The merits (and de-merits) of the Silver Channel at the Neutrino Factory

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with thanks to Enrique Fernández-Martínez, Patrick Huber, Jacobo López-Pavón, Davide Meloni, Pasquale Migliozzi, Stefano Rigólin

Outline

- The Golden Channel: $\nu_e \rightarrow \nu_\mu$
- The degeneracy problem
- The Silver Channel: $\nu_e \rightarrow \nu_\tau$
- Limitations of the Silver Channel
- How to improve the Silver Channel
- The $\nu_\mu \rightarrow \nu_\tau$ Channel
- $\nu_e \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_\tau$ for other means:
  - unitarity of the PMNS matrix
  - sterile neutrinos
  - ...

Oscillation Parameters

- What we already know (at 2σ)
  - Solar sector
    $$\left\{ \begin{array}{lcl} \Delta m^2_{12} & = & 7.9^{+0.7}_{-0.7} \times 10^{-5} \mathrm{eV}^2 \\ \sin^2\theta_{12} & = & 0.314^{+0.06}_{-0.05} \end{array} \right.$$
    $\theta_{12} = 33^o–35^o$
  - Atm. sector
    $$\left\{ \begin{array}{lcl} |\Delta m^2_{23}| & = & 2.6^{+0.4}_{-0.4} \times 10^{-3} \mathrm{eV}^2 \\ \sin^2\theta_{23} & = & 0.45^{+0.16}_{-0.09} \end{array} \right.$$
    $\theta_{23} = 36^o–52^o$
- What we still don't know
  - $\sin^2\theta_{13} < 0.031$ — $\theta_{13} < 10^o$
  - δ
  - Mass hierarchy $\quad s_{atm} = \mathrm{sign}(\Delta m^2_{23})$
  - θ_{23} octant $\quad s_{oct} = \mathrm{sign}(\tan 2\theta_{23})$

G.L. Fogli hep-ph/0608060

The Golden Channel

- The $\nu_e \rightarrow \nu_\mu$ oscillation probability in matter

$$P^{\pm}_{e\mu} = X^{\pm}_{\mu} \sin^2 2\theta_{13} + Y^{\pm}_{\mu} \sin 2\theta_{13} \cos\left(\delta \mp \frac{\Delta_{atm} L}{2}\right) + Z_{\mu}$$

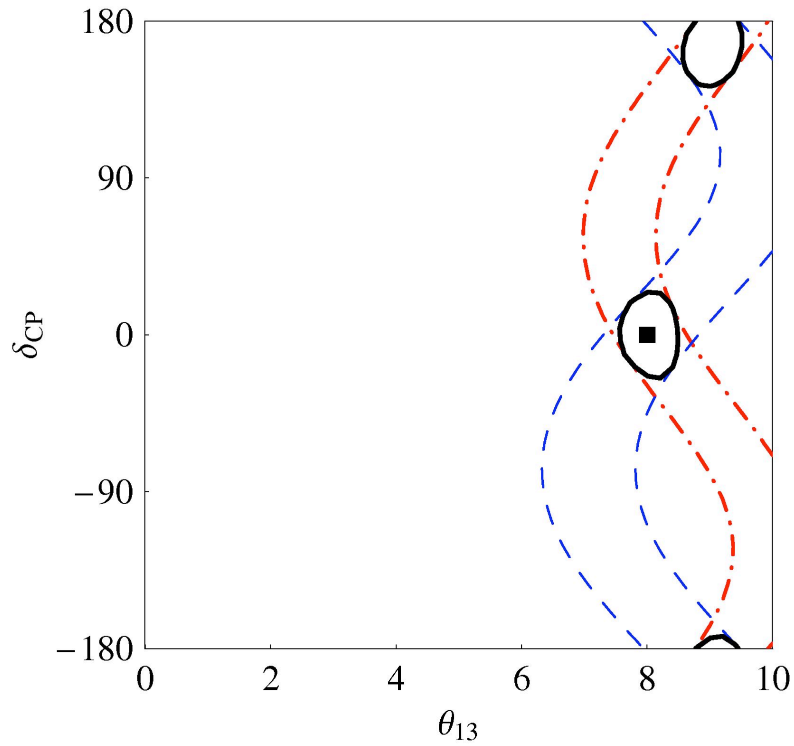
At the Neutrino Factory:

$$\mu^+ \longrightarrow \begin{cases} e^+ & \\ \bar{\nu}_\mu \longrightarrow \bar{\nu}_\mu \longrightarrow \mu^+ \\ \nu_e \longrightarrow \nu_\mu \longrightarrow \mu^- \end{cases}$$

Need for a magnetized detector

The degeneracy problem

- Black square = input "true" value
- There is a curve of solutions
- If we add antineutrinos the two curves intersect in 2 regions: The true solution and an intrinsic degeneracy

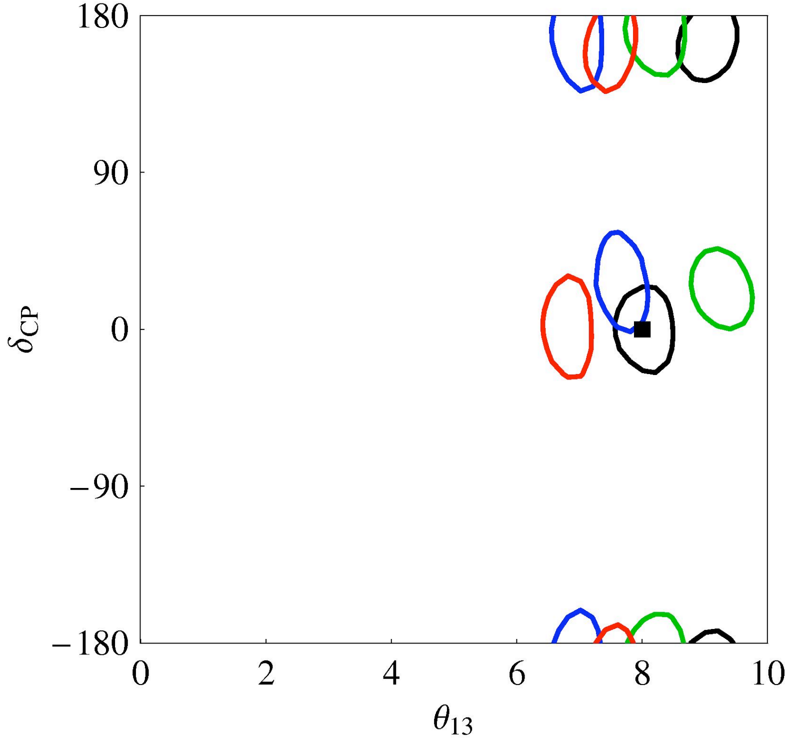


J. Burguet-Castell et al. hep-ph/0103258

The degeneracy problem

- Two other unknown parameters: Satm, Soct
- There are 4 different sets of curves for different choices of Satm, Soct
- 2 Intersections each

Eightfold degeneracy:
Intrinsic sign octant mixed



H. Minakata et al. hep-ph/0108085
G.L.Fogli et al. hep-ph/9604415
V. Barger et al. hep-ph/0112119

The Silver Channel

- The $\nu_e \rightarrow \nu_\tau$ oscillation probability in matter

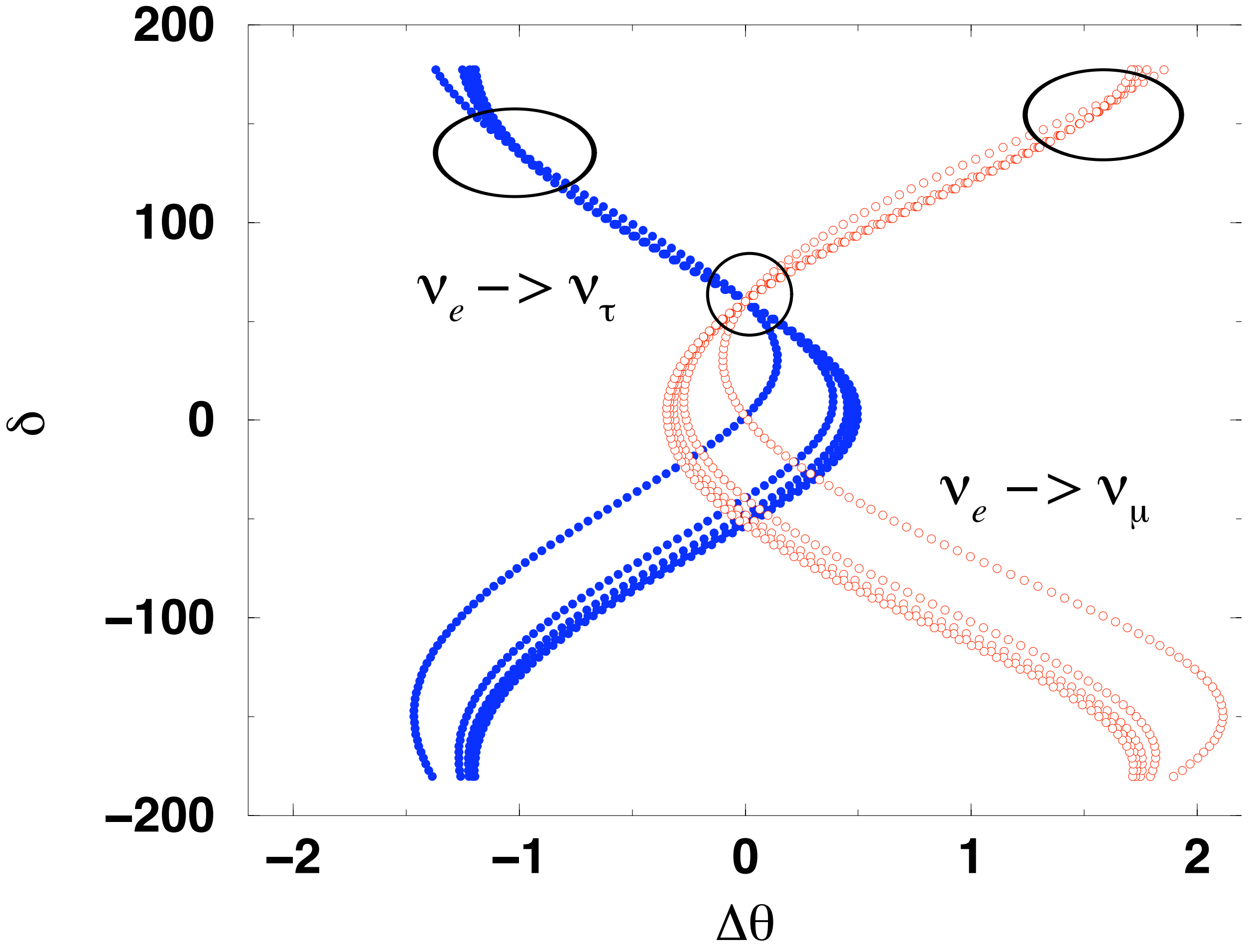
$$P_{e\tau}^{\pm} = X_\tau^{\pm} \sin^2 2\theta_{13} - Y_\tau^{\mp} \sin 2\theta_{13} \cos\left(\delta \mp \frac{\Delta_{atm} L}{2}\right) + Z_\tau$$

At the Neutrino Factory:

$$\mu^+ \rightarrow \begin{cases} e^+ \\ \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \rightarrow \mu^+ \\ \nu_e \rightarrow \nu_\tau \rightarrow \tau^- \rightarrow \mu^- \end{cases}$$

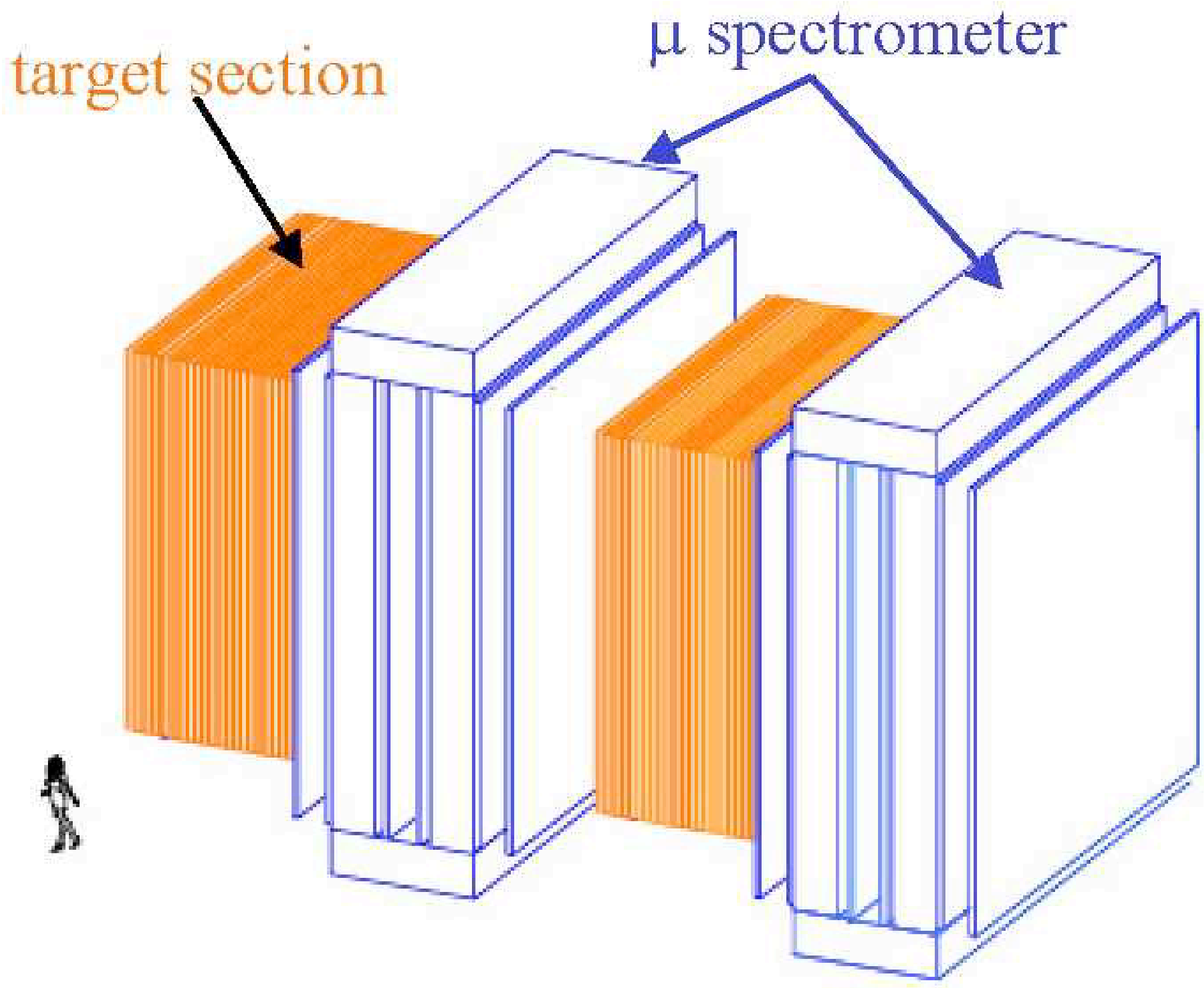
Need to identify the decay vertex and the muon charge

Event curves for golden and silver muons



A. Donini, D. Meloni and P. Migliozzi, hep-ph/0206034

The Detector: an OPERA-like 5 Kton ECC



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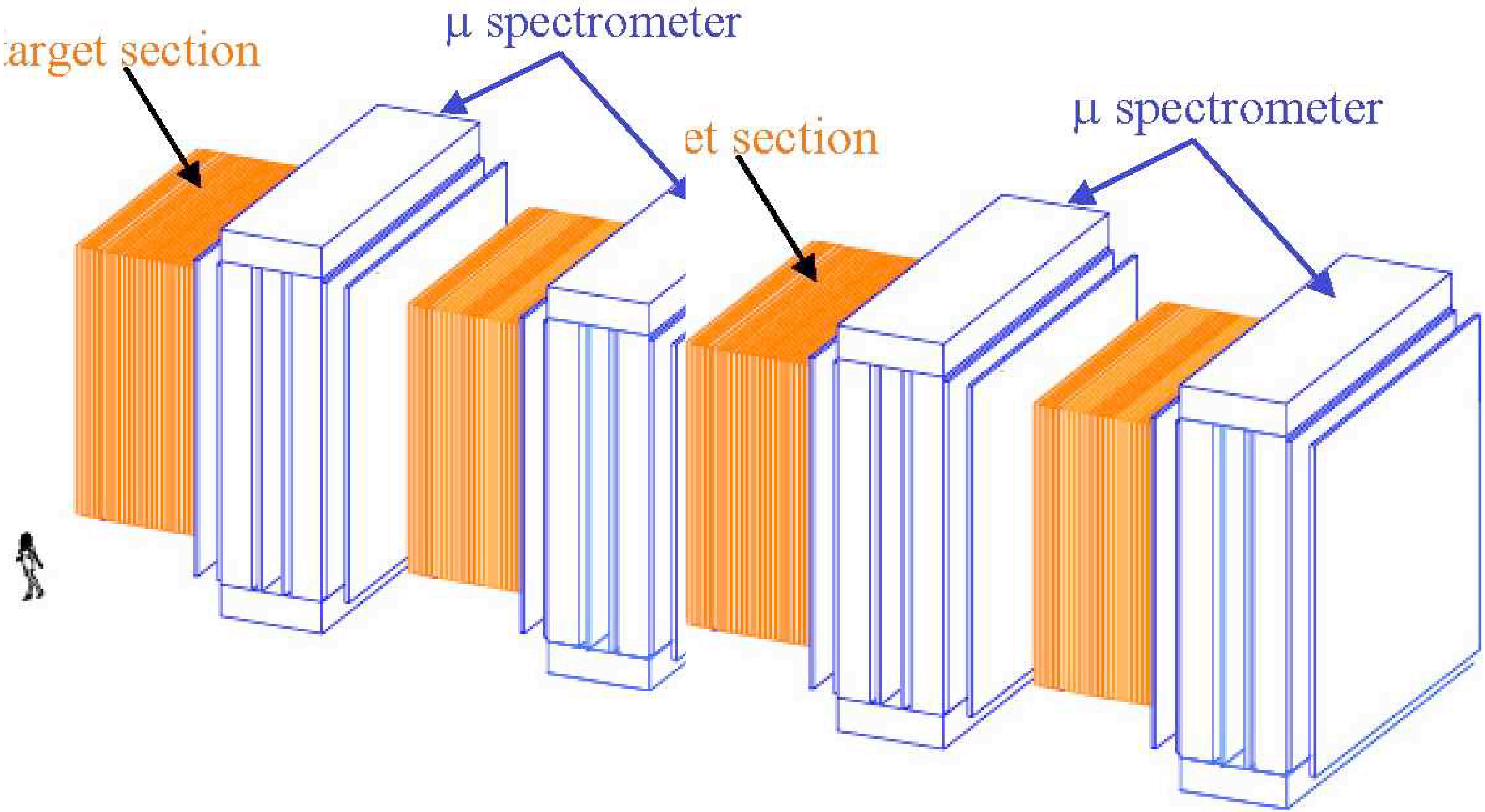
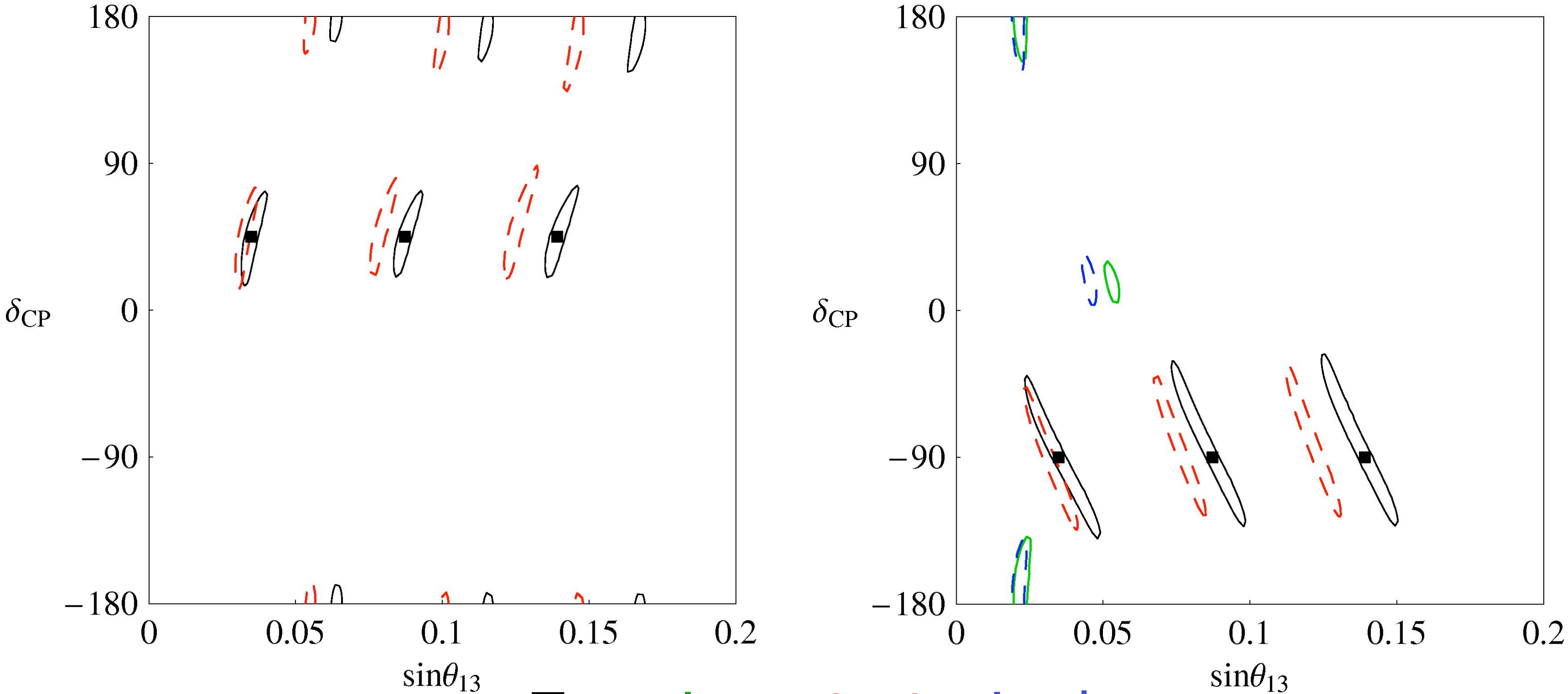


The Golden channel at the NuFact



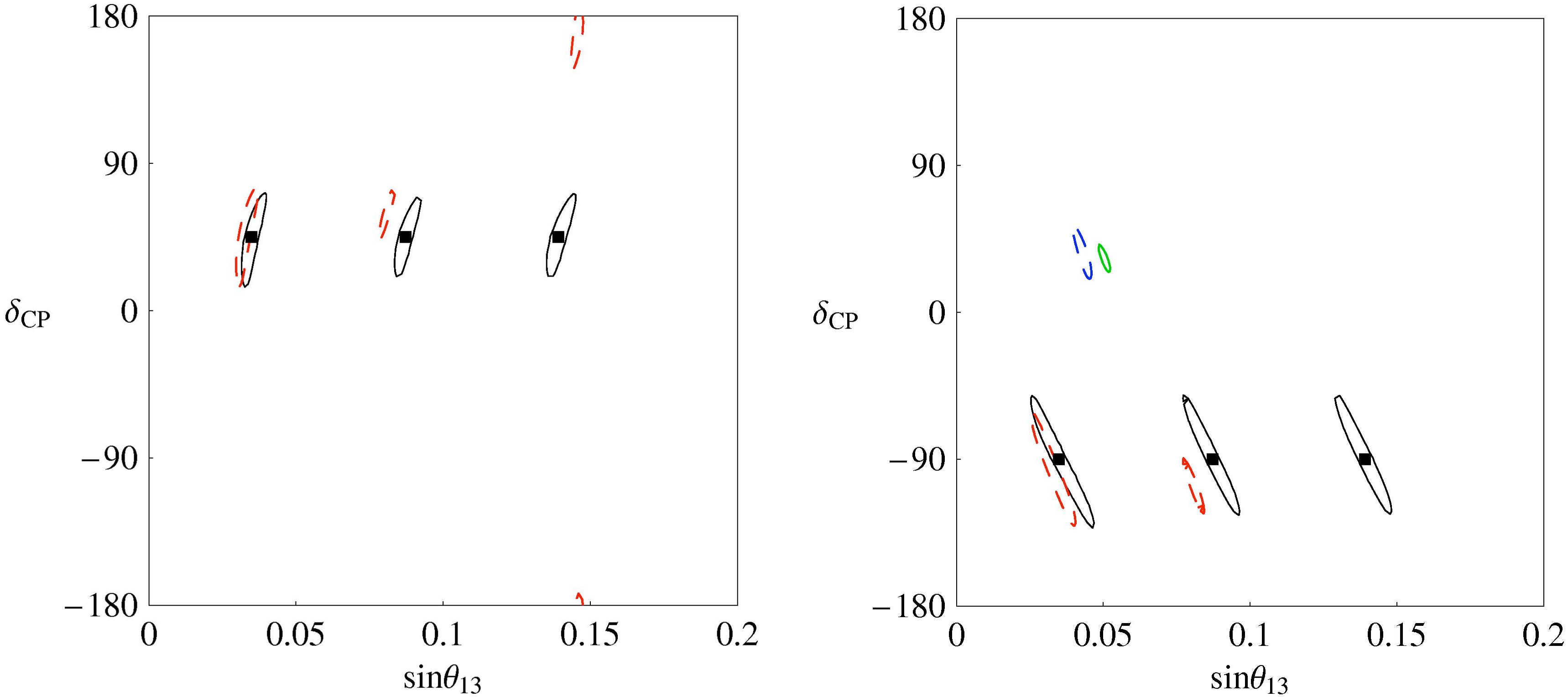
True sign octant mixed

Golden channel at 3000km

Input values θ_{13} = 2º, 5º and 8º δ = 45º, -90º

90% CL contours with 2% systematic error

The Golden and Silver channels at the NF



True sign octant mixed

Golden and Silver channel at 3000km

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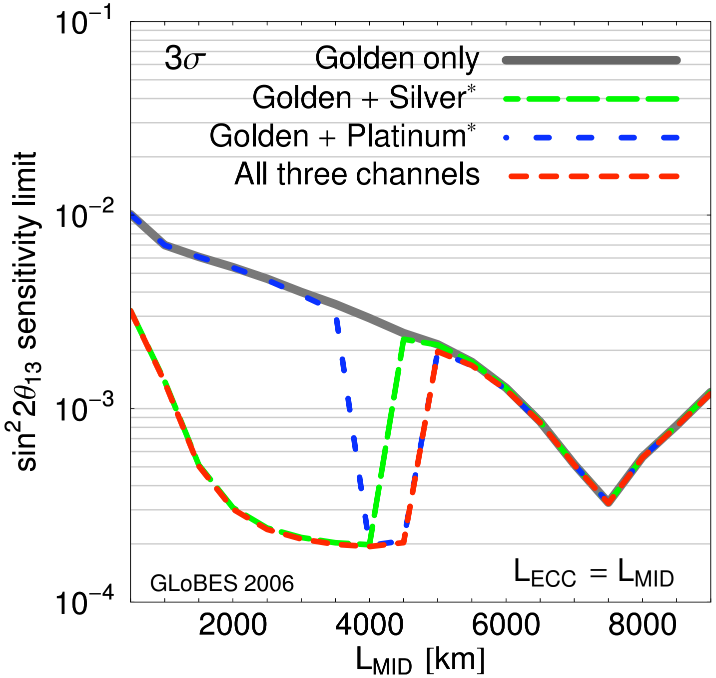
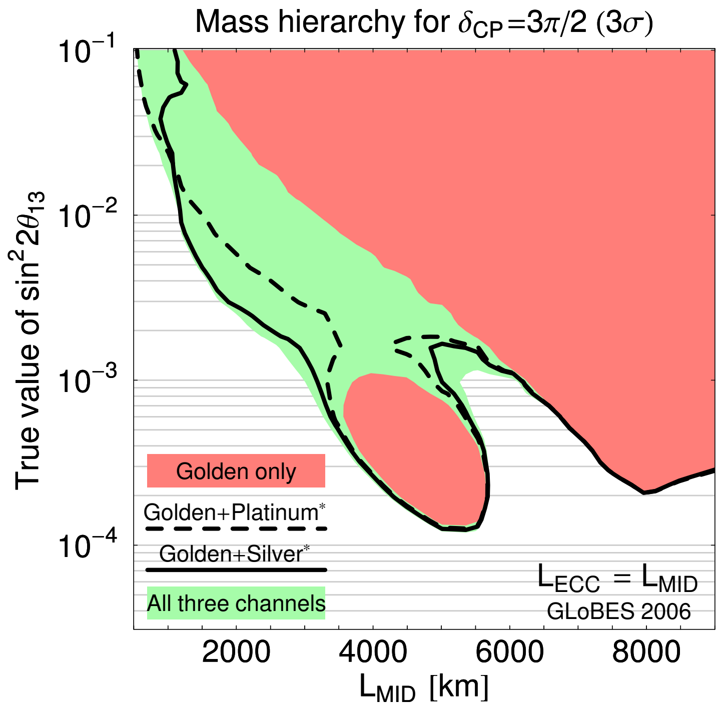
90% CL contours with 2% systematic error

Limitations of the Silver Channel

- The main limitation is STATISTICS.

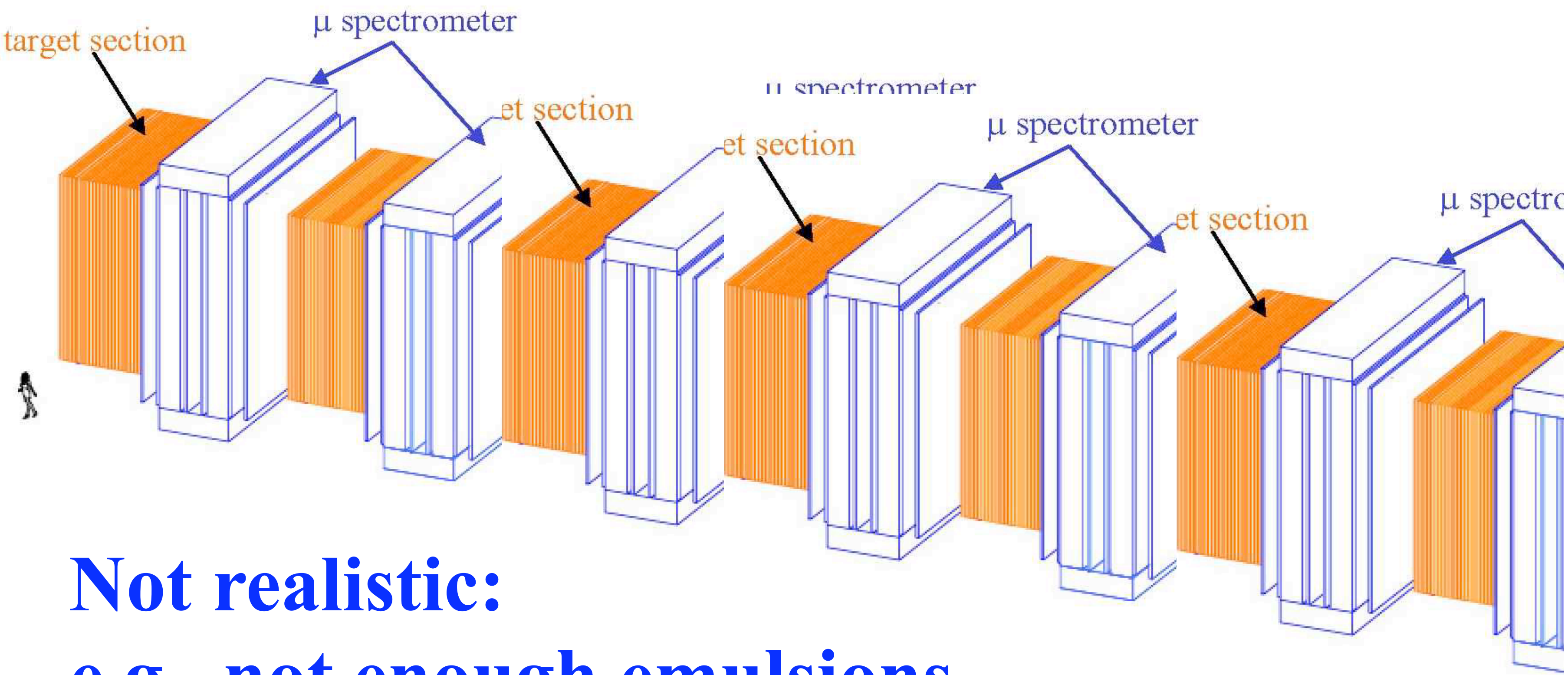




P. Huber, M. Lindner, M. Rolinec and W. Winter, hep-ph/0606019

How to improve the Silver Channel?

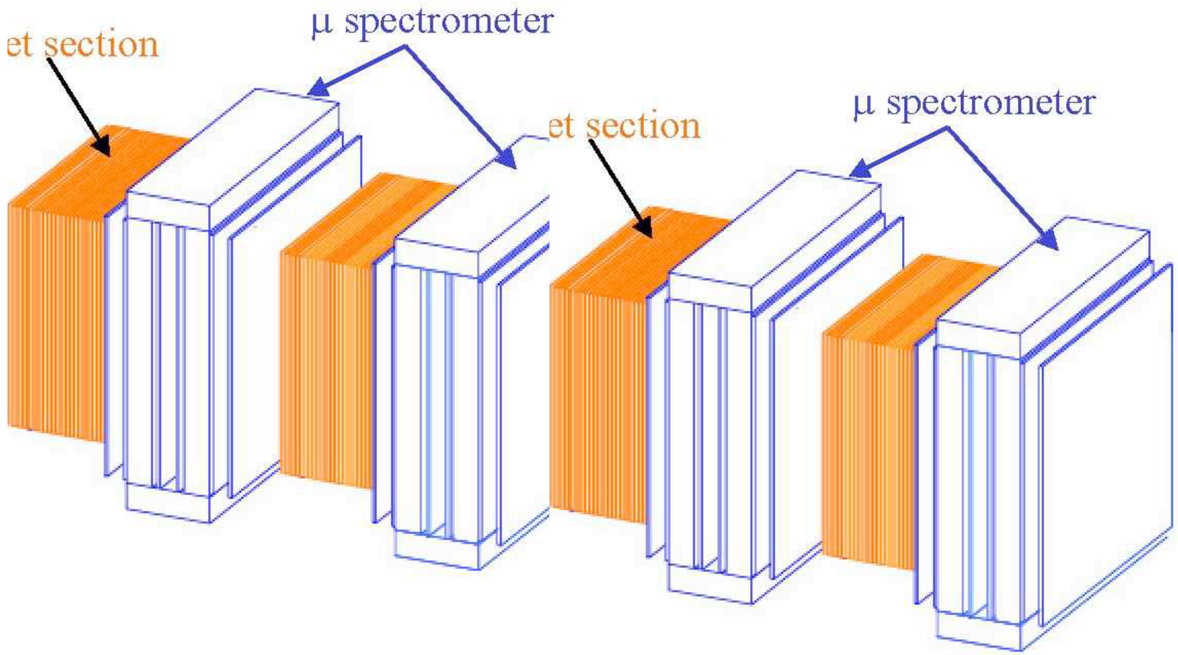
- Difficult:
  - increase the mass?



Not realistic:
e.g., not enough emulsions....

How to improve the Silver Channel?

- Difficult:
  - Increase the mass?
  - Magnetize the detector to use more τ decay channels?



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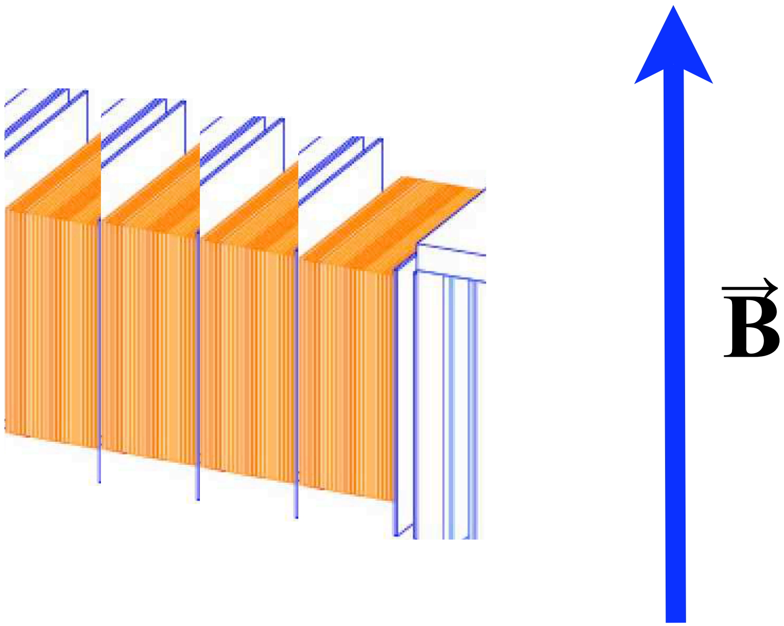
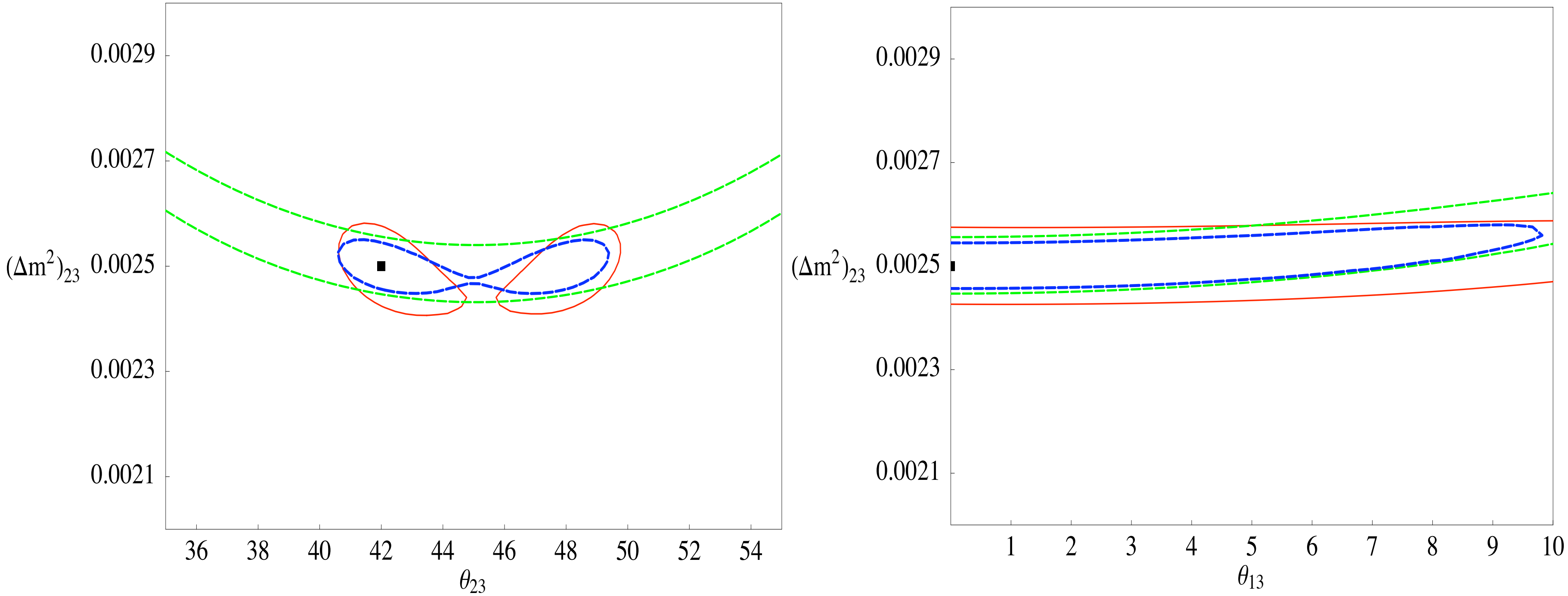


See the ISS Detector Working Group Report

The $\nu_\mu \to \nu_\tau$ channel

- Limited impact at the Neutrino Factory for the standard scenario



$\nu_\mu \to \nu_\tau$ $\nu_\mu \to \nu_\mu$ $\nu_\mu \to \nu_\tau + \nu_\mu \to \nu_\mu$

The $\nu_\mu \rightarrow \nu_\tau$ channel

- Crucial beyond the three-family oscillation scenario
  - to test unitarity of the PMNS matrix

$$P_{\mu\tau} = \sin^2 2\theta_{\mu\tau} \sin^2 \frac{\Delta_{atm} L}{2} + 2Im(\epsilon_{\mu\tau}) \sin 2\theta_{\mu\tau} \sin \frac{\Delta_{atm} L}{2} + 4|\epsilon_{\mu\tau}|^2$$

Atmospheric term

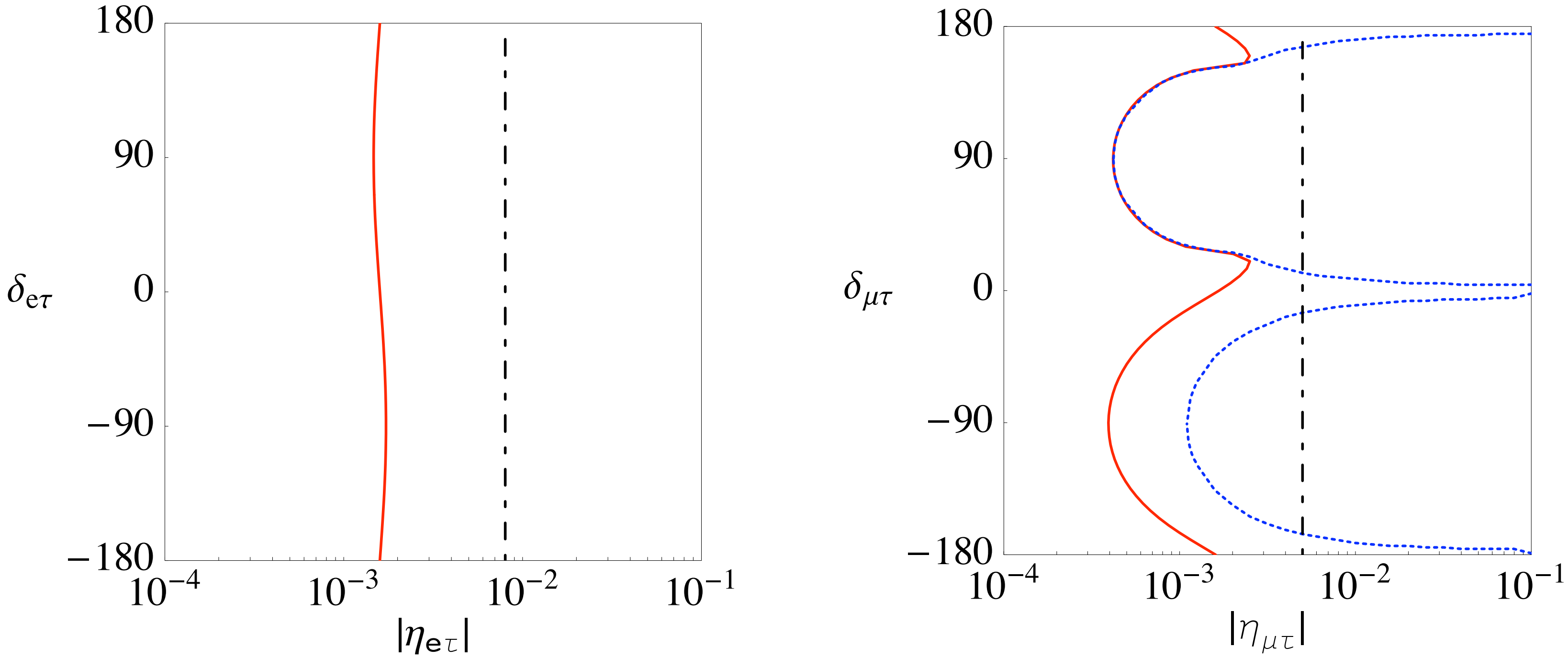
CP-interference

Zero distance effect

At a 50 GeV Neutrino Factory with L = 130 Km
the atmospheric term is suppressed

The $\nu_\mu \rightarrow \nu_\tau$ channel

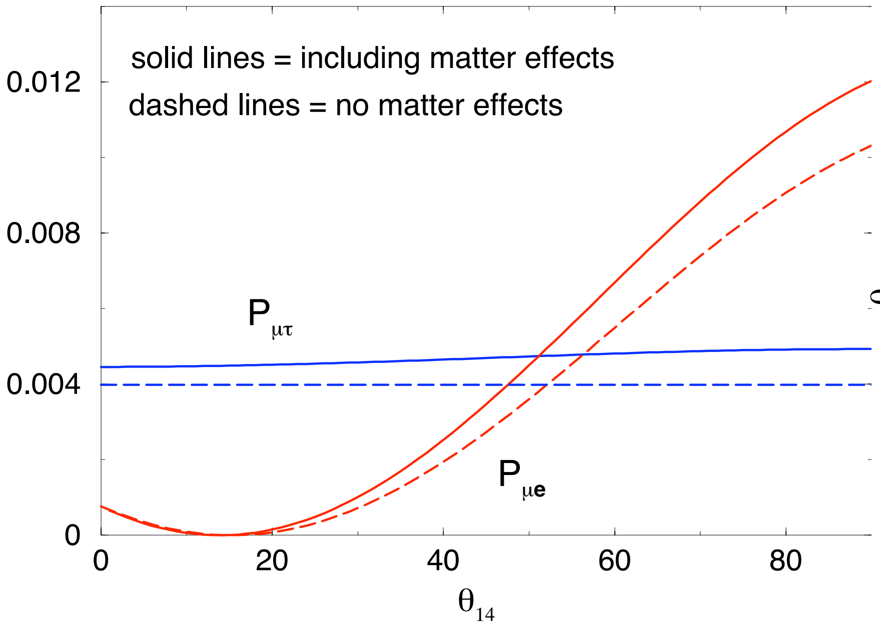
- Crucial beyond the three-family oscillation scenario
  - to test unitarity of the PMNS matrix

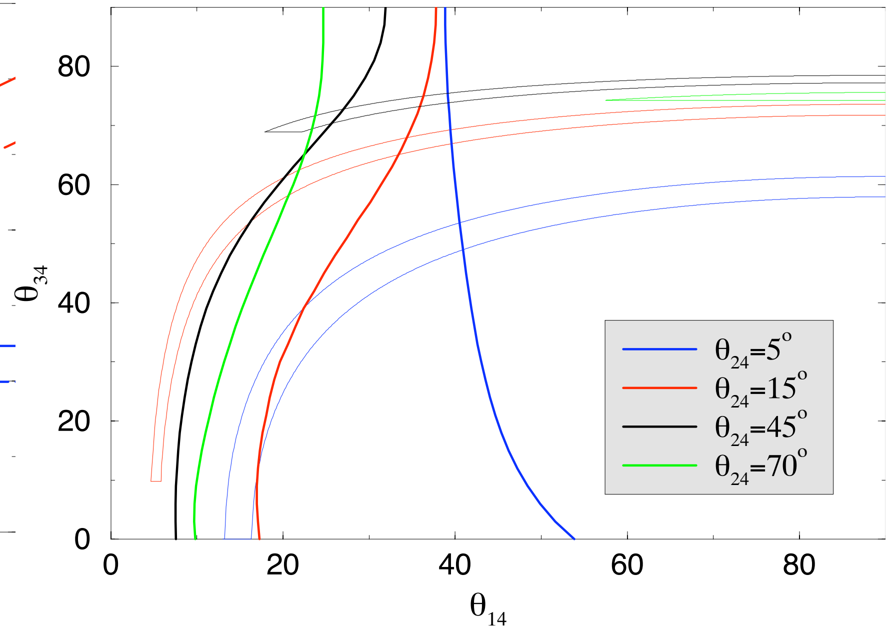


E. Fernández-Martínez, M.B. Gavela, J. López-Pavón and O. Yasuda, hep-ph/0703098

The $\nu_\mu \rightarrow \nu_\tau$ channel

- Crucial beyond the three-family oscillation scenario
  - to test unitarity of the PMNS matrix
  - to look for sterile neutrinos





A. Donini et al., in preparation

Conclusions

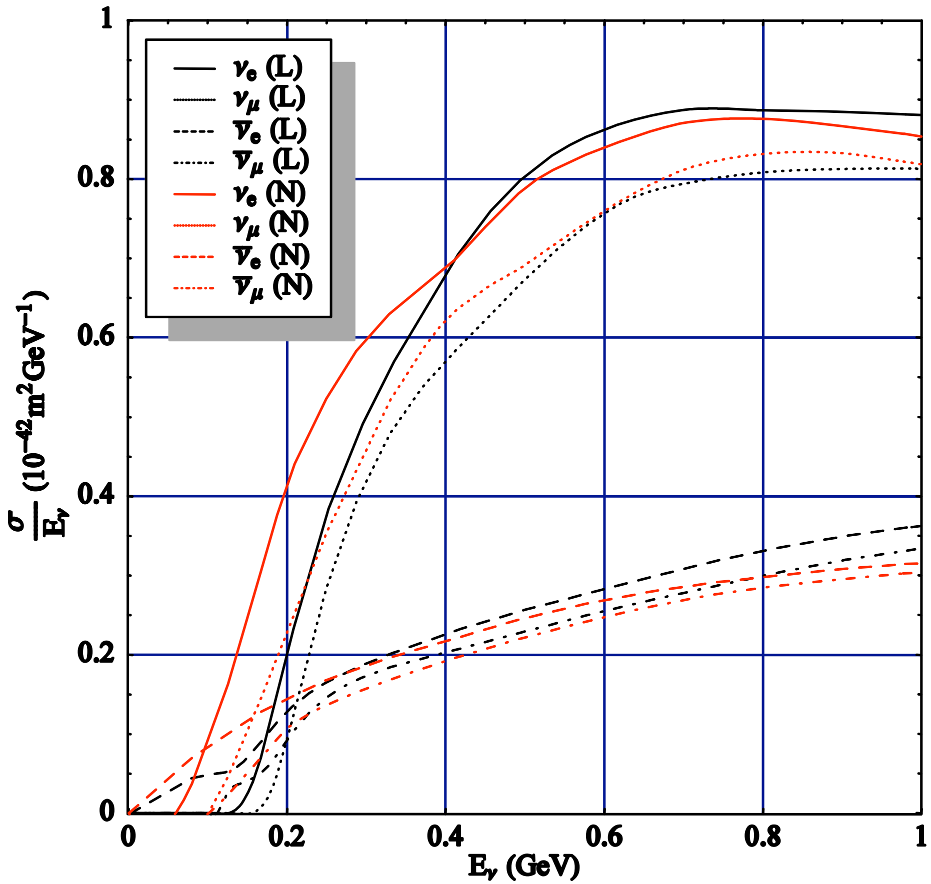
- The Golden Channel at the Neutrino Factory is extremely powerful to measure θ_{13} and δ. However, it is strongly affected by degeneracies

- The Silver Channel can be used to solve part of the degeneracies for θ_{13} not too small: $\theta_{13} \geq 1°$-$2°$

- The Silver Channel and the Platinum Channel gave similar results in degeneracy-solving in this region of θ_{13}. They are both statistically limited: is it possible to increase the signal?

- An ECC can be used also to look for $\nu_\mu \rightarrow \nu_\tau$ oscillation:
  - this channel is of limited interest for standard three-family oscillation, since $\nu_\mu \rightarrow \nu_\mu$ disappearance at the MIND detector gives same results in any case
  - however, it is extremely interesting to look for new physics beyond three-family oscillation

Cross sections



- 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