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Plans for Theory Interfaces

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March 15, 2021

Overview

- The theory community is producing a rich spectrum of models for the different neutrino interactions, including charged current quasi-elastic, resonance, deep inelastic, meson change current, coherent, neutral current…
- Some available theoretical models are not available in the event generators
- Having common interface between event generators will allow neutrino experiments to fully benefit from recent theoretical advances in a timely manner
- Common interface means the neutrino community would be able to plug the model immediately into any of the available event generator (GENIE, NuWro, NEUT and GIBUU)
- The community might need different interfaces to accommodate the different calculations available
- At the workshop we discussed different approaches for interfaces

Interfacing Theory with Event Generators

- Different approaches were discussed at the workshop
  - Table approach: Theorists provide the model in a standard format, for example a differential cross section in some combination of variables
  - Hard-scatter events: This strategy is based on an interface developed by Collider Physics community,
  - Interface using lepton and hadronic tensors: Theorists would provide both tensors, recalculated and presented in a standard format or provide the code that computes these
  - Fortran interface: develop a uniform computer code format that allows the theorists to implement cross section calculation directly into the event generator, for example a Fortran wrapper that attaches an event generator (C++) to theory code (Fortran)

Several Models available

Table 1: Summary of responders to the neutrino interaction modeling survey

Authors	Processes
Saori Pastore et al. [35]	QE and MEC
Gil Paz et al.[37]	QE
Artur Ankowski et al.[38]	QE
Alessandro Lovato et al.[39]-[42]	Elastic scattering, low energy transition, QE
Luis Alvarez et al.[43]-[49]	QE, (coherent) pion, eta production and photon emission
Noemi Rocco et al.[32]-[34]	QE, MEC, 1 and 2 pion production
Raul Jimenez et al.[50]-[51]	QE
Minoo Kabirnezhad. et al.[52]-[53]	Single pion production
Natalie Jachowicz et al. [54]-[62]	Elastic scattering, low-energy excitations, QE, MEC, SRC and single pion production
Toru Sato et al.[63]	Meson(pion,kaon,eta,2pi) production for nucleon in nucleon resonance region
Huma Haider et al.[64]	Deep Inelastic Scattering
Juan Nieves et al. [65]-[90]	QE+SpectralFunctions+RPA+2p2h+pion production (Delta, chiral background, some other N*)
Maria Barbaro et. al. [91]	Quasi-elastic scattering, two-nucleon emission (2p2h), pion production, higher resonances, deep inelastic scattering, both CC and NC processes.

- Full report is available at: https://indico.fnal.gov/event/24164/sessions/7454/attachments/127928/154529/Survey.pdf
- Some models are not included in the different event generators and experiments analysis chain

Ongoing Efforts

- A working group sponsored by FNAL made of neutrino theorists, collider theorists, neutrino experimentalists and GENIE developers has been working since 2017
- We are making progress with the following topics:
  - Interface theory and GENIE neutrino event generator
    - Nuclear ab initio, RES and DIS, Lattice QCD
    - Leptonic interface framework
- The group meets once a month to discuss progress https://indico.fnal.gov/category/724/
  - We have been having discussions about interfaces:
    - https://indico.fnal.gov/event/15600/sessions/2981/attachments/20336/25384/talk20171025.pdf
    - https://indico.fnal.gov/event/44949/contributions/194171/attachments/133501/164684/Automating_Leptonic_Tensor_Talk.pdf
    - https://indico.fnal.gov/event/48251/contributions/210619/attachments/140883/177213/te_meeting_mar2021.pdf

Table Approach

- Use a very general form to provide differential prediction for lepton kinematics
- Steven Gardiner is leading this effort
  - Hadronic tensor pre-calculated and tabulated for efficient evaluation

$$\frac{d^2\sigma}{dE'_\ell \, d\cos(\theta'_\ell)} = \frac{|\boldsymbol{k}'|}{|\boldsymbol{k}|} \frac{G_F^2}{2\pi} L_{\mu\nu} W^{\mu\nu}$$

  - Elements expressed as a function of

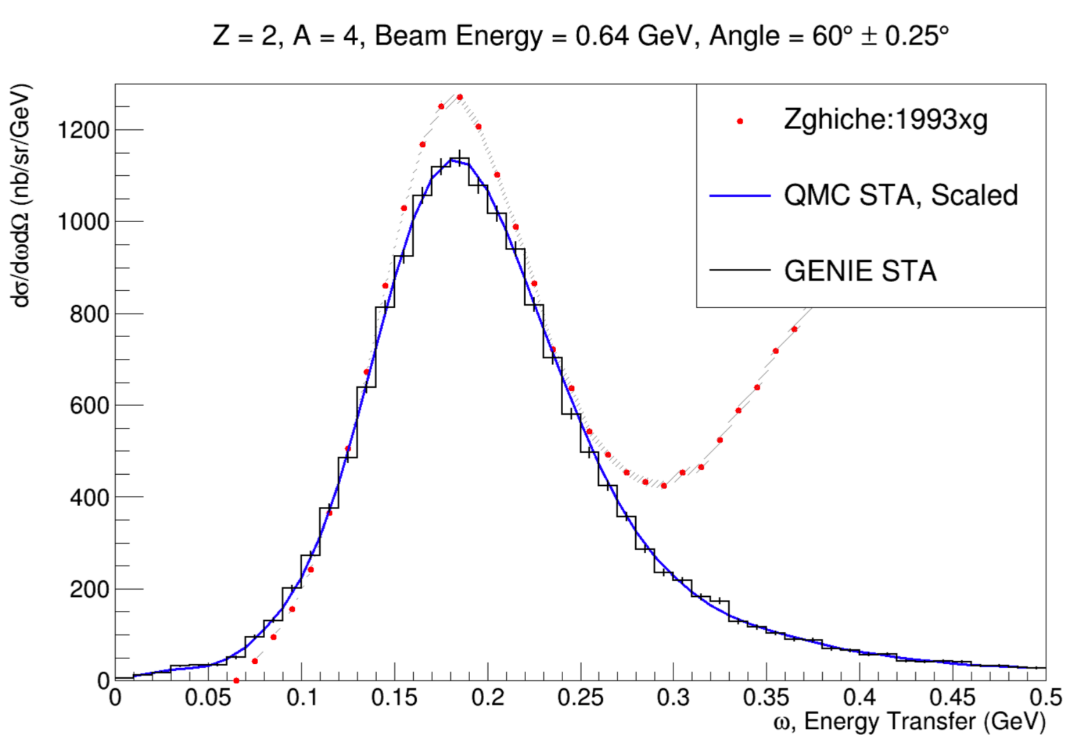
$$\omega = E_\ell - E_{\ell'}$$
$$q = |\mathbf{p}_\ell - \mathbf{p}_{\ell'}|$$

  - Valencia MEC available using this method in GENIE, NuWro and NEUT
- More details in Steven's GENIE talk (New Physics Model developments in GENIE)
- Disadvantages to the table approach: large number of tables for each nucleus, neutrino scattering process, neutrino energies, tables are fully inclusive and less accurate

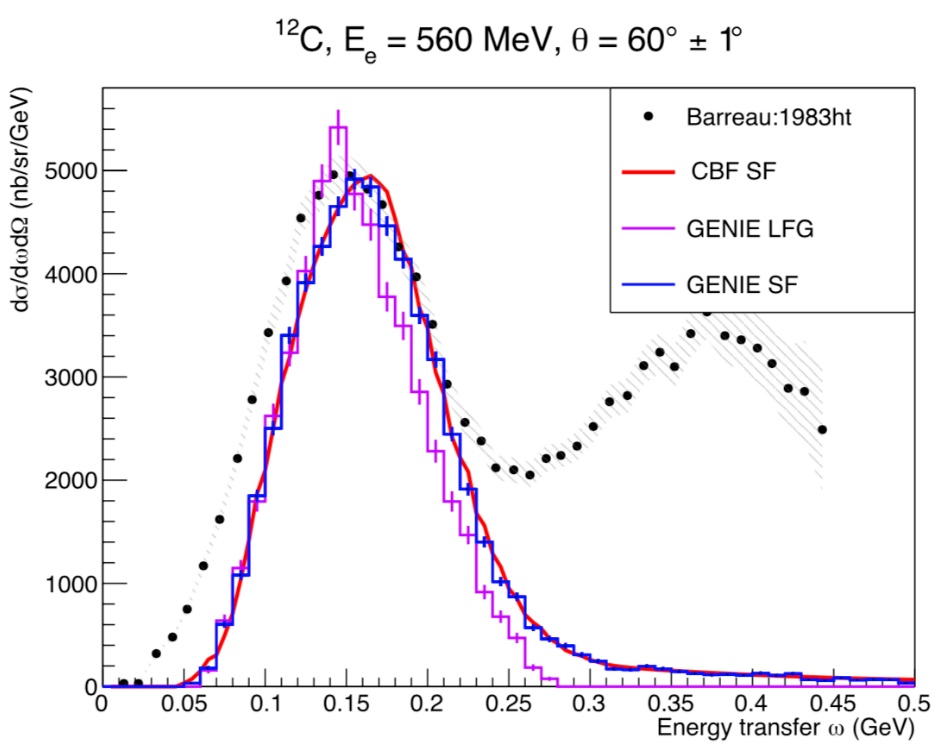
Table Approach

- Implementing other models using the table approach
  - Spectral function approach: Combines a realistic description of the initial target state with a fully relativistic interaction vertex and kinematics from Noemi R. et al.
  - Short-time approximation: Accounts for two-nucleon dynamics, including correlations and currents, and provide information on back to back nucleons, see Saori's presentation
- Validating with electron scattering mode

Short-Time approximation in GENIE for Helium



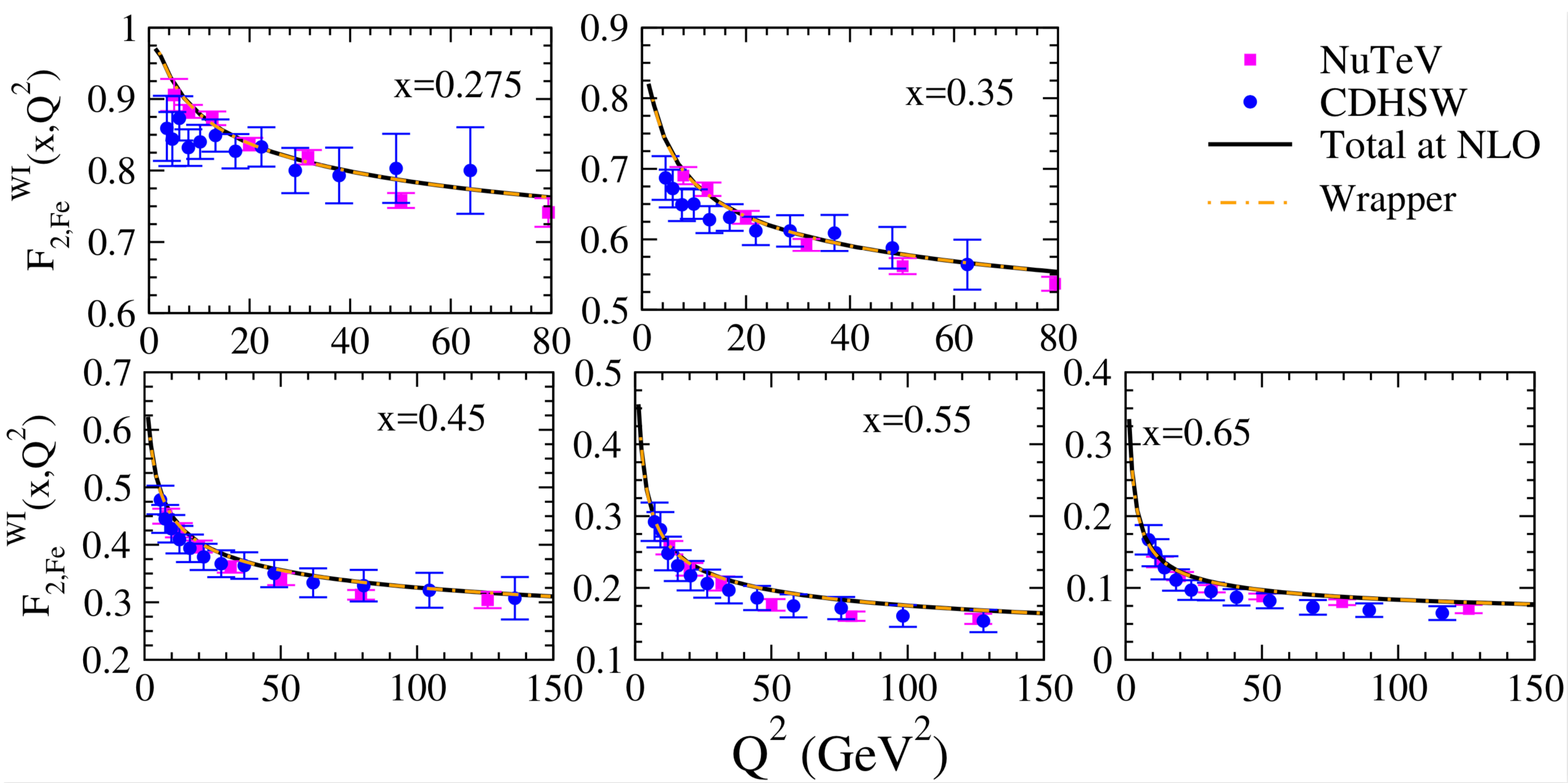
Spectral function in GENIE for Carbon



J. Barrow, S. Gardiner et al., Phys. Rev. D 103, 052001 (2021)

Fortran Interface

- Some models are written in Fortran, another interface could be a Fortran wrapper that attaches an event generator to theory code
- An example was presented at the workshop, a Fortran wrapper that takes the structure functions F1, F2 and F3, using the deep inelastic interaction calculation from Huma Haider
- Validation: Fortran original calculation (black) and GENIE wrapper (dashed yellow)



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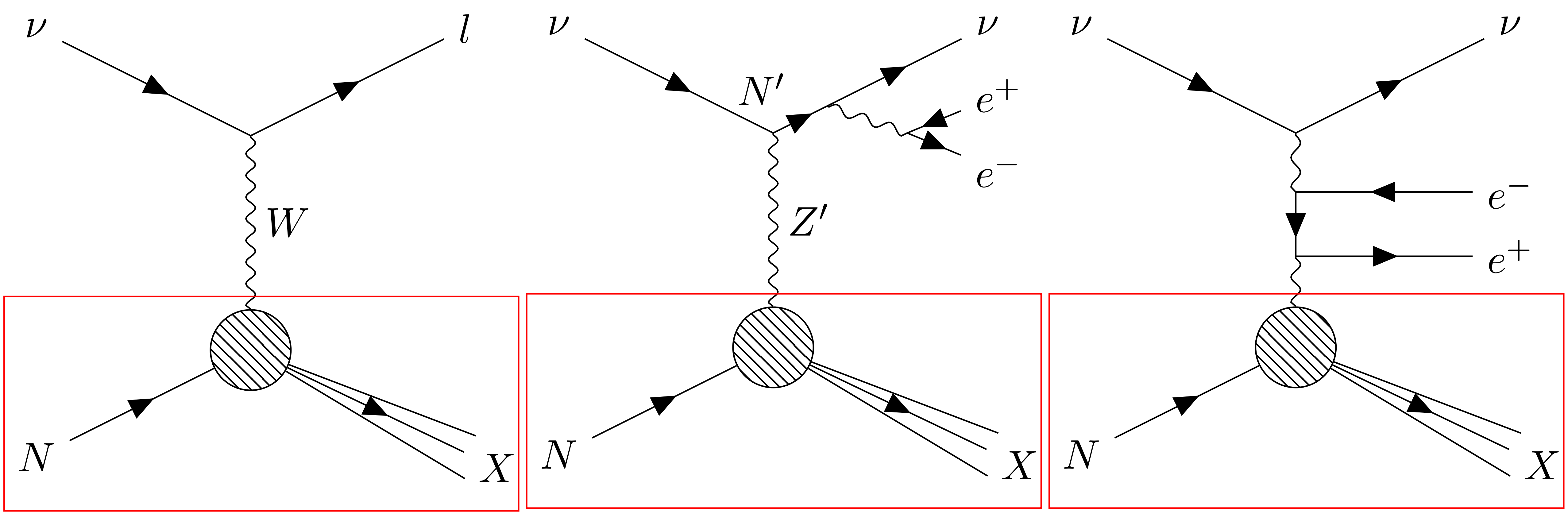
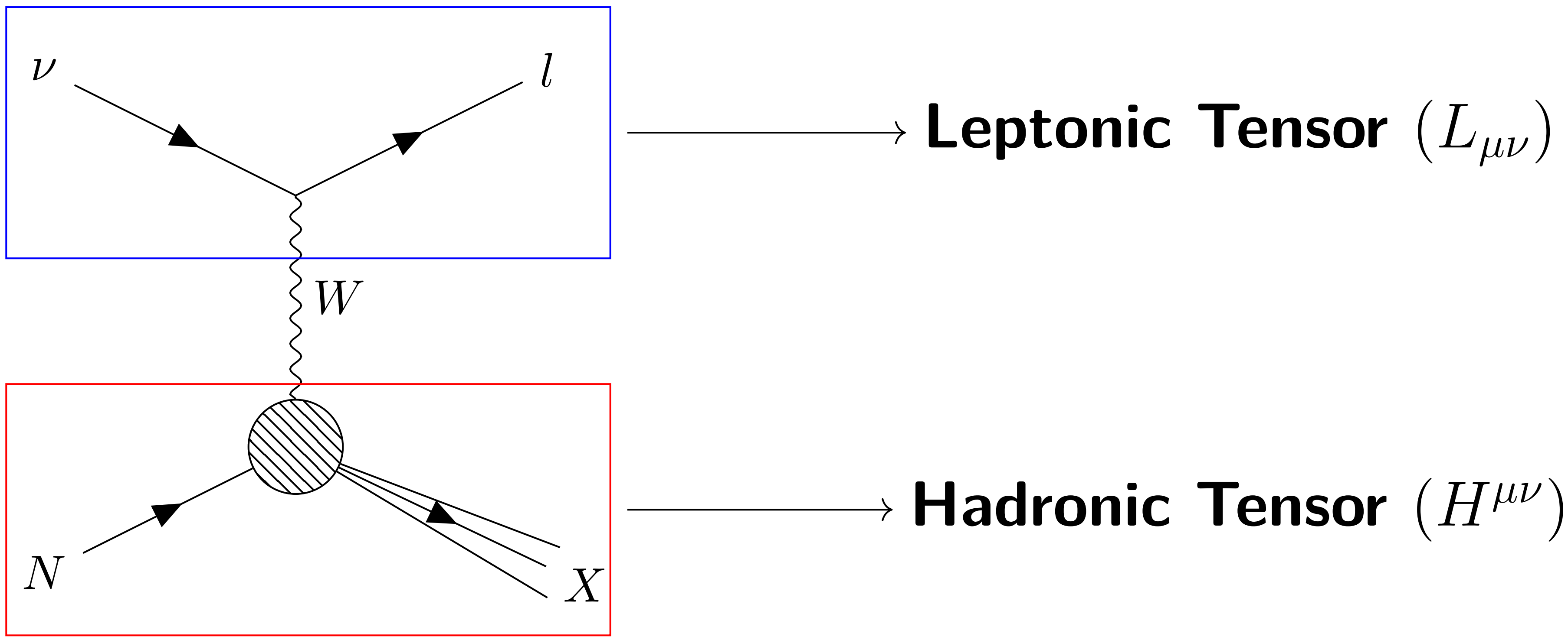
Lepton and Hadronic Tensor



- What do all the diagrams above have in common?

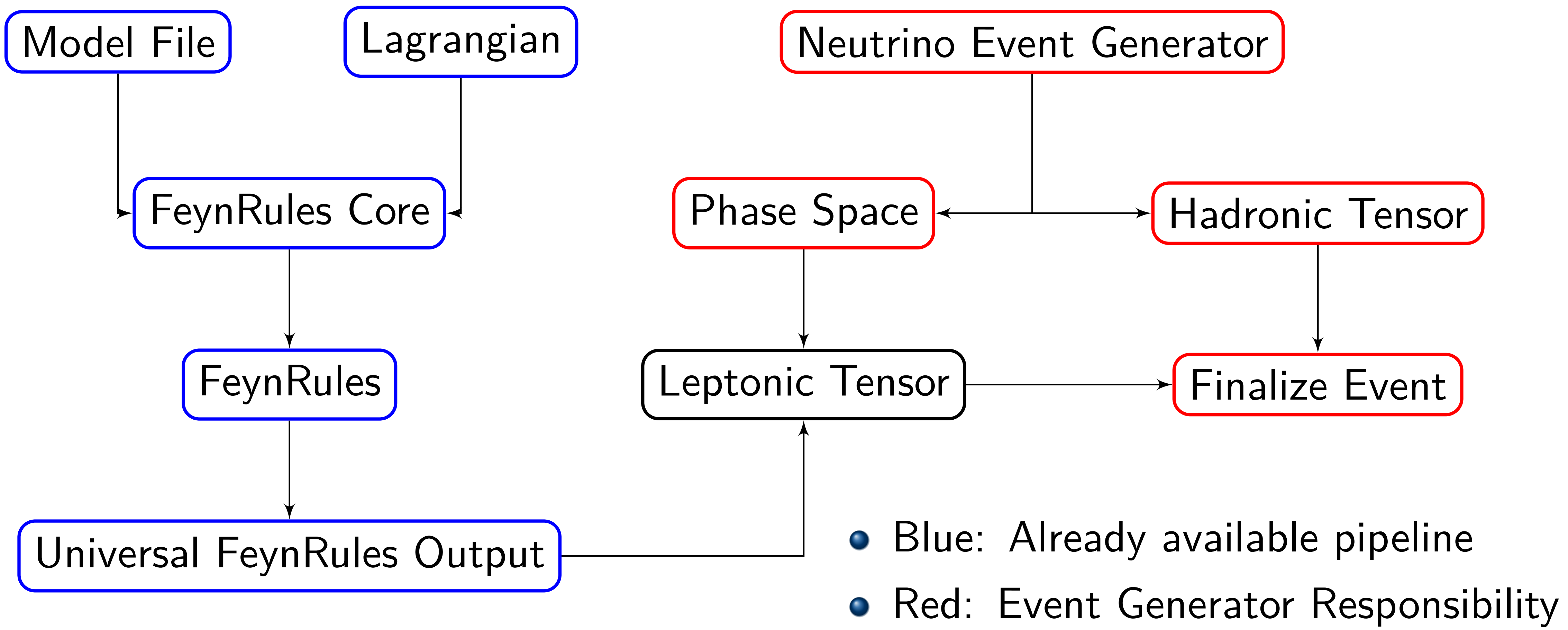
Lepton and Hadronic Tensor



- Leptonic tensor only contains perturbative physics
- Can use LHC tools to calculate Leptonic tensor
- Hadronic tensor is difficult, but event generators have these calculations implemented already
- Joshua Isaacson is leading this effort

Future/Proposed Interface

- Proposed Interface



- Validation using Noemi's and BSM models will be performed

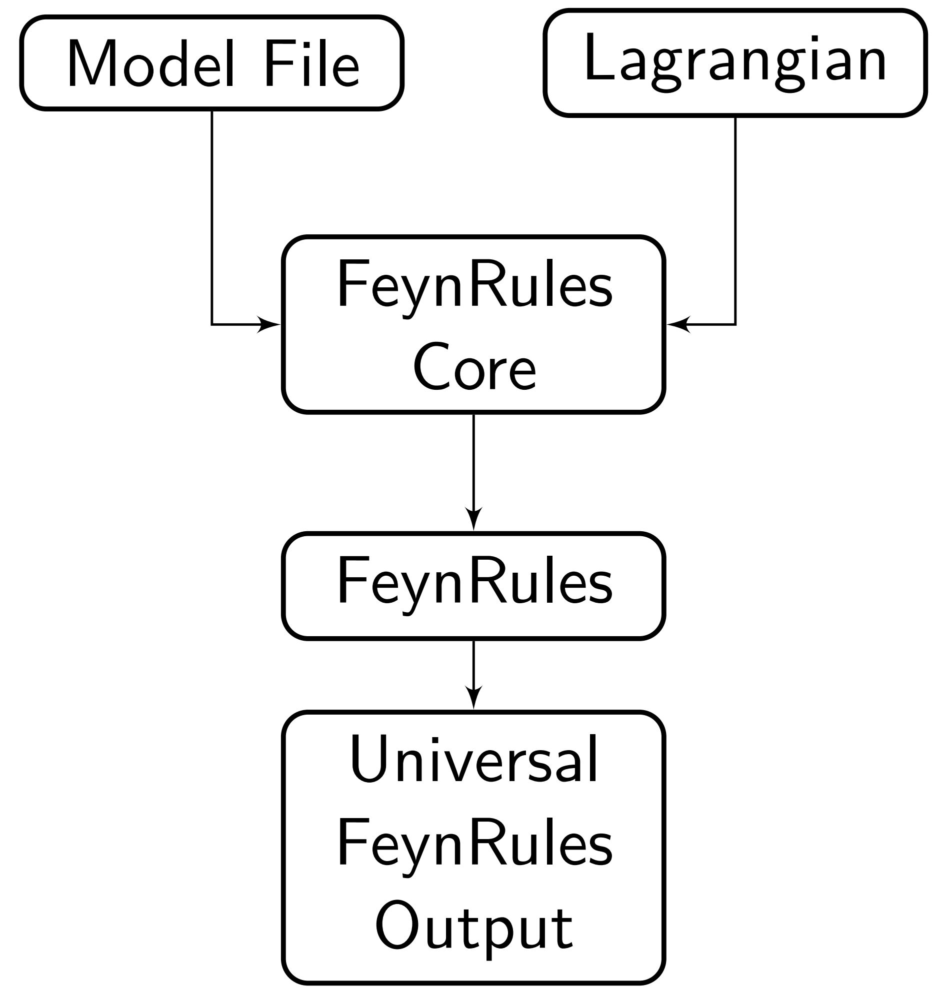
Summary and Planning

- FNAL working group is developing interfaces theory-event generator
  - Table approach
  - Automating Leptonic tensor
  - Fortran interface
  - Discussing interfaces from collider community and exploring how we could use the approaches in the neutrino community
- This is a community effort, more support to develop proper tools to allow rapid implementation of modern calculations in event generator is needed
- New collaborators are welcome

Backup Slides

FeynRules

- *Mathematica* Program
- Takes model file and Lagrangian as input
- Calculates the Feynman rules
- Outputs in Universal FeynRules Output (UFO) format



[arXiv:0806.4194, arXiv:1108.2040, arXiv:1310.1921]

Recursive Matrix Element Generation

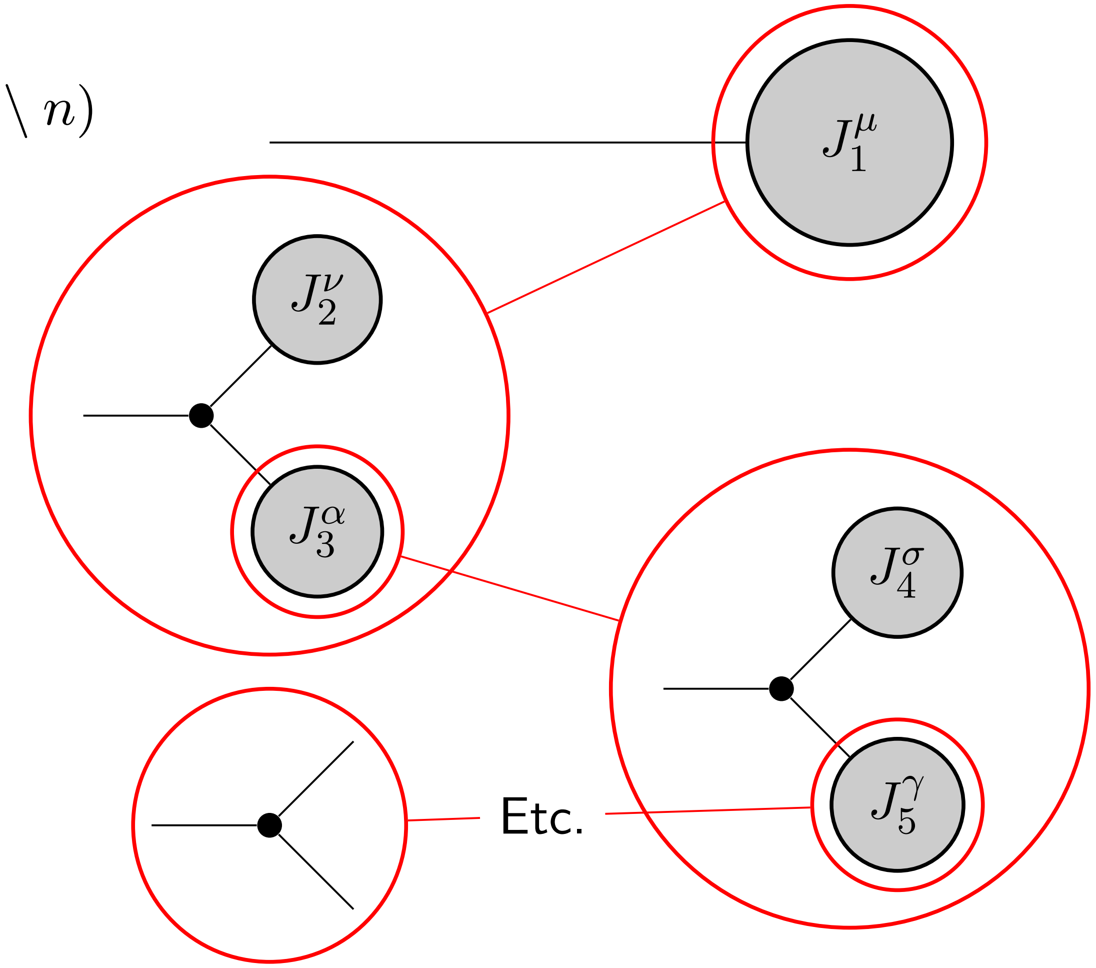
$$\mathcal{J}_\alpha(\rho) = P_\alpha(\rho) \sum_{\mathcal{V}_\alpha^{\alpha_1,\alpha_2}} \sum_{\mathcal{P}_2(\rho)} \mathcal{S}(\rho_1,\pi_2) V_\alpha^{\alpha_1,\alpha_2}(\rho_1,\rho_2) \mathcal{J}_{\alpha_1}(\rho_1) \mathcal{J}_{\alpha_2}(\rho_2)$$

$$\mathcal{A}(\rho) = \mathcal{J}_{\alpha_n}(n) \frac{1}{P_{\bar{\alpha}_n}(\rho \setminus n)} \mathcal{J}_{\bar{\alpha}}(\rho \setminus n)$$

Brends-Giele Recursion

- Reuse parts of calculation
- Most efficient for high multiplicity
- Reduces computation from $\mathcal{O}(n!)$ to $\mathcal{O}(3^n)$

[Nucl. Phys. B306(1988), 759]



Leptonic and Hadronic Tensor: Possible issues

- Which part is responsible for phase space generation
- Handling of g_L and g_R (g_V and g_A) for nuclear side
- Can't handle multiple boson exchanges
- More issues will probably arise