Measurement of the $\bar{\nu}_\mu$- Hydrogen Charged-Current Elastic Cross Section in the NOvA Near Detector

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(for the NOvA collaboration)

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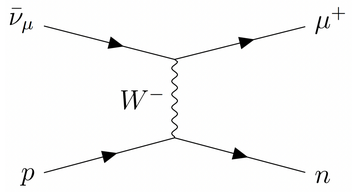
1. $\bar{\nu}_\mu$- Hydrogen Charged-Current Elastic Interactions

(Anti)neutrino-Hydrogen Interactions are free of nuclear effects. The CCE ($\bar{\nu}_\mu \mathrm{H} \to \mu^+ n$) interactions can be used to determine the axial-vector form factor and radius of the proton and the absolute $\bar{\nu}_\mu$ flux.

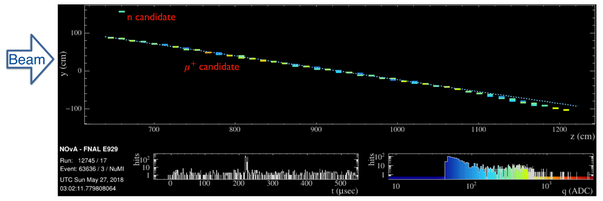


Feynman diagram for $\bar{\nu}_\mu \mathrm{H} \to \mu^+ n$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2}\left(E_\nu, Q^2\right) = \frac{\mathrm{G_F^2}\,|V_{ud}|^2}{2\pi}\frac{M^2}{E_\nu^2}\left[\left(\tau + r_\ell^2\right)A(\nu, Q^2) + \frac{\nu}{M^2}B(\nu, Q^2) + \frac{\nu^2}{M^4}\frac{C(\nu, Q^2)}{1+\tau}\right]$$

The structure functions A, B, and C encode the nucleon vector form factors ($\mathrm{F_1^v}$, $\mathrm{F_2^v}$) and the axial form factor $\mathrm{F_A}(\mathrm{Q^2})$.

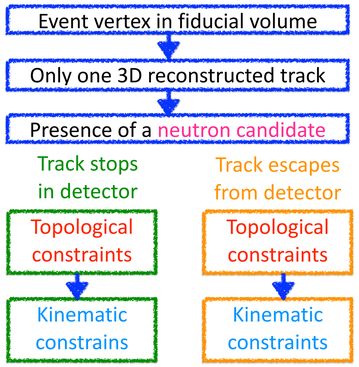
2. The NOvA Near Detector



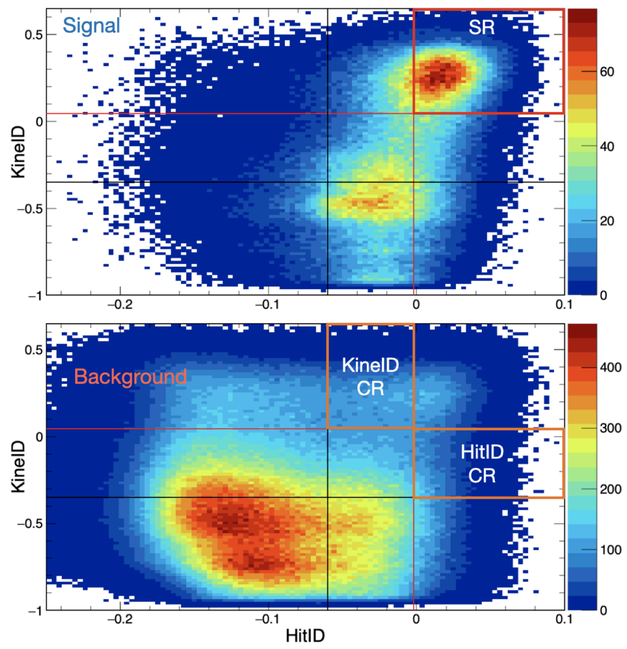
Display of a CCE like event from NOvA data

- Antineutrino NuMI beam:
  93% $\bar{\nu}_\mu$, $\langle E \rangle \sim 1.9\,\mathrm{GeV}$, 1.2×10^{21}POT.
- Near Detector (ND): Liquid scintillator ($\mathrm{CH_2}$) inside PVC cells containing 10.8% hydrogen by mass.
- CCE signature : Long reconstructed track associated with isolated object originating from neutron interaction.

3. Selection of $\bar{\nu}_\mu \mathrm{H} \to \mu^+ n$ events



- Neutron Candidate: Closest isolated object to the calculated neutron line of flight.
- HitID: Topological constraint based on the location and energy of hits/tracks (14 input variables).
- KineID: Global event kinematics to select H at rest (7 input variables).

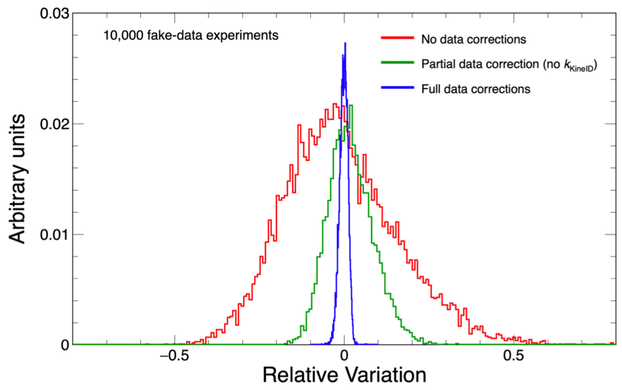


Definition of SR and CR in HitID-KineID plane

4. Data Corrections

- Signal Region (SR): selected events.
- Control Regions (CR): Data-driven background constraints obviating the limitations of the Monte Carlo (MC) simulations.
- Data corrections derived from the CRs :

$$\varepsilon_{\mathrm{Bkg}} = \varepsilon_{\mathrm{MC}} \times \frac{\varepsilon^{\mathrm{CR}}_{\mathrm{Data}}}{\varepsilon^{\mathrm{CR}}_{\mathrm{MC}}} = \varepsilon_{\mathrm{MC}} \times k_{\mathrm{cut}}$$



Variation of background in SR pre and post data corrections

5. Systematic Uncertainties

- Repeat complete analysis after shifting each parameter.
- Three Data Correction Factors : k_{nc}, k_{HitID} and k_{KineID}.
- The correction factors are re-evaluated for each variation.
- Systematic uncertainties obtained from comparing the shifted results from the nominal.

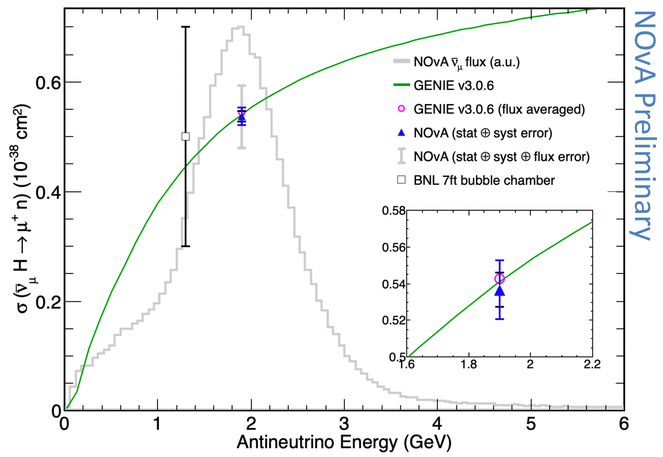
Source	Contained (%)	Uncontained (%)	Correlation
Normalization	0.9	0.9	1.00
Background estimate	1.2	1.3	0.96
QE modelling	0.8	1.3	0.30
Neutron detection	1.1	1.1	-0.47
Muon energy scale	0.6	0.2	-0.07
Muon angle scale	0.6	0.2	-0.23
Detector	1.0	0.5	-0.58
Systematics (w/o flux)	**2.4**	**2.4**	

- All systematic uncertainties related to detector and reconstruction effects are anti-correlated for the two samples.

6. Results for Total Cross Section

	Signal	Background	Total	Data	Data/Expected
Contained	15,103	27,839	42,941	43,644	$0.985 \pm 0.008 \pm 0.013$
Uncontained	20,670	43,544	64,214	63,248	$1.016 \pm 0.010 \pm 0.013$

- Total signal — Observed : 35,509±679(stat), Expected : 35,773
  Largest (anti)neutrino-hydrogen sample measured to date.



- $\sigma_{CCE} = 0.538 \pm 0.009(\mathrm{stat}) \pm 0.010(\mathrm{syst}) \pm 0.055(\mathrm{flux}) \times 10^{-38}\,\mathrm{cm}^2$
  Most precise CCE cross section to date.

[1] S. Abubakar et al. (NOvA), Phys. Rev. Lett. **136**, 011802 (2026), arXiv:2509.04361 [hep-ex].
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[3] H. Duyang, B. Guo, S. R. Mishra, and R. Petti, Phys Lett. B795, 424 (2019), arXiv:1902.09480 [hep-ph].
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