Physics Reach of β-Beams and ν-Factories

(and the problem of Degeneracies)

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1 Introduction

- **Present Status of Neutrino Oscillation Parameters**

$\boxed{\text{Solar Sector}}$
$$\left\{\begin{array}{c} \mathbf{\Delta m^2_{SOL} = (8.2 \pm 0.5) \cdot 10^{-5}\ eV^2} \\ \mathbf{0.70\ <\ \sin^2 2\theta_{12}\ <\ 0.95} \end{array}\right.$$

$\boxed{\text{Atm Sector}}$
$$\left\{\begin{array}{l} \mathbf{\Delta m^2_{ATM} = (2.5 \pm 0.5) \cdot 10^{-3}\ eV^2} \\ \mathbf{0.90\ <\ \sin^2 2\theta_{23}\ <\ 1.00} \end{array}\right.$$

1 Introduction

- **Present Status of Neutrino Oscillation Parameters**

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$\boxed{\text{Atm Sector}}$ $\left\{ \begin{array}{ll} \mathbf{\Delta m^2_{ATM} = (2.5 \pm 0.5) \cdot 10^{-3}\ eV^2} & \mathbf{(sign(\Delta m^2_{ATM})\ ?)} \\ \mathbf{0.90 \ < \ \sin^2 2\theta_{23} \ < \ 1.00} & \mathbf{(sign(tan 2\theta_{23})\ ?)} \end{array} \right.$

STILL MISSING

$\theta_{\mathbf{13}}$ **poorly known** ($\theta_{\mathbf{13}} < \mathbf{11.5^\circ}$) $\longrightarrow$ **3 Family Oscillations ?**

$\delta_{\mathbf{CP}}$ **completely unknown** $\longrightarrow$ **Leptonic CP-violation ?**

- The GOAL of present (and planned) SOLAR and REACTOR experiments (SK, SNO, KamLAND, Borexino, ...) on a 10 years timescale will be to:

  - $\boxed{\text{Improve the precision on the SOLAR PARAMETERS}}$

    at the 10% level (or even BETTER: $\delta(\Delta m^2_{sol}) \leq 5\%$);

- The GOALS of present (and planned) ATMOSPHERIC and neutrino ACCELERATOR experiments (SK, K2K, MINOS, T2K, ...) on a 10 years timescale will be to:

  - $\boxed{\text{Improve the precision on the ATMOSPHERIC PARAMETERS}}$

    depending on the central value of Δm^2_{23} to $\delta(\Delta m^2_{23}) \approx 5\% - 10\%$ and $\delta(\sin^2 2\theta_{23}) \approx 1\% - 3\%$

  - $\boxed{\text{Give the first indication of a nonzero } \theta_{13}}$

    or, in case of null measure, IMPROVE CHOOZ bound of one order of magnitude, constraining $\sin^2 2\theta_{13} \leq 0.01$;

- Future Super-Beams (NOνA, T2HK, SPL), β-Beams and Neutrino Factories will represent the **NEXT GENERATION** (i.e. $>$ 10 years) of neutrino facilities. Their GOALS will be:

  1. MEASURE θ_{13} with high accuracy (if already known) or IMPROVE the limits on θ_{13} (of at least 1-2 orders of magnitude);
  2. If $\theta_{13} \neq 0$ is determined, MEASURE with good precision the CP violating phase δ (or at least discriminate $\delta = 0, \pi/2, \pi$);
  3. SOLVE the neutrino HIERARCHY measuring the $\mathrm{sign}(\Delta m^2_{23})$;
  4. DISCRIMINATE maximal/non-maximal θ_{23} (as much as possible);

DEEP IMPACT in understanding the leptonic FLAVOUR SECTOR

To PERFORM all (or some) these tasks NEXT GENERATION of neutrino experiments has COMPULSORILY to

⋆ FACE and SOLVE the problem of DEGENERACIES ⋆

2 The Eightfold Degeneracy in (θ_{13}, δ) Measure

- **Measuring θ_{13} and δ in Disappearance Channels**

$\boxed{\nu_e(\bar{\nu}_e) \text{ Disappearance Channel}}$ (i.e. Reactors, β-Beam ...)

$$P^{\pm}_{\nu_e \nu_e} \approx 1 - \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m^2_{12} L}{4E} \right) - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2_{23} L}{4E} \right)$$

- **NO SENSITIVITY** to the CP violating phase $\delta_{\mathbf{CP}}$ (neither to θ_{23});
- If $L/E \geq 10^3$ **LARGER UNCERTAINTIES** from SOLAR parameters;
- Needs very **GOOD CONTROL** over **FLUXES**, **SYS** and **BACK**;

$$\boxed{\textbf{At best SENSITIVITY in } \boldsymbol{\theta_{13} \in [5^\circ, 10^\circ]}}$$

(i.e. $\mathbf{0.03} \leq \sin^{\mathbf{2}} \mathbf{2\theta_{13}} \leq \mathbf{0.10}$)

- **Measuring θ_{13} and δ in Disappearance Channels**

$\boxed{\nu_\mu(\bar\nu_\mu)\ \textbf{Disappearance Channel}}$ (i.e. Super-Beam, Nu-Factory ...)

$$P^{\pm}_{\nu_\mu\nu_\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2(\frac{\Delta m^2_{23}\, L}{4E}) + \mathcal{O}(\theta^2_{13} \sin^2 \left(\Delta m^2_{23}\, L/4E\right))$$
$$+ \quad \mathcal{O}(\cos\delta_{CP} \cdot \theta_{13} \cdot \Delta_{12} \cdot \sin(\Delta m^2_{23}\, L/4E)) + \mathcal{O}(\Delta^2_{12})$$

- Needs very **GOOD CONTROL** over **FLUXES**, **SYS** and **BACK**;
- The **ATMOSPHERIC** term **ALWAYS DOMINATES**: $P^{\pm}_{\nu_\mu\nu_\mu} \approx 1/2$;
- Needs **EXTREME PRECISION** on ATMOSPHERIC parameters;

$\boxed{\textbf{Almost NO INFORMATIONS on } (\theta_{13}, \delta)}$

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$$+ \quad \mathcal{O}(\cos\delta_{CP} \cdot \theta_{13} \cdot \Delta_{12} \cdot \sin(\Delta m^2_{23} L/4E)) + \mathcal{O}(\Delta^2_{12})$$

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Almost NO INFORMATIONS on (θ_{13}, δ)

★ **DIS not Optimal for Measuring (θ_{13}, δ)** ★

- **Measuring (θ_{13}, δ) in Appearance Channels** (DeRujula99, Cervera00)

$\boxed{\nu_e \to \nu_\mu \; (\nu_\mu \to \nu_e) \text{ Appearance (Golden) Channel}}$ (i.e. BB, SB, NF)

$$P^{\pm}_{\nu_e \nu_\mu}(\theta_{13}, \delta) \quad \approx \quad X_\pm \sin^2 2\,\theta_{13} \; + \; \left(Y^c_\pm \cos\delta \; \mp \; Y^s_\pm \sin\delta \right) \sin 2\,\theta_{13} \; + \; Z$$

with $X_\pm, Y^c_\pm, Y^s_\pm$ and Z functions of the known parameters:

$$\begin{cases} X_\pm & = \quad \boxed{\sin^2\theta_{23}} \left(\dfrac{\Delta_{23}}{\tilde{B}_\mp} \right)^2 \sin^2 \left(\dfrac{\tilde{B}_\mp L}{2} \right) \\ Y^c_\pm & = \quad \boxed{\sin 2\theta_{23}} \sin 2\theta_{12} \; \dfrac{\Delta_{12}}{A} \; \dfrac{\Delta_{23}}{\tilde{B}_\mp} \sin \left(\dfrac{A\,L}{2} \right) \sin \left(\dfrac{\tilde{B}_\mp \; L}{2} \right) \boxed{\cos \left(\frac{\Delta_{23} L}{2} \right)} \\ Y^s_\pm & = \quad \boxed{\sin 2\theta_{23}} \sin 2\theta_{12} \; \dfrac{\Delta_{12}}{A} \; \dfrac{\Delta_{23}}{\tilde{B}_\mp} \sin \left(\dfrac{A\,L}{2} \right) \sin \left(\dfrac{\tilde{B}_\mp \; L}{2} \right) \boxed{\sin \left(\frac{\Delta_{23} L}{2} \right)} \\ Z & = \quad \boxed{\cos^2\theta_{23}} \sin^2 2\theta_{12} \left(\dfrac{\Delta_{12}}{A} \right)^2 \sin^2 \left(\dfrac{AL}{2} \right) \end{cases}$$

where $\Delta_{ij} = \Delta m^2_{ij}/2E$, $B_\mp = |A \mp \Delta_{23}|$ and A is the matter parameter.

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with $X_\pm, Y^c_\pm, Y^s_\pm$ and Z functions of the known parameters:

$\boxed{\textbf{Strong Correlation between } \theta_{13} \textbf{ and } \delta}$

- Changing δ one can mimic a different θ_{13};
- Changing θ_{13} one can mimic a different δ;
- NOTE: sensitive to $\mathrm{sign}(\Delta m^2_{atm})$ and $\mathrm{sign}(\tan 2\theta_{23})$

★ **Degeneracies in (θ_{13}, δ) Measure** ★

- **Measuring (θ_{13}, δ) in Appearance Channels** (Donini02)

$\boxed{\nu_e \rightarrow \nu_\tau \text{ Appearance (Silver) Channel}}$ (i.e. Nu-Factory ...)

$$P^{\pm}_{\nu_e \nu_\tau}(\theta_{13}, \delta) \approx X^\tau_\pm \sin^2 2\theta_{13} + \left(Y^{\tau,c}_\pm \cos\delta \mp Y^{\tau,s}_\pm \sin\delta \right) \sin 2\theta_{13} + Z^\tau$$

with $\boxed{X^\tau_\pm}$, $\boxed{Y^{\tau,c}_\pm}$, $\boxed{Y^{\tau,s}_\pm}$ and $\boxed{Z^\tau}$ functions of the known parameters:

$$\begin{cases} X^\tau_\pm = \boxed{\cos^2\theta_{23}} \left(\dfrac{\Delta_{23}}{\tilde{B}_\mp} \right)^2 \sin^2 \left(\dfrac{\tilde{B}_\mp L}{2} \right) \\ Y^{\tau,c}_\pm = \boxed{-}\ Y^c_\pm \\ Y^{\tau,s}_\pm = \boxed{-}\ Y^s_\pm \\ Z^\tau = \boxed{\sin^2\theta_{23}} \sin^2 2\theta_{12} \left(\dfrac{\Delta_{12}}{A} \right)^2 \sin^2 \left(\dfrac{AL}{2} \right) \end{cases}$$

where $\Delta_{ij} = \Delta m^2_{ij}/2E$, $B_\mp = |A \mp \Delta_{23}|$ and A is the matter parameter.

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Strong Correlation between θ_{13} and δ

– Changing δ one can mimic a different θ_{13};

– Changing θ_{13} one can mimic a different δ;

– NOTE: the different $-$ sign and θ_{23} dependence between the oscillation channels $\nu_e \to \nu_\mu$ and $\nu_e \to \nu_\tau$;

★ Degeneracies in (θ_{13}, δ) Measure ★

- **Degeneracies in (θ_{13}, δ) Measure: INTRINSIC CLONE** (Burguet01)

  - At a given experiment (L, E_ν) measure $P_+(\theta_{13}, \delta)$; How many solutions (θ_{13}, δ) give the same probability as the TRUE $(\bar{\theta}_{13}, \bar{\delta})$?

$$\boxed{P_+(\bar{\theta}_{13}, \bar{\delta}) \;=\; P_+(\theta_{13}, \delta)}$$

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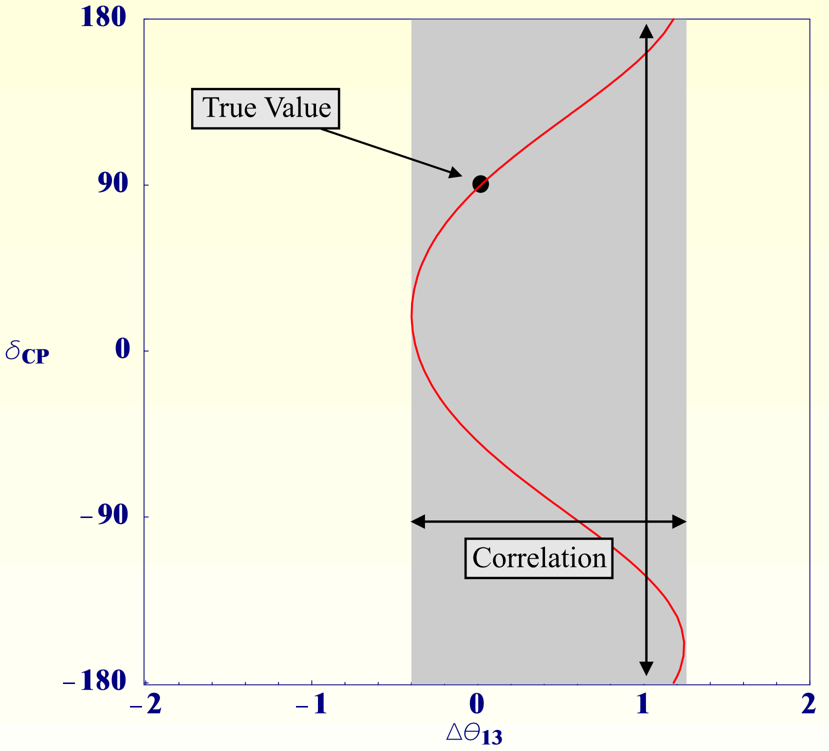

INFINITE number of DEGENERACIES

NB: Counting exp that measure only neutrinos has no sensitivity to δ !!

- We need more INFORMATIONS for solving the parameter degeneracy;
  - Suppose to measure at the SAME EXPERIMENT both $P_{\pm}(\theta_{13}, \delta)$; how many pairs (θ_{13}, δ) give the same probabilities as $(\bar{\theta}_{13}, \bar{\delta})$?

$$\boxed{P_{+}(\bar{\theta}_{13}, \bar{\delta}) = P_{+}(\theta_{13}, \delta)}$$
$$\boxed{P_{-}(\bar{\theta}_{13}, \bar{\delta}) = P_{-}(\theta_{13}, \delta)}$$

- We need more INFORMATIONS for solving the parameter degeneracy;
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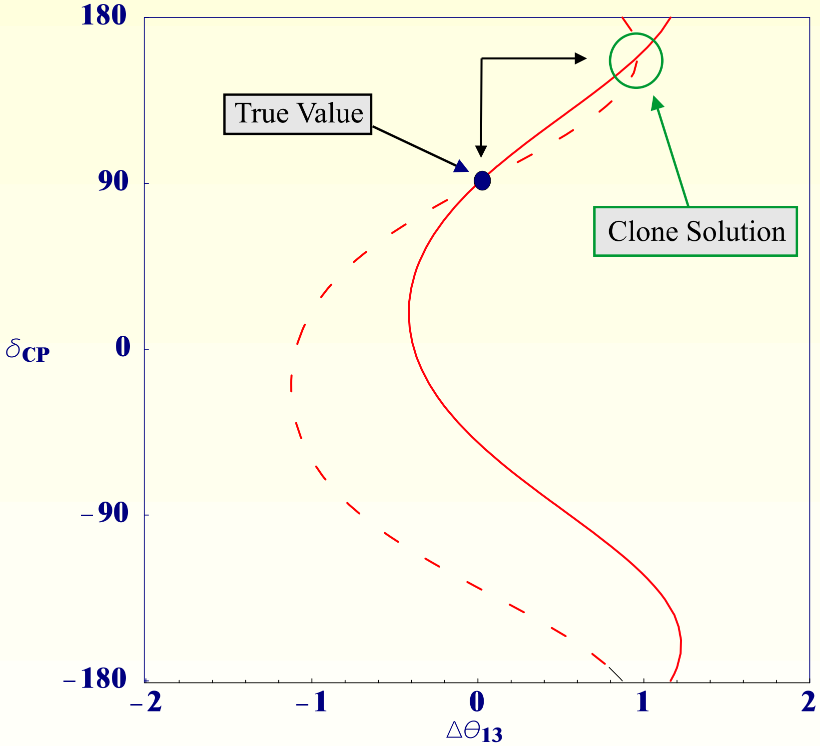

TWO: TRUE SOLUTION + INTRINSIC CLONE

- Not enough: We still need MORE INFORMATIONS $\rightarrow$ **1st WAY**

★ Using **DIFFERENT "EXPERIMENTS"** (same "channel"):

  - Sending the same ν beam to different BASELINES L;
  - Binning in the neutrino energy E (each bin equivalent to 1 EXP);

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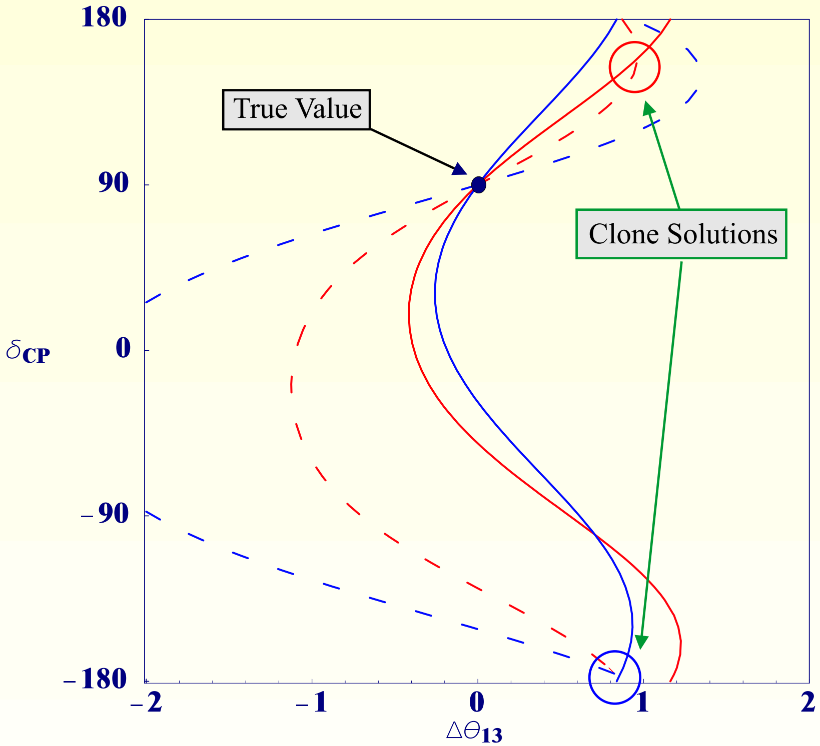

Different L/E $\rightarrow$ **Solve the Degeneracy**

- Not enough: We still need MORE INFORMATIONS $\rightarrow$ **2nd WAY**

★ Using **DIFFERENT "CHANNELS"** (same "experiment"):

  – Measuring the $\nu_e \rightarrow \nu_\mu$ $\boxed{\text{GOLDEN}}$ Appearance Channel;

  – Measuring the $\nu_e \rightarrow \nu_\tau$ $\boxed{\text{SILVER}}$ Appearance Channel;

- Not enough: We still need MORE INFORMATIONS $\rightarrow$ **2nd WAY**

★ Using **DIFFERENT "CHANNELS"** (same "experiment"):

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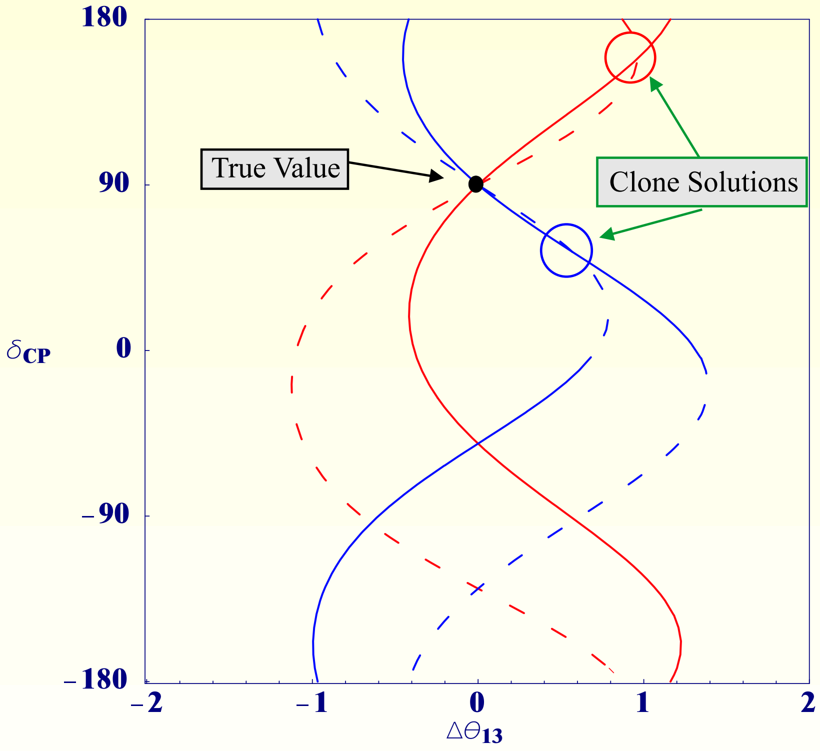


Golden + Silver $\rightarrow$ **Solve the Degeneracy**

- **Degeneracies in (θ_{13}, δ) Measure: EIGHTFOLD DEGENERACY**

Besides θ_{13} and δ other two (discrete) quantities will be unknown in 5-10 years at the time of next generation neutrino experiments:

– The SIGN of the ATM mass difference $\boxed{s_{atm} = \mathrm{sign}(\Delta m^2_{23})}$

– The OCTANT of the ATM angle $\boxed{s_{oct} = \mathrm{sign}(\tan 2\theta_{23})}$

Consequently, for taking into account **ALL OUR IGNORANCE** on the neutrino masses and mixings one has to make a simultaneous fit to these 4 parameters, i.e. to solve the following equation:

$$\boxed{N_i^{\pm} \underbrace{(\bar{\theta}_{13}, \bar{\delta}; \bar{s}_{atm}, \bar{s}_{oct})}_{\text{"true parameters"}} = N_i^{\pm} \underbrace{(\theta_{13}, \delta; s_{atm}, s_{oct})}_{\text{"guessed parameters"}}}$$

One has to solve ALL the following FOUR systems of equations, each of them having in general two distinct solutions:

intrinsic degeneracy (Burguet01)

$$\boxed{N_i^{\pm}(\bar\theta_{13},\bar\delta;\bar s_{atm},\bar s_{oct}) = N_i^{\pm}(\theta_{13},\delta;s_{atm}=\bar s_{atm},s_{oct}=\bar s_{oct})}$$

sign degeneracy (Minakata01)

$$\boxed{N_i^{\pm}(\bar\theta_{13},\bar\delta;\bar s_{atm},\bar s_{oct}) = N_i^{\pm}(\theta_{13},\delta;s_{atm}=-\bar s_{atm},s_{oct}=\bar s_{oct})}$$

octant degeneracy (Fogli96, Barger01)

$$\boxed{N_i^{\pm}(\bar\theta_{13},\bar\delta;\bar s_{atm},\bar s_{oct}) = N_i^{\pm}(\theta_{13},\delta;s_{atm}=\bar s_{atm},s_{oct}=-\bar s_{oct})}$$

mixed degeneracy (Barger01)

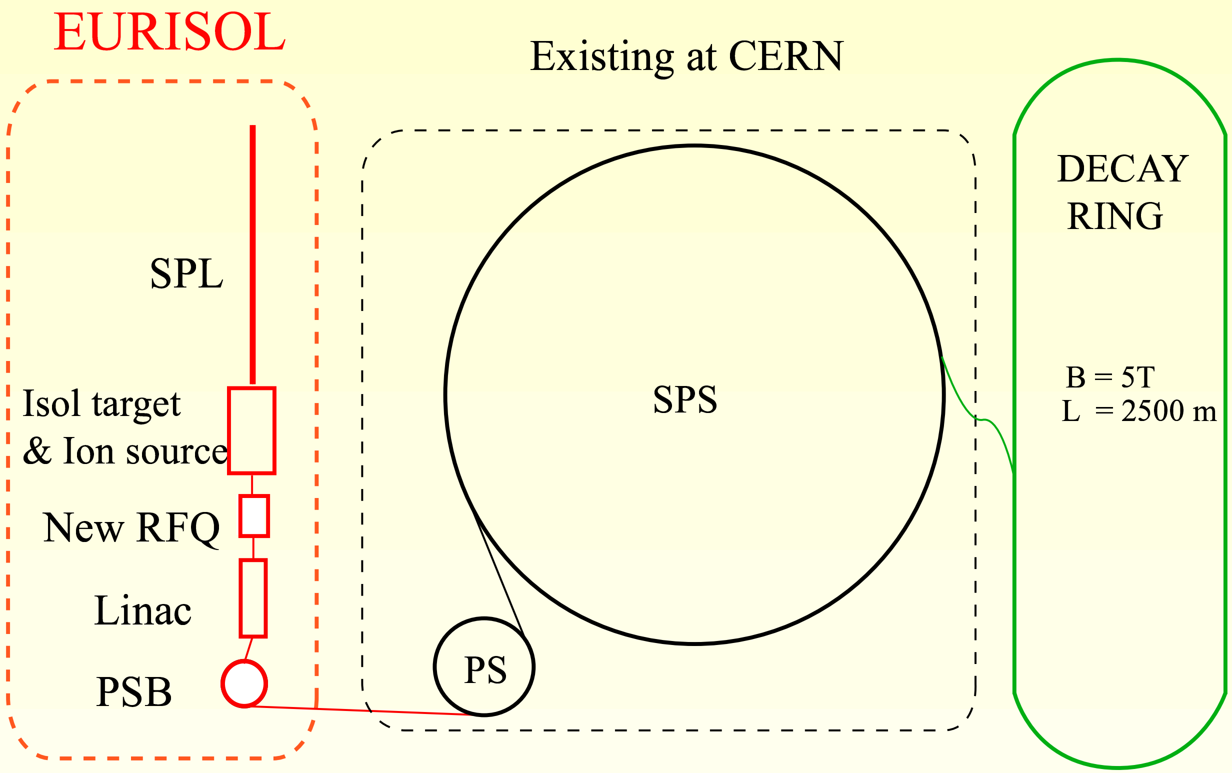
$$\boxed{N_i^{\pm}(\bar\theta_{13},\bar\delta;\bar s_{atm},\bar s_{oct}) = N_i^{\pm}(\theta_{13},\delta;s_{atm}=-\bar s_{atm},s_{oct}=-\bar s_{oct})}$$

The Eightfold Degeneracy

NB: Also In Disappearance One Has Clones. No INTRINSIC correlation between (θ_{13},δ) but still **DISCRETE AMBIGUITIES** s_{atm}, s_{oct}

3 Physics Reach of β-Beam Neutrino Facilities

- **"Standard" CERN to Frejus β-Beam Setup** (Zucchelli02, Bouchez03)



- β and/or β-inverse IONS BEAM produced by EURISOL ($^{6}\mathrm{He}$ and $^{18}\mathrm{Ne}$);
- Accelerated by PS and SPS to $\gamma \approx 100$ and accumulated in a decay ring;
- Expected 1.1×10^{18} Ne and 2.9×10^{18} He decays/year towards Frejus ($L = 130$ km) where a 1 Mton Water Cerenkov detector is placed;
- PURE $\bar{\nu}_e$ and ν_e BEAMS permit to study $\boxed{\nu_e \to \nu_e,\ \nu_e \to \nu_\mu \text{ oscillations}}$.

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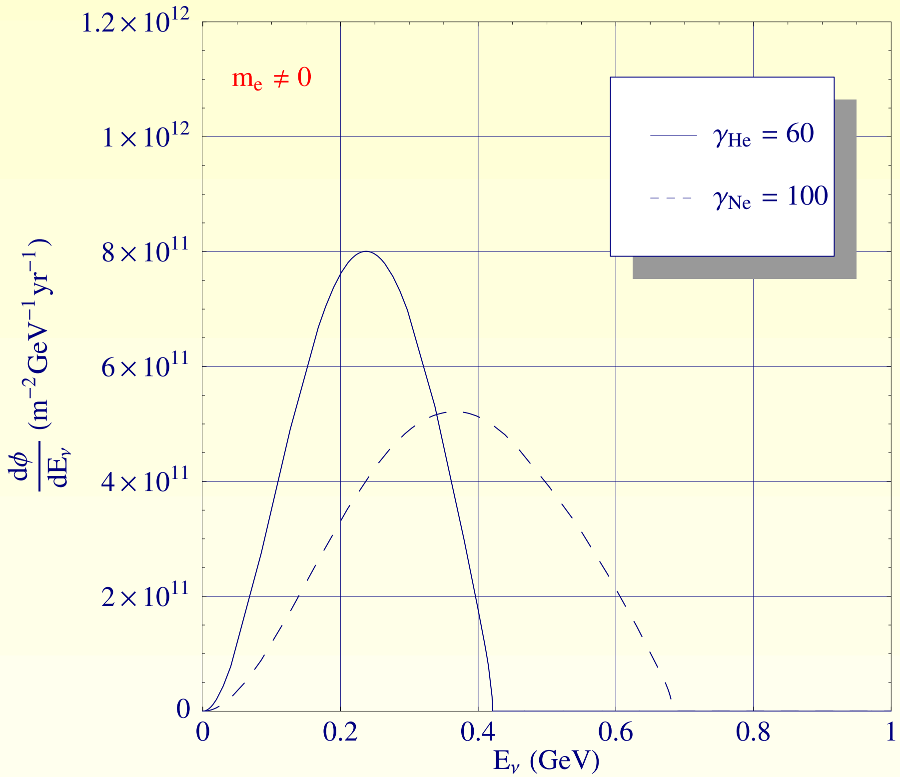


β Beam	N_{ν_e}	$N_{\bar{\nu}_e}$
$\langle E_\nu \rangle$	0.37 GeV	0.23 GeV
CC (10+10)	133205	19557
CHOOZ (D_+)	86910	11727
CHOOZ (A_+)	1918	445
Beam Bck.	0	0
Det. Bck.	360	1

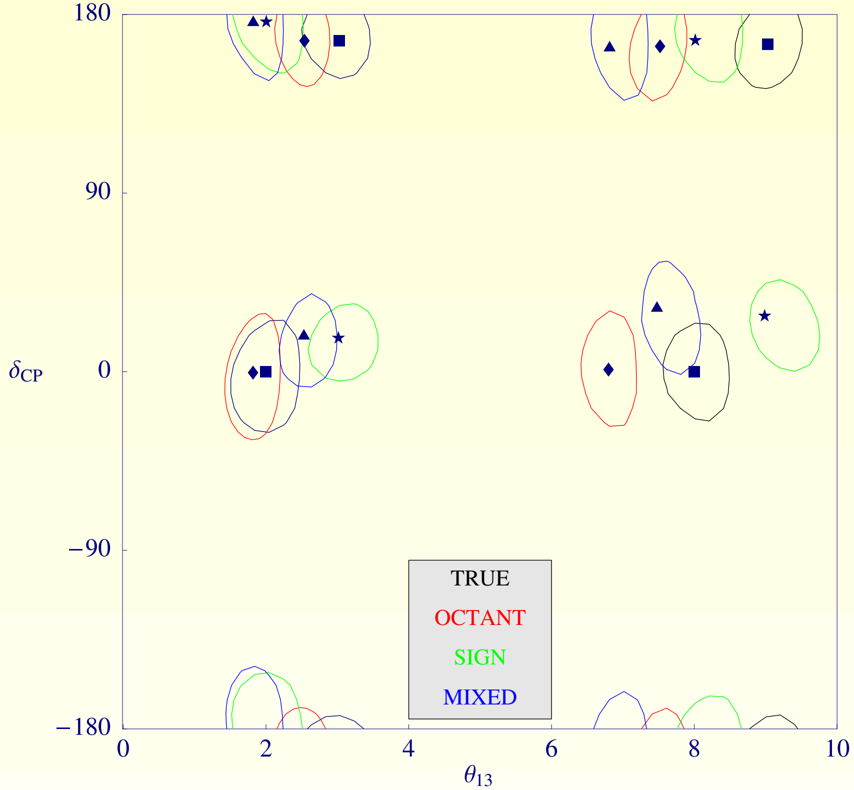
– ν_e ($\bar{\nu}_e$) flux from ^{18}Ne (^{6}He) ions accelerated at $\gamma = 100$ ($\gamma = 60$). The average neutrino energy is γE_0 ($E_0 = \beta$-decay threshold energy at rest);

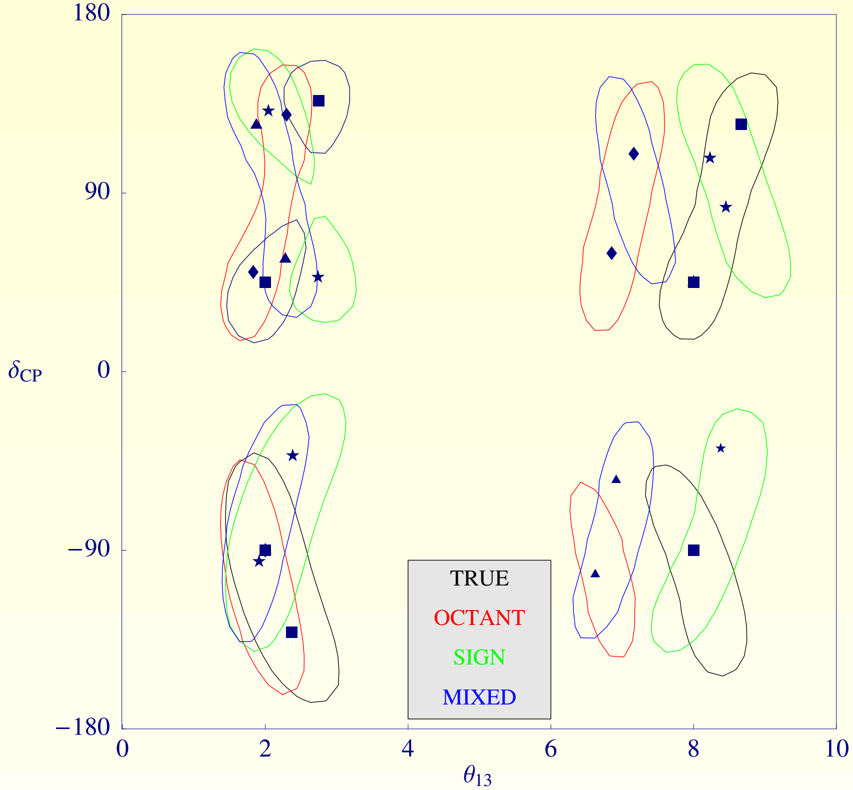
– NO BINNING considered: Just a **COUNTING EXPERIMENT**; 10 yrs ν_e + 10 yrs $\bar{\nu}_e$ simultaneous running considered;

– **NO BEAM BACK;** DETECTOR BACK mainly due to NC (π^0);

3.1 The Eightfold Degeneracy at the standard βB

- **Measuring (θ_{13}, δ) at β-Beam $\nu_e \to \nu_\mu$ Appearance Channel**



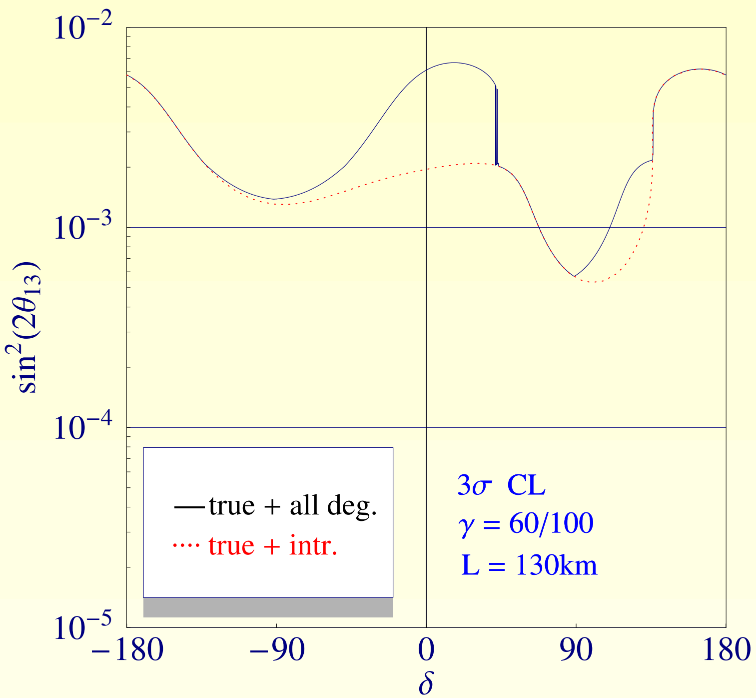


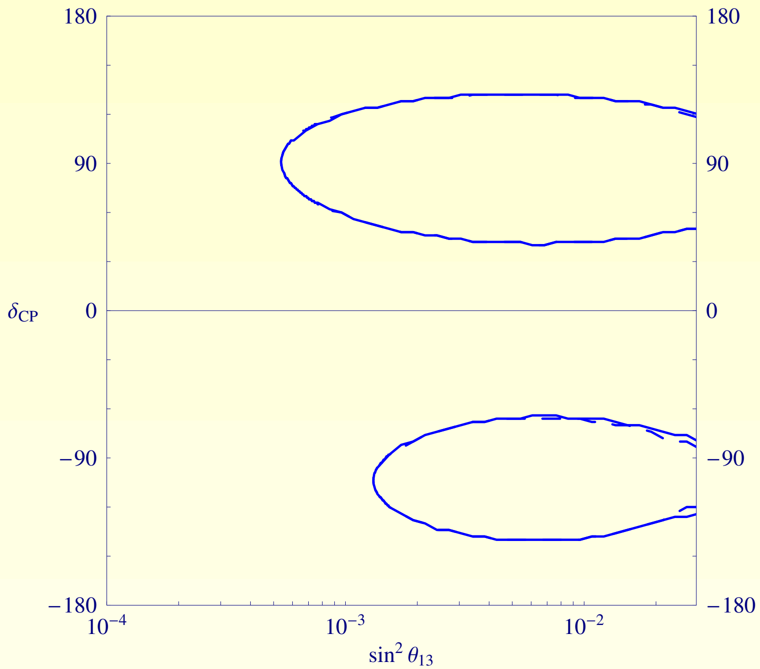
(plots from A. Donini et al, hep-ph/0406132)

– Typical βB Appearance fits (90% CL) for $\theta_{13} = 2, 8$ and $\delta_{CP} = 0, 45, -90$. Backgrounds (see βB table) and Systematics (5%) included;

– Eightfold Degeneracy clearly visible (see for example $\theta_{13} = 8$ and $\delta_{CP} = 0$); Induce large uncertainties in θ_{13} (for large θ_{13}) and δ_{CP};

- β**B Sensitivity to** θ_{13} **and** δ **- "standard" setup**





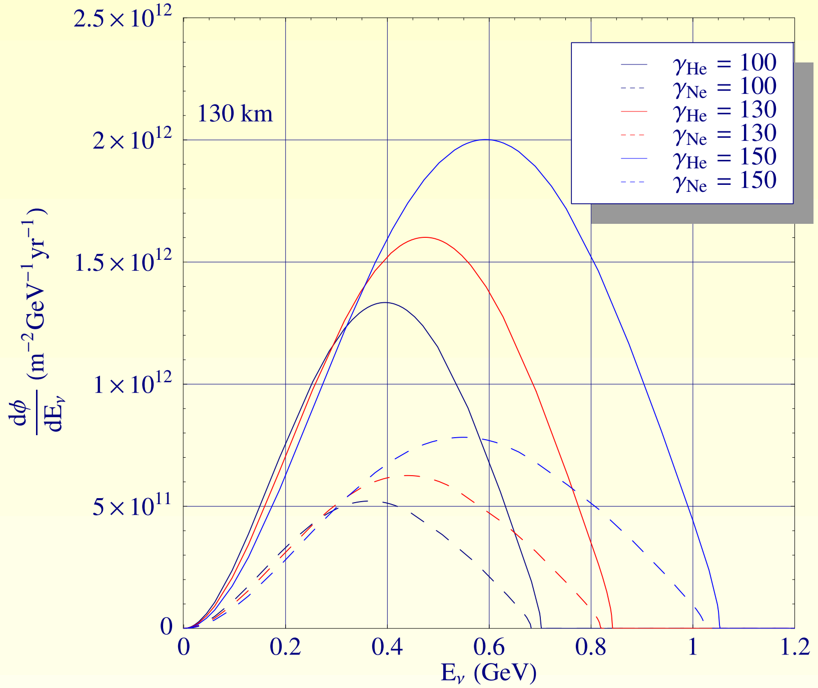
- 3σ sensitivity to θ_{13} as function of δ for the "standard" β-Beam (LEFT); Notice the effect of including all the degeneracies (especially at $\delta = 0$); BEST sensitivity for $\delta_{CP} = \pm 90$ where the number of ν, $\bar{\nu}$ is max;

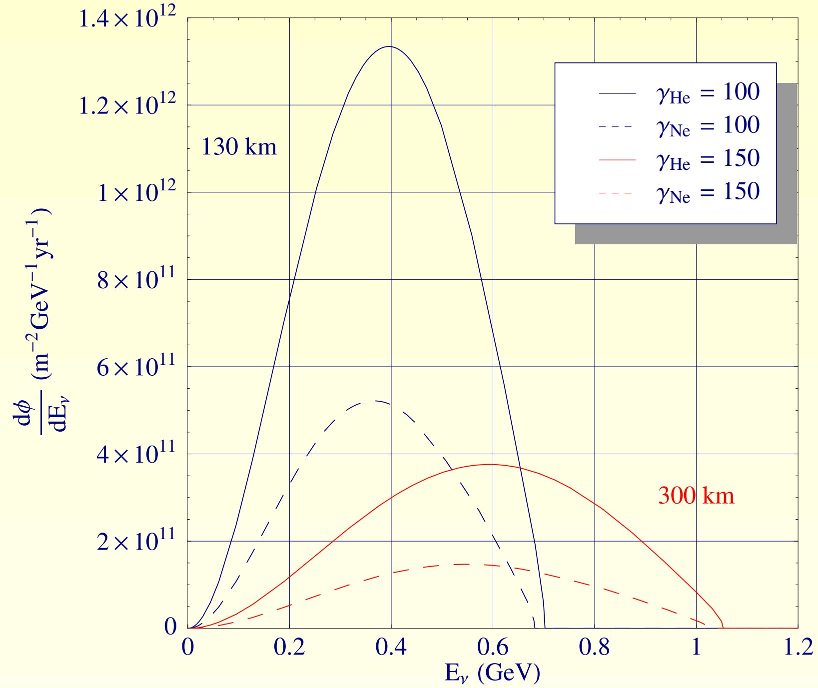
- 3σ CP discovery potential after 10 years of standard β-Beam (RIGHT); sensitivity to max CP violation dowtn to $\sin^2\theta_{13} \approx 10^{-3}$

- Be careful as χ^2 analysis not rigorous in presence of small background ($\bar{\nu}_e$-channel – $\delta = 90$); Feldman-Cousins analysis should be performed;

3.2 Optimization of β-Beam setups

- **β-Beam fluxes for different γ and L**



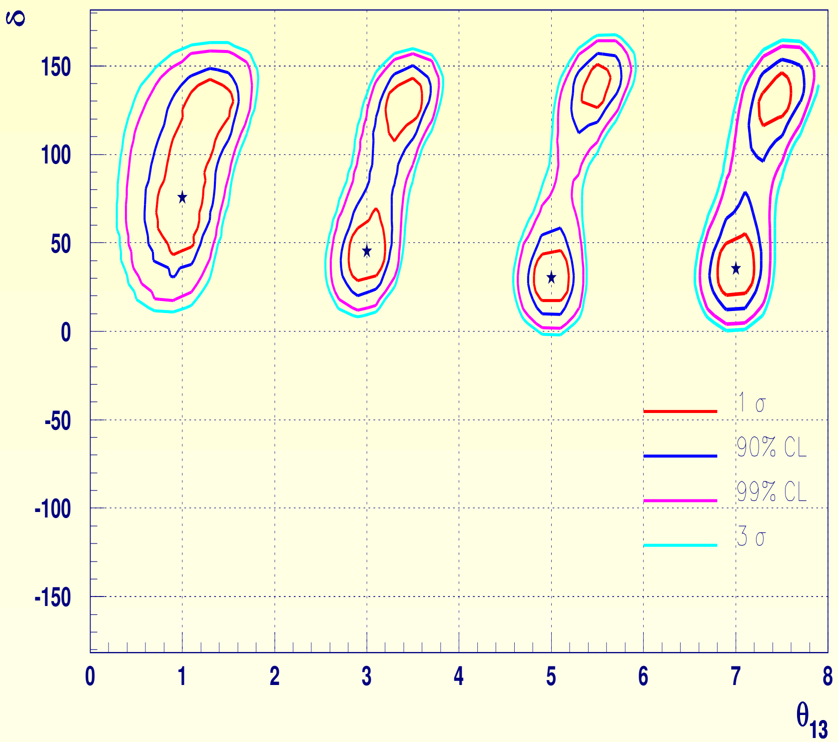


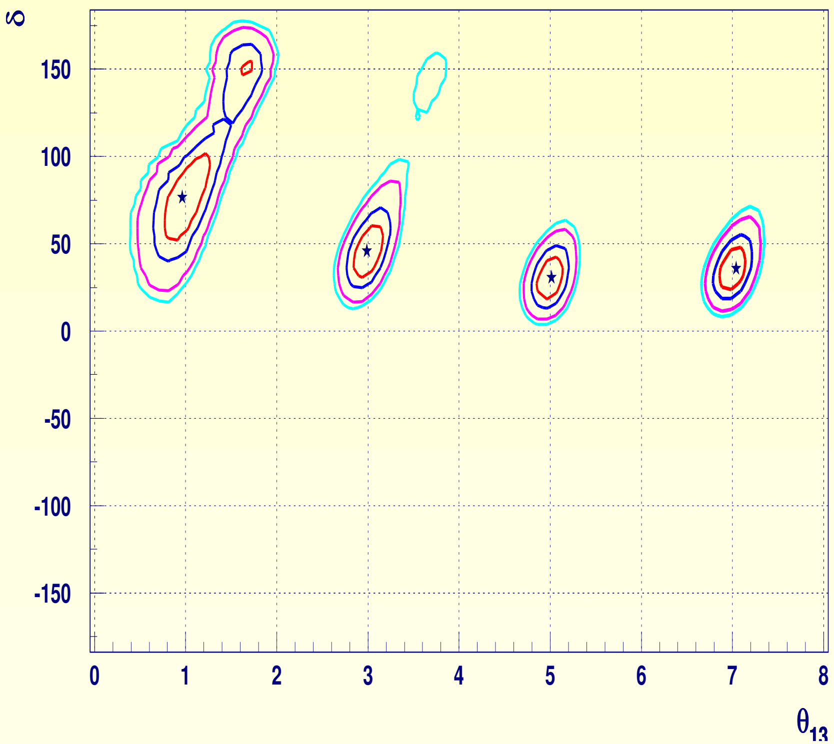
– At fixed L, β-Beam fluxes increase with γ with NO FLUX PENALTY at lower energies, similar to what happens for Neutrino Factory fluxes;

– Fluxes suppression at higher L at higher γ are also compensated by higher cross section (rapidily growing in the sub-GeV region);

– NOTE: γ-independence of the total number of ions is assumed (see Lindroos talk for more details on technical challenges of β-Beams);

- **"Standard" vs New setups** (plots from M. Mezzetto, hep-ex/0410083)



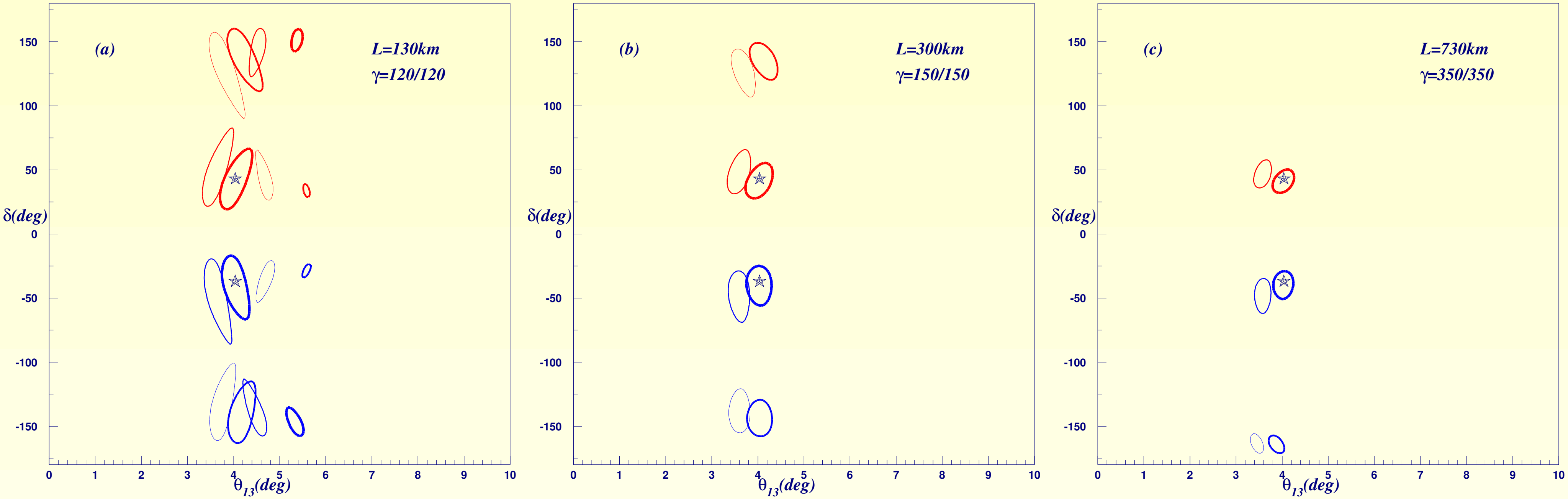


– True solution and Intrinsic clone for different values of θ_{13} and δ for the "standard" $\gamma = (60, 100)$ (LEFT) and new $\gamma = (100, 100)$ (RIGHT) setup;

– The inclusion of binning (250 MeV) starts to lift away the Intrinsic clone for $\theta_{13} \geq 4°$ (thanks of INDEPENDENT L/E INFORMATIONS) ;

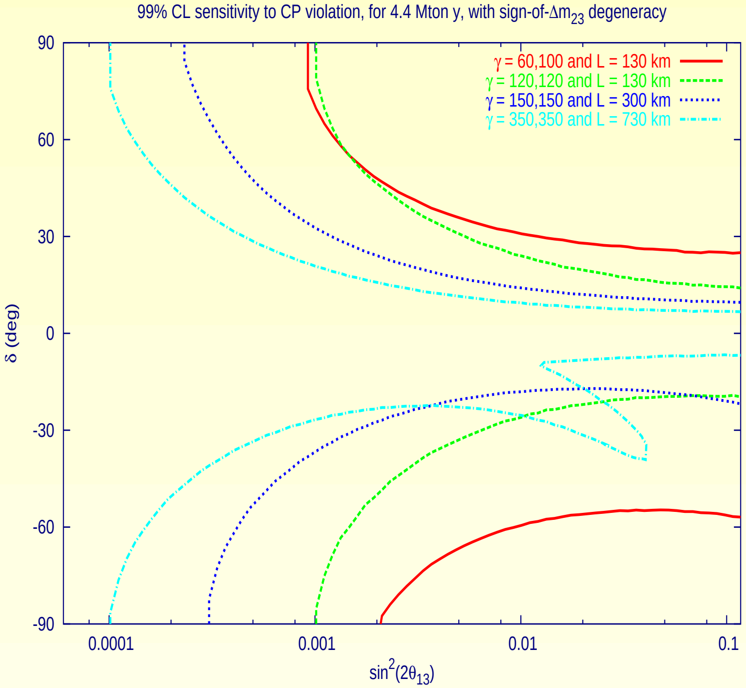
– The new results (RIGHT) benefit also from an higher antineutrino statistics and the reduction of background estimation for ^{18}Ne;

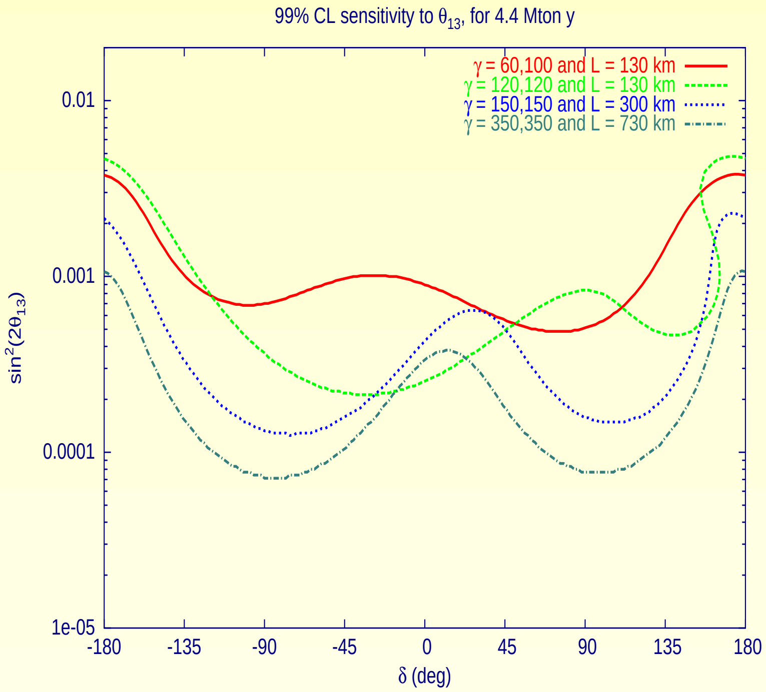
- **Optimization of β-Beam setup** (plots from Burguet et al, hep-ph/0503021)



  - 99% CL fit for $\theta_{13} = 4°, \delta = \pm 40°$, for three different setups (γ,L);
  - Binning of 250 MeV is implemented using migration matrices for signals and backgrounds; ONLY SMALL IMPROVEMENTS at $\gamma \leq 120$.
  - At higher $\gamma = 150$ binning informations permits to solve the energy dependent part of the degenerations (fourfold degeneration);
  - At 730 km and $\gamma = 350$ also the s_{atm} clone start to be solved as matter effect becomes non-negligible; only the octant clone remains;
  - More details on β-Beam analysis in M. Mezzetto and E. Couce talks;

- **Sensitivity to CP violation and θ_{13} (new setups)**



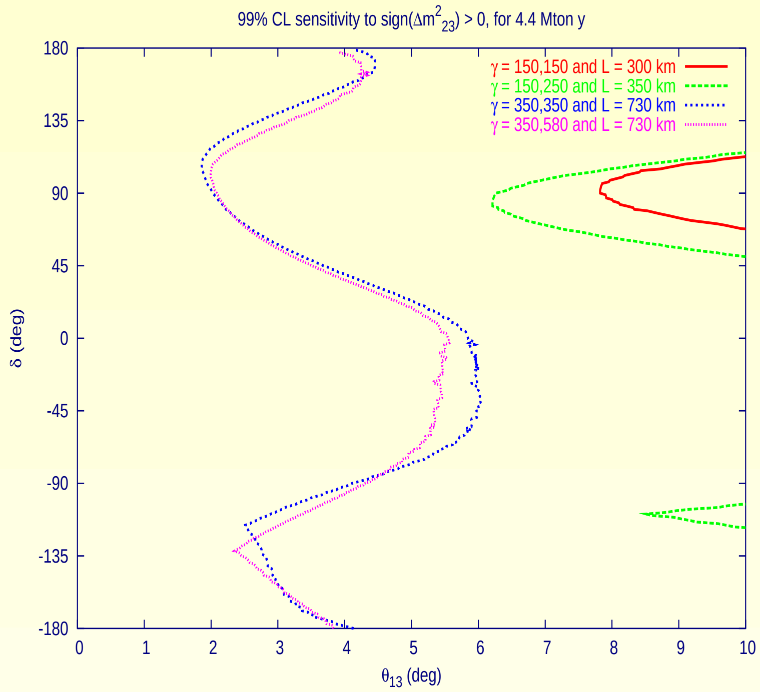


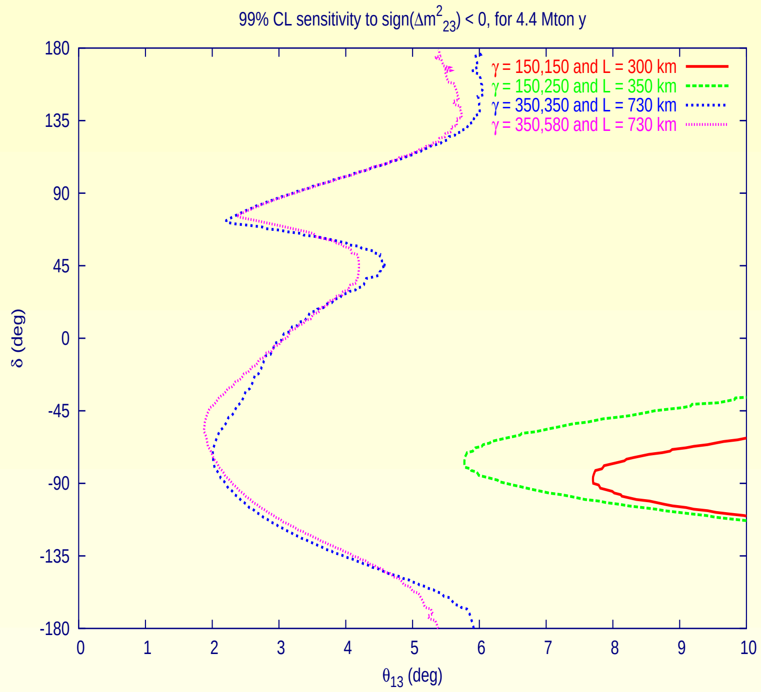
(plots from Burguet et al, hep-ph/0503021)

- 99% CL sensitivity to CP-violation (LEFT) and to θ_{13} (RIGHT) for the setups considered (at three different baselines: 130, 300, 730 km);
- Higher Energies (and Longer Baselines) usually outperform in a large part of the parameter space; The $\gamma = 350$ option can measure θ_{13} down to $\sin^2 2\theta_{13} \approx 10^{-3} - 10^{-4}$ and δ with a precision of 20°;
- MOTIVATION for a β-Beam experiment at $\gamma \geq 150, L \geq 500$ km;

BETTER SENSITIVITY

- **Sensitivity to $\mathrm{sign}(\Delta m^2_{23})$ with new setups**





(plots from Burguet et al, hep-ph/0503021)

– 99% CL sensitivity to the $\mathrm{sign}(\Delta m^2_{atm})$ assuming normal hierarchy (LEFT) or inverted hierarchy (RIGHT);

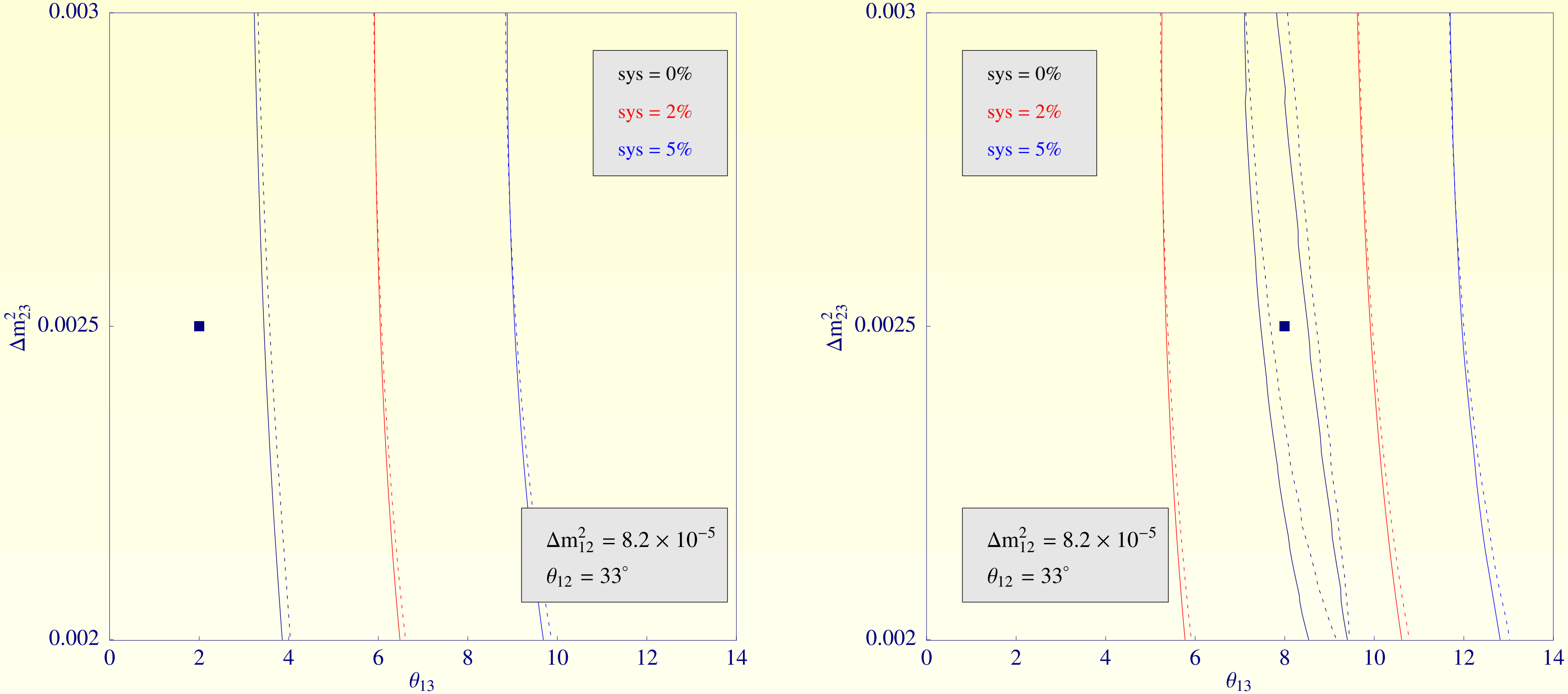
– The setup with $(\gamma = 350, L = 730)$ is sensitive to the hierarchy down to $\theta_{13} \in [2^\circ - 5^\circ]$ depending on δ; At lower L almost no sensitivity to s_{atm};

– MOTIVATION for a β-Beam experiment at $\gamma \geq 150, L \geq 500$ km;

BETTER SENSITIVITY + MASS HIERARCHY MEASURE

3.3 Study of βB Disappearance Channel

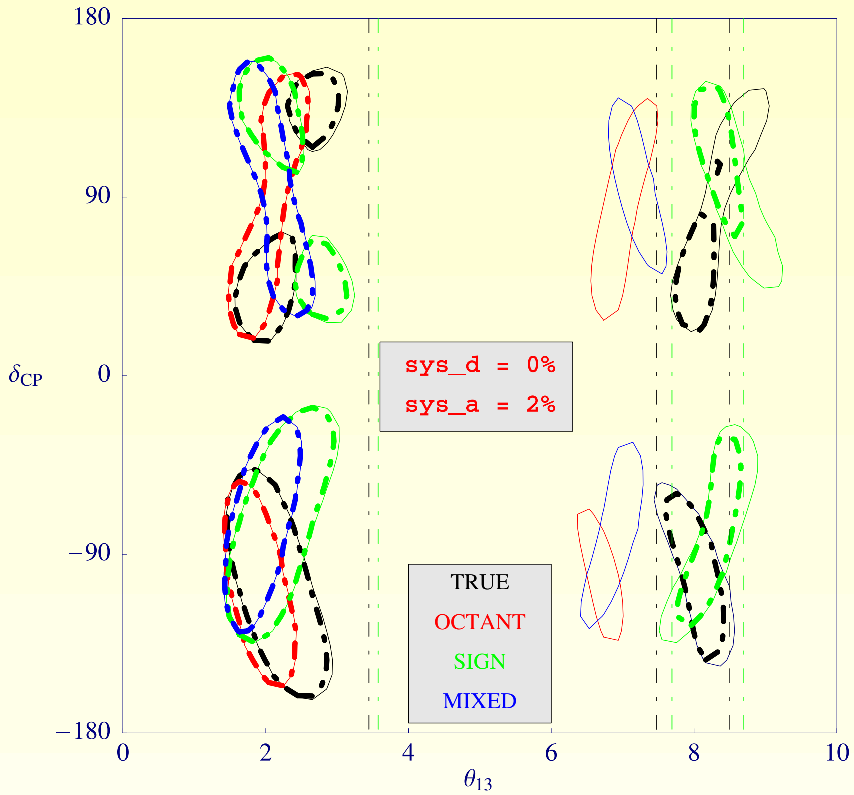
- **Measuring θ_{13} at β-Beam $\nu_e \to \nu_e$ Disappearance Channel**

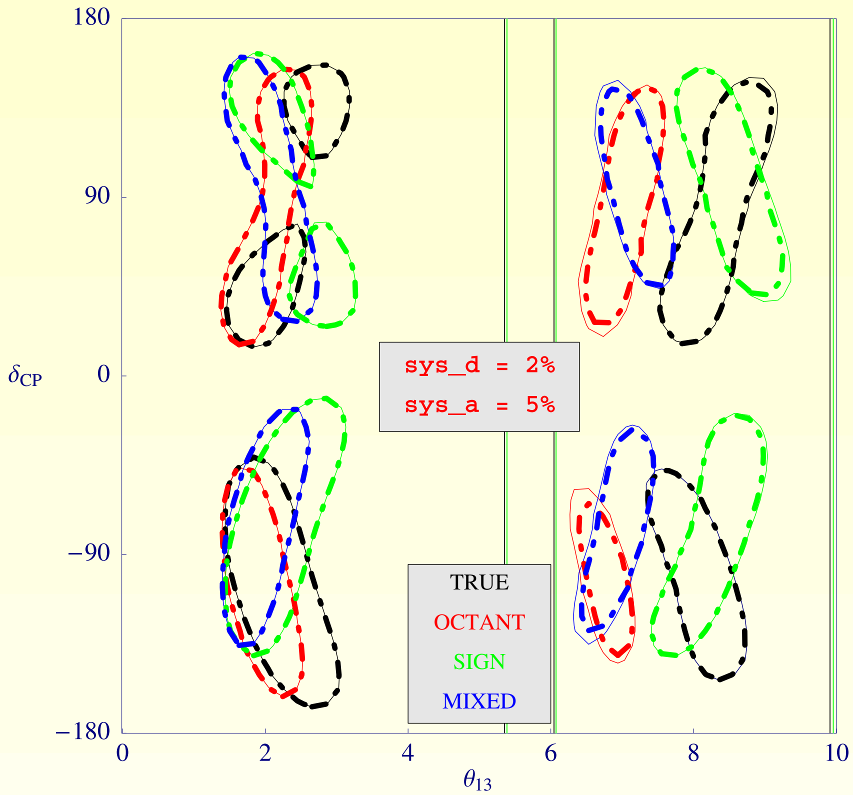


(plots from Donini et al, hep-ph/0411402)

- βB DIS fits (90% CL) for three different systematic errors;
- All the parameters values shown (no dependence on θ_{23} and δ_{CP});
- NOTE: Could be useful for constraining (large) θ_{13} ONLY if $\mathrm{sys} < 2\%$;

- **Combining β-Beam Appearance and Disappearance**





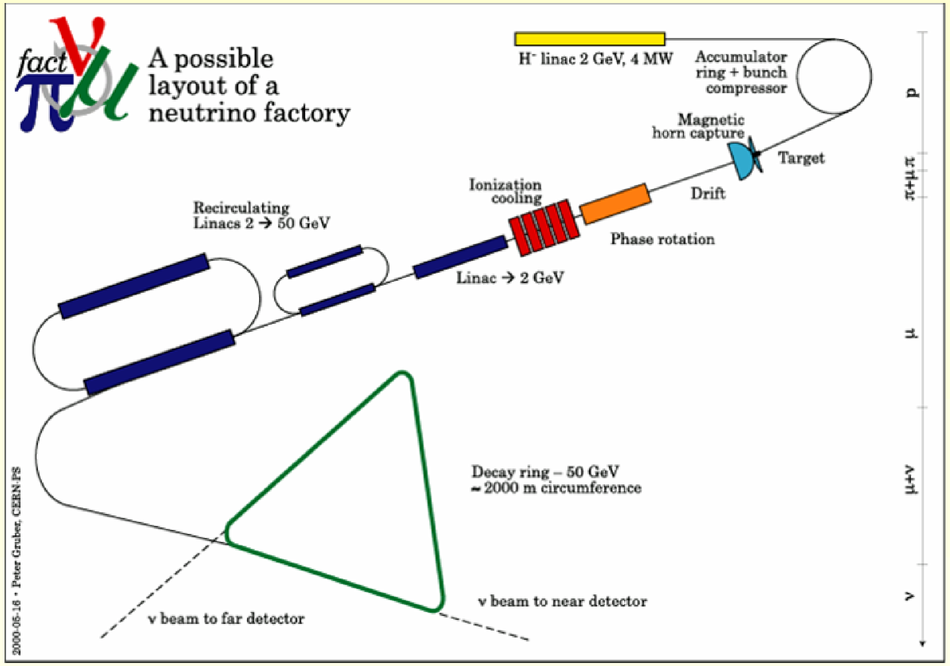
– βB APP + DIS fits (90% CL) for two different setups: LEFT=Ultimate Reach vs RIGHT=Realistic Reach;

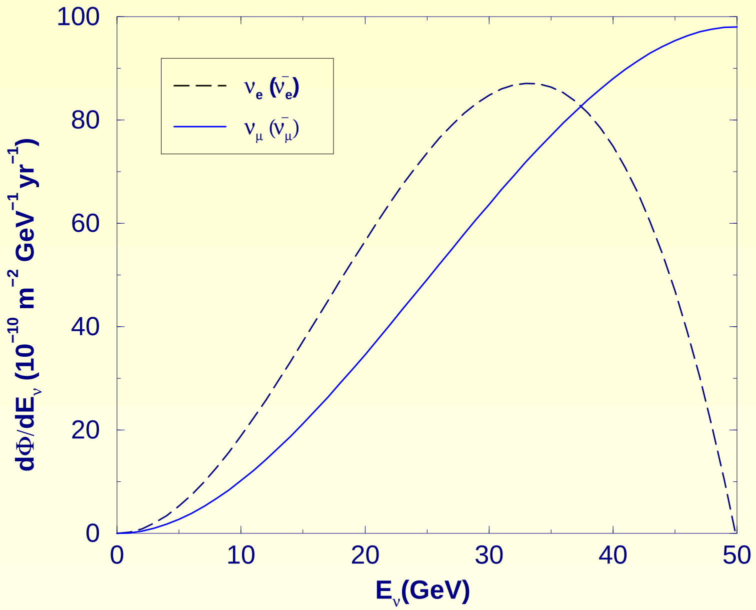
– The Octant (and Mixed) clone can be solved IN PRINCIPLE using the disappearance channel; The presence of a systematic error $\geq 2\%$ makes the ν_e disappearance channel completely NOT USEFUL;

3.4 Conclusions (β-Beams)

- β-Beam has (unfortunately) ONLY ONE USEFUL CHANNEL: $\nu_e \to \nu_\mu$ APPEARANCE CHANNEL; $\nu_e \to \nu_e$ NOT useful if sys $\geq$ 2%
- The "standard" β-Beam setup is affected by the FULL EIGHTFOLD degeneracy; no much effect if binning is introduced: too low energies;
- New β-Beam setups with "symmetric" $100 \leq \gamma \leq 150$ and baselines of L=130-300 km slightly improve the standard setup due to a more effective binning; the intrinsic degeneracy and its clones can be solved;
- "Optimal" β-Beam setup should point to the $\mathrm{HIGHER}\ \gamma\ (350)$ and LONGER DISTANCES (730 km) where also good sensitivity to s_{atm} ($\theta_{13} \geq 3^\circ - 4^\circ$) is obtained. Would require technological upgrades; **BUT I think it's WORTH TRYING!**
- **WARNING!** Serious (undergoing) studies on the accelerator side are indispensable for clarifying β-Beam physics reach (see Lindroos talk):
  - Are these ions fluxes achievable? Are $^{18}\mathrm{Ne}$ and $^{6}\mathrm{He}$ the best ions?
  - Do (and how) ions fluxes decrease with γ?

4 Physics Reach of Neutrino Factories



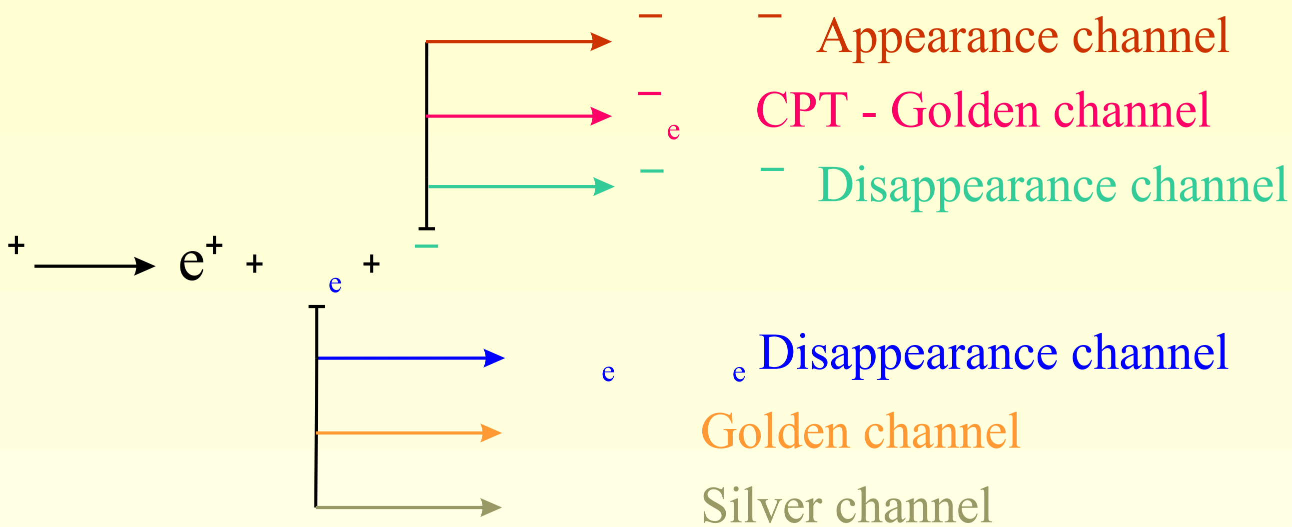


– $\pi^\pm$ and $K^\pm$ produced by 2.2 GeV proton on target (4 MWatt);

– $\pi^\pm, K^\pm$ let decay and $\mu^\pm$ collected and accelerated to 10-50 GeV;

– O($10^{20} - 10^{21}$) $\mu^\pm$ per year stored and let decay (possibly) towards two the following baselines: (700,3000,7000) km. One of the two detectors is usually a Large Magnetized Iron Calorimeter of O(50 kTon);

- **The “Channel Multiplicity” at the ν-Factory**



– $\boxed{\nu_e \rightarrow \nu_\mu \text{ GOLDEN CHANNEL}}$ measured at 3000 km by 40 (50) kTon Iron Magnetized Calorimeter gives the best sensitivity to θ_{13} and δ;

– $\boxed{\nu_e \rightarrow \nu_\tau \text{ SILVER CHANNEL}}$ measured at 730 km by a 4 (5) kTon Emulsion Cloud Chamber (Opera like);

– $\boxed{\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \text{ DISAPPEARANCE CHANNEL}}$ measured at 3000 (or 7000) km (better sensitivity to atmospheric parameters around 7000 km);

★ Many CHANNELS still OVERLOOKED: For example $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$ could be very interesting (see hep-ph/0112297); $\nu_e \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ could ADD USEFUL INFORMATIONS also without charge identification;

4.1 Study of NF Appearance Channels

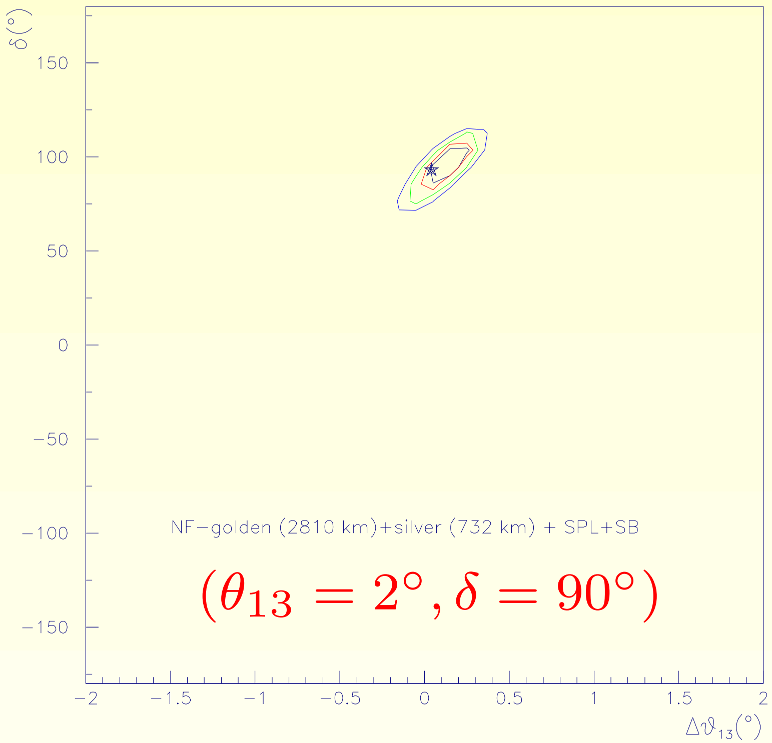
- **Combining NF Golden and Silver channels**

(plots from A. Donini, hep-ph/0310014)

- Four-fold degeneracy from GOLDEN channel measurement at 3000 km (LEFT); s_{atm} DEGENERACIES solved at this distance for $\theta_{13} = 2^\circ$;
- Adding the SILVER channel (RIGHT) helps in solving the INTRINSIC DEGENERACY leaving a twofold degeneracy (true + octant); silver channel could solve the θ_{23} degeneracies with a larger ($\times 2$) detector;

4.1 Study of NF Appearance Channels

- **Combining NF Golden and Silver channels with Super-Beam**

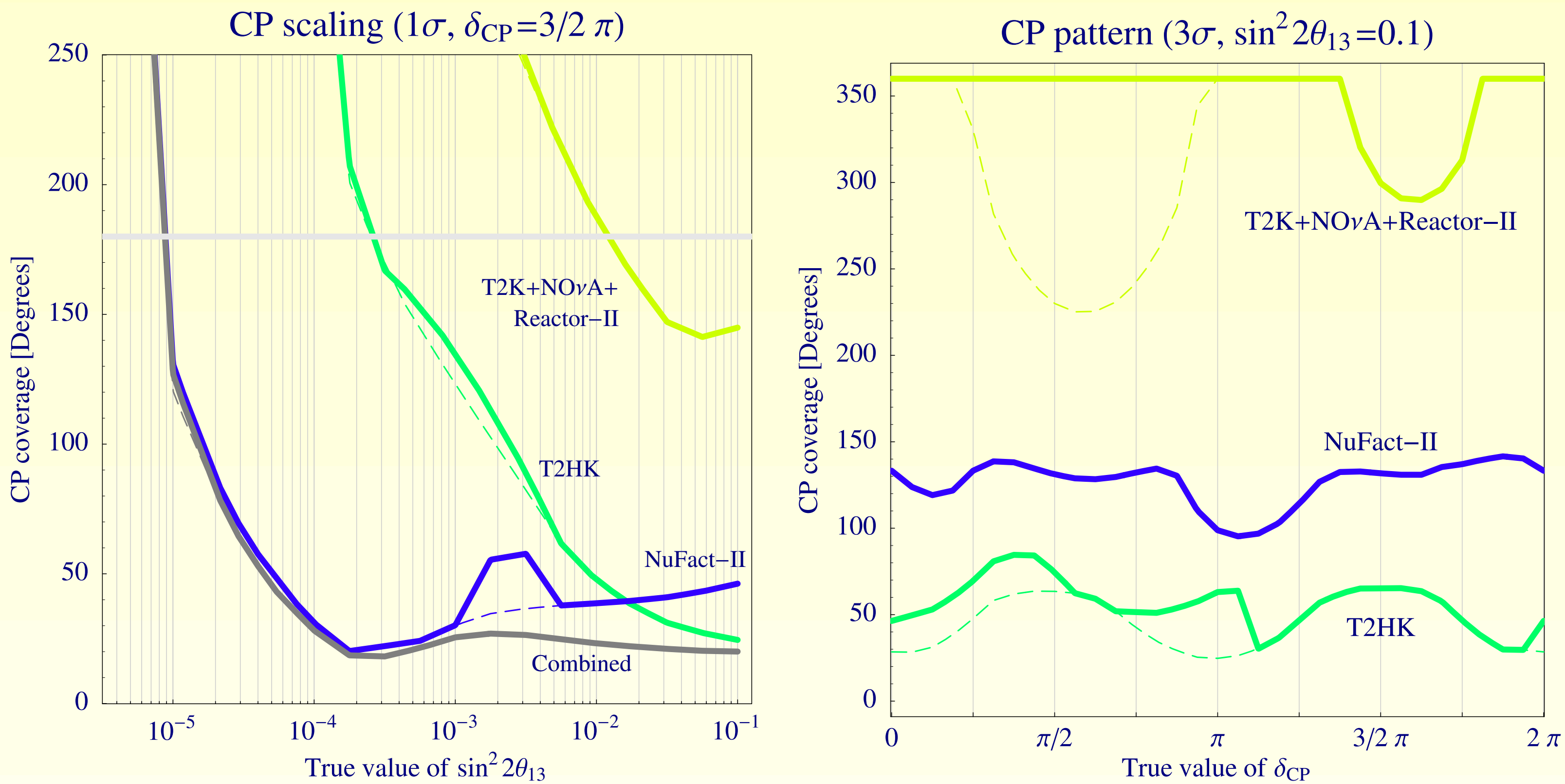


(plot from hep-ph/0310014)

– The combination of GOLDEN + SILVER + SB (SPL or T2HK with 1 MTon Water Cerenkov) remove ALL the degeneracies;

– CAVEAT: NF analysis still rely on OLD detector simulation (optimized for max sensitivity in (θ_{13}, δ) before the appearance of degenerations); More effective binning at low energy and new channels have to be included in the analysis; maybe SB informations not necessary anymore;

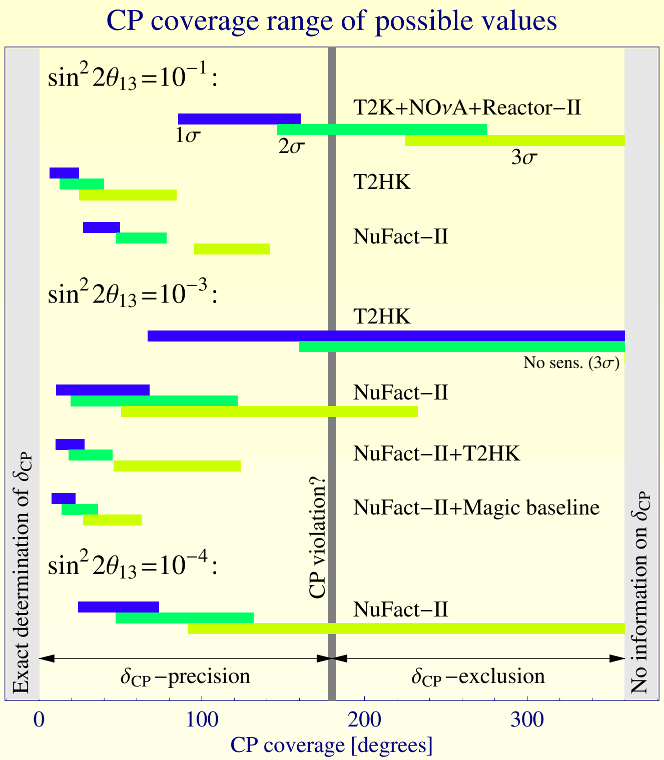
- **CP scaling and CP pattern at the ν-Factory**

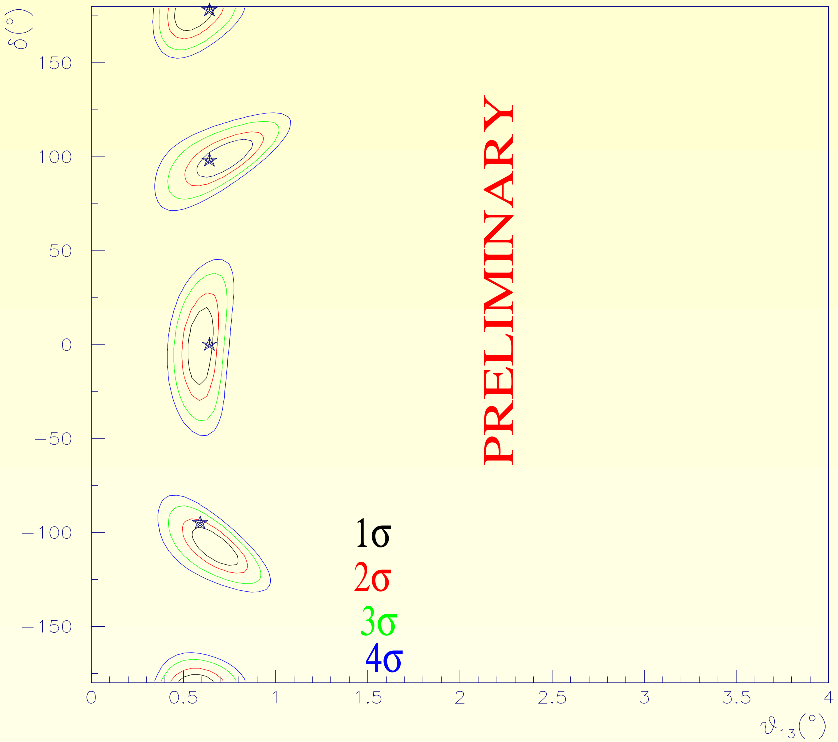


(plots from Huber et al, hep-ph/0412199)

- Comparison of CP scaling reach for different SB facilities vs ν-Factory (LEFT); ν-Factory always outperforms SB except for very large values of $\sin^2 2\theta_{13} \geq 0.01$ (large uncertainties from matter effect);
- NF has sensitivity to maximal CP violation down to $\sin^2 2\theta_{13} = 10^{-5}$;
- CP coverage of Super-Beams and ν-Factory (RIGHT) for $\sin^2 2\theta_{13} = 0.1$ (where T2HK better than NF) almost constant for any δ;

- **The final sensitivity of ν-Factories**





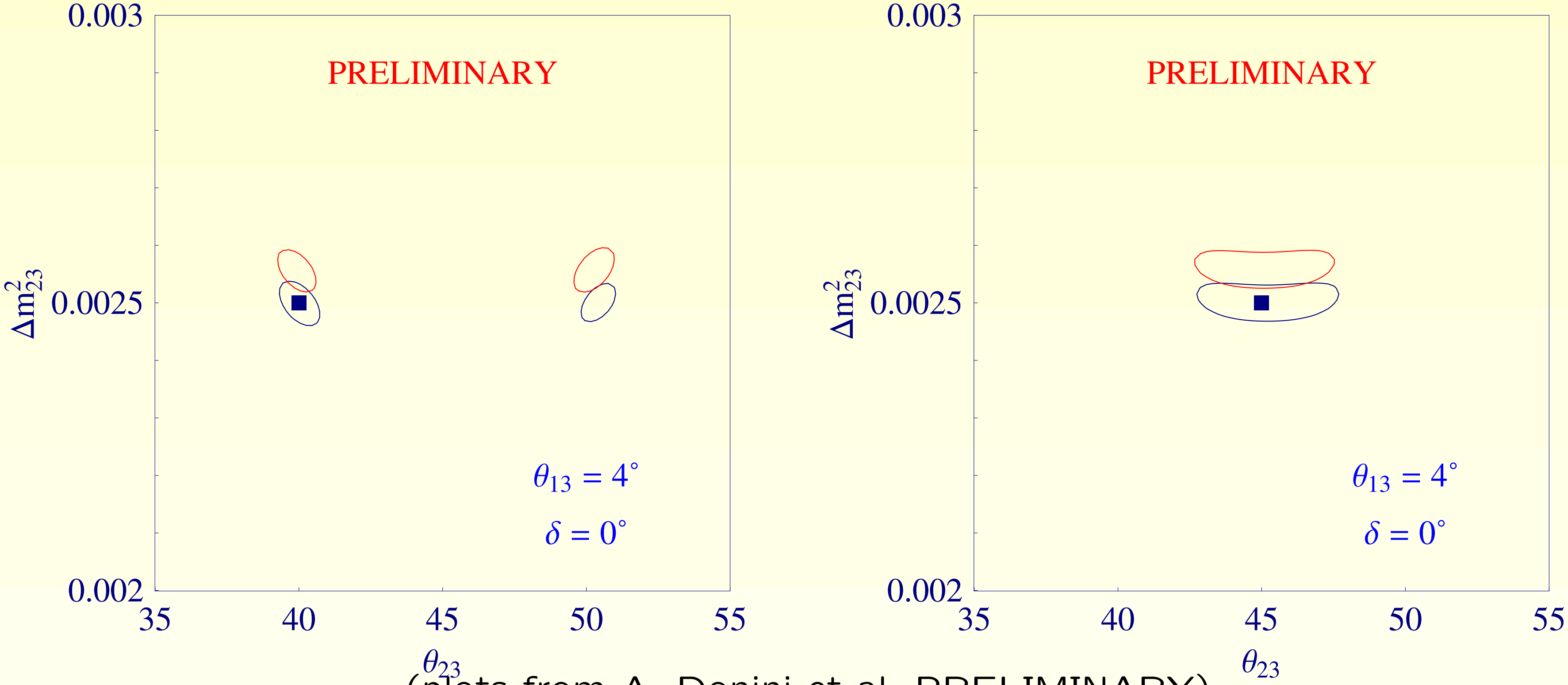
(plot from Huber et al, hep-ph/0412199) (plot from O. Mena, hep-ph/0503097)

– CP coverage range for different experiment and for different values of θ_{13} (LEFT); at large θ_{13} T2HK and NF can have similar performance; for smaller θ_{13} NF is the ONLY OPTION for CP violation discovery; Inclusion of additional channels HELPS in improving NF CP coverage;

– Expected (OPTIMISTIC) sensitivity at $\theta_{13} = 0.5^\circ$ ($\sin^2 2\theta_{13} = 3 \times 10^{-4}$), including golden (2810 km), silver (732 km) and CERN SPL (130 km);

4.2 Study of NF Disappearance Channel

- ν_μ **Disappearance Channel at different Baselines (L=3000 km)**

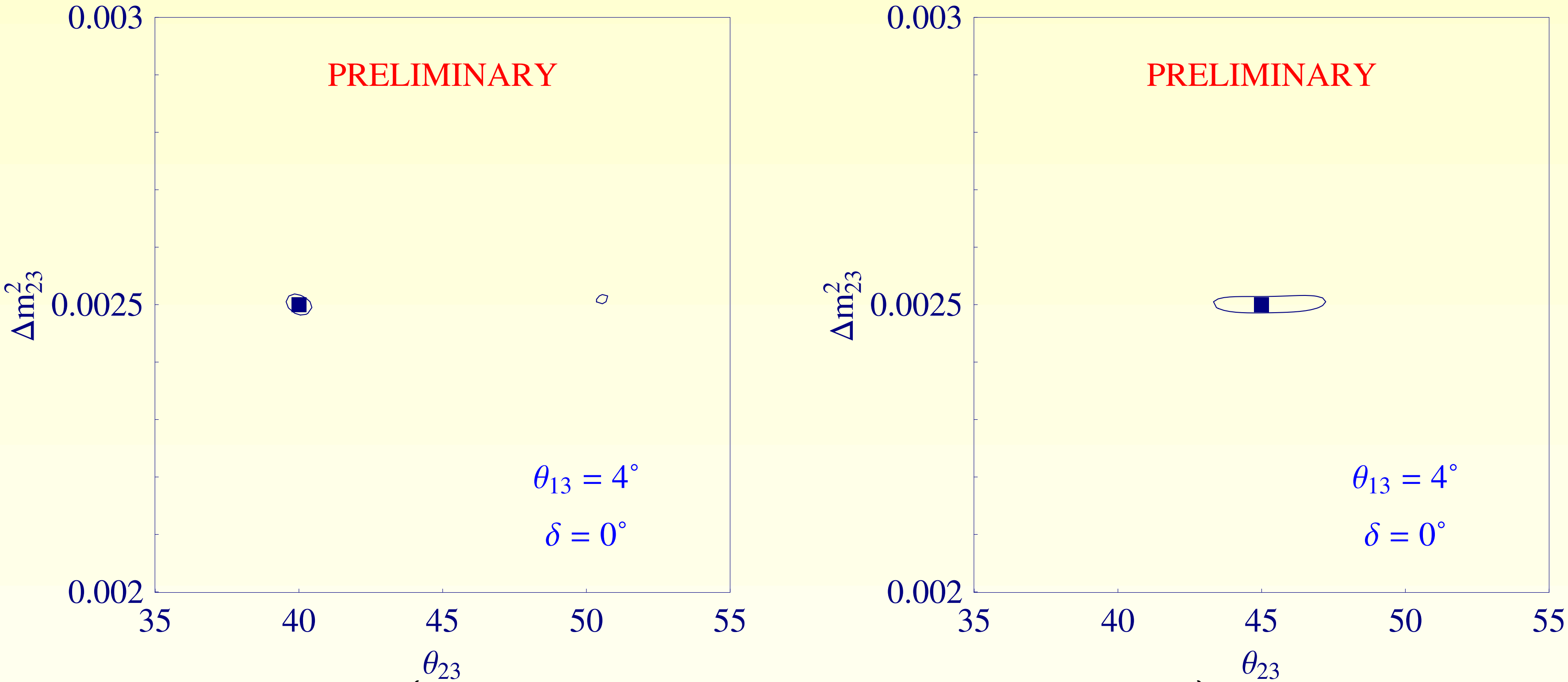


(plots from A. Donini et al, PRELIMINARY)

- NF DIS fits (90% CL) with $\mathrm{sys} = 2\%$ for $\theta_{23} = 40^\circ, 45^\circ$ for a 20 GeV ν-Factory setup at 3000 km for $\theta_{13} = 4^\circ, \delta = 0$ (bins of 4 GeV);
- The fourfold degeneracy due to sign and octant clones is clearly visible; there is a small θ_{23} asymmetric term proportional to θ_{13};
- Improvement respect to T2K results (see Donini talk);

4.2 Study of NF Disappearance Channel

- ν_μ **Disappearance Channel at different Baselines (L=7000 km)**



(plots from A. Donini et al, PRELIMINARY)

- NF DIS fits (90% CL) with $\mathrm{sys} = 2\%$ for $\theta_{23} = 40^\circ, 45^\circ$ for a 50 GeV beam at 7000 km for $\theta_{13} = 4^\circ$ (bins of 5 GeV);
- The disappearance channel alone can SOLVE s_{atm} and s_{oct} ambiguities down to $\theta_{13} \leq 4$; Notice that in Super-Beam DIS with few hundreds km baseline (T2K or SPL) DEGENERACIES are always PRESENT;

4.3 Conclusions (ν-Factory)

- Neutrino Factory has (fortunately) **MANY USEFUL CHANNELS**:
  – $\nu_e \to \nu_\mu$ ($\nu_\mu \to \nu_e$) and $\nu_e \to \nu_\tau$ ($\nu_\mu \to \nu_\tau$) APPEARANCE channels
  – $\nu_\mu \to \nu_\mu$ ($\nu_e \to \nu_e$) DISAPPEARANCE channels;
- Including NF (GOLDEN + SILVER) and Super-Beam degeneracies are removed and δ_{CP} measured precisely up to $\sin^2 2\theta_{13} \approx 10^{-4}$;
- New analysis of degeneracies at Neutrino Factory NEEDED:
  - anti-degeneracies OPTIMIZED DETECTOR (in old analysis detector optimized for $\theta_{13} - \delta_{CP}$ sensitivity); Informations from first energy bins important as Super-Beam REPLACEMENT;
  - inclusion in the analysis of AS MANY appearance/disappearance channels AS POSSIBLE (within affordable detectors budget); In latest analysis only ν_μ disappearance and golden and (sometimes) silver appearance are included;
- NF still to be thought as the ULTIMATE NEUTRINO OSCILLATION facility; could provide precise measure of θ_{13}, δ and it will resolve both the $\mathrm{sign}(\Delta m^2_{ATM})$, $\mathrm{sign}(\sin 2\theta_{23})$ to very small θ_{13};

5 Outlook

- **DEGENERACIES must be BEATED** otherwise they can severely affect the precise measure of (θ_{13}, δ):
  - using DIFFERENT L/E INFORMATIONS;
  - using ALL possible CHANNEL INFORMATIONS;

β-Beam is a very INTERESTING and CLEAN facility

- Only one useful channel: $\nu_e \to \nu_\mu$ APPEARANCE;
- Extensive use of BINNING and long BASELINE (help in solving the hierarchy) point toward higher γ options (even if more challenging);

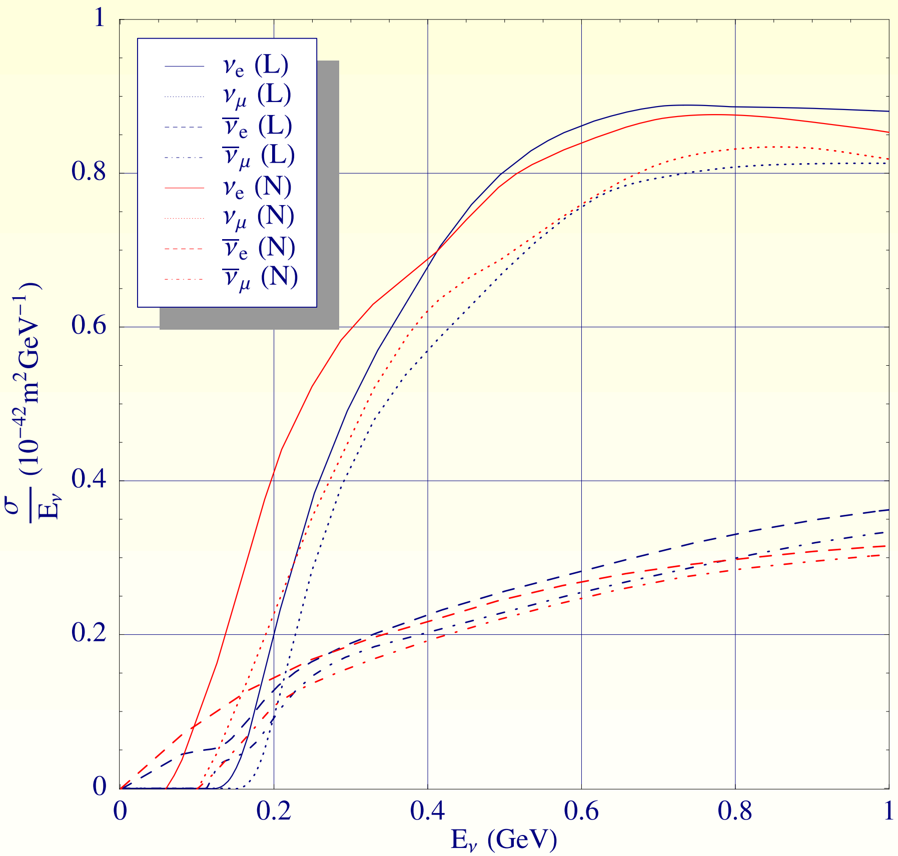
Neutrino Factory is the ULTIMATE NEUTRINO facility

- Advantage of having many APPEARANCE and DISAPPEARANCE channels has not all fully exploited yet;
- BINNING and long BASELINE by default; more effort should be done in gaining sensitivity to the low energy ($\leq$ 10 GeV) region;

6 Backup Transparencies

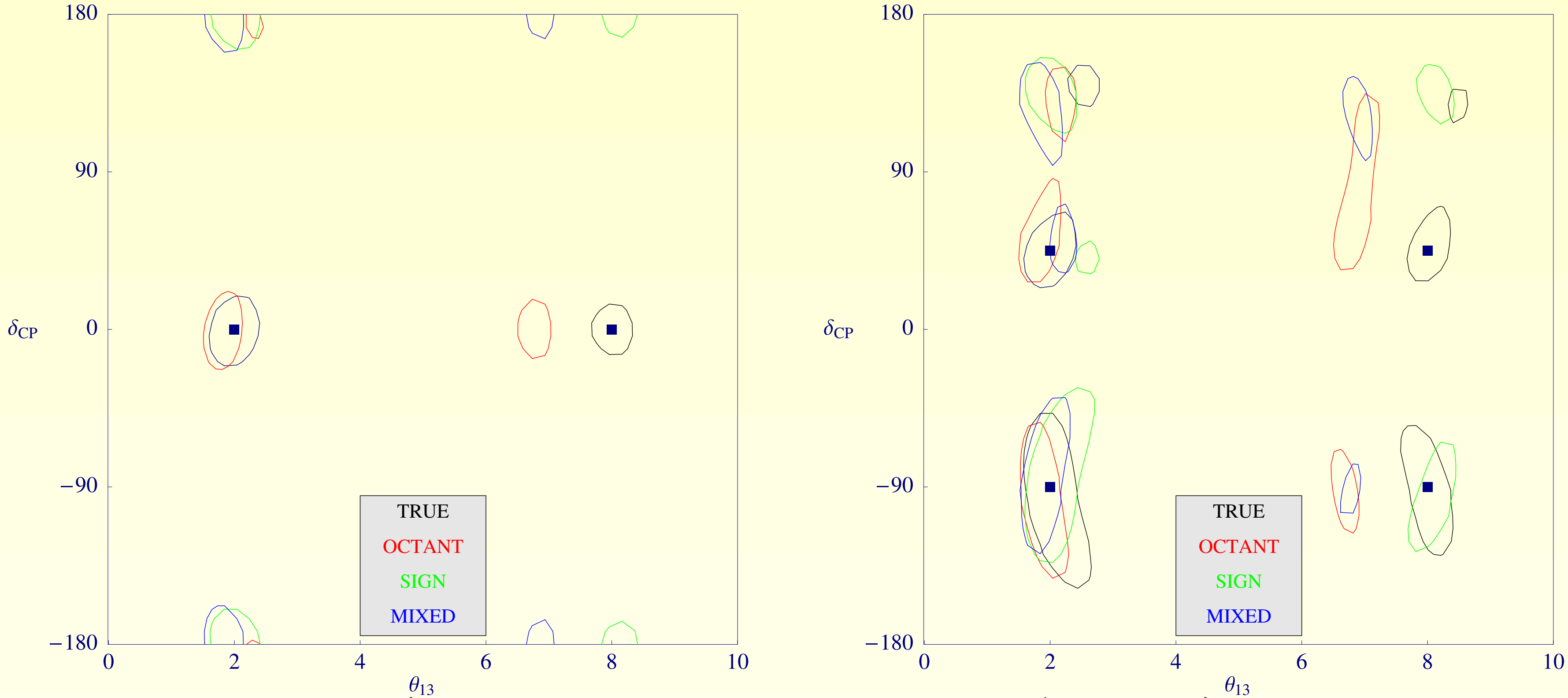
- **The Cross Section "Problem": Lipari vs NUANCE**

  The Cross Section used by different collaborations are quite different for energies below 0.5 GeV due to the few experimental measures available and inclusion (or not) of nuclear effects.



- Comparison of LIPARI (black) vs NUANCE (red) cross sections;
- Large difference especially for ν_e and ν_μ (factor 2 @ 0.2 GeV);
- Measured by the experiments itself, but problems now in comparison;
- We used the (courtesy of) LIPARI water cross section including threshold nuclear effects (relevant at $E_\nu \approx 0.2$ GeV);

- **Measuring (θ_{13}, δ) combining "standard" β-Beam and SPL**



(plots from A. Donini et al, hep-ph/0406132)

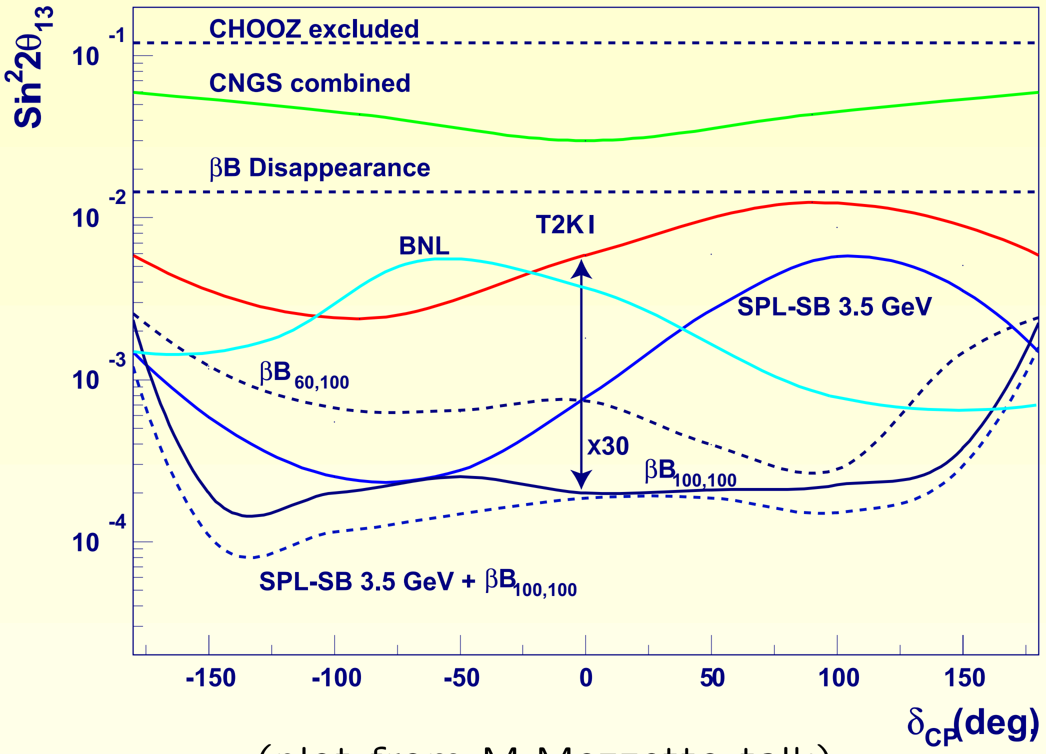
– Typical βB + SB Appearance fits (90% CL) for $\theta_{13} = 2, 8$ and $\delta_{CP} = 0, 45, -90$. Backgrounds and Systematics (5%) included;

– Some clones disappear but only for some value of δ_{CP};
Not solving completely any of the s_{atm} or s_{oct} ambiguities;

– The effect seems more due to **STATISTICS** than **SYNERGIES** !!

NOT enough INDEPENDENT informations

- **Comparison between β-Beam options and Super-Beams**



(plot from M.Mezzetto talk)

- Comparison of θ_{13} sensitivity (90% CL) for different β-Beam setups and combination of β-Beam plus Super-Beam (SPL);
- Binning informations don't help in improving the θ_{13} sentitivity; Improvements due to higher statistics at (100,100) compared to (60,100) and lower backgrounds extimations;
- Adding β-Beam and Super-Beam it always helps but it's mainly consequence of doubling the statistics (more than synergy);