Degeneracies in the Determination of Oscillation Parameters

Enrique Fernández Martínez
Departamento de Física Teórica and IFT
Universidad Autónoma de Madrid

Mainly based on a collaboration with A. Donini, P. Migliozzi, S. Rigolin, L. Scotto Lavina
hep-ph/0406132

Outline

- Introduction
  - Oscillation parameters
  - The eightfold degeneracy
- Measurements with the CERN low-g bB and SPL SB
  - Appearance channel
  - Disappearance channel
- Measurements with the T2K PHASE 2 SB
  - Appearance channel
  - Disappearance channel
- Conclusions

Why Neutrinos?

- Only evidence for physics beyond SM
- Neutrino masses and mixing add to the flavour puzzle
  - 7 or more new parameters, only 4 measured yet
- More open questions than answers
- Mass scale and mass hierarchy?
  - Normal or inverted?
  - Hierarchical or Degenerate?
- Mixings?
  - Why so large angles compared to CKM?
  - Is there CP violation in the leptonic sector?
- Dirac or Majorana?
  - Can Majorana neutrinos explain baryon asymmetry?

The oscillation parameters

- What we already know
  - Solar sector
$$\begin{cases} \Delta m^2_{12} = 8.2^{+0.3}_{-0.3} \cdot 10^{-5}\,\mathrm{eV}^2 \\ \tan^2 q_{12} = 0.39^{-0.05}_{-0.04} \end{cases}$$
  - Atm sector
$$\begin{cases} \left|\Delta m^2_{23}\right| = 2.2^{+0.6}_{-0.4} \cdot 10^{-3}\,\mathrm{eV}^2 \\ \tan^2 q_{23} = 1^{+0.35}_{-0.26} \end{cases}$$
- What we still don't know
  - $q_{13} < 11.7^{o}$
  - δ_{cp}
  - Mass hierarchy $s_{atm} = sign\left(\Delta m^2_{23}\right)$
  - Octant of q_{23} $s_{oct} = sign\left[\tan\left(2q_{23}\right)\right]$

The eightfold degeneracy

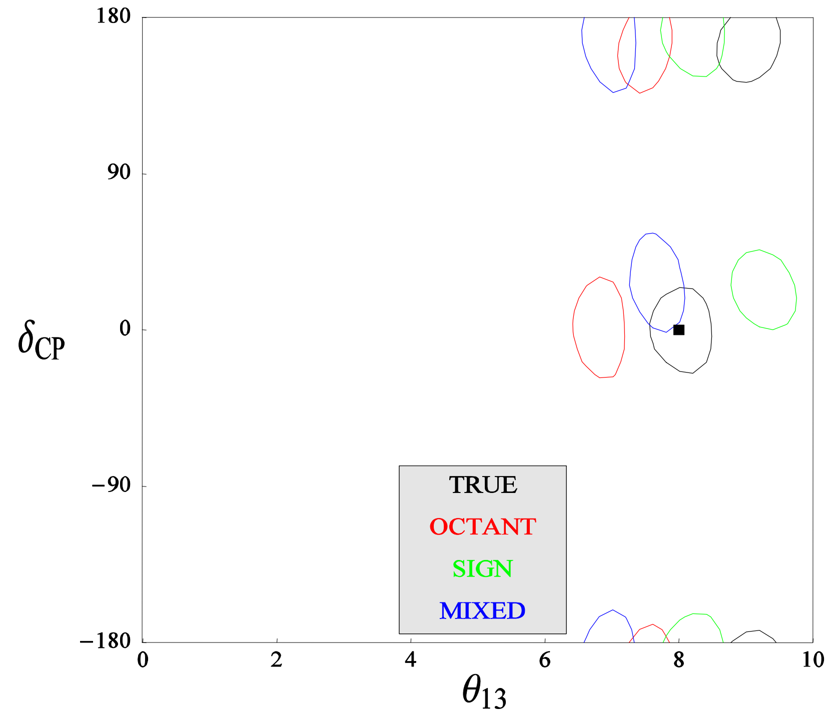
- Suppose true values of the unknown parameters

$$\bar{q}_{13}, \bar{d}; \bar{s}_{atm}, \bar{s}_{oct}$$

- An appearance experiment at fixed E and L measures

$$N^{\pm}(\bar{q}_{13}, \bar{d}; \bar{s}_{atm}, \bar{s}_{oct})$$

- To extract q_{13} and d we have to solve



$$N^{\pm}(\bar{q}_{13}, \bar{d}; \bar{s}_{atm}, \bar{s}_{oct}) = N^{\pm}(q_{13}, d; s_{atm} = \pm\bar{s}_{atm}, s_{oct} = \pm\bar{s}_{oct})$$

- Eight different solutions, the true one and 7 clones

J. Burget-Castell *et al.* hep-ph/0103258
H. Minakata *et al.* hep-ph/0108085
G. L. Fogli *et al.* hep-ph/960441
V. Barger *et al.* hep-ph/0112119

CERN SB and *b*B event rates

$n_e \rightarrow n_e, n_m$ L=130Km $n_m \rightarrow n_m, n_e$

b-Beam	l^-	l^+
No osc. N_e	133205	19557
$N_e\,(q_{13}=10^o)$	86910	11727
$N_m\,(q_{13}=10^o)$	2444	463
Beam Bck.	0	0
Detector Bck.	360	1

Super-Beam	l^-	l^+
No osc. N_m	24245	25467
$N_m\,(q_{13}=10^o)$	1715	1585
$N_e\,(q_{13}=10^o)$	1148	1002
Beam Bck.	92	110
Detector Bck.	24	56

10yr n_e + 10yr $\bar{n}_e$ exposure with a 440Kt water cerenkov detector for the βB

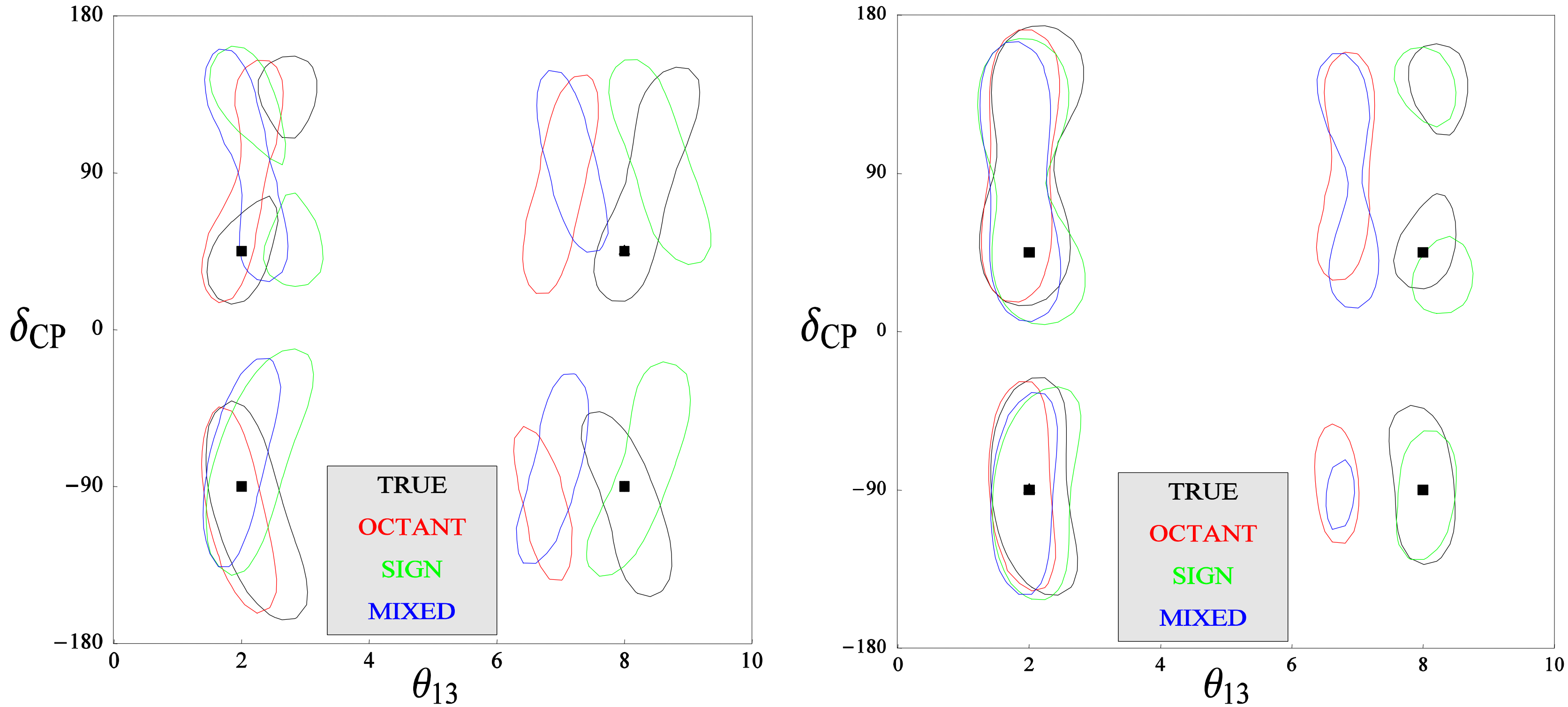
2yr n_m + 8yr $\bar{n}_m$ exposure with a 440Kt water cerenkov detector for the SB

E/L sets $n_m \rightarrow n_e, n_t$ at a maximum but $n_m \rightarrow n_m$ at a minimum

The *b*B and SB appearance channel

β-Beam

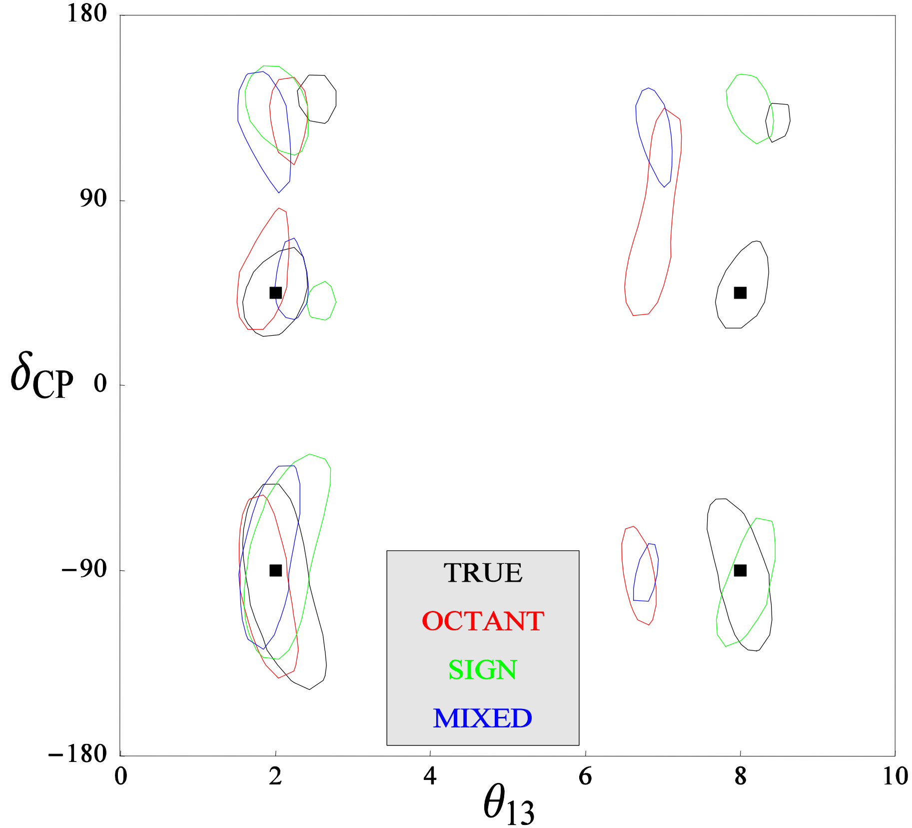
Super-Beam



- Fits for 90% CL for q_{13} = 2º, 8º and d = 45º, -90º
- Backgrounds quoted before and systematic error of 5% included
- SB better for large q_{13}

A. Donini *et al.* hep-ph/0406132

The SB + *b*B appearance channel

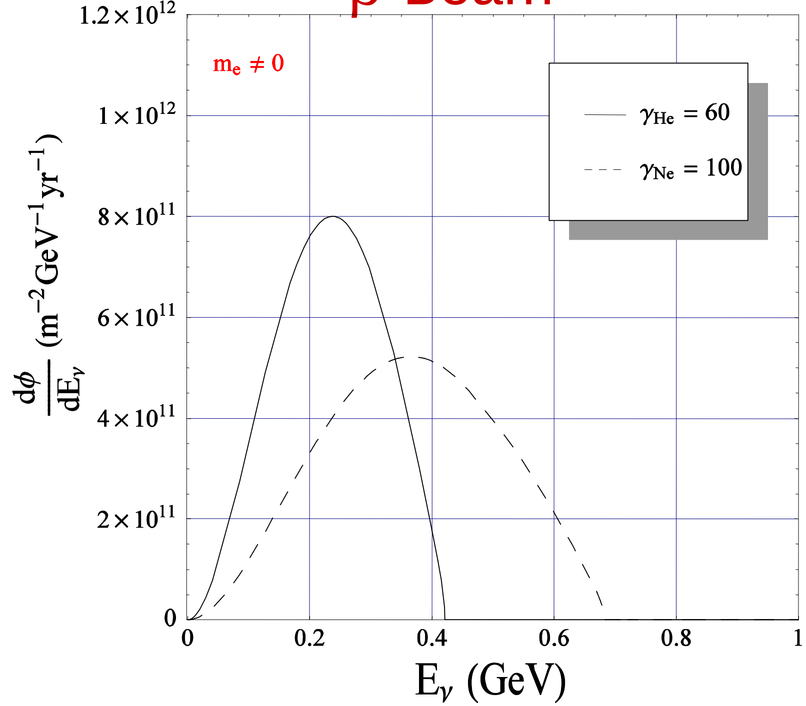


- Fits for 90% CL for q_{13} = 2º, 8º and d = 45º, -90º
- Many clones remain unsolved
- The discrete parameters s_{oct} and s_{atm} are not measured

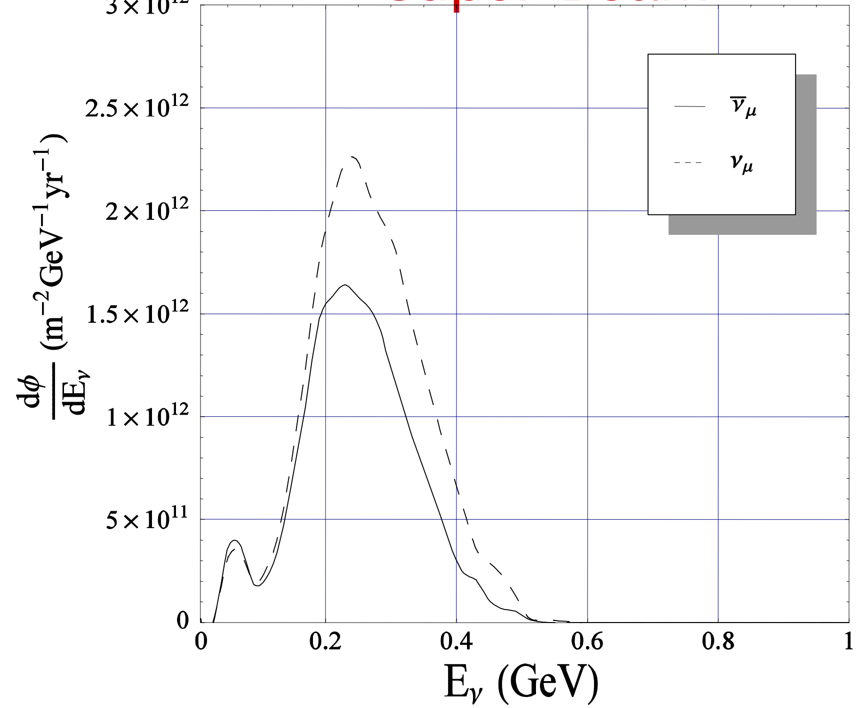
CERN SB and *b*B fluxes at Frejus

L=130Km

β-Beam



Super-Beam

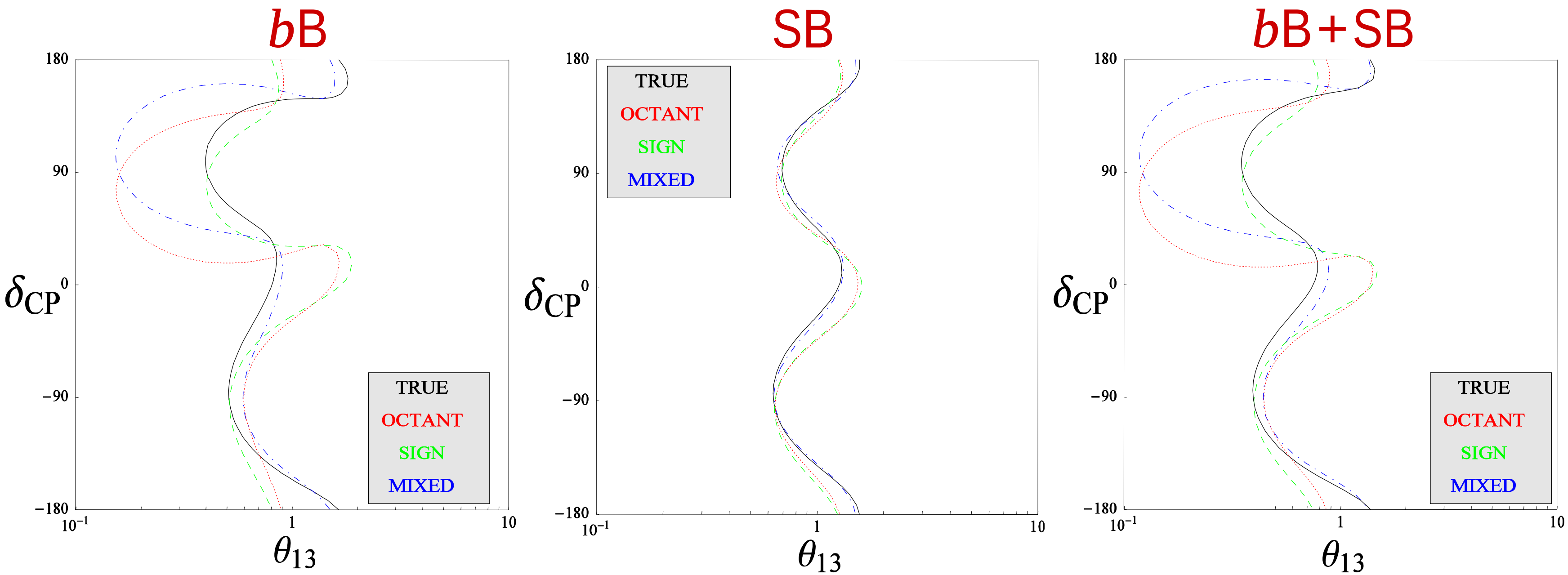


n_e flux from ^{18}Ne decay at γ = 100 $\langle E_n \rangle = 0.37GeV$ n_m flux from p^+ decay $\langle E_n \rangle = 0.27GeV$

$\bar{n}_e$ flux from ^{6}He decay at γ = 60 $\langle E_{\bar{n}} \rangle = 0.23GeV$ $\bar{n}_m$ flux from p^- decay $\langle E_{\bar{n}} \rangle = 0.25GeV$

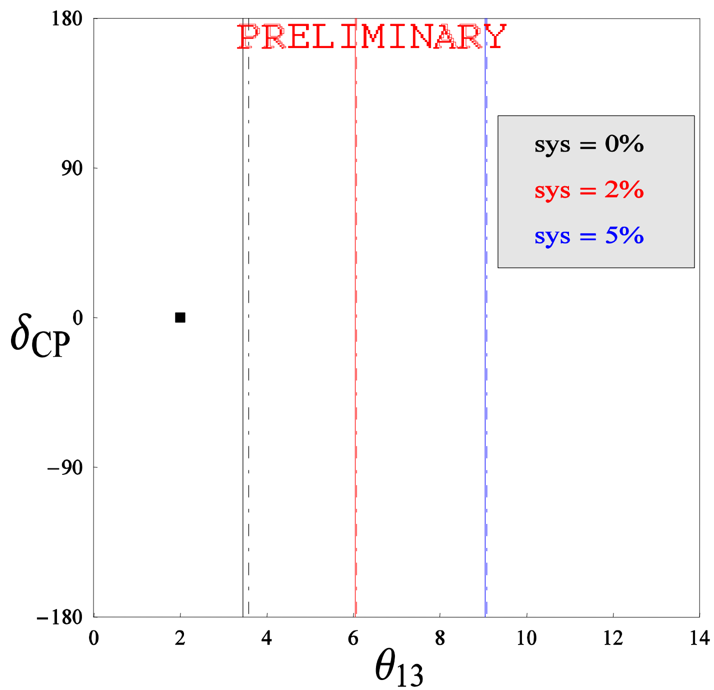
SB fluxes courtesy of Gilardoni

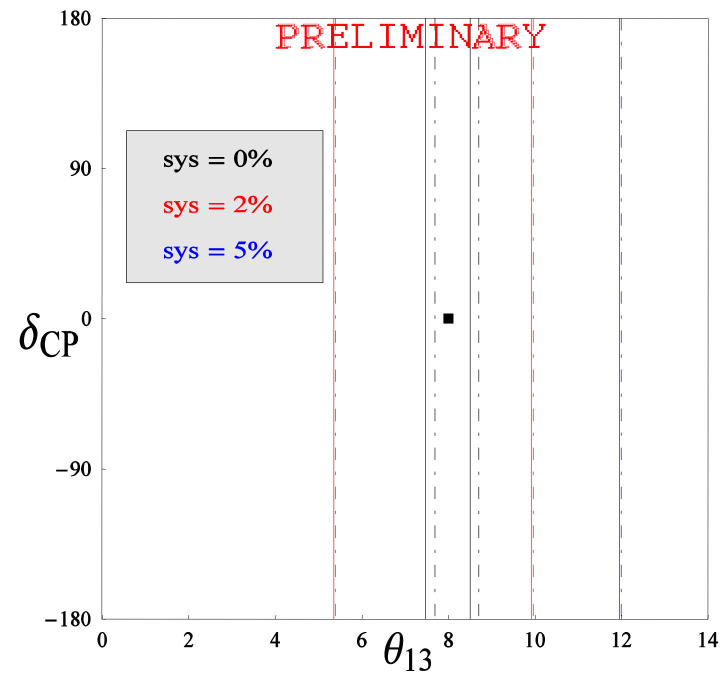
Sensitivity to q_{13}



- Computed for 90% CL and 5% systematic error
- Sensitivity between 1° and 0.5° for both experiments
- Best sensitivity for $d = \pm 90^{o}$ where there is a maximum of n , $\bar{n}$
- The combined sensitivity is not significantly improved

The *b*B disappearance channel



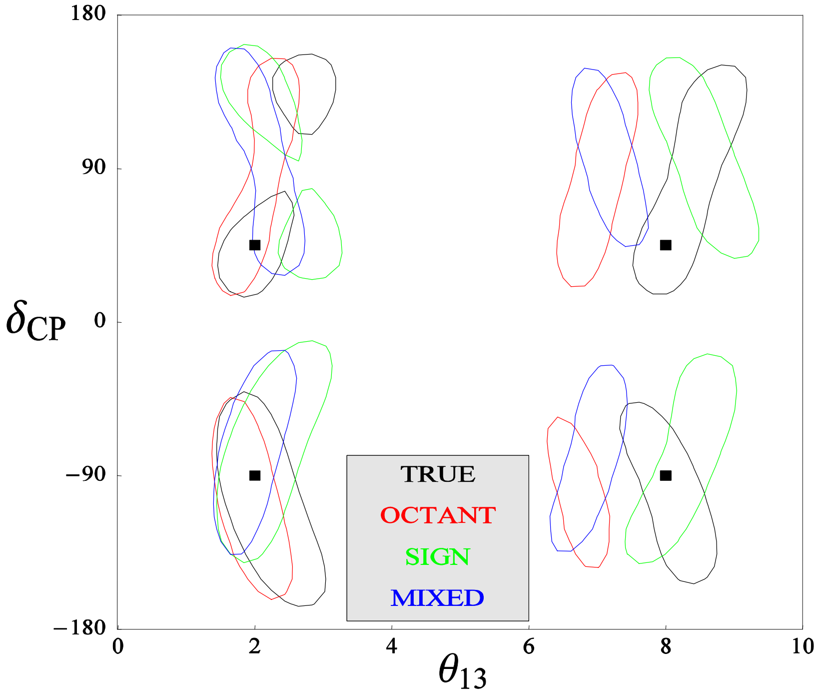


- Fits for 90% CL and systematic error = 0, 2 and 5%
- Dashed lines = sign clone. Not relevant
- $q_{13} = 2^{o}$ left, $q_{13} = 8^{o}$ right
- It is only useful for large values of q_{13} and if sys < 2%

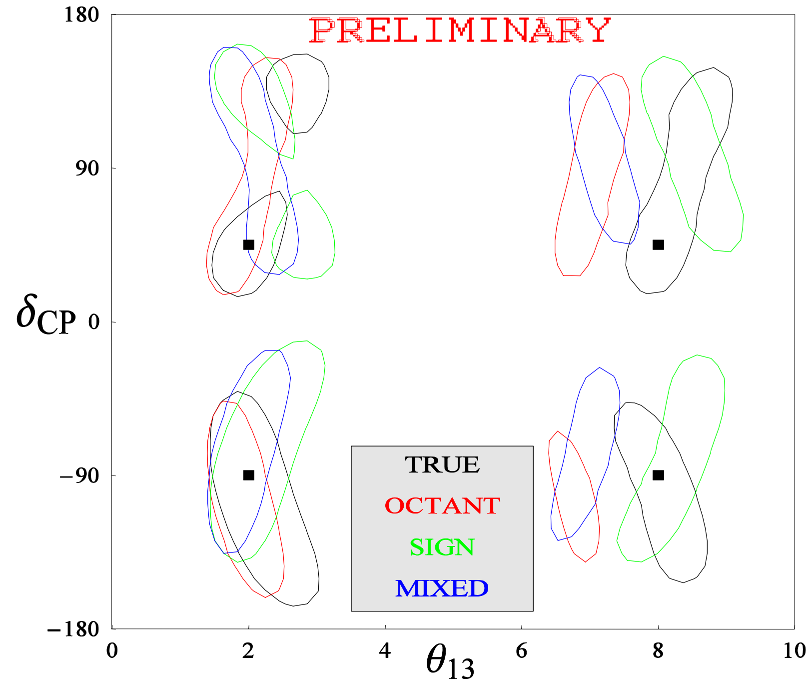
S. Rigolin NOW 2004

The *b*B channels combined

Appearance only

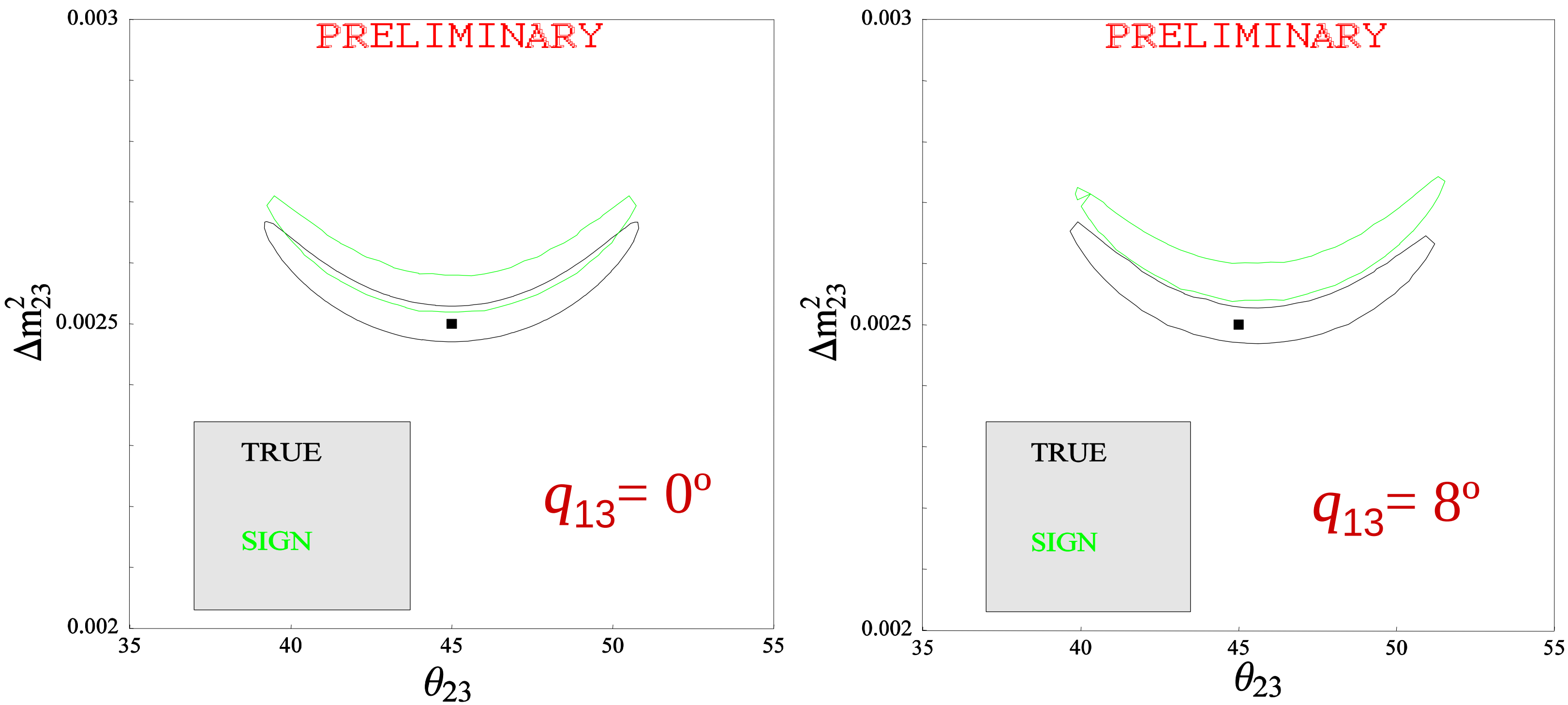


Appearance + Disappearance



- Fits for 90% CL
- Systematics of 5% in the appearance channel and 2% in disappearance

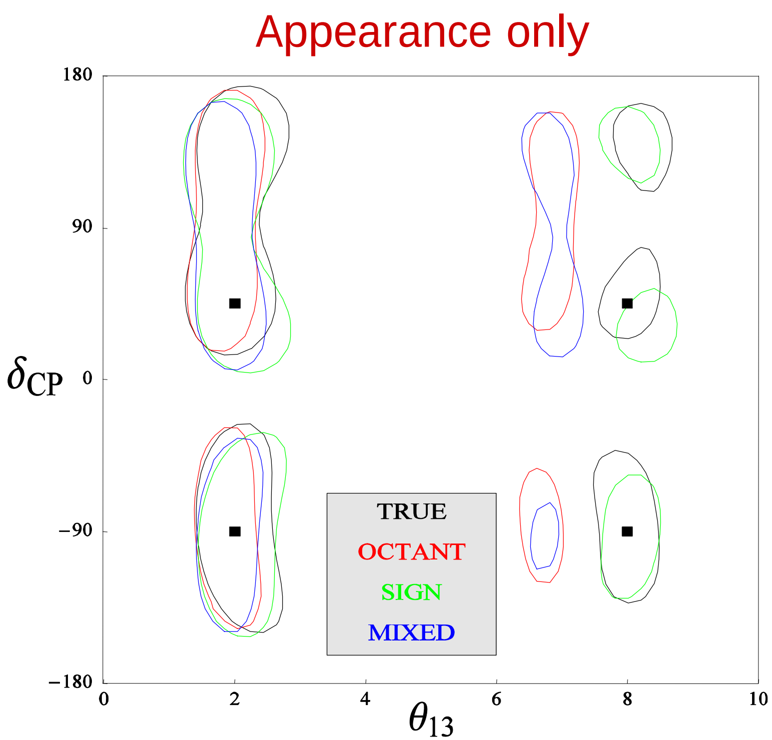
The SB disappearance channel

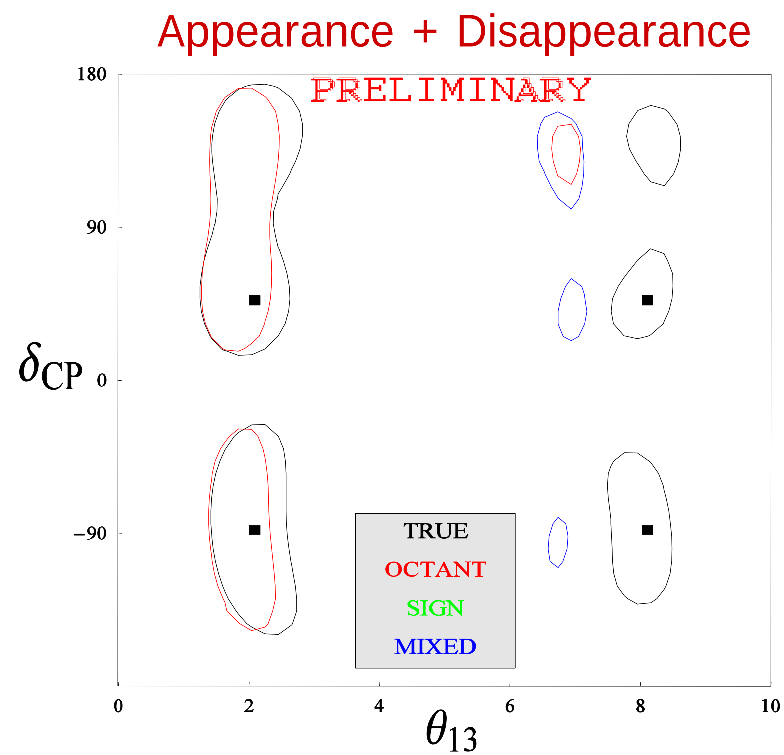


- Fits for 90% CL and systematic error = 2%
- Left side for $q_{13} = 0^o$, right side $q_{13} = 8^o$, $d = 0^o$
- The sign degeneracy doubles the error on Δm^2_{23}
- But combined with appearance it can reduce this degeneracy

S. Rigolin NOW 2004

The SB channels combined



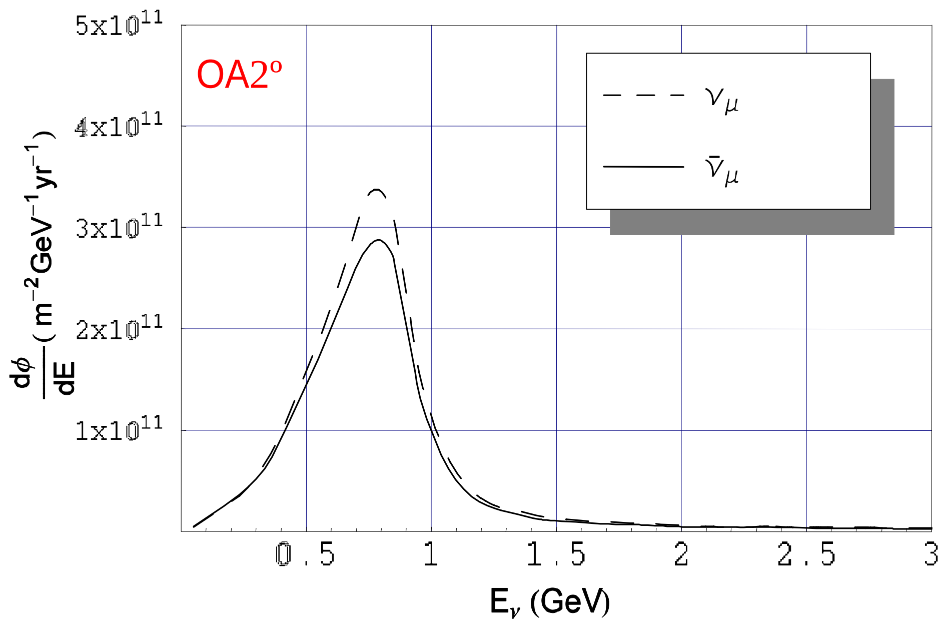


- Fits for 90% CL and systematics of 5% in appearance and 2% in disappearance
- The sign degeneracy is very constrained
- 4 parameter fits on the way

T2K PHASE 2 fluxes

L=295Km

2° off axis



No E binning

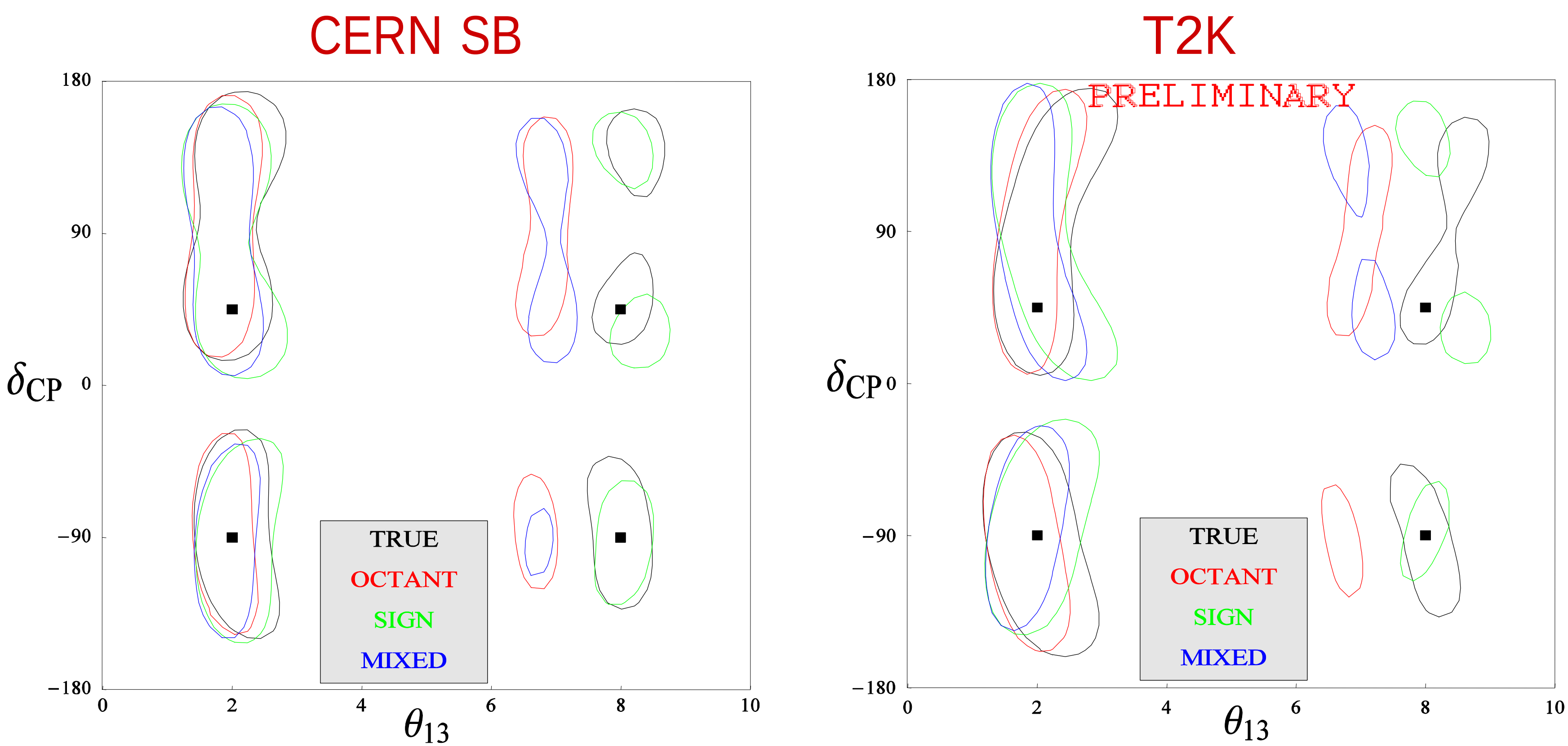
$n_m \rightarrow n_m, n_e$

n_m flux from p^+ decay $\langle E_n \rangle = 0.74 GeV$

$\bar{n}_m$ flux from p^- decay $\langle E_{\bar{n}} \rangle = 0.73 GeV$

2yrn_m + 8yr $\bar{n}_m$ exposure with a 440Kt water cerenkov detector for the T2K

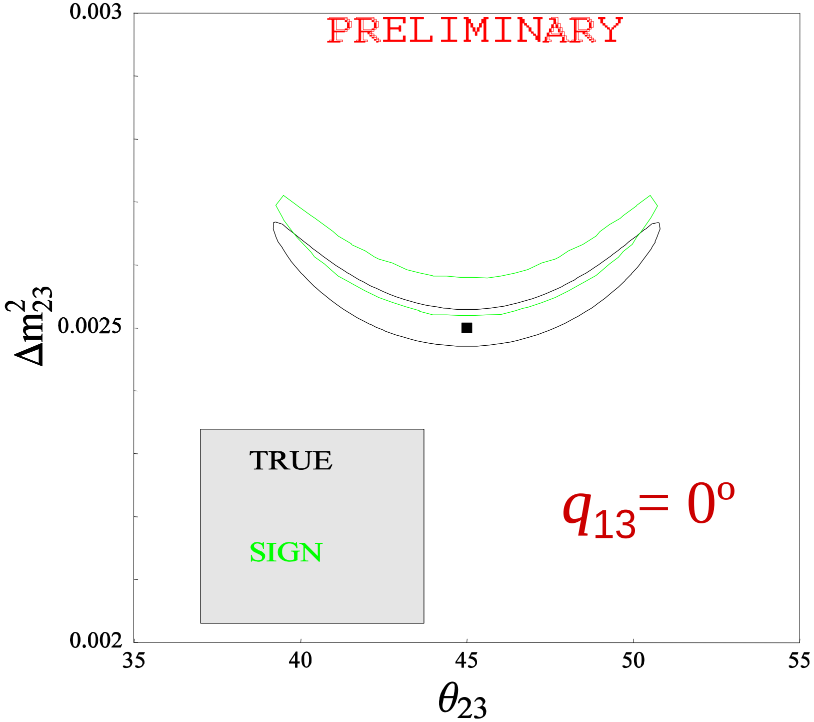
The T2K appearance channel



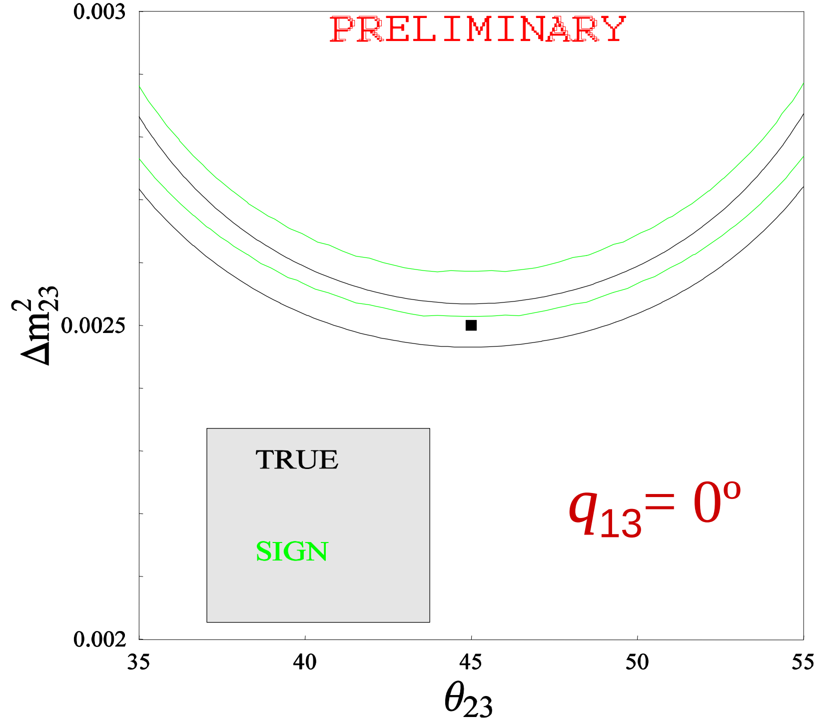
- Fits for 90% CL for q_{13} = 2º, 8º and d = 45º, -90º
- Backgrounds quoted before and systematic error of 5% included
- Very similar to the CERN SB but slightly worse for small q_{13}

The T2K disappearance channel

CERN SB



T2K



- Fits for 90% CL and systematic error = 2%
- The sign degeneracy doubles the error on Δm^2_{23}
- T2K now worse, will improve with binning information

Conclusions

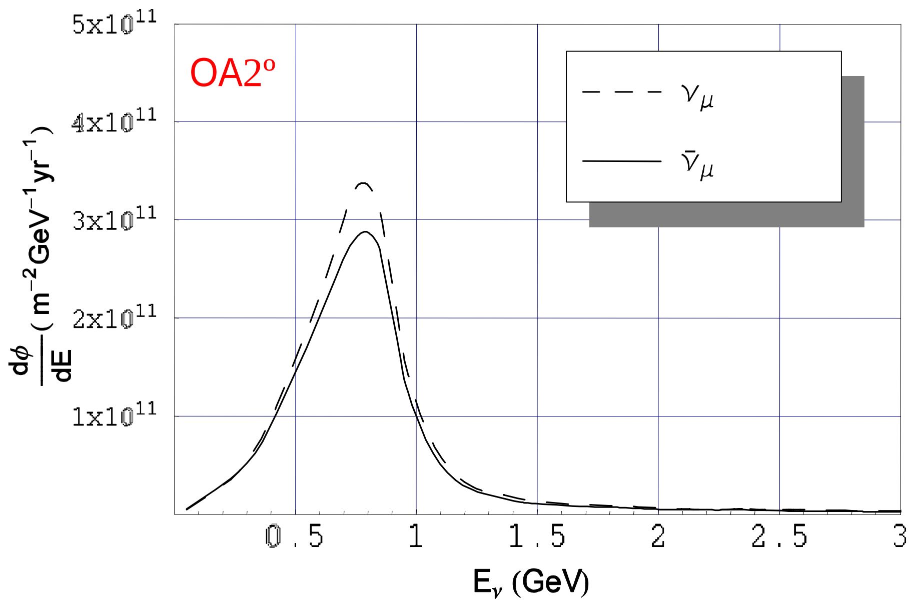
- The combination of low-γ *b*B and SB can help to solve some of the degeneracies but at least one of each kind remains. No synergy between them, only increased statistics
- The disappearance channel in the *b*B is only useful if q_{13} is not too small and for very small unrealistic systematic errors
- The disappearance channel in the SB more useful. Gives independent measure of q_{23} and Δm^2_{23} Combined with appearance it could help to solve the sign degeneracy
- SB better by itself than *b*B and not much improvement when combined

Conclusions and Outlook

- The SB measures q_{23} and Δm^2_{23} apart from q_{13} and δ
  - 3 or 4 parameter fit necessary for correct analysis
- The low-g bB is not very useful but it can be improved:
  - New ions like ^{8}Li can increase the statistics and change the n energy so that the complementarity with the SB increases
  - Higher g scenarios with wider n spectra allow binning in E which solves many degeneracies J. Burguet-Castell *et al.* hep-ph/0312068
  - Very high g also adds the silver channel $n_e \rightarrow n_t$
- The mass hierarchy can only be measured through matter effects at very long baselines
  - Atmospheric n could be used to measure the mass hierarchy with large enough detector

T2K fluxes and rates

L=295Km $n_m \rightarrow n_m, n_e$



T2K	l^-	l^+
No osc. N_m	293977	387811
$N_m(q_{13}=10^o)$	44851	62314
$N_e(q_{13}=10^o)$	7457	9680
Beam Bck.	731	497
Detector Bck.	1526	1857

2° off axis

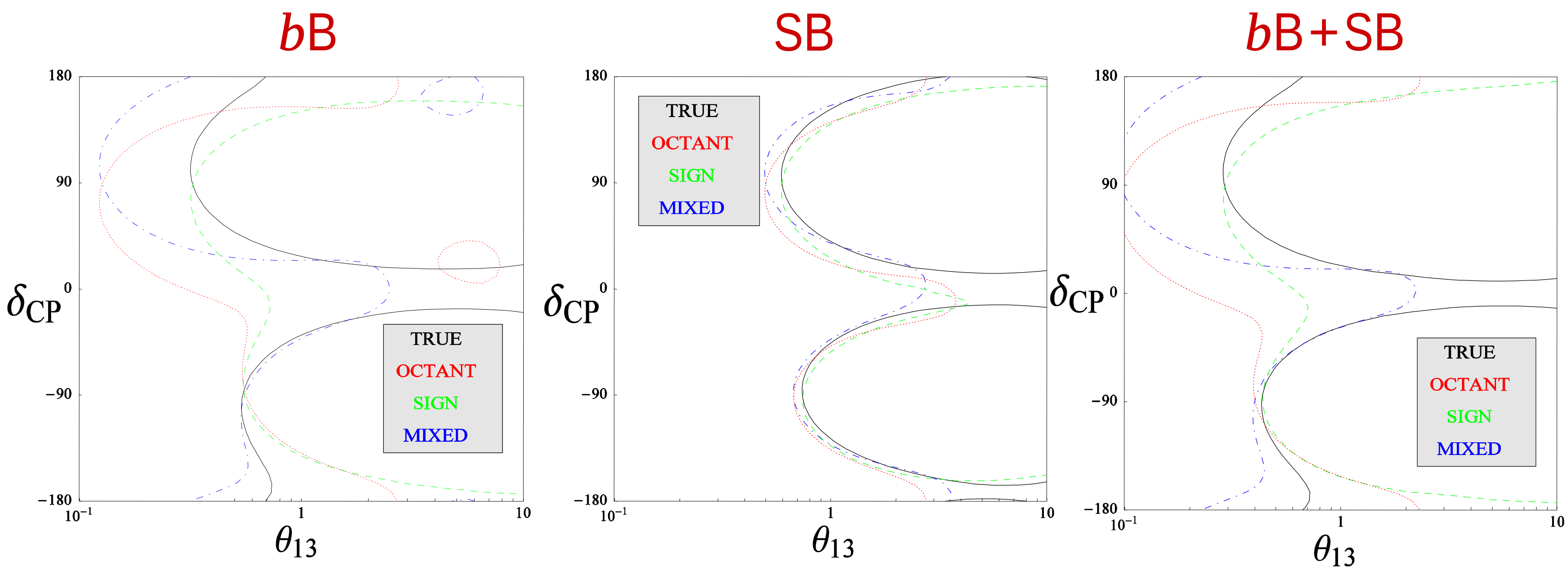
n_m flux from p^+ decay $\langle E_n \rangle = 0.74 GeV$

$\bar{n}_m$ flux from p^- decay $\langle E_{\bar{n}} \rangle = 0.73 GeV$

No E binning

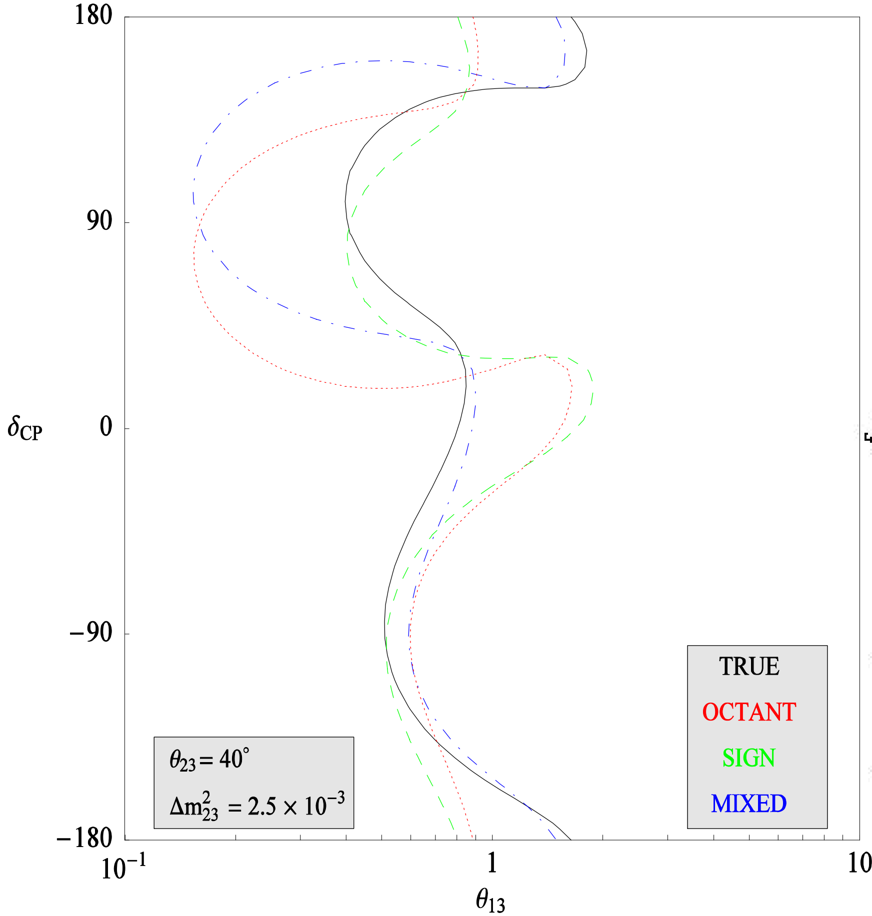
2yr n_m + 8yr $\bar{n}_m$ exposure with a 440Kt water cerenkov detector for the T2K

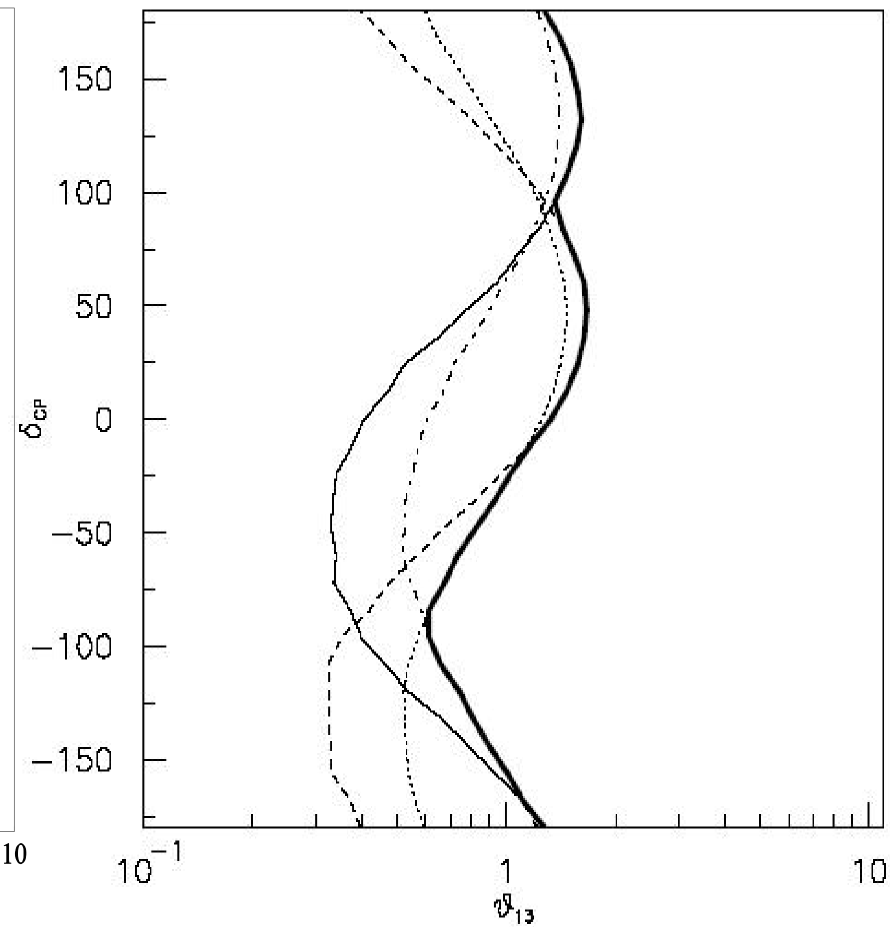
Sensitivity to *d*



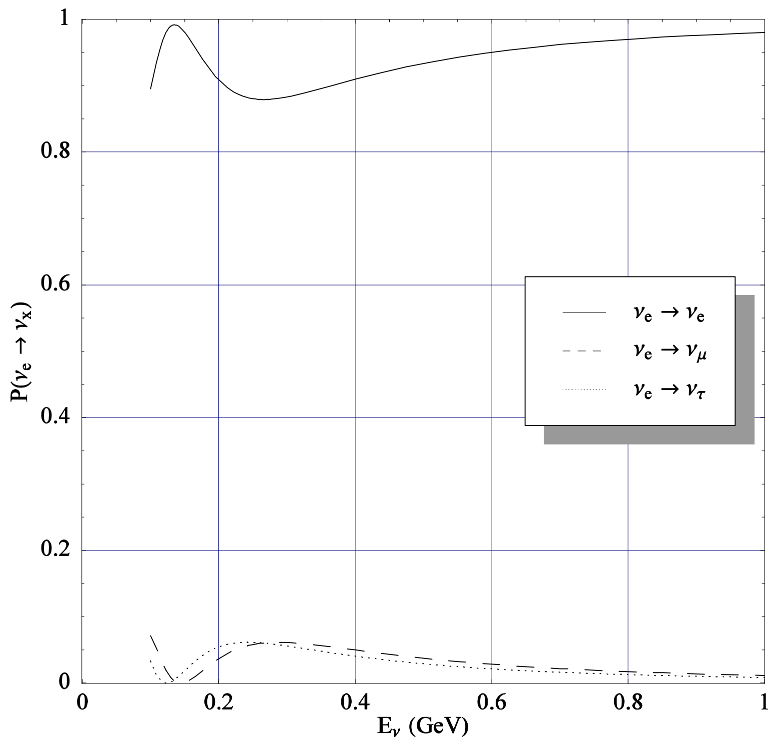
- Computed for 90% CL and 5% systematic error
- Both experiments can distinguish $d > 30^{o}$ if $q_{13} > 1^{o}$
- $d = \pm 90^{o}$can be distinguished from 0^{o} for $q_{13} > 0.5^{o}$
- The combined sensitivity is not significantly improved

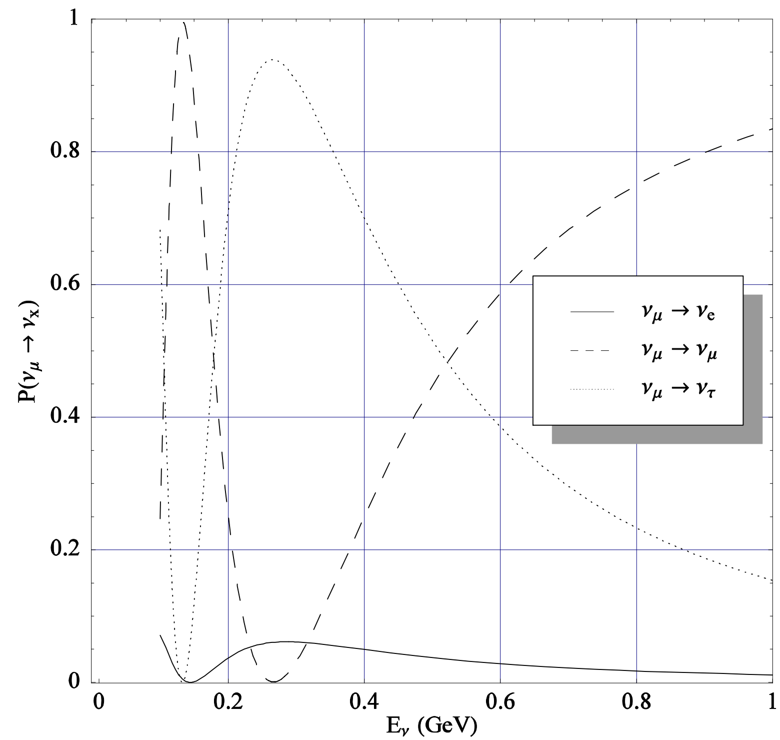
*b*B Feldman and Cousins analysis





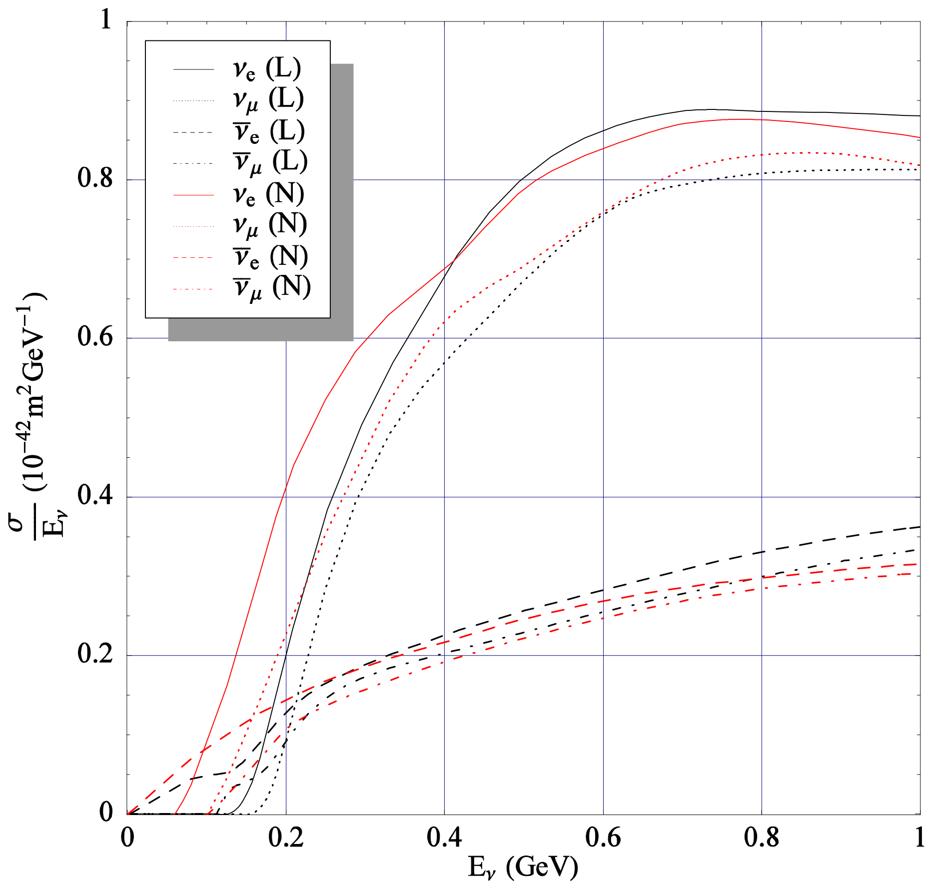
Probabilities





- For $d = 0^{o}$ and $q_{13} = 10^{o}$

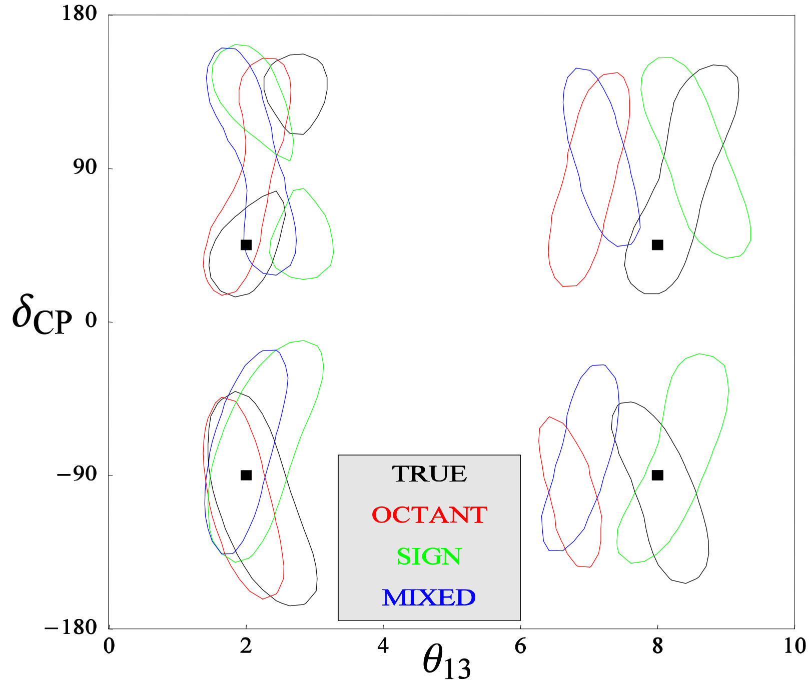
Cross-sections in water



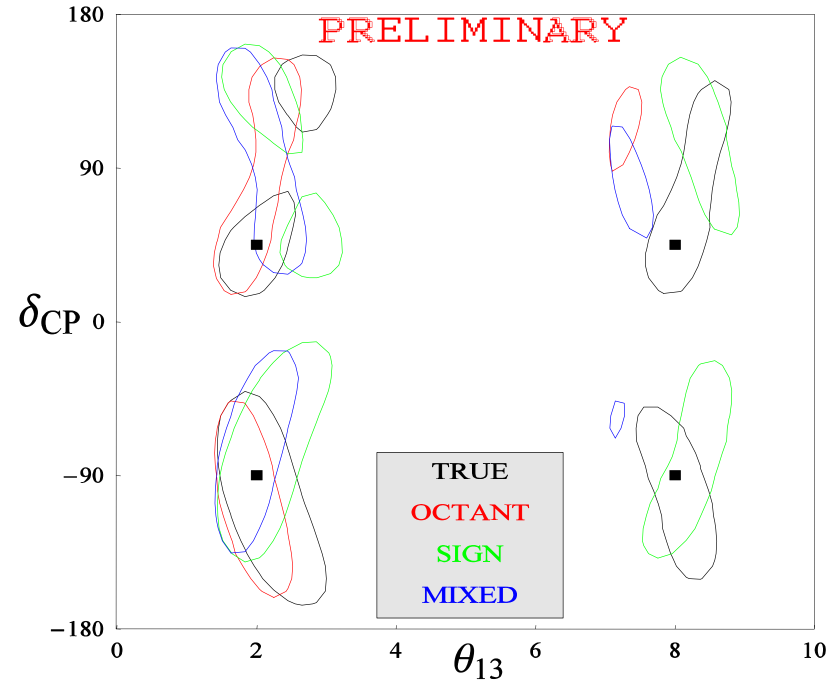
- Different cross-sections can differ up to a factor of 2 below 0.5GeV (at 0.2GeV)
- Comparison of LIPARI (black) and NUANCE (red) cross-section
- We used the LIPARI cross-section that takes into account nuclear effects important below 0.2GeV
- The cross-sections will be measured by the experiments

The *b*B channels combined

Appearance only



Appearance + Disappearance



- Fits for 90% CL
- Systematics of 5% in the appearance channel and 0.6% in disappearance