

---

# NuSTEC Publications Working Group

**Conveners: Andy Furmanski, Jorge G. Morfín and Kajetan Niewczas**

## **NuSTEC Review: Current Experimental and Theoretical Challenges of Neutrino-Nucleus Scattering**

This is an update of the NuSTEC White Paper (68 pages) from June 2017

Jorge G. Morfín  
Fermilab

# NuSTEC Review Publication

---

- ◆ After much discussion, including Linda Cremonesi the original third convener of the working group, began contacting NuSTEC Board members to assume responsibility for various sections of the publication in April 2023.
- ◆ We finally had leaders for all proposed sections and began actual writing a little over a year ago. To announce our first meeting with all section leaders we tried to set the time scale:
  - ◆ We should aim to have a complete **first-draft in September (2023)**, giving us time to complete the writing in advance of the P5 report coming out in October.
    - ▼ Please **come up with a plan to have your sections written on this timescale** (which can, and probably should, involve recruiting other experts to assist with the writing).
    - ▼ If you think this timeline is unachievable, please let us know.
  - ◆ Fine, a dose of optimism to start off a project – no one said impossible, but we all knew it would be a real challenge.

# NuSTEC Review – current status

---

<b>I</b>	<b>Executive Summary</b>	<b>5</b>
<b>II</b>	<b>Introduction and Overview of the Current Challenges</b>	<b>7</b>
A	Introduction: General Challenges . . . . .	7
B	Challenges: The impact of neutrino-nucleus interaction physics in determining neutrino oscillation parameters—C. WRET . . . . .	10
C	Challenges: Determining the Nuclear Model - K. NIEWCZAS, N. JACHOWICZ, N. ROCCO . . . . .	11
D	Challenges: Determining the Flux - J. PALEY . . . . .	11
E	Challenges: Generators - S. GARDINER, S. DYTMAN, J. ISAACSON . . . . .	12
F	Challenges: Final State Interactions - S.DYTMAN, L. PICKERING, J. SOBCZYK, Y. HAYATO, J. ISAACSON . . . . .	12
G	Challenges: Electron-nucleus Scattering - A. ASHKENAZI , V. PANDEY, A. ANKOWSKI . . . . .	13
H	Challenges: Pionless Interactions - A. FURMANSKI, S. DOLAN, A. NIKOLAKOPOULOS . . . . .	13
I	Challenges: The Resonance Region - M. KABIRNEZHAD, R. GONZALEZ JIMENEZ . . . . .	14
J	Challenges: Shallow and Deep-Inelastic Scattering Region - S. ATHAR, J.G. MORFIN, (FARHANA ZAIDI) . . . . .	15
K	Challenges: Strange Particle Production - J. NOWAK, C. THORPE . . . . .	16
L	Challenges: Coherent Meson Production - L. ALVAREZ RUSO, J.G. MORFIN, M. HOSTERT	16

# NuSTEC Review – current status

---

<b>III The Impact of Neutrino Nucleus Interaction Physics on Oscillation Physics Analyses</b>	
- C. WRET	18
A Introduction . . . . .	18
B The role of the near detector . . . . .	19
1 Matching selections . . . . .	20
2 NOvA . . . . .	20
3 T2K . . . . .	22
4 Atmospheric neutrinos . . . . .	24
C Impact of neutrino interactions on experiments . . . . .	26
D Mitigation . . . . .	27
1 Fake-data studies . . . . .	27
E Summary of current challenges . . . . .	28
<b>IV Determining the Nuclear Model - K. NIEWCZAS, N. JACHOWICZ, N. ROCCO</b>	30
A Nuclear dynamics in primary interactions . . . . .	30
1 Fermi gas models . . . . .	31
2 Mean-field approaches . . . . .	31
3 Data driven spectral functions . . . . .	31
4 Ab initio spectral functions . . . . .	31
5 Ab initio techniques . . . . .	32
6 Short time approximation . . . . .	33
7 Superscaling phenomena . . . . .	33
B Nuclear dynamics in final-state interactions . . . . .	33
1 Nucleon-nucleus degrees of freedom . . . . .	33
2 Nucleon-nucleon degrees of freedom . . . . .	33
C Challenges and open questions . . . . .	33
<b>V Determining the Neutrino Flux - J. PALEY</b>	34
A Introduction . . . . .	34
B Hadron Spectra from Real Neutrino Production Targets and Focusing Horns . . . . .	34
C Hadron Scattering and Production Uncertainties on Thin Targets . . . . .	35
D In-situ Constraints from Neutrino Scattering . . . . .	36

# NuSTEC Review – current status

---

<b>VI</b>	<b>Neutrino Event Generators - S. GARDINER, S. DYTMAN, J. ISAACSON</b>	<b>38</b>
A	Organizational challenges . . . . .	38
B	Software challenges . . . . .	40
C	Physics challenges . . . . .	41
<b>VII</b>	<b>Final State Interactions - S. DYTMAN, L. PICKERING, J. SOBCZYK, Y. HAYATO, J. ISAACSON</b>	<b>43</b>
A	Introduction . . . . .	43
B	Model Descriptions . . . . .	43
1	NuWro . . . . .	43
2	GENIE . . . . .	44
3	NEUT . . . . .	45
4	ACHILLES . . . . .	45
C	FSI Challenges . . . . .	46
1	Neutral particle production . . . . .	46
2	Transparency . . . . .	46
3	Low energy nucleon production . . . . .	47
D	FSI Study Investigating Challenges . . . . .	47
E	Open challenges, future prospects . . . . .	48
<b>VIII</b>	<b>Electron-nucleus scattering as input to neutrino-nucleus scattering - A. ANKOWSKI, A. ASHKENAZI, V. PANDEY</b>	<b>50</b>
A	Introduction . . . . .	50
B	Current and Future Experimental Efforts . . . . .	51
C	Expected challenges . . . . .	53

# NuSTEC Review – current status

---

<b>IX Quasi-elastic, quasi-elastic-like scattering - A. FURMANSKI, S. DOLAN, A. NIKOLAKOPOULOS</b>	<b>54</b>
A History . . . . .	54
B Inclusive pionless interactions . . . . .	55
1 Theory . . . . .	55
2 Experiment . . . . .	56
3 Current model-measurement comparisons . . . . .	56
4 Prospects . . . . .	58
C Status and prospects of semi-inclusive measurements . . . . .	59
1 Experiment . . . . .	59
2 Prospects . . . . .	60
3 Theory . . . . .	61
4 Current model-measurement comparisons . . . . .	62
D Determining the single-nucleon response . . . . .	62
1 Theory . . . . .	62
2 Experiment . . . . .	63
E Challenges and open questions in pionless interactions . . . . .	65
<b>X Resonance Model - M. KABIRNEZHAD, R. GONZALEZ JIMENEZ</b>	<b>67</b>
A Introduction . . . . .	67
B The domain of resonance production . . . . .	67
C Status and prospects of theory . . . . .	68
1 neutrino-nucleon interactions . . . . .	68
2 neutrino-nucleus interactions . . . . .	70
D Status and prospects of measurements . . . . .	71
1 nucleon (deuterium) target . . . . .	71
2 Recent and Prospective Measurements . . . . .	72

# NuSTEC Review – current status

---

<b>XI Shallow and Deep Inelastic Scattering - S.ATHAR, J.G. MORFIN, (FARHANA ZAIDI)</b>	<b>75</b>
A    Deep inelastic scattering . . . . .	75
B    Shallow Inelastic Scattering . . . . .	76
1    Non-perturbative QCD correction in the SIS region . . . . .	76
2    Quark-Hadron Duality . . . . .	77
C    Nuclear medium effects . . . . .	77
D    Experimental Measurements . . . . .	80
E    Comparisons between Models and Measurements . . . . .	81
F    Challenges . . . . .	81
1    Modeling Issues . . . . .	81
2    Experimental Issues . . . . .	83
<b>XII Strange Particle Production - J. NOWAK, C. THORPE</b>	<b>84</b>
A    Cabibbo suppressed quasi-elastic processes . . . . .	84
B    Associated production . . . . .	84
C    SIS/DIS scattering on strange sea quark/antiquark . . . . .	85
D    Nuclear effects . . . . .	85
E    Modelling of strange particle production and re-interactions . . . . .	85
<b>XIII Coherent processes, - L. ALVAREZ RUSO, J.G. MORFIN, M. HOSTERT</b>	<b>86</b>
A    General Introduction . . . . .	86
B    Coherent meson production . . . . .	87
1    Experimental update . . . . .	88
C    Coherent photon emission (to be completed; can be skipped in a first reading) . . . . .	91
1    Experimental update . . . . .	91
D    Beyond-the-Standard Model coherent processes . . . . .	91
1    Neutrino trident scattering . . . . .	91
2    Neutrino upscattering . . . . .	92
3    Other new-physics channels . . . . .	93
4    Tools for Beyond-the-SM processes . . . . .	94
E    Open questions . . . . .	94
<b>XIV Acknowledgements</b>	<b>95</b>
<b>References</b>	<b>96</b>

# NuSTEC Review – next steps

---

- ◆ Even with close to 100 pages, several sections are still not complete.
- ◆ When all section leaders confirm their sections are complete Andy, Kajetan and I will start the overall edit checking for obvious problems and making sure all sections are in the same “voice”. At this stage we will release the draft to the complete Board asking for you to review your favorite section(s) and get back to us with your thoughts/concerns.
- ◆ When the edit is complete, including the thoughts/concerns of the Board, we will write the executive summary, post it on the arXiv and send it off for publication.
- ◆ The concept of NuSTEC Publications covers more than this massive review. Other publications that are initiated by NuSTEC Board members or have heavy NuSTEC involvement should have NuSTEC recognition in the title or, more probable, list of “authors”. Somehow acknowledge that NuSTEC activities have contributed to the content of the publication.