Probing the physics of the elusive neutrino using electron scattering data with two nucleons at the final state

Alon Sportes | Tel-Aviv University | alonsportes@mail.tau.ac.il

1 Neutrino experiments

Neutrino oscillation experiments extract **oscillation parameters** from **measured neutrinos** of flavor α at the detector:

$$\underbrace{N_\alpha(E_{rec},L)}_{\text{measured}} \propto \int \underbrace{\Phi_\alpha(E_{\text{true}},L)}_{\nu\text{ flux}}\, \underbrace{\sigma_\alpha(E_{\text{true}})R_{\sigma_\alpha}(E_{\text{true}},E_{\text{rec}})}_{\text{interaction model}}\, dE_{\text{true}}$$

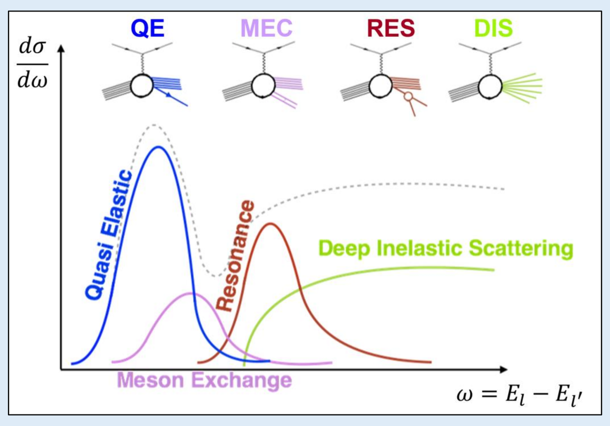
where:

$$\Phi_\alpha(E_{\text{true}},L) \propto \Big[1 - \underbrace{P_{\nu_\alpha\to\nu_\beta}(E_{\text{true}},L)}_{\propto\text{ oscillation parameters}}\Big]\,\Phi_\alpha(E_{\text{true}},\sim 0)$$

$\boldsymbol{\Phi_\alpha}$ is deconvoluted from the measured $\boldsymbol{N_\alpha(E_{rec},L)}$, using the modeled cross-section σ_α, and a smearing matrix R_{σ_α}. Improved oscillation measurements require accurate **modelling**.

The cross-sections σ_α are a leading source of uncertainty, since:

- Event generators are using phenomenological or semi-classical models
- The overlapping kinematic regions of individually modeled processes is complicated
- Complex nuclear physics



2 Electrons for neutrinos

Improving neutrino modeling requires external data. Yet, neutrino scattering has *limited statistics* and *unknown incident energies*.

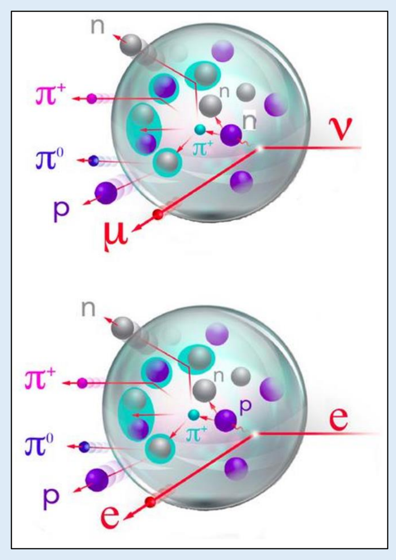
So, where can we find the data? ***in electron experiments!***

Electrons vs. neutrinos:

- **Similar interactions with nuclei: vector** (V) vs. **vector** *minus* **axial vector** ($V-A$) currents:

$$j^\mu_{EM} = \bar{u}\gamma^\mu u, \quad j^\mu_{CC} = -\frac{ig_W}{2\sqrt{2}}\bar{u}\,(\gamma^\mu - \gamma^\mu\gamma^5)u$$

- **Many identical nuclear effects:**
  - Ground state & final state interactions



Benefits of electron scattering:

- High statistics
- Known energy

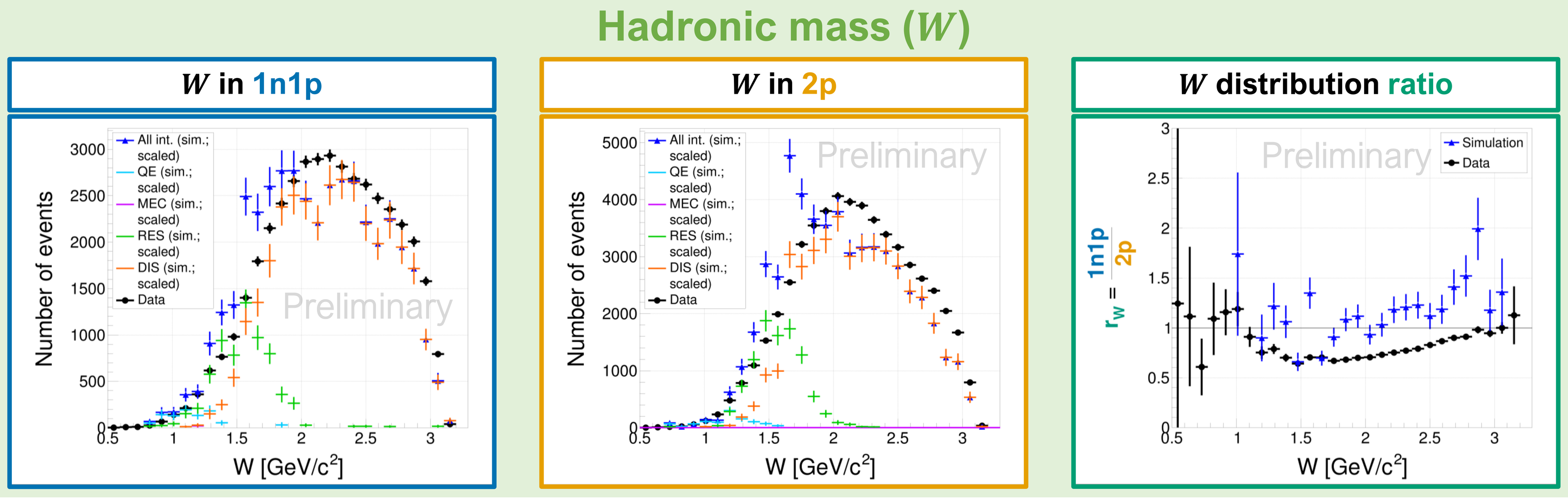
The electrons-for-neutrinos ($e4\nu$) collaboration strategy:

- Measure many new high-statistics cross-sections
- Neutrino-relevant targets and energies
- Inclusive & exclusive measurements
- Validate and tune the electron scattering part of neutrino event generators
- ***Profit – improve neutrino models.***

e4ν

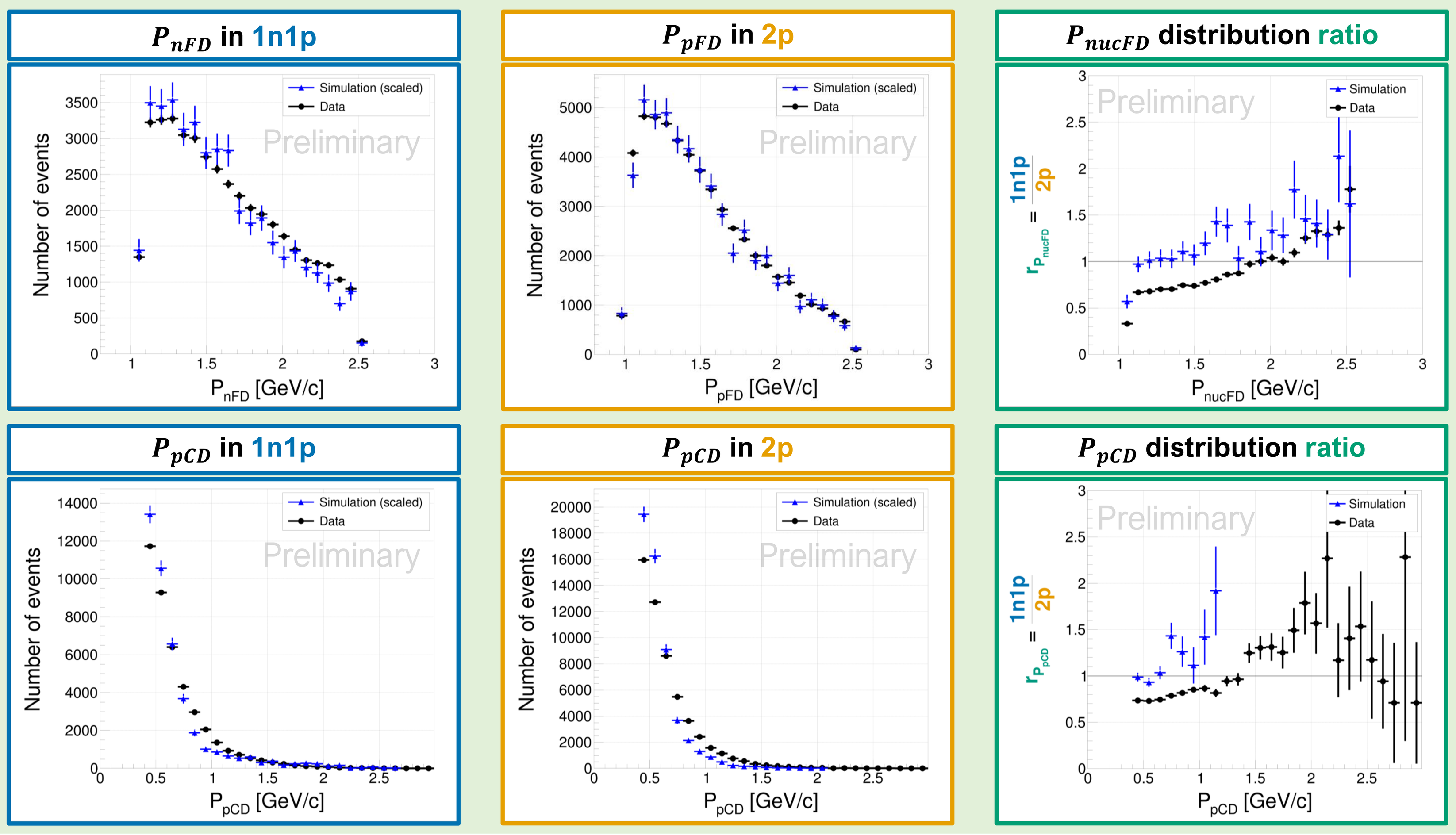
5 Results – 6 GeV electrons on Carbon

Hadronic mass (W)



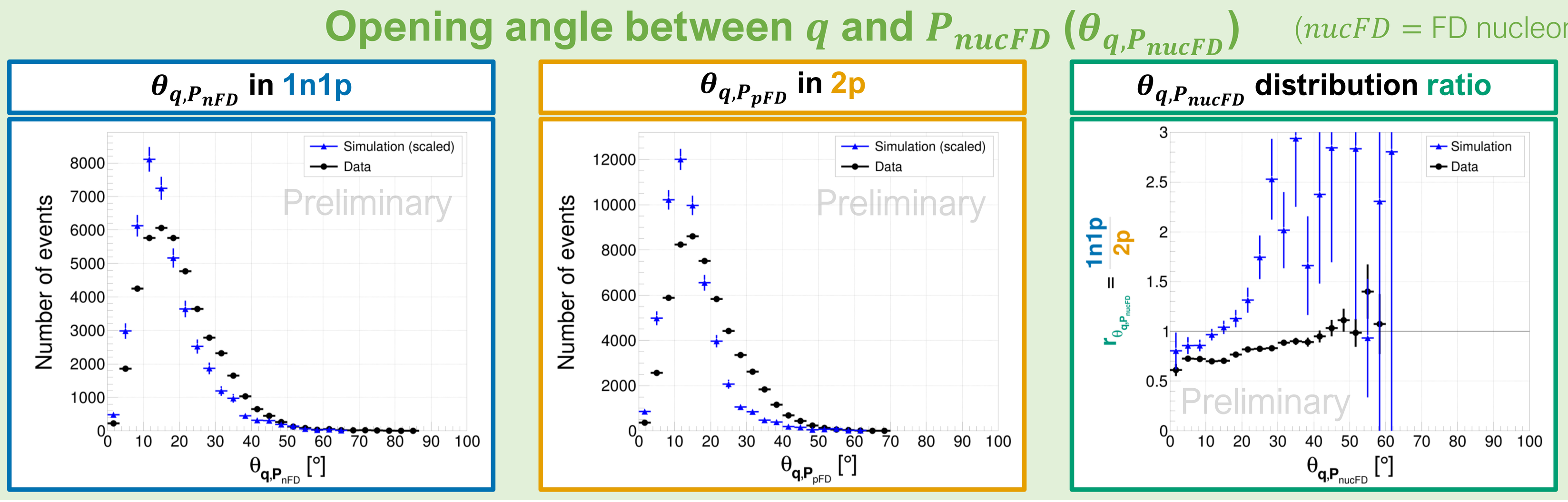
Nucleon momenta

($nucFD$ = FD nucleon)



Opening angle between q and P_{nucFD} ($\theta_{q,P_{nucFD}}$)

($nucFD$ = FD nucleon)



4 2N analysis

What are 2N topologies? Events with two nucleons at the final state

Why analyze 2N?

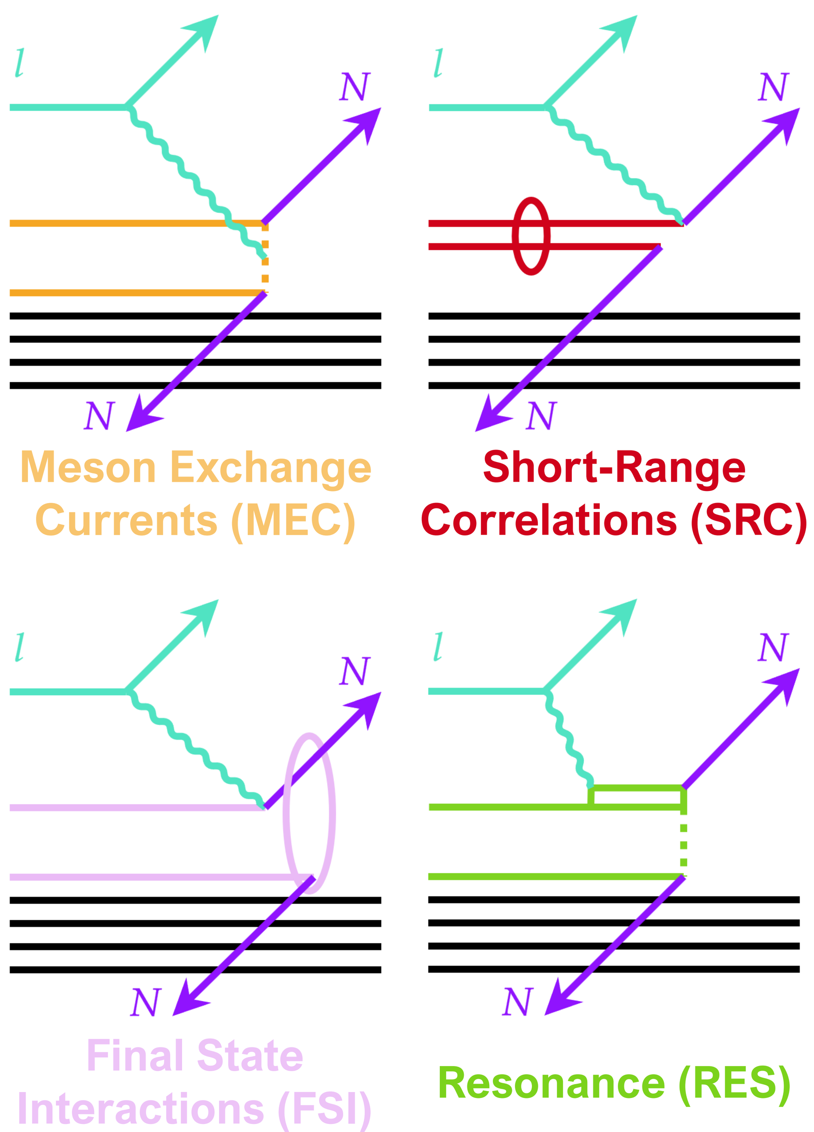
- Neutrino experiments – usually look for QE-like events
- **2N – a major background; second nucleon not detected!**
  - Not yet well-constrained
  - Contributions from various processes!

Caveats:

- Simulation sample ⇒ low statistics!
- **Number of 2N events in the data: 2p:1n1p** ≃ 50K:31K
- **2p:1n1p** ≠ 1 ⇒ only ratio trend matters!

Highlights of 2N analysis results (see 5):

- **In W**: differences in hadronic mass ratio suggests that **2p** has more RES contributions while **1n1p** has more DIS
- **In P_{nucFD}, P_{pCD}**: nucleon momenta shape is nicely predicted, the ratio between **1n1p** and **2p** is yet to be understood
- **In $\theta_{q,P_{nucFD}}$**: major differences are apparent, could help improve FSI and nuclear structure models



3 CLAS12

Properties:

- **Max. luminosity:** $10^{35}\ cm^{-2}s^{-1}$
- **Electron beams:** up to ~11 GeV
- **Large acceptance (~4π):**
  - Forward Detector (FD)
  - Central Detector (CD)
- **Detection thresholds:**
  - 400 MeV/c for p and n
  - 200 MeV/c for $\pi^\pm$
  - 300 MeV/c for γ
- Open Trigger

Acquired data:

- **Energies:** 1, 2, 4, **6** GeV
- **Targets:** H, ^{4}He, ^{12}**C**, ^{40}Ar, ^{56}Fe and more

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