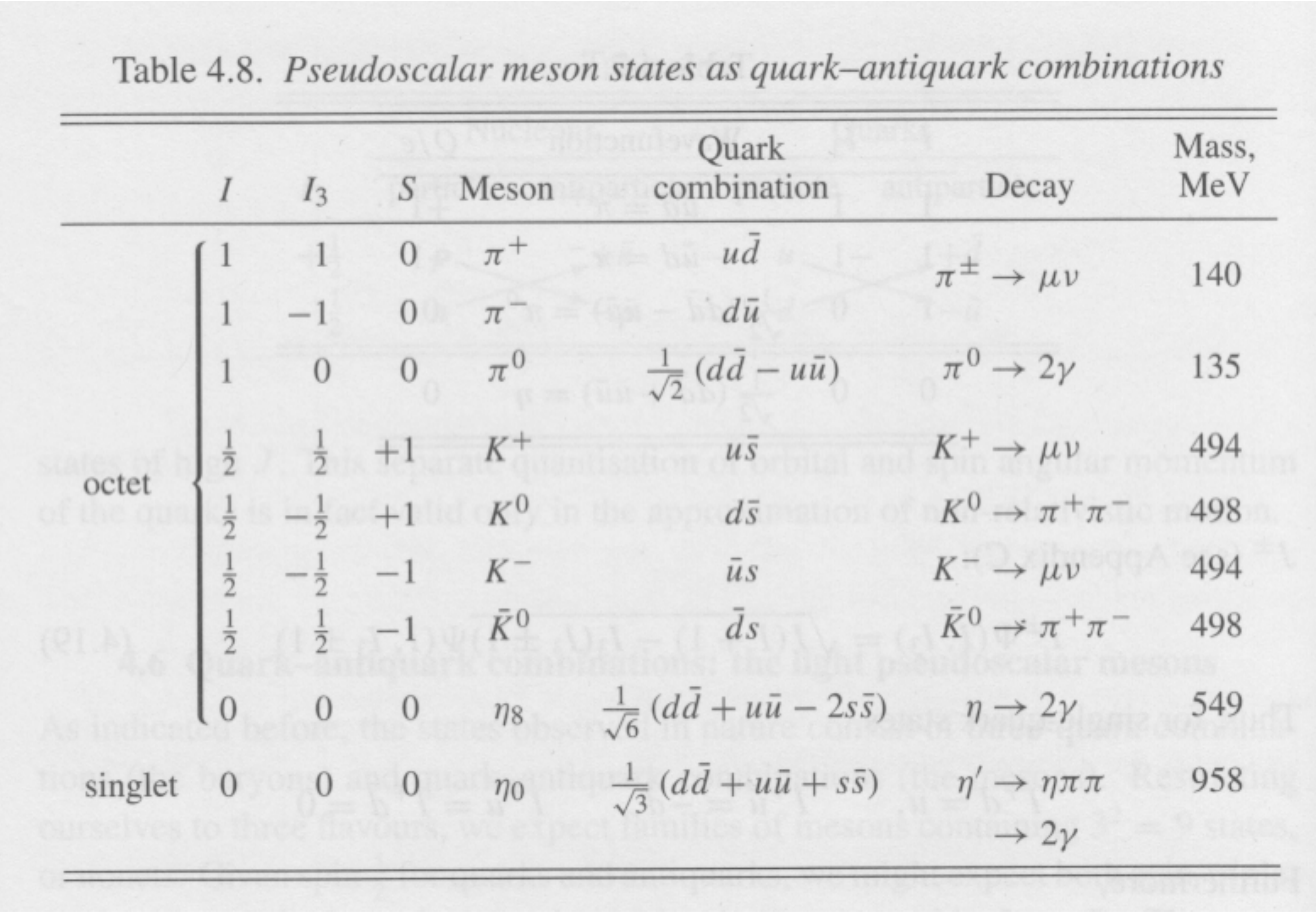


Table 4.8. *Pseudoscalar meson states as quark–antiquark combinations*

	I	I_3	S	Meson	Quark combination	Decay	Mass, MeV
octet	1	1	0	π^+	$u\bar{d}$	$\pi^\pm \to \mu\nu$	140
	1	−1	0	π^-	$d\bar{u}$		
	1	0	0	π^0	$\frac{1}{\sqrt{2}}(d\bar{d} - u\bar{u})$	$\pi^0 \to 2\gamma$	135
	$\frac{1}{2}$	$\frac{1}{2}$	+1	K^+	$u\bar{s}$	$K^+ \to \mu\nu$	494
	$\frac{1}{2}$	$-\frac{1}{2}$	+1	K^0	$d\bar{s}$	$K^0 \to \pi^+\pi^-$	498
	$\frac{1}{2}$	$-\frac{1}{2}$	−1	K^-	$\bar{u}s$	$K^- \to \mu\nu$	494
	$\frac{1}{2}$	$\frac{1}{2}$	−1	$\bar{K}^0$	$\bar{d}s$	$\bar{K}^0 \to \pi^+\pi^-$	498
	0	0	0	η_8	$\frac{1}{\sqrt{6}}(d\bar{d} + u\bar{u} - 2s\bar{s})$	$\eta \to 2\gamma$	549
singlet	0	0	0	η_0	$\frac{1}{\sqrt{3}}(d\bar{d} + u\bar{u} + s\bar{s})$	$\eta' \to \eta\pi\pi$ $\to 2\gamma$	958

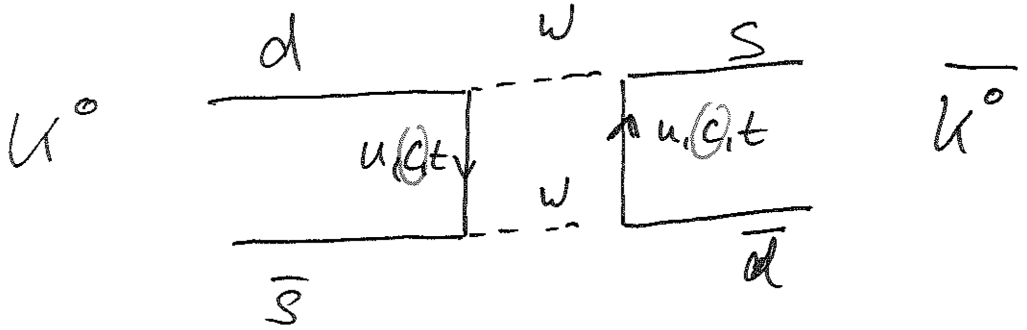
(Aus Perkins)

$K^0, \bar{K}^0$ Intensitäten oszillieren mit einer Frequenz

$\Delta m = m_L - m_S \quad (= E_L - E_S = \omega_L - \omega_S = \underline{\underline{\omega'}}) \quad (\hbar = c = 1)$

Aus Exp. Beobachtung : $\Delta m = (3{,}491 \pm 0{,}009) \cdot 10^{-12}$ MeV

$\frac{\Delta m}{m} = 7 \cdot 10^{-15}$, $\Delta m \, \tau_S \simeq$



$\Delta S = 2$

Δm kann aus Box-Diagramm berechnet werden (wenn m_q, V_{CKM} bekannt)

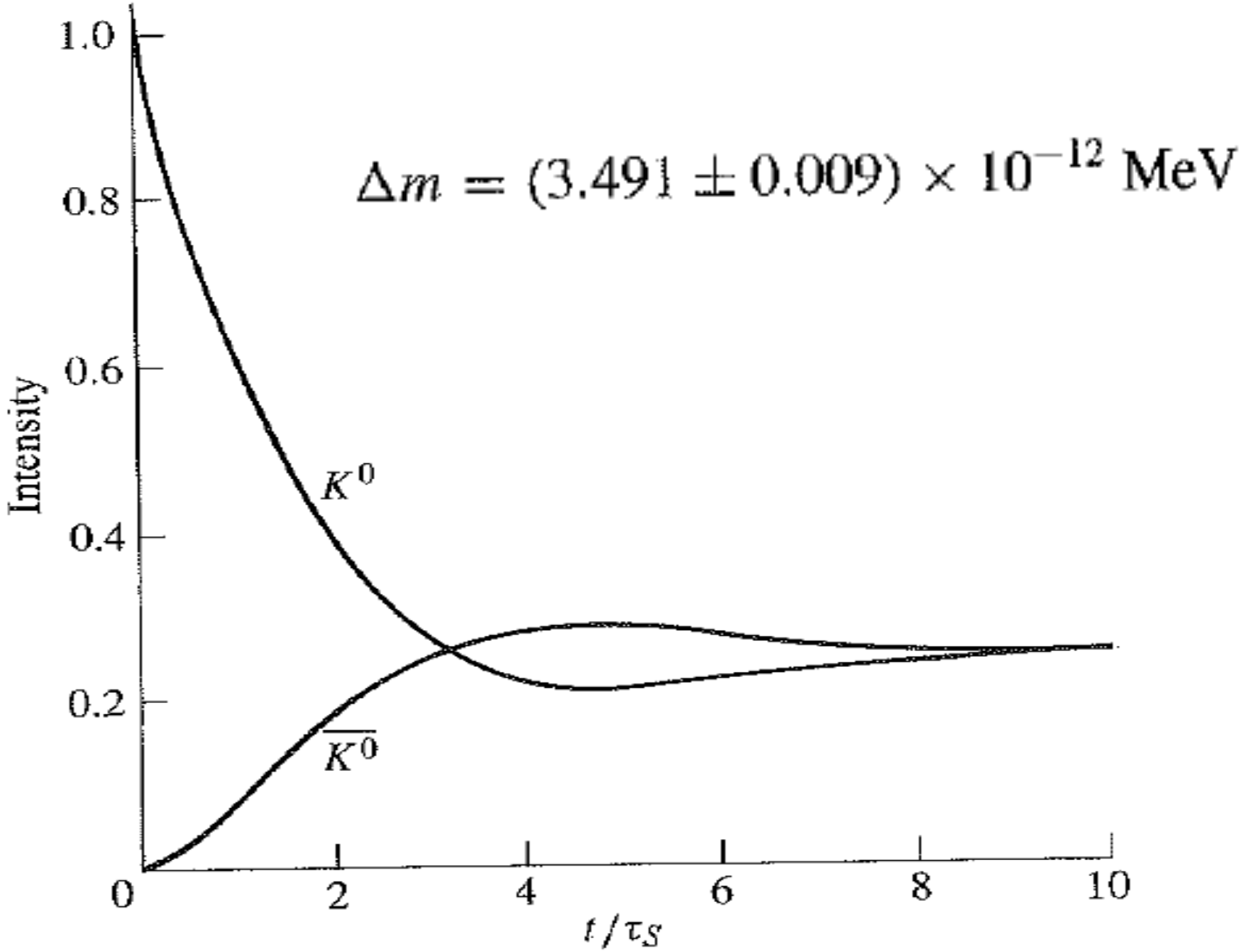
$$\Delta m \simeq \frac{G^2}{4\pi} m_K f_K^2 m_c \cos^2\theta_c \sin^2\theta_c$$

m_K : Kaon-Masse

f_K : Kaon Decay Konstante $\approx 1{,}2\, m_\pi$

m_c : Charm-Quark Masse (c-Quark dominiert wg. CKM Matrix)

Ko Ko-bar oscillations



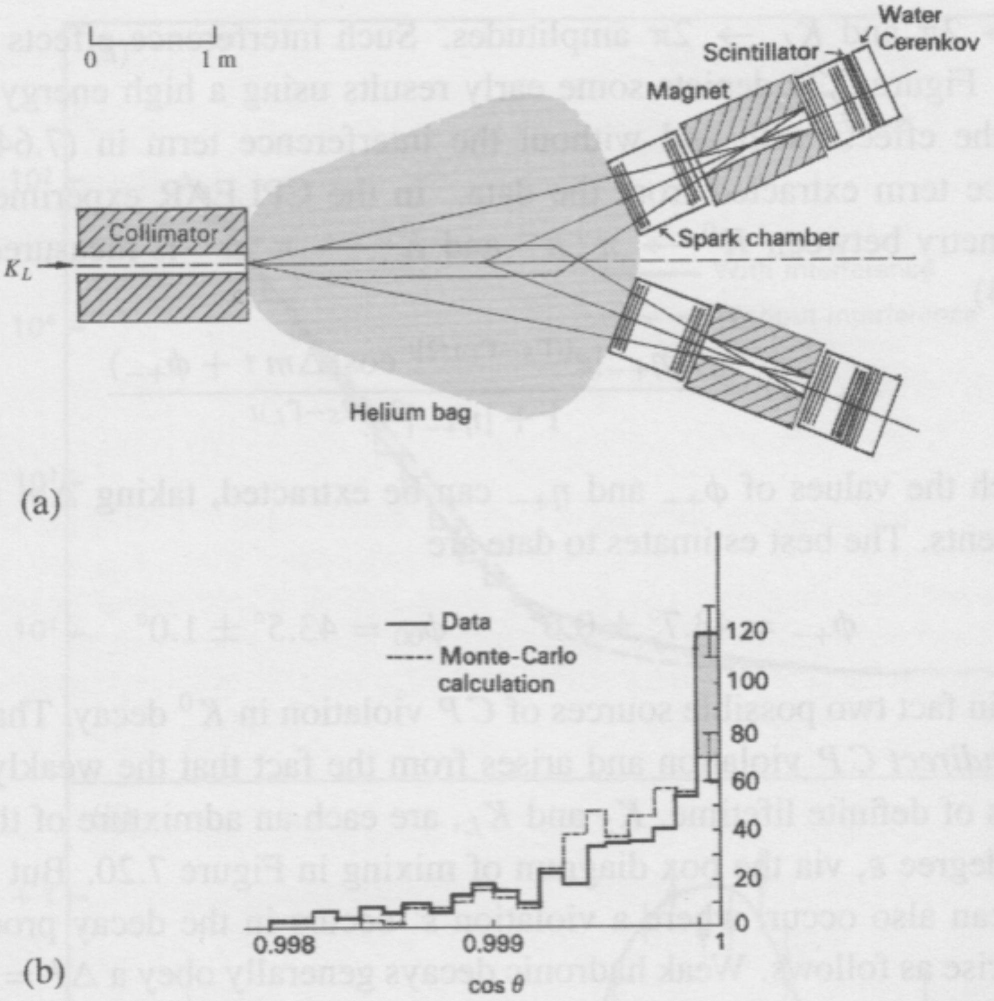


Fig. 7.22. (a) Arrangement of Christenson *et al.* (1964) demonstrating the CP-violating decay $K_L \rightarrow \pi^+\pi^-$. K_L decays are observed in a helium bag, the charged products being analysed by two magnet spectrometers instrumented with spark chambers and scintillators. (b) Rare two-pion decays are distinguished from the common three-pion decays by the invariant mass of the pair (490 MeV $< M_{\pi\pi} <$ 510 MeV) and the direction, θ, of the resultant momentum vector. The $\cos\theta$ distribution is that expected from three-body decays, plus 50 events (shaded) collinear with the beam and attributed to the two-pion decay mode.

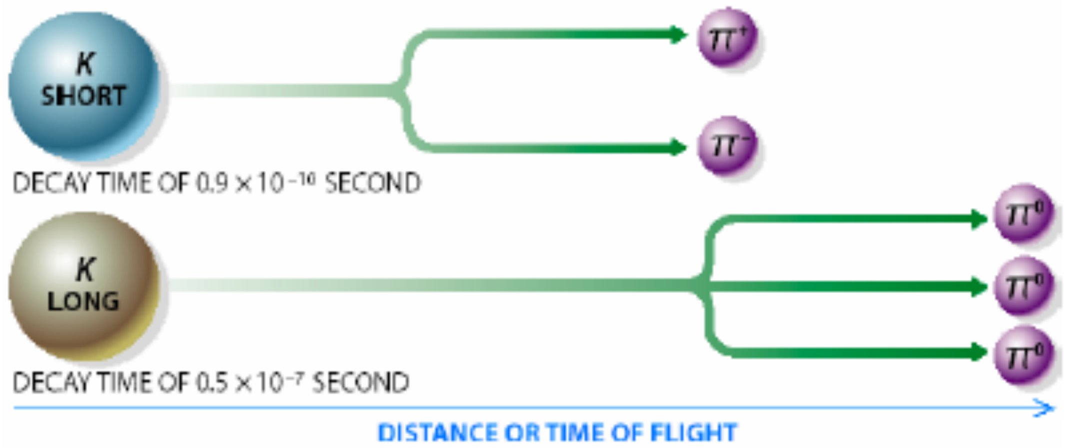
(Aus Perkins)

CP violation in K_L decays

- CP conservation implies

$CP = +1$

$CP = -1$



- CP violation in K_L decay observed in 1964

0.2% of the time!

Fundamental difference between matter and anti-matter vice versa: aus $K^0 - \bar{K}^0$ Oszillation konnte die Masse des Charm-Quarks vorhergesagt werden.

CP-Verletzung im K^0 Zerfall

Christenson, Cronin, Fitch und Turlay (1966), (Nobelpreis 1980)

Beobachtung: $K_L \to \pi^+ \pi^-$ mit Branching ratio $Br\left(\frac{2\pi}{3\pi}\right) \simeq 2 \cdot 10^{-3}$

Interpretation: kleine Beimischung einer $CP = +1$ Amplitude in K_L
(bzw. $CP = -1$ in K_S)

$$|K_L\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}} \Big(\underset{\substack{\uparrow \\ CP=-1}}{|K_2\rangle} + \varepsilon \underset{\substack{\uparrow \\ CP=+1}}{|K_1\rangle} \Big)$$

$$|K_S\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}} \Big(\underset{CP=+1}{|K_1\rangle} - \varepsilon \underset{CP=-1}{|K_2\rangle} \Big)$$

mit reinen Zuständen $|K_1\rangle$ $(CP=+1)$ und $|K_2\rangle$ $(CP=-1)$

ε kleiner Parameter, der Grad der CP Verletzung quantifiziert

übliche Notation

$$|\eta_{+-}| = \frac{\text{ampl}(K_L \to \pi^+\pi^-)}{\text{ampl}(K_S \to \pi^+\pi^-)} = (2{,}29 \pm 0{,}02)\cdot 10^{-3}$$

ähnlich

$$|\eta_{00}| = \frac{\text{ampl}(K_L \to \pi^0\pi^0)}{\text{ampl}(K_S \to \pi^0\pi^0)} = (2{,}28 \pm 0{,}02)\, 10^{-3}$$

Da nun beide K_L und K_S in 2π zerfallen können, erwartet man eine Modifizierung der Intensität aufgrund Interferenzeffekte

$$I_{2\pi}(t) = I_{2\pi}(t=0)\left[e^{-\Gamma_S t} + |\eta_{+-}|^2 e^{-\Gamma_L t} + 2|\eta_{+-}|\, e^{-((\Gamma_L+\Gamma_S)/2)\, t} \cdot \cos(\Delta m t + \phi_{+-})\right.$$

mit ϕ_{+-} Phasenverschiebung zw. $K_S \to 2\pi$ und $K_L \to 2\pi$, $\phi_{+-} = 44°$

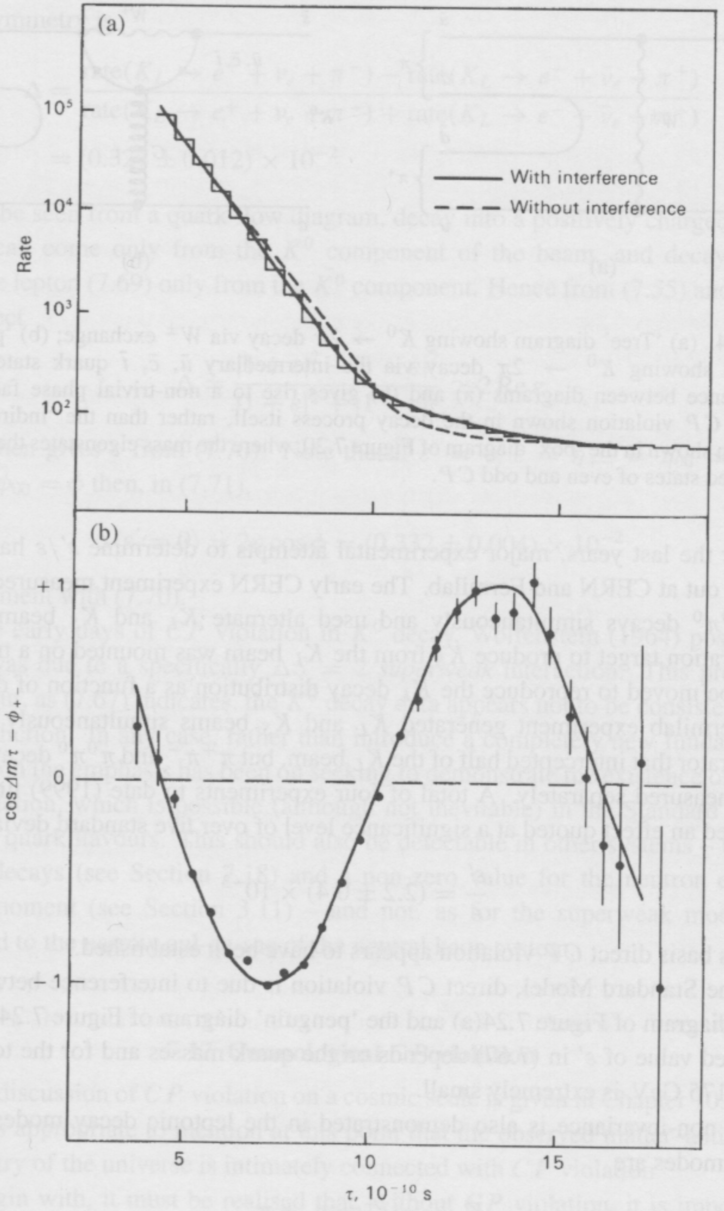


Fig. 7.23. (a) Event rates for $K^0 \rightarrow \pi^+\pi^-$ decays as a function of proper time. The best fit in the upper graph needs the existence of interference between K_L and K_S amplitudes. (b) The interference term extracted from the results: from the fit one can obtain the $K_L - K_S$ mass difference Δm and the phase angle ϕ_{+-} between the two amplitudes. (After Geweniger *et al.* 1974.)

(Aus Perkins)

ε : indirekte CP-Verletzung über Box-Diagramme

ε' : direkte CP-Verletzung im Zerfallsprozess

siehe Folien

CP-Verletzung auch in semi-leptonischen Zerfälle von K_L beobachtet:

$$K_L \to e^+ + \nu_e + \pi^-$$

$$K_L \to e^- + \bar{\nu}_e + \pi^+$$

Assymetrie :

$$\Delta \equiv \frac{\text{Rate}(K_L \to e^+ \nu_e \pi^-) - \text{Rate}(K_L \to e^- \bar{\nu}_e \pi^+)}{\text{Rate}(\;\;"\;\;) + \text{Rate}(\;\;"\;\;)}$$

$$= (0{,}327 \pm 0{,}012)\, 10^{-2}$$

- Ohne CP Verletzung : unmöglich Materie von Anti-Materie zu unterscheiden (zumindest auf kosmischen Skalen). Auf Erde haben wir e^- :≡ Materie ⇒ e^+ ⇒ Anti-Materie
  Mit CP-Verletzung im Kaonensystem haben wir eine eindeutige Definition von Materie und Anti-Materie machen

⇒ Positronen (Anti-Materie) ist detektiert als das Lepton welches häufiger (0,3%) in K_L-Zerfällen produziert werden

- CP Verletzung nötig, damit heutige Dominanz der Materie über Anti-Materie erklärt werden kann (Sacharov Kriterien)

Aber: Stärke der CP Verletzung im SM ist nicht ausreichend!

Aktuell: Messung CP Verletzung im B-Mesonen
⇒ Belle-II (Gruppe TUM, MPI)

Zukunft: • Messung der CP-Verletzung im Lepton-Sektor
⇒ Long baseline Experimente TUM (Laguna LBNO)
USA: 2014 „P5": LBN Facility)
long baseline ν

Fermilab $\xrightarrow[10^3 km]{}$ Homestake (LAr-Detektor)
(auch Proton-Zerfall)

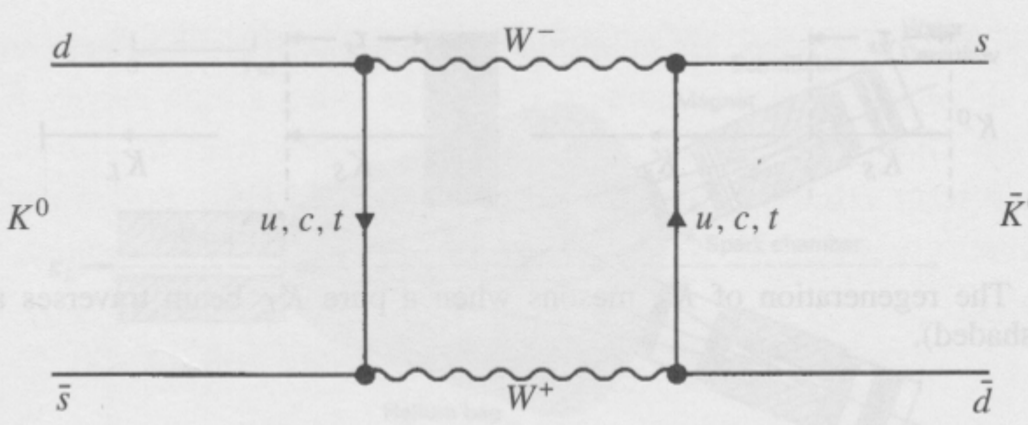


Fig. 7.20. Box diagram for $K^0 \to \bar{K}^0$ transition.

'indirekte' CP Verletzung

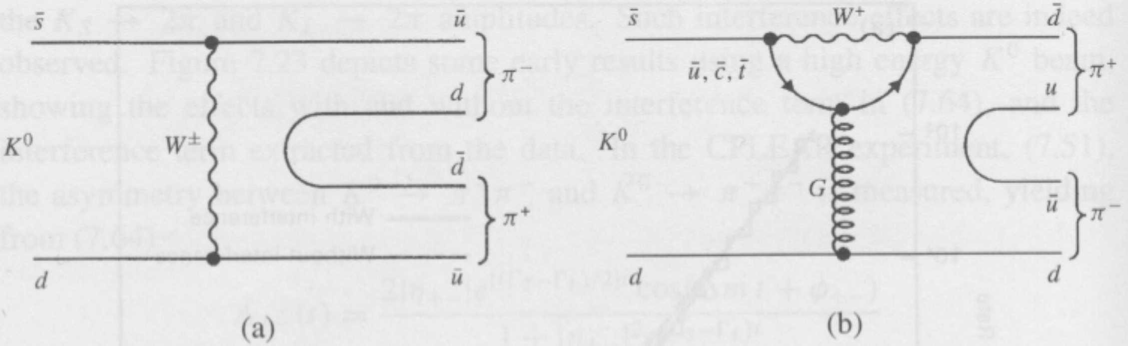


Fig. 7.24. (a) 'Tree' diagram showing $K^0 \to 2\pi$ decay via $W^\pm$ exchange; (b) 'penguin' diagram showing $K^0 \to 2\pi$ decay via the intermediary $\bar{u}$, $\bar{c}$, $\bar{t}$ quark states. The interference between diagrams (a) and (b) gives rise to a non-trivial phase factor and 'direct' CP violation shown in the decay process itself, rather than the 'indirect' CP violation shown in the 'box' diagram of Figure 7.20, where the mass eigenstates themselves are mixed states of even and odd CP.

'direkte' CP Verletzung

(Aus Perkins)

CP violation with D and B Mesons

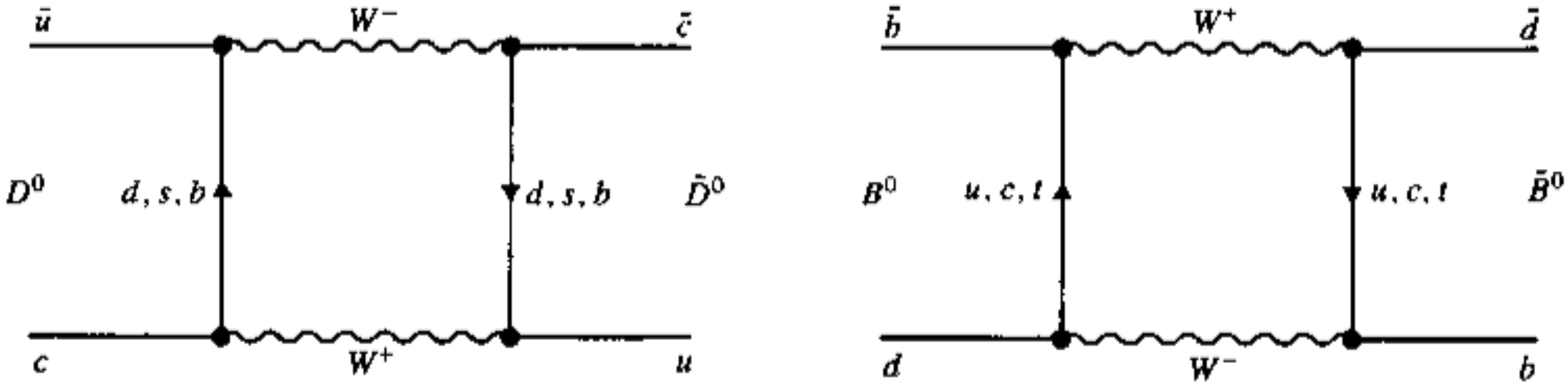


Fig. 7.25. Box diagrams for D^0–$\bar{D}^0$ mixing and B^0–$\bar{B}^0$ mixing, analogous to that for K^0–$\bar{K}^0$ in Figure 7.22.

B-Mesons favored for CPV studies: BaBar, Belle/Belle-II

- Beobacht $0\nu\beta\beta$ Zerfall ⇒ CP Verletzung
  Majorana Phasen $(\alpha_1, \alpha_2)\,(\neq \delta)$ zusätzlich
  zu δ-Phase von Dirac Teilch!

ν-Oszillationen:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

$$\left.\begin{aligned}\nu_1(t) &= \nu_1(0)\, e^{-iE_1 t}\\ \nu_2(t) &= \nu_2(0)\, e^{-iE_2 t}\end{aligned}\right\} \quad \nu_e(t) = \nu_e\left(\cos^2\theta\, e^{-iE_1 t} + \sin^2\theta\, e^{-iE_2 t}\right)$$

$$P_{ee} = \left|\frac{\nu_e(t)}{\nu_e(0)}\right|^2$$

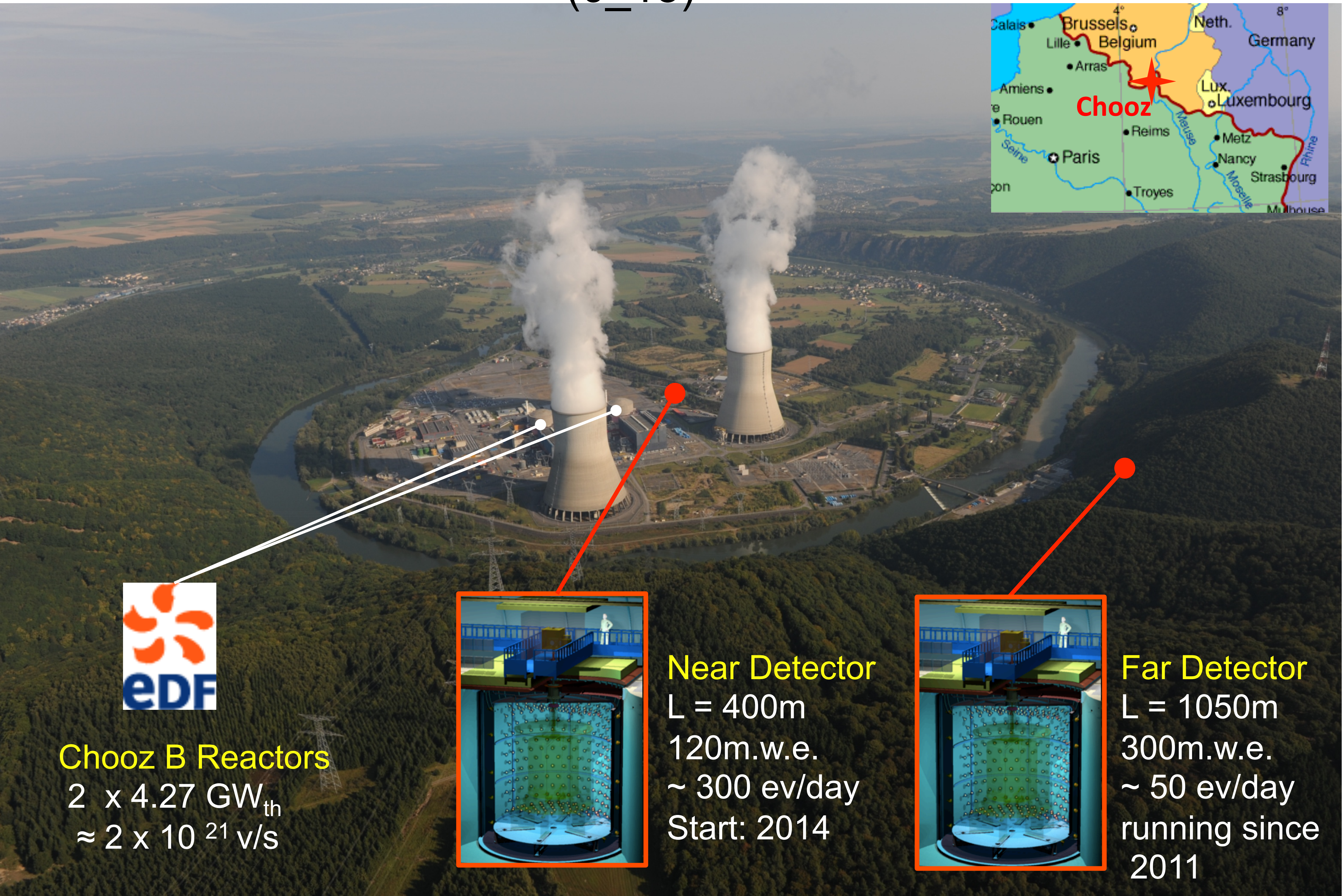
$$= \cos^4\theta + \sin^4\theta + \sin^2\theta\cos^2\theta\left\{e^{i(E_2-E_1)t} + e^{-i(E_2-E_1)t}\right\}$$

$$E_i \simeq p + \frac{m_i^2}{2p}$$

$$P_{ee} = 1 - \underset{\substack{\uparrow\\ \text{Amplitude}}}{\sin^2 2\theta}\ \sin^2\left[\frac{\Delta m^2\, t}{4\underset{\substack{\uparrow\\ \text{Frequenz}}}{E}}\right]$$

$$\Delta m^2 := m_2^2 - m_1^2$$

Neutrino oscillation: The Double Chooz Experiment (θ_13)



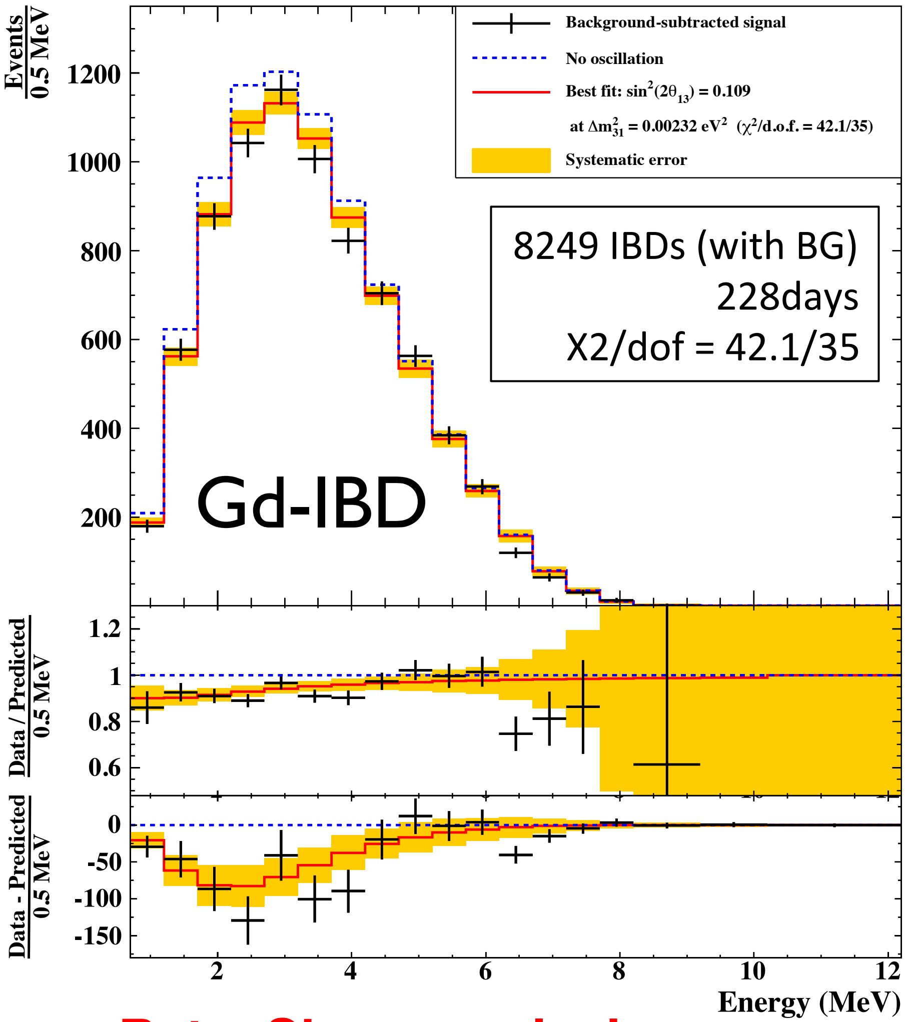
Chooz B Reactors
2 x 4.27 GW_{th}
≈ 2 x 10^{21} ν/s

Near Detector
L = 400m
120m.w.e.
~ 300 ev/day
Start: 2014

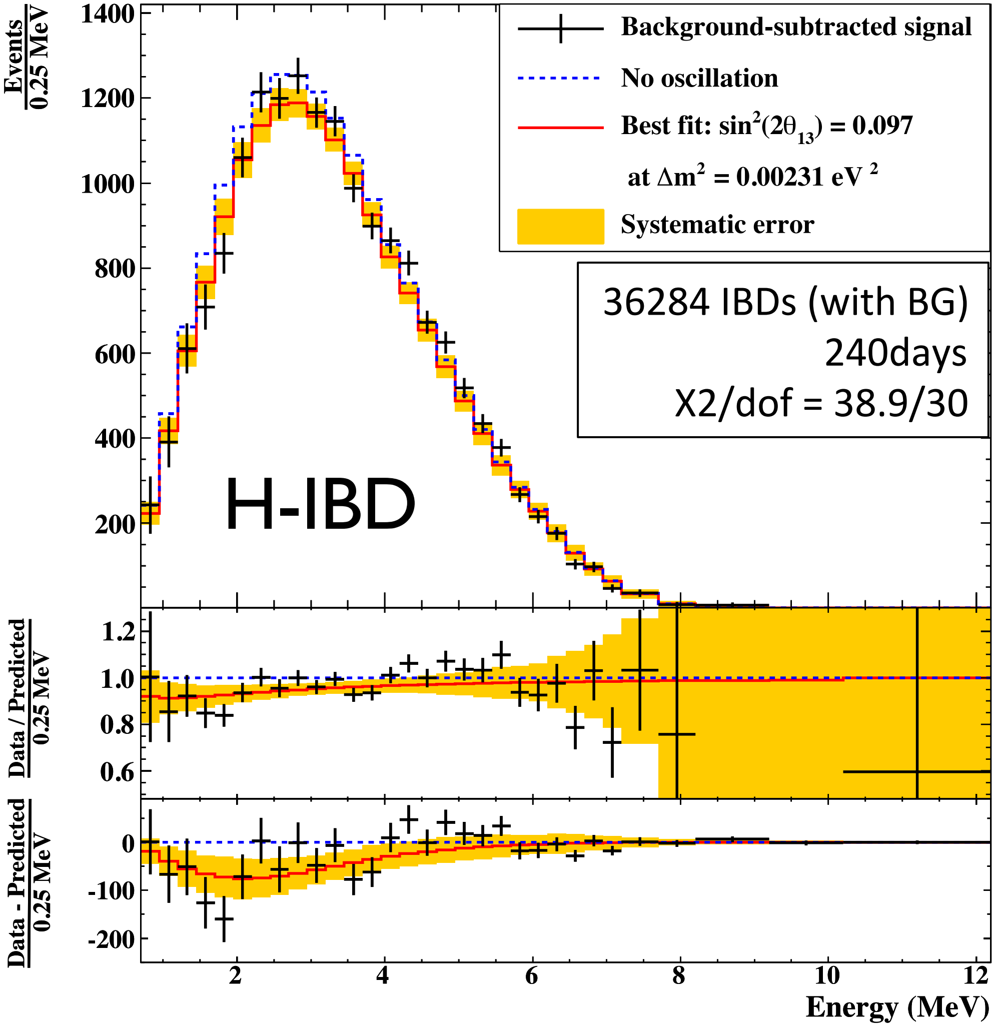
Far Detector
L = 1050m
300m.w.e.
~ 50 ev/day
running since 2011

Double Chooz – Published Resu

Phys. Rev. D86 (2012) 052008



Phys. Lett. B723 (2013) 66-70



Rate+Shape analysis:
$\sin^2 2\theta_{13} = 0.109 \pm 0.039$

$\sin^2 2\theta_{13} = 0.097 \pm 0.048$

Double Chooz – latest results

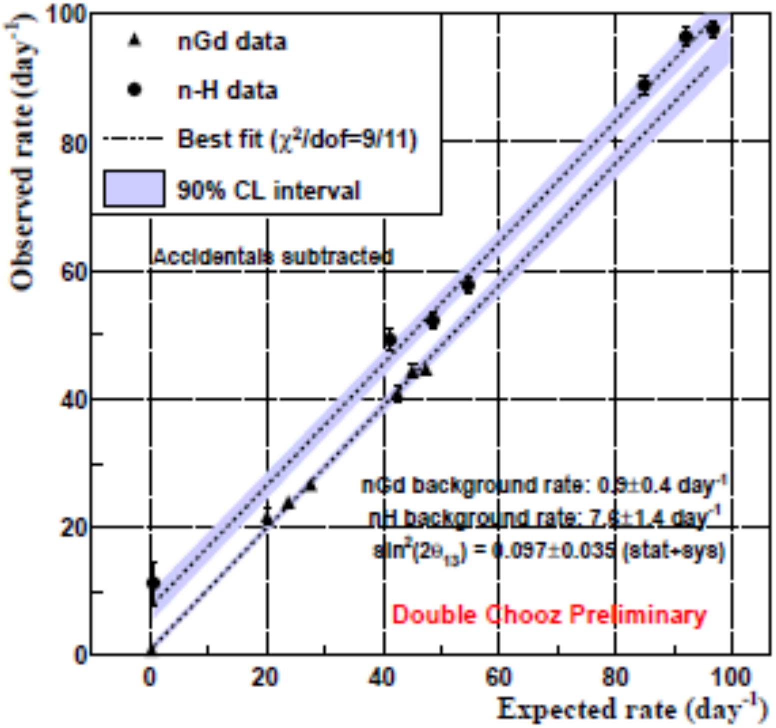
- **Reactor Rate Modulation analysis**

  rate only, Gd + H combined

  $\sin^2 2\theta_{13}$= 0.097 ±0.035

  arXiv 1401.5981

  accepted by PLB



- **Combined Gd + H analysis**

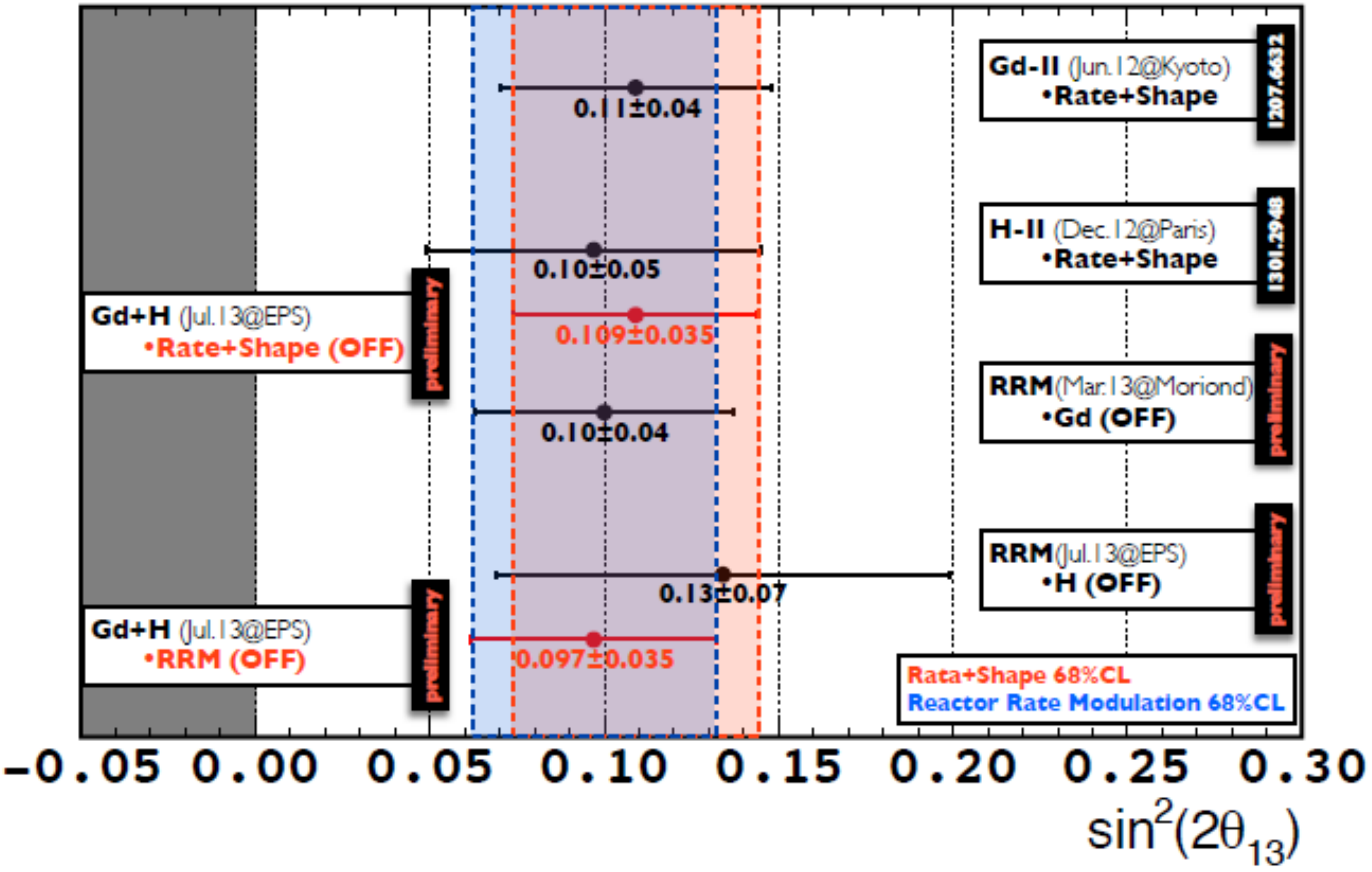
  rate + shape fit

  $\sin^2 2\theta_{13}$= 0.109 ±0.035

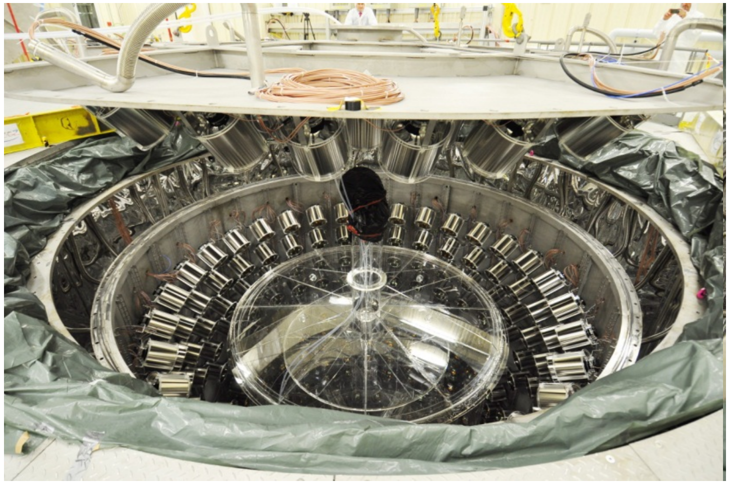
in agreement with previous results

Double Chooz Results - Summary

DC $\sin^2(2\theta_{13})$ Measurements (data set II)



Double Chooz – Status and Future



Near detector

- construction ongoing
- expected to begin data taking fall 2014

Data analysis

- far detector only:

  working on combined analysis with

  expanded data set (~ 490 live days)

  with improved selection cuts

  projected sensitivity: σ~ 0.03

- with two detectors:

  reactor uncertainties nearly cancel

  projected final sensitivity σ~ 0.01