# Can beam optimisation help in separating NSI and SI?

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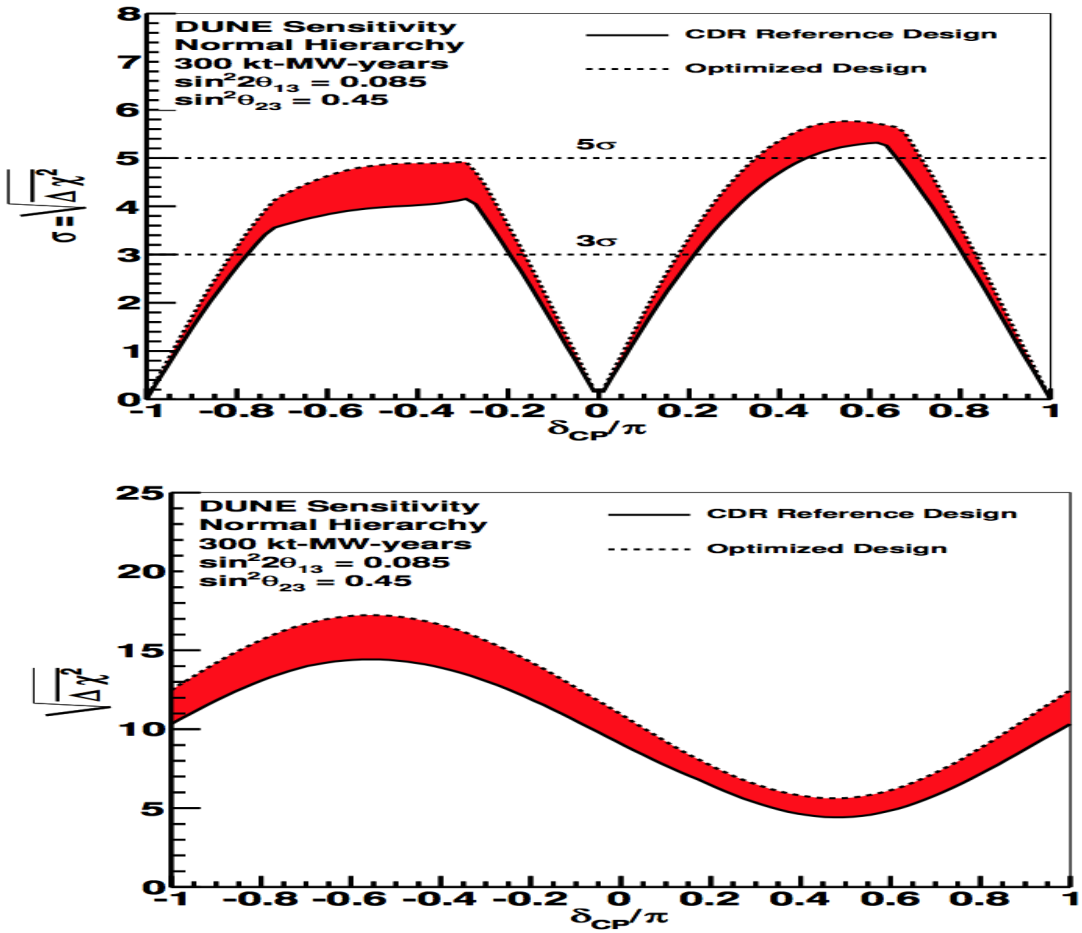
Based on ongoing work with M. Bishai & P. Mehta

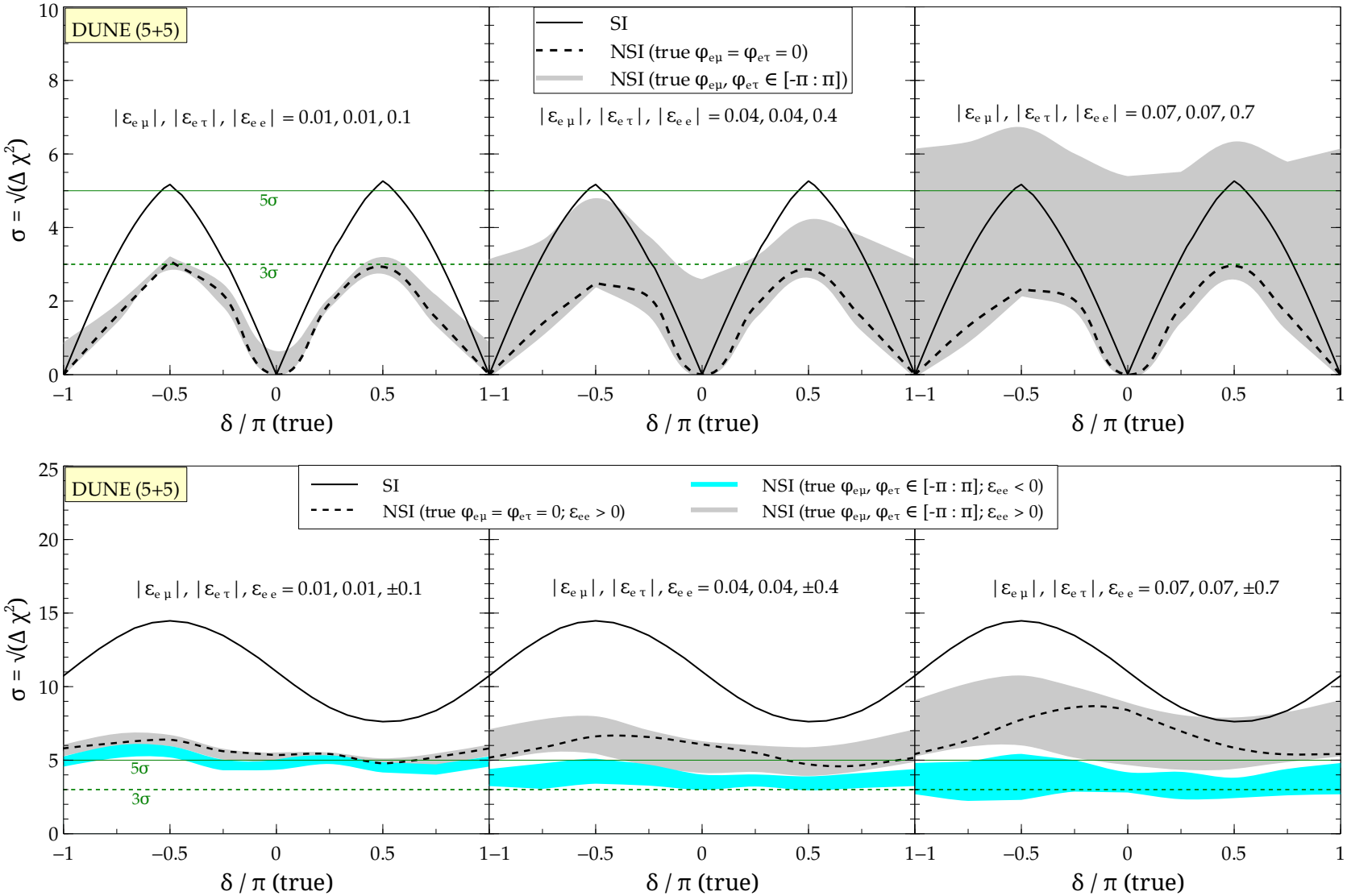
# CPV (top) and MH sensitivity (bottom): results from collaboration

R. Acciarri *et al.* *1512.06148*



# NSI can significantly spoil CPV and MH sensitivity at DUNE

MM, P.Mehta *PRD 94(2016)013014 & PRD 94(2016)053007*



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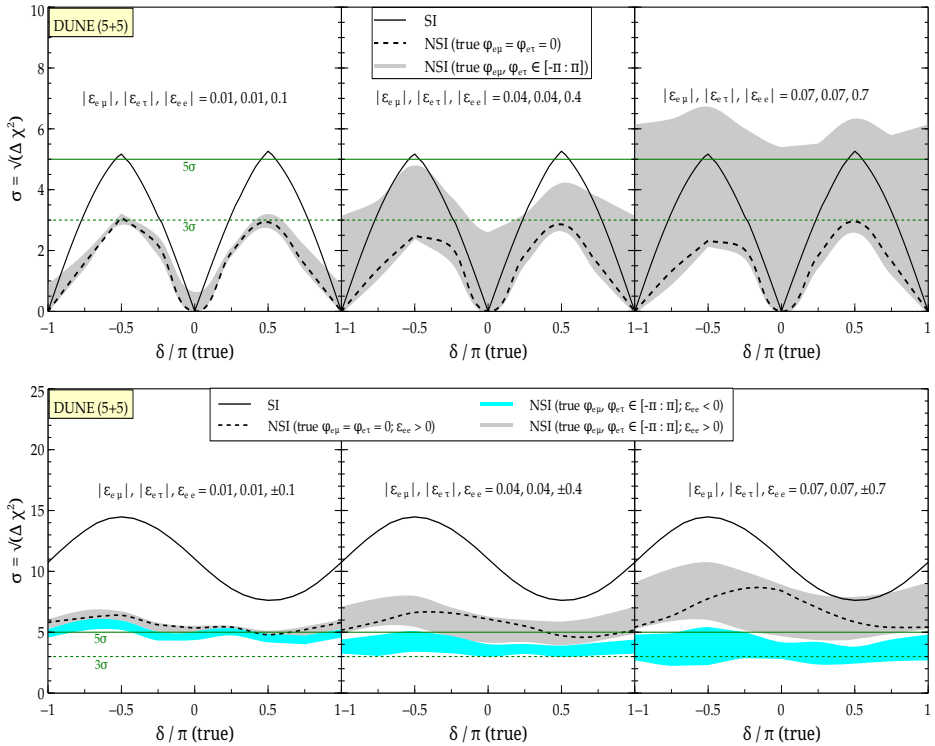
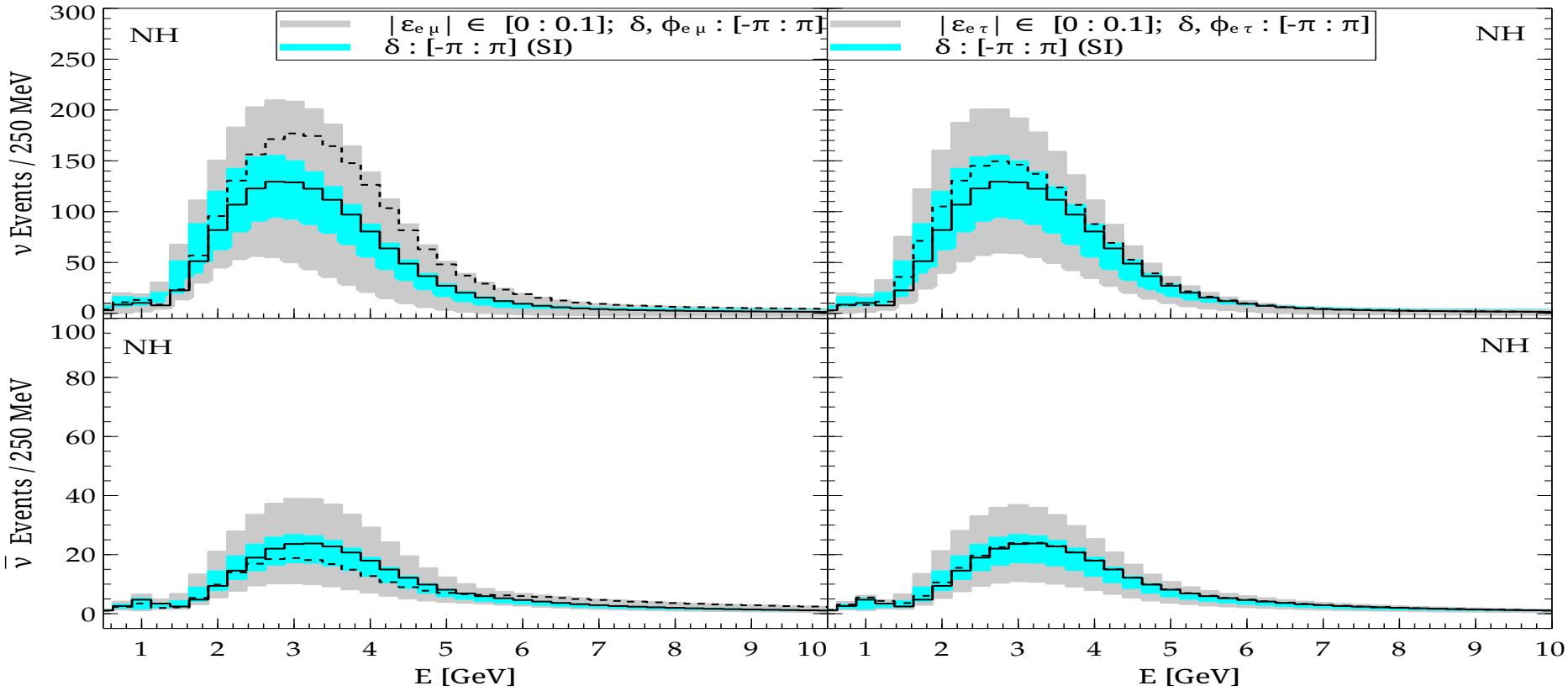



It is important to separate NSI from SI to be able to make clean inferences...

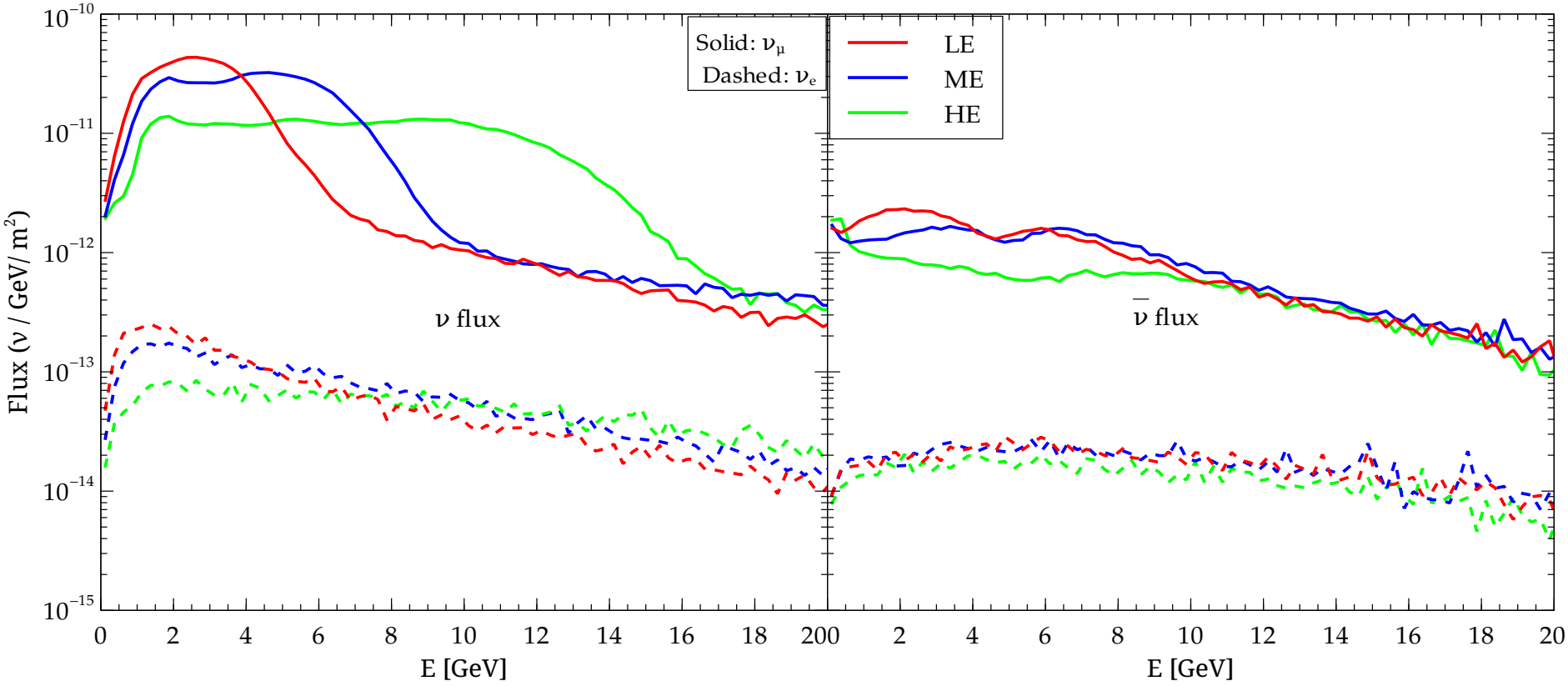
# Why LE only beam is not ideal for the purpose?

MM, A.Chatterjee, P.Mehta *J.Phys. G43 (2016) no.9, 095005*



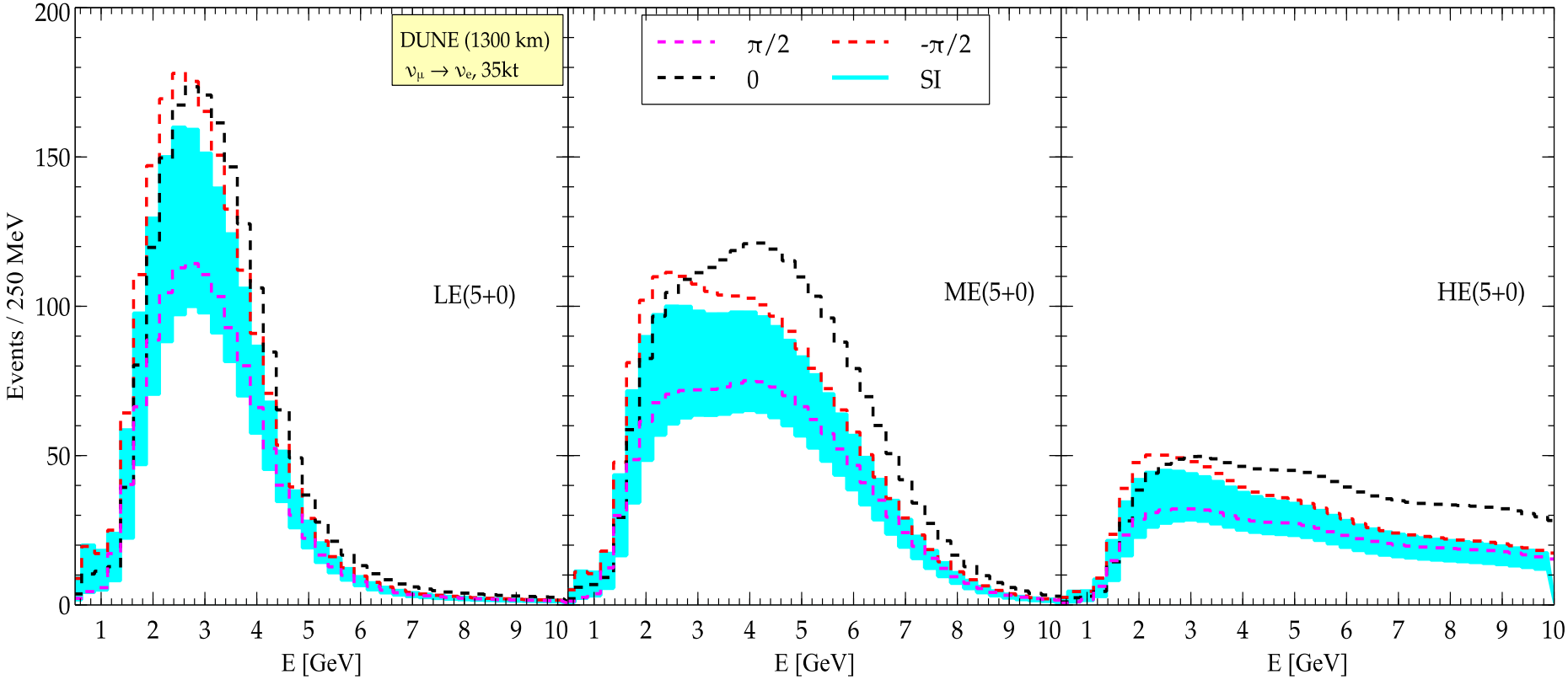

- Cyan band: SI with $\delta$ variation; grey band: NSI with $\delta, \varphi$ variation; Black solid: SI with $\delta = 0$; Black dashed: NSI with $\delta, \varphi = 0$.
- The events tail off at $E \gtrsim 5$ GeV onwards
  $\Longrightarrow$ Difficult to distinguish between NSI and SI spectra at higher energies.

# A comparison of LE (*i.e.*, optimised), ME, HE flux




- Left panel: $\nu$ beam  Right panel: $\bar{\nu}$ beam.
- For $\nu$-beam, LE beam peaks (*i.e.*, optimized) $\in$ [1.5 — 4] GeV
  ME beam peaks $\in$ [1.5 — 6] GeV
  HE beam peaks $\in$ [1.5 — 10] GeV but with about 3 times less amplitude.
- ME and HE beams do not allow the events to fall very sharply at higher energies.

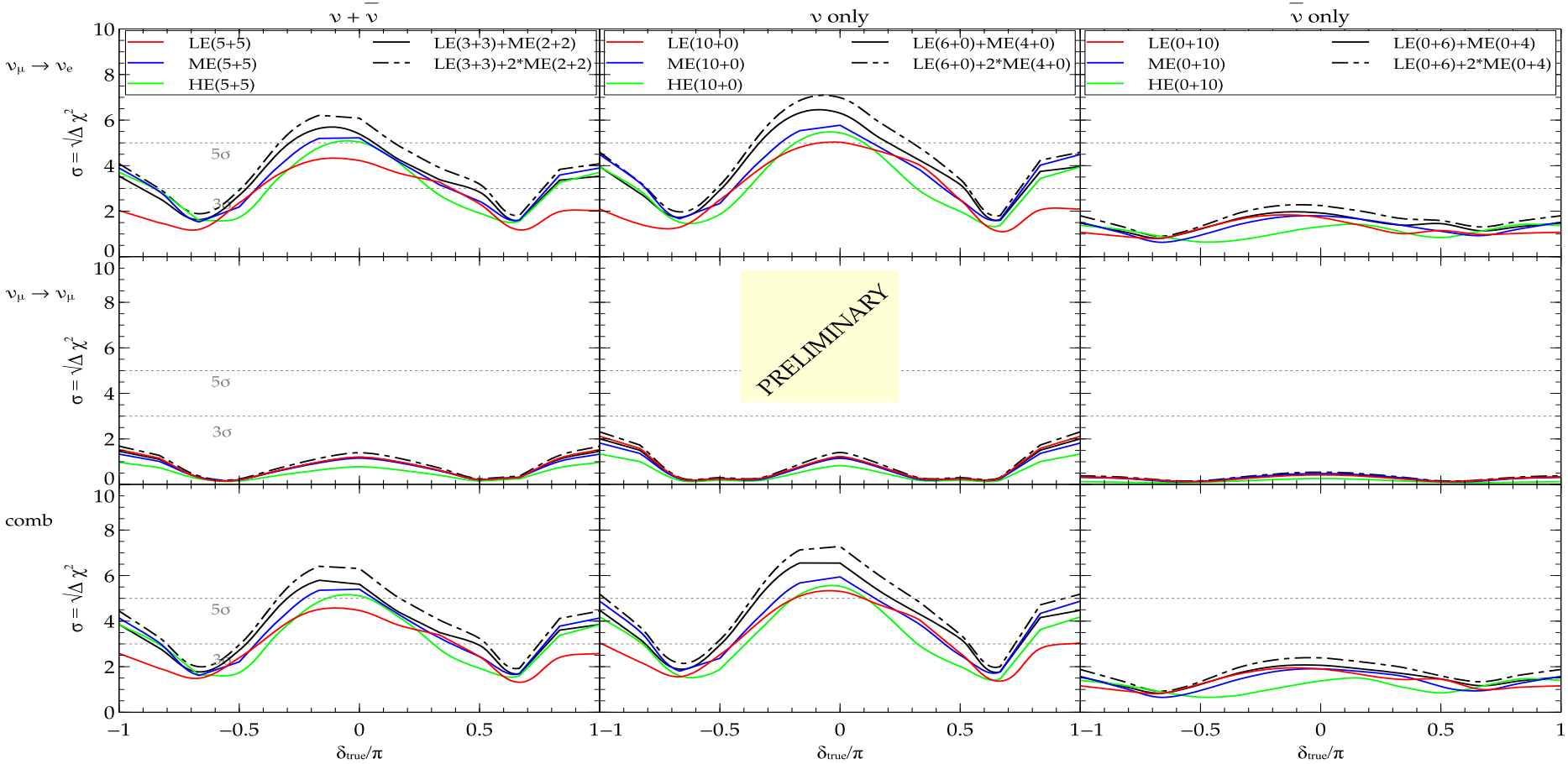
# How the event spectrum changes for higher energy beams




- The events do not fall off sharply at higher energies for ME and HE beams.

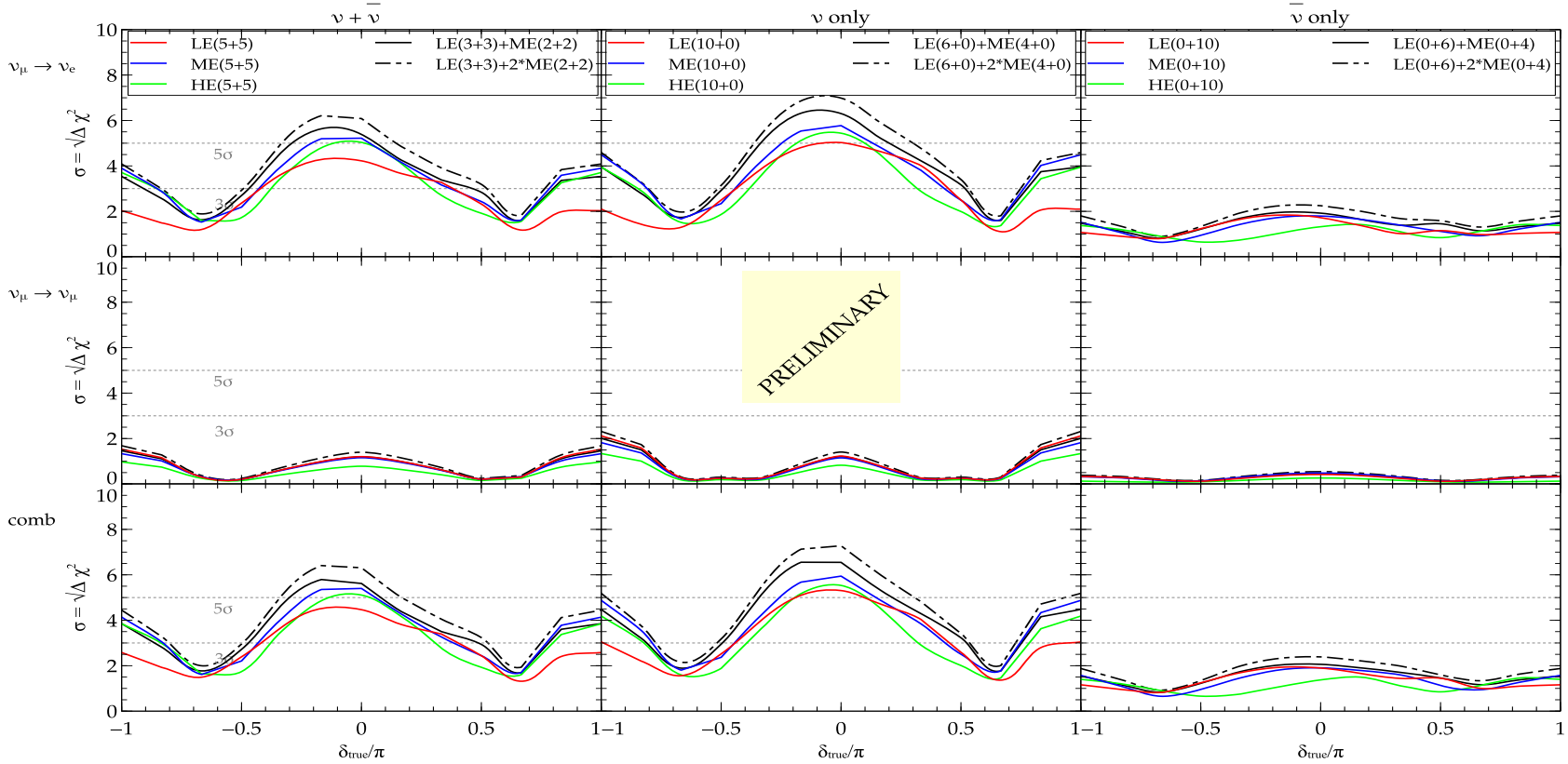
Is it possible to combine LE with ME or HE to distinguish between SI and NSI?

# Sensitivity to distinguish NSI-SI (Combine LE and ME)




- Top row: $\nu_\mu \to \nu_e + \bar{\nu}_\mu \to \bar{\nu}_e$; Middle row: $\nu_\mu \to \nu_\mu + \bar{\nu}_\mu \to \bar{\nu}_\mu$; Bottom row: Combined
- LE + ME (Black) offers some improvement to the NSI-SI sensitivity.
- $\nu$ only gives slightly better sensitivity and $\bar{\nu}$ contribution is small.
- Sensitivity peaks near $\delta_{true} \simeq 0$ and trough is near $\pm\pi/2$.

# Sensitivity to distinguish NSI-SI (Combine LE and ME)...

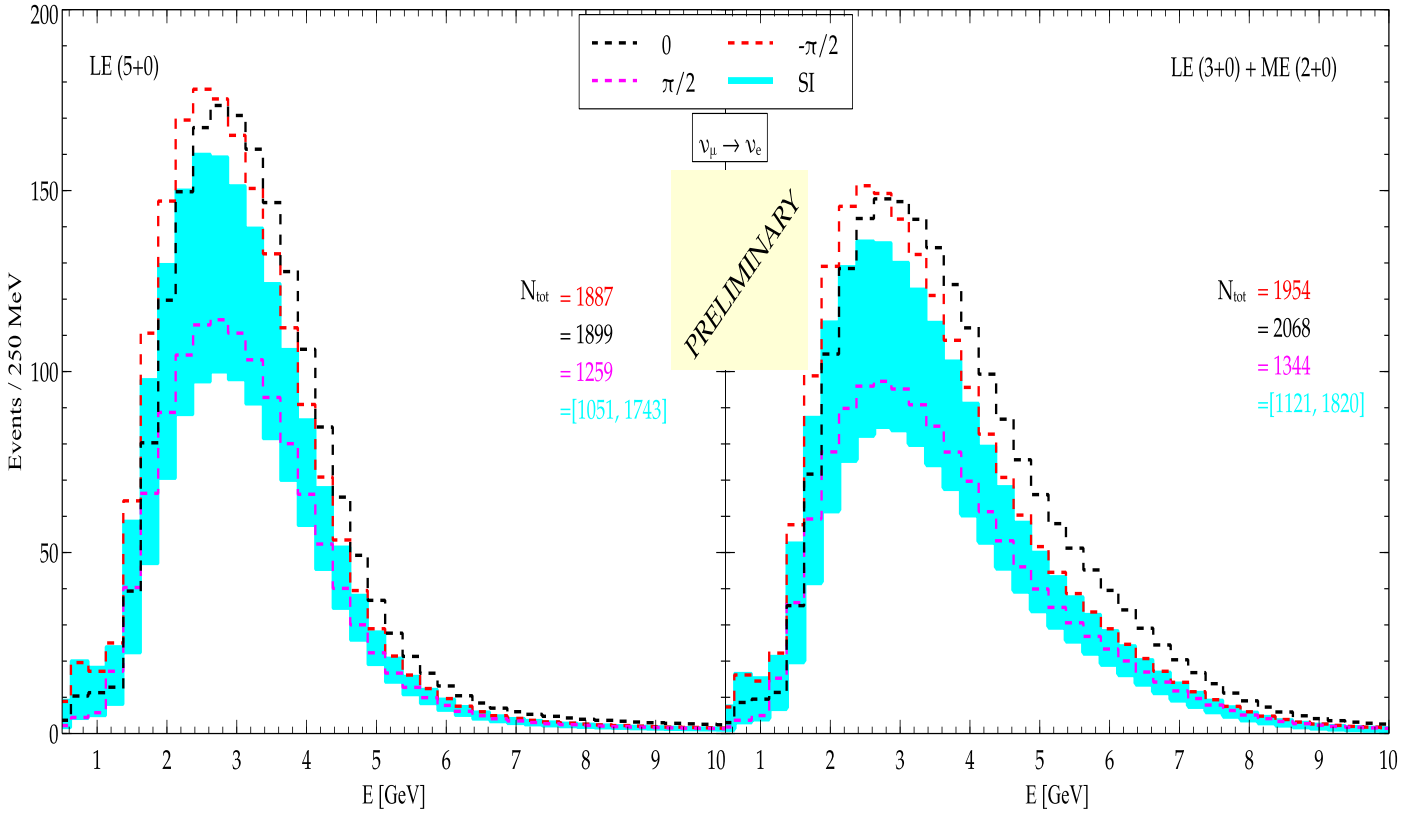



Done numerically using GLoBES and snu.c

$$\chi^2(\delta_{tr}, |\varepsilon|, \varphi) \quad = \quad \min_{\delta_{ts}} \sum_{i=1}^{x} \sum_{j}^{2} \frac{\left[ N^{i,j}_{NSI}(\delta_{tr}, |\varepsilon|, \varphi) - N^{i,j}_{SI}(\delta_{ts} \in [-\pi, \pi]) \right]^2}{N^{i,j}_{NSI}(\delta_{tr}, |\varepsilon|, \varphi)},$$

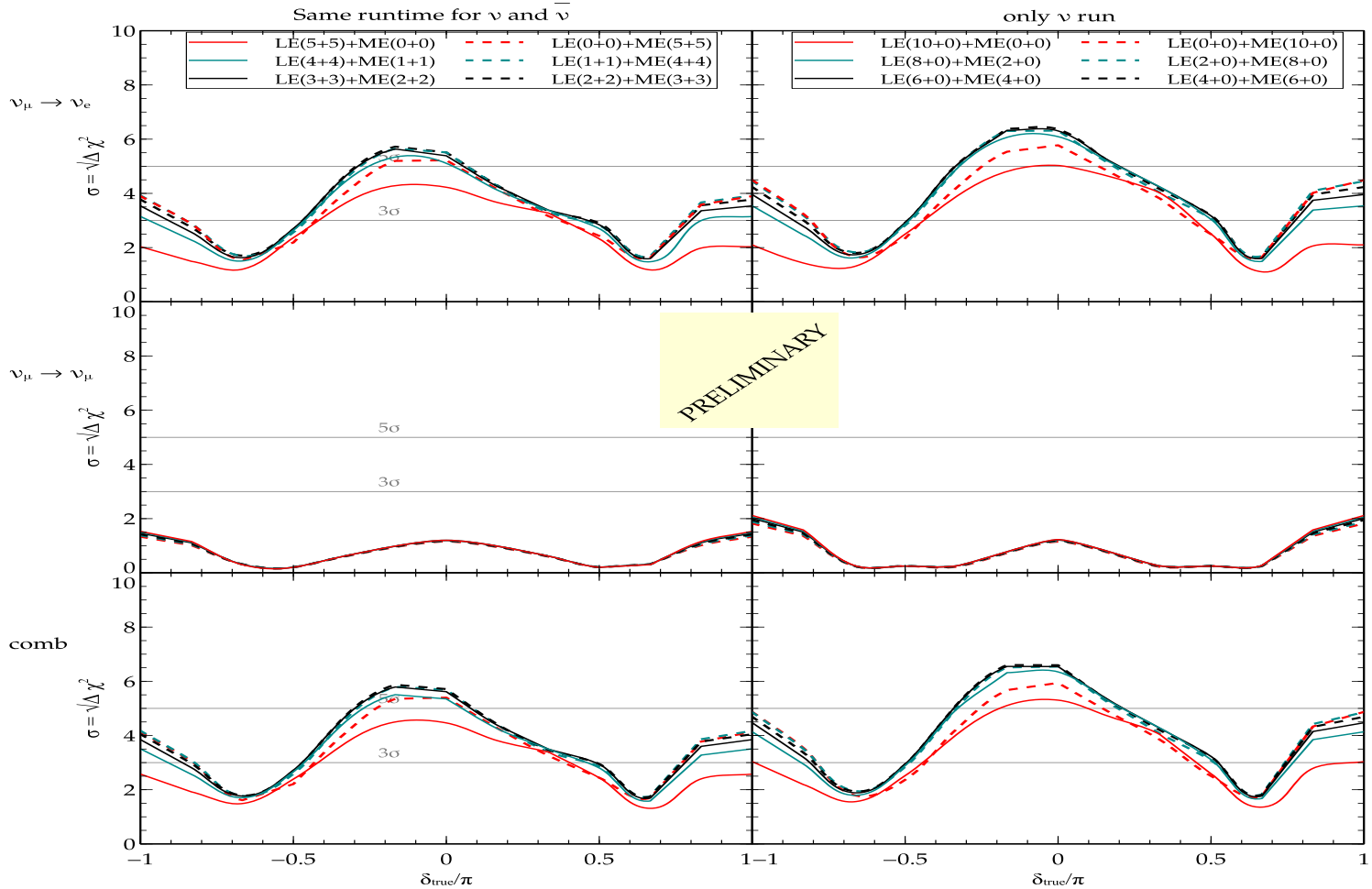
where $N^{i,j}_{SI}$ is the no. of events in the i-th energy bin and corresponding to the j-th channel ($\nu_\mu \to \nu_e$, $\nu_\mu \to \nu_\mu$ or their $\bar{\nu}$ counterparts.).

# Another look at event spectra with LE+ME combination



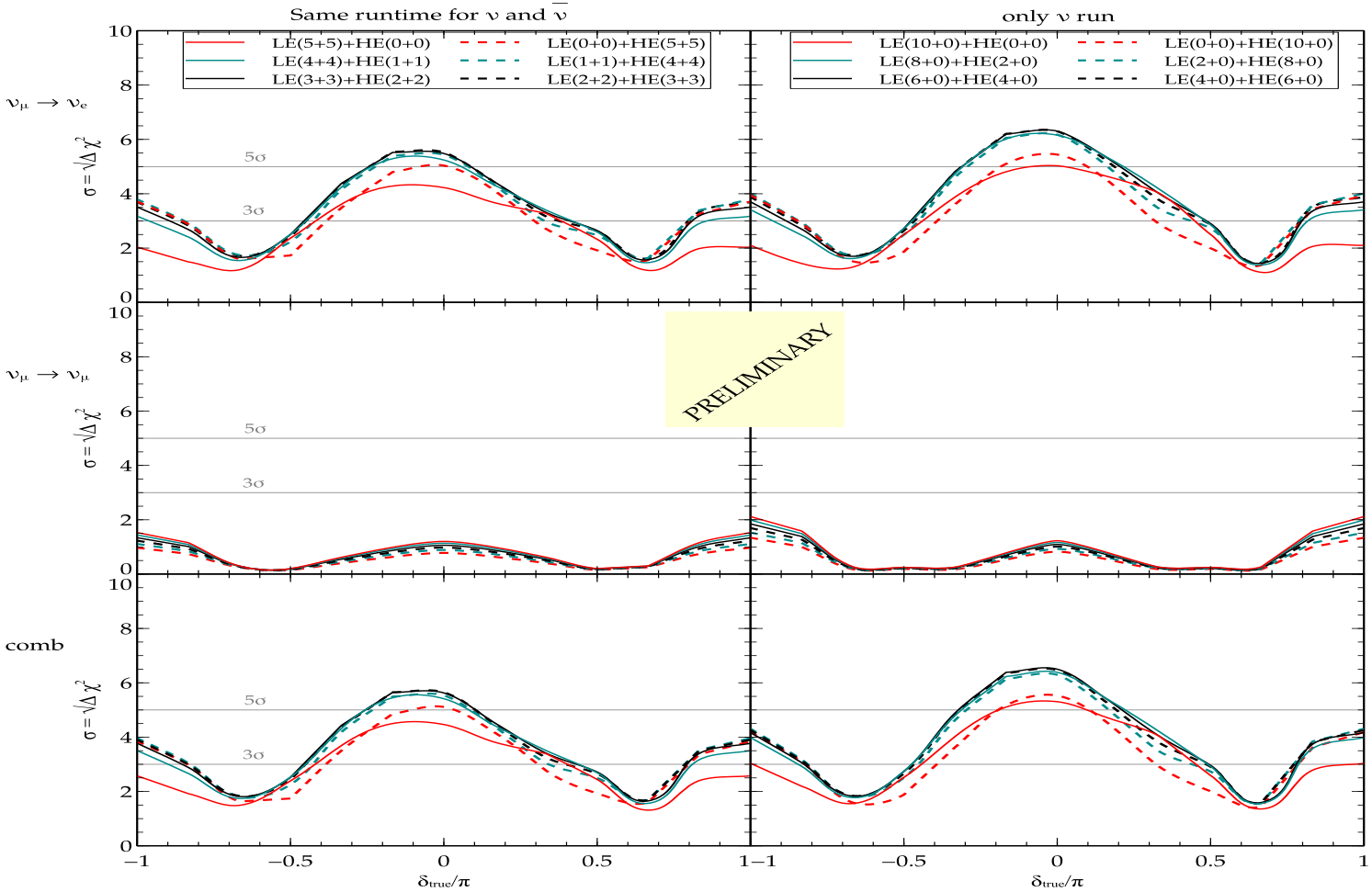

- Only neutrino events ($\nu_\mu \to \nu_e$) for illustration.
- Relatively higher separation between black dashed curve (NSI with zero phases) and the cyan band (SI).
- LE+ME beam combination (right panel) gives nonzero events even at larger energies.
- Although the amplitude of the event spectrum decreases, the total no. of events increases giving high statistics for LE+ME.

# An effort to optimize LE and ME beam combination



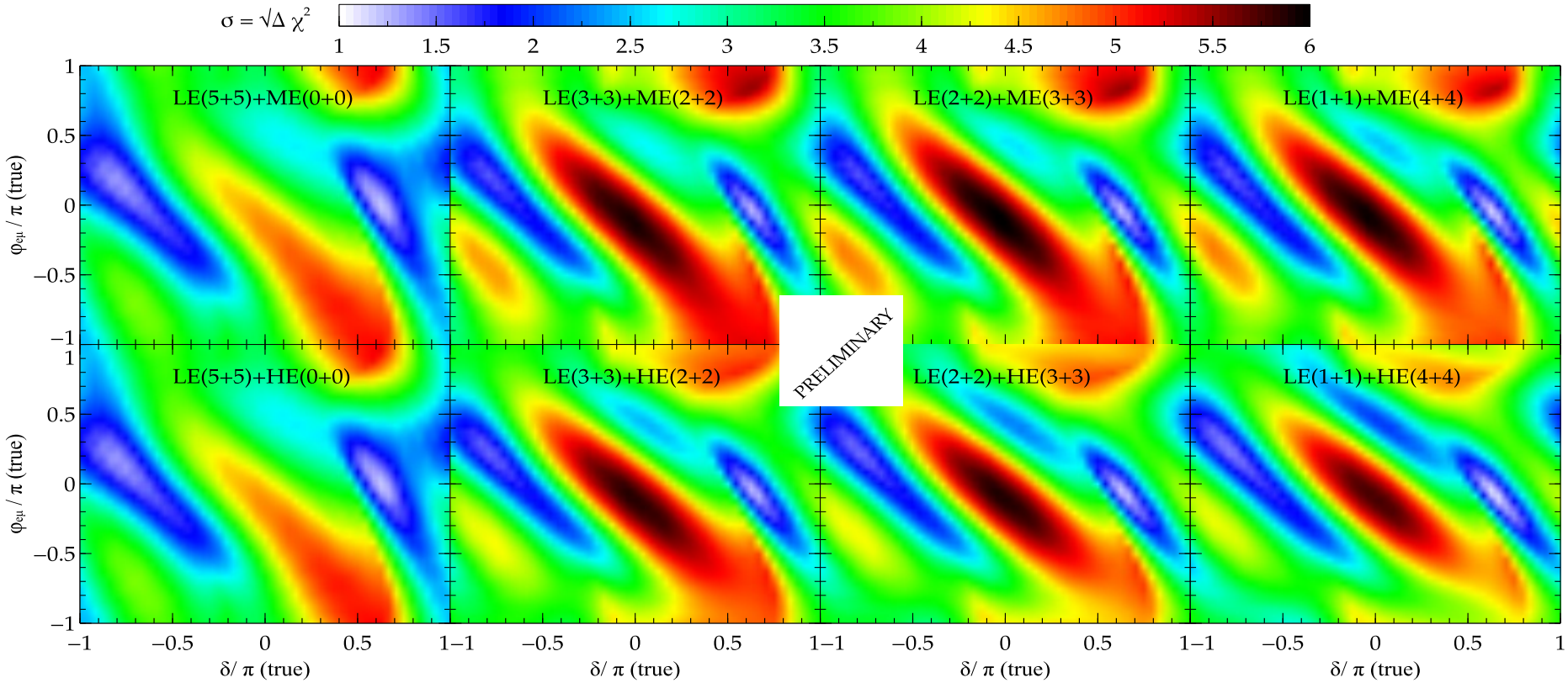

- Runtimes are distributed among LE and ME beam to study NSI-SI separation.
- All combinations of LE+ME, including using the ME beam alone (red dashed) offers substantial improvement. than LE alone (solid red).

# An effort to optimize LE and HE beam combination



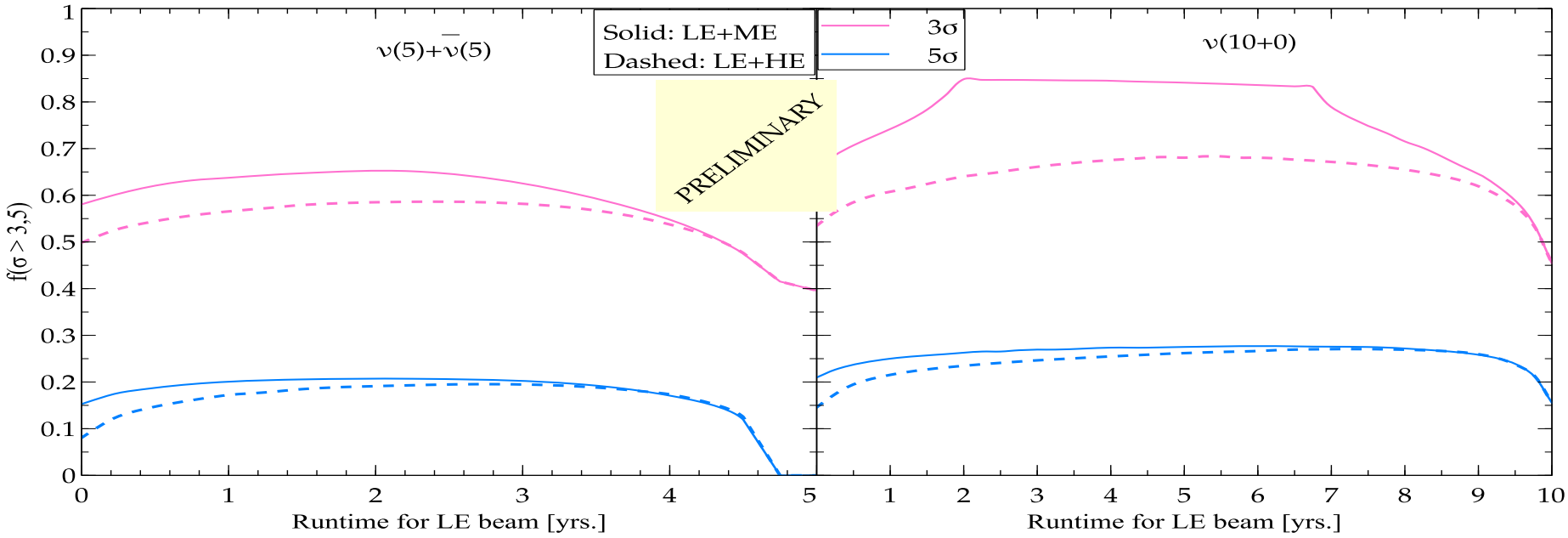

Features similar to LE+ME combinations are observed here also.

# Generalisation to the case of nonzero $\varphi_{e\mu}$




- Shows the sensitivity for nonzero $\varphi_{e\mu}$ for both LE + ME (top row) and LE + HE (bottom row) in terms of coloured oscillogram/ heatmap.
- Consistency check: Highest sensitivity ($\gtrsim 6\sigma$: black patch) is obtained for zero $\varphi_{e\mu}$ at true $\delta \simeq 0$ and lowest (whitish patch) at true $\delta \simeq \pm\pi/2$.
- The amplitude of the sensitivity and position of maxima/minima seem to shift with nonzero $\varphi_{e\mu}$.

# Fraction of true $\delta$ separating NSI/SI




- Shows what fraction of the true $\delta$-space resolves NSI-SI sensitivity above $3\sigma$ (magenta) or $5\sigma$ (blue).
- Left panel: $\nu + \bar{\nu}$ run. It shows the results of $\big[(x + x)$ yrs. of LE run$\big] + \big[\big((5 - x) + (5 - x)\big)$ yrs. of ME or HE run.$\big]$.
- Right panel: $\nu$-only run. It shows the results of $\big[(x + 0)$ yrs. of LE run$\big] + \big[\big((10 - x) + 0\big)$ yrs. of ME or HE run.$\big]$.
- An approximately evenly distributed runtime (*i.e.*, around the middle of the horizontal axis) among LE and the higher energy beams seems to be the optimal case.
- A sharp drop for all curves at the right edge
  $\Longrightarrow$ *LE only* is not a wise choice as far as NSI-SI separation is concerned.

# Conclusion

- Combining higher energy beams with LE gives better sensitivity for separating NSI and SI, as compared to LE beam alone.
- The fraction of true $\delta$-space is larger when higher energy beams are combined with LE beams.
- CP conserving NSI ($\varphi_{\alpha\beta} = 0, \pm\pi$) gives highest sensitivity around true $\delta \simeq 0$ and it dips around $\pm\pi/2$. These positions shift and the curve becomes flatter for nonzero $\varphi_{\alpha\beta}$.