FERMILAB-POSTER—25-0238-PPD

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QED Radiative Corrections to CC Neutrino Scattering in NOvA

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1. Introduction

δ_{CP} is the least constrained oscillation parameter NOvA measures. Much of the systematic uncertainty is driven by cross section uncertainties, especially radiative corrections.

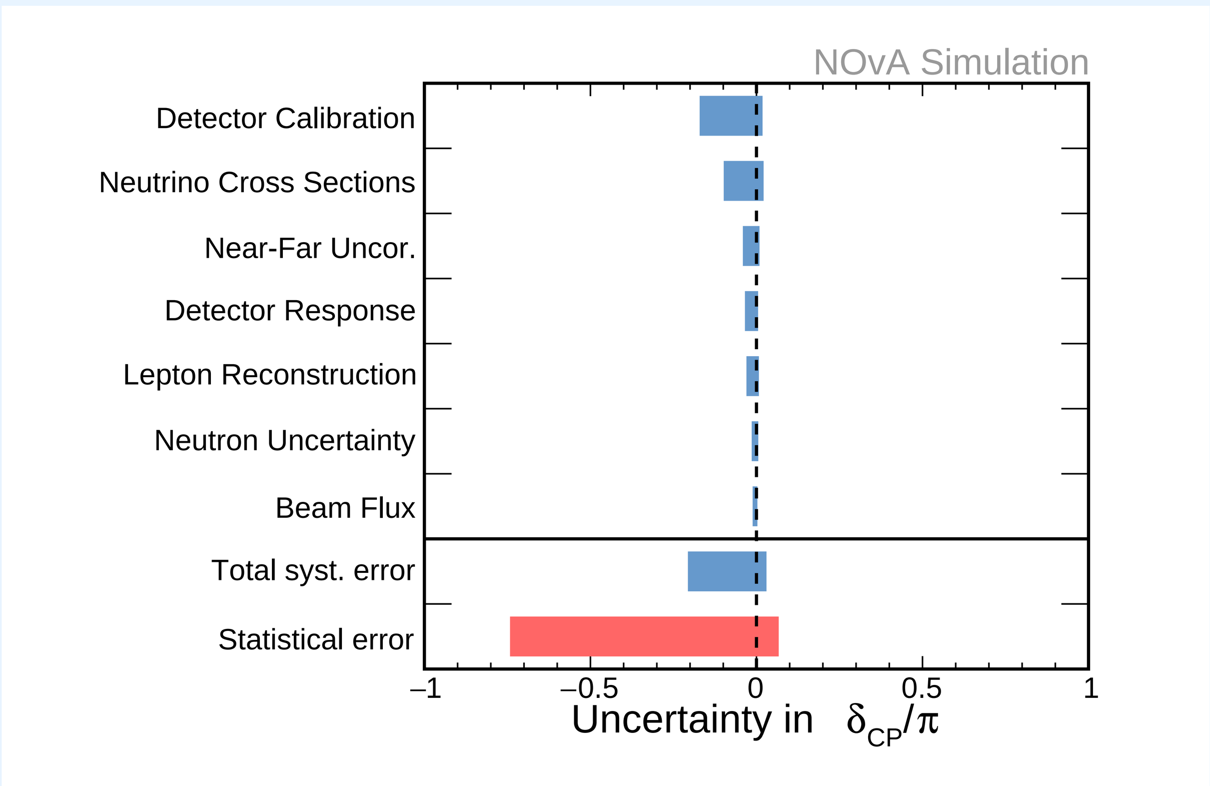


Figure 1. NOvA's uncertainties on δ_{CP} by source [1].

- **Currently**, NOvA employs a 2% uncertainty on **only** ν_e and $\bar{\nu}_e$ events to account for radiative corrections.
- **This work** aims to implement newer physics-driven calculations by Tomalak et. al. [2][3].

2. Radiative Corrections

The GENIE event generator accounts for the lowest order charged current scattering processes.

- These processes account for most of the cross section, but not the whole story.
- At the next leading order, we consider interactions with one photon **radiated, correcting** the total cross section.

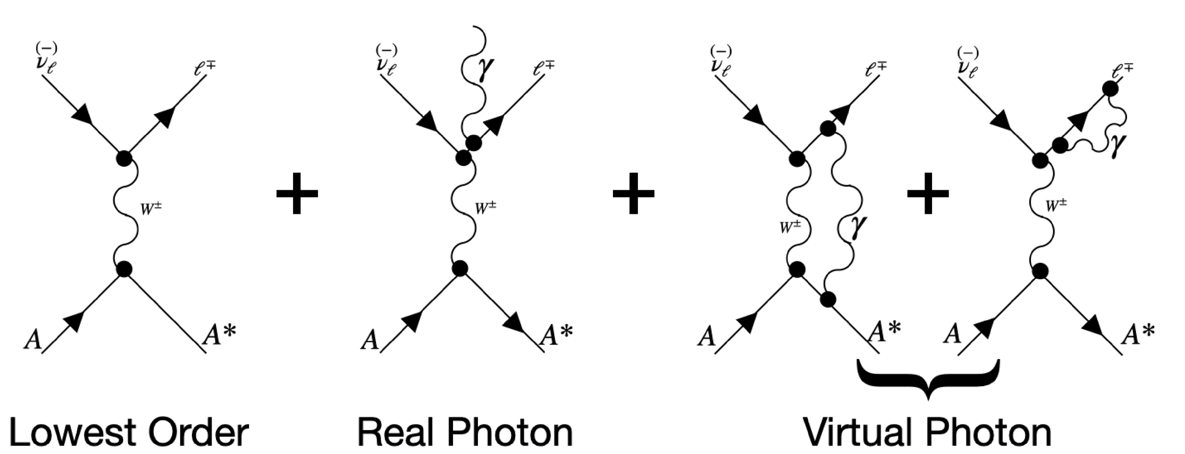


Figure 2. Diagrams depicting the tree-level scattering process and those with one real or one virtual photon included.

Virtual photons are not observable, but still impact the cross section. Additionally, real photons will alter observed event topology.

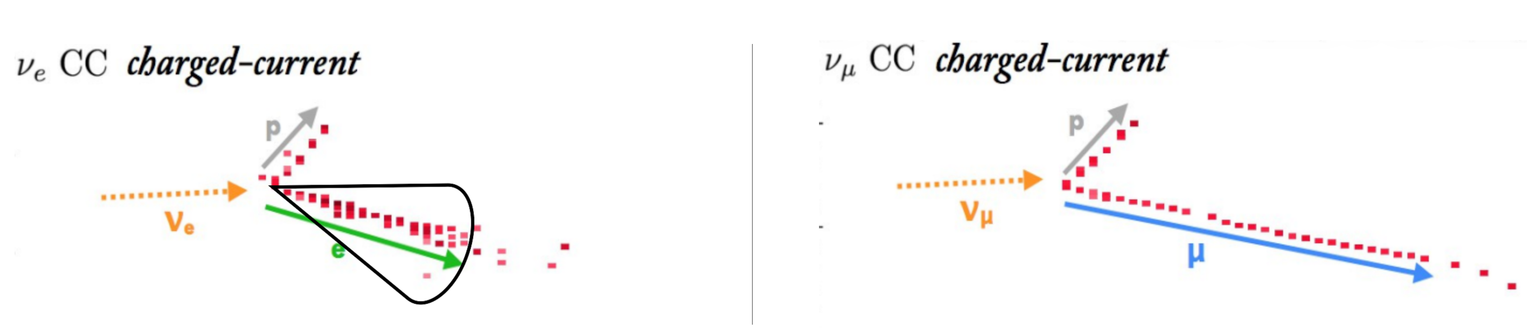


Figure 3. NOvA event displays showing the ν_e and ν_μ CCQE event topologies.

- Photons radiated near an electron are **collected with the leptonic system**.
- Muon energy is calculated from track length. **Energy from real photons is lost**.

3. Implementation

A **reweighting scheme** [2], [3] is used to apply radiative corrections to NOvA's oscillation predictions. We anticipate this effect to be largest for CCQE events, so we apply the same weights to all CC channels as a conservative estimate.

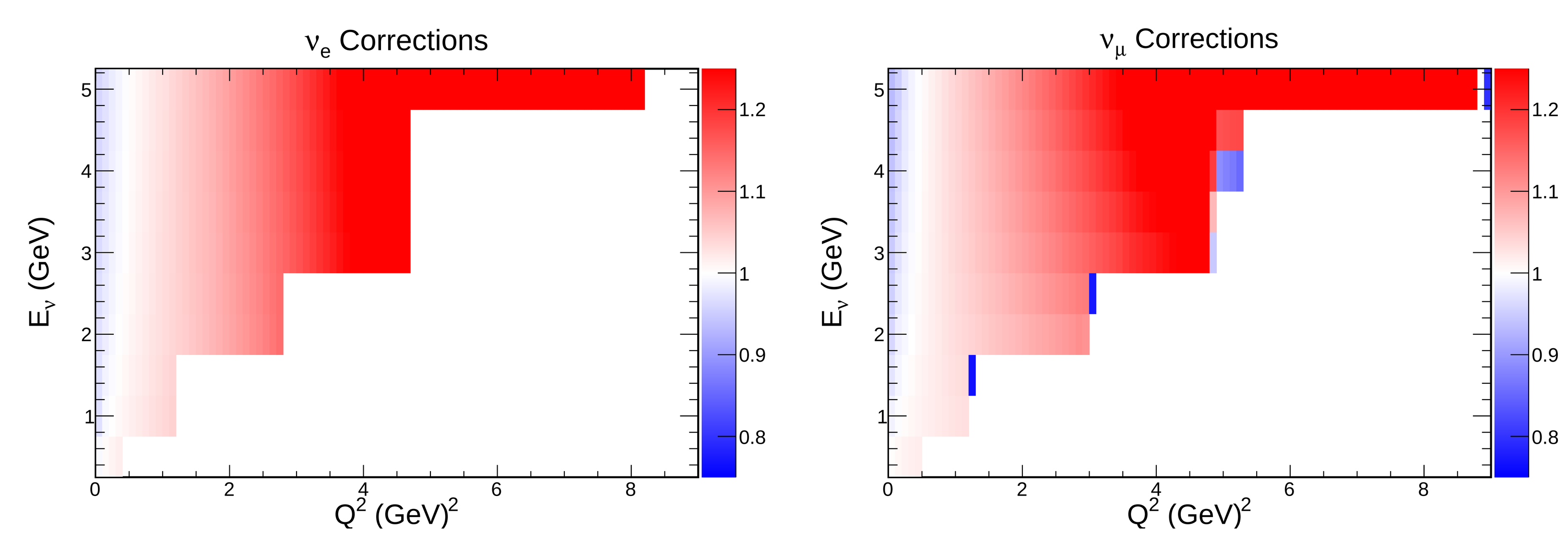


Figure 4. Histograms of weights used for the new radiative corrections systematic

- Real photons leech four-momentum from the event. The corrections are a shift up in Q^2.
- E_ν dependance arises largely from the increase in the kinematic limit on Q^2.
- Corrections now impact **muon-flavored events**.

4. Far Detector Predictions

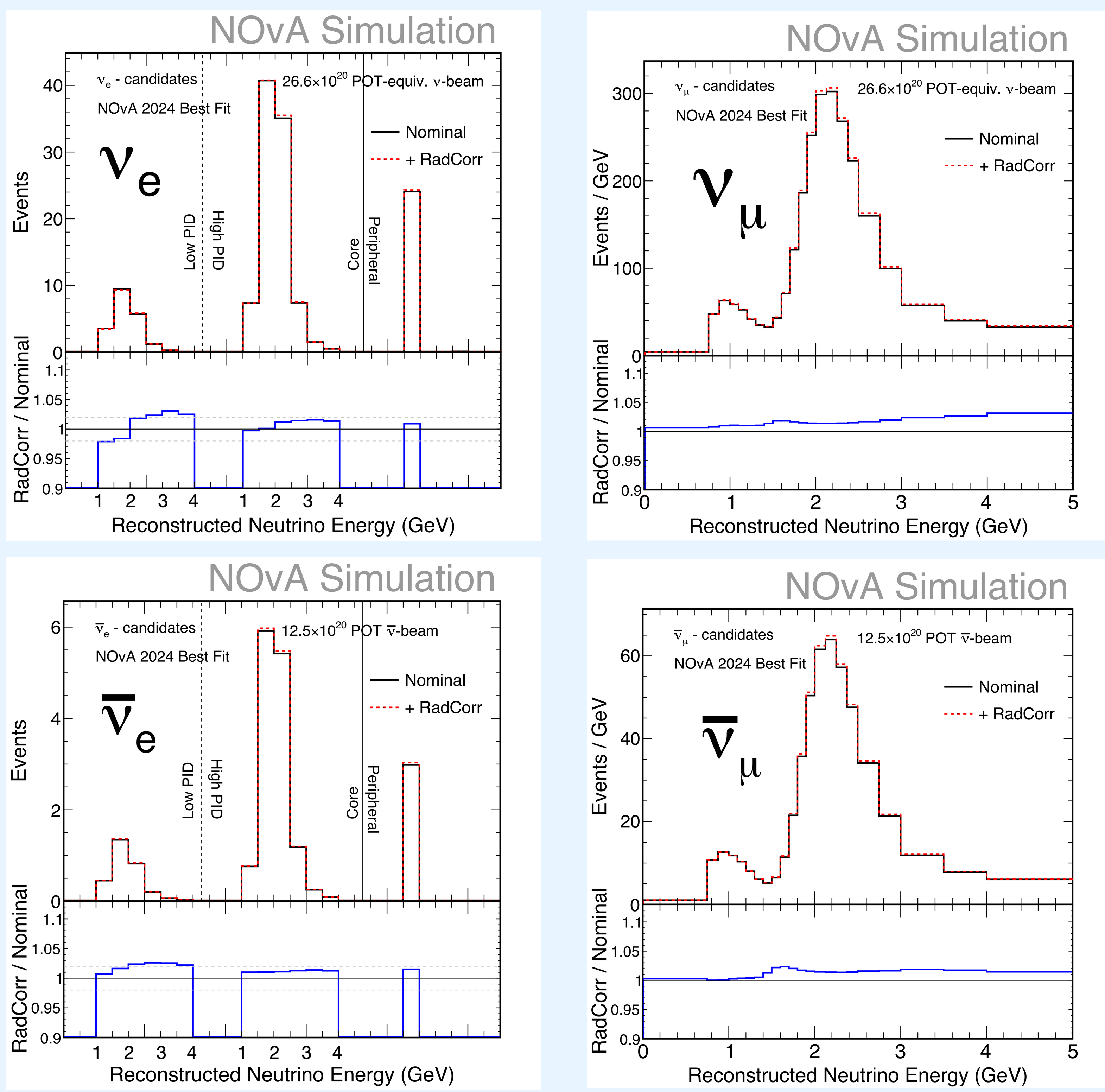
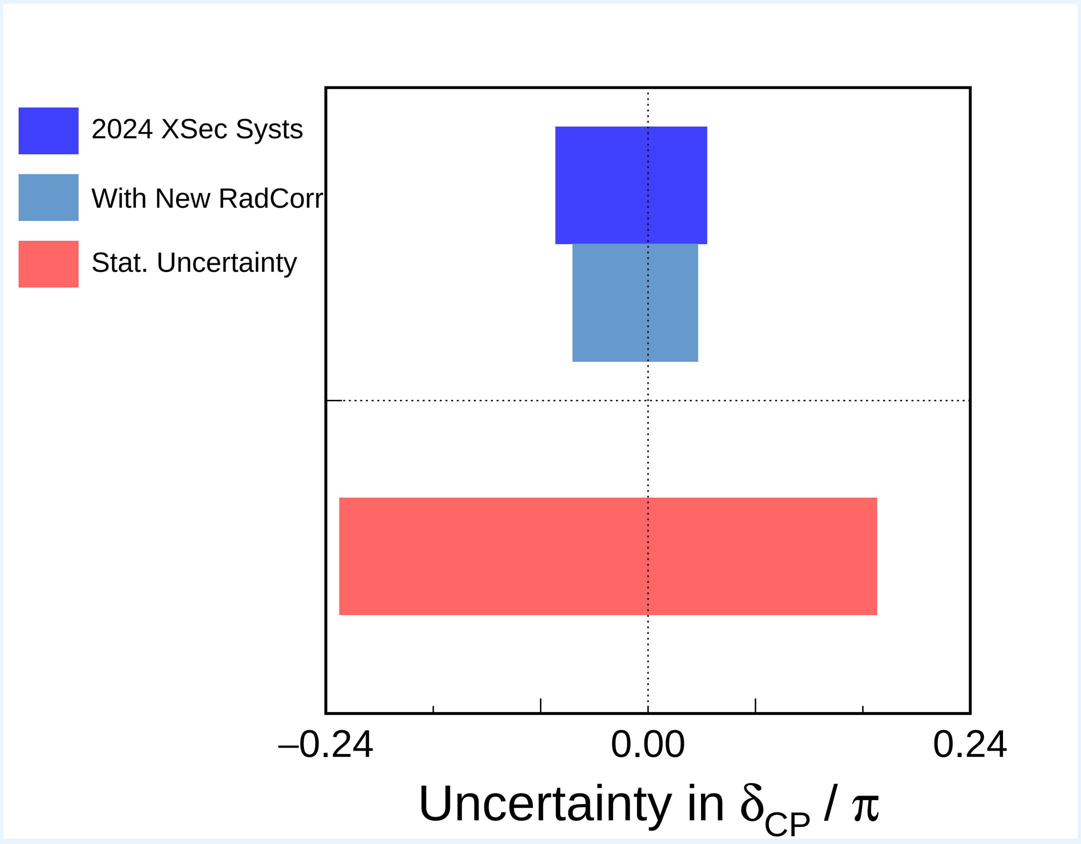


Figure 5. Predicted (Monte-Carlo) neutrino candidate events at NOvA's Far detector.

- **For Electrons**, larger shifts occur in lower PID confidence sample.
- **For Muons**, the effect is small but nonzero. A feed down effect causes a bump near the disappearance dip.

5. Impact on Analysis



- The reduction in uncertainty of δ_{CP} comes primarily from the effect correlating the effect on ν_e and $\bar{\nu}_e$.
- Reducing cross section uncertainties is critical for the next generation of neutrino oscillation experiments.

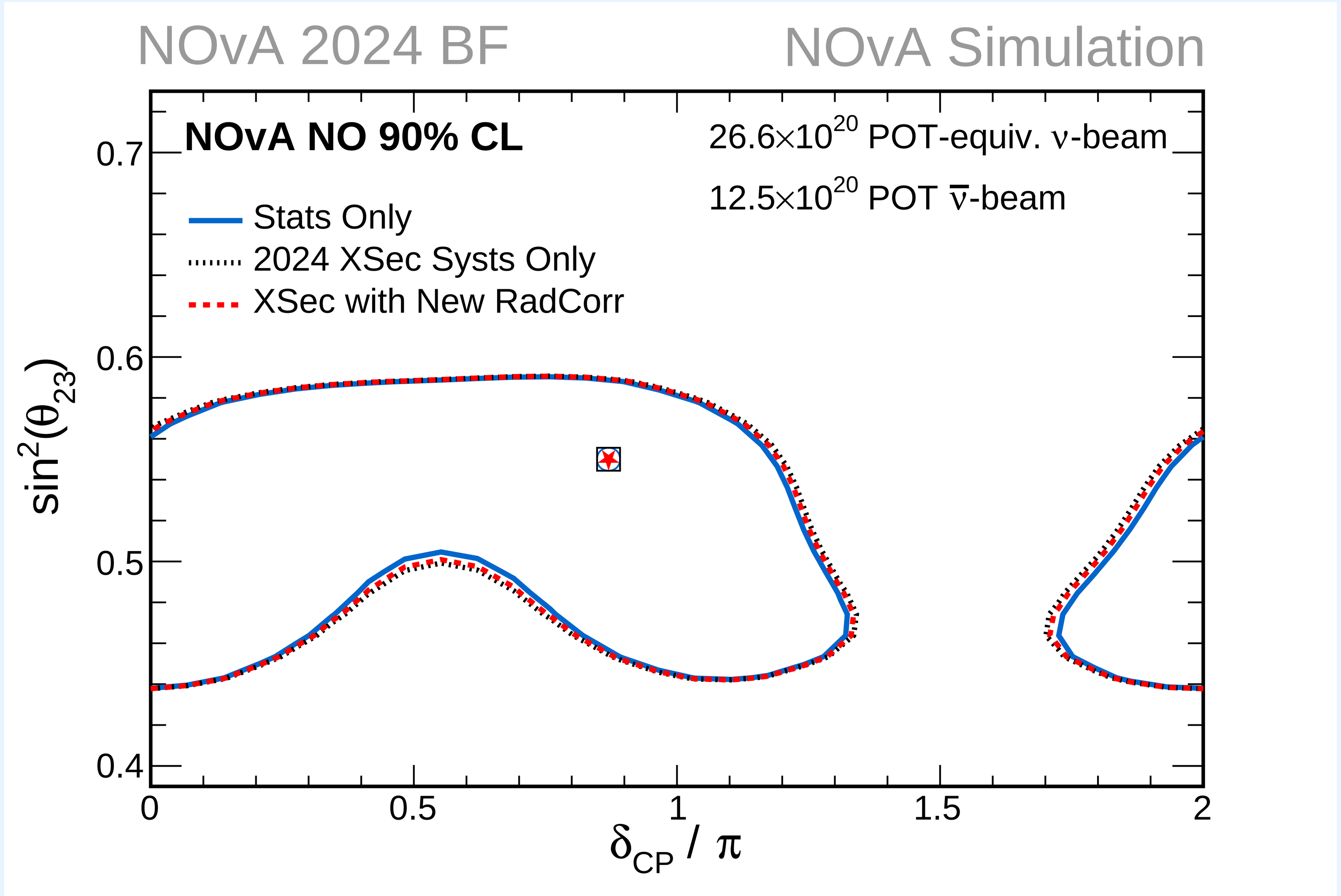


Figure 6. Simulated measurements of $\sin^2(\theta_{23})$ vs δ_{CP} with different sets of XSec systematics.

- At NOvA's 2024 best fit point a small, but noticeable reduction in uncertainty occurs with the new systematic.
- As expected, this effect is largest for δ_{CP}, but reduction is present for $\sin^2(\theta_{23})$ as well.

References

[1] The NOvA Collaboration. Precision measurement of neutrino oscillation parameters with 10 years of data from the nova experiment. 2025.

[2] Oleksandr Tomalak, Qing Chen, Richard J. Hill, Kevin S. McFarland, and Clarence Wret. Theory of qed radiative corrections to neutrino scattering at accelerator energies. *Phys. Rev. D*, 106:093006, Nov 2022.

[3] Oleksandr Tomalak, Qing Chen, Richard J. Hill, and Kevin S. McFarland. Qed radiative corrections for accelerator neutrinos. *Nature Communications*, 13(1):5286, 2022.

[4] Melanie Day and Kevin S. McFarland. Differences in quasi-elastic cross-sections of muon and electron neutrinos. *FERMILAB-PUB-12-314-PPD*, 06 2012.

Acknowledgements

We would like to thank gratitude to Clarence Wret, Kevin McFarland, and Oleksander Tomalak for doing the theory work that this relies on, and for their assistance with this project. Additionally, We would like to thank the NOvA collaboration and Tufts Neutrino Group for their valuable insights and feedback throughout this project.

This work has been supported by Tufts University and the U.S. Department of Energy Office of Science Grant Number: **DE-SC0019032**. This document was prepared by The NOvA Collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, Office of High Energy Physics HEP User Facility. Fermilab is managed by Fermi Forward Discovery Group, LLC, acting under **Contract No. 89243024CSC000002**.

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