Wrocław

NuWro

NuFACT 2024

Uniwersytet Wrocławski

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Overview

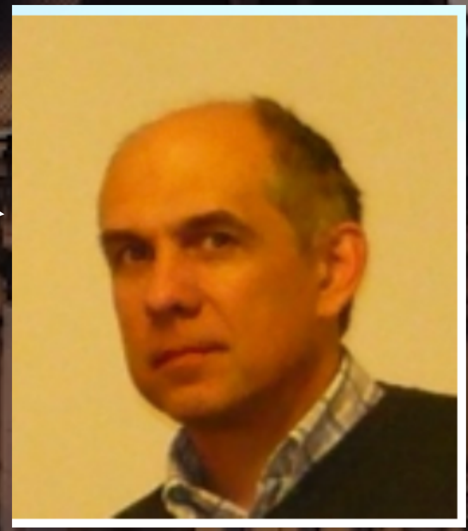
- NuWro
  - History of NuWro.
  - NuWro timeline
  - NuWro scheme.
  - eWro.
- Recent Developments in NuWro
  - New argon spectral function in Quasi elastic scattering.
  - New hadronic model for Nieves et. al. 2p2h model.
  - Hybrid Single pion production model.
- Incorporation of machine learning techniques.

History of NuWro

Founder: Jan T. Sobczyk ~ 2004

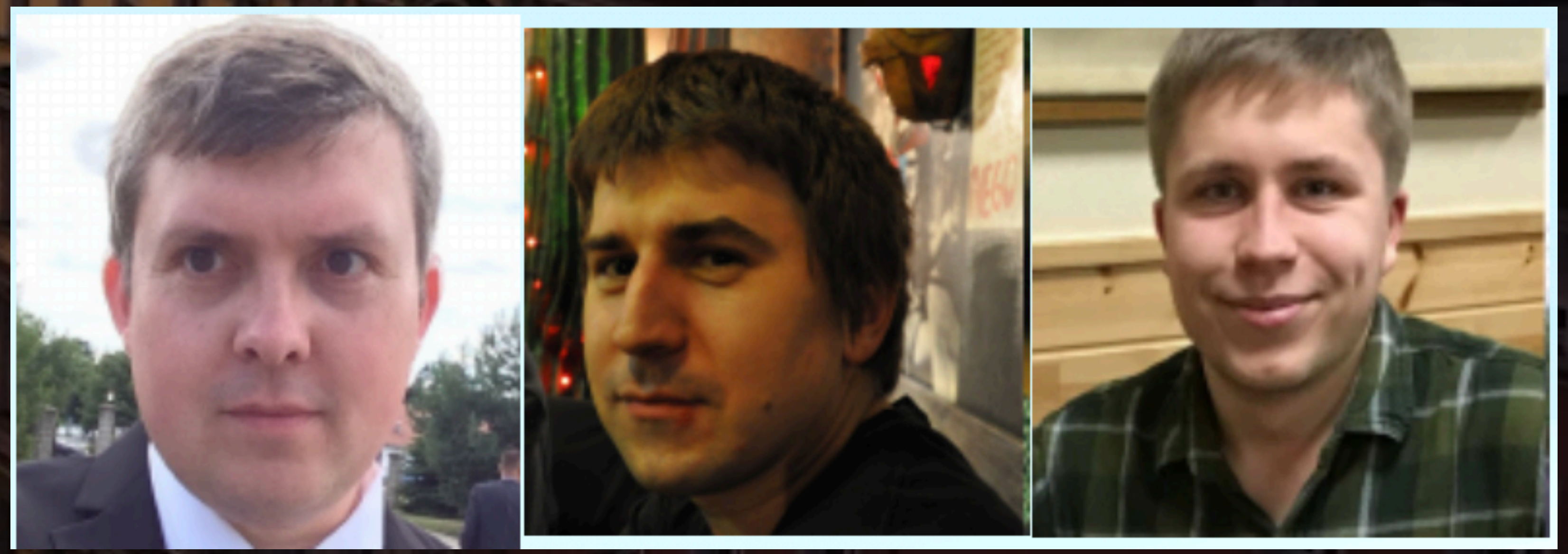
- Inspired from Danka Kiełczewska.

A structure of the code was constructed by Cezary Juszczak.



A major part of NuWro physics models were added by previous PhD students

- Jarosław Nowak
- Tomasz Golan
- Kajetan Niewczas



Important contributions from

- Krzysztof Graczyk
- Artur Ankowski
- Chris Thorpe
- Dmitry Zhuridov
- Jakub Żmuda

Some technical additions by Luke Pickering and Patrick Stowell.

New additions

- Beata Kowal (Post Doc.)
- Luis Bonilla (Post Doc.) ~ 2024
- Rwik Dharmapal Banerjee (PhD) ~ 2022
- Hemant Prasad(PhD) ~2022

NuWro Timeline

- Physics Highlights
  - **Phenomenological 2p2h model.**
  - **Hyperon production** and their FSI.
  - Neutrino **scattering off atomic electrons**.
  - Validated **QE electron scattering.**

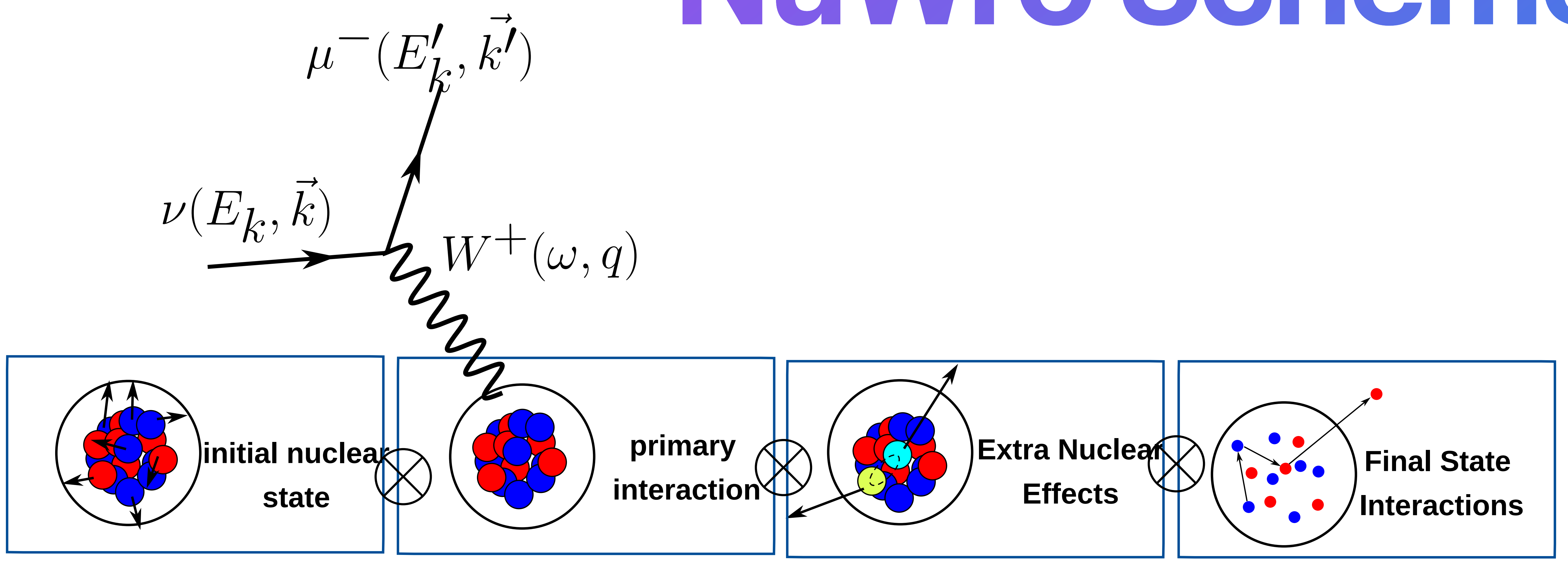
NuWro 24.XX.X.

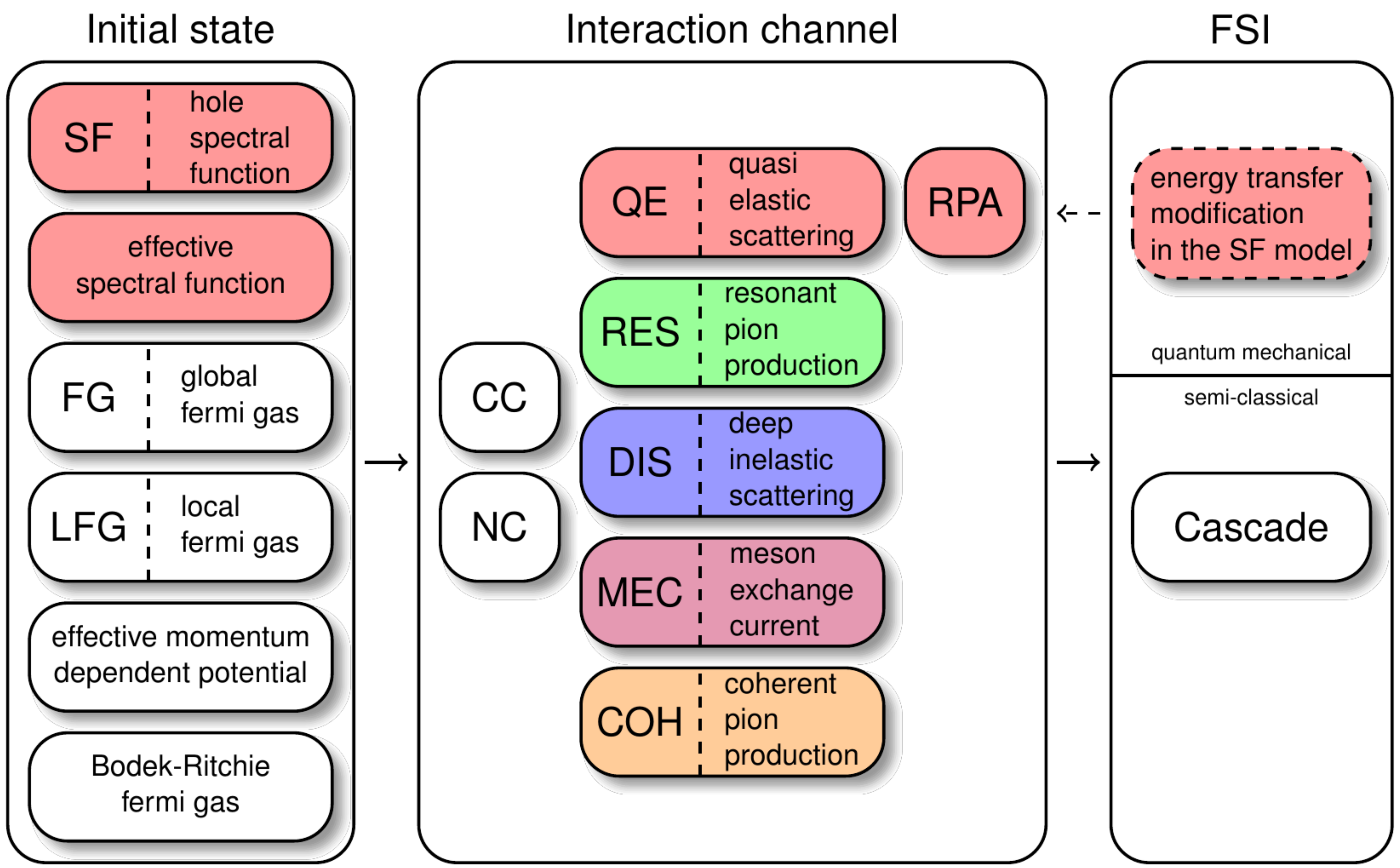
???

Current version 21.09.2

- Technical developments in this version
  - *cmake* support.
  - support of atmospheric neutrino fluxes.
  - more elastic input for detector geometries.
  - **bug fixes and optimization.**
- Development of new physics models.

NuWro Scheme

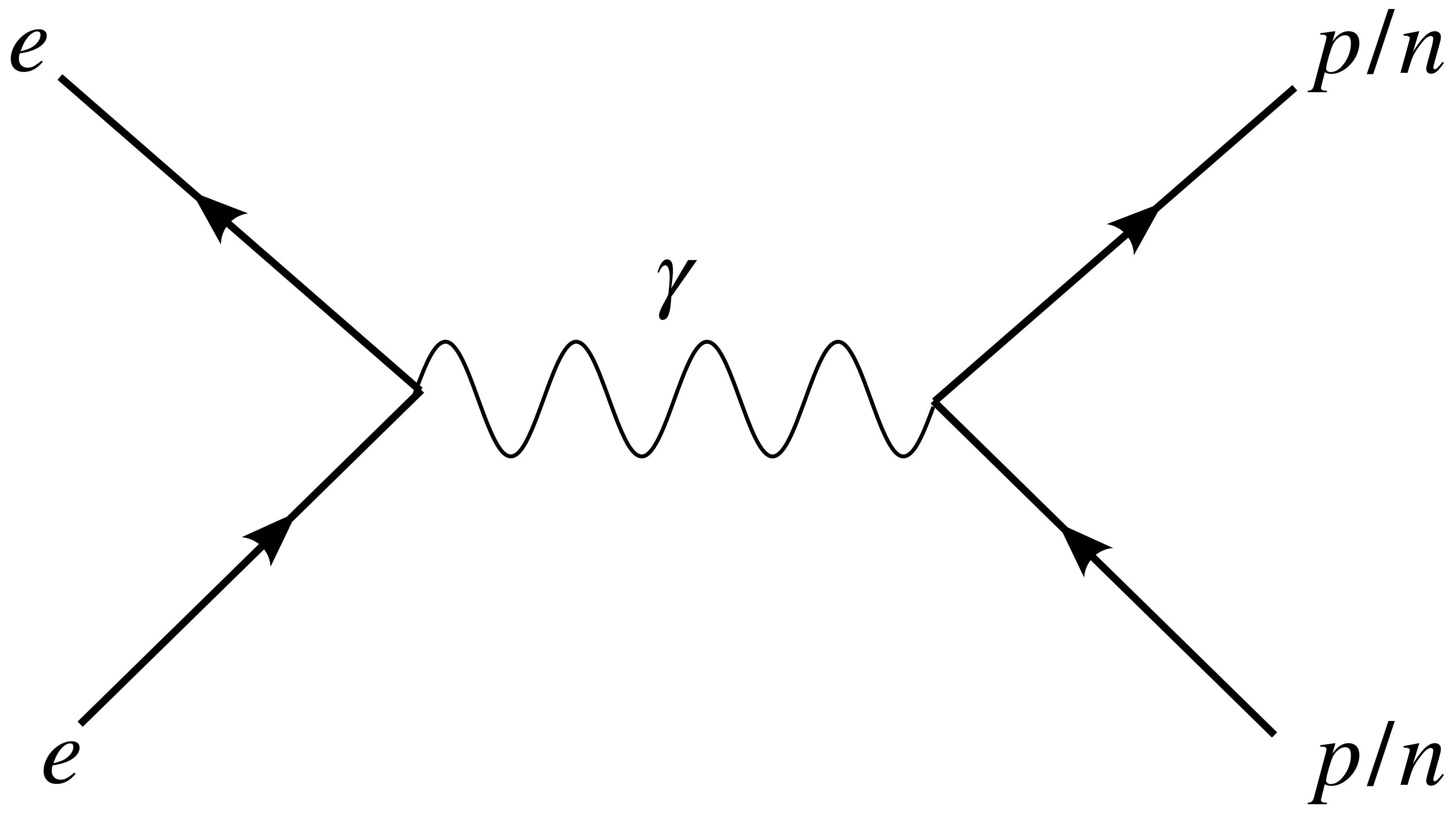




- Event simulation is based on **factorisation scheme.**
- Nuclear effects are treated in **impulse approximation (IA).**
- **Initial State**
  - Generate neutrino (flavor, energy, direction, starting point) according to beam definition (composition, energy profile…).
  - Select nucleus (isotope, position) from target definition (should lie on neutrino trajectory inside detector geometry)
  - Select nucleon(s) (position, momentum, removal energy) from nuclear density profile and nuclear model: FG, LFG, SF, other.
- **Primary Interaction**
  - Select interaction channel: QEL, RES, DIS, MEC, COH …
  - Generate interaction kinematics specific for the channel.
  - Calculate event weight as the differential cross section.
- **Final State interactions**
  - Propagate hadrons and let them interact with nuclear matter subtract binding energy from nucleons leaving nucleus.
  - Apply Coulomb corrections.
- **Accept and save event with probability proportional to its weight.**

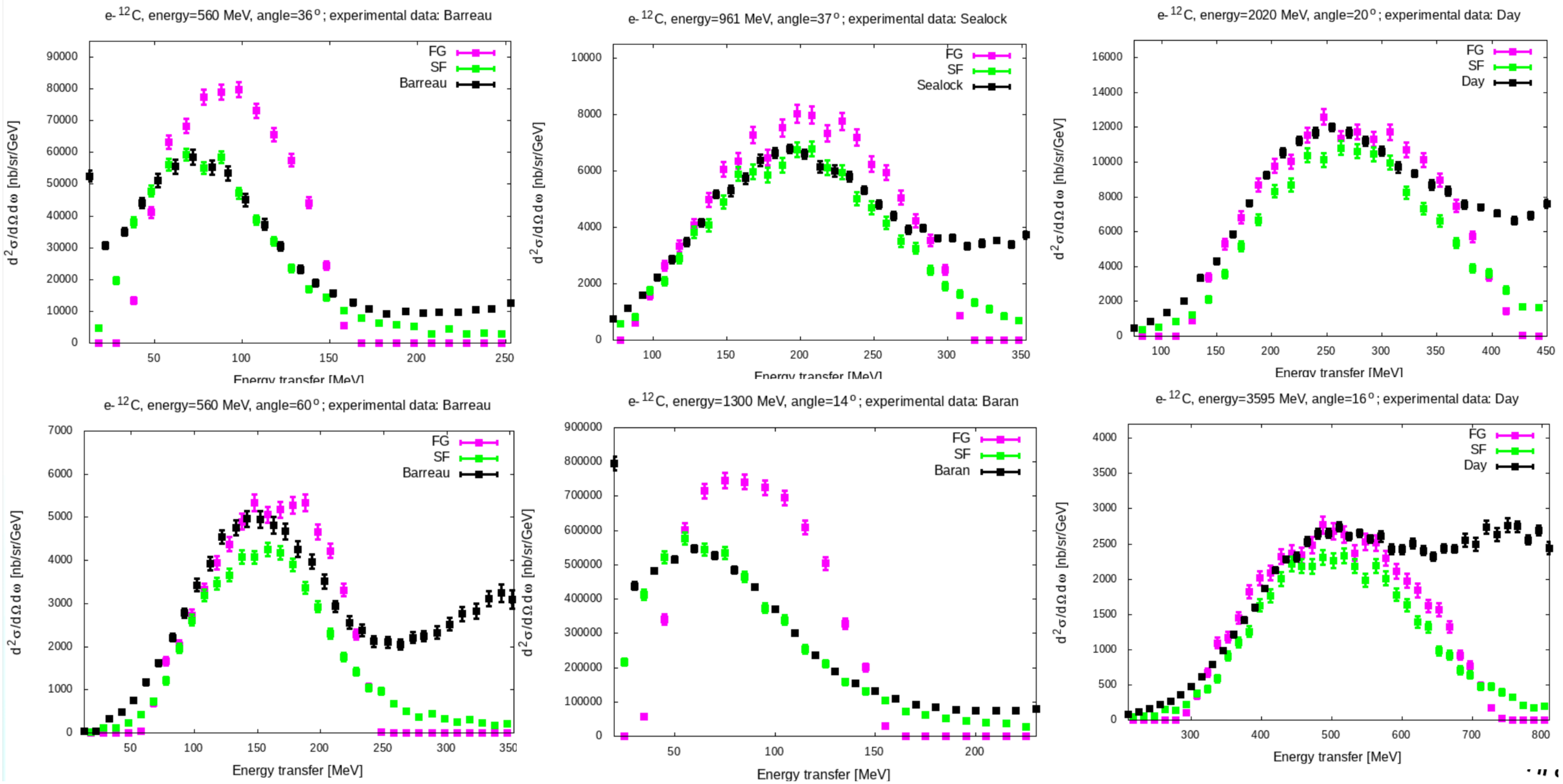
eWro

- A general idea is to use precise electron scattering data to test implemented models.
- The structure is very similar to NuWro, in particular
  - Select initial nucleons.
  - Assign kinematics
  - Generate event.
  - Final state interactions



~ Currently, eWro is available for QE dynamics only

eWro



~ Currently, eWro is available for QE dynamics only

NuWro

Upcoming projects in NuWro:*

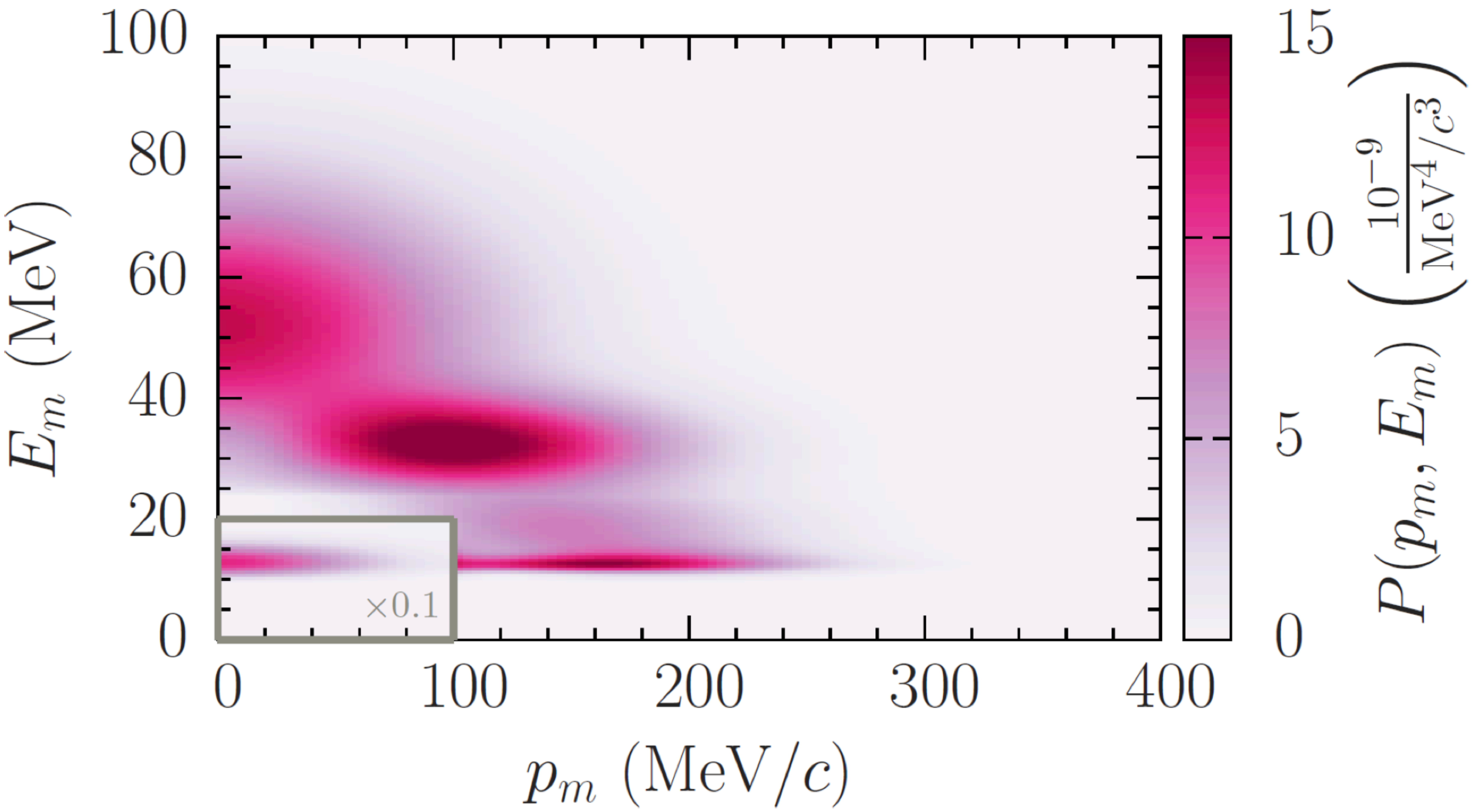
- ➡ **Argon spectral function**.
- ➡ New **hybrid single pion production model** in RES channel.
- ➡ New **2p2h Valencia model** (exclusive model).
- ➡ Incorporation of machine learning techniques.

```
git clone https://github.com/NuWro/nuwro.git
```

** Will be covered in this talk*

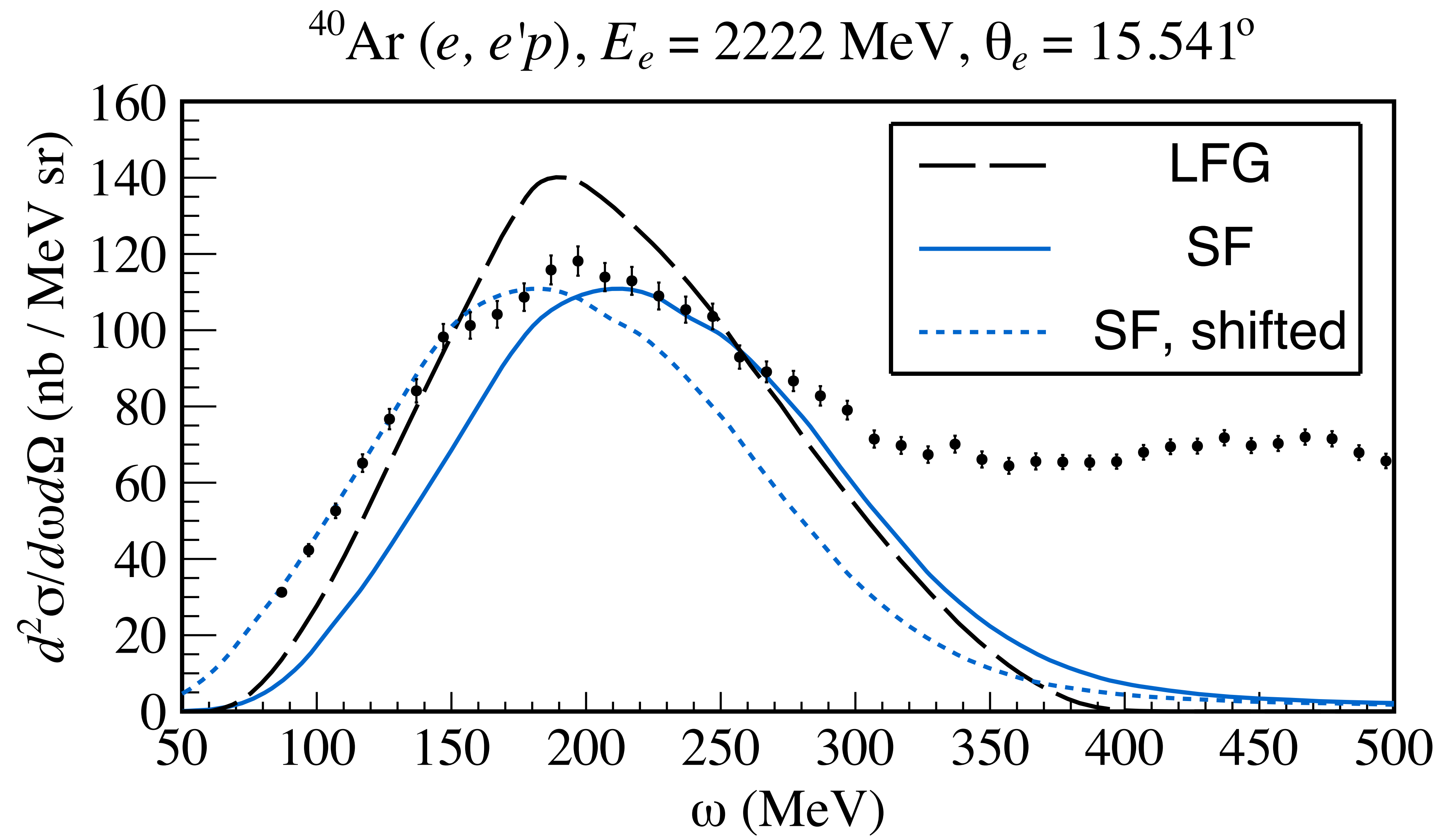
Quasi Elastic Scattering

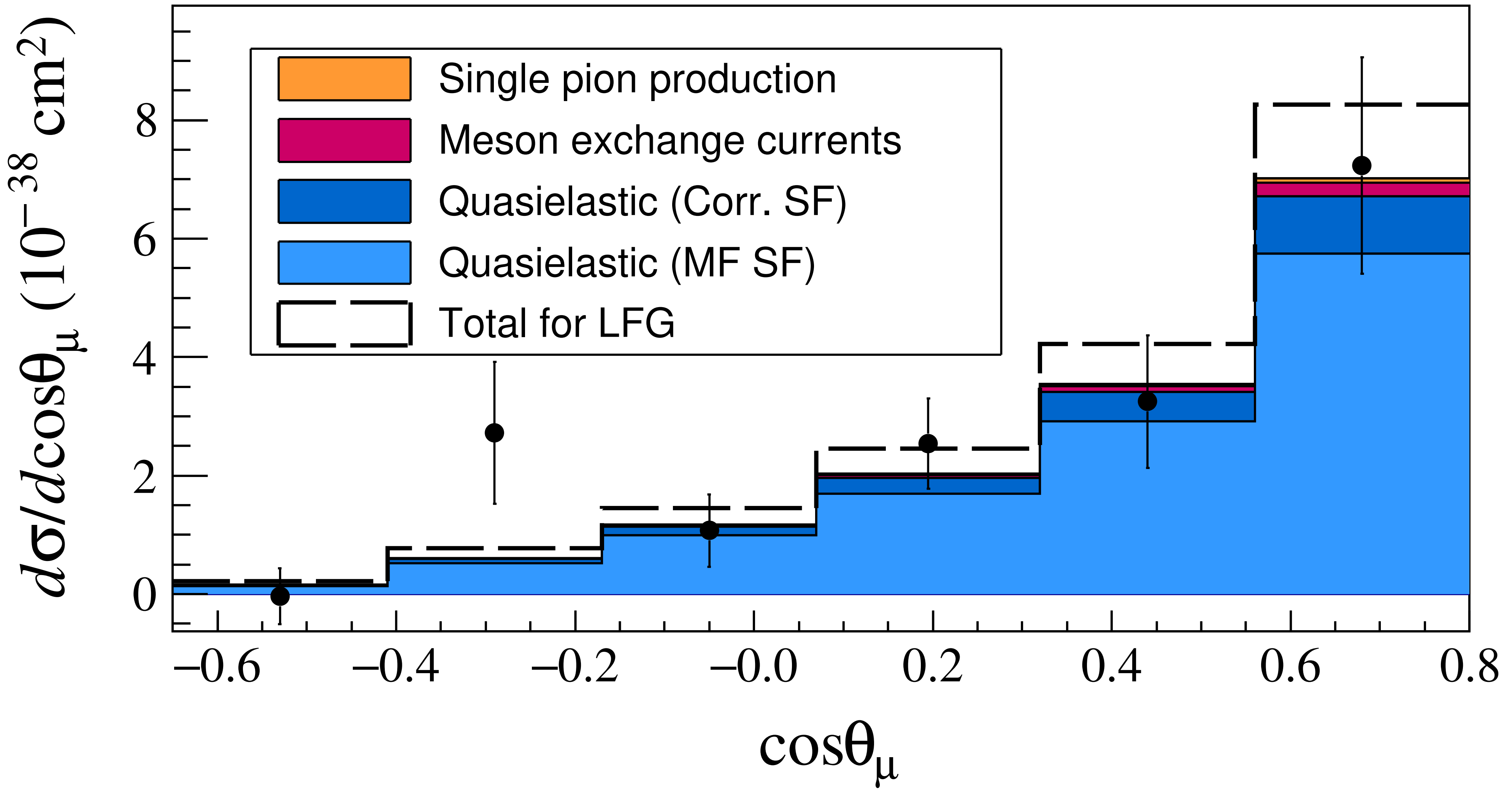
- JLab spectral functions of argon are implemented **[L. Jiang et al., PRD 105, 112002 (2022); PRD 107, 012005 (2023)]**



Quasi Elastic Scattering

- Low-energy treatment improved for the short-baseline program in Fermilab
  - Coulomb effects in the QE channel.
  - proton-neutron energy level difference.
  - nuclear recoil.

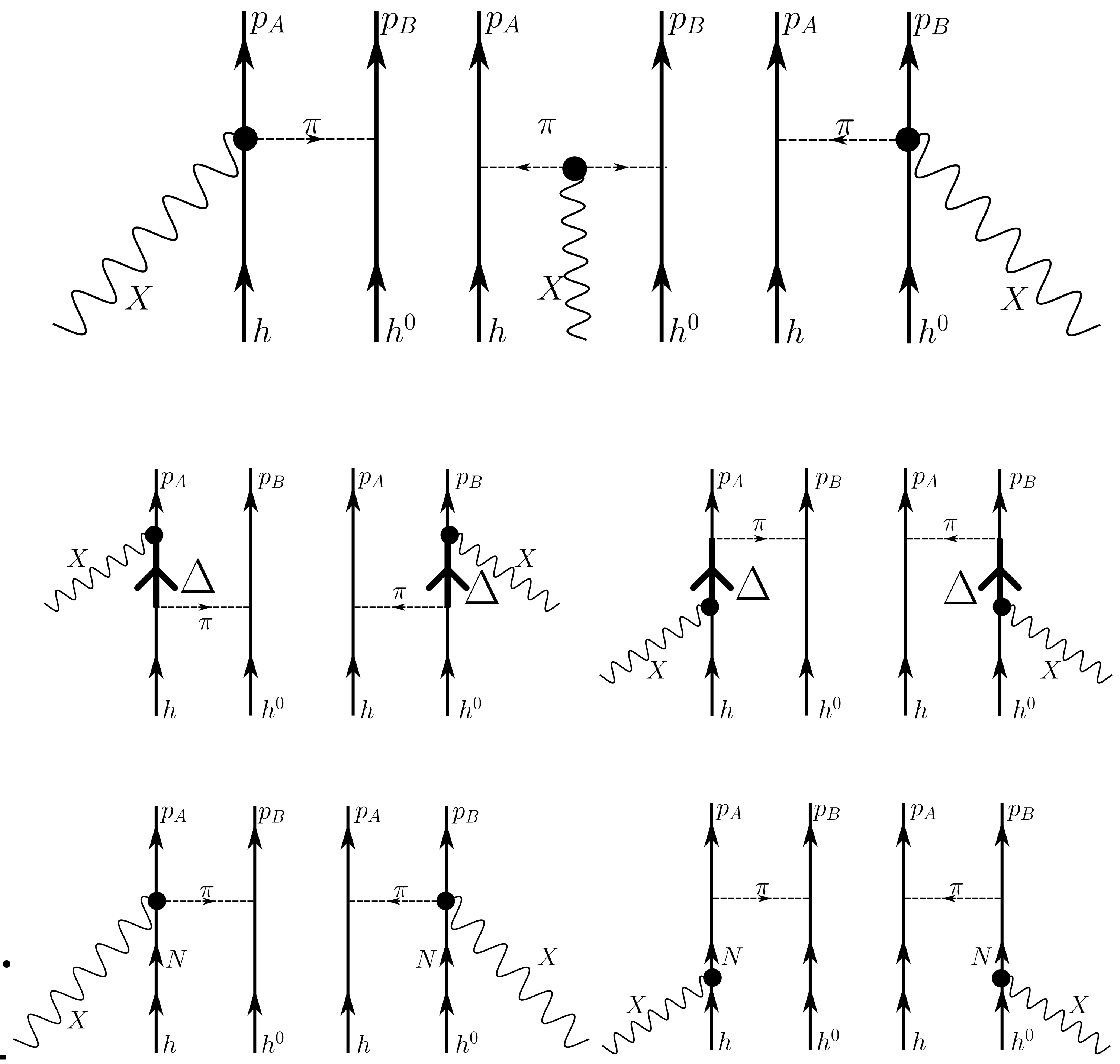


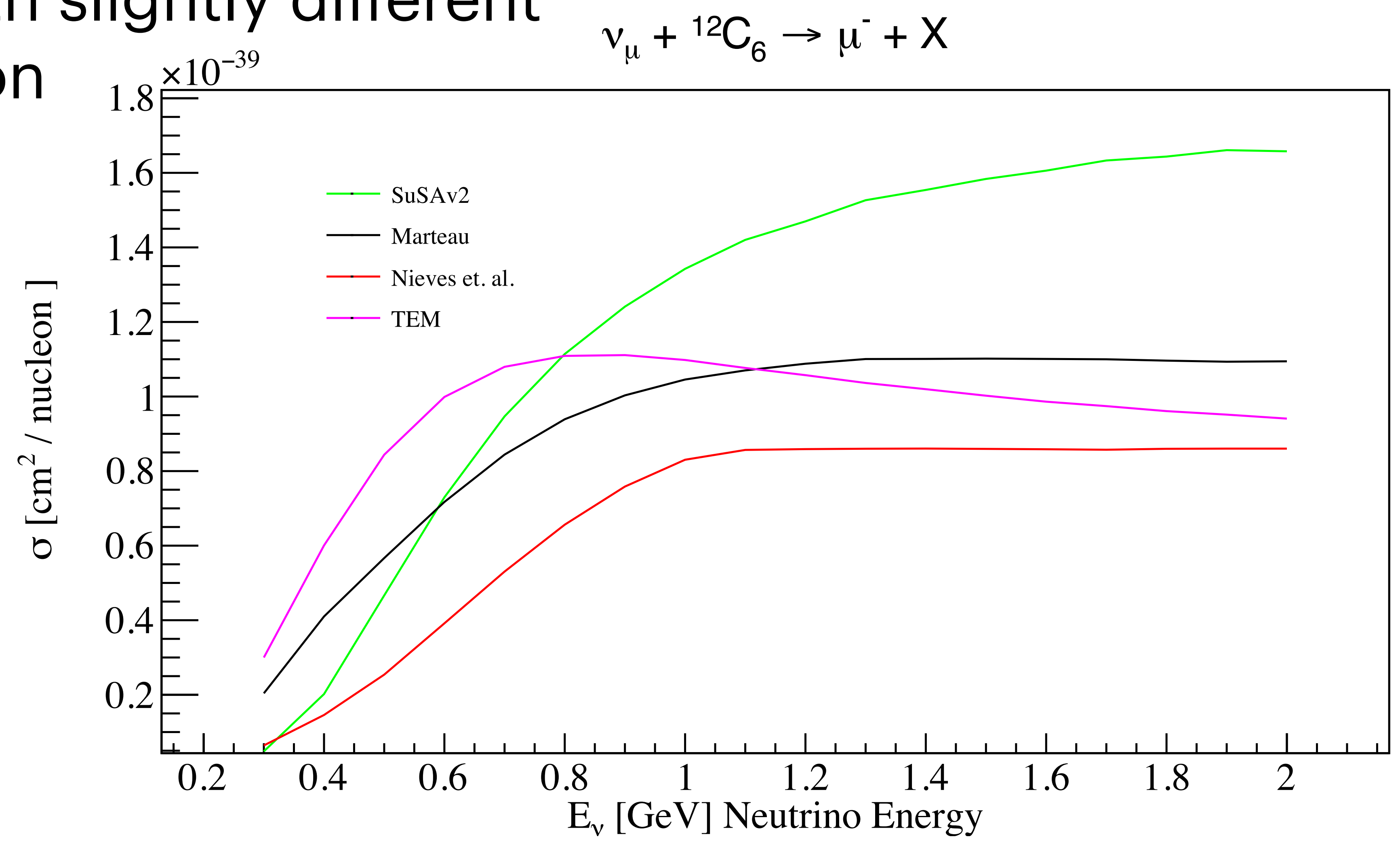


- Axial form factor from MINERvA also implemented **[R. Dharmapal Banerjee et al., PRD 109, (2024) 073004]**
- Combined for the MicroBooNE data for the restricted phase space is 1.0 for the local Fermi gas and 0.7 for the spectral function approach. $\chi2$ /d. o. f. CC1p0π(cos θμ < 0.8)

Meson Exchange Currents

- Motivated by electron-nucleus scattering data.
- Excitation of spectator nucleon(s).
  - Energy exchange through in-medium pion production
- A multi-nucleon knockout process.
- Significant contribution around ~ 1 GeV
  - An important dynamics for all upcoming neutrino experiments
- Two body current interactions dominated by meson exchange currents.
  - Small contribution coming from three body current interactions as well (3p3h).
- Currently NuWro offers 4 n particles -n holes (np-nh) models with slightly different leptonic model resulting into prediction of different cross section
  - Marteau et. al.
  - Nieves et. al.
  - SuSAv2
  - Transverse Enhanced model (TEM).

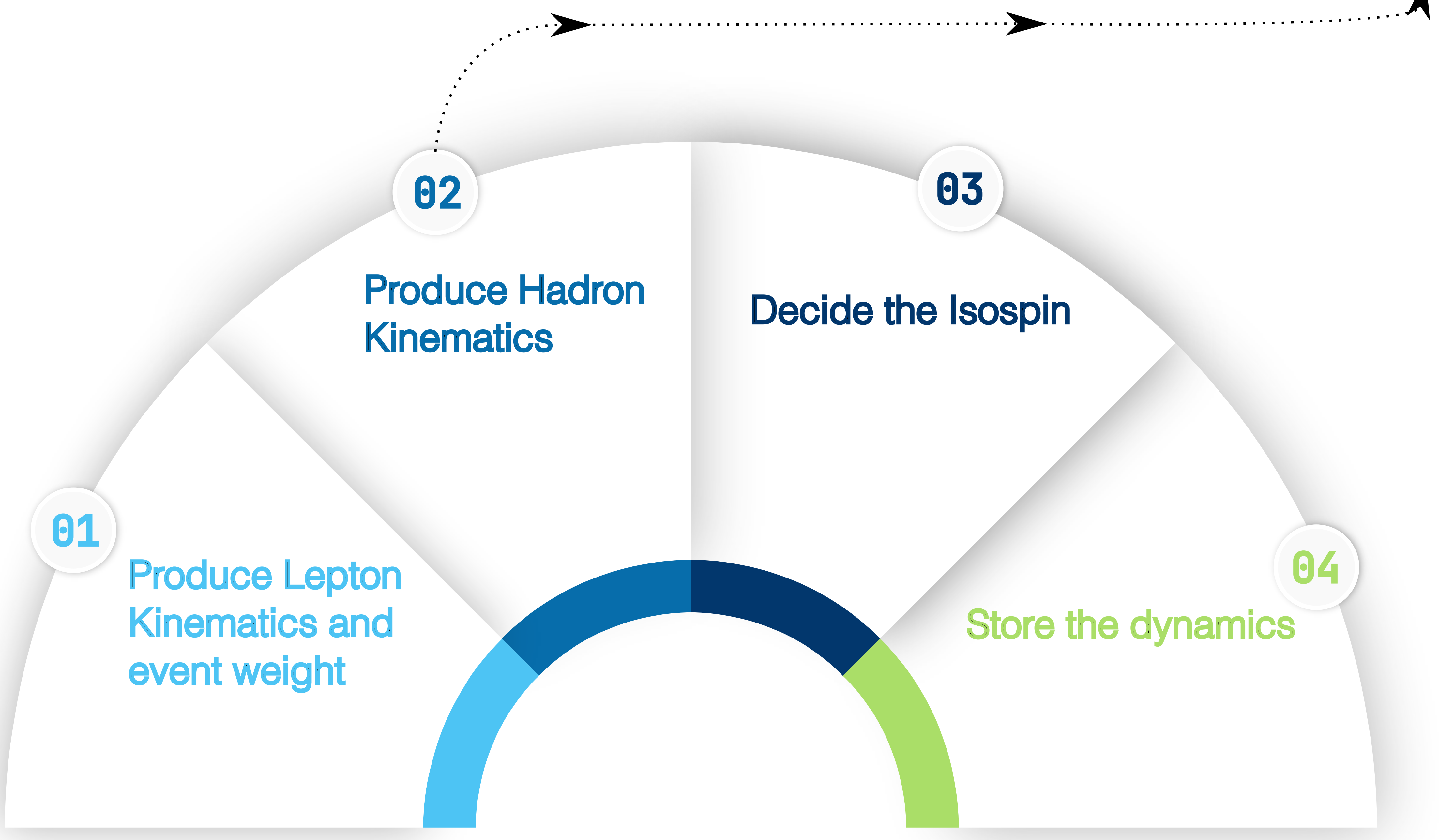


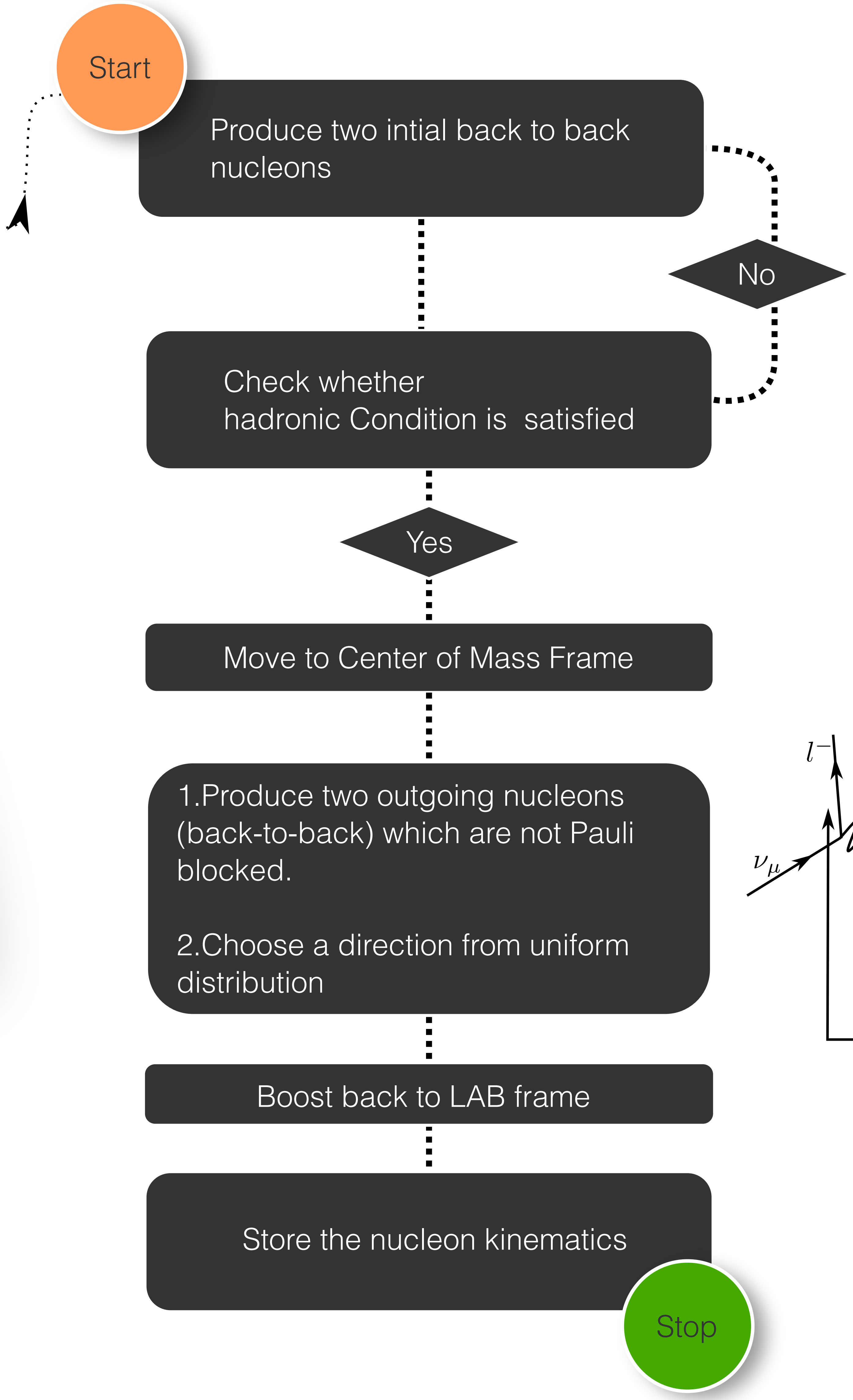


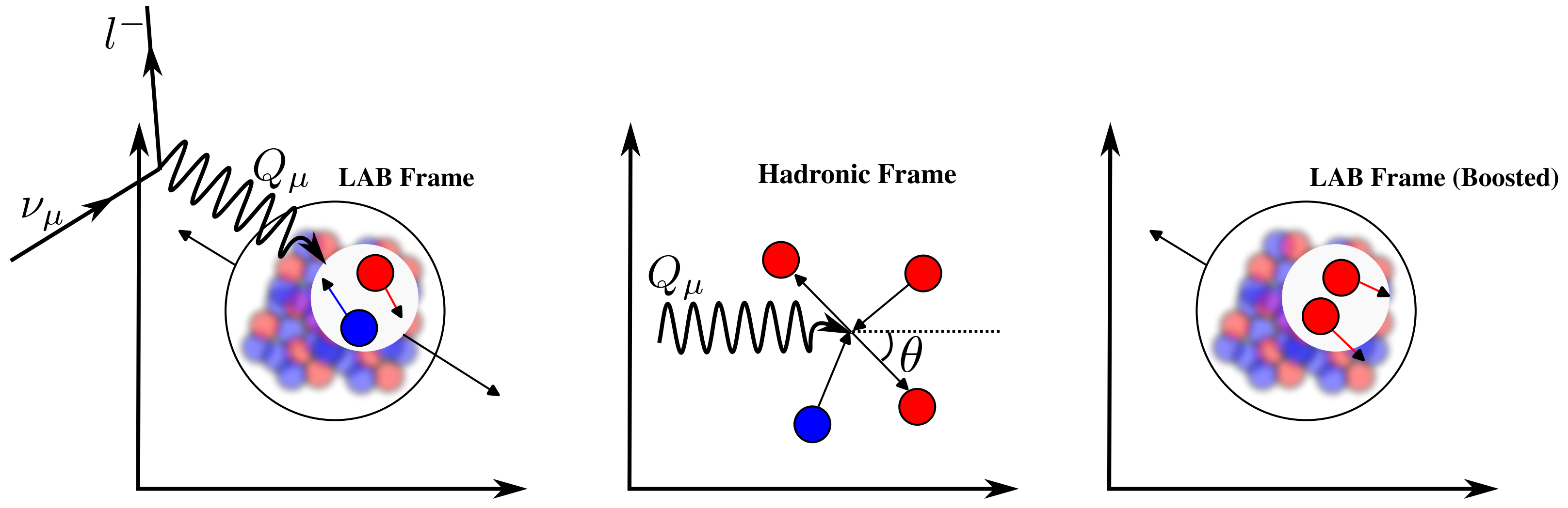
Meson Exchange Currents

Nuwro v21.09.xx

Current MEC scheme







Meson Exchange Currents

- Implementation of **Nieves et. al. 2p2h model** with predictions on momenta of outgoing nucleons in nucleon phasespace in NuWro.
  - New hadronic grids
  - New nucleon sampling functions : for controlling the correlations of outgoing nucleon momenta.

- Addition of Nieves et. al 3p3h model on top of 2p2h model

PHYSICAL REVIEW C **102**, 024601 (2020)

Exclusive-final-state hadron observables from neutrino-nucleus multinucleon knockout

J. E. Sobczyk,[1,2] J. Nieves,[1] and F. Sánchez[3]
[1]*Instituto de Física Corpuscular (IFIC), Centro Mixto CSIC-Universidad de Valencia, Institutos de Investigación de Paterna, Apartado 22085, E-46071 Valencia, Spain*
[2]*Institut für Kernphysik and PRISMA+ Cluster of Excellence, Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany*
[3]*Université de Genève, Faculté des Sciences, Département de Physique Nucléaire et Corpusculaire (DPNC) 24, Quai Ernest-Ansermet, CH-1211 Genève 4, Switzerland*

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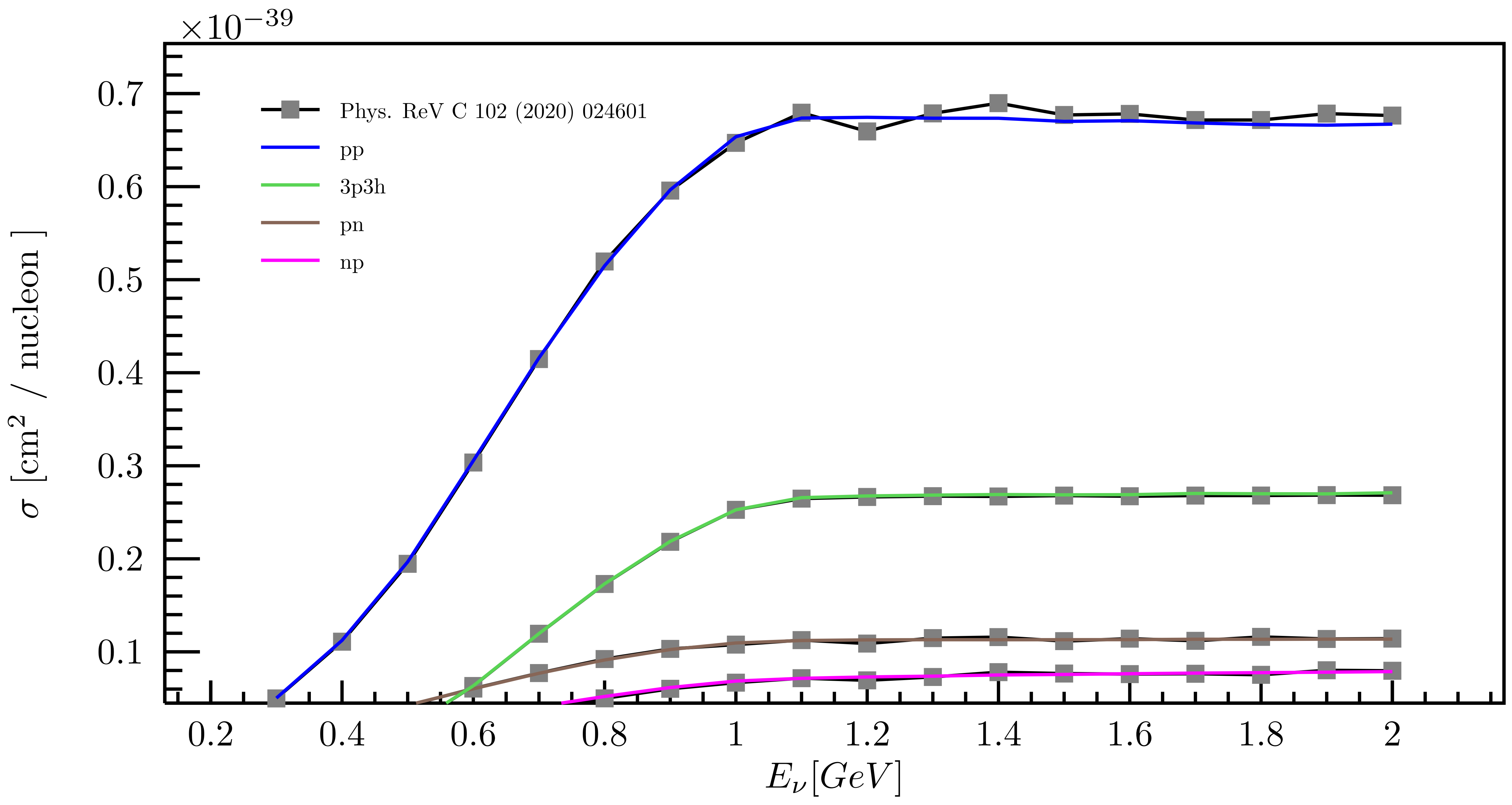
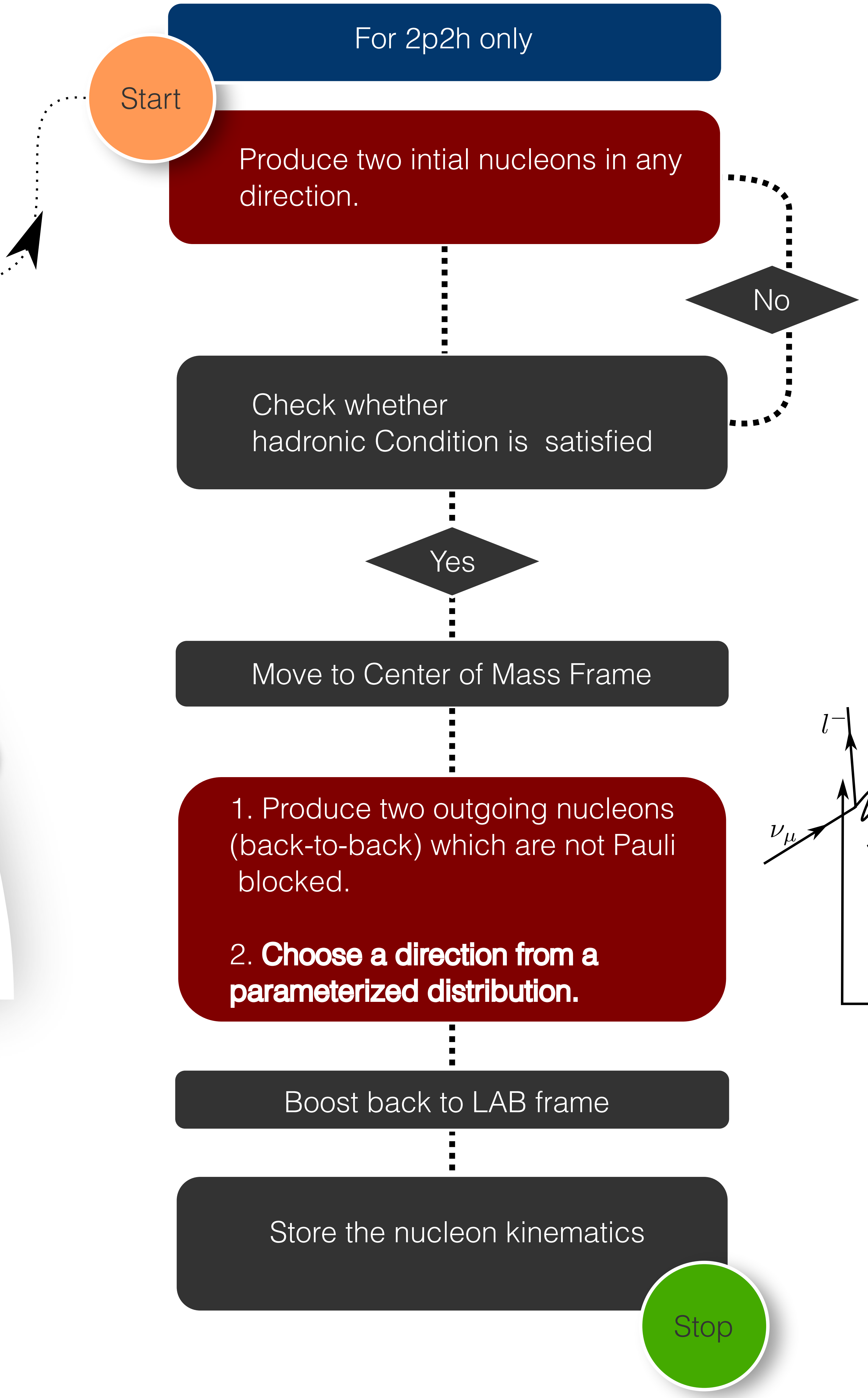
$$\nu_\mu + ^{12}C_6 \rightarrow \mu^- + X$$

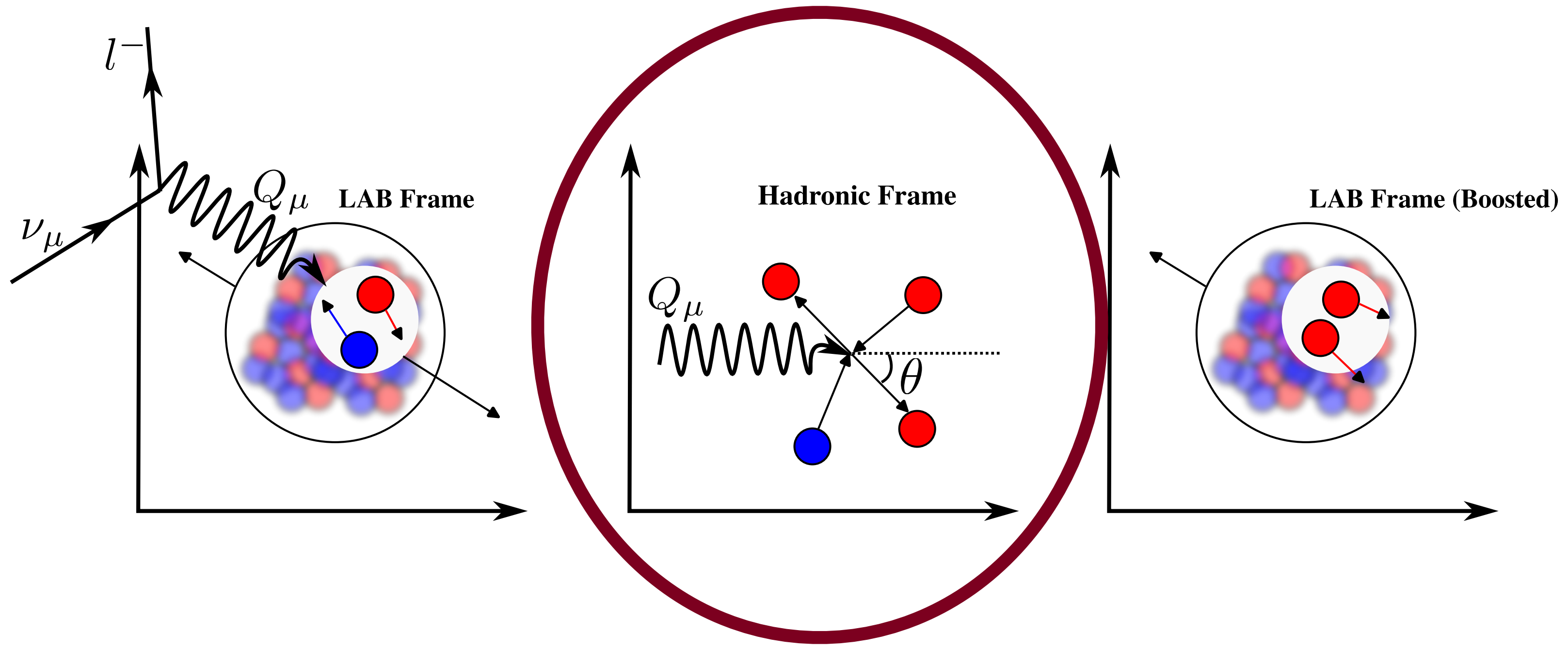


New Hadronic Model: NuWro

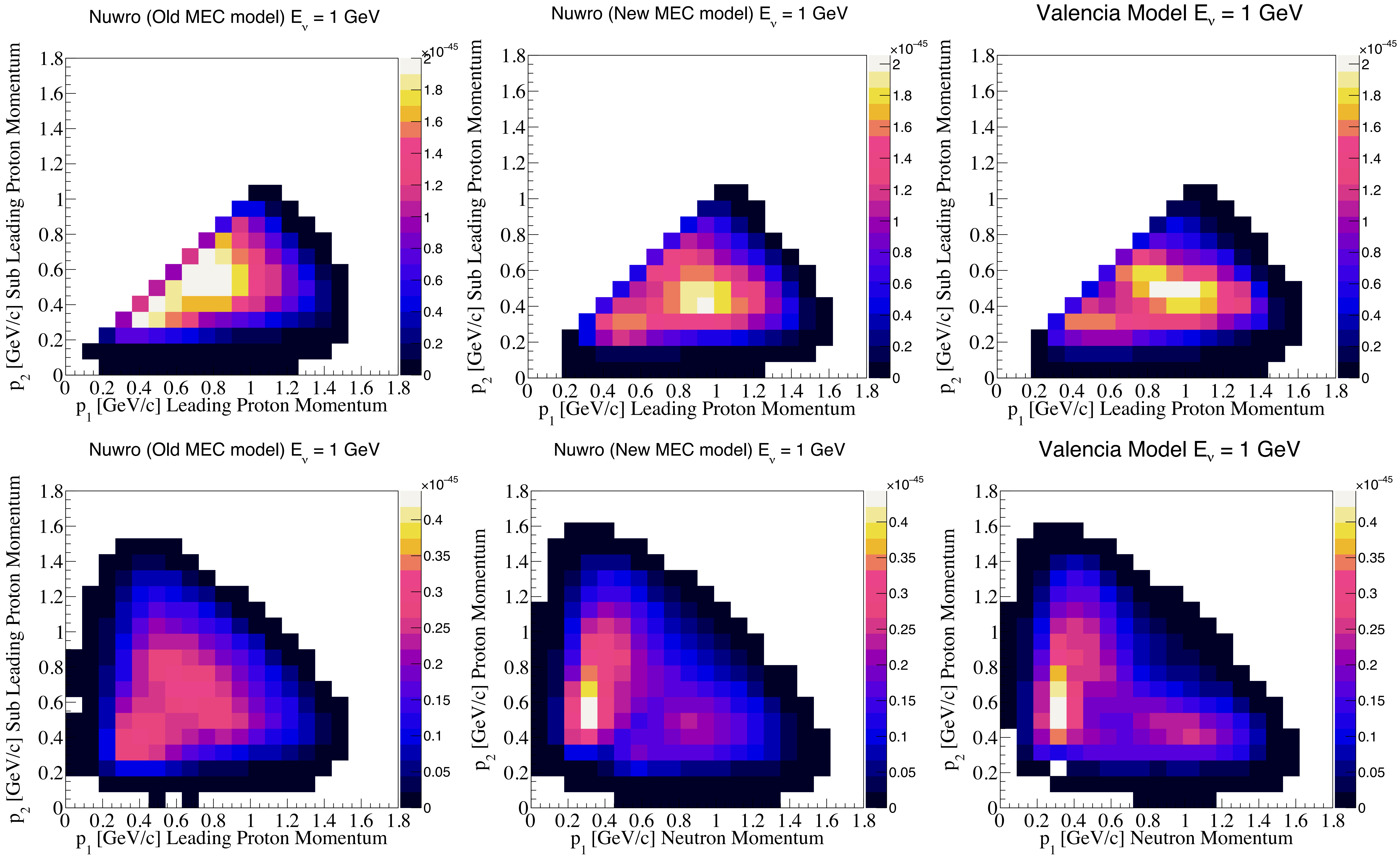
Nuwro v24.xx.?

New MEC scheme and Hadronic Model





New Hadronic Model: NuWro



New Hadronic Model: NuWro

Minor difference will be washed out after
Adding FSI on top of this

~ 50% contribution from FSI to final picture

Resonant single π production

- NuWro relies on a simple model including explicitly only one $\Delta(1232)$ resonance.
- For Large W quark-hadron duality argument holds
  - Inclusive cross section from Bodek-Yang
  - Hadronization uses Pythia 6.
  - Linear interpolation

$$\frac{d\sigma^{SPP}}{dW} = \beta(W)\frac{d\sigma^{\Delta}}{dW} + \alpha(W)\frac{d\sigma^{DIS,SPP}}{dW}$$

$$\beta(W) = 1 - \alpha(W)$$

Here $\alpha(W) = \begin{cases} \frac{W - W_{thr}}{W_{min} - W_{thr}}\alpha_0 & W < W_{min} \\ \frac{W - W_{min} + \alpha_0(W_{max} - W)}{W_{max} - W_{min}} & W_{min} \le W \le W_{max} \\ 1 & \end{cases}$

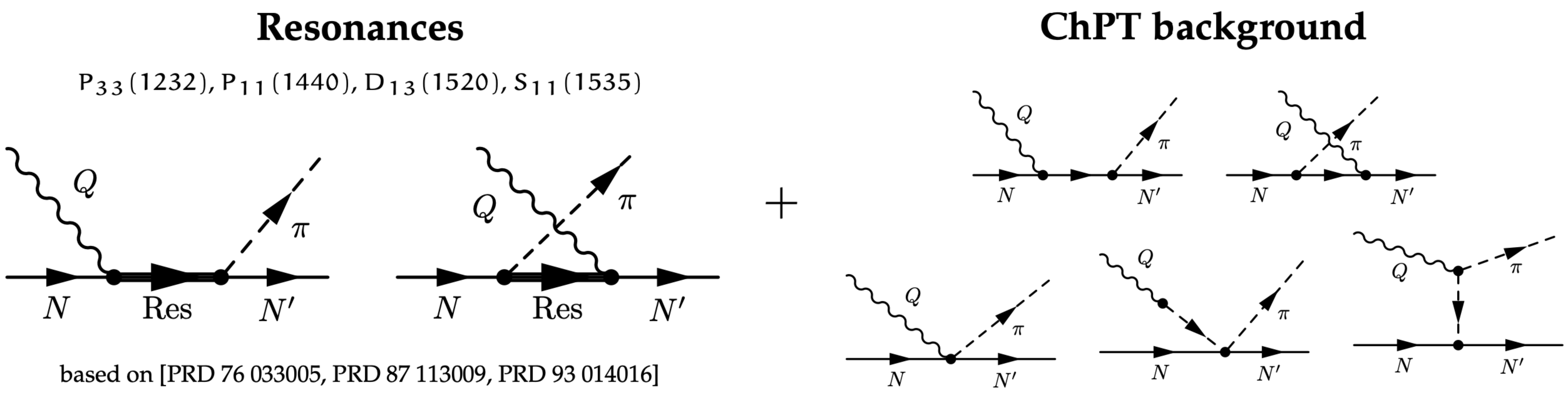
$W_{thr} = M + m_\pi \quad W_{min} = 1.3GeV \quad W_{max} = 1.6GeV$

Resonant single π production

- "Hybrid Model" from Ghent Group **R. Gonzalez-Jimenez, N. Jachowicz, K. Niewczas, et al, Phys.Rev. D 95 (2017) 11, 113007**
- Contribution from resonances $P_{33}(1232)(\Delta), D_{13}(1520), S_{11}(1535), P_{11}(1440)$ low-energy background, and high energy background.

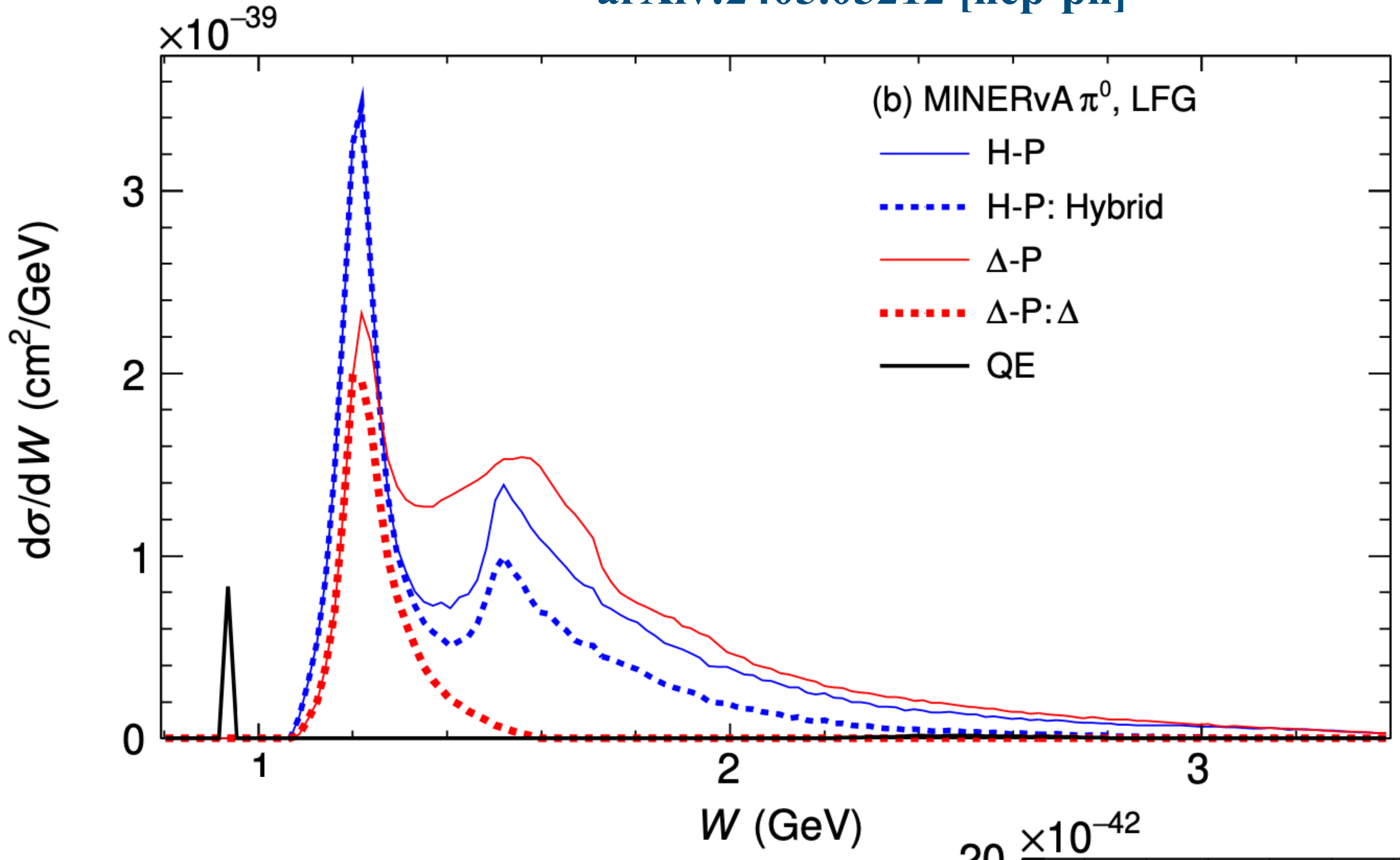
$$J^{\nu}_{Hybrid} = J^{\nu}_{RES} + \cos^2\phi(W)J^{\nu}_{EM} + \sin^2\phi(W)J^{\nu}_{ReChi}$$

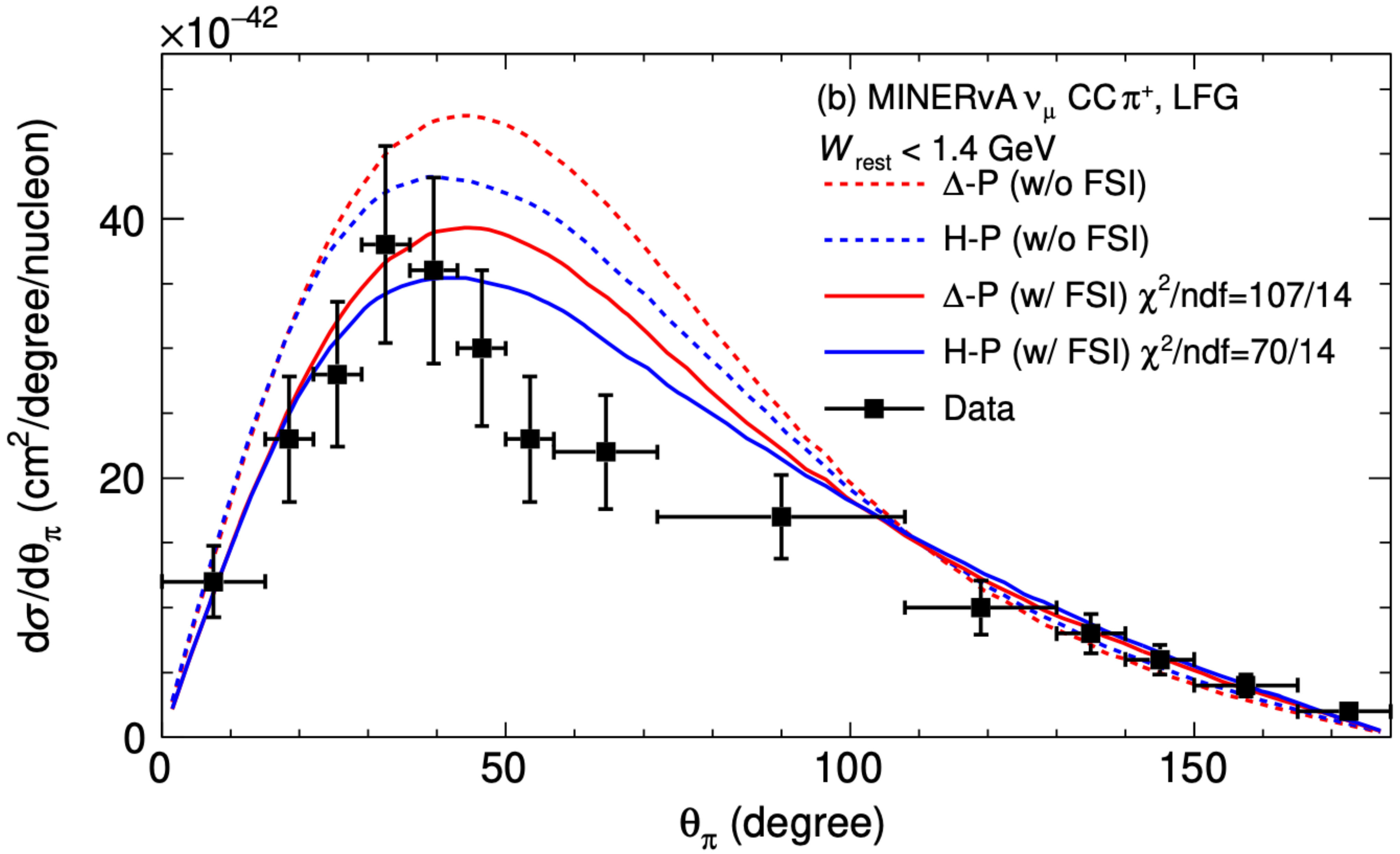
$$\phi(W) = \frac{\pi}{2}\left[1 - \frac{1}{1 + exp(\frac{W - W_0}{L})}\right] \quad W_0 = 1.5GeV \quad L = 0.1GeV$$

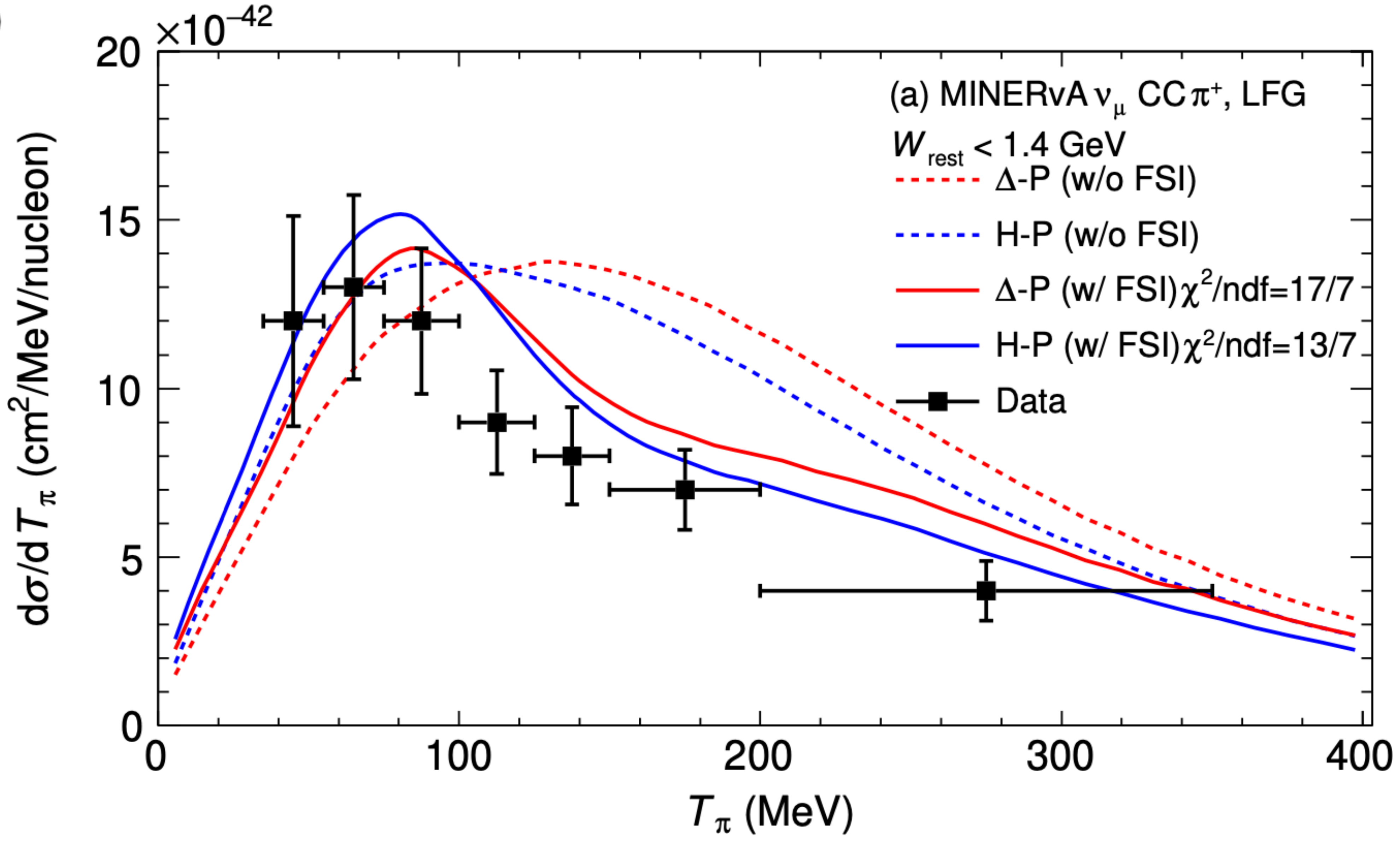


Resonant single π production

arXiv:2405.05212 [hep-ph]







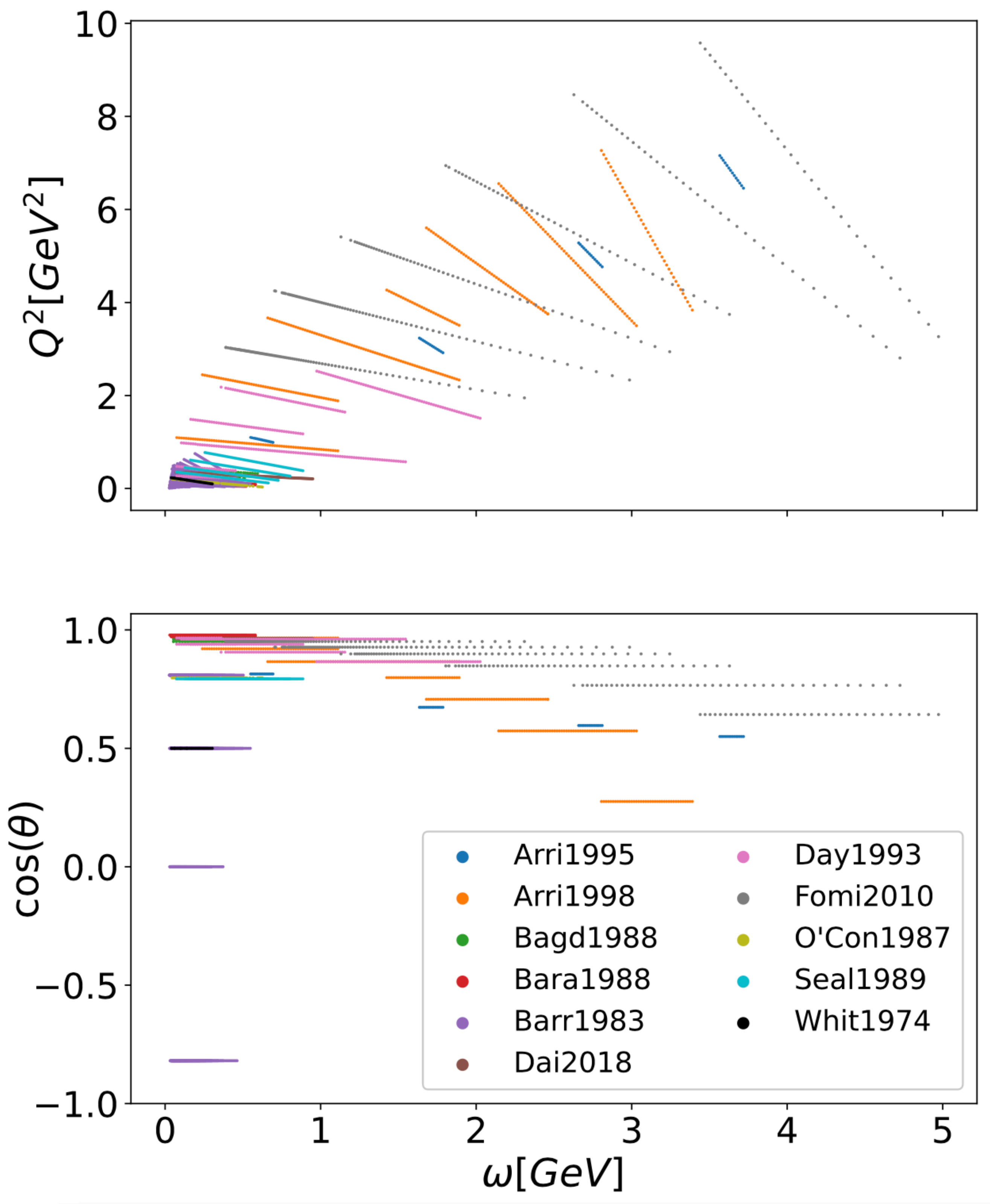
Incorporation of machine learning techniques in our neutrino group

Modelling lepton-carbon interaction using DNN

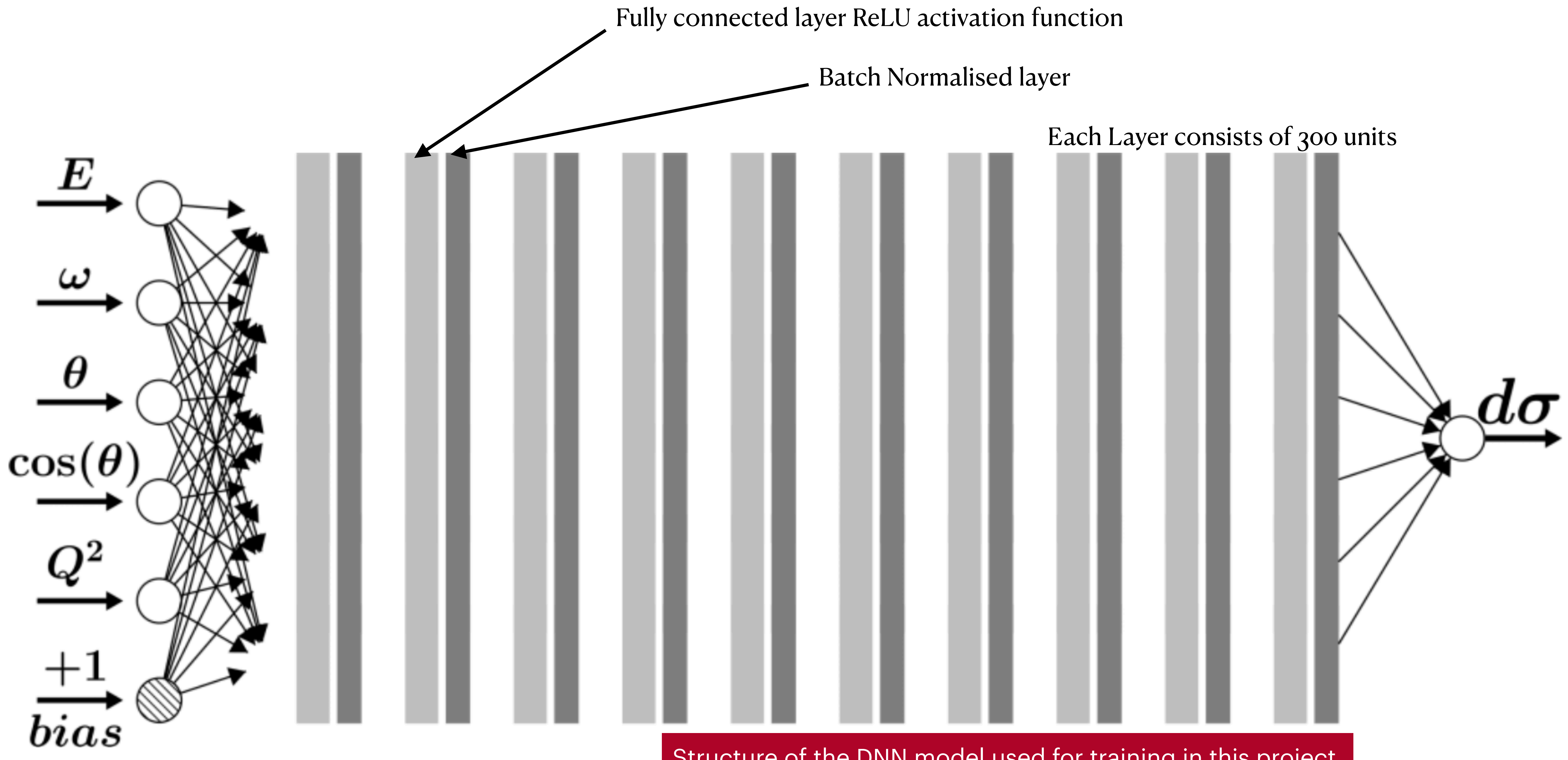
New

Beata E. Kowal, Krzysztof M. Graczyk et. al. Phys.Rev. C 110 (2024) 025501

- Modelling deep neutral networks (DNN) and training over experimental datasets.
- Emphasis on "**Parameterisations of electron-scattering cross section, independent from nuclear model assumptions**"



Kinematical Region of experimental dataset over which the model was trained



Structure of the DNN model used for training in this project.
Credits: Beata E. Kowal

Modelling lepton-carbon interaction using DNN

Beata E. Kowal, Krzysztof M. Graczyk et. al. Phys.Rev. C 110 (2024) 025501

New

Model A

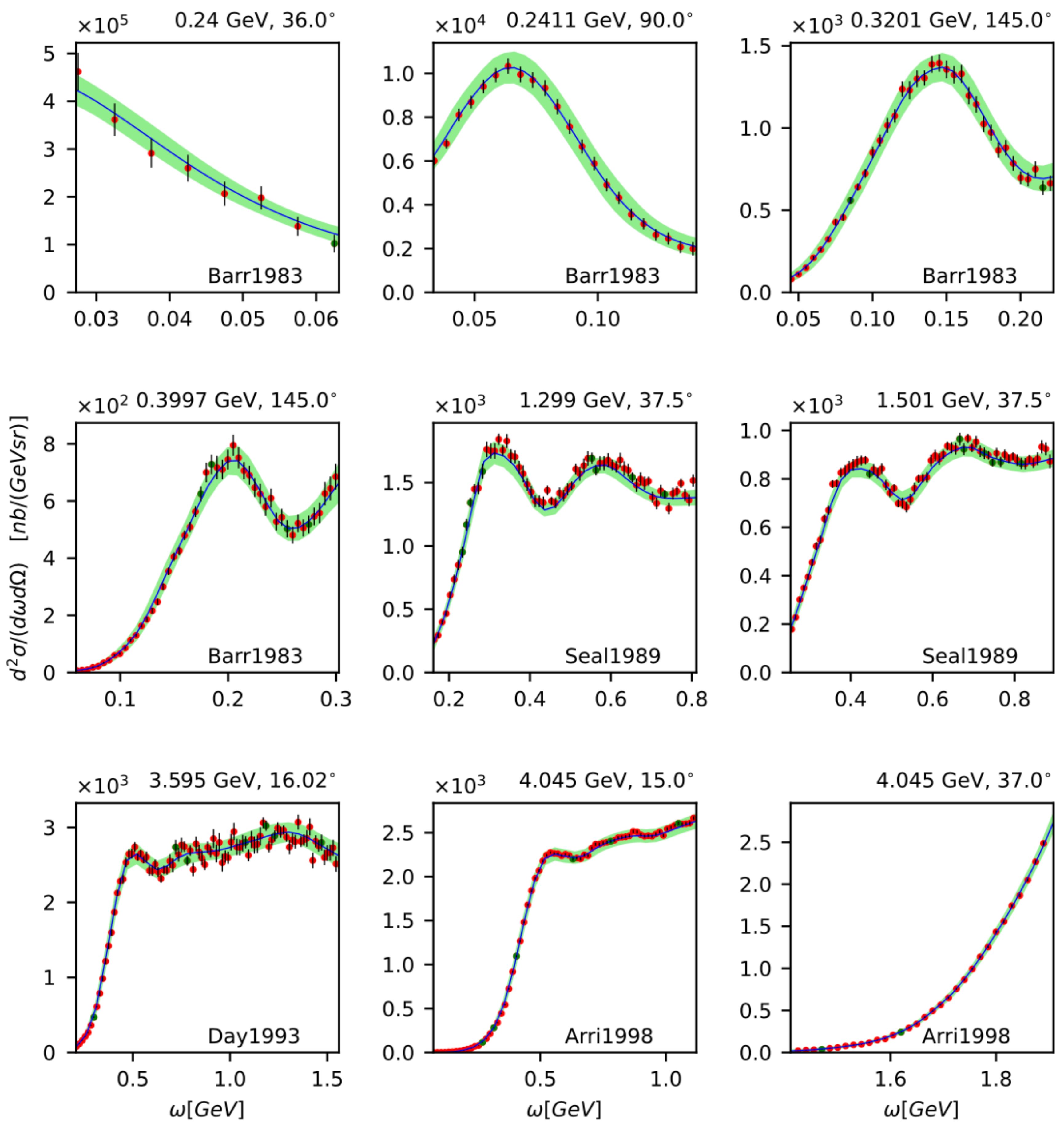
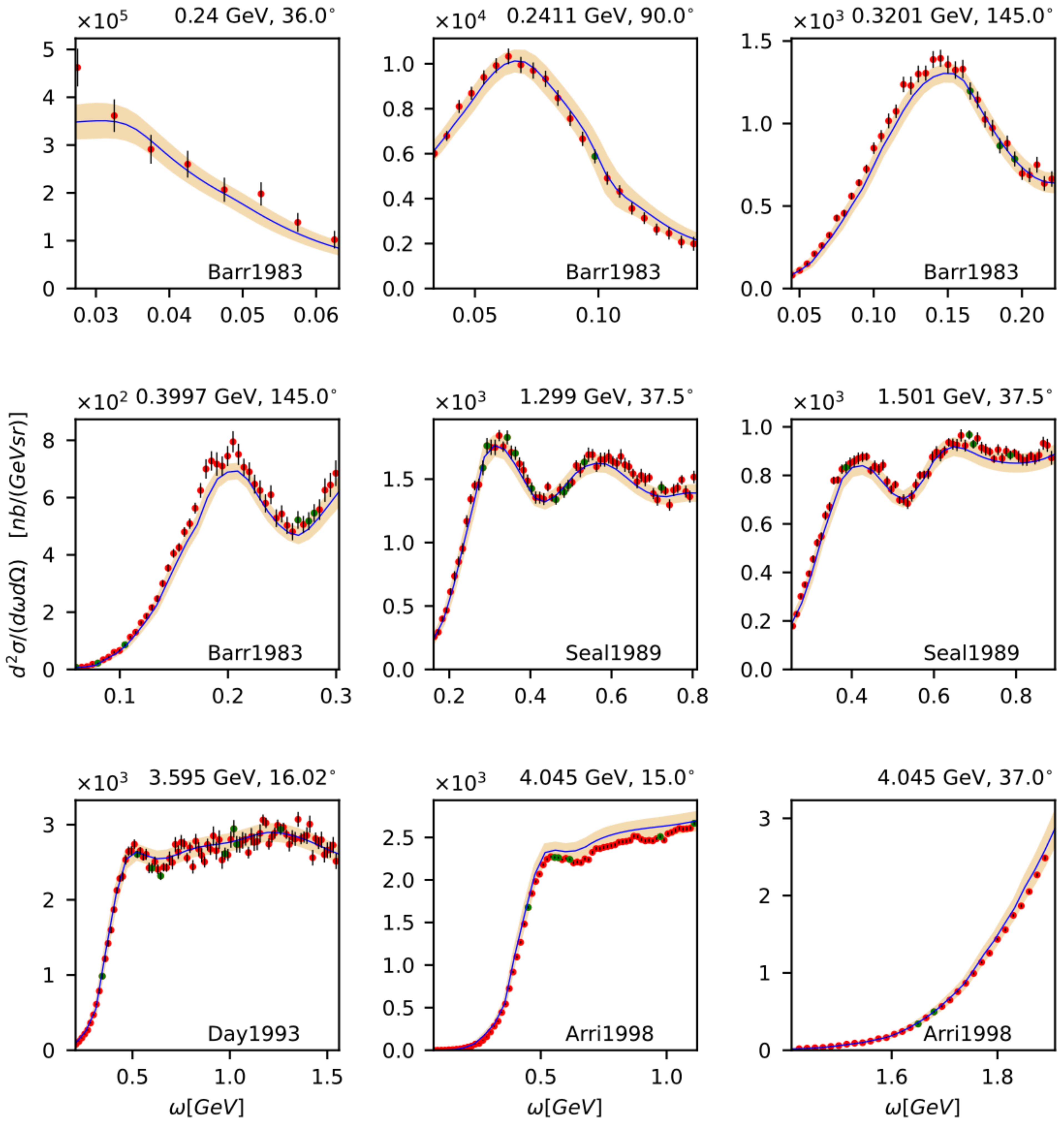


FIG. 6. Double-differential cross section $d^2\sigma/d\omega d\Omega$ for inclusive electron scattering on carbon. We compare the predictions of model A to the experimental data from Refs. [29,32,34,37]. The shaded areas denote the 1σ uncertainties. The panels are labeled with the beam energy and scattering angle values. The red (blue) points represent the training (test) dataset. The predictions are not rescaled according to the determined normalization parameters.

Model B



Modelling lepton-carbon interaction using DNN

Beata E. Kowal, Krzysztof M. Graczyk et. al. Phys.Rev. C 110 (2024) 025501

New

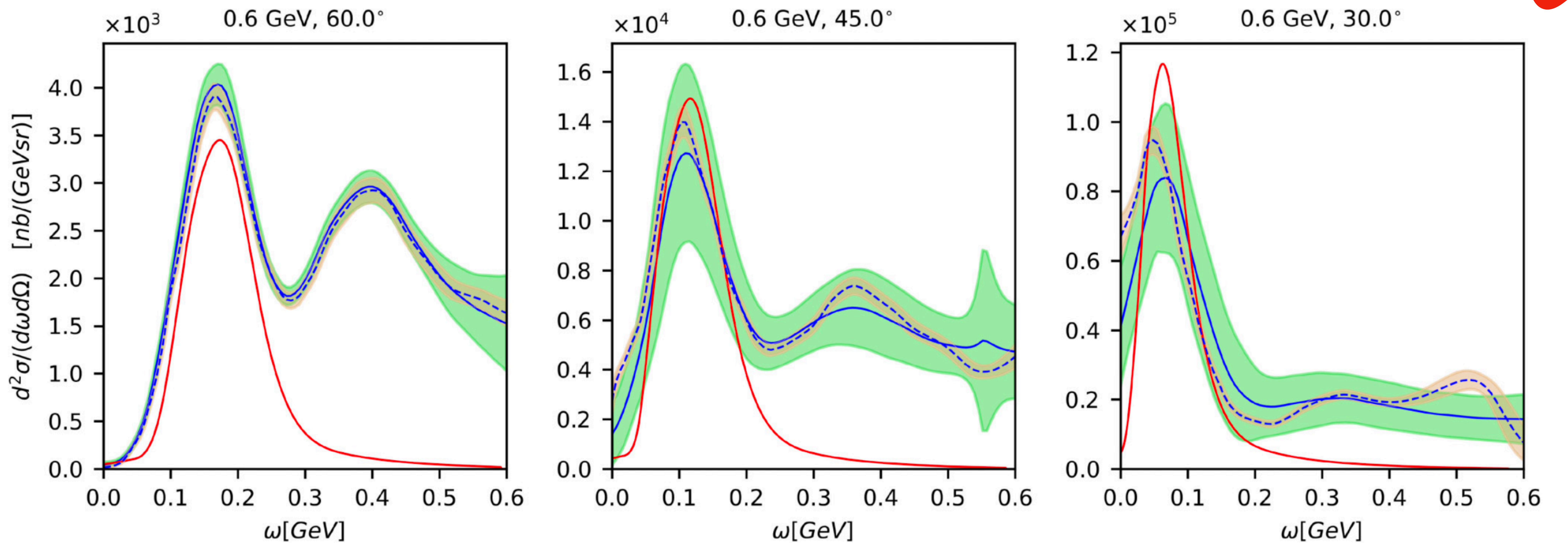


FIG. 8. Interpolation tests of the obtained fits for beam energy 0.6 GeV and scattering angles 30°, 45°, and 60°. We compare the spectral function calculations [20] of the quasielastic cross section, depicted by the solid red lines, with the predictions of model A (model B), represented by the solid (dashed) blue lines. The green (orange) areas correspond to the 1σ uncertainties.

Prediction of DNN on lepton-nucleus interaction From transfer learning

Krzysztof M. Graczyk et. al. Beata E. Kowal, arXiv:2408.09936 [hep-ph]

New

- The aim is to test pre-trained DNN model from electron-carbon scattering data on datasets from lithium to iron.

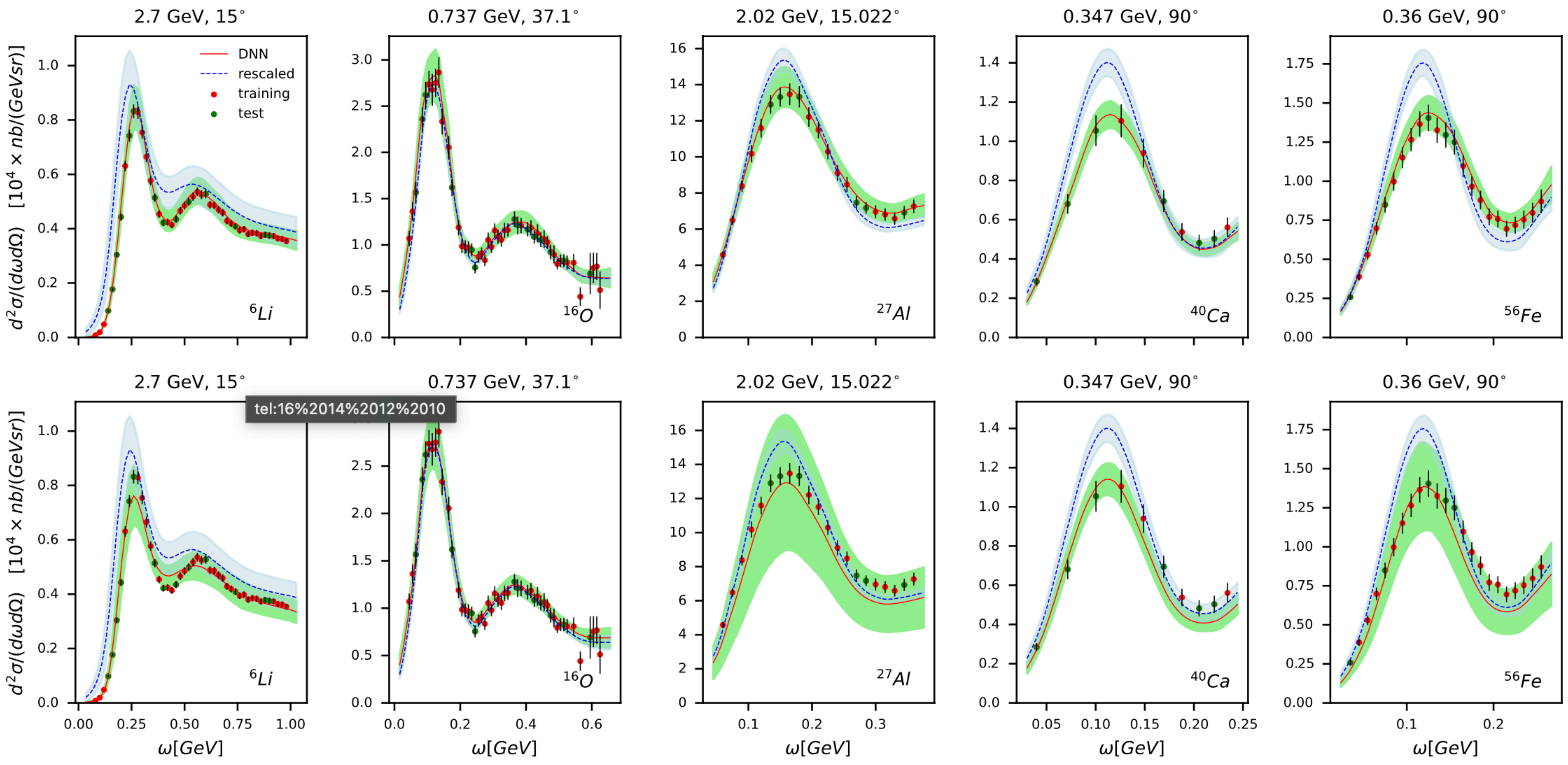


FIG. 1. Double-differential cross section $d^2\sigma/d\omega d\Omega$ for inclusive electron scattering on lithium [15], oxygen [11], aluminum [16], calcium [17], and iron [18] for selected kinematics. The fits obtained for the proportion of training to test datasets 7:3. The red line denotes the DNNs predictions, and the green area denotes 1σ uncertainty. The results for DNN with all/two last layers fine-tuned are shown in the top/bottom row. The electron-carbon DNN predictions multiplied by factor A/12 are shown by blue-dashed lines corresponding to 1σ uncertainty denoted by a light blue area. The red (green) points represent the training (test) dataset.

Prediction of DNN on lepton-nucleus interaction From transfer learning

Krzysztof M. Graczyk et. al. Beata E. Kowal, arXiv:2408.09936 [hep-ph]

New

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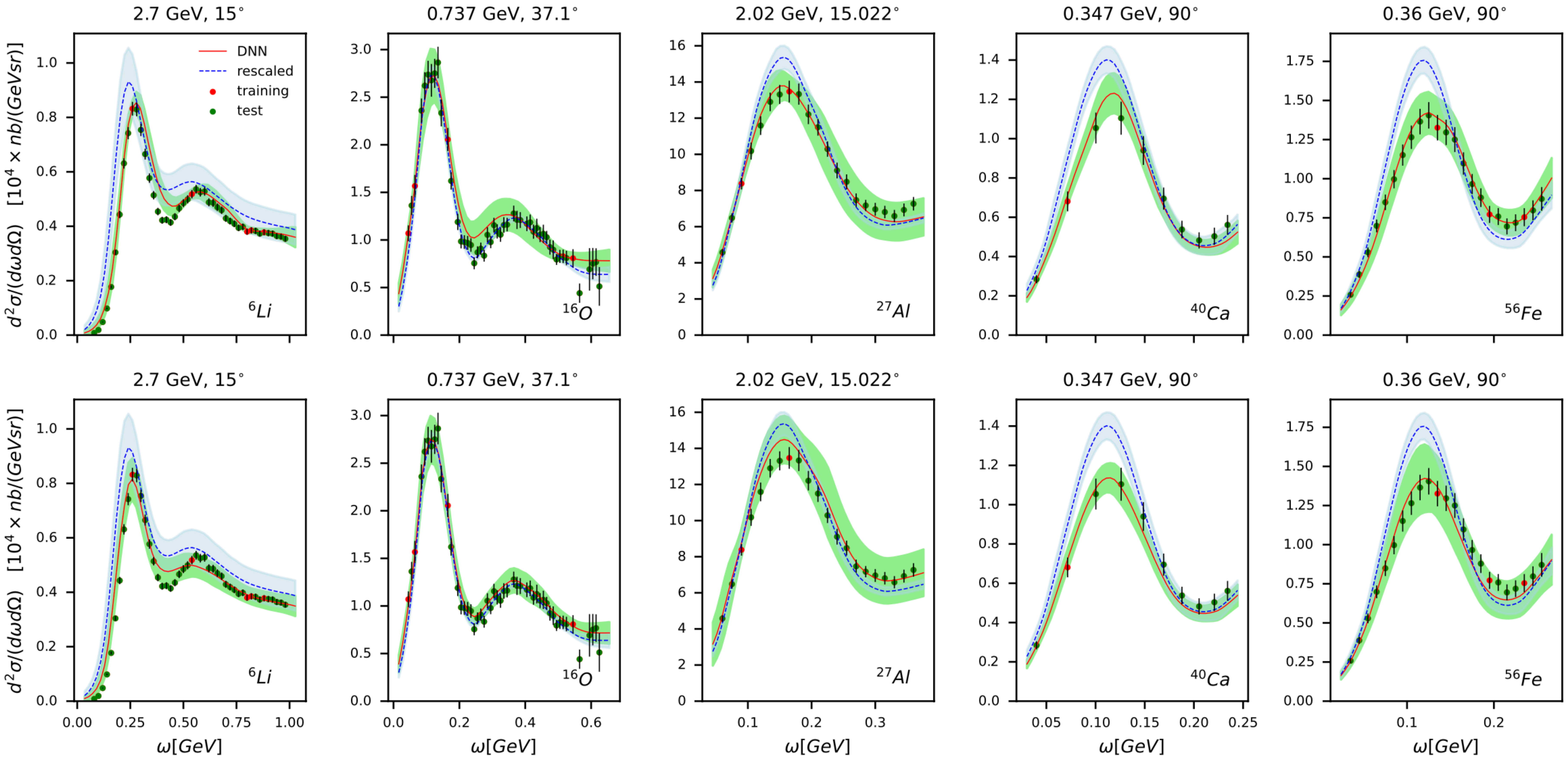


Performance of DNN with only 10 percent training dataset

Summary

✓ We implemented

- **Argon spectral function**
- Correction from nuclear effects affecting lepton.

✓ We implemented **exclusive MEC model**

- Modelling final state isospin and momenta.
- Contribution from 3p3h mechanism.

✓ We are about to include Ghent Hybrid model for single pion production

- A model independent framework based on kinematics.

✓ **Machine Learning techniques** are employed for reconstruction of **model independent lepton-nucleus interaction** in NuWro

Thank you for your attention

Frequently Asked Questions

~ NuWro Workshop, Dec 2017

1. **When will the new version of NuWro be released?**
   - New NuWro version is most likely to be released within the end of this year in the beginning of next year.
2. **How will ML techniques be incorporated into NuWro?**
   - Right now there are some work going in the field of modelling neutrino-nucleus interaction using DNN. Is too early to say how things will go.

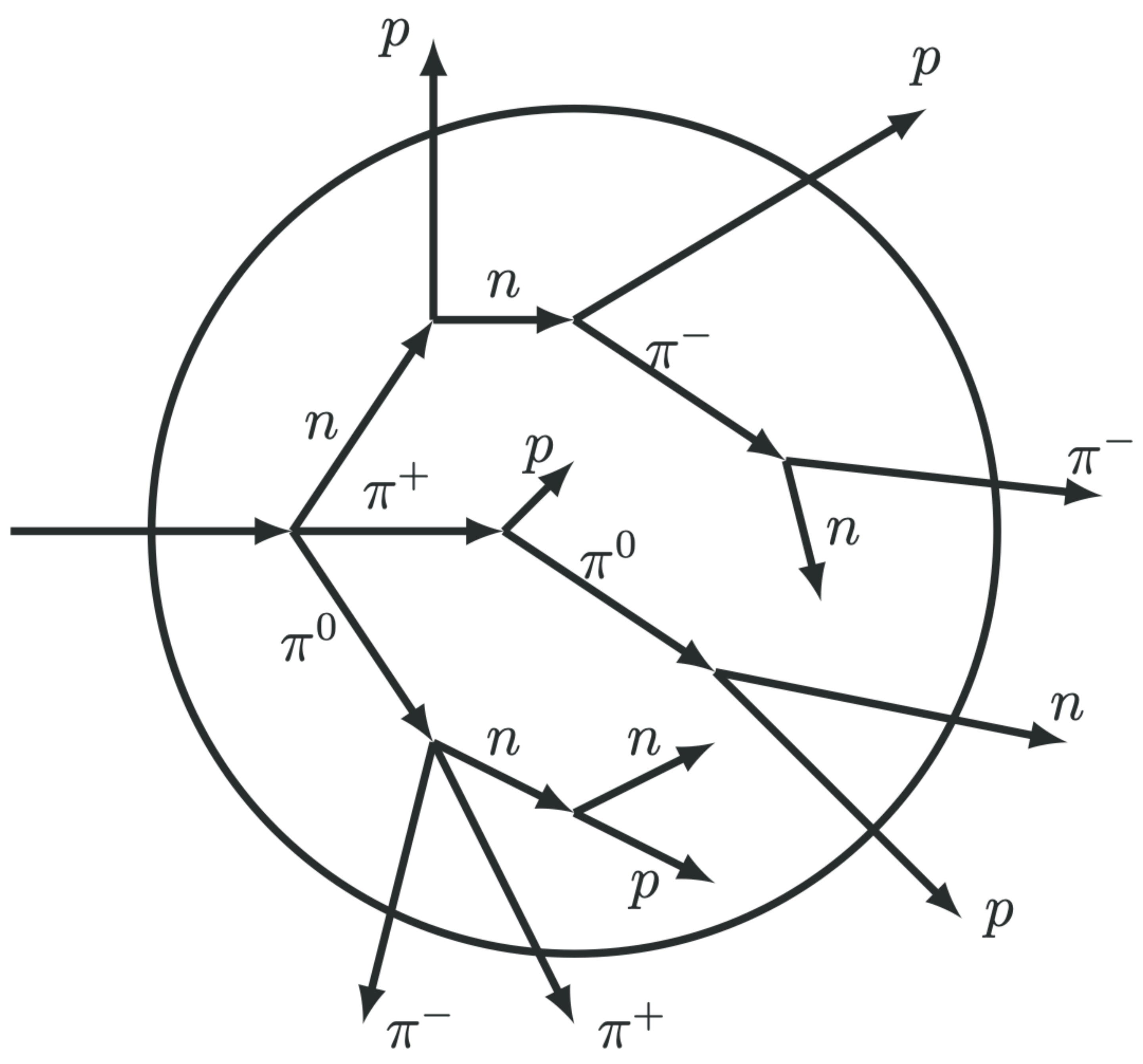
"Progress, not perfection"

Backup slides

Final State interactions

- NuWro uses intra nuclear cascade (INC) to simulate final state interactions.
- The original idea is due to Metropolis: N. Metropolis et al., Phys. Rev. 110 (1958) Nucleons, and pions from primary vertex are propagated in nuclear matter

Credit: Tomasz Golan



Possible scenario of final state interactions

Final State interactions

Credit: Tomasz Golan

- NuWro uses intra nuclear cascade (INC) to simulate final state interactions.
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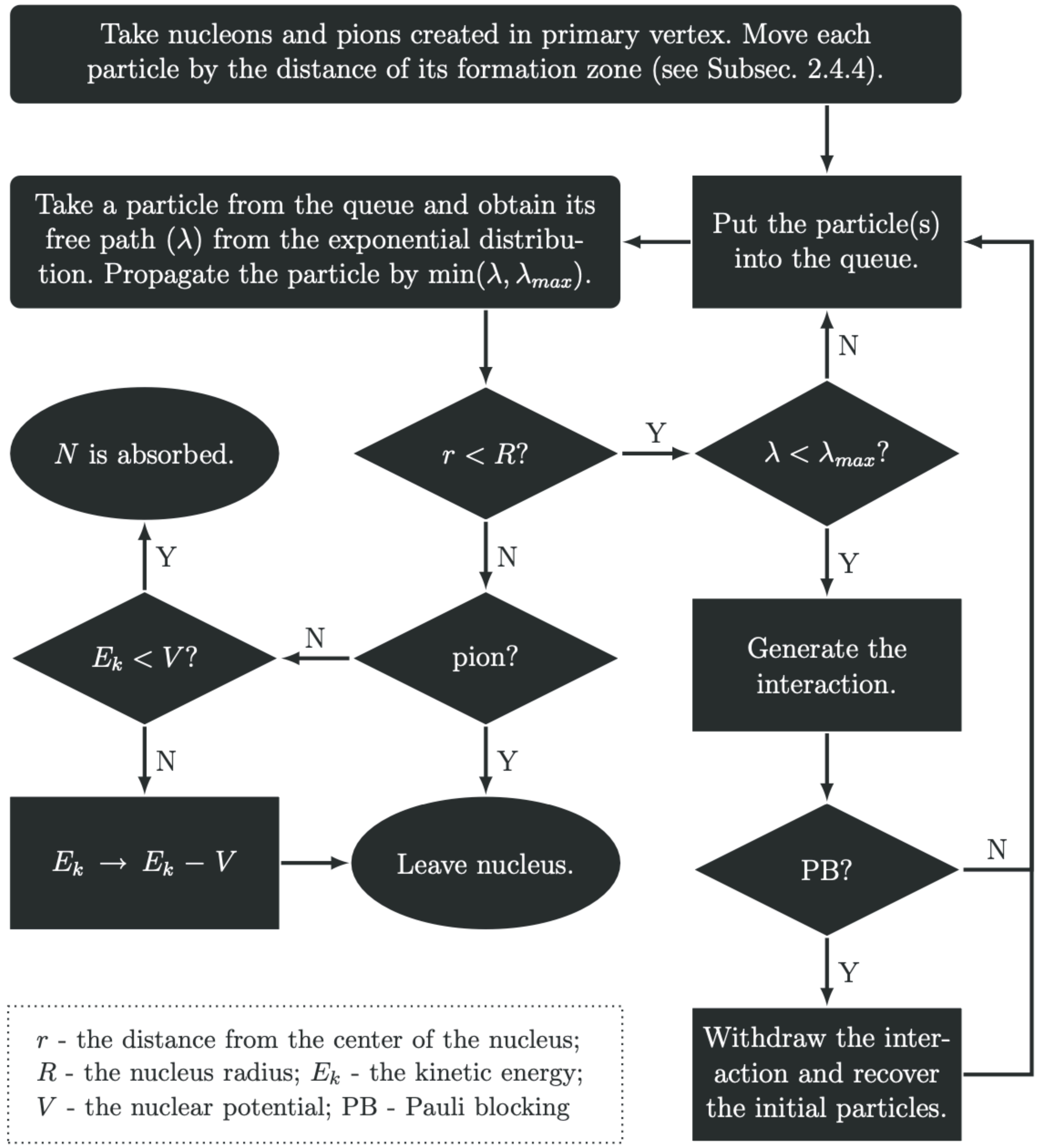

Figure 2.17: A block diagram of the NuWro INC algorithm.

Final State interactions

Credit: Tomasz Golan

- NuWro uses intra nuclear cascade (INC) to simulate final state interactions.
- The original idea is due to Metropolis: N. Metropolis et al., Phys. Rev. 110 (1958) Nucleons, and pions from primary vertex are propagated in nuclear matter
    - Nucleons…
        - Can be scattered elastically.
        - Can exchange electric charge.
        - Can produce more pions.

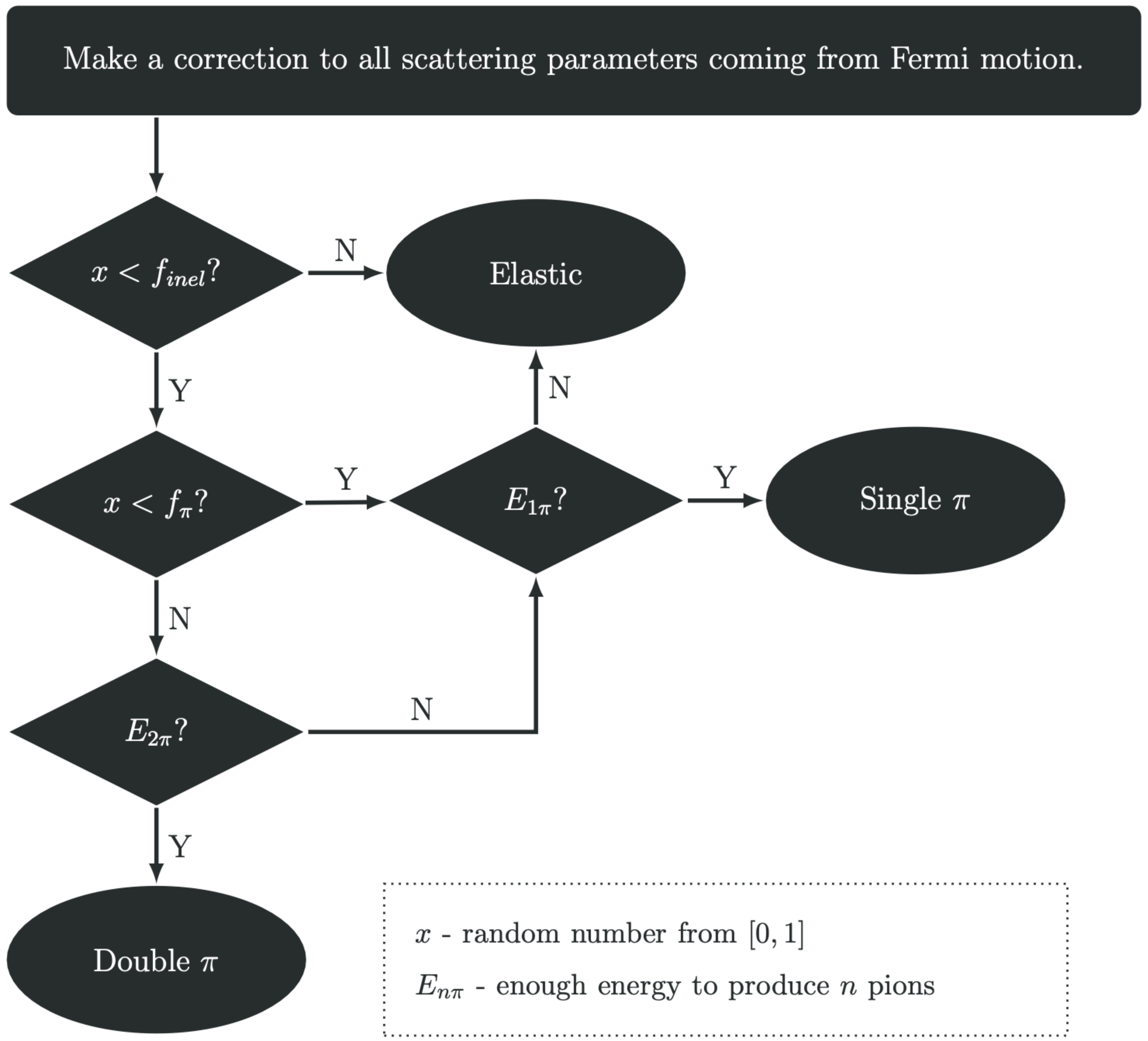

Figure 2.18: A block diagram of the algorithm for "Generate the interaction" from Fig. 2.17 in the case of nucleon-nucleon scattering.

Final State interactions

Credit: Tomasz Golan

- NuWro uses intra nuclear cascade (INC) to simulate final state interactions.
- The original idea is due to Metropolis: N. Metropolis et al., Phys. Rev. 110 (1958) Nucleons, and pions from primary vertex are propagated in nuclear matter
    - Pions
        - Can be absorbed
        - Can be scattered elastically
        - (If energetic enough) can produce new pions
        - Can exchange electric charge with nucleons

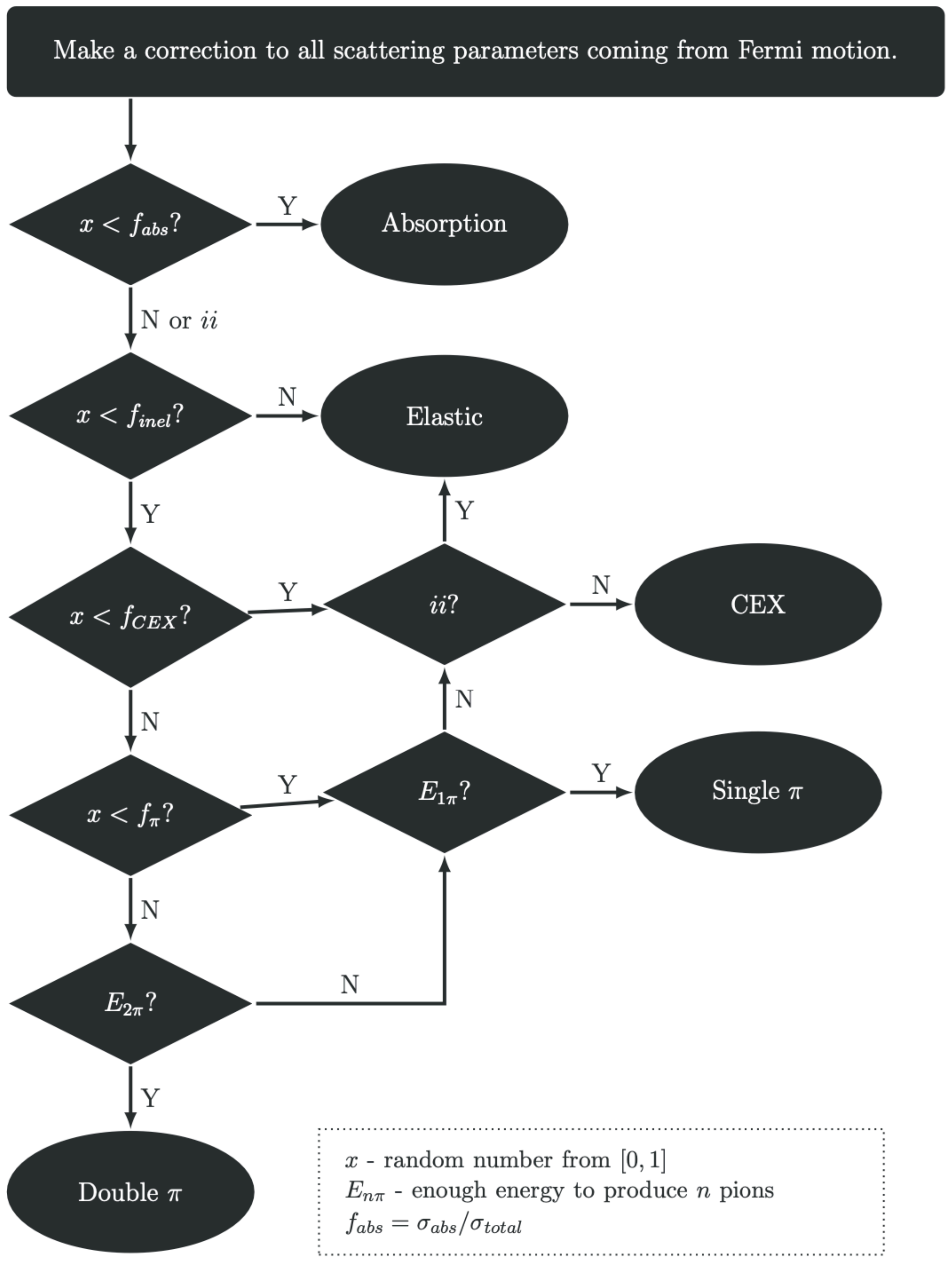

Figure 2.20: A block diagram of the algorithm for "Generate the interaction" from Fig. 2.17 in the case of pion-nucleon scattering.