Synergies between the first-generation JHF and NuMI experiments

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in collaboration with
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based on
hep-ph/0211300

Outline

Definition of synergy effects

- statistics $\Leftrightarrow$ complementarity

Combination of similar experiments

- JHF-SK and NuMI
- initial setups* (as proposed in the LOIs)
- identical boundary conditions
  - running time, confidence levels etc.

Joint optimization

- free parameters
  $\Rightarrow$ new physics opportunities

Full three flavour analysis

*in contrast to V. Barger, D. Marfatia and K. Whisnant, hep-ph/0210428.

Definition of synergy effects

$$\boxed{1+1=?}$$

synergy

...the simultaneous action of separate agencies which, together have greater total effect than the sum of their individual effects...

(Webster's)

$$\boxed{\text{synergy} \Leftrightarrow 1+1>2}$$

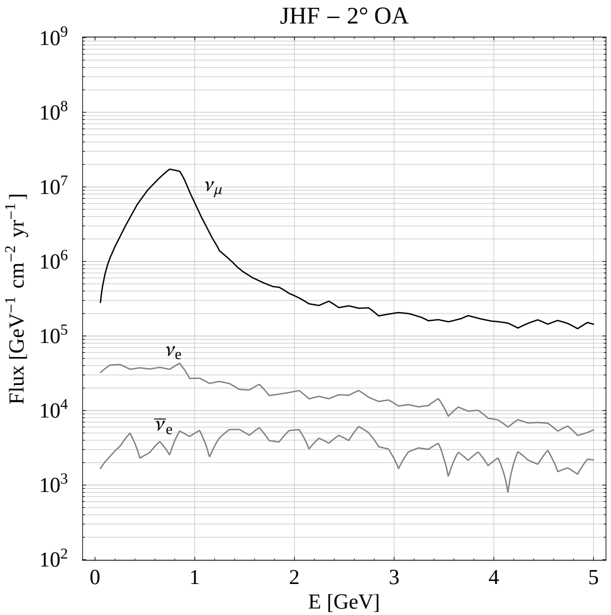
- two experiments always better than one
  $\Rightarrow$ increased statistics

$$\boxed{1+1=2}$$

- method for subtracting effects of increased statistics
  - double the luminosity of each individual experiment and compare it to their combination (at single luminosity)

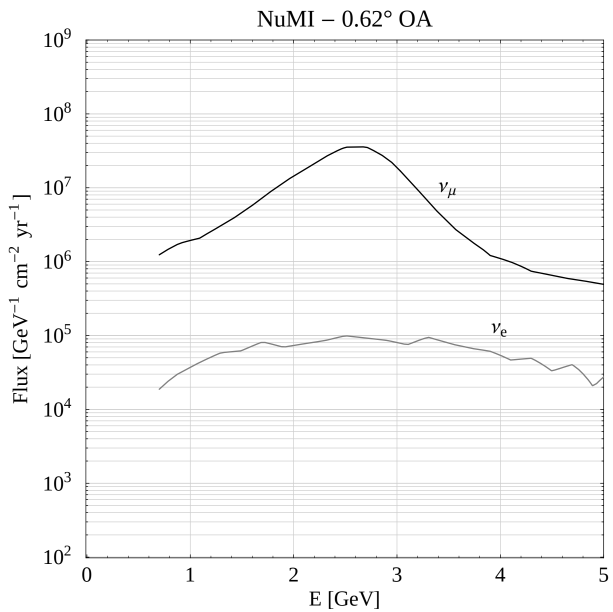
The two experiments

JHF



- mean energy $0.51\,\mathrm{GeV}$
- peak intensity $1.7 \cdot 10^7\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{yr}^{-1}$ at $0.78\,\mathrm{GeV}$
- ν_μ/ν_e-ratio at peak 0.2%

NuMI



- mean energy $2.78\,\mathrm{GeV}$
- peak intensity $3.6 \cdot 10^7\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{yr}^{-1}$ at $2.18\,\mathrm{GeV}$
- ν_μ/ν_e-ratio at peak 0.2%

The two experiments

JHF

- $295\,\mathrm{km}$
- water Cherenkov detector – SuperK
- fiducial mass $22.5\,\mathrm{kt}$
- running period of 5 years
- NC-rejection ~ 0.01
- efficiency for $\nu_e \sim 0.5$
- 61% QE-interactions at E_{peak}
- energy range $0.4 - 1.2\,\mathrm{GeV}$
- 5% uncertainty on all backgrounds

NuMI

- $712\,\mathrm{km}$
- low-Z calorimeter
- fiducial mass $17\,\mathrm{kt}$
- running period of 5 years
- NC-rejection ~ 0.005
- efficiency for $\nu_e \sim 0.4$
- 22% QE-interactions at E_{peak}
- energy range $1.6 - 2.8\,\mathrm{GeV}$ for 0.72°
- energy range $1.2 - 2.5\,\mathrm{GeV}$ for 0.97°
- 5% uncertainty on all backgrounds

Y. Itow *et al.*, hep-ex/0106019.

D. Ayres *et al.*, hep-ex/0210005.

A. Para and D. A. Harris, private communication.

The two experiments

	JHF-SK	NuMI
Signal	137.8	132.0
Background	22.6	19.0

- very similar numbers
- more QE events in JHF sample
- more matter effects in NuMI sample

similar performance ?

Oscillation framework

Analytic approximation of the appearance probability – expansion in powers of $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$

$$
\begin{aligned}
P_{\nu_e\to\nu_\mu} \quad &\approx \quad \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta) \\
&\pm \quad \alpha \quad \frac{\sin\delta_{\mathrm{CP}}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta) \\
&+ \quad \alpha \quad \frac{\cos\delta_{\mathrm{CP}}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta) \\
&+ \quad \alpha^2 \quad \frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)
\end{aligned}
$$

$$\Delta = \Delta m^2_{31}L/4E;\ \hat{A} = A/\Delta m^2_{31} = 2VE/\Delta m^2_{31};\ V = \sqrt{2}G_F n_e.$$

$P_{\nu_e\to\nu_\mu}$ depends on solar parameters only via the product $\sin 2\theta_{12}\cdot\Delta m^2_{21}$

M. Freund, Phys. Rev. **D64**, 053003 (2001).

A. Cervera *et al.*, Nucl. Phys. **B579**, 17 (2000).

Oscillation framework

Central values and 3 σ ranges

$$\begin{aligned}
\Delta m^2_{31} &= 3^{+3}_{-2} \cdot 10^{-3}\,\mathrm{eV}^2 \\
\sin^2 2\theta_{23} &= 1^{+0}_{-0.2} \\
\Delta m^2_{21} &= 5^{+32}_{-2.7} \cdot 10^{-5}\,\mathrm{eV}^2 \\
\sin^2 2\theta_{12} &= 0.8^{+0.2}_{-0.2}
\end{aligned}$$

External input

$$\begin{aligned}
\delta(\Delta m^2_{21} \cdot \sin 2\theta_{12}) &= 15\% \\
\delta\rho &= 5\%
\end{aligned}$$

M. C. Gonzalez-Garcia and M. Maltoni, hep-ph/0202218.
J. N. Bahcall, M. C. Gonzalez-Garcia and C. Peña-Garay, JHEP **07**, 054 (2002).

Oscillation framework

Degeneracies

$\mathrm{sgn}(\Delta m^2_{31})$ - second solution with the opposite sign of Δm^2_{31}
lies close to the $\delta - \theta_{13}$-plane, can be lifted by matter effects

(δ, θ_{13}) - second solution exactly in the $\delta - \theta_{13}$-plane
two separate solutions only when ν and $\overline{\nu}$ analyzed together
otherwise one very large solution, tracking the iso-event-rate curve

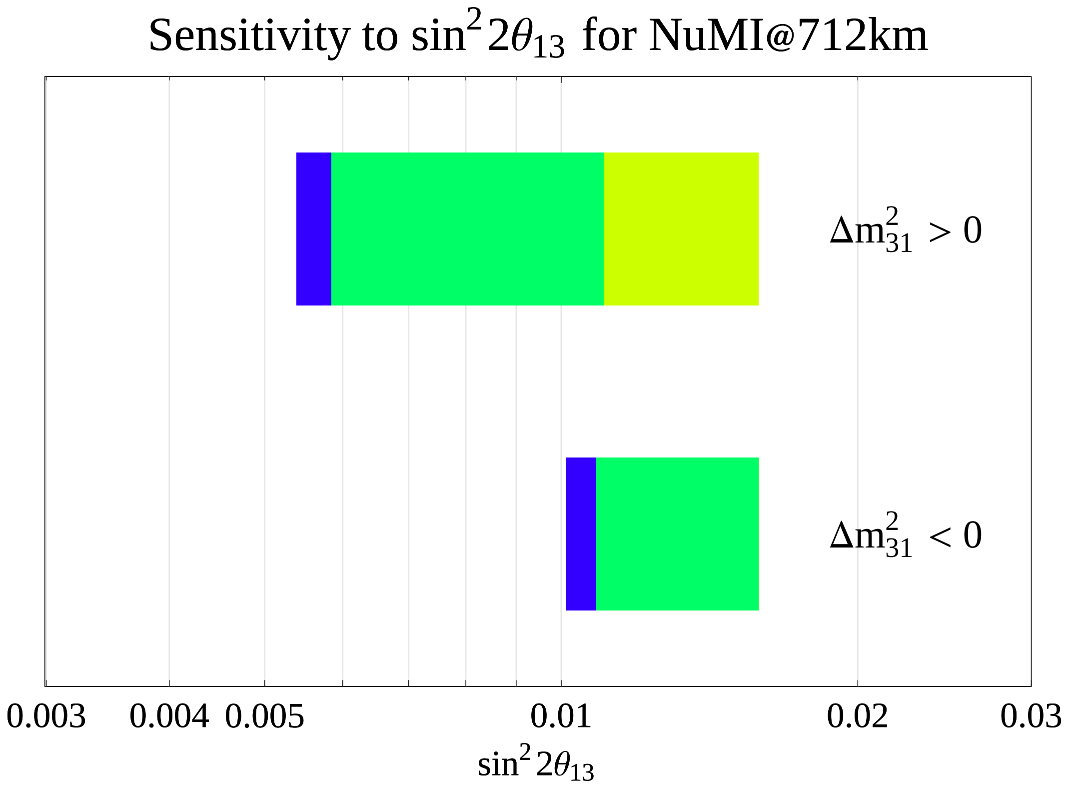
$(\theta_{23}, \pi/2 - \theta_{23})$ - not present for $\theta_{23} = \pi/4$, as in our work

H. Minakata and H. Nunokawa, JHEP **10**, 001 (2001).

J. Burguet-Castell *et al.*, Nucl. Phys. **B608**, 301 (2001).

V. Barger, D. Marfatia and K. Whisnant, Phys. Rev. **D65**, 073023 (2002).

Definition of the θ_{13}-limit



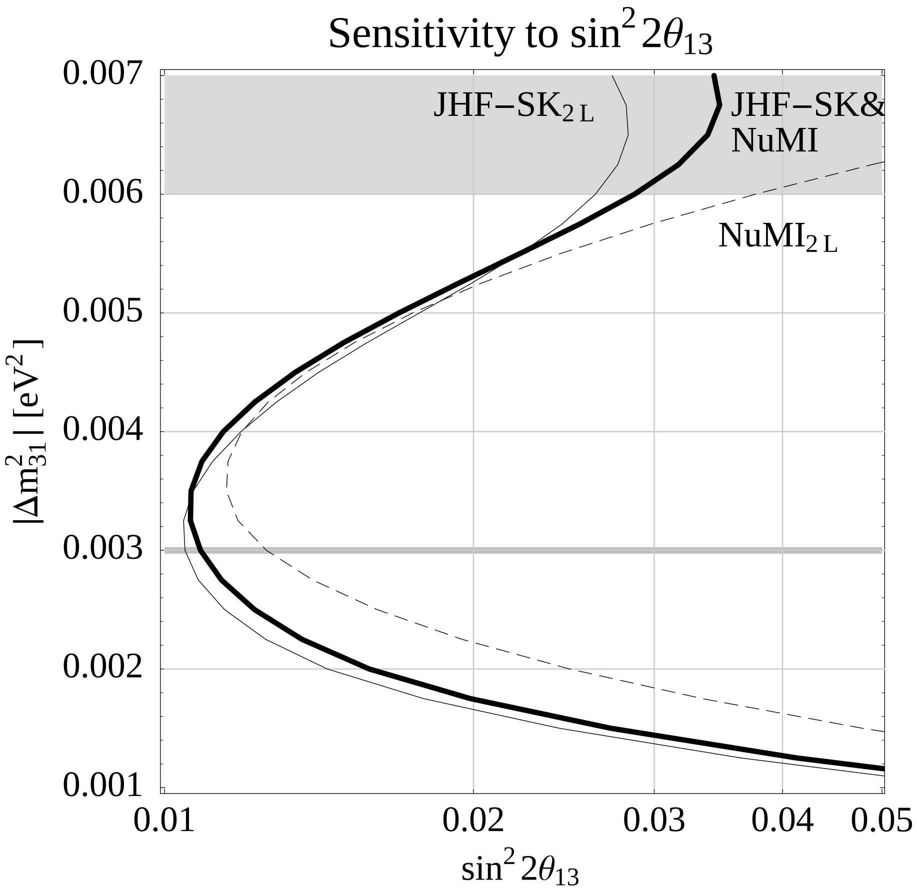
- limit is a one sided interval derived from a null result

$\Rightarrow$ all sets of parameters which fit the null result have to be taken into account

- null result ($\theta_{13} \equiv 0$) is independent of the sign of Δm^2_{31}

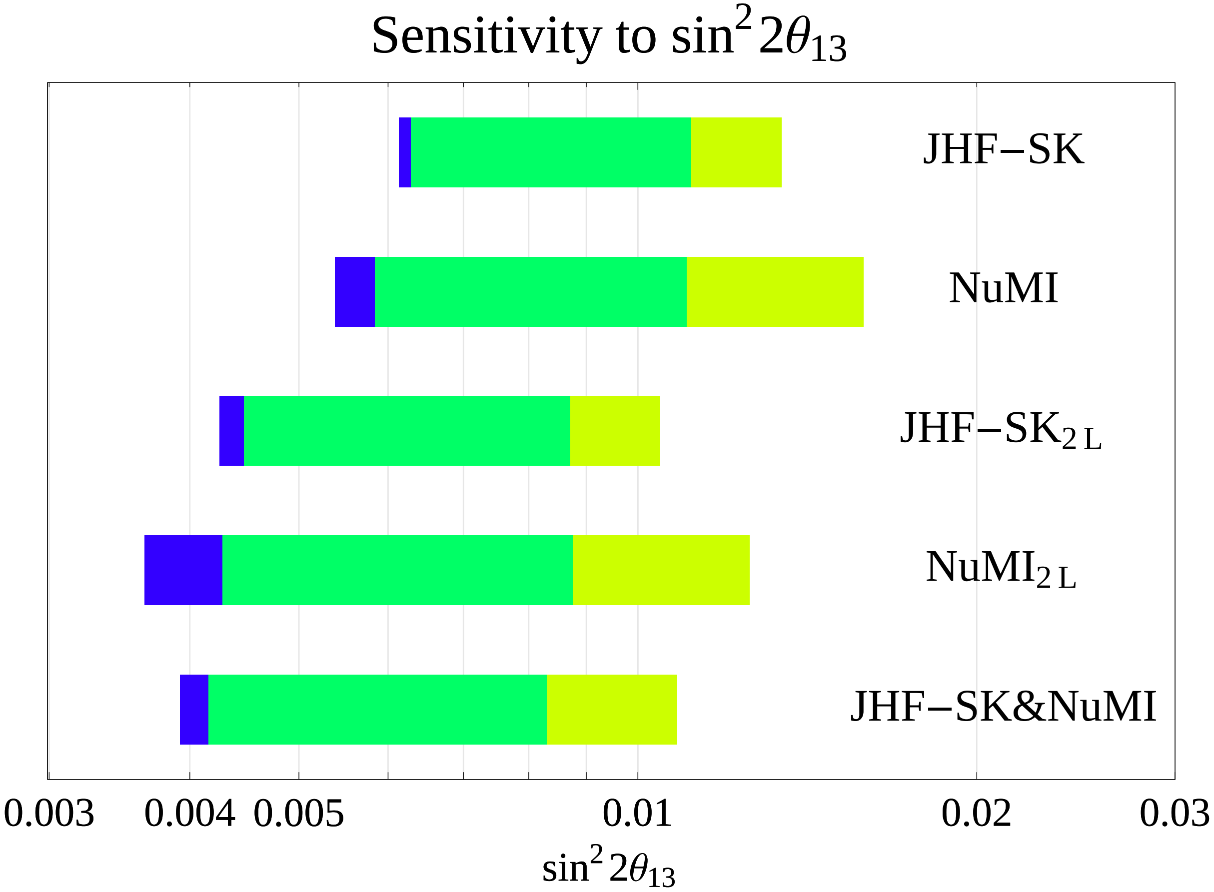
$\Rightarrow$ limit is also independent of the sign of Δm^2_{31}

JHF and NuMI as proposed



- very similar performance
- slight differences in Δm^2_{31}-dependence
- combination flattens Δm^2_{31}-dependence
- no strong synergy

JHF and NuMI as proposed



- combination a little worse than JHF at double luminosity

$\Rightarrow$ negative synergy at $\Delta m^2_{31} = 3.0 \cdot 10^{-3}\,\mathrm{eV}^2$

- no reduction of correlations and degeneracies

no CP violation – no mass hierarchy

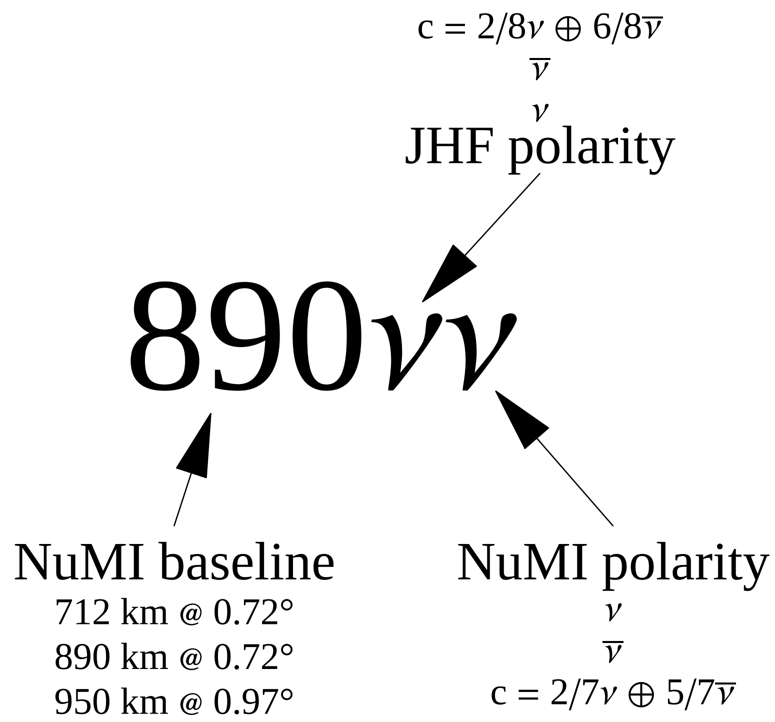
Free parameters

JHF-SK

- source and detector location fixed
  - horn polarity free
  - off-axis angle free*

NuMI

- source and decay pipe fixed
  - horn polarity free
  - detector site free
  - certain combinations of off-axis angle and baseline free



Two additional NuMI detector sites

$890\,\mathrm{km}$ at $0.72°$ ($\sim$ Fort Frances, Ontario)

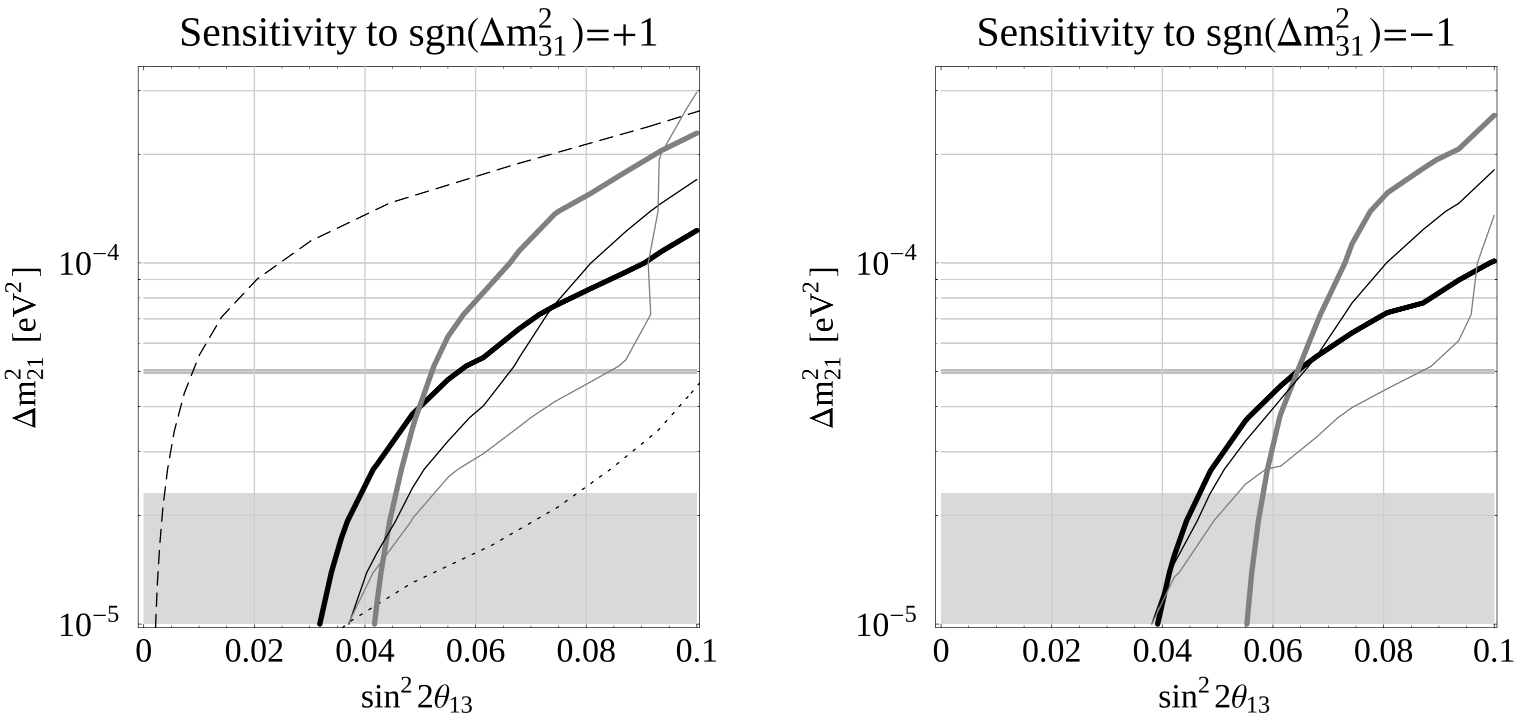
$950\,\mathrm{km}$ at $0.97°$ (Vermilion Bay, Ontario)

*not considered here because of lacking fluxes for other angles

Free parameters – options

No.	JHF-SK ν	JHF-SK $\overline{\nu}$	NuMI ν	NuMI $\overline{\nu}$	NuMI L [km]	NuMI OA angle	Combined Label
1	1	0	1	0	712	0.72°	712$\nu\nu$
2	1	0	1	0	890	0.72°	890$\nu\nu$
3	1	0	1	0	950	0.97°	950$\nu\nu$
4	2/8	6/8	2/7	5/7	712	0.72°	712cc
5	2/8	6/8	2/7	5/7	890	0.72°	890cc
6	2/8	6/8	2/7	5/7	950	0.97°	950cc
7	1	0	0	1	712	0.72°	712$\nu\overline{\nu}$
8	1	0	0	1	890	0.72°	890$\nu\overline{\nu}$
9	1	0	0	1	950	0.97°	950$\nu\overline{\nu}$
10	0	1	1	0	712	0.72°	712$\overline{\nu}\nu$
11	0	1	1	0	890	0.72°	890$\overline{\nu}\nu$
12	0	1	1	0	950	0.97°	950$\overline{\nu}\nu$

Mass hierarchy

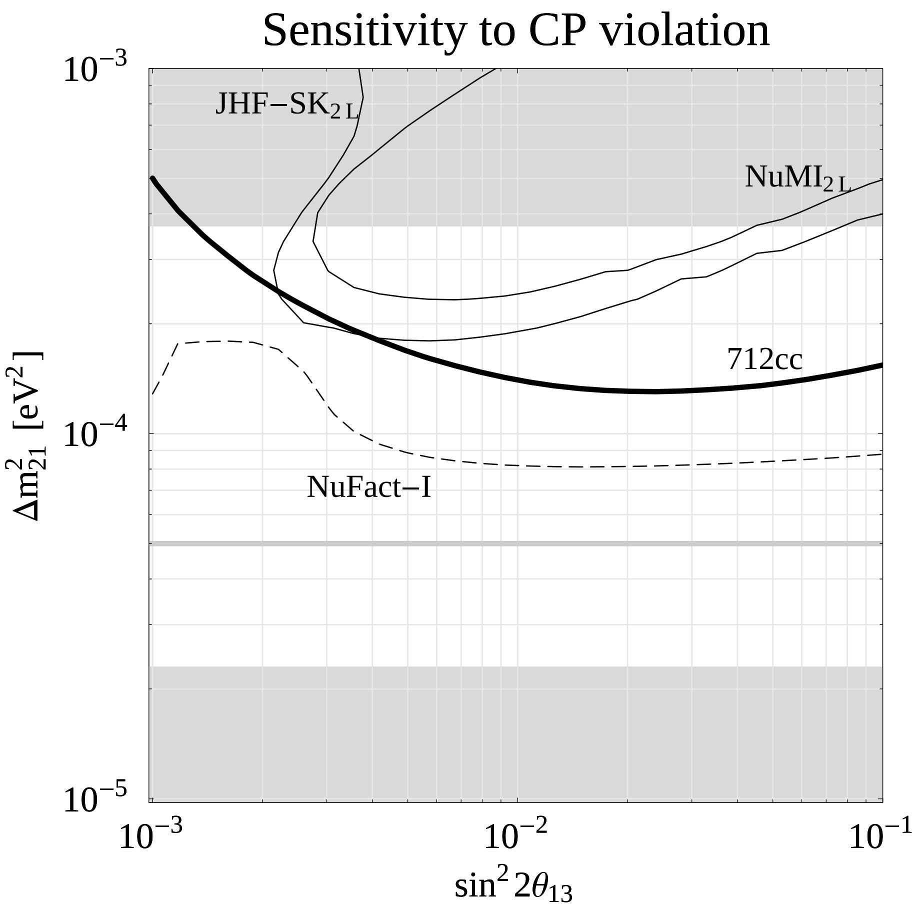


- longer baseline essential $\Rightarrow$ matter effects
- exclusive neutrino running in both experiments best
- optimum baseline depends on Δm^2_{21}

Mass hierarchy – options

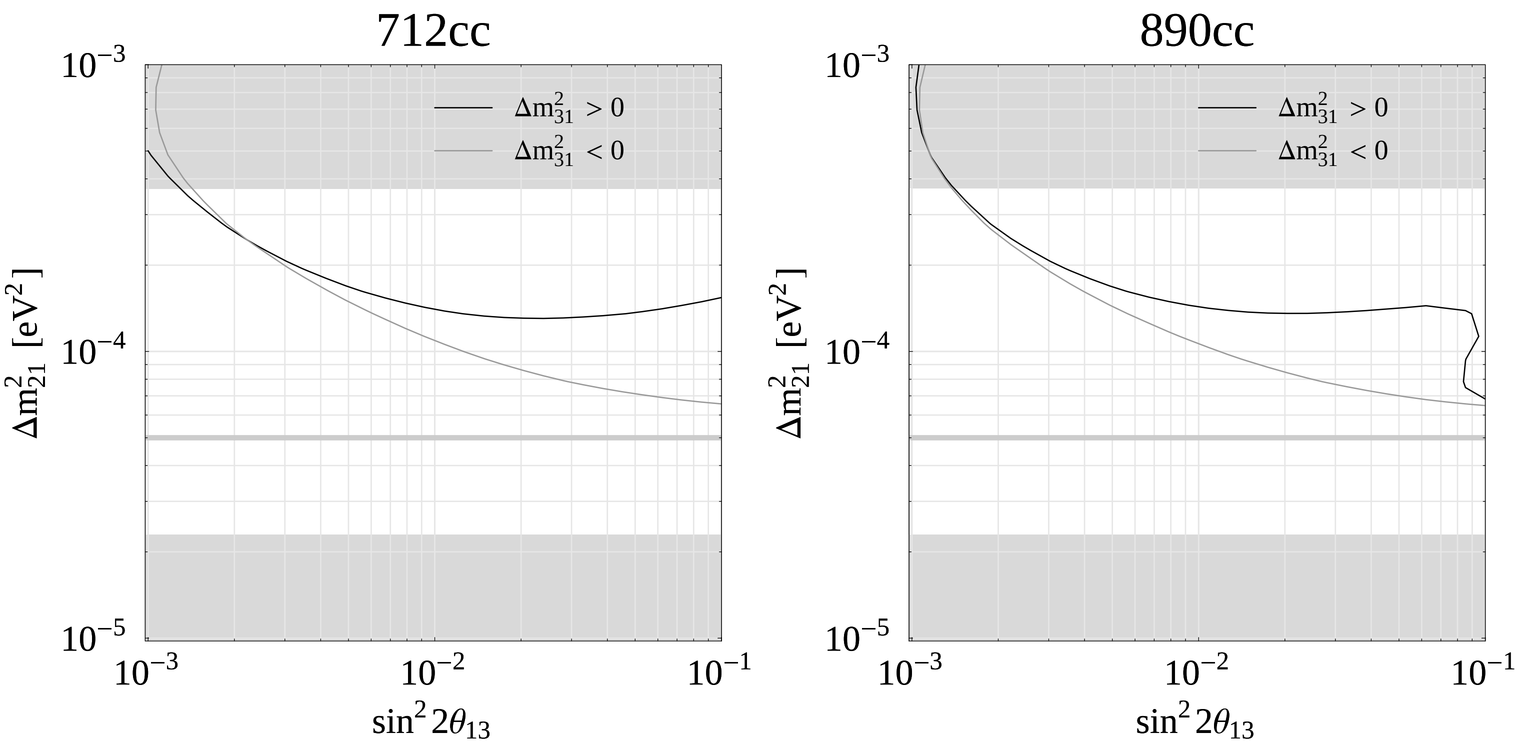
	JHF-SK			NuMI				Combined	
No.	ν	$\overline{\nu}$	Sensitivity	ν	$\overline{\nu}$	L [km]	Sensitivity	Label	Sensitivity
1	1	0	None	1	0	712	None	$712\nu\nu$	None
2	1	0	None	1	0	890	None	$890\nu\nu$	Good
3	1	0	None	1	0	950	None	$950\nu\nu$	Good
4	2/8	6/8	None	2/7	5/7	712	Marginal	712cc	Marginal
5	2/8	6/8	None	2/7	5/7	890	Marginal	890cc	Poor
6	2/8	6/8	None	2/7	5/7	950	Marginal	950cc	Good
7	1	0	None	0	1	712	None	$712\nu\overline{\nu}$	Marginal
8	1	0	None	0	1	890	None	$890\nu\overline{\nu}$	Poor
9	1	0	None	0	1	950	None	$950\nu\overline{\nu}$	Poor
10	0	1	None	1	0	712	None	$712\overline{\nu}\nu$	Marginal
11	0	1	None	1	0	890	None	$890\overline{\nu}\nu$	Poor
12	0	1	None	1	0	950	None	$950\overline{\nu}\nu$	Poor

CP violation



- substantial fraction of $\overline{\nu}$ essential
  - any distribution of $\overline{\nu}$ is okay, besides all $\overline{\nu}$ at JHF-SK
- the longest NuMI baseline does not perform good
- only possible for a large Δm^2_{21}

CP violation



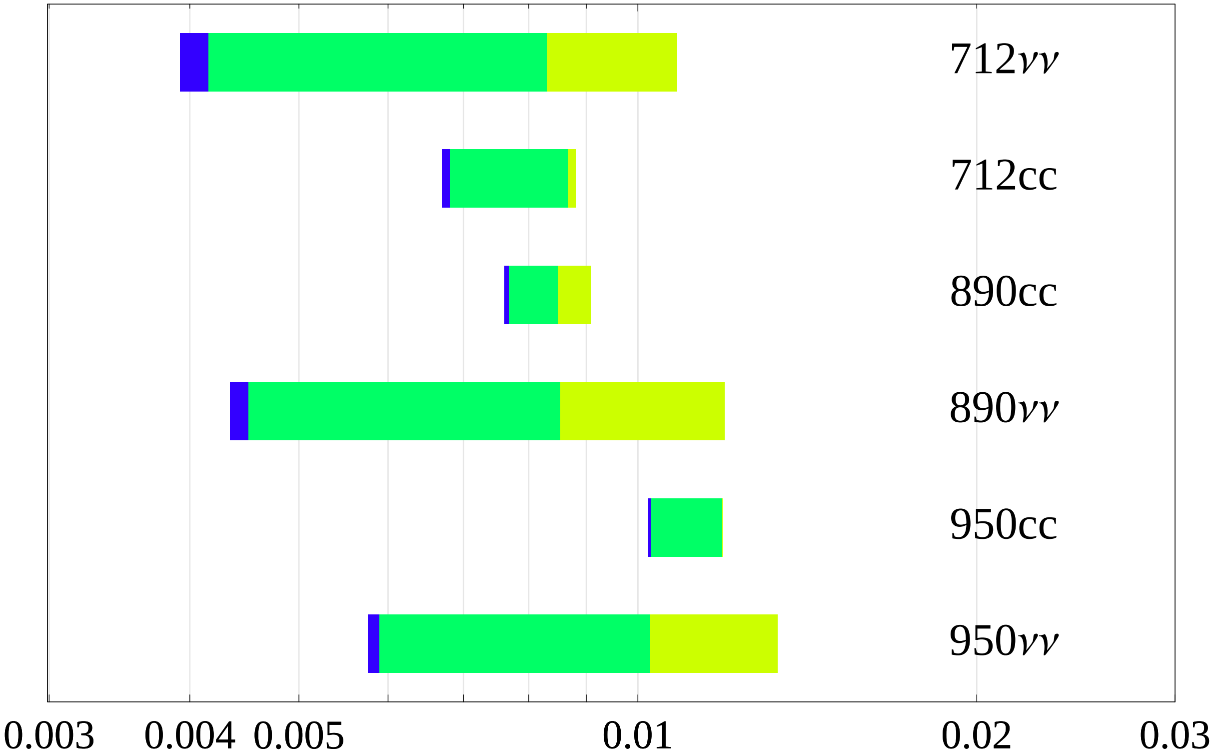
- the two shorter NuMI baselines perform very similar
- result weakly dependent of mass hierarchy
- result nearly unchanged whether $\delta = \pm\pi/2$

CP violation – options

	JHF-SK			NuMI				Combined	
No.	ν	$\overline{\nu}$	Sensitivity	ν	$\overline{\nu}$	L [km]	Sensitivity	Label	Sensitivity
1	1	0	None	1	0	712	None	712$\nu\nu$	Poor
2	1	0	None	1	0	890	None	890$\nu\nu$	Poor
3	1	0	None	1	0	950	None	950$\nu\nu$	Poor
4	2/8	6/8	None	2/7	5/7	712	None	712cc	Good
5	2/8	6/8	None	2/7	5/7	890	None	890cc	Good
6	2/8	6/8	None	2/7	5/7	950	None	950cc	Suboptimal
7	1	0	None	0	1	712	None	712$\nu\overline{\nu}$	Good
8	1	0	None	0	1	890	None	890$\nu\overline{\nu}$	Good
9	1	0	None	0	1	950	None	950$\nu\overline{\nu}$	Suboptimal
10	0	1	None	1	0	712	None	712$\overline{\nu}\nu$	Poor
11	0	1	None	1	0	890	None	890$\overline{\nu}\nu$	Poor
12	0	1	None	1	0	950	None	950$\overline{\nu}\nu$	Poor

θ_{13} sensitivity

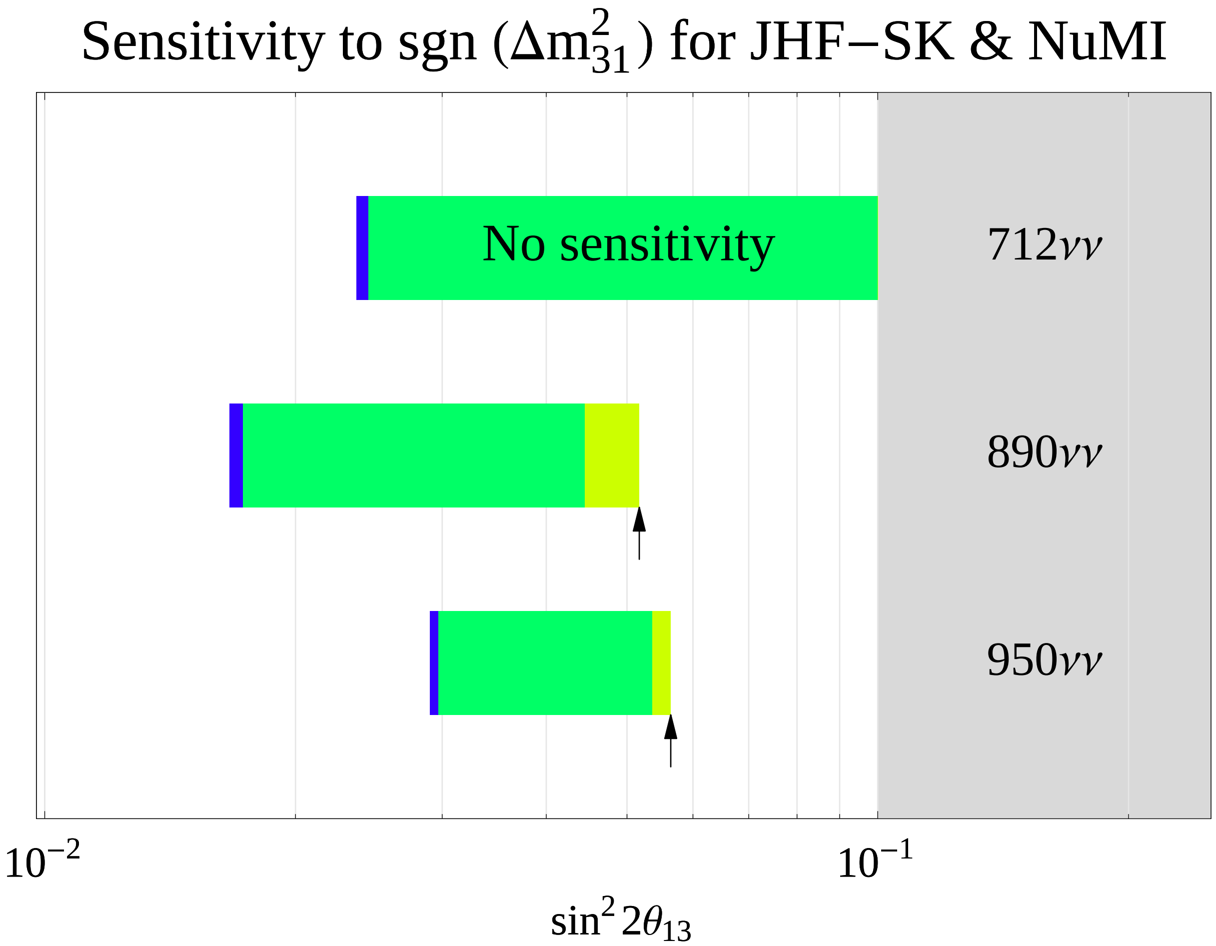
Sensitivity to $\sin^2 2\theta_{13}$ for JHF−SK & NuMI



- θ_{13} primary goal
- $890\,\mathrm{km}$ performs better
- any combination is fairly good

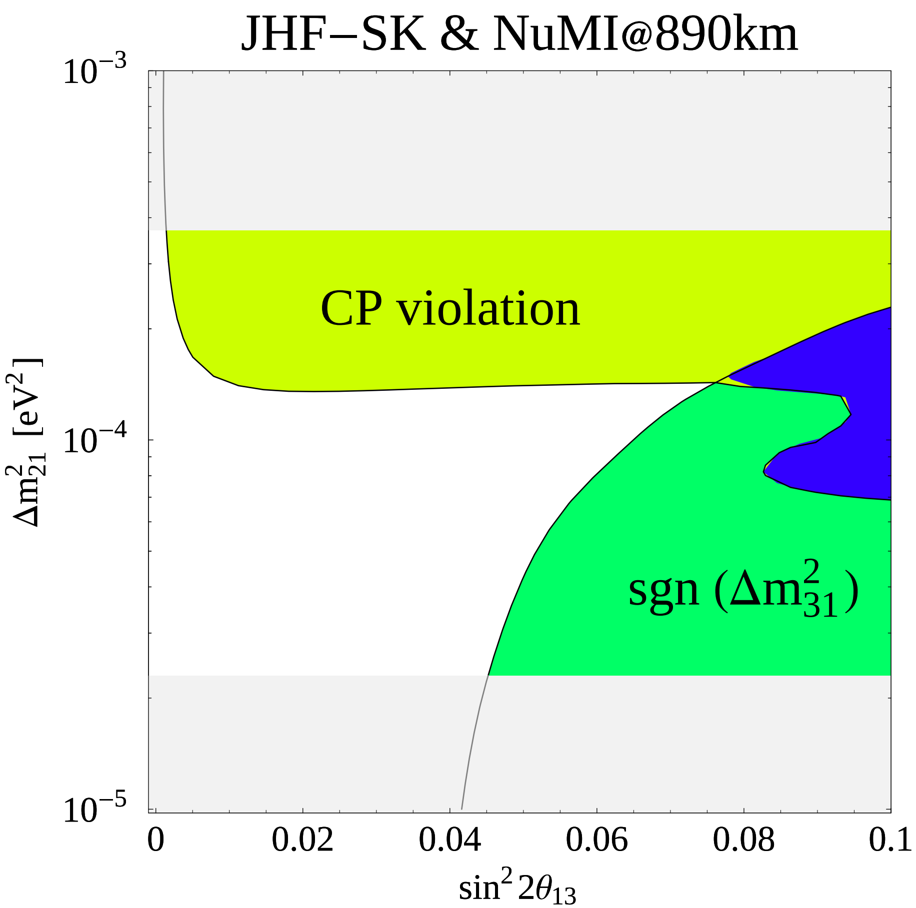
new opportunities without compromising θ_{13}

Summary



- only possible with longer baseline
- requires small Δm^2_{21}

Summary



- depending on Δm^2_{21}
  - large Δm^2_{21}
  $\Rightarrow$ CP violation
  - small Δm^2_{21}
  $\Rightarrow$ mass hierarchy

in any case there is important physics

Conclusion

- synergy $\Leftrightarrow$ effects beyond adding statistics
- JHF and NuMI as planed right now $\Rightarrow$ no synergies
- with realistic modifications $\Rightarrow$ richer physics program already in the initial stage
- same modifications also beneficial with long-term upgrades[†]

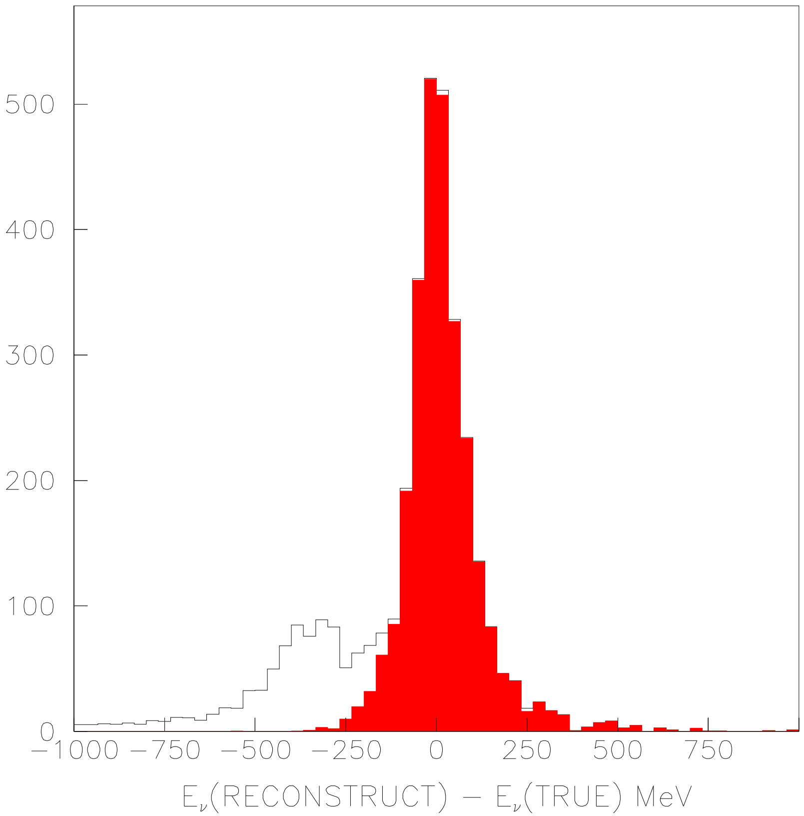
Possibilities within this decade

- small Δm^2_{21} $\Rightarrow$ mass hierarchy
- large Δm^2_{21} $\Rightarrow$ CP violation
- $890\,\mathrm{km}$ NuMI baseline seems to be optimal
- θ_{13} sensitivity is not compromised

$\boxed{\text{joint planing essential}}$

[†] see V. Barger, D. Marfatia and K. Whisnant, hep-ph/0210428.

Energy resolution



for QE-events energy resolution is determined by Fermi motion $\Longrightarrow$ it is well described by a Gaussian with a nearly constant $\sigma \sim 80 - 100\,\mathrm{MeV}$

- 60% are QE-events at the peak energy $0.8\,\mathrm{GeV}$
- the energy resolution at the peak energy is $10\% - 13\%$

Y. Itow *et al.*, hep-ex/0106019.

T. Nakaya, private communication.