Unraveling Neutrino Parameters with a Magical Beta-Beam at INO

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work done in collaboration with

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Based on arXiv:0711.1459

See also hep-ph/0610333, arXiv:0802.3621 & arXiv:0804.3007

Nufact 08

!!! Muchas Gracias !!!

Where do we stand today?

Parameter	Best fit	3σ (1 d.o.f)
Δm^2_{21} $[10^{-5}\ eV^2]$	7.6	7.1–8.3
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\ eV^2]$	2.4	2.0–2.8
$\sin^2\theta_{12}$	0.32	0.26–0.40
$\sin^2\theta_{23}$	0.50	0.34–0.67
$\sin^2\theta_{13}$	0.007	$\leq$ 0.050

M. Maltoni, T. Schwetz, M.A. Tortola, J.W.F. Valle, hep-ph/0405172v6

Best-fit values under 3 flavour scheme

Data from Solar + Atmospheric + Reactor (KamLAND and CHOOZ) + Accelerator (K2K and MINOS) expts

Unsolved Issues

- The sign of Δm^2_{31} ($m^2_3 - m^2_1$) is not known.
  Mass ordering can be normal or inverted hierarchical
- Only an upper limit on $\sin^2 2\theta_{13}$ (< 0.17 at 3σ) exists
- The Dirac CP phase (δ_{CP}) is unconstrained

!!! How can we probe these missing links? !!!

!!! Best Bet : Golden Channel !!!

Golden Channel ($P_{e\mu}$)

The appearance probability ($\nu_e \to \nu_\mu$) in matter, upto second order in the small parameters $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin 2\theta_{13}$,

$$
\begin{aligned}
P_{e\mu} \quad &\simeq \quad \sin^2 2\theta_{13}\, \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
&\pm \quad \alpha \sin 2\theta_{13}\, \xi \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
&+ \quad \alpha \sin 2\theta_{13}\, \xi \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
&+ \quad \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2};
\end{aligned}
$$

where $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\xi \equiv \cos\theta_{13}\, \sin 2\theta_{21}\, \sin 2\theta_{23}$,
and $\hat{A} \equiv (\pm 2\sqrt{2} G_F n_e E)/\Delta m^2_{31}$

Cervera *et al.*hep-ph/0002108 & Freund, Huber, Lindner, hep-ph/0105071

Eight-fold Degeneracy & Magic Baseline

- $(\theta_{13}, \delta_{CP})$ intrinsic degeneracy

  Burguet-Castell, Gavela, Gomez-Cadenas, Hernandez, Mena, hep-ph/0103258

- $(sgn(\Delta m^2_{31}), \delta_{CP})$ degeneracy

  Minakata, Nunokawa, hep-ph/0108085

- $(\theta_{23}, \pi/2 - \theta_{23})$ degeneracy

  Fogli, Lisi, hep-ph/9604415

Degeneracies create “Clone” Solutions

Barger, Marfatia, Whisnant, hep-ph/0112119

Kill the “Clones” at the “Magic” Baseline

Huber, Winter, hep-ph/0301257

Smirnov, hep-ph/0610198

Magic Baseline

If one chooses : $\sin(\hat{A}\Delta) = 0$

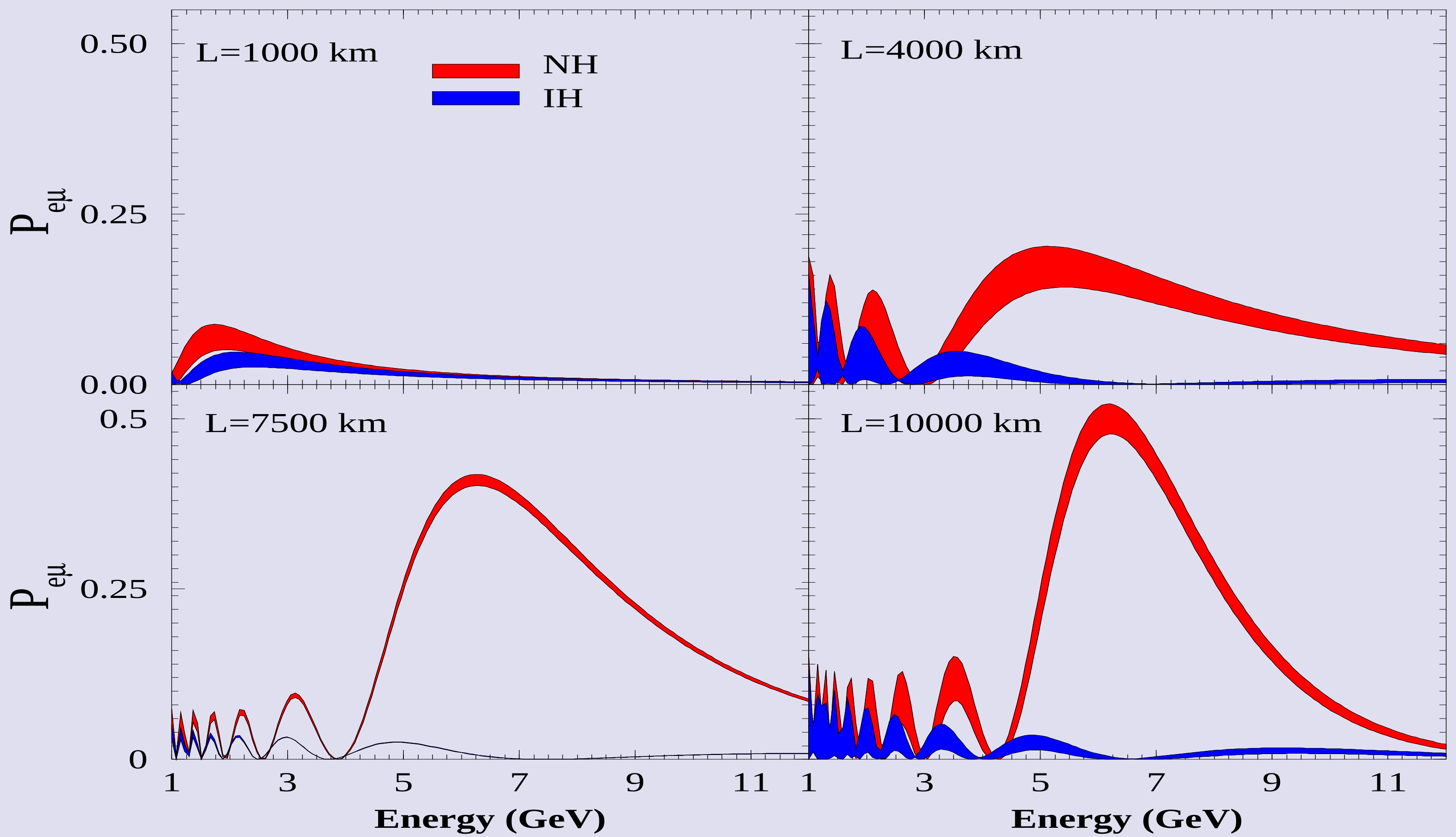
- The δ_{CP} dependence disappears from $P_{e\mu}$
- Golden channel enables a clean determination of θ_{13} and $sgn(\Delta m^2_{31})$

First non-trivial solution: $\sqrt{2} G_F n_e L = 2\pi$ **(indep of E)**

- Isoscalar medium of constant density ρ :
  $L_{\rm magic}[{\rm km}] \approx 32725/\rho[{\rm gm/cm^3}]$
- **According to PREM, the "Magic Baseline"**

$L_{\rm magic}$ = 7690 km

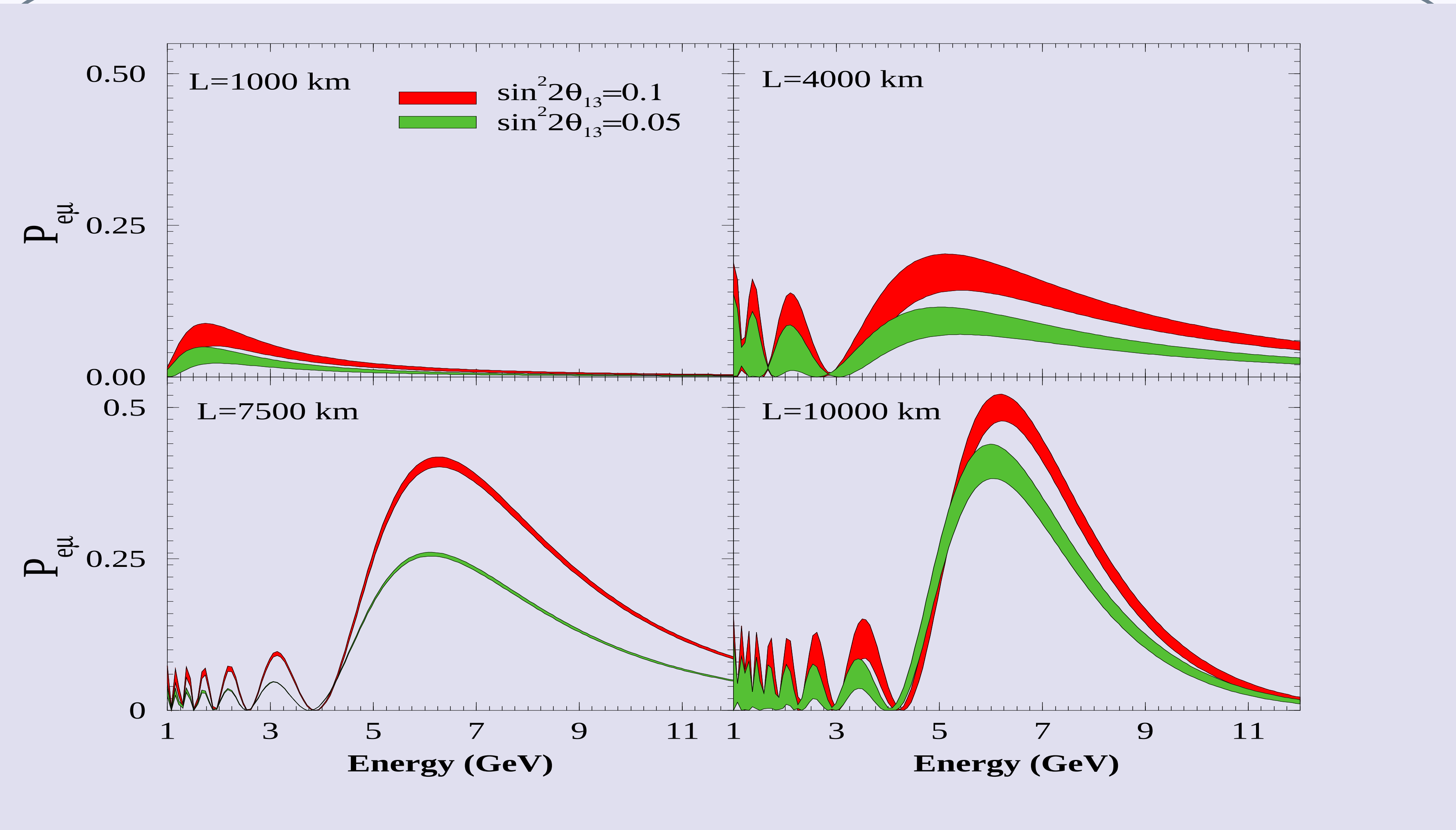
Transition Probability $P_{e\mu}$



Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

Normal .vs. Inverted hierarchy $\sin^2 2\theta_{13} = 0.1$

Transition Probability $P_{e\mu}$

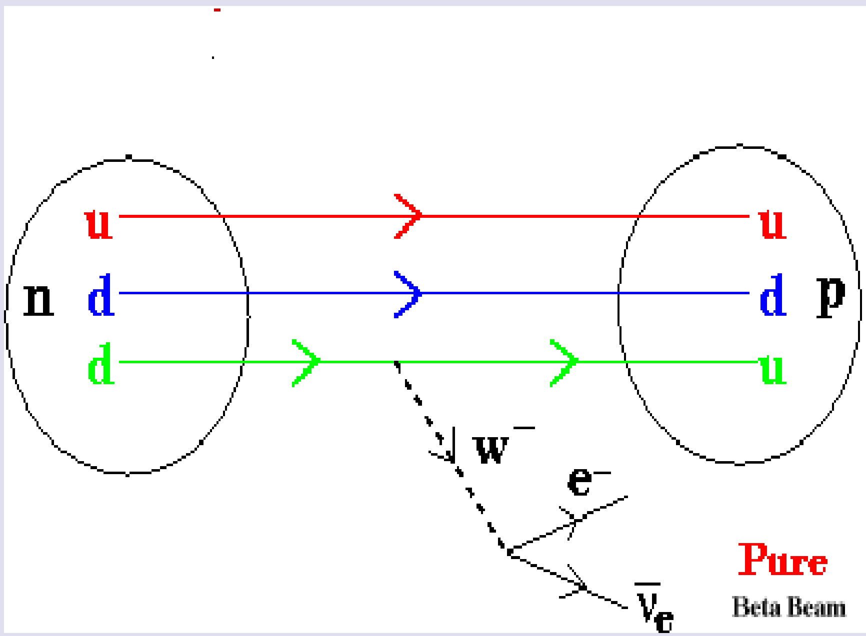


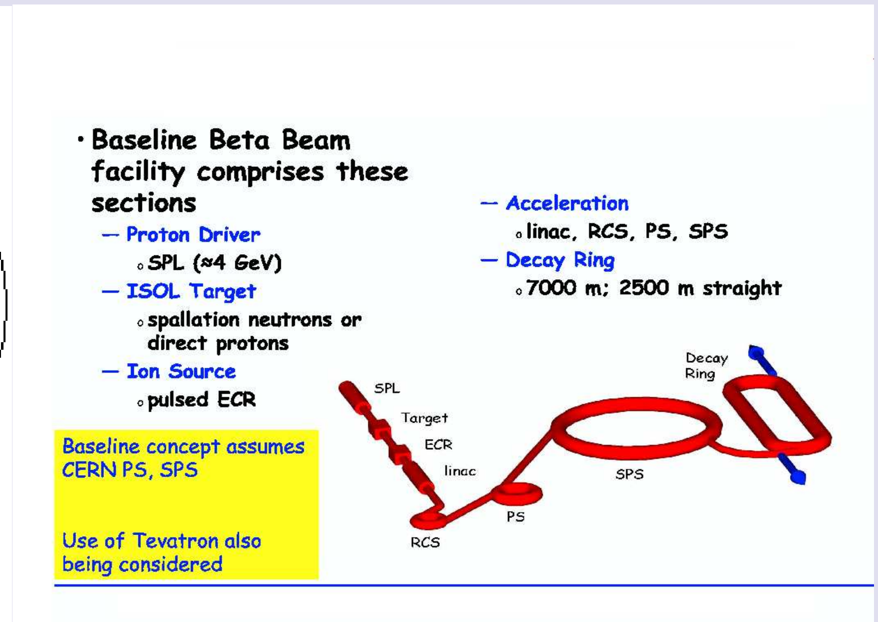
Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

Two different values of $\sin^2 2\theta_{13}$ **Normal hierarchy**

What is a Beta-Beam?

A pure, intense, collimated beam of ν_e or $\bar{\nu}_e$, essentially background free





P. Zucchelli, Phys. Lett. B 532 (2002) 166

Detailed R&D by Prof. Mats Lindroos and his team

Beta decay of completely ionized, radioactive ions circulating in a storage ring. No contamination of other types of neutrinos

Beta-Beam : Ion sources

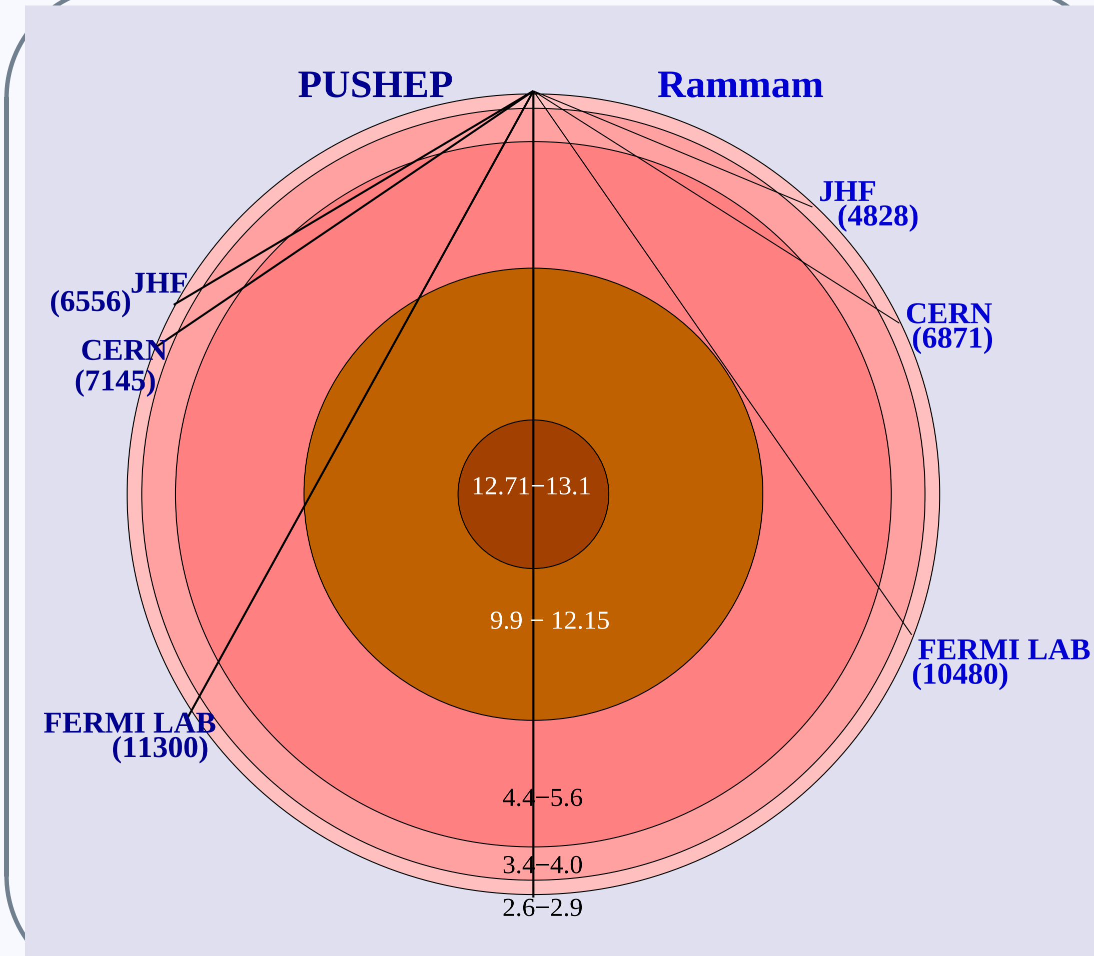
Ion	τ (s)	E_0 (MeV)	f	Decay fraction	Beam
$^{18}_{10}$Ne	2.41	3.92	820.37	92.1%	ν_e
$^{6}_{2}$He	1.17	4.02	934.53	100%	$\bar{\nu}_e$
$^{8}_{5}$B	1.11	14.43	600684.26	100%	ν_e
$^{8}_{3}$Li	1.20	13.47	425355.16	100%	$\bar{\nu}_e$

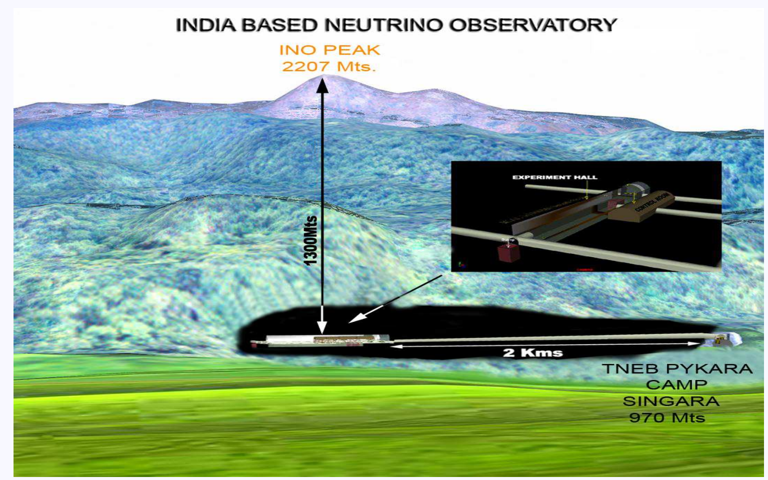
Comparison of different source ions

Low-γ design, useful decays in case of anti-neutrinos can be 2.9×10^{18}/year and for neutrinos 1.1×10^{18}/year

Large (Small) E_0 $\Rightarrow$ Preferred for long (short) baseline

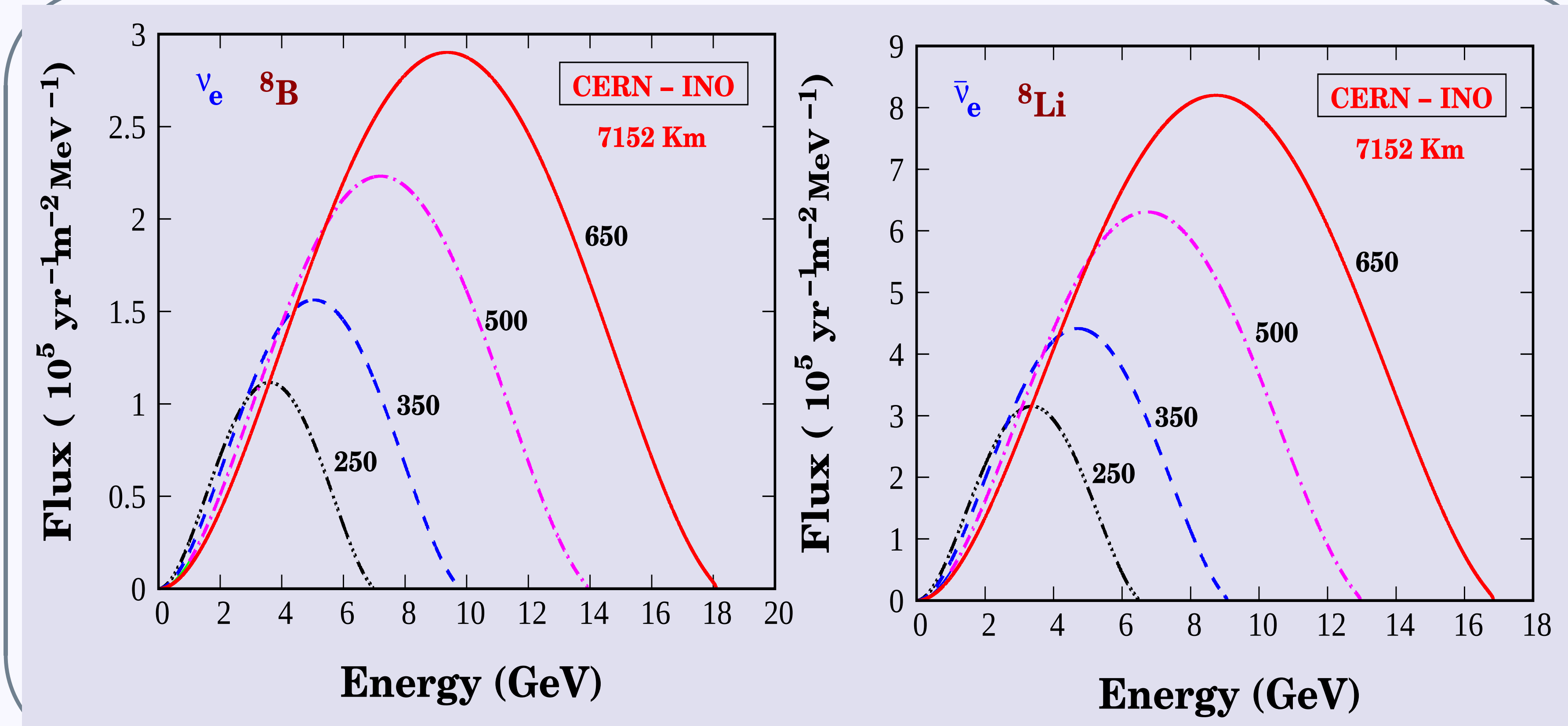
Magical Set-up : CERN-INO





$L_{\rm magic}$ = 7690 km   CERN-INO = 7152 km   50 kt Iron calorimeter

Beta-Beam flux at INO-ICAL



Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

Boosted on-axis spectrum of ν_e and $\bar{\nu}_e$ at the far detector assuming no oscillation

Resonance in matter effect

The very long CERN - INO baseline provides an excellent avenue to pin-down matter induced contributions

In particular, a resonance occurs at

$$E_{res} \equiv \frac{|\Delta m^2_{31}| \cos 2\theta_{13}}{2\sqrt{2} G_F N_e}$$

= 7.45 GeV

with $|\Delta m^2_{31}| = 2.5 \times 10^{-3}$ **eV^2,** $\sin^2 2\theta_{13} = 0.1$ **and** $\rho_{av} = 4.17$ **gm/cc (PREM) for the baseline of 7152 km**

Maximal oscillations when $\sin^2 2\theta^m_{13}$ **= 1 and** $\sin^2 \left[1.27 (\Delta m^2_{31})^m L/E\right]$ **= 1 simultaneously. At the magic baseline, largest oscillations occur at** $E \simeq$ **6 GeV**

Gandhi *et al.* hep-ph/0408361

CERN - INO Long Baseline

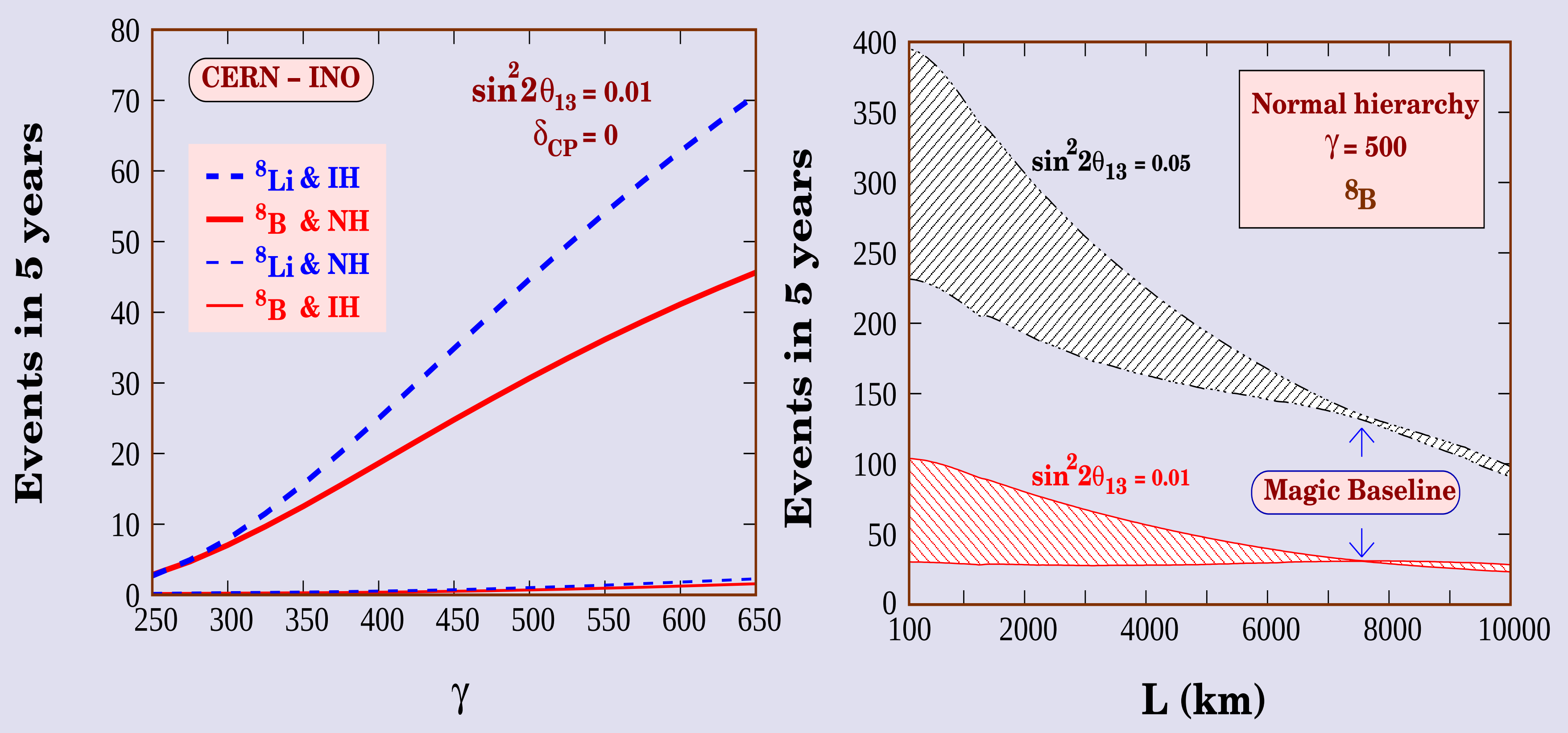
$L_{\mathrm{CERN-INO}}$ **= 7152 km**

The longer baseline captures a matter-induced contribution to the neutrino parameters, essential for probing the sign of Δm^2_{31}

The CERN - INO baseline, close to the 'Magic' value, ensures essentially no dependence of the final results on δ_{CP}. This 'Magic' value is independent of E

This permits a clean measurement of θ_{13} avoiding the degeneracy issues which plague other baselines

See the “Magic” at CERN-ICAL@INO



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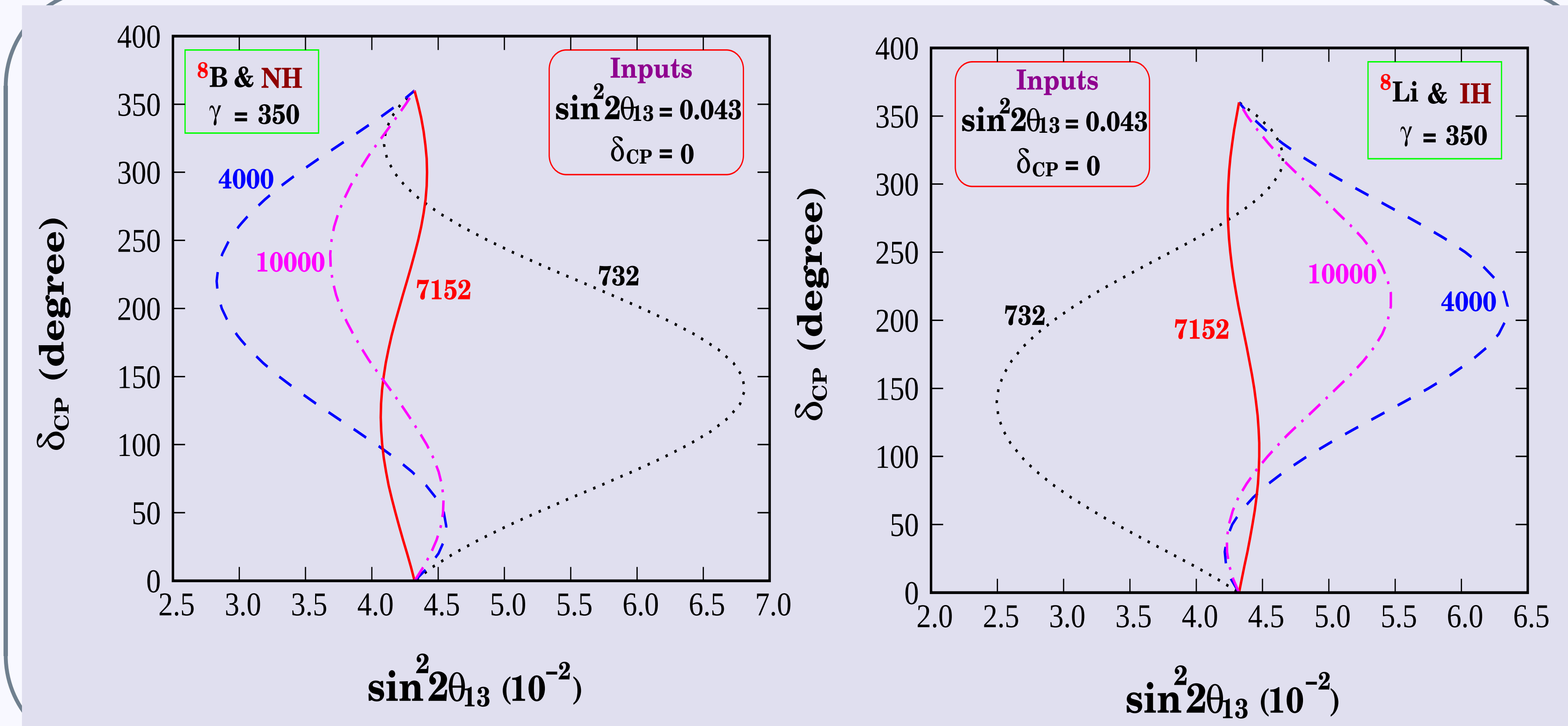
Event rates sharply depend on mass ordering and θ_{13}

Effect of δ_{CP} is negligible at magic baseline

Iso-event curves



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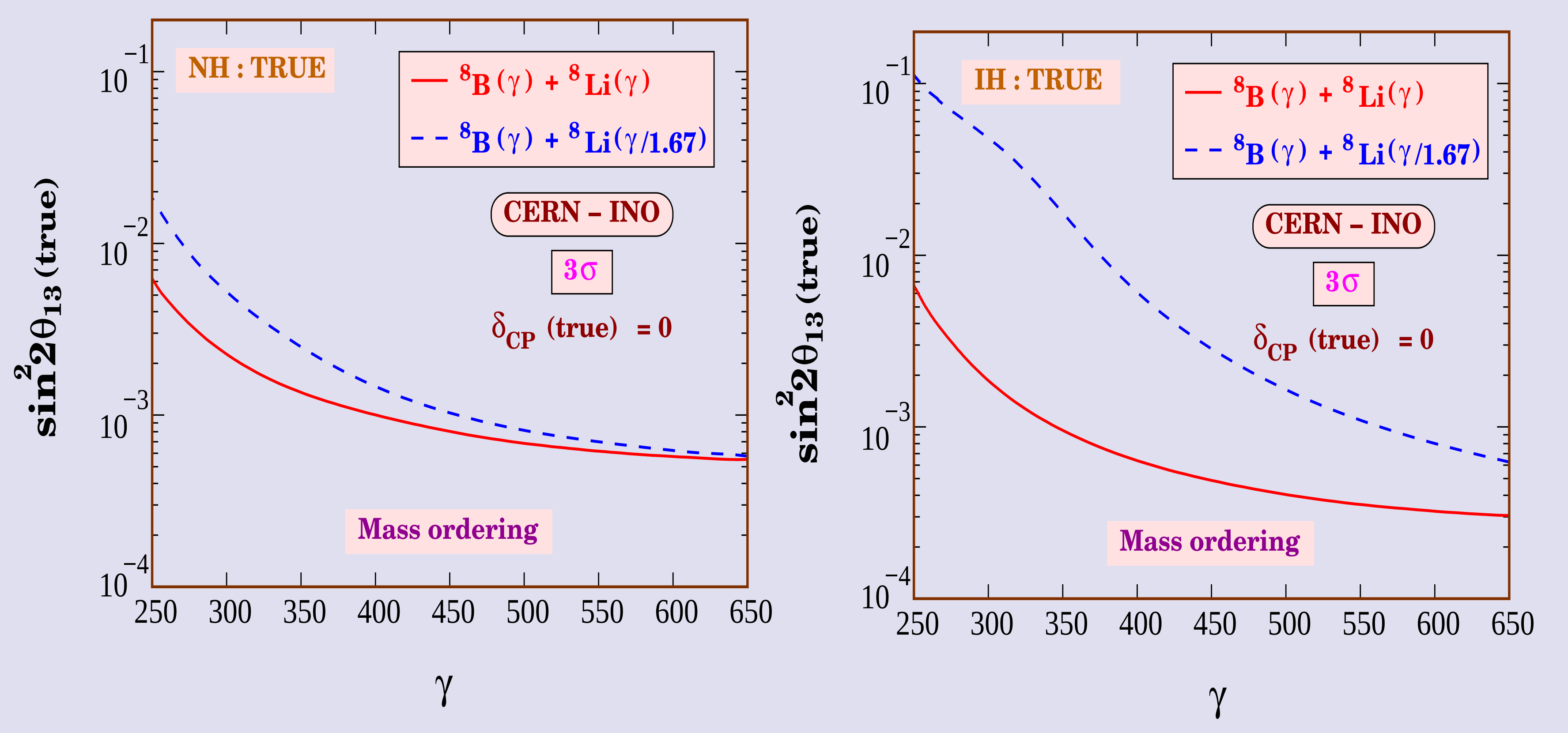
At CERN-INO distance, the effect of δ_{CP} on the measurement of θ_{13} is less

$Sgn(\Delta m^2_{31})$ Search at CERN-ICAL@INO



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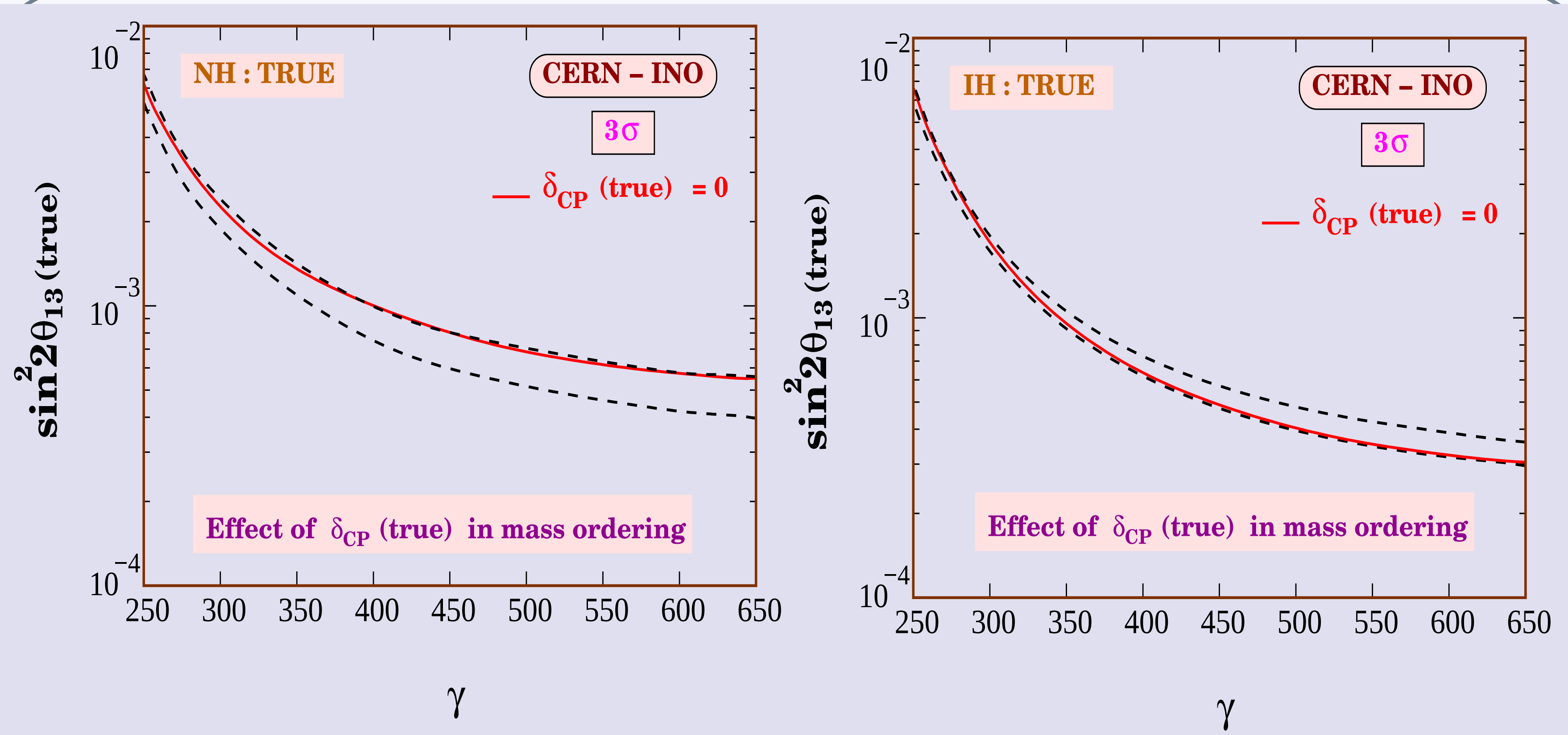
- NH:TRUE $\Rightarrow \sin^2 2\theta_{13}$(true) $\geq 5.51 \times 10^{-4}$ (3σ) with γ = 650
- IH:TRUE $\Rightarrow \sin^2 2\theta_{13}$(true) $\geq 3.05 \times 10^{-4}$ (3σ) with γ = 650

Impact of δ_{CP} (true) on the Hierarchy Sensitivity



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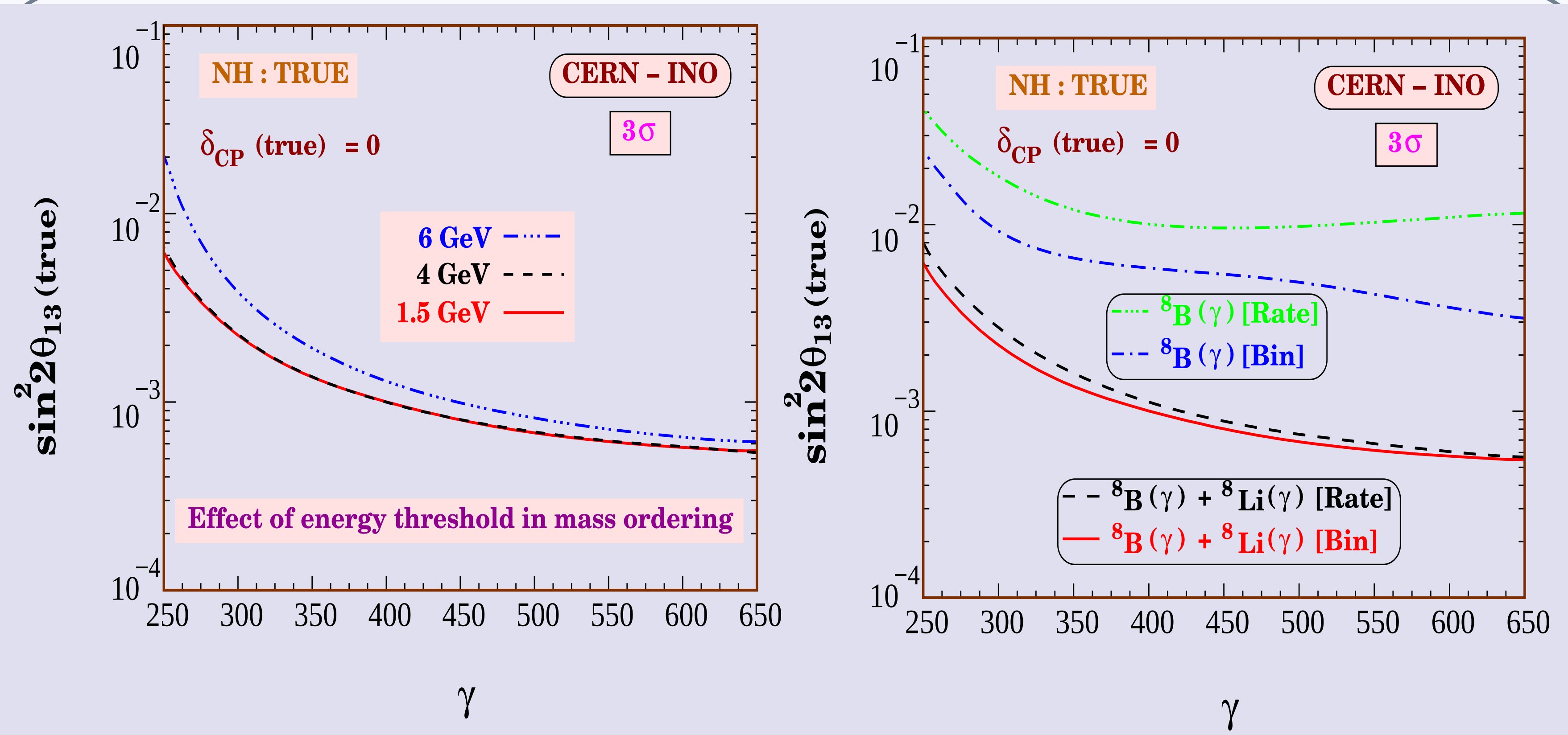
- NH:TRUE $\Rightarrow \sin^2 2\theta_{13}$(true) $\geq 3.96 \times 10^{-4}$ (3σ) with γ = 650
- IH:TRUE $\Rightarrow \sin^2 2\theta_{13}$(true) $\geq 2.96 \times 10^{-4}$ (3σ) with γ = 650

Energy threshold and Binned Analysis



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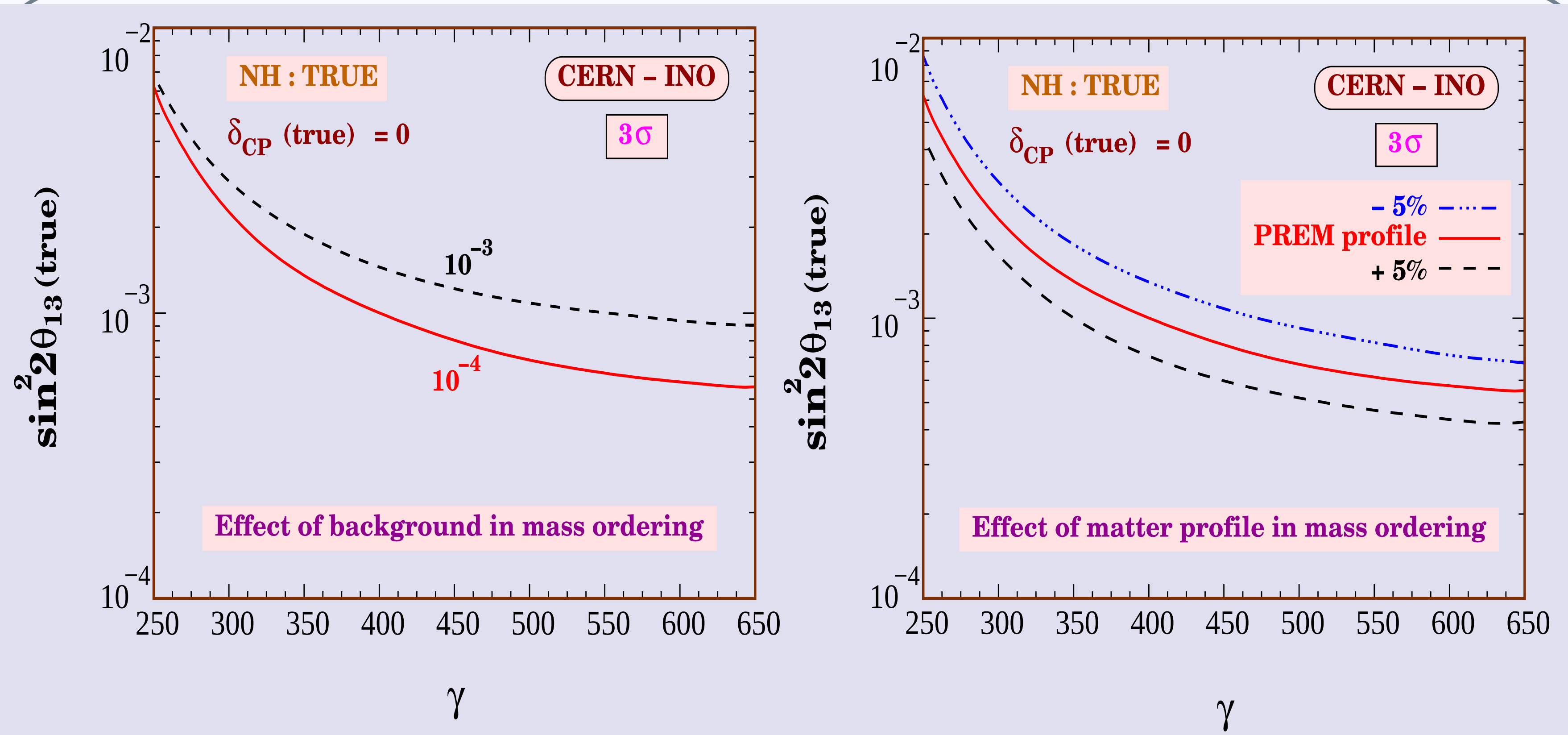
- Energy threshold upto 4 GeV is fine
- Spectral information and $(\nu + \bar{\nu})$ data helps

Impact of Background and Density Profile



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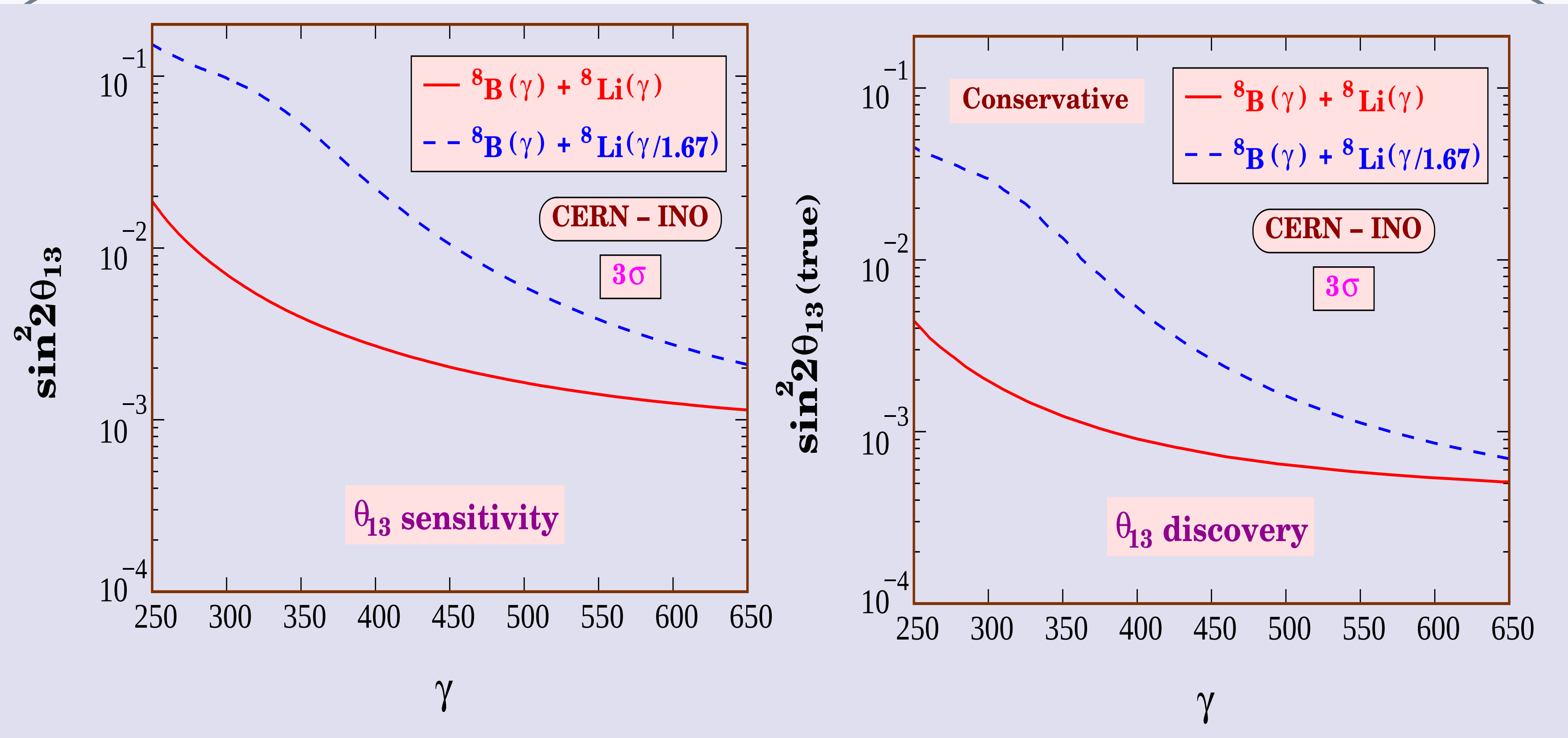
- Effect of backgrounds is severe at higher γ values
- Matter Density ↑ Matter effects ↑ Sensitivity ↑

$\sin^2 2\theta_{13}$ Sensitivity and Discovery



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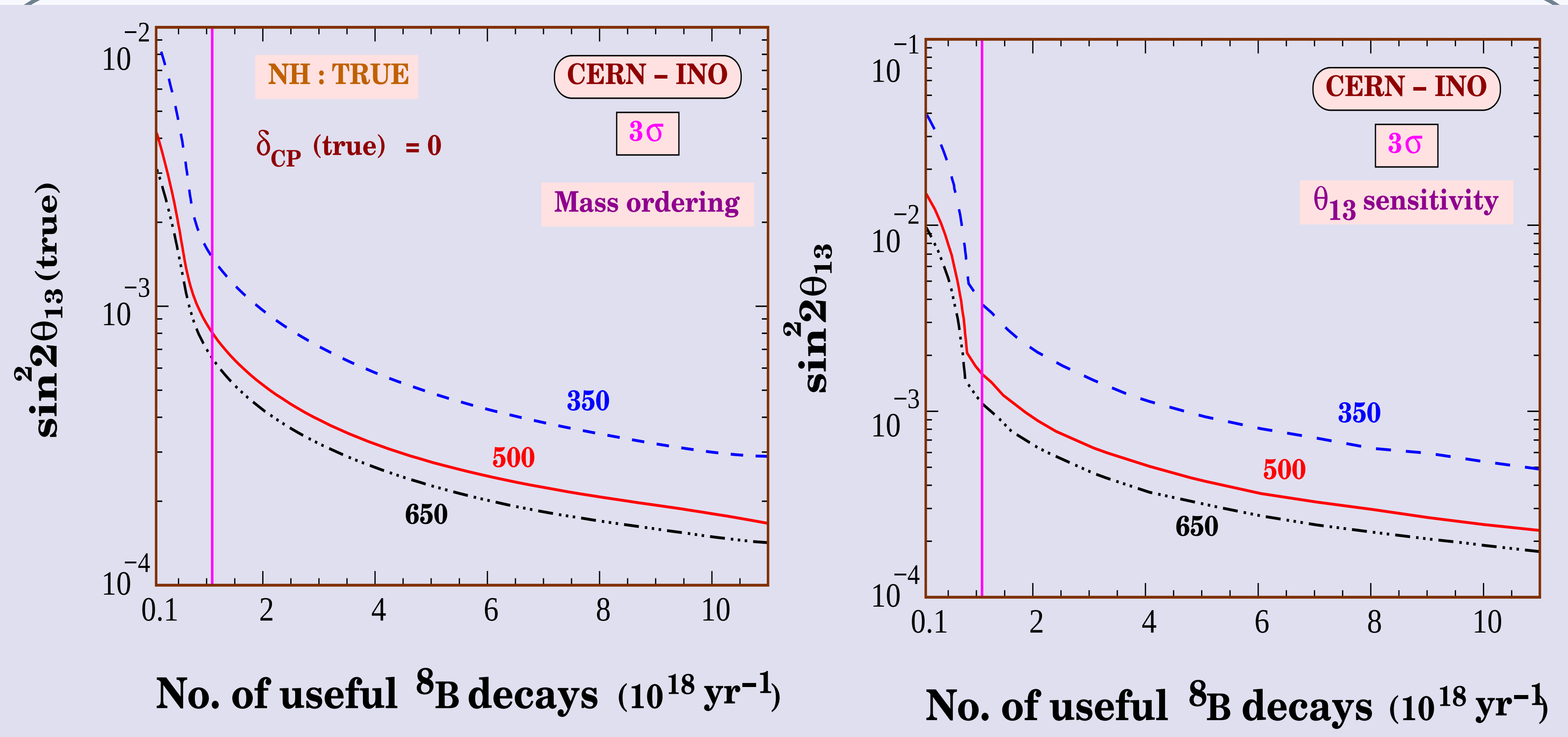
- Upper bound on θ_{13} at 3σ : $\sin^2 2\theta_{13}$(true) $\leq 1.14 \times 10^{-3}$
- Signal for θ_{13} at 3σ if $\sin^2 2\theta_{13}$(true) $\geq 5.1 \times 10^{-4}$

Impact of Luminosity



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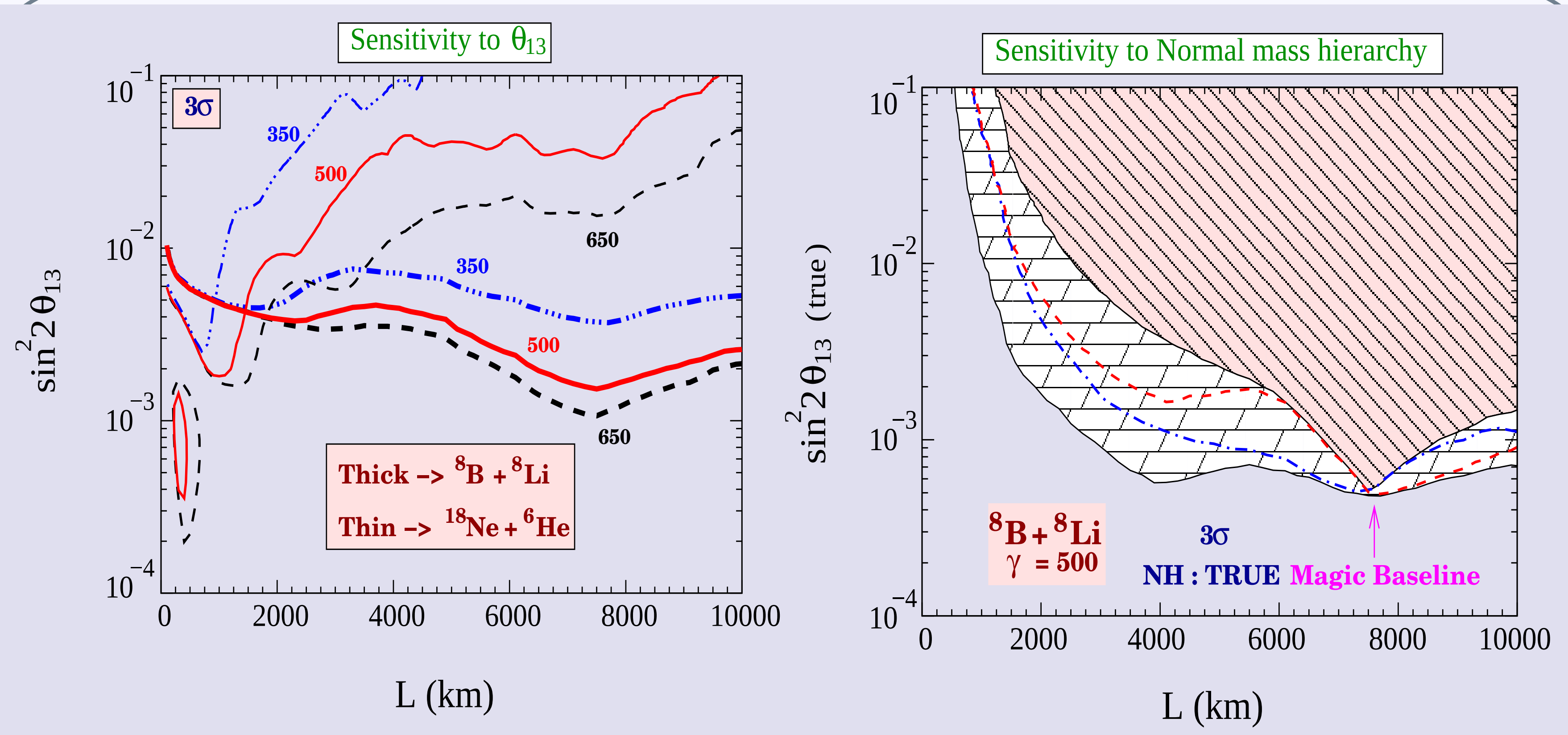
- Sensitivity increases very fast initially and then comparatively flattens out

What does optimization study say?

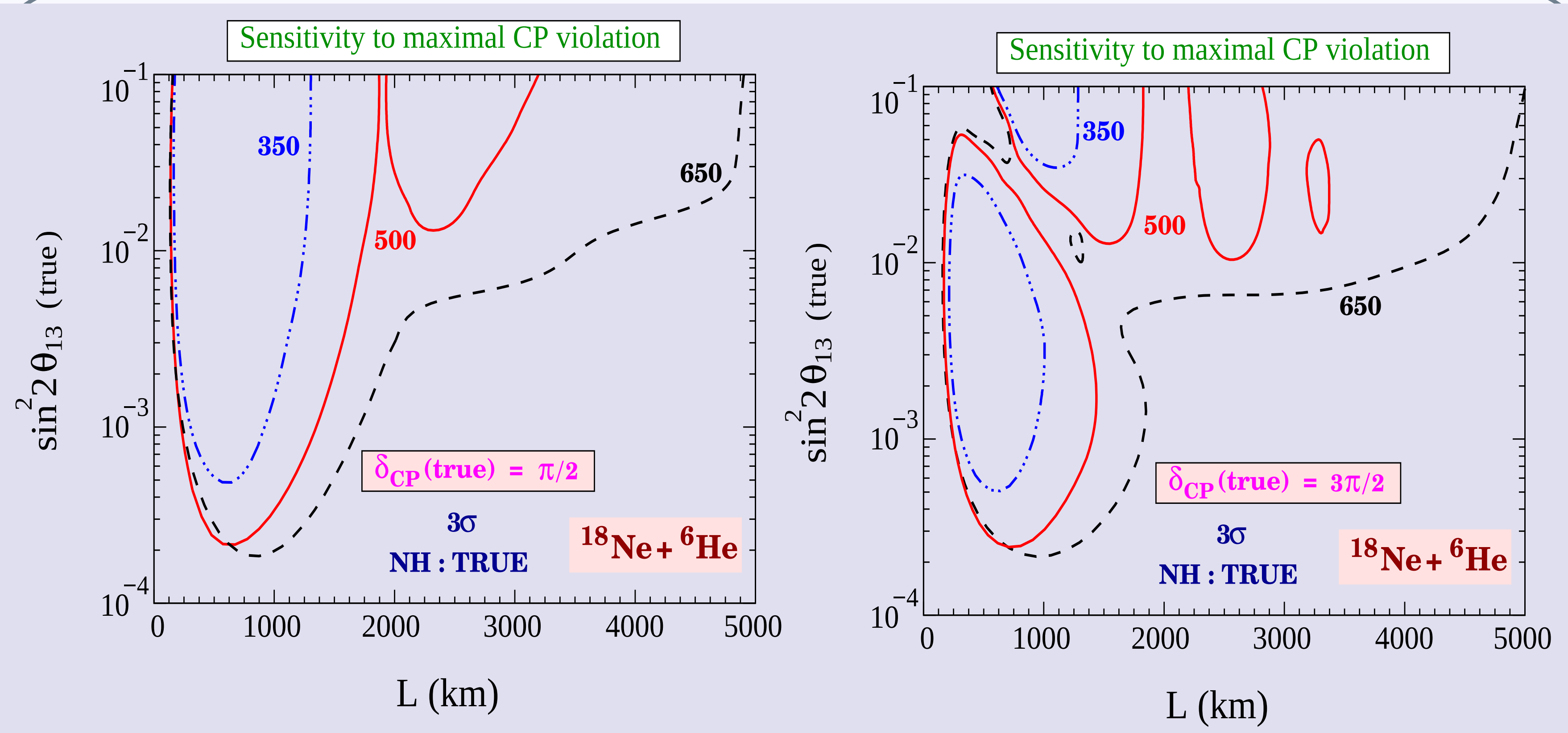


Agarwalla, Choubey, Raychaudhuri, Winter, 0802.3621

See the talk by Walter Winter

- With $\gamma \sim 500$, use ^{18}Ne+^{6}He at short baseline for θ_{13} and ^{8}B+^{8}Li at the magic baseline for θ_{13} and $Sgn(\Delta m^2_{31})$

What does optimization study say?

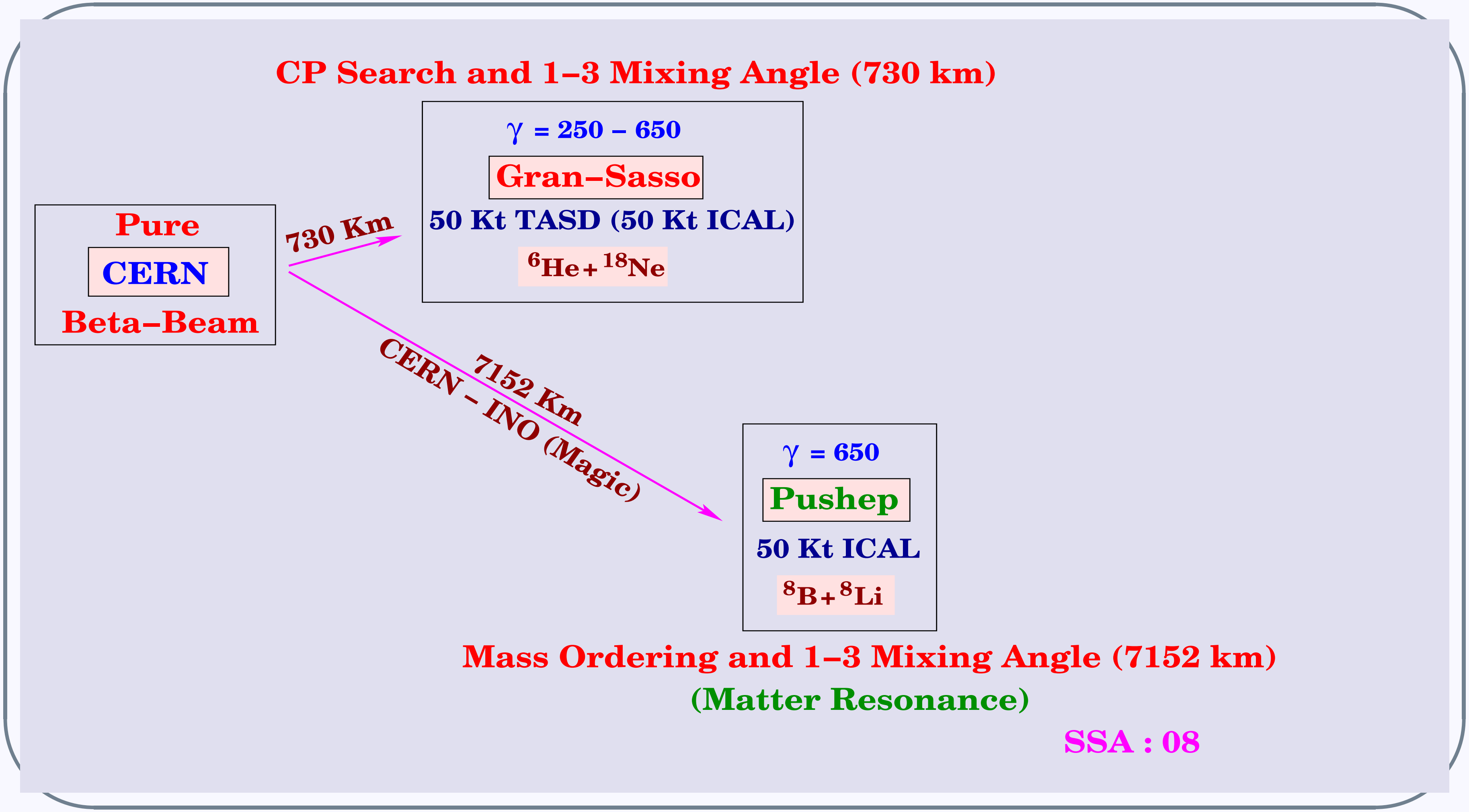


Agarwalla, Choubey, Raychaudhuri, Winter, 0802.3621

See the talk by Walter Winter

- With $\gamma \sim 500$, use ^{18}Ne+^{6}He at the short baseline for CP violation

Two-Baseline Beta-Beam Set-up



Schematic layout of the proposed set-up

CERN - INO $\oplus$ CERN - LNGS

$L_{\rm CERN-INO}$ = 7152 km $L_{\rm CERN-LNGS}$ = 730 km

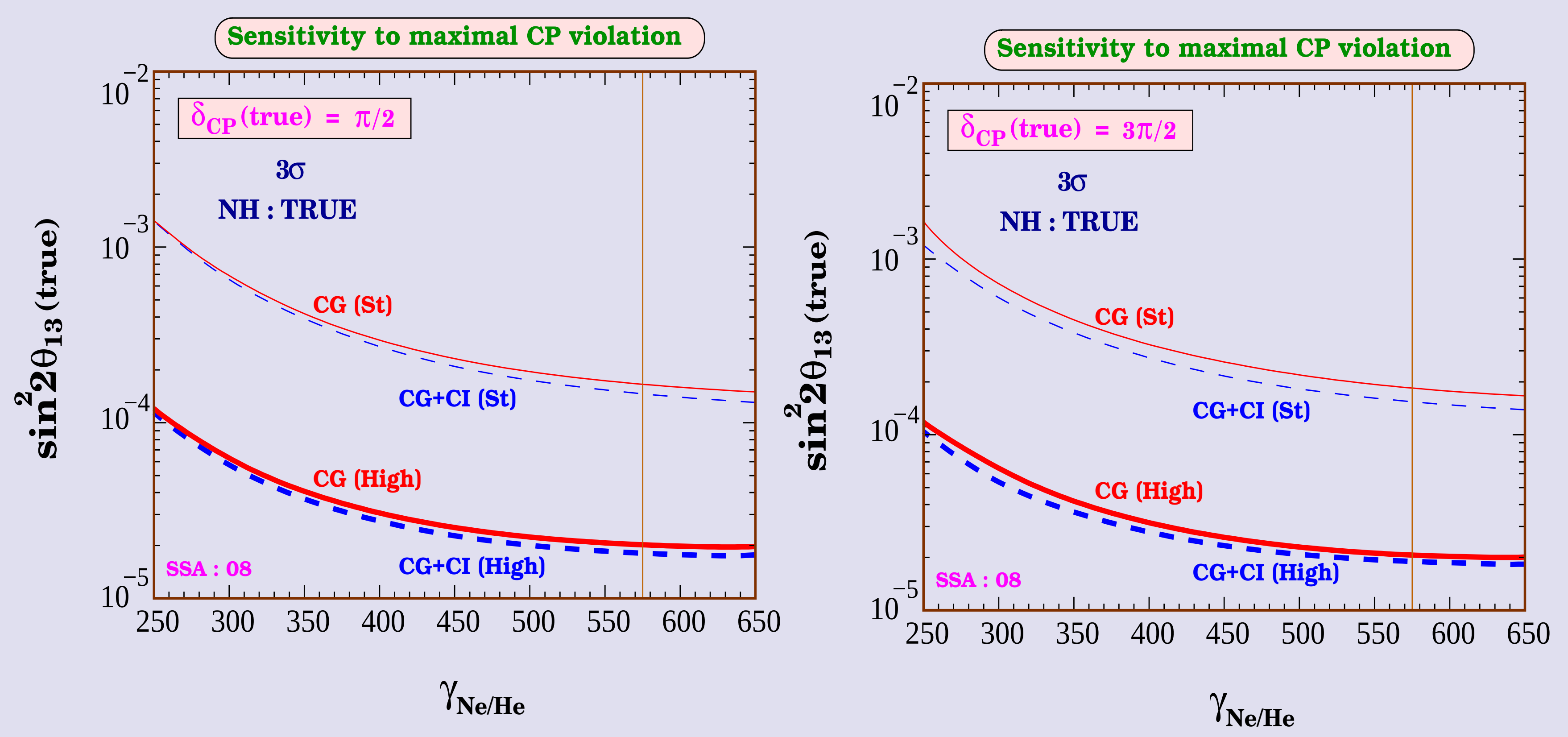
Measure $sgn(\Delta m^2_{31})$ and θ_{13} at CERN-INO "Magic" baseline : No δ_{CP}

- Large matter effects help to probe sgn(Δm^2_{31})
- Close to "Magic", degeneracy free measurement of θ_{13}
- No information about CP phase

Measure δ_{CP} and θ_{13} at CERN-LNGS baseline : Full of δ_{CP}

- No fake CP asymmetry due to Earth matter
- Probes lower oscillation wavelength, vital for CP search

Quest for CP at CERN-TASD@LNGS

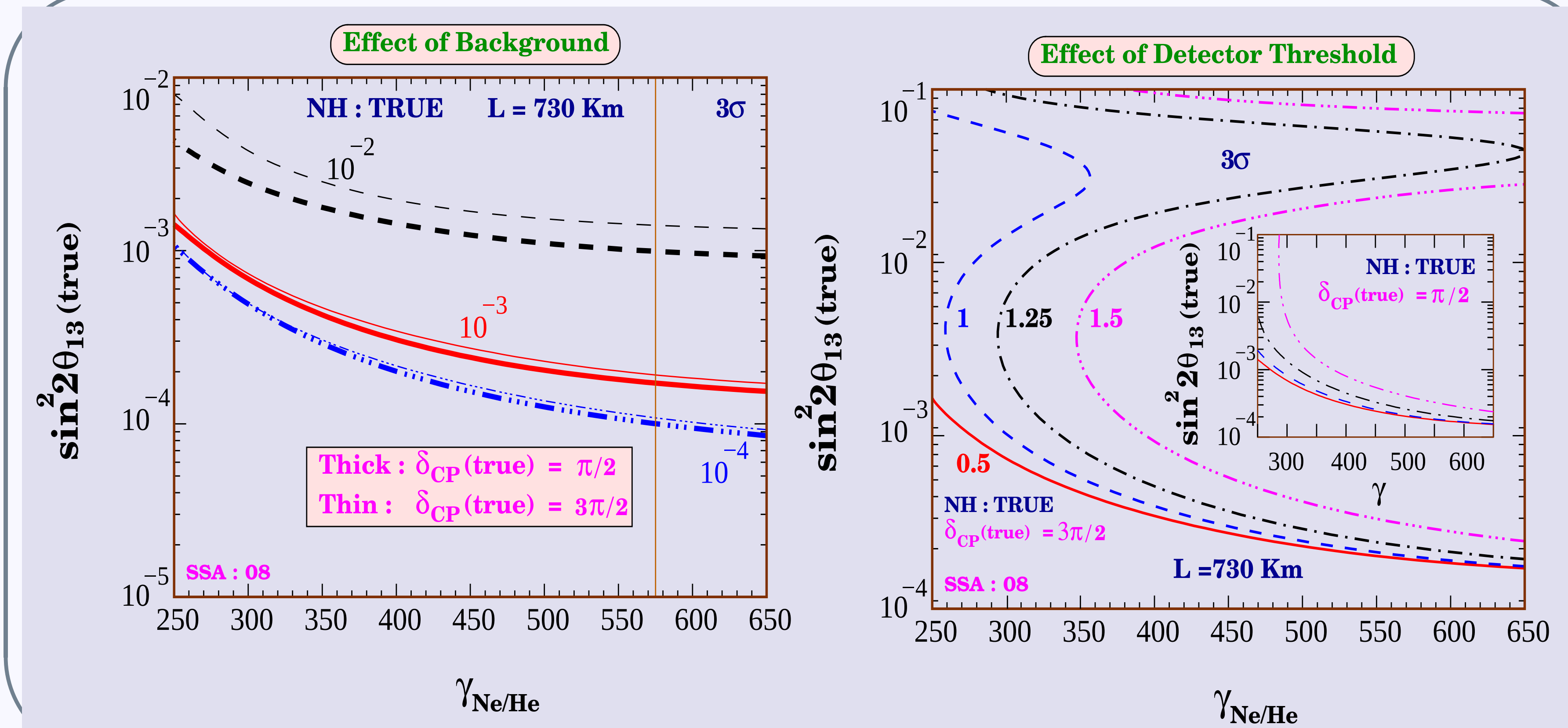


Agarwalla, Choubey, Raychaudhuri, 0804.3007

The $3\sigma \sin^2 2\theta_{13}$ (true) reach for sensitivity to "maximal CP violation"

Sensitivity improves sharply with γ and saturates beyond $\gamma \gtrsim 500$

Impact of Detector parameters at L = 730 km



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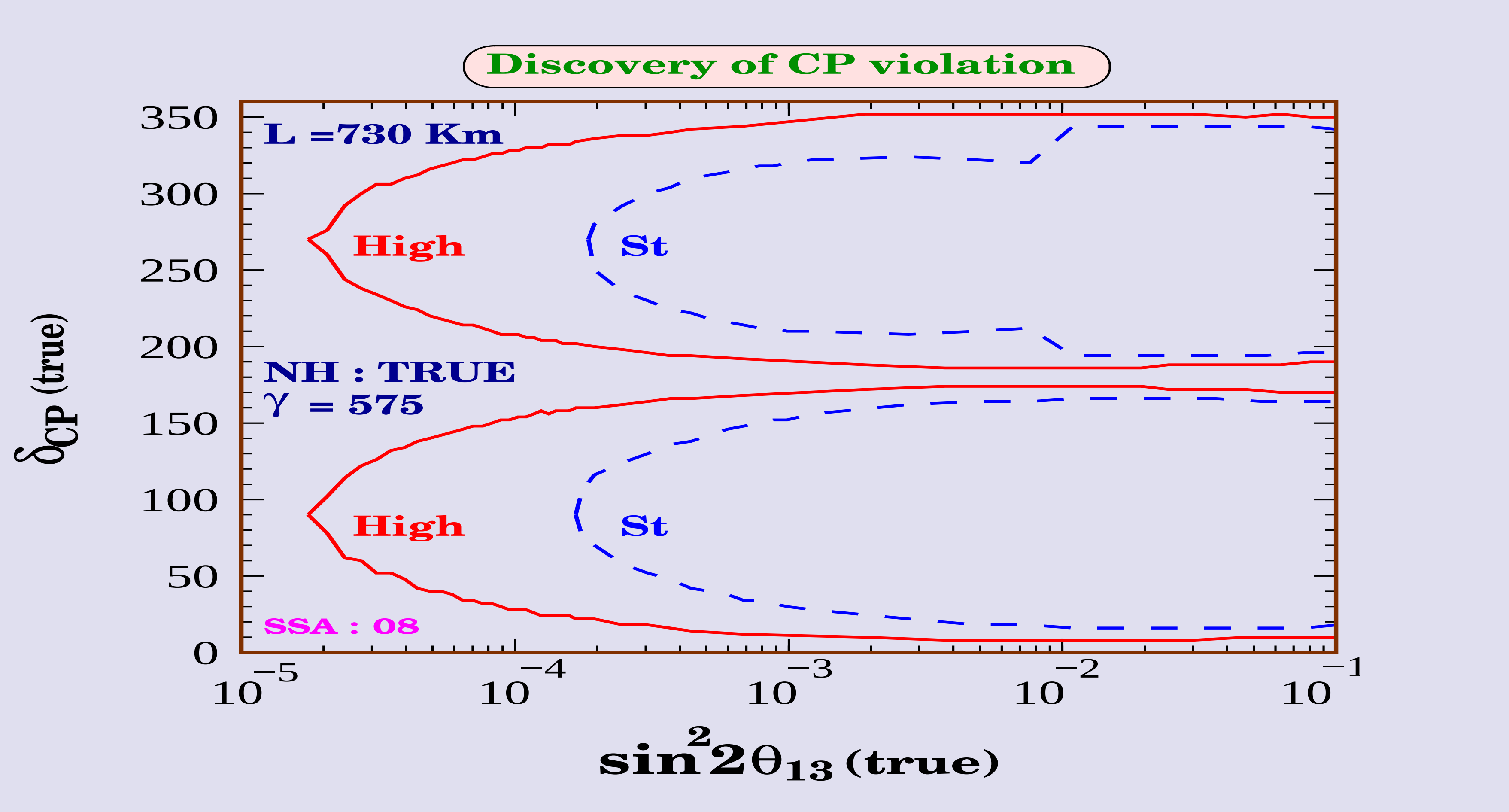
Sensitivity to “maximal CP violation” (5-year run & standard luminosities)

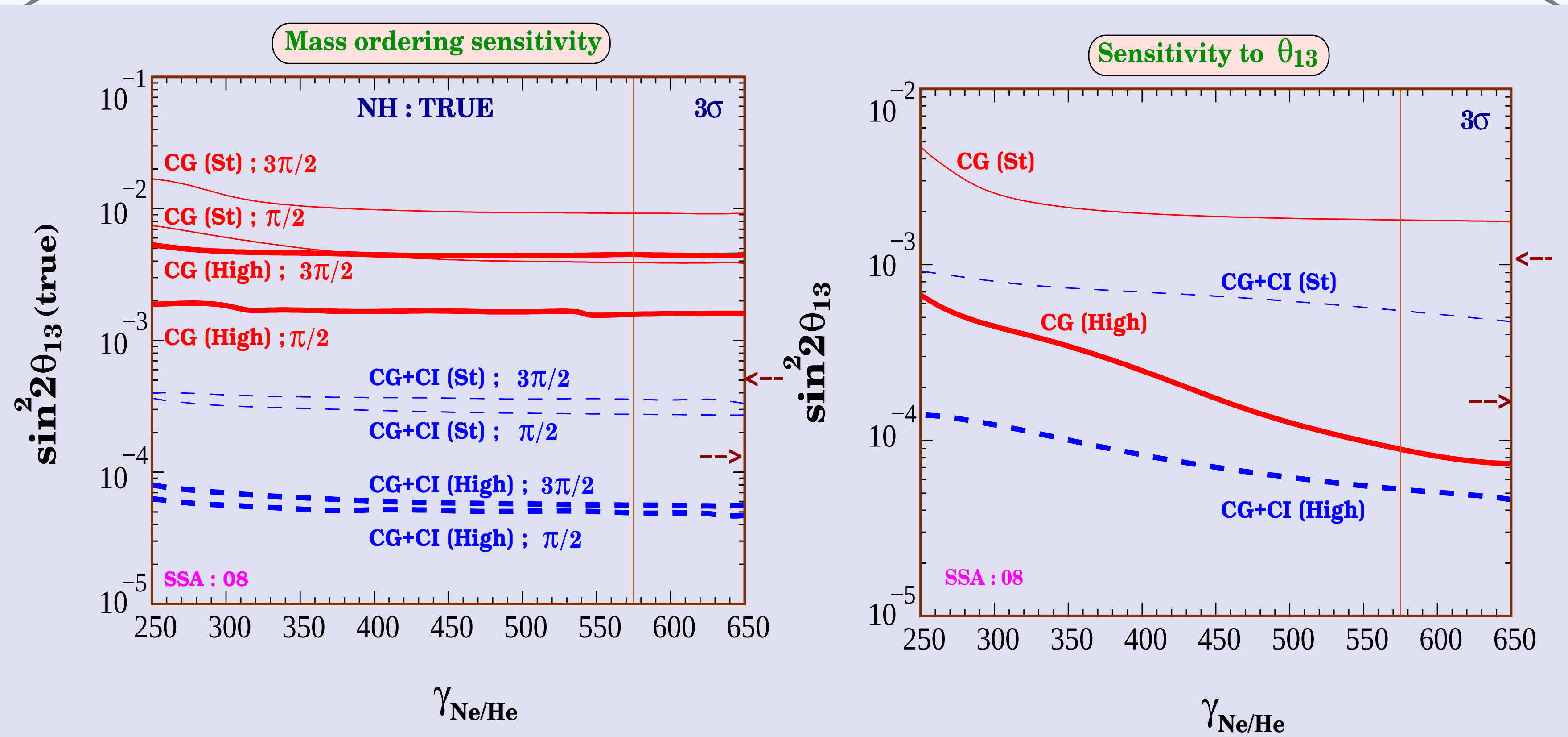
Backgrounds affect the reach. Higher threshold causes degenerate solutions

Discovery of CPV at CERN-TASD@LNGS



$\sin^2 2\theta_{13}$ **(true)** $\geq 10^{-3}$ **allows CP violation discovery for 64% of** $\delta_{\rm CP}$ **(true) values**

Two-Baseline combined results with Beta-Beam



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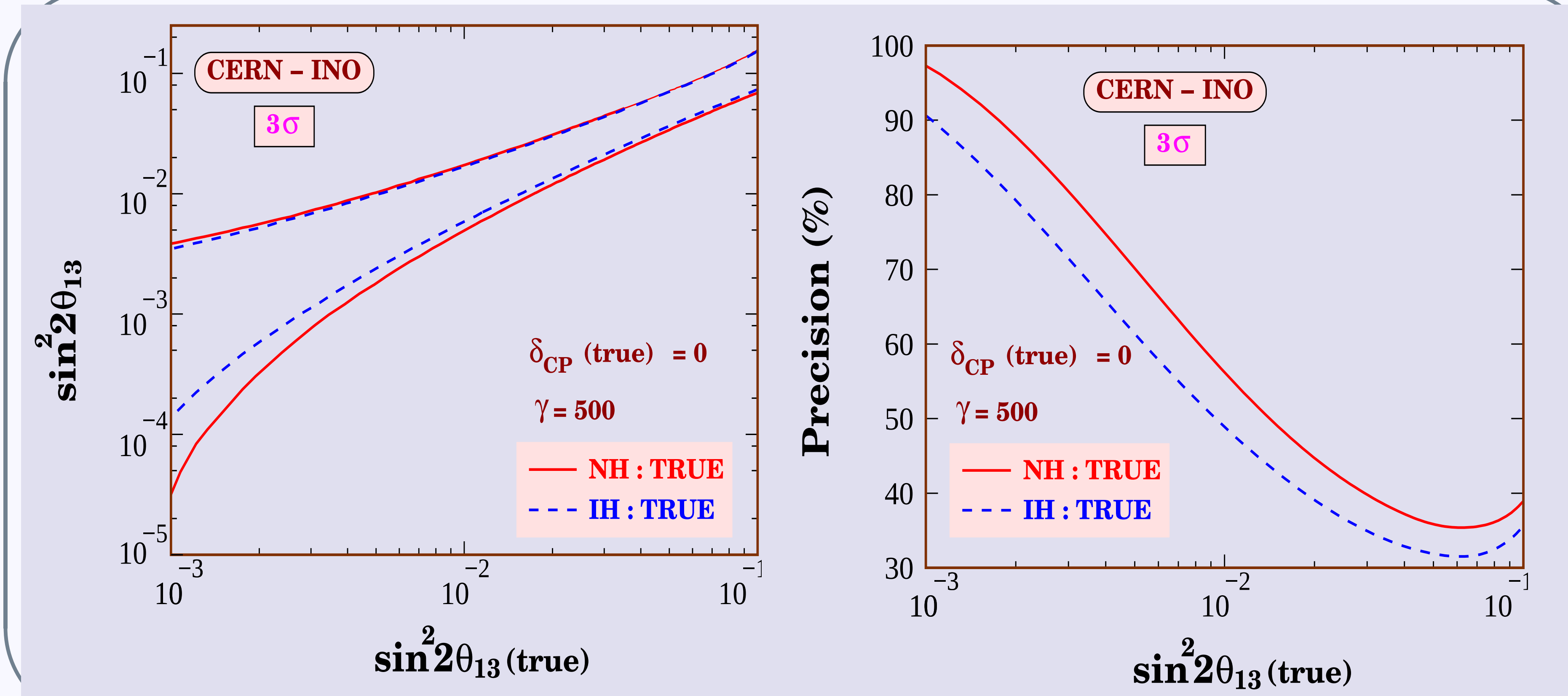
Left (right) panel depicts the $sgn(\Delta m^2_{31})$ ($\sin^2 2\theta_{13}$) sensitivity reach at 3σ

Tremendous Sensitivity : Have a look !!

Set-up	$\sin^2 2\theta_{13}$ Discovery (3σ)	Mass Ordering (3σ)	Maximal CP violation (3σ)
CERN-INO ^{8}B+^{8}Li, $\gamma = 650$	9.5×10^{-5}	9.4×10^{-5}	Not possible
CERN-LNGS ^{18}Ne+^{6}He, $\gamma = 575$	2.07×10^{-5} 1.27×10^{-5}	1.58×10^{-3} 1.84×10^{-3}	1.97×10^{-5} 1.23×10^{-5}
CERN-LNGS ^{18}Ne+^{6}He, $\gamma = 575$ $+$ CERN-INO ^{8}B+^{8}Li, $\gamma = 650$	1.88×10^{-5} 1.2×10^{-5}	4.64×10^{-5} 4.34×10^{-5}	1.78×10^{-5} 1.13×10^{-5}
Optimized Neutrino Factory	1.5×10^{-5}	1.5×10^{-5}	1.5×10^{-5}

1.1×10^{19} (2.9×10^{19}) useful ion decays / year in the ν ($\bar{\nu}$) mode

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



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- How precisely the mixing angle $\sin^2 2\theta_{13}$ will be measured?