EXTRACTING OSCILLATION PARAMETERS FROM NEUTRINO DATA

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Outline of the course

Introduction

Lecture I: Solar Neutrinos (θ_{12}, Δm^2_{12})

Lecture II: Atmospheric Neutrinos (θ_{23}, Δm^2_{23})

Lecture III: Bounds on θ_{13} and δ; sterile neutrinos

Lecture IV: Future facilities

FUTURE FACILITIES AND THE QUEST FOR δ

Outline

- Correlations and degeneracies
- Super-Beams
- Neutrino Factory
- Beta-Beams

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- Super-Beams
- Neutrino Factory
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I am not covering reactors, although they can be important (see Lecture3).

The PMNS matrix

The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix is the leptonic analogous of the CKM matrix

"Atmospheric" oscillation

"Solar" oscillation

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

$\theta_{23} = 39^o$–48^o

$\theta_{13} < 11^o$

$\theta_{12} = 32^o$–35^o

Majorana phases

Gonzalez-García and Maltoni '07

The PMNS matrix

Solar parameters:

$$\Delta m^2_{21} = 7.67\,^{+0.22}_{-0.21}\,\left(^{+0.67}_{-0.61}\right) \times 10^{-5}\ \mathrm{eV}^2$$

$$\theta_{12} = 34.5 \pm 1.4\,\left(^{+4.8}_{-4.0}\right)$$

Atmospheric parameters:

$$\Delta m^2_{31} = \begin{cases} -2.37 \pm 0.15\,\left(^{+0.43}_{-0.46}\right) \times 10^{-3}\ \mathrm{eV}^2 & \text{(inverted hierarchy)}, \\ +2.46 \pm 0.15\,\left(^{+0.47}_{-0.42}\right) \times 10^{-3}\ \mathrm{eV}^2 & \text{(normal hierarchy)}, \end{cases}$$

$$\theta_{23} = 42.3\,^{+5.1}_{-3.3}\,\left(^{+11.3}_{-7.7}\right),$$

Gonzalez-García and Maltoni '08

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θ_{23}-octant

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Unknown parameters (maybe less, by the time of NF):

- $\theta_{13} < 11.5^\circ$
- Dirac CP-violating phase δ
- Sign of Δm^2_{13}
- θ_{23}-octant

CORRELATIONS AND DEGENERACIES

The Golden Channel

$$P_{e\mu}^{\pm} = X_{\mu}^{\pm} \sin^2 2\theta_{13} + \left(Y_c^{\pm}\ cos\delta \mp Y_s^{\pm}\ sin\delta\right) \sin 2\theta_{13} + Z_{\mu}$$

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

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

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Strong sensitivity to θ_{13}

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Sensitivity to the sign of Δm^2_{13}

Strong sensitivity to θ_{13}

Sensitivity to δ

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Sensitivity to the θ_{23}-octant

Sensitivity to the sign of Δm^2_{13}

Strong sensitivity to θ_{13}

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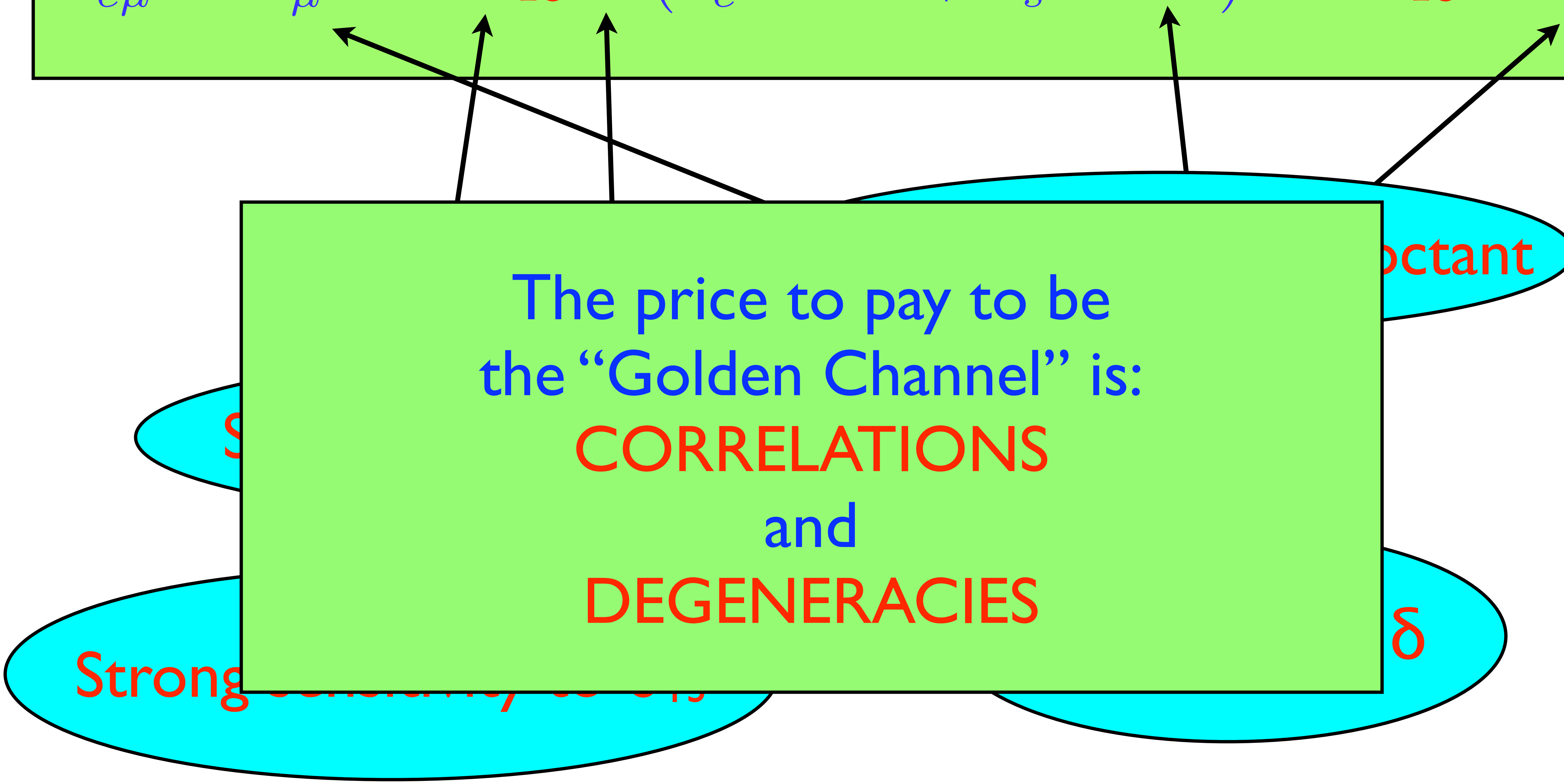

The price to pay to be
the "Golden Channel" is:
CORRELATIONS
and
DEGENERACIES

The (θ_{13}, δ) correlation

The signal is:

$$N_{\mu}(\bar{\theta}_{13}, \bar{\delta}) = \left\{\epsilon_{\mu} \otimes \sigma_{\nu_\mu} \otimes P^{+}_{e\mu}(\bar{\theta}_{13}, \bar{\delta}) \otimes \Phi_{\nu_\mu}\right\}_{E}^{E+\Delta E}$$

$$N^{i}_{\pm}(\bar{\theta}_{13}, \bar{\delta}) = N^{i}_{\pm}(\theta_{13}, \delta)$$

By changing (θ_{13}, δ) accordingly,
curves are drawn in the (θ_{13}, δ) plane.

The (θ_{13}, δ) correlation (2)

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$$N^{i}_{\pm}(\bar{\theta}_{13}, \bar{\delta}, \bar{s}_{atm}, \bar{s}_{oct}) = N^{i}_{\pm}(\theta_{13}, \delta, s_{atm}, s_{oct})$$

where

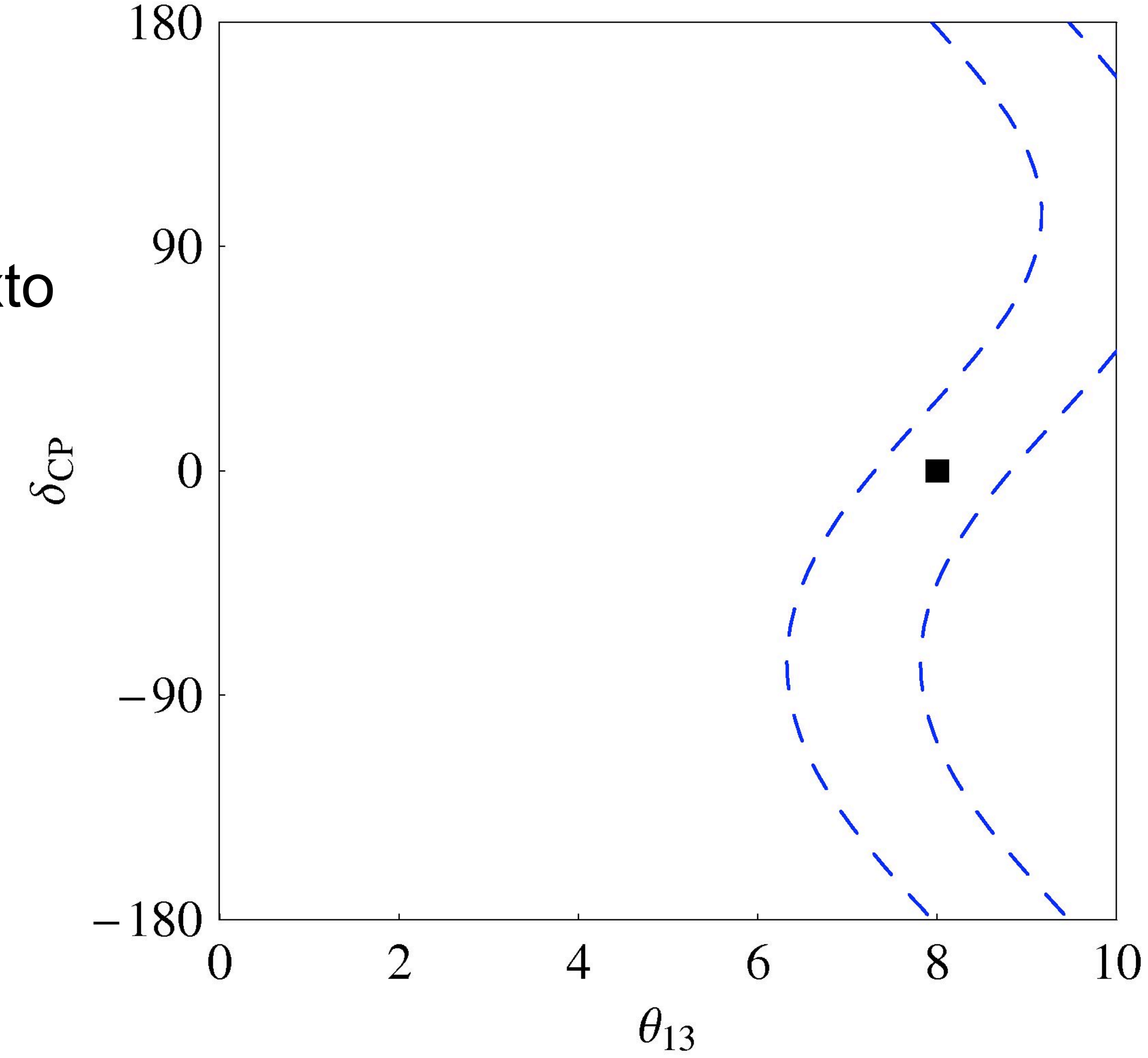
$$\begin{cases} s_{atm} = sign(\Delta m^2_{atm}) = \pm 1 \\ s_{oct} = sign(\tan 2\theta_{23}) = \pm 1 \end{cases}$$

Correlations

- Black square = input "true" value

Texto

- There is a curve of solutions: θ_{13}-δ correlation



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

Correlations

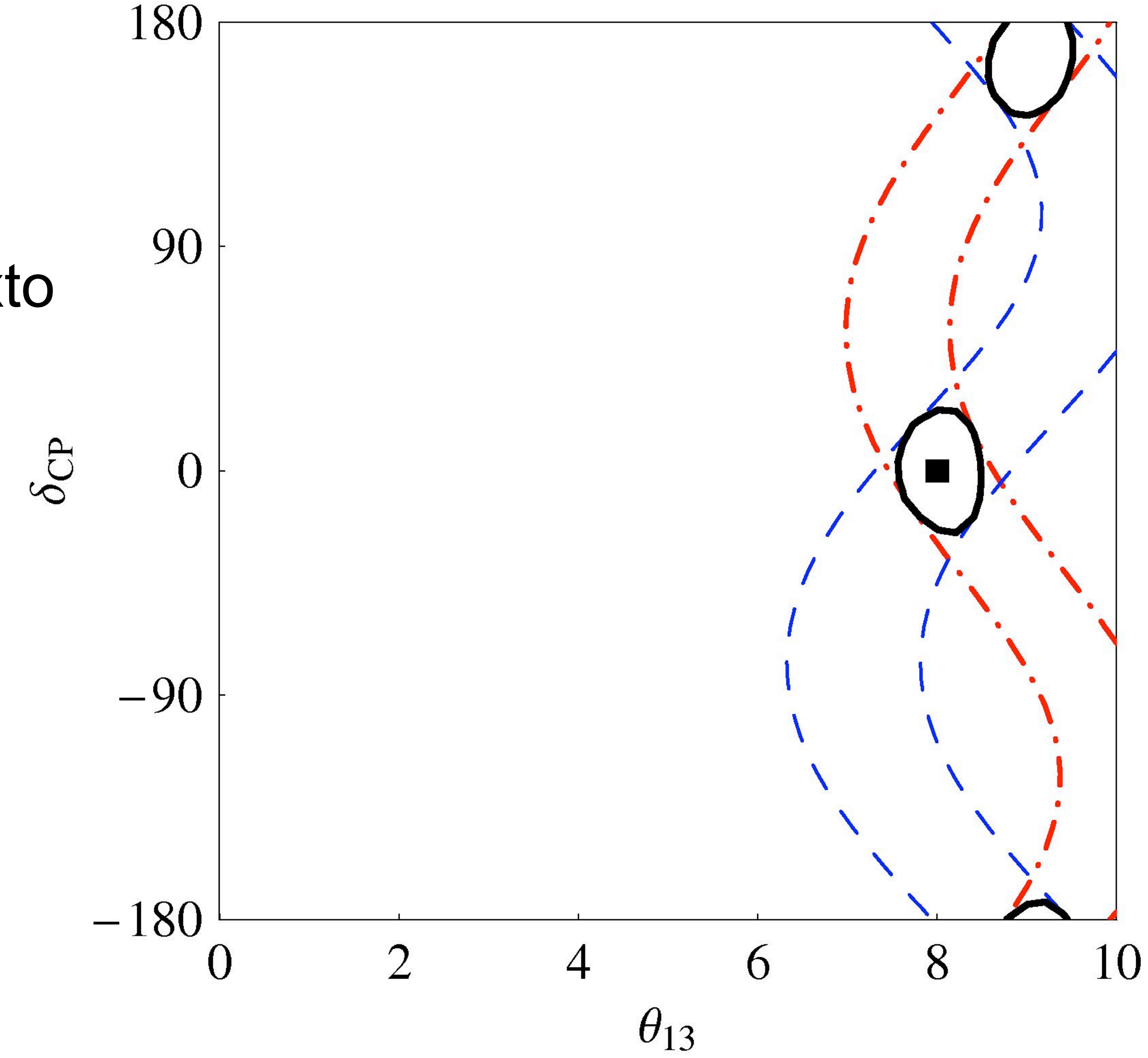
- Black square = input "true" value
- There is a curve of solutions: θ_{13}-δ correlation
- If we add antineutrinos the two curves intersect in 2 regions:

The true solution

and

an intrinsic degeneracy

Texto



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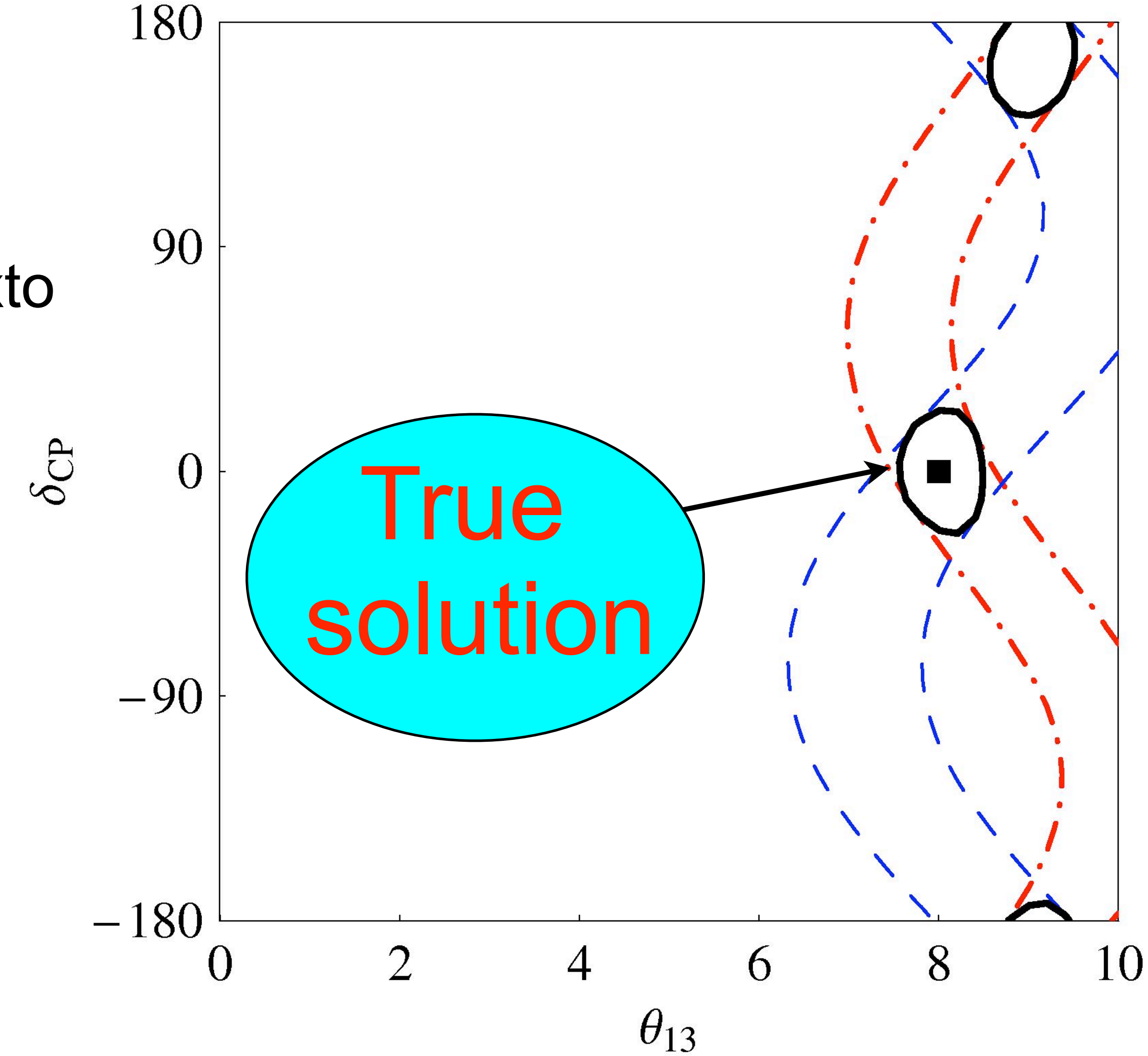

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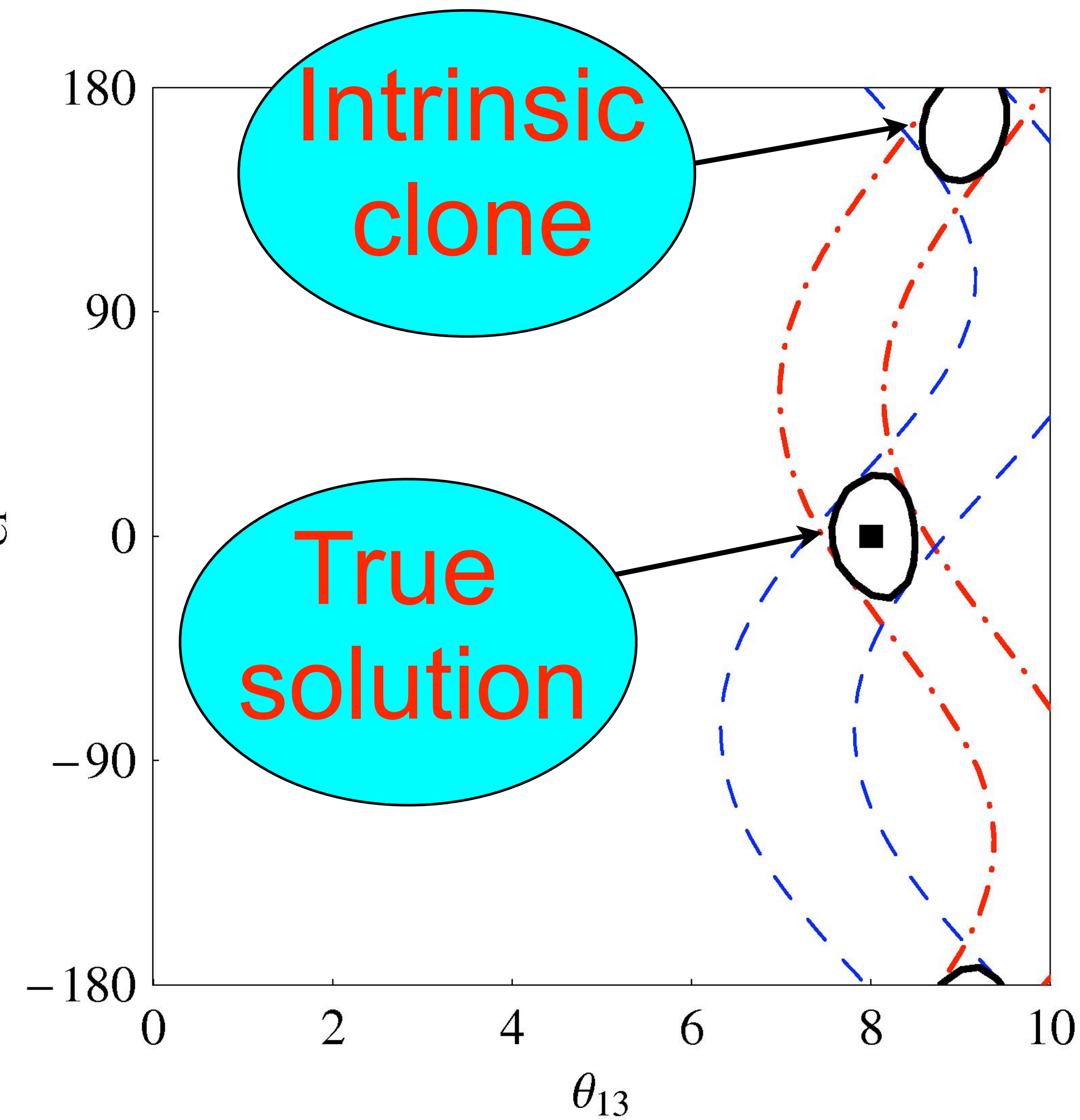

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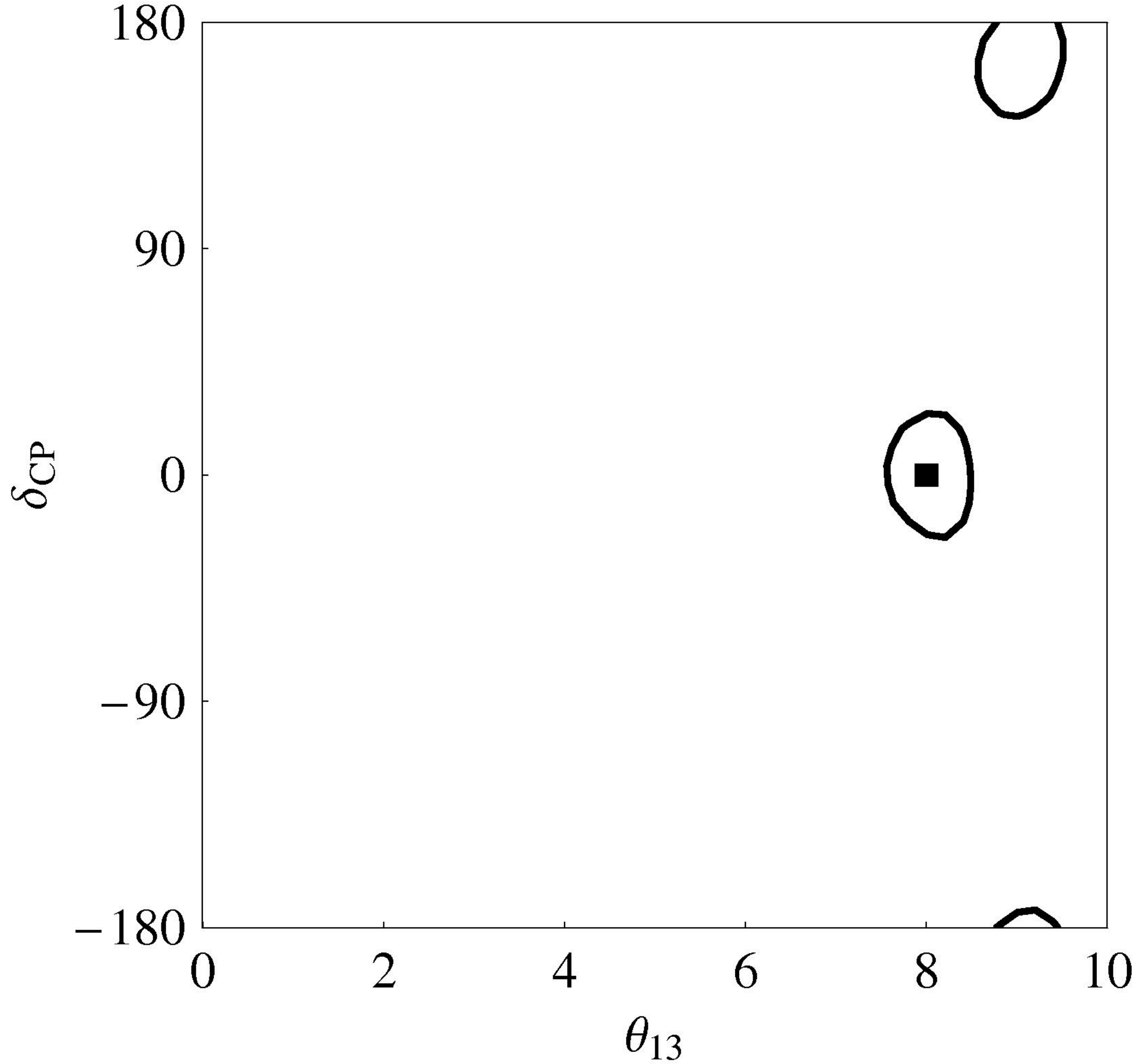
Of other degeneracies

- Two unknown discrete parameters: s_{atm}, s_{oct}
- There are 4 different sets of curves for different choices of s_{atm}, s_{oct}



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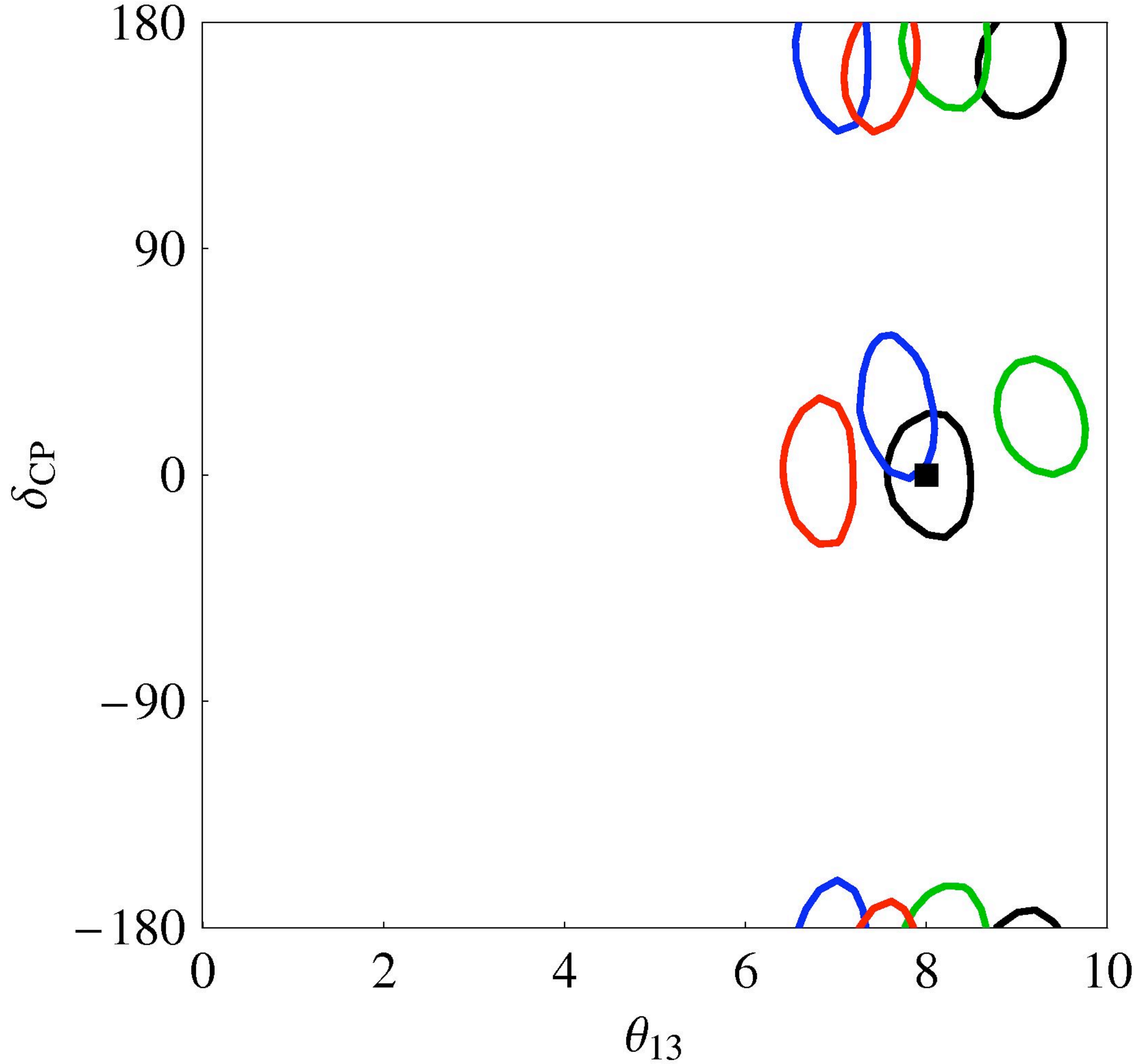
Eightfold degeneracy:

Intrinsic sign octant mixed



H. Minakata and H. Nunokawa hep-ph/0108085
G.L.Fogli and E. Lisi hep-ph/9604415
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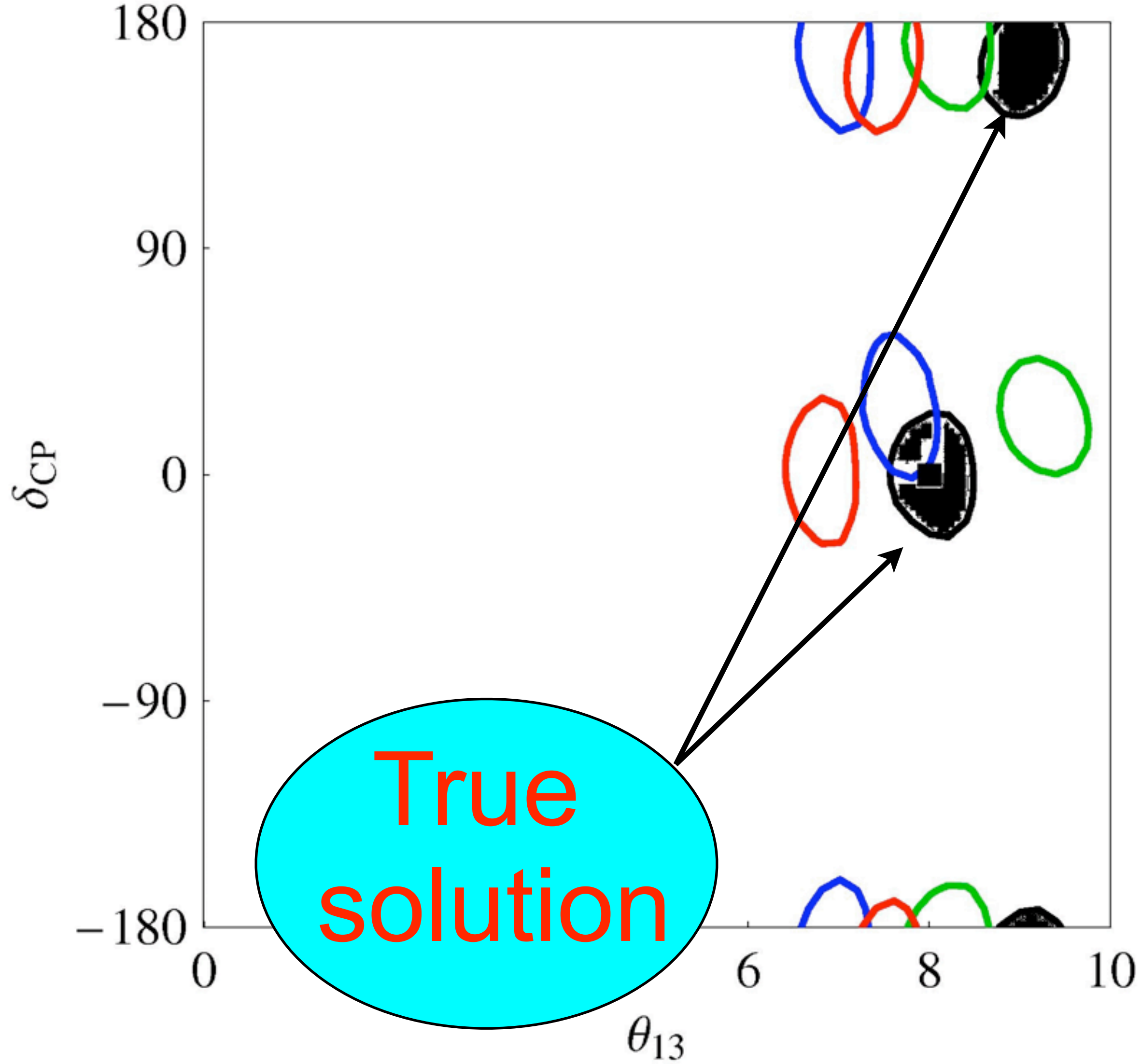

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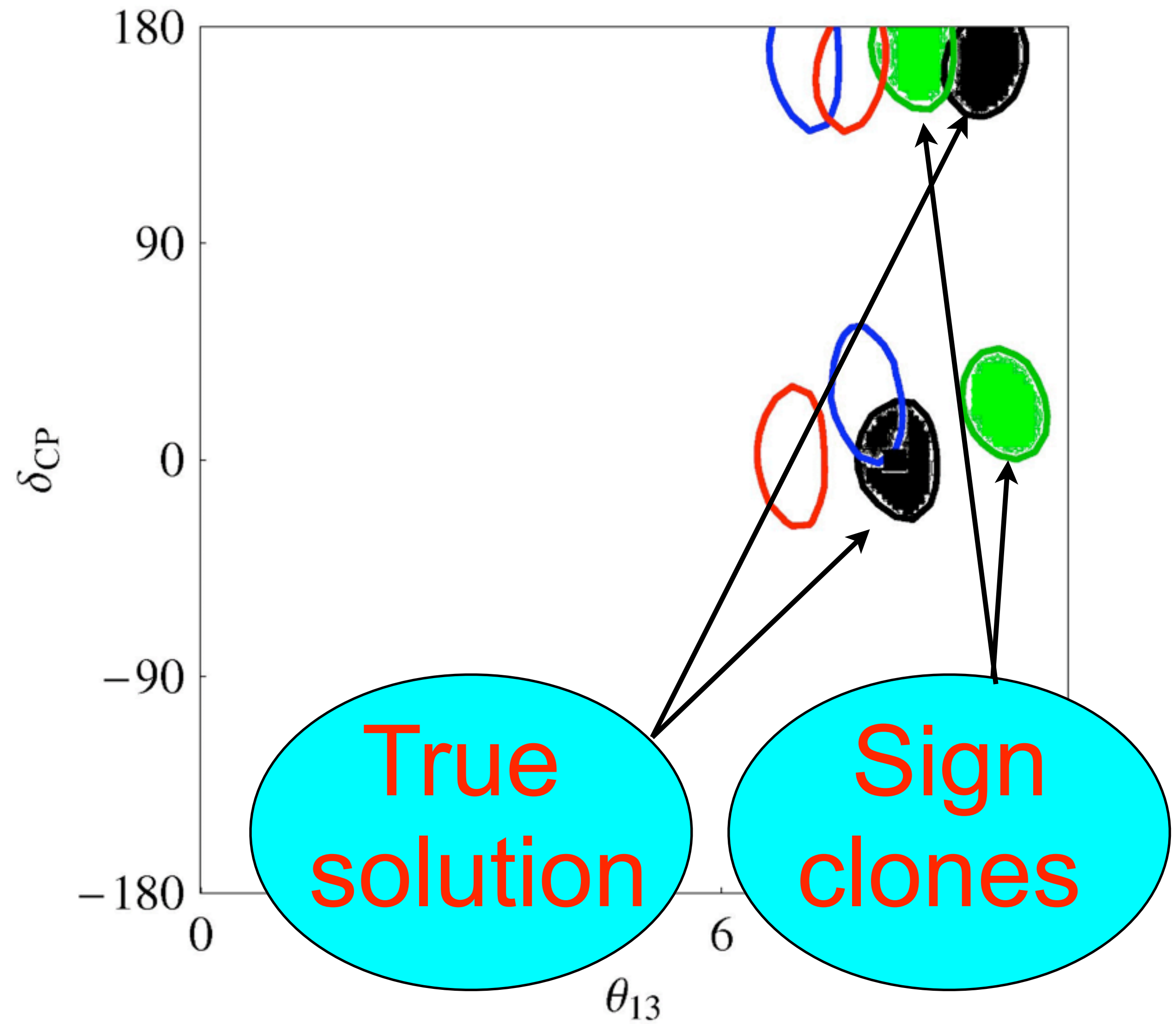

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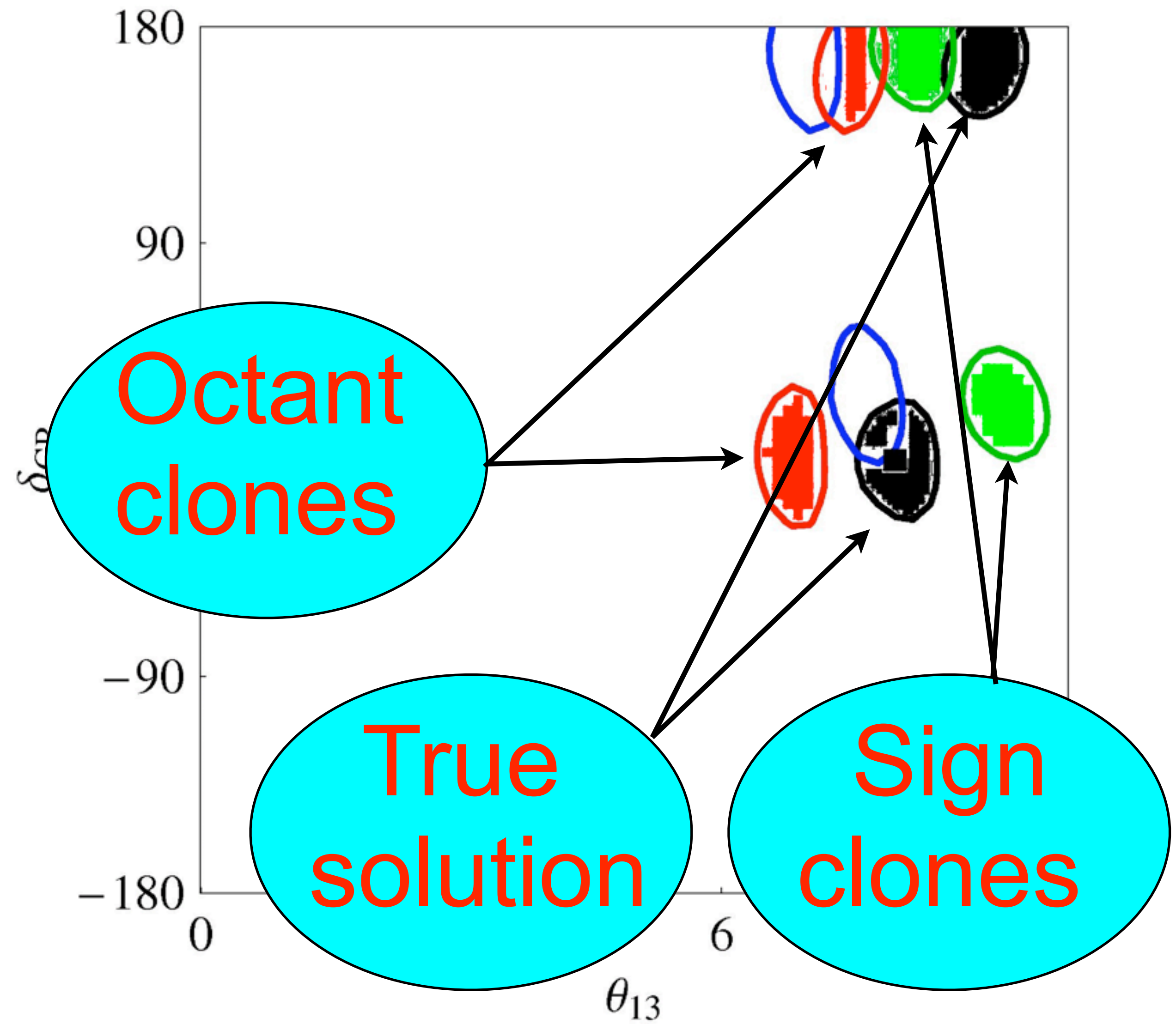

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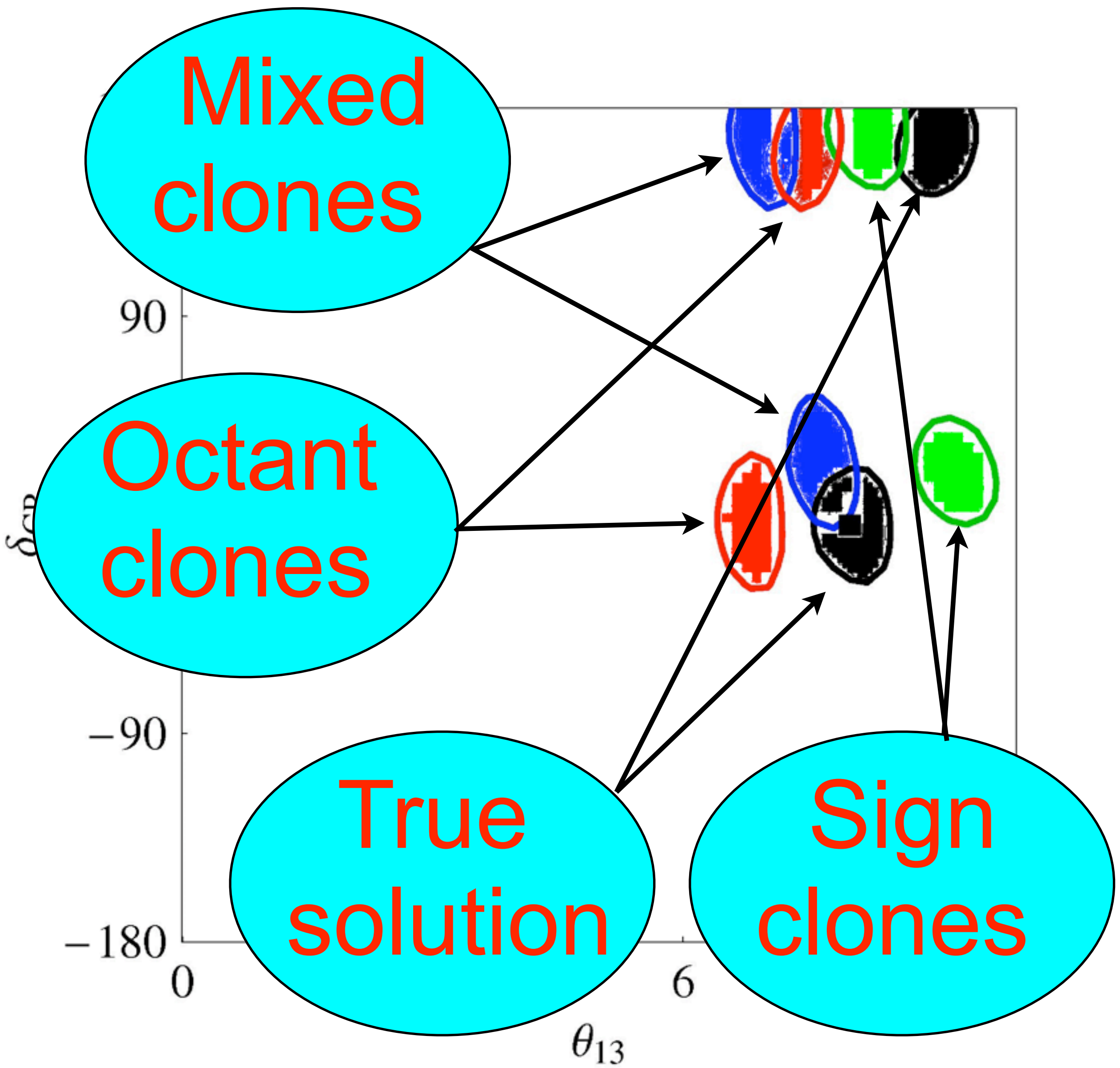

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- The goal: measure at the same time the four parameters that we do not yet know: θ_{13}, δ, the sign of Δm^2_{23} and the θ_{23}-octant

- To achieve our goal, we must then solve the problem of degeneracies.

SUPERBEAMS

Sensitivity bounds by T2K and NOνA

EXP	θ_{13}	$\sin^2(2\theta_{13})$	$\sin^2\theta_{13}$
Global Fit	10.8°	0.135	0.035
SBEAMS			
T2K-I	2.2°	0.006	0.0015
(JHF)	$\to 3.3^\circ$	$\to 0.013$	$\to 0.0030$
NOνA	2°	0.005	0.0010
(NUMI-OA)	$\to 3.5^\circ$	$\to 0.015$	$\to 0.0040$

$$P_{\mu e} = s_{23}^2 \sin^2(2\theta_{13}) \sin^2\left[\frac{\Delta_{atm} L}{2}\right] + \mathcal{O}\left[\left(\frac{\Delta_{sol}}{\Delta_{atm}}\right) \sin(2\theta_{13}) \cos\delta\right] + \mathcal{O}\left[\left(\frac{\Delta_{sol}}{\Delta_{atm}}\right) \sin(2\theta_{13}) \sin\delta\right]$$

Sensitivity loss due to $(\theta_{13} - \delta)$-correlations

Around 2012...

After the wave of conventional beams and first generation superbeams, and of high-power reactors experiments, we will know something more on the PMNS matrix:

- ▷ mass differences Δm^2_{atm}, Δm^2_{sol} at some $\%$;

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Precision measurements of LEPTONIC MIXING will start with the next-to-next generation experiments, using SuperBeams or BetaBeams with 1 Mton Water Čerenkov or/and the Neutrino Factory.

An intermediate phase?

After T2K and NOνA, we will face a forking path:

★ $\nu_\mu \to \nu_e$ oscillation has been observed!
A good option: increase detector mass,
same source: T2-HK or SPL+UNO
(really a good option?)

- No signal has been observed: $\theta_{13} \leq 3^\circ - 4^\circ$!
Go to new sources:
Neutrino Factory or the Beta-Beam.

Appearance Signal at a SB

$$\pi^+ \rightarrow \begin{cases} \mu^+ \rightarrow \bar{\nu}_\mu, \nu_e \rightarrow e^- & \textit{Background} \\ \nu_\mu \rightarrow \nu_e \rightarrow e^- & \textit{Signal} \end{cases}$$

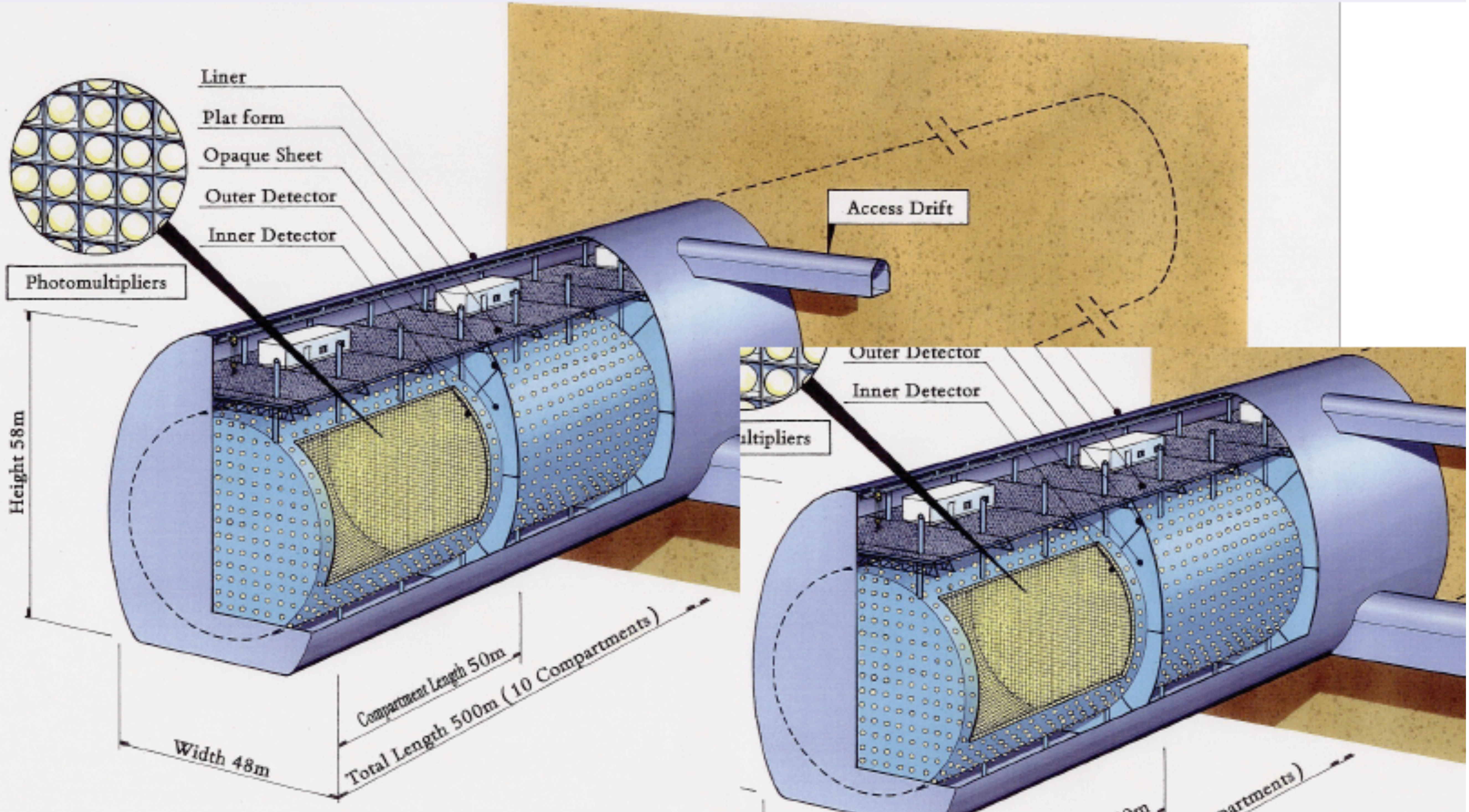
The oscillation probability is

$$P^{\pm}_{\mu e} \simeq X_\pm \sin^2(2\,\theta_{13})$$

$$+Y_\pm \cos\left(\delta \pm \frac{\Delta_{atm} L}{2}\right) \cos\theta_{13} \sin(2\,\theta_{13})$$

$$+Z + \ldots$$

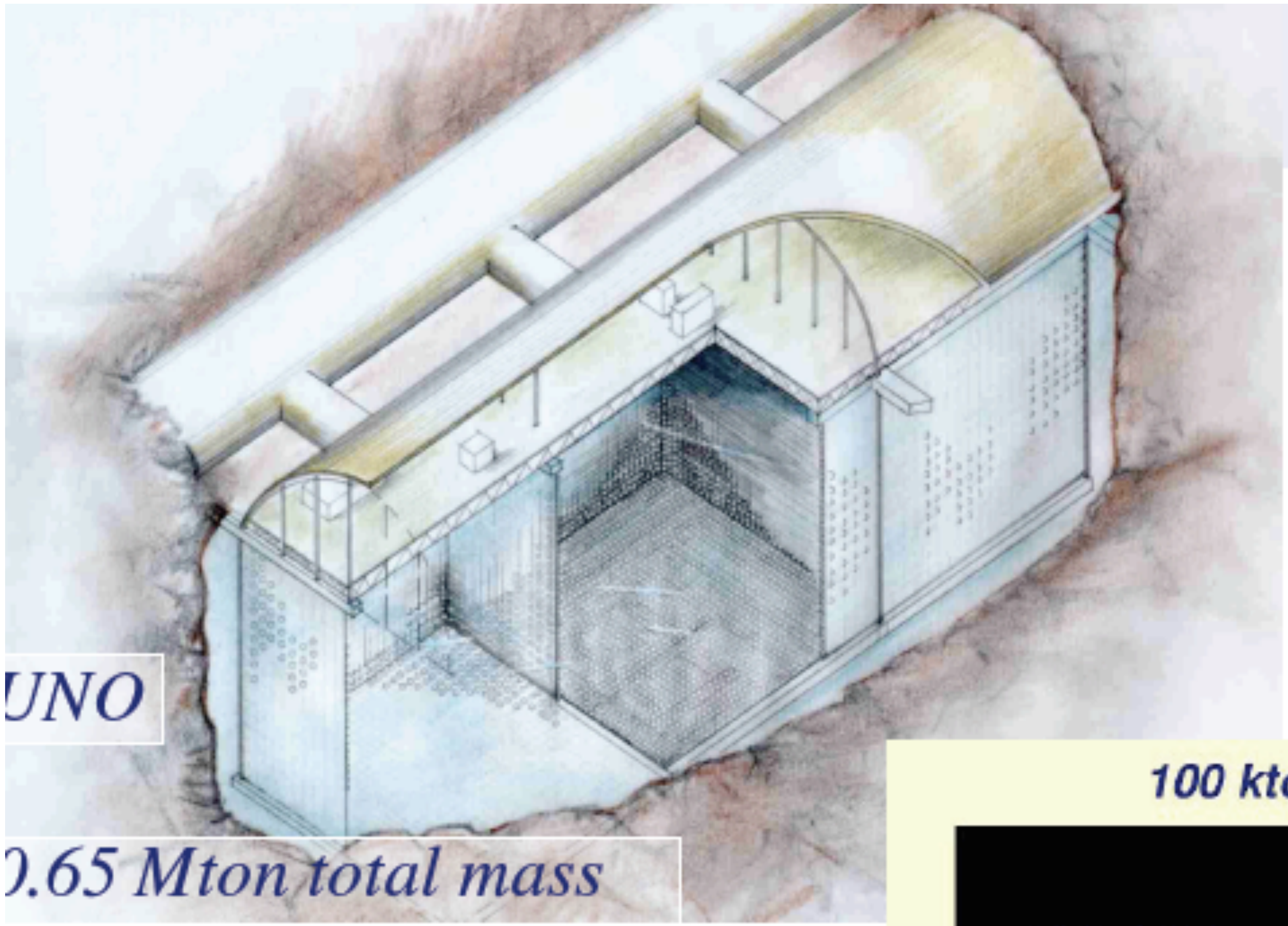
Hyper-Kamiokande

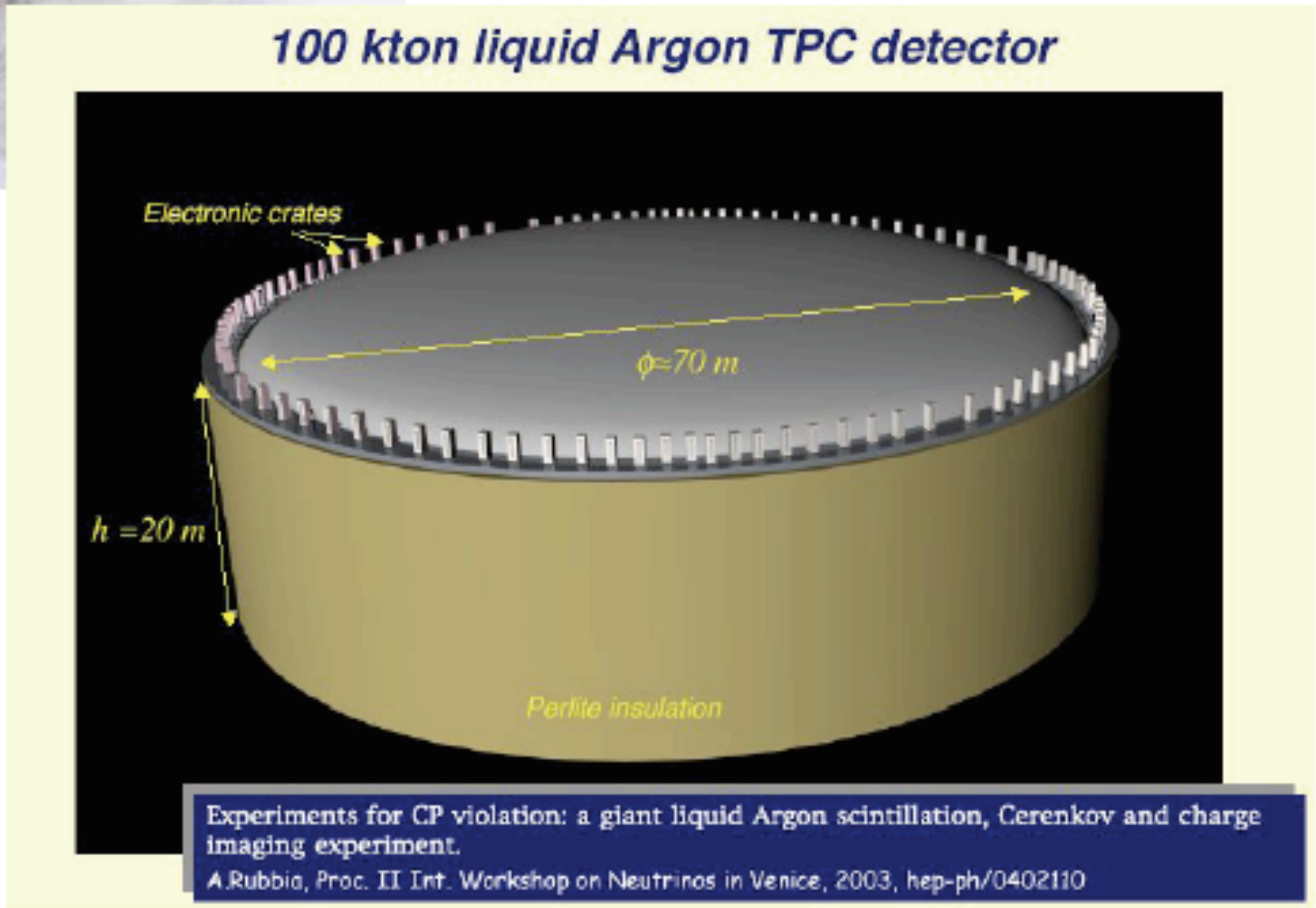


2 detectors 48m x 50m x 250 m
1 Mton total mass

The CERN-Memphys project

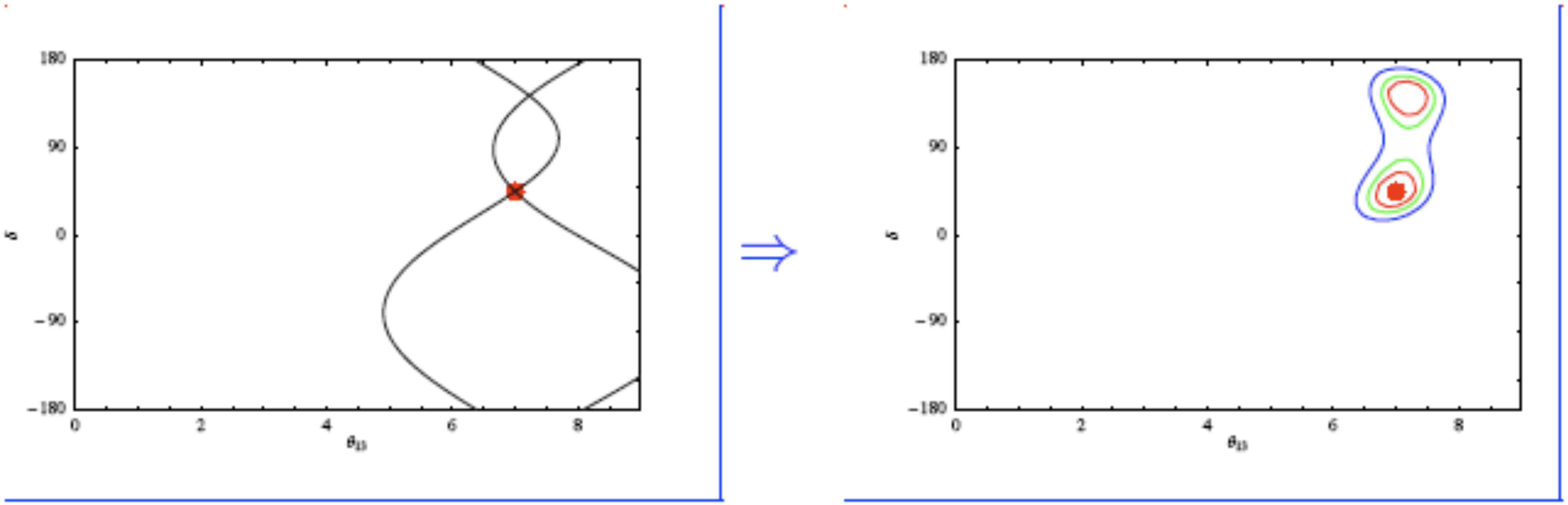
Detector options





Degeneracy in (θ_{13}, δ) at the SPL

2 years for π^+ and 8 years for π^-



$L = 130$ Km, $\bar{E}_{\nu_\mu} = 0.27$ GeV, $\bar{E}_{\bar{\nu}_\mu} = 0.25$ GeV

Input parameters: $\bar{\theta}_{13} = 7°, \bar{\delta} = 45°$

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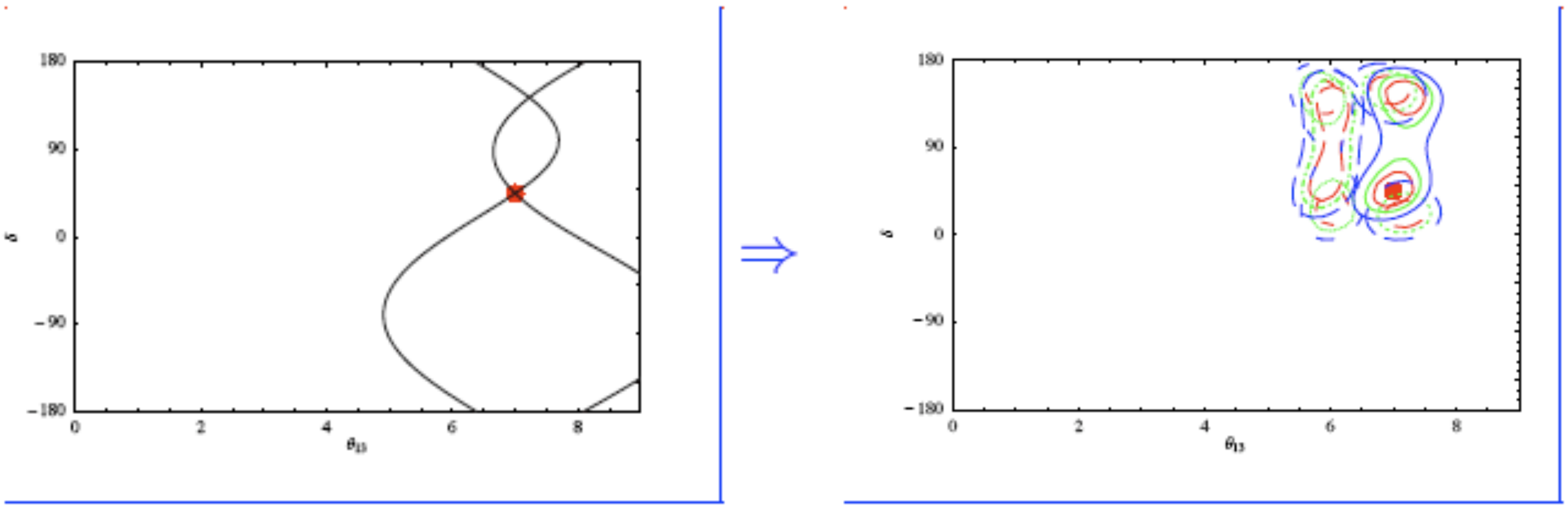

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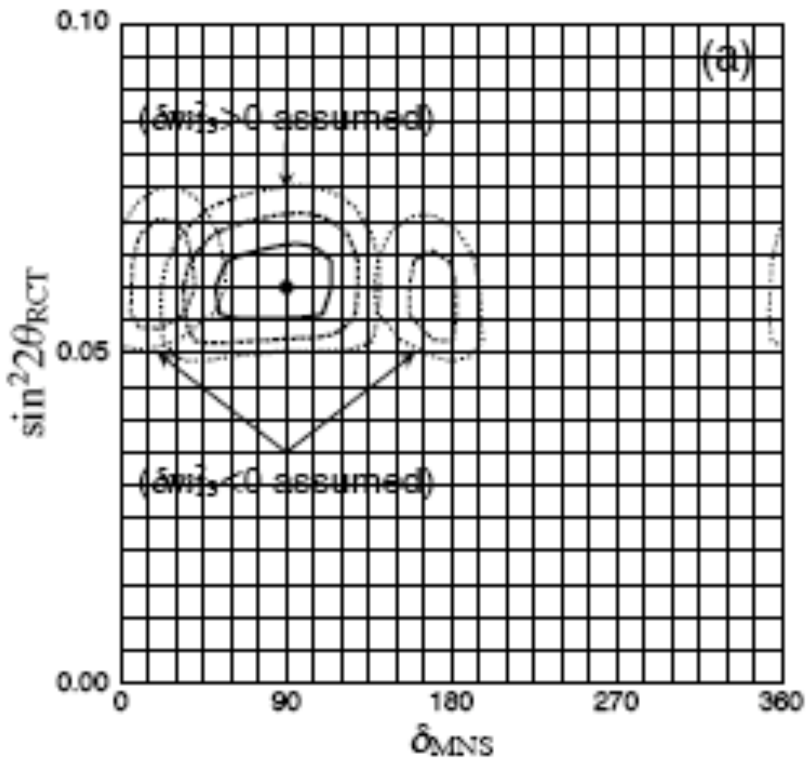
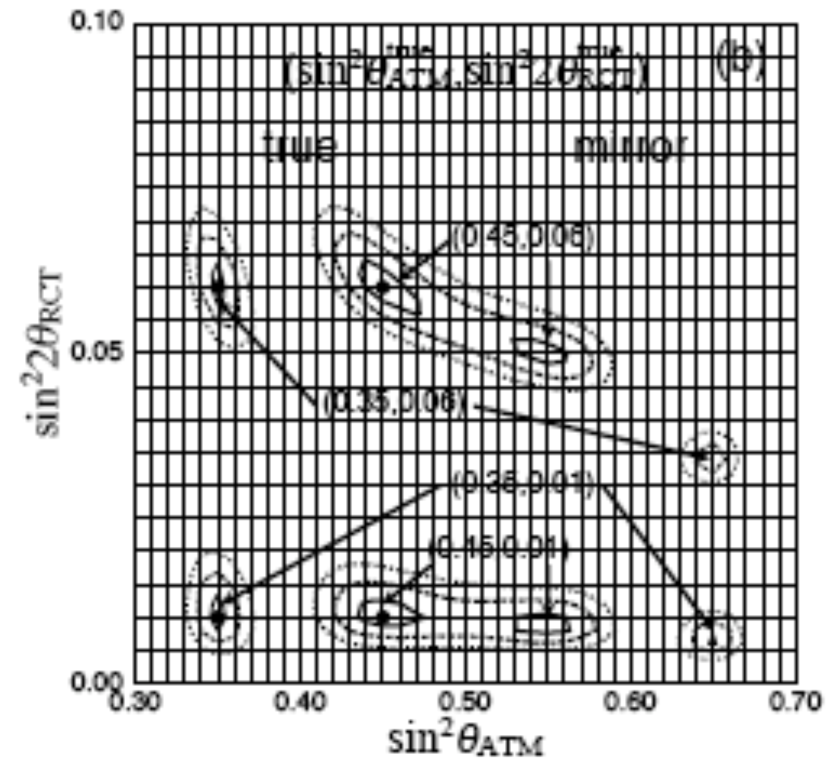
The same at T2-HK

The sign degeneracy



The octant degeneracy



K. Hagiwara, hep-ph/0410229

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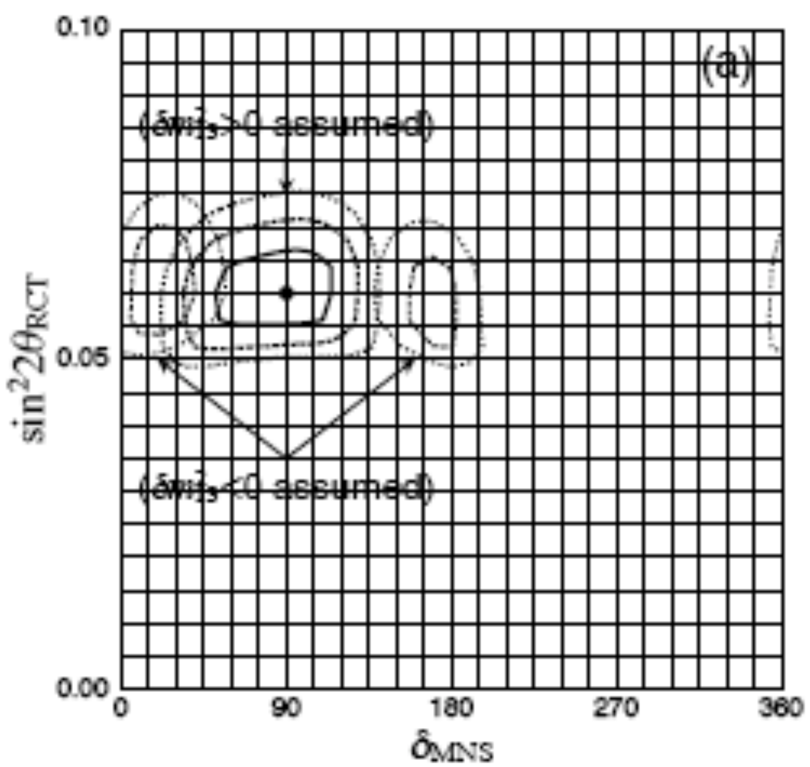

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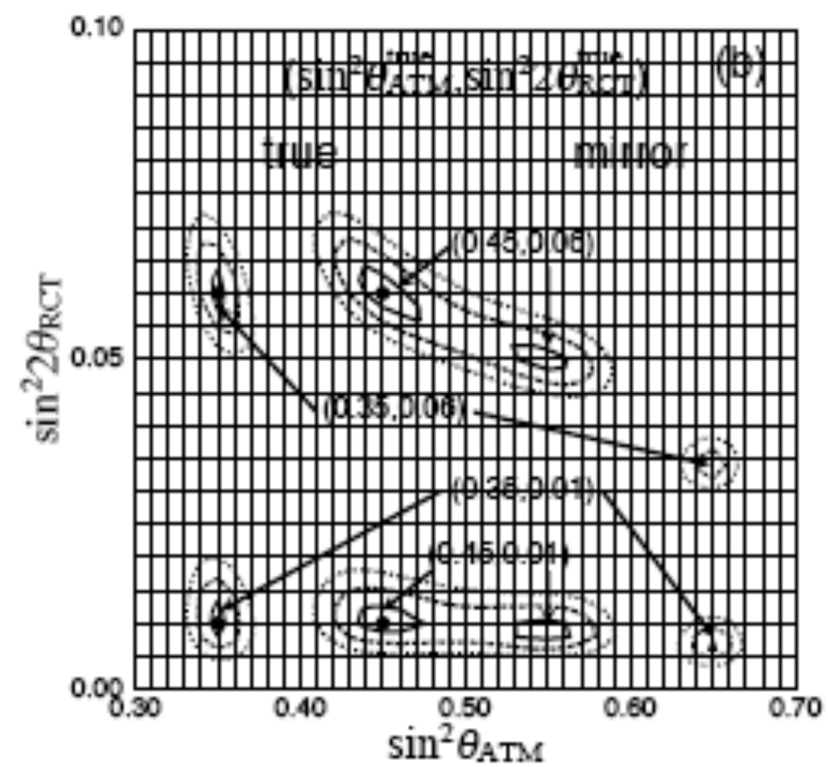

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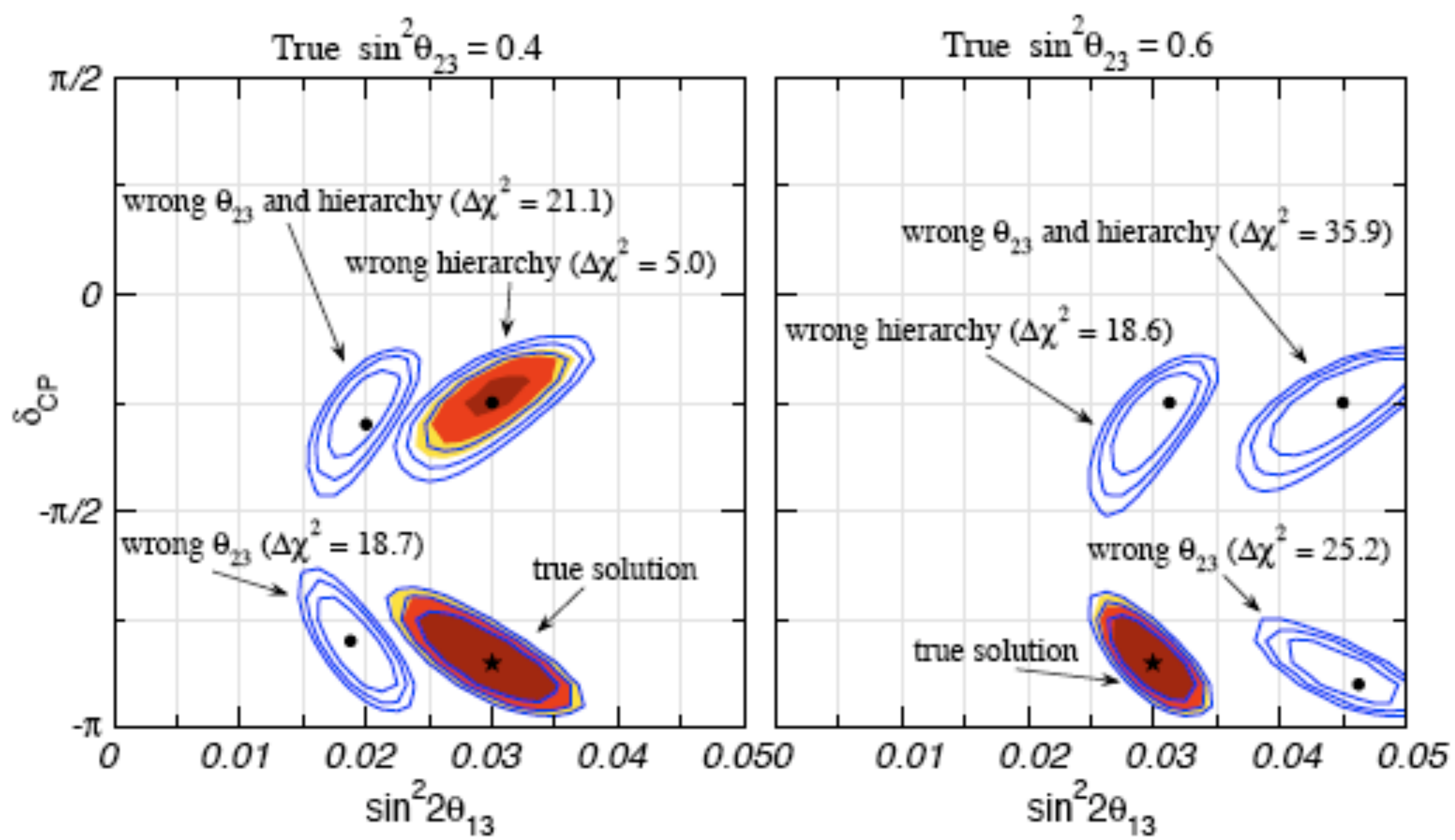
The problem: the sign of Δm^2_{23} is not measured

Solving parameter degeneracies with atmospheric data

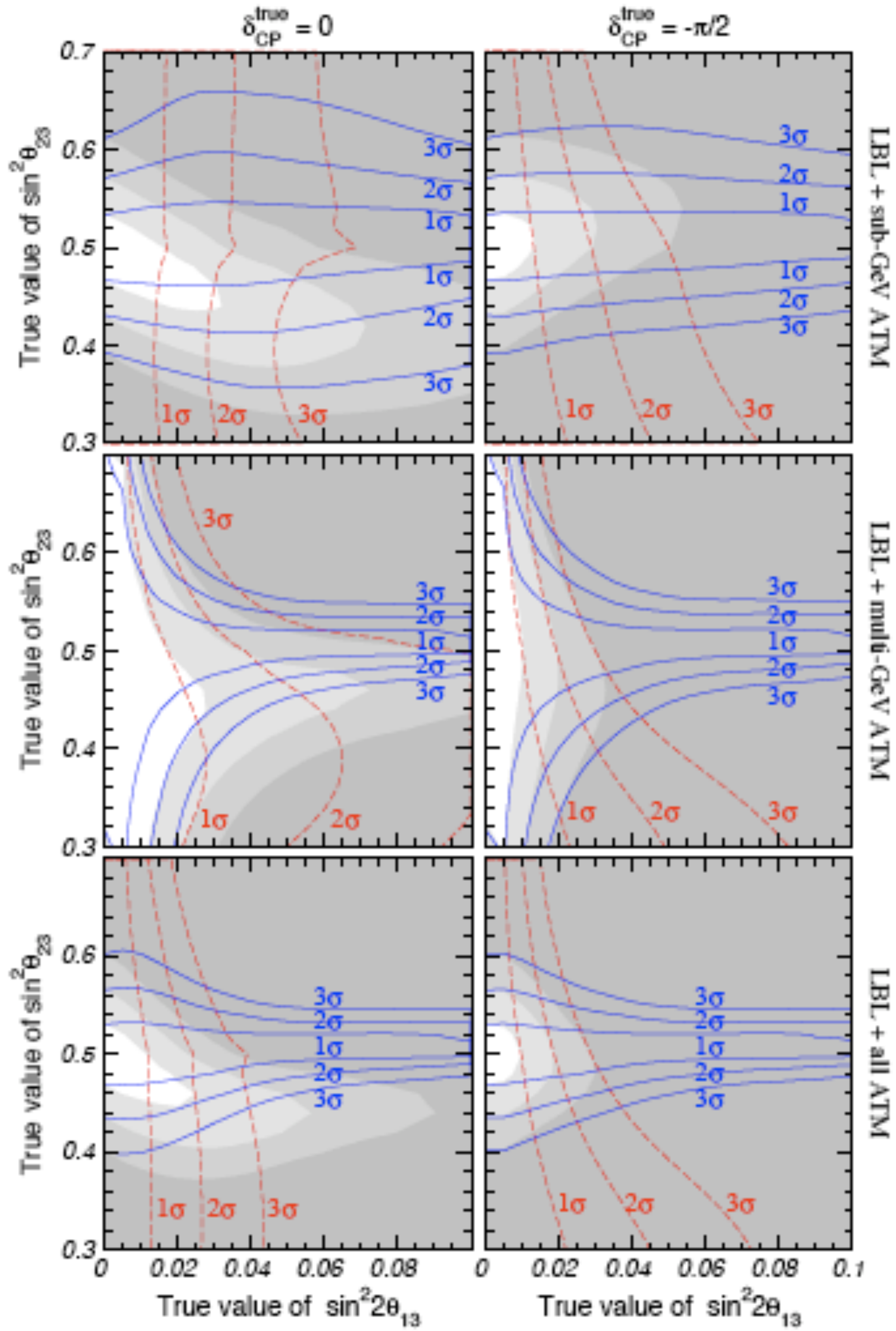
- The HK detector of T2K-II will also record ATM events. We assume 9 yr of data. When these events are combined with the LBL ones:
  - the **octant degeneracy** is completely solved regardless of the **true octant**;
  - the **hierarchy degeneracy** is solved if **true octant** is the dark one.
- **solid**: LBL only;
- **colored**: LBL + ATM;
- regions at 2σ, 99%, 3σ CL (2 dof);
- true values:
  $\delta_{CP} = -0.85\pi$,
  $\sin^2\theta_{13} = 0.03$,
  $\Delta m^2_{31} = 2.2 \times 10^{-3}\ \mathrm{eV}^2$,
  $\Delta m^2_{21} = 7.9 \times 10^{-5}\ \mathrm{eV}^2$.



[Huber, MM, Schwetz, PRD 71 (2005) 053006, hep-ph/0501037]

Resolving parameter degeneracies

- sensitivity to the **octant** (blue lines):
  - given by **sub-GeV** events for $\theta_{13} \approx 0$;
  - given by **multi-GeV** events for $\theta_{13} \gtrsim 0.04$;
  - only mildly dependent on δ_{CP};
- sensitivity to the **hierarchy** (red lines):
  - dominated by **multi-GeV** for $\theta_{23} > 45°$;
  - **sub-GeV** events relevant if $\theta_{23} < 45°$;
  - strongly depends on δ_{CP} in the latter case;
- sensitivity to **octant+hierarchy** (gray regions):
  - mostly given by "sum" of blue and red lines;
  - δ_{CP} interference terms may be relevant.



NEUTRINO FACTORY

The Neutrino Factory

Geer '97
De Rujula, Gavela
and Hernandez '98

The Neutrino Factory

$$\pi^+ \to \mu^+ \nu_\mu$$

Geer '97
De Rujula, Gavela
and Hernandez '98

The Neutrino Factory

$\pi^+ \to \mu^+ \nu_\mu$ ⟶ $\nu_\mu \to \nu_e$ A SuperBeam

Geer '97
De Rujula, Gavela
and Hernandez '98

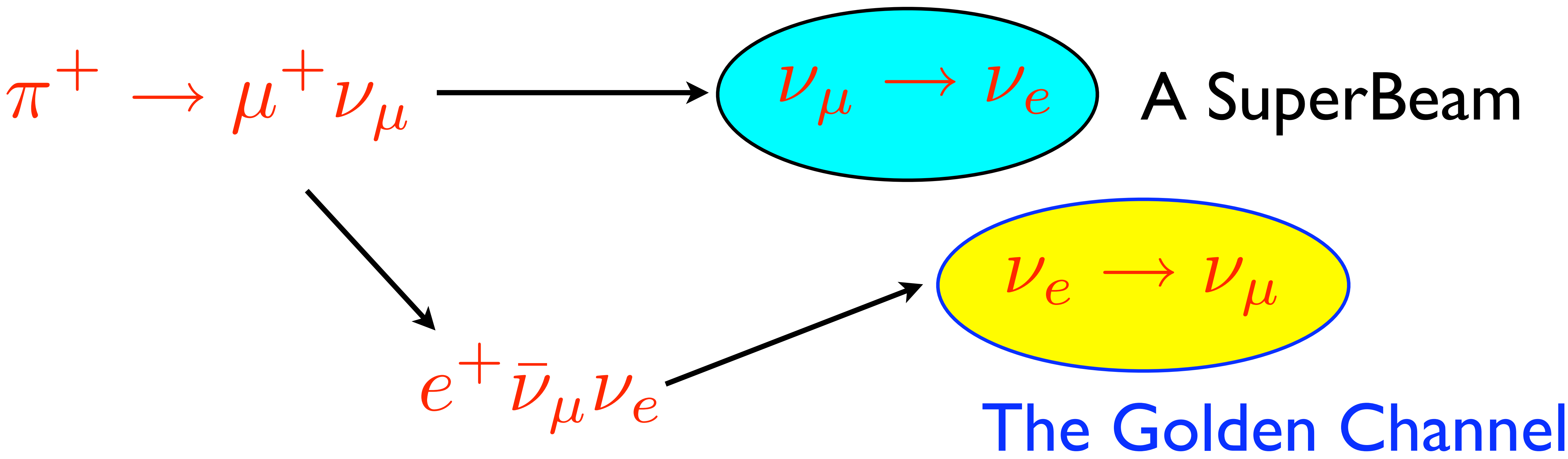
The Neutrino Factory

$\pi^+ \to \mu^+ \nu_\mu$ ⟶ $\nu_\mu \to \nu_e$ A SuperBeam

$e^+ \bar{\nu}_\mu \nu_e$

Geer '97
De Rujula, Gavela
and Hernandez '98

The Neutrino Factory



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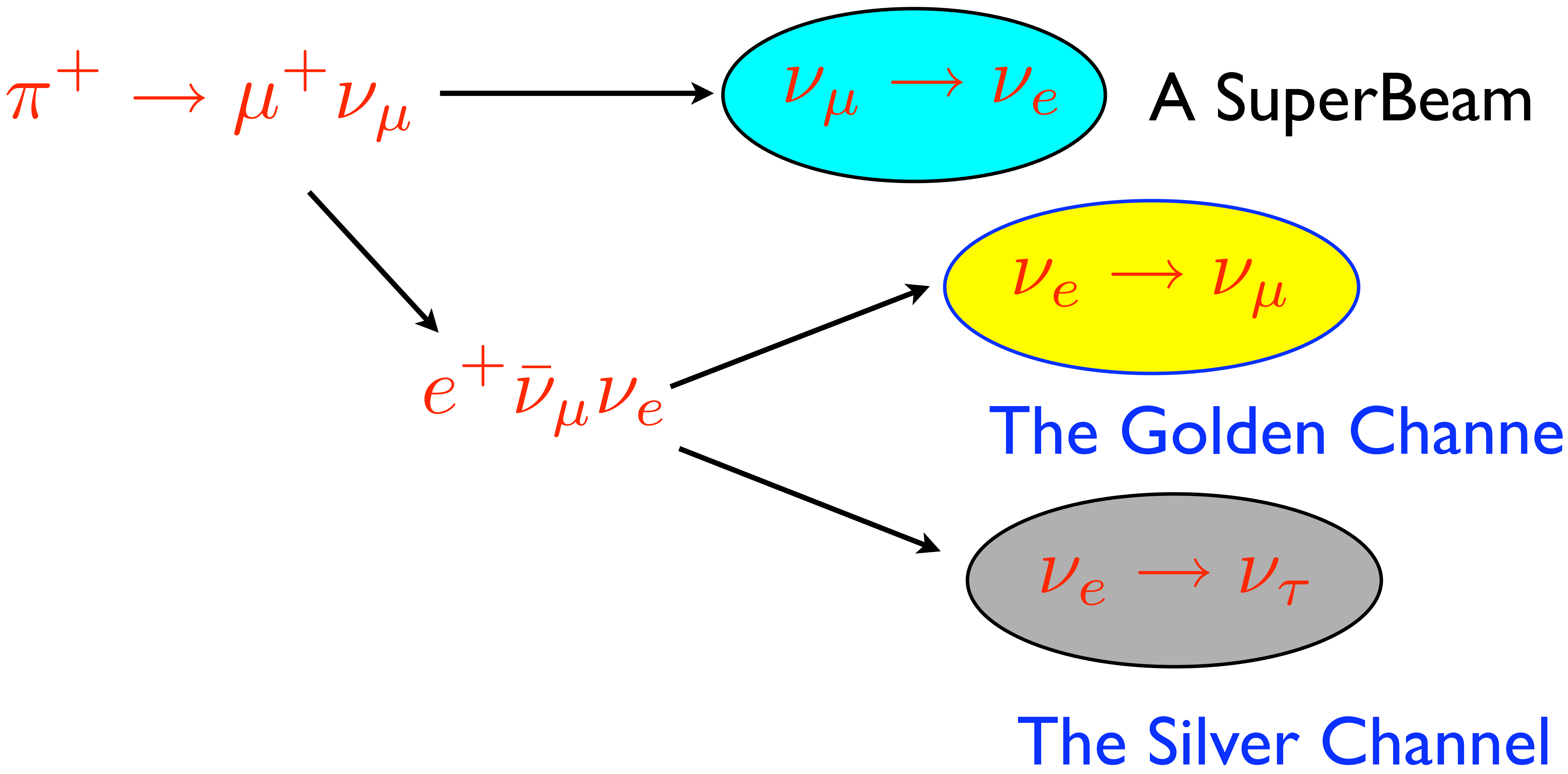

Geer '97
De Rujula, Gavela and Hernandez '98

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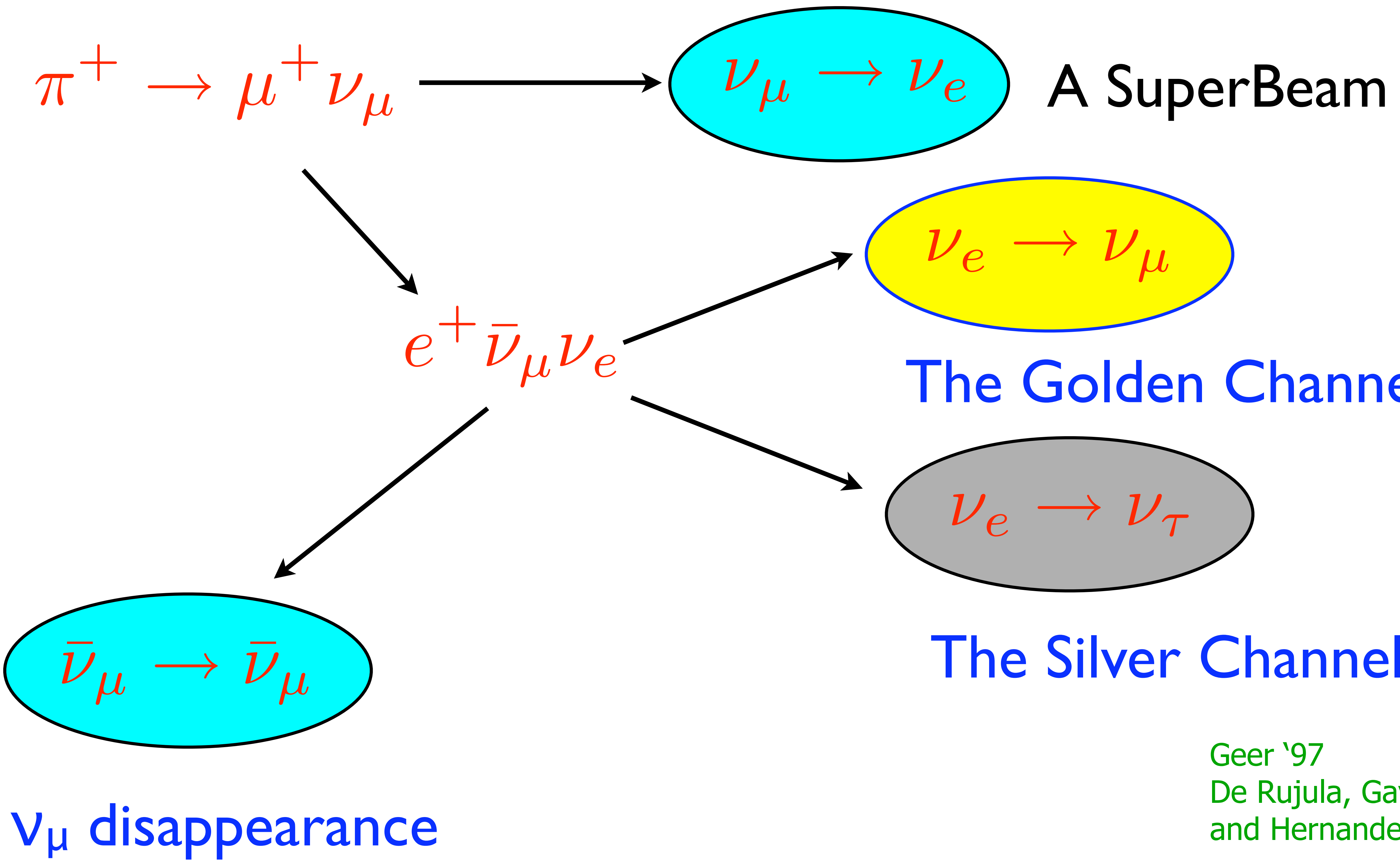

Geer '97
De Rujula, Gavela
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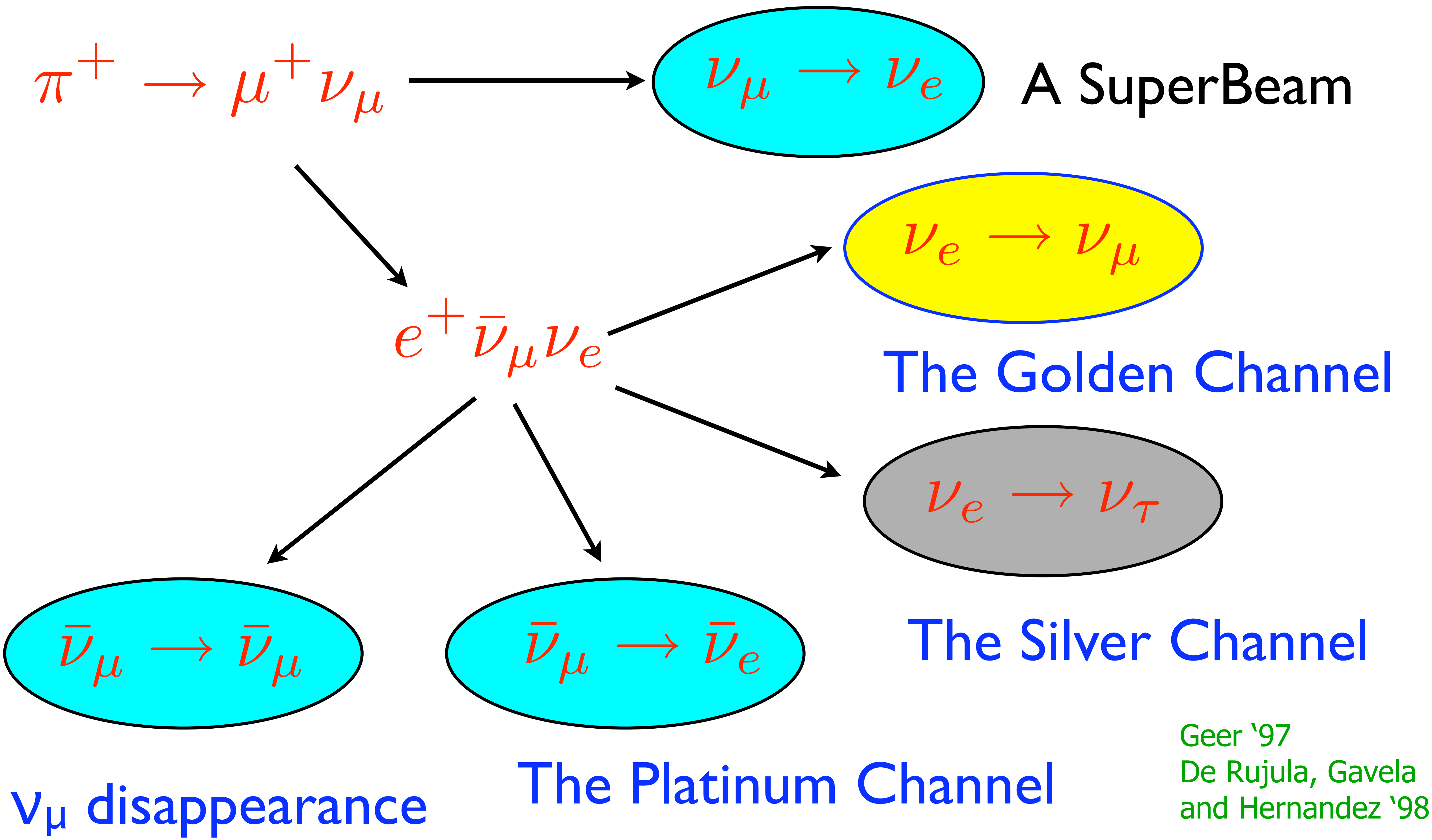
The Neutrino Factory



The Neutrino Factory

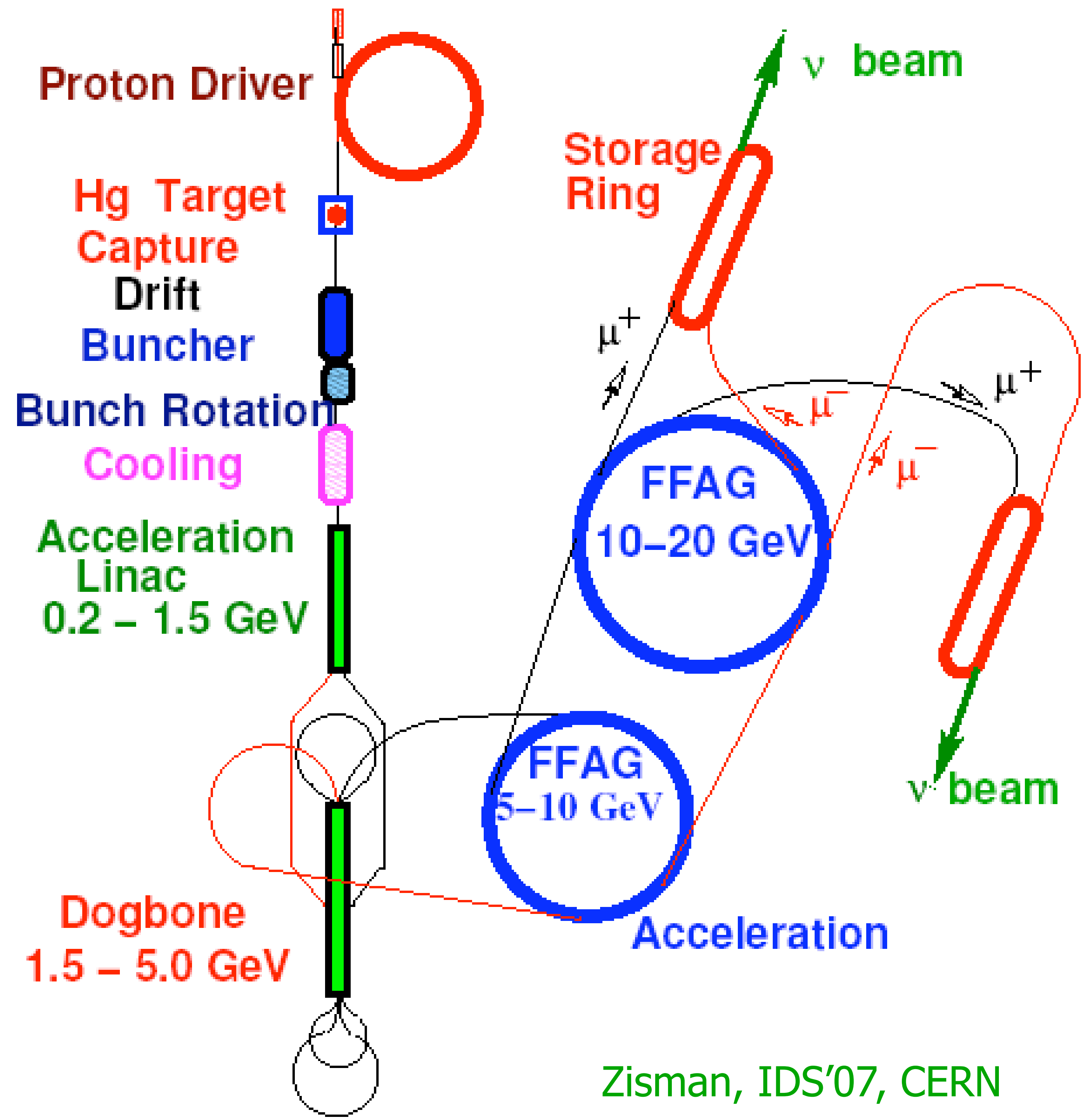
Proton Driver
 primary beam on production target

Target, Capture, Decay
Bunching
Phase Rotation reduce E of bunch

Cooling
 reduce transverse emittance

Acceleration (LINAC/FFAG)
 130 MeV 20–40 GeV

Decay Ring
 store for ~500 turns; long straight section



Zisman, IDS'07, CERN

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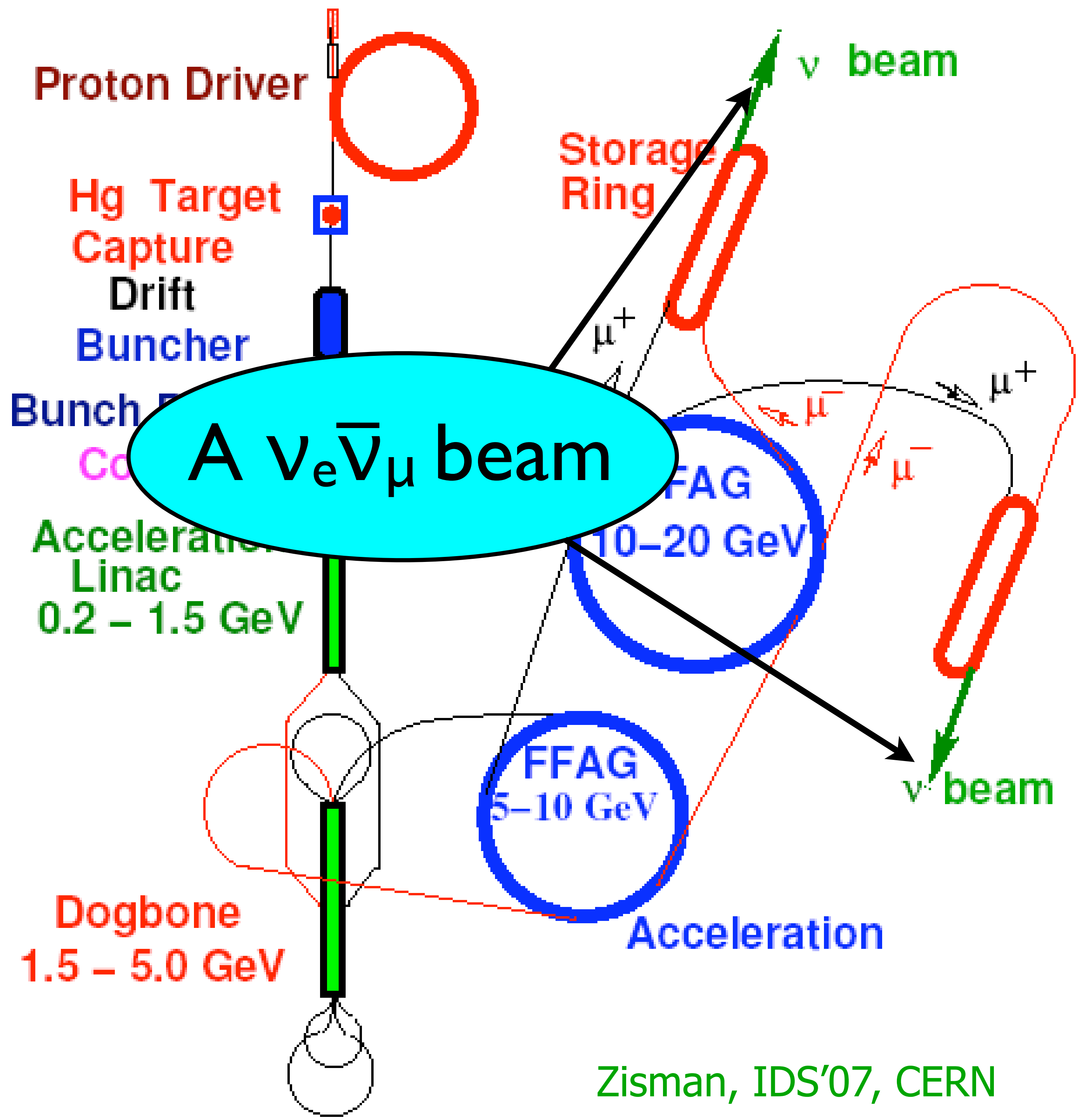

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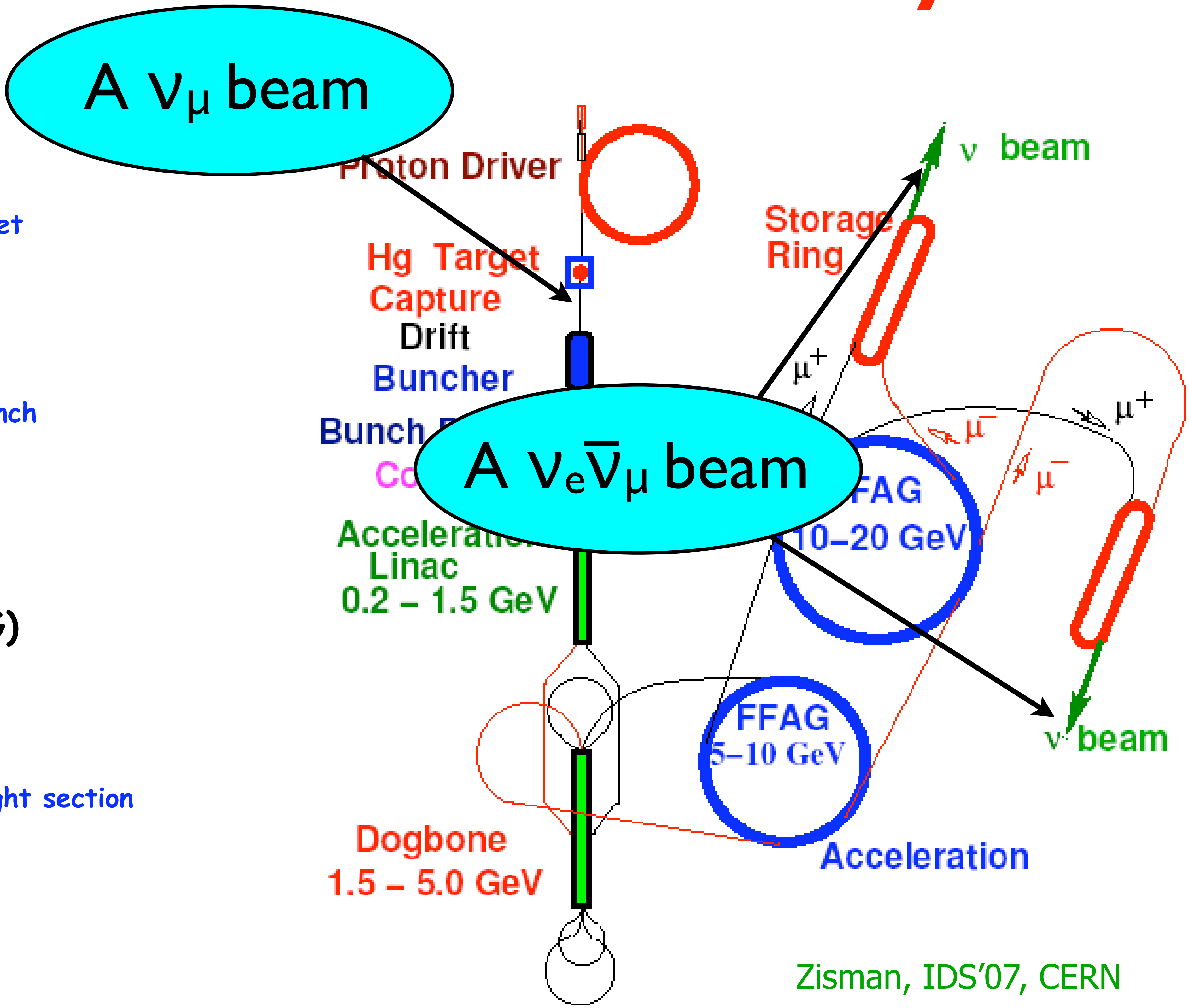


Zisman, IDS'07, CERN

The Golden Channel

A. Cervera et al, hep-ph/0002108

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

The Golden Channel

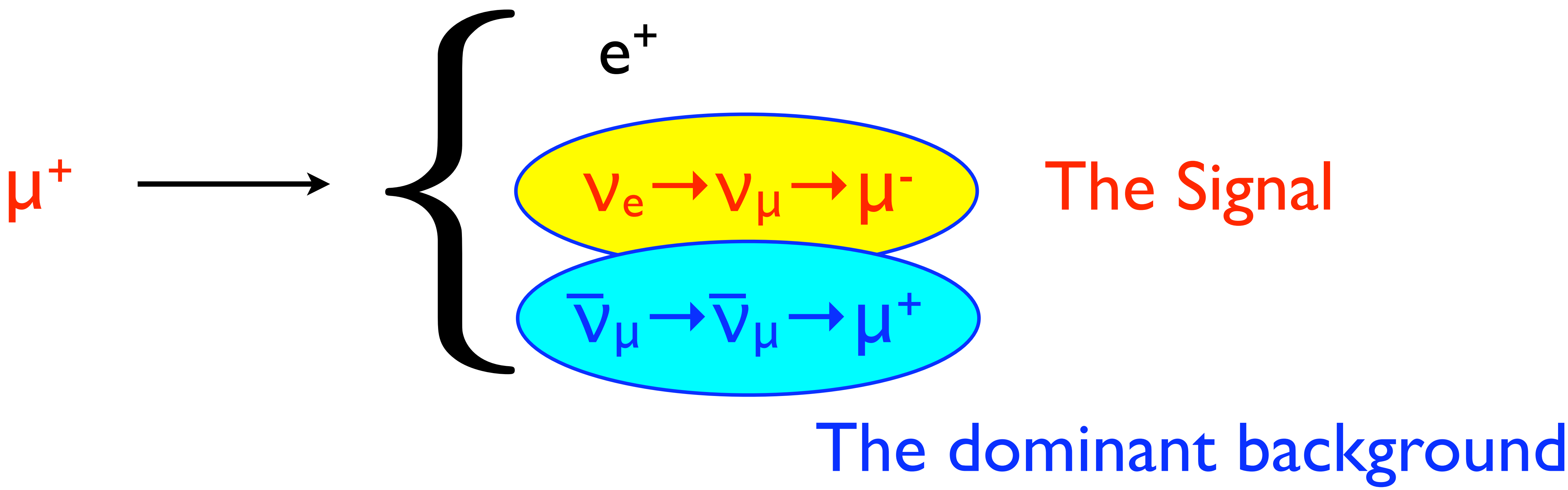
A. Cervera et al, hep-ph/0002108

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

The Signal: $\nu_e \to \nu_\mu \to \mu^-$

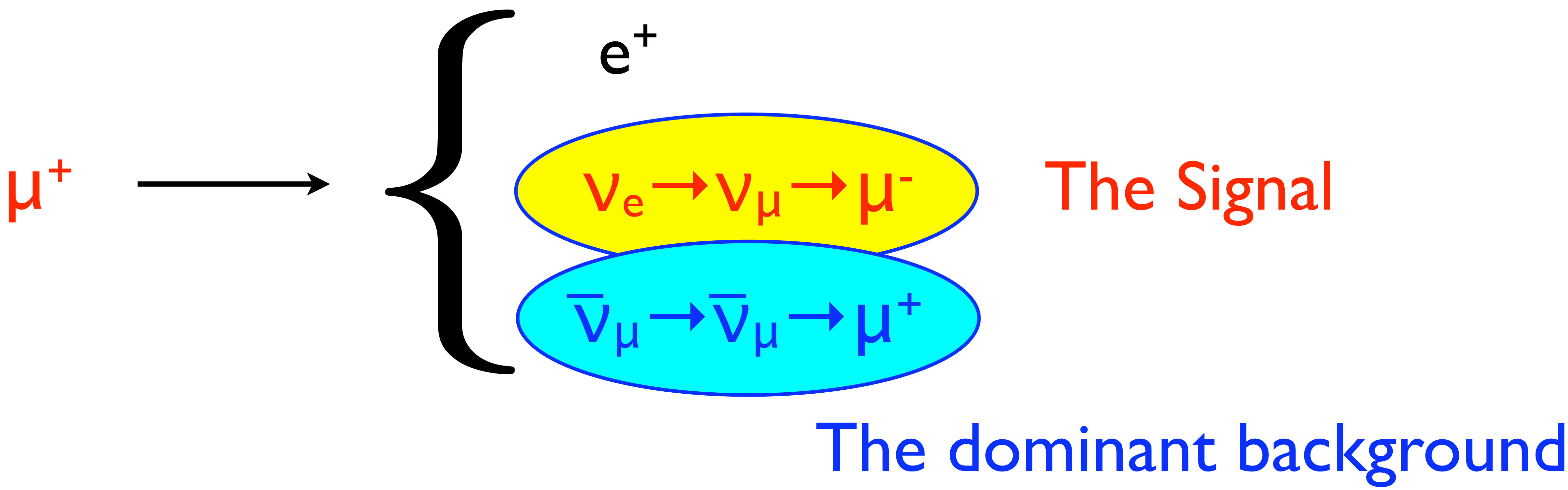
The Golden Channel

A. Cervera et al, hep-ph/0002108



The Golden Channel

A. Cervera et al, hep-ph/0002108



To look for the signal, at the Neutrino Factory we need μ charge identification

The Golden Channel

A. Cervera et al, hep-ph/0002108

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

The Signal: $\nu_e \to \nu_\mu \to \mu^-$

The dominant background: $\bar{\nu}_\mu \to \bar{\nu}_\mu \to \mu^+$

To look for the signal, at the Neutrino Factory we need μ charge identification

Magnetized detector

The Golden Channel

A. Cervera et al, hep-ph/0002108

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

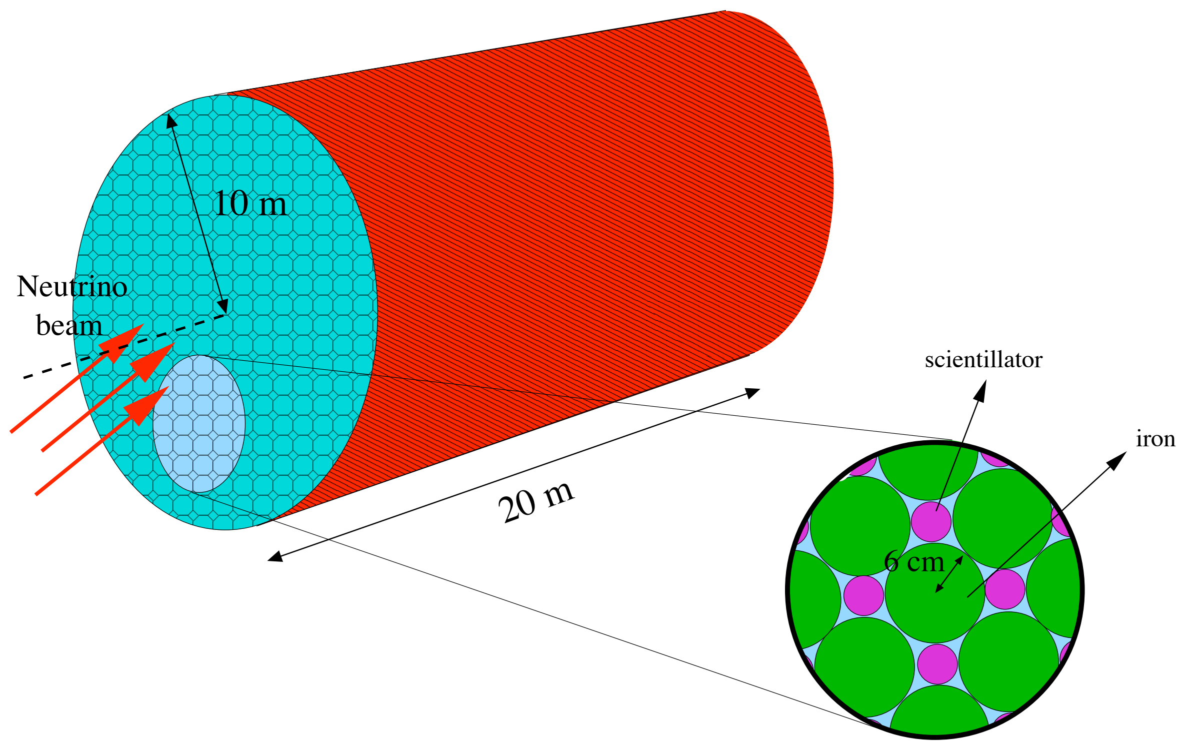
The Signal: $\nu_e \rightarrow \nu_\mu \rightarrow \mu^-$

The dominant background: $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$

To look for the signal, at the Neutrino Factory we need μ charge identification

→ Magnetized detector → MIND

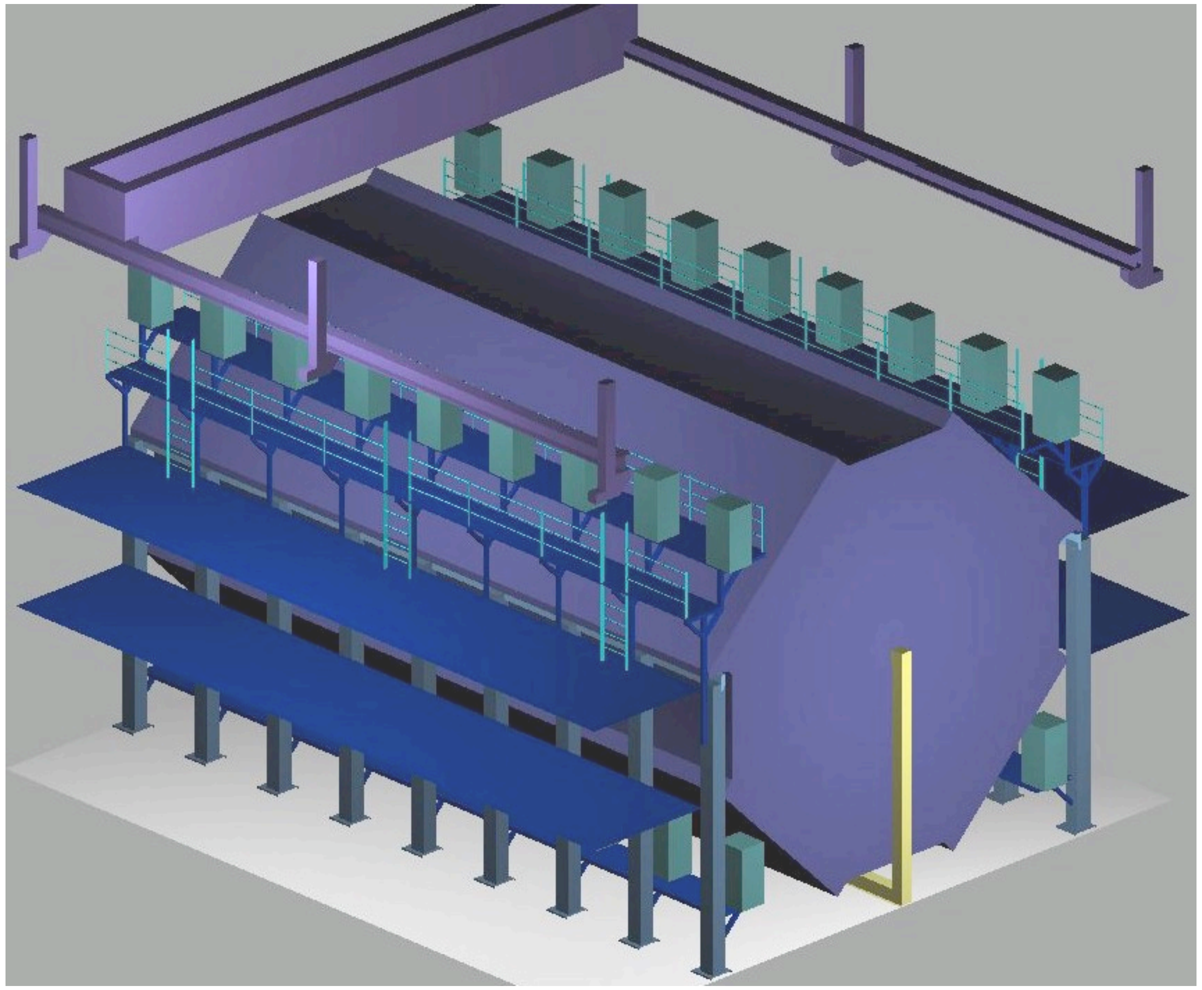
Magnetized Iron Detector



40-50 Kton Mass

Good Muon Charge Identification

Magnetized Iron Detector



40-50 Kton Mass

Good Muon Charge Identification

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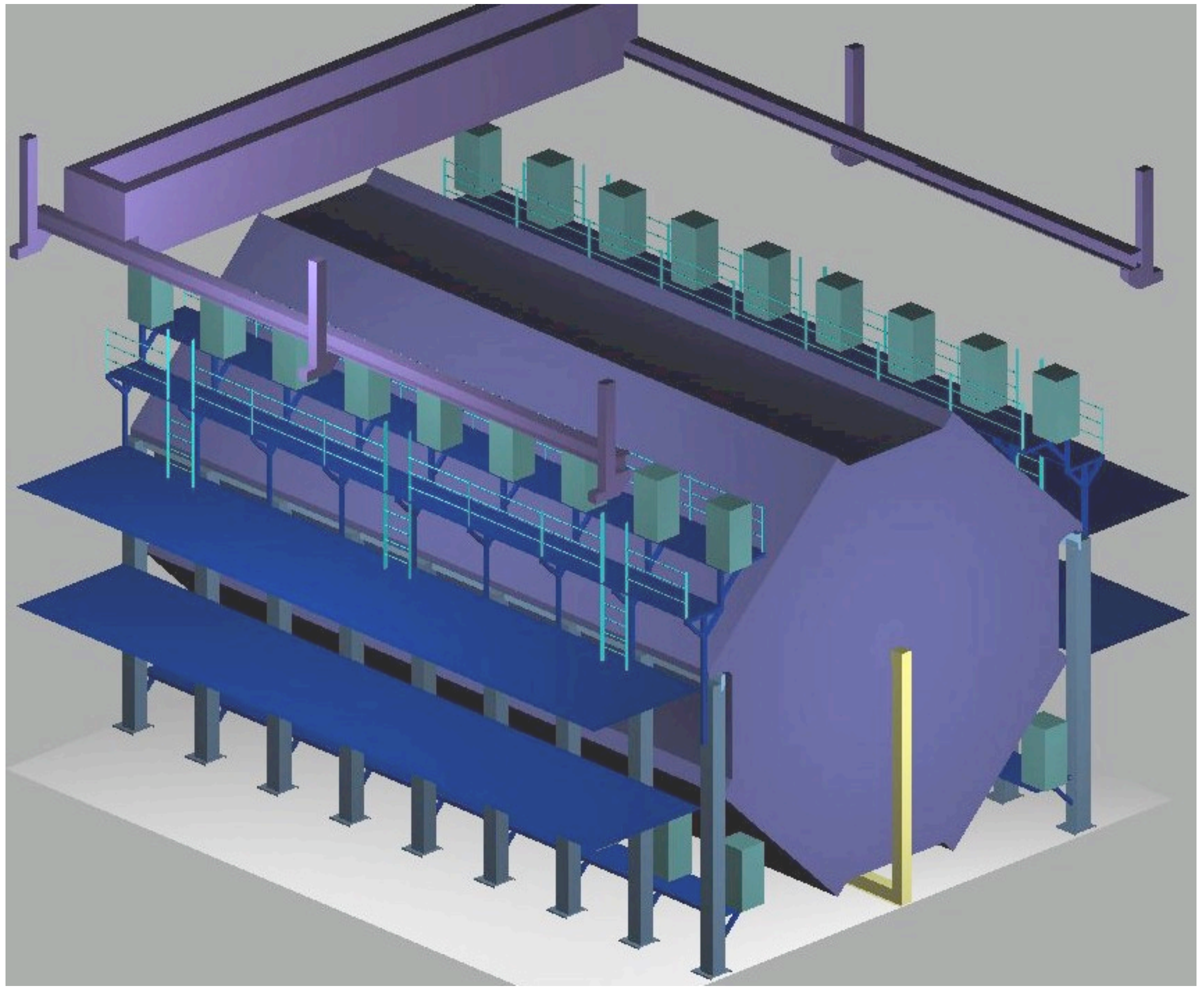
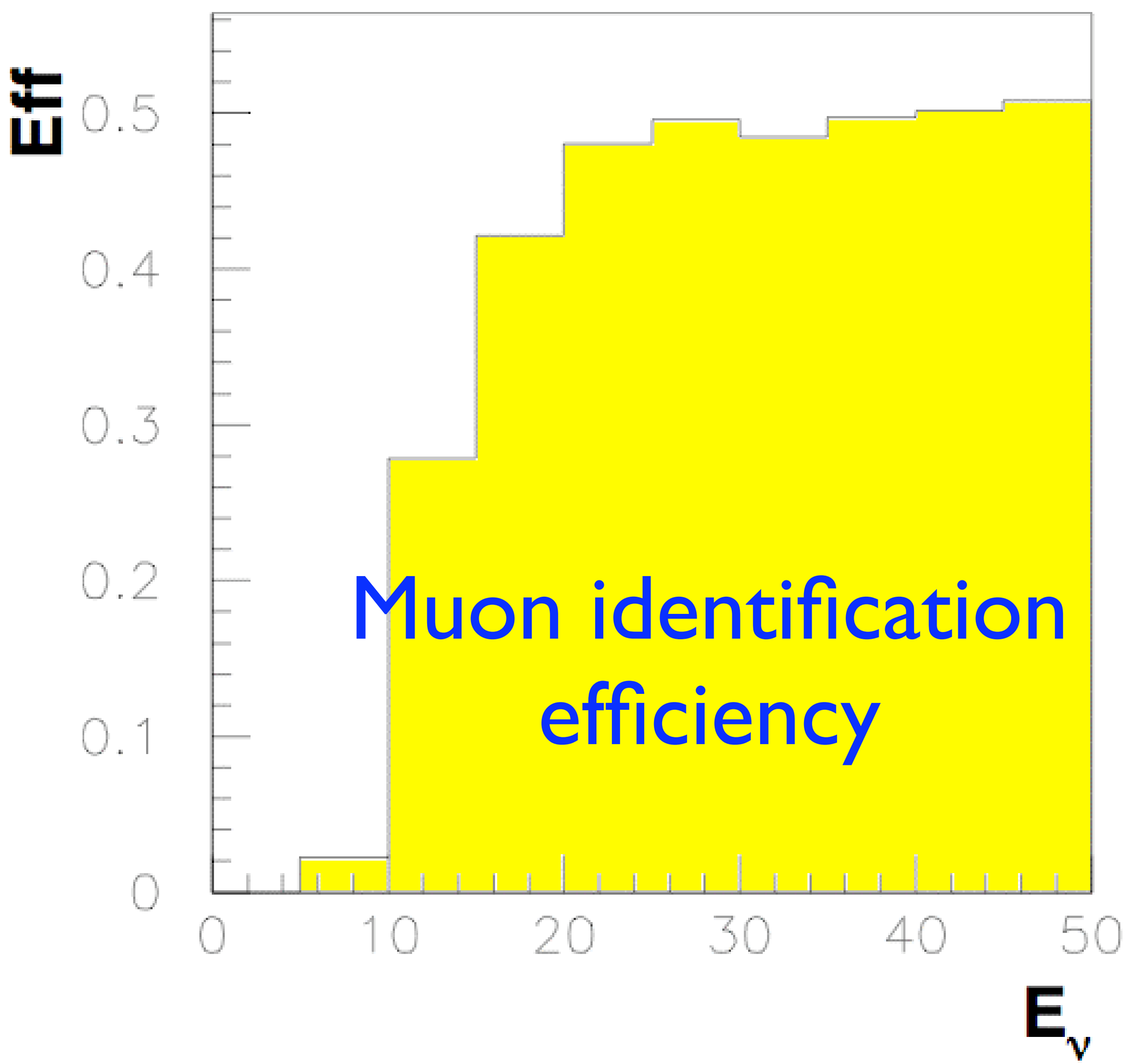
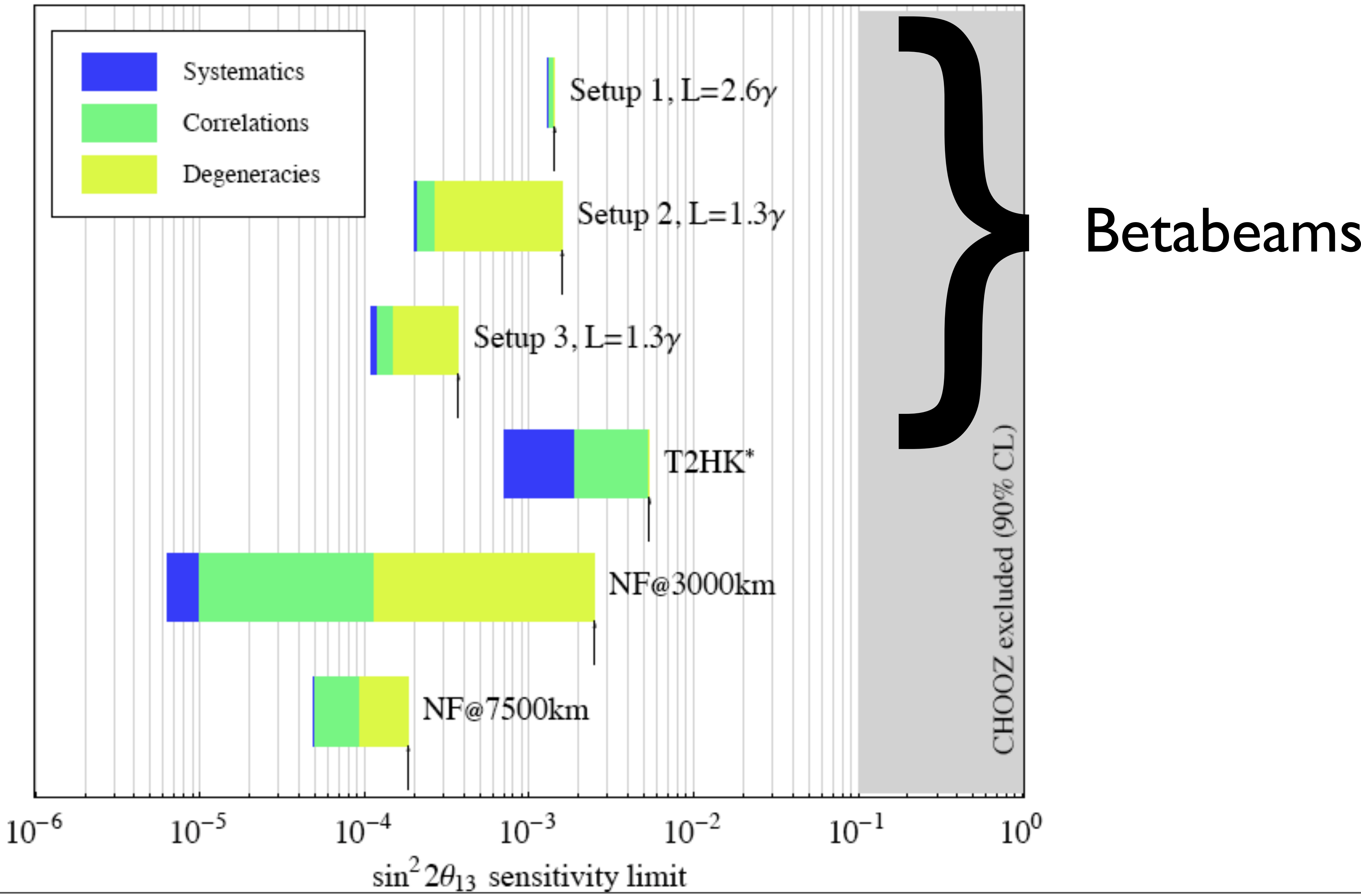


Good Muon Charge Identification

40-50 Kton Mass



Solving degeneracies



Solving degeneracies

- Combining channels: Silver and Platinum
- Combining baselines: the Magic baseline
- Combining energies: improving the detector

The Silver Channel

$$P_{e\tau}^{\pm} = X_\tau^{\pm} \sin^2 2\theta_{13} - \left(Y_c^{\pm} cos\delta \mp Y_s^{\pm} sin\delta\right) \sin 2\theta_{13} + Z_\tau$$

$$X_\tau^{\pm} = \frac{c_{23}^2}{s_{23}^2} X_\mu^{\pm} \qquad Z_\tau = \frac{s_{23}^2}{c_{23}^2} Z_\mu$$

Donini, Meloni and Migliozzi '02

The Silver Channel

$$P^{\pm}_{e\tau} = X^{\pm}_{\tau} \sin^2 2\theta_{13} - \left(Y^{\pm}_{c} cos\delta \mp Y^{\pm}_{s} sin\delta\right) \sin 2\theta_{13} + Z_{\tau}$$

$$X^{\pm}_{\tau} = \frac{c^2_{23}}{s^2_{23}} X^{\pm}_{\mu} \qquad Z_{\tau} = \frac{s^2_{23}}{c^2_{23}} Z_{\mu}$$

Donini, Meloni and Migliozzi '02

Same sensitivities as the Golden Channel

The Silver Channel

$$P_{e\tau}^{\pm} = X_{\tau}^{\pm} \sin^2 2\theta_{13} - (Y_c^{\pm} cos\delta \mp Y_s^{\pm} sin\delta) \sin 2\theta_{13} + Z_{\tau}$$

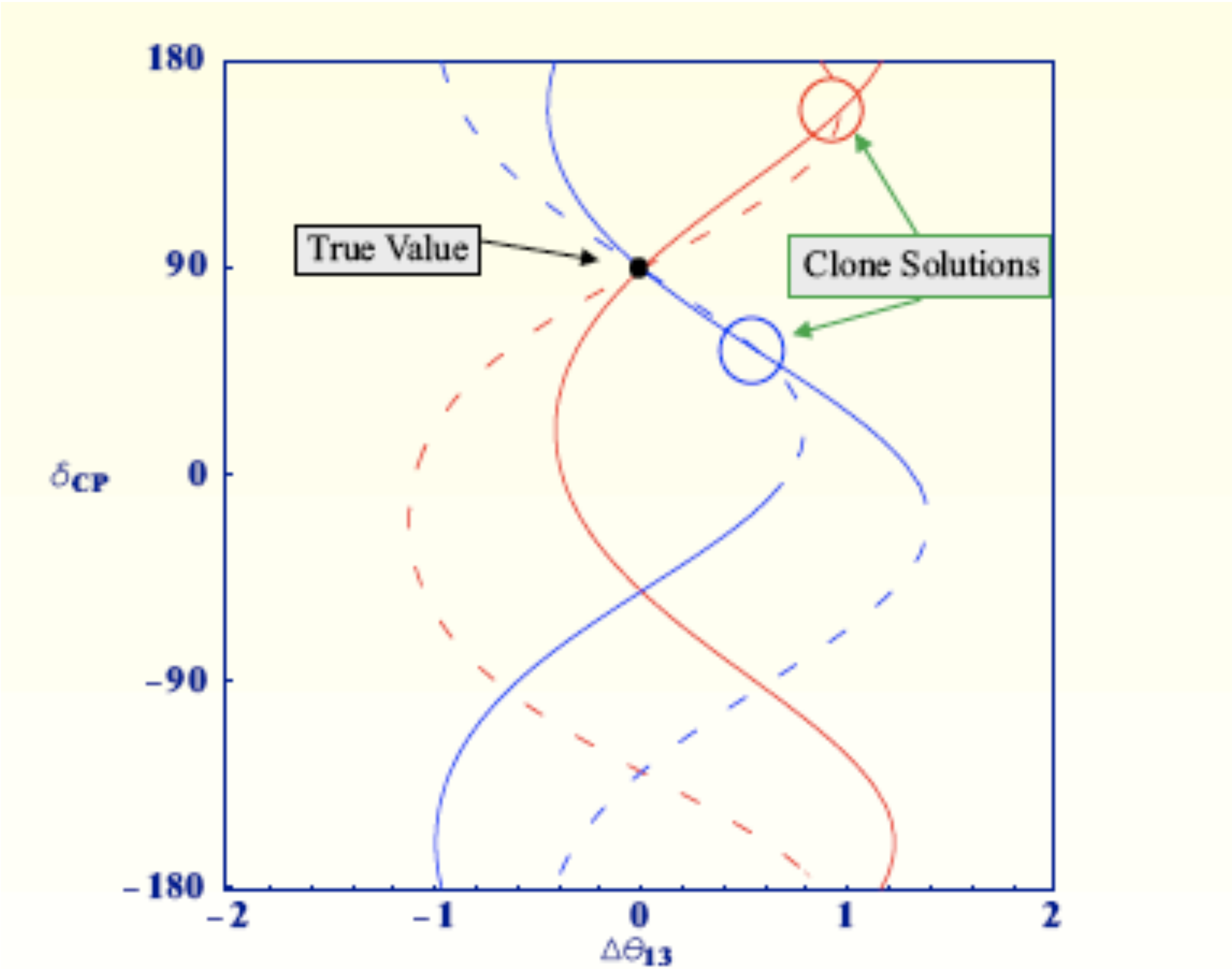
$$X_{\tau}^{\pm} = \frac{c_{23}^2}{s_{23}^2} X_{\mu}^{\pm} \qquad Z_{\tau} = \frac{s_{23}^2}{c_{23}^2} Z_{\mu}$$

Donini, Meloni and Migliozzi '02

Different θ_{13}-δ correlation

Same sensitivities as the Golden Channel

How the silver channel solve the intrinsic degeneracy



The Silver Channel

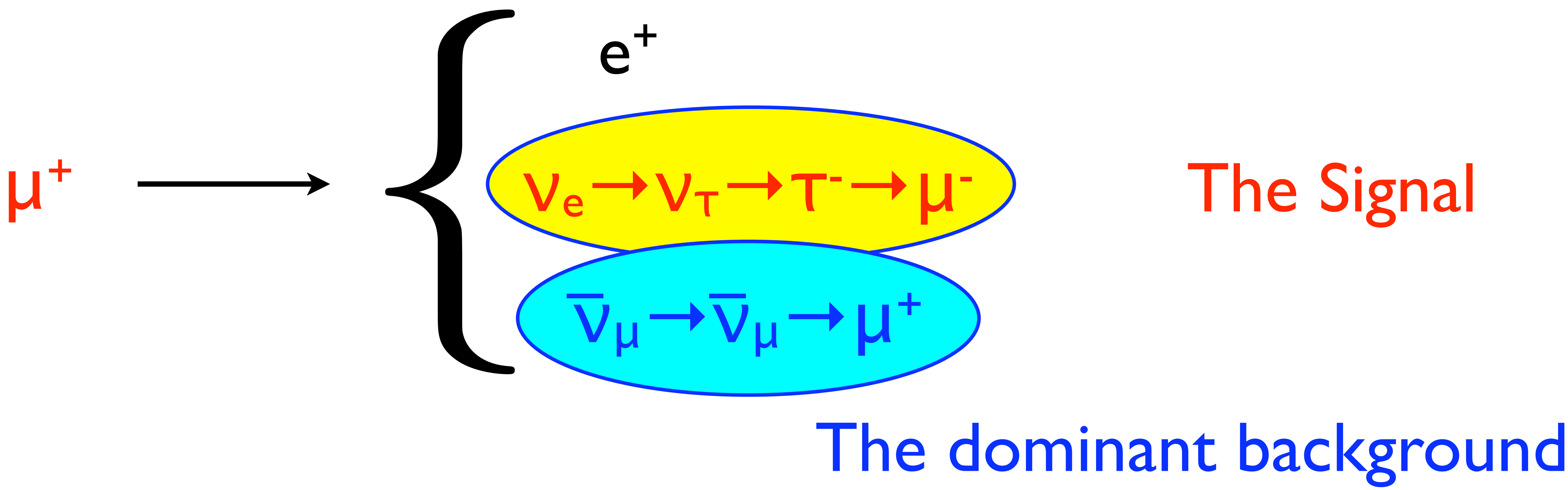
$$\mu^+ \longrightarrow \begin{cases} e^+ \\ \nu_e \rightarrow \nu_\tau \rightarrow \tau^- \rightarrow \mu^- \\ \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \rightarrow \mu^+ \end{cases}$$

The Silver Channel

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

The Signal

The Silver Channel



The Silver Channel

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

The Signal ($\nu_e \to \nu_\tau \to \tau^- \to \mu^-$)

The dominant background ($\bar{\nu}_\mu \to \bar{\nu}_\mu \to \mu^+$)

To look for the signal, we need μ charge identification and τ decay vertex identification

The Silver Channel

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

The Signal: $\nu_e \rightarrow \nu_\tau \rightarrow \tau^- \rightarrow \mu^-$

The dominant background: $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$

To look for the signal, we need μ charge identification and τ decay vertex identification

→ Emulsions + Spectrometers

The Silver Channel

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

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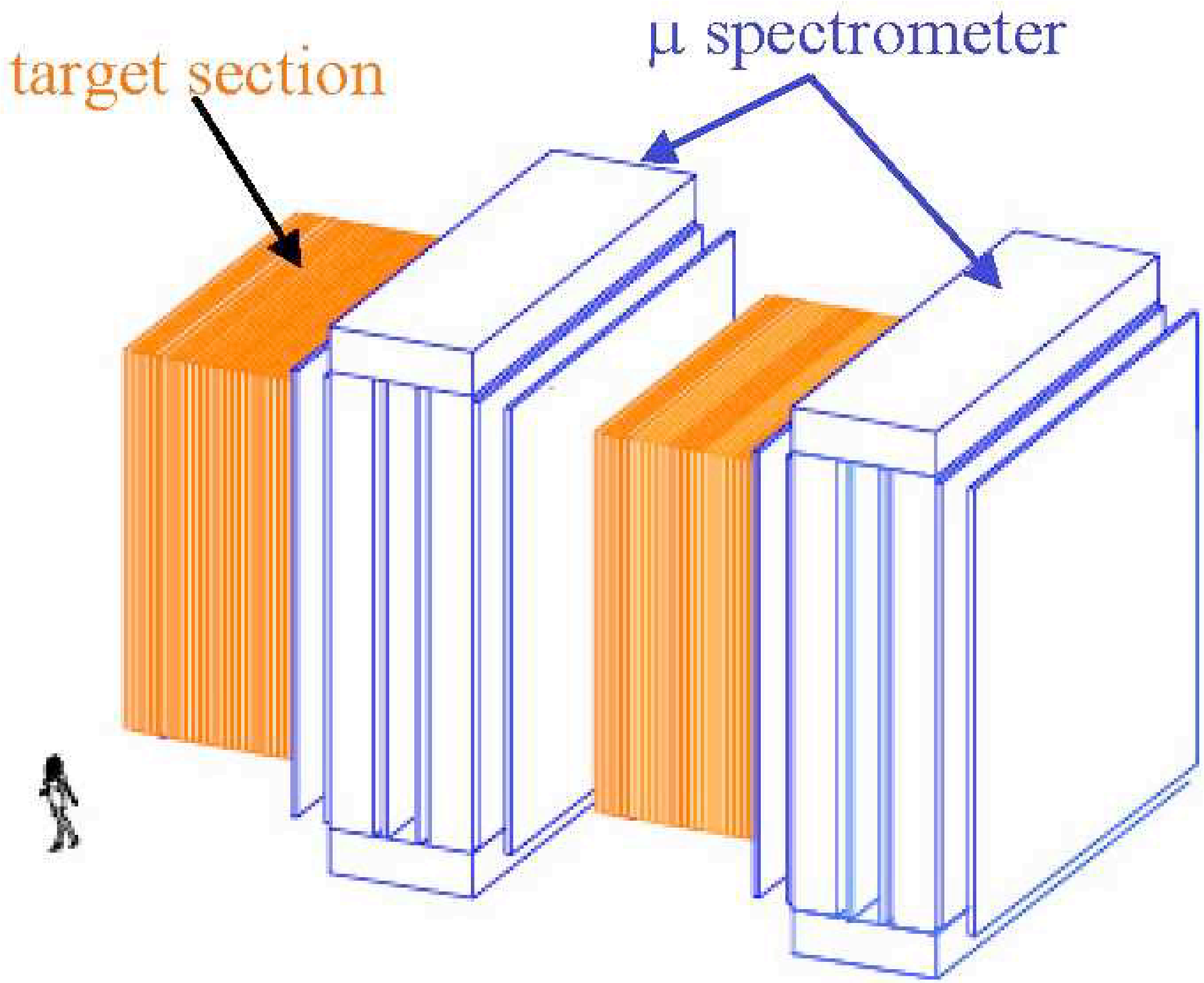
To look for the signal, we need μ charge identification and τ decay vertex identification

→ Emulsions + Spectrometers → "OPERA"

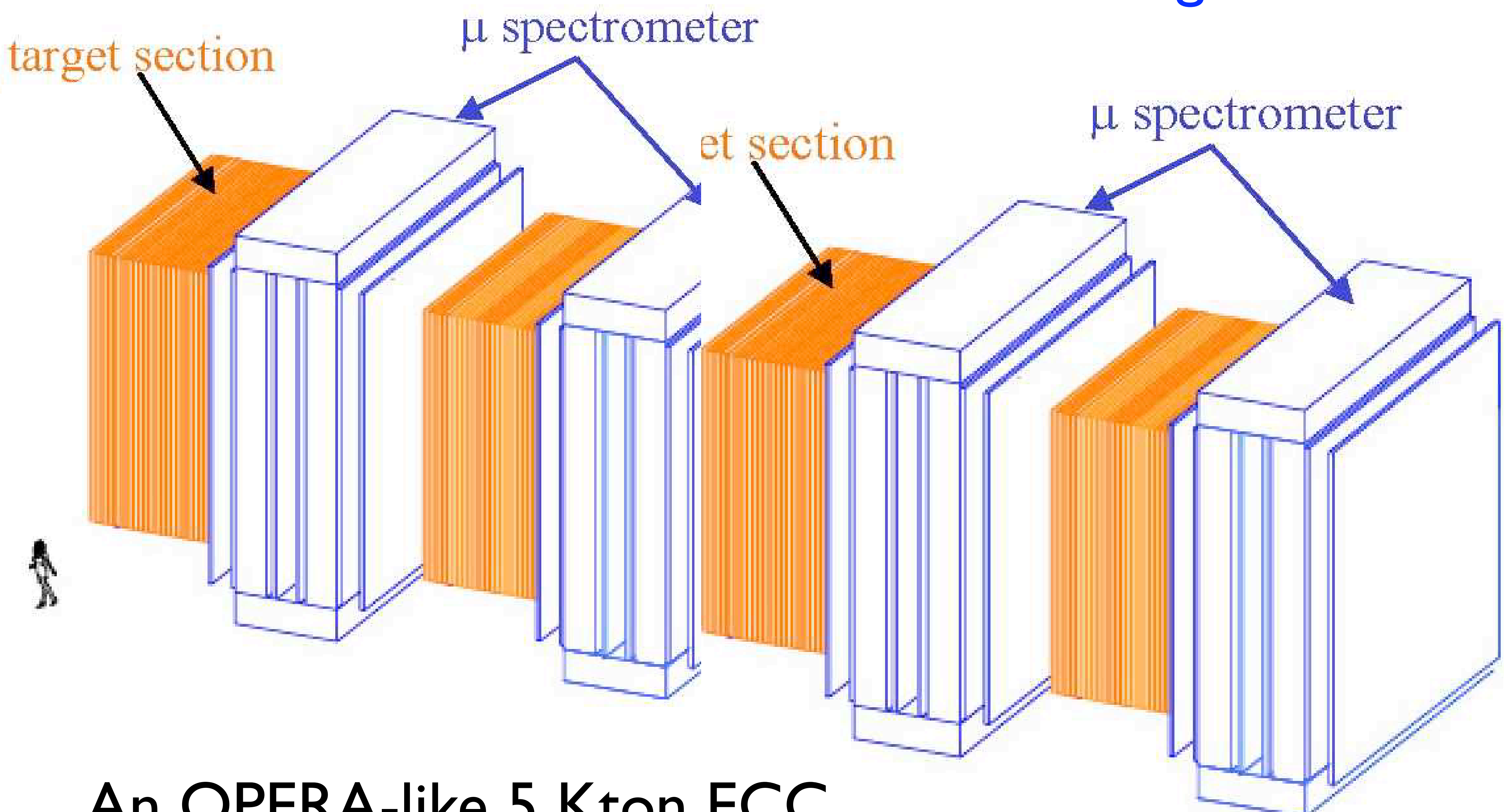
Emulsion Cloud Chamber

Evolution: Magnetized ECC



Emulsion Cloud Chamber

Evolution: Magnetized ECC



An OPERA-like 5 Kton ECC

The Platinum Channel

$$P_{\mu e}^{\pm} = X_{\mu}^{\mp} \sin^2 2\theta_{13} + \left(Y_c^{\mp} cos\delta \pm Y_s^{\mp} sin\delta\right) \sin 2\theta_{13} + Z_{\mu}$$

Bueno, Campanelli and Rubbia ‘00

$X_{\mu}^{\pm} \to X_{\mu}^{\mp}$ $\quad Y_{s,c}^{\pm} \to Y_{s,c}^{\mp}$

Same sensitivities as the Golden Channel

The Platinum Channel

$$P_{\mu e}^{\pm} = X_{\mu}^{\mp} \sin^2 2\theta_{13} + \left(Y_c^{\mp} cos\delta \pm Y_s^{\mp} sin\delta\right) \sin 2\theta_{13} + Z_{\mu}$$

Bueno, Campanelli and Rubbia '00

$X_{\mu}^{\pm} \to X_{\mu}^{\mp}$ $\quad$ $Y_{s,c}^{\pm} \to Y_{s,c}^{\mp}$

Different θ_{13}-δ correlation

Same sensitivities as the Golden Channel

The Platinum Channel

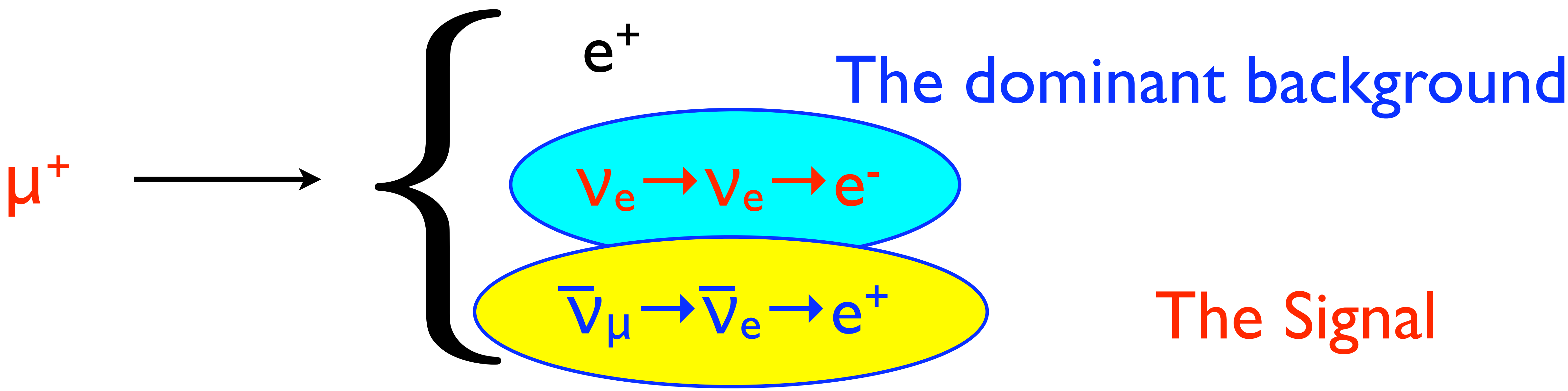
$$\mu^+ \longrightarrow \begin{cases} e^+ \\ \nu_e \rightarrow \nu_e \rightarrow e^- \\ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \rightarrow e^+ \end{cases}$$

The Platinum Channel

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

The Signal: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e \rightarrow e^+$

The Platinum Channel



The Platinum Channel

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

The dominant background: $\nu_e \to \nu_e \to e^-$

The Signal: $\bar{\nu}_\mu \to \bar{\nu}_e \to e^+$

To look for the signal, we need e charge identification

The Platinum Channel

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

$\nu_e \rightarrow \nu_e \rightarrow e^-$ The dominant background

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e \rightarrow e^+$ The Signal

To look for the signal, we need e charge identification

→ Liquid Argon

The Platinum Channel

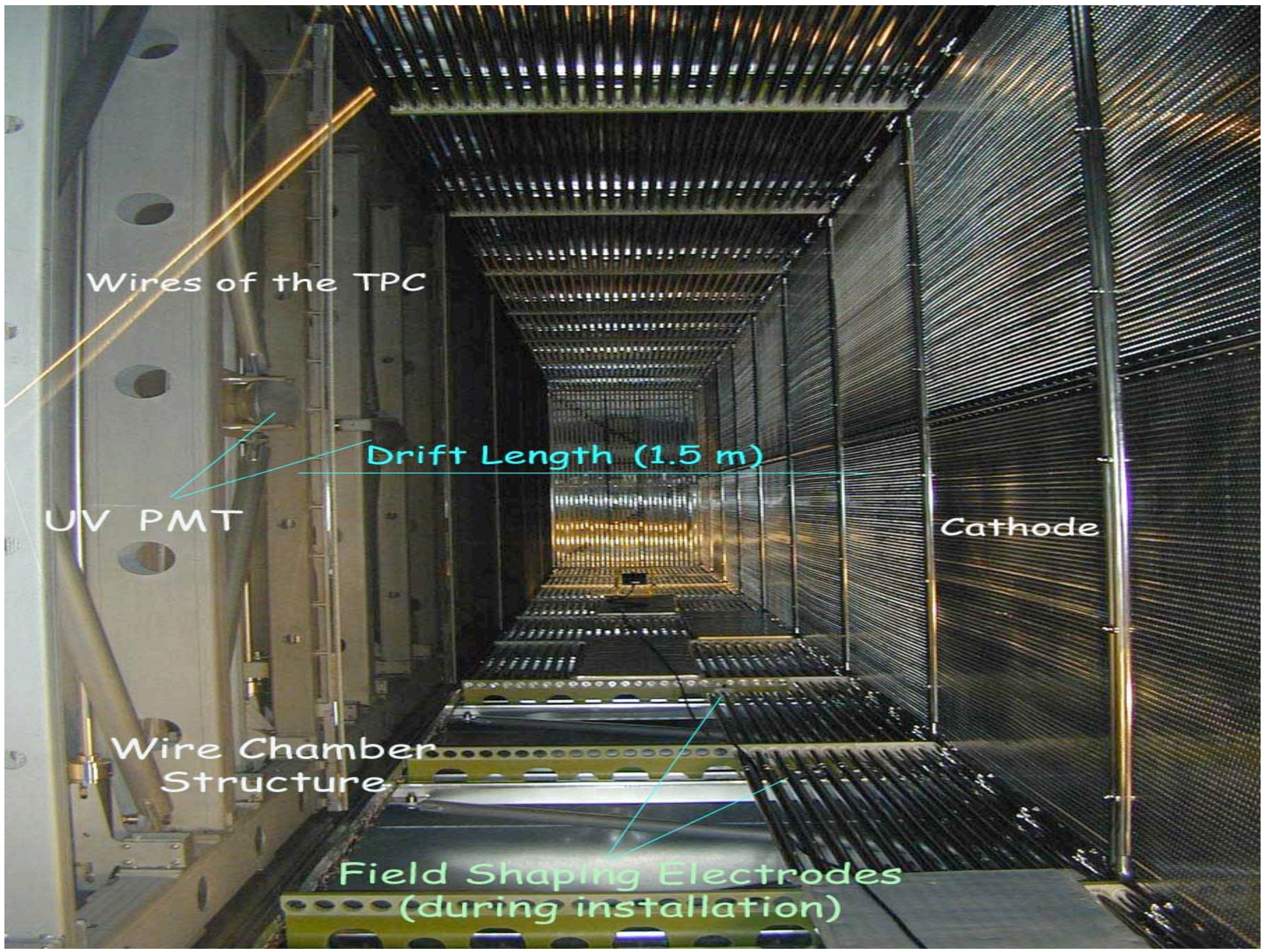
$\mu^+ \longrightarrow \begin{cases} e^+ & \\ \nu_e \rightarrow \nu_e \rightarrow e^- & \text{The dominant background} \\ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \rightarrow e^+ & \text{The Signal} \end{cases}$

To look for the signal, we need e charge identification

→ Liquid Argon → LAr TPC

Liquid Argon TPC

Feasibility proved at T600



158 MeV

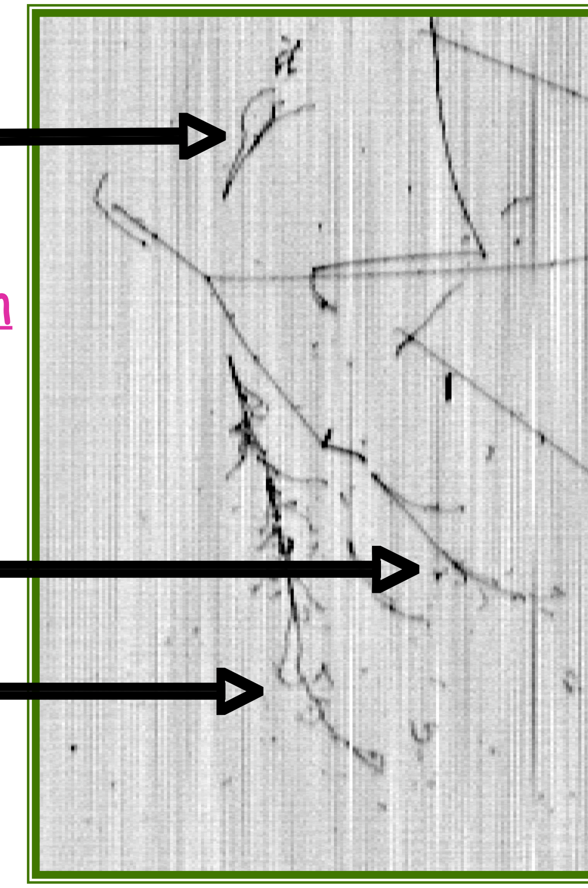
π^0 reconstruction

140 MeV

752 MeV

$\theta = 25^o$

M_{inv} =140 MeV

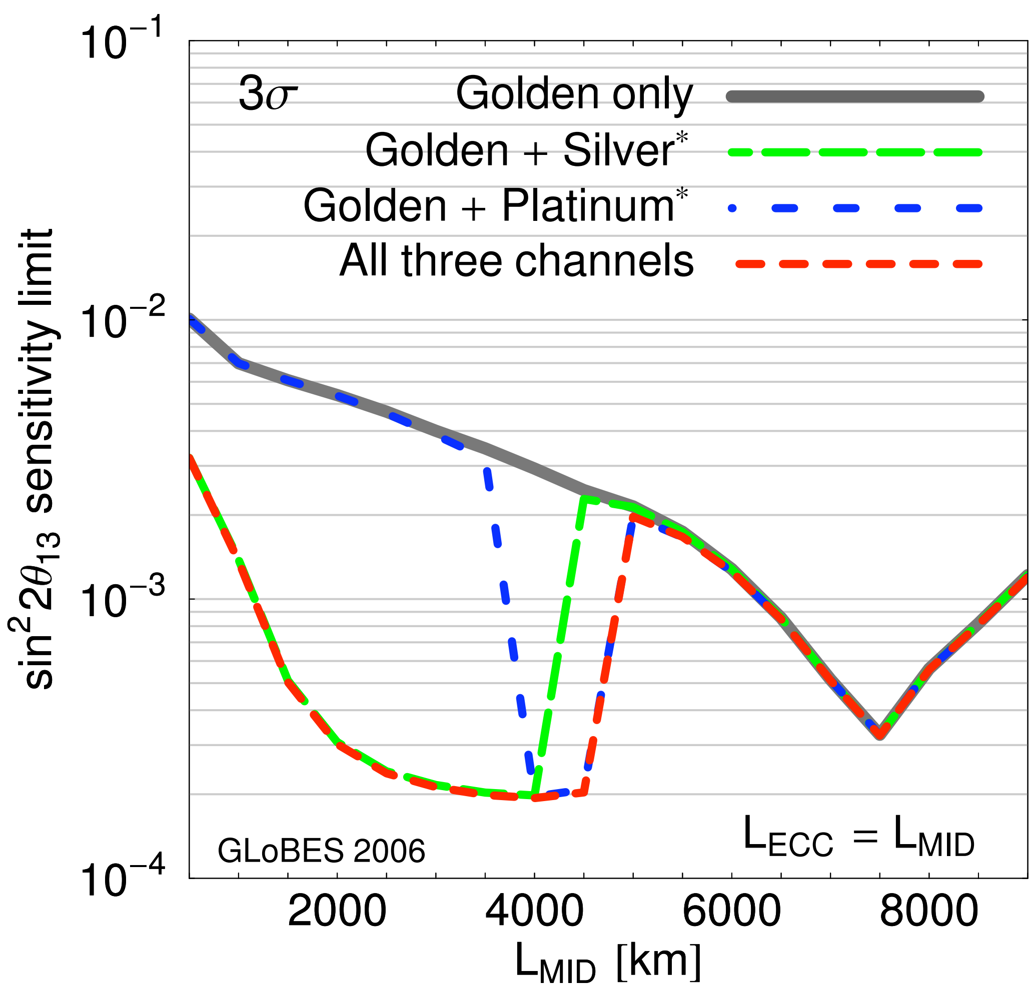


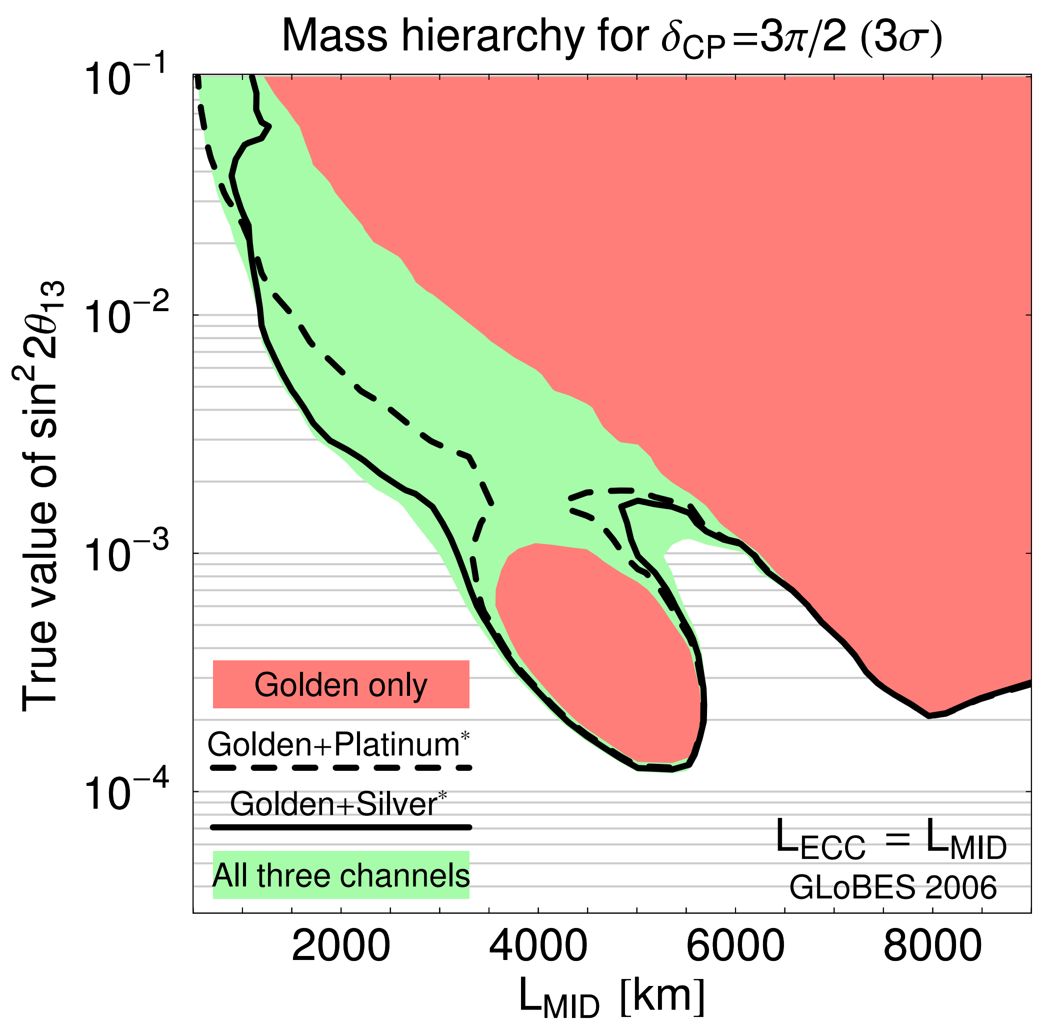
T600 test @ Pavia:
Run 201 - Evt 12

10-100 Kton Mass

Channels Combination

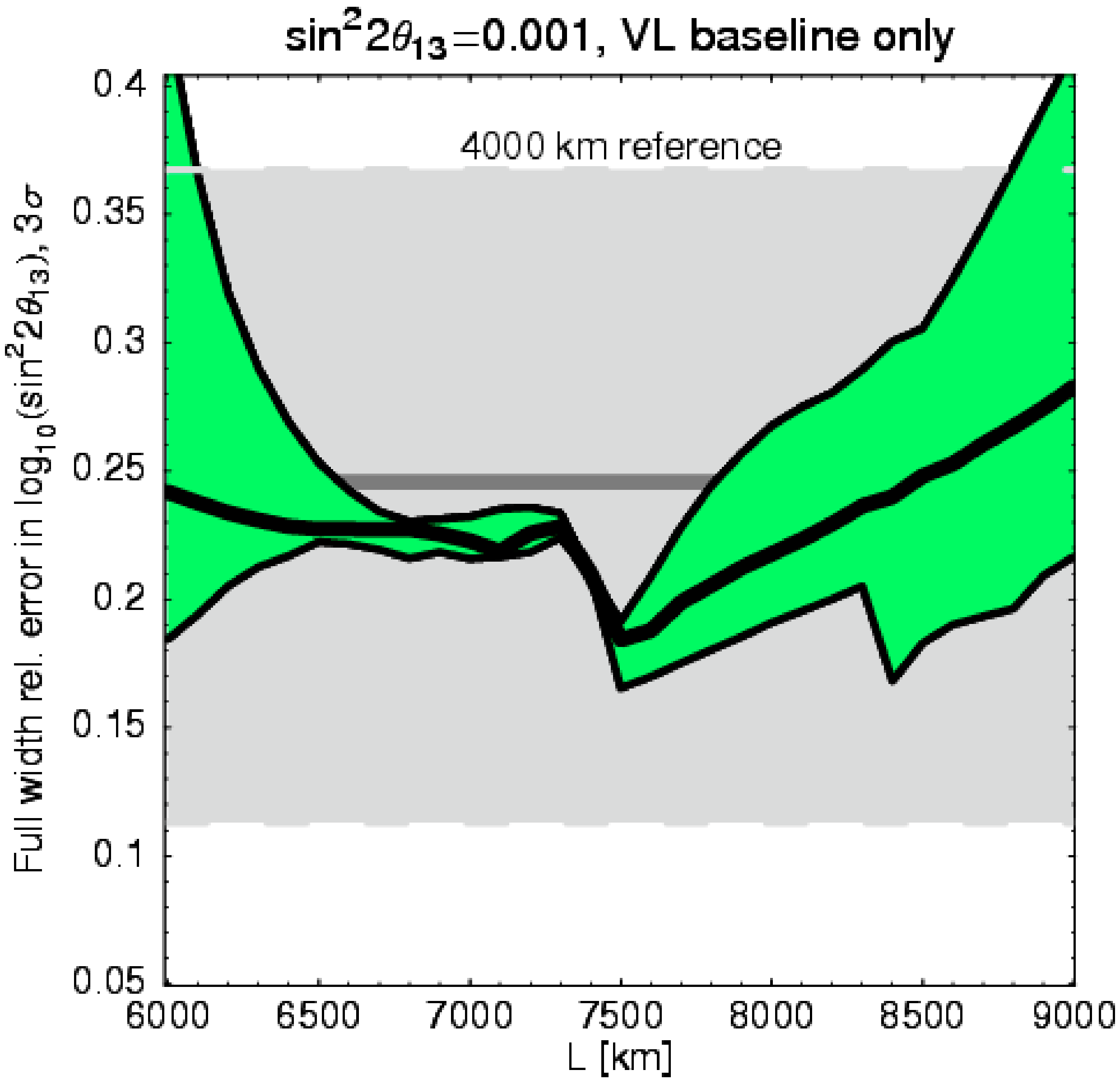
The main limitation of silver and platinum channels is statistics





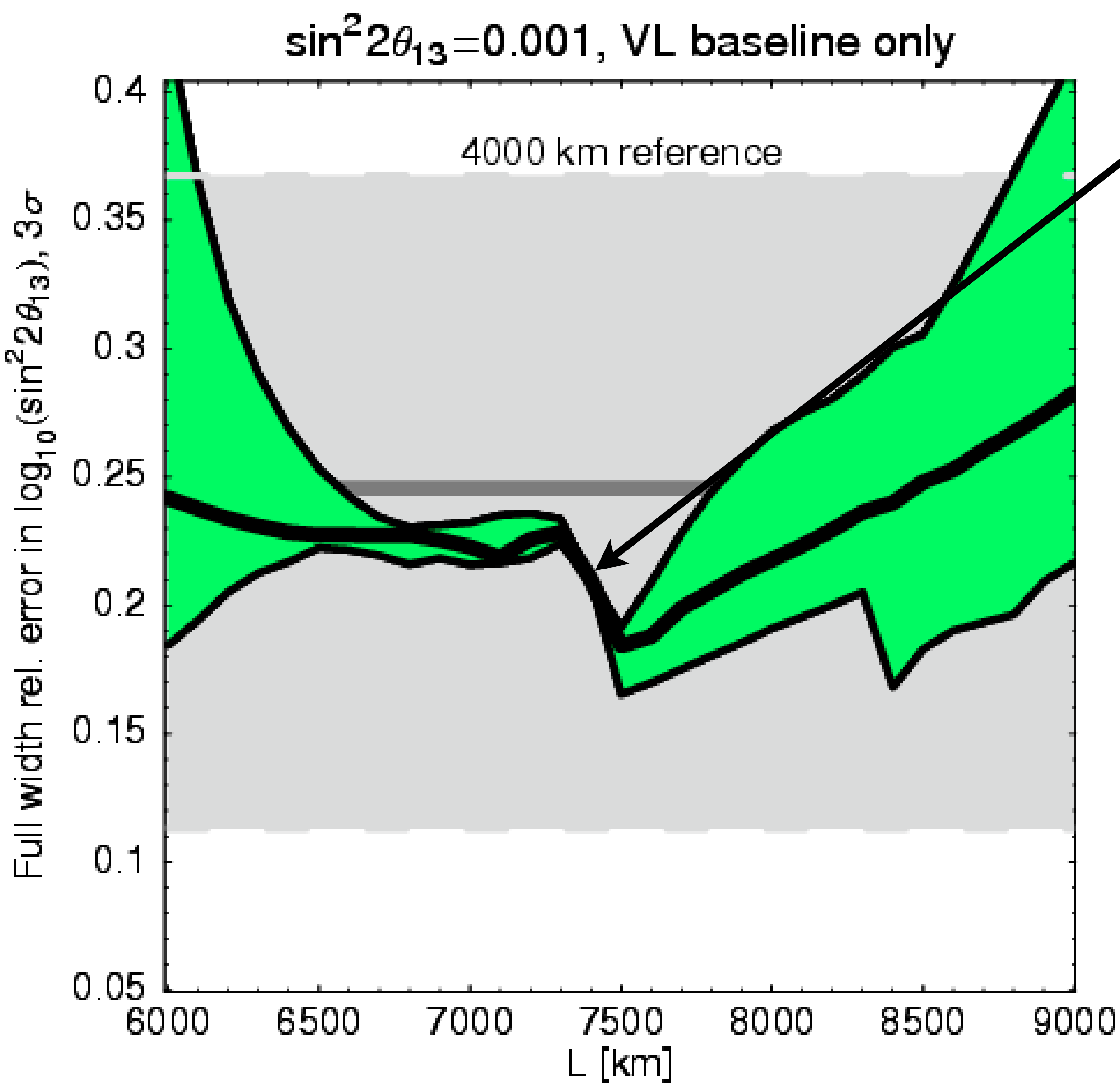
Huber, Lindner, Rolinec and Winter '06

The Magic Baseline



Huber and Winter '03

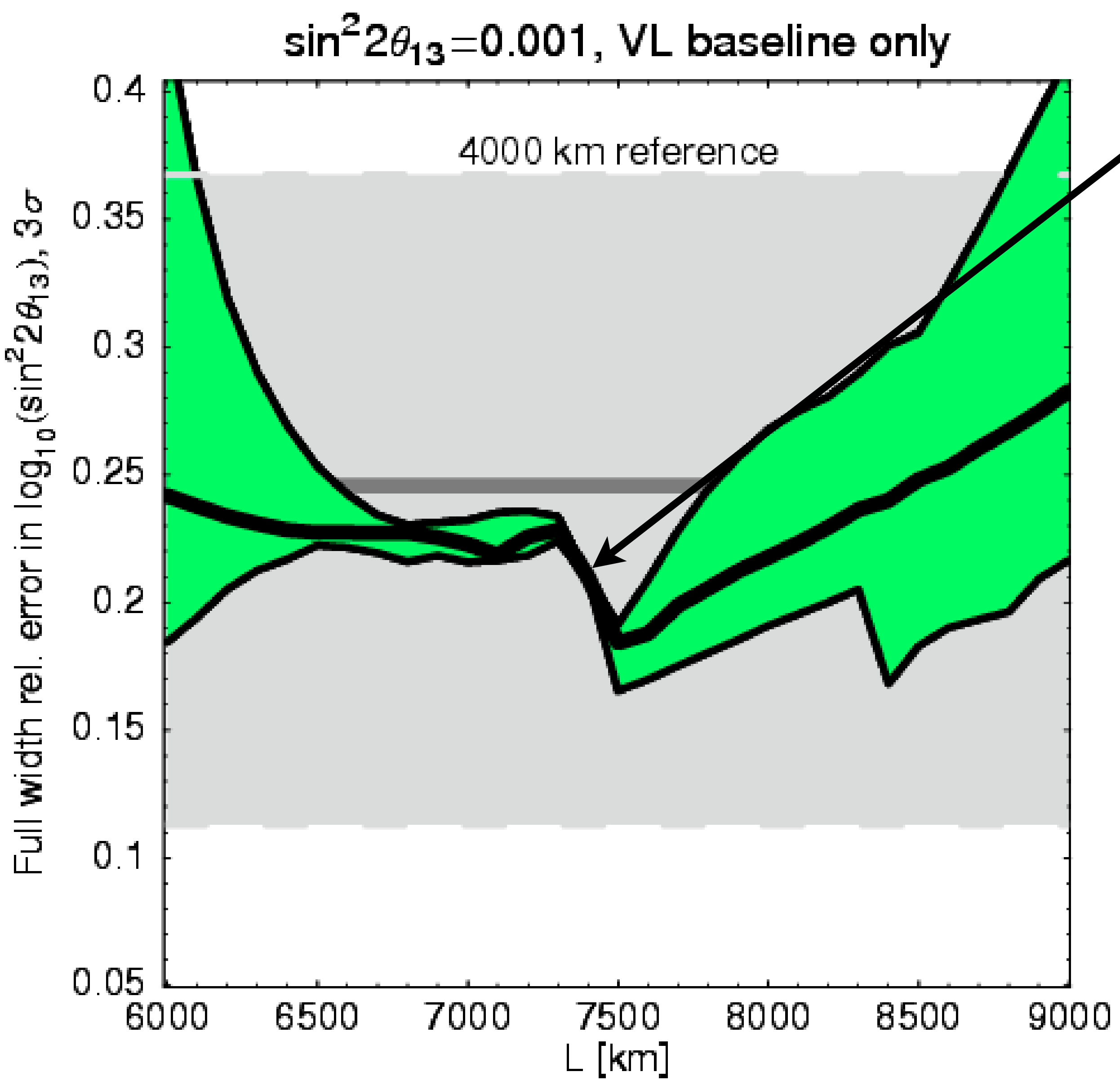
The Magic Baseline



At this baseline, no dependence on δ

Huber and Winter '03

The Magic Baseline

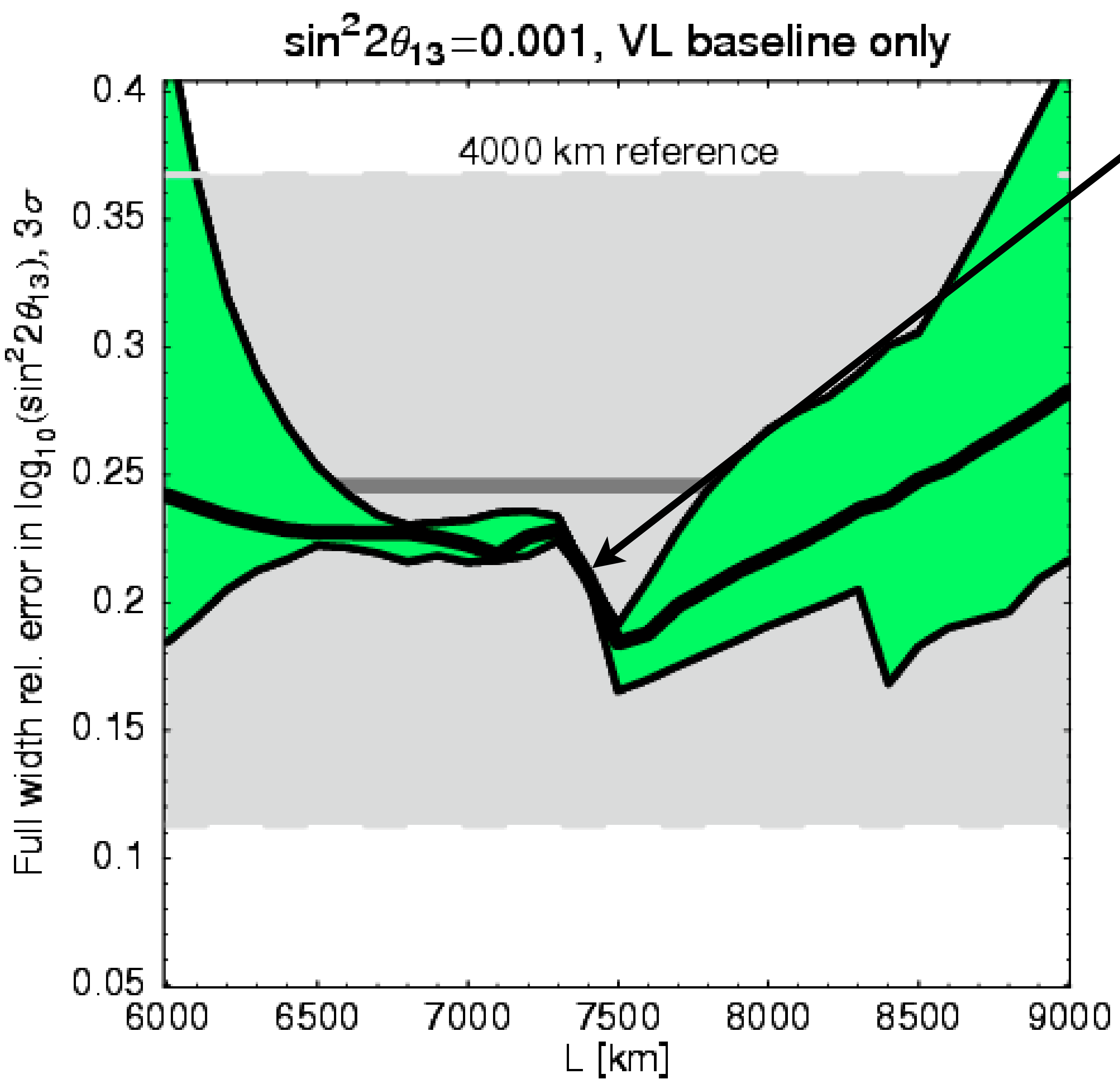


At this baseline, no dependence on δ

Also, no sensitivity at all....

Huber and Winter '03

The Magic Baseline



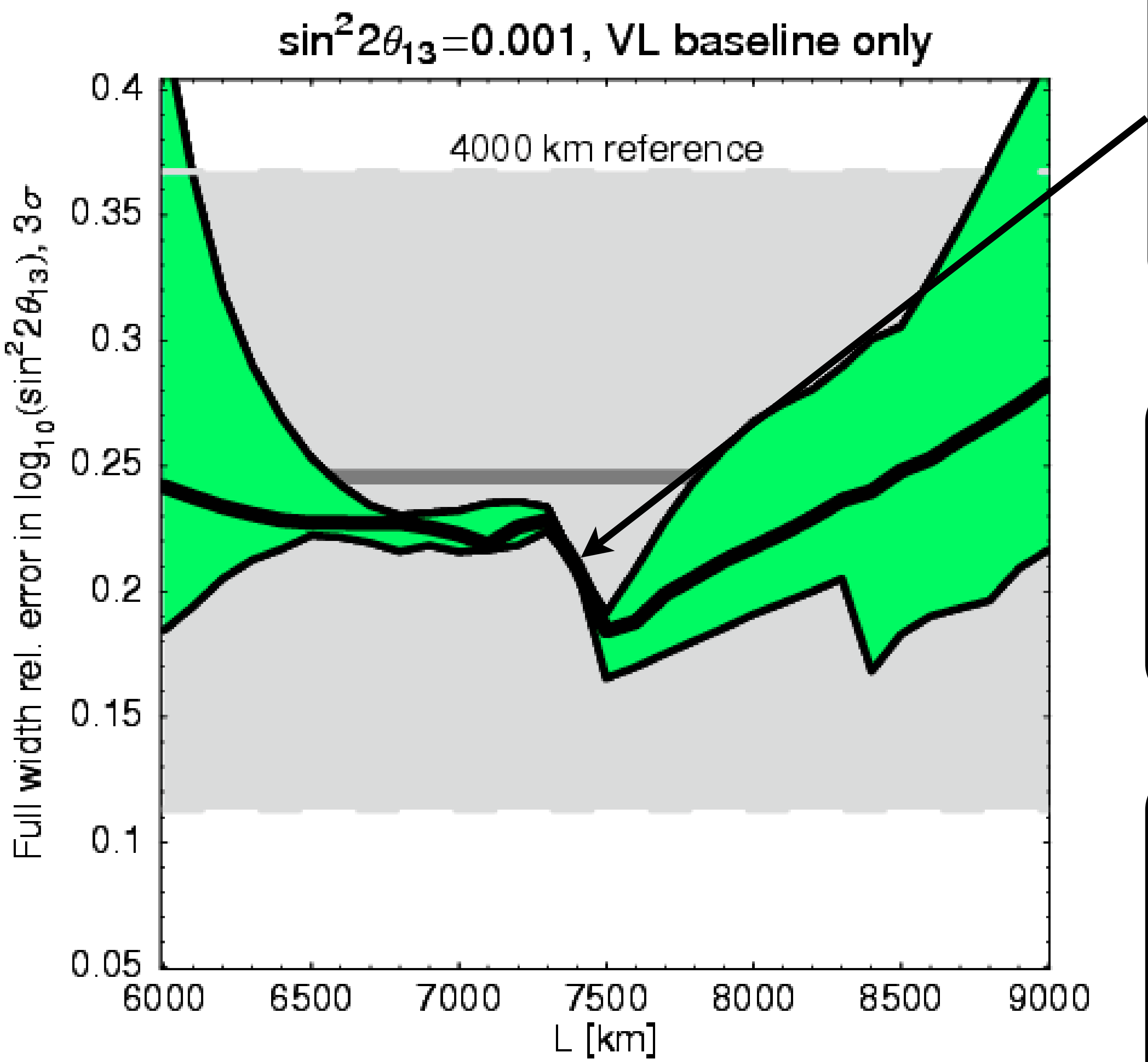
At this baseline, no dependence on δ

Also, no sensitivity at all....

Good to measure θ_{13} and the sign of Δm^2_{13}

Huber and Winter '03

The Magic Baseline



Huber and Winter '03

At this baseline, no dependence on δ

Also, no sensitivity at all....

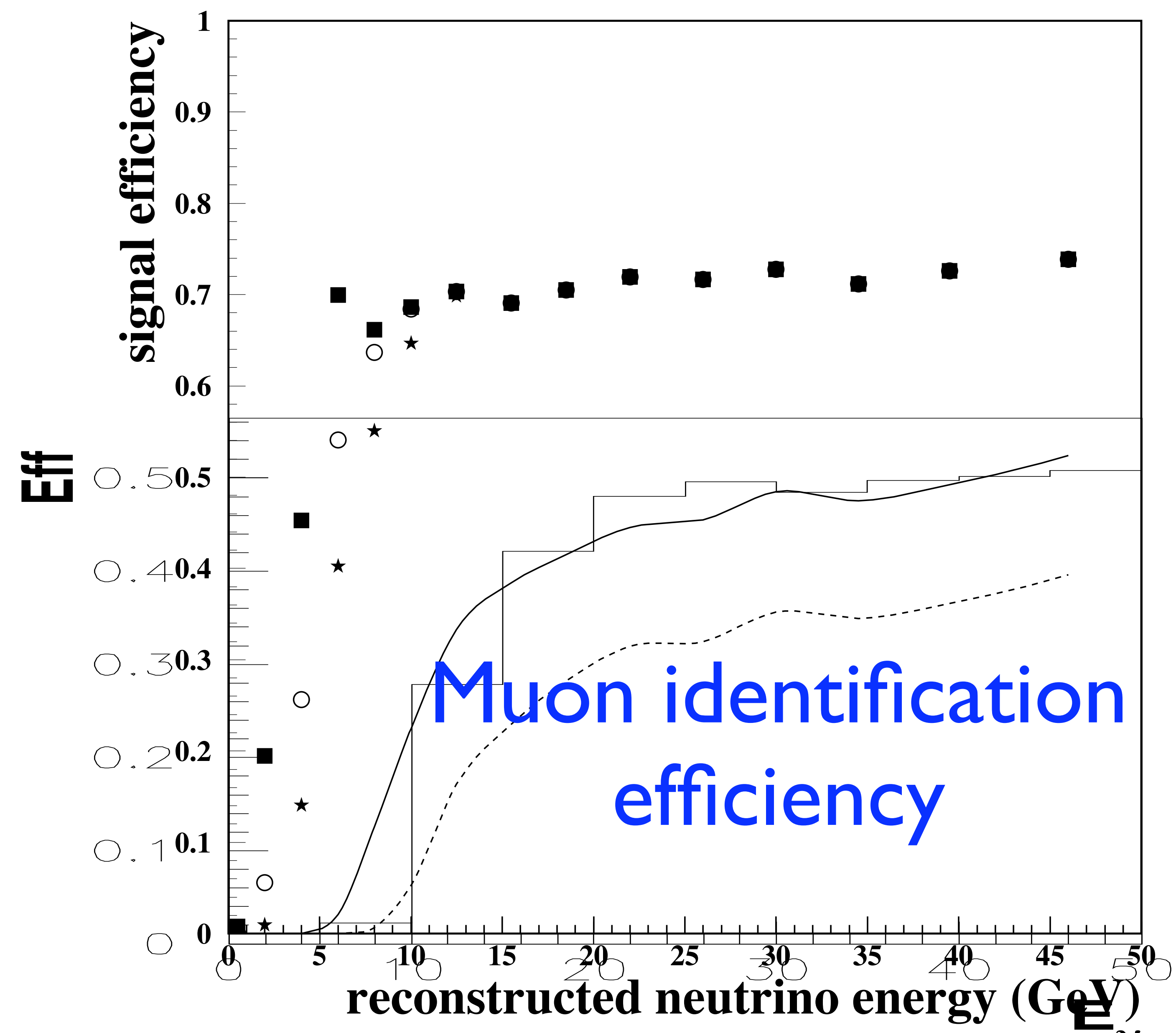
Good to measure θ_{13} and the sign of Δm^2_{13}

Combined with another baseline, acts as a degeneracy-solver

Enlightened MINDs

The crucial improvement is
to lower the threshold
for muon identification

From the ISS Detector Group Final Report

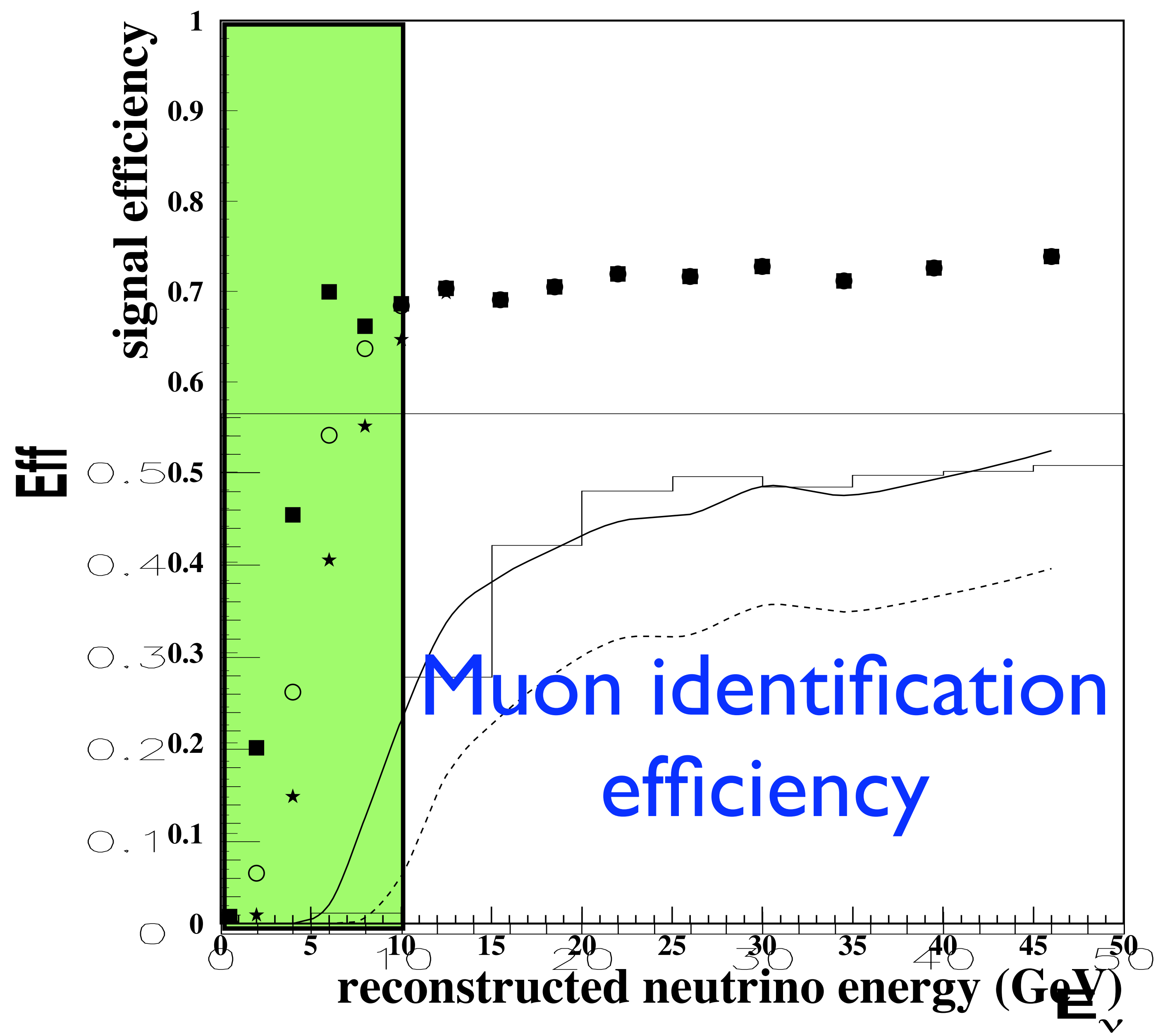


Enlightened MINDs

The crucial improvement is to lower the threshold for muon identification

For the standard NF setup, the first oscillation peak is around 7 GeV: a good efficiency below this value acts as a degeneracy-solver

From the ISS Detector Group Final Report



The ν_μ disappearance channel

$$P(\nu_\mu \to \nu_\mu) = 1 - (\sin^2 2\theta_{23} - s_{23}^2 \sin^2 2\theta_{13} \cos^2 2\theta_{23}) \sin^2\left(\frac{\Delta_{atm} L}{2}\right)$$

$$- \left(\frac{\Delta_{sol} L}{2}\right) [s_{12}^2 \sin^2 2\theta_{23} + \tilde{J} s_{23}^2 \cos\delta] \sin(\Delta_{atm} L)$$

$$- \left(\frac{\Delta_{sol} L}{2}\right)^2 [c_{23}^4 \sin^2 2\theta_{12} + s_{12}^2 \sin^2 2\theta_{23} \cos(\Delta_{atm} L)]$$

Where

$$\tilde{J} = \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$$

$$\Delta_{sol} = \frac{\Delta m_{12}^2}{2E}$$

$$\sin 2\theta_{13} < 0.4$$

$$\Delta_{atm} = \frac{\Delta m_{23}^2}{2E}$$

$$\left(\frac{\Delta_{sol} L}{2}\right) \cong 0.05$$

Preliminar analysis at the NuFactory

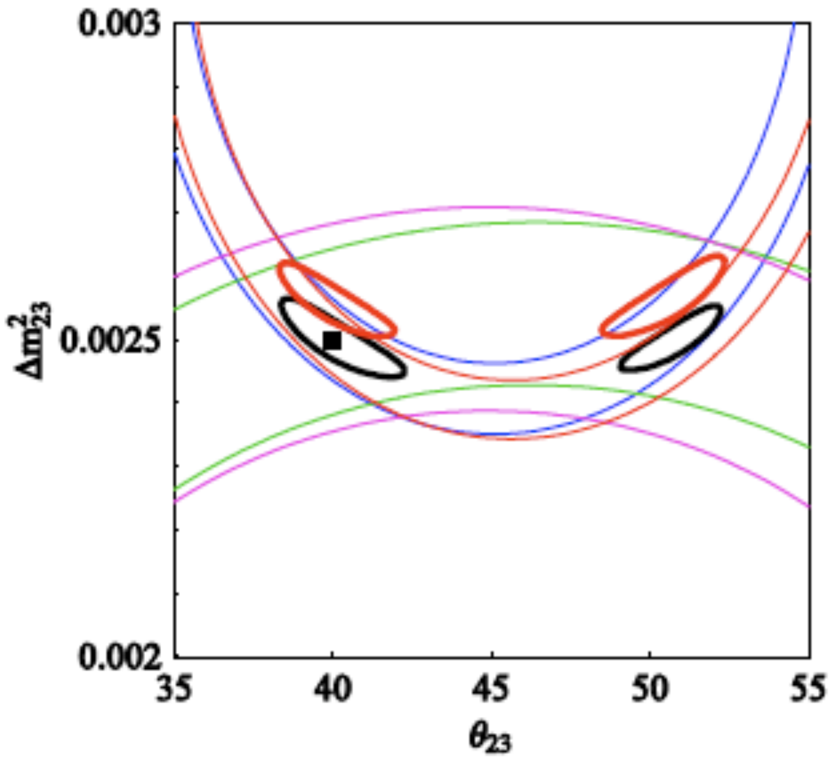
5yr ν_μ + 5yr $\bar{\nu}_\mu$ exposure with a 40Kt iron calorimeter for the NF

- Possible Setups:
  - L = 3000Km E = 20, 50 GeV
  - L = 7000Km E = 50 GeV
- 5 GeV bins considered
- Efficiency:
  - ε_μ = 0.5 for neutrinos
  - ε_μ = 0.33 for antineutrinos
- Systematics = 2%

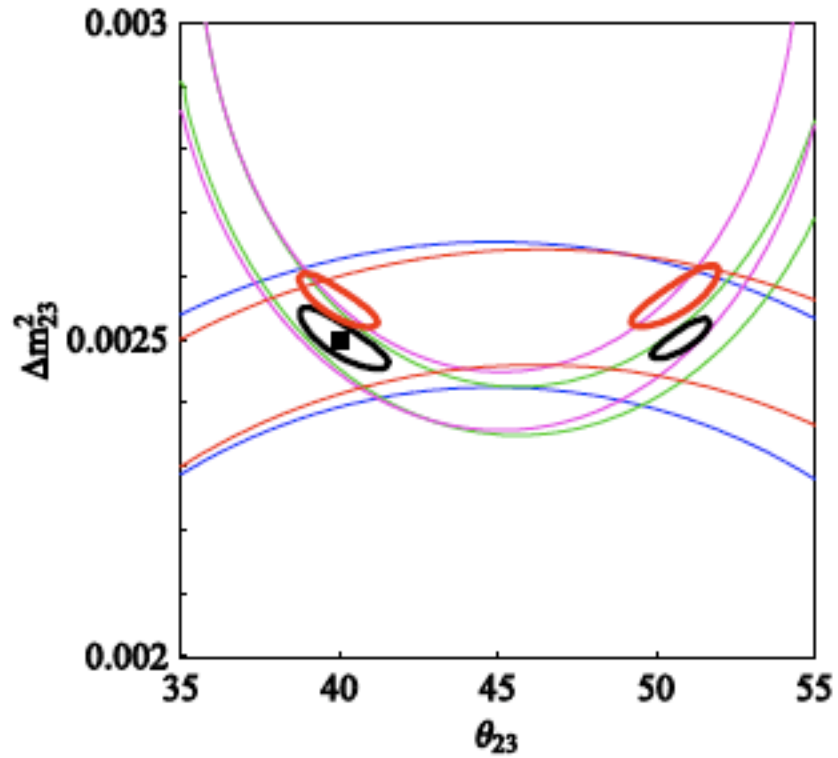
"Cervera *et al.* hep-ph/0002108"

See e.g. Bueno *et al.* hep-ph/0005007 for an Icarus analysis

Neutrino Factory



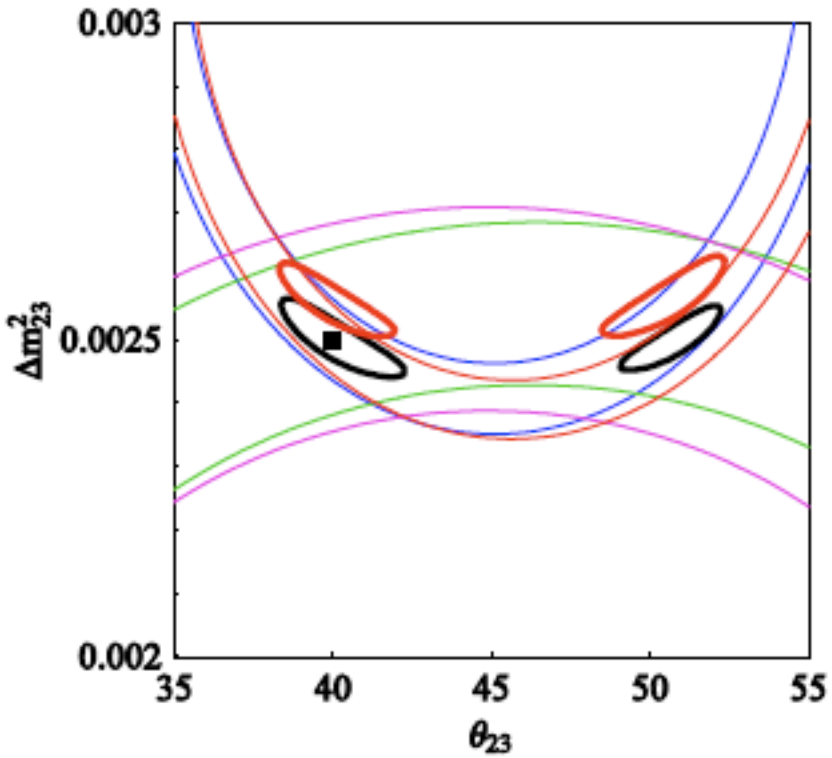
E = 50 GeV
L = 3000 Km



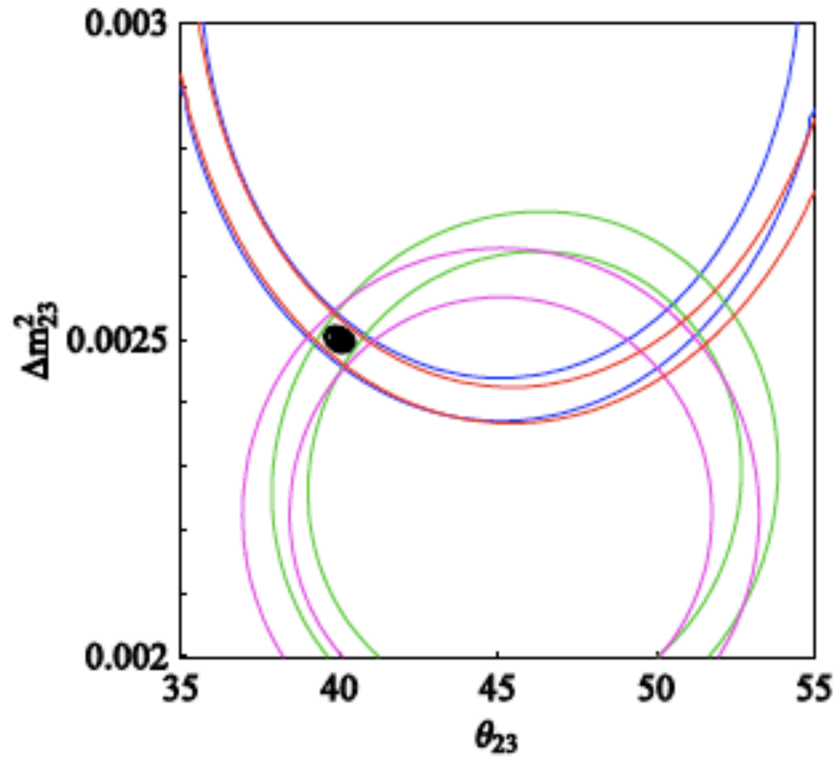
E = 20 GeV
L = 3000 Km

Input: $\theta_{23} = 40^o, \quad \theta_{13} = 6^o, \quad \delta = 0^o$

Neutrino Factory



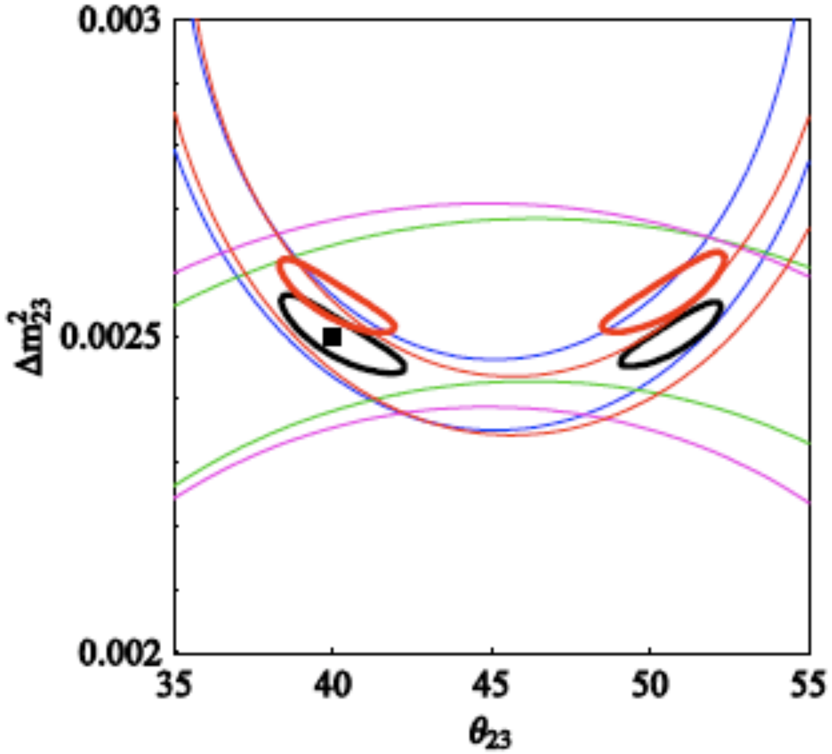
E = 50 GeV
L = 3000 Km



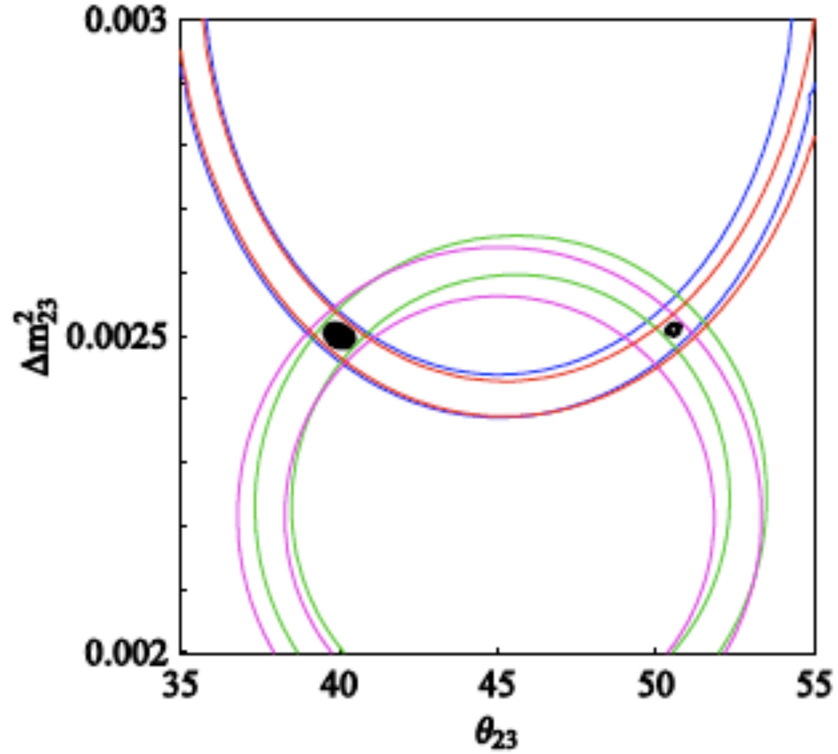
E = 50 GeV
L = 7000 Km

Input: $\theta_{23} = 40^o$, $\theta_{13} = 6^o$, $\delta = 0^o$

Neutrino Factory



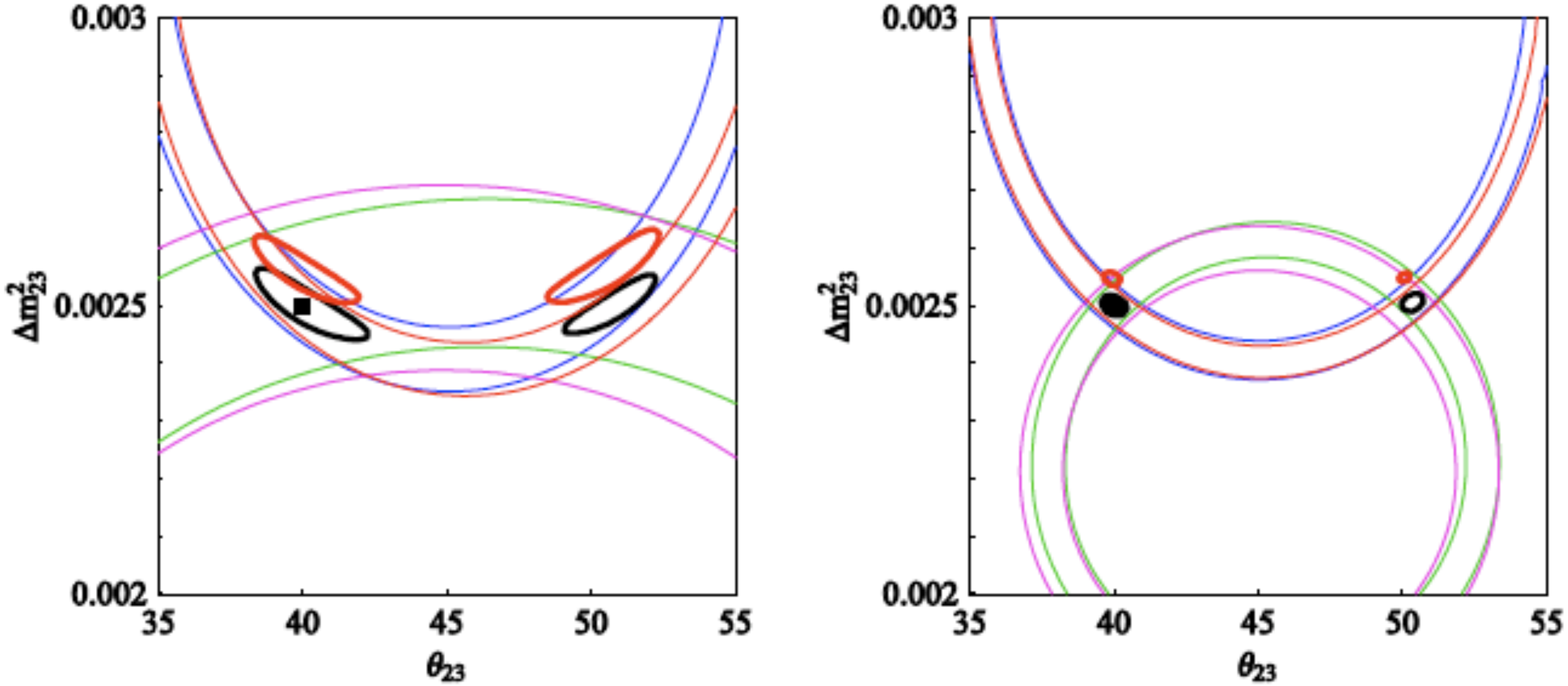
E = 50 GeV
L = 3000 Km



E = 50 GeV
L = 7000 Km

Input: $\theta_{23} = 40^o$, $\theta_{13} = 4^o$, $\delta = 0^o$

Neutrino Factory

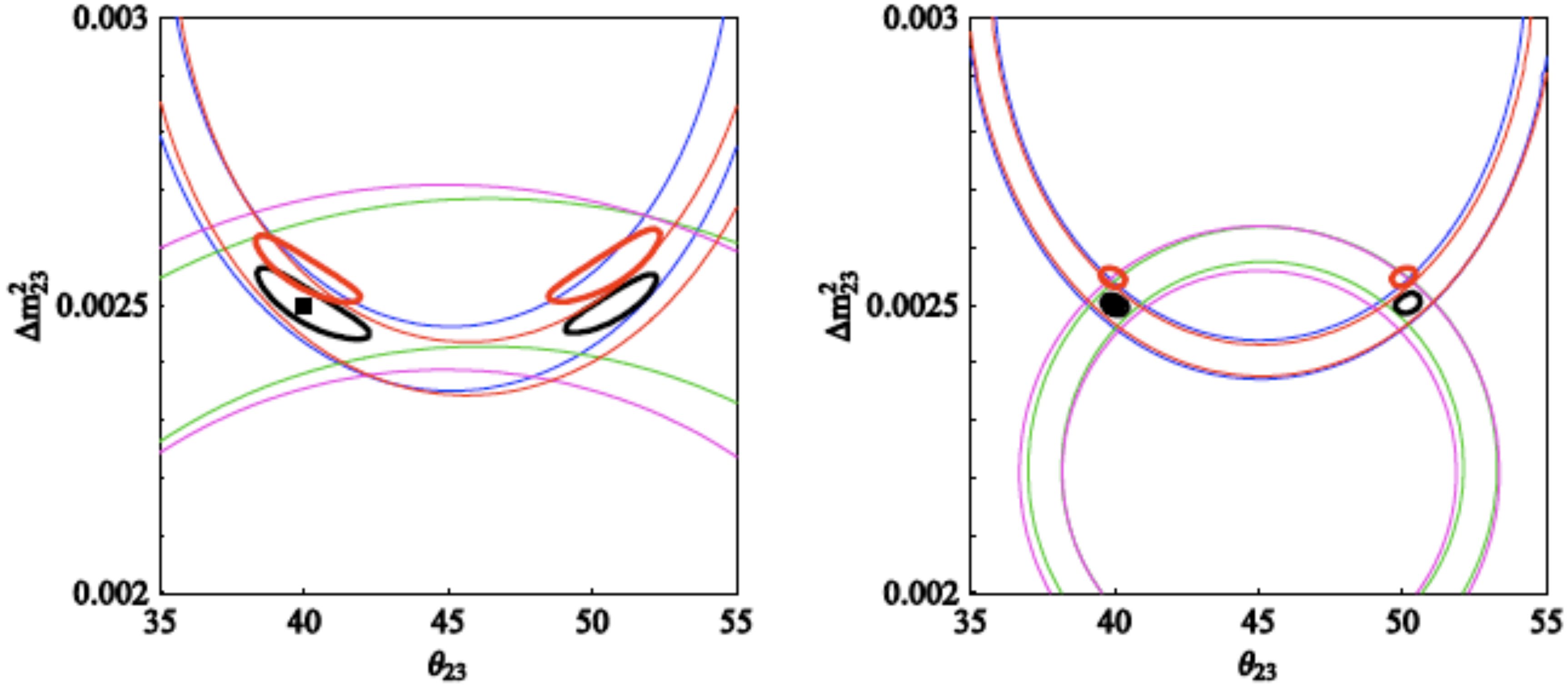


E = 50 GeV
L = 3000 Km

E = 50 GeV
L = 7000 Km

Input: $\theta_{23} = 40^o$, $\theta_{13} = 3^o$, $\delta = 0^o$

Neutrino Factory



E = 50 GeV
L = 3000 Km

E = 50 GeV
L = 7000 Km

Input: $\theta_{23} = 40^o$, $\theta_{13} = 2^o$, $\delta = 0^o$

(...the forgotten channel...)

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

$\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau \rightarrow \tau^+ \rightarrow \mu^+$ — The Signal

$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \rightarrow \mu^+$ — The dominant background

(...the forgotten channel...)

$$\mu^+ \longrightarrow \begin{cases} e^+ \\ \nu_e \\ \bar{\nu}_\mu \to \bar{\nu}_\tau \to \tau^+ \to \mu^+ \end{cases}$$

$\bar{\nu}_\mu \to \bar{\nu}_\tau \to \tau^+ \to \mu^+$ — The Signal

$\bar{\nu}_\mu \to \bar{\nu}_\mu \to \mu^+$ — The dominant background

Best channel to look for new physics

(...the forgotten channel...)

$\mu^+ \longrightarrow \begin{cases} e^+ \\ \nu_e \\ \bar{\nu}_\mu \to \bar{\nu}_\tau \to \tau^+ \to \mu^+ \\ \bar{\nu}_\mu \to \bar{\nu}_\mu \to \mu^+ \end{cases}$

$\bar{\nu}_\mu \to \bar{\nu}_\tau \to \tau^+ \to \mu^+$ The Signal

$\bar{\nu}_\mu \to \bar{\nu}_\mu \to \mu^+$ The dominant background

Best channel to look for new physics

→ Emulsions + Spectrometers

(...the forgotten channel...)

$\mu^+ \longrightarrow \begin{cases} e^+ \\ \nu_e \\ \bar{\nu}_\mu \to \bar{\nu}_\tau \to \tau^+ \to \mu^+ \end{cases}$

$\bar{\nu}_\mu \to \bar{\nu}_\tau \to \tau^+ \to \mu^+$ The Signal

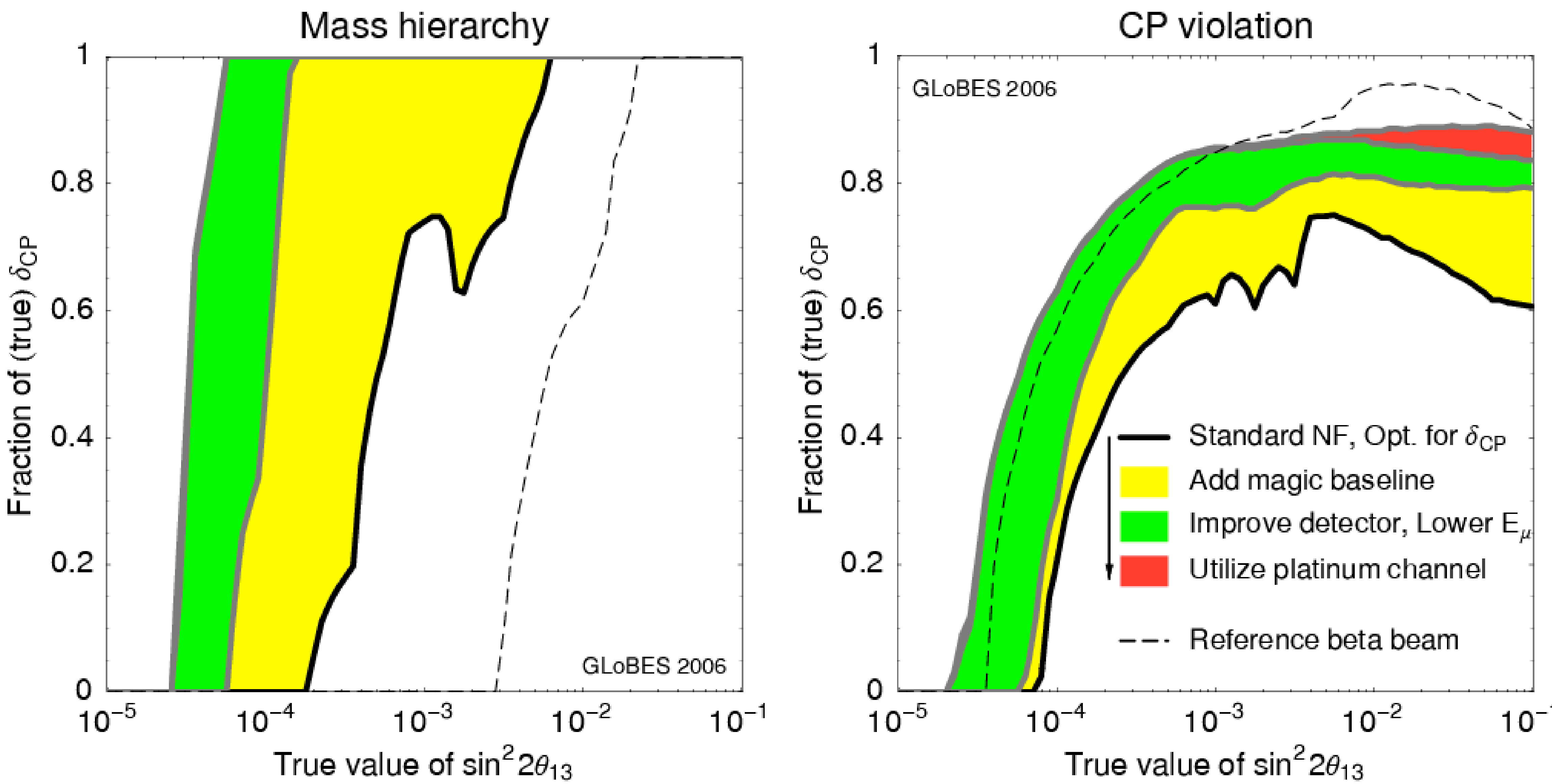
$\bar{\nu}_\mu \to \bar{\nu}_\mu \to \mu^+$ The dominant background

Best channel to look for new physics

→ Emulsions + Spectrometers → "OPERA"

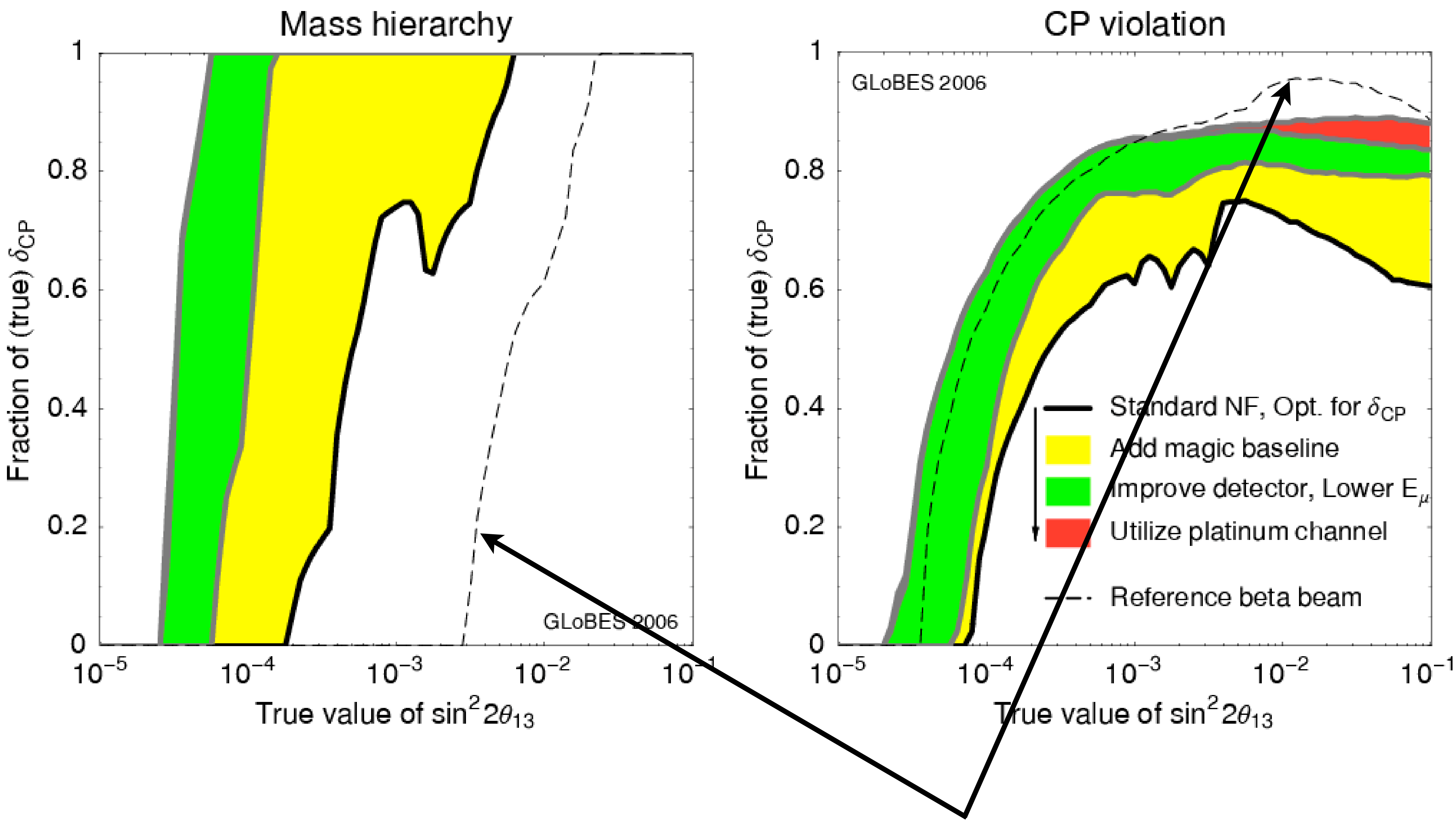
The NuFact Sensitivity

Huber, Lindner, Rolinec and Winter '06



The NuFact Sensitivity

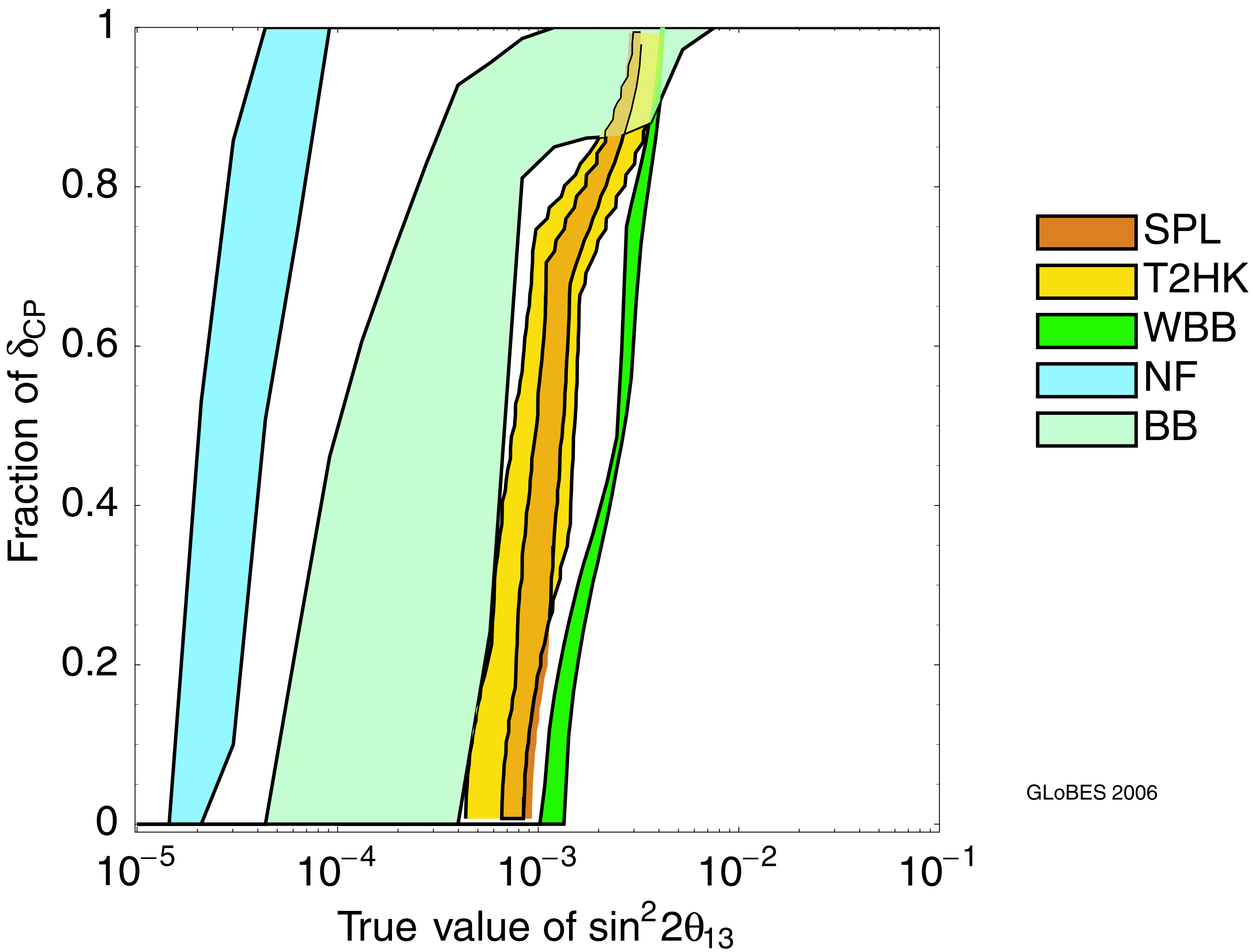
Huber, Lindner, Rolinec and Winter ‘06



Burguet-Castell, Casper, Couce, Gómez-Cadenas and Hernández ‘05

The NuFact Sensitivity

Discovery reach in $\sin^2 2\theta_{13}$



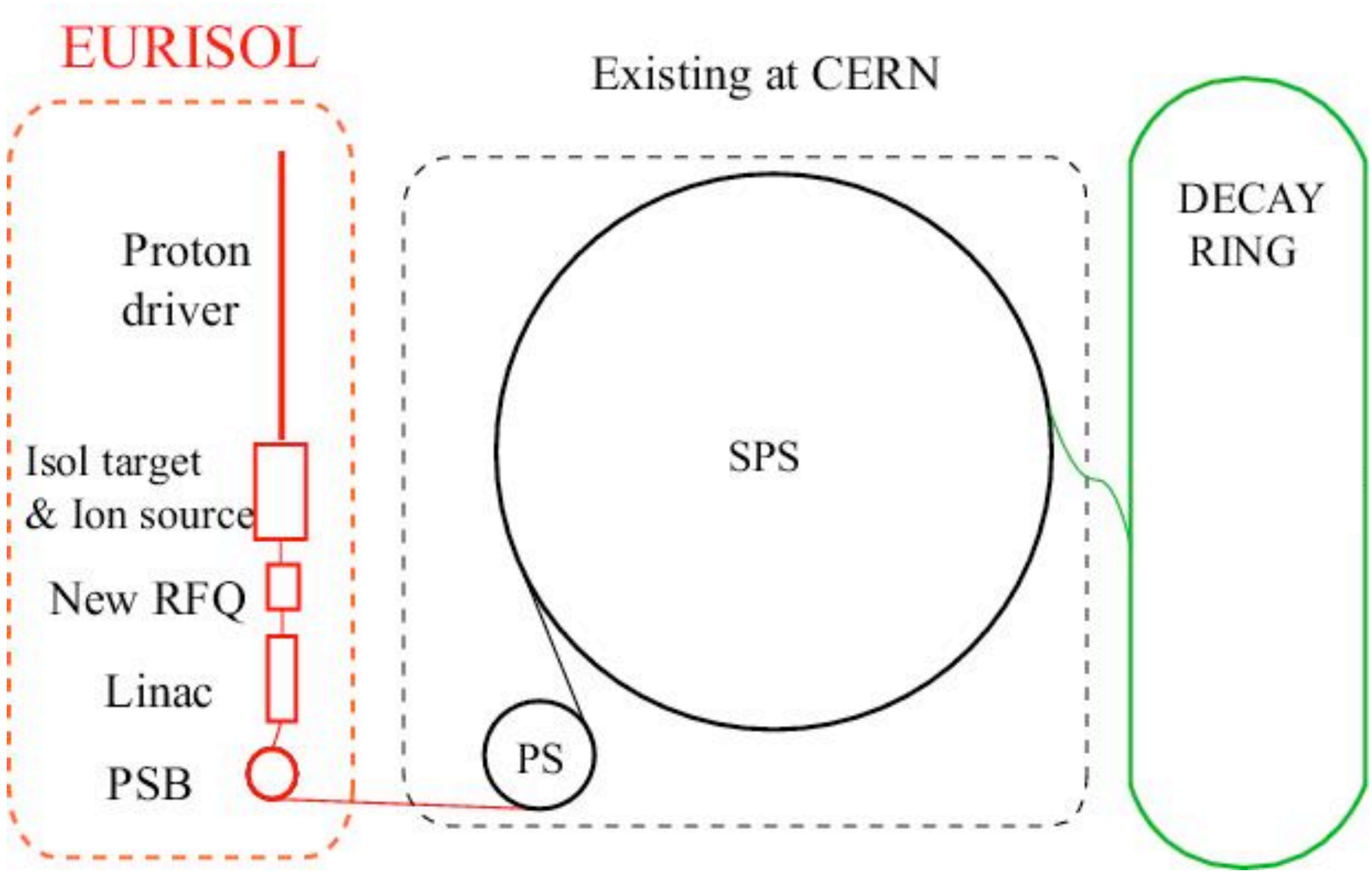
ISS final report:
25 GeV muons
Two E-MIND detectors
1. L = 3000-4000 Km
2. L = 7500 Km
$(0.5/1)10^{21}$ useful muons
per year per baseline

From the ISS Physics Group Final Report

BETABEAMS

βBeam

1. with $^{6}He/^{18}Ne$



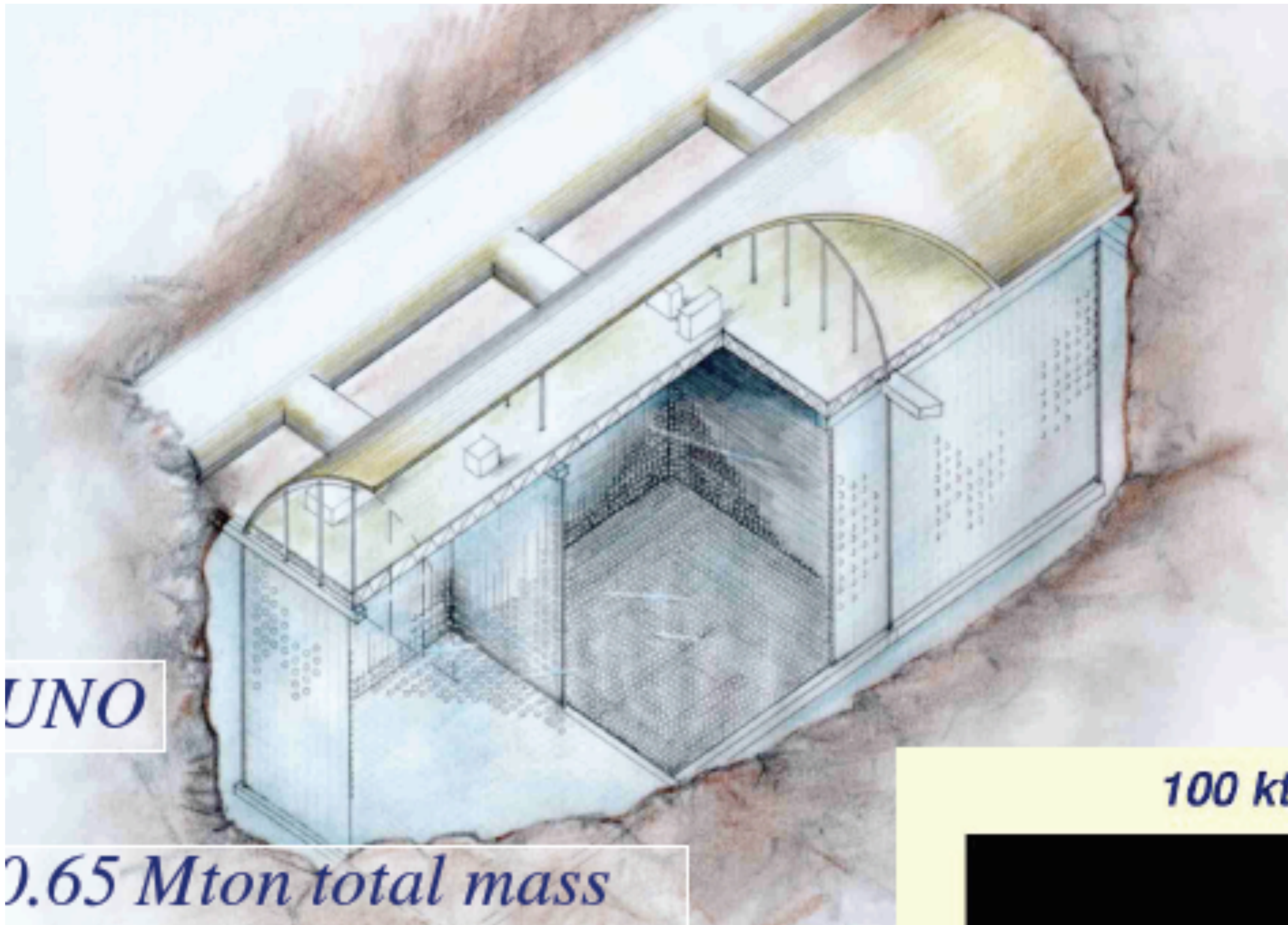
$\langle E_\nu \rangle = 300$ MeV

$\gamma \sim 100$

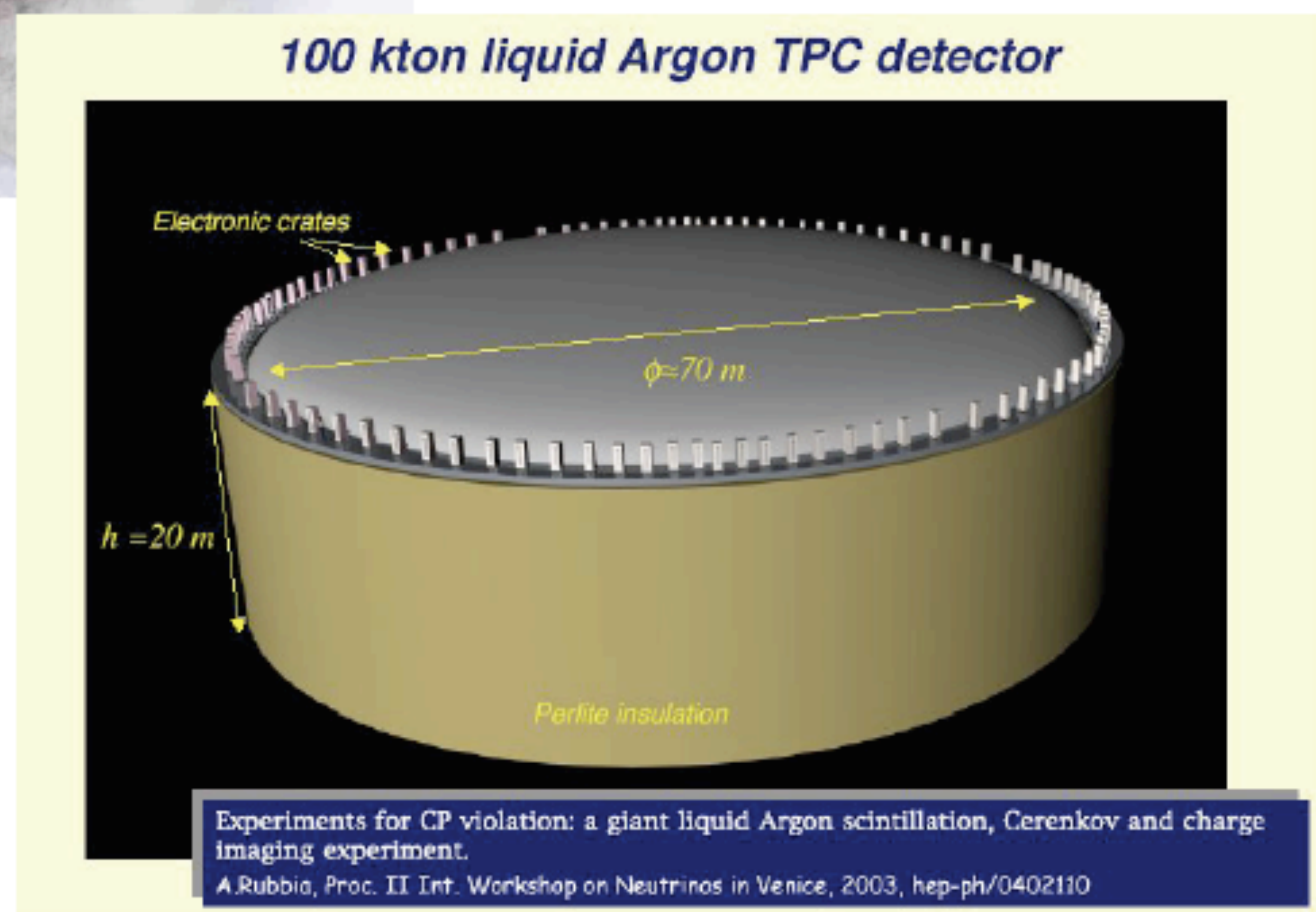
P. Zucchelli hep-ph/0107006

L = 130 Km

The CERN-Memphys project

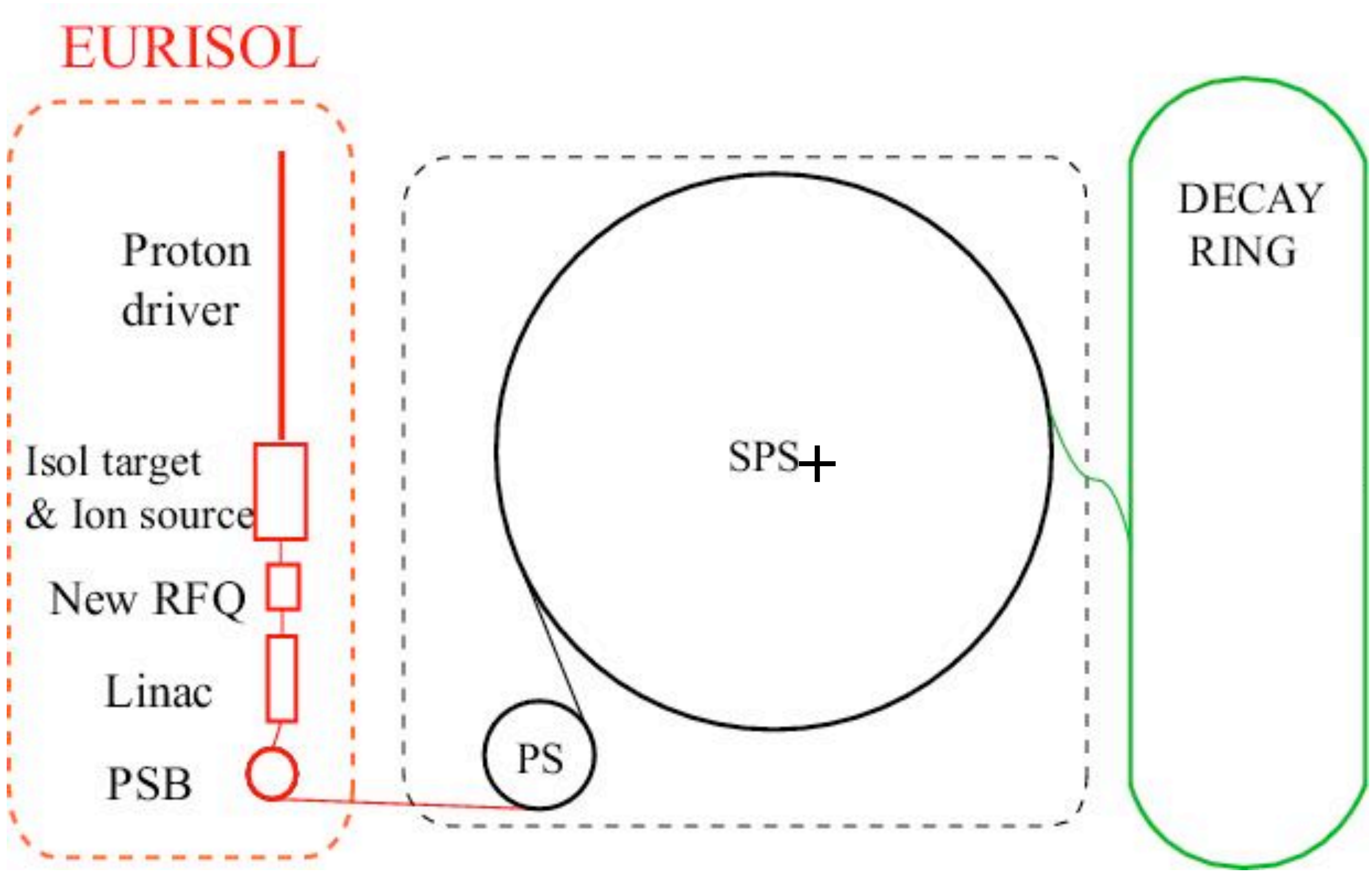


Detector options



βBeam

2. with $^{6}He/^{18}Ne$



$\langle E_\nu \rangle = 1.2$ GeV

$L = 650$ Km

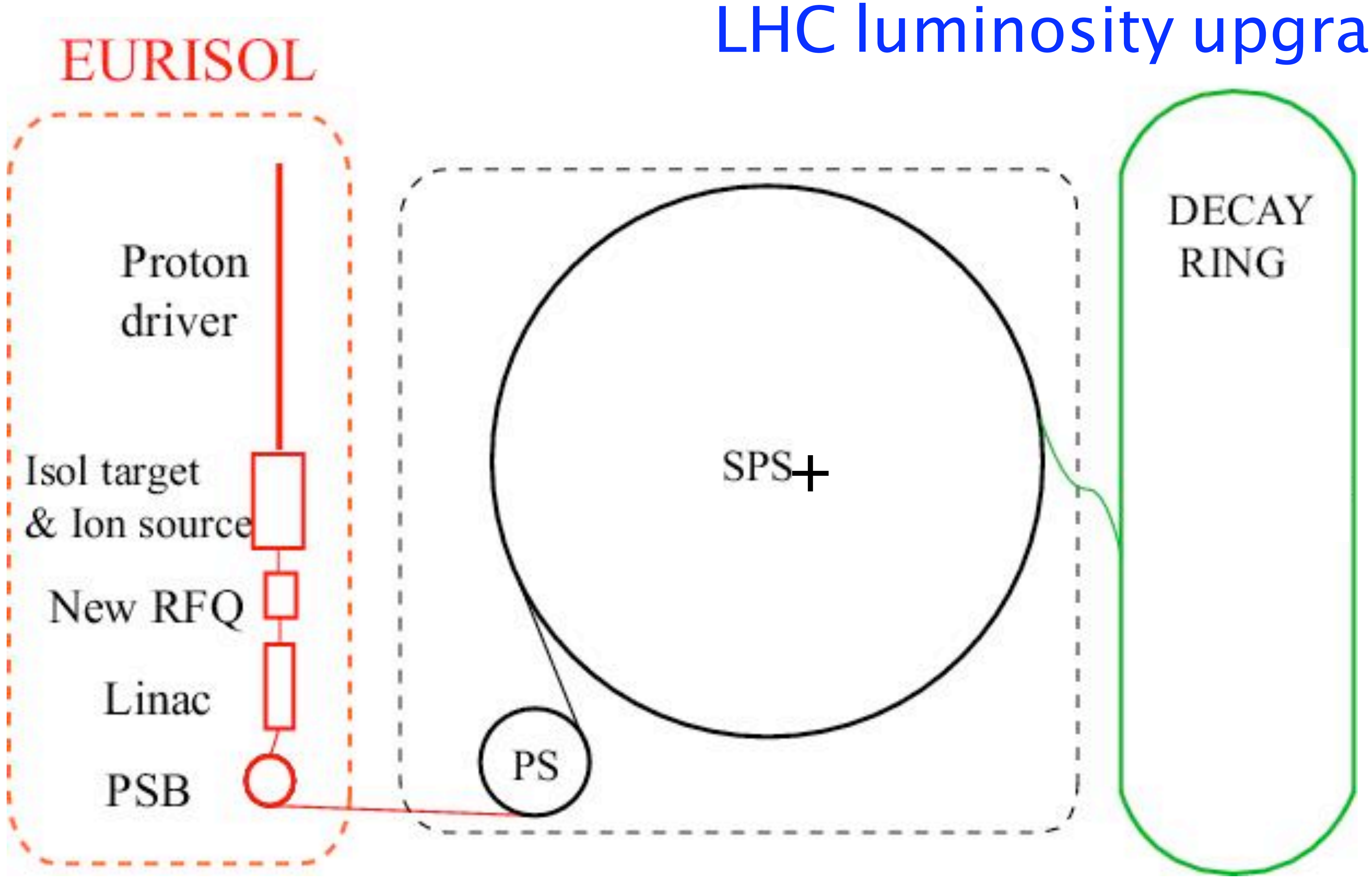
$\gamma \sim 350$

J. Burguet-Castell et al. hep-ph/0312068
J. Burguet-Castell et al. hep-ph/0503021

βBeam

2. with $^{6}He/^{18}Ne$

LHC luminosity upgrade



$\langle E_\nu \rangle = 1.2$ GeV

L = 650 Km

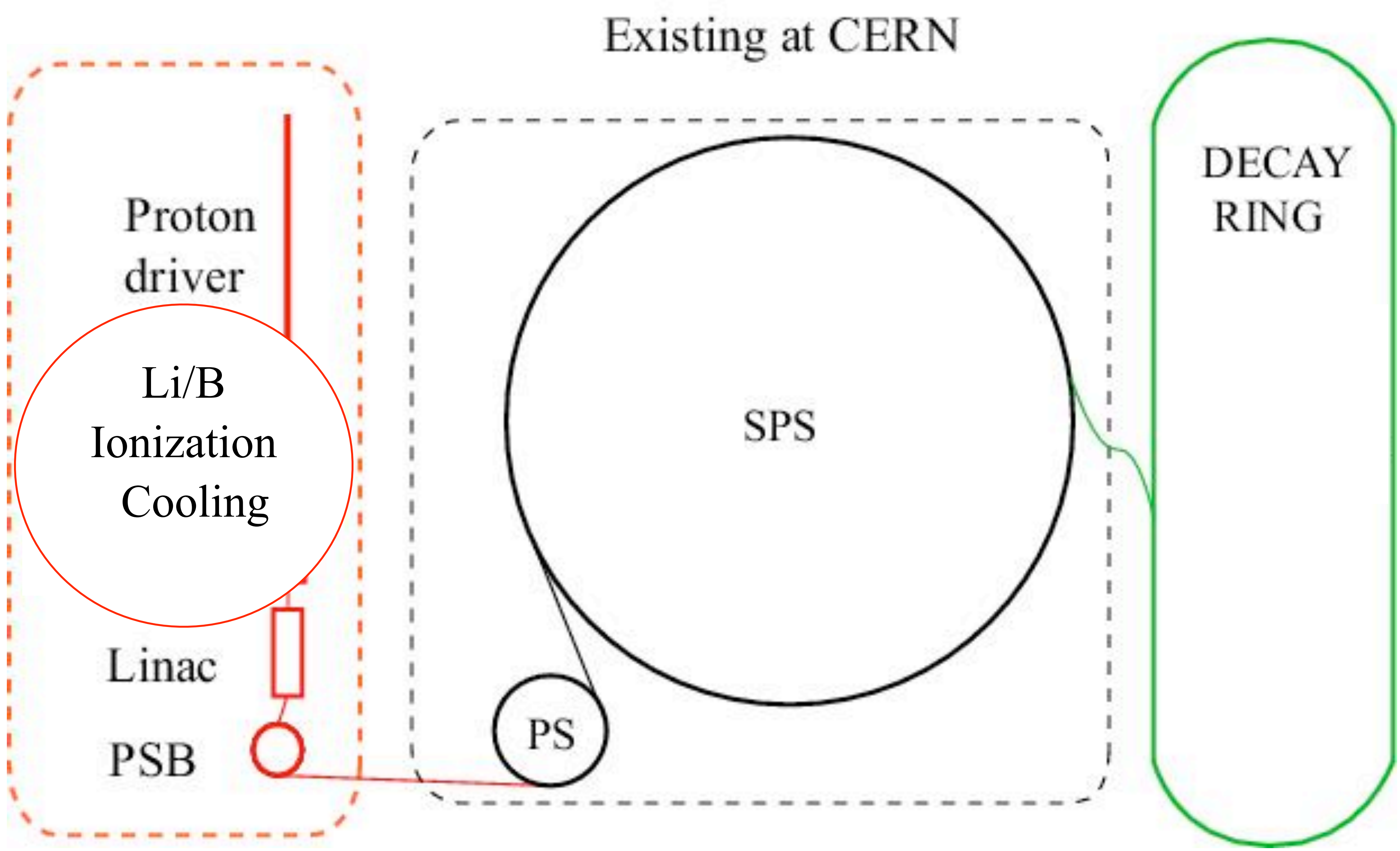
$\gamma \sim 350$

J. Burguet-Castell et al. hep-ph/0312068

J. Burguet-Castell et al. hep-ph/0503021

βBeam

3. with $^8Li/^8B$



$\langle E_\nu \rangle = 1.3$ GeV

$L = 650$ Km

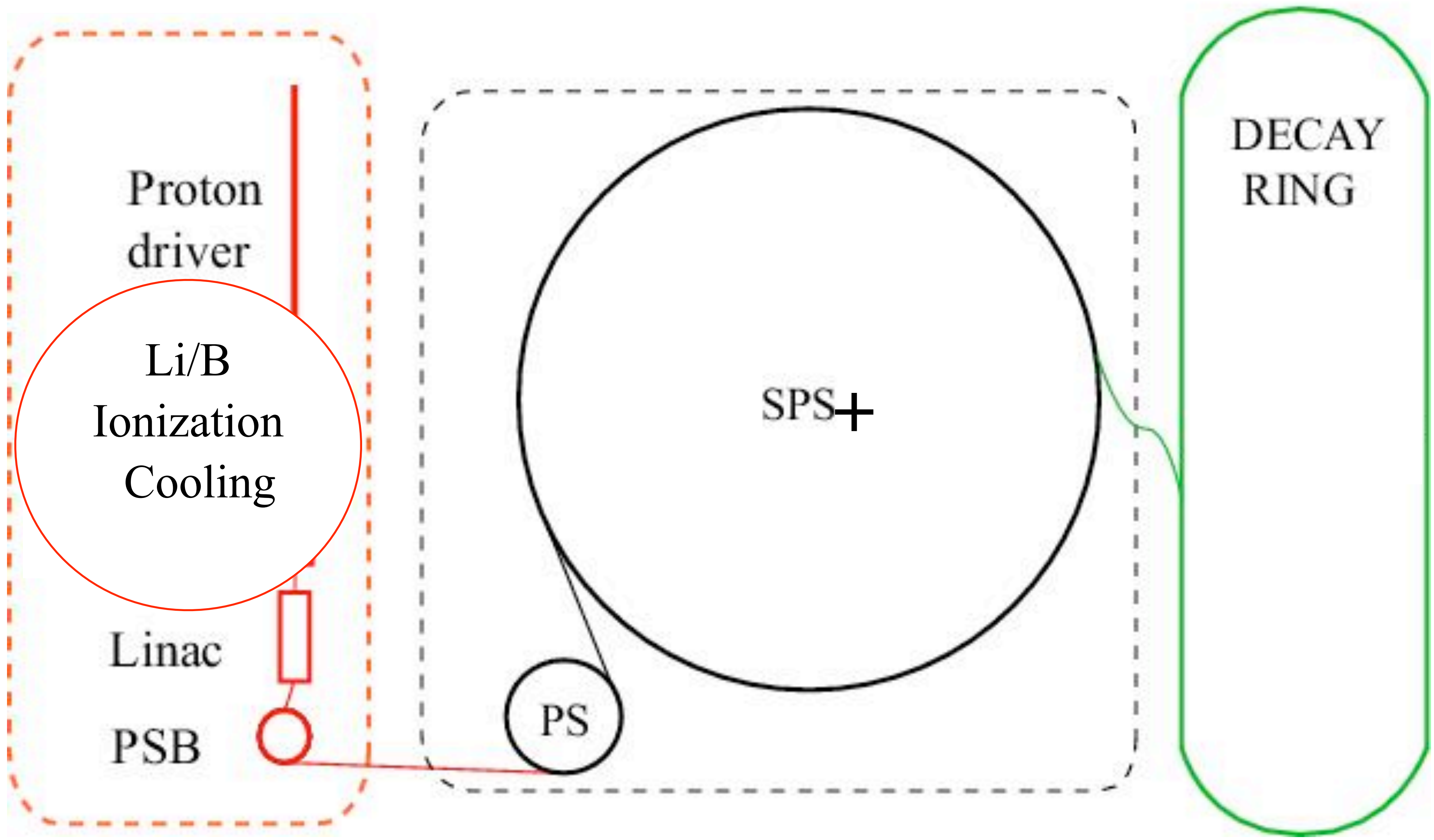
$\gamma \sim 100$

C. Rubbia et al. hep-ph/0602032

C. Rubbia et al. hep-ph/0609235

βBeam

4. with $^8Li/^8B$



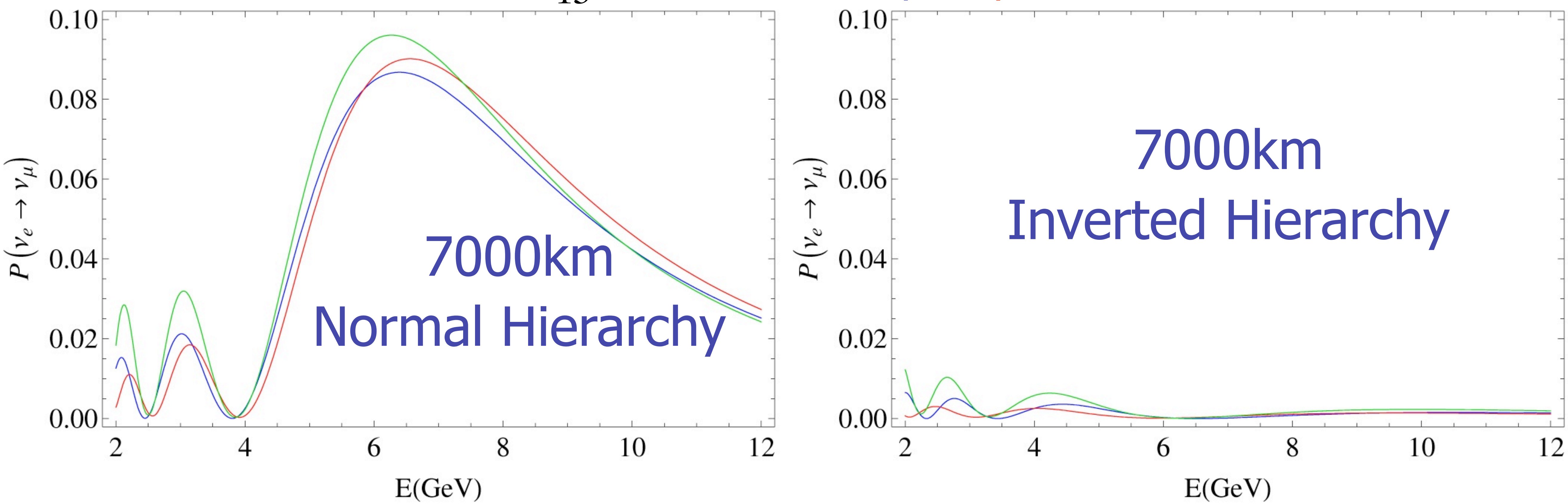
$\langle E_\nu \rangle = 4.5$ GeV
L = 7000 Km
Magic Baseline!

$\gamma \sim 350$

S. K. Agarwalla et al. hep-ph/0610333
S. K. Agarwalla et al. hep-ph/0611233
S. K. Agarwalla et al. arXiv:0711.1459

Resonant enhancement at the MB

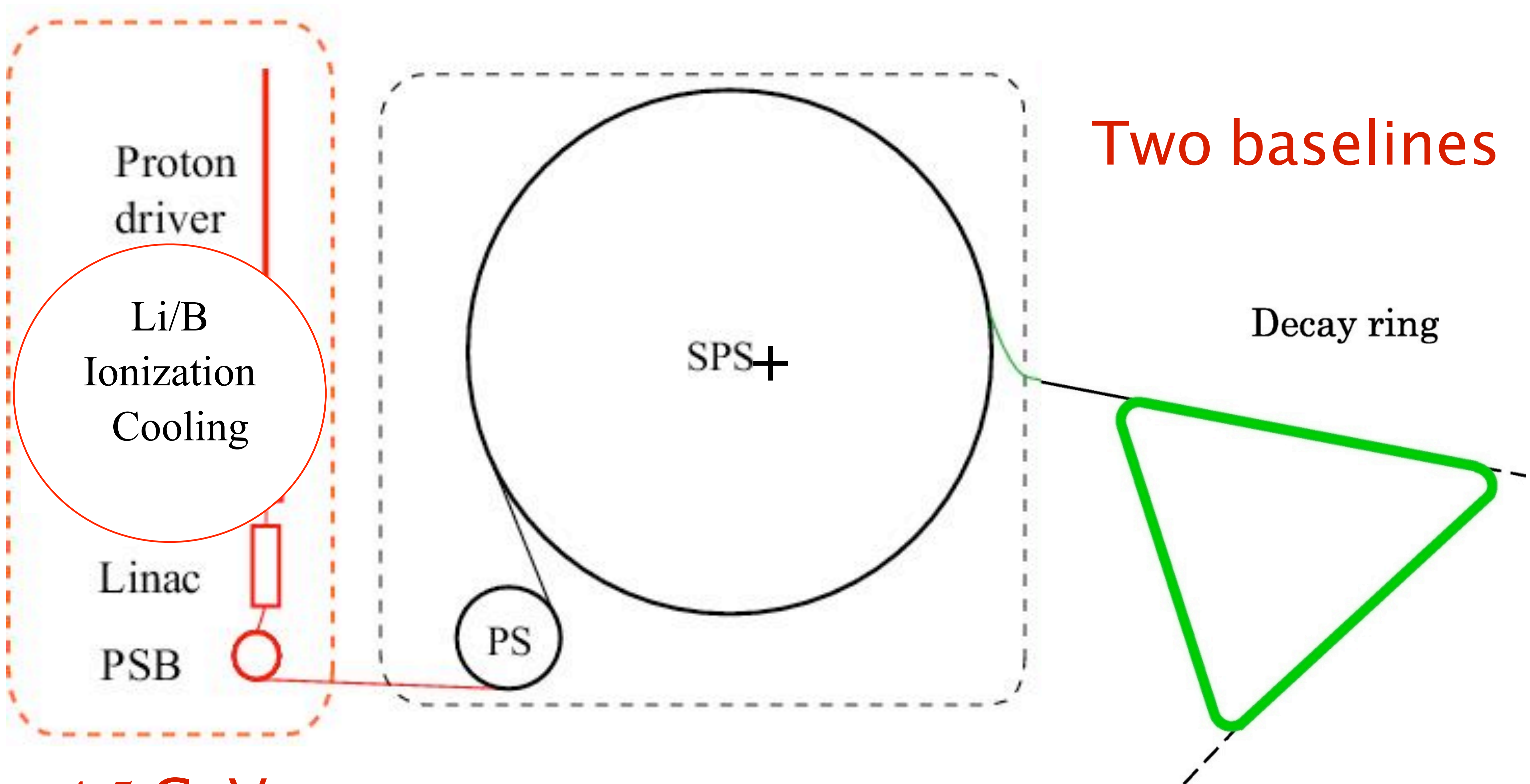
$\theta_{13} = 5^{\circ}$ $\delta = 0, 90, -90^{\circ}$



Resonant enhancement depending on the hierarchy

Sensitivity to the mass hierarchy
down to $\sin^2 2\theta_{13} = 10^{-3}$ for $\gamma = 350$

4. with $^8Li/^8B$



Two baselines

$\langle E_\nu \rangle = 4.5$ GeV

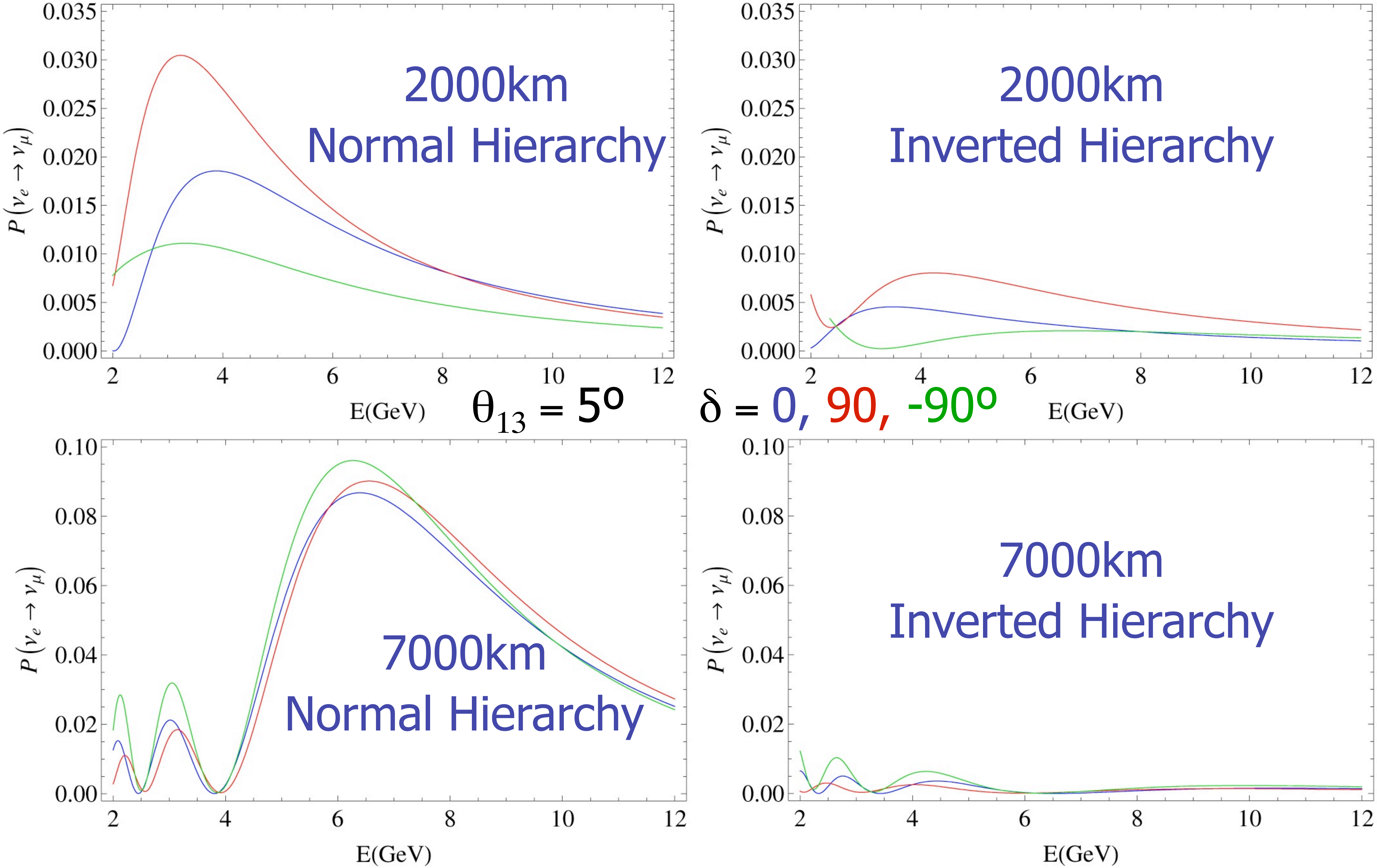
L ~ 1500 Km

L = 7000 Km

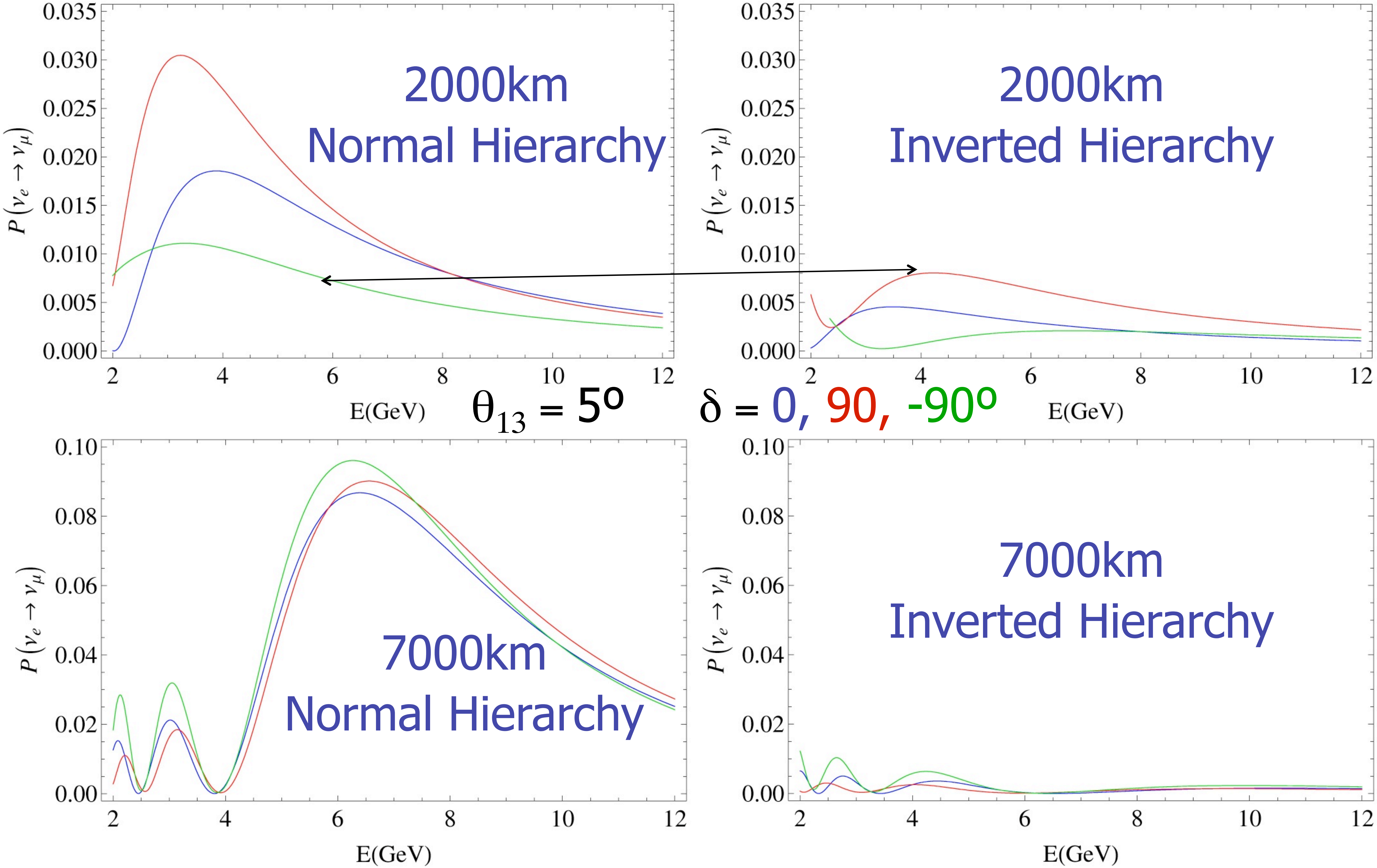
$\gamma \sim 350$

S. K. Agarwalla et al. hep-ph/0610333
S. K. Agarwalla et al. hep-ph/0611233
S. K. Agarwalla et al. arXiv:0711.1459
P. Coloma et al. arXiv:0712.0796

Add a second baseline and look for δ

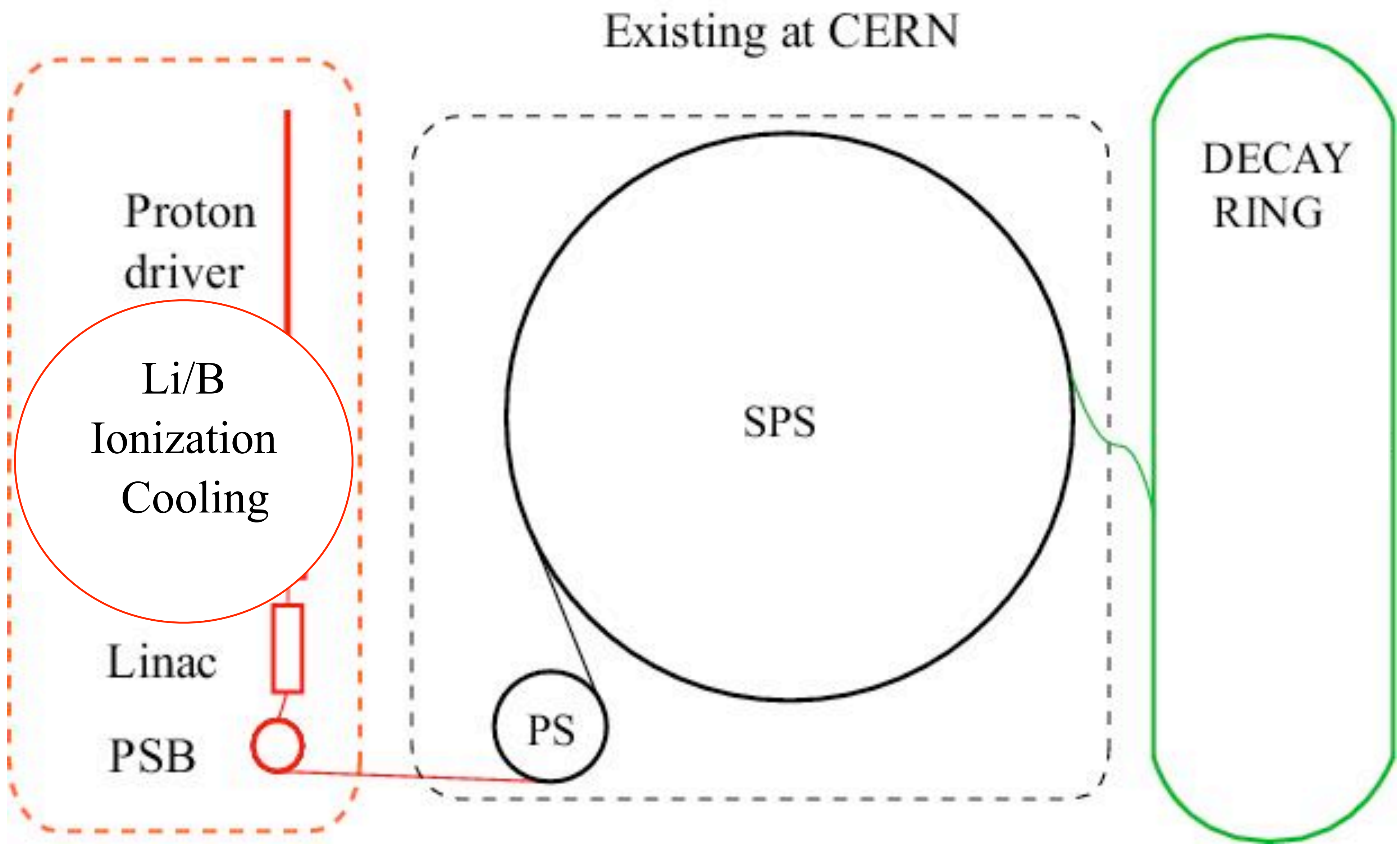


Add a second baseline and look for δ



βBeam

5. A “cocktail” of $^8Li/^8B$ and $^6He/^{18}Ne$



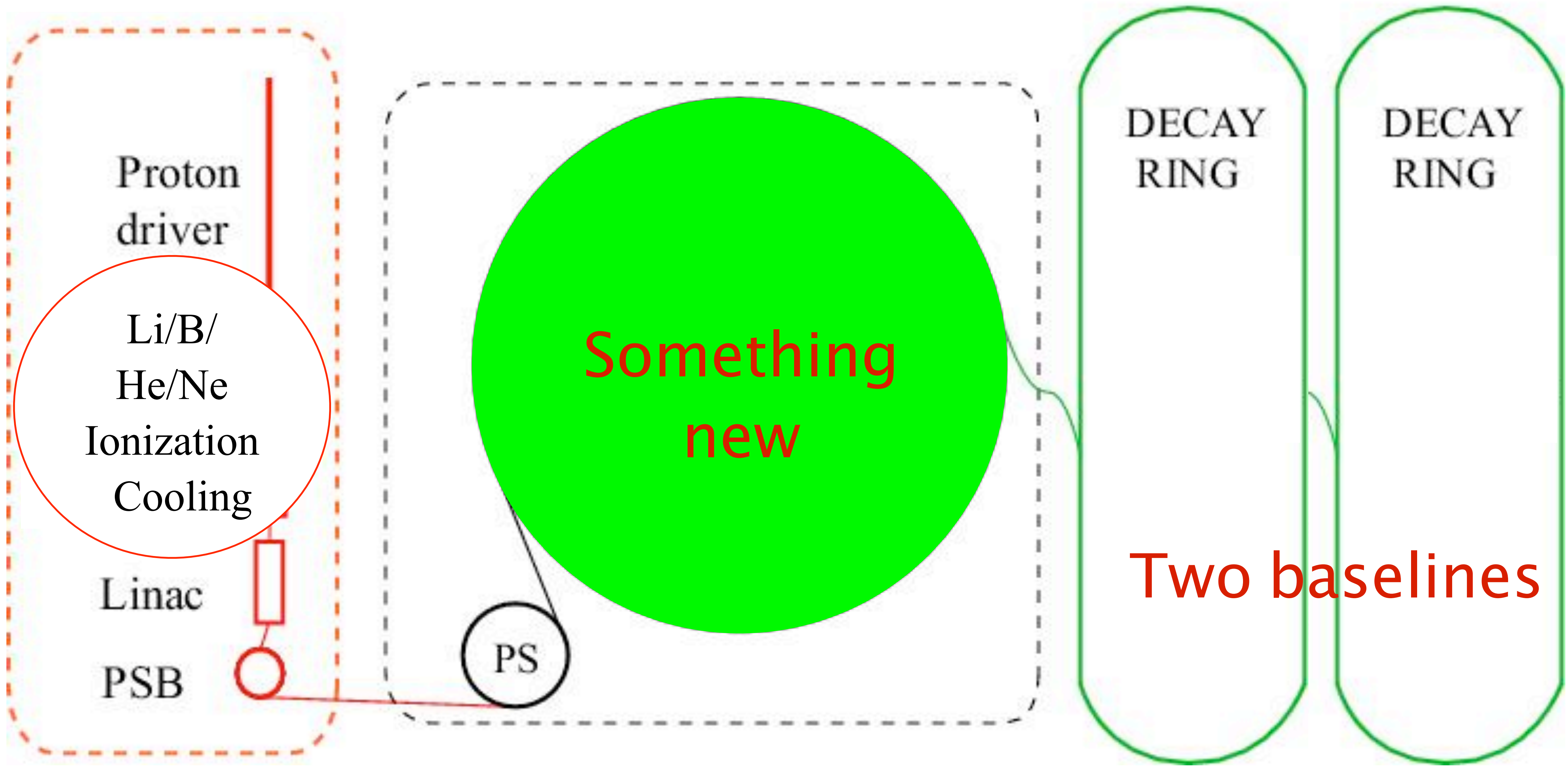
$\langle E_\nu \rangle = 1.2/1.3$ GeV

L = 650 Km

$\gamma \sim 100$ A. Donini and E. Fernández Martínez hep-ph/0603261

First and second peak at the same baseline

6. A “cocktail” of $^{8}Li/^{8}B$ and $^{6}He/^{18}Ne$



$\langle E_\nu \rangle = 2/8$ GeV

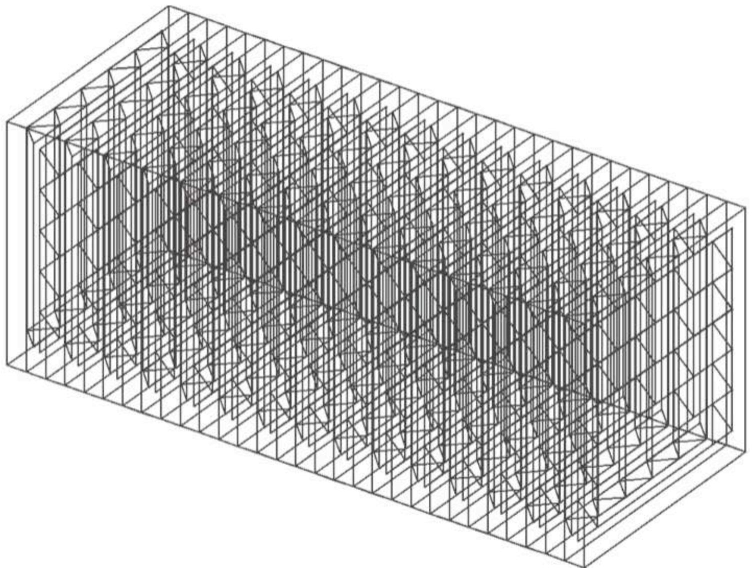
L = 1000 Km

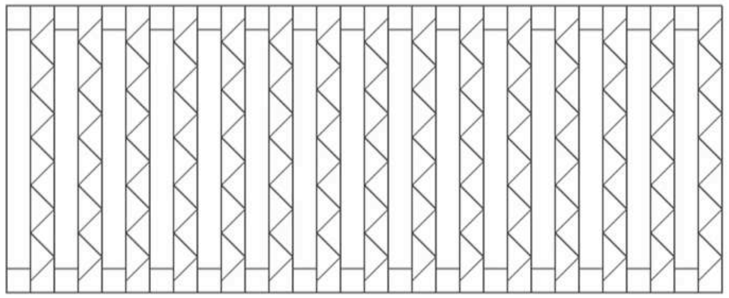
L = 7000 Km

$\gamma \sim 100$ A. Donini and E. Fernández Martínez hep-ph/0603261

$\gamma \sim 650$ S. K. Agarwalla et al. arXiv:0804.3007

TASD



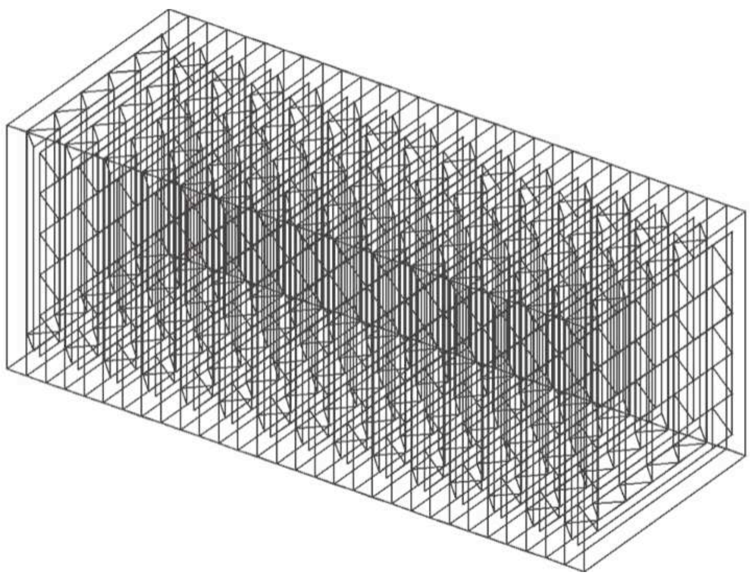


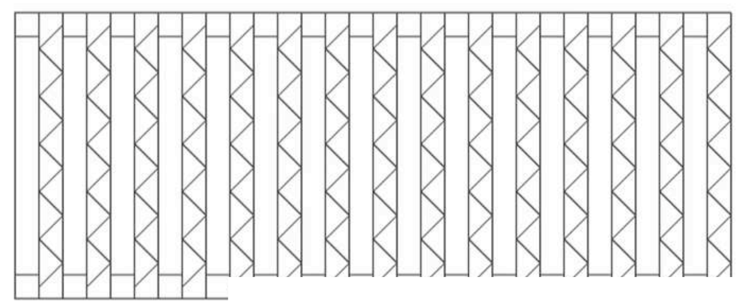
22.5 Kton Mass

An extrapolation of Minerνa

Suited for low energy muons

TASD

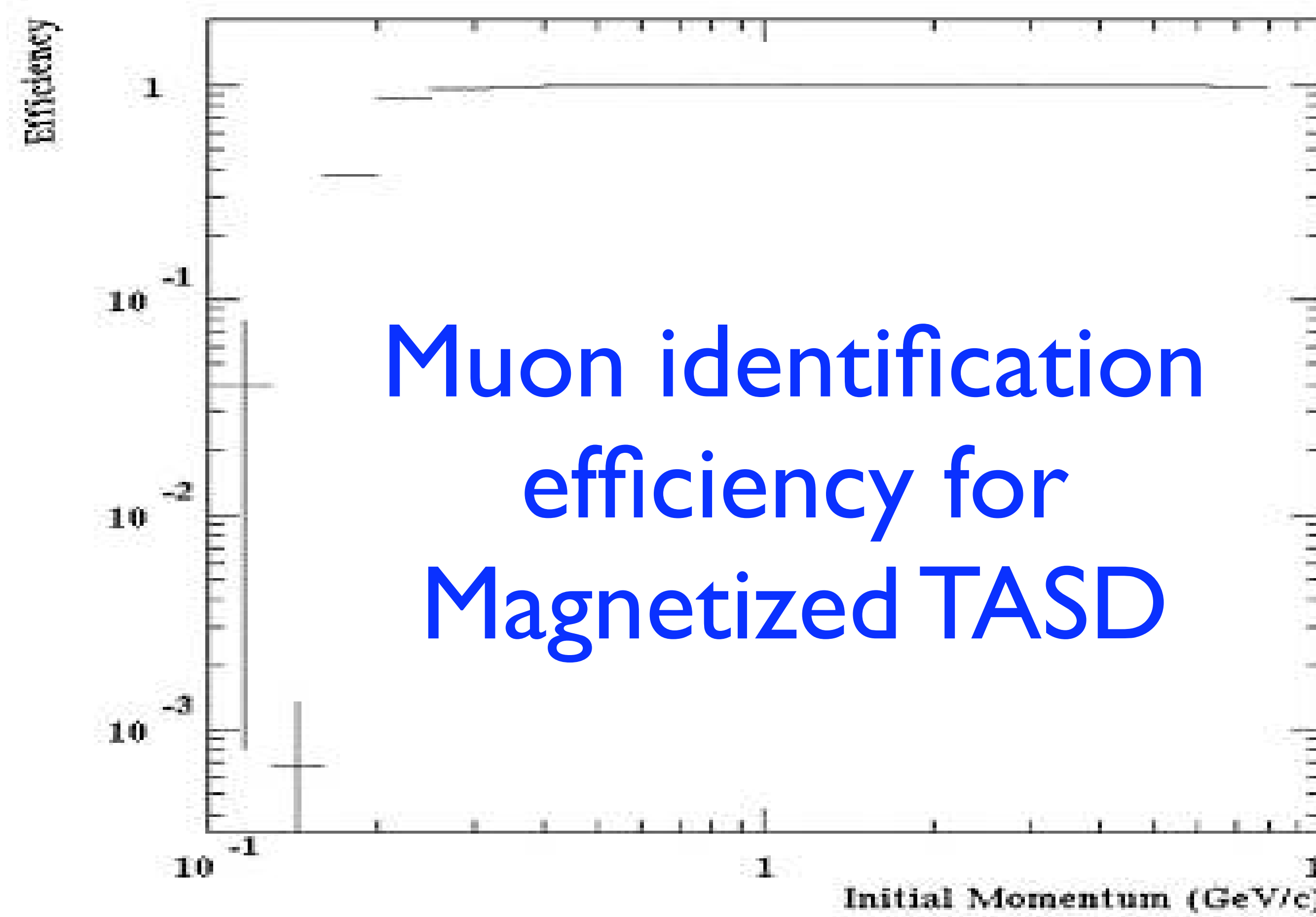




22.5 Kton Mass

An extrapolation of Minerνa

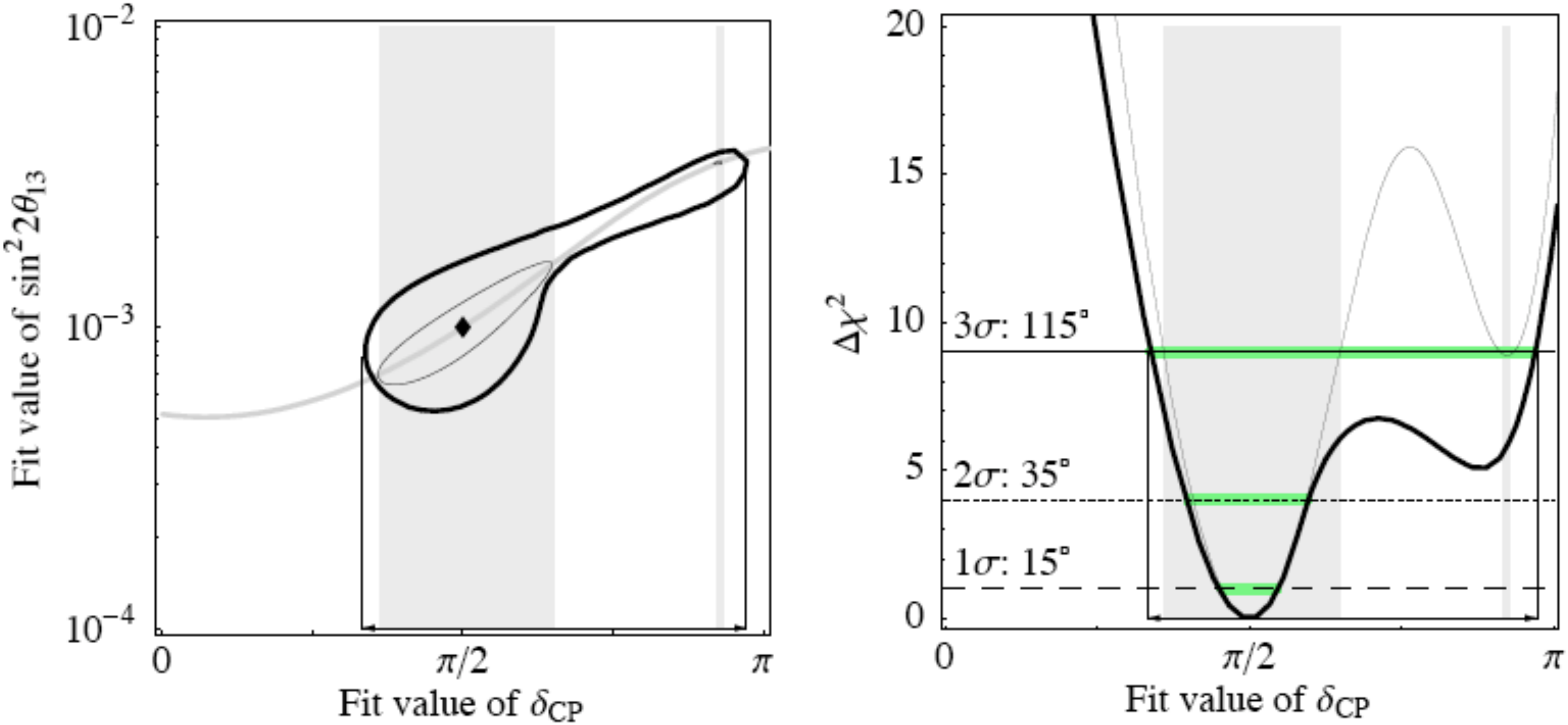
Suited for low energy muons



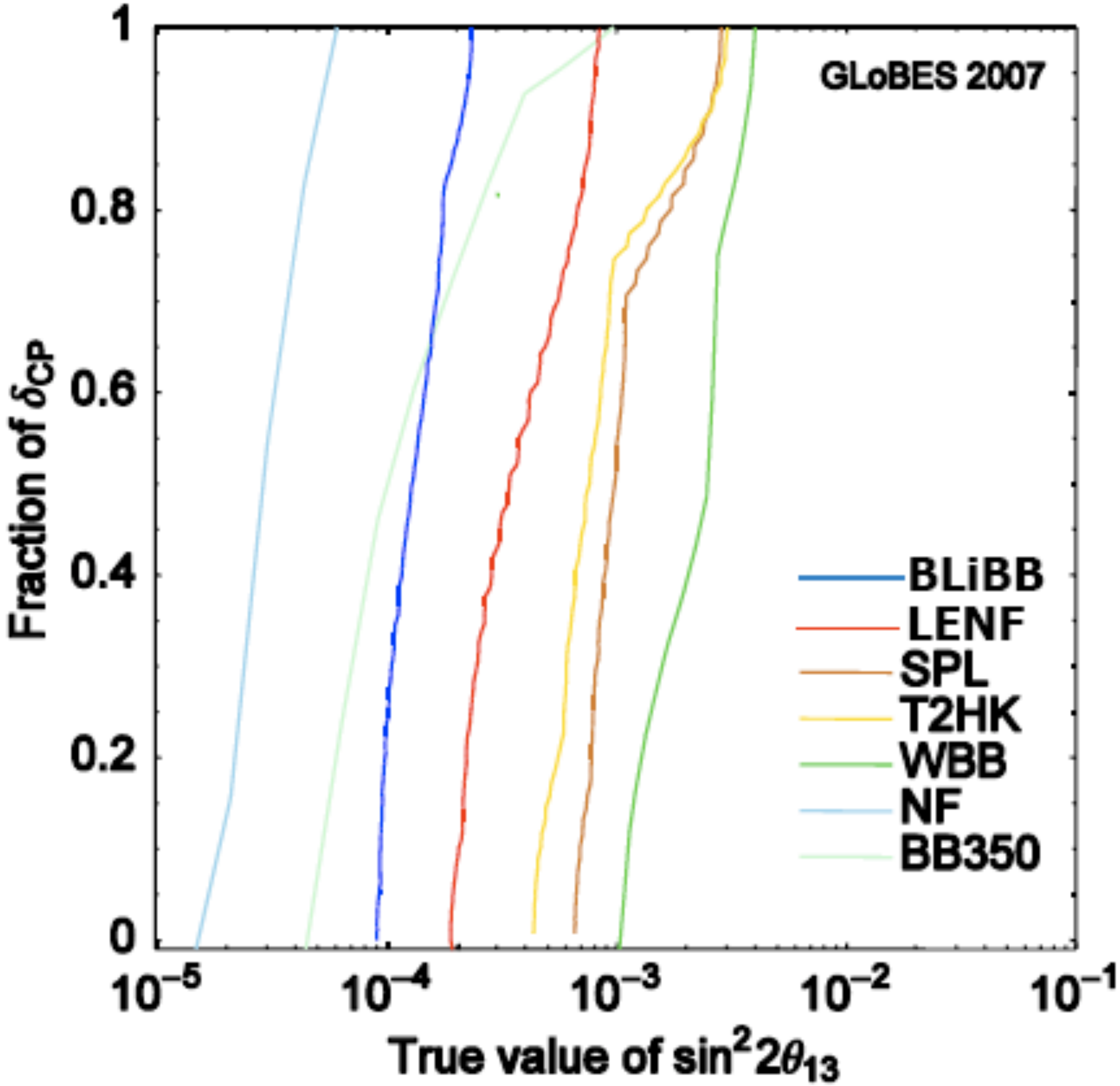
Muon identification efficiency for Magnetized TASD

CONCLUSIONS

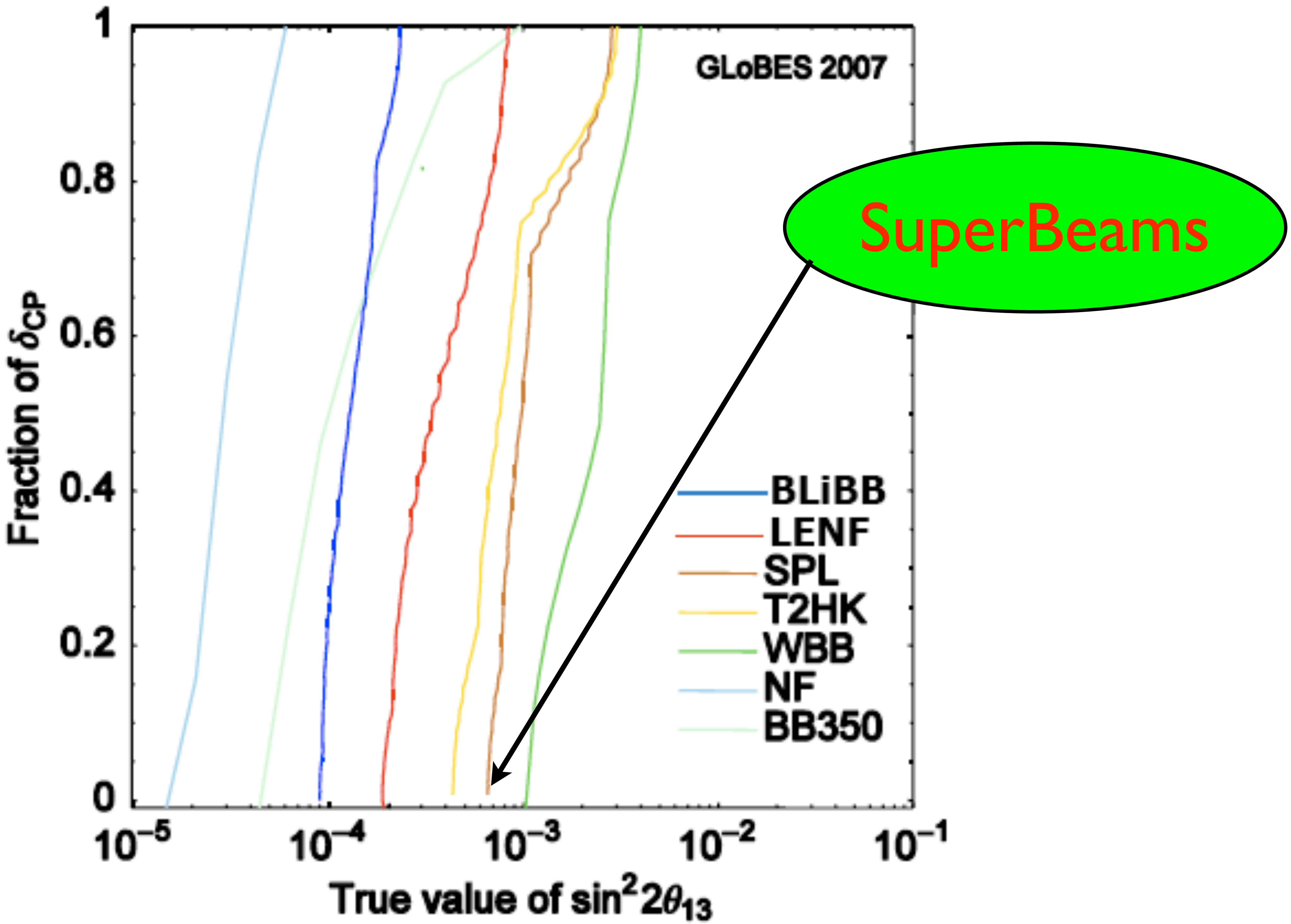
Definition of the CP-fraction



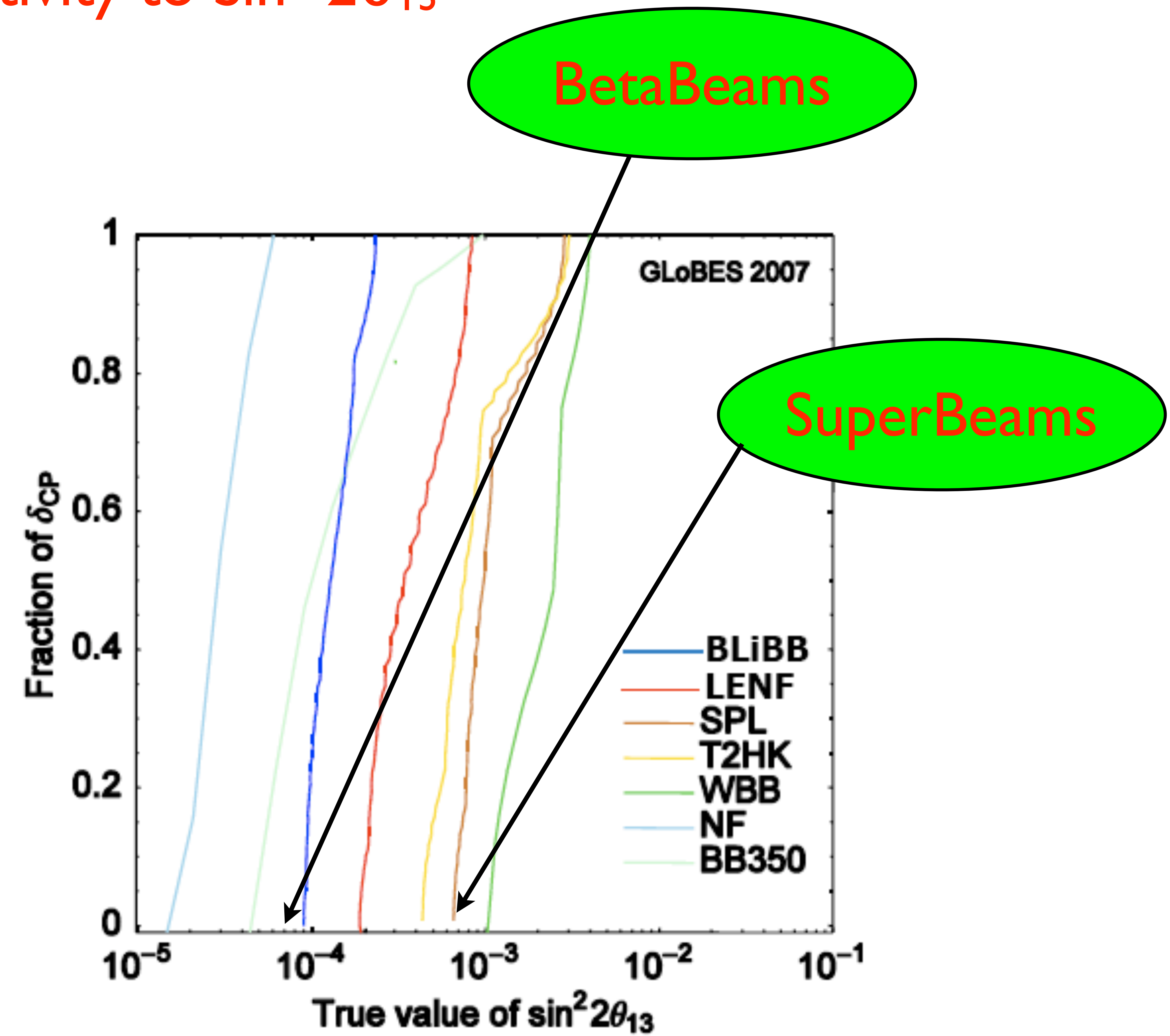
Sensitivity to $Sin^2\ 2\theta_{13}$



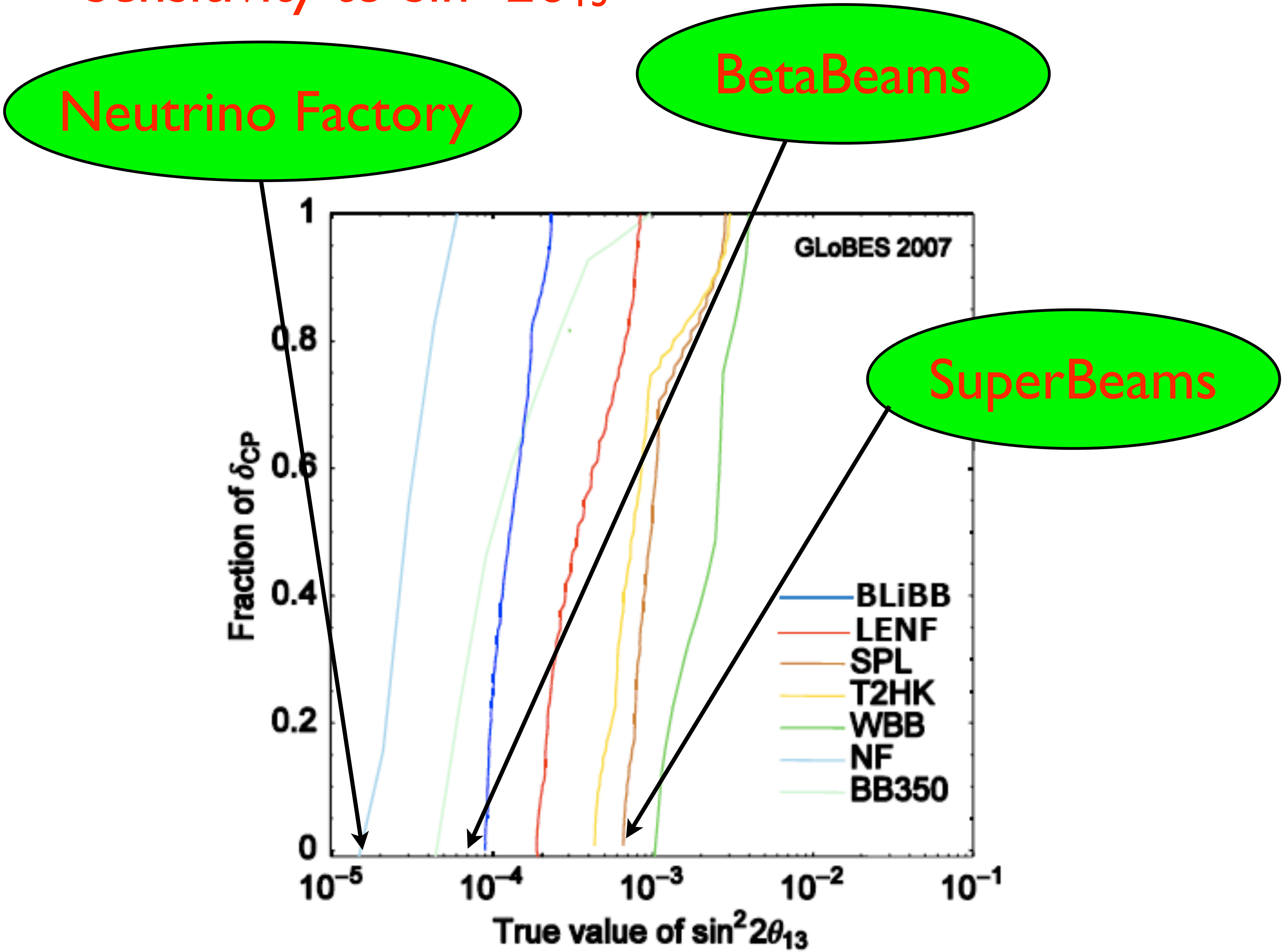
Sensitivity to $Sin^2 2\theta_{13}$

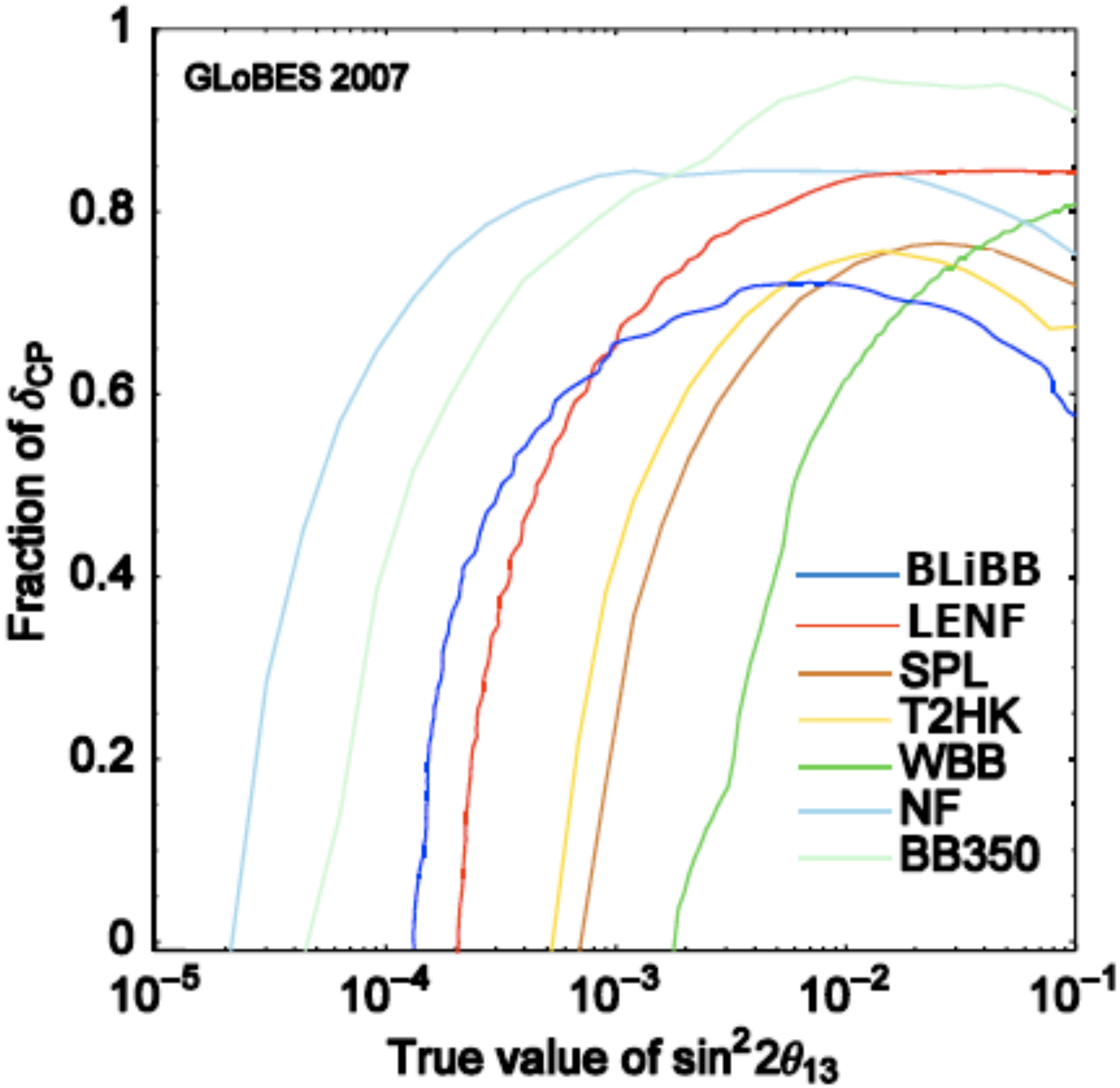


Sensitivity to $\sin^2 2\theta_{13}$

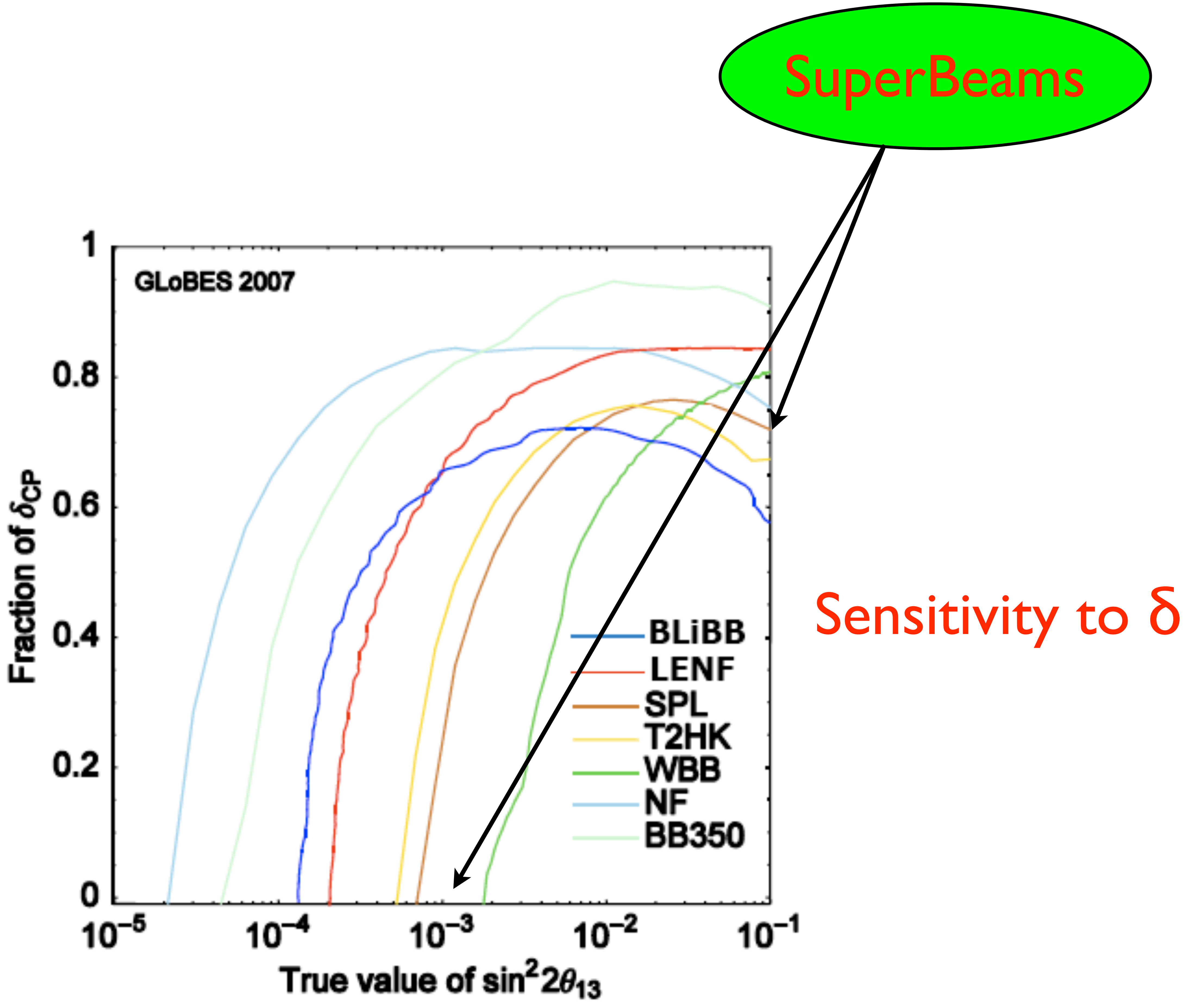


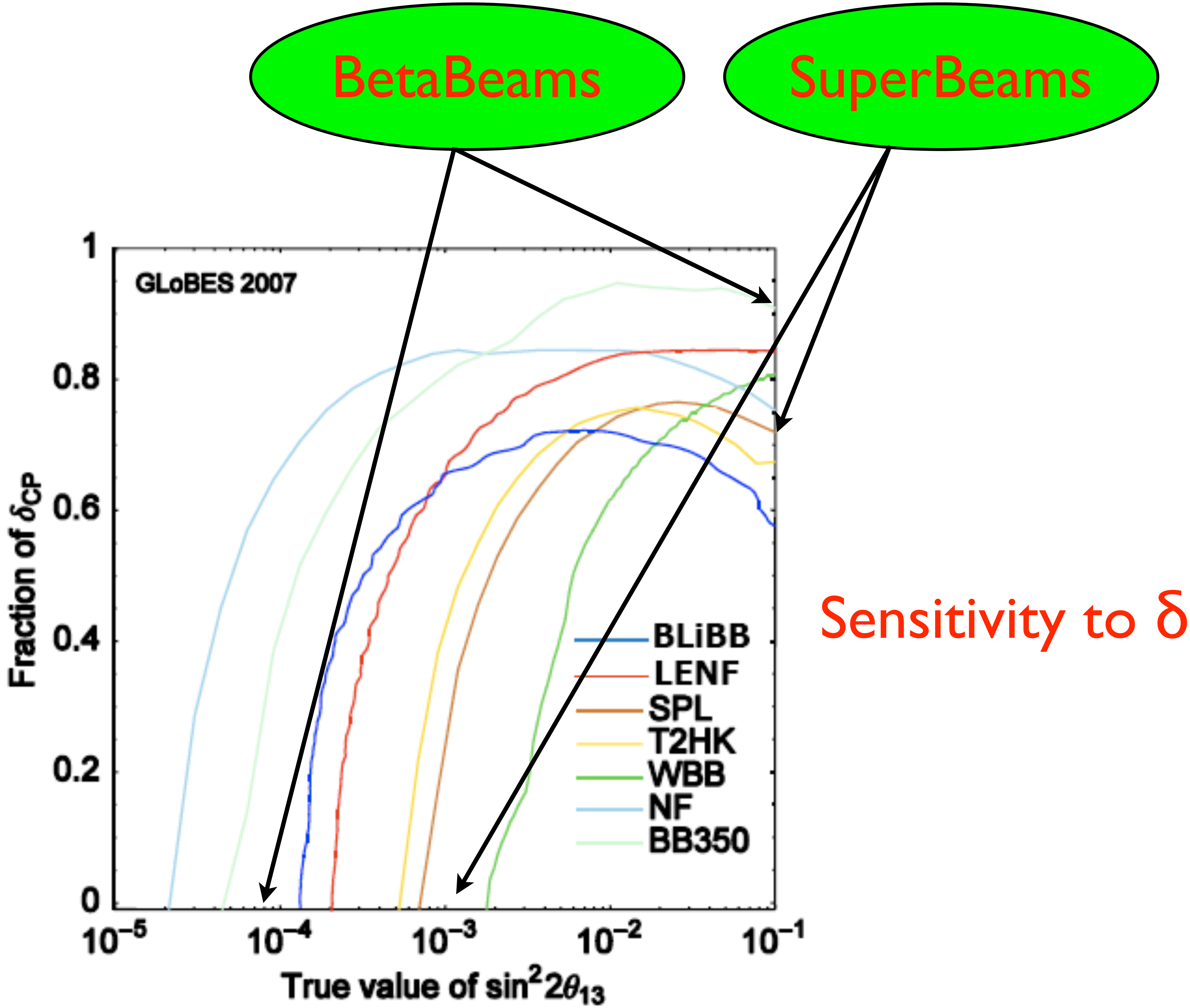
Sensitivity to $\sin^2 2\theta_{13}$

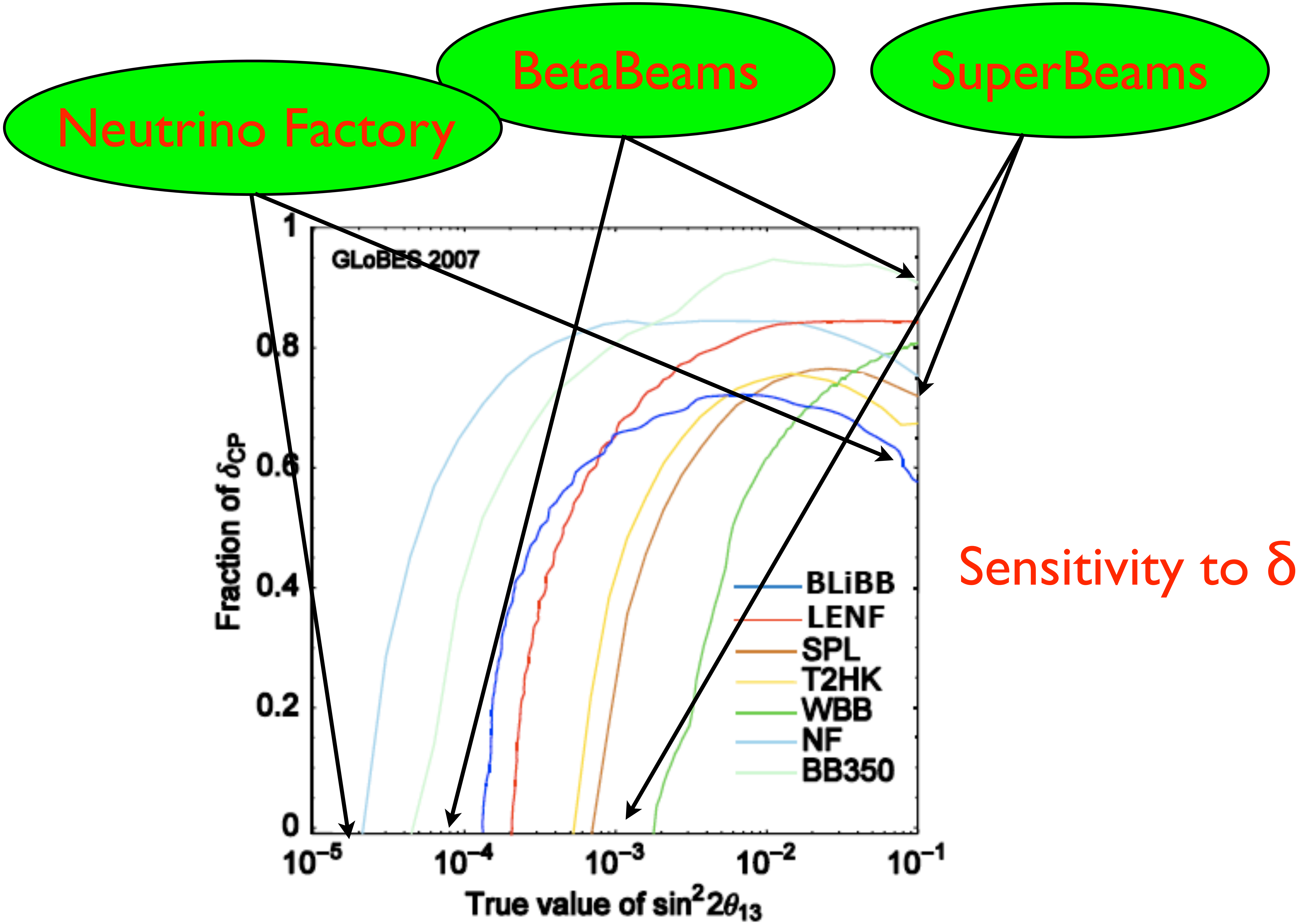




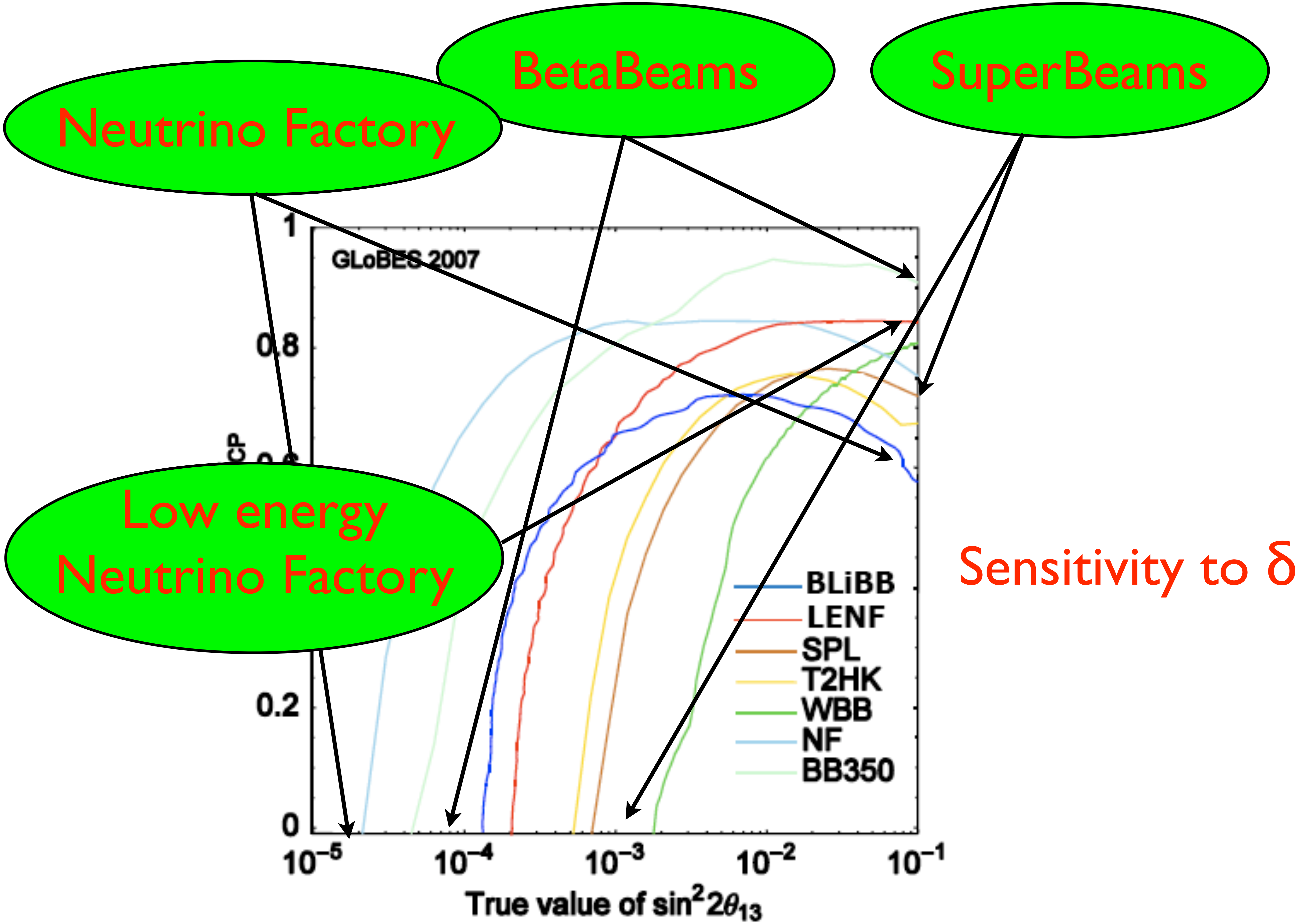
Sensitivity to δ


SuperBeams
GLoBES 2007
Fraction of δ_{CP}
1
0.8
0.6
0.4
0.2
0
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
True value of $\sin^2 2\theta_{13}$
BLiBB
LENF
SPL
T2HK
WBB
NF
BB350
Sensitivity to δ


BetaBeams
SuperBeams
GLoBES 2007
Fraction of δ_{CP}
True value of $\sin^2 2\theta_{13}$
BLiBB
LENF
SPL
T2HK
WBB
NF
BB350
Sensitivity to δ

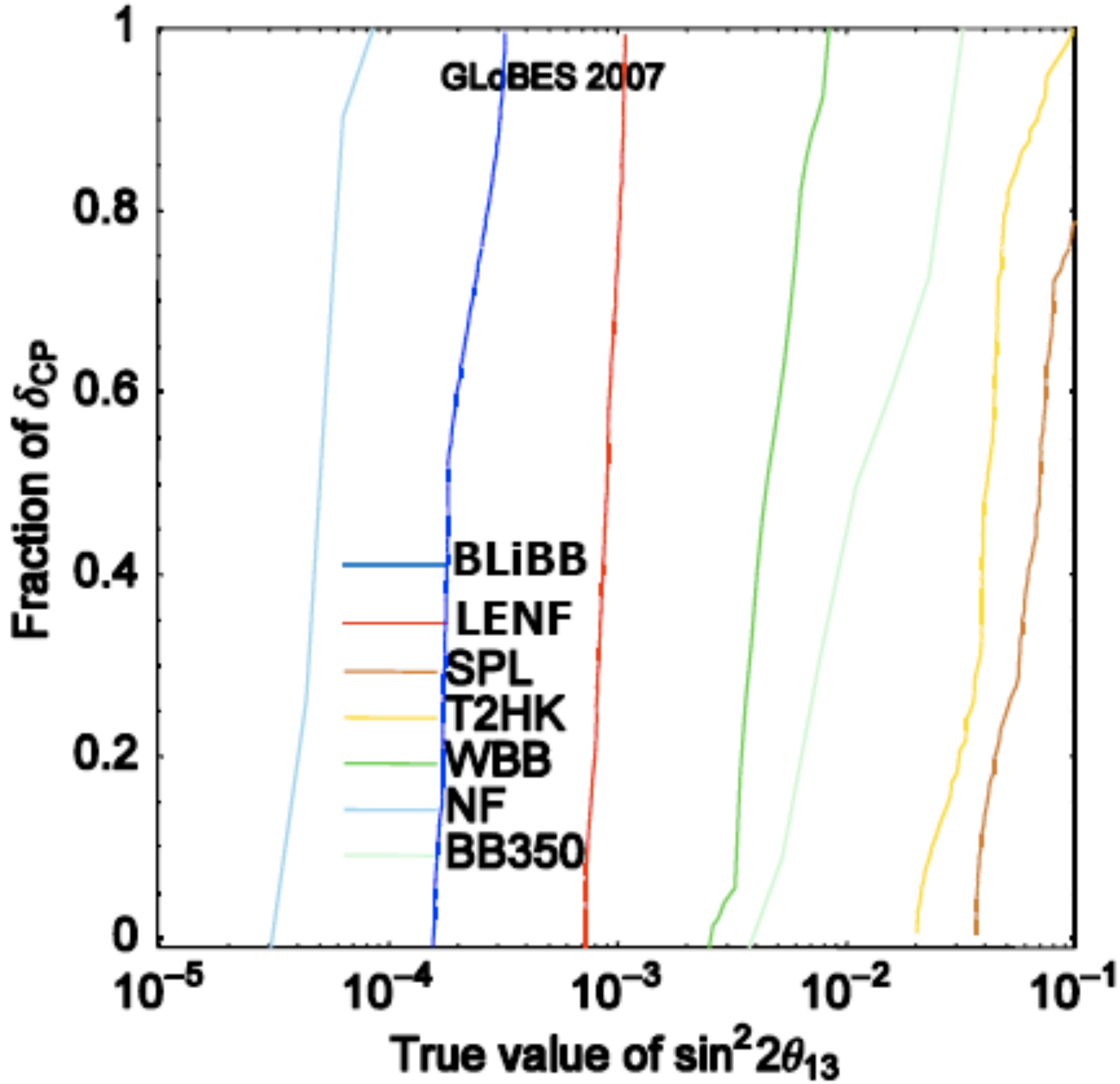


Neutrino Factory
BetaBeams
SuperBeams
GLoBES 2007
Fraction of δ_{CP}
True value of $\sin^2 2\theta_{13}$
BLiBB
LENF
SPL
T2HK
WBB
NF
BB350
Sensitivity to δ

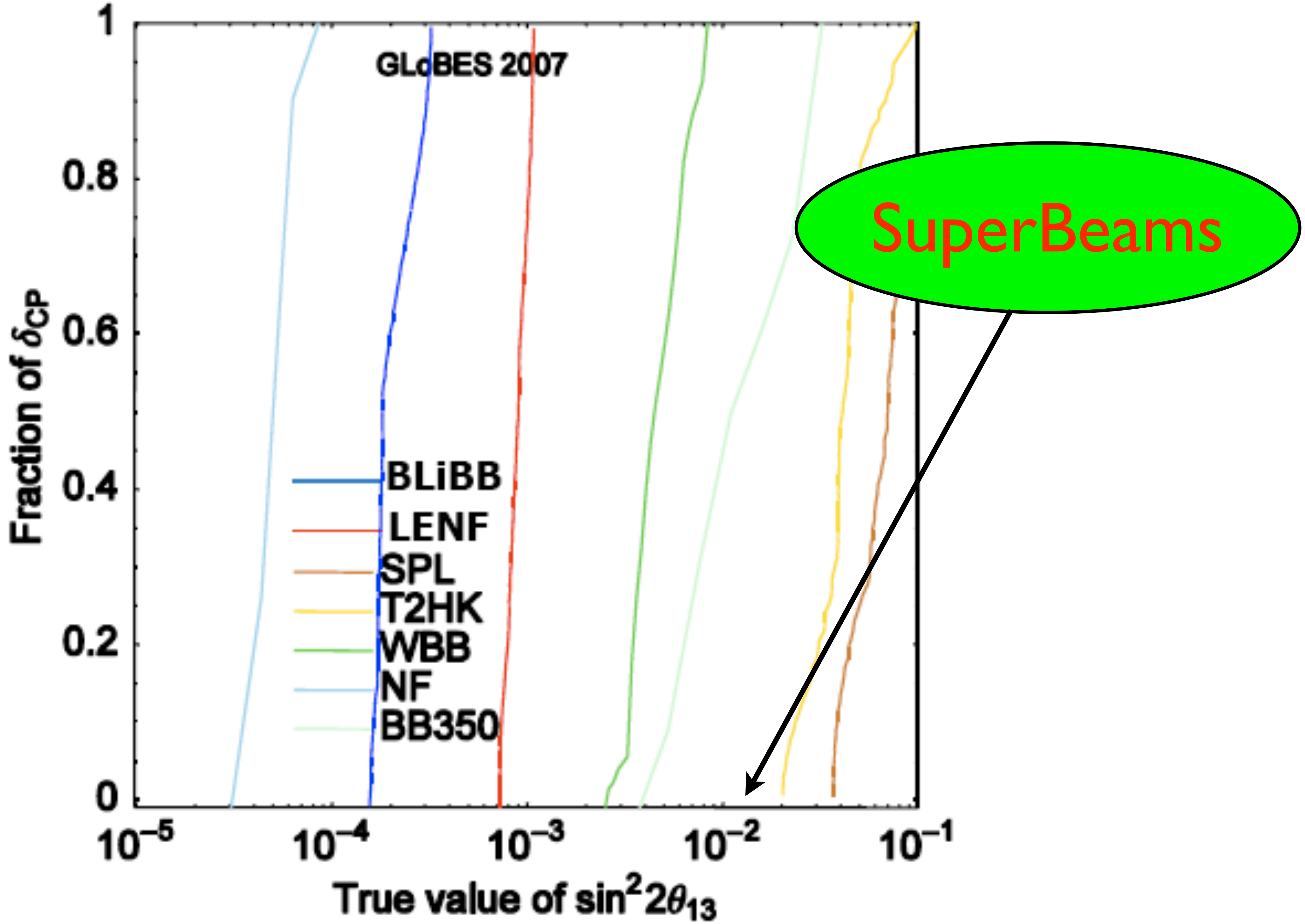


Neutrino Factory
BetaBeams
SuperBeams
Low energy Neutrino Factory
GLoBES 2007
BLiBB
LENF
SPL
T2HK
WBB
NF
BB350
True value of $\sin^2 2\theta_{13}$
Sensitivity to δ

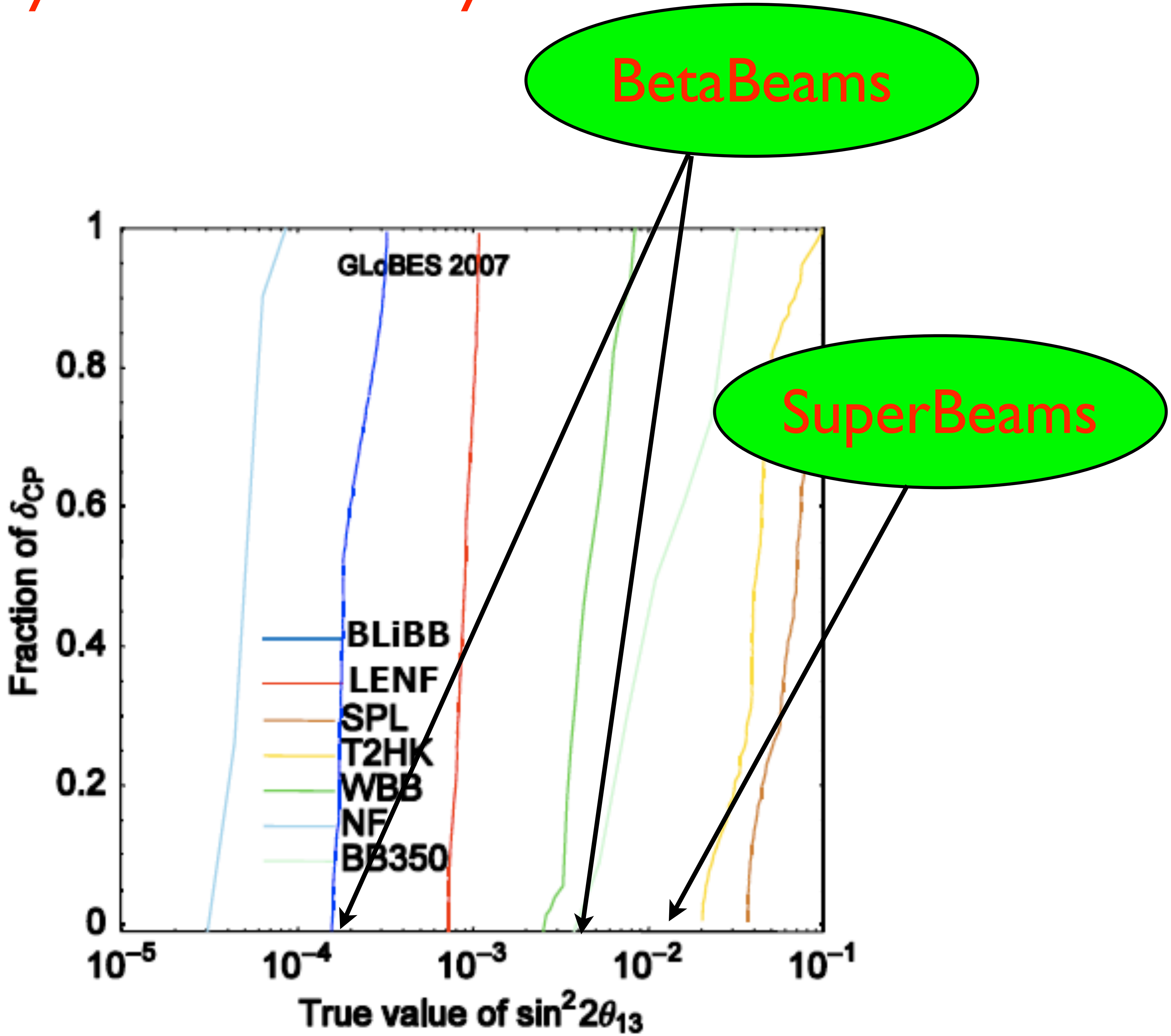
Sensitivity to the hierarchy



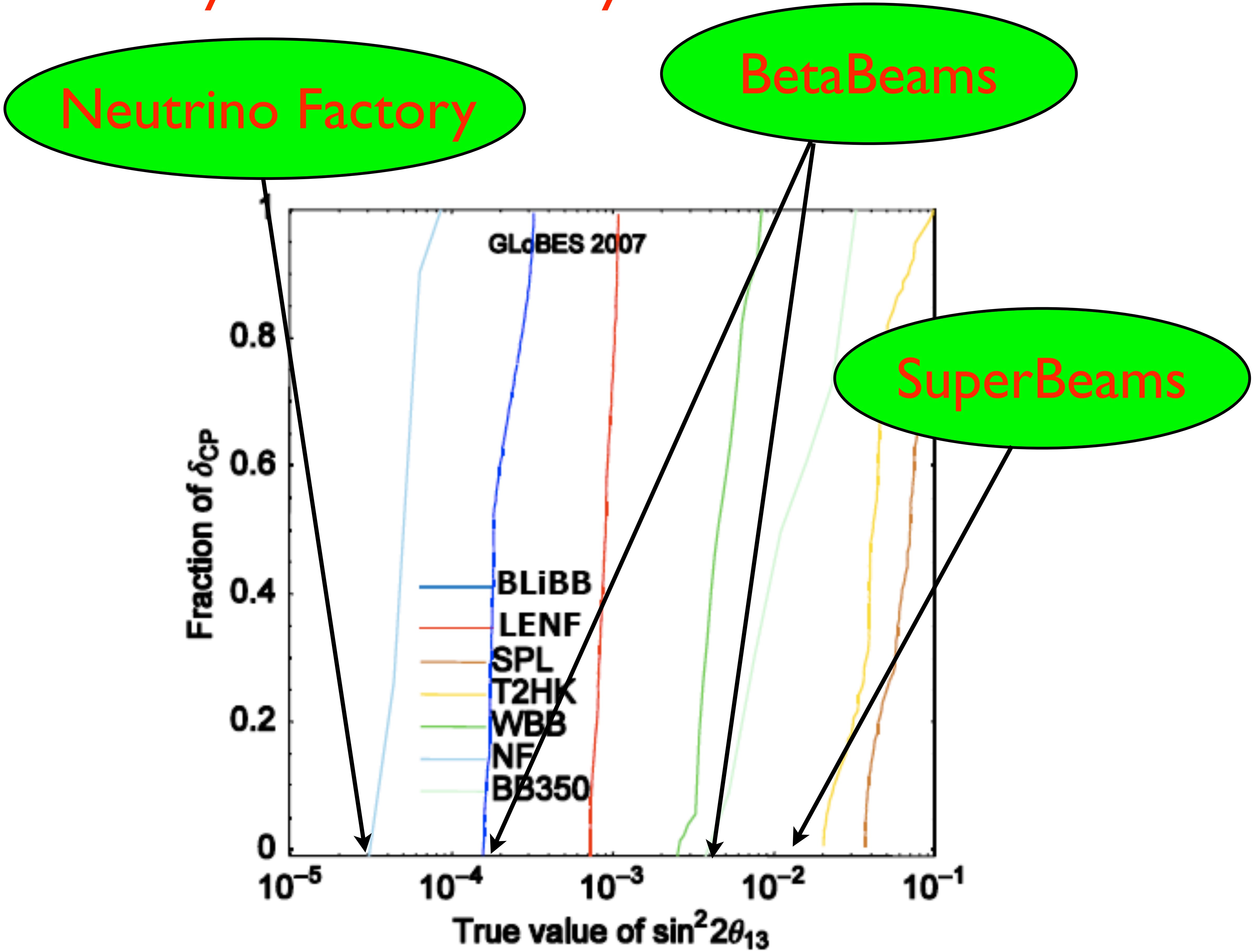
Sensitivity to the hierarchy



Sensitivity to the hierarchy



Sensitivity to the hierarchy



- The goal: measure at the same time the four parameters that we do not yet know: θ_{13}, δ, the sign of Δm^2_{23} and the θ_{23}-octant

- A plethora of possibilities (and we are still thinking....). It is crucial to take a decision to see which are the results of D-Chooz, T2K and NOνA.

- If θ_{13} is large, then it is time for precision phyics AND to look for new physics

μ→eγ in supersymmetric models with heavy right-handed neutrinos

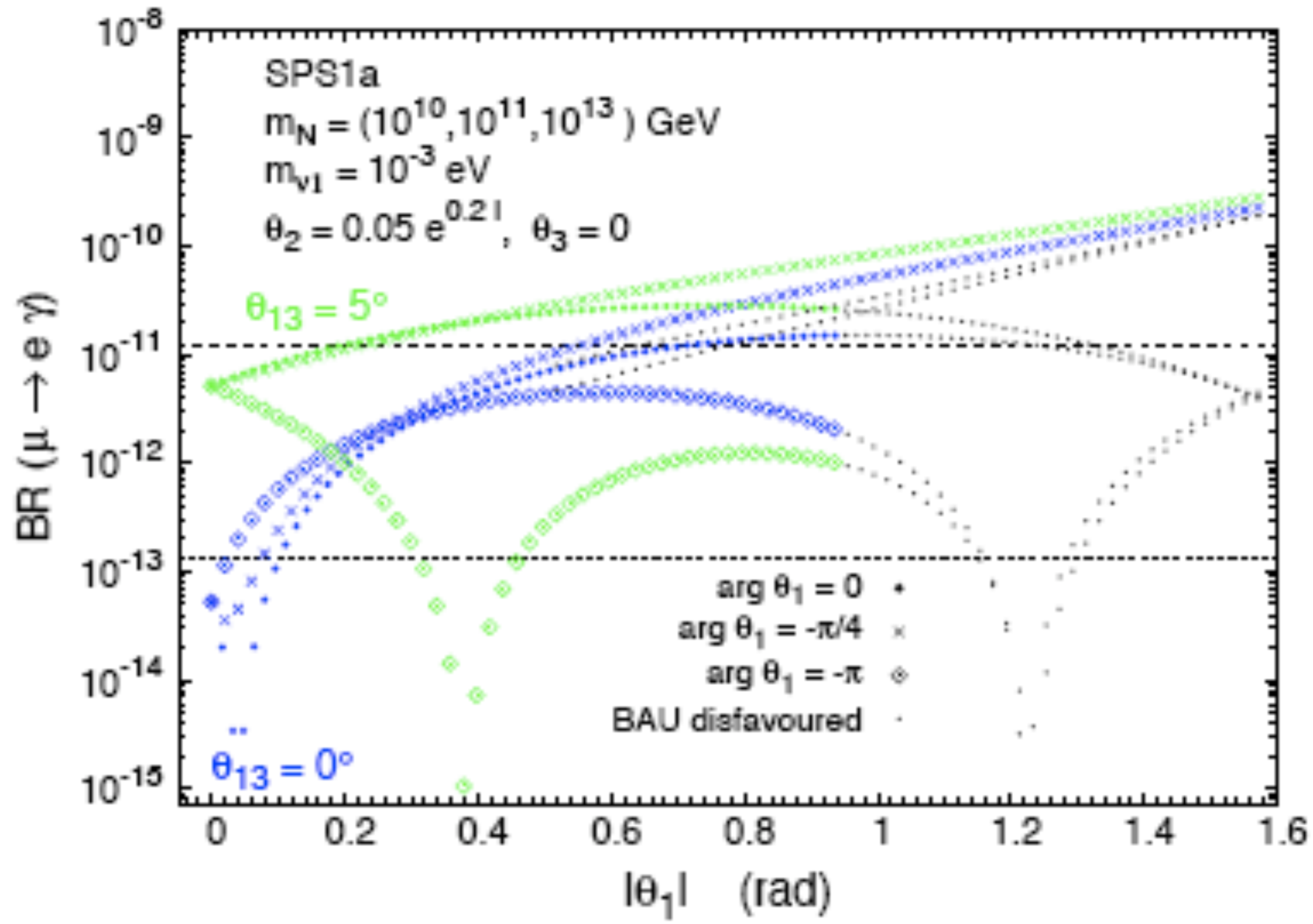


Figure 7: BR($\mu \to e\,\gamma$) as a function of $|\theta_1|$, for $\arg\theta_1 = \{0\,, -\pi/4\,, -\pi\}$ (dots, times, diamonds, respectively) and $\theta_{13} = 0°\,, 5°$ (blue/darker, green/lighter lines). BAU is enabled by the choice $\theta_2 = 0.05\,e^{0.2i}$ ($\theta_3 = 0$). In all cases black dots represent points associated with a disfavoured BAU scenario and a dashed(dotted) horizontal line denotes the present experimental bound (future sensitivity).

E. Arganda et al. hep-ph/0607263

- It is also crucial that accelerator studies continue to understand the feasability of the more extreme setups, such as the Neutrino Factories or the (high-γ) BetaBeams

- The european neutrino community must take a decision by 2012, according to what we have signed in the FP7 of the EU