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# Theory interfaces to generators: a summary

Fermilab Generator Tools  
workshop 1 / 10 / 2020

# What the community wants

## Now

### Charged-current interactions

- CCQE
- Resonant
- DIS
- Coherent

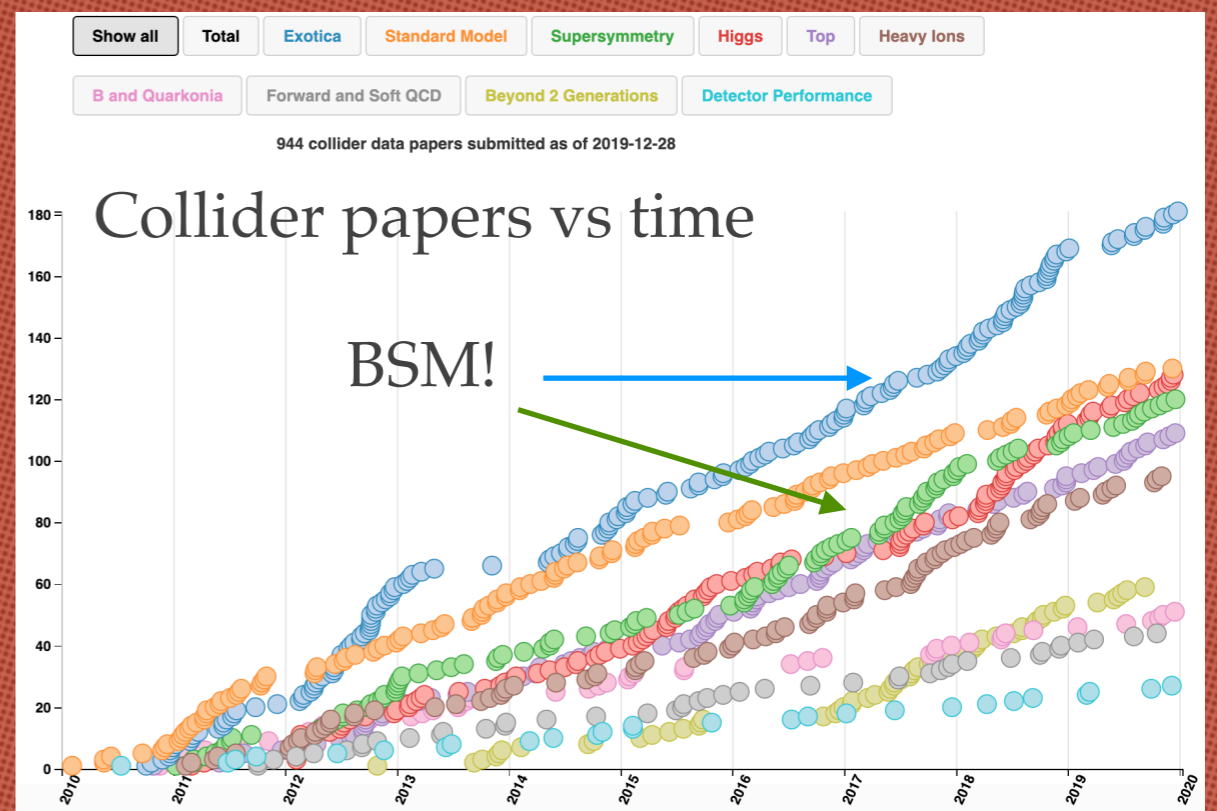
### Neutral-current interactions

### Electron scattering?

## In future

### BSM interactions

- DUNE is a large (LHC-like) collaboration
- Should do more than just measure the basics...



# Theory example - Green's function Monte Carlo

$$\left(\frac{d\sigma}{dE'd\Omega}\right)_{\nu/\bar{\nu}} = \frac{G^2}{4\pi^2} \frac{k'}{2E_\nu} \left[ \hat{L}_{CC} R_{CC} + 2\hat{L}_{CL} R_{CL} + \hat{L}_{LL} R_{LL} + \hat{L}_T R_T \pm 2\hat{L}_T R_{T'} \right]$$

## What is it good for?

- ❖ Accurate cross sections in QE region, including 2-body effects
- ❖ Electron scattering; CC and NC neutrino scattering
- ❖ Ab initio method - only available for nuclei up to  $^{12}\text{C}$

## What is the output?

- ❖ Table of responses as function of  $q$  and  $W$ . Can be transformed to cross sections
- ❖ Summed over final states (generator throws FS particles). No pions.
- ❖ Uncertainties - yet to come

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# Theory example - Spectral functions

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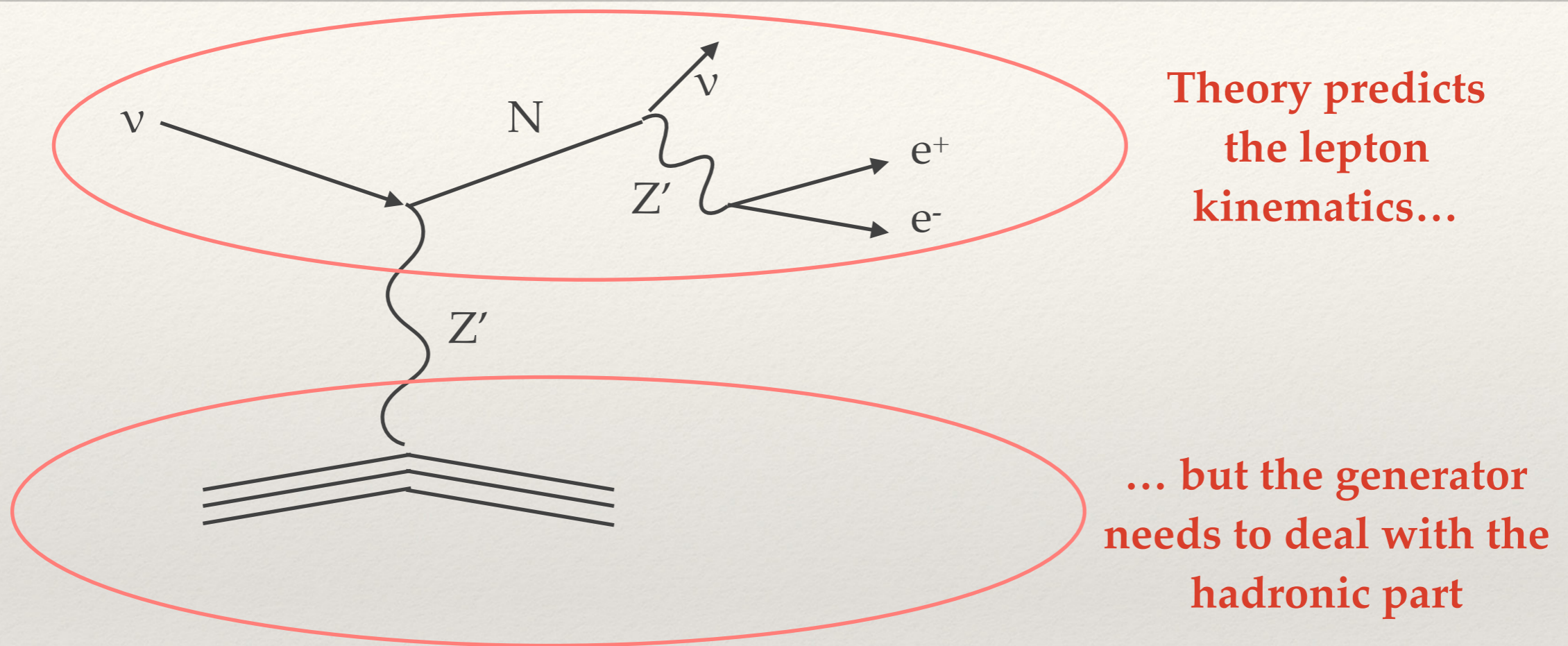
## What is it good for?

- ❖ Includes QE, MEC, and 1-pion production - 2-pion and DIS to come
- ❖ Two different approaches (SCGF, CBF) for electron- and neutrino scattering
- ❖ Calculated for several nuclei including Ar
- ❖ Exclusive meaning individual final states are not summed
- ❖ FSI included - affects energies but not particle multiplicity

## What is the output?

- ❖ Table of responses as function of  $q$  and  $W$ .
- ❖ Individual particle momenta are integrated out - could be added to tables
- ❖ MC method - could provide routine to simulate individual events

# Hypothetical example: BSM physics



- ❖ If DUNE is like LHC, it's going to want to test BSM models
- ❖ How can we make this easy for theorists?
- ❖ They might only calculate part of the final state

# Two approaches (both currently in use)

## Code interface

- ❖ Pass in neutrino energy; get out some final-state particles on event by event basis
- ❖ Devise a standard interface to theorists' MC code

## Tables of values

- ❖ Cross sections / response functions as functions of some variables
- ❖ Generator samples from that distribution and generates final-state particles constrained by those parameters
- ❖ Vectors of final-state particle momentum combinations?

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# Consider: The human factor

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- ❖ Theorists are often PhD students / postdocs
- ❖ Need to test theories in generators on short timescales (develop and test  $\sim 3$  theories in duration of a postdoc...)
- ❖ Possibly not programmers - maybe develop in e.g. mathematica

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# Consider: re-weighting

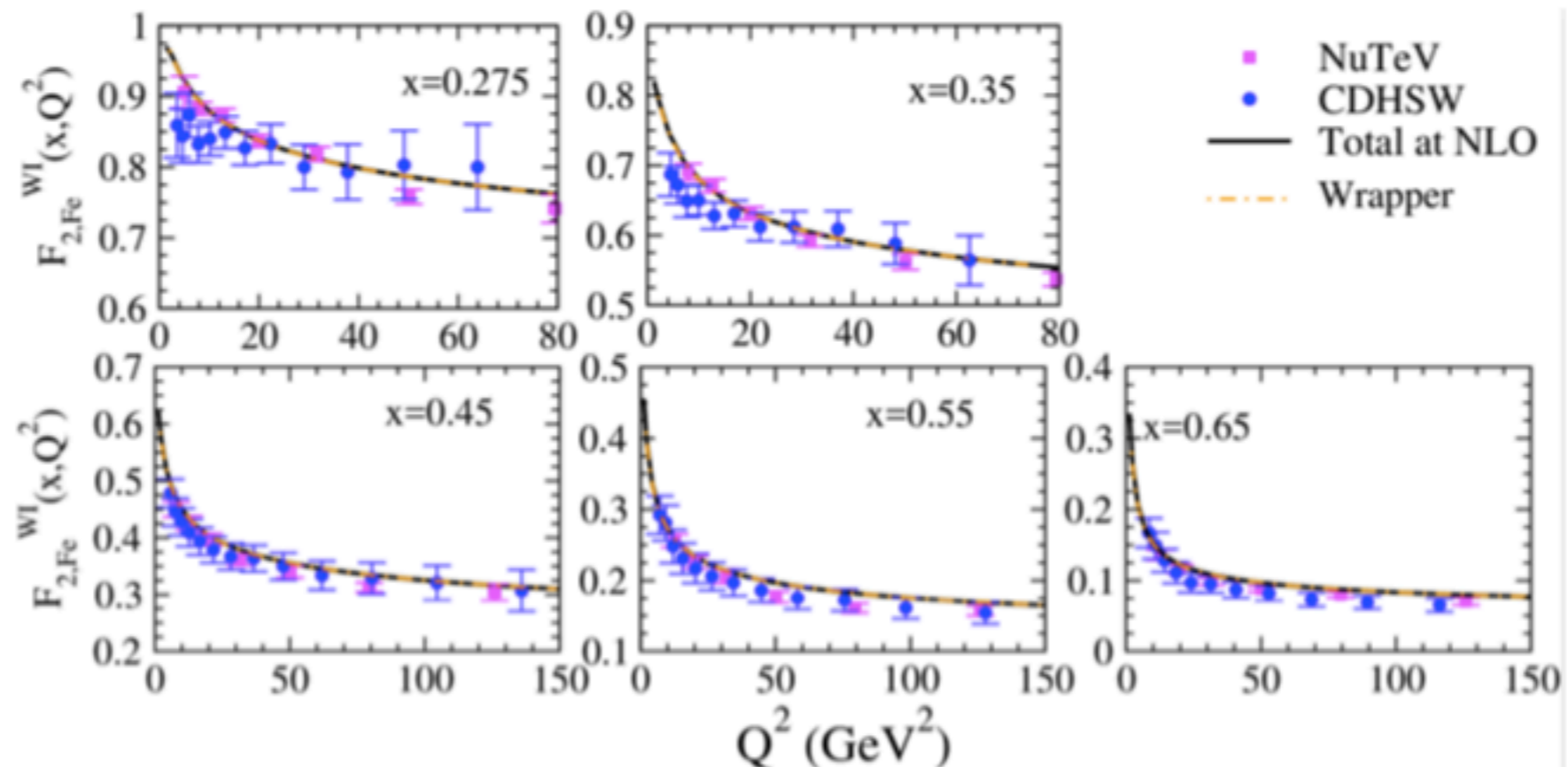
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- ❖ Experiments evaluate uncertainty by changing some parameter
  - ❖ E.g. how would cross section change if  $m_A$  were 10% higher?
- ❖ Mechanism fairly clear with code interface
- ❖ What is the mechanism to do it with tables?
  - ❖ It's being done now...
  - ❖ ... but it's rather *ad hoc*
  - ❖ Is there a way to standardise how to do this?

# Steven's code example

## Fortran wrapper example

- $F_2(x, Q^2)$  structure function from H. Haider
  - Plot shows Fortran original calculation (black) and GENIE wrapper (dashed yellow)
  - Original calculation from [H. Haider et al., PRC84, 054610 \(2011\)](#)



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# Code interfaces – advantages

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- ❖ Get actual “final”-state products for each event (possibly before FSI)
- ❖ Run calculation each time: easy to use vary a physics parameter
- ❖ Can be faster than table look-up
- ❖ Cooperate between generators by sharing code?

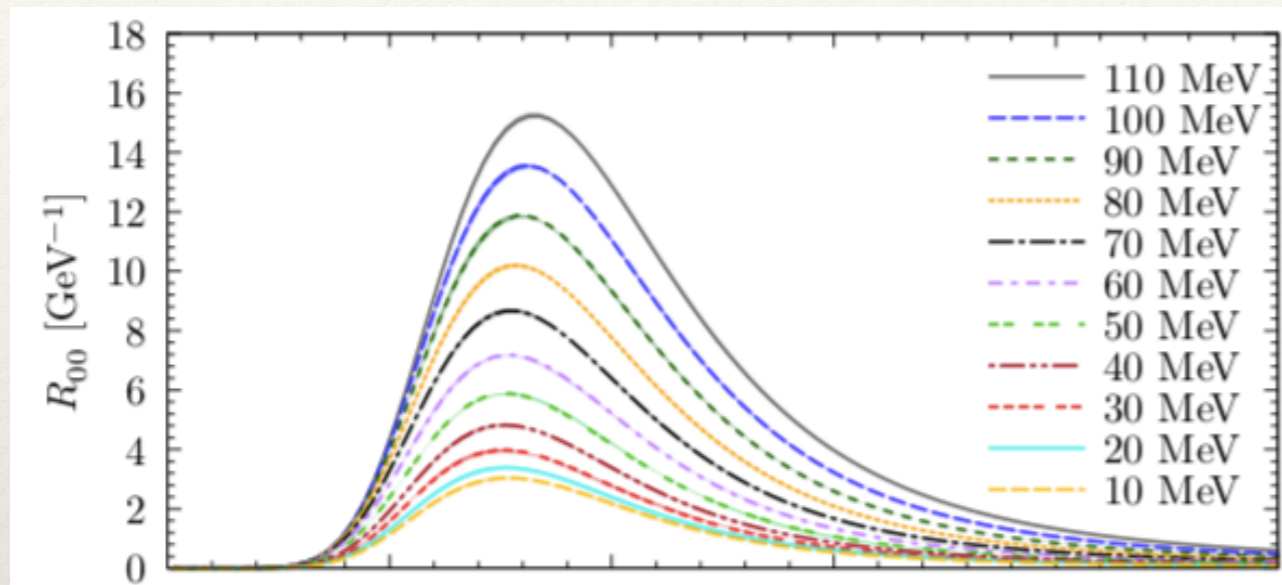
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# Code interfaces - challenges

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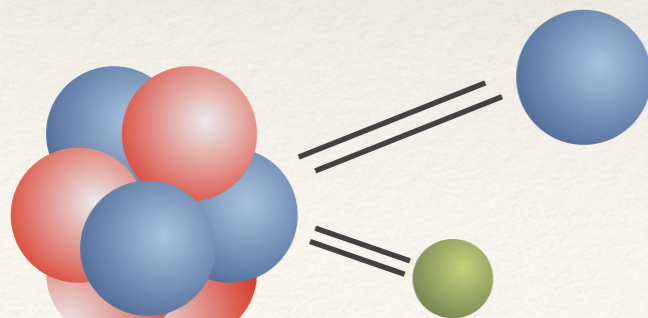
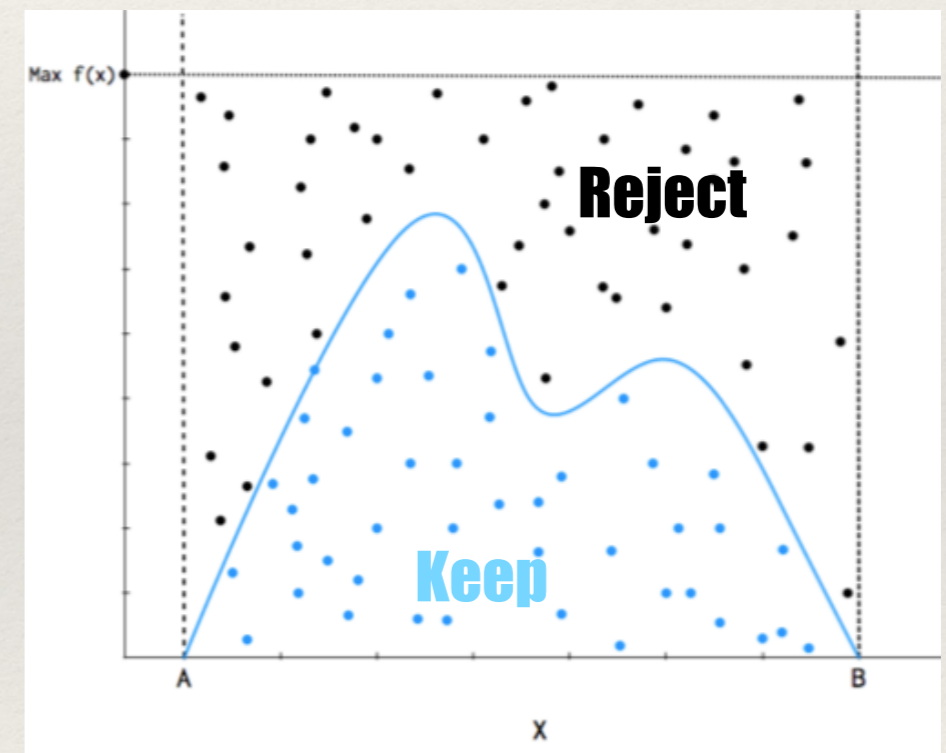
- ❖ Too constraining for theorists to make them code to a standard interface / parameter-passing mechanism?
- ❖ Too much to ask of a Mathematica user?!
- ❖ If the model's made already, who converts it to our format?
- ❖ Could be slow depending on calculation
- ❖ Doesn't work for calculations that sum over final states etc (e.g. GFMC)

# Lookup tables



The generator samples the space and gets back some information (e.g.  $q$  and  $W$  values)

Theorists provide (in standard format) a differential cross section table in some variables



Generator resamples based on those values to generate the momenta/multiplicity of particles produced (which may be an input to FSI model)

# Steven's table example

## Table-based example: hadronic tensor

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

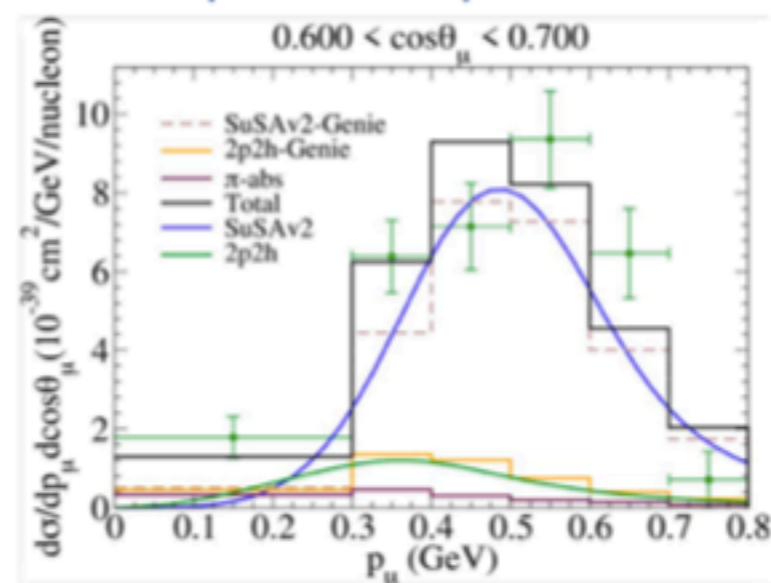
$$\omega = E_\ell - E_{\ell'}$$

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

- 5 elements at each  $(\omega, q)$  grid point
- Other variables integrated out  
→ inclusive prediction only

$$\frac{d^2\sigma}{dE_{\ell'} d\cos(\theta_{\ell'})} = \frac{|\mathbf{k}'|}{|\mathbf{k}|} \frac{G_F^2}{2\pi} L_{\mu\nu} W^{\mu\nu}$$

SuSAv2 prediction compared to T2K data



[SuSAv2 implementation note](#)

- Pros and cons discussed in detail at **ECT\* workshop** in June 2019 (slides by S. Dolan)
- Valencia MEC available using this method in GENIE, NEUT, NuWro
- SuSAv2 also expected for GENIE v3.2 (other generators?)

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# What's in the tables?

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- ❖ Most basic is a **differential cross section** in some set of variables
- ❖ Noemi's models return response functions of  $q$  and  $W$  - need to **transform** to a cross section. *Need some kind of code wrapper/interface to transform different formats.*
- ❖ Some models may return more specific information e.g. **particle momenta**: no need to resample, BUT can we deal with highly multi-dimensional spaces?
  - ❖ Tricks to speed up sampling when most of the space is “reject”
  - ❖ Large tables / slow lookup (LHC can deal with up to 35 dimensions; Jessica Turner has a good method...)

**Action: survey how people deal with multi-dimensional tables**

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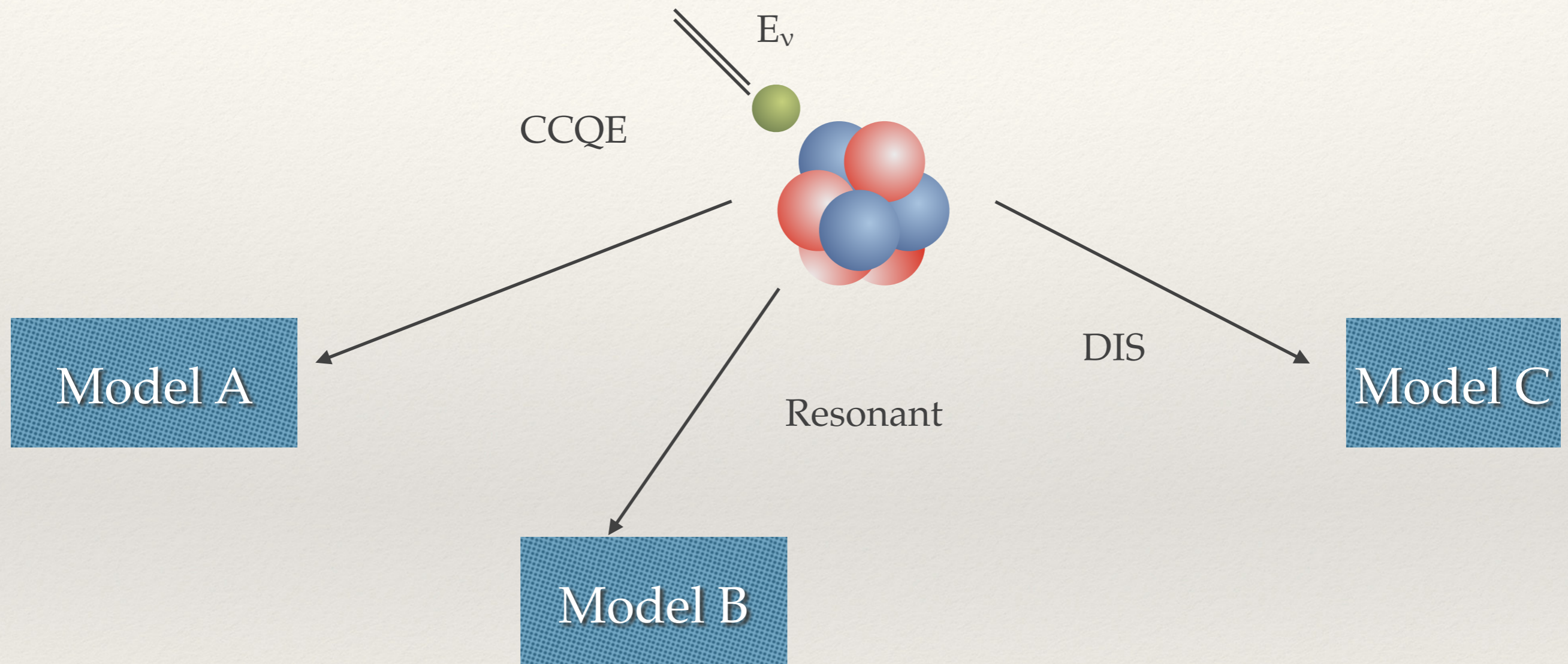
# Parameter variations in tables

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- ❖ Experiments want to re-weight to evaluate the effect on cross sections of uncertainties on physical constants
- ❖ Multiple versions of tables to vary parameters?
  - ❖ How quickly does this become too big?
- ❖ Transformation rule for central-value table?
  - ❖ Being used for some models now
  - ❖ How to standardise these?

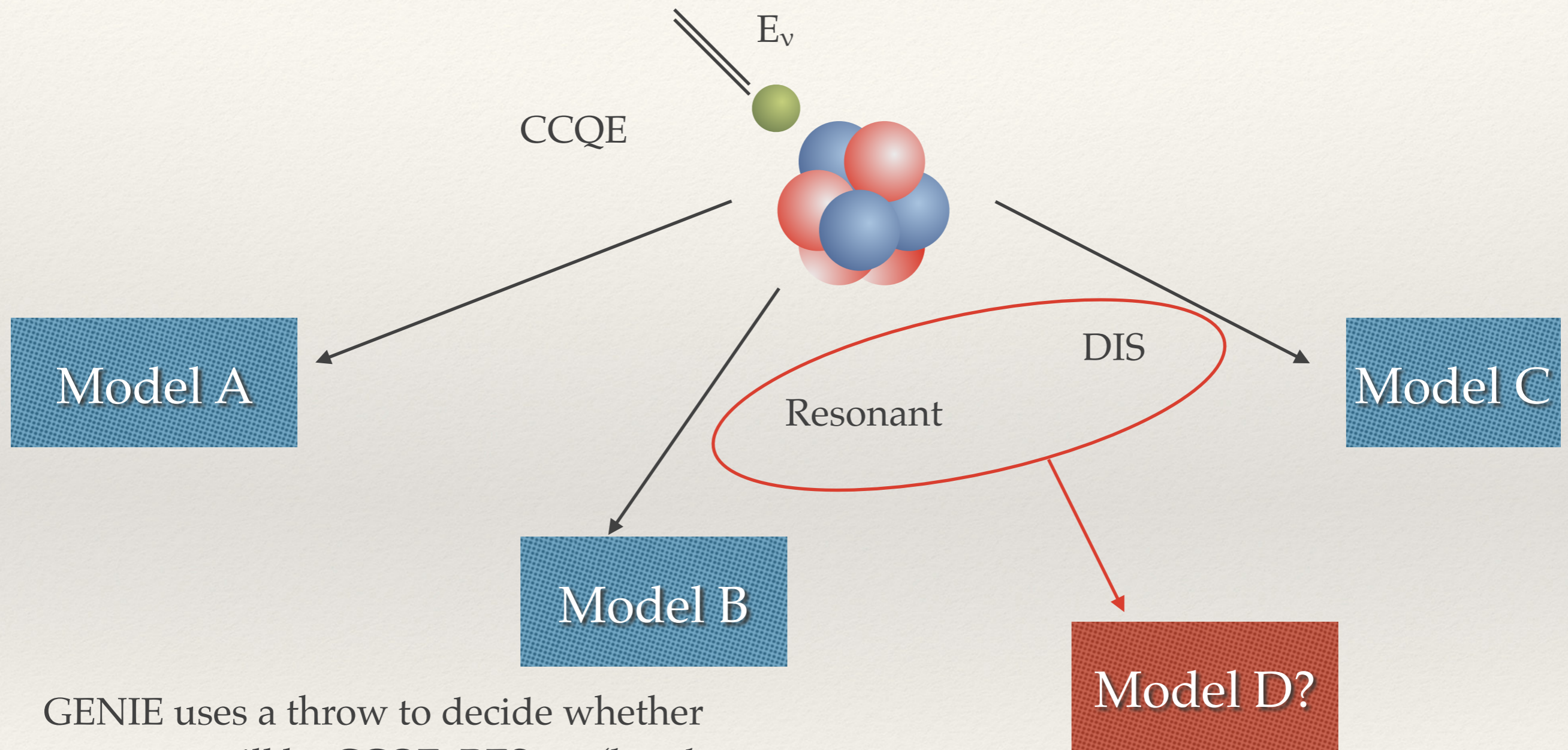
**Action: survey how variations are currently managed**

# Exclusive models



GENIE uses a throw to decide whether an event will be CCQE, RES etc (*based on total cross sections vs energy?*)

# Exclusive models



GENIE uses a throw to decide whether an event will be CCQE, RES etc (*based on total cross sections vs energy?*)

but for some models, these boundaries might not line up...

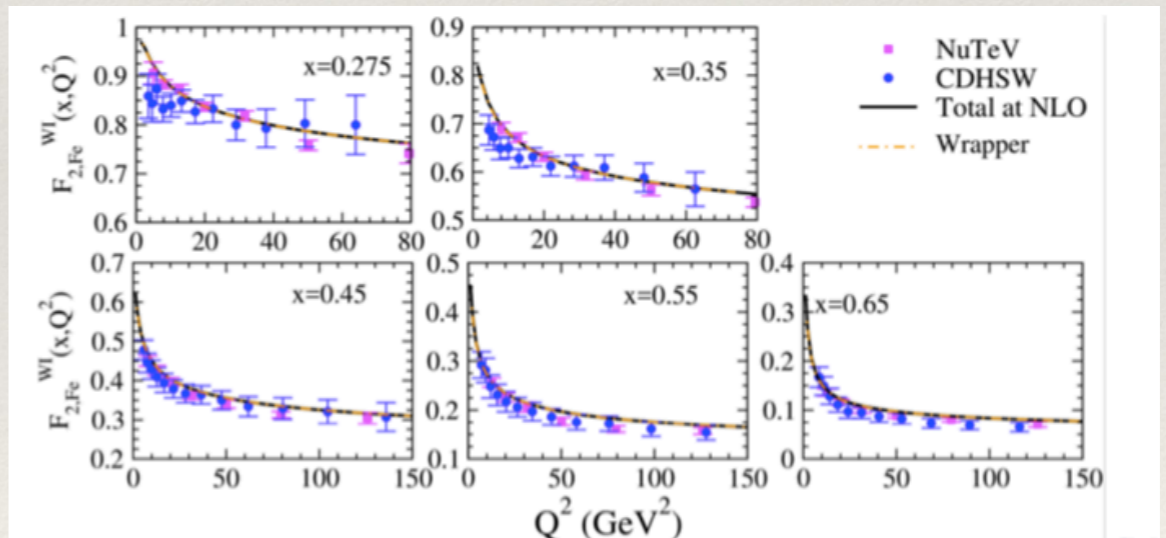
# What if the theory predicts part of the story?

BSM theory might predict  
leptonic tensor

$$\frac{d^2\sigma}{d\Omega_\ell dE_{\ell'}} = L_{\mu\nu} W^{\mu\nu}$$

Nuclear model might  
predict hadronic tensor

Haider theory predicts  $F_2$   
structure function only



How do we incorporate these models in a standard way?

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# Possible strategies

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- ❖ Event-by-event simulation
  - ❖ Code all models in C++ (generator owns the model code)
  - ❖ Standardised interface to FORTRAN (theorist owns the model code)
- ❖ Extrapolate from a sample of events
  - ❖ Technique has been used on LHC
- ❖ Tables of cross sections (or response functions etc)
  - ❖ Standardised procedure to manage how the generator interacts with these different information
  - ❖ Procedure needed to deal with parameter variations

**Action: document how existing models are integrated in generators**

# Surveying available models

- ❖ In what regime is the model valid?
- ❖ What output information is available?
  - ❖ How do we transform to a differential cross section?
  - ❖ What does the generator need to resample?
  - ❖ Does the output constrain particle trajectories?
  - ❖ Are there options for choice of variables & binning (to ease comparison)
- ❖ Is it appropriate to interface to code (event-by-event)?
  - ❖ Language? Configuration parameters?
- ❖ What parameter variations are appropriate?
- ❖ Do you model FSI? Constrain validity of FSI models/potentials?

*Other  
suggestions?*

**Action: survey current available / in progress models**