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Quantum Monte Carlo Implementations for $e\,{}^{4}_{2}\mathrm{He}$ Scattering in the GENIE Monte Carlo Event Generator

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FNAL Joint Theory/Experiment Seminar

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How electron scattering can inform neutrino scattering

- For electron scattering, one can parametrize the cross section in terms of longitudinal and transverse nuclear response functions

$$\frac{\boldsymbol{d^2\sigma}}{\boldsymbol{dE'd\Omega'}} = \boldsymbol{\sigma_M[\nu_L R_L(q,\omega) + \nu_T R_T(q,\omega)]} = \sigma_M\left[\left(\frac{Q}{q}\right)^4 R_L(q,\omega) + \left(\frac{Q^2}{2q^2} + \tan^2\frac{\theta}{2}\right) R_T(q,\omega)\right]$$

  – For a full model of V and $V-A$ generalized lepton scattering, one can parametrize the cross section in terms of five similar nuclear response functions

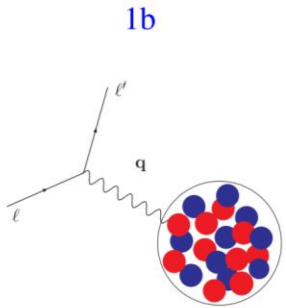
  – *If the underlying theoretics are identical*, one can in principle *validate* a ν scattering model using electron scattering comparisons

    - The underlying intranuclear dynamics should be identical! ***It's the same nucleus!***

STA: The Inclusion of Two-Body Physics: Nuclear Response

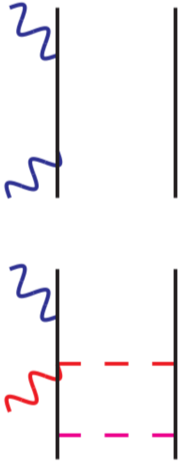
- The second order correction to a Hamiltonian describing a system of bound nucleons comes from two-body interaction terms in a high-order expansion:

Considering the modes of possible lep... ...al and transverse responses ρ and $\mathbf{j}$, respectively:



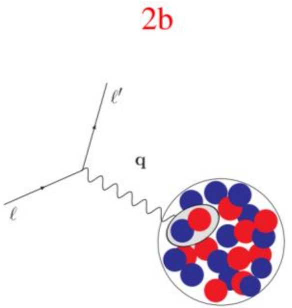
$$O_L \sim \rho = \sum_{i=1}^{A}$$

$$O_T \sim \mathbf{j} = \sum_{i=1}^{A}$$



$$\langle \mathbf{j}_{1b}^{\dagger} \ \mathbf{j}_{1b} \rangle > 0$$

$$\langle \mathbf{j}_{1b}^{\dagger} \ \mathbf{j}_{2b} \ v_\pi \rangle \propto \langle v_\pi^2 \rangle > 0$$



- The total inclusive cross section can be parametrized in terms of the nuclear response:

$$\frac{d^2\sigma}{dE'd\Omega'} = \sigma_M[\nu_L R_L(q^\mu) + \nu_T R_T(q^\mu)] = \sigma_M \sum_f \delta(\omega + E_0 - E_f)[|\langle f|\nu_L O_L(q^\mu)|0\rangle|^2 + |\langle f|\nu_T O_T(q^\mu)|0\rangle|^2] = \cdots$$

$$\cdots = \sigma_M \int dt[\langle 0|O_L^\dagger(q^\mu)e^{i(\hat{H}-\omega)t}O_L(q^\mu)|0\rangle + \langle 0|O_T^\dagger(q^\mu)e^{i(\hat{H}-\omega)t}O_T(q^\mu)|0\rangle]$$

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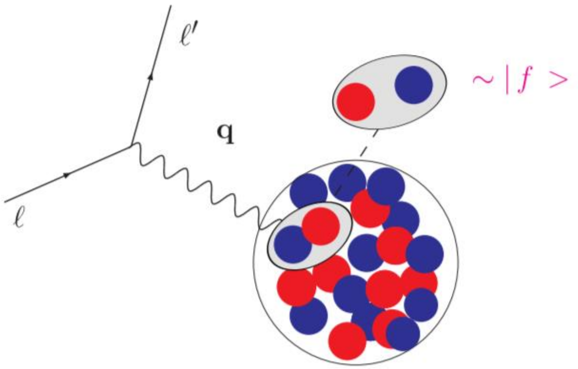
STA: The Inclusion of Two-Body Physics: 1b-1b, 1b-2b, 2b-1b, 2b-2b

- The nuclear response in a mode α can be expanded to include two-body terms **for short times**, where

$$e^{i(\hat{H}-\omega)t} = e^{i\left(\sum_i t_i + \sum_{i<j} v_{i,j} - \omega\right)t} \approx \sum_i t_i + \sum_{i<j} v_{i,j} = P(t)$$

$$\Rightarrow R_\alpha(q^\mu) = \int dt\left[\langle 0|O_\alpha^\dagger(q^\mu)e^{i(\hat{H}-\omega)t}O_\alpha(q^\mu)|0\rangle\right] \approx \int dt\left[\langle 0|O_\alpha^\dagger(q^\mu)P(t)O_\alpha(q^\mu)|0\rangle\right]$$

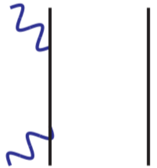
$$\Longrightarrow R_\alpha \sim O_{\alpha;i}^\dagger P(t) O_{\alpha;i} + \boldsymbol{O_{\alpha;i}^\dagger P(t) O_{\alpha;j}} + \boldsymbol{O_{\alpha;i}^\dagger P(t) O_{\alpha;i,j}} + O_{\alpha;i,j}^\dagger P(t) O_{\alpha;i,j}$$



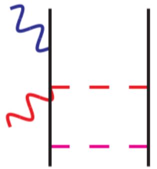
- This naturally leads us to consider lepton scattering off of pair objects

$$|f\rangle \sim \left|\psi_{p',P',J,M,L,S,T,M_T}(r,R)\right\rangle$$

  – Correlated two-nucleon wave-functions allow for a full solve of the Schrödinger equation
  – Retains all nuclear and electroweak interactions induced by an e or ν
    - Does not directly include Δ-resonance



$\langle \mathbf{j}_{1b}^\dagger \ \mathbf{j}_{1b}\rangle > 0$



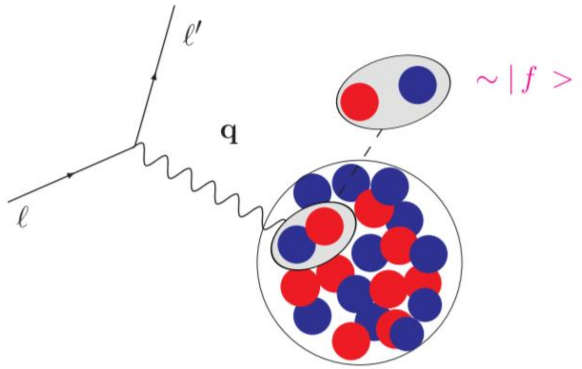
$\langle \mathbf{j}_{1b}^\dagger \ \mathbf{j}_{2b} \ v_\pi\rangle \propto \langle v_\pi^2\rangle > 0$

STA: The Inclusion of Two-Body Physics: Densities

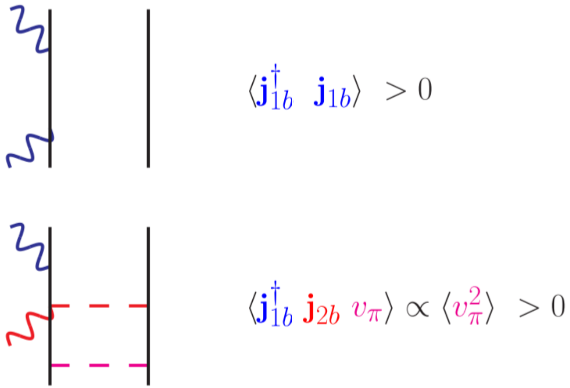
- One can encode all of this structure within *response densities*, $\mathcal{D}$

$$R_\alpha(q^\mu) \sim \int d\Omega_{P'}\, d\Omega_{p'}\, dP'\, dp'\, \delta(\omega + E_0 - E_f) \cdot \left[p^{\mu'2} P^{\mu'2} \langle 0 | O_\alpha^\dagger(q^\mu) | p^{\mu'}, P^{\mu'} \rangle \langle p^{\mu'}, P^{\mu'} | O_\alpha^\dagger(q^\mu) | 0 \rangle\right] = \cdots$$

$$\cdots = \int dP'\, dp'\, \delta(\omega + E_0 - E_f) \cdot \boldsymbol{\mathcal{D}}(\boldsymbol{p^{\mu'}}, \boldsymbol{P^{\mu'}}; \boldsymbol{q^\mu})$$

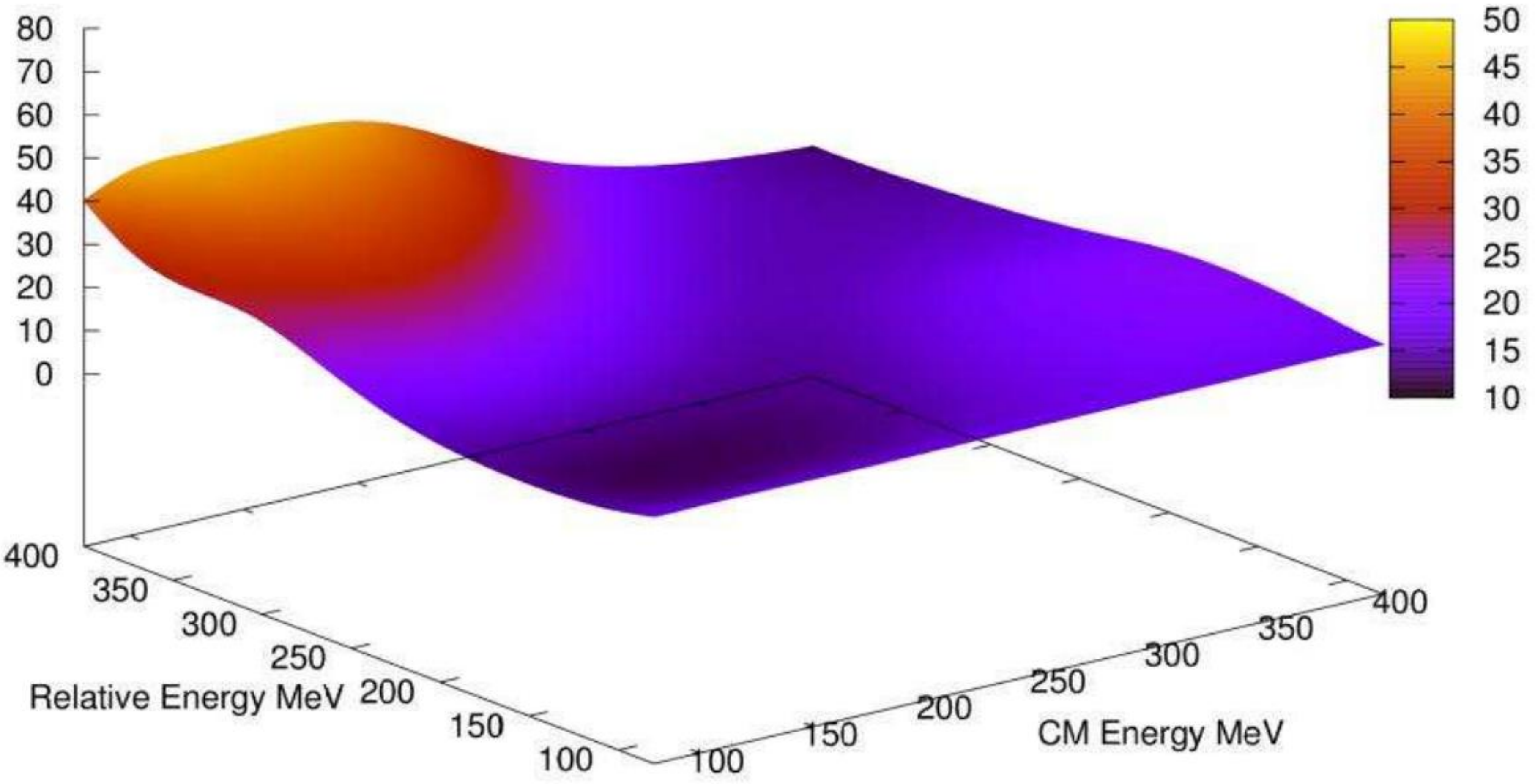


- Contains information about…
  - **…the contents of the nucleus *after* the probe interacts** with the pair
  - "Exclusive" information on specific nucleon pair kinematics
  - Correctly accounts for interference terms
    - Leads to enhancement of the transverse response, and thus, the overall cross section



Current QMC STA Response Density Outputs for $e\,{}^{4}_{2}\mathrm{He}$

ep(i),	EP(j),	s1dia,		s1off,		s2b,		sinterf	
-3.00	45.00	0.050	0.006	0.143	0.027	0.025	0.002	0.136	0.006
3.00	45.00	113.331	17.522	141.536	40.624	47.566	2.376	235.977	11.865
9.00	45.00	186.794	15.781	39.516	35.231	32.404	1.354	186.854	7.073
15.00	45.00	305.190	14.678	33.075	26.301	27.865	0.982	179.861	5.435
21.00	45.00	456.554	14.122	40.020	19.453	25.923	0.786	181.912	4.588
27.00	45.00	626.606	13.866	39.480	14.544	25.063	0.672	186.540	4.031
33.00	45.00	801.265	13.304	30.970	11.206	24.736	0.603	191.038	3.601
39.00	45.00	966.206	12.483	16.138	8.904	24.690	0.560	193.883	3.272
45.00	45.00	1108.040	11.633	-4.086	7.383	24.791	0.534	194.245	3.037
51.00	45.00	1216.391	10.926	-28.344	6.288	24.967	0.519	191.820	2.870
57.00	45.00	1285.269	10.560	-54.234	5.469	25.175	0.512	186.707	2.735
63.00	45.00	1313.351	10.540	-78.794	4.896	25.392	0.510	179.275	2.604
69.00	45.00	1303.386	10.610	-99.390	4.474	25.604	0.512	170.040	2.468
75.00	45.00	1261.053	10.500	-114.335	4.144	25.802	0.518	159.570	2.327
81.00	45.00	1193.636	10.104	-123.049	3.891	25.981	0.525	148.404	2.188
87.00	45.00	1108.799	9.454	-125.845	3.671	26.140	0.535	137.017	2.056
93.00	45.00	1013.675	8.642	-123.571	3.463	26.277	0.545	125.789	1.937
99.00	45.00	914.317	7.761	-117.278	3.298	26.391	0.557	115.006	1.831
105.00	45.00	815.467	6.888	-108.013	3.207	26.483	0.569	104.861	1.739
111.00	45.00	720.564	6.070	-96.720	3.174	26.553	0.582	95.470	1.659
117.00	45.00	631.888	5.331	-84.232	3.167	26.601	0.595	86.888	1.587
123.00	45.00	550.769	4.679	-71.279	3.168	26.628	0.608	79.123	1.522
129.00	45.00	477.807	4.111	-58.491	3.171	26.635	0.620	72.150	1.462
135.00	45.00	413.069	3.619	-46.390	3.177	26.622	0.633	65.924	1.408
141.00	45.00	356.263	3.199	-35.363	3.192	26.590	0.645	60.389	1.359
147.00	45.00	306.863	2.843	-25.640	3.229	26.539	0.657	55.484	1.319
153.00	45.00	264.214	2.545	-17.298	3.290	26.472	0.668	51.147	1.286
159.00	45.00	227.606	2.298	-10.273	3.362	26.387	0.679	47.321	1.262
165.00	45.00	196.324	2.094	-4.400	3.427	26.287	0.689	43.952	1.245
171.00	45.00	169.684	1.926	0.533	3.484	26.171	0.699	40.991	1.234
177.00	45.00	147.051	1.785	4.740	3.544	26.042	0.709	38.393	1.226
183.00	45.00	127.855	1.667	8.399	3.620	25.899	0.717	36.121	1.220
189.00	45.00	111.591	1.566	11.629	3.704	25.744	0.726	34.136	1.213
195.00	45.00	97.818	1.478	14.486	3.779	25.578	0.733	32.406	1.205
201.00	45.00	86.154	1.401	16.976	3.826	25.401	0.740	30.899	1.195
207.00	45.00	76.268	1.331	19.073	3.845	25.214	0.747	29.585	1.182


80
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300
250
200
150
100
Relative Energy MeV
100
150
200
250
300
350
400
CM Energy MeV

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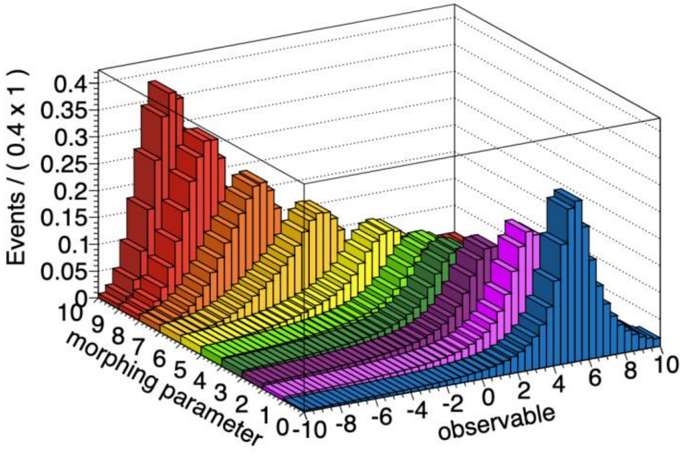
Interpolation of response densities: technique

- We adopt a technique called "moment morphing"
  - Developed for interpolating generator predictions for LHC analyses
  - Available in RooFit package, but limited documentation
  - See arXiv:1410.7388 for more details

Example: 1D distribution with morphing parameter m



- Steps
  - Pre-calculate n reference distributions (response density tables in our case)
  - Apply a Taylor expansion of order $n-1$ about a given parameter value
  - Interpolated prediction depends on references and distances in parameter space

$$f_{\mathrm{pred}}(\mathbf{x}|m') = \sum_{i=0}^{n-1} c_i(m') f(\mathbf{x}|m_i)$$

$$c_i(m') = \sum_{j=0}^{n-1} (m' - m_0)^j \left(M^{-1}\right)_{ji}$$

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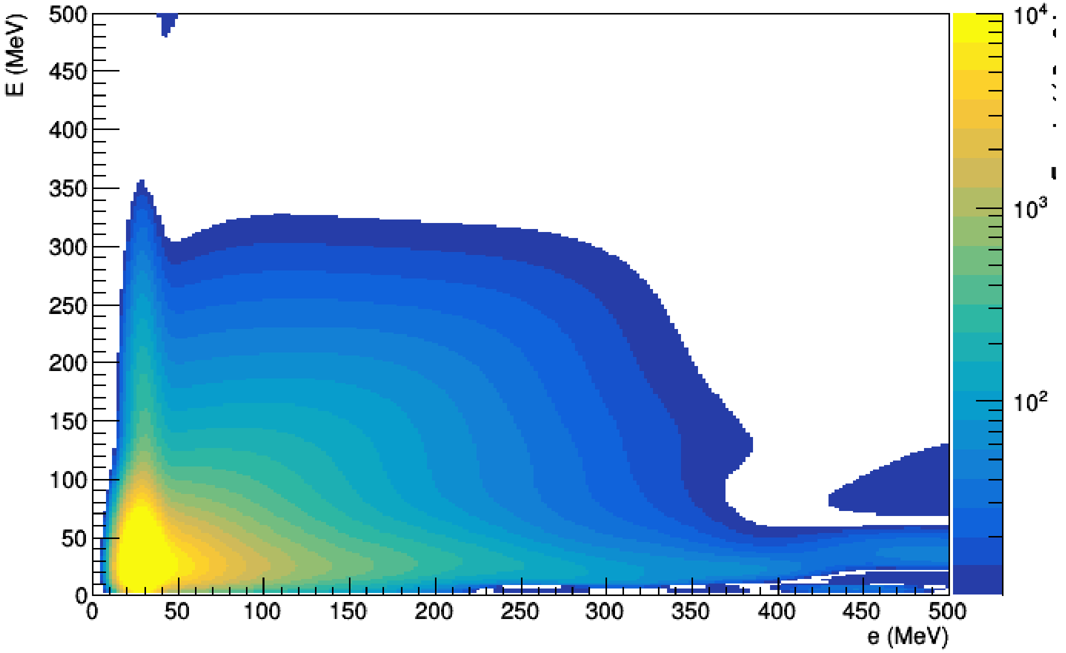
Interpolation of response densities: first tests

- 2D distributions dependent on lepton 3-momentum transfer $|\vec{q}|$
  - Observables are the relative (e) and total (E) energies of the outgoing nucleon pair (pre-FSIs)
- Computationally expensive!
  - Saori needs many CPU hours to produce, even on a sparse grid
- Moment morphing smoothly varies between tabulated inputs
  - 50 MeV spacing is enough?!?
  - Further validation in progress...
    - …some variance around the zero plane…

Longitudinal response density, q = 300 MeV (arbitrary units)



$$\mathbf{p} = \frac{\mathbf{p}_1 - \mathbf{p}_2}{2} \qquad e = \frac{\mathbf{p}^2}{m} \qquad \mathbf{P} = \mathbf{p}_1 + \mathbf{p}_2 \qquad E = \frac{\mathbf{P}^2}{4m}$$

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Leptonic cross section modeling: hadron tensor framework

- Use a very general form to provide differential prediction for lepton kinematics
  - Hadronic tensor pre-calculated and tabulated for speedy evaluation in GENIE
  - Elements expressed as a function of

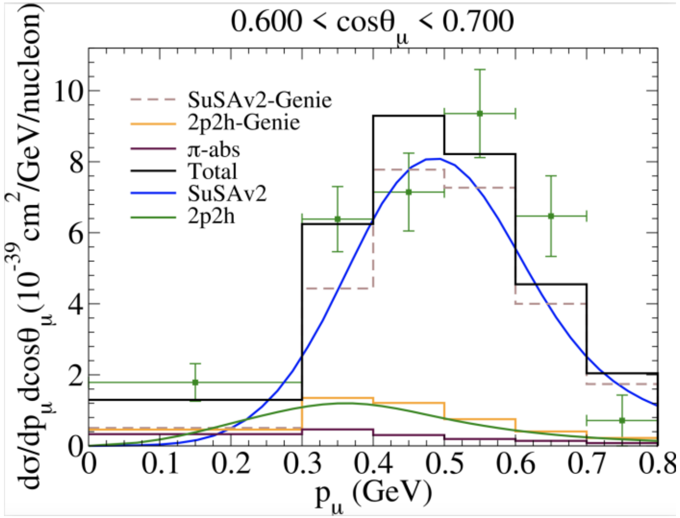
$$\omega = E_\ell - E_{\ell'}$$

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

- First new GENIE model that uses these: SuSAv2 (G. Megias et al.)
  - Expected in next public release (v3.2)!!
  - Still missing important hadronic physics that the STA calculation can provide!

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

SuSAv2 prediction compared to T2K data



SuSAv2 implementation note

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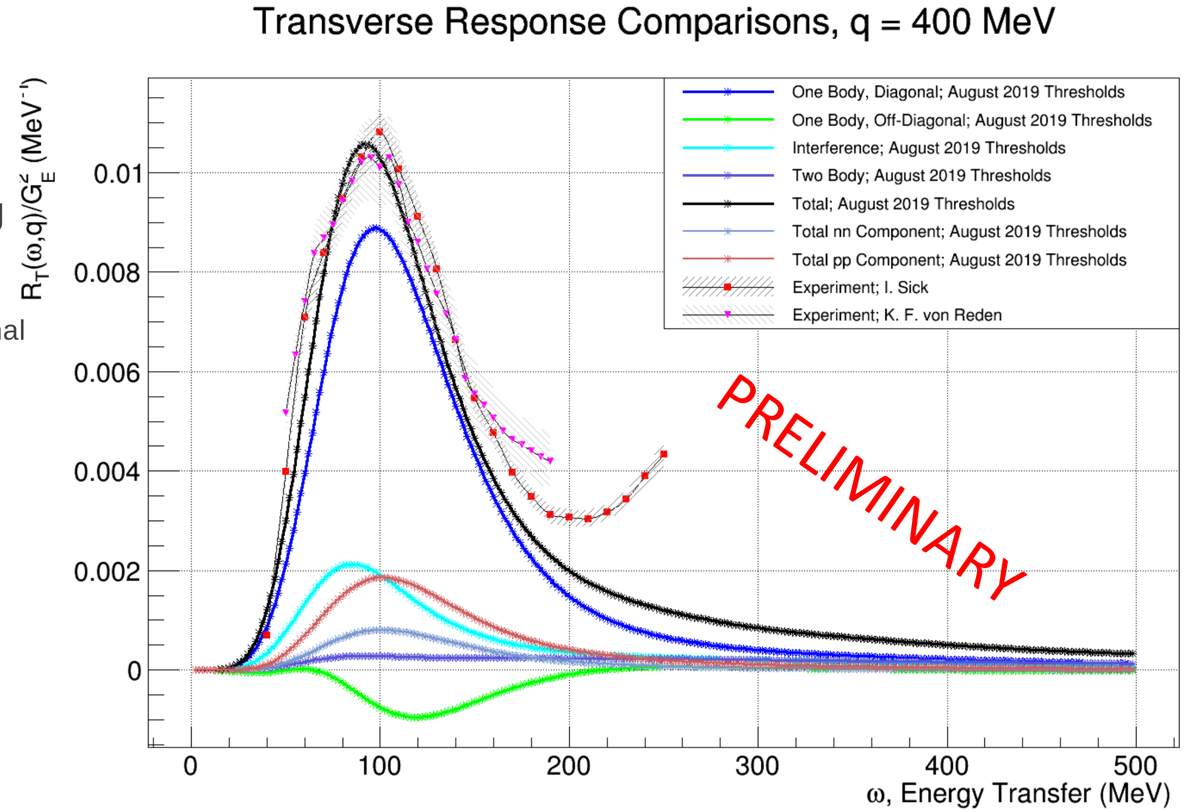
QMC STA $e\,^4_2\mathrm{He}$ Response Comparisons Used in GENIE for Interpolation

- The *interference* and *one-body off-diagonal* terms show asymmetric and even destructive behavior to the total response
  - Exclusive nuclear responses are available for $\{np, pp, nn\}$ scattering
    - pp responses are nonzero for both longitudinal and transverse modes
    - nn is effectively zero for the longitudinal response
- Current experimental response data interpolated by I. Sick and K. F. von Reden for $e\,^4_2\mathrm{He}$
  - Both match rather well using different data and independent interpolation methods
  - Shows great agreement at larger values of $|\vec{q}| \geq 400\ \mathrm{MeV}/c$ when outside of the lower energy elastic response regime



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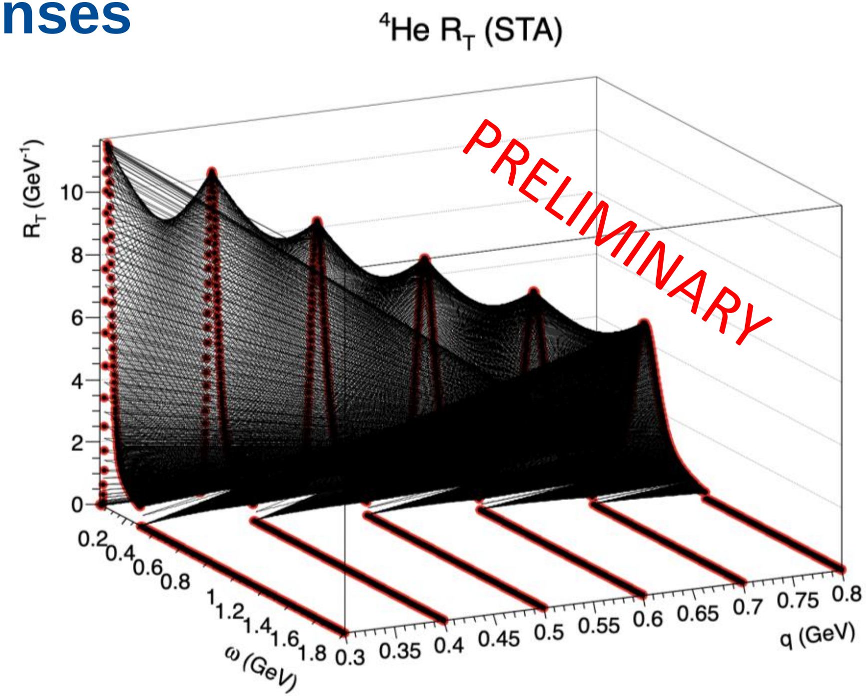
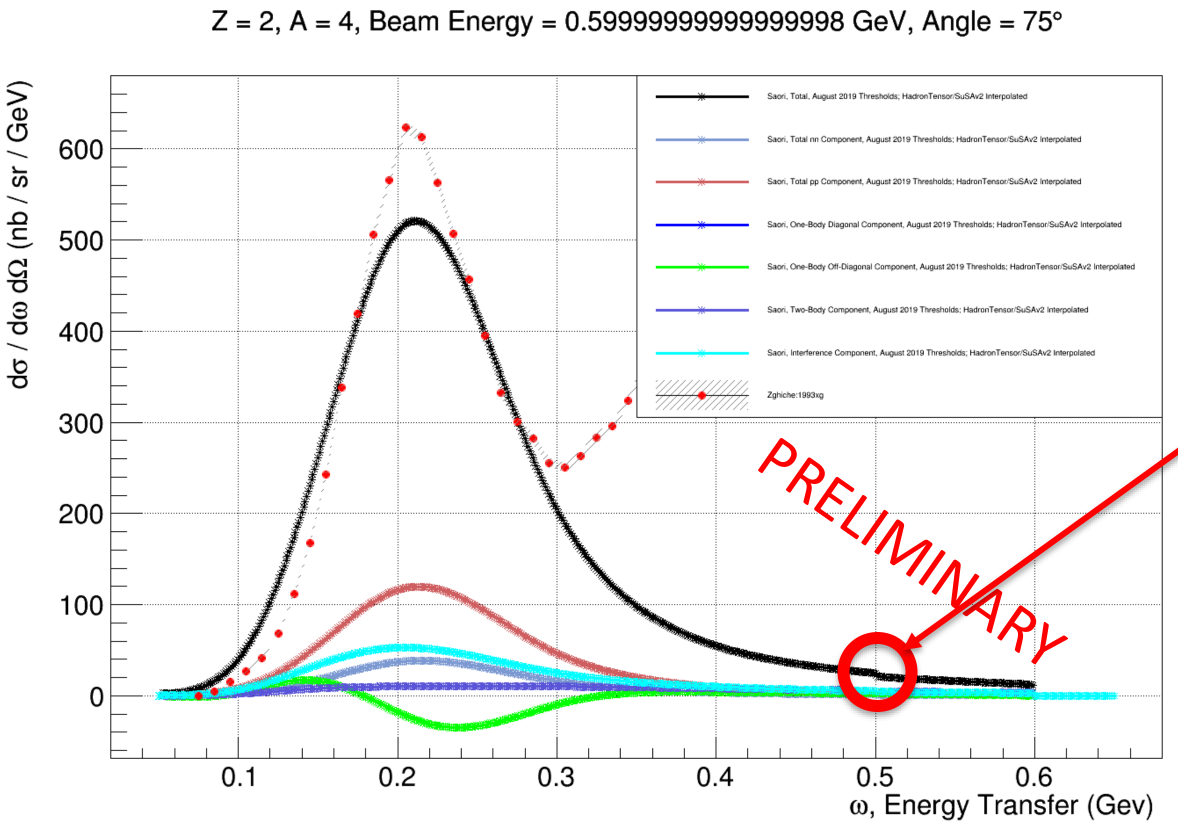
Current Interpolation of STA responses

- Saori has provided STA tables to use for interpolation
  - Integrated responses (hadron tensor elements)
  - Response densities (for future use in sampling hadronic final states)
- Plots show current status of *bilinear interpolation*
  - Correct at the grid points, but q grid is too coarse
  - Currently leads to “Brooklyn Bridge” artifacts
- Will attempt to apply moment morphing to these distributions similarly
  - Hope to smooth things out?



"Kinks" are an artifact of nearest-neighbor bilinear interpolation on a coarse grid

Some simple, first-pass comparisons of models and data for $e\,^4_2\mathrm{He}$ cross sections



- Apparent continuity of QE cross section sections is heavily influenced by presence of more q grid points
  - Makes interpolation more complete
  - This shows a rather continuous example using only five nuclear responses distributions:

    $\{300,400,500,600,700\}\ \mathrm{MeV/c}$
  - **Artifacts** can occur—need to compute more responses with a finer grid in q
  - Can also potentially extend to $\sim 1\ \mathrm{GeV/c}$
- Things yet to do…
  - Elastic peak in STA needs to be removed
    - Cross section is too high at lower energies near the elastic peak
  - Compare longitudinal and transverse cross section components at various kinematics

Current and Future Generator Validation

- Ample amounts of data are available for $e\,{}^3_2\mathrm{He}$, $e\,{}^4_2\mathrm{He}$ and $e\,{}^{12}_{6}\mathrm{C}$ scattering
  - Some even exist for tritium!→Recent JLab thesis from Jason Bane
  - Will serve as a good testing ground for models of total inclusive electromagnetic quasielastic cross sections (*before electroweak* modeling)
  - Will compare to other GENIE nuclear models (χ^2 **analyses to follow**)
  - Publication in preparation now of initial implementation
  - JLab two-body final state data should also be investigated eventually!
- Once our full generator is complete, tested, and validated on e data, we will proceed to ν generation
  - Will involve more response densities (five in total) for CC/NC interactions
  - Will similarly compare to data where available…
  - …and other GENIE nuclear and interaction models
    - Publication(s) will follow soon after

Summary

- Neutrino MC generators must grow and evolve their capabilities as we enter the precision era for oscillation studies
  - One step in this evolution is implementation of the QE QMC STA model using *semi-final states* **and** extensively *validated on electromagnetic data*
  - Avoids phenomenological nuclear models of initial states in Monte Carlo
- A new series of total inclusive electromagnetic scattering cross sections are now available from $e\,^4_2\mathrm{He}$ nuclear responses with $|\vec{q}|\tilde{\epsilon}(300{,}800]\,\mathrm{MeV}/c$
  - Employs two-body physics in an inherent way (exclusive cross sections!)
- Full implementation of this model is progressing for GENIE
  - Must still formulate algorithms to efficiently and accurately pass two-body kinematics and particle identity information to the intranuclear cascade
  - This will eventually allow for the study of potential final state topologies in experimental detectors

Collaborators—Thank-you!

The Roses Between The Thorns

Saori Pastore, WUSTL

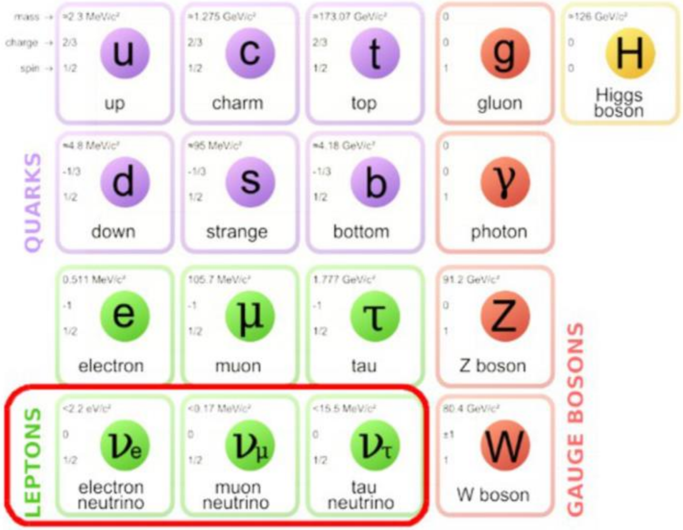
Steven Gardiner, FNAL

Joshua Barrow, UTK

Minerba Betancourt, FNAL

Backup slides

Neutrinos in the Standard Model

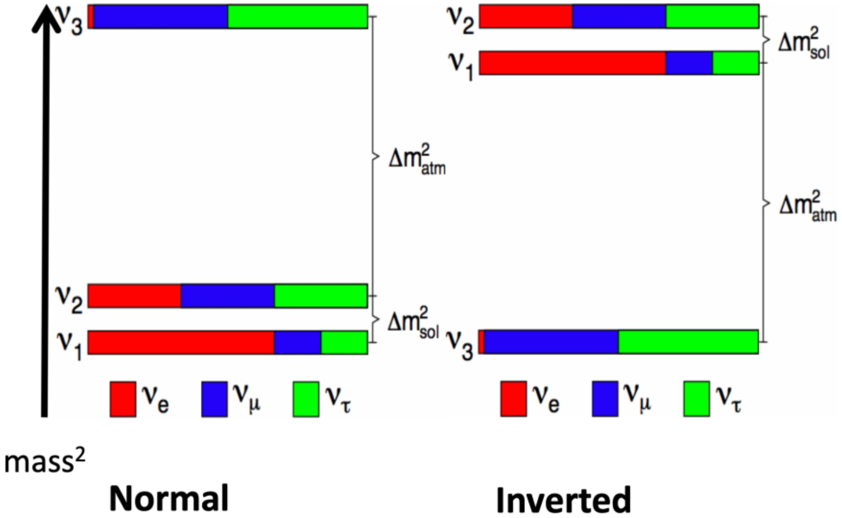


- First **postulated by Pauli in 1930** to explain the missing energy in β decays
- **Discovered in 1956** by Reines and Cowan (reactor neutrinos)
- **3 flavors (v_e, v_μ, v_τ)**, neutral leptons, **massive** but extremely **light** ($<10^{-6}$ m_e)
- Only participate in **weak interactions** (and gravitation)

Neutrino Oscillations

- Compelling evidence from solar and atmospheric neutrino experiments
- The 3 known neutrino flavors represent mixtures of at least 3 mass states
  - 3-flavor model parameterized by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
- Key questions remain:
  - Do neutrinos and antineutrinos oscillate differently? (**CP violation**)
  - Is v3 the heaviest or lightest of the known mass states? (**Mass ordering**)
  - Is the 3-flavor model sufficient to describe nature? (**Sterile neutrinos**)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



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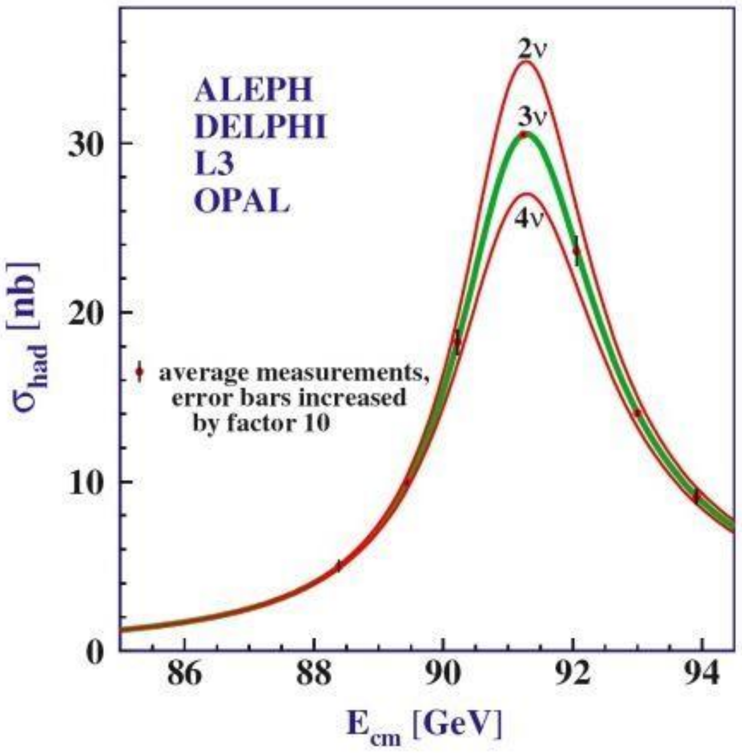
Strong evidence for 3 **active** neutrino flavors



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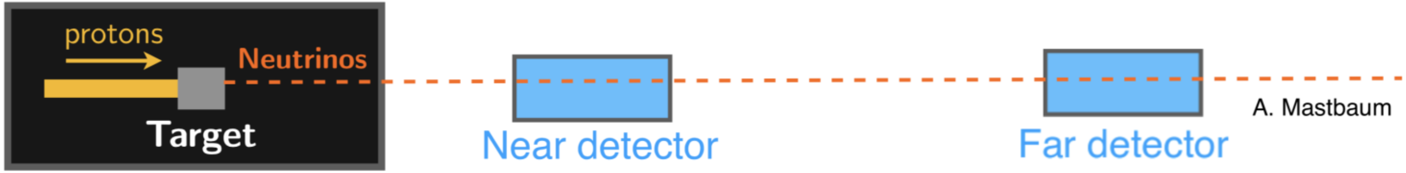
Importance of neutrino cross sections for answering the big questions

Do neutrinos and antineutrinos oscillate differently? (leptonic CP violation)

Is ν_3 the heaviest or the lightest mass eigenstate? (mass ordering)

Are there more than three kinds of neutrinos? (sterile neutrinos)

Oscillation measurements can provide answers



$$N_{FD}(E_{\nu,reco}) \sim P_{osc}(E_\nu) \times \Phi(E_\nu) \times \sigma(E_\nu) \times R(E_\nu, E_{\nu,reco}) - N_{bg}$$

Oscillation probability depends on **true neutrino energy** E_ν (unobserved)

Cross section model needed to relate $E_{\nu,reco}$ to E_ν

- Correct for unseen particles (neutrals, sub-threshold)
- Estimate backgrounds

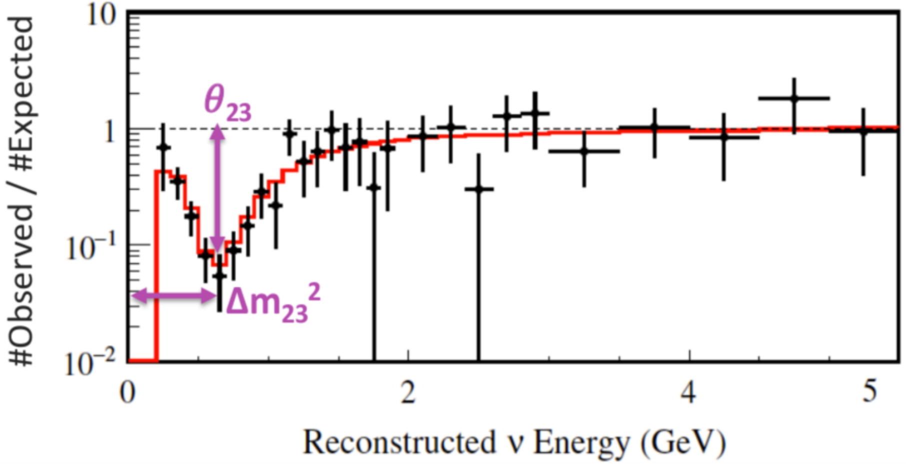
Example analysis from the T2K experiment

- Disappearance
  - Measure deficit of detected νμ relative to expectation without oscillations
  - Fit as a function of reconstructed energy
  - Extract PMNS matrix parameters

- We can't measure the neutrino energy directly
  - Instead, we estimate it event-by-event based on the final particles we can see

- Modeling deficiencies in the cross section prediction can lead to bias!

$$P(\nu_\mu \to \nu_\mu) = \sin^2(2\theta_{23}) \times \sin^2\left(\frac{\Delta m_{32}{}^2 L}{4E_\nu}\right)$$



T2K Collaboration, Phys. Rev. D **91**, 072010

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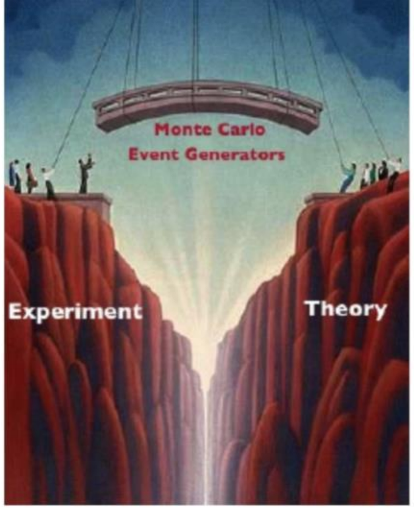
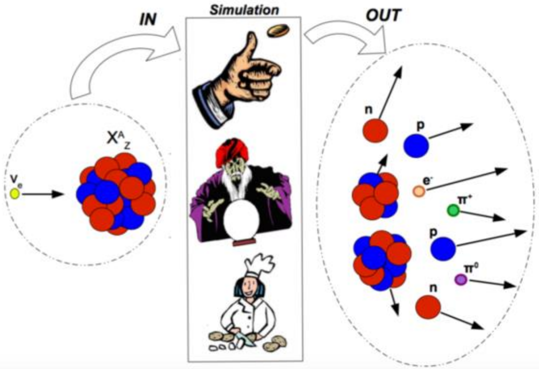
What do event generators do?

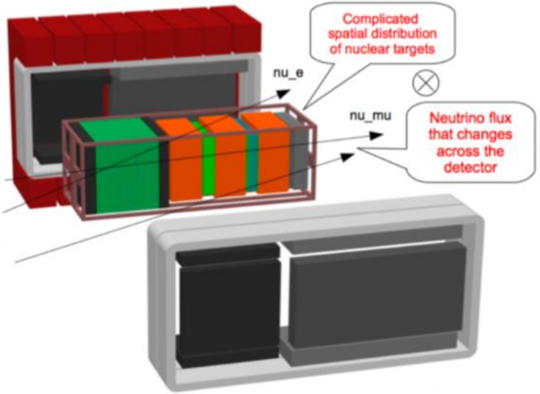
- "Bridge" between theory and experiment
  - Translate a set of models into the particles observed in a detector (multiplicities, 4-momenta, locations)
  - **GENIE** (**G**enerates **E**vents for **N**eutrino **I**nteraction **E**xperiments) is a widely-used neutrino event generator, particularly at Fermilab
  - Others on the market as well (NuWro, GiBUU, NEUT, MARLEY, NUANCE, etc.)



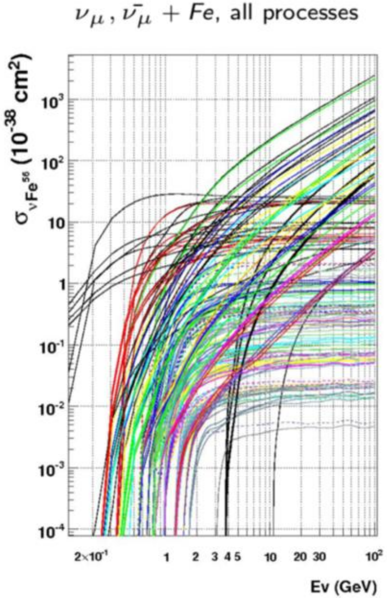


What tasks are involved in predicting event rates?

Propagation of spatially non-uniform, broadband neutrino fluxes through complicated detector geometries (and surrounding dirt, etc.)

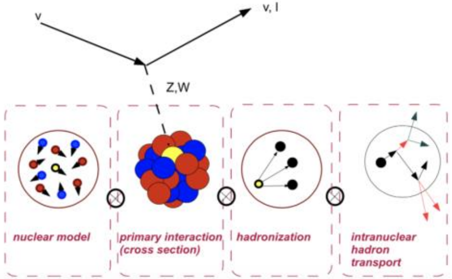


Calculation of total and differential cross sections for all relevant reaction modes, target nuclei, and neutrino energies



Images by C. Andreopoulos

Account for hadronization, FSI, etc. and pass a vertex position and a full set of 4-momenta for all outgoing particles to the detector simulation



Provide a means of assessing interaction uncertainties that can be propagated into an analysis

What tasks are involved in predicting event rates?

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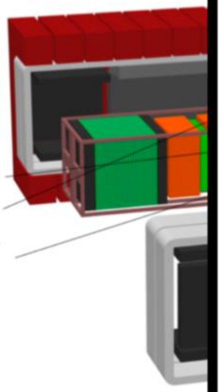

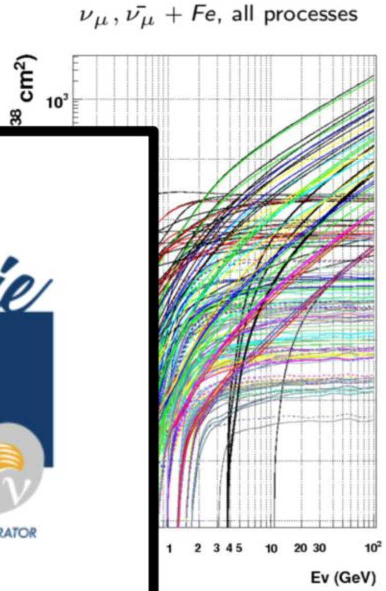

. . . and it needs to be fast!

A fully rigorous solution is not available, but experiments can't wait for one to emerge.

GENIE and other generators are attempts to solve these problems in a way that is "good enough" for experiments to make progress

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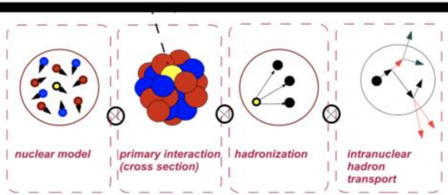
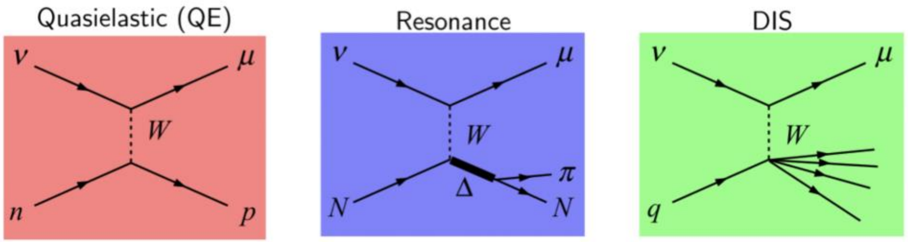
Account for hadror
etc. and pass a vertex position and a full set of 4-momenta for all outgoing particles to the detector simulation

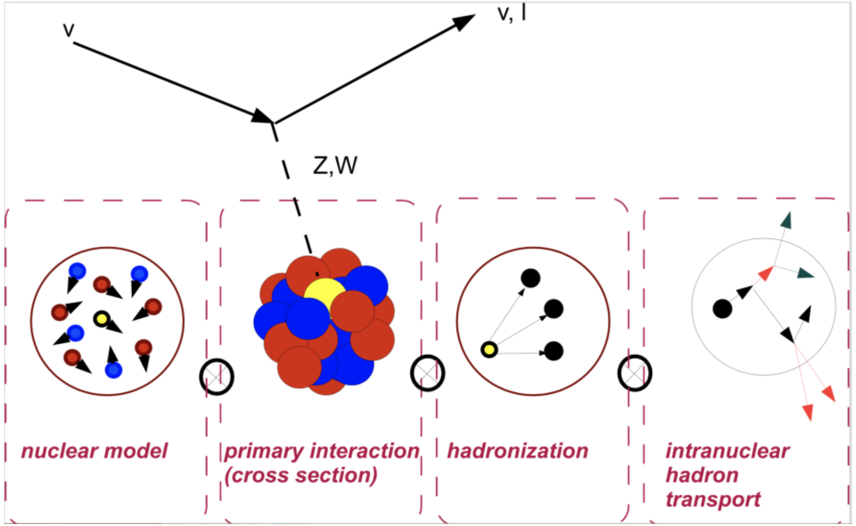


Provide a means of assessing interaction uncertainties that can be propagated into an analysis

Generators resort to an approximate picture of the relevant physics

- "Traditional" treatment includes
  - Fermi gas model of initial nuclear state
    - No shell structure, correlations, etc.
  - Neutrino scatters on a single bound nucleon
    - Two-nucleon contributions known to be important!
  - Interference between processes neglected
    - "Square then sum" → Not what you learned in quantum mechanics class . . .
  - Semi-classical transport of hadrons out of the nucleus
    - Rescattering cross sections based on hadron-nucleus data





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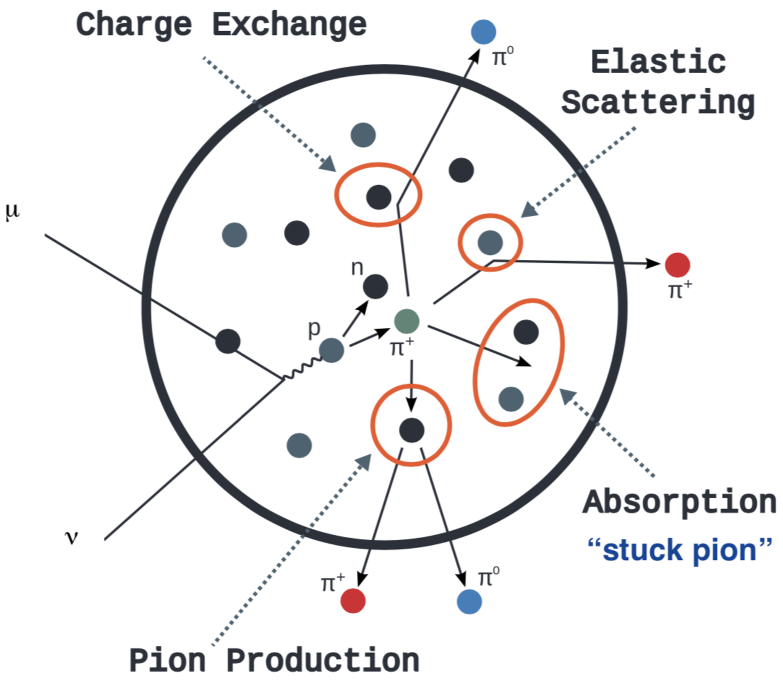
  - Semi-classical transport of hadrons out of the nucleus
    - Rescattering cross sections based on hadron-nucleus data
- **High-precision needed to definitively answer open questions: can we do better?**



L. Alvarez-Ruso et al., *Prog. Part. Nucl. Phys.* 100, 1–68 (2018)

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Two-nucleon physics in event generators: "nucleon cluster model"

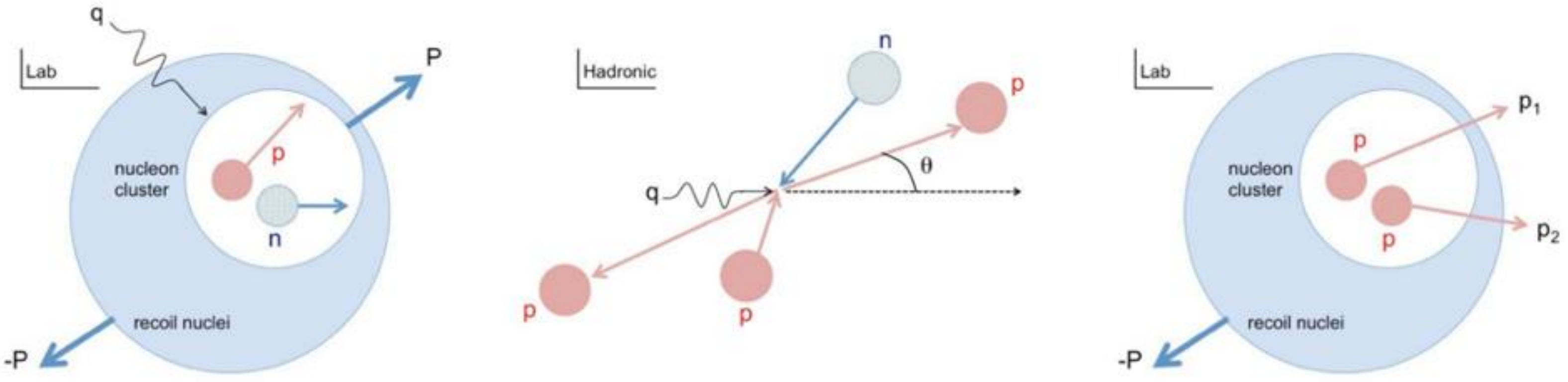

FIGURE 3. Nucleon cluster model in GENIE. First, 2 nucleons are chosen from the Fermi sea (left). Then 2 nucleons and energy-momentum transfer 4-vector make the hadronic system (middle). Finally, the system is boosted back, and 2 outgoing nucleons are generated in the lab frame (right).

- Generators are beginning to include these contributions, but in a very rough way
- STA calculations allow us to do this much more rigorously

Some future plans on a full GENIE generator module…

→Putting it all together!

What new things need to be considered within GENIE?

The GENIE Generator

```
  .oooooo.     oooooooooooo ooooo      ooo ooooo oooooooooooo
 d8P'  `Y8b    `888'     `8 `888b.     `8' `888' `888'     `8
888             888          8 `88b.    8   888   888
888             888oooo8     8   `88b.  8   888   888oooo8
888     ooooo   888    "     8     `88b.8   888   888    "
`88.    .88'    888       o  8       `888   888   888       o
 `Y8bood8P'    o888ooooood8 o8o        `8  o888o o888ooooood8
```

```
|-------------------------------
|GENIE GHEP Event Record [pr
|-------------------------------
| Idx |           Name | Ist
|-------------------------------
|   0 |          nu_mu |   0
|   1 |            C12 |   0
|   2 |        neutron |  11
|   3 |            C11 |   2
|   4 |            mu- |   1
|   5 |       HadrSyst |  12
|   6 |         proton |  14
|   7 |            pi0 |  14
|   8 |            pi0 |  14
|   9 |            pi0 |  14
|  10 |         proton |   1
|  11 |            pi0 |   1
|  12 |         proton |   1
|  13 |            pi0 |   1
|  14 |            pi0 |   1
|  15 |       HadrBlob |  15
|-------------------------------
|       Fin-Init:
|------------------------------------------------------------------------------------------------------
|       Vertex:         nu_mu @ (x =     0.00000 m, y =     0.00000 m, z =     0.00000 m, t =    0.000000e+00 s) |
|------------------------------------------------------------------------------------------------------
| Err flag [bits:15->0] : 0000000000000000    |  1st set:                                          none |
| Err mask [bits:15->0] : 1111111111111111    |  Is unphysical:    NO |   Accepted:    YES              |
|------------------------------------------------------------------------------------------------------
| sig(Ev) =       4.45912e-38 cm^2  | d2sig(x,y;E)/dxdy =      2.09365e-37 cm^2       | Weight =       1.00000 |
|------------------------------------------------------------------------------------------------------
```

Description	*GHepStatus_t*	As *int*
Undefined	*kIStUndefined*	-1
Initial state	*kIStInitialState*	0
Stable final state	*kIstStableFinalState*	1
Intermediate state	*kIStIntermediateState*	2
Decayed state	*kIStDecayedState*	3
Nucleon target	*kIStNucleonTarget*	11
DIS pre-fragm. hadronic state	*kIStDISPreFragmHadronicState*	12
Resonant pre-decayed state	*kIStPreDecayResonantState*	13
Hadron in the nucleus	*kIStHadronInTheNucleus*	14
Remnant nucleus	*kIStFinalStateNuclearRemnant*	15

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GENIE Implementation

- We have begun the implementation of the QMC STA within GENIE using semi-final states from tabulated response densities
- This will be tricky, to say the least…
  - GENIE's normal operating mode is almost always dependent on an predominately *single particle* paradigm
    - Initial state preparation—**avoidable**?
      - *Single* nucleon lepton scattering
      - *Single* nucleon momentum distributions in nuclear models
      - *Single* nucleon initial positions
      - *Some* two-body dynamic options becoming available as we speak (SuSA), but initial correlations are highly approximate
    - Final state preparation—**unavoidable**!
      - Propagation of *single particle<u>s</u>* through the nucleus using an intranuclear cascade

```
   .oooooo.      oooooooooooo ooooo      ooo ooooo oooooooooooo
  d8P'  `Y8b     `888'     `8 `888b.     `8' `888' `888'     `8
 888              888          8 `88b.    8   888   888
 888              888oooo8     8   `88b.  8   888   888oooo8
 888     ooooo    888    "     8     `88b.8   888   888    "
 `88.    .88'     888       o  8       `888   888   888       o
  `Y8bood8P'     o888ooooood8 o8o        `8  o888o o888ooooood8
```

```
|------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                            |
|------------------------------------------------------------------------------------------------------|
| Idx |          Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |       m |
|------------------------------------------------------------------------------------------------------|
|   0 |         nu_mu |   0 |         14 |  -1 |  -1 |   4 |   4 |   0.000 |   0.000 |   2.261 |   2.261 |   0.000 |
|   1 |           C12 |   0 | 1000060120 |  -1 |  -1 |   2 |   3 |   0.000 |   0.000 |   0.000 |  11.175 |  11.175 |
|   2 |       neutron |  11 |       2112 |   1 |  -1 |   5 |   5 |   0.141 |  -0.105 |  -0.119 |   0.919 | **0.940 | M = 0.894
|   3 |           C11 |   2 | 1000060110 |   1 |  -1 |  15 |  15 |  -0.141 |   0.105 |   0.119 |  10.256 |  10.254 |
|   4 |           mu- |   1 |         13 |   0 |  -1 |  -1 |  -1 |  -0.006 |  -0.343 |  -0.017 |   0.359 |   0.106 | P = (0.018,0.999,0.051)
|   5 |      HadrSyst |  12 | 2000000001 |   2 |  -1 |   6 |   9 |   0.147 |   0.238 |   2.160 |   2.820 | **0.000 | M = 1.792
|   6 |        proton |  14 |       2212 |   5 |  -1 |  10 |  10 |   0.202 |  -0.123 |   0.958 |   1.362 |   0.938 | FSI = 1
|   7 |           pi0 |  14 |        111 |   5 |  -1 |  11 |  12 |  -0.006 |   0.116 |  -0.006 |   0.178 |   0.135 | FSI = 3
|   8 |           pi0 |  14 |        111 |   5 |  -1 |  13 |  13 |   0.001 |   0.227 |   0.589 |   0.646 |   0.135 | FSI = 1
|   9 |           pi0 |  14 |        111 |   5 |  -1 |  14 |  14 |  -0.049 |   0.018 |   0.618 |   0.635 |   0.135 | FSI = 1
|  10 |        proton |   1 |       2212 |   6 |  -1 |  -1 |  -1 |   0.202 |  -0.123 |   0.958 |   1.362 |   0.938 |
|  11 |           pi0 |   1 |        111 |   7 |  -1 |  -1 |  -1 |   0.059 |  -0.028 |   0.044 |   0.156 |   0.135 |
|  12 |        proton |   1 |       2212 |   7 |  -1 |  -1 |  -1 |  -0.028 |   0.173 |  -0.161 |   0.968 |   0.938 |
|  13 |           pi0 |   1 |        111 |   8 |  -1 |  -1 |  -1 |   0.001 |   0.227 |   0.589 |   0.646 |   0.135 |
|  14 |           pi0 |   1 |        111 |   9 |  -1 |  -1 |  -1 |  -0.049 |   0.018 |   0.618 |   0.635 |   0.135 |
|  15 |      HadrBlob |  15 | 2000000002 |   3 |  -1 |  -1 |  -1 |  -0.178 |   0.076 |   0.229 |   9.310 | **0.000 | M = 9.305
|------------------------------------------------------------------------------------------------------|
|       Fin-Init:                                            |   0.000 |   0.000 |   0.000 |   0.000 |           |
|------------------------------------------------------------------------------------------------------|
|       Vertex:         nu_mu @ (x =     0.00000 m, y =     0.00000 m, z =     0.00000 m, t =    0.000000e+00 s) |
|------------------------------------------------------------------------------------------------------|
| Err flag [bits:15->0] : 0000000000000000    |  1st set:                                         none |
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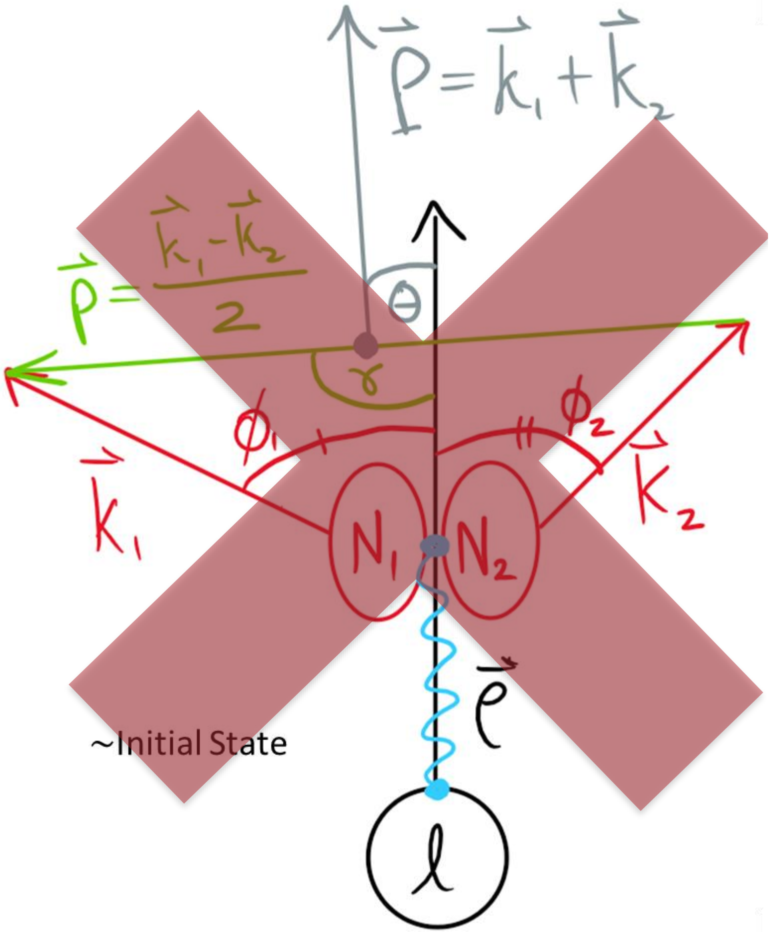

$\vec{P} = \vec{k}_1 + \vec{k}_2$
$\vec{p} = \frac{\vec{k}_1 - \vec{k}_2}{2}$
θ
γ
ϕ_1
ϕ_2
$\vec{k}_1$
$\vec{k}_2$
N_1
N_2
$\vec{e}$
ℓ
~Initial State

Scripts for Comparisons Against World Data are Working

- Simple interfaces between GENIE's SuSAv2 HadronTensor framework have been made for easy plotting of interpolated cross sections from given theoretical nuclear response functions
  - Some validation of responses and their interpolation within GENIE to $\frac{d^2\sigma}{dE' d\Omega'}(|\vec{q}|, \omega)$ still needs to be completed
- Scripts run interpolations within the HadronTensor framework
- Create table outputs for input to simple plotting scripts
  - Can compare all available outputted model cross sections for $e\,^4_2\mathrm{He}$ to available World Data

Requirements Going Forward with GENIE for Two-Body Physics

- An attempt at a general framework is being pursued
  - When new nuclear responses and response density tables become available for larger nuclei, can simmply “drop something in”
- Must hand off two-nucleon configurations properly to GENIE…
  - Attain particle identities
  - Select all angles (currently integrated out) via some method…
    - The geometric interpretation of electromagnetic nuclear responses is well understood, but how to define this generically for electroweak processes needs much more consideration
  - Derive individual nucleon momenta via law of cosines
  - Track individual nucleons through the intranuclear cascade
    - Critically dependent upon initial positions and separations
    - One or both nucleons may not be emitted due to low momentum transfer
      - A phenomenological momentum cutoff must be considered for each struck nucleon