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Summary of ECT* Workshop on Modeling Neutrino Interactions

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Fermilab
With much help from
Federico Sanchez, U de Geneve

October 19, 2018

What is ECT*?

- European Center for Theoretical Studies in Nuclear Physics and Related Areas
- Located in Trento, Italy
- They support research in nuclear physics:
  - **Nuclear Structure** and **Nuclear Reactions**, **Quantum Chromodynamics** and **Hadron Physics**, **Physics of Matter under Extreme Conditions** and **Ultra-relativistic Heavy Ion Collisions**, with related areas including topics in **Astrophysics**, **Particle Physics**, **Condensed Matter Physics**, **Many-Body Theory**, **Bose-Einstein Condensation**, and **Computational Physics**.
- They hosted a workshop on neutrino interaction modeling 9-13 July, 2018 : should add **Electroweak Nuclear Physics** to list

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Workshop Goal

- To improve the Neutrino-Nucleus event generators used by neutrino experiments

- Steps taken at the workshop:
  - Learn what models nuclear physics community have
  - Tell that community what's in our generators now
  - Tell them how we MODIFY ("tune") what's there now
  - Wait for them to stop laughing
  - Ask for help to put better models in our generators

Why haven't we joined forces already?

- Inclusive vs Exclusive
  - Neutrino Interaction experiments need valid predictions for different interaction channels
    - Had big discussion about "what do oscillation experiments really need", focused on the need to reconstruct neutrino energy, across many different final states
  - Electron Scattering experiments measure (and the theories predict) inclusive rates vs energy transfer
- Nuclei under study
  - Lots of work done on lower A nuclei

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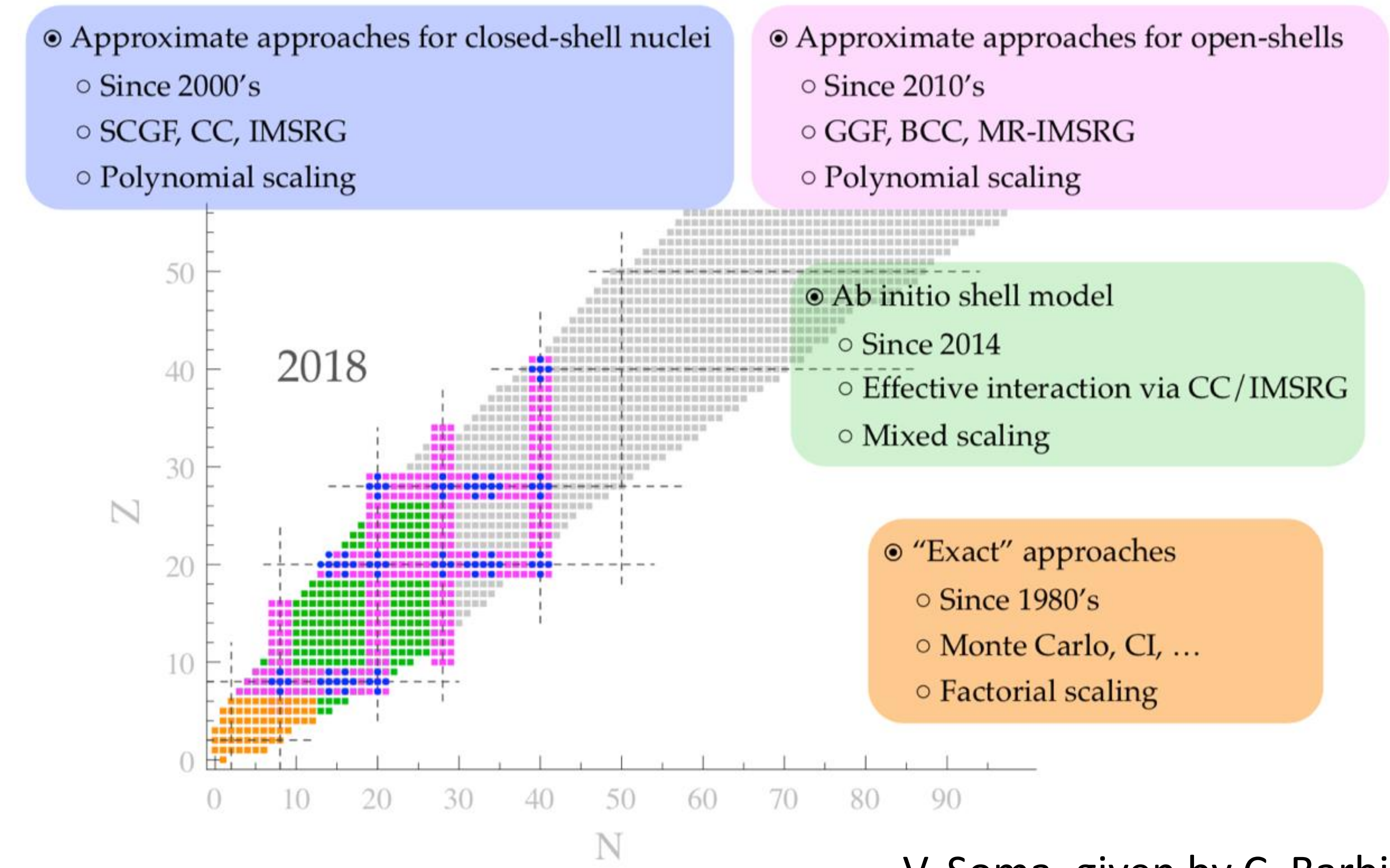
Nuclei studied by Ab Initio Methods



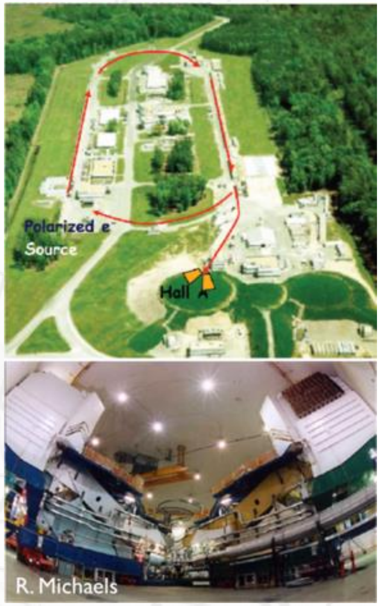
V. Soma, given by C. Barbieri

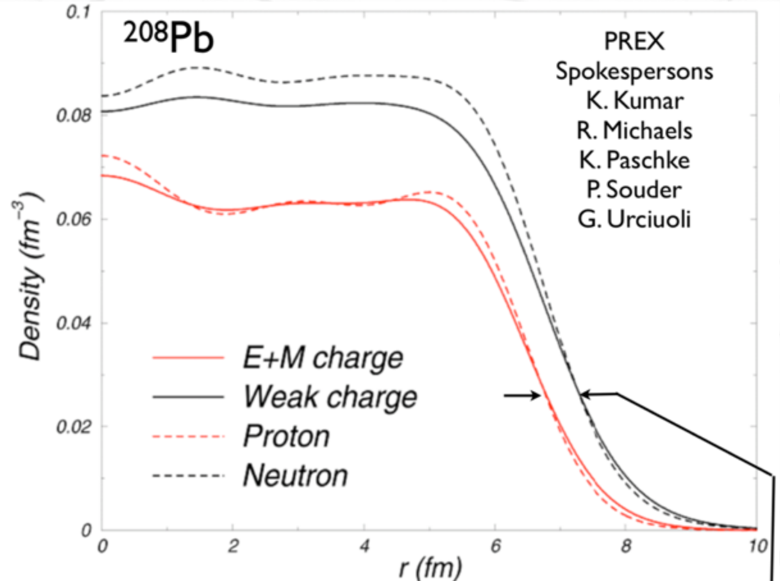
Topics covered at Workshop

- Modeling electron scattering on nuclei and potential impact in ν scattering
- Detailed description of ν event generators : GiBUU, GENIE, NEUT, NuWro (and introduction to FLUKA ν event generator!)
  - Quasielastic
  - Pion production
  - Shallow and deep inelastic interactions
- Inclusive vs. exclusive interaction descriptions and effects on experimental observables.
- Applying advanced mathematical tools: deep learning,
- Experimental approaches to ν interaction modelling: DUNE, T2K, NOvA, MINERvA, etc…

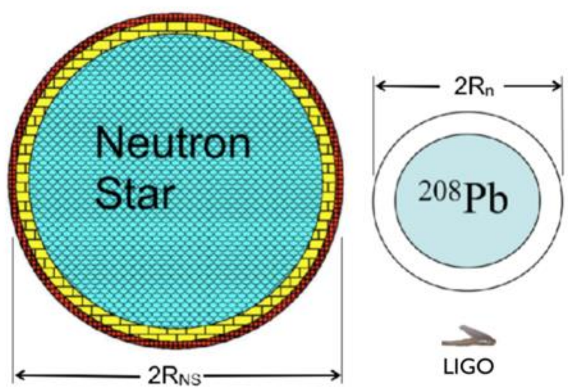
Believe it or not: "Neutron skin"

- This is something that is under study in e- scattering community
- PREX: e- scattering experiment at JLAB
- Able to measure weak charge & "EM" vs radius
- Relevant for studies of neutron stars!
  - Relevant across 18 orders of magnitude
- Not in isoscalar nuclei





- PREX measures how much neutrons stick out past protons (neutron skin).



C. Horowitz, ECT

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Modeling tools Described

- SuperScaling and possible applications in generator models (also shown here, Amaro, Megias)
- Mean Field approximations and potential implementations in generator models
- Cascade and transport models in nuclei
- Nuclear initial state description
- Spectral functions
- Nucleon-nucleon correlations
- Meson exchange currents

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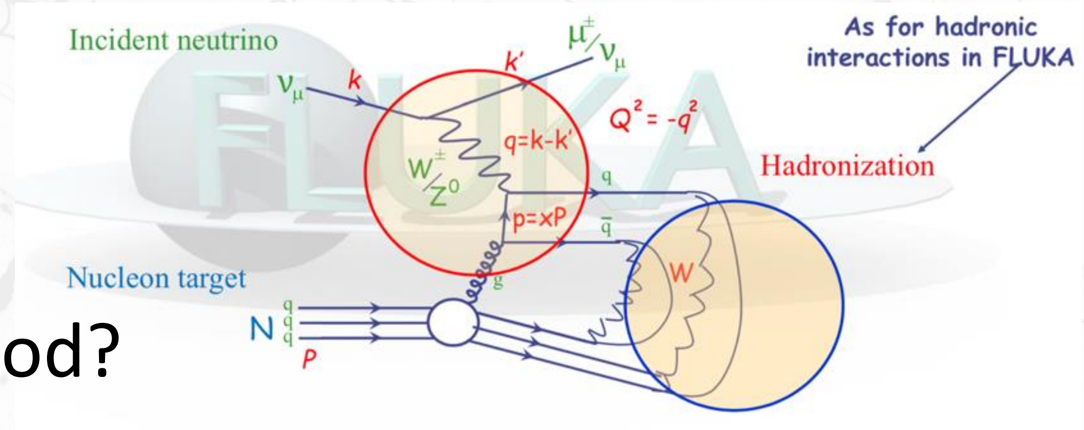
FLUKA does Neutrinos

- New ν Event Generator: nunDIS
  - See P. Sala's talk here for more
- Different approach to modeling FSI
  - Δ decay in medium included
  - Formation zone followed by intranuclear cascade
- State of the art DIS simulations
  - GRV98 pdfs available (LO, NLO MSBAR, NLO DIS)
- Able to run in e- scattering or ν- scattering mode
- Looking forward to more comparisons to FLUKA
  - How long till we see this in NUISANCE?

Consistency: luxury or necessity?

- Much time at ECT discussing consistency:
  - Nuclear Ground state should be same for all channels
  - FSI should be consistent across processes
  - Initial state effects should also be consistent
- Simulations of e- Scattering get this "for free"
  - Calculations are mostly for exclusive cross sections
- FLUKA also gets this by design
- Does a generator have to be consistent to be good?



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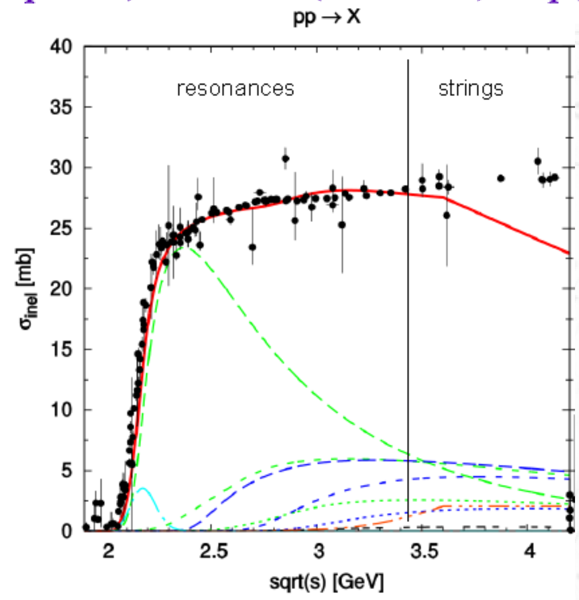
GIBUU NEUT/GENIE

Cascade vs Transport

- Two approaches:
  - Cascade treats the particles as projectiles inside the nuclei (Local Femi Gas). It follows each one as in the case of GEANT4.
  - Transport builds a model for the full nuclei (Local Femi Gas) including interactions and propagates it in time slices.

$$[\partial_t + (\nabla_p H_i)\nabla_r - (\nabla_r H_i)\nabla_p]\, f_i(\vec{r}, t, \vec{p}) = C\,[f_i, f_j, \ldots]$$



Excellent results in different interactions beyond neutrinos.

Semi-Inclusive Reactions

- Are we describing the full degrees of freedom of our system ?
- Poor description has serious implications in:
  - Reconstruction efficiency including vertex activity definition
  - Transverse variables

Semi-Inclusive Reactions

Example of CC neutrino reactions on ^{12}C

$$
\begin{aligned}
\nu_\ell + {}^{12}\mathrm{C} &\rightarrow \ell^- + {}^{12}\mathrm{N} \\
&\rightarrow \ell^- + p + {}^{11}\mathrm{C} \\
&\rightarrow \ell^- + n + {}^{11}\mathrm{N} \\
&\rightarrow \ell^- + p + p + {}^{10}\mathrm{B} \\
&\rightarrow \ell^- + p + n + {}^{10}\mathrm{C} \\
&\quad \vdots \\
&\rightarrow \ell^- + \pi^\pm + \mathrm{X} \\
&\quad \vdots \\
&\rightarrow \ell^- + (\mathrm{d}, {}^3\mathrm{H}, {}^3\mathrm{He}, {}^4\mathrm{He}, \cdots) + \mathrm{X} \\
&\rightarrow \ell^- + \gamma + \mathrm{X} \\
&\quad \vdots
\end{aligned}
$$

1 discrete state that β–decays into ^{12}C

25 discrete states below ^{10}C+n
11 discrete states below ^{10}B+p

Σ All open channels

$= \sigma$ inclusive

... assuming only that the muon is detected

Most of our models use impulse approximation and the integration of the nuclear states: semi-inclusive.

Donnely. B

Semi-Inclusive Reactions

$$W^{CC}_{semi} = \frac{1}{\rho^2}\{\rho^2 X_1 + \rho\nu^2 X_2 + X_3 + 2\sqrt{\rho}\nu X_4 + H^2 X_5 + 2\sqrt{\rho}\nu H X_6 + 2H X_7\}$$

$$W^{CL}_{semi} = \frac{\nu}{\rho^2}\left\{\rho X_2 + X_3 + \sqrt{\rho}(\frac{1}{\nu}+\nu)X_4 + H^2 X_5 + \sqrt{\rho}(\frac{1}{\nu}+\nu) H X_6 + 2H X_7\right\}$$

$$W^{LL}_{semi} = \frac{1}{\rho^2}\{-\rho^2 X_1 + \rho X_2 + \nu^2 X_3 + 2\sqrt{\rho}\nu X_4 + \nu^2 H^2 X_5 + 2\sqrt{\rho}\nu H X_6 + 2\nu^2 H X_7\}$$

$$W^{T}_{semi} = -2X_1 + X_5 \eta_T^2$$

$$W^{TT}_{semi} = -X_5 \eta_T^2 \cos 2\phi_N$$

$$W^{TC}_{semi} = \frac{2\sqrt{2}}{\rho}\eta_T\{H X_5 + \sqrt{\rho}\nu X_6 + X_7\}\cos\phi_N$$

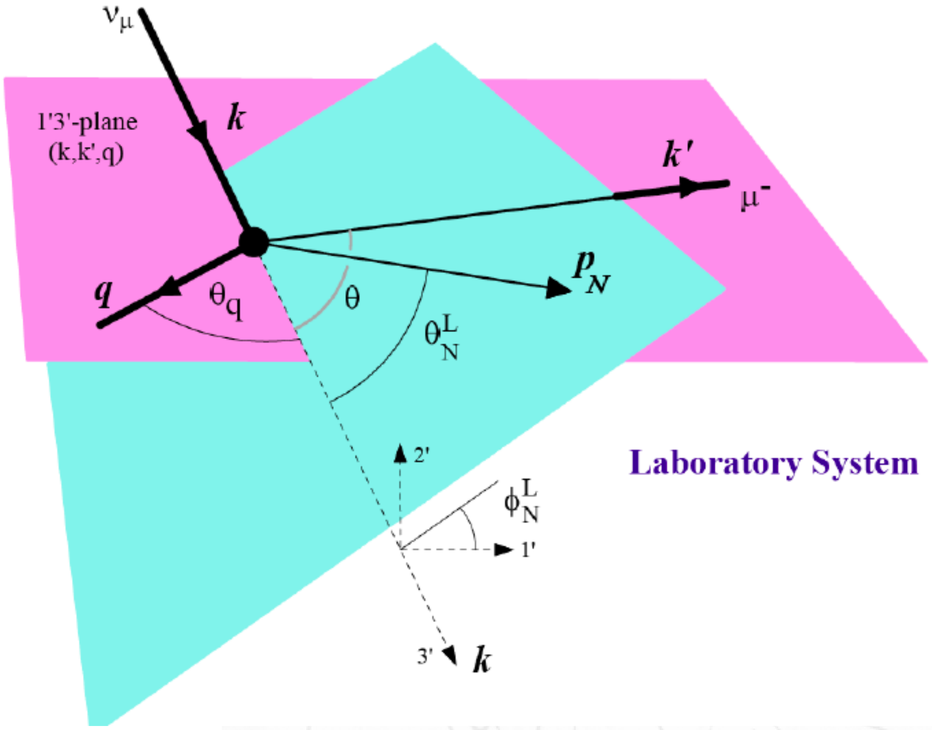
$$W^{TL}_{semi} = \frac{2\sqrt{2}}{\rho}\eta_T\{\nu H X_5 + \sqrt{\rho} X_6 + \nu X_7\}\cos\phi_N$$

$$W^{T'}_{semi} = \frac{1}{\sqrt{\rho}}\{Z_1 + H Z_2\}$$

$$W^{TC'}_{semi} = \frac{2\sqrt{2}}{\rho}\eta_T\{-(\sqrt{\rho}\nu Y_2 + Y_3)\sin\phi_N + (\sqrt{\rho} Z_2 + \nu Z_3)\cos\phi_N\}$$

$$W^{TL'}_{semi} = \frac{2\sqrt{2}}{\rho}\eta_T\{-(\sqrt{\rho} Y_2 + \nu Y_3)\sin\phi_N + (\sqrt{\rho}\nu Z_2 + Z_3)\cos\phi_N\},$$

The ϕ_N dependence can be made explicit, leaving 6 responses, each a function of 5 variables



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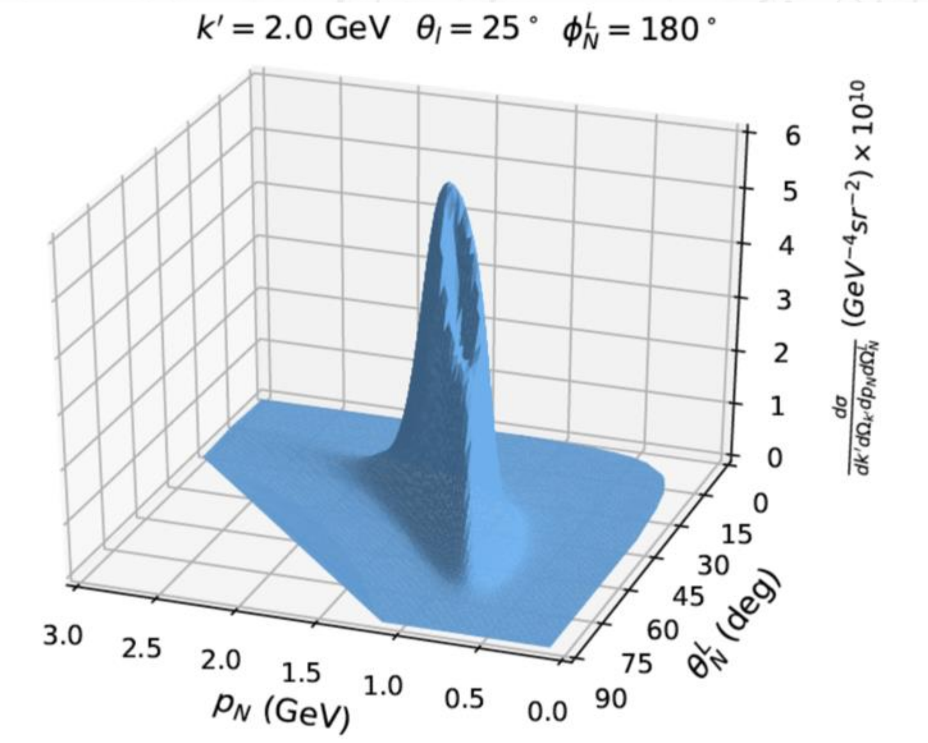
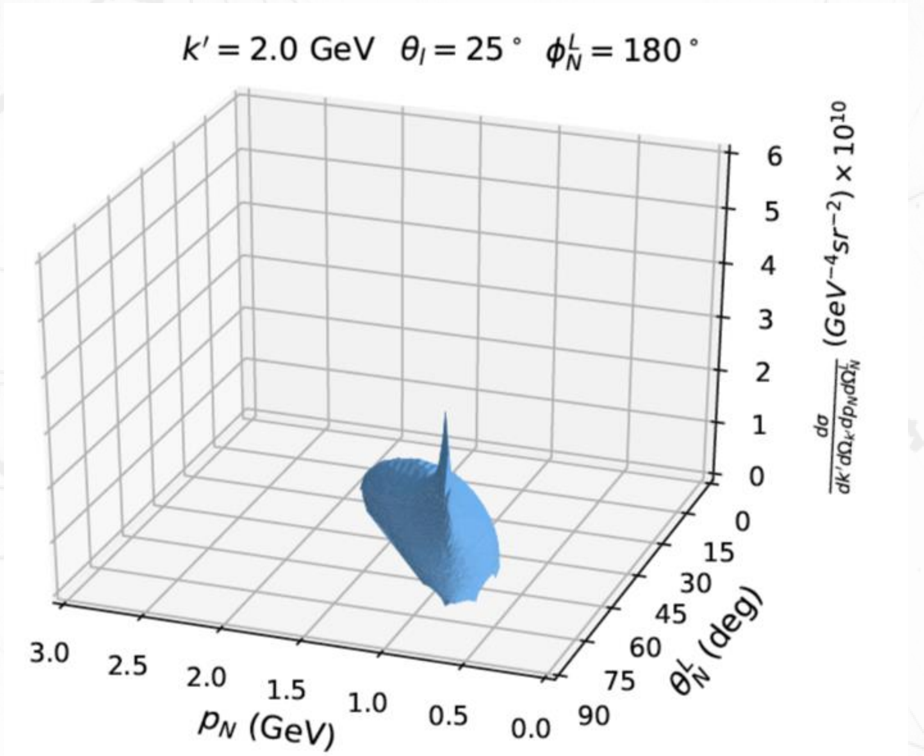
Semi-Inclusive Results

Using Spectral Function from Omar



Using the Local Fermi Gas approximation



Note: one angle, one outgoing lepton momentum, one lepton angle

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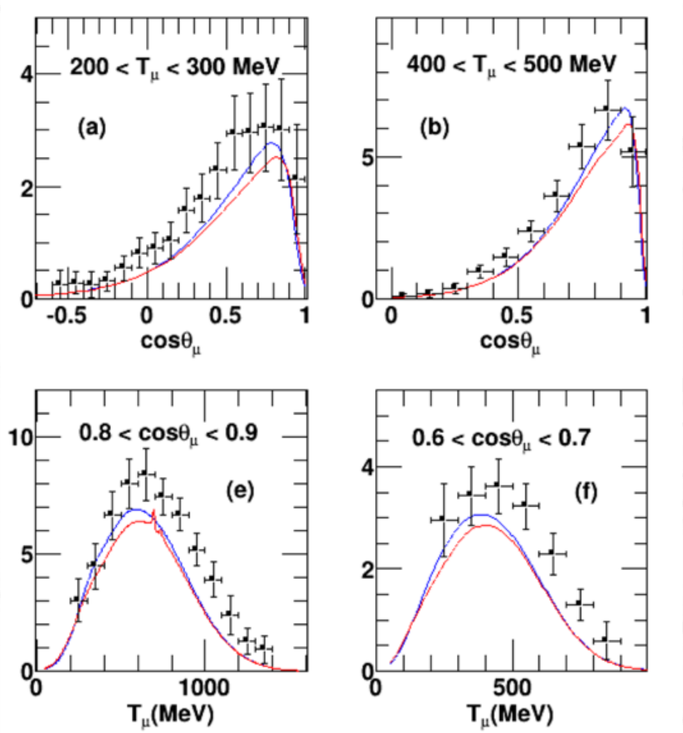
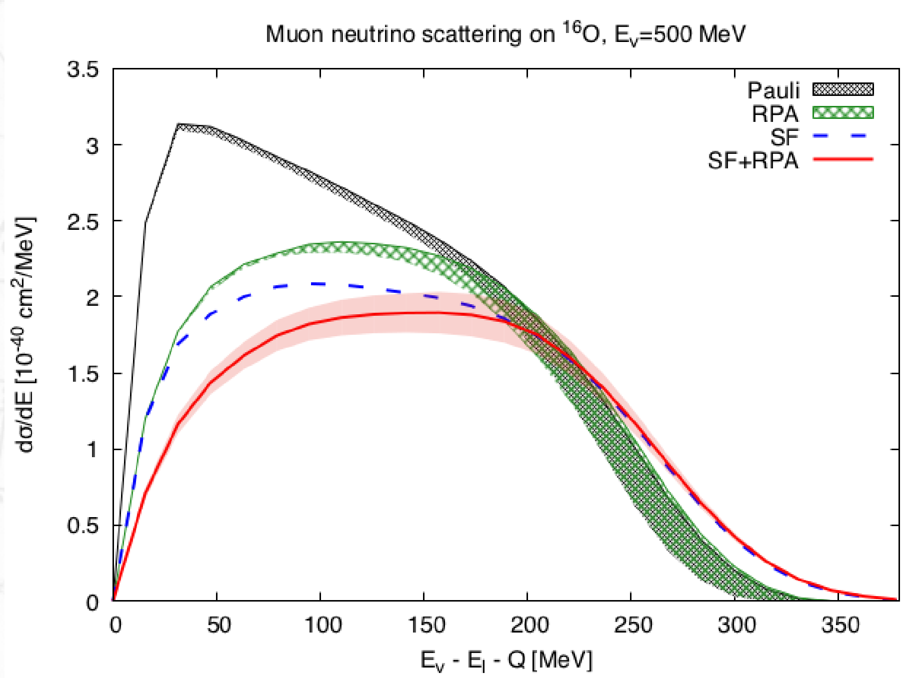
CCQE-like Channel

- Recent development by several groups with better nucleus description



Mean Field approximation and continuum Random Phase. Ghent

Phys.Rev. C92 (2015) no.2, 024606



Approximative Spectral Function

Annals Phys. 383 (2017) 455-496
Phys.Rev. C97 (2018) no.3, 035506

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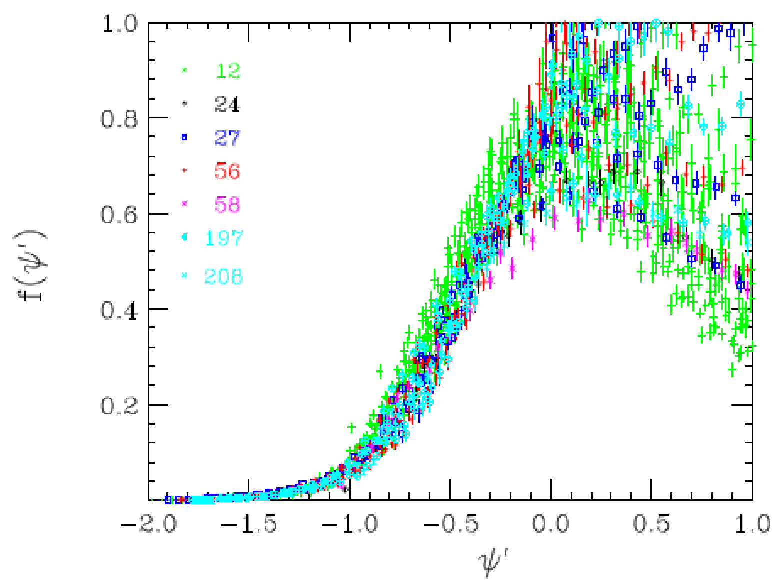
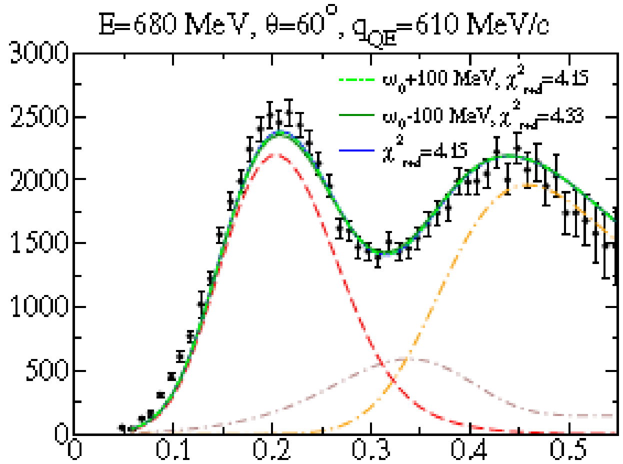
SuSa model

Sevilla, Turin, MIT, Granada





- SuperScaling is a quasi-phenomenological approach.
- All cross-sections behave the same independently of the momentum transfer (1st order scaling) and nuclei (superscaling) up to QE peak as function of

$$\psi' \equiv \frac{1}{\sqrt{\xi_F}} \frac{\lambda' - \tau'}{\sqrt{(1+\lambda')\tau' + \kappa\sqrt{\tau'(\tau'+1)}}}$$

- All models should reproduce this dependency.
- Excellent results with electron-scattering.

Excellent check to be done for your preferred MC.

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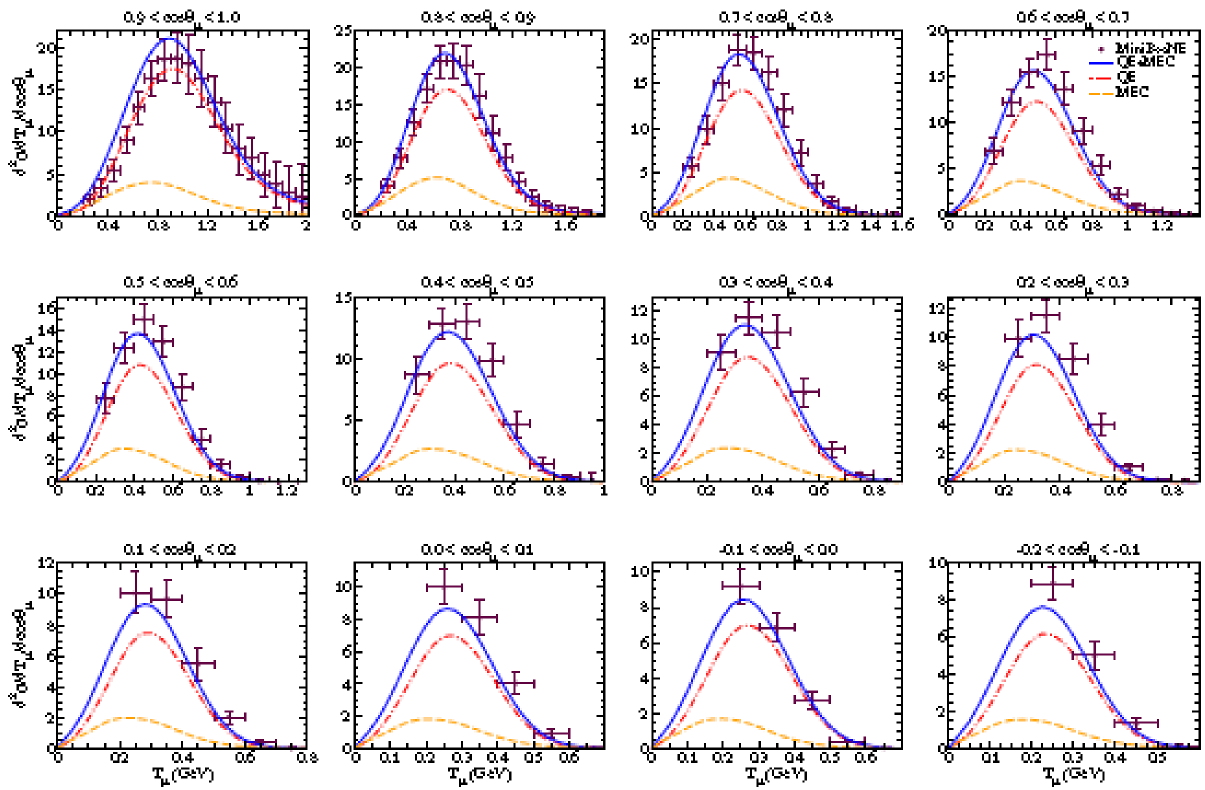
SusaV2 and Mean Field

- SusaV2 is an extension of the Susa model based on numerical models that also includes 2p2h
- A complete Relativistic Mean Field Approximation and 2p2h model developed within the SUSA model.

J.Phys.Conf.Ser. 724 (2016) no.1, 012020

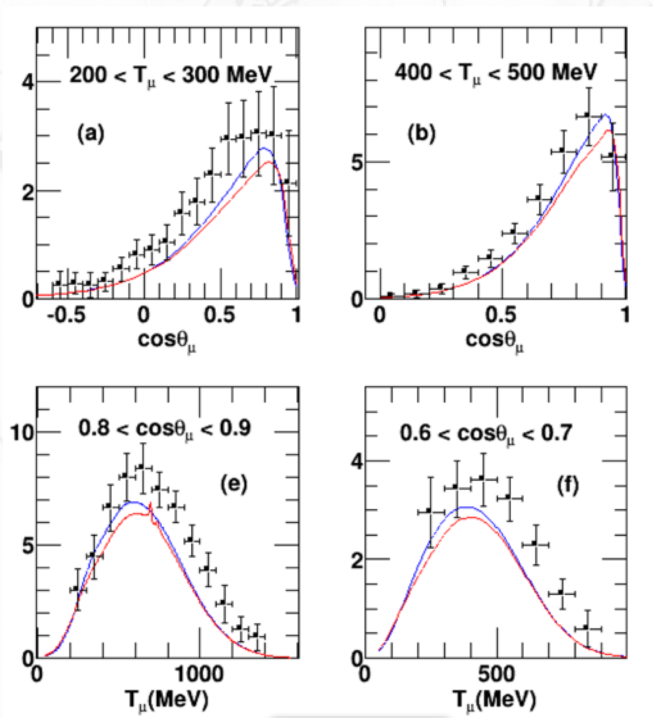


Model overlap

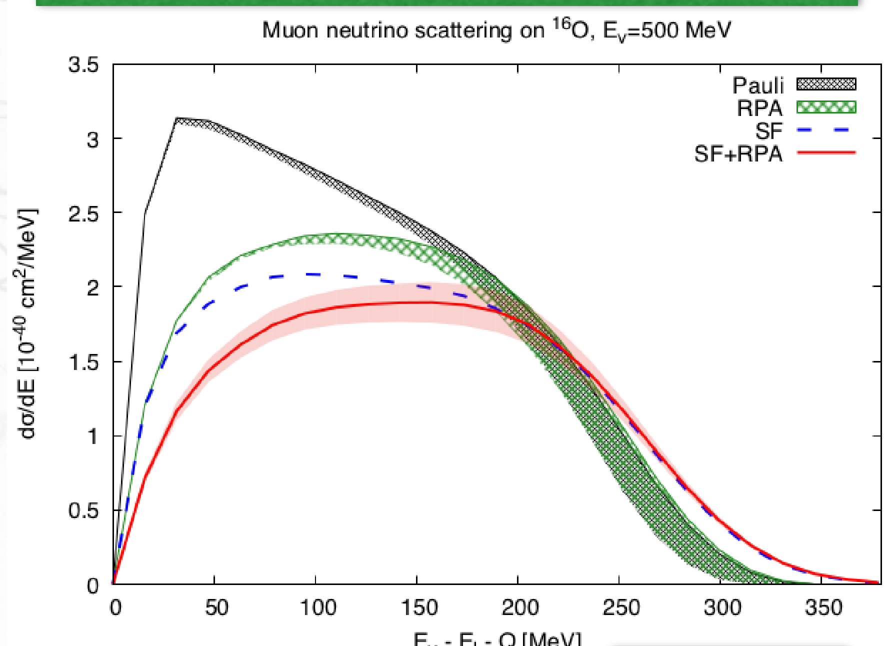
- A lot of progress in the relation between models.
  - CRPA and Mean Field.
  - Spectral functions + RPA

Traditional RPA seems to absorb defects on the underlying model.

It is worth asking yourself if your model is consistent and compare with other approaches.



Ghent



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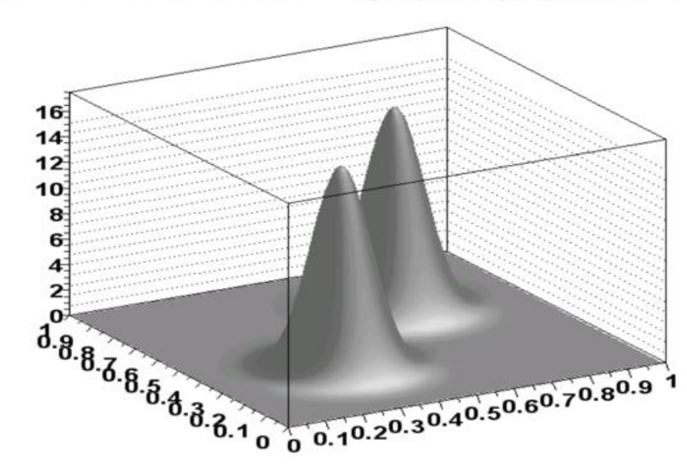
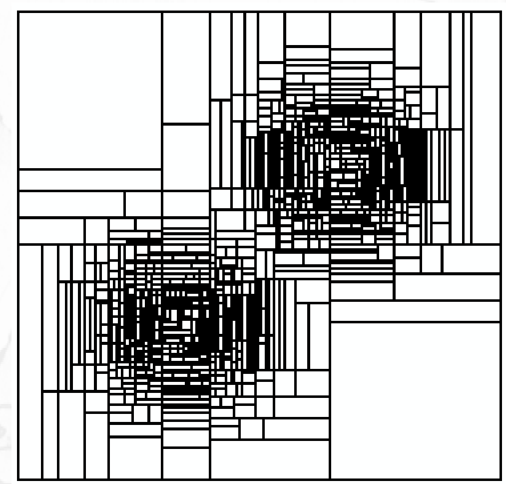
Efficient MC

- Neutrino experiments require millions of events to be generated:
  - Simulation of passive material around the active fiducial volume.
  - Several model simulations
    - Sometimes done through reweighting techniques.
  - More and more complex models:
    - Fully exclusive models requires also a large face space to cover.
- New MC techniques might help in speeding up the simulations, allowing them to become more complex.

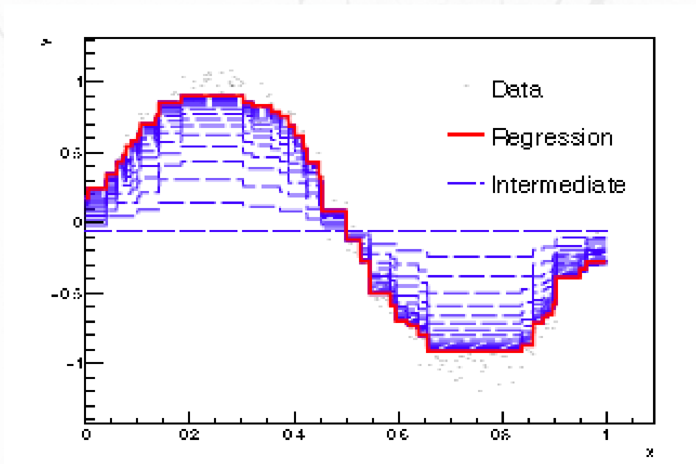
Modern approaches

G. Perdue, ECT





Optimized multidimensional sampling function.
Need to get around slow calculation speeds



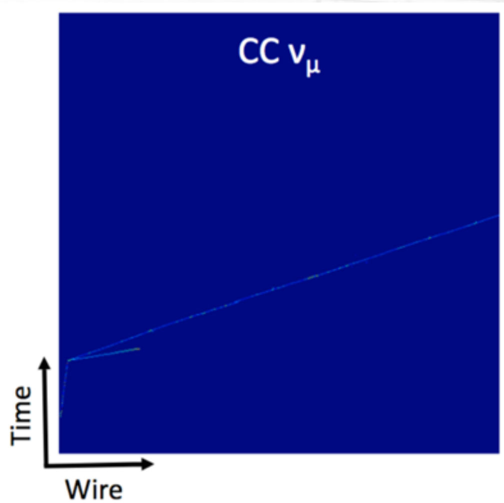
G: generating network
Z: input space
X: output space
Generating probability g comes from Jacobian determinant

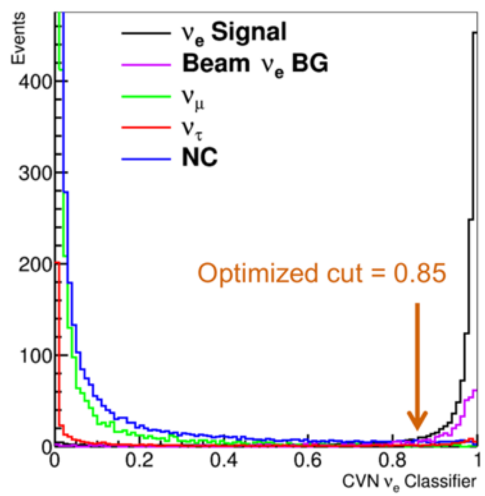
$$p(\bar{z}) = g(\bar{x}) \left\| \frac{\partial \bar{G}(\bar{z})}{\partial \bar{z}} \right\|$$

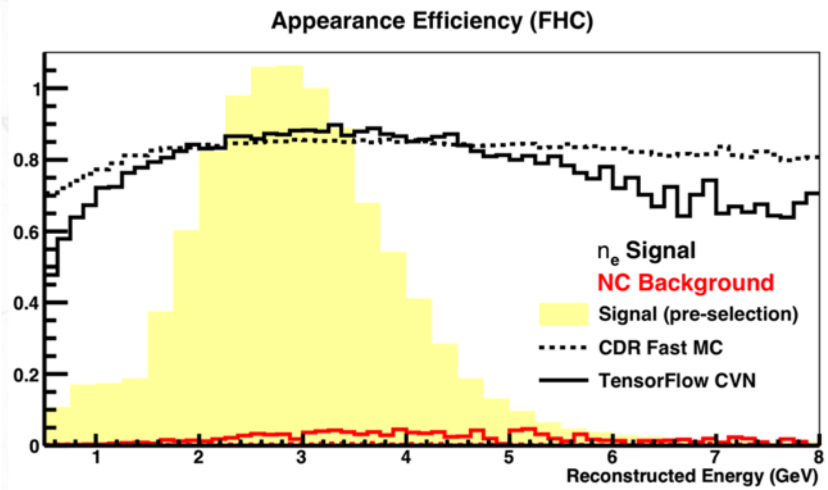
Another Modern Approach: Machine Learning

G. Perdue, ECT

- Recent success in machine learning dominated by 2 kinds of data:
  - Visual data—images, video, very high-dimensional
  - Sequence data—speech recognition, language processing, revolve around patterns buried in the sequences
- We can map neutrino physics problems into these domains







J. Nowak, ECT

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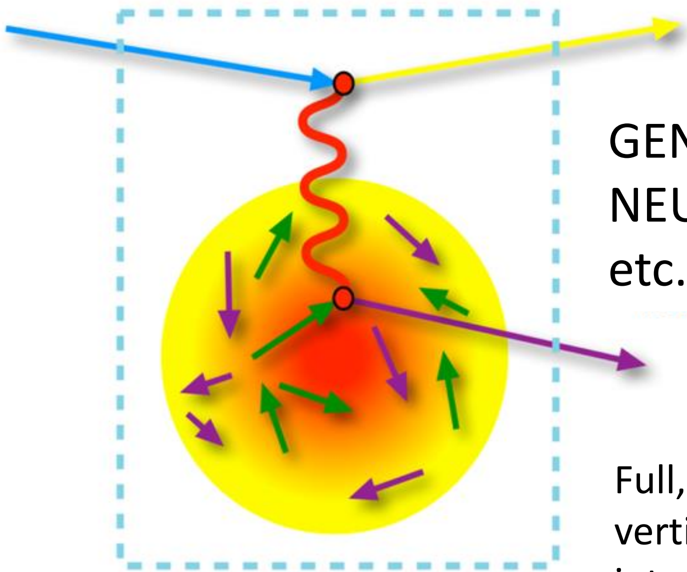
What can we learn about generators from the Collider Community?

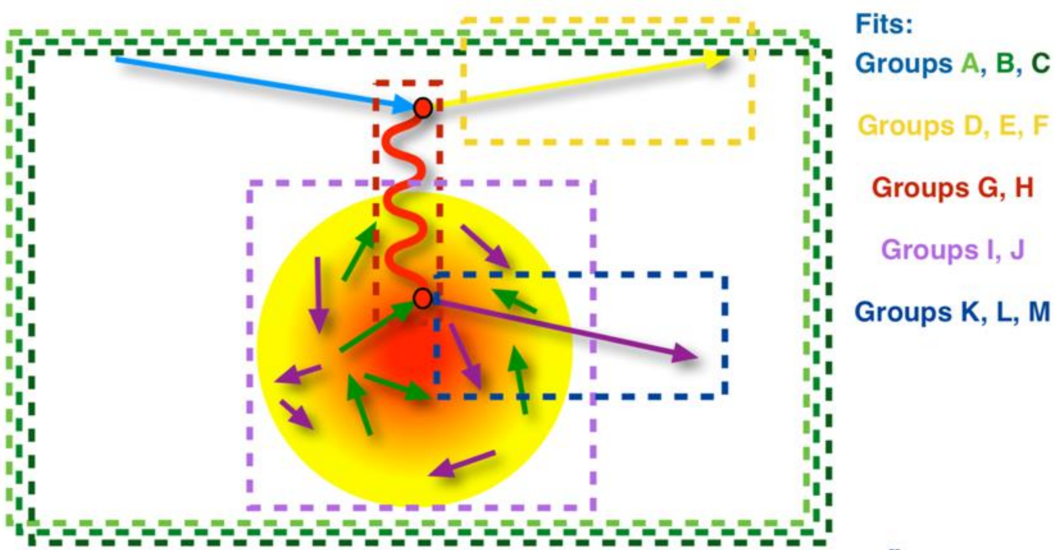
What we look like:



GENIE, NEUT, etc…

Full, vertical integrated solution

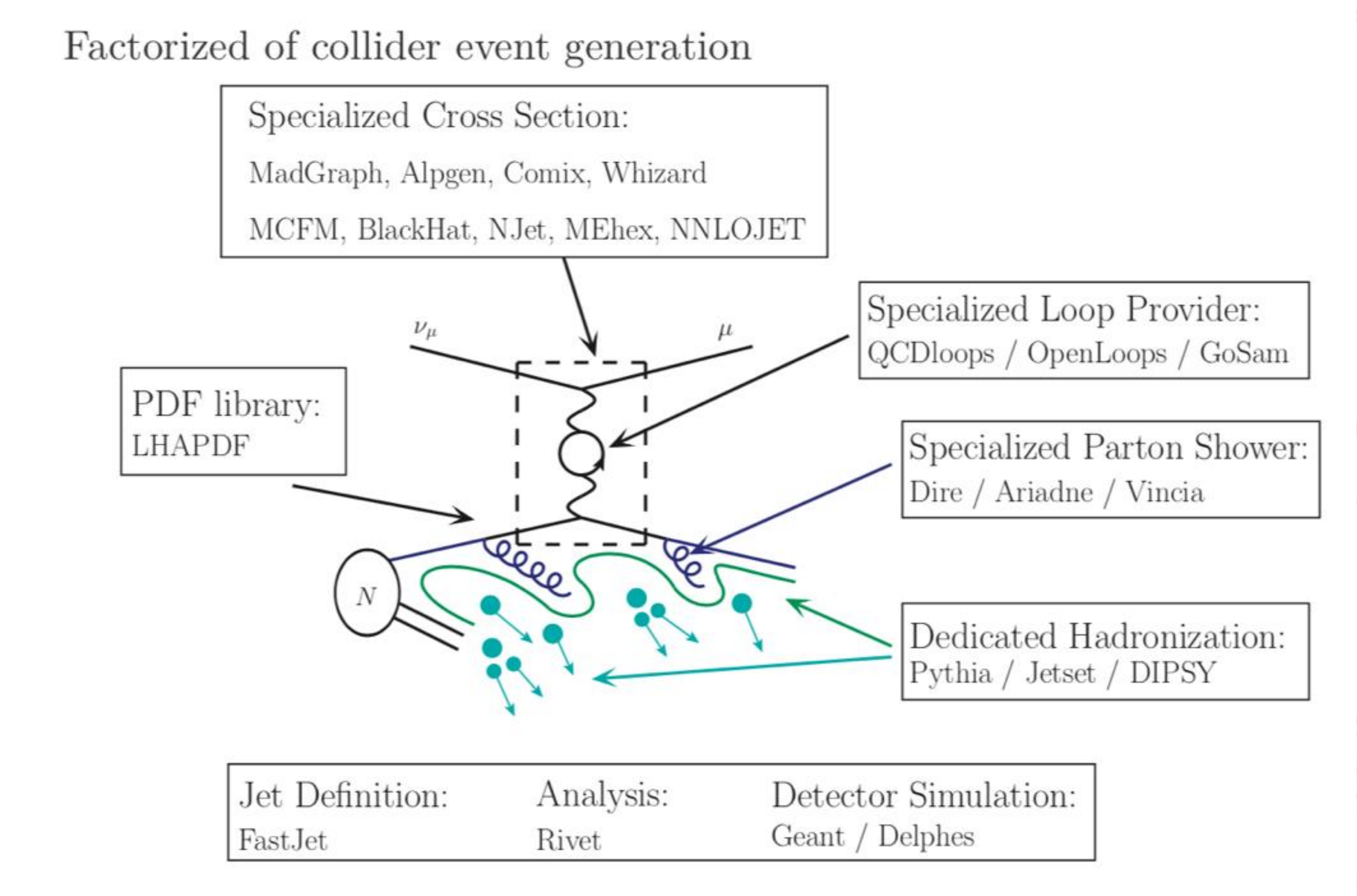
How we would look if we were at the LHC



G. Perdue, ECT

- Also many examples in business world…(remember how Amazon started as a place to buy books?)

If you could use tools from LHC:



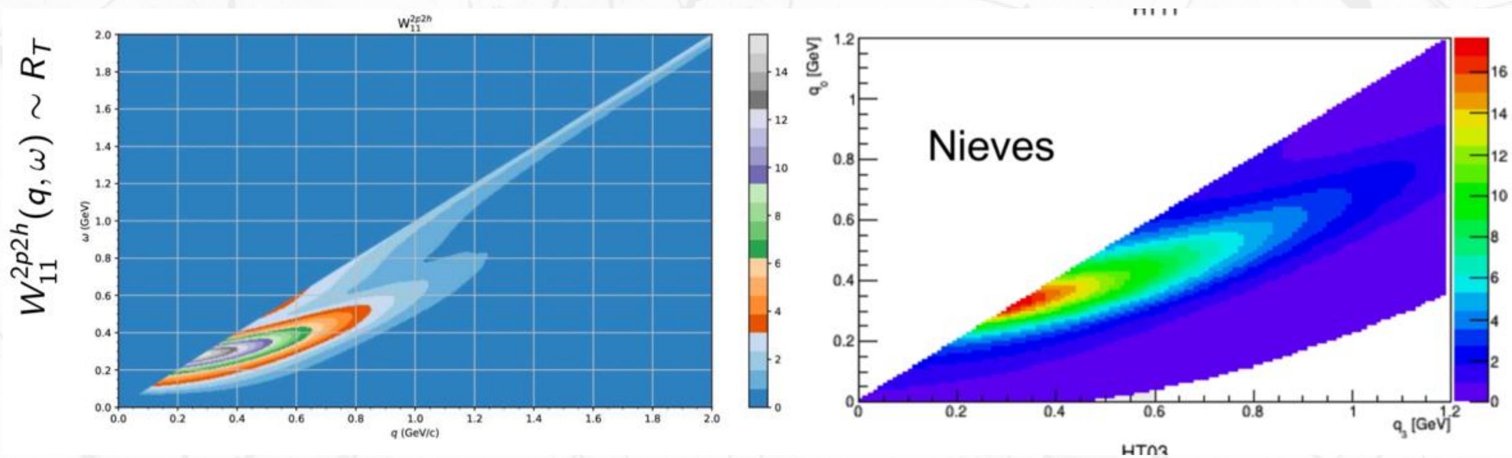
From S. Prestel: All but one of these programs really exist!

- Source: Theory-Experimental group at FNAL, lead by M. Betancourt

G. Perdue, ECT

We’ve already started doing this

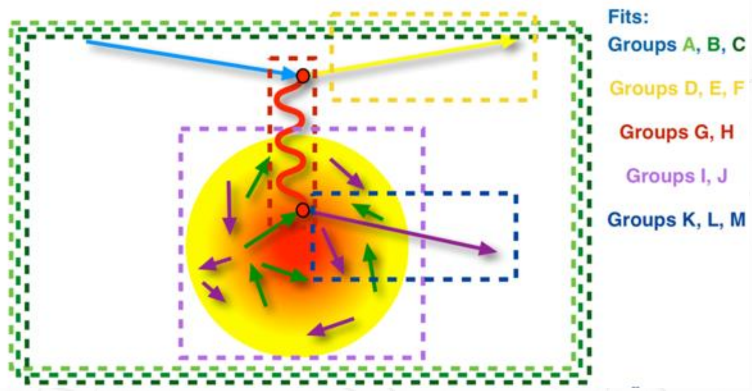
- GIBUU in NOvA:
  - Take advantage of GENIE’s flux and geometry driver, hooks into GENIE event structure
- SuSA in GENIE (S. Dolan, G. Miegas)



- Need to expand on this!

Next Steps

- Need to make it easier to bring in new state of the art models to our experimental community
  - SuSA, Ghent, Valencia
  - FLUKA-NUNDIS
  - Your Model Here
- Take advantage of flux and geometry drivers we already have to make this easier



- Planning a new workshop where this gets more real (Federico Sanchez, Kevin McFarland, et al)

Testing and Improving Models of Neutrino Nucleus Interactions

- Goals of the next workshop
  - Continuation of the 2018 workshop focused on a critical comparison and model deficits.
  - Systematic comparisons of generators (GENIE, GiBUU, NEUT) to data
  - This critically includes variants of these models
  - Focus is Neutrino data, but there may be result models where electron scattering data is also helpful (single pion production)
  - Incorporation of improved models into generators and comparisons among predictions and with data

2019 Workshop Details

- Structure
  - Assign homework in advance
  - Opening presentations on this homework
  - Review task list for the meeting
  - Work (Will prepare infrastructure to be able to run code on site or remotely)
  - Ending presentation on progress and plans
- Participants
  - Generator Representatives: GENIE, NEUT, NuWRO, GIBUU, NUNDIS
  - Theory groups with models to go into generators: Valencia, GENT, SuSA
  - NUISANCE Representatives: facilitate comparisons
  - GENIE Tuners

Testing and Improving Models of Neutrino Nucleus Interactions

- June 3-7, 2019
- ECT* in Trento
- Not many presentations planned, real working group time planned to bring models together
- Contact Federico Sanchez for more information!