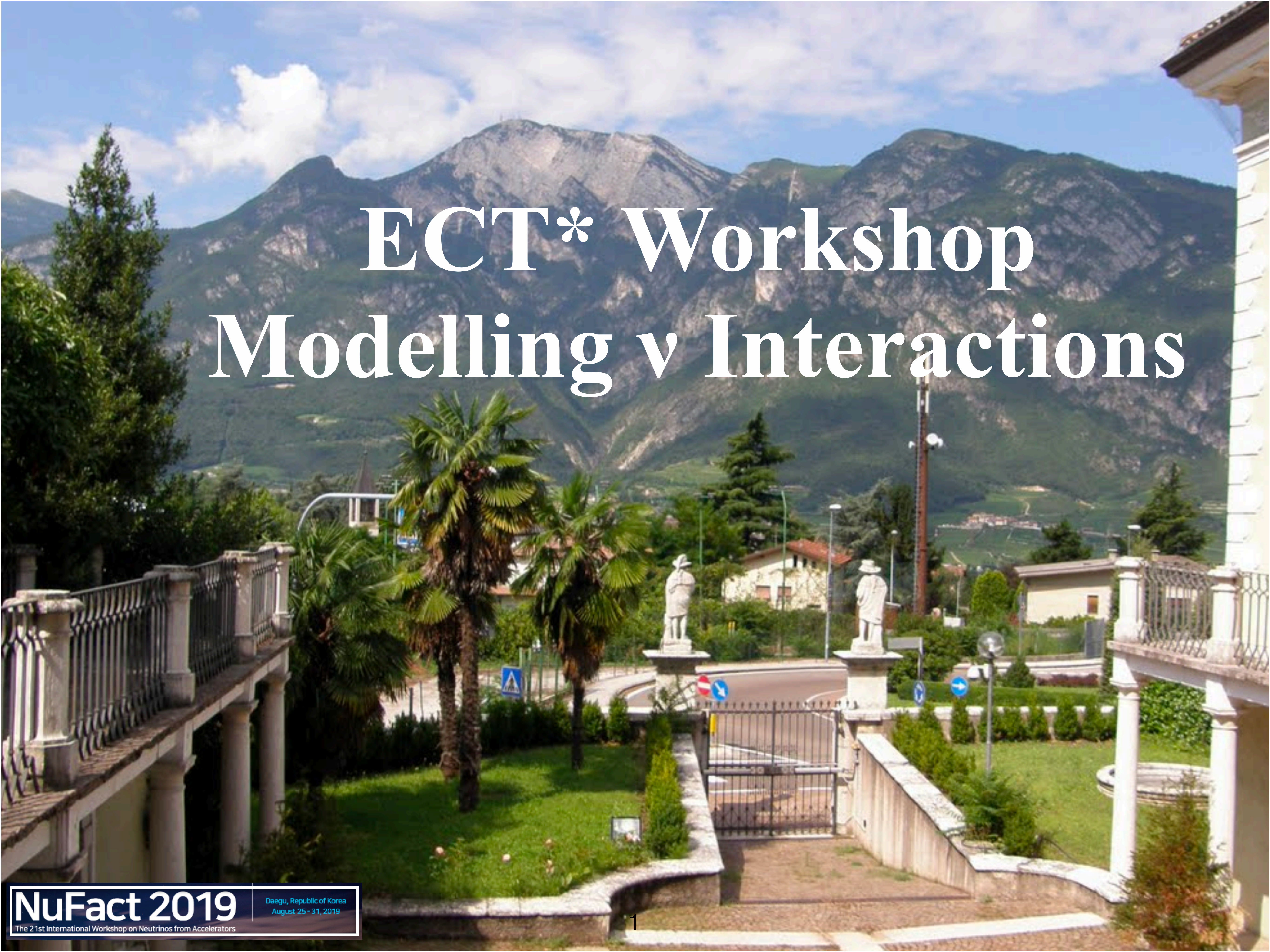
ECT* Workshop
Modelling ν Interactions



NuFact 2019
The 21st International Workshop on Neutrinos from Accelerators
Daegu, Republic of Korea
August 25 - 31, 2019

ECT* - European Centre for Theoretical Studies

Located in beautiful Trento, Italy

ECT* Support research in:

Nuclear Structure and **Nuclear Reactions**, and related topics

Hosting workshops

Modelling ν interactions Workshop

Goals:

To improve the neutrino-nucleus events generators

by:

- Learning from the nuclear physics community
- Share models, tunes and methods inside the generators community

Modelling ν interactions Workshop

Organisers:

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Participants:

Generator representative, Theory groups, Electron scattering experimentalists

Structure:

4 main working group with assigned homework in advance

Review task list for the meeting

Ending presentation on progress and plans

Website: https://indico.ectstar.eu/event/53/

This workshop followed a theory oriented one: https://indico.ectstar.eu/event/48/

Bridging between ν and N communities

The neutrino community needs:

The electron scattering experiments measures and theorist predicts:

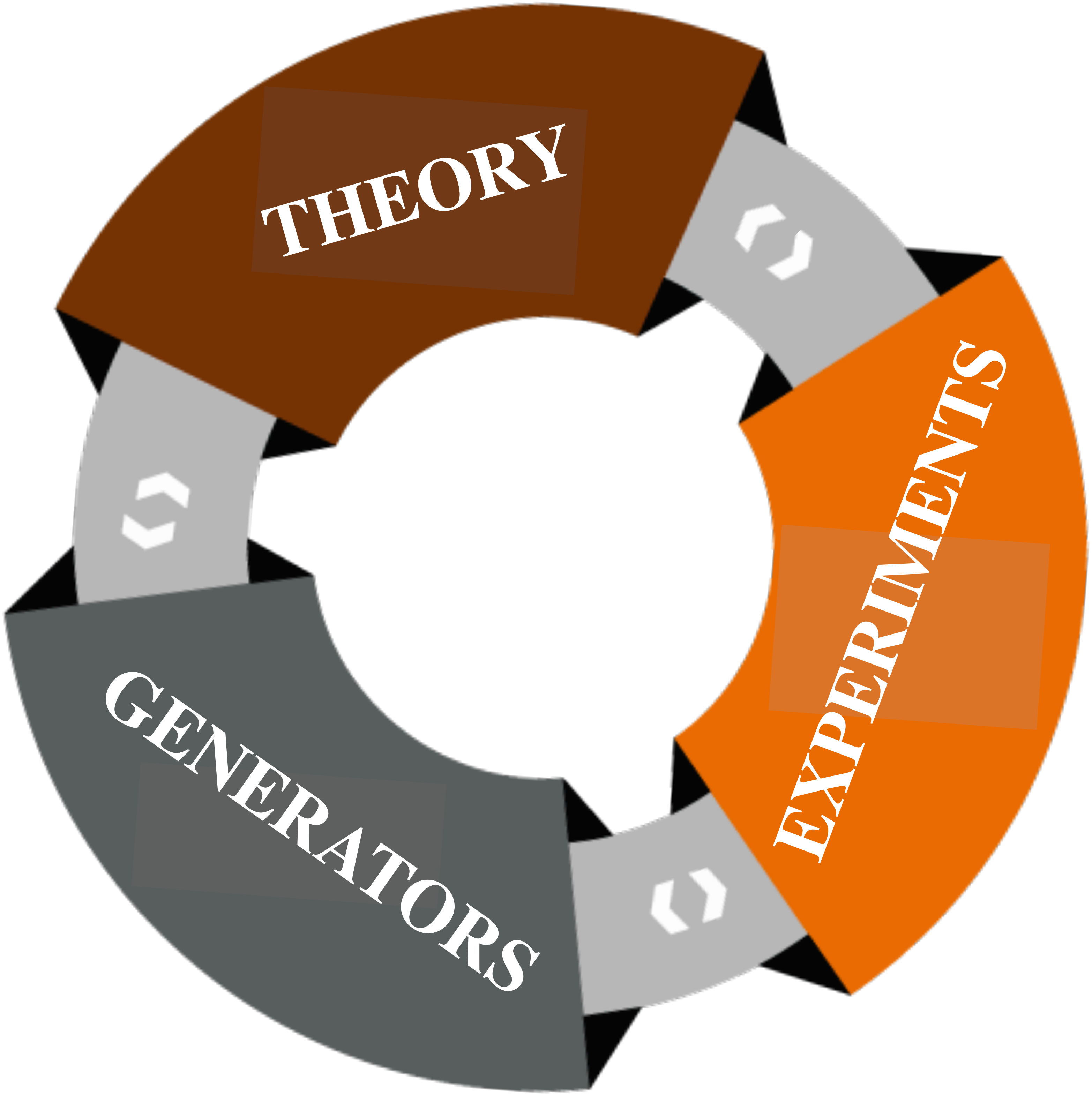
Valid predictions for different interaction channels

Inclusive rates vs. energy transfer

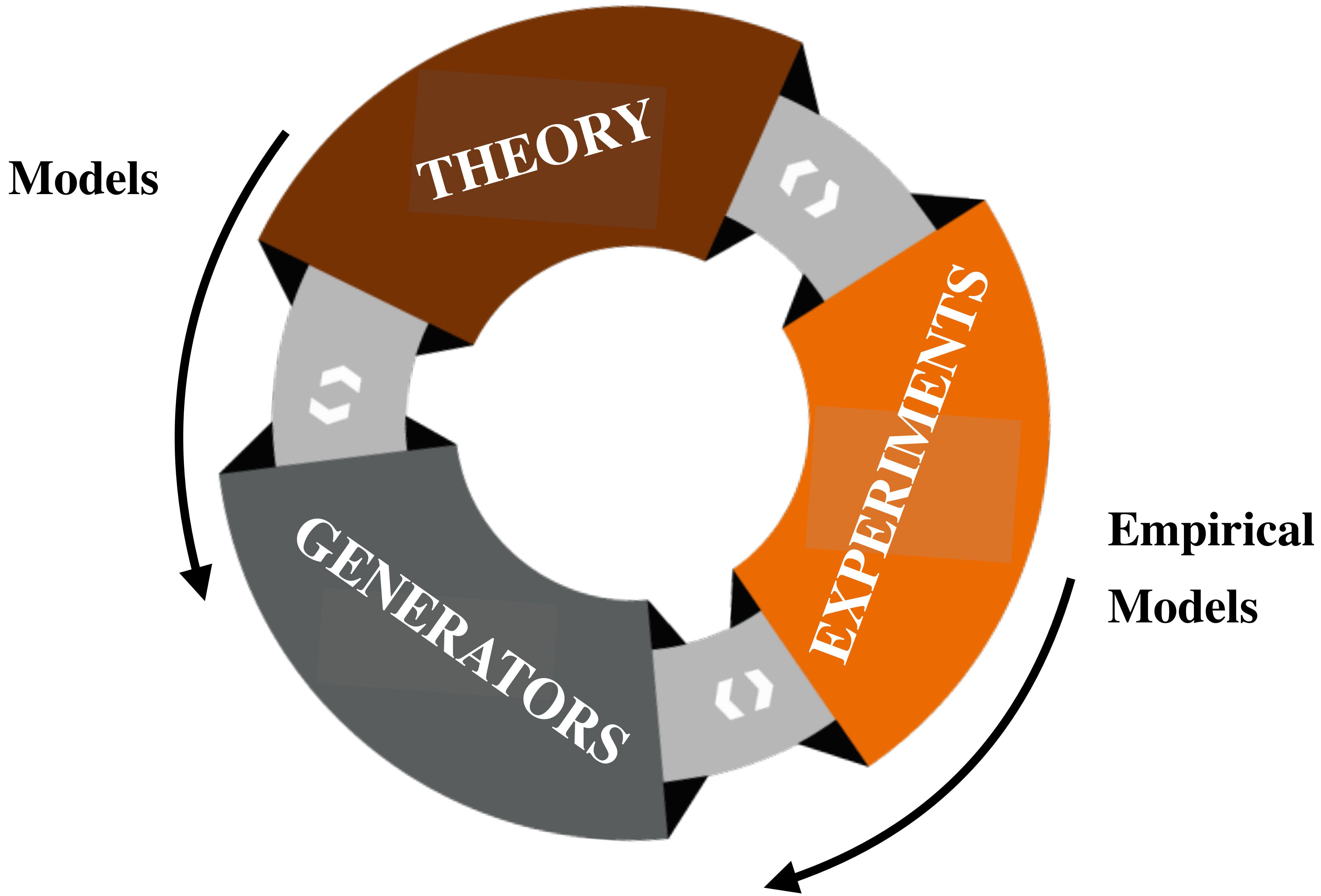
Heavy nuclei studies

Only lower A nuclei till now

WG2 Cross Section Focus



WG2 Cross Section Focus



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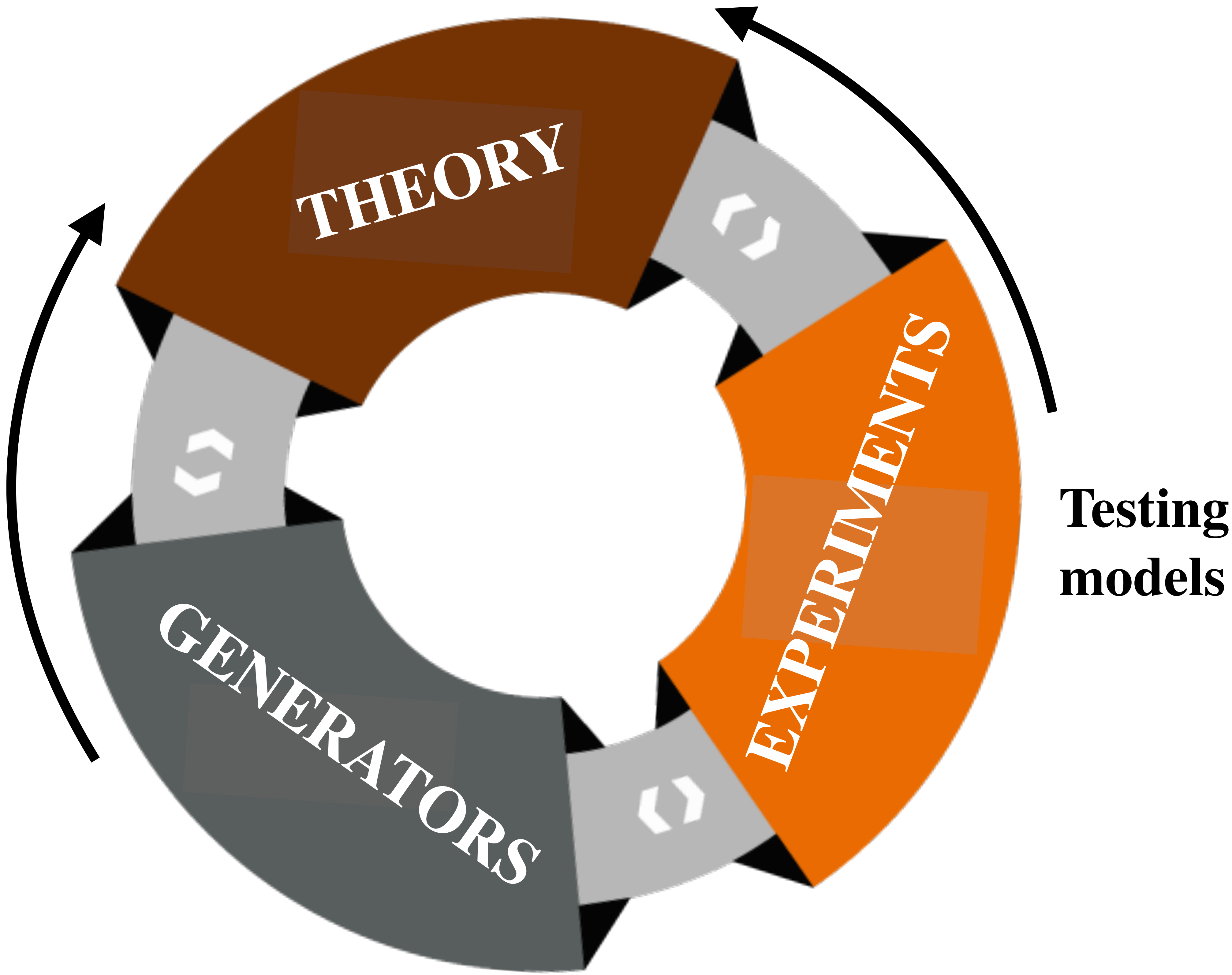
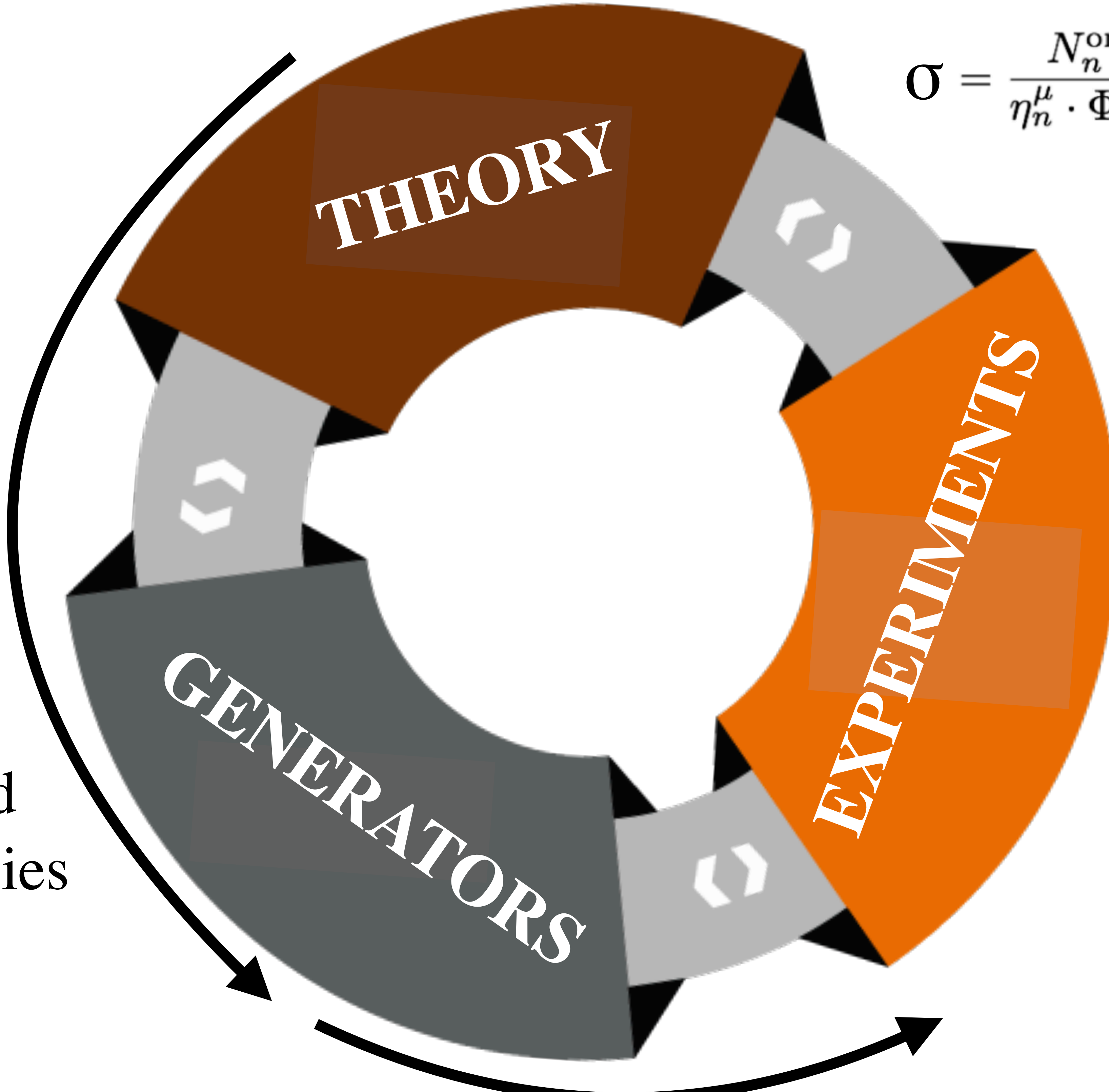


WG2 Cross Section Focus



$$\sigma = \frac{N_n^{\text{on}} - N_n^{\text{off}} - B_n}{\eta_n^{\mu} \cdot \Phi_{\nu} \cdot N_{\text{targets}} \cdot \Delta_n^{\mu}}$$

The background & efficiencies are model dependent

Modelling ν interactions Workshop

Generators goals

Comparison between models

Implementing specific models

Unified models for neutrino and electrons scattering

Generators goals

1. Structure for exclusive models
2. Design an interface for theorists to provide models.
3. Better ability to compare multiple models and generators
4. Improved reweighting functionality and documentation of reweighting
5. More information about, and ability to interact with and modify, the tuning of the parameters in interactions

Factorisation

$$\frac{d^2\sigma}{dq_0q_3} = \sigma_0\eta_{ij}(q_0, q_3)W_{ij}(q_0, q_3)$$

Contraction of leptonic and hadronic tensors.

Expanding in general way one get 10 response functions most of them cancel when integrating over the hadronic kinematics.

The leptonic part is easily calculated

The hadron tensor elements are sorted in tables per target in q_0, q_3 space

Adapted from: https://indico.ectstar.eu/event/19/contributions/221

Factorisation

Generators like GENIE predict hadron kinematics:

1. Start with inclusive prediction
2. Pick random initial state nucleon momentum (irrespective to q_0 and q_3)
3. Get removal energy from RMF (re-throw if nucleon is pauli blocked)
4. Transfer all q_0 q_3 to nucleon (none to remnant)
5. conserve energy / momentum at the vertex to predict hadron kinematics (under impulse approximation)
6. add FSI cascade

In reality the components are not separable

e.g hadron tensors in primary interaction should encapsulate the nuclear model.

Factorisation

This method is useful for speeding up new models implementation

limitations:

- Lepton kinematics only
- No ability to tune or reweight parameters used to make the tables

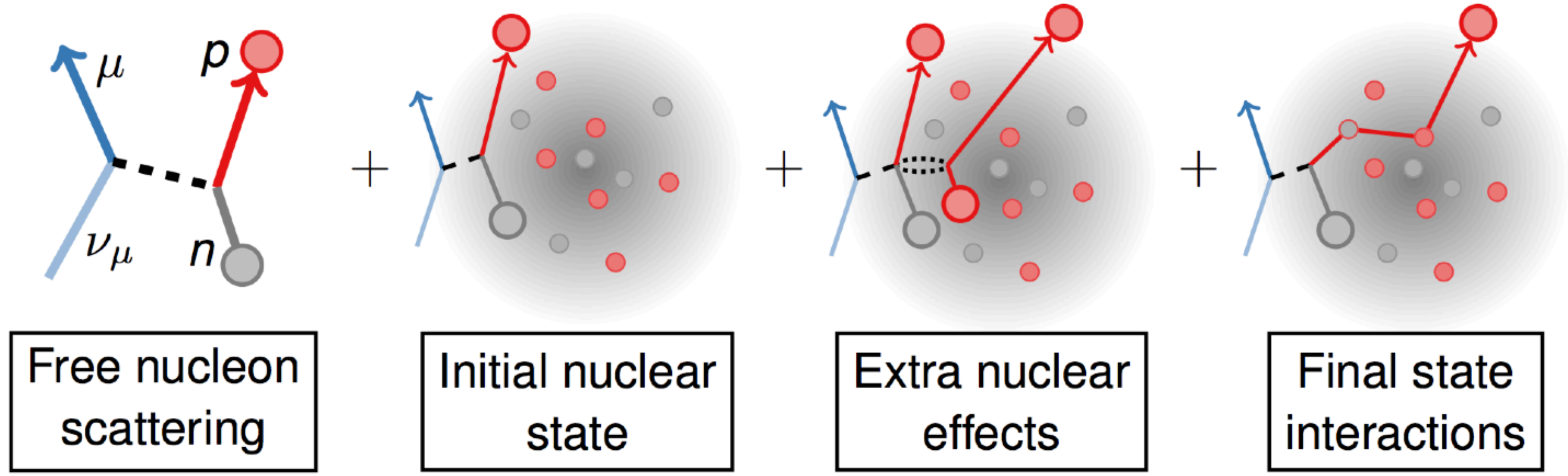
Possible to add hadron kinematics by including more tabulated responses.

Testing the factorisation approach:

compute exclusive results using theory, compare to same theory implemented in generator

Note, the spectral function formalism in does not have this problem

Consistency



Kajetan Niewczas @ NuFact2018

Nuclear ground state should be same for all channels

FSI should be consistent across processes

initial state effects should be consistent

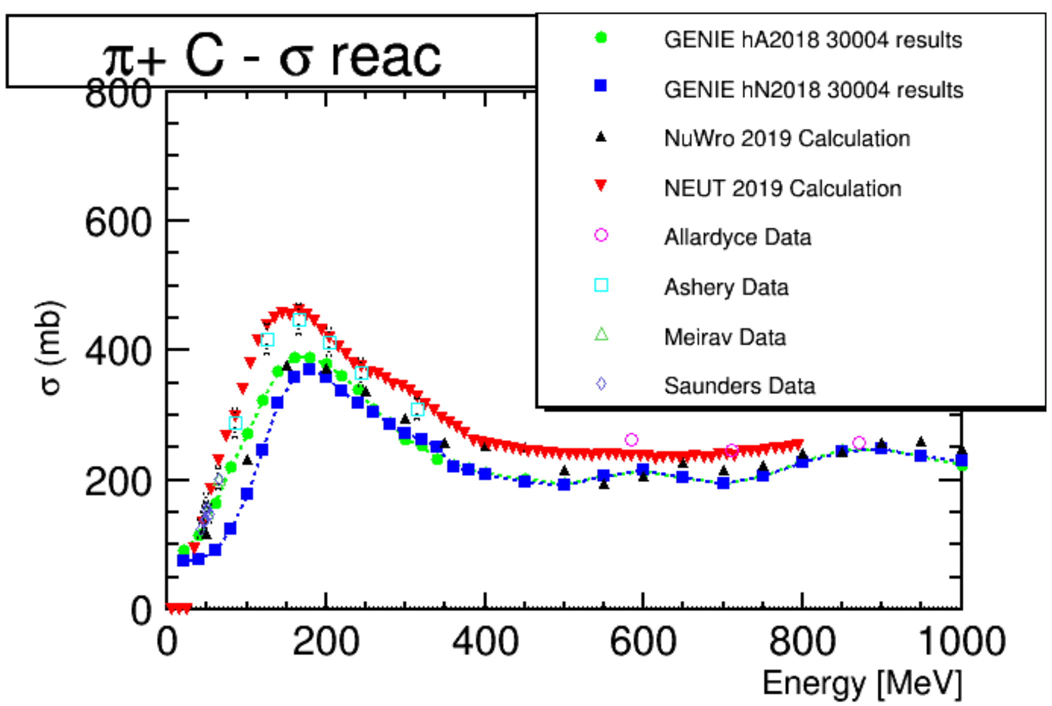
FLUKA & GiBUU get this by design

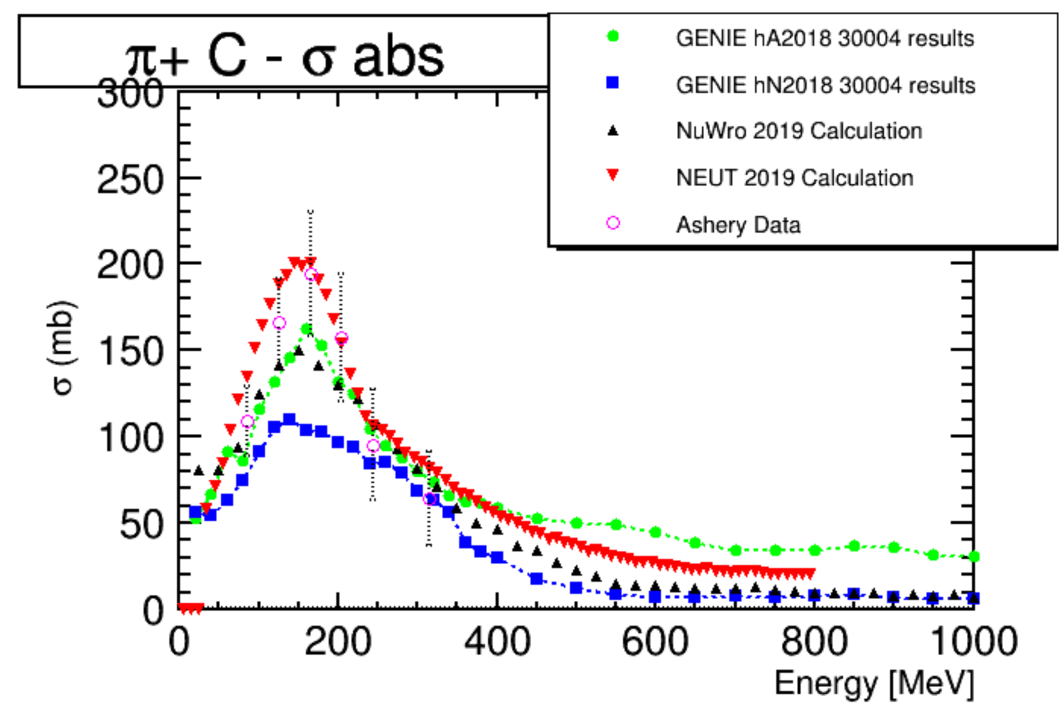
Comparing Generatros and models

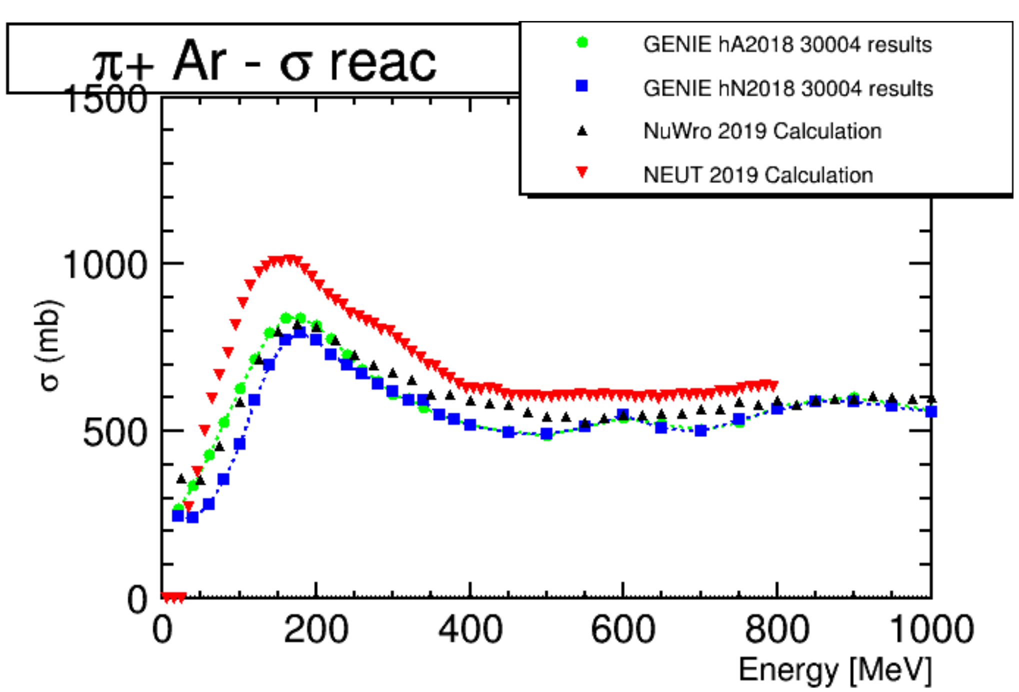
Final State Interaction

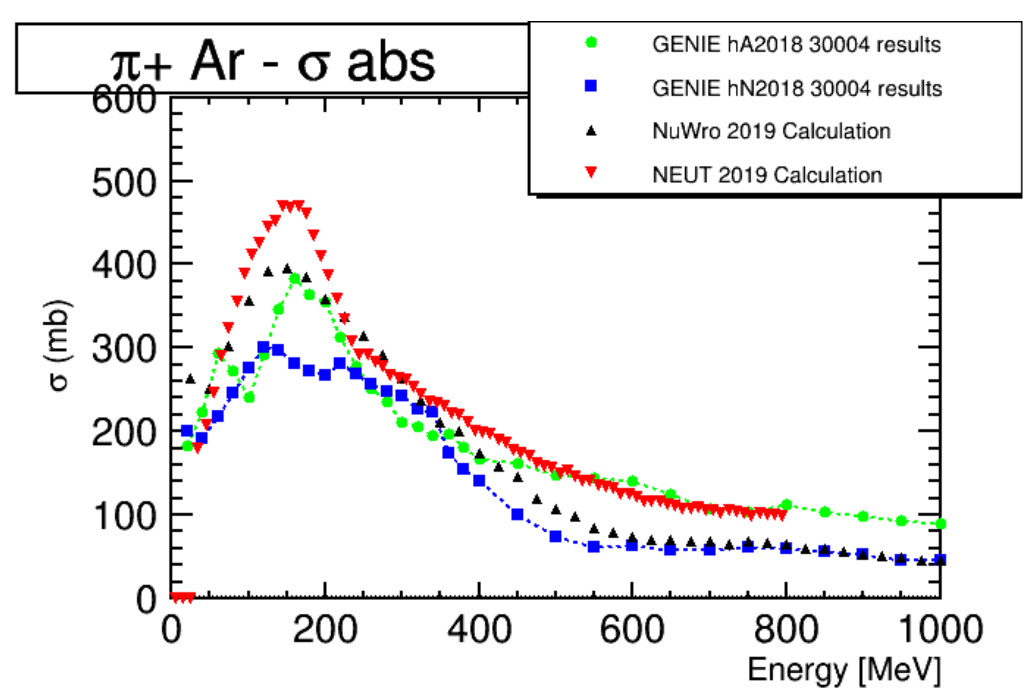
Generator	for π	for nucleons	comments
NEUT	Based on **Oset et al** with later fit to pion-nucleus data	**Bertini** model	
Genie UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT	**Oset et al**	**Pandharipande-Pieper** with in medium modifications	Also available: hA data driven model
NuWro Wroclaw Neutrino Event Generator	**Oset et al**	**Pandharipande-Pieper** and nucleon-nucleon correlation eects arXiv:1902.05618 [hep-ex]	

π production



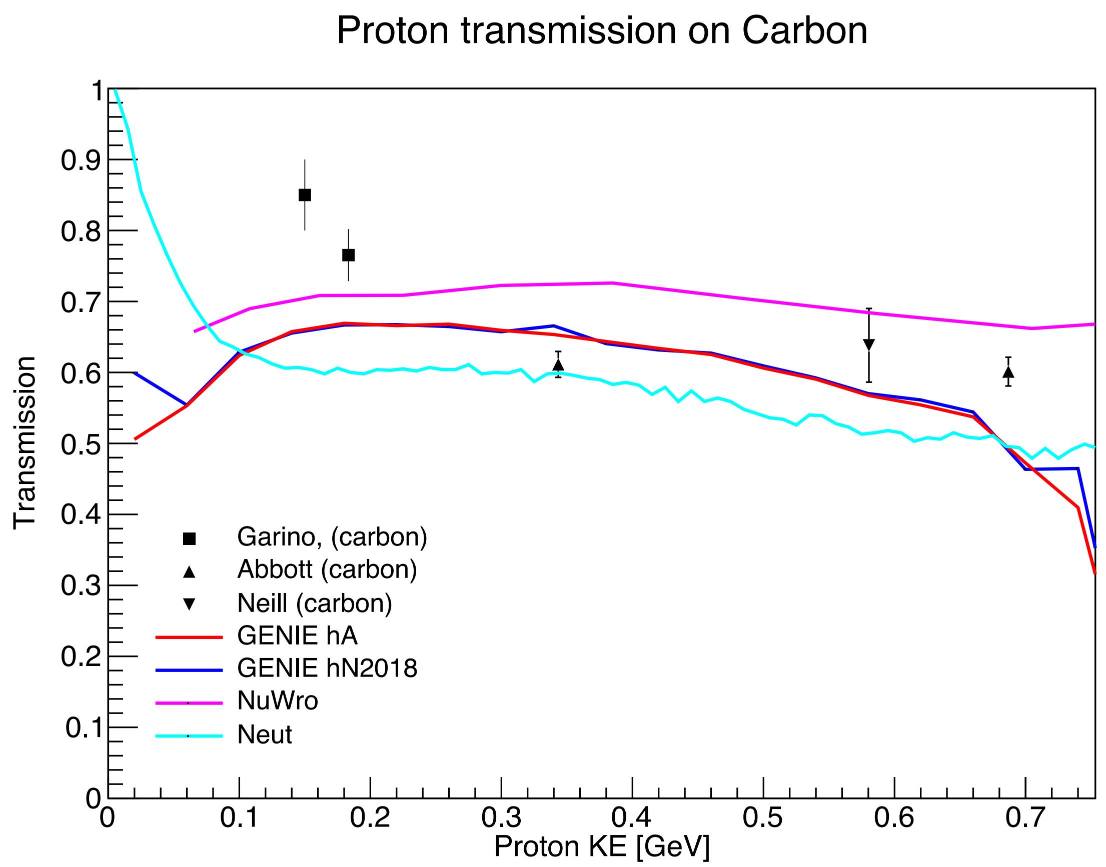


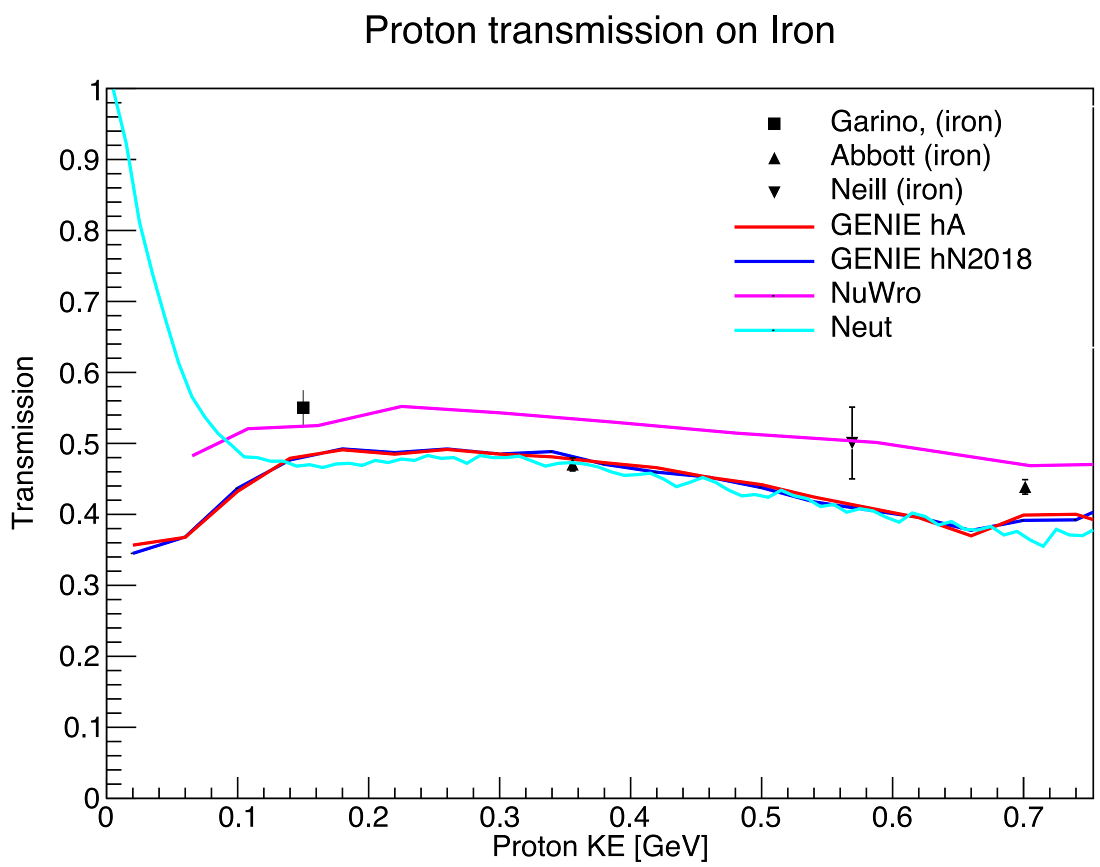




Transparency

Calculated as the ratio of counted protons before and after FSI





Reasonable agreement at high kinetic energy

Implementing specific models

Relativistic Mean field models

1. Write a nucleon-nucleon interaction Hamiltonian

   For the relativistic case, extension of σ-ω Walecka model Ann. Phys.83.491(1974)

2. Solve the equations of motion in the mean-field

   All nucleons feel the same average interaction

   Solve equations self-consistently until the solutions converge.

3. Obtain bound-states, binding energy and potentials

4. Solve the final state wave function in the same potential

$$\frac{d^5\sigma}{dE_f d\Omega_f d\Omega_N} = \mathcal{F}\frac{p_N E_N k_f \varepsilon_f}{(2\pi)^5 f_{rec}} l_{\mu\nu} h^{\mu\nu}_{QE}, \quad ($$

$$h^{\mu\nu} = \overline{\sum_{s_N, m_j}} \langle \Psi_f | \mathcal{O} | \Psi_i \rangle^\dagger \langle \Psi_f | \mathcal{O} | \Psi_i \rangle$$

See Alexis Talk from yesterday

Relativistic Mean field models

- Relativistic mean field model describes well the νA interaction
- Features consistency and orthogonality.
- Can be used as an input to the MC generators without double counting the FSI.
- To implement the RMF fully one needs to sample the fivefold cross section and not decouple the momentum distribution.

See Alexis Talk from yesterday

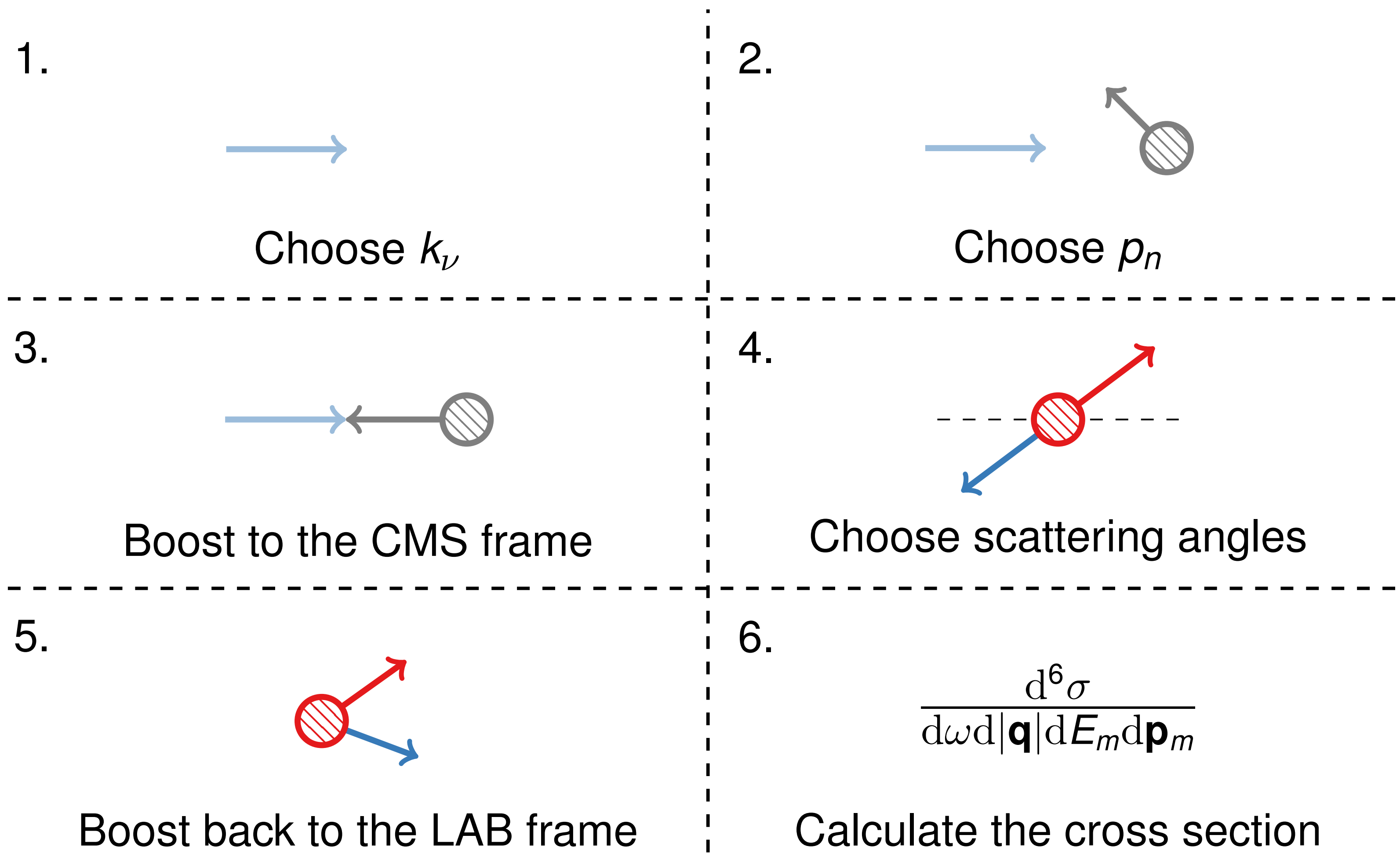
Spectral functions

Spectral Function is the probability distribution of removing a nucleon with momentum p and leaving the residual nucleus with the excitation energy E

$$S(E_m, \mathrm{p}_m) = \sum_n \left| \left\langle \Psi_n^{A-1} \right| a_{p_m} \left| \Psi_0^A \right\rangle \right|^2 \delta(E_m + E_0 - E_n)$$

Spectral functions

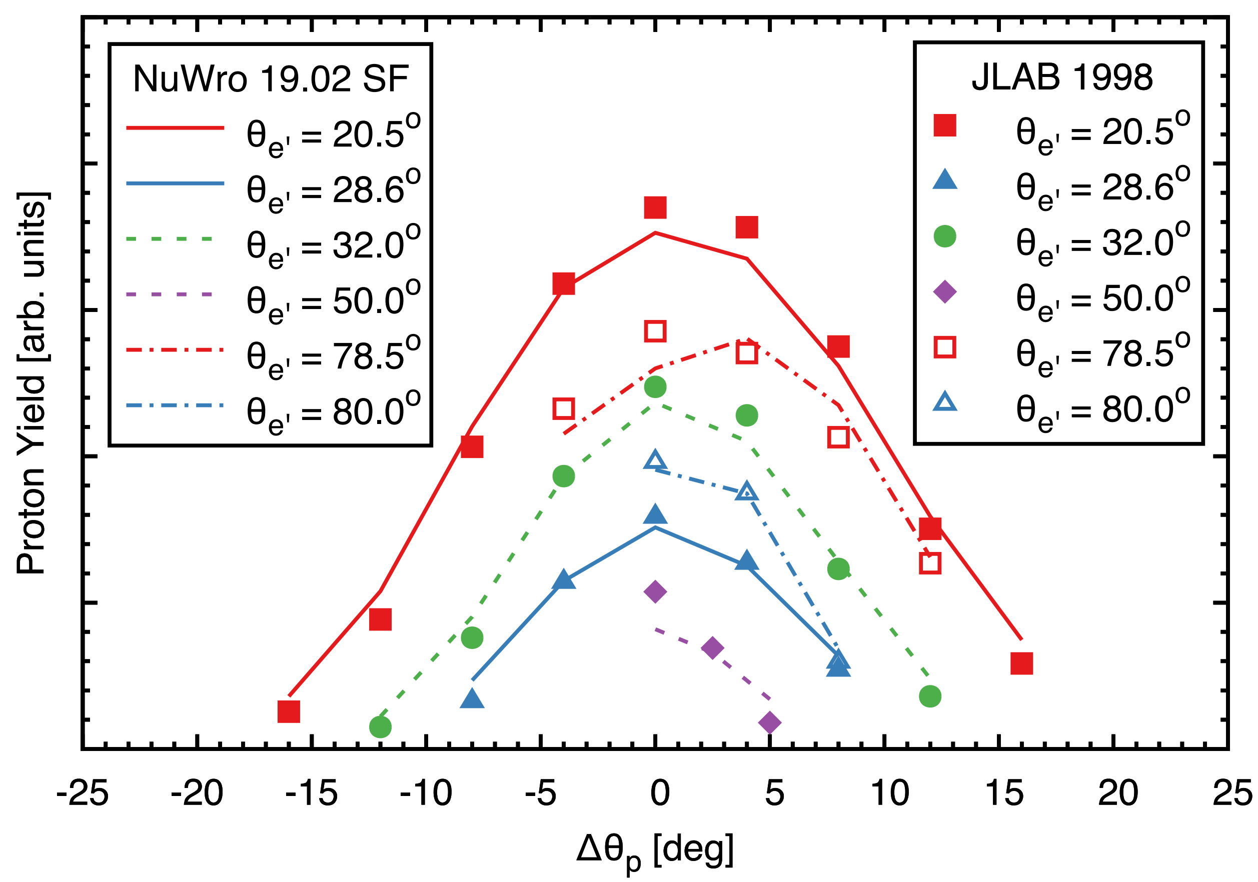
Available for: Carbon, Oxygen, Calcium, Argon, and Iron



Spectral functions

Available for: Carbon, Oxygen, Calcium, Argon, and Iron

Exclusive results



Neutral current scattering of ν_e on protons, arXiv:1902.05618

Spectral functions

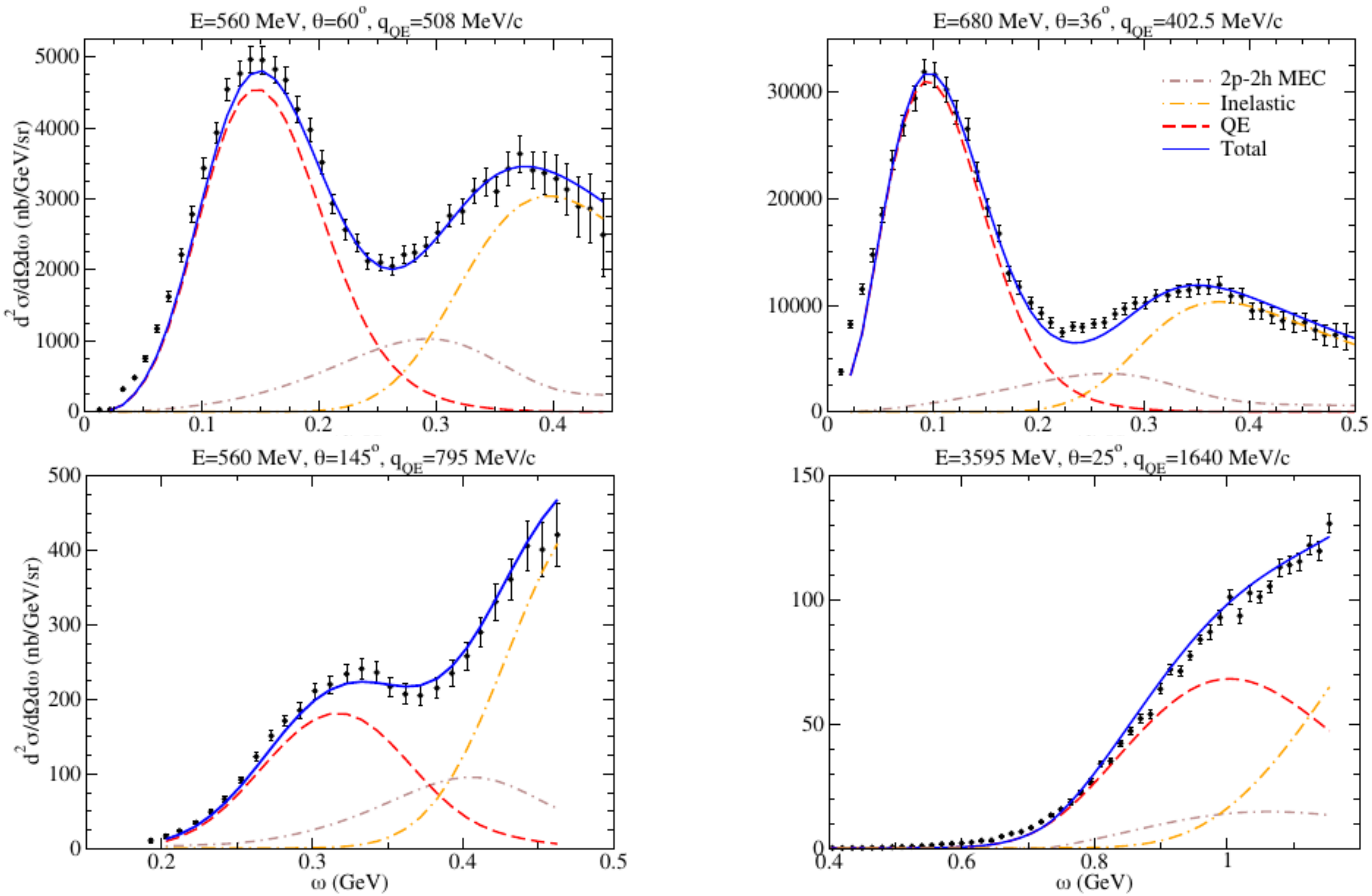
The default models are using RFG

Currently working on first implementation of SF using Self Consistent Green's Function Model

SuSAv2

Describes well inclusive data

$^{12}C(e,e')$



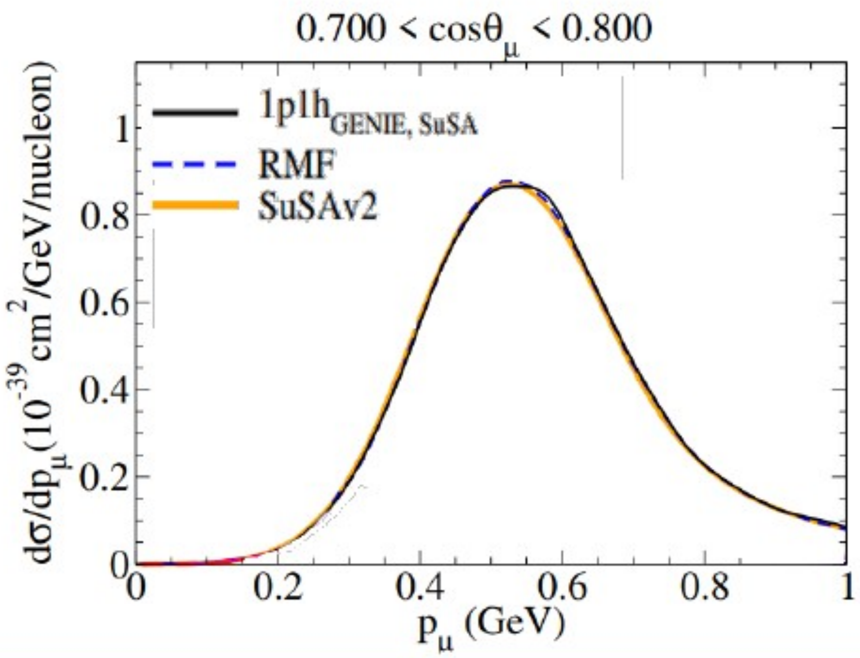
G. D. Megias PRD 94, 013012 (2016)

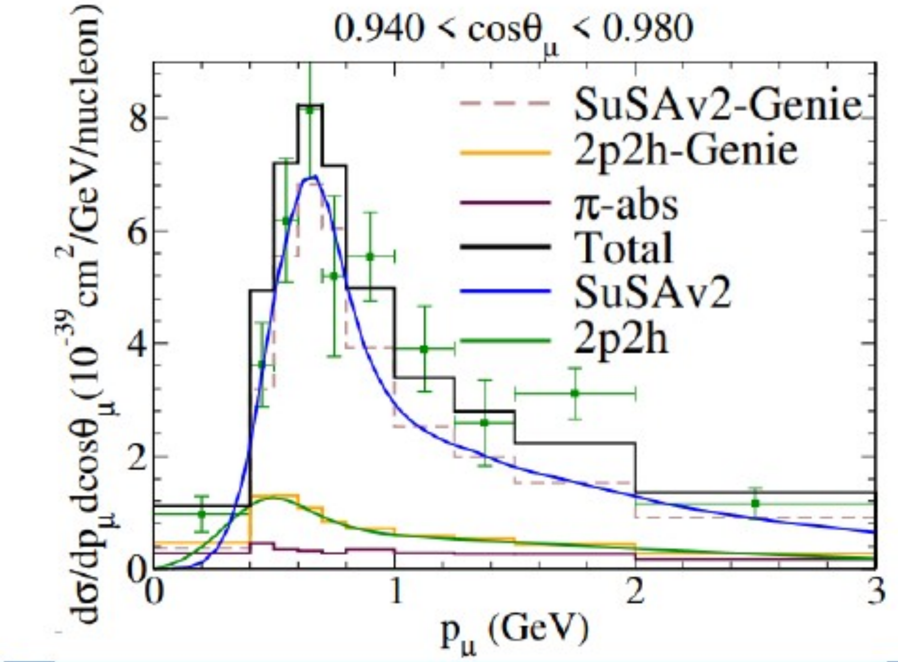
SuSAv2

Super Scaling 1p1h and 2p2h models were recently implemented in GENIE

Based on the Valencia model implementation using Hadronic Tensors

Successfully reproducing inclusive predictions





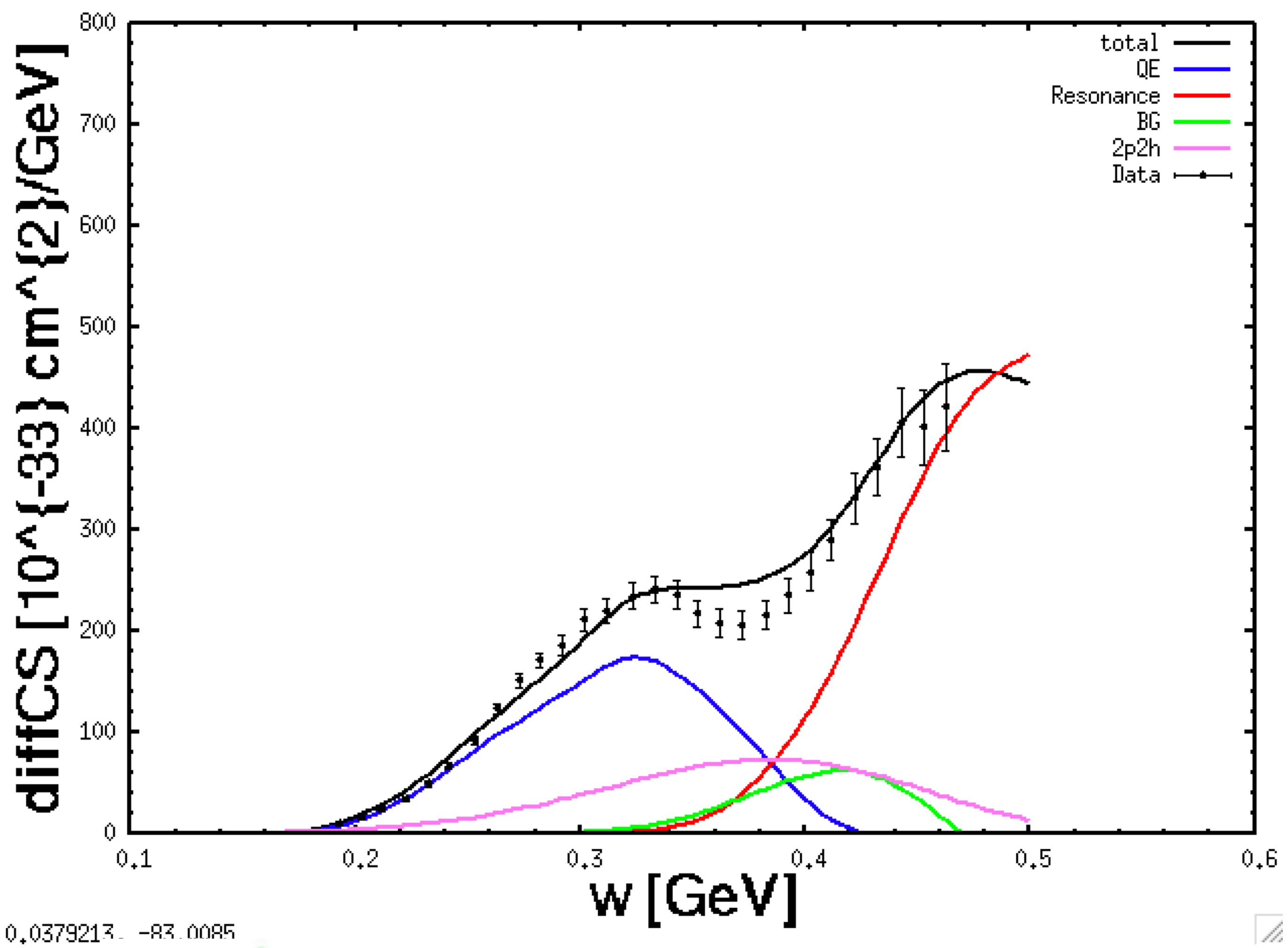
S. Dolan Based on: arXiv:1905.08556

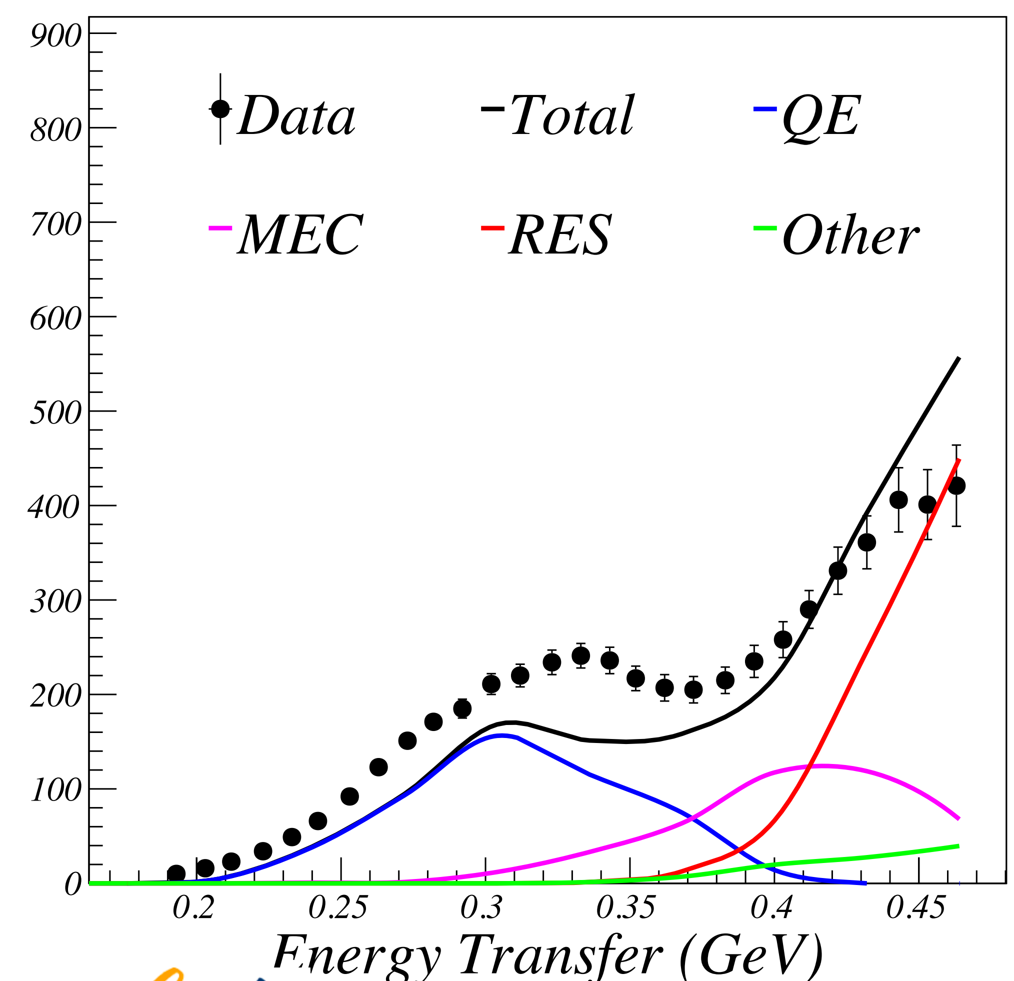
Unified models for ν and e scattering

Learning from electron scattering data

Comparing neutrino generators to electron scattering data can help benchmark the models and constrain their vector part

$$^{12}C\ @E = 0.56\ GeV\ \&\ \theta = 145^{o}$$





GiBUU

Learning from electron scattering data

The e4ν project deals with the following challenges:

1. The detector acceptance
2. Removing irrelevant background
3. Radiative effects
4. How to probe relevant phase space

In addition the community has learnt about Short Range Correlation studies done with electron scattering.

Generators

We've created a database for all e and ν model implementation in all relevant generator.

See backup slides for more

Genie	Model Name	v	e	Detailed electron mode implementation
COherent	Ahrens	+	-	
	Coherent pion	+	-	
Quasi **E**lastic	Rosenbluth	-	+	Stand alone code only for electrons
	Llewellyn Smith	+	+	Calculating for v, if probe is electron modify coupling constants (release candidate for v3.2)
	SUSA	+	+	SDo: Works for nu and e in the same code using hadron tensor table framework (although of course the nu and e tensors are different). Inclusive model implementation.
	Nieves dipole	+	-	
	Nieves z exp	+	-	
Meson **E**x**C**hange	Empirical Dytman model	+	+	Calculating for v, if probe is electron modify coupling constants.
	Nieves	+	-	
	SUSA	+	+	SDo: Works for nu and e in the same code using hadron tensor table framework (although of course the nu and e tensors are different). Inclusive model implementation. Can predict the different contributions from different initial state pairs for e and for nu.
RESonance	Rein Sehgal	+	+	Calculating for v, if probe is electron modify coupling constants
	Berger Sehgal	+	+	Calculating for v, if probe is electron modify coupling constants
Deep **I**nelastic **S**cattering	Bodek-Yang			

GiBUU	Model Name	v	e	Detailed electron mode implementation
COherent				
Quasi **E**lastic	QE[1]	+	+	The electron σ is calculated using the formfactor BBA2003 parametrization. For the neutrino cross section, the vector form factors are extracted from the electrons ones based on CVC, the axial form factor is using the dipole form with the axial vector constant, gA, taken from β decay, and Q2 dependence tuned to neutrino data.
Meson **E**x**C**hange	SuSA	+	+	?
	Empirical	+	+	The cross section for electrons is obtained from a data analysis by Bosted and Christy, and the neutrino one is then extracted based on the relations between the e and v structure functions used by the Lyon group[2]
RESonance	Phenomenological FF	+	+	For the e σ calculation, the helicity amplitudes are determined in the MAID analysis[3] For σv , the vector form factors, C_{6V} C_{5V} C_{4V} , are extracted from the electrons ones based on the CVC. $C_{5A}(0)$ is obtained by fitting the available pion production data on an elementary target. C_{3V} is taking the modified dipole form. C_{3A} is set to zero. C_{6A} can be related to C_{5A} by PCAC. C_{5A} parametrization is given in Leitner et al..
Deep **I**nelastic **S**cattering	[4]	+	?	1. lepton interacts with a nucleon, modeled by Pythia (nucleon is treated as free or bound + Fermi motion, Pauli blocking). 2. (pre-)hadrons are propagated through the surrounding nuclear medium according to the BUU transport description. This is exactly the same for e and v all other hadron-induced reactions on nuclei.

	Model Name	v	e	Detailed electron mode implementation
COherent	Pion production: Rein-Sehgal, Berger-Sehgal	+	-	
Quasi **E**lastic	Factorized with Llewellyn -Smith elementary xsec: FG, LFG, BR-FG, momentum-dependent potential	+	+	FG, LFG and SF. Elementary electron-nucleon cross section calculated explicitly (includes de Forest treatment of binding energy) + an equivalent implementation to the neutrino side
	Benhar's spectral function + elastic FSI, optional effective spectral functions by A. Ankowski	+	-	
Meson **E**x**C**hange	Marteu-like model (inclusive only)	+	-	
	Valencia model (inclusive only)	+	-	
	TEM model (inclusive only)	+	-	
	SuSAv2 (inclusive only)	+	-	
RESonance	Delta production within Adler-Rarita-Schwinger formalism, Oset, Salcedo in-medium modifications, decay parametrized using ANL, BNL data, nonresonant background extrapolated from DIS	+	-	
	Valencia model for SPP, Delta(1232) and	-	+	
Deep **I**nelastic **S**cattering	Bodek-Yang model (grv94)	+	-	

Generators

Calculate the cross section for ν and e in one chosen model.

In the past, had some separate models and codes for ν and e (QE Rosenbluth for e wrt to Llewellyn Smith for ν)

Until recently calculates cross section for ν and scaling it to e.

Possible to read different hadronic tensors for e, not yet used.

Recent developments will allow reading the different hadronic tensors in a joint QE MEC environment.

Started at the workshop to implement the QE model

Generators

GiBUU

Single calculation

Genie

Allows various model sets (referred to as tunes)

Each model has it free parameters which can be tuned

The frameworks allows comparison and reweighting of one tune to the other

Unified models - methods

Separate calculation / Scaling approach

Zeroing out the axial-vector contribution to the cross section and modifying the coupling constants and if needed also the used form factors

Right now this is the method being used in GENIE and GiBUU

During the workshop:

- Suggest what can be done to ensure the consistency is kept in subsequent evolutions of the code

Unified models - method

Hadronic tensors approach

Currently each model supplies different tables for ν and e.

Challenges: hard to reweight, alter the model if need-be, estimate errors

Hadron tensors implicitly integrate over the momenta of outgoing particles, don't have final state

During the workshop:

- Using the equivalent tables for both e and ν modes.
- Using the same model for (same ground state) QE & 2p2h tensor.

Summary

Many of the topics have been actually opened during this week and will need time to produce results.

A survey among participants consulting their opinion about the workshop organisation.

Most participants considered the selected topics and discussions very useful and most of them consider this workshop the beginning of a series of similar events in the future.

Summary

Especially useful were:

1. Comparisons between the implementation of some models such as Spectral Functions and on the other hand FSI in different generators

2. Discussion about the importance for exclusive predictions and the way to obtain those.

3. Discussion about the need for common reweighing and tuning infrastructure for models.

4. The lively discussion about the optimal implementation of electron scattering models in the neutrino interaction generators.


Thank you
& see you in Trento