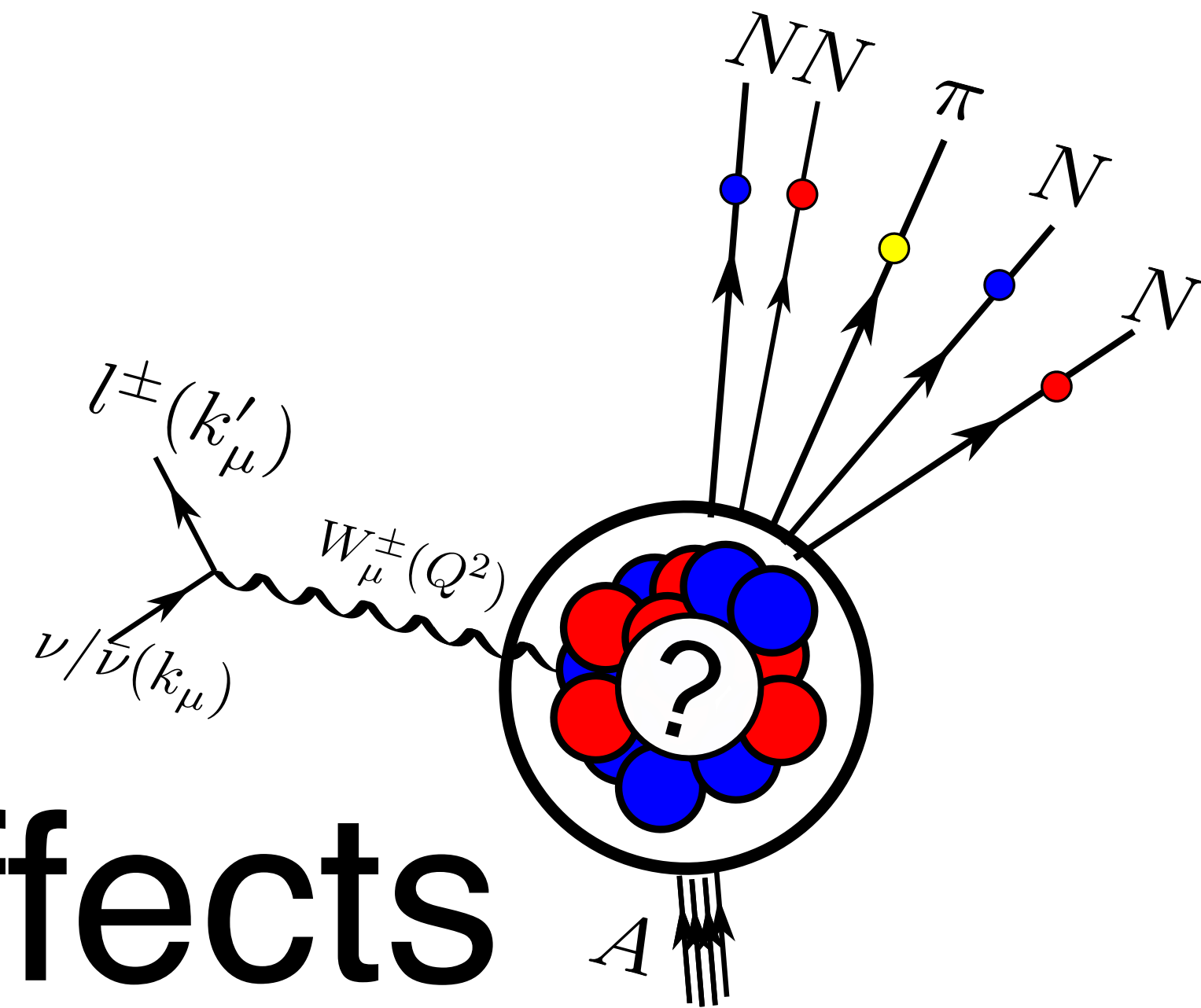


Modelling nuclear effects in l / ν_l - nucleus interactions

Hemant Prasad



Uniwersytet
Wrocławski



Knowns and Unknowns (1/3)

Knowns and Unknowns (1/3)

2

Sterile neutrinos?

Knowns and Unknowns (1/3)

2

Sterile neutrinos?
Neutrino masses?

Knowns and Unknowns (1/3)

2

Oscillation parameters!

Sterile neutrinos?
Neutrino masses?

Knowns and Unknowns (1/3)

2

Sterile neutrinos?
Neutrino masses?

Oscillation parameters!
CP violation?!

Knowns and Unknowns (1/3)

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Oscillation parameters!
Normal ordering or inverted ordering?!
CP violation?!
Sterile neutrinos?
Neutrino masses?

Knowns and Unknowns (1/3)

2

Oscillation parameters!
Normal ordering or inverted ordering?!
CP violation?!
Sterile neutrinos?
Neutrino masses?

Answer: Acc-based neutrino experiments

Knowns and Unknowns (1/3)

2

T2K-S



μ BooNE

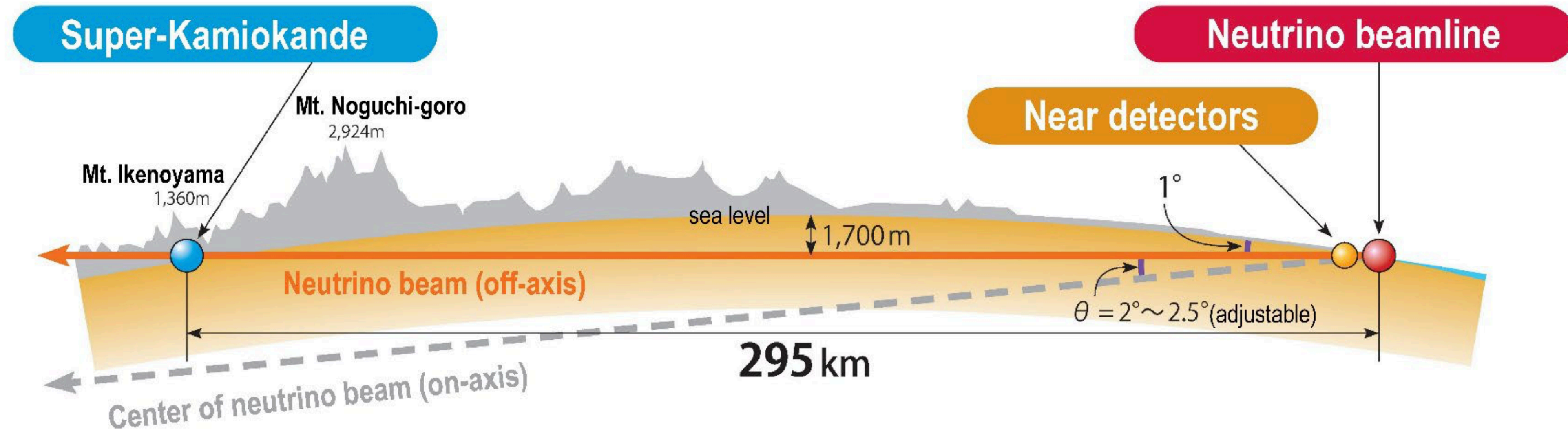


Knowns and Unknowns (1/3)

2

- 1 Producing a neutrino beam in Tokai ----- Neutrino beamline
- 2 Observing neutrinos from the neutrino beam in Tokai ----- Near detectors
- 3 Observing neutrinos from the neutrino beam in Kamioka-- Super-Kamiokande

T2K

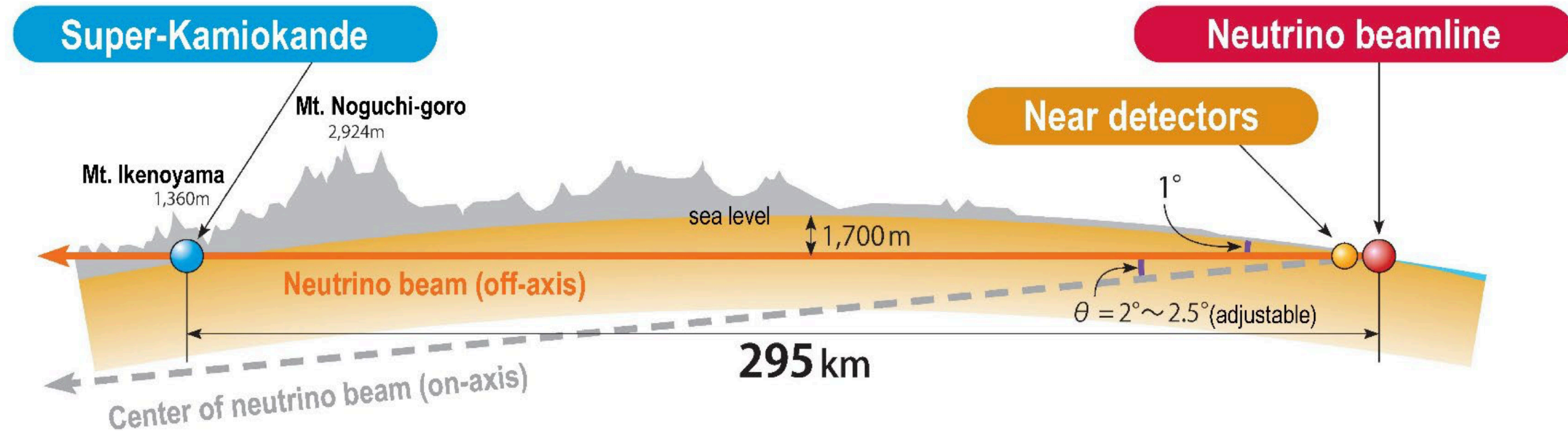


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T2K



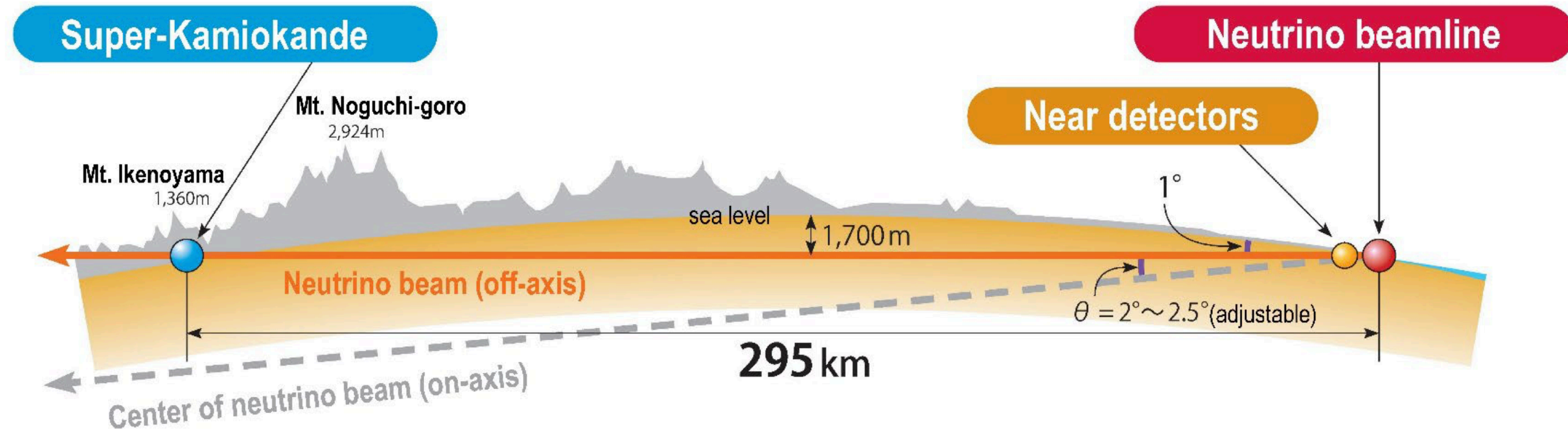
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Knowns and Unknowns (1/3)

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- 1 Producing a neutrino beam in Tokai ----- Neutrino beamline
- 2 Observing neutrinos from the neutrino beam in Tokai ----- Near detectors
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T2K



$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}$$

=

$$U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$U =$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{bmatrix}$$

Atmospheric, Acc. Based expts

Acc. and reactor based experiments

$$\begin{bmatrix} \cos \theta_{13} & 0 & e^{-i\delta} \sin \theta_{13} \\ 0 & 1 & 0 \\ \sin \theta_{13} & 0 & \cos \theta_{13} \end{bmatrix}$$

$$\begin{bmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

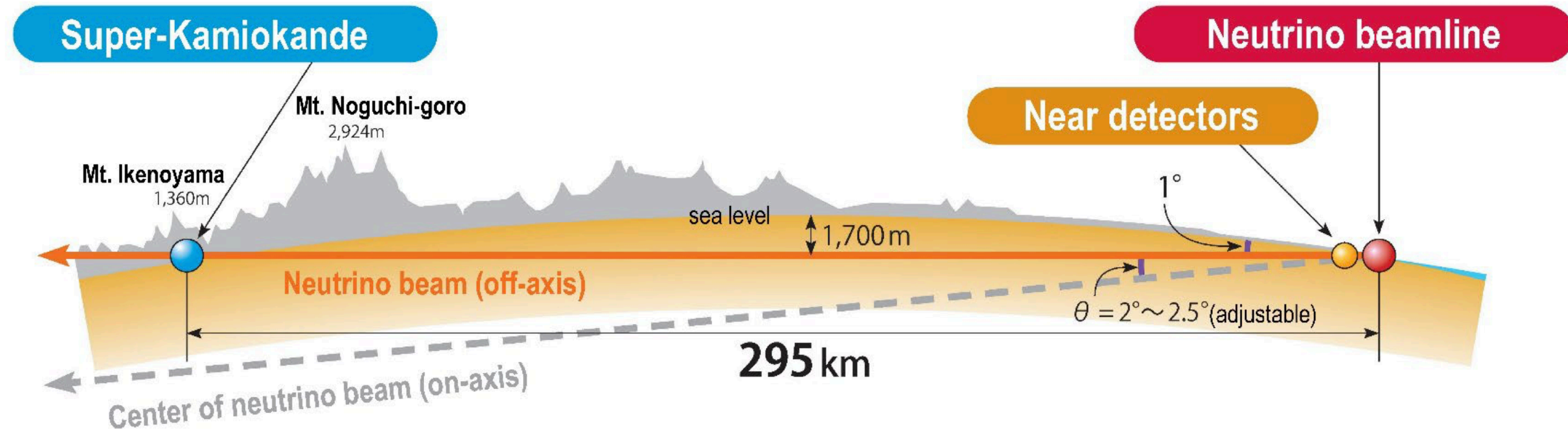
Solar neutrino experiments

Knowns and Unknowns (1/3)

2

- 1 Producing a neutrino beam in Tokai ----- Neutrino beamline
- 2 Observing neutrinos from the neutrino beam in Tokai ----- Near detectors
- 3 Observing neutrinos from the neutrino beam in Kamioka-- Super-Kamiokande

T2K



$$\begin{array}{c}
 \text{Number of events} \\
 \frac{N_{FD}}{N_{ND}} \propto \frac{\int \frac{d\phi_i^{FD}}{dE_\nu} \overset{\text{Neutrino flux}}{P(\nu_i \rightarrow \nu_j; E_\nu)} \overset{\text{Oscillation probability}}{\sigma_j(E_\nu)} \overset{\text{Detector effects}}{M_i^{FD}(E_\nu, E_{reco})}}{\int dE_\nu \frac{d\phi_i^{ND}}{dE_\nu} \underset{\text{Cross-section}}{\sigma(E_\nu)} M_i^{ND}(E_\nu, E_{reco})}
 \end{array}$$

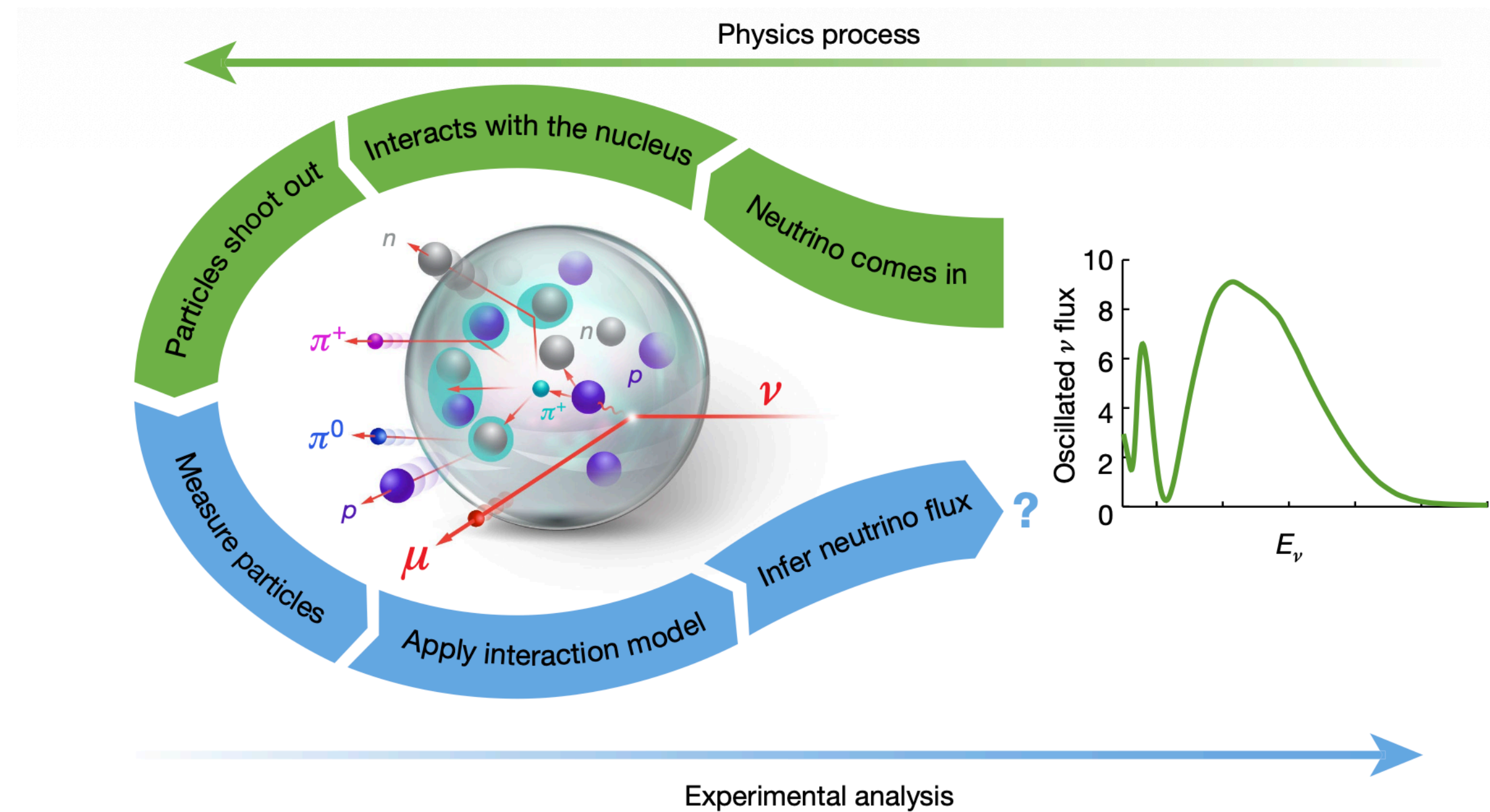
PLOT THICKENS (2/3)

PLOT THICKENS (2/3)

Neutrinos cannot be measured directly!!

PLOT THICKENS (2/3)

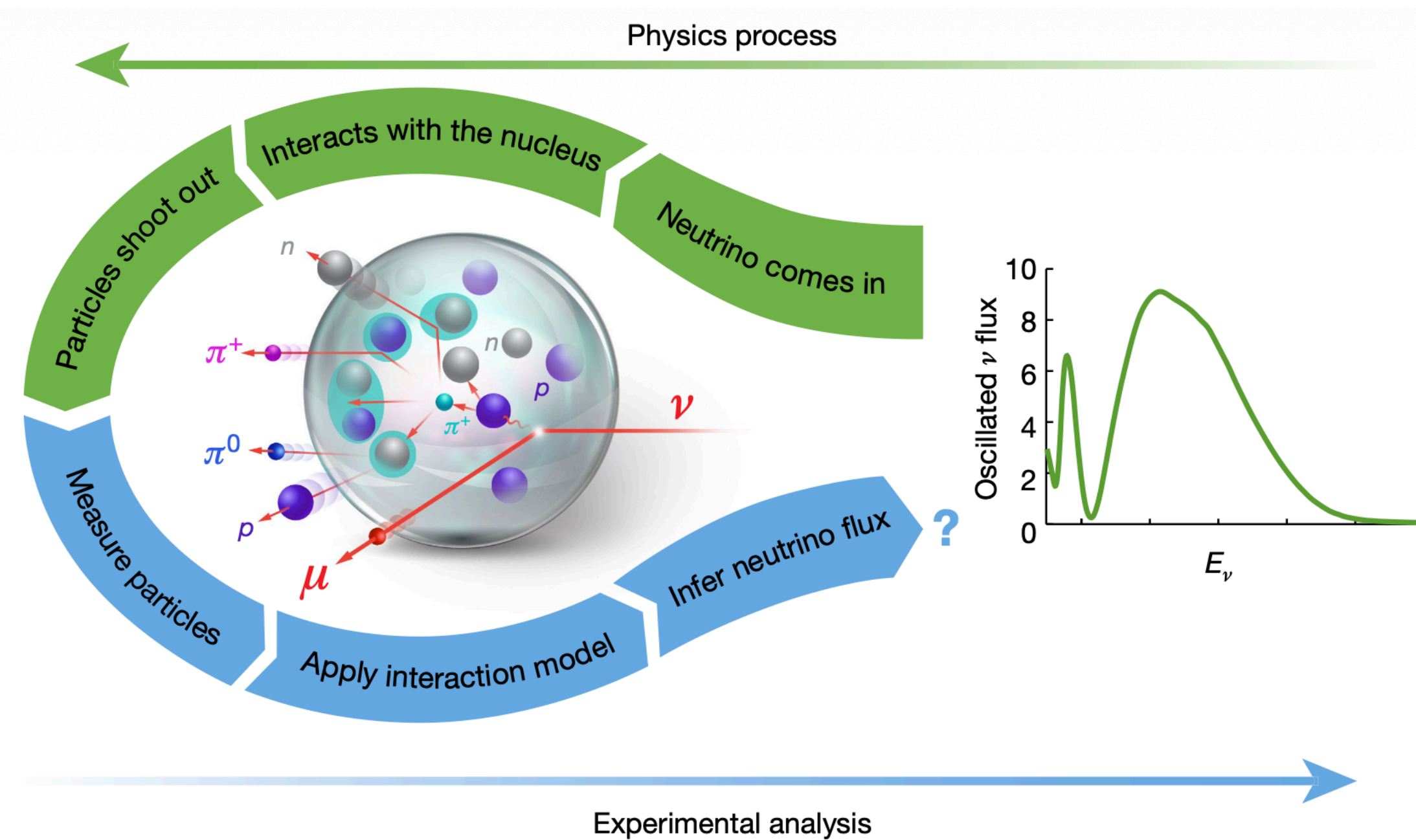
Neutrinos cannot be measured directly!!



PLOT THICKENS (2/3)

Neutrinos cannot be measured directly!!

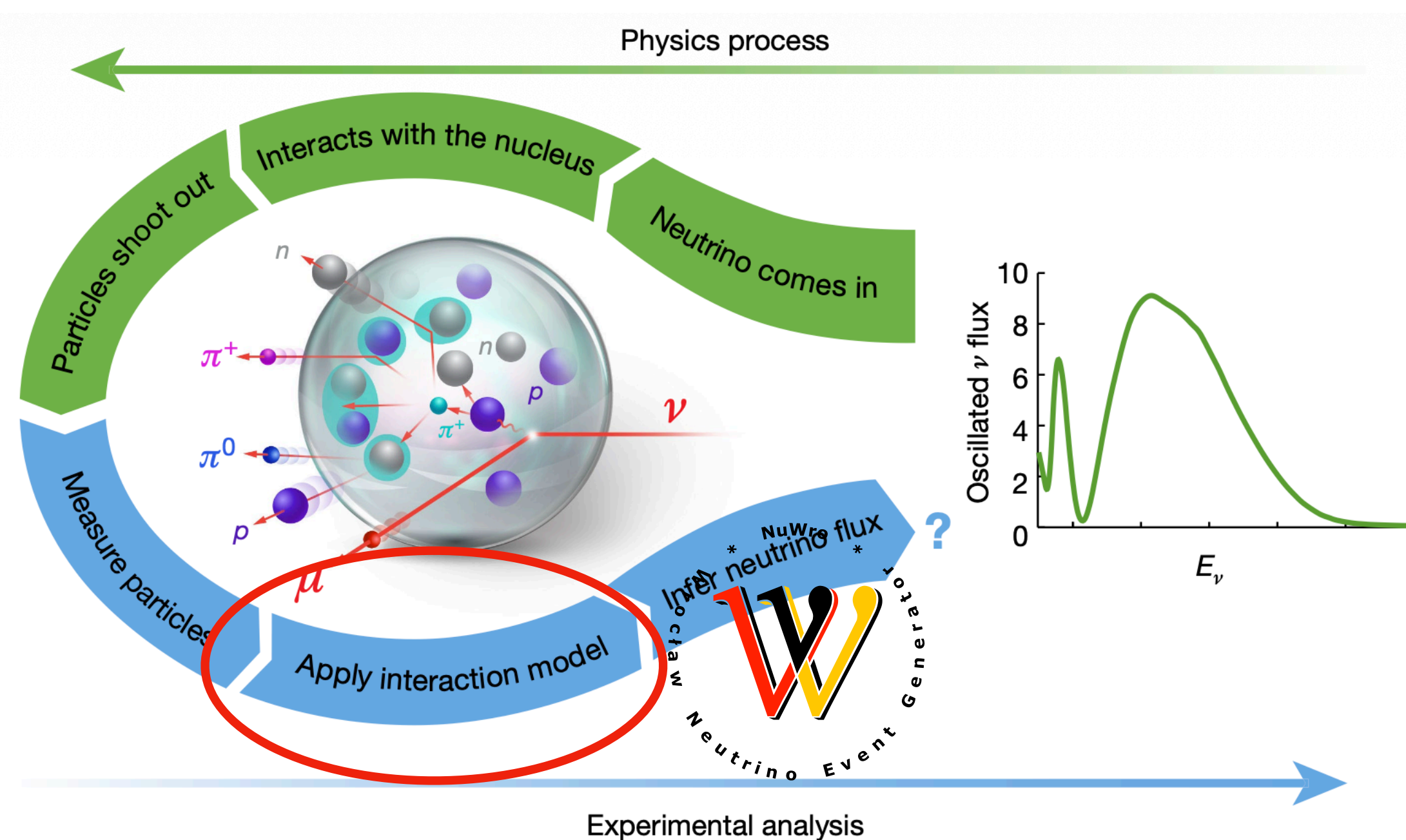
Reconstruct incoming
neutrino energy ?!!!!!!



PLOT THICKENS (2/3)

Neutrinos cannot be measured directly!!

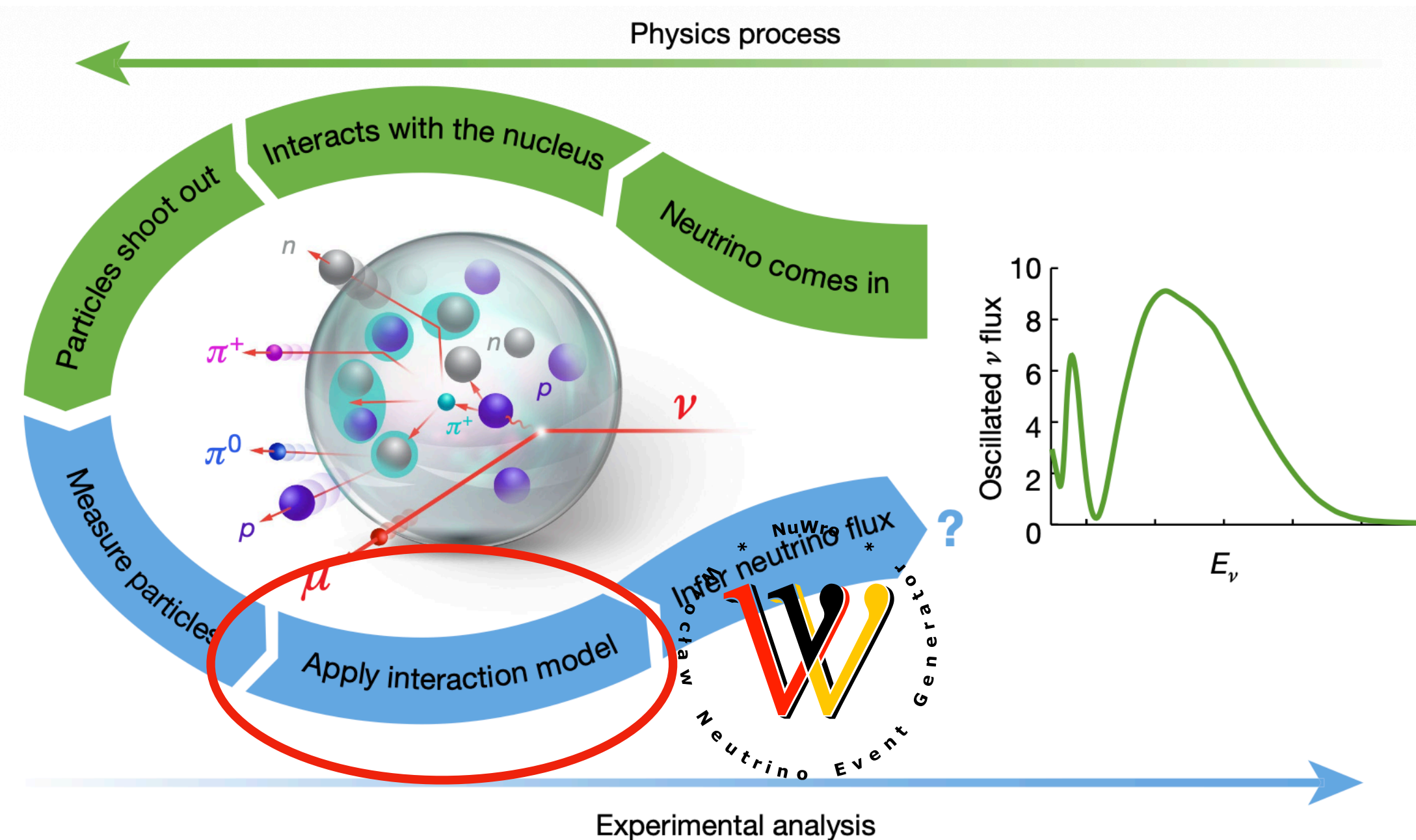
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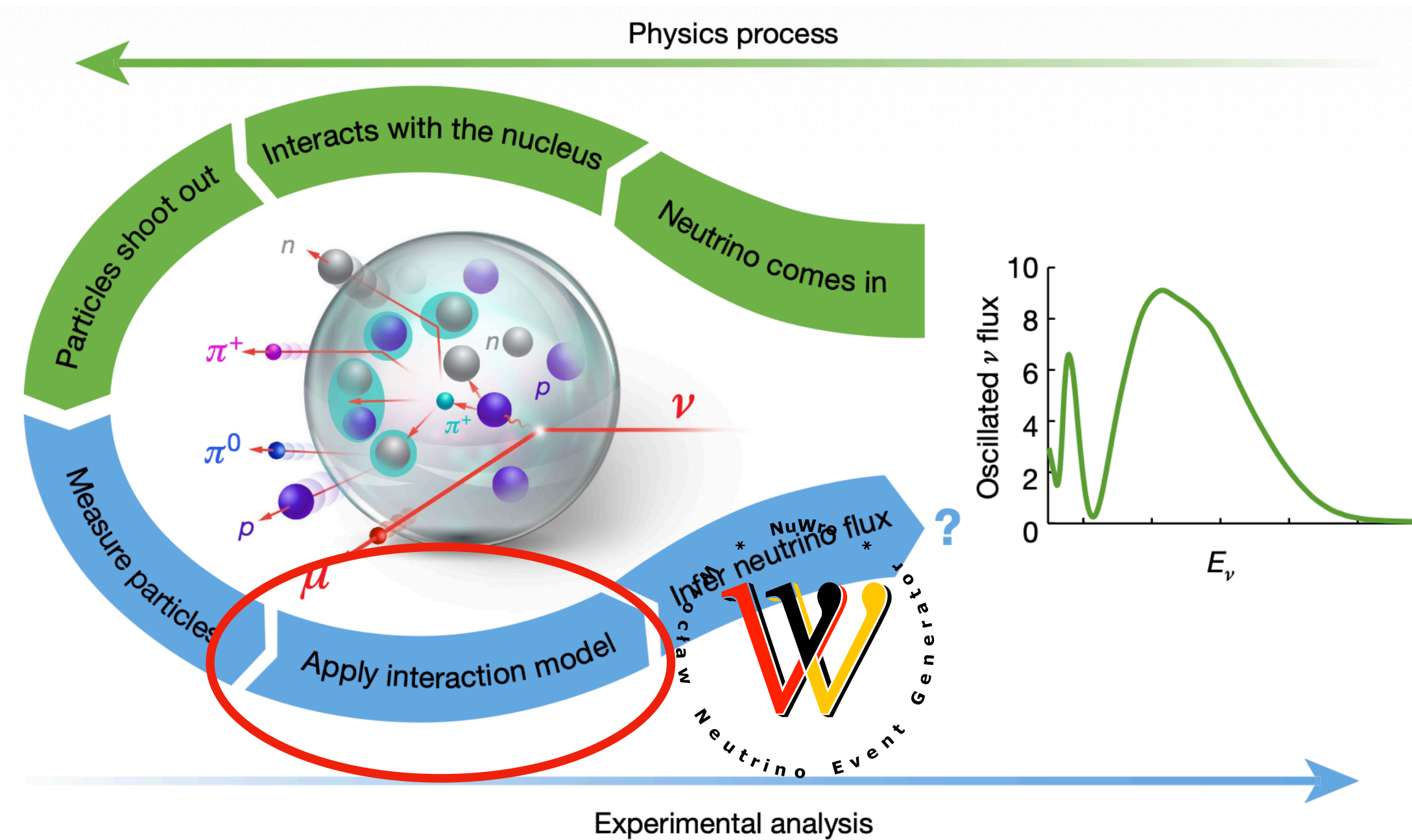
Neutrino-nucleus interactions!

- Quasielastically
- Via meson-exchange currents
- Via Delta(1232)-resonance
- Deep inelastic scattering (DIS)!

PLOT THICKENS (2/3)

Neutrinos cannot be measured directly!!

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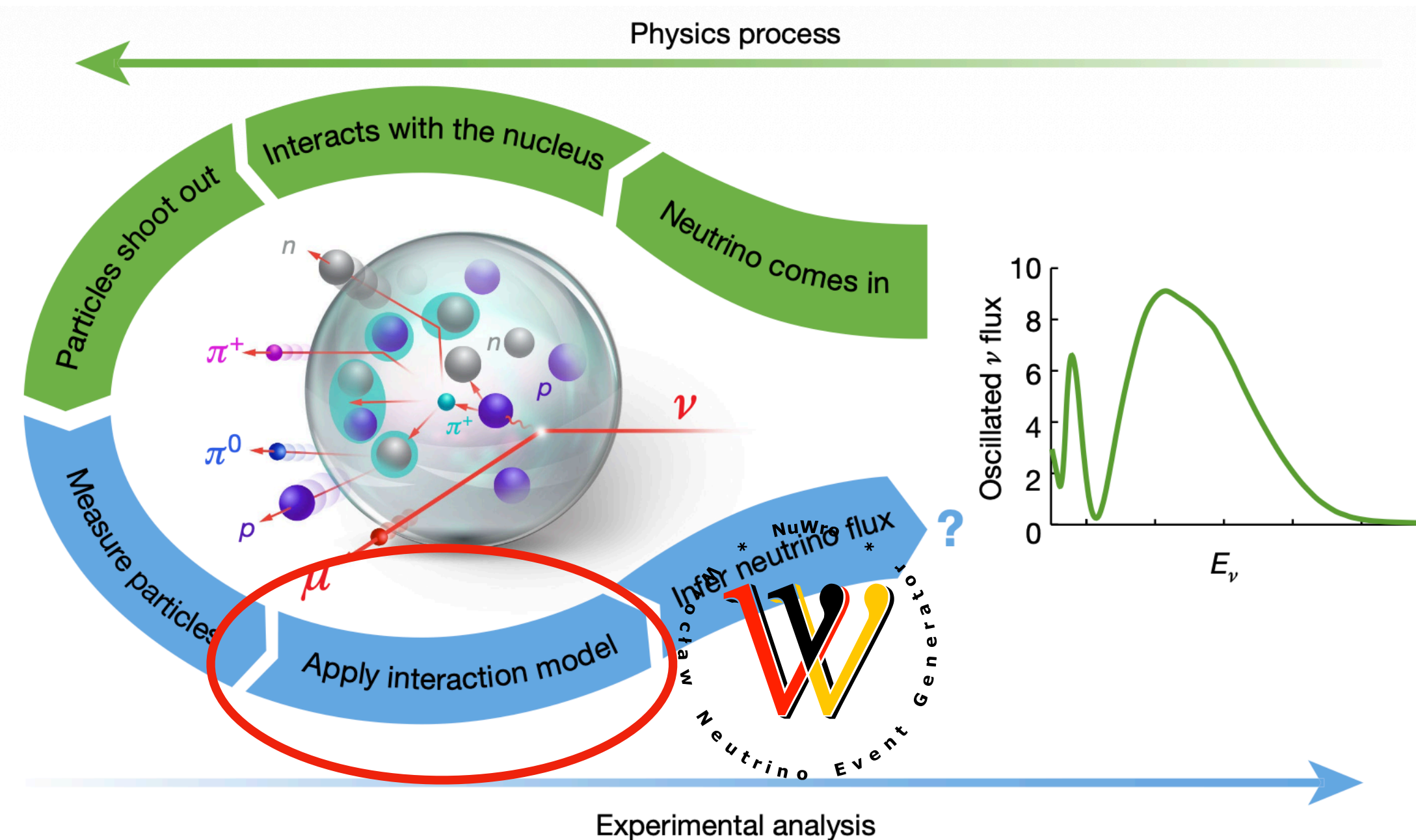
Neutrino-nucleus interactions!

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Neutrino-nucleus interactions!

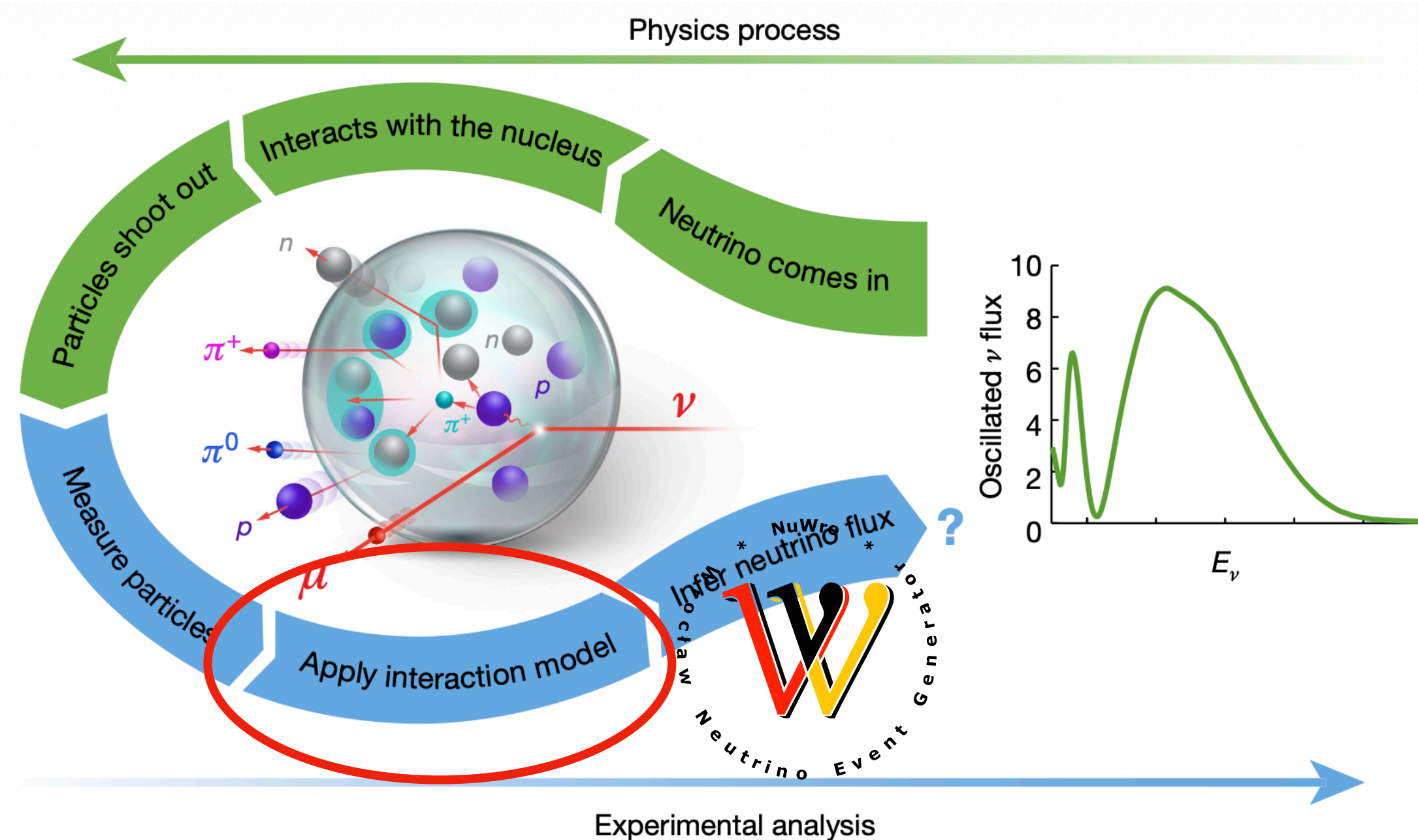
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- Via meson-exchange currents ✓
- Via Delta(1232)-resonance
- Deep inelastic scattering (DIS) ✓

Impulse approximation (incoming lepton sees one nucleon instead of the whole nucleus)

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Neutrinos cannot be measured directly!!

Reconstruct incoming neutrino energy ?!!!!!!

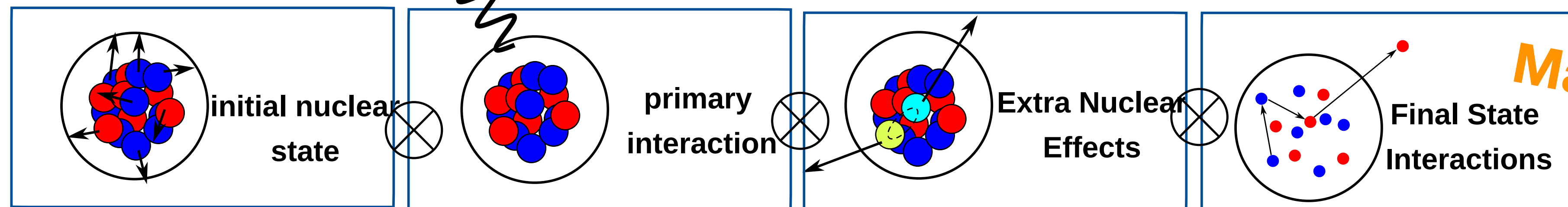


Neutrino-nucleus interactions!

- Quasielastically ✓
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$$\nu(E_k, \vec{k}) \rightarrow W^+(\omega, q)$$

Impulse approximation (incoming lepton sees one nucleon instead of the whole nucleus)

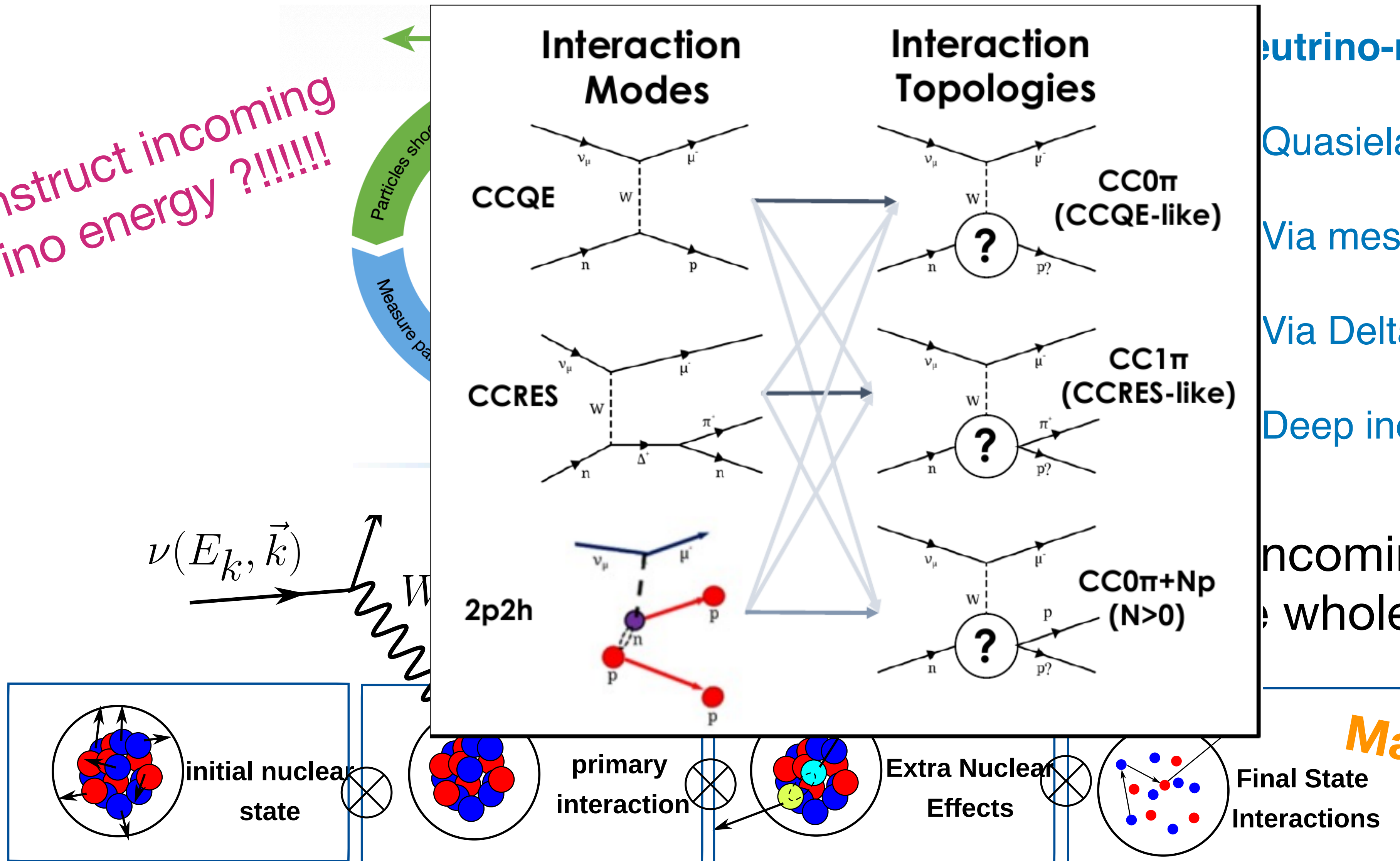


Many-body effects !!

PLOT THICKENS (2/3)

Neutrinos cannot be measured directly!!

Reconstruct incoming
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Neutrino-nucleus interactions!

Quasielastically ✓

Via meson-exchange currents ✓

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Deep inelastic scattering (DIS) ✓

Incoming lepton sees
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Many-body effects !!

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Neutrinos cannot be measured directly!!

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Neutrino-nucleus interactions!

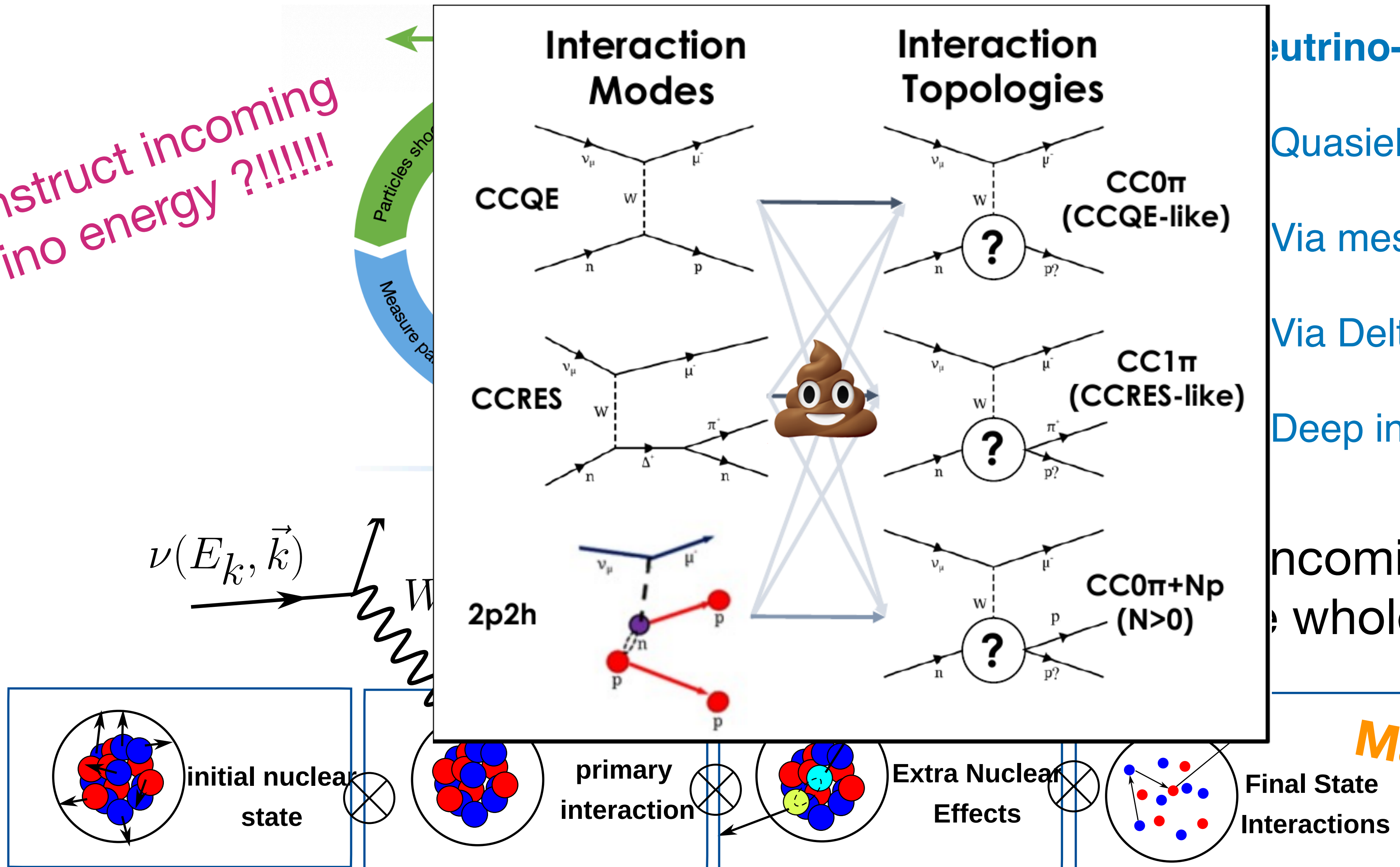
Quasielastically ✓

Via meson-exchange currents ✓

Via Delta(1232)-resonance

Deep inelastic scattering (DIS) ✓

Incoming lepton sees the whole nucleus



Many-body effects !!

THE BEGINNING IS THE END, AND THE END IS THE BEGINNING **(3/3)** 4

PHYSICAL REVIEW D **111**, 036032 (2025)

New multinucleon knockout model in the NuWro Monte Carlo generator

Hemant Prasad^{id},* Jan T. Sobczyk^{id},[†] Artur M. Ankowski^{id}, J. Luis Bonilla^{id}, Rwik Dharmapal Banerjee^{id},
Krzysztof M. Graczyk^{id}, and Beata E. Kowal^{id}

Institute of Theoretical Physics, [University of Wrocław](#), Plac Maxa Borna 9, 50-204 Wrocław, Poland

PHYSICAL REVIEW D 113, 096023 (2026)

**Fine-tuning final state interactions model
in the NuWro Monte Carlo event generator**

Hemant Prasad^{ID,*}, Jan T. Sobczyk^{ID,†}, Rwik Dharmapal Banerjee^{ID}, J. Luis Bonilla,
Krzysztof M. Graczyk^{ID}, and Beata E. Kowal

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Institute of Theoretical Physics, University of Wrocław, Plac Maxa Borna 9, 50-204, Wrocław, Poland

PHYSICAL REVIEW D 109, 073004 (2024)

**JLab spectral functions of argon in NuWro and their implications
for MicroBooNE**

Rwik Dharmapal Banerjee^{ID}, Artur M. Ankowski^{ID},* Krzysztof M. Graczyk^{ID}, Beata E. Kowal^{ID},
Hemant Prasad^{ID}, and Jan T. Sobczyk^{ID}
Institute of Theoretical Physics, University of Wrocław, plac Maxa Borna 9, 50-204, Wrocław, Poland

PHYSICAL REVIEW D 113, 096023 (2026)

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Krzysztof M. Graczyk^{ID}, and Beata E. Kowal

Institute of Theoretical Physics, University of Wrocław, Plac Maxa Borna 9, 50-204, Wrocław, Poland

**Spectral function approach in NuWro:
modeling of multinucleon final states in quasielastic scattering**

Artur M. Ankowski^{*}, Rwik Dharmapal Banerjee, Jan T. Sobczyk,
José L. Bonilla, Krzysztof M. Graczyk, Beata E. Kowal, and Hemant Prasad
Institute of Theoretical Physics, University of Wrocław, plac Maxa Borna 9, 50-204, Wrocław, Poland
(Dated: August 15, 2025)
Rwik Dharmapal Banerjee^{ID}, Artur M. Ankowski^{*}, Hemant Prasad^{ID}, and Jan T. Sobczyk^{ID}
Institute of Theoretical Physics, University of Wrocław, plac Maxa Borna 9, 50-204, Wrocław, Poland

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Plac Maxa Borna 9, 50-204 Wrocław, Poland*

PHYSICAL REVIEW C 110, 025501 (2024)

Empirical fits to inclusive electron-carbon scattering data obtained by deep-learning methods

Beata E. Kowal^{ID,*}, Krzysztof M. Graczyk^{ID,†}, Artur M. Ankowski^{ID},
Rwik Dharmapal Banerjee^{ID}, Hemant Prasad, and Jan T. Sobczyk

Institute of Theoretical Physics, University of Wrocław, Plac Maxa Borna 9, 50-204 Wrocław, Poland

**Spectral function
modeling of multinucleon**

Artur M. Ankowski^{ID,*}, Rwik Dharmapal Banerjee^{ID},
José L. Bonilla^{ID}, Krzysztof M. Graczyk^{ID}, Beata E. Kowal^{ID},
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Hemant Prasad^{ID}, Jan T. Sobczyk^{ID},
Institute of Theoretical Physics, University of Wrocław, Plac Maxa Borna 9, 50-204 Wrocław, Poland

PHYSICAL REVIEW LETTERS 135, 052502 (2025)

Electron-Nucleus Cross Sections from Transfer Learning

Krzysztof M. Graczyk^{ID},* Beata E. Kowal^{ID}, Artur M. Ankowski^{ID}, Rwik Dharmapal Banerjee^{ID}, Jose Luis Bonilla^{ID},
Hemant Prasad^{ID}, and Jan T. Sobczyk^{ID}
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**Spectral function
modeling of multinucleon**

Artur M. Ankowski^{ID},* Rwik Dharmapal Banerjee^{ID},
José L. Bonilla, Krzysztof M. Graczyk^{ID},
Institute of Theoretical Physics, University of Wrocław, Plac Maxa Borna 9, 50-204 Wrocław, Poland

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PHYSICAL REVIEW D 113, 096023 (2026)

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Hemant Prasad^{ID},* Jan T. Sobczyk^{ID},† Rwik Dharma

Institute of Theoretical Physics, University of Wrocław

Hemant Prasad^{ID}, Jan T. Sobczyk^{ID},†

Institute of Theoretical Physics, University of Wrocław

PHYSICAL REVIEW C 112, 055504 (2025)

**Re-optimization of a deep neural network model for electron-carbon
scattering using new experimental data**

Beata E. Kowal^{ID},* Krzysztof M. Graczyk^{ID},† Artur M. Ankowski^{ID}, Rwik Dharmapal Banerjee^{ID},
Jose L. Bonilla, Hemant Prasad^{ID}, and Jan T. Sobczyk

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PHYSICAL REVIEW D 113, 096023 (2026)

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Institute of Theoretical Physics

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2025)

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al data

Artur M. Ankowski^{ID}, Rwik Dharmapal Banerjee^{ID},
and Jan T. Sobczyk

Institute of Theoretical Physics, University of Wrocław,
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modeling of multinu

Artur M. Ankowski,*

José L. Bonilla, Krzysztof M.

Institute of Theoretical Physics, University

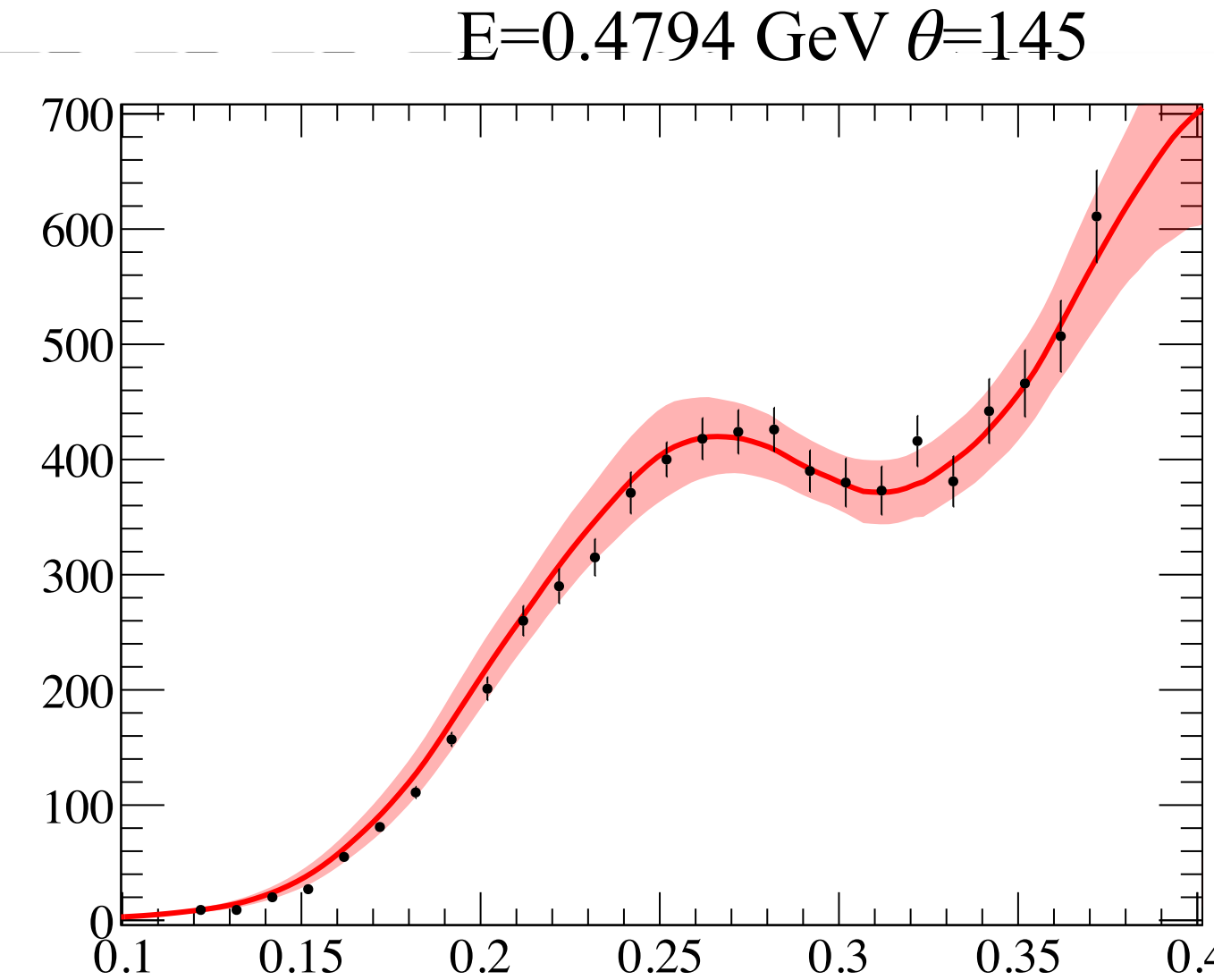
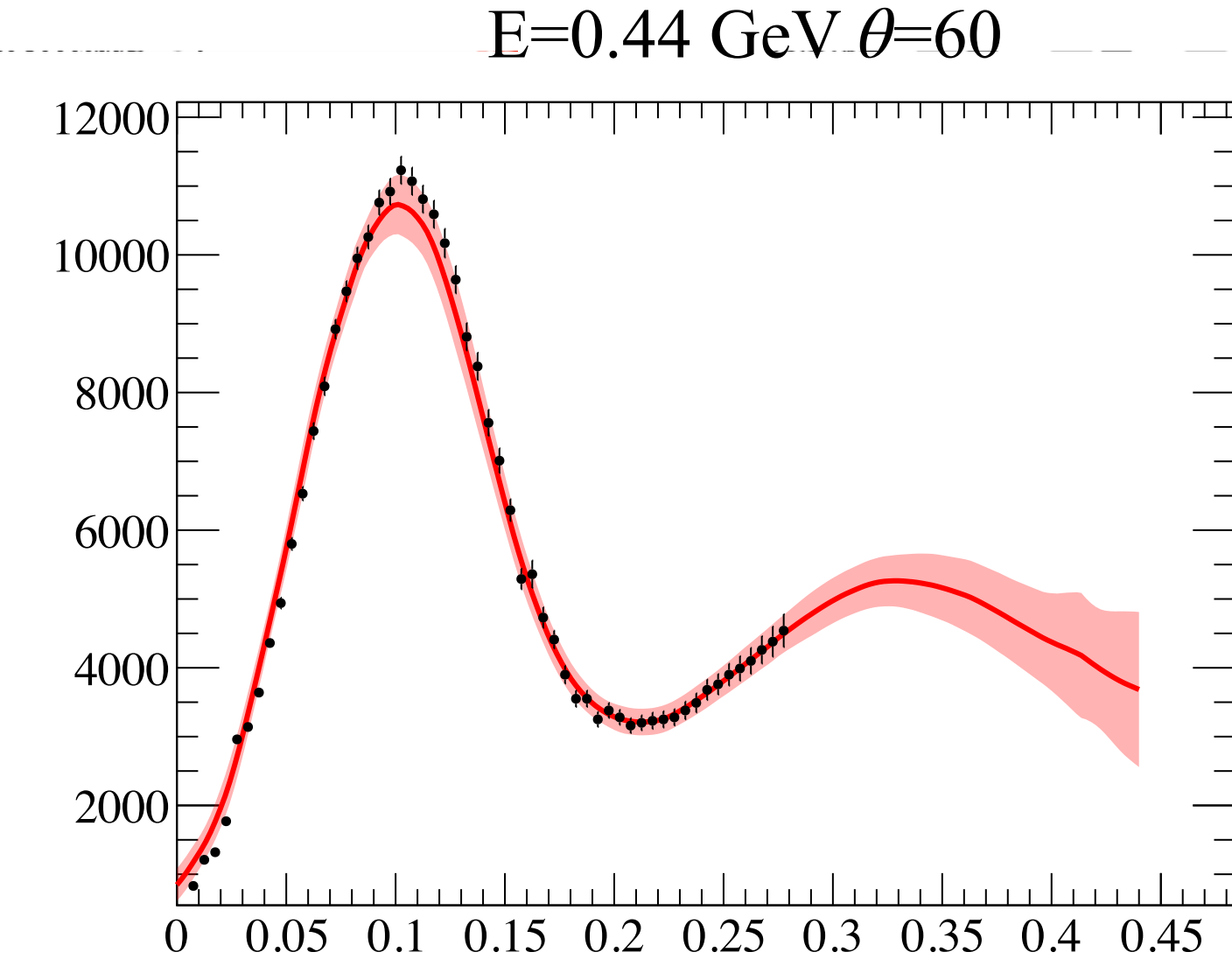
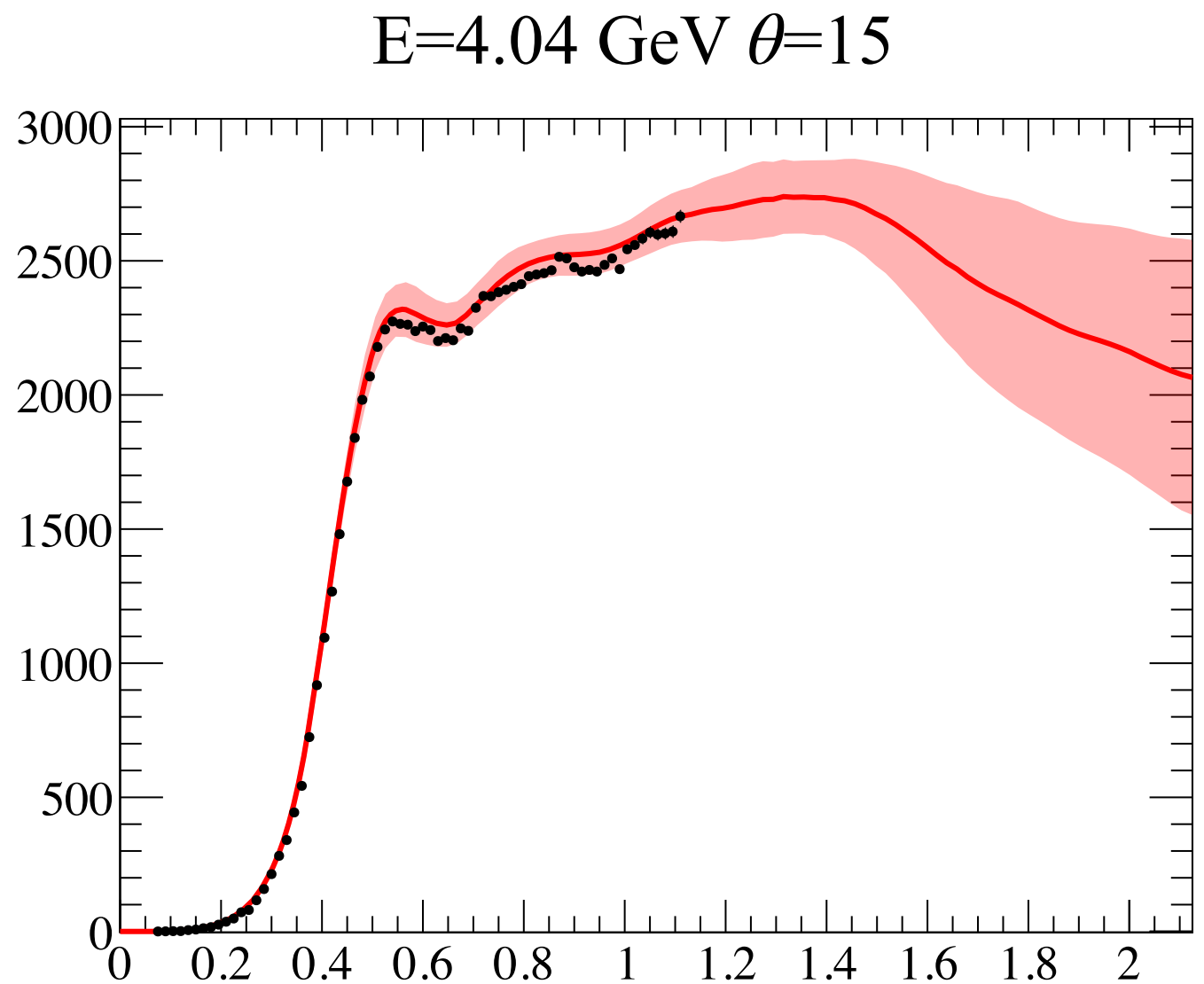
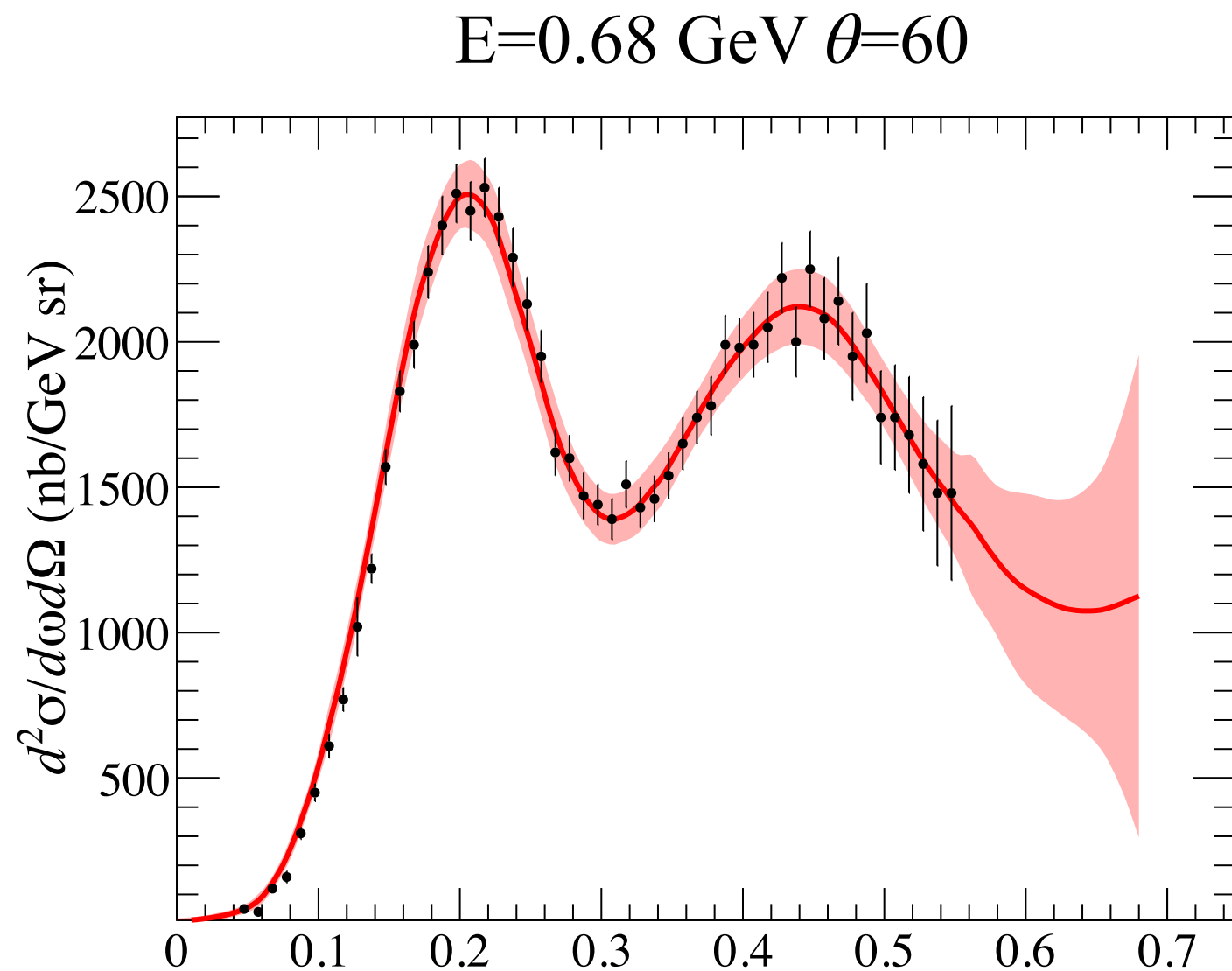
Rwik Dharmapal Banerjee^{ID}, Artur M. Ankowski^{ID},
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Institute of Theoretical Physics, University of Wrocław,

Re-optimization of a
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Beata E. Kowal^{ID},* Krzysztof M. Graczyk^{ID},† Artur M. Ankowski^{ID}, Rwik Dharmapal Banerjee^{ID},
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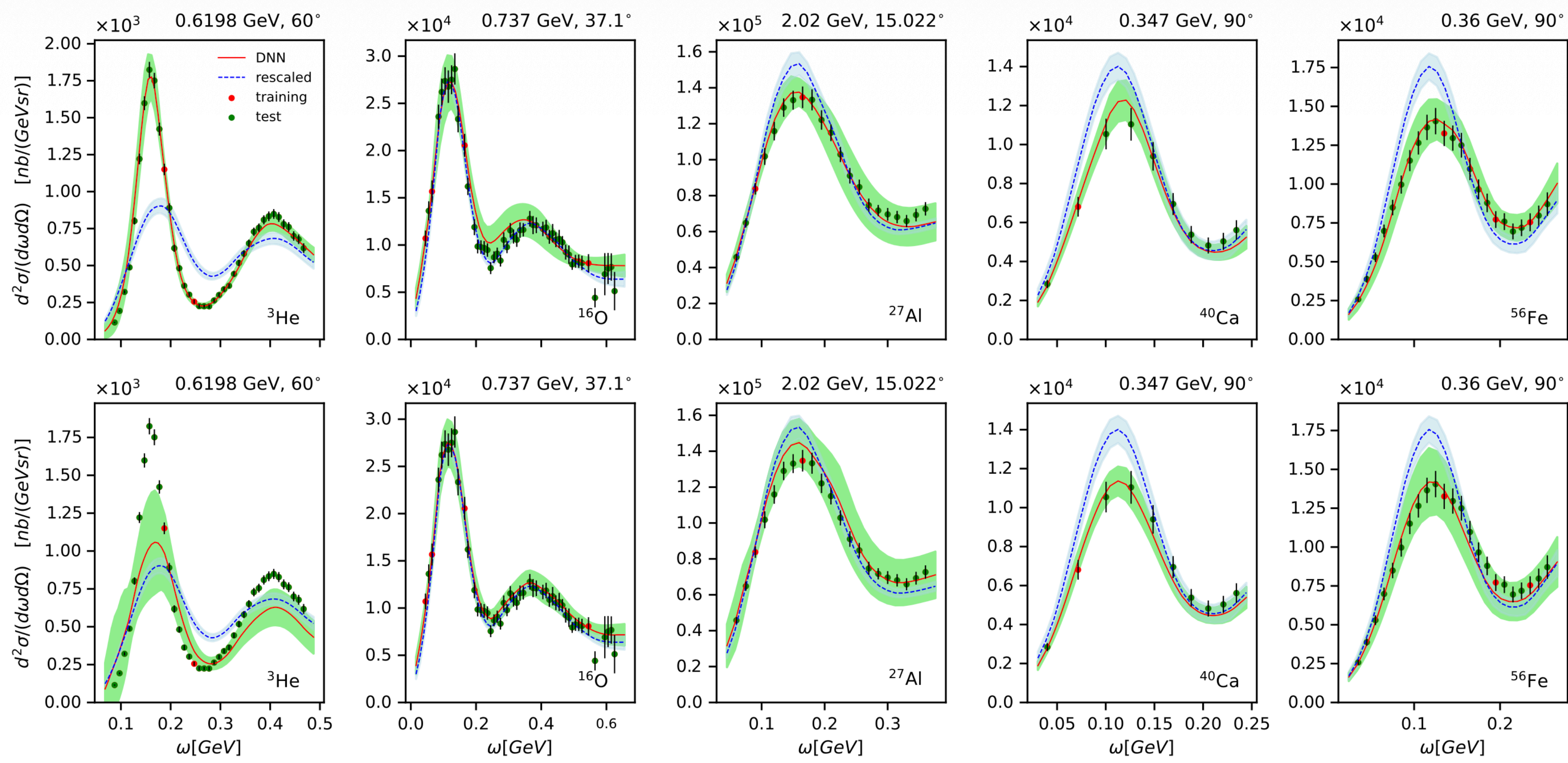
n-carbon

Armapal Banerjee ^{ID},
-204 Wrocław, Poland

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owski ^{ID},
obczyk
-204 Wrocław, Poland

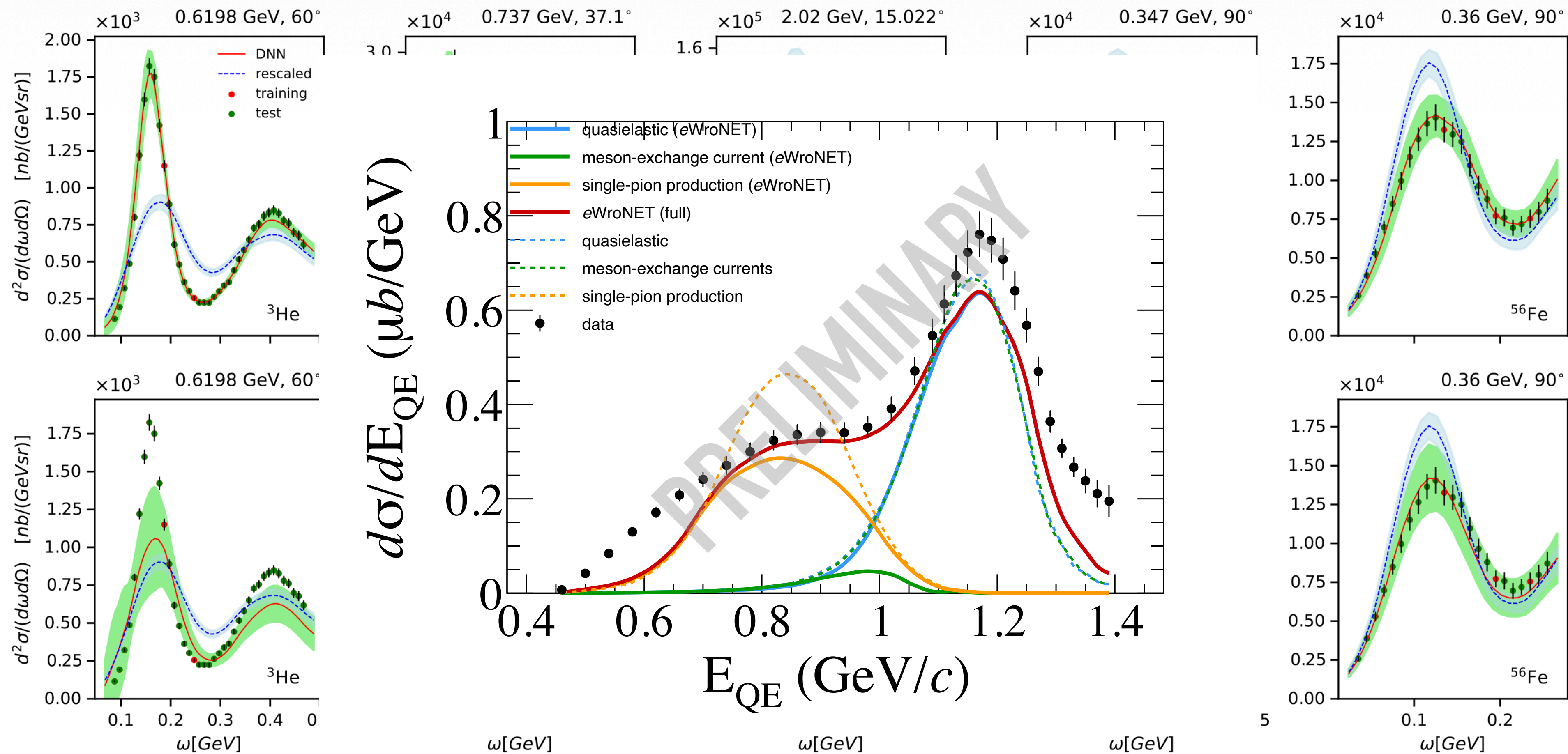
Extention of prediction to other nuclei by **Transfer Learning**



Rwik Dharmapal Banerjee, Artur M. Ankowski, Hemant Prasad, and
Institute of Theoretical Physics, University of Wrocław,

Beata E. Kowal, Institute of Theoretical Physics, University of Wrocław,
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Rwik Dharmapal Banerjee¹, Artur M. Ankowski²,
Hemant Prasad¹, and
Institute of Theoretical Physics, University of Wrocław,

Beata E. Kowal¹, Jose²,
Institute of Theoretical Physics, Univ²,
50-204, Wrocław, Poland

Questions? Discussions



Wyspa słodowa, Wrocław, Poland