Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Updates on Quantum Monte Carlo Implementations for $\ell\,{}^{4}_{2}\mathrm{He}$ and $\ell\,{}^{12}_{6}\mathrm{C}$ Scattering in GENIE

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Joint Theory/Experiment Meeting on Lepton-Nucleus Scattering

Tuesday, October 1st, 2019

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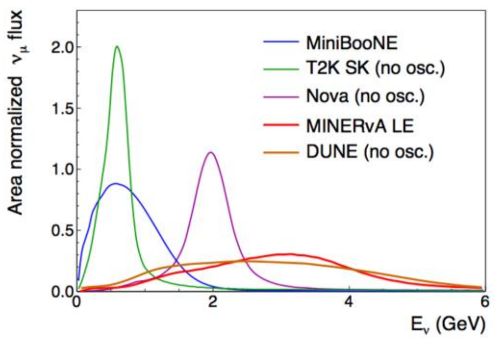
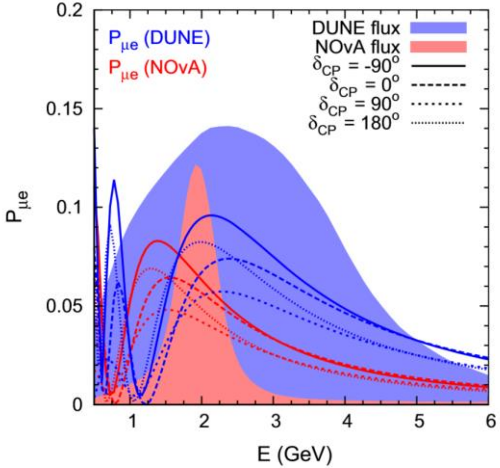
The Need for Accurate and Precise ℓ Monte Carlo Generators

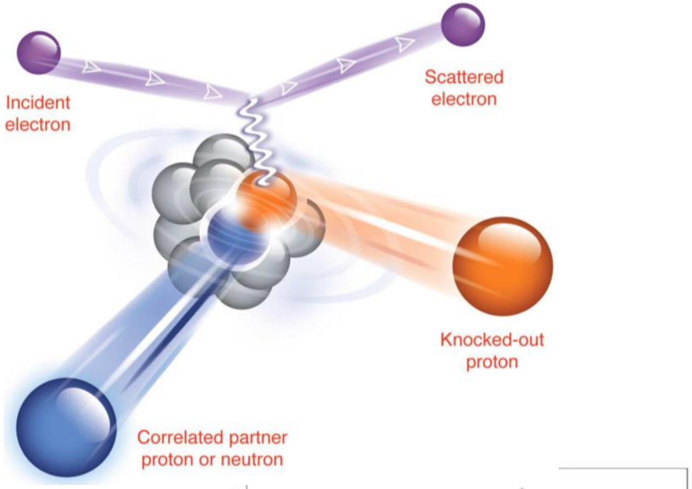


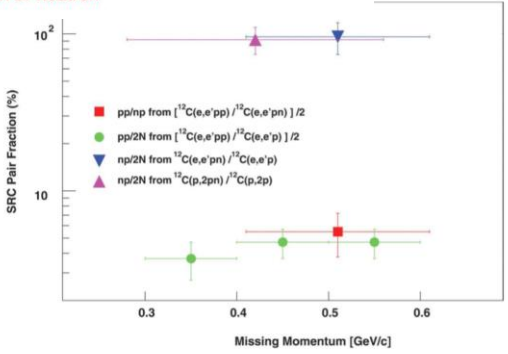
CernCourier 2017



Ghosh *et al*. Eur. Phys. J. C (2016)76

- See Artur's talk, along with Kendall and Joe
- We require good ν energy and position reconstruction to nail down SM ν interactions
  - Understanding of in/exclusive cross sections, fluxes, etc.
  - PMNS matrix elements (flavor changing oscillations), associated θ_{ij} values
  - Value of δ_{CP}
  - Supernovae ν's, masses, mass hierarchy, majorana-nature, etc., etc…
- The same can be said for limits on BSM interactions
  - Lorentz/CPT violation
- We require accurate simulations of *atmospheric neutrino backgrounds* for BSM searches
  - p-decay, $n \to \bar{n}$, and other baryon number violating modes
  - Dark matter
- All of these require ample theoretical and computational study across large swaths of energy and momentum transfer





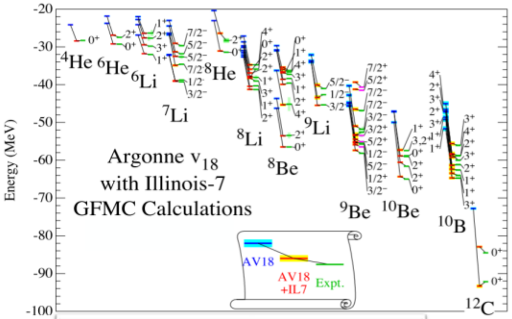
JLab, Subedi *et al.* Science320(2008)1475

A unified dynamical model for the nuclear response

- Nuclear interactions are described by a realistic phenomenological Hamiltonian

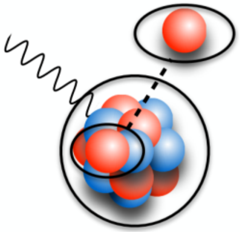
$$H = \sum_i \frac{\mathbf{p}_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \dots$$

The Green's Function Monte Carlo

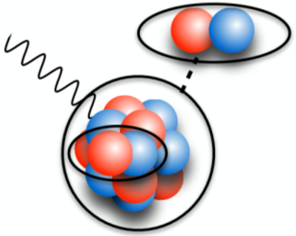


J. Carlson et al. RMP 87, 1067 (2015)

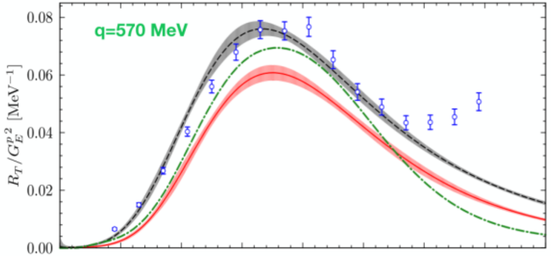
CBF Spectral Function



Short-time Approximation



Saori Pastore et al



Alessandro Lovato et al. PRL 117 082501 (2016)

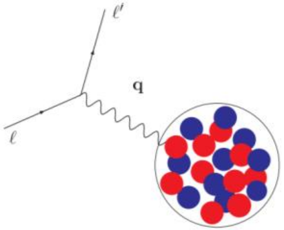
- Ab initio methods provide strict benchmarks valuable to constrain more approximate models at low |**q**|

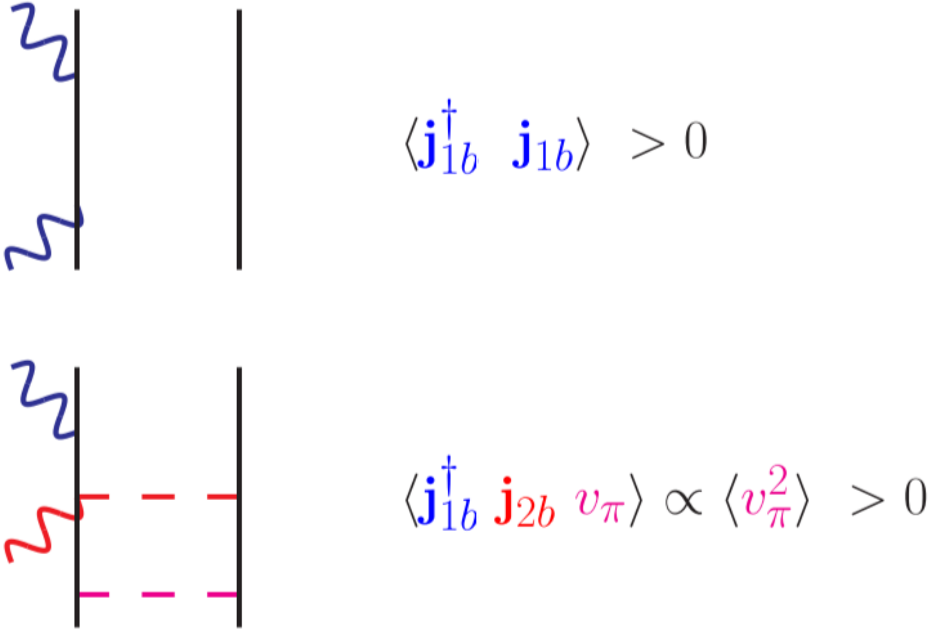
STA: The Inclusion of Two-Body Physics: Nuclear Response

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

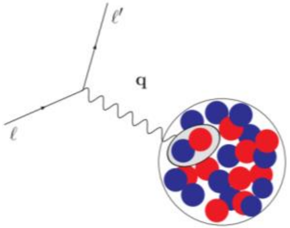
Considering the modes … al and transverse responses ρ and $\mathbf{j}$, res …

1b





2b



– The total inclusive c … esponse:

$$\frac{d^2\sigma}{dE'd\Omega'} = \sigma_M[\nu_L R_L(q^\mu \cdots \cdot |\langle f|\nu_T O_T(q^\mu)|0\rangle|^2] = \cdots$$

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

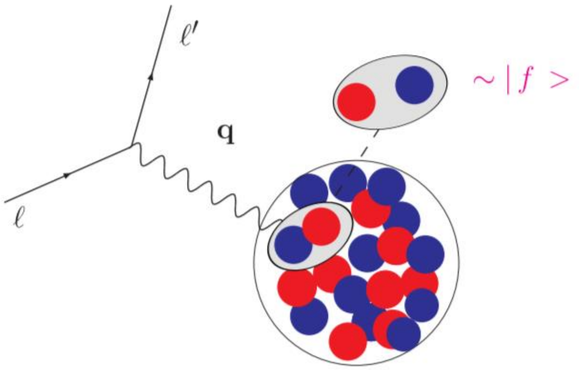
STA: The Inclusion of Two-Body Physics: 1b-1b, 1b-2b, 2b-1b, 2b-2b

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

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

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

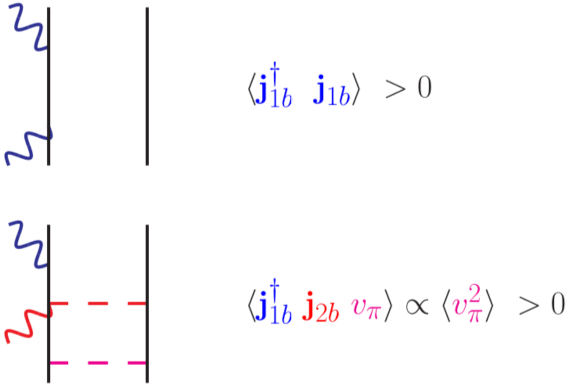
$$\Rightarrow R_\alpha \sim O^\dagger_{\alpha;i}P(t)O_{\alpha;i} + \boldsymbol{O^\dagger_{\alpha;i}P(t)O_{\alpha;j}} + \boldsymbol{O^\dagger_{\alpha;i}P(t)O_{\alpha;i,j}} + O^\dagger_{\alpha;i,j}P(t)O_{\alpha;i,j}$$



- 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

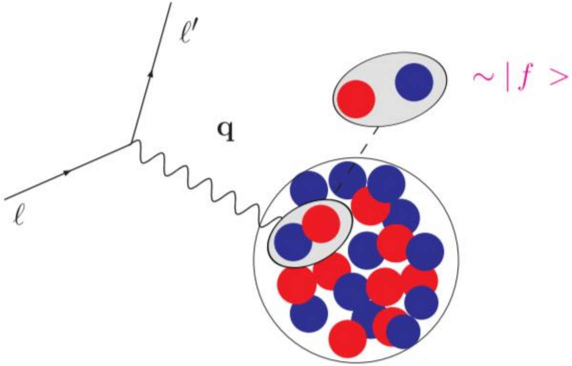


STA: The Inclusion of Two-Body Physics: Densities

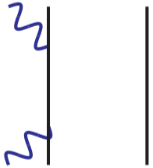
- One can encode all of this structure within *response densities*, $\mathcal{D}$

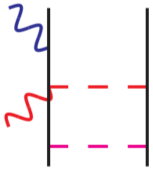
$$R_\alpha(q^\mu) \sim \int d\Omega_{P'} d\Omega_{p'} dP' dp' \delta(\omega + E_0 - E_f) \cdot \left[p^{\mu'2} P^{\mu'2} \left\langle 0 \middle| O_\alpha^\dagger(q^\mu) \middle| p^{\mu'}, P^{\mu'} \right\rangle \left\langle p^{\mu'}, P^{\mu'} \middle| O_\alpha^\dagger(q^\mu) \middle| 0 \right\rangle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

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



- Contains information about…
  - **…the contents of the nucleus *<u>after</u>* the probe interacts** with the pair
  - “Exclusive” information on specific nucleon pair kinematics
  - Correctly accounts for interference terms





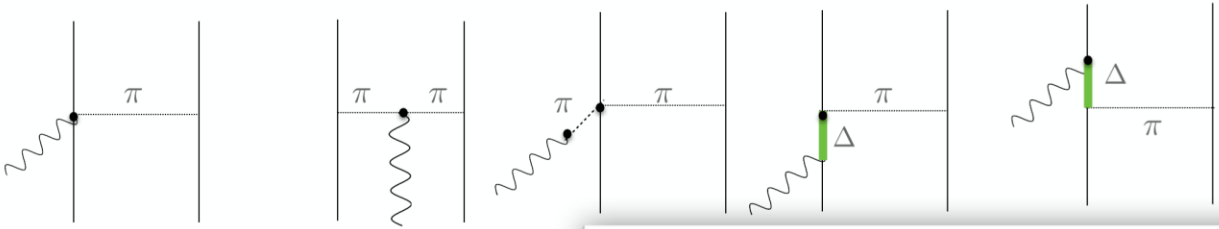
(Anti)neutrino -^{12}C scattering cross sections

- We generalized the SF formalism to include vector and axial vector relativistic two-body currents

$$W^{\mu\nu}_{2b}(\mathbf{q},\omega) \propto \int d\tilde{E}\frac{d^3k}{(2\pi)^3}d\tilde{E}'\frac{d^3k'}{(2\pi)^3}P_h(\mathbf{k},\tilde{E})P_h(\mathbf{k}',\tilde{E}')\sum_{ij}\langle k\,k'|j^{\mu\,\dagger}_{ij}|p\,p'\rangle\langle p\,p'|j^{\nu}_{ij}|k\,k'\rangle$$

- NN correlations are accounted for by the including the product of two one-hole spectral functions

- We extended the calculation to include vector and axial vector relativistic two-body currents



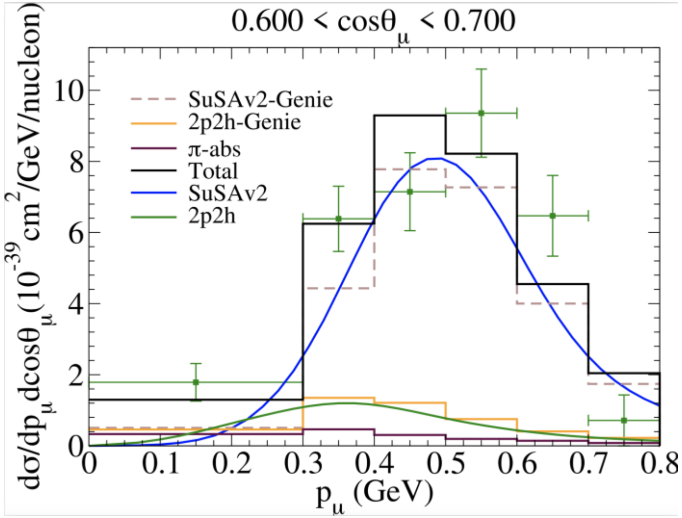
NR, C.Barbieri, O. Benhar, A. De Pace, A. Lovato, arXiv:1810.07647

- The calculation of the MEC current matrix is carried out automatically
- 9d-integral + use of realistic SFs implies dealing with a broader phase space: we developed an highly parallel Monte Carlo code, importance sampling procedure

Hadron tensor framework & SuSAv2 implementation

- Hadronic tensor framework for GENIE
  - Based on Valencia CCMEC implementation in v2, generalized and expanded
  - SuSAv2 CCQE+MEC implementation under GENIE review, expected in next release (v3.2)
- Bilinear interpolation used to evaluate tensor elements in $(\omega, |\vec{q}|)$ space
- Used by our STA implementation to select lepton kinematics
- Noemi has also provided tensor tables for 2-body contribution
  - QE cross section for SF approach computed directly within GENIE
- HadronTensor framework technical note now available

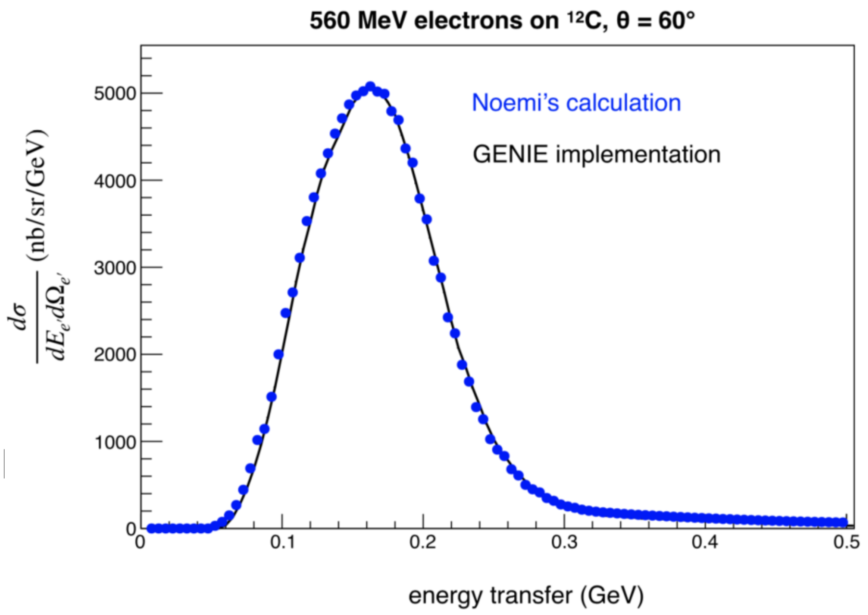
$$\frac{d^2\sigma}{dE'_\ell\, d\cos(\theta'_\ell)} = \frac{|\boldsymbol{k}'|}{|\boldsymbol{k}|} \frac{G_F^2}{2\pi} L_{\mu\nu} W^{\mu\nu}$$



SuSAv2 implementation note

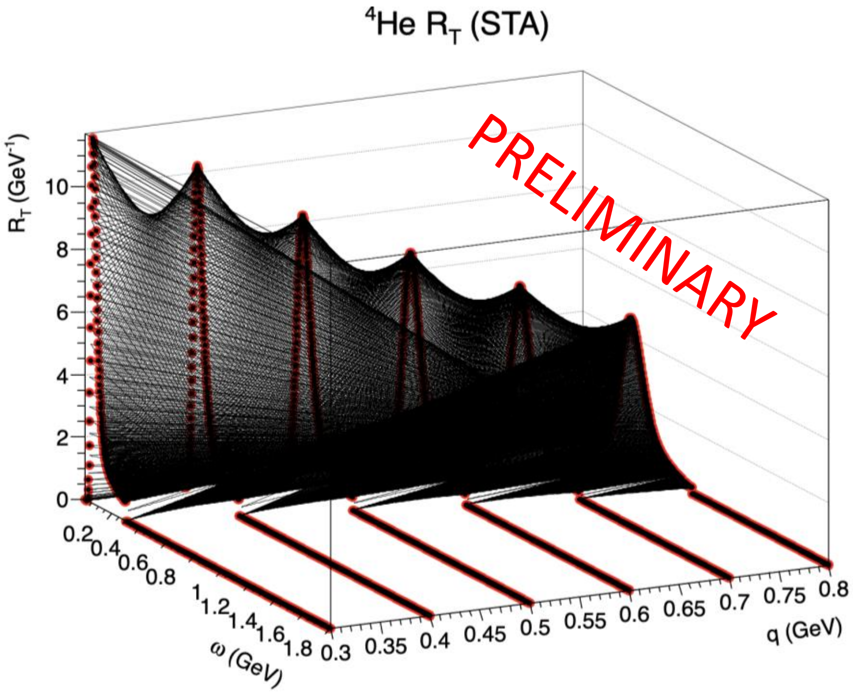
GENIE spectral function implementation status

- Spectral function code & tabulated data for ^{12}C updated to reflect latest calculation provided by Noemi
- Checks of GENIE QE differential cross section look good
  - EMQE example shown
  - Weak interactions show similar agreement
- Two-body EM hadronic tensor table in hand, testing in progress
  - Will employ the same code as Valencia, SuSAv2
- Currently troubleshooting a problem with EM event generation
  - Maximum cross section estimate fails during sampling
  - Low Q^2 cut needed to avoid divergence → appears related
- When resolved, will prepare for GENIE review soon



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
  - **Production of more tables underway**
    - Use of more sophisticated interpolation methods are also possible if number of tables becomes too unwieldy
- STA/SF/GFMC technical note is *developing*
  - Will eventually include…
    1. Full validation of cross section/response comparisons
    2. Writeup of (forthcoming) generator module processes



"Kinks" are an artifact of interpolation on a coarse grid

Scripts for Comparisons Against World Data

- Simple interfaces between GENIE's SuSAv2 HadronTensor framework have been made for easy plotting of interpolated cross sections
  - Some validation of Noemi's responses and their interpolation within GENIE to $\frac{d^2\sigma}{dE' d\Omega'}(|\vec{q}|, \omega)$ still needs to be completed (unit checks?)
- build_XX.sh and test_XX.cc scripts run interpolations within the HadronTensor framework
  - Within SuSA fork: ./build_XX.sh; ./test_XX
- Create table outputs for input to simple ValidationCode.C plotter
  - Will compare all available outputted model cross sections for all targets to available World Data: root –l ValidationCode.C;

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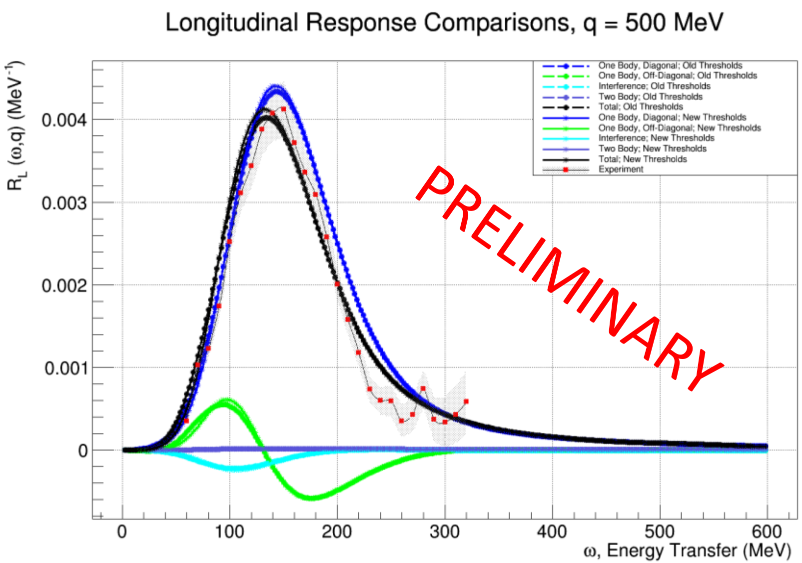
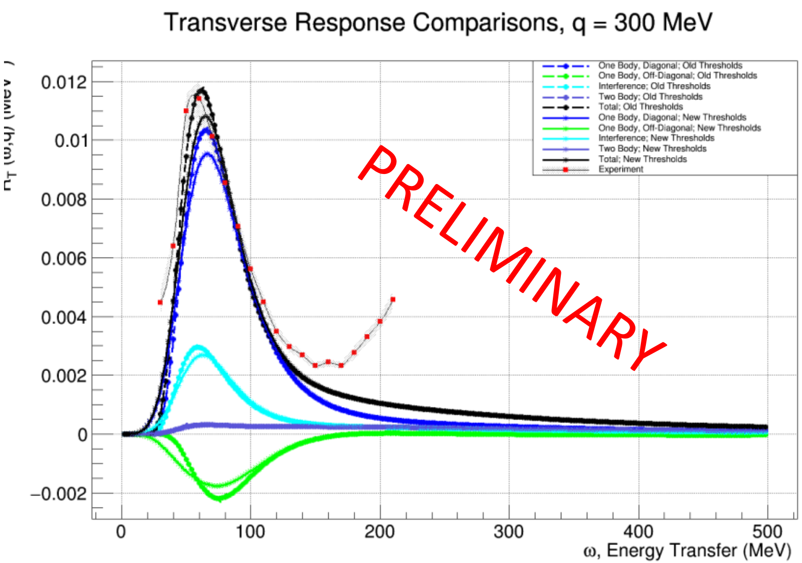
STA ^4_2He Responses Used in GENIE for Interpolation (GFMC coming soon!)





Dark Blue: one-body diagonal; Green: one-body off-diagonal; Light Blue: interference; Purple: two-body

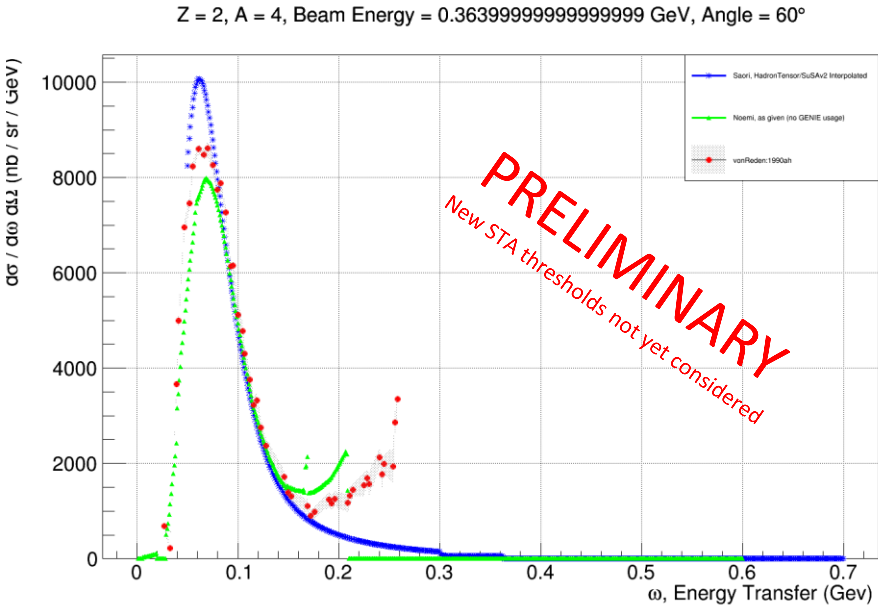
Saori's STA is shown here component by component for two different shifts/thresholds.

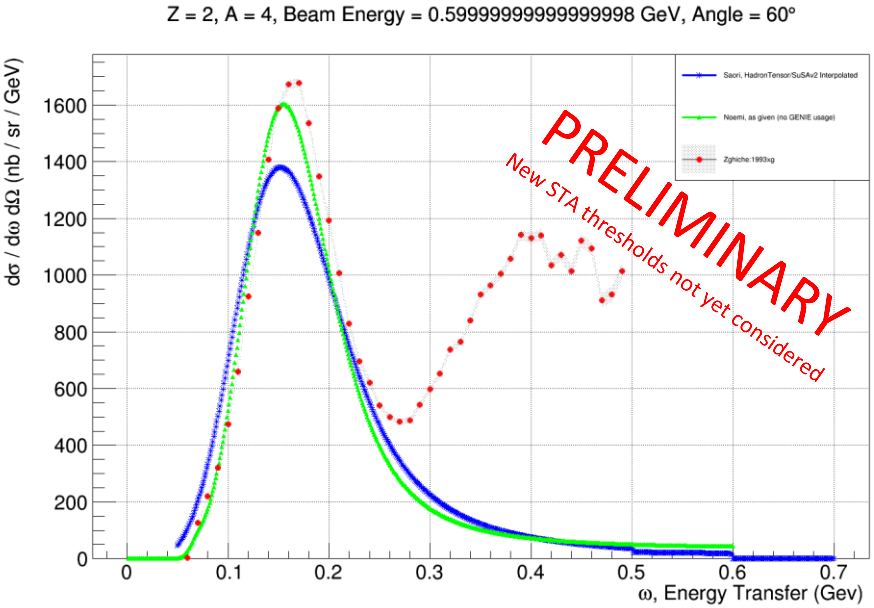
The *interference* and one-body *off-diagonal* terms show asymmetric and even destructive behavior to the total response (shown in black)

New threshold predominately effect the *transverse response*

Current experimental response data interpolated by Ingo Sick for ^4_2He only, so far; some others exist (Dytman) and will integrated for comparisons

Some simple, first-pass comparisons between models and data for ^4_2He





Green-Noemi, GFMC (*as given*)

Blue-Saori, STA (*GENIE interpolated*)

Red-Cross section data, with uncertainty bands

Elastic peak in STA needs to be removed still

***Some** of the resonant production seems to be included*

Green-Noemi, GFMC (*as given*)

Blue-Saori, STA (*GENIE interpolated*)

Red-Cross section data, with uncertainty bands

No apparent resonant production from Noemi's model here?

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Collaborators—Thank-you!

The Roses

Between

The Thorns

Saori Pastore, WUSTL

Steven Gardiner, FNAL

Joshua Barrow, UTK

Minerba Betancourt, FNAL

Backup Slides

Requirements Going Forward with GENIE

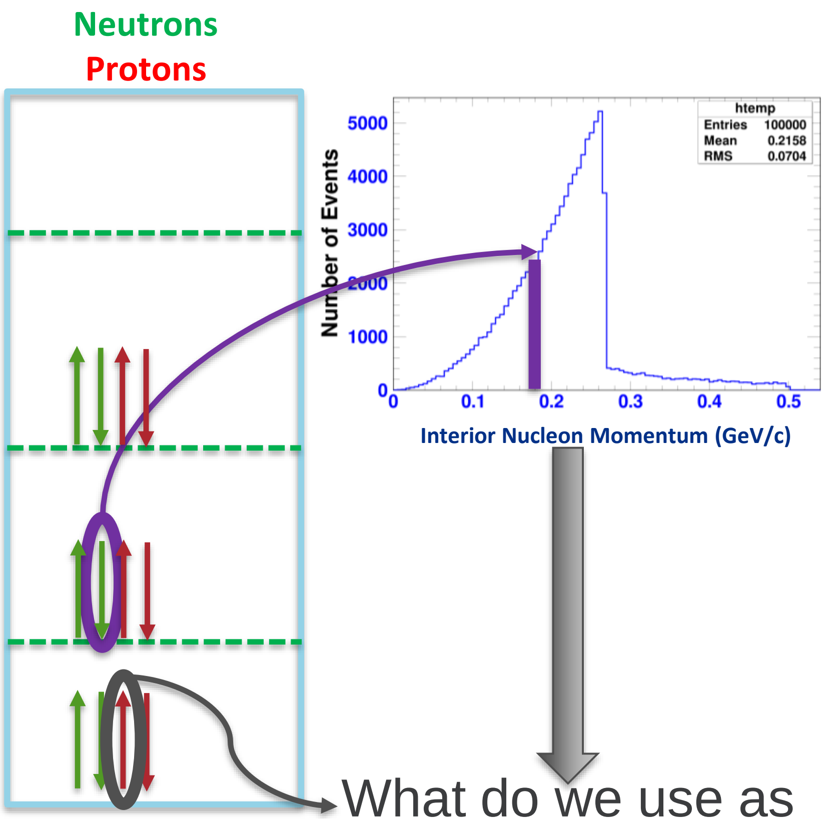
- An attempt at a general framework should be considered
  - When new response densities are ready for larger nuclei from future calculations, we should want to be able to simply “drop something in”
- Must streamline table reading, or avoid it altogether with another structure
- Must hand off two-nucleon configurations properly to GENIE…
  - Attain particle identities
  - Select all angles (currently integrated out)
  - Derive individual nucleon momenta
  - Track individual nucleons through the intranuclear cascade
    - Could be 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

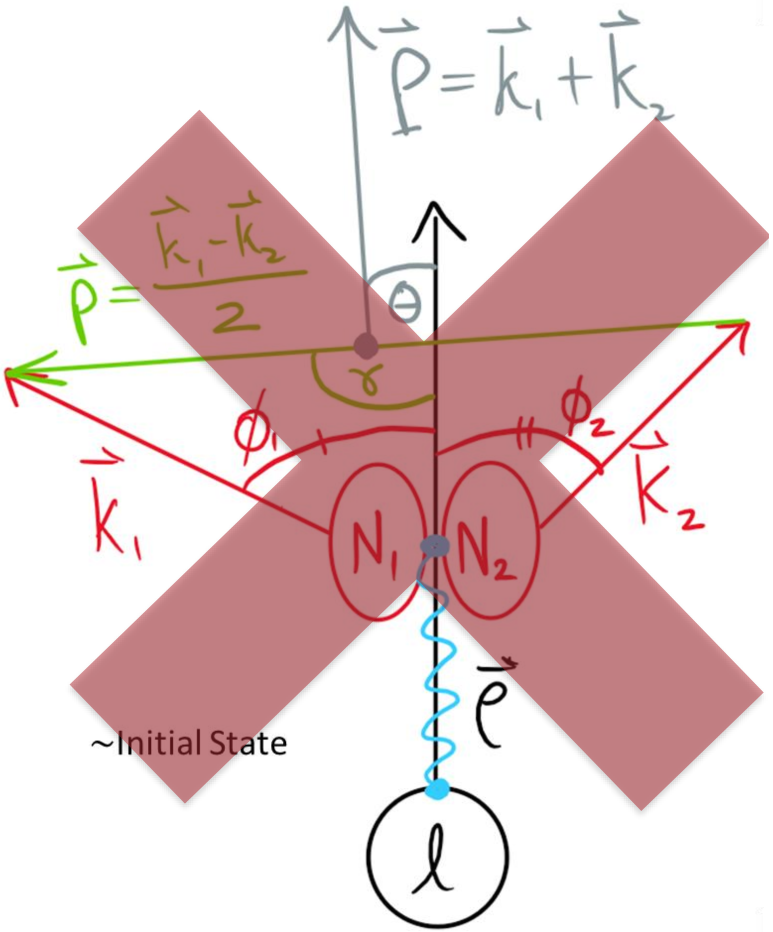
Future Generator Validation

- Ample amounts of data are available for e_2^4He and $e_6^{12}C$ scattering
  - Will serve as a good comparison for total inclusive cross sections
  - Will compare to other GENIE nuclear models
  - I would highly encourage everyone to investigate any BSM contributions your models could make to electron interactions
    - Can they already be constrained?
- Once the generator is complete, tested, and validated on e data, we will proceed to ν generation
  - Will involve more response densities (five in total) for inclusion of CC interactions
  - Will similarly compare to data where available…
  - …and other GENIE nuclear and interaction models
- Publication will follow soon after

Nucleon Correlations: A Requirement for Future Simulations

- There are QM problems with the assumptions made when throwing momenta for *multiple* nucleons from *single* nucleon momentum distributions
  - By making a choice from a distribution of *all* ***single*** *nucleons*, we have ***changed the remaining distribution***
- Furthermore, it has been found that ***nucleons are choosey about their neighbors***
  - **Neutrons spend more time around protons** in the nucleus
  - These pairs can have ***inextricably linked momenta***
- **More JLAB data** interpretation on LAr coming? See also recent cross section measurements
- ***Can we use ~two body momentum distributions instead?***
  - ⟶ **Noemi et al.**
- ***Or, can we deal solely with accurate semi-final states induced by vertex interactions?***
  - ⟶ **Saori et al.**





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

Current QMC STA 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

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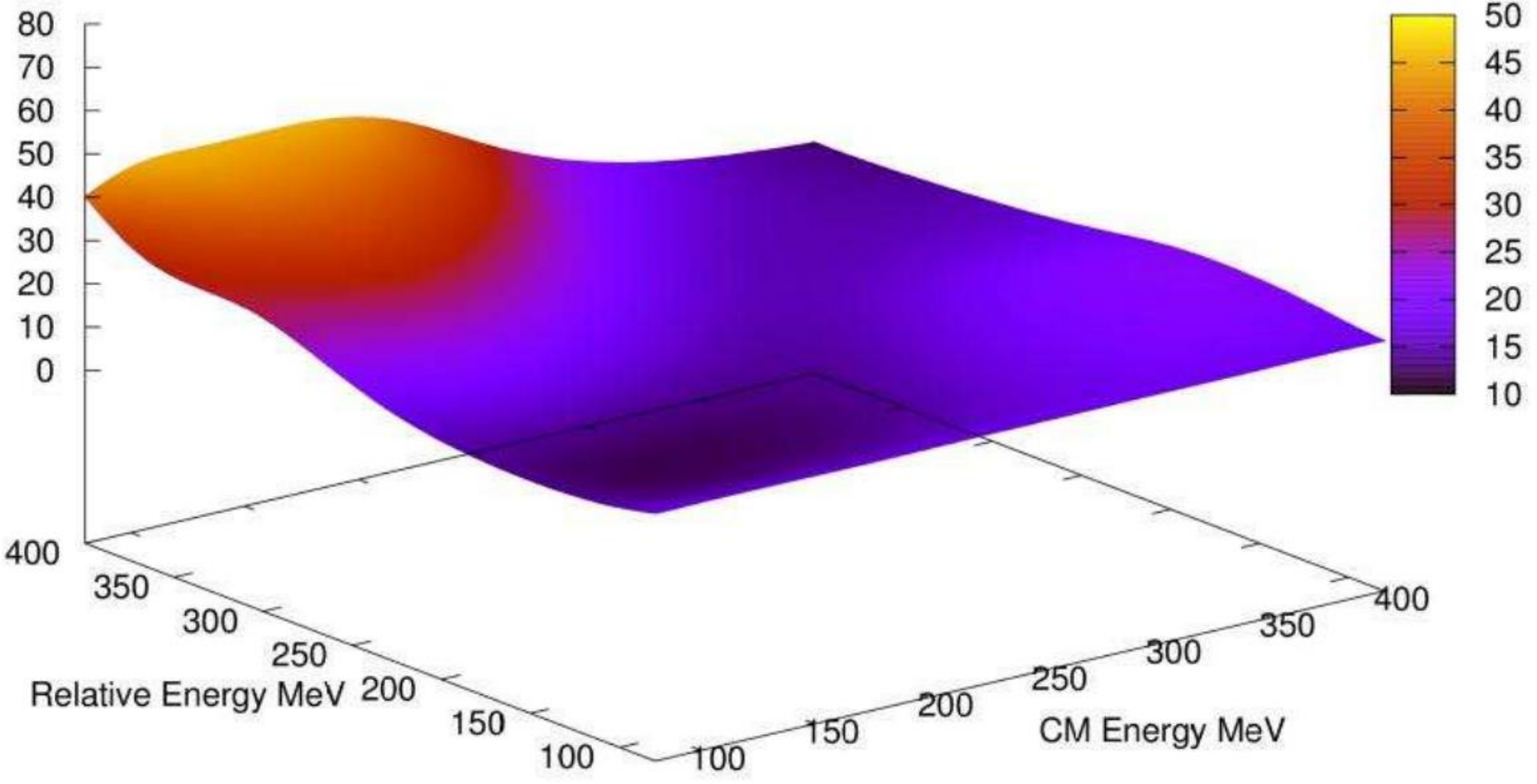
80
70
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Relative Energy MeV
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200
250
300
350
400
CM Energy MeV
50
45
40
35
30
25
20
15
10

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

Genie
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GENIE Implementation

- We will soon begin implementation of 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 only approximate
    - Final state preparation—**unavoidable**!
      - Propagation of *single* particle***s*** 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) |
|------------------------------------------------------------------------------------------------------------|
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Summary

- Neutrino generators must grow and evolve their capabilities as we enter the precision and intensity frontiers
  - One step in this evolution is implementation of a generator dependent only upon semi-final states
  - Avoids phenomenological nuclear models of initial states in MC
- A new series of total inclusive lepton scattering cross section calculations for $\omega\tilde{\epsilon}(300,800]MeV$ are now available for $\ell\,{}^{4}_{2}\mathrm{He}$ and $\ell\,{}^{12}_{6}\mathrm{C}$ responses
  - Employs two-body physics in an inherent way
- Implementation of this model is beginning for GENIE
  - Will likely depend on many developments from Steven Gardiner (SuSAv2)
  - Efficient table reading implementation is necessary, or another structure
  - Will pass much of the particle information to the intranuclear cascade for transport