Long Baseline Neutrino Physics

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3. The Future of Neutrino Oscillations

Theree Flavour Oscillation Physics

<u>Δm^2 and θ_{ij} regions</u> ➔ improved oscillation experiments
➔ controlled sources & detectors

➔ long baseline experiments with neutrino beams
➔ reactor experiments with identical near & far detector

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

x Majorana-CP-phases

θ_{23} **S_{13} ➔ 3 flavour effects ➔ S_{13} ➔ δ** **θ_{12}** **matter effects**

<u>Aims:</u> ➔ improved precision of the leading 2x2 oscillations
➔ detection of generic 3-neutrino effects: θ_{13}, CP violation

➔ precision neutrino physics

Three Flavour Oscillations

$$\left.\begin{matrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{matrix}\right\} \xrightarrow{oscillation} \left\{\begin{matrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{matrix}\right.$$

$$\left.\begin{matrix}\overline{\nu}_e\\ \overline{\nu}_\mu\\ \overline{\nu}_\tau\end{matrix}\right\} \xrightarrow{oscillation} \left\{\begin{matrix}\overline{\nu}_e\\ \overline{\nu}_\mu\\ \overline{\nu}_\tau\end{matrix}\right.$$

2 flavour approximations:

$P_{ab} = \sin^2(2\theta)\ \ \sin^2(\Delta m^2 L/4E)$
$P_{aa} = 1 - P_{ab}$

➔ **precision not sufficient**

3 flavour-oscillations

$$J_{ij}^{e_l e_m} := U_{li} U_{lj}^* U_{mi}^* U_{mj} \qquad \Delta_{ij} := \frac{\Delta m_{ij}^2 L}{4E} = \frac{(m_i^2 - m_j^2)L}{4E}$$

$$P(\nu_{e_l} \to \nu_{e_m}) = \underbrace{\delta_{lm} - 4\sum_{i>j} \mathrm{Re} J_{ij}^{e_l e_m} \sin^2 \Delta_{ij}}_{P_{CP}} \underbrace{-2\sum_{i>j} \mathrm{Im} J_{ij}^{e_l e_m} \sin 2\Delta_{ij}}_{P_{\not{C}P}}$$

+ matter effects ➔ sgn(Δm^2)

- **2→3 flavours ➔ more mixings & CP phase**
- **MSW matter effects**

Analytic Approximations

- $\Delta = \Delta m^2_{31} L/4E$
- qualitative understanding $\Rightarrow$ expand in $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin^2 2\theta_{13}$
- matter effects $\hat{A} = A/\Delta m^2_{31} = 2VE/\Delta m^2_{31}$; $V = \sqrt{2} G_F n_e$

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \cos^2\theta_{13} \sin^2 2\theta_{23} \sin^2\Delta + 2\,\alpha\, \cos^2\theta_{13} \cos^2\theta_{12} \sin^2 2\theta_{23} \Delta \cos\Delta$$

$$\begin{aligned} P(\nu_e \to \nu_\mu) \approx\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\ \pm\ & \sin\delta_{\rm CP}\ \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\ +\ & \cos\delta_{\rm CP}\alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\ +\ & \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2} \end{aligned}$$

➔ analytic discussion / full simulations
➔ degeneracies, correlations ➔ $(\sin^2 2\theta_{13})_{\rm eff}$

Cervera et al.
Freund, Huber, ML
Akhmedov, Johansson , ML, Ohlsson, Schwetz

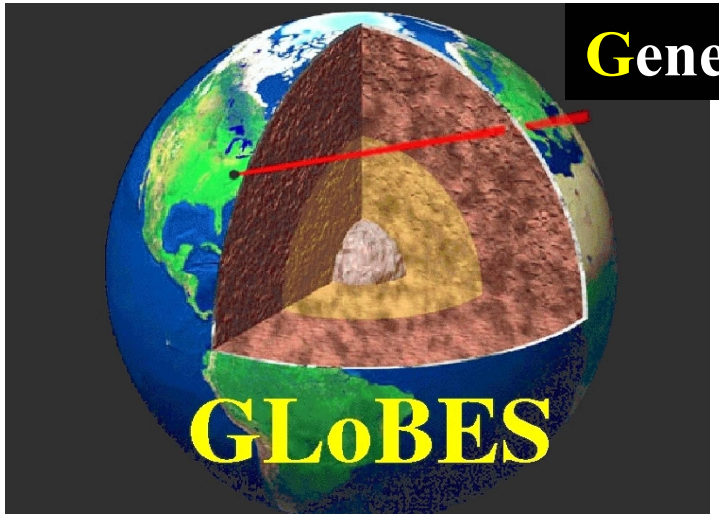
Simulation of Future Experiments

- **select a setup (beam, detector, baseline, ...)**
- **take „most realistic“ parameters ←→ best guess!**
- **simulate all relevant aspects as good as possible**

Source ⊗	Oscillation ⊗	Detector
- neutrino energy E	- oscillation channels	- effective mass, material
- flux and spectrum	- realistic baselines	- threshold, resolution
- flavour composition	- MSW matter profile	- particle ID (flavour, charge, event reconstruction, ...)
- contamination	- degeneracies	- backgrounds
- symmetric $\nu/\overline{\nu}$ operation	- correlations	- x-sections (at low E)

- **determine the potential: „true“ ←→ fitted parameters**
- **compare only realistic simulations (<u>all relevant</u> effects, errors & uncertainties)**

A Powerful Simulation Tool



General Long Baseline Experiment Simulator

Comp. Phys. Comm. 167 (2005) 195, hep-ph/0407333

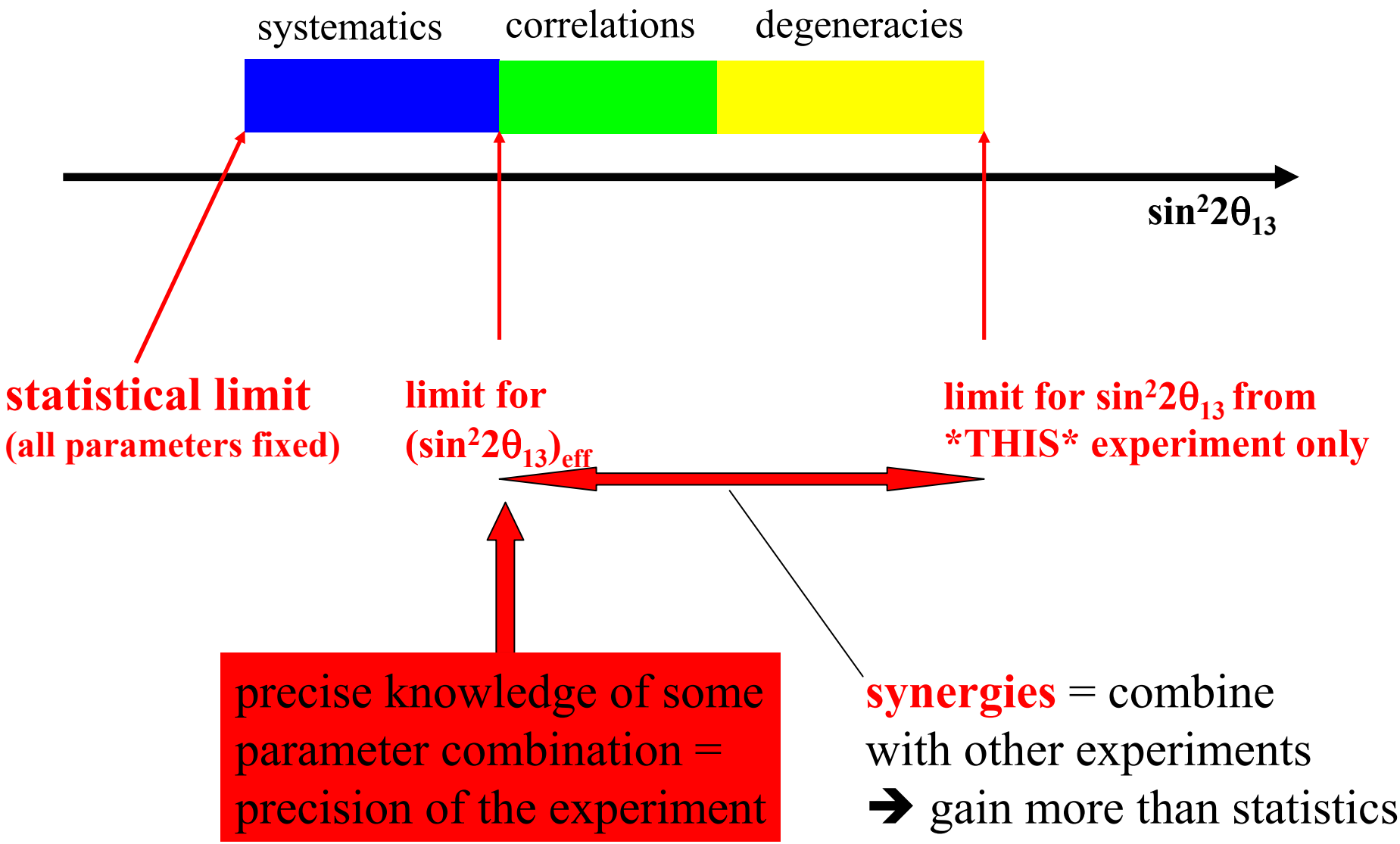
`http://www.ph.tum.de/~globes`

P. Huber, ML, W. Winter
M. Freund, M. Rolinec

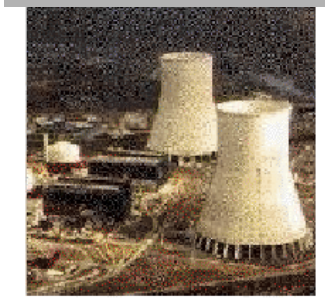
- **C-based simulation software (GPL = free)**
- **extensive documentation & examples**
- **3 phase approach:**

1) **AEDL** (**Abstract Experiment Definition Language**)
2) simulation of an experiment ➔ 3-ν oscillations; scan „true values“
3) analysis ➔ event distriutions, ..., sensitivities, ...

Sensitivity Plots



New Reactor Experiments



$\overset{\overline{\nu}_e}{\Longrightarrow}$ **near detector** (170m) $\overset{\overline{\nu}_e}{\Longrightarrow}$ **far detector** (1700m)

identical detectors ➔ many errors cancel

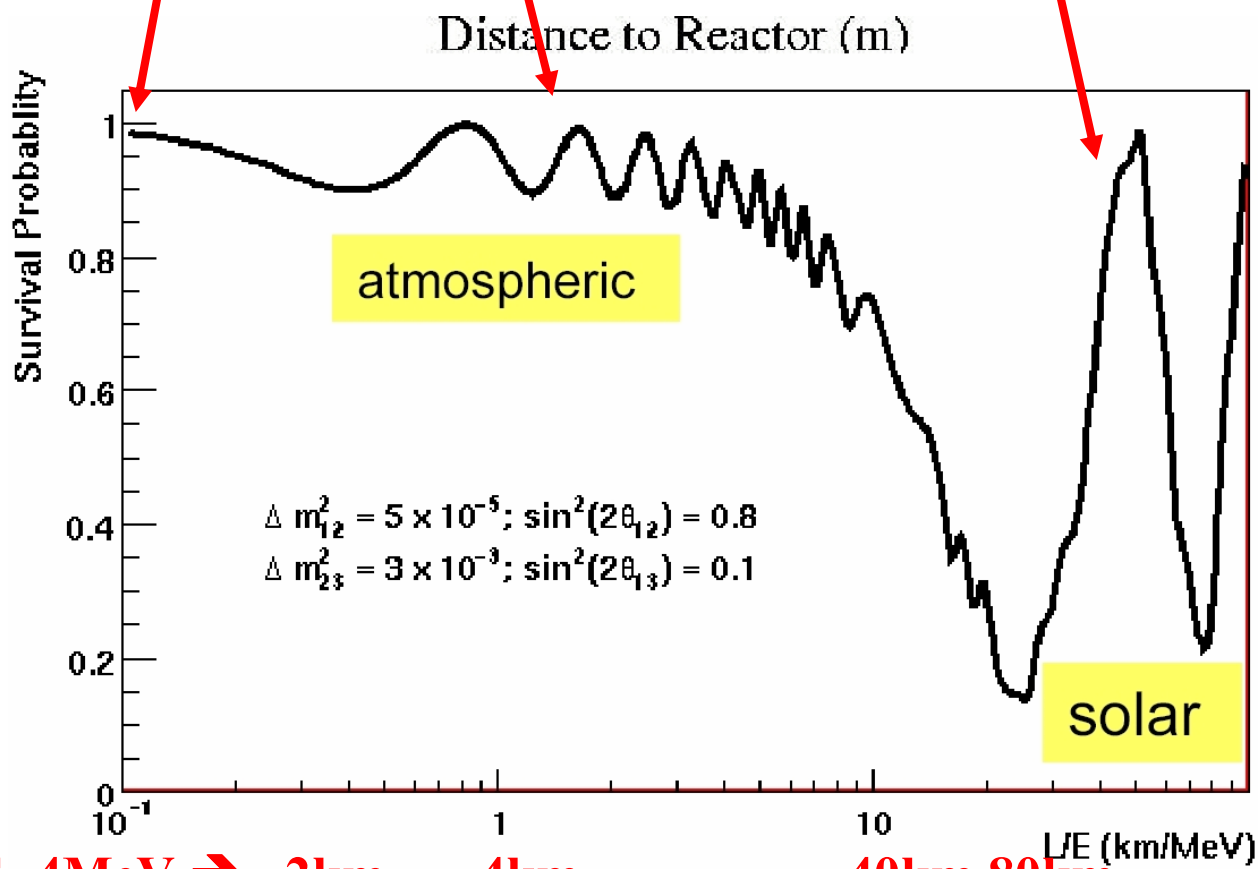
- **The survival probability:**
  - expand in small quantities

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)^2 \cos^4\theta_{13} \sin^2 2\theta_{12}$$

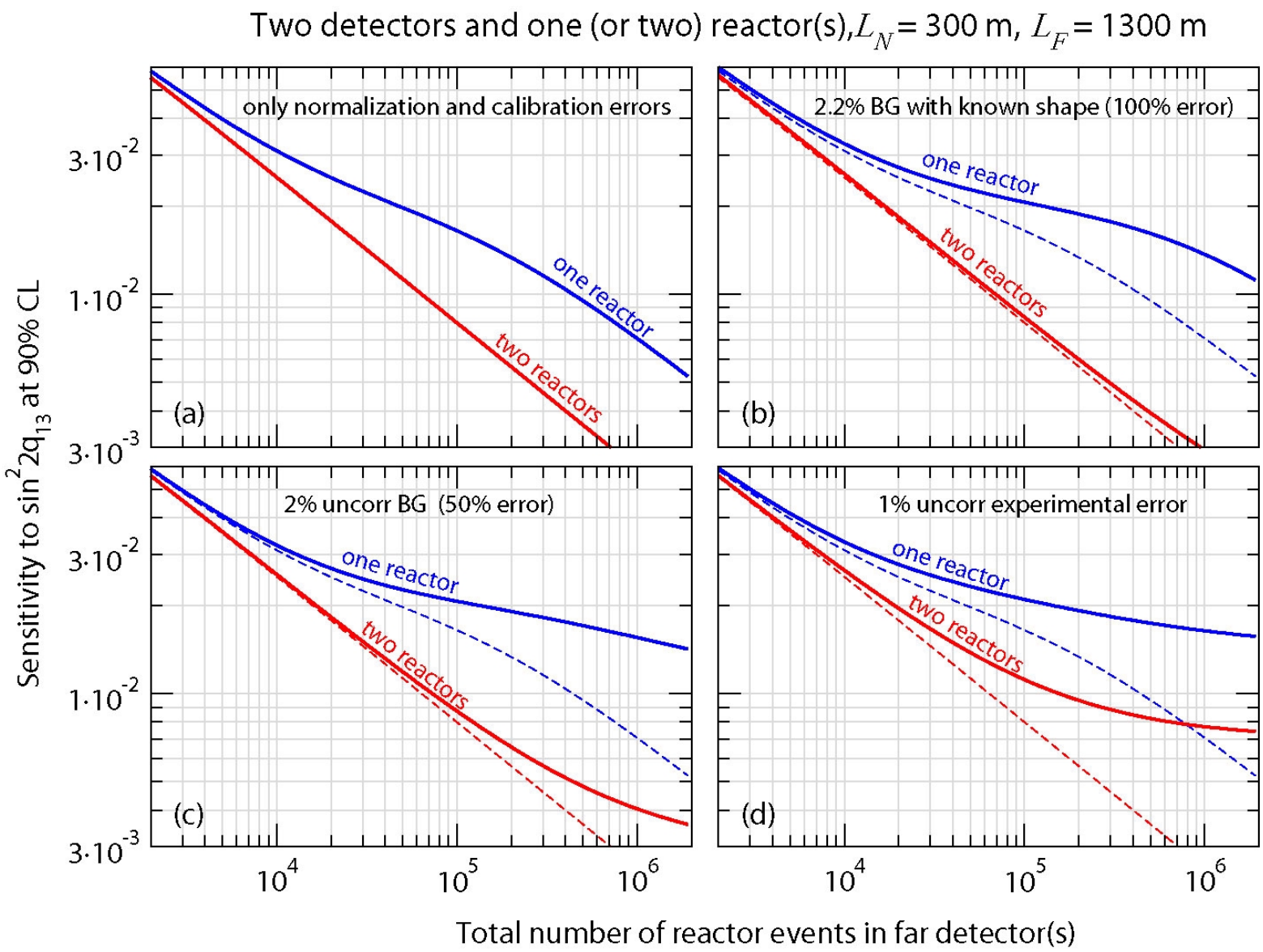
  - last term negligible for $\frac{\Delta m^2_{31} L}{4E_\nu} \sim \pi/2$ and $\sin^2 2\theta_{13} \gtrsim 10^{-3}$
  - atmospheric frequency is dominant
  - most important:

- **No degeneracies!**
- **Practically no correlations!**
- **No matter effects!**

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)^2 \cos^4\theta_{13} \sin^2 2\theta_{12}$$

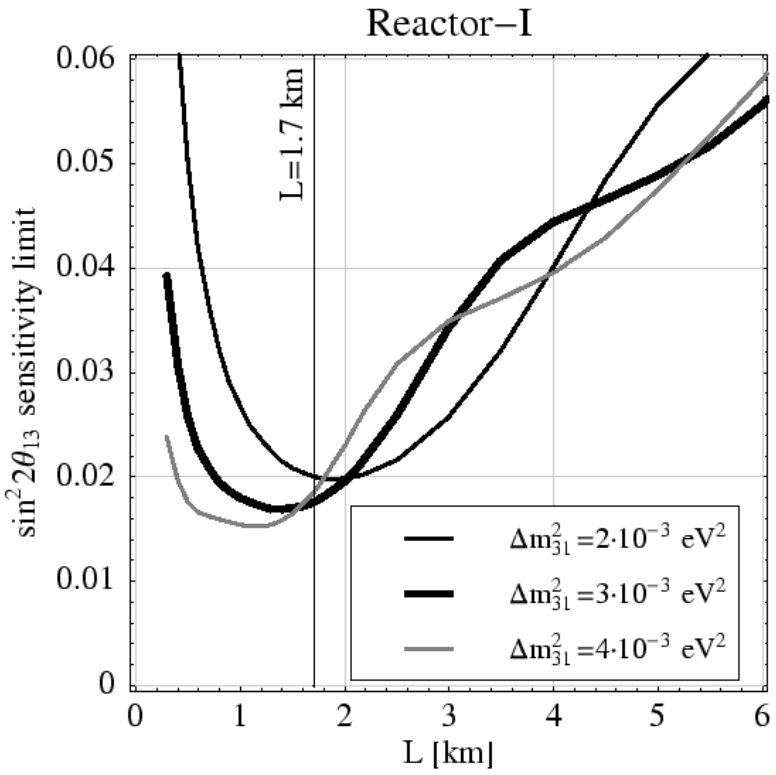


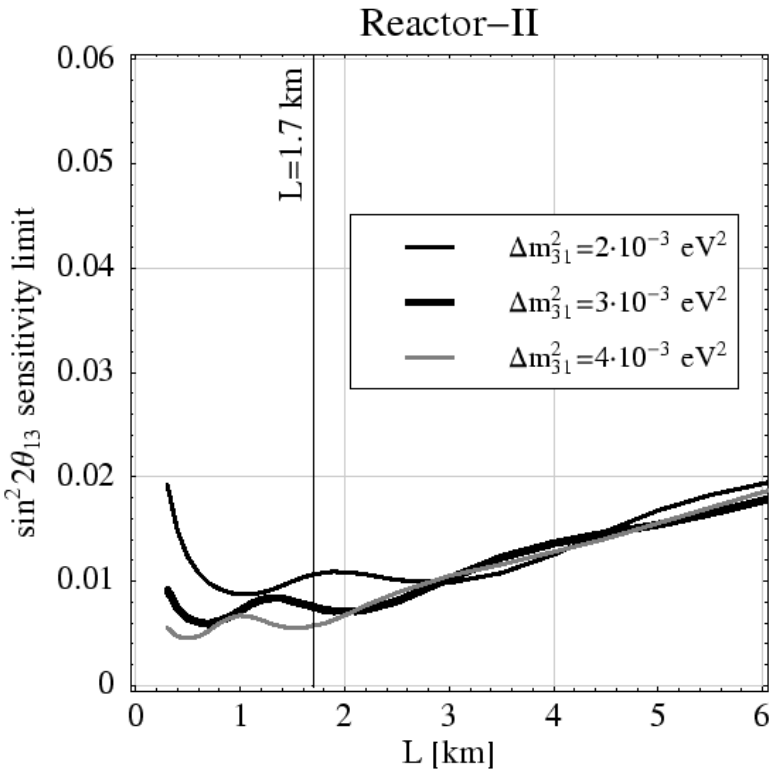
For E=4MeV ➔ 2km 4km 40km 80km


Two detectors and one (or two) reactor(s), L_N = 300 m, L_F = 1300 m
only normalization and calibration errors
2.2% BG with known shape (100% error)
2% uncorr BG (50% error)
1% uncorr experimental error
one reactor
two reactors
(a)
(b)
(c)
(d)
Sensitivity to $\sin^2 2q_{13}$ at 90% CL
$3\cdot10^{-2}$
$1\cdot10^{-2}$
$3\cdot10^{-3}$
10^4
10^5
10^6
Total number of reactor events in far detector(s)

• Scenarios and optimal distance

setup	$\mathcal{L}$	# of events (no osc)	baseline
Reactor-I	400 t GW y	31 500	1.7 km
Reactor-II	8000 t GW y	630 000	1.7 km

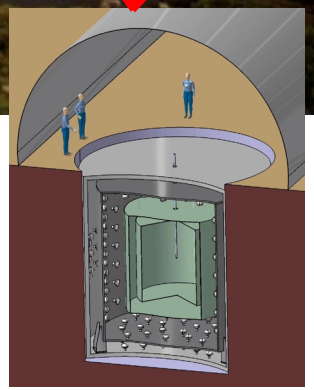




Most advanced: Double Chooz

existing far detector hall

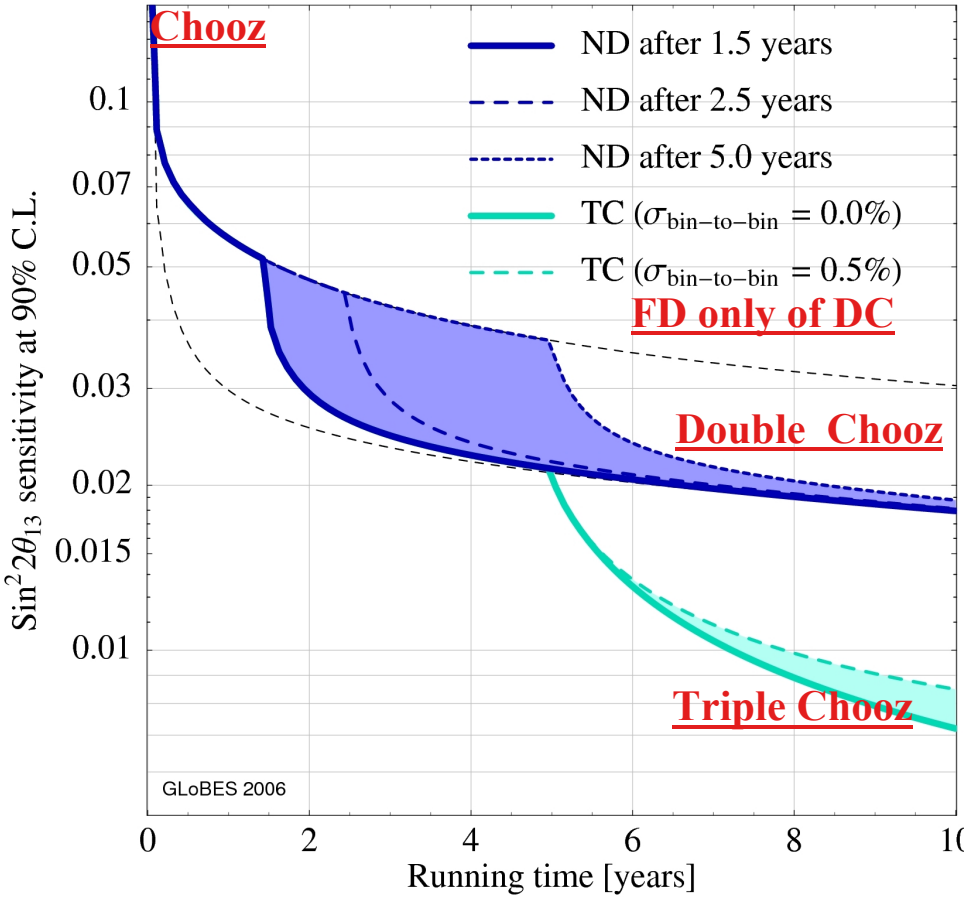
… + another existing big hall!

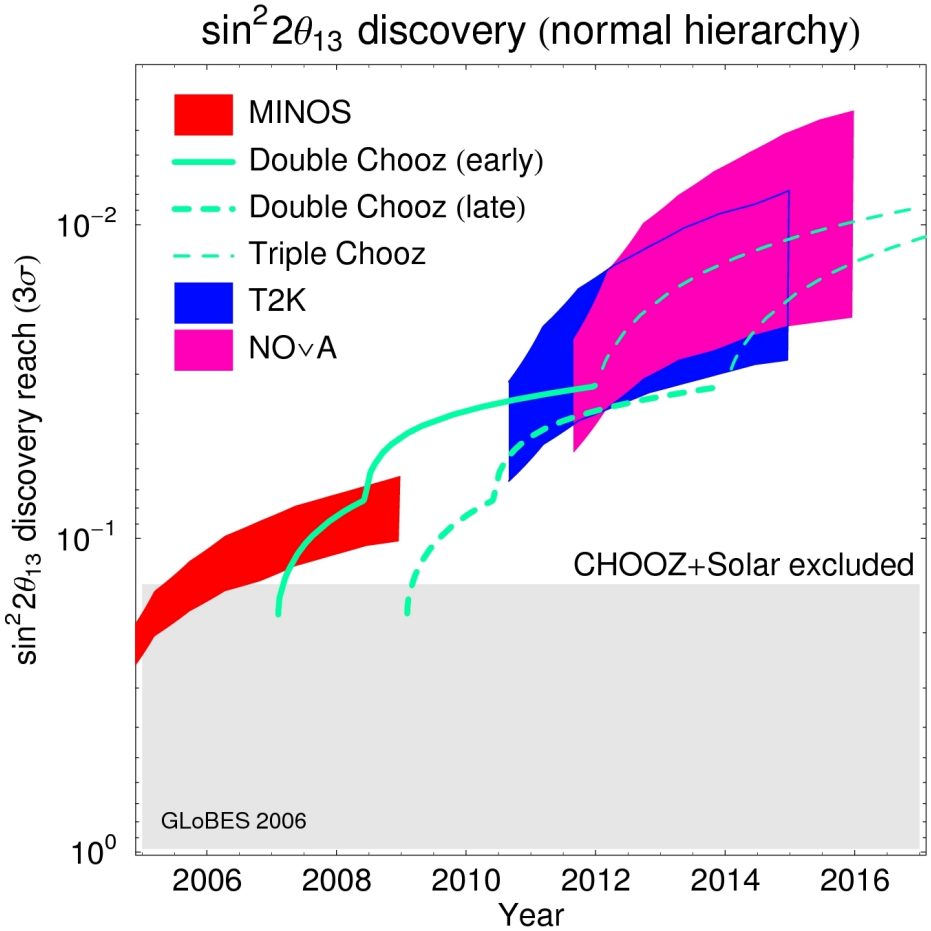


Other proposals:

Daya Bay
KASKA
RENO
ANGRA

Double Chooz and Triple Chooz



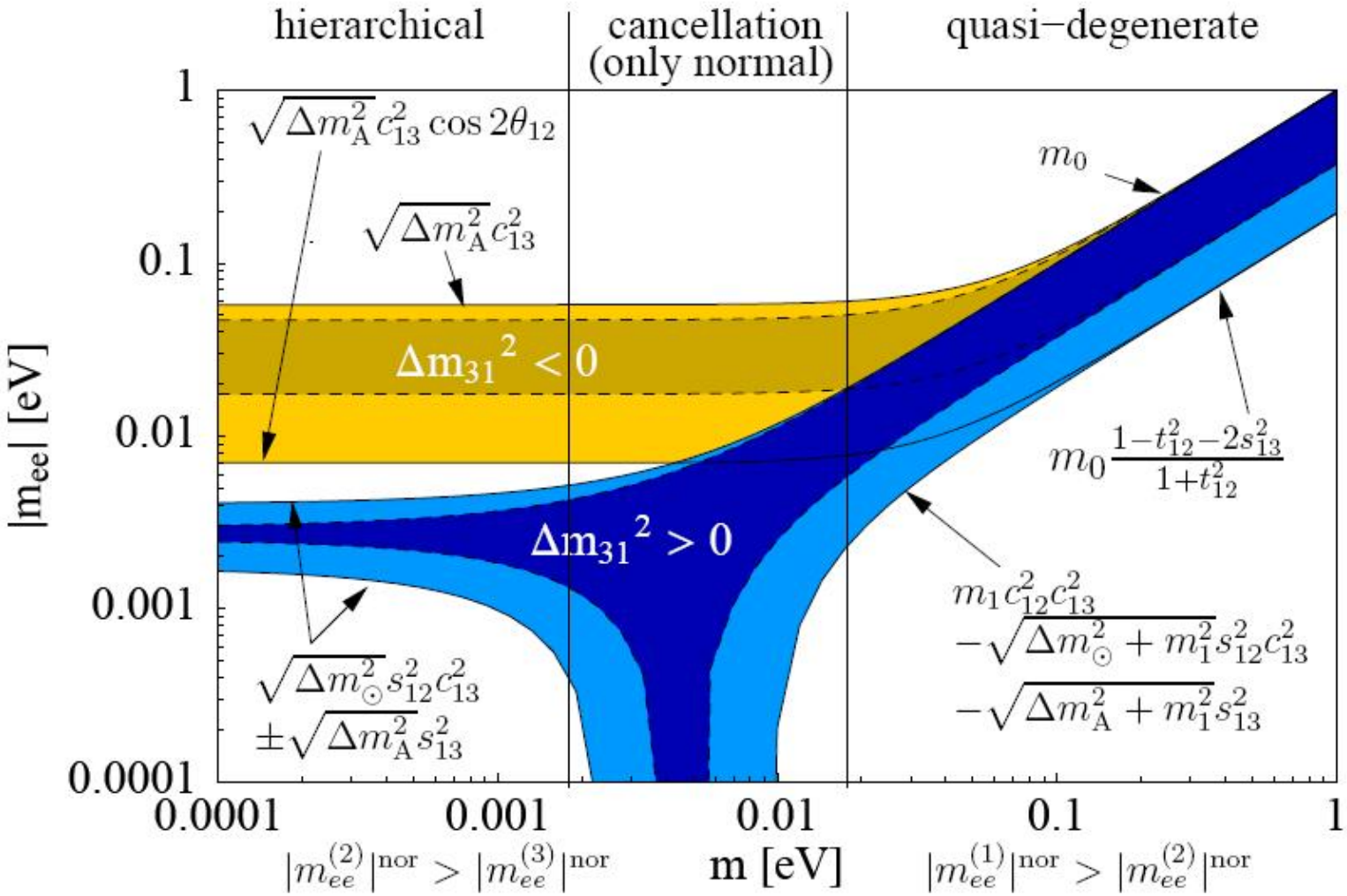


$\sin^2 2\theta_{13}$ sensitivity

Chooz limit	< 0.20
Double Chooz	< 0.02
Triple Chooz ?	< 0.008

Huber, Kopp, ML, Rolinec, Winter

Features of the 0ν2β Mass Plot



Double Chooz and 0ν2β

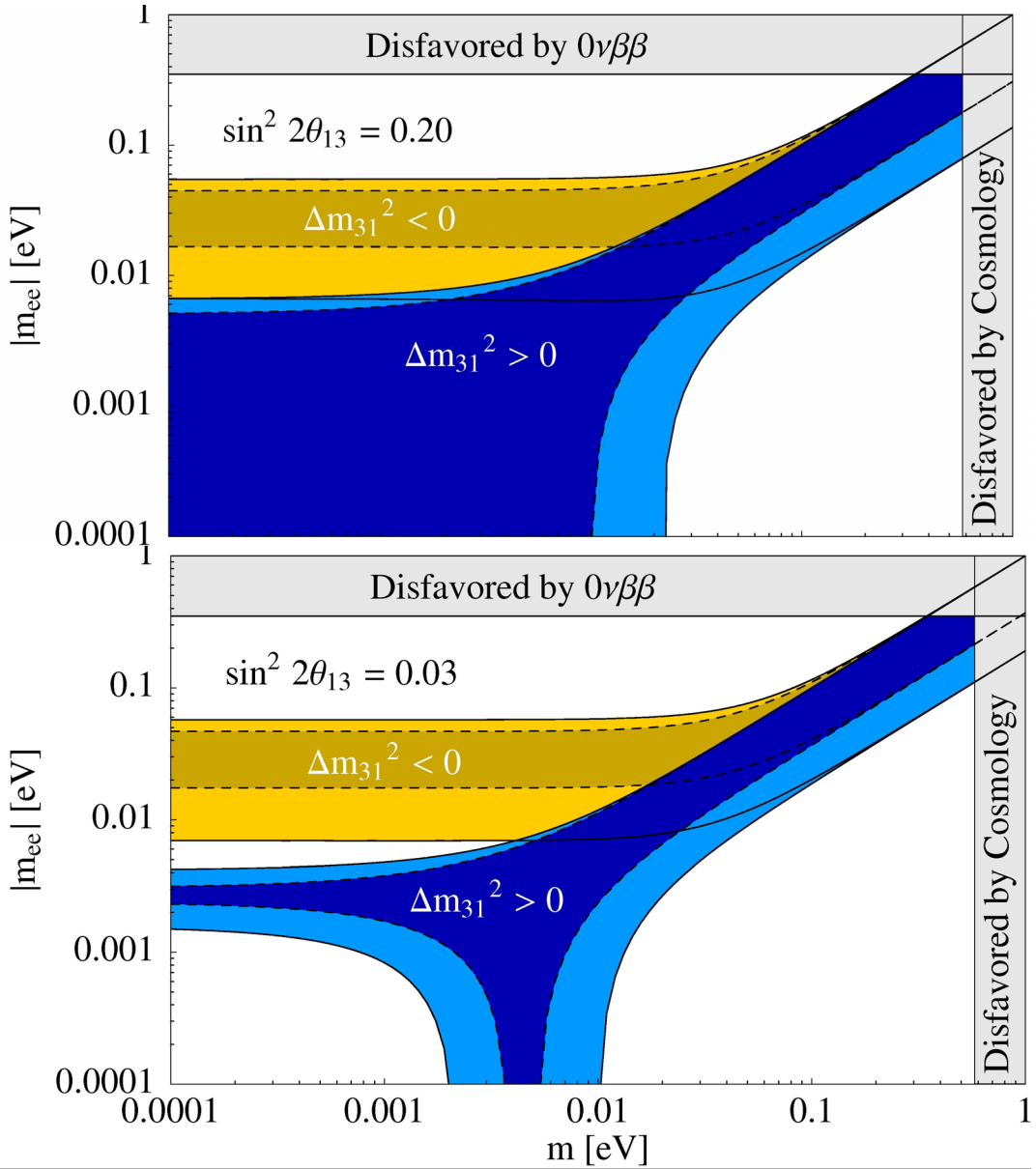
- m_{ee} versus m_1

for $\sin^2 2\theta_{13} = 0.2$

for $\sin^2 2\theta_{13} = 0.03$

➔ Double Chooz important for separation and lower bound of m_{ee}

ML,Merle, Rodejohann



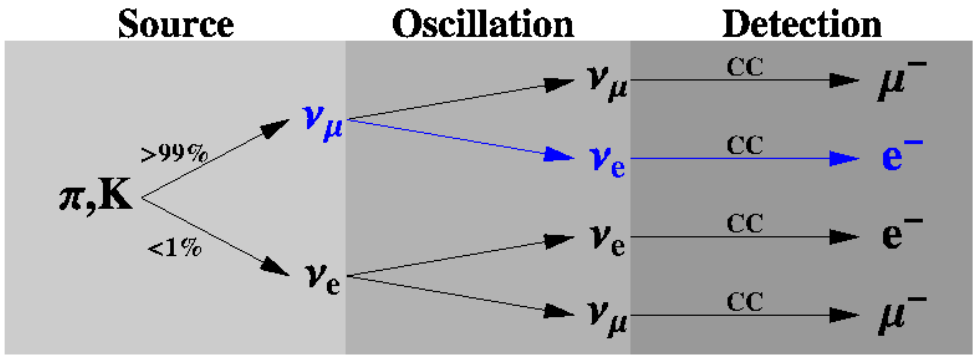
Precison with New Neutrino Beams

- **conventional beams, superbeams**
  ➔ **MINOS, CNGS, T2K, NOνA, T2H,…**
- **β-beams**
  ➔ **pure ν_e and $\bar{\nu}_e$ beams from radioactive decays; $\gamma \simeq 100$**
- **neutrino factories**
  ➔ **clean neutrino beams from decay of stored μ's**

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) \approx\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\
\pm\ & \sin\delta_{CP}\ \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+\ & \cos\delta_{CP}\alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+\ & \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

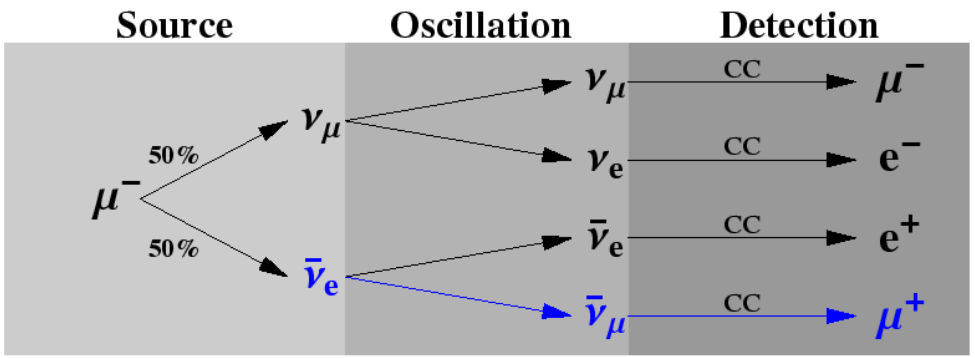
correlations & degeneracies

A) Conventional ν-Beams from Beam Dumps $\Rightarrow$ Superbeams



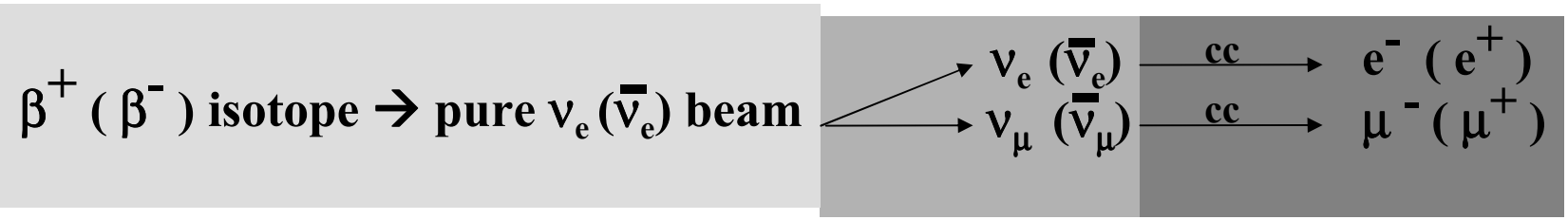
$\nu_\mu \to \nu_e$ oscillation most interesting
ν_e contamination $\Leftrightarrow$ off-axis
good electron detection efficiency
good NC background rejection
near detector
$\overline{\nu}$-beam $\simeq$ different experiment

B) Neutrino Factories



$\overline{\nu}_e \to \overline{\nu}_\mu$ oscillation most interesting
excellent beam properties
very good charge ID required
good NC background rejection
μ^+ mode very symmetric

C) β-beams

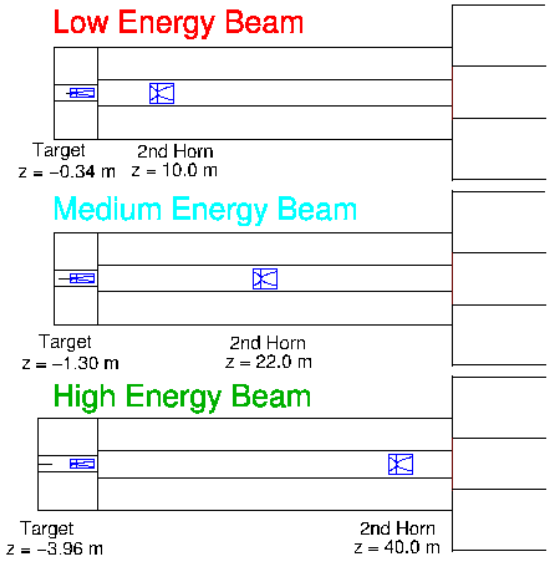


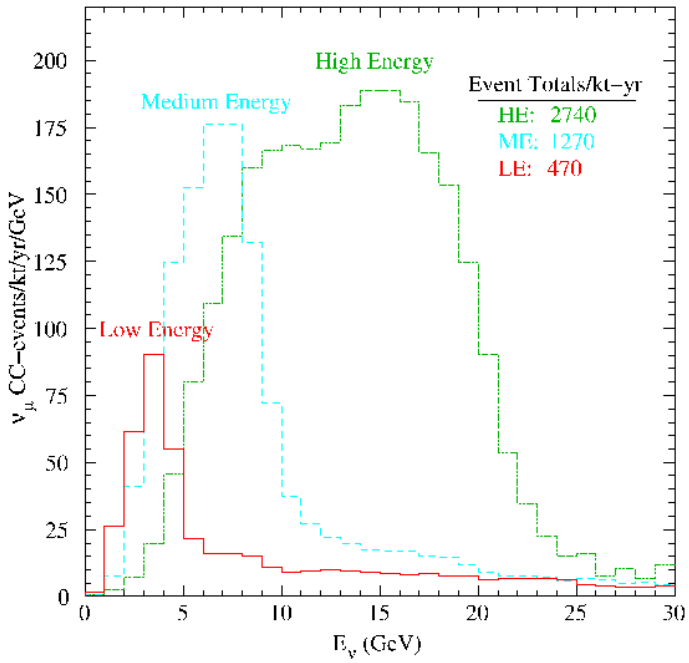
Conventional Neutrino Beams

- Send an intense proton beam on a target $\Rightarrow$ flux of pions $\Rightarrow$ focussing horn(s)
  flux limited by cooling of the target (MW)
- Decay pipe: $\pi^+ \to \mu^+ + \nu_\mu \Rightarrow$ ν_μ beam
- contaminations:
  μ^+-decay $\Rightarrow$ $\overline{\nu}_\mu$, ν_e
  π^-, K decay $\Rightarrow$ $\overline{\nu}_e$

MINOS spectrum:

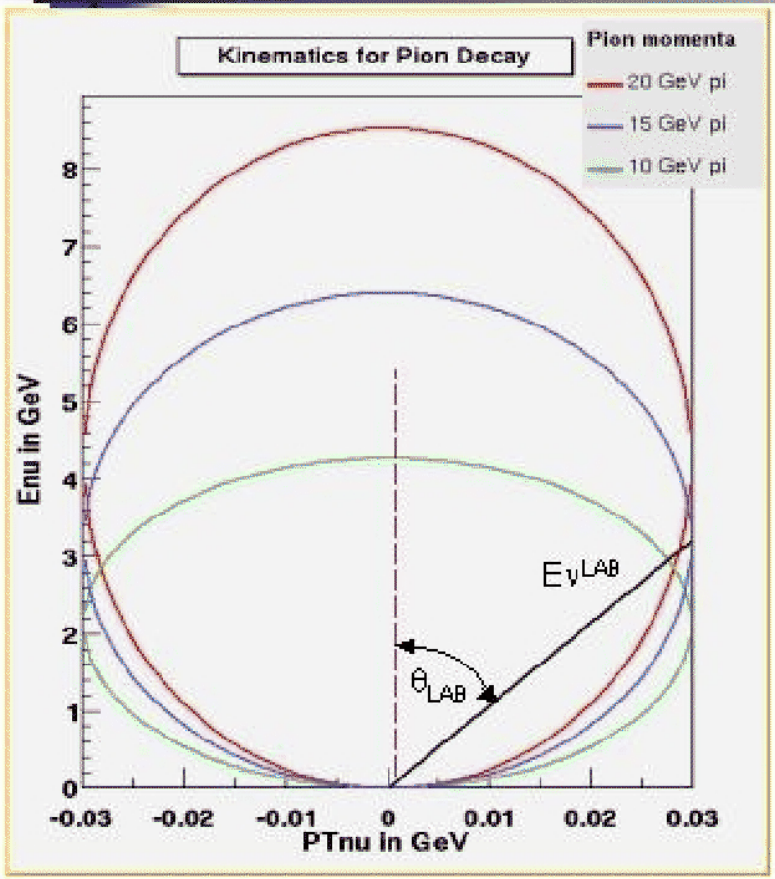
p on target $\Rightarrow$ pions





Off-Axis Beams

Kinematics of π Decay

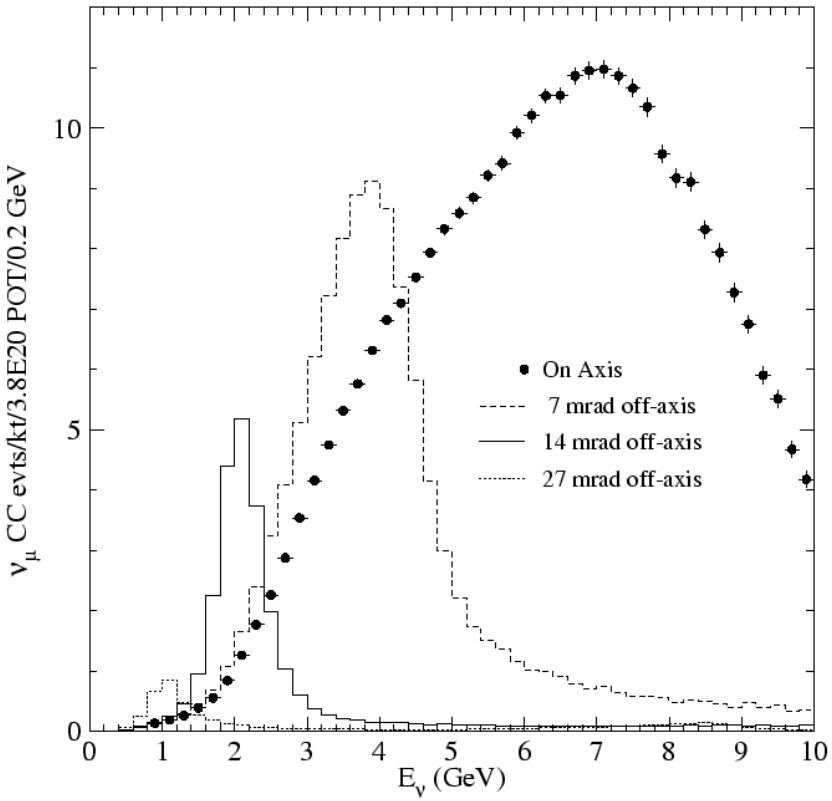


Compare E_ν spectra from 10,15, and 20 GeV π's

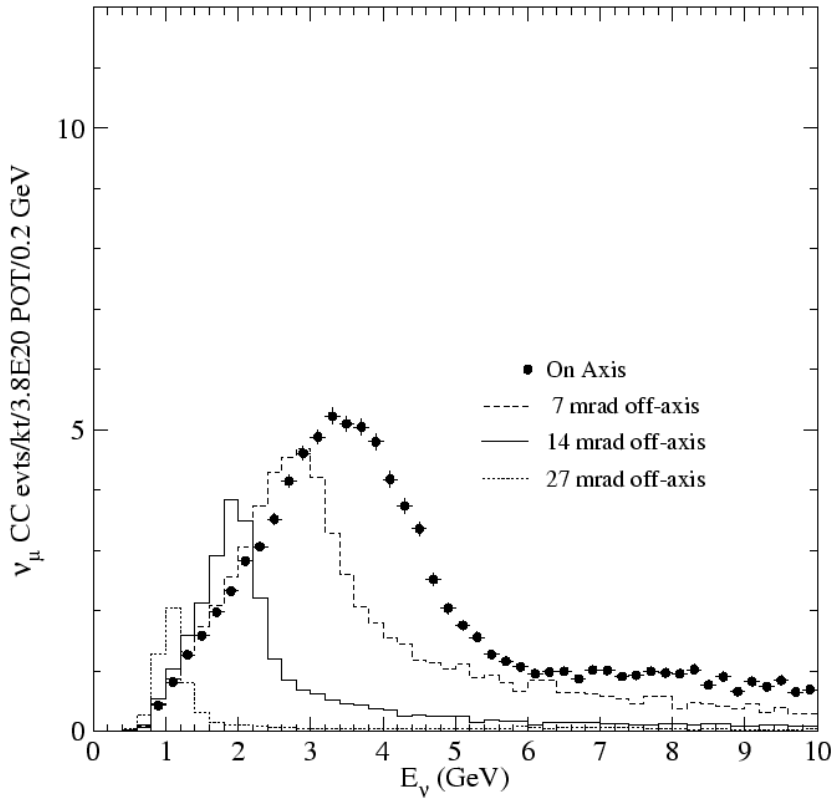
- Lab energy given by length of vector from origin to contour
- Lab angle by angle wrt vertical
- Energy of ν is relatively independent of π energy
- Both higher and lower π energies give ν's of somewhat lower energy
- There will be a sharp edge at the high end of the resultant ν spectrum
- Energy varies linearly with angle
- Main energy spread is due to beam divergence

NuMI Off-Axis Spectra

MEDIUM ENERGY

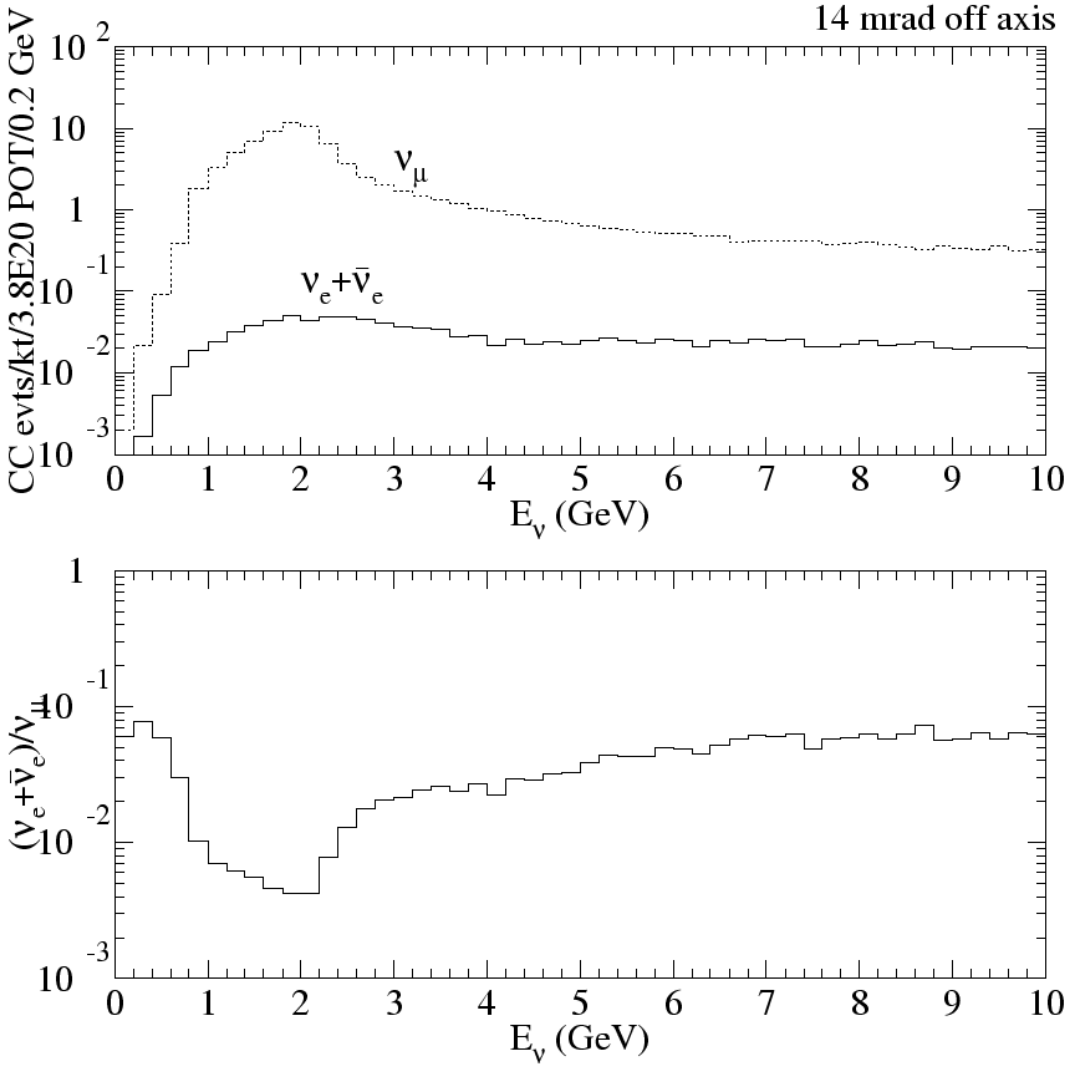


LOW ENERGY



- $\overline{E}$ is lower $\Rightarrow$ constant L/E gives somewhat smaller baselines
- flux at low energies increased $\Rightarrow$ flux $\times$ cross-section
- spectrum gets narrower $\Rightarrow$ more monochromatic $\Rightarrow$ good, L/E less smeared

NuMI off axis ν_e and $\bar{\nu}_e$ beam contamination



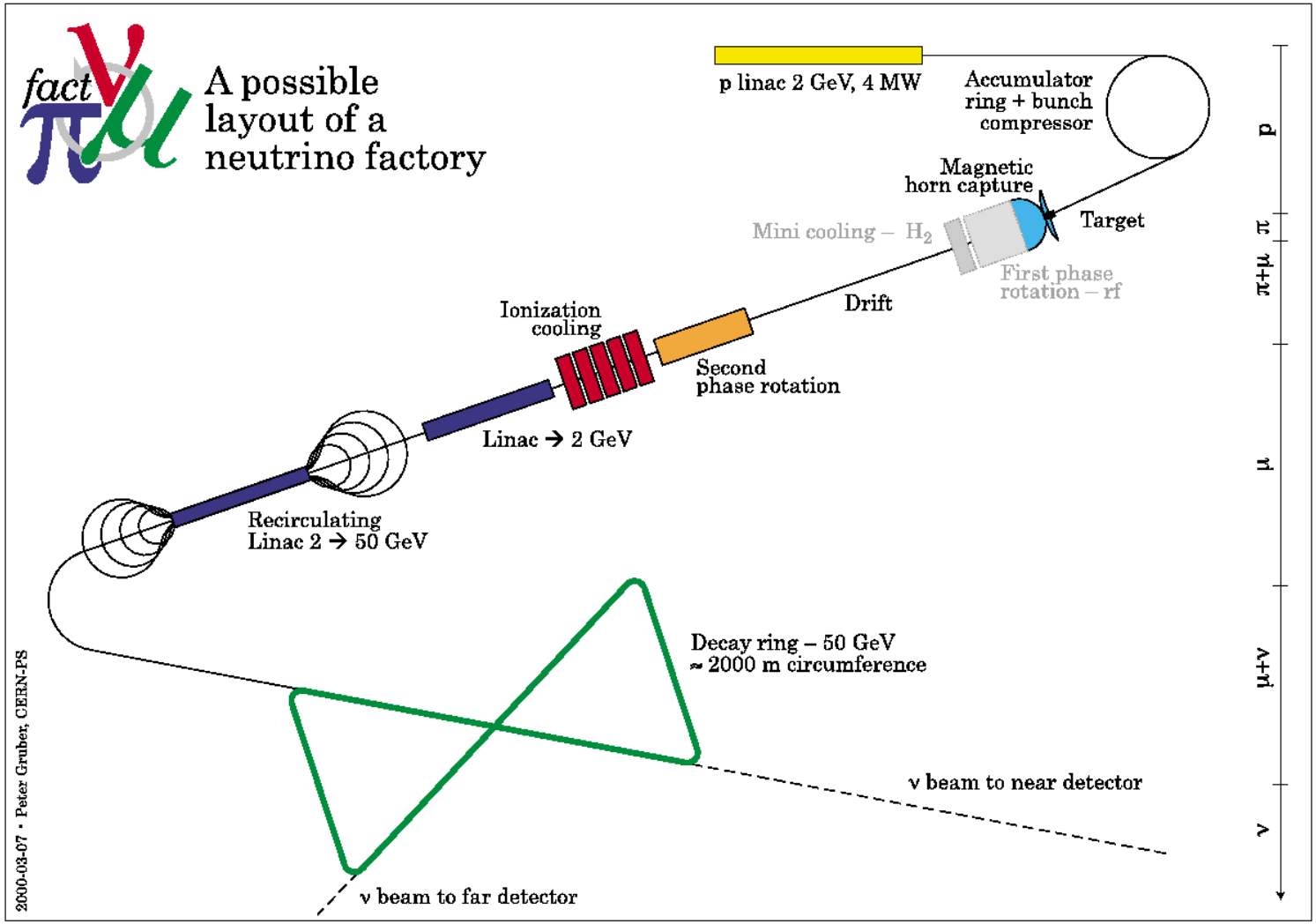
Superbeam Oscillation Channels

$$\text{beam} \Longrightarrow \nu_\mu \xrightarrow{oscillation} \begin{cases} \nu_e \Rightarrow e^- & \text{appearance} \\ \nu_\mu \Rightarrow \mu^- & \text{disappearance} \\ \nu_\tau \Rightarrow \tau^- & \text{detection!?} \end{cases}$$

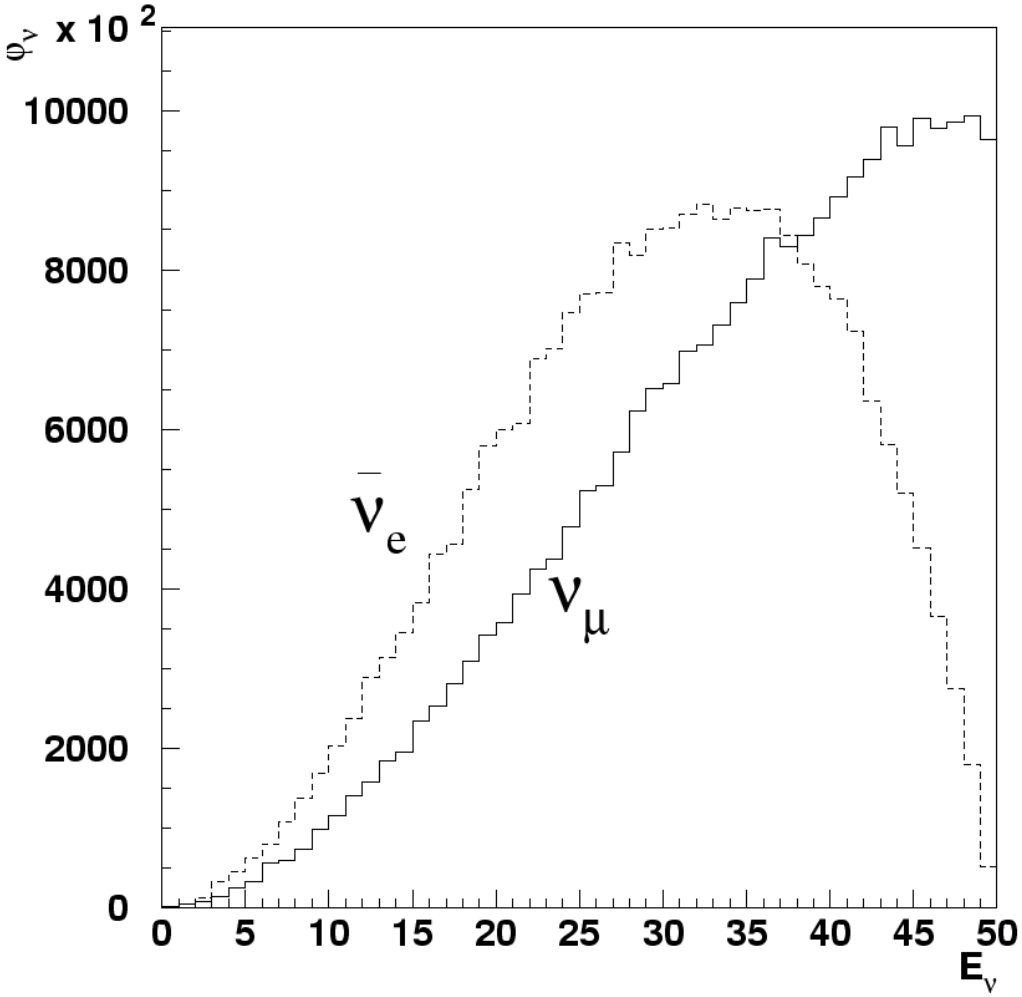
$$\text{background} \Longrightarrow \begin{cases} \overline{\nu}_\mu \xrightarrow{oscillation} \begin{cases} \overline{\nu}_e \Rightarrow e^+ \\ \overline{\nu}_\mu \Rightarrow \mu^+ \\ \overline{\nu}_\tau \Rightarrow \tau^+ \end{cases} \\ \nu_e \xrightarrow{oscillation} \begin{cases} \nu_e \Rightarrow e^- \\ \nu_\mu \Rightarrow \mu^- \\ \nu_\tau \Rightarrow \tau^- \end{cases} \\ \overline{\nu}_e \xrightarrow{oscillation} \begin{cases} \overline{\nu}_e \Rightarrow e^+ \\ \overline{\nu}_\mu \Rightarrow \mu^+ \\ \overline{\nu}_\tau \Rightarrow \tau^+ \end{cases} \end{cases}$$

backgrounds$\Rightarrow$ limits measurements

Neutrino Factory



Neutrino factory spectrum: Muon decay kinematics

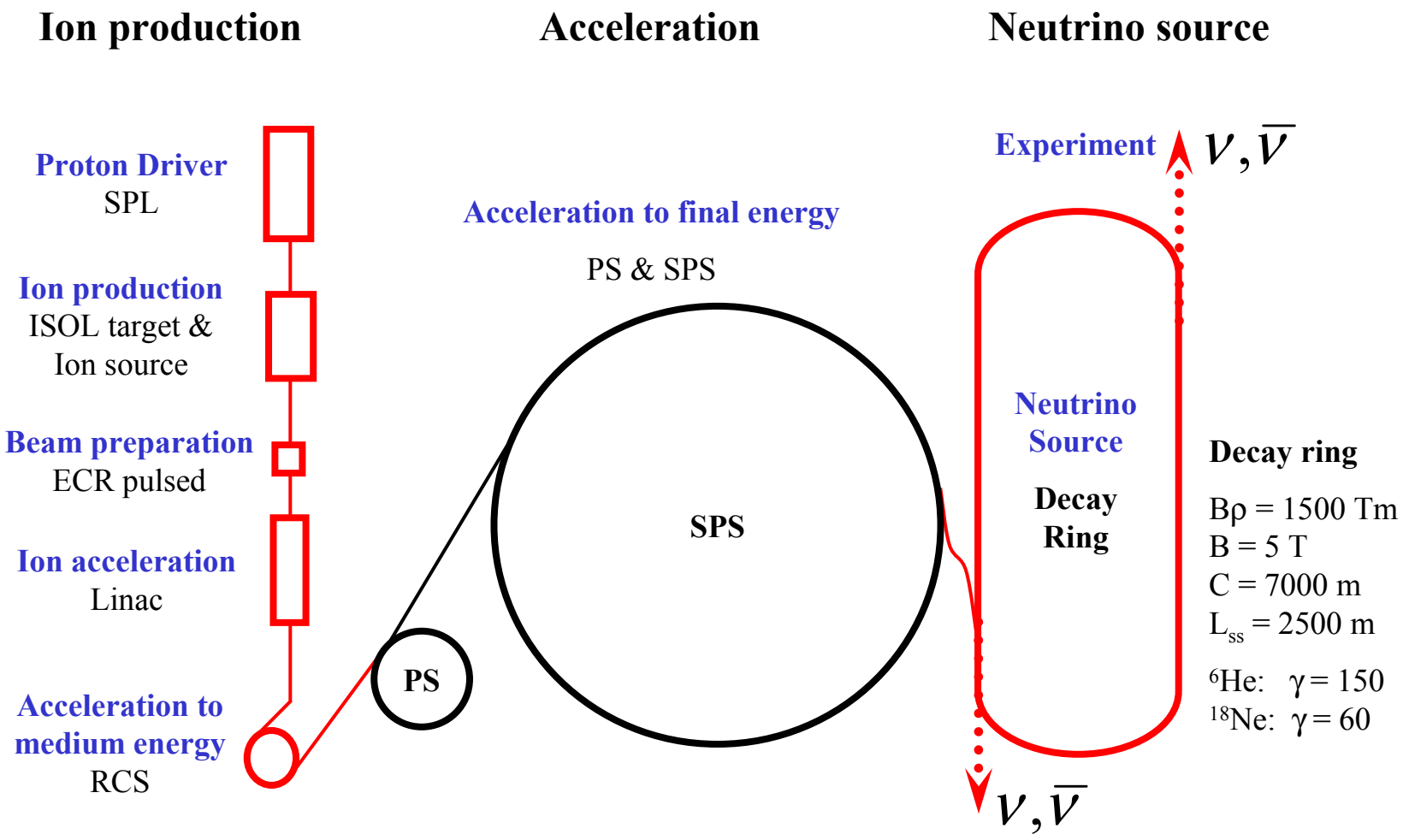


Neutrino Factory Oscillation Channels

$$\mu^- \Longrightarrow \begin{cases} \overline{\nu}_e \xrightarrow{oscillation} \begin{cases} \overline{\nu}_e \Rightarrow e^+ & n_{\mu^-}(e^+) \\ \overline{\nu}_\mu \Rightarrow \mu^+ & n_{\mu^-}(\mu^+) \\ \overline{\nu}_\tau \Rightarrow \tau^+ \end{cases} & \text{wrong sign } \mu's \\ \nu_\mu \xrightarrow{oscillation} \begin{cases} \nu_e \Rightarrow e^- \\ \nu_\mu \Rightarrow \mu^- & n_{\mu^-}(\mu^-) \\ \nu_\tau \Rightarrow \tau^- \end{cases} & \text{same sign } \mu's \end{cases}$$

$$\mu^+ \Longrightarrow \begin{cases} \nu_e \xrightarrow{oscillation} \begin{cases} \nu_e \Rightarrow e^- & n_{\mu^+}(e^-) \\ \nu_\mu \Rightarrow \mu^- & n_{\mu^+}(\mu^-) \\ \nu_\tau \Rightarrow \tau^- \end{cases} & \text{wrong sign } \mu's \\ \overline{\nu}_\mu \xrightarrow{oscillation} \begin{cases} \overline{\nu}_e \Rightarrow e^+ \\ \overline{\nu}_\mu \Rightarrow \mu^+ & n_{\mu^+}(\mu^+) \\ \overline{\nu}_\tau \Rightarrow \tau^+ \end{cases} & \text{same sign } \mu's \end{cases}$$

Beta-beams: Design Example



Ion Choice

- Possibility to produce reasonable amounts of ions
- Noble gases preferred - simple diffusion out of target, gas phase at room temperature
- Not too short half-life to get reasonable intensities
- Not too long half-life as otherwise no decay at high energy
- Avoid potentially dangerous and long-lived decay products

- **Best compromise**
  - ^{6}Helium^{2+} to produce antineutrinos:

$$^{6}_{2}He \rightarrow ^{6}_{3}Li\, e^{-}\, \bar{\nu}$$

$$\text{Average } E_{cms} = 1.937 \text{ MeV}$$

  - ^{18}Neon^{10+} to produce neutrinos:

$$^{18}_{10}Ne \rightarrow ^{18}_{9}Fe\, e^{+} \nu$$

$$\text{Average } E_{cms} = 1.86 \text{ MeV}$$

Detectors in a Nutshell

Most important features:

- which leptons can be detected: e, μ, τ
- can particles and anti-particles be distinguished $\Leftrightarrow$ magnetic fields
- detector threshold and beam energy $\Rightarrow$ defines energy window
- ...

Main players:

- water Cherenkov detectors a la SuperK
  sees $e^{\pm}$, $\mu^{\pm}$, i.e. no charge id
  very good for QE scattering at lower energies
- low Z calorimeter as proposed for NuMI
  sees $e^{\pm}$, $\mu^{\pm}$, i.e. no charge id
  best for medium energies were QE/DIS both contribute
- magnetized iron detectors
  sees μ^{+}, μ^{-}, no e and τ

Other players:

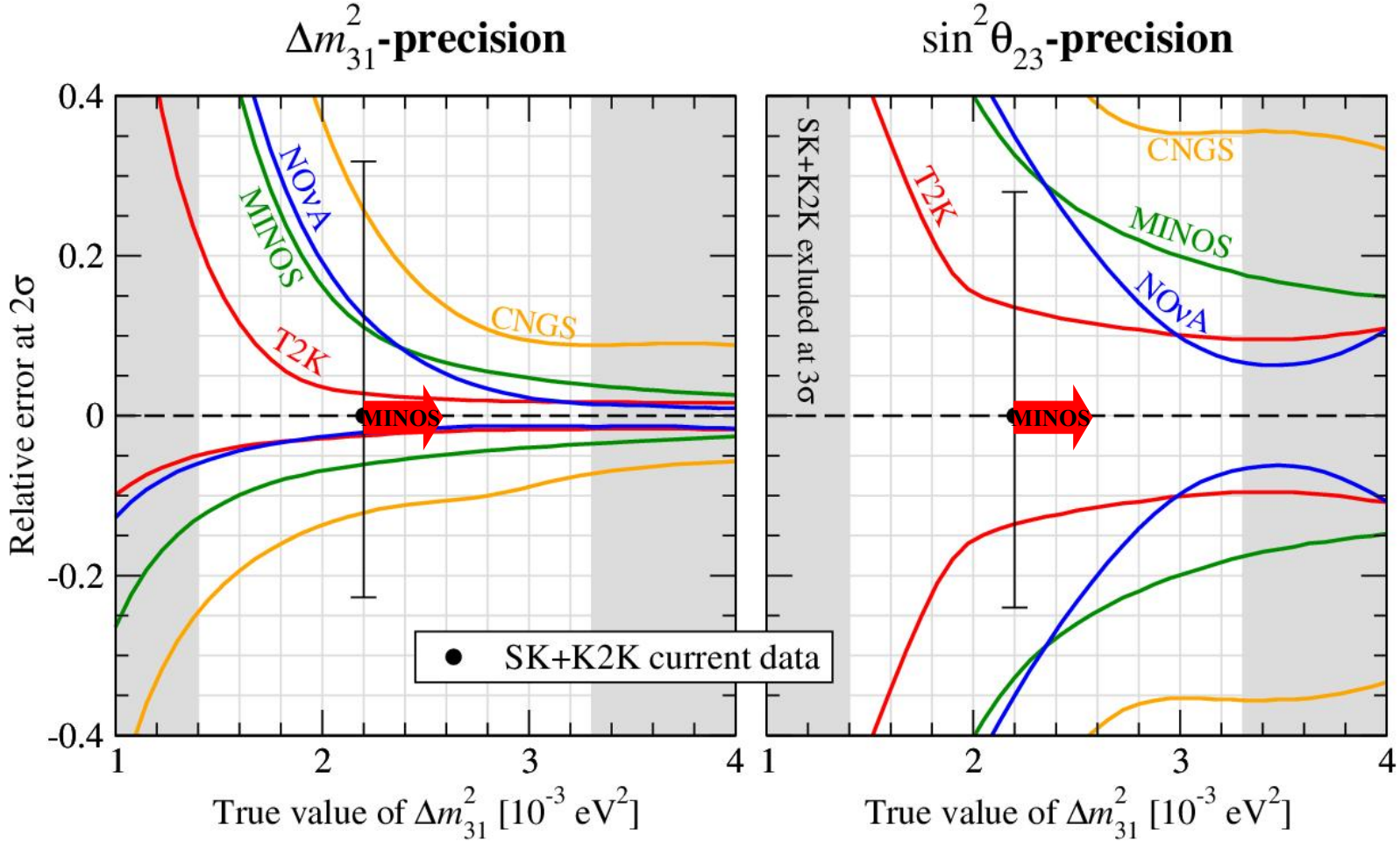
- liquid Argon a la ICARUS $\Rightarrow$ τ
- emulsion detectors a la OPERA $\Rightarrow$ sees all channels

Future Long Baseline Experiments

K2K	analysis	establish atmospheric oscillations with beam
MINOS OPERA , ICARUS	running construction	expected precision: 8% for Δm^2_{13} , 25% for $\sin^2\theta_{23}$, θ_{13} ?
T2K	approved	4% for Δm^2_{13} , 15% for $\sin^2\theta_{23}$, ➔ θ_{13}
NOνA	pre-approved	3% for Δm^2_{13} , 15% for $\sin^2\theta_{23}$ (combined with T2K) , ➔ θ_{13} , ➔ δ ? , ➔ sgn(Δm^2_{13})
T2H	R&D	⬇
β-beams	R&D	precision neutrino physics
neutrino factory	R&D	
...muon collider	...	

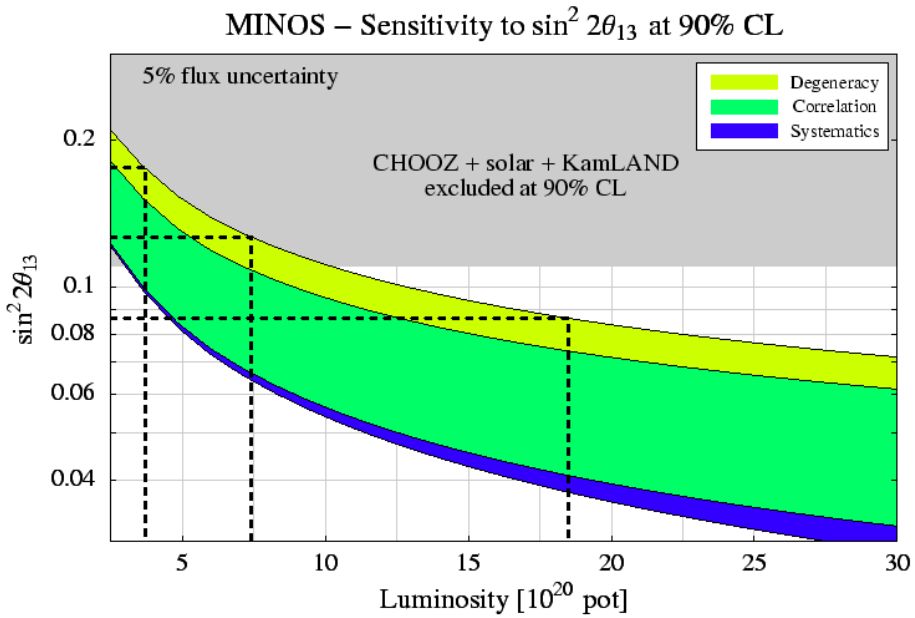
- every stage is a necessary prerequisite for the next
- continuous line of improvements for beams, detectors, physics

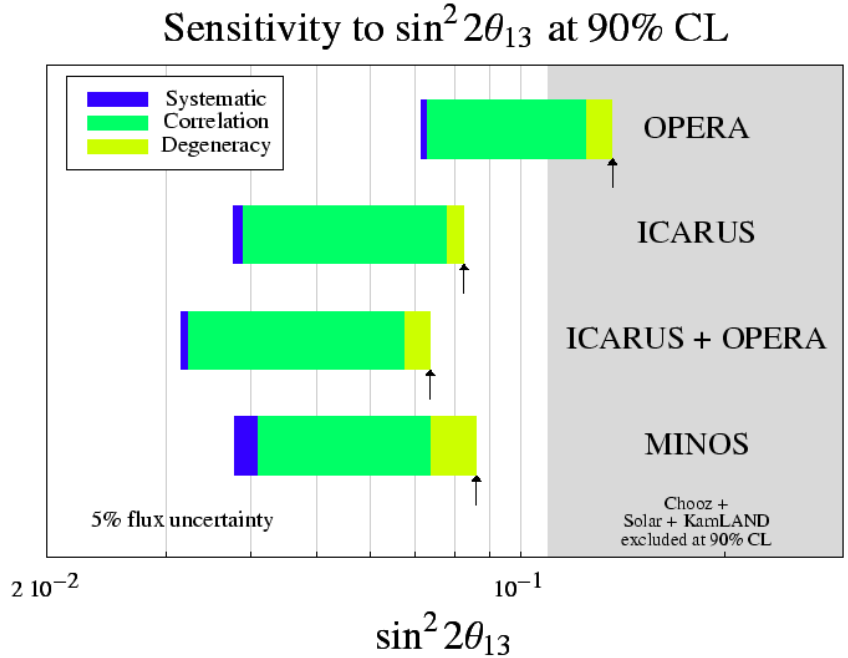
Improvement of Δm^2_{31} and $\sin^2\theta_{23}$



Huber, ML, Rolinec, Schwetz, Winter

θ_{13} in the Coming LBL Generation





MINOS sensitivity as a funtion of time:

– MINOS: $3.7 \cdot 10^{20}$ pot/y

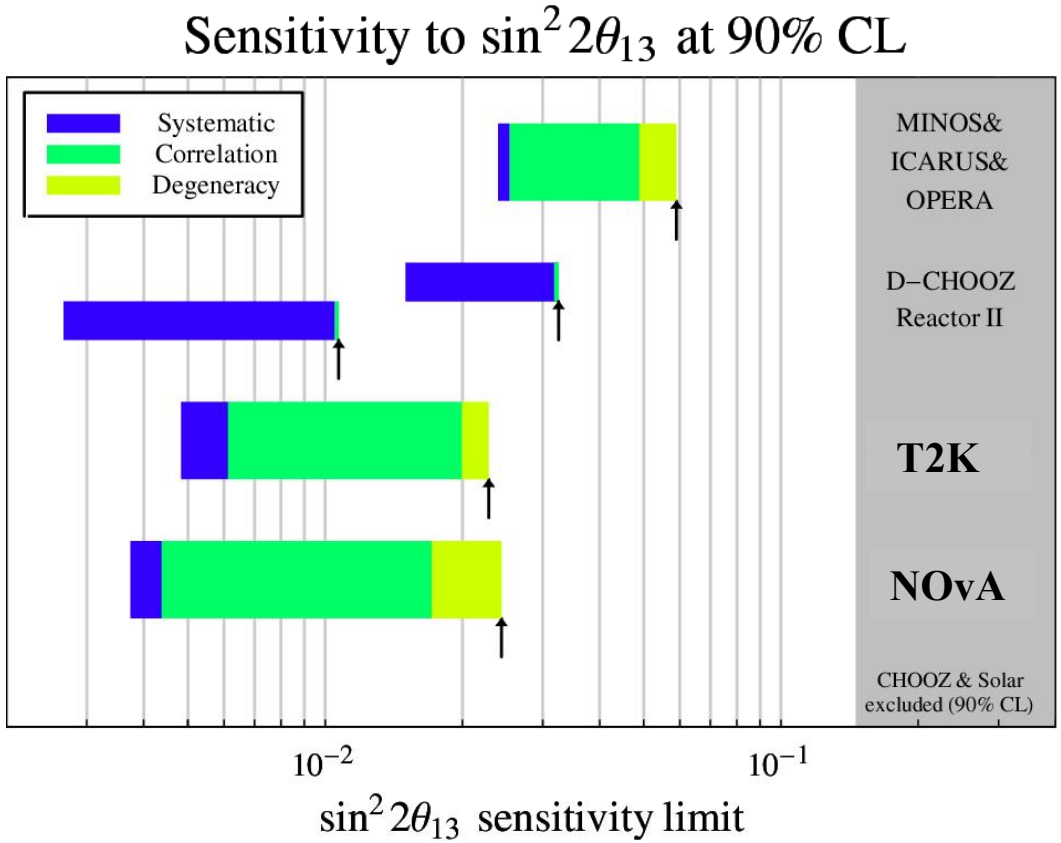
– 1,2,5 years

Compare: 5 years, 5% flux uncertainty

– CNGS: $4.5 \cdot 10^{19}$ pot/y

- **only modest improvements for θ_{13}**
- **other objectives...**

θ_{13} Sensitivity in the Next Generation



coming long baseline experiments

1 reactor +2 detectors

next generation long baseline experiments

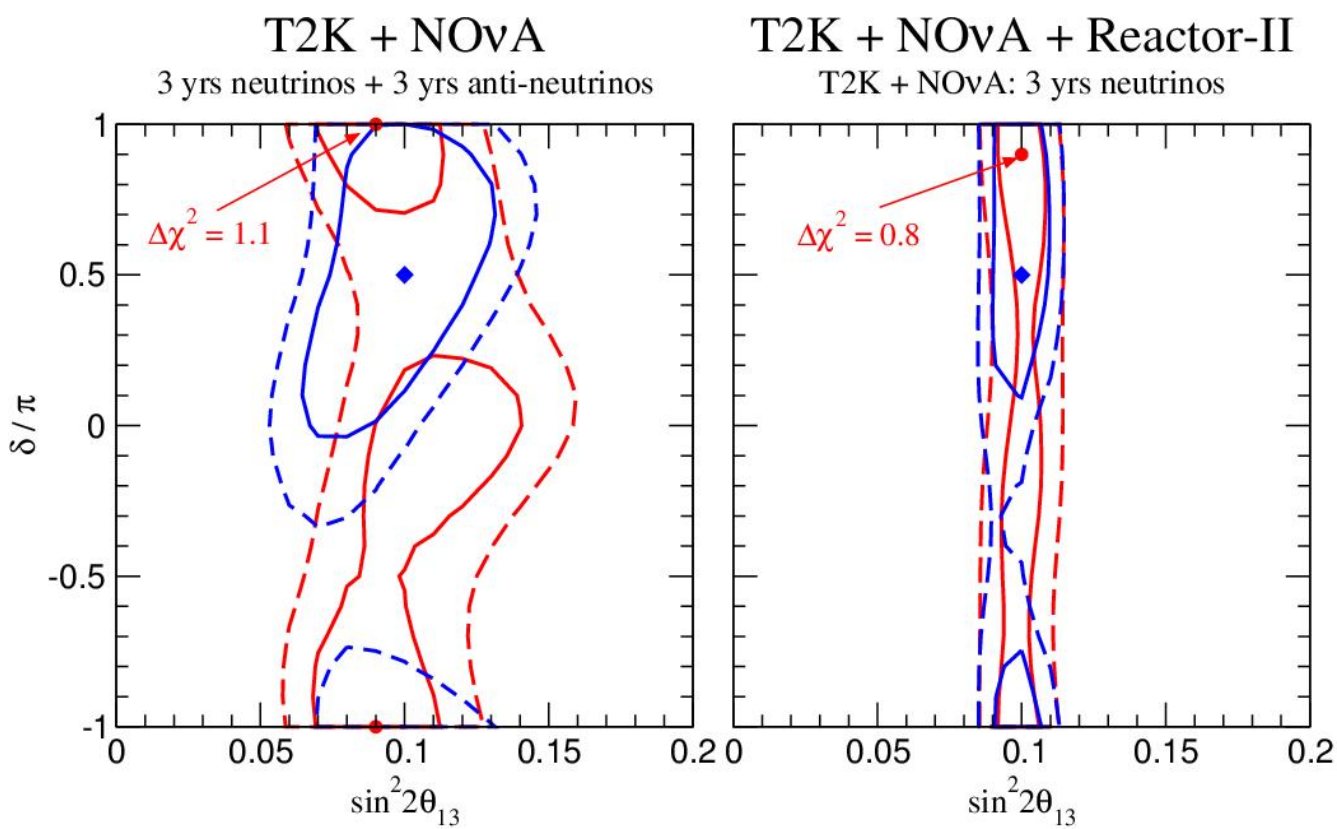
Compare:

- **5 years each**
- **5% flux uncertainty**

- one order of magnitude improvement for θ_{13}
- synergies between reactor and accelerator experiments
  - reactor anti-neutrinos $\Rightarrow$ only neutrino beams (x-section)
  - reactor: uncorrelated θ_{13} $\Rightarrow$ combine with beams & resolve correlations
- synergy between beams $\Rightarrow$ NOvA at larges baseline $\Rightarrow$ matter effects

Leptonic CP Violation – Best Case

<u>assume:</u> $\sin^2 2\theta_{13} = 0.1$, $\delta = \pi/2$ ➔combine: T2K+NOνA+Reactor



$\Delta m^2 > 0$

$\Delta m^2 < 0$

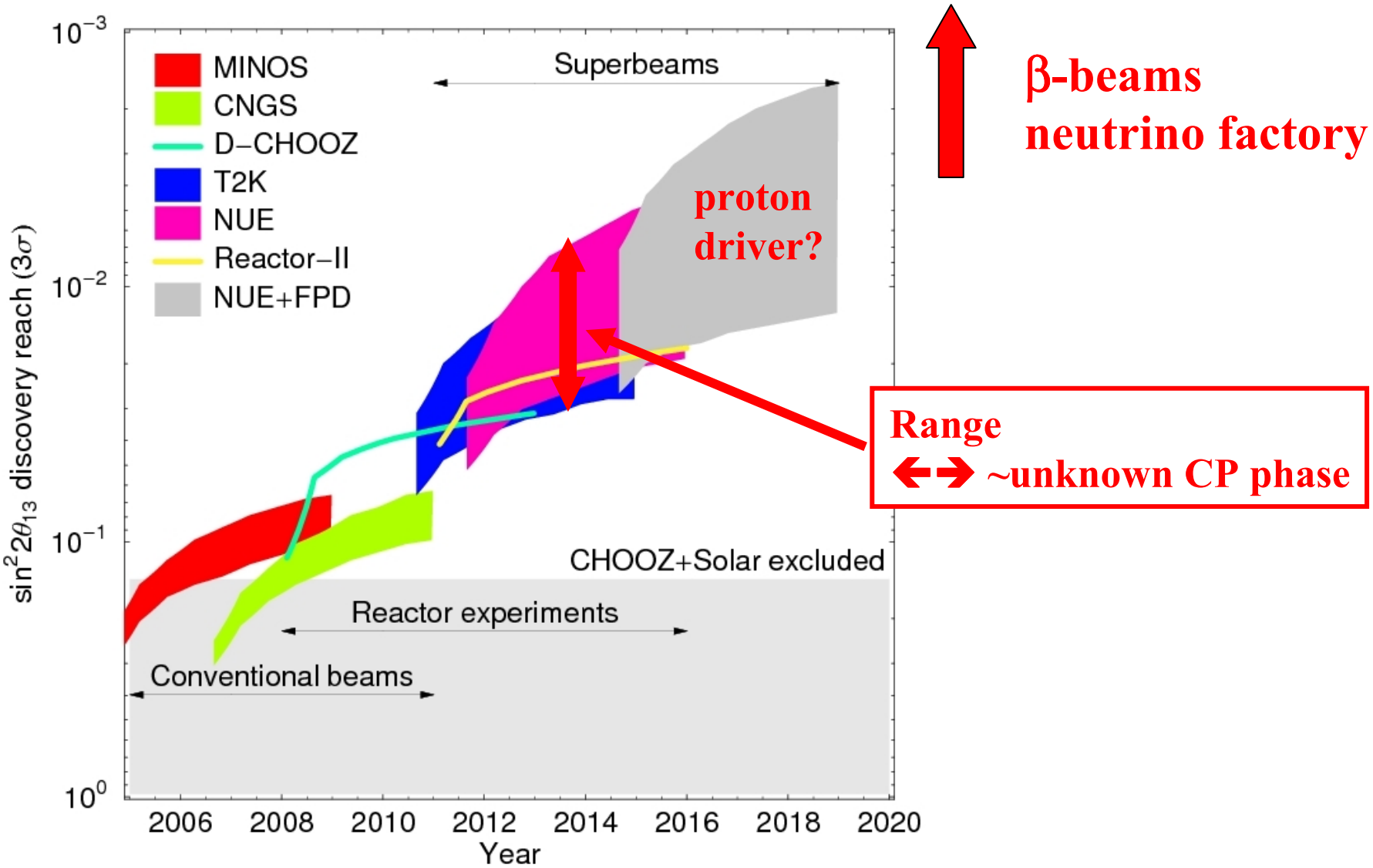
—— 90%CL

····· 3σ

➔ limits or measurement of leptonic CP violation

Huber, ML, Rolinec, Schwetz, Winter

Sensitivity Versus Time



Long Term Perspectives

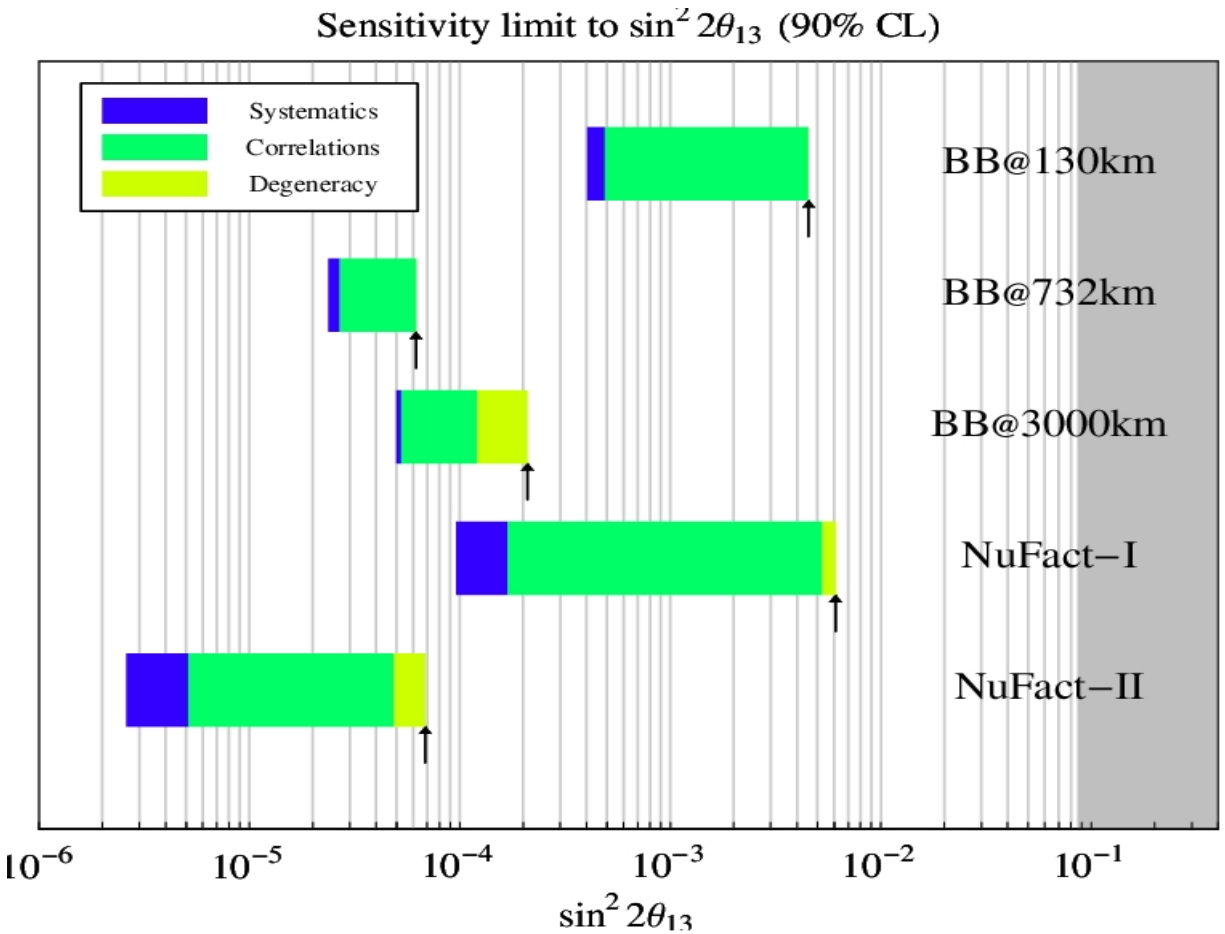
- **superbeams: $E_\nu \approx$ GeV** ➔ large low Z sampling calorimeters ≈ 50 kt
- **superbeams, β-beams: $E_\nu \approx$GeV** ➔huge Cerenkov detectors ≈ 1000 t
  ➔huge liquid Ar detectors ≈ 100 kt
  ➔huge scintillator detectors ≈ 30 kt
- **neutrino factory: $E_\nu \approx$20-50 GeV** ➔large magnetized iron Calorimeters ≈ 40kt
  ➔large magnetized liquid Ar detectors ≈20kt
  ➔large OPERA-like emulsion detectors ≈5kt

L=3000km, magnetized iron ➔ wrong sign muons

	P(MW)	μ's/year	$T_\nu+T_{\bar{\nu}}$ (y)	M(kt)
Neutrino factory I:	0.75	10^{20}	5	10
Neutrino factroy II:	4.00	$5.3*10^{20}$	8	50

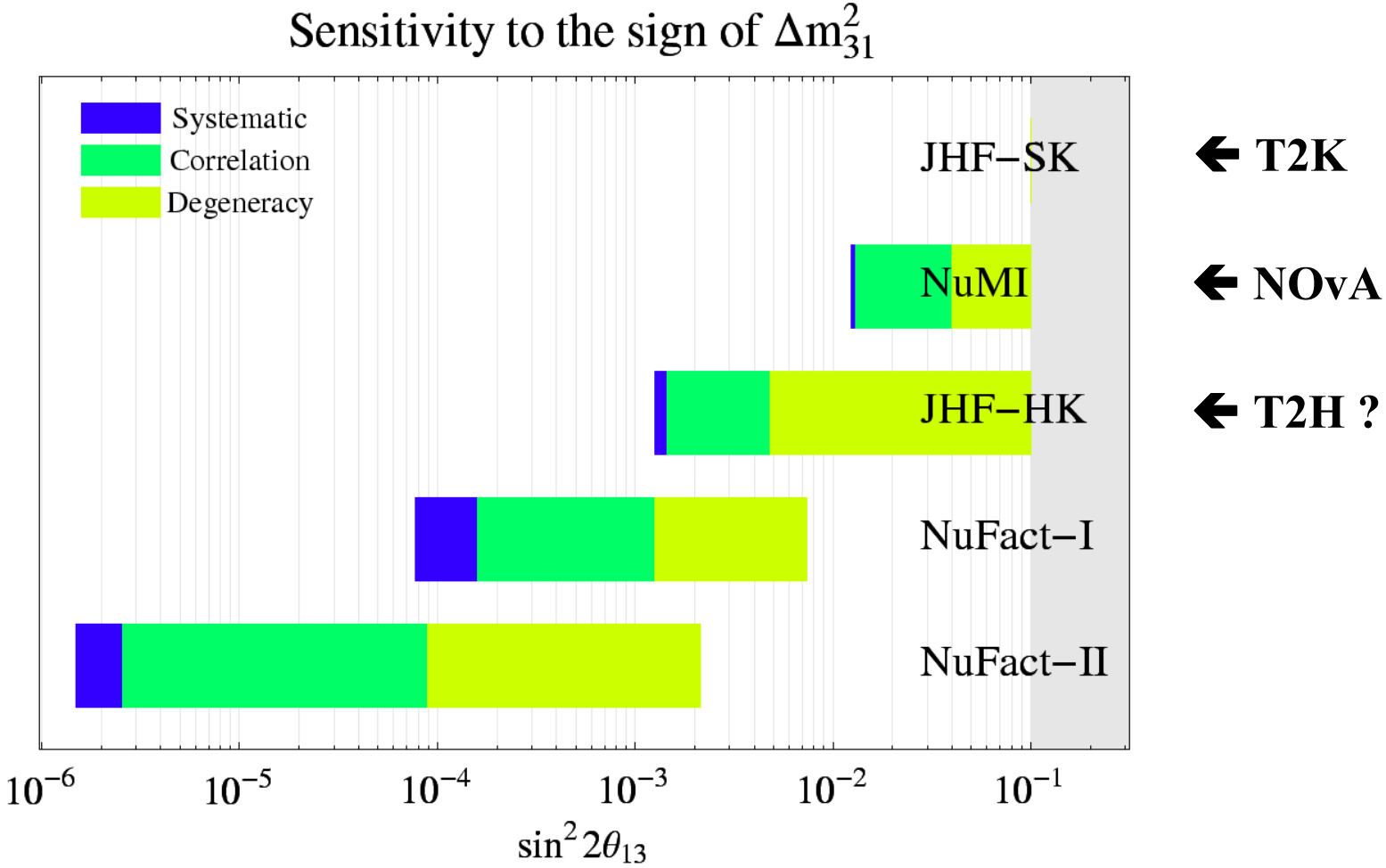
Long Term Ideas: β-Beam & ν-Factory

β-beam idea: Store instable isotopes in accelerators ➔ pure ν_e beams
ν-factory idea: Produce and store μ's ➔ decay: pure $\bar{\nu}_e + \nu_\mu$ beams



- very powerful
- interesting options
- many good ideas
- ...technological challenges

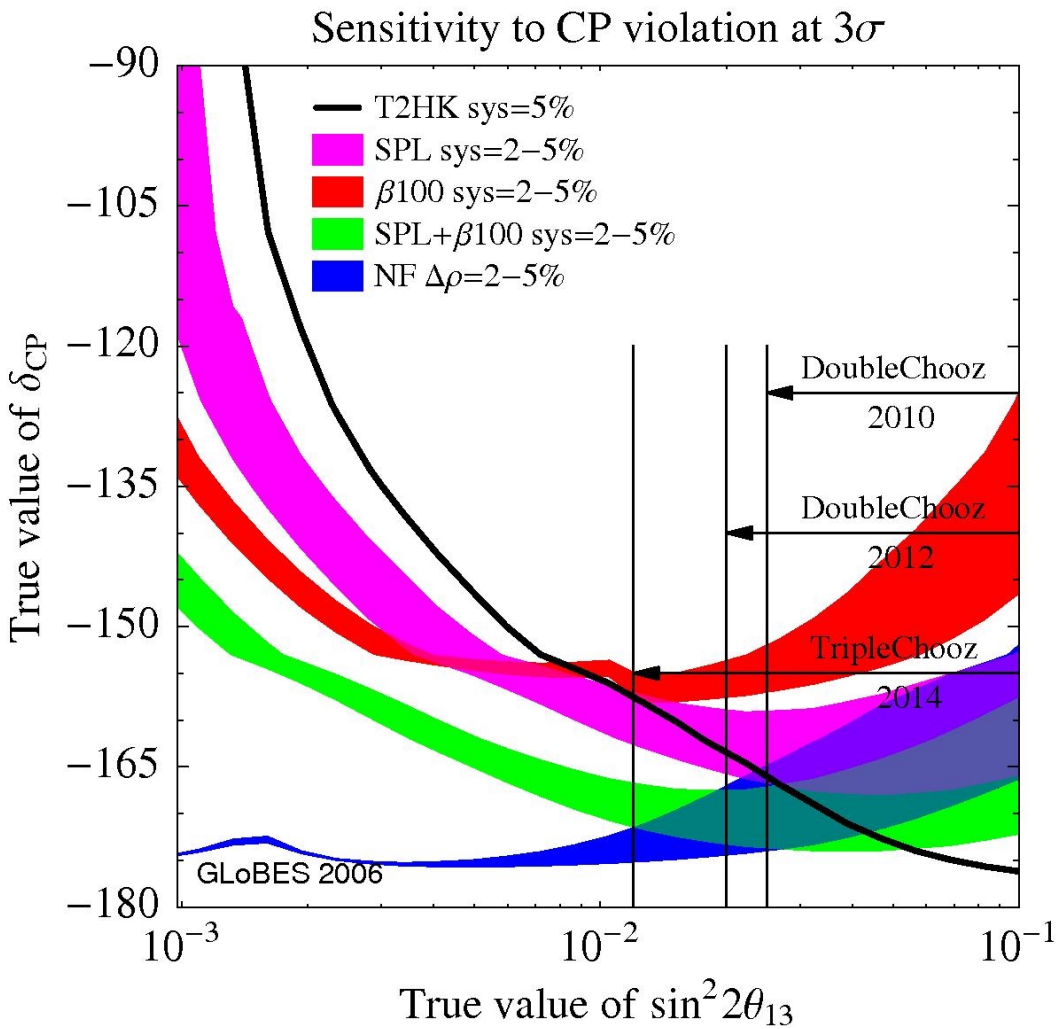
➔ further R&D required



- $sign(\Delta m^2_{31})$ very hard to determine with superbeams
- degeneracies with δ_{CP} are the main problem

  $\Rightarrow$ combine experiments!

θ_{13} and Road Maps



How to Break Degeneracies & Correlations

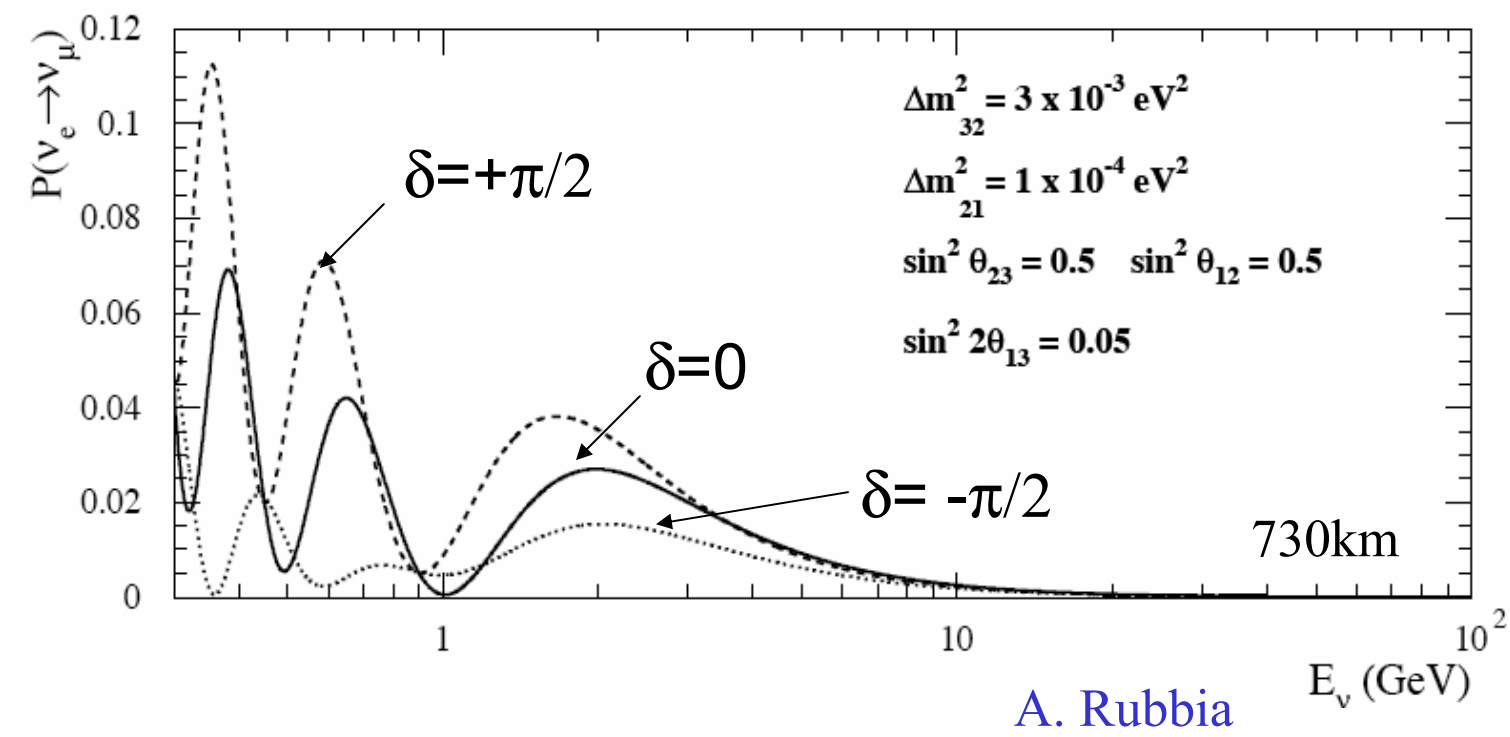
Rates only ➔ degeneracies ...broken by

- ➔ combination of different oscillation channels
- ➔ use different baselines
- ➔ combine different energies
- ➔ use energy spectrum
- ➔ go to „magic baseline“

All degeneracies can in principle be broken
Optimal strategy (physics output / time, money, feasibility) depends on further R&D

Energy Resolution

Rate based degeneracies have different energy spectra



A. Rubbia

➔ use energy resolution to break degeneracies

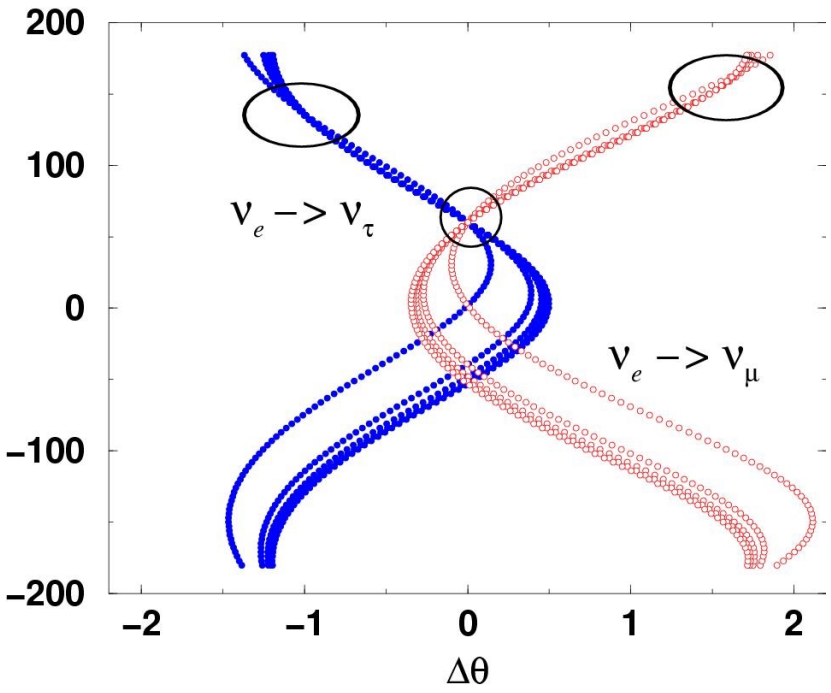
Silver Channels

Neutrino factory:

- **golden channel: wrong sign μ's**
- **silver channel : τ's**

➔different oscillation probabilities

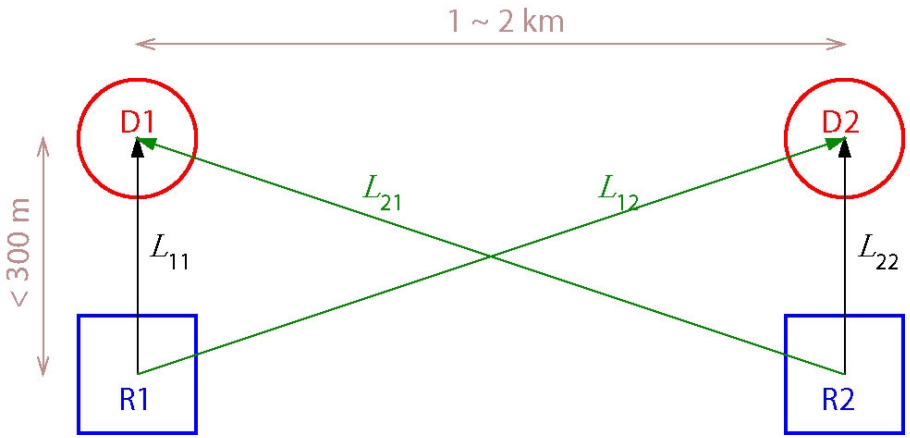
➔ break degeneracies!

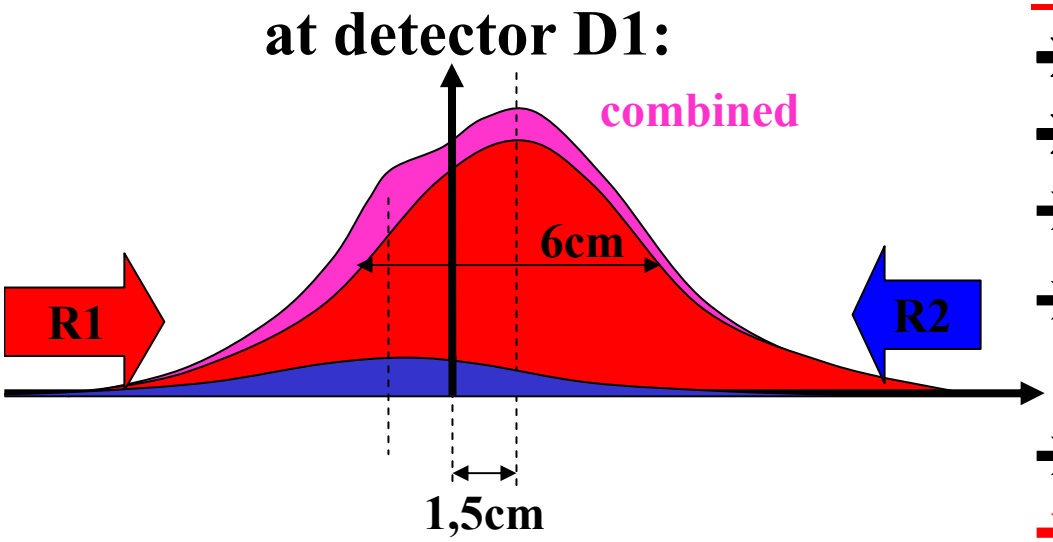


Donini, Meloni, Migliozzi
Autiero, et al.

New Ideas: R2D2 - Reactor Experiments

- **Symmetric reactors,detectors:**
  - **R1, R2, D1, D2 - may be different**
  - **$L_{11}=L_{22}$ and $L_{12}=L_{21}$**
- **Separate events from R_1 and R_2**
  - **R1 and R2 on/off times**
  - **Neutron displacement**
- **Simplest case: 1d line-up**





High statistics:

➔ **precise statistical separation**

➔ **N11, N21, N12, N22**

➔ **self-calibration: N11/N21=N22/N12**

➔ $\frac{N11 * N22}{N21 * N12} = \frac{r^4}{R^4}$ ⇔ oscillation

➔ **stable against size, backgrounds, ...**

➔ **Improved sensitivity**

Oscillations Outlook

➔ very precise neutrino oscillation parameters
➔ long term: most precise flavour information
➔ $\sin^2 2\theta_{13}$, sign(Δm^2) and CP phase will be measured

➔ unique impact on our understanding of flavour
- model building (symmetries, GUTs, mixing angle relations,...)
- quantum corrections
- limits on 3ν unitarity, decay, decoherence

➔ tests also
- coherent forward scattering , matter profiles
- NSI
- MVN, extra dimensions, ...

➔ very promising program!