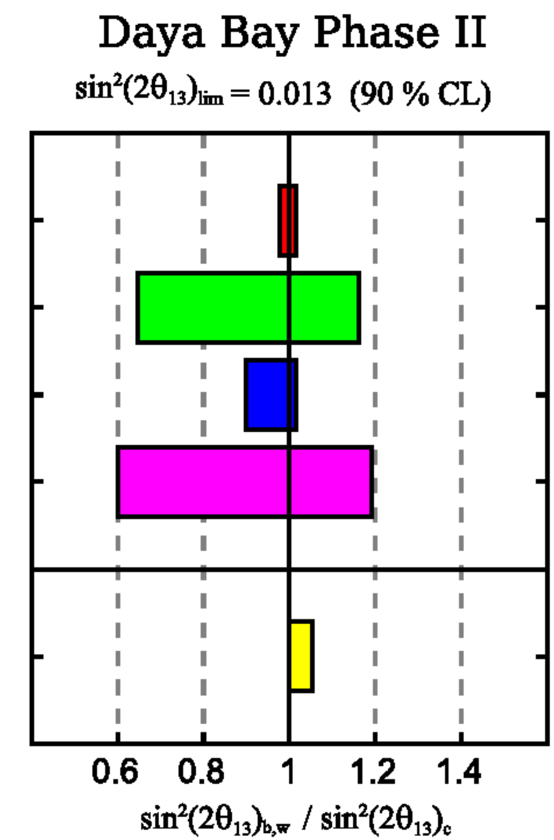
Sensitivity robustness w.r.t. systematics Daya Bay

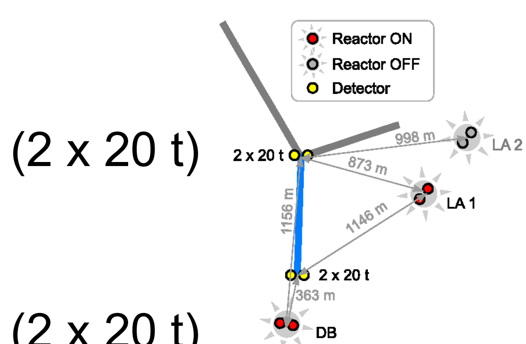
Base line option

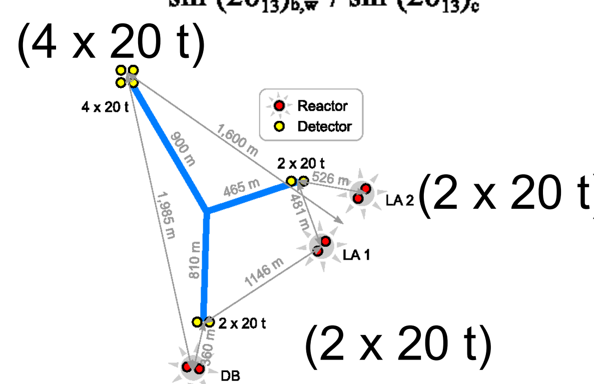
σ_{abs}	2.0 %
σ_{shp}	2.0 %
σ_{rel}	0.45 %
σ_{pwr}	2.0 %
σ_{scl}^{abs} σ_{scl}^{rel}	0.5 %
Δm^2_{31}	2.5 10^{-3}

	Best	Worst
σ_{pwr}	0.6 %	3.0 %
σ_{rel}	0.2 %	0.6 %
σ_{scl}^{abs} σ_{scl}^{rel}	0.0 %	1.0 %
Δm^2_{31}	3.0 10^{-3}	2.0 10^{-3}







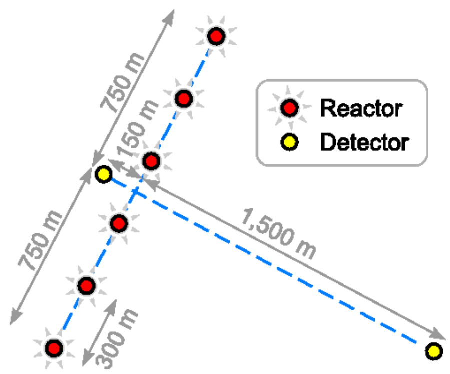


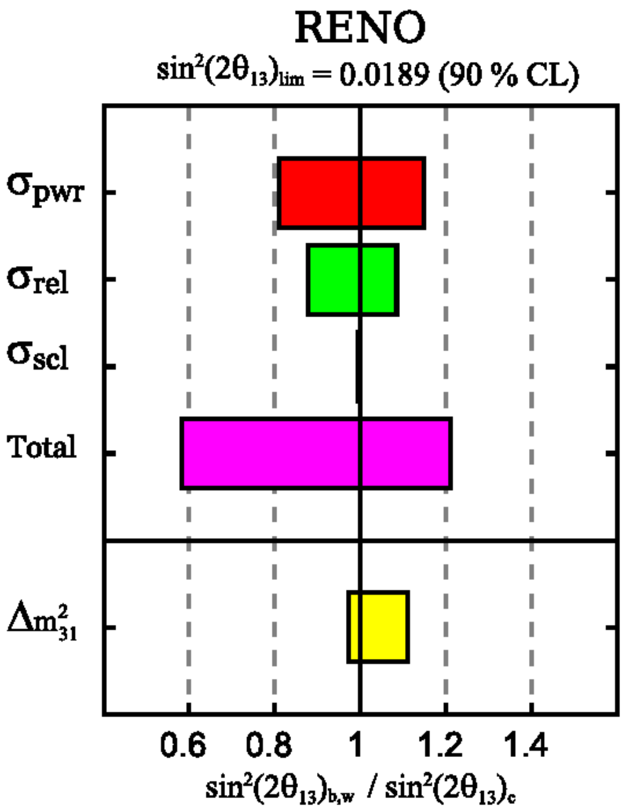
Sensitivity robustness w.r.t. systematics RENO

Base line option

σ_{abs}	2.0 %
σ_{shp}	2.0 %
σ_{rel}	0.45 %
σ_{pwr}	2.0 %
σ_{scl}^{abs} σ_{scl}^{rel}	0.5 %
Δm^2_{31}	2.5 10^{-3}

	Best	Worst
σ_{pwr}	0.6 %	3.0 %
σ_{rel}	0.2 %	0.6 %
σ_{scl}^{abs} σ_{scl}^{rel}	0.0 %	1.0 %
Δm^2_{31}	3.0 10^{-3}	2.0 10^{-3}





Global conclusion

arXiv:0704.0498v1 [hep-ex]

- ➔ 3 first generation experiments: **Double Chooz**, **RENO**
  sensitivity ~ 0.02 to 0.03 (depending on sytematics, Δm^2 value, and backgrounds)
  and **Daya Bay Phase I** with sensitivity ~ 0.04 to 0.05 (1 year) ~ 0.03 to 0.035 (3 years)
- A second generation experiment: **Daya Bay** with forseen sensitivity ~ 0.01.
- ➔ To go below 0.01 with reactor experiments seems difficult.

Specific conclusion

First generation

- **Double Chooz**: ~ 0.02-0.03
  - Few reactors, good relative power. Overburden sufficient.
  - Detector locations => insensitive to fuel composition and power uncertainties of the cores;
    Full performence of the far detector position (for $\Delta m^2 > 2.5\ 10^{-3}\ eV^2$) for a 0.02-0.03 sensitivity.
  - To go below 0.01, one need to go farther...
- **RENO**: ~ 0.02-0.03
  - Good site: overburden/available power.
  - Core locations = disfavorable (same sensitivity with only the 2 central cores of the NPP)
  - Sensitive to fuel composition and power uncertainties of the cores (even with 3 small detectors of 200-300 kg).
  - => even with 2 x more events than DC, same field of sensitivity as DC.
- **Daya Bay Phase I (?)**: ~ 0.03-0.05 (1 to 3 years?)
  - Clearly suffers from the NPP cores spread.
  - Sensitive to a lot of systematics => sensitivity will rely on difficult analyses, estimations of all these systematics
  - 2 x 40 tons is already a large experiment...!

Specific conclusion

Second generation

- **Daya Bay**: ~ 0.01
  - Very good site for its overburden
  - The power appealing is a lure especially for Daya Bay Phase I: the 2 cores of Daya Bay alone (w/o LA I) gives a better sensitivity
  - It remains some impact of the uncertainty on the NPP core powers on the sensitivity