FUTURE PHYSICS REACH OF ELECTRON NEUTRINO APPEARANCE MEASUREMENTS IN NOvA

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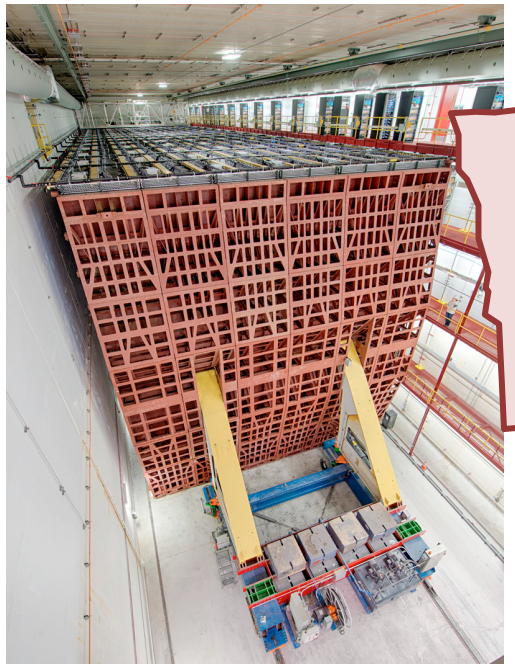
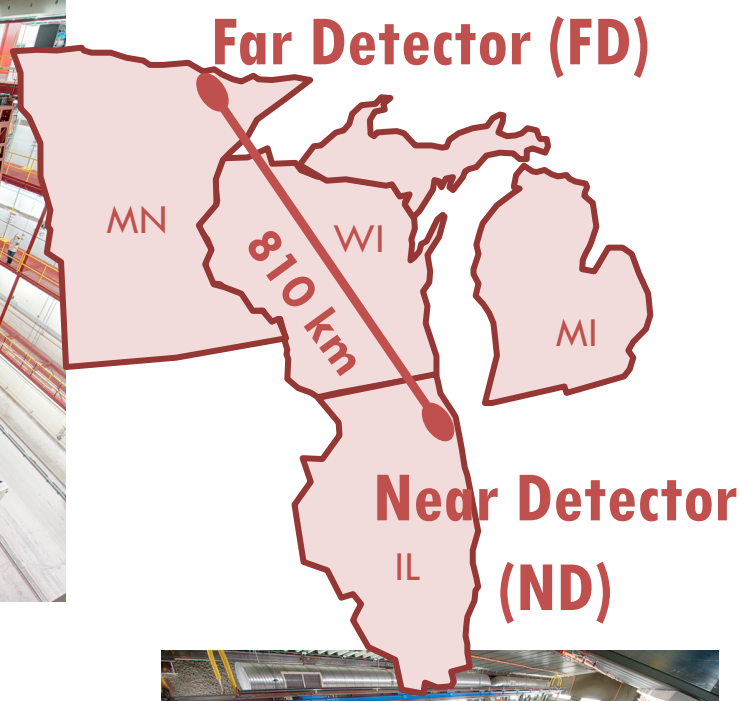
Iowa State University
For the NOvA Collaboration
DPF2017

THE NOvA NEUTRINO EXPERIMENT





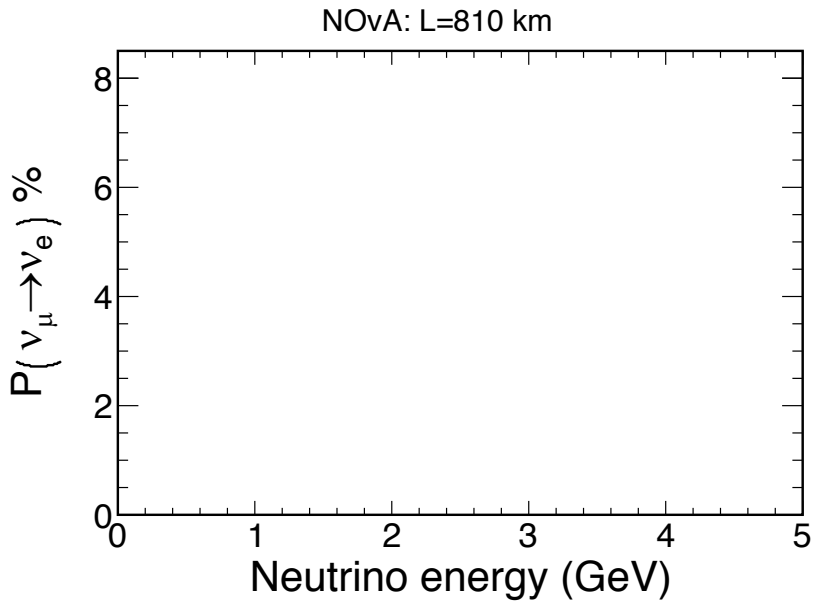
4 things to remember:

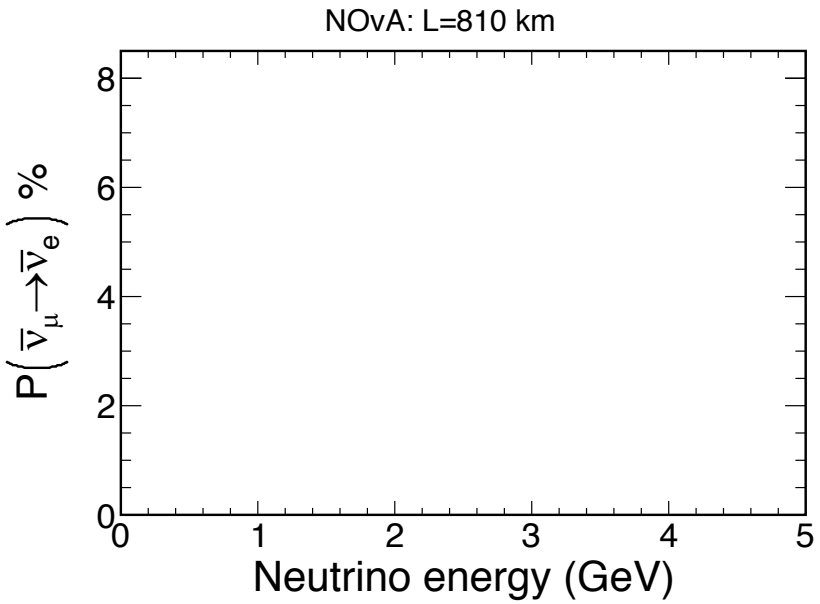
1. Two-detector experiment
   - Near detector (ND), 0.3 kton, 100 m underground, 1 km from beam target, Fermilab
   - Far detector (FD), 14 kton, on the surface, Ash River (MN)
2. Long baseline: 810 km
3. NuMI muon neutrino (or antineutrino) beam; narrow spectrum centered ~2 GeV
   - 14 mrad off-axis
4. Dominant oscillation modes:
   Muon neutrino survival
   Electron neutrino appearance

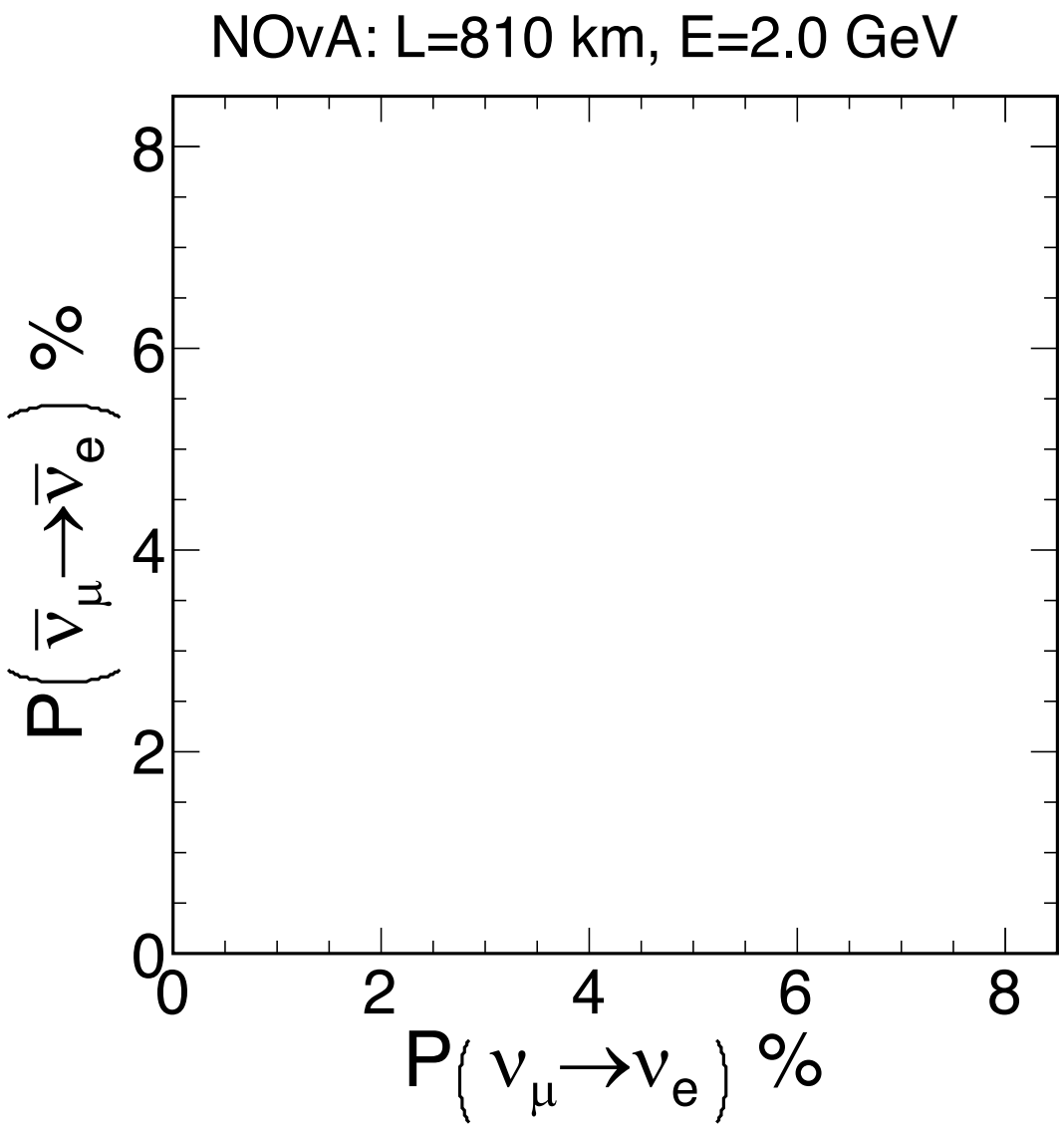
ELECTRON NEUTRINO APPEARANCE PROBABILITIES

"Electron neutrino appearance":
3-flavor oscillations

$\nu_\mu \rightarrow \nu_e$
$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$



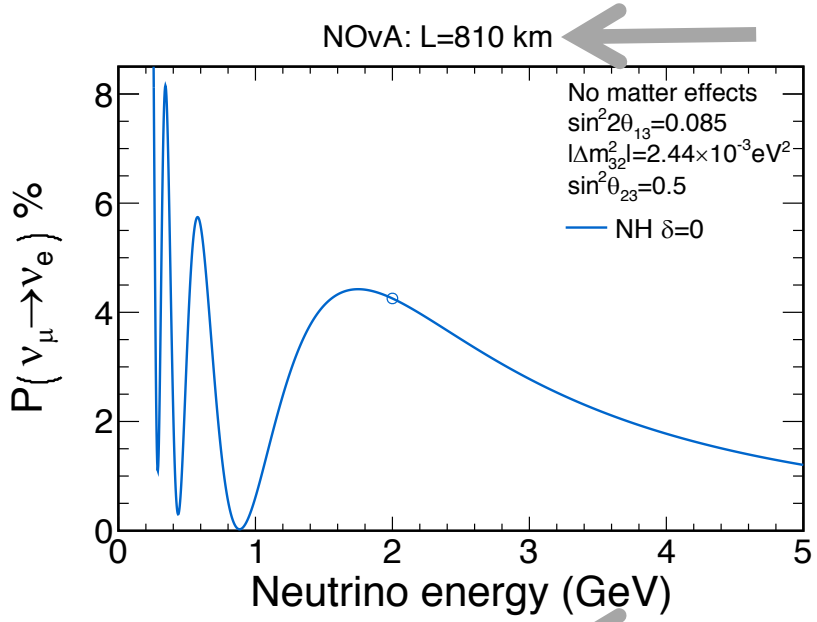


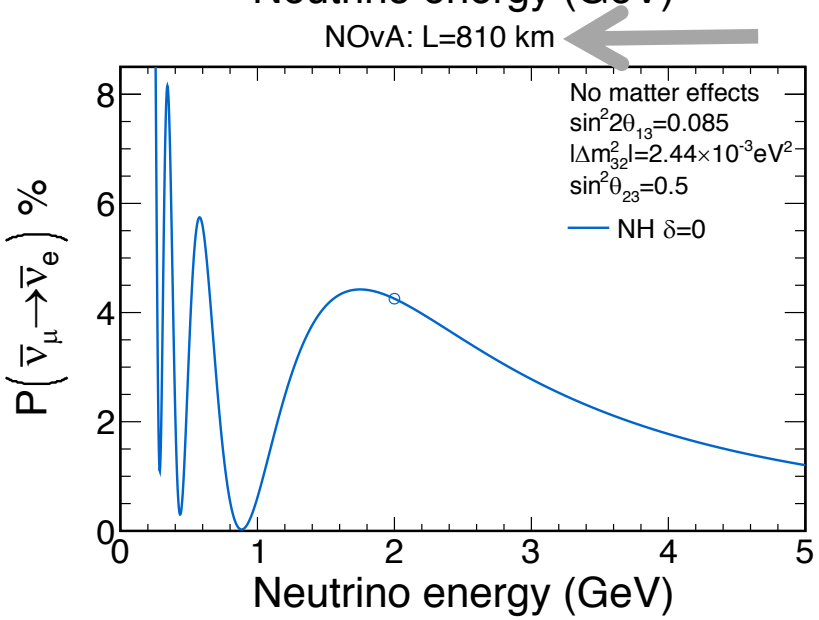


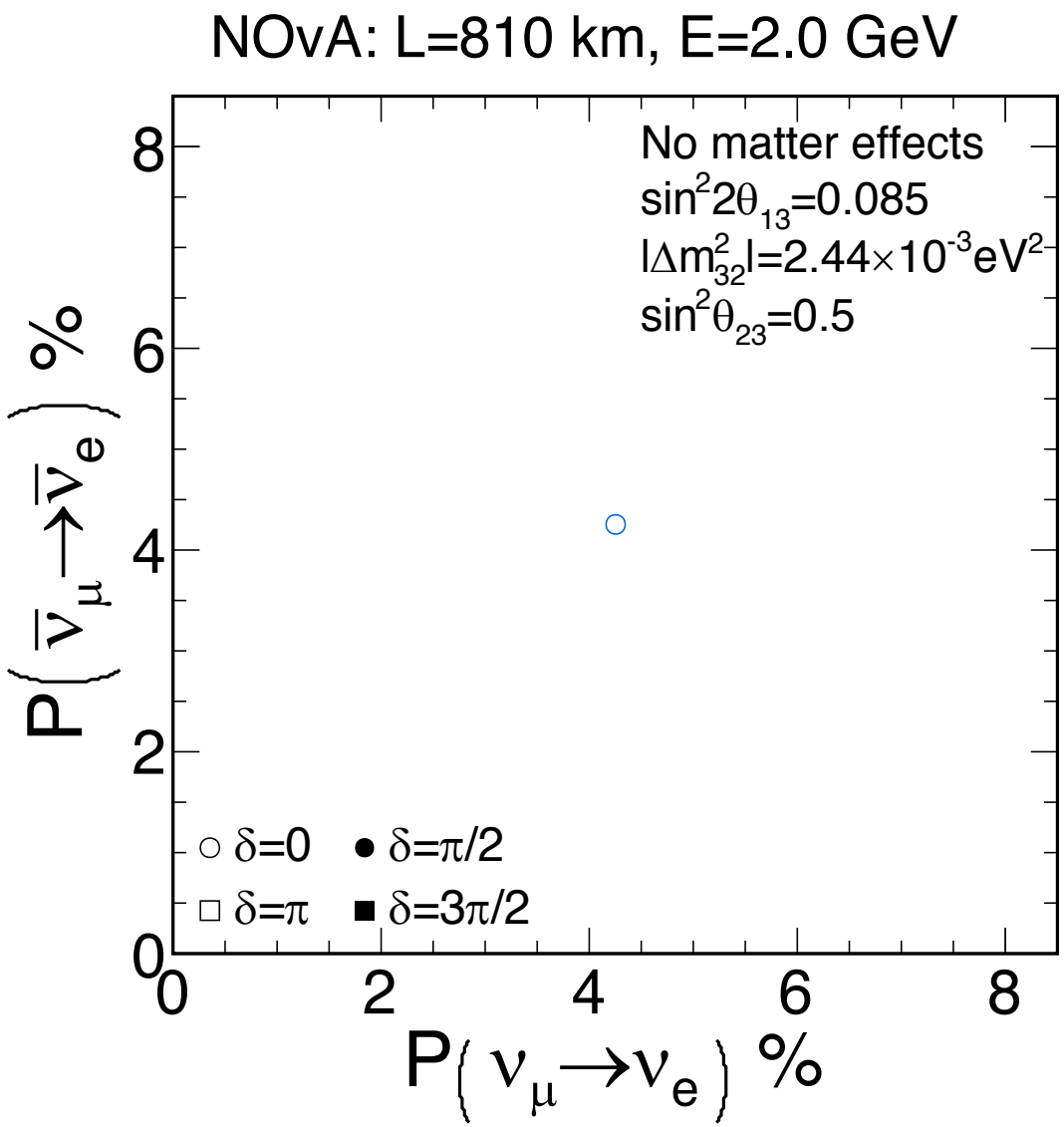
ELECTRON NEUTRINO APPEARANCE PROBABILITIES

Oscillation probabilities depend on:

- Source-detector distance (L)







ELECTRON NEUTRINO APPEARANCE PROBABILITIES

Oscillation probabilities depend on:

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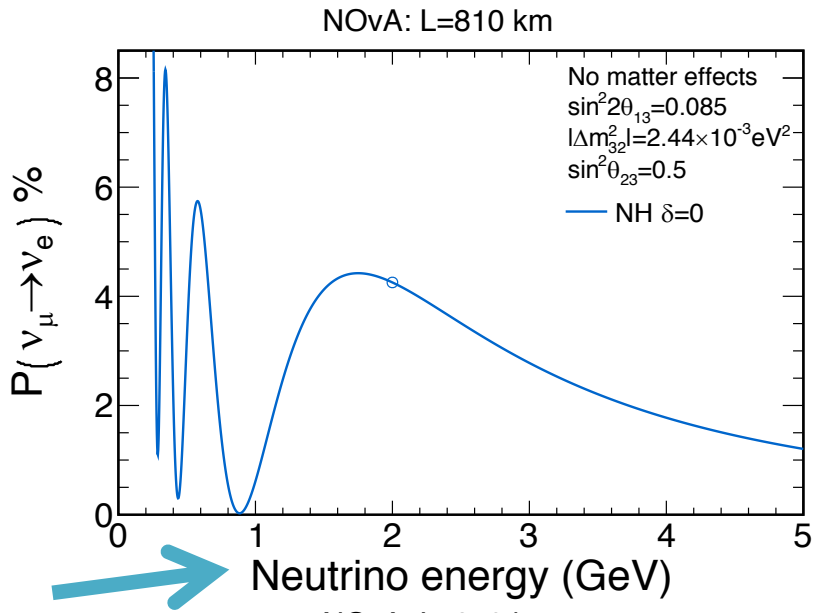
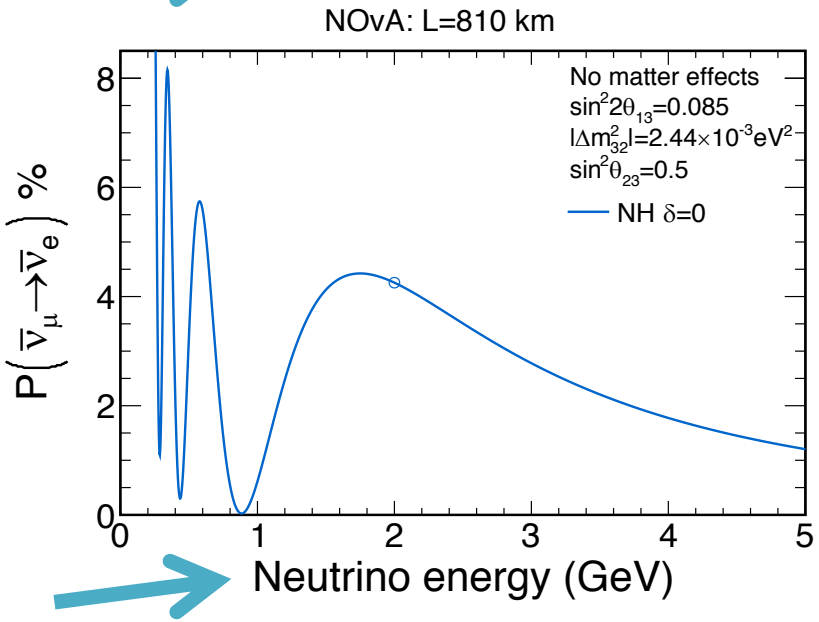
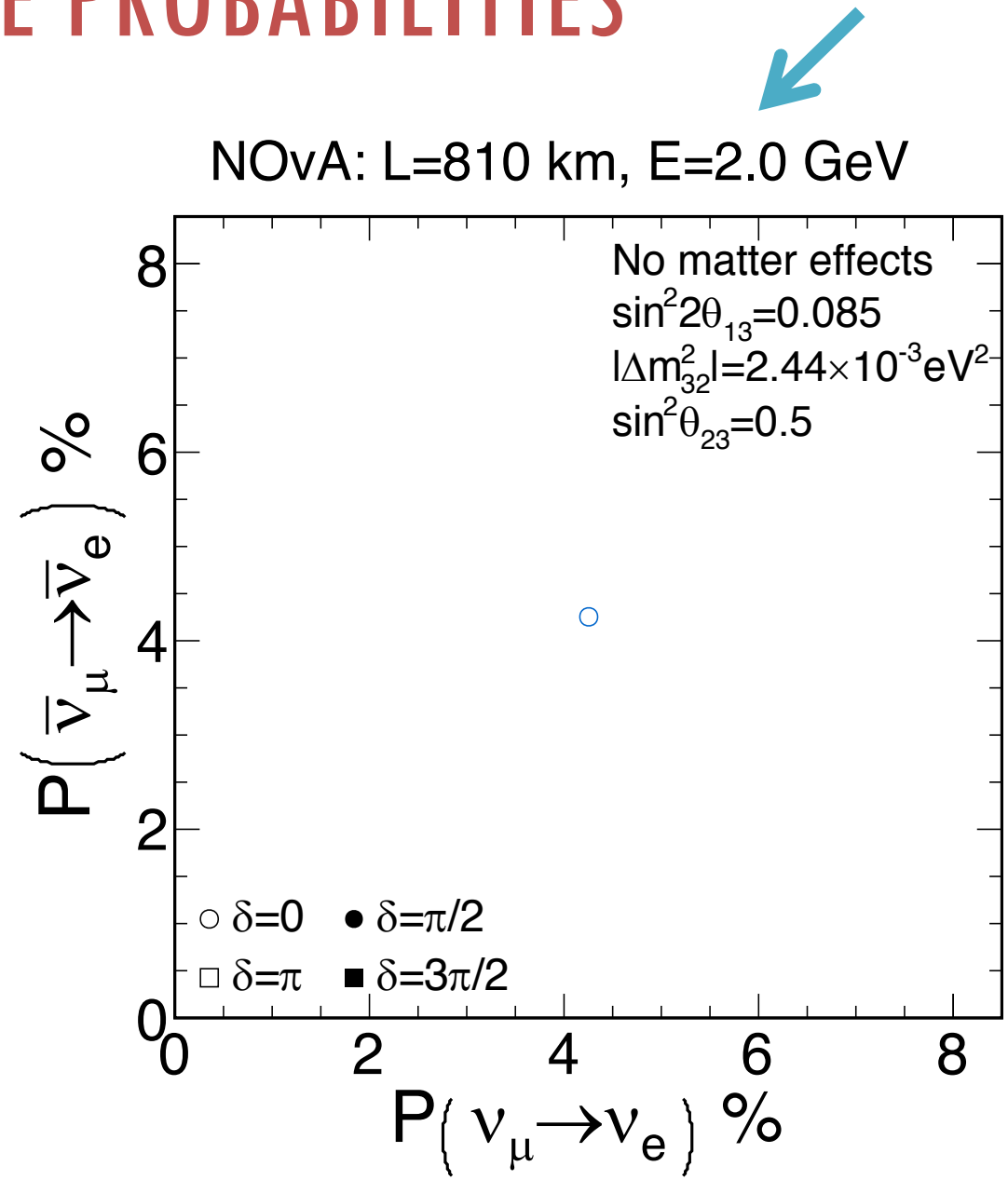
- Neutrino energy (E_ν)







ELECTRON NEUTRINO APPEARANCE PROBABILITIES

Oscillation probabilities depend on:

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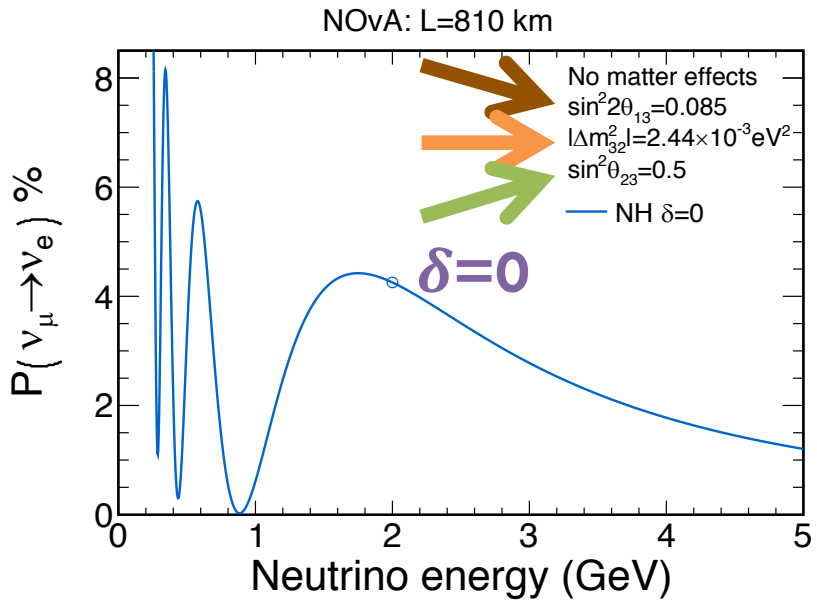
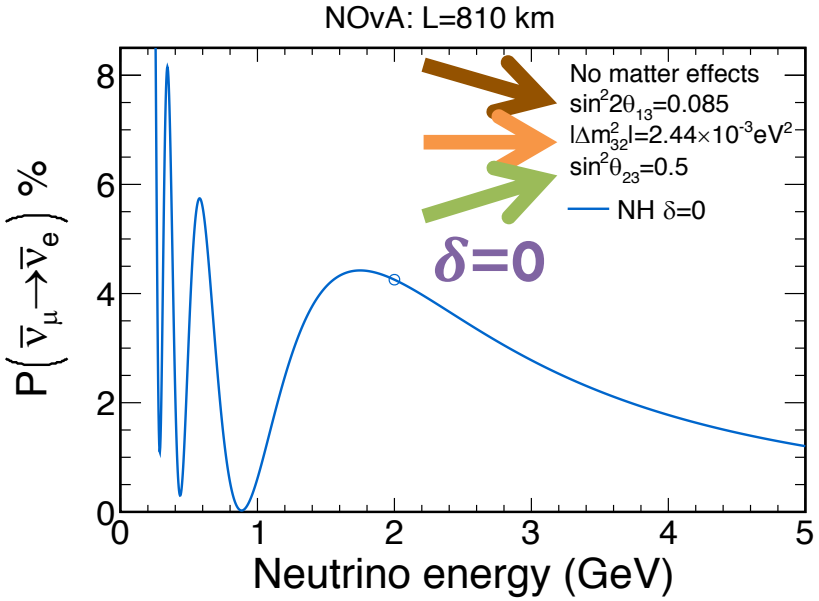
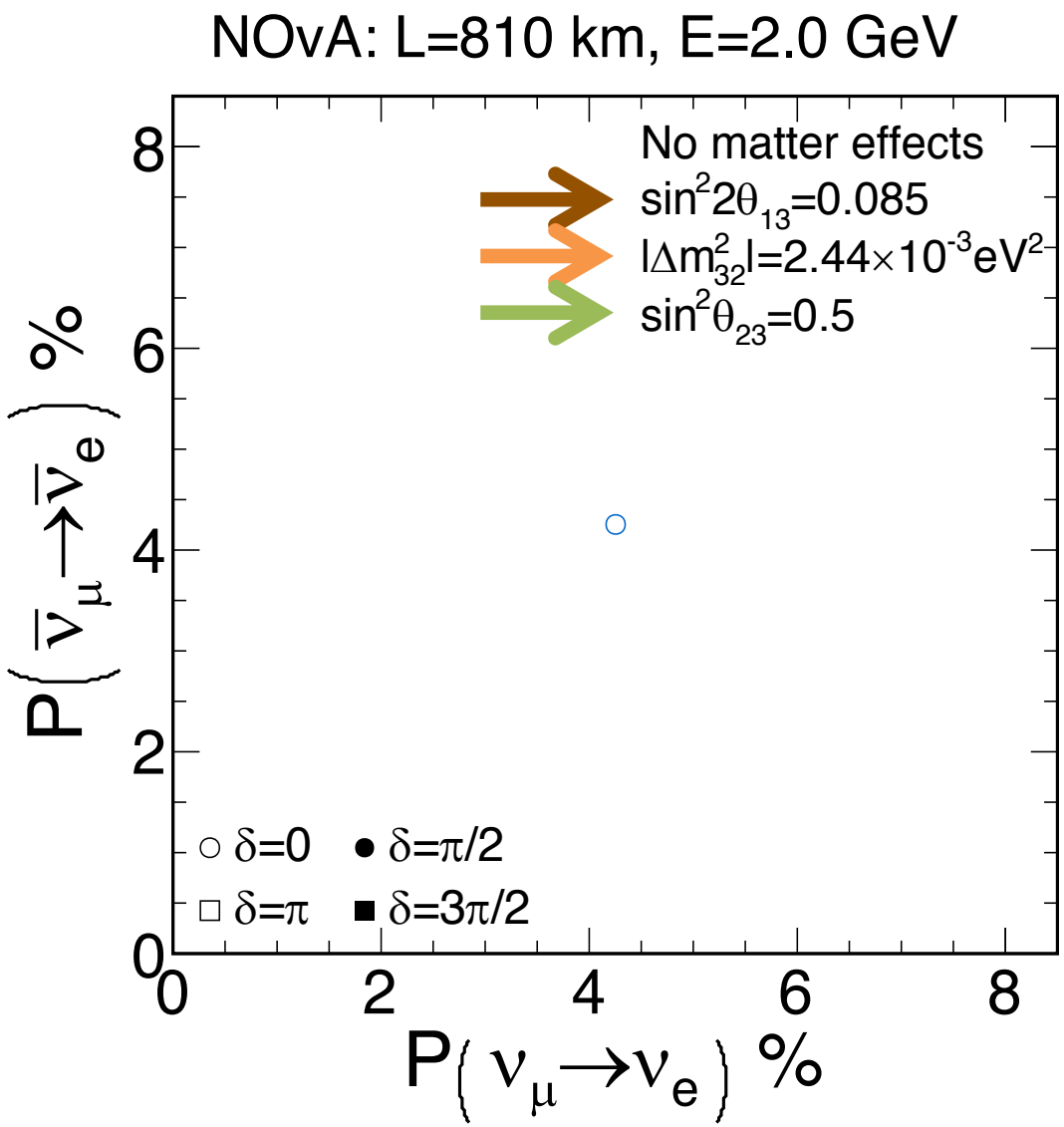
- Osc. parameters ($\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}$)
- Mass squared differences (Δm^2_{21}, $|\Delta m^2_{32}|$)







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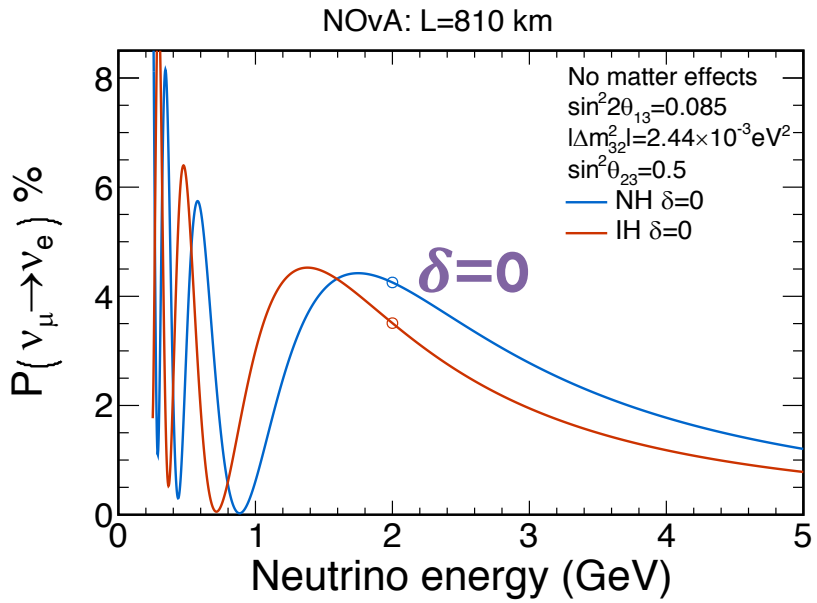
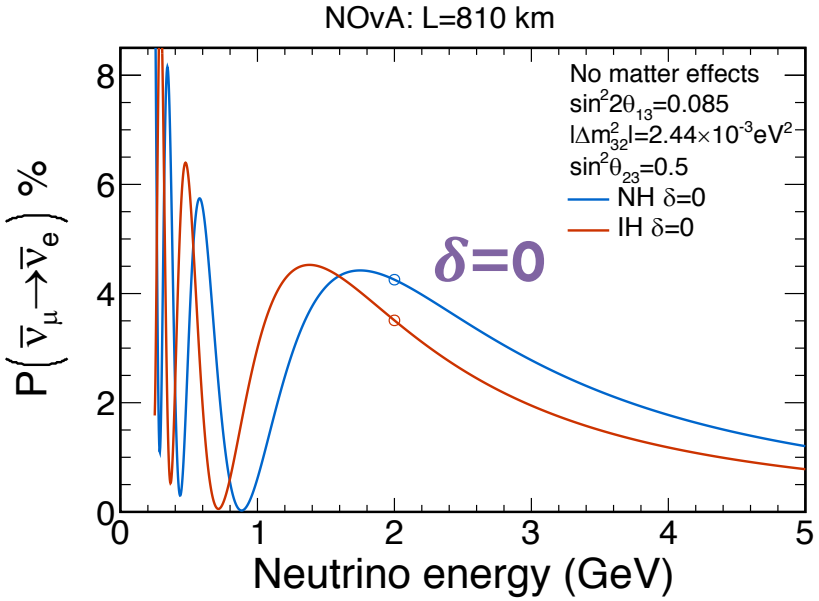
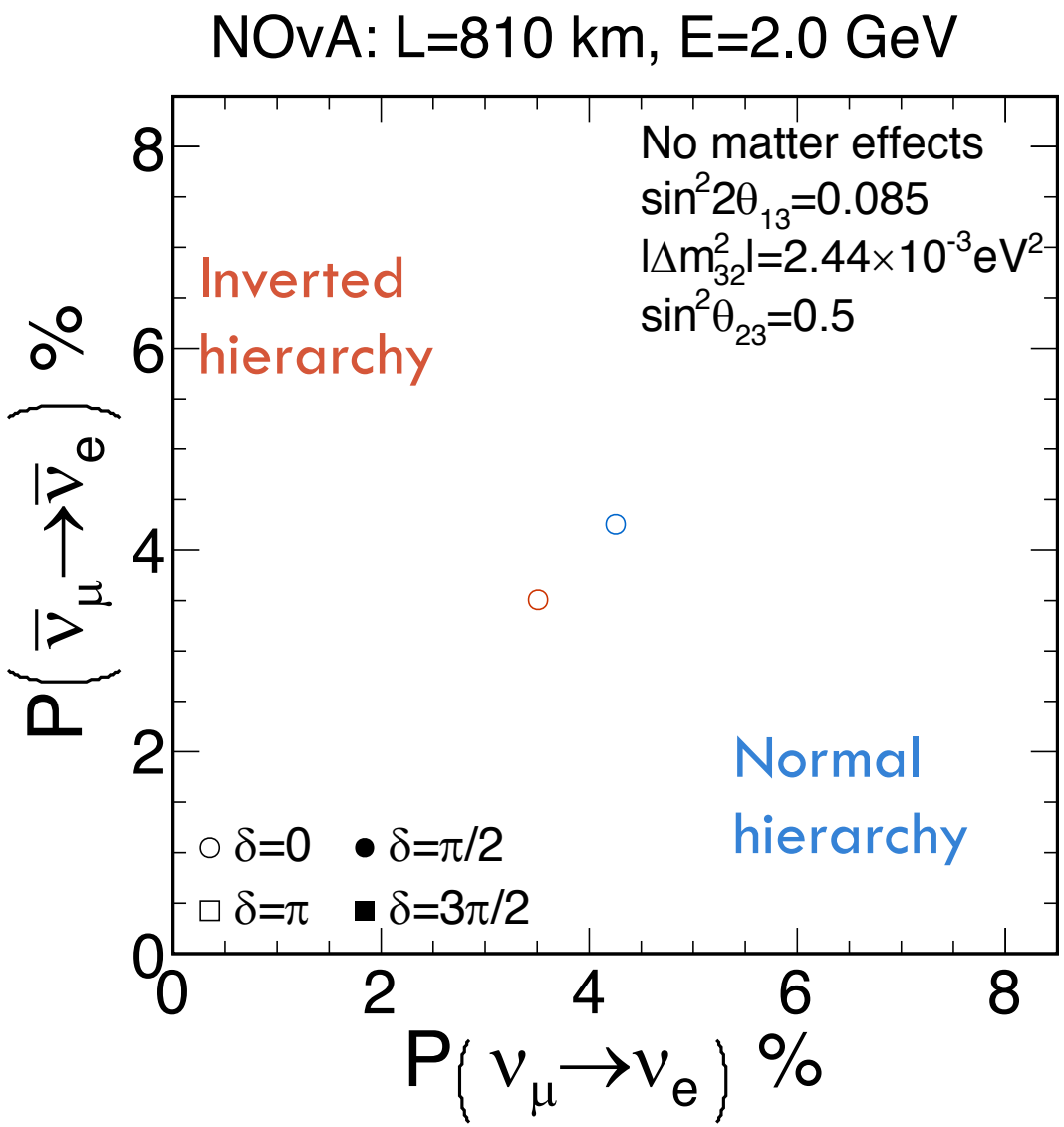
- Mass squared differences ($\Delta m^2_{21}, |\Delta m^2_{32}|$)
- Neutrino mass hierarchy ($\mathrm{sign}(\Delta m^2_{32})$)

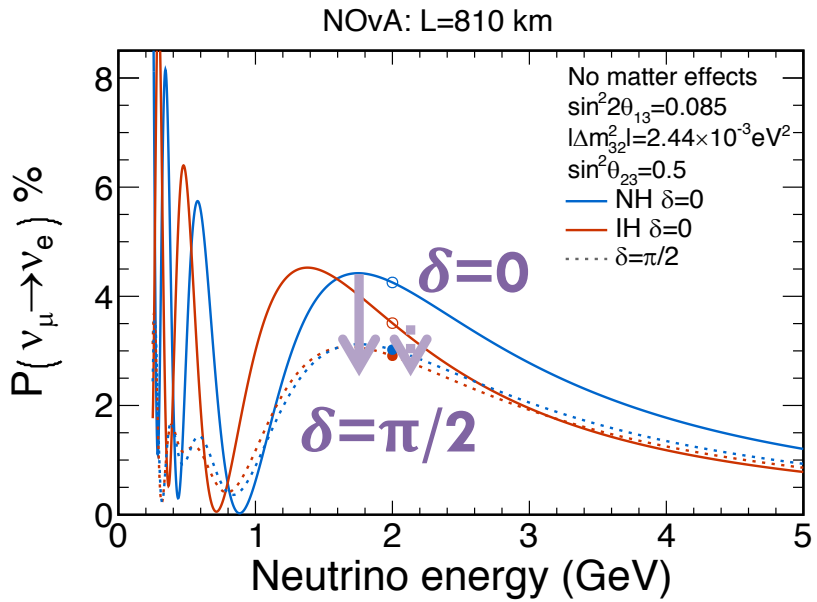


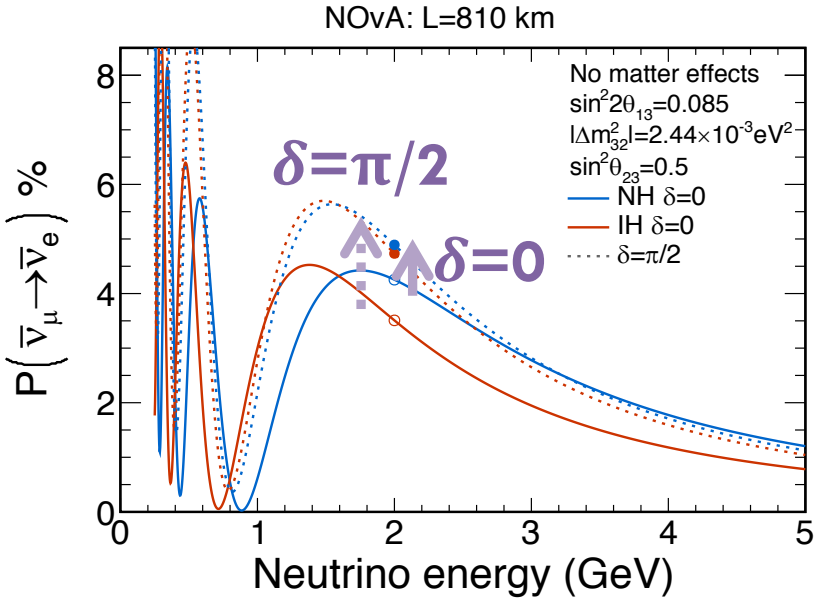


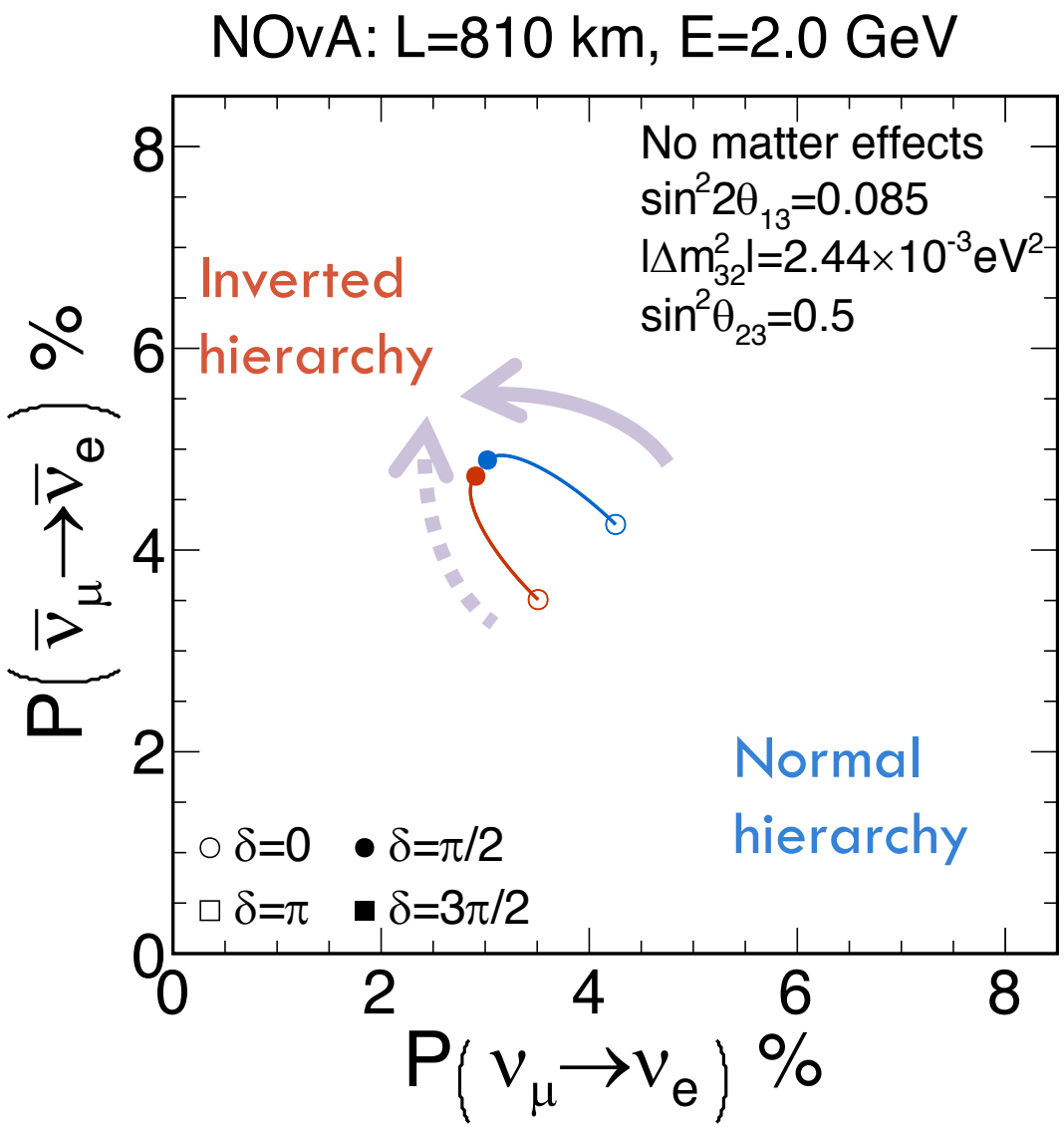


ELECTRON NEUTRINO APPEARANCE PROBABILITIES

- Allowed range for $\delta_{CP} \in [0,2\pi)$
- CP-conservation: $\delta_{CP} = 0, \pi$
- Max. CP violation: $\delta_{CP} = \pi/2, 3\pi/2$







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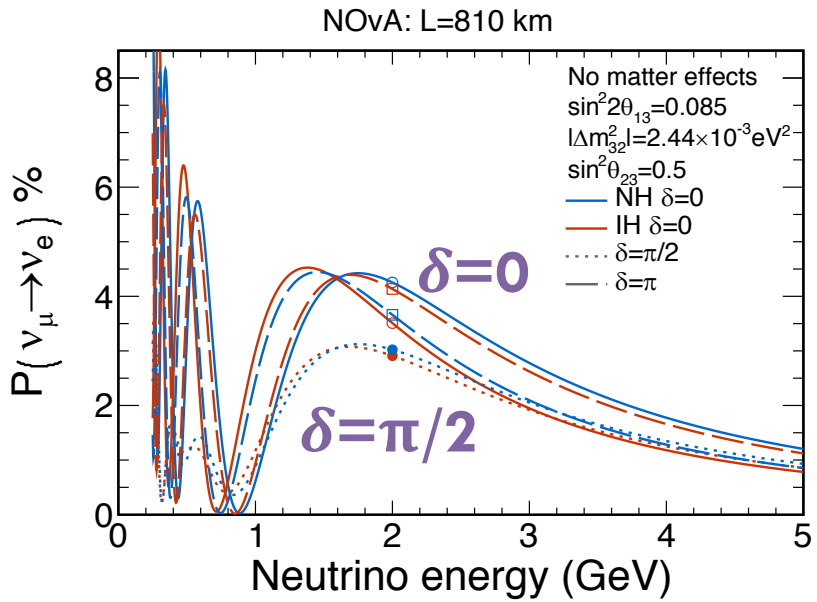

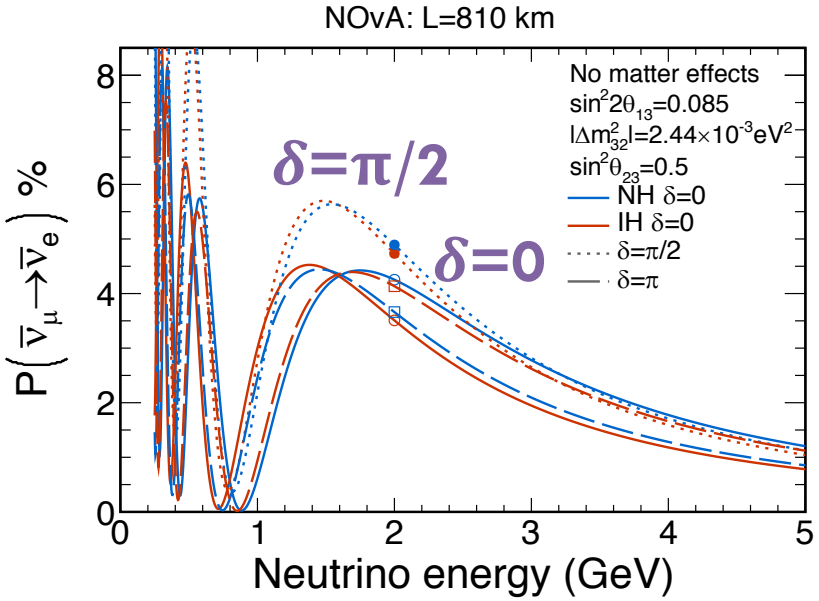

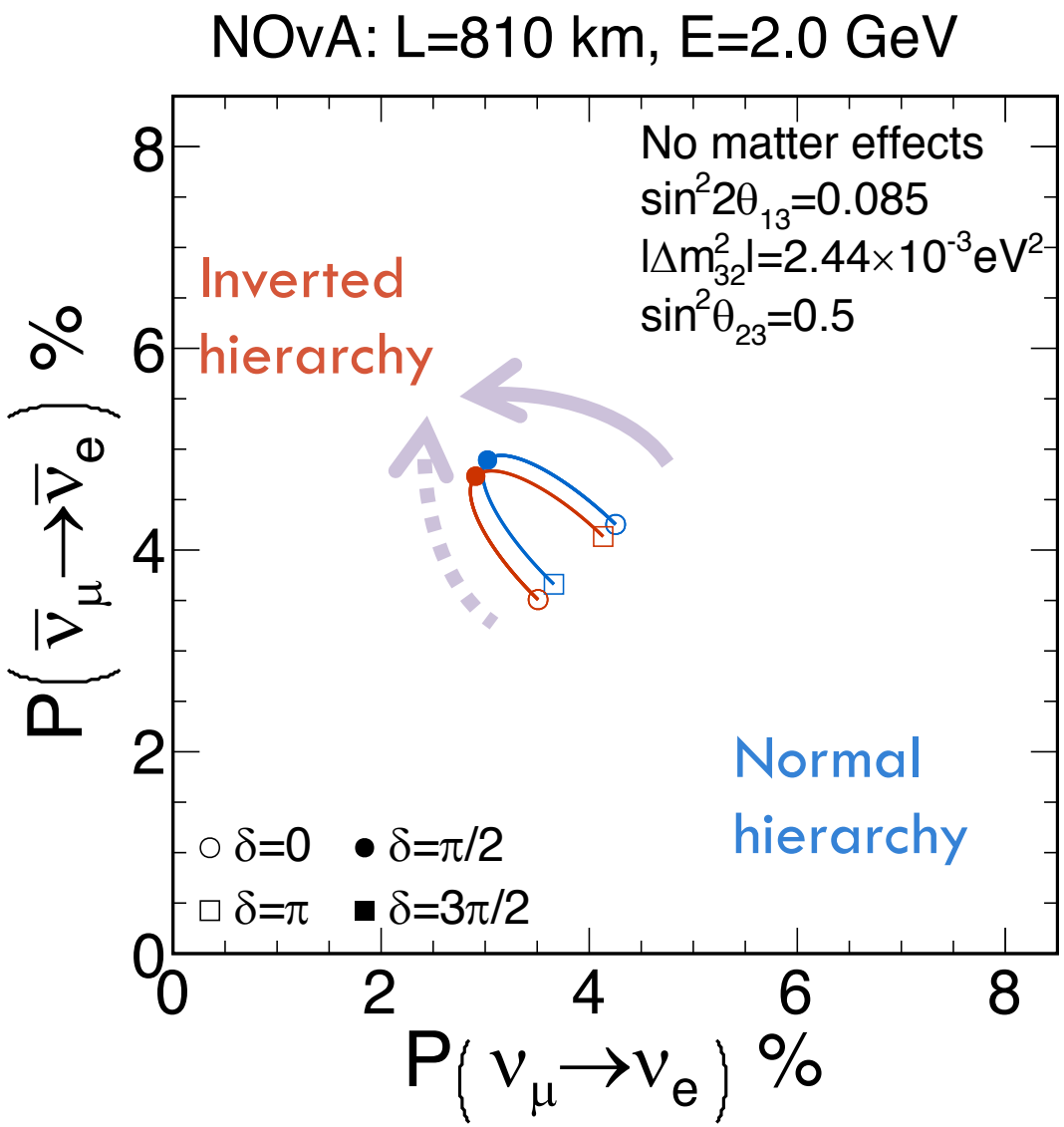

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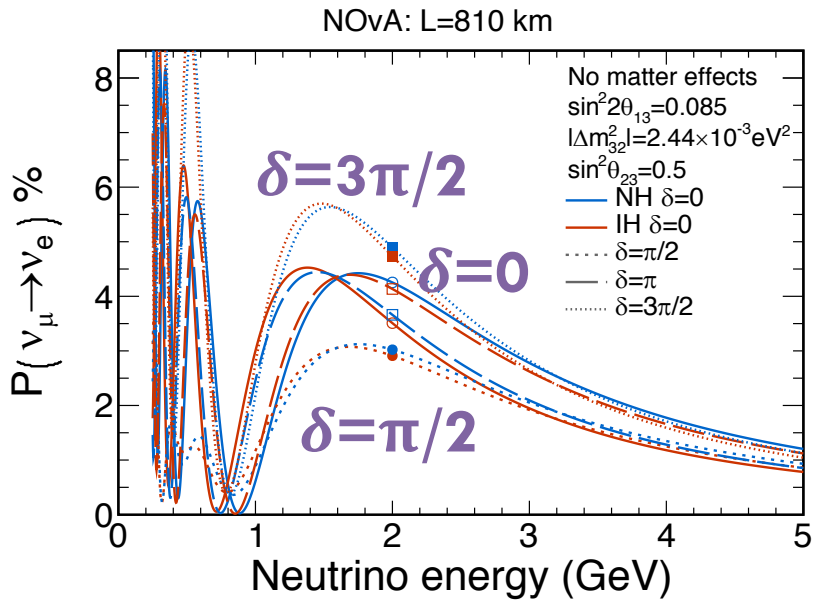
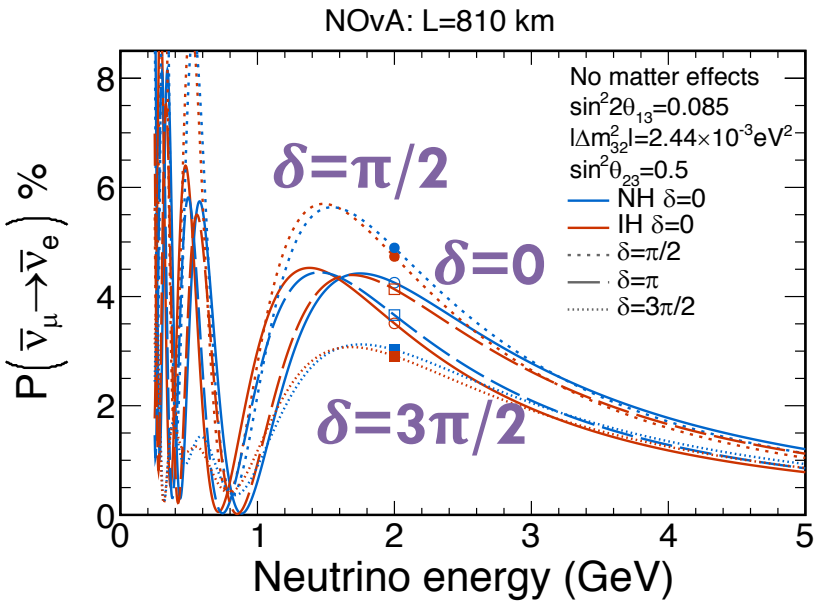
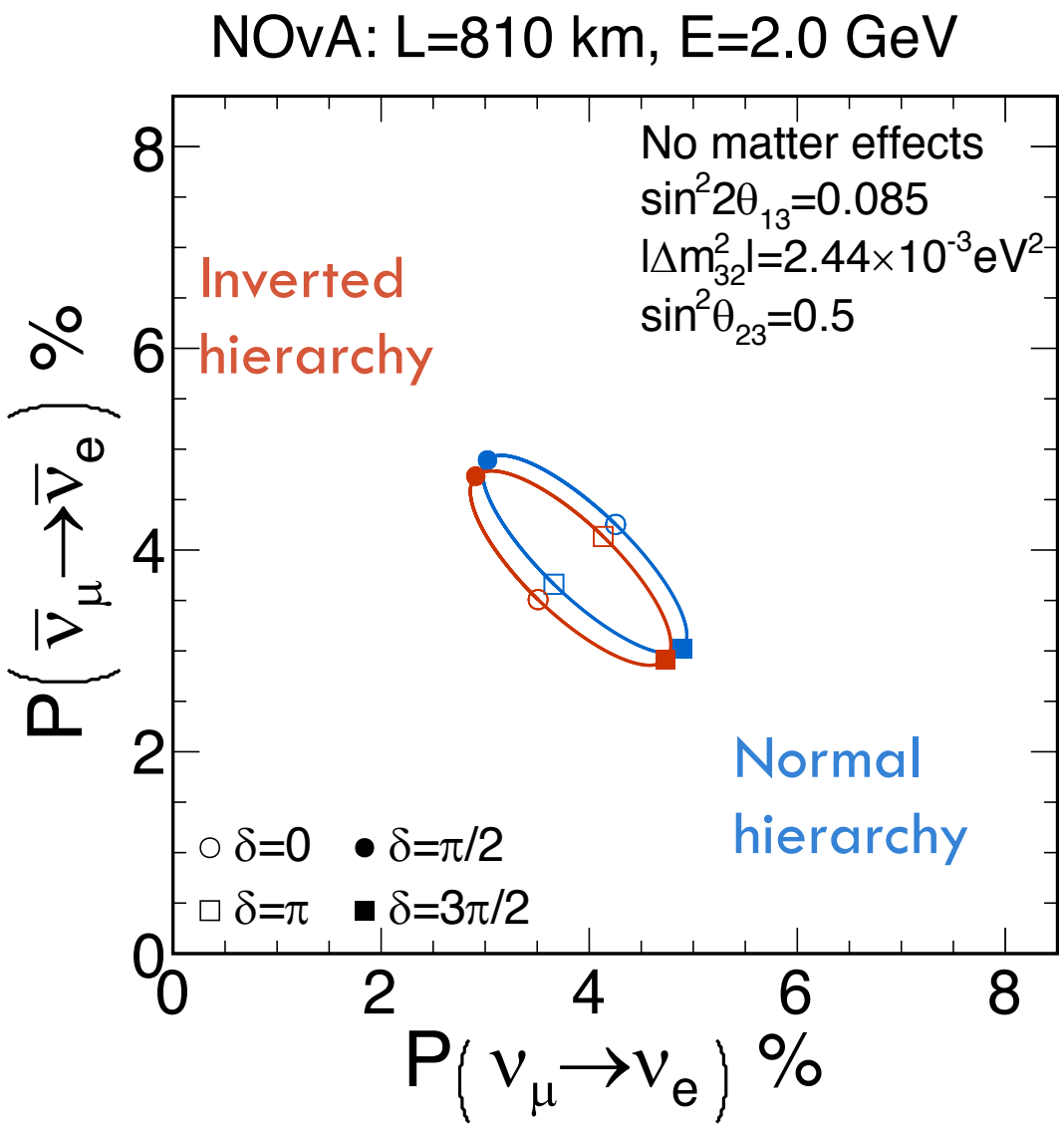
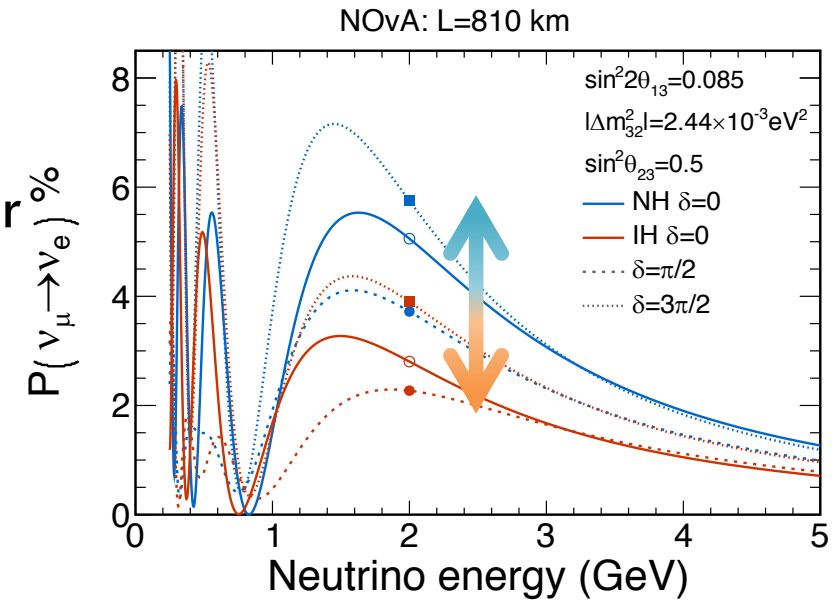


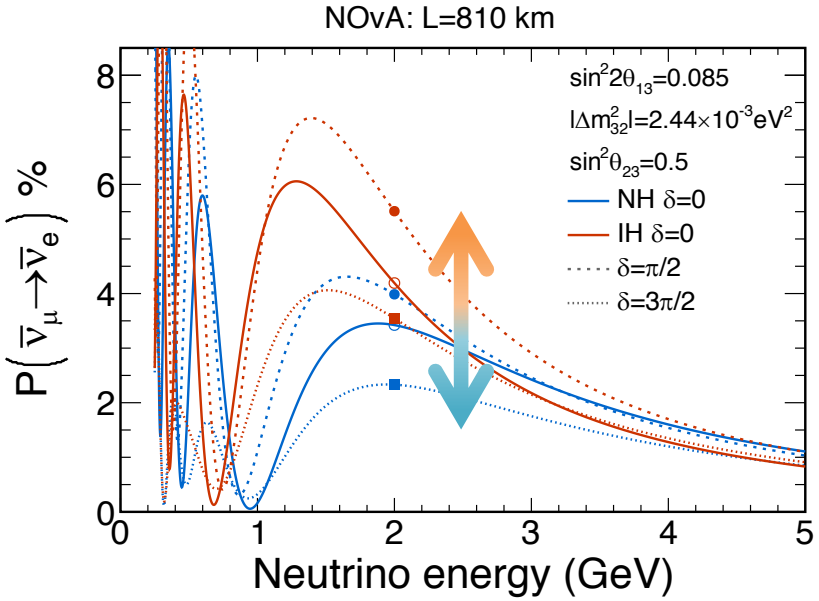


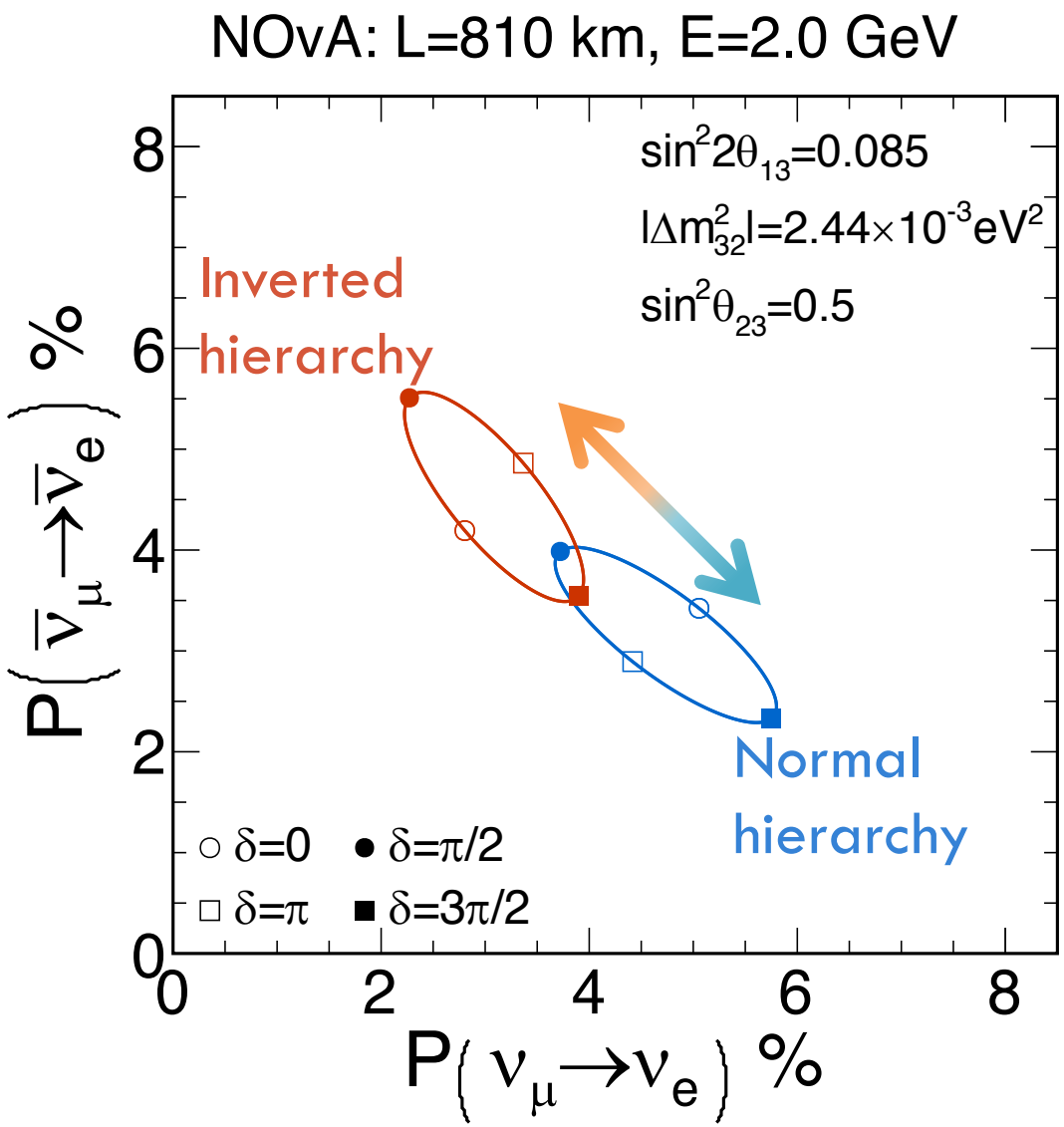


ELECTRON NEUTRINO APPEARANCE PROBABILITIES

Matter effects: in the normal hierarchy, increase for neutrinos and decrease for antineutrinos. Opposite effect for inverted hierarchy.

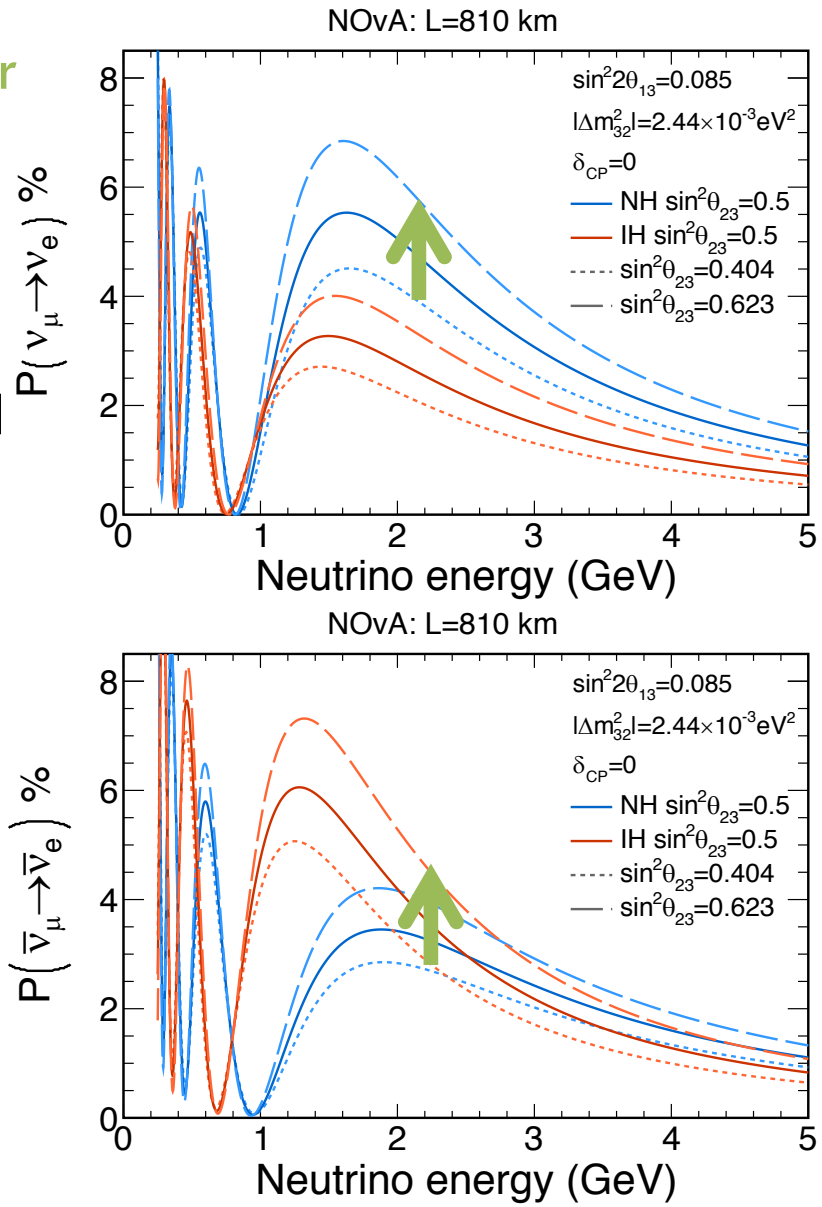


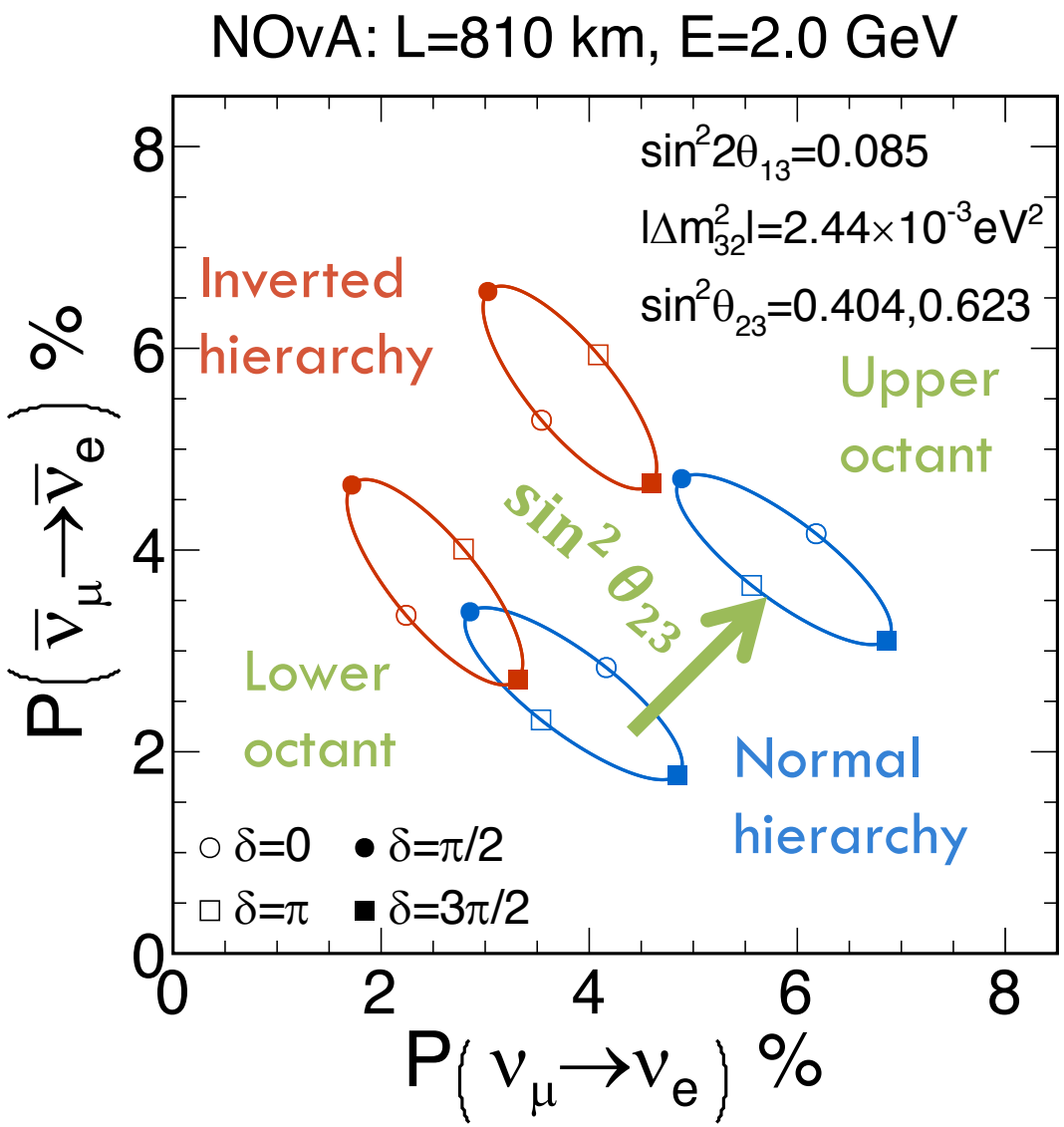




ELECTRON NEUTRINO APPEARANCE PROBABILITIES

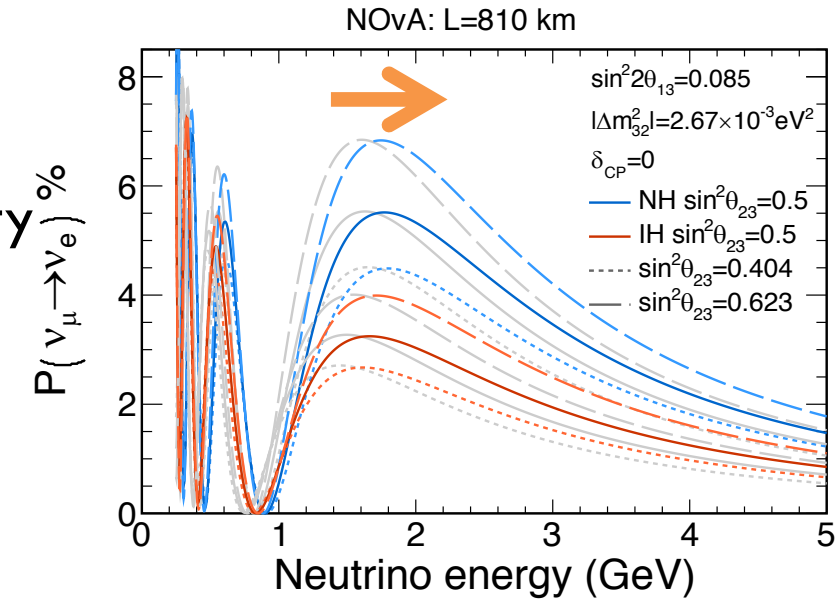
Moving from the lower octant ($\sin^2\theta_{23}$<0.5) to the upper octant ($\sin^2\theta_{23}$>0.5): probabilities increase for both neutrinos and antineutrinos, both hierarchies.

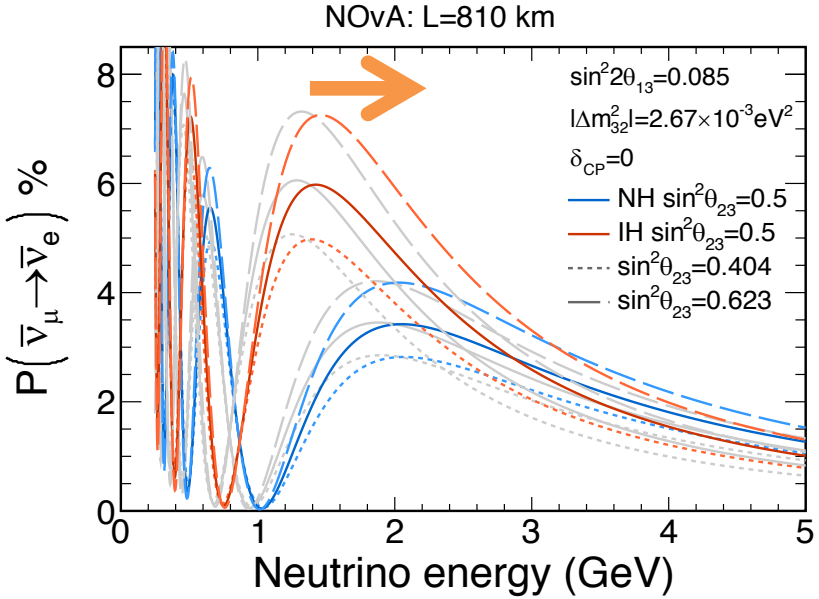


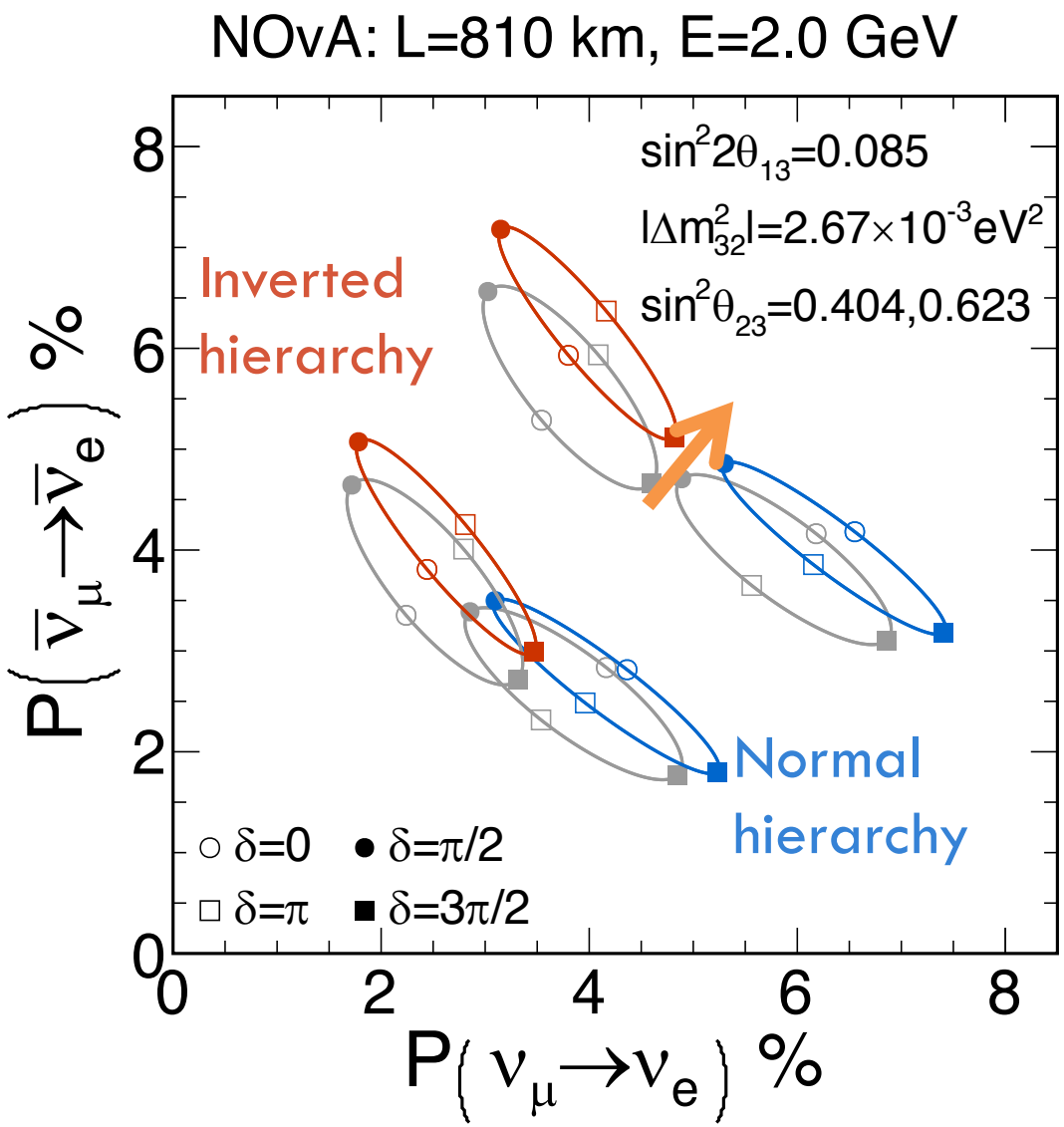


ELECTRON NEUTRINO APPEARANCE PROBABILITIES

A different $|\Delta m^2_{32}|$ results in an overall shift of the probability curves





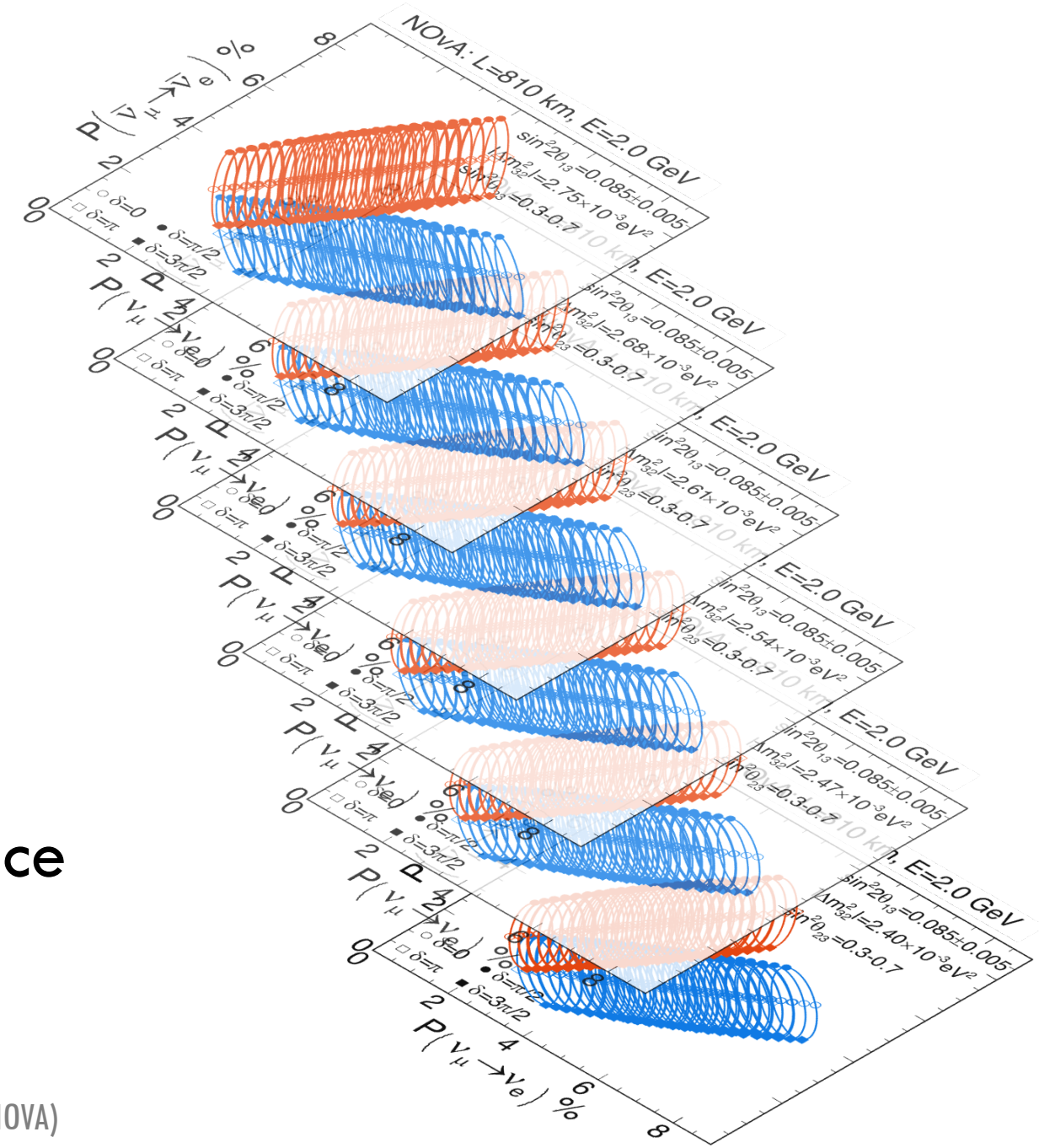


PHYSICS GOALS

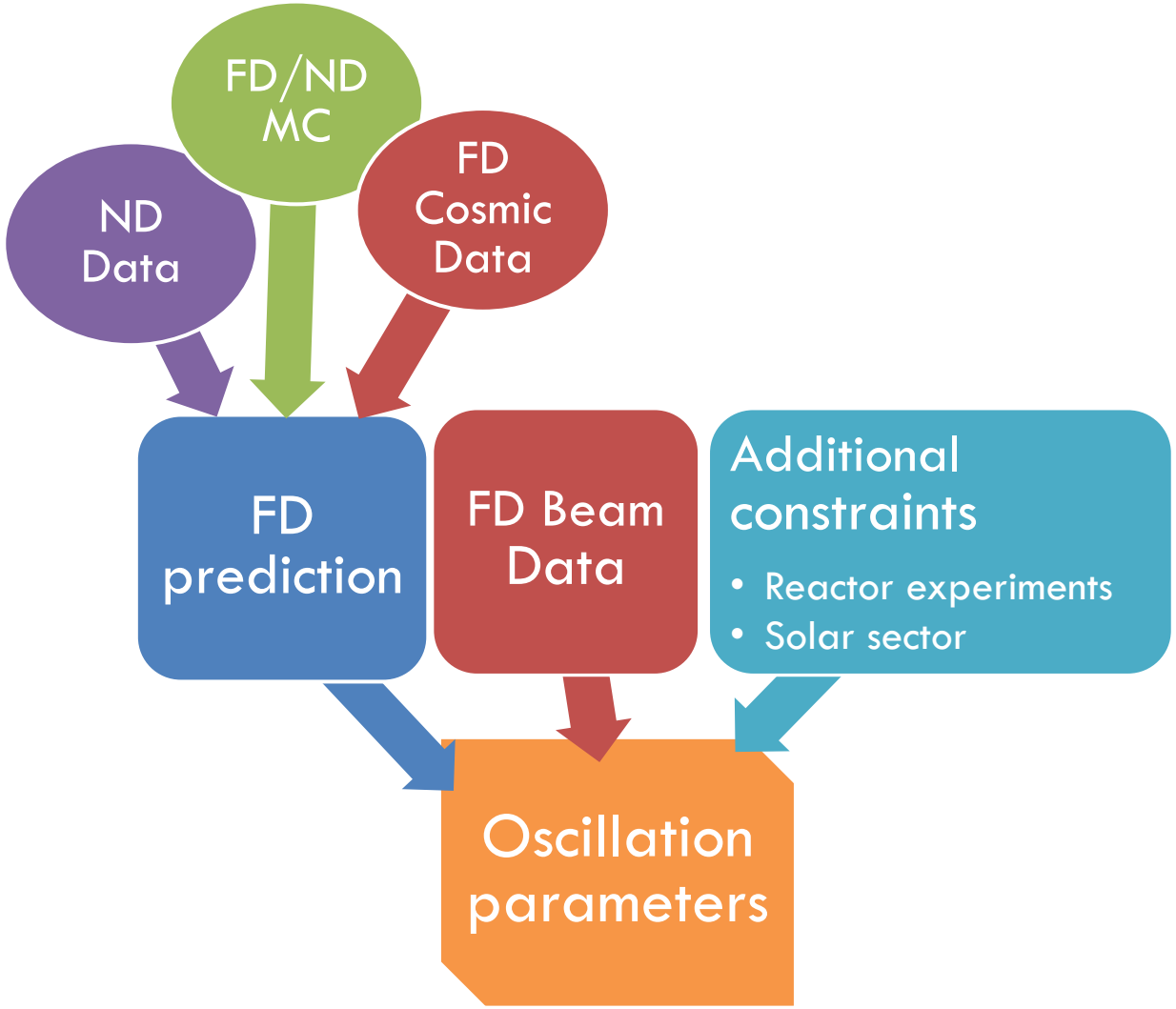
- **Electron neutrino appearance:** Sensitive to θ_{23}, δ_{CP}, and the neutrino mass hierarchy
- **Muon neutrino disappearance:** Sensitive to θ_{23} and Δm^2_{32}

Joint $\nu_e + \nu_\mu$ analysis

Constrain the parameter space



NOvA'S OSCILLATION ANALYSIS



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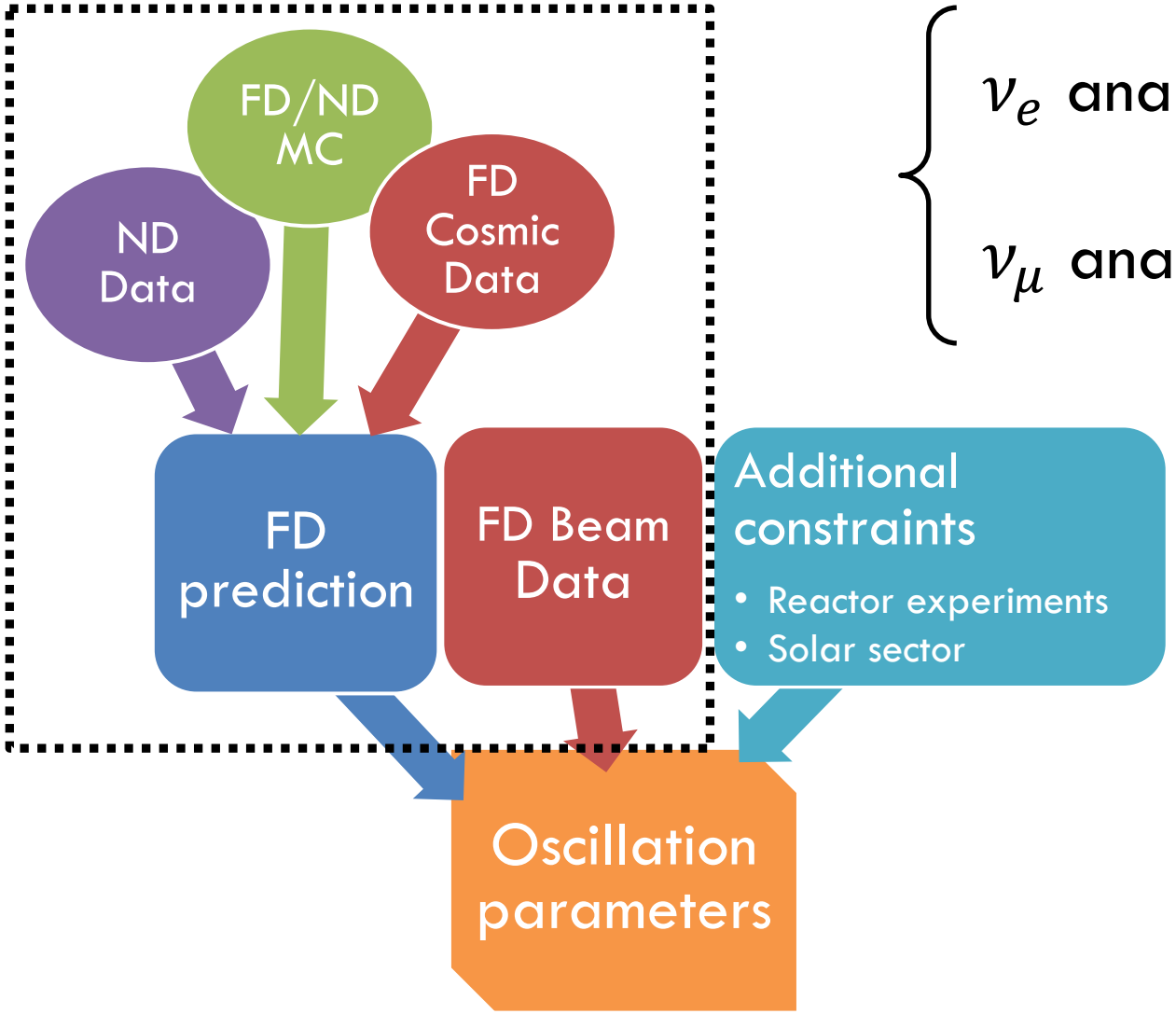

ν_e analysis

ν_μ analysis

Neutrino beam

Antineutrino beam

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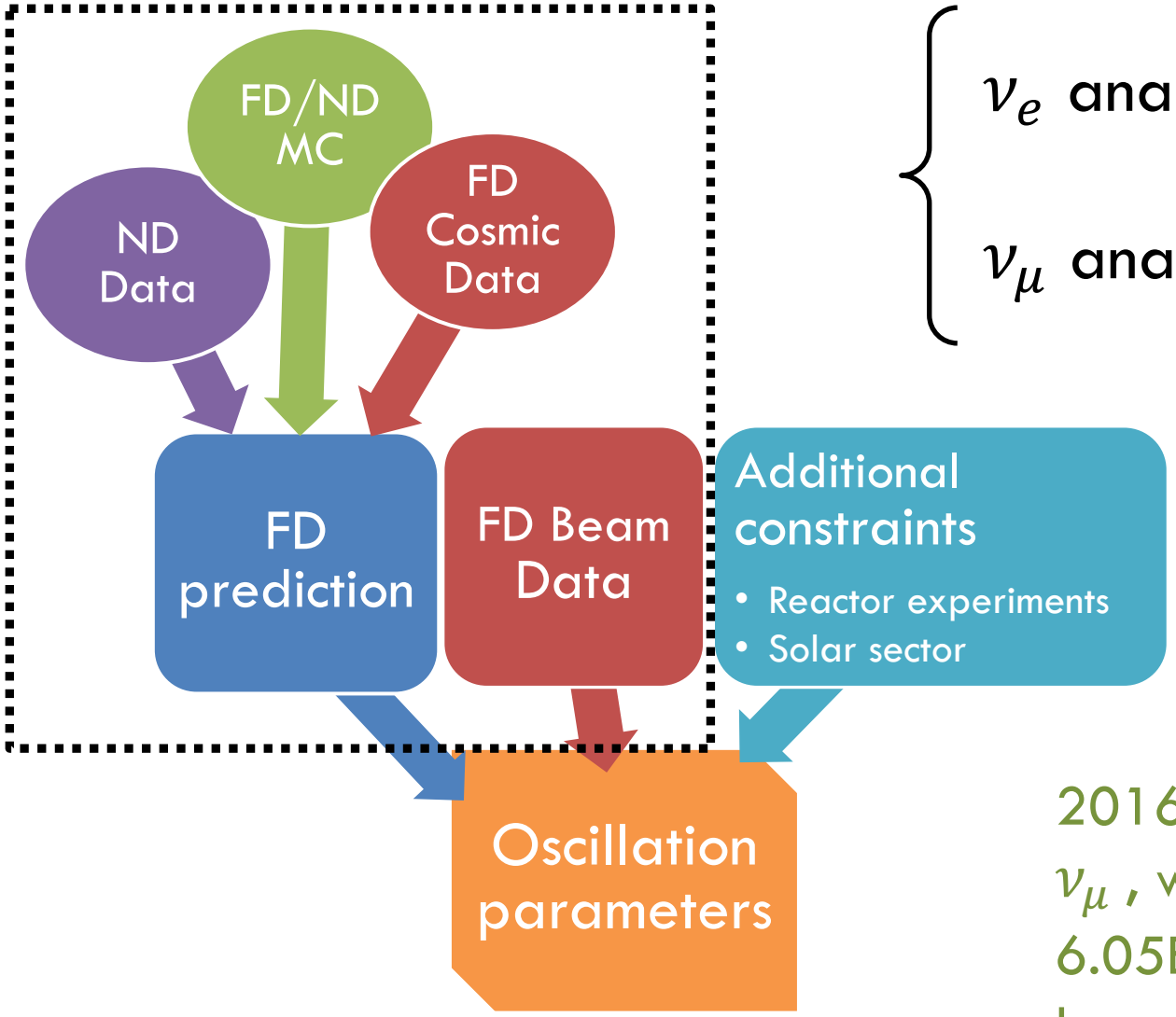

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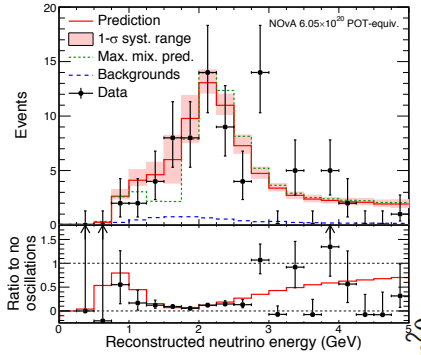
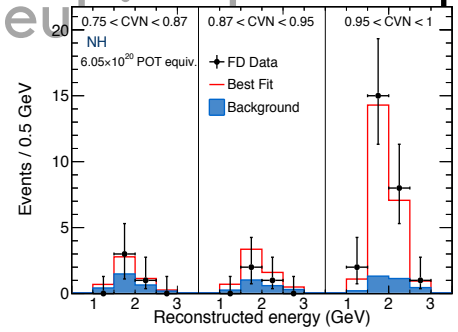
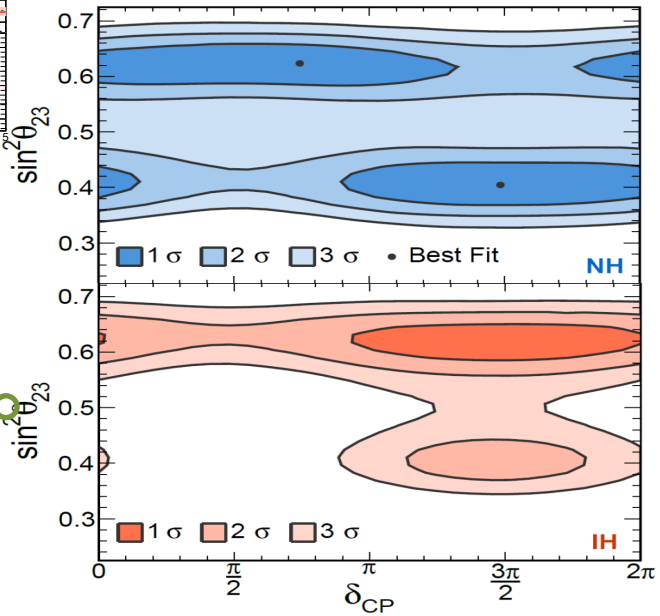




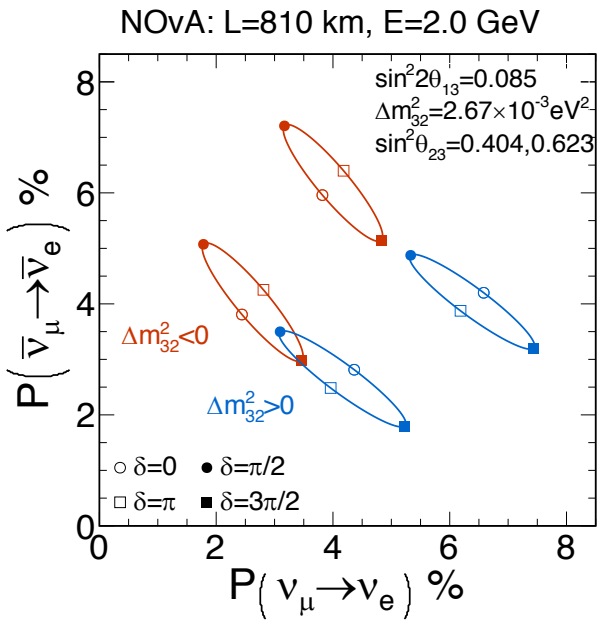


2016 results: joint $\nu_e + \nu_\mu$, with an exposure of 6.05E20 POT of neutrino beam

PUTTING IT ALL TOGETHER

FD prediction

x



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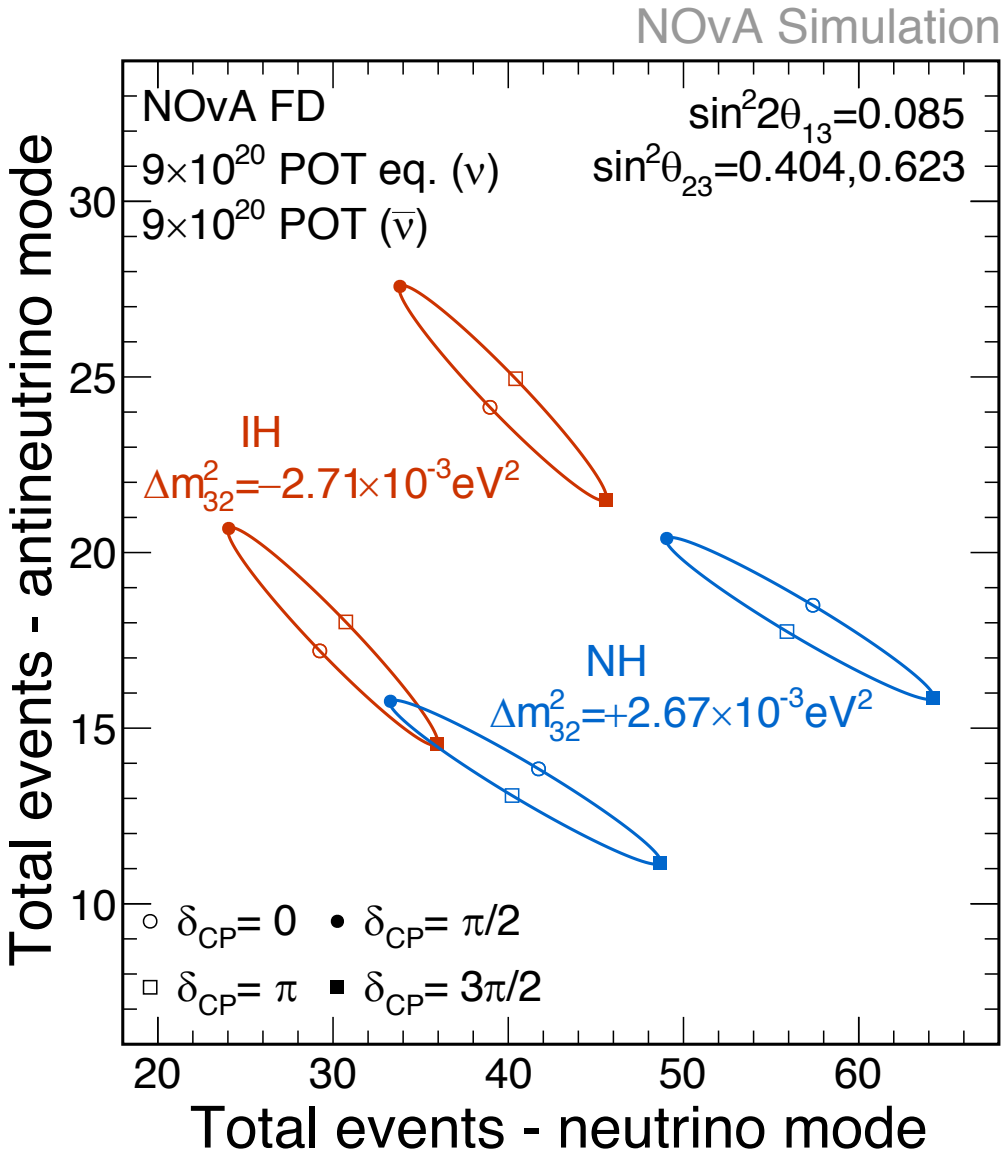
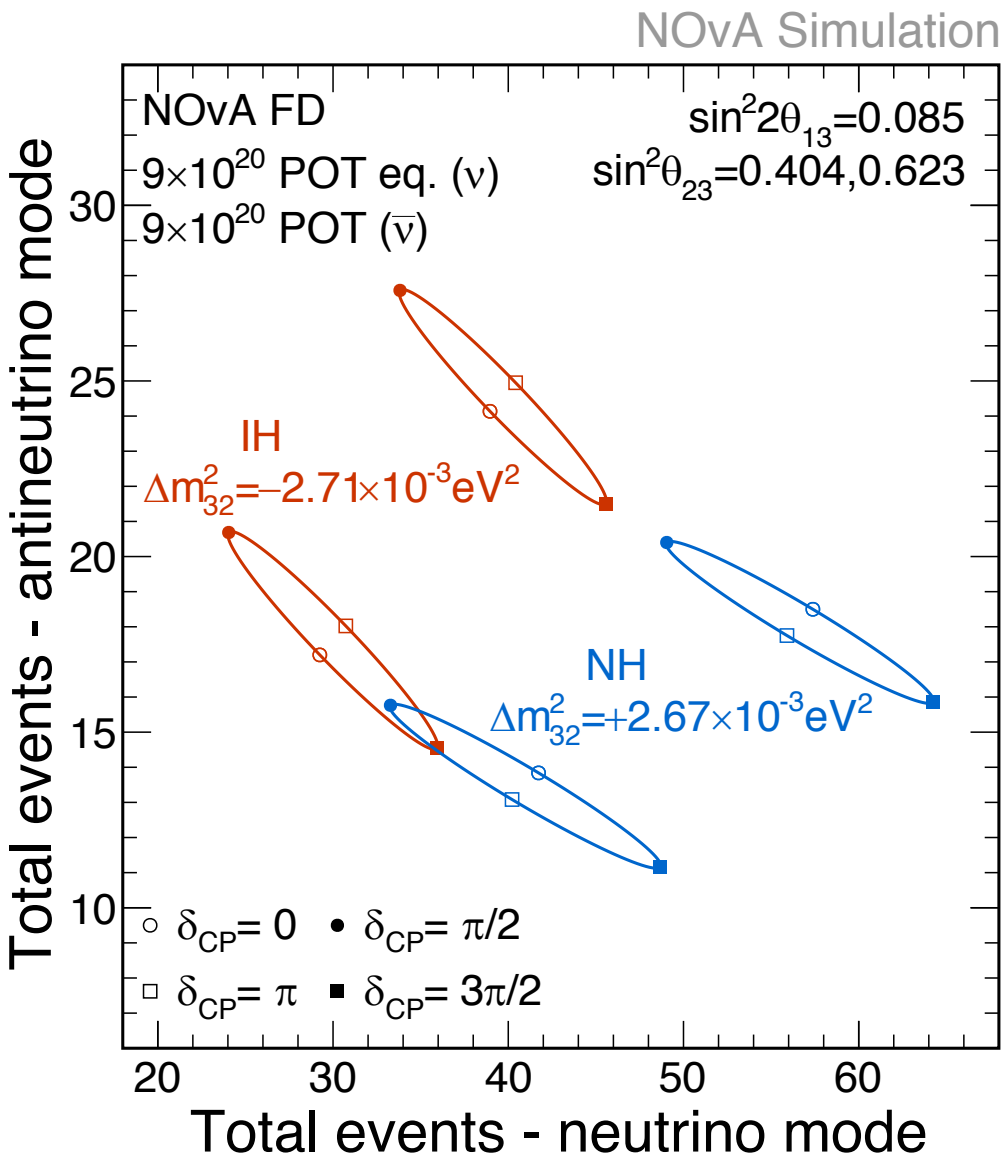


ASIDE: NEUTRINO VS ANTINEUTRINO BEAM

- Probabilities: dCP, matter effects, show opposing effects for neutrinos vs antineutrinos
- Difference in the beam flux:
  - Lower event counts in antineutrino mode
  - Wrong sign contamination: proportion of intrinsic ν in a $\overline{\nu}$ beam higher than intrinsic $\overline{\nu}$ in a ν beam

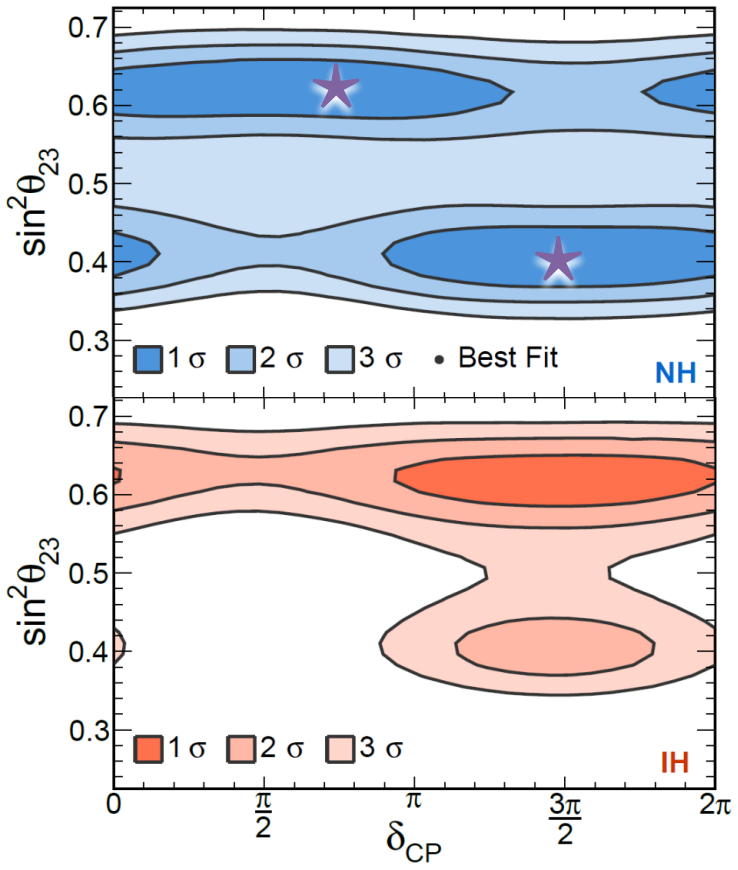
9E20 POT	**Neutrino**	**Antineutrino**
Total events	24-64	11-28
Signal	51-82%	48-81%
Wrong sign	0.4-2.6%	2.2-12.5%
Other beam background	17-46%	16-40%



2016 JOINT ANALYSIS RESULTS

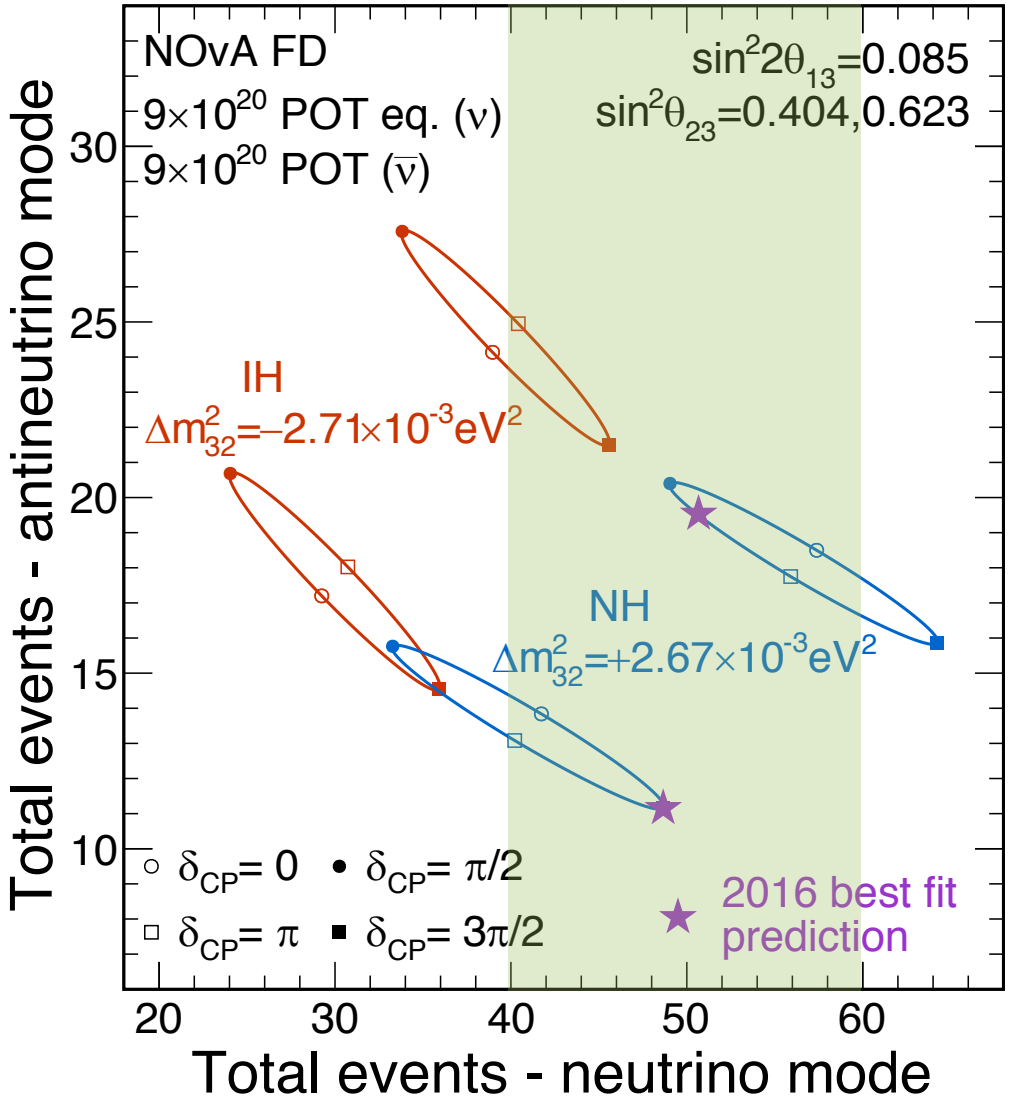
2016: 6E20 POT neutrino

2 best fit points + range of allowed values



Cartoon!

NOvA Simulation



2017 AND 2018 EXPECTATIONS

2016: 6E20 POT neutrino

2 best fit points + range of allowed values

2017: 9E20 POT neutrino

Increased statistics = narrower ranges

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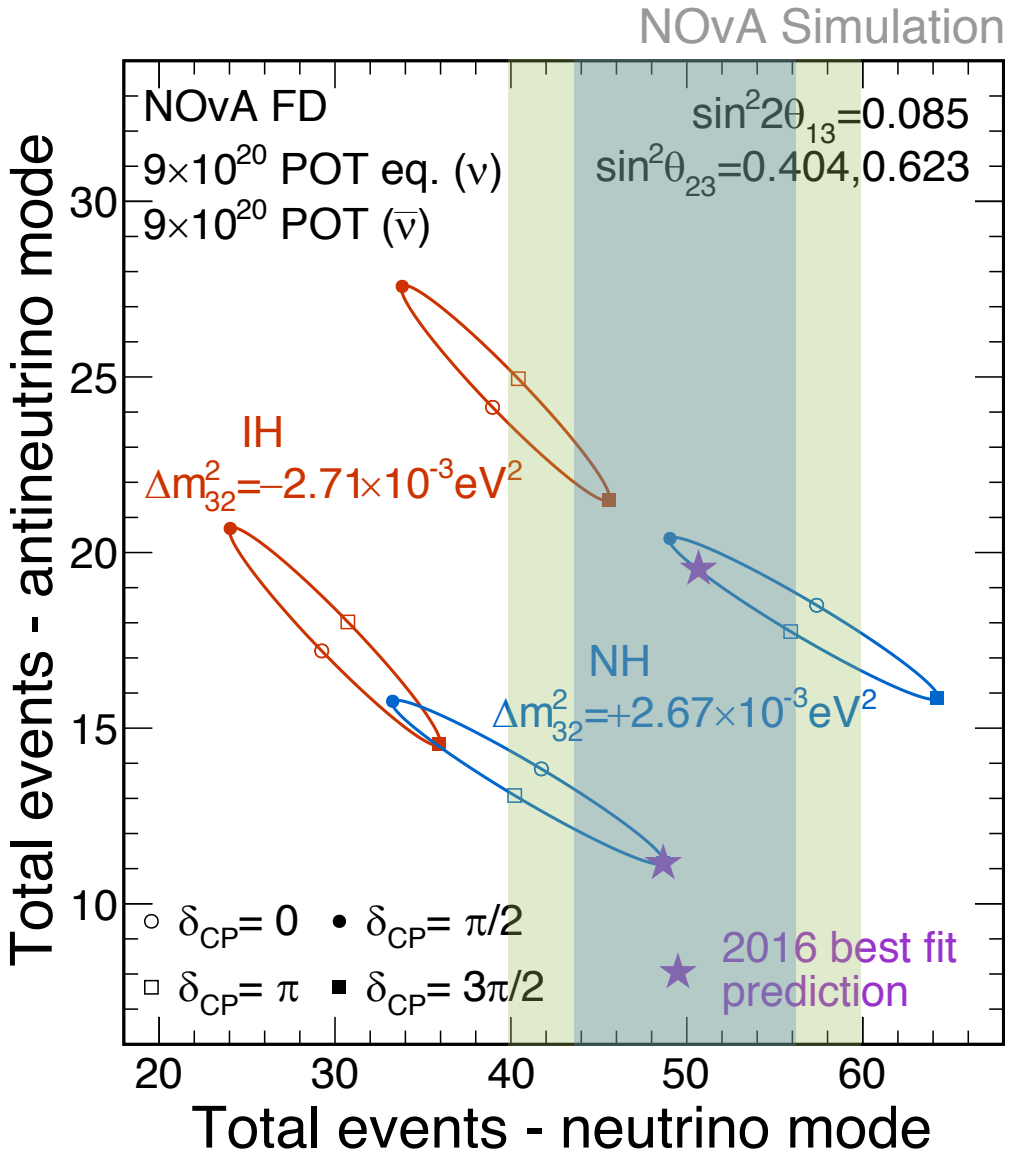

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Low/high count could resolve the octant degeneracy

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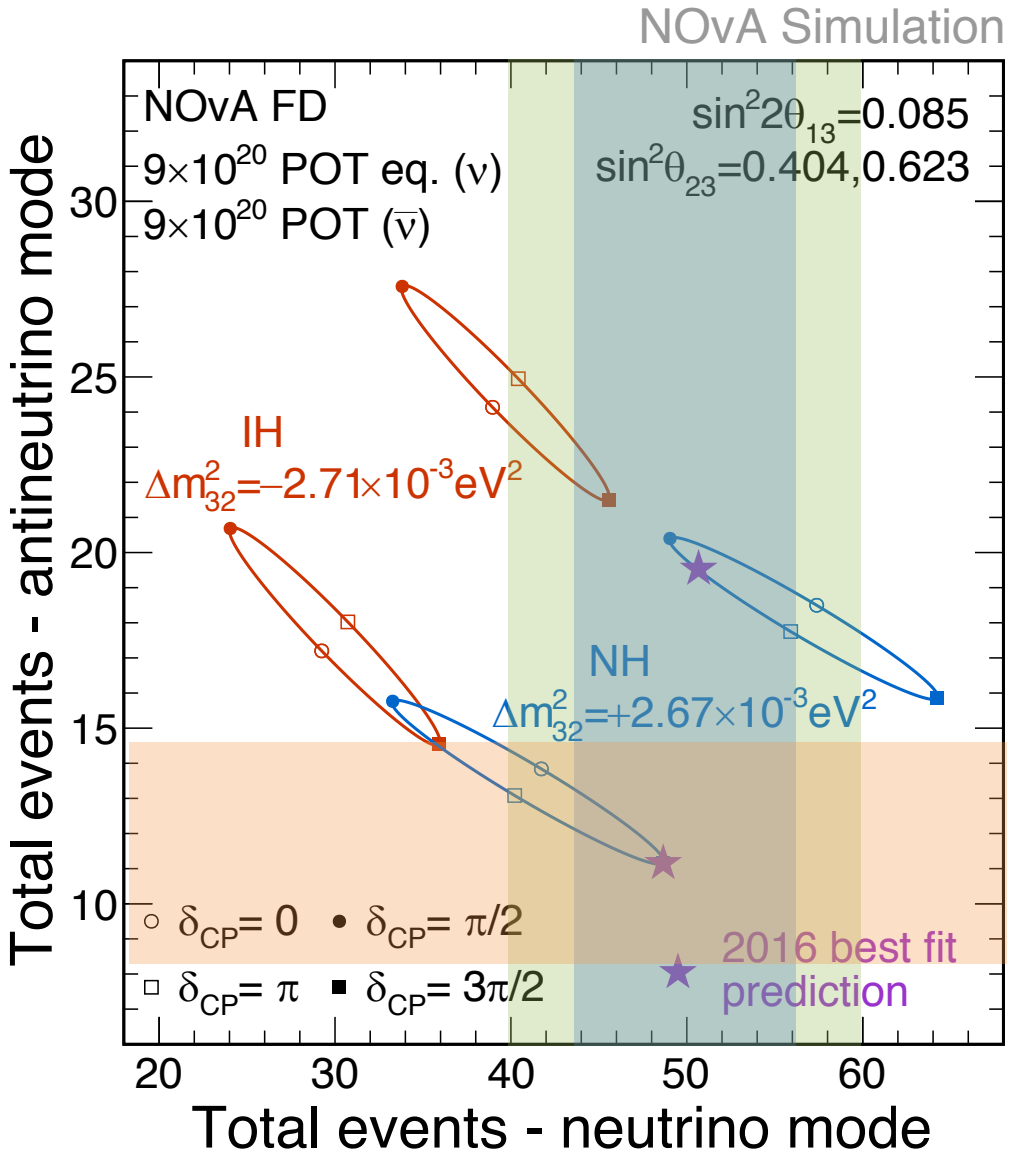

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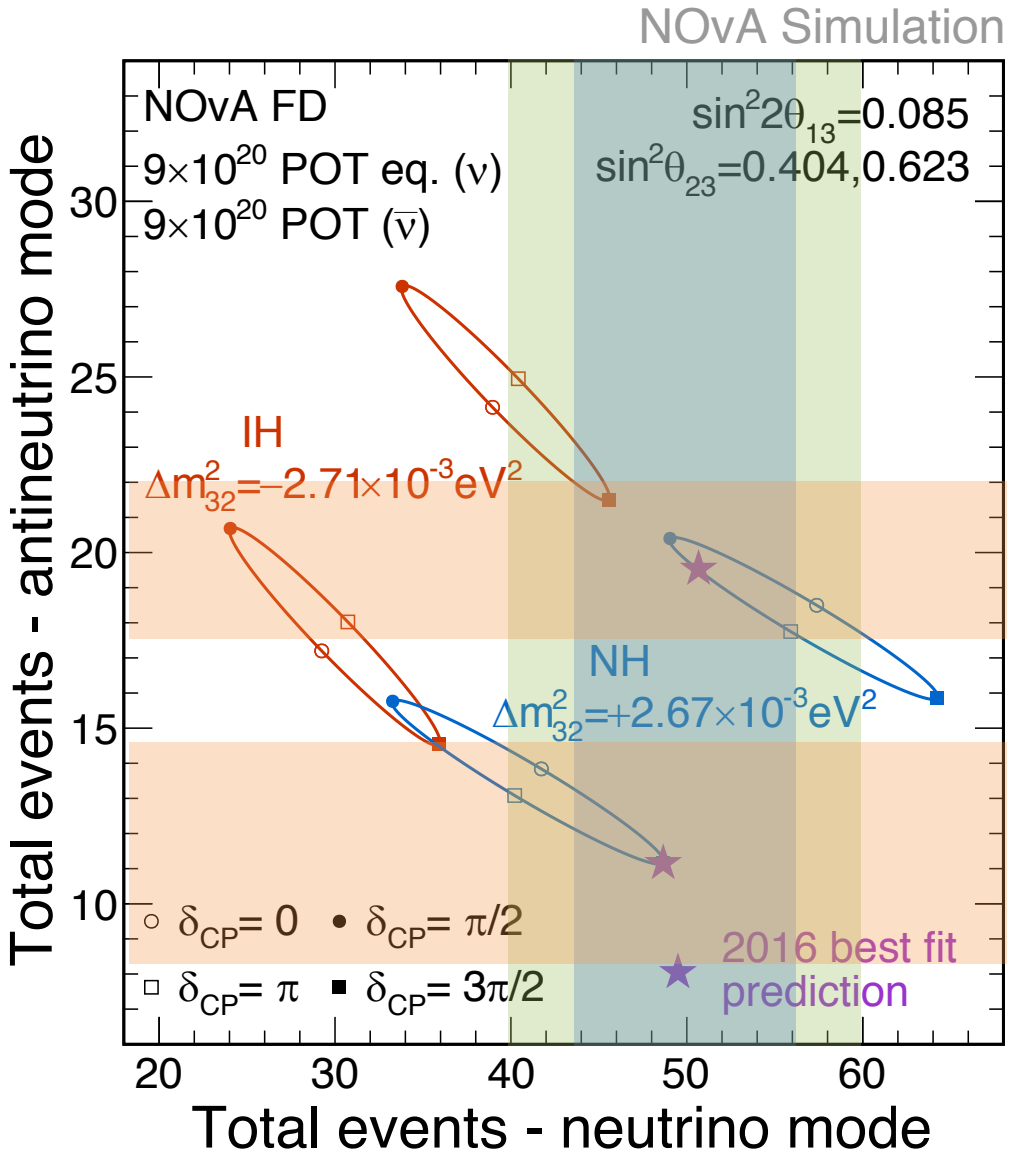

FUTURE PHYSICS REACH

4 measurements:

- CP violation
  - Significance of rejection of $\delta_{CP} = 0, \pi$
- Mass hierarchy ν_e appearance
  - Rejection of the wrong hierarchy

- Maximal mixing
  - Reject $\sin^2\theta_{23}$=0.5
- Octant ν_μ disappearance
  - Rejection of the wrong octant assuming a fixed $\sin^2\theta_{23}$

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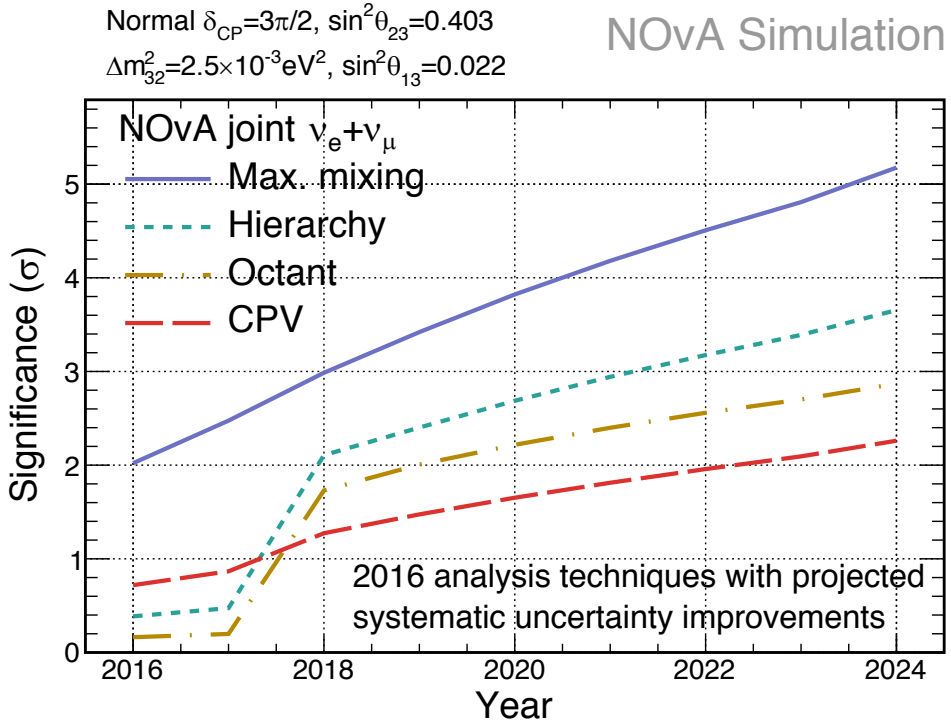
  - Reject $\sin^2\theta_{23}$=0.5
- Octant — ν_μ disappearance
  - Rejection of the wrong octant assuming a fixed $\sin^2\theta_{23}$

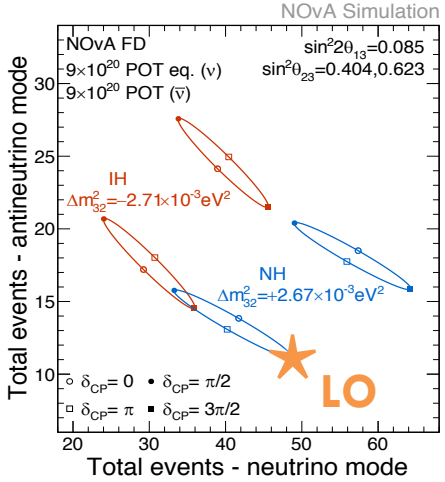
Assumptions:

- Joint analysis
- True oscillation parameters
  - Normal hierarchy
  - $\delta_{CP} = \pi/2, 3\pi/2$
  - $\sin^2\theta_{23}$=0.403, 0.625
- Run plan: adding ~6E20 POT each year, 50/50 proportion between neutrino and antineutrino beam after 2018
- Improvements to the analysis: reduced systematic effects
- "Extra" improvements: after 2019, gain effective exposure: 25% from analysis, increased beam power (800/900 W), 17% from beam target

REACH

Lower octant, $\delta_{CP} = 3\pi/2$





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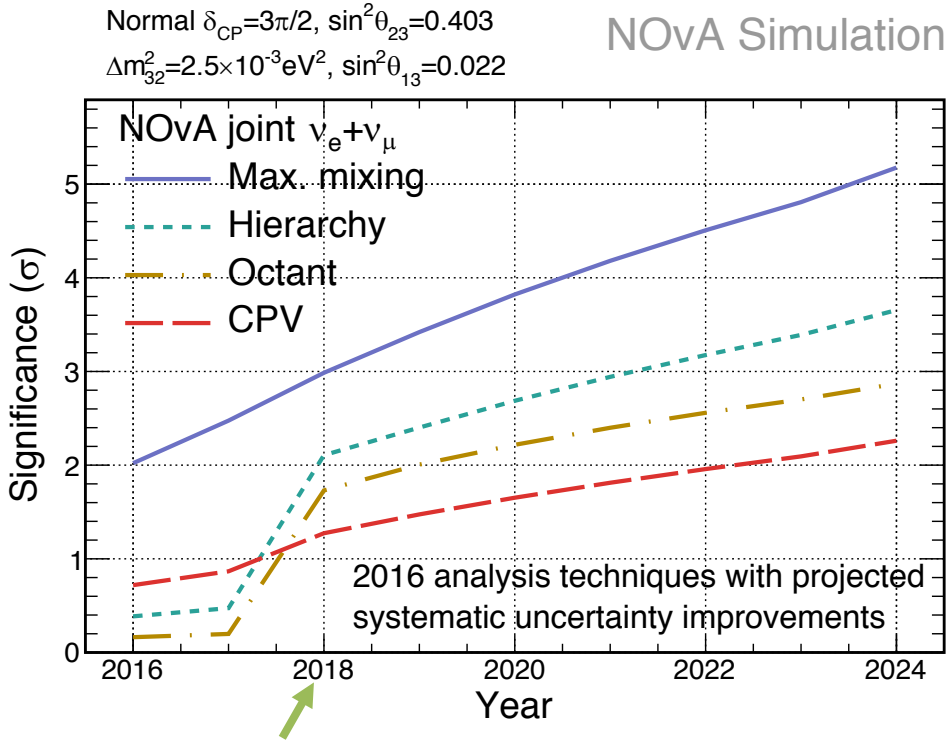
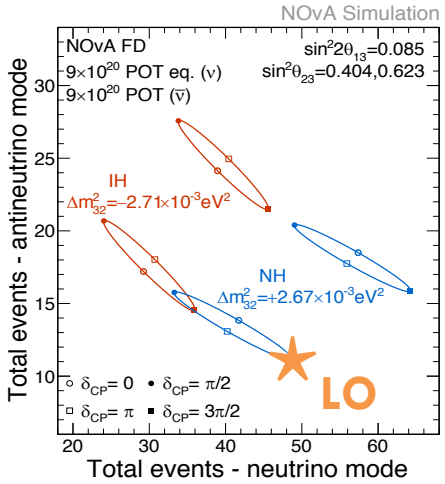


Complete first analysis with antineutrino data



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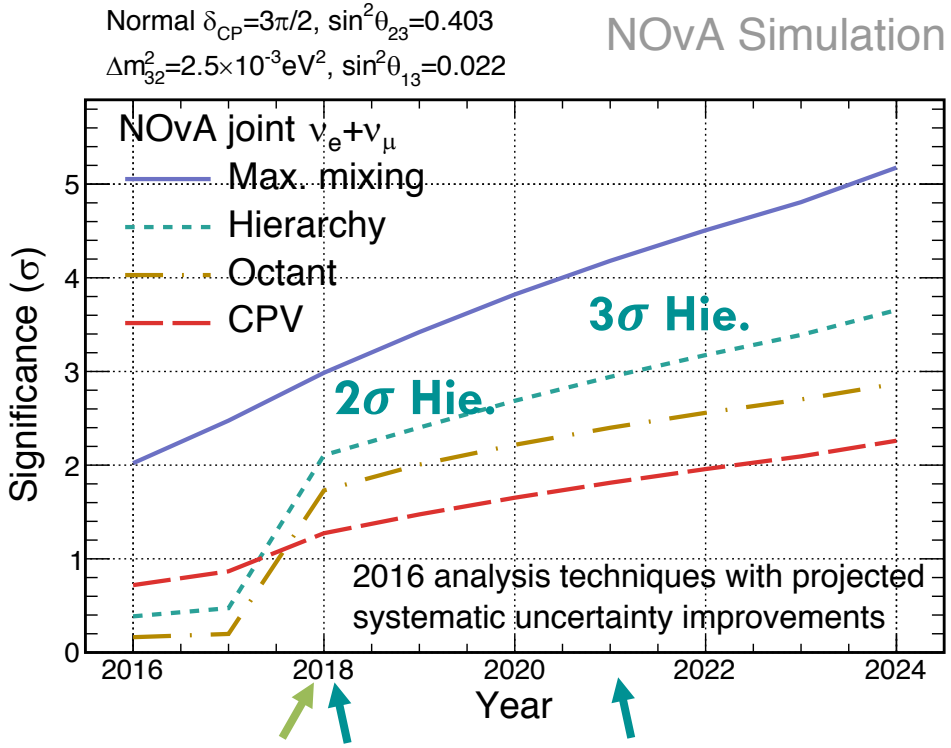

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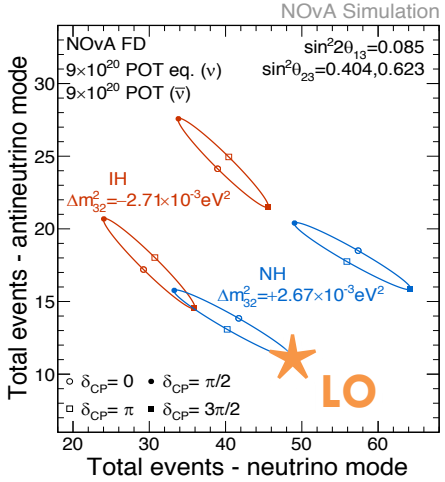

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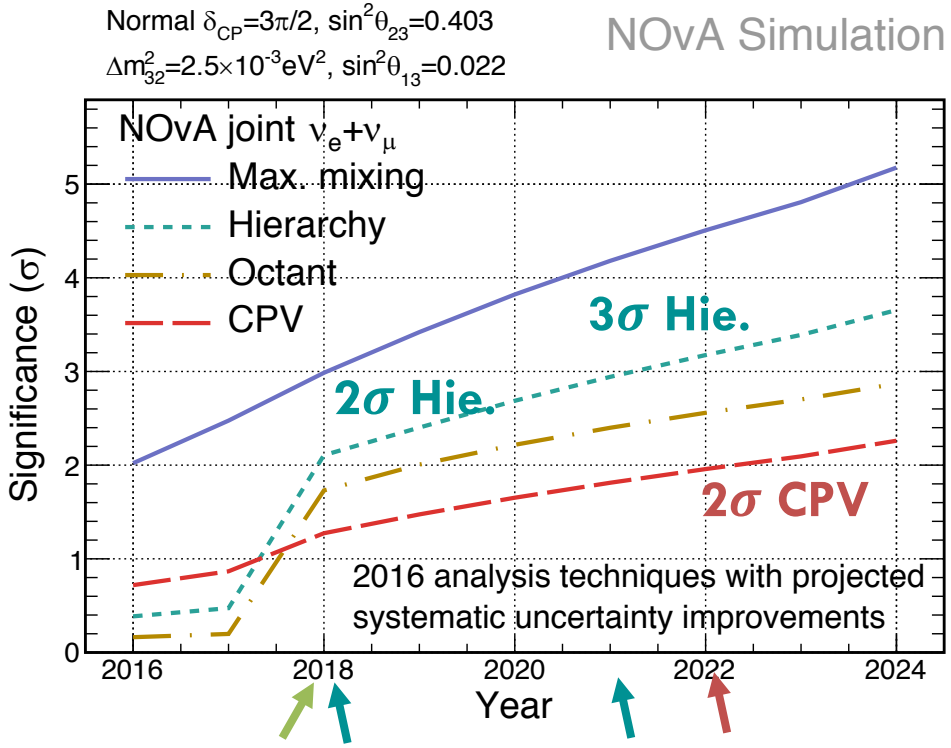

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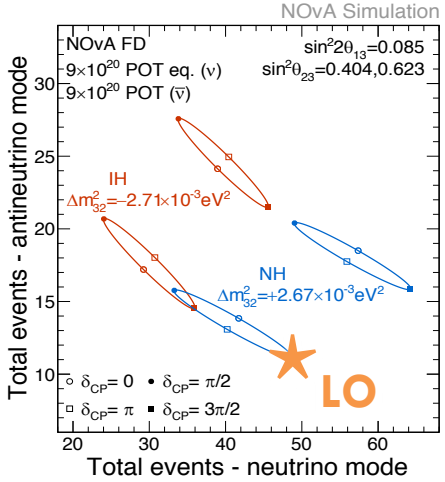

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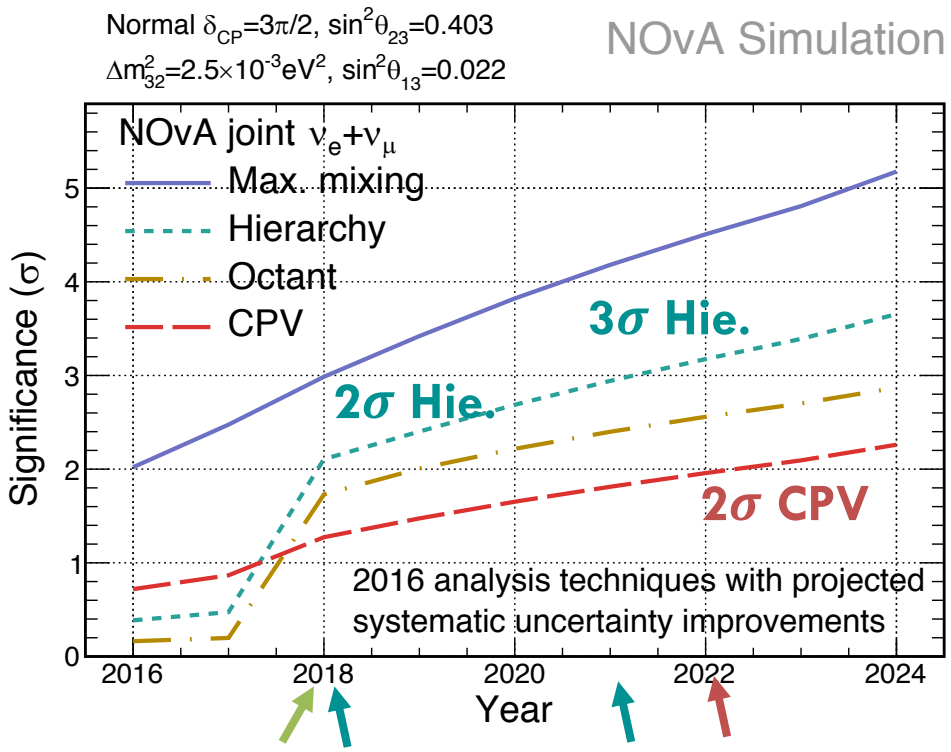

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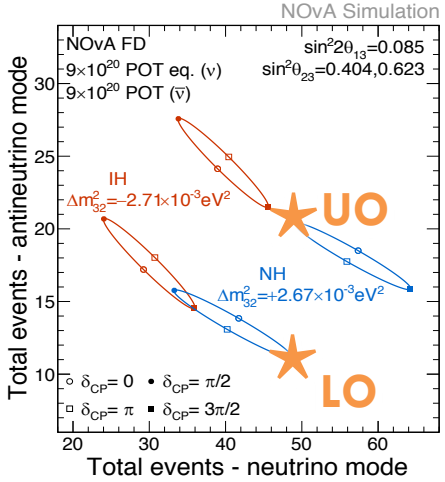
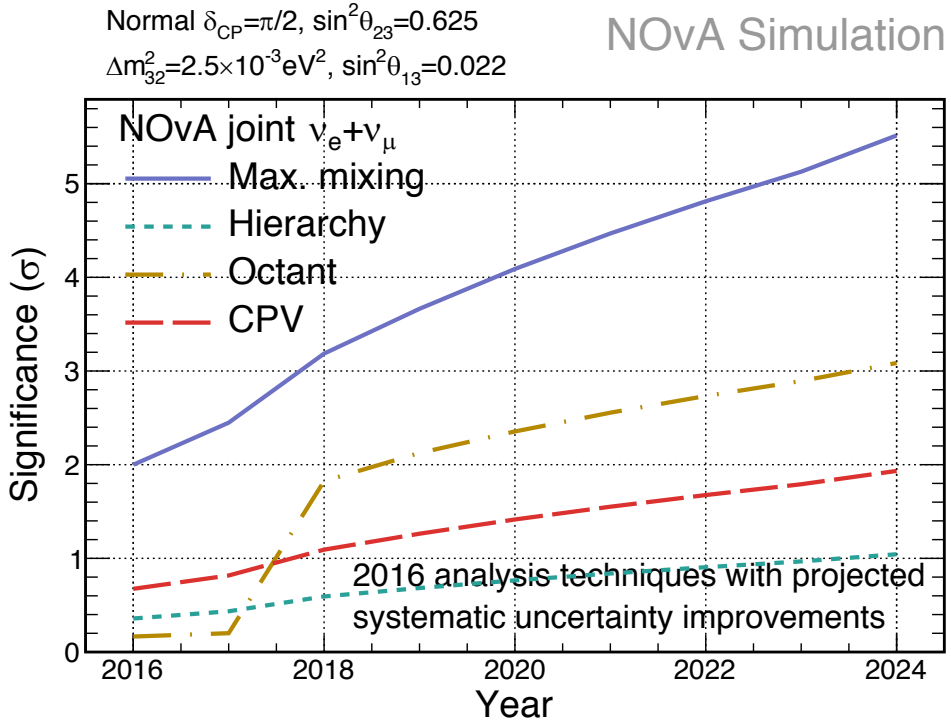


Upper octant, $\delta_{CP} = \pi/2$



REACH

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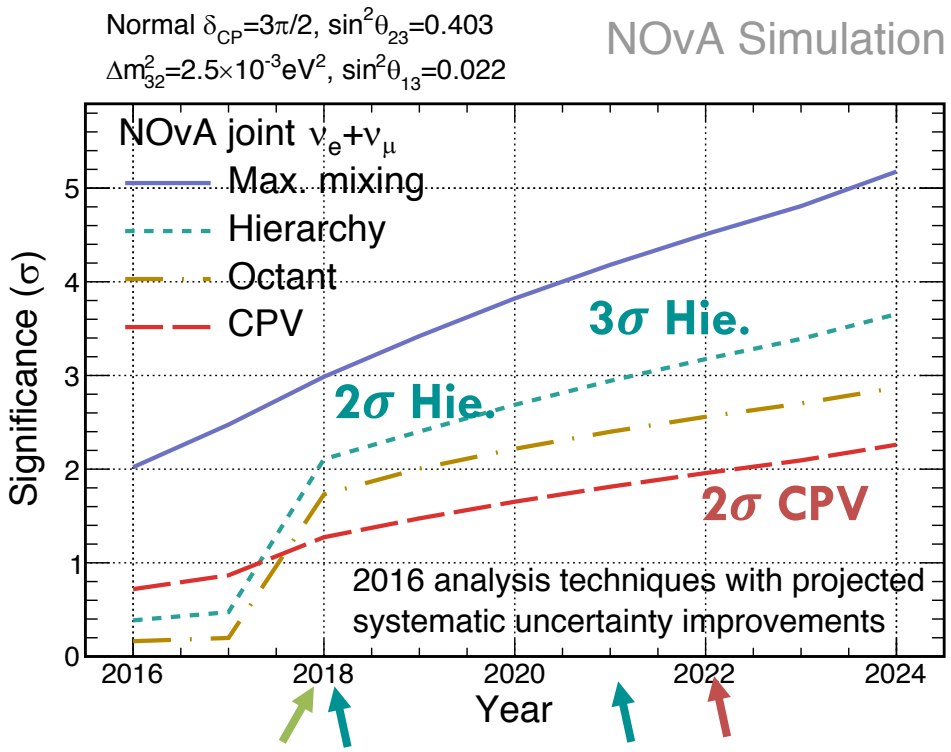
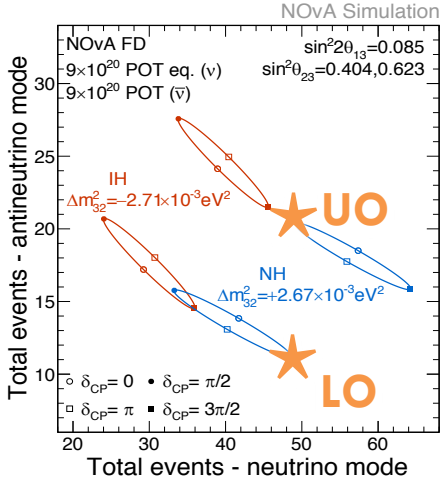


Complete first analysis with antineutrino data



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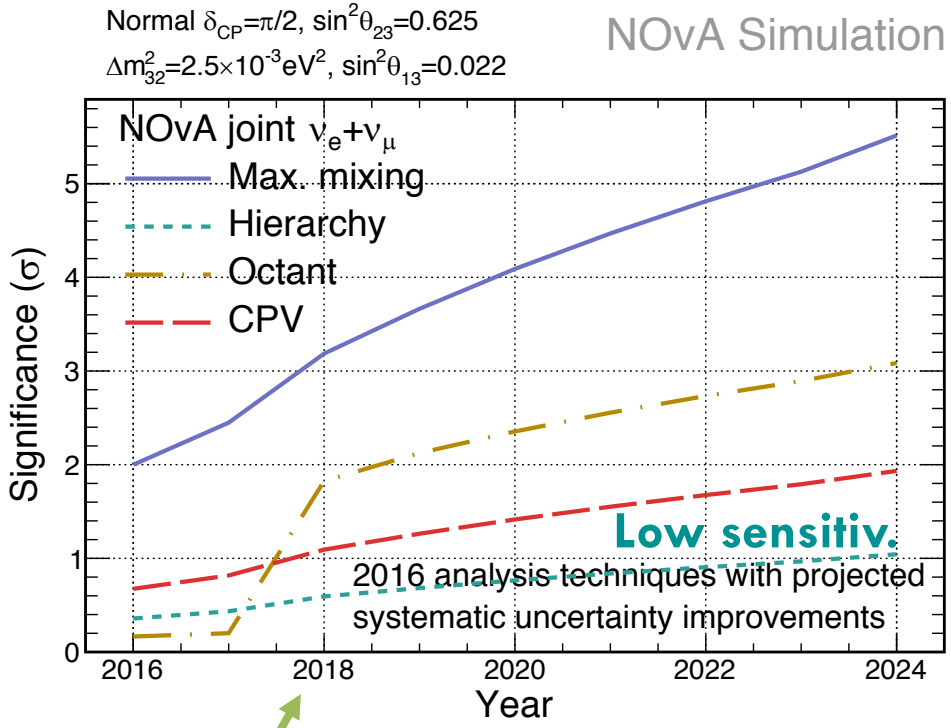

Complete first analysis with antineutrino data

REACH

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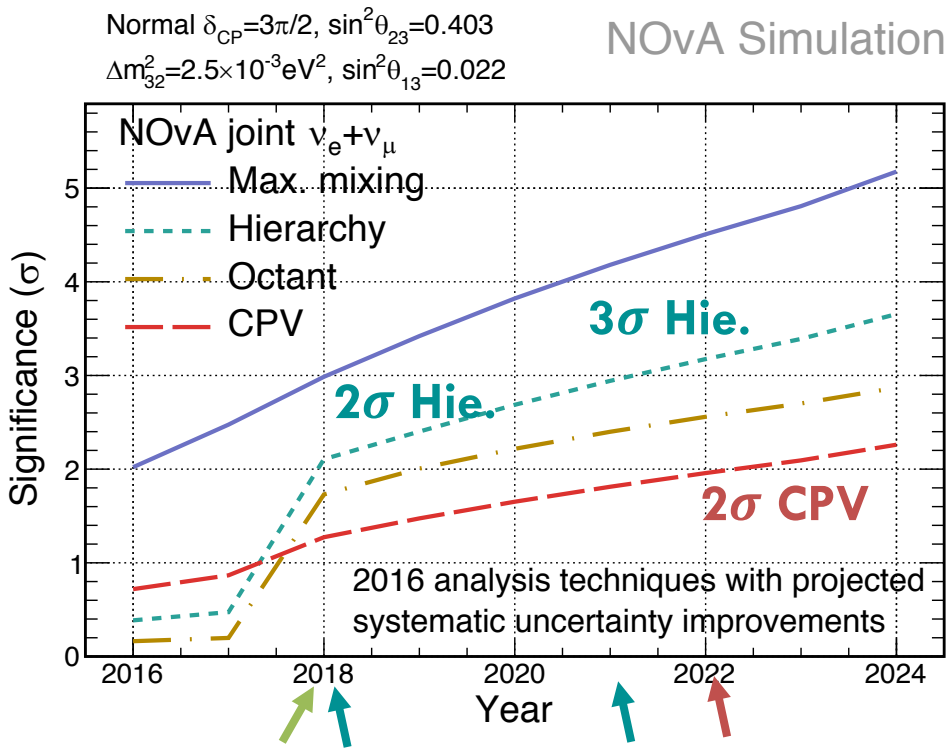

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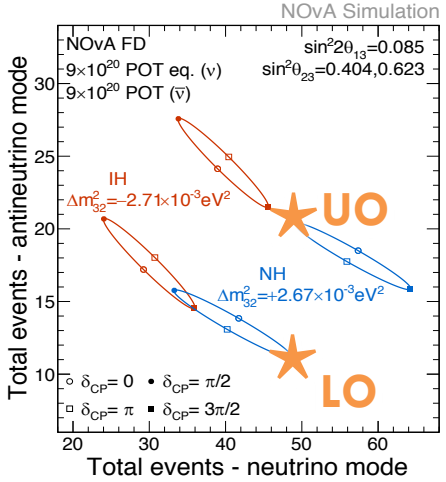

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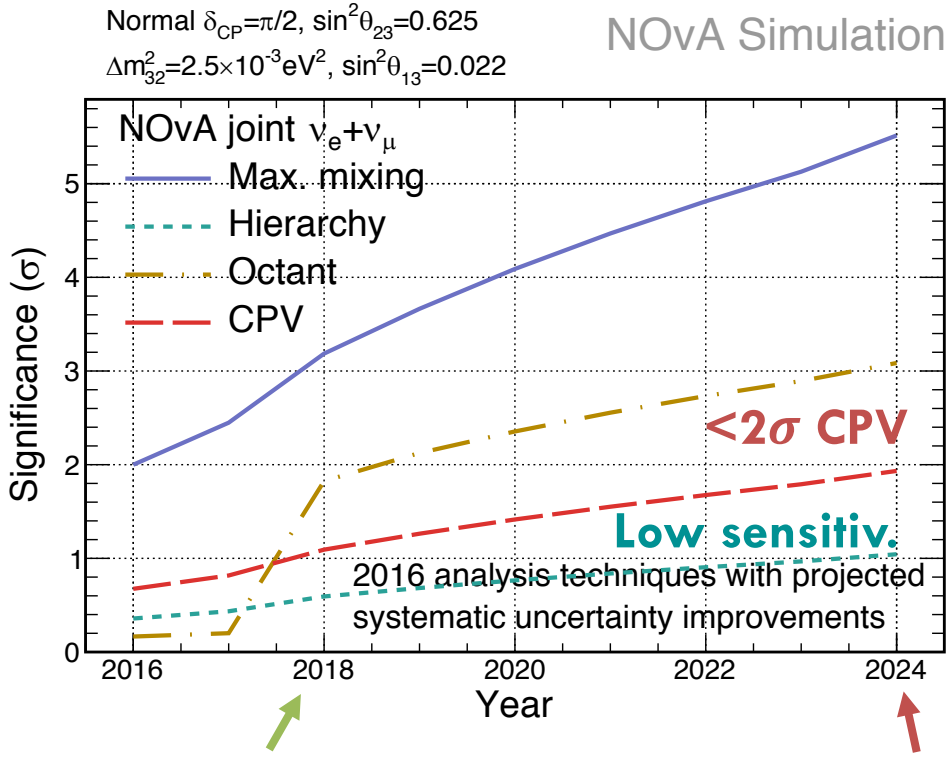
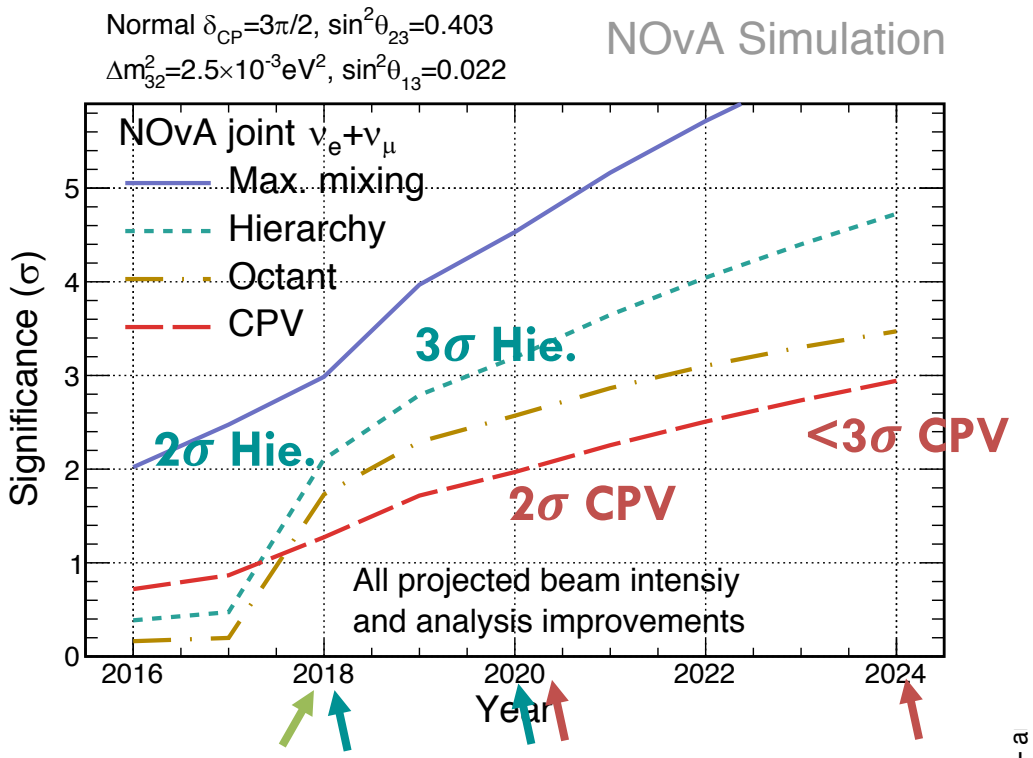


Complete first analysis with antineutrino data

REACH (WITH EXTRA IMPROVEMENTS)

Lower octant, $\delta_{CP} = 3\pi/2$



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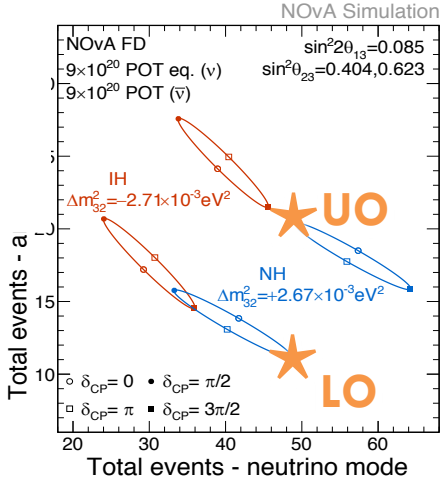
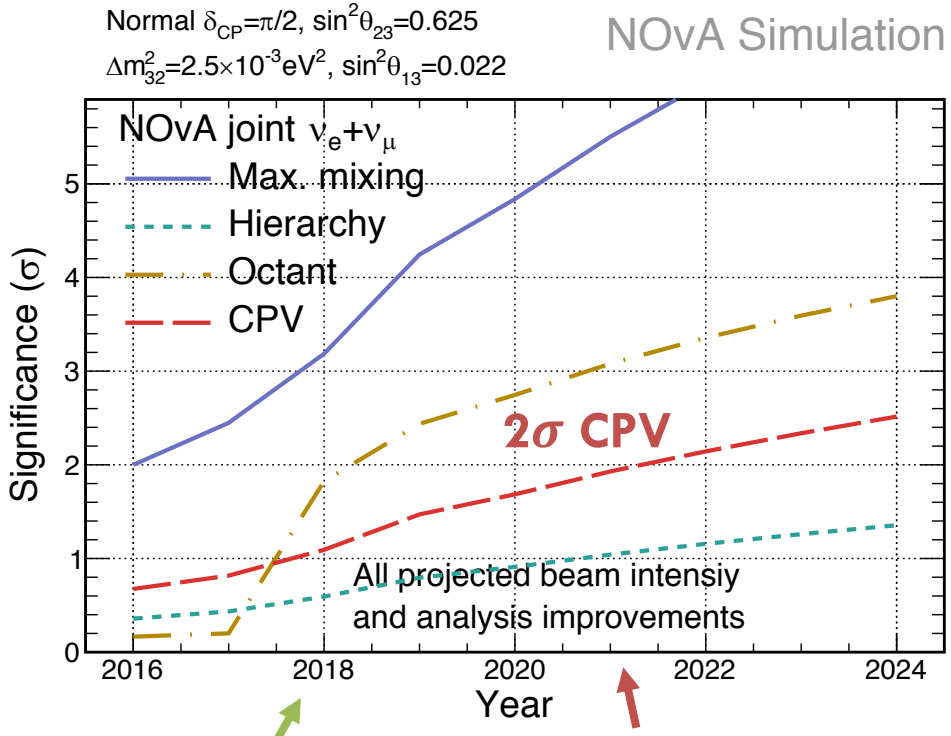


Upper octant, $\delta_{CP} = \pi/2$



Complete first analysis with antineutrino data

CP VIOLATION

We don't know the true value of δ_{CP} → For what percentage of values in the 0-2π range can we make the measurement at 95% CL?

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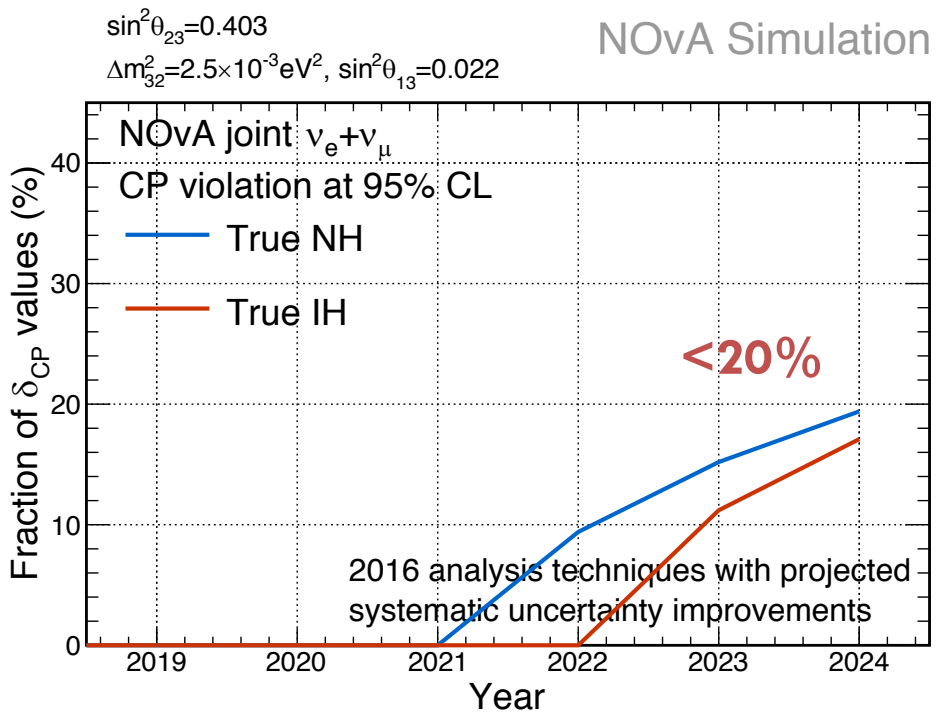
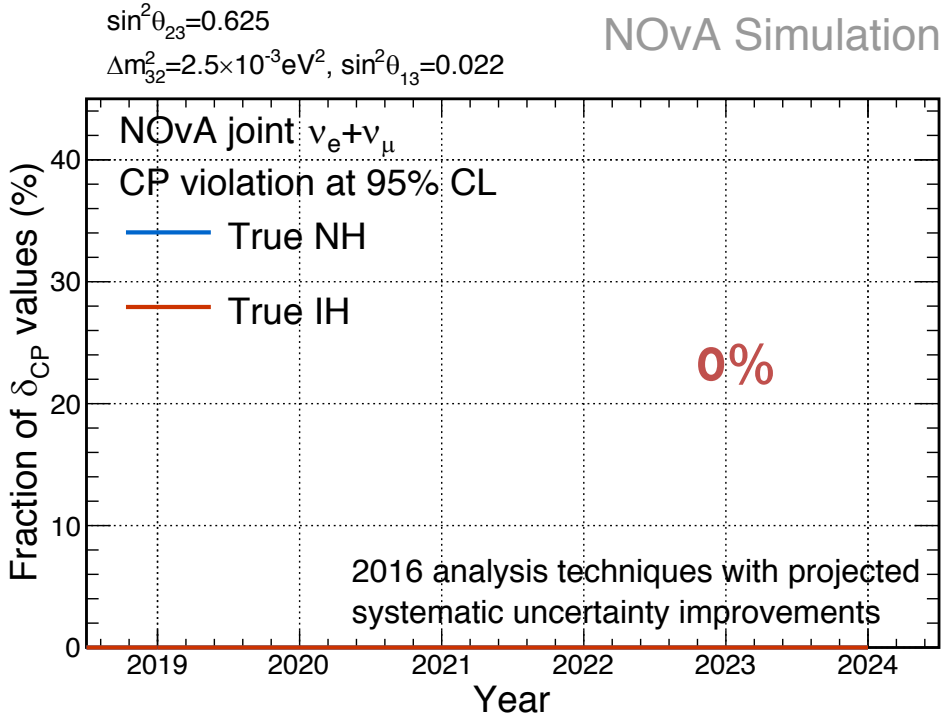


Upper octant



CP VIOLATION (WITH EXTRA IMPROVEMENTS)

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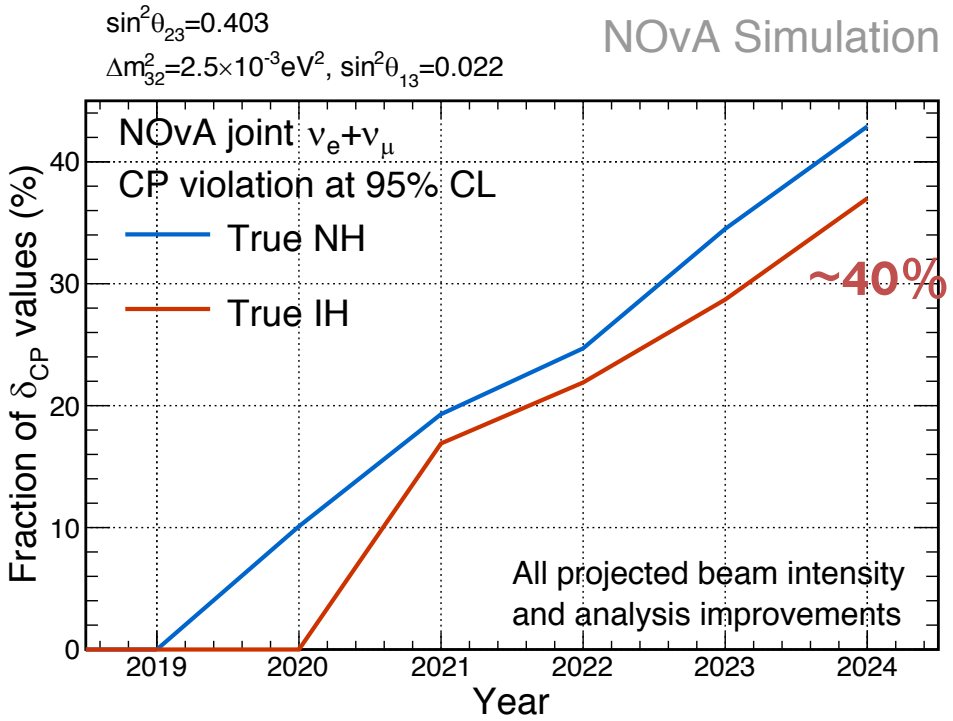
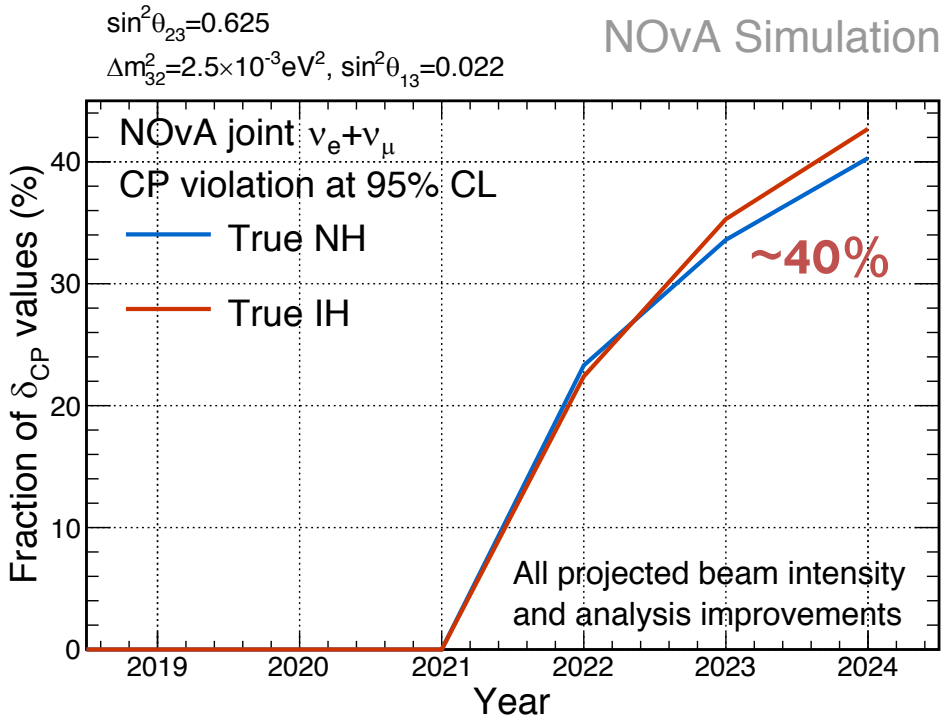
Lower octant



Upper octant



MASS HIERARCHY

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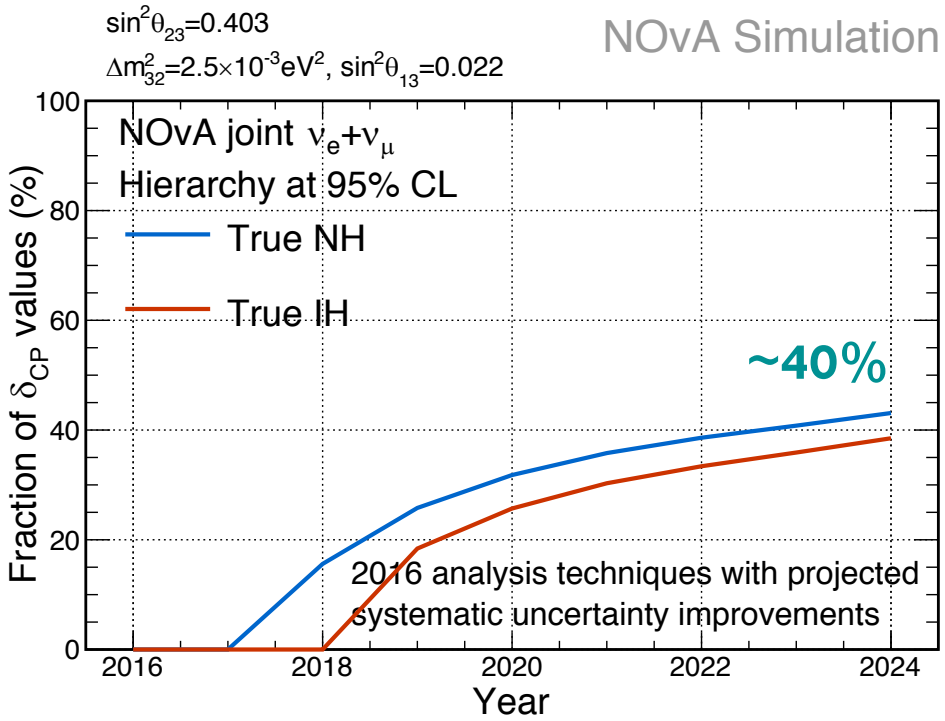
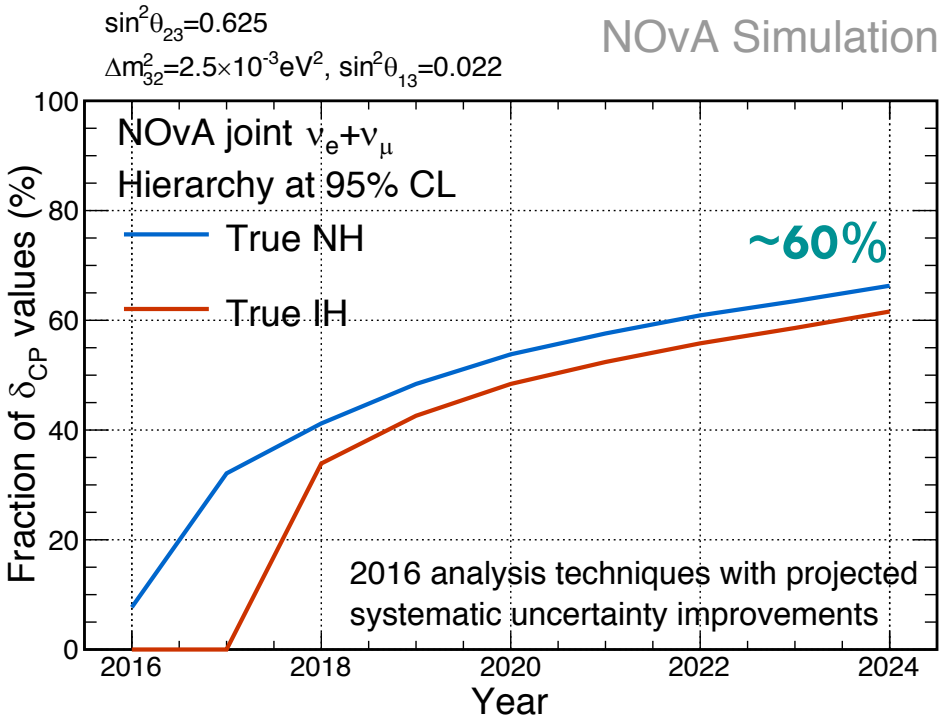
Lower octant



Upper octant



MASS HIERARCHY (WITH EXTRA IMPROVEMENTS)

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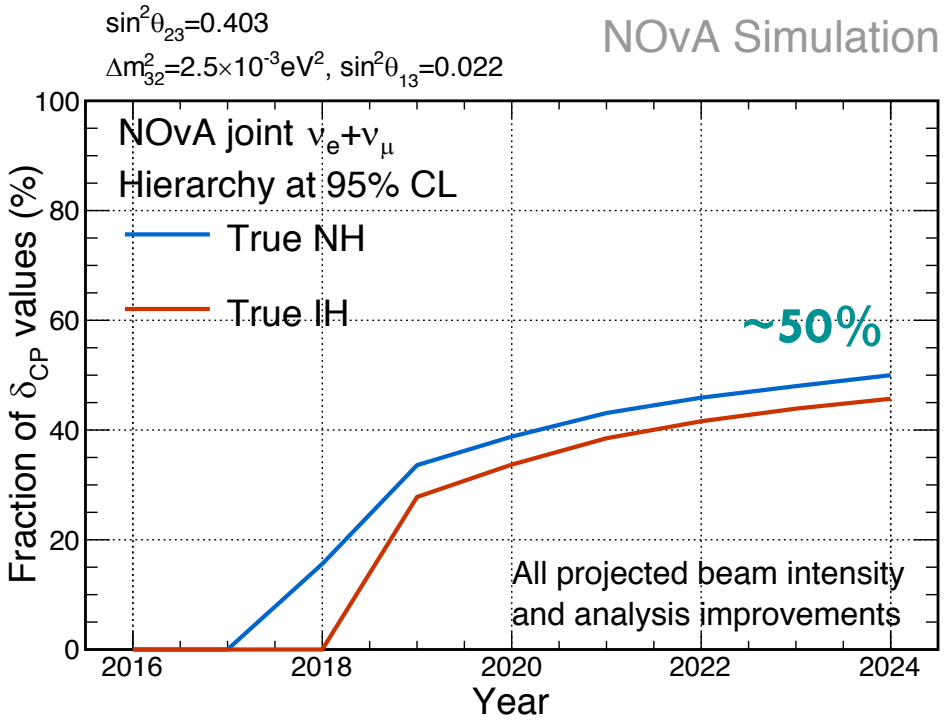
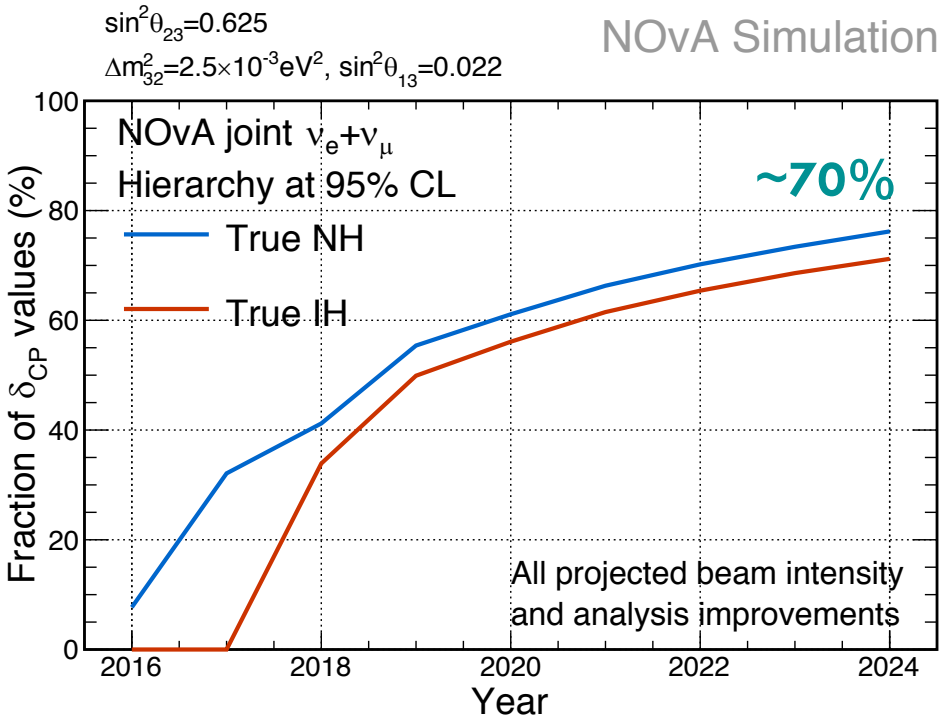


Upper octant



SUMMARY AND OUTLOOK

- The electron neutrino appearance analysis in NOvA is particularly sensitive to the neutrino mass hierarchy, CP phase and mixing angle θ_{23}
- The joint $\nu_e + \nu_\mu$ fit allows us to put constraints on the parameter space
- Future analyses benefit from increased statistics and the combination of neutrino and antineutrino data
- Potential for measurements of rejection of IH (2-3σ) and rejection of CP conservation (2σ)

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- Potential for measurements of rejection of IH (2-3σ) and rejection of CP conservation (2σ)

- Global effort! Make the best measurement before the DUNE era
- NOvA:
  - Already demonstrated good performance with 2015 and 2016 analyses
  - Always striving for better simulation, analysis techniques
  - Getting better each year!
- Fermilab:
  - Home! Offers a lot of support
  - ♥ the NuMI beam. Potential improvements accelerate the program
- Neutrino community:
  - External constraints inform our results + plans
- Mother Nature:
  - Certain true parameters make our lives easier

The NOvA team