Planning for a Common Generator Toolchain

```
float nudir[3];
//In Neutrino nu-nucl scattering
```

2021/3/15

Luke Pickering For the Generator Tools Effort

MICHIGAN STATE UNIVERSITY

Disclaimer: I am a T2K and DUNE collaborator.

I also work on NUISANCE which interfaces to NEUT/GENIE/NuWro/(GiBUU).

I maintain/develop NEUT for T2K analysis needs.

This Talk

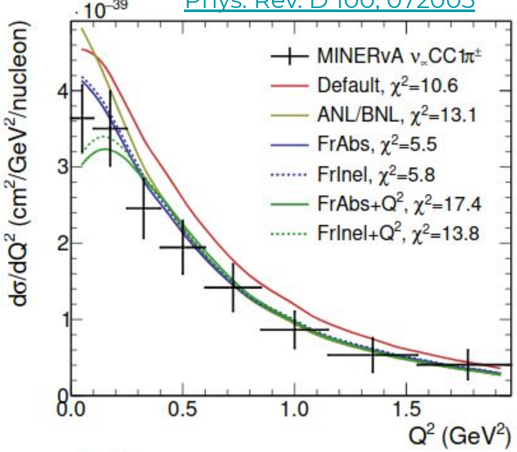
- Anatomy of a Neutrino Interaction Simulation
- What tools are on the Market?
- Considerations
    - Flux/Geometry
    - Formats
    - Toolchain factorisation
- Plans for the Future

Anatomy of a Neutrino Interaction Simulation

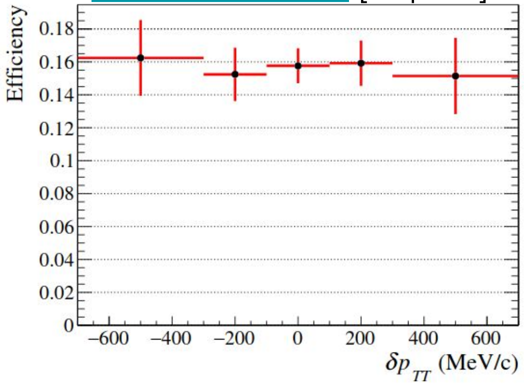
We need simulated neutrino interactions to *e.g.*:

- Study analysis sensitivities
- Study event selections
- Error propagation
- Perform Analyses
- ...

Phys. Rev. D 100, 072005



arXiv:2102.03346 [hep-ex]



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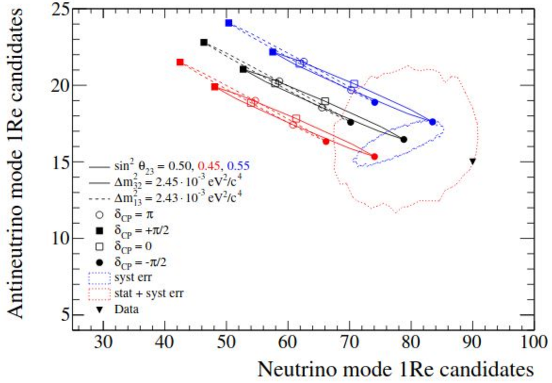

MC 'Events'!

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Goals of This Effort

- We want to develop tools to facilitate collaboration with theorists developing new interaction models
- Lower the barrier for using current and future interaction models in analyses across the community
  - *de facto* experimental usage of a single set of tools (and thus models)
  - Aim to make more tools and models accessible to analysers
- Improve plug-and-play-ability of factorisable simulation components
  - Collider tools have a definite leg-up on us here

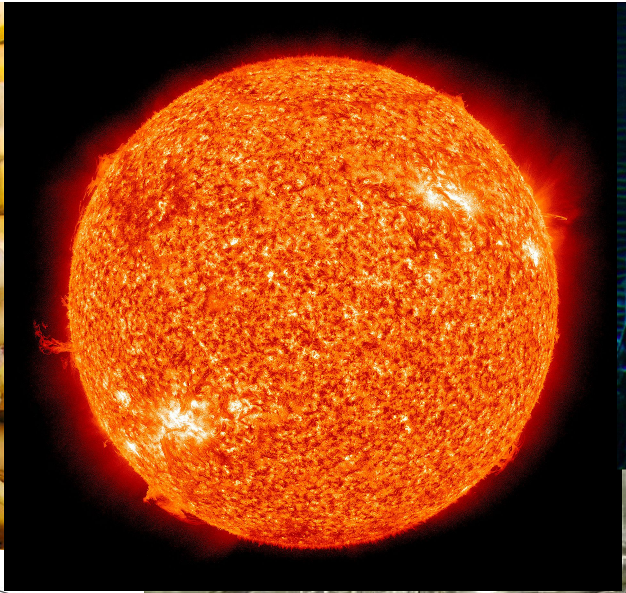
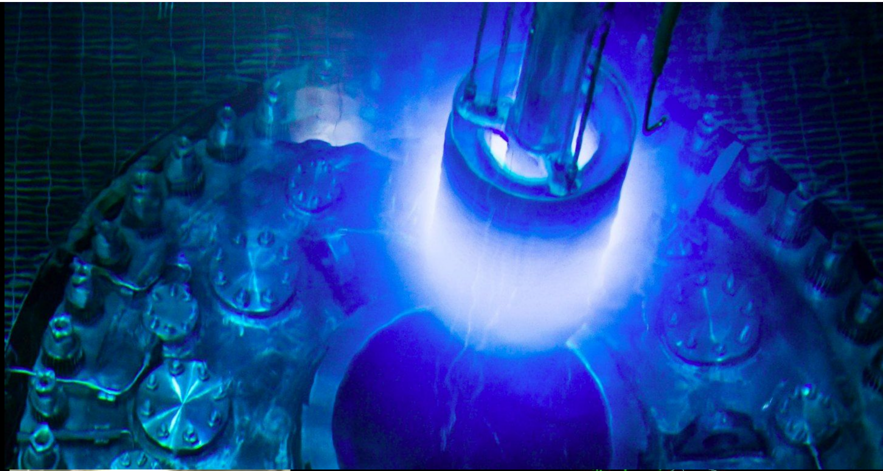
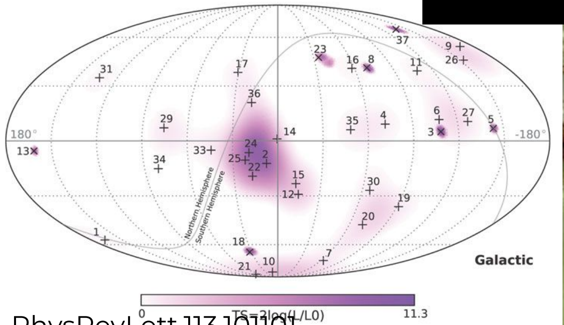
MC 'Events'!

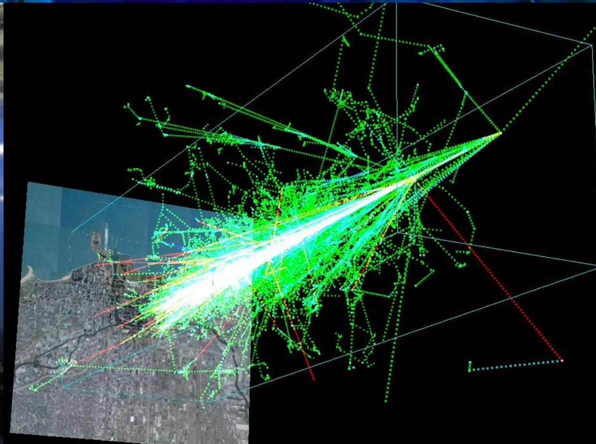
Anatomy of a Neutrino Interaction Simulation

Neutrino Sources

MC 'Events'!

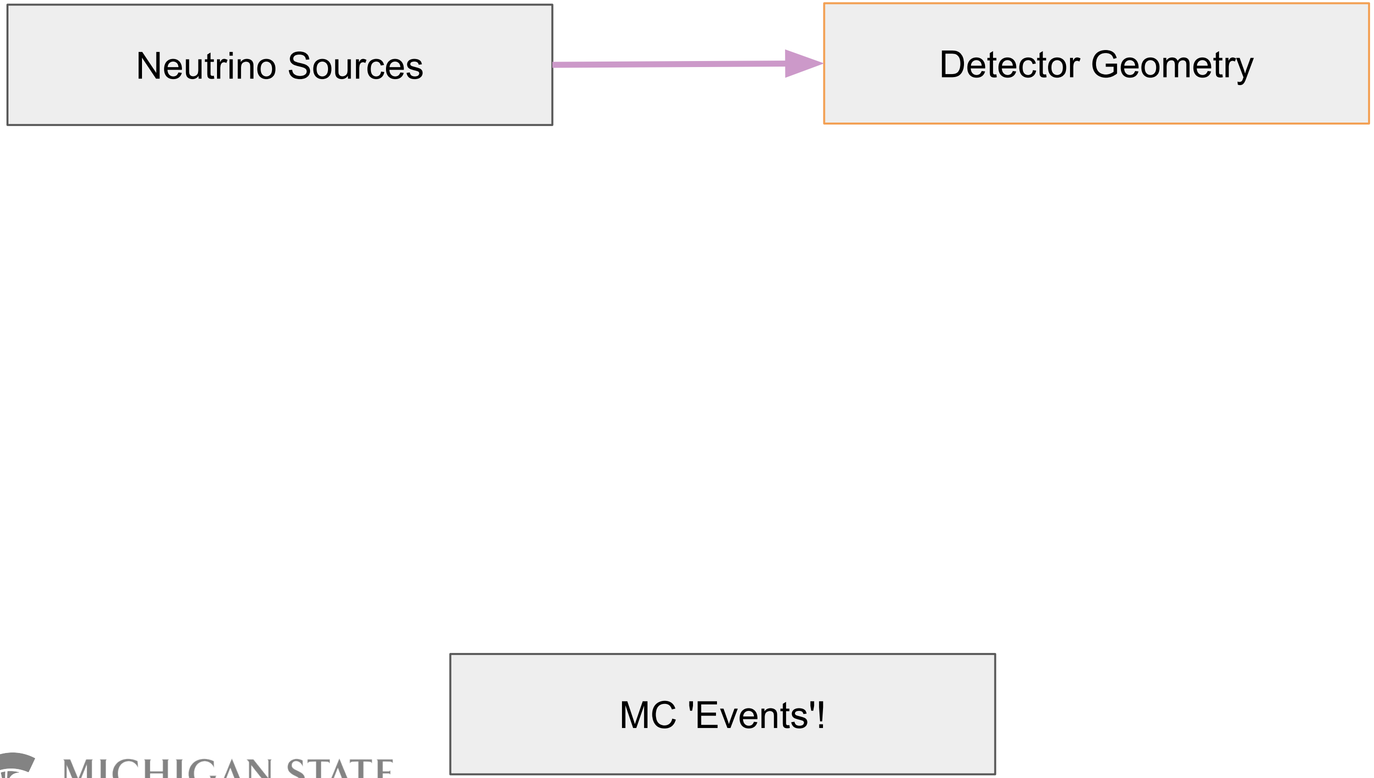
It all starts with a neutrino...

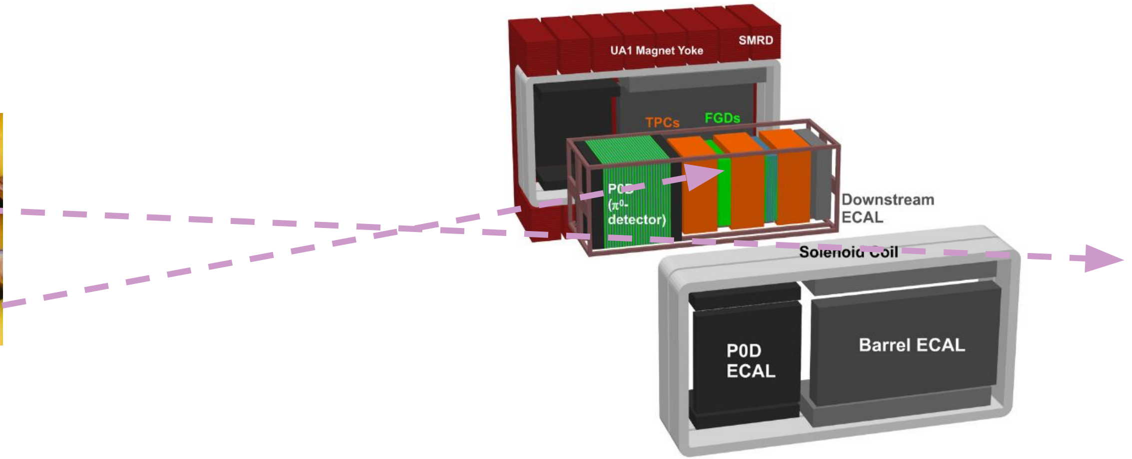
PhysRevLett.113.101101

Anatomy of a Neutrino Interaction Simulation



Neutrino Life-cycle

- Neutrino (species, 4-momentum) sampled from a source
- Neutrino ray is then stepped through a geometry (volumes of materials)
- Need to ask an interaction model for the probability of interaction.



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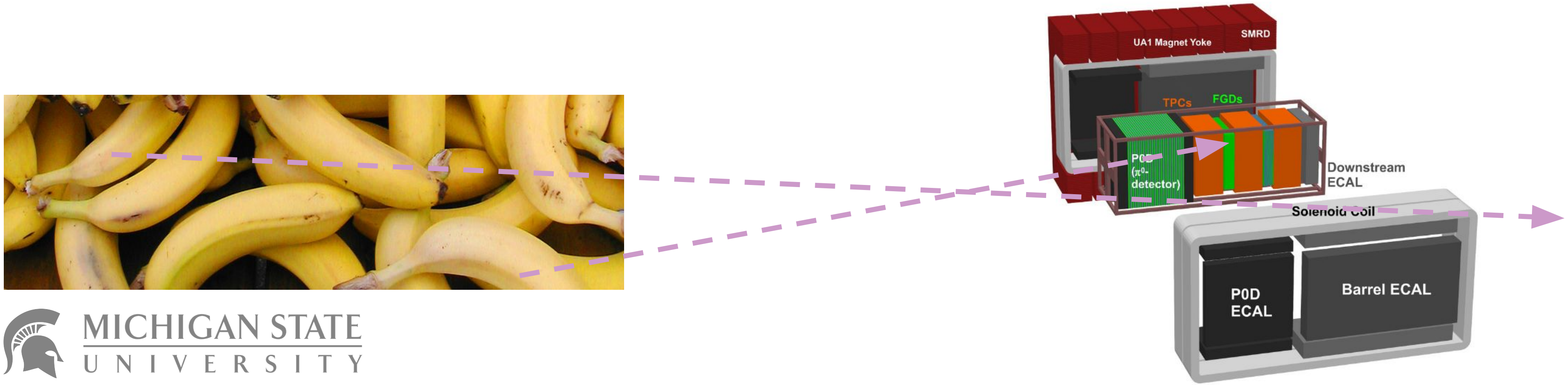

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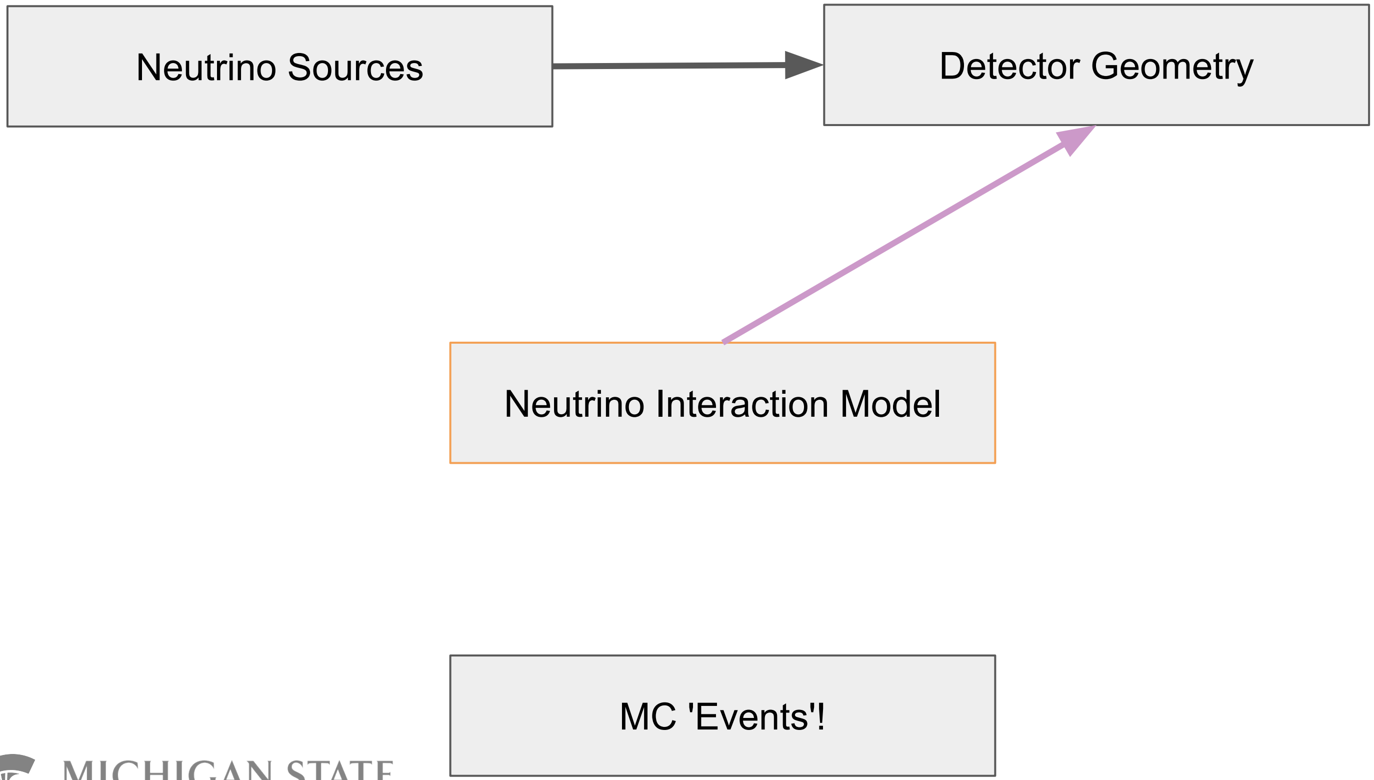

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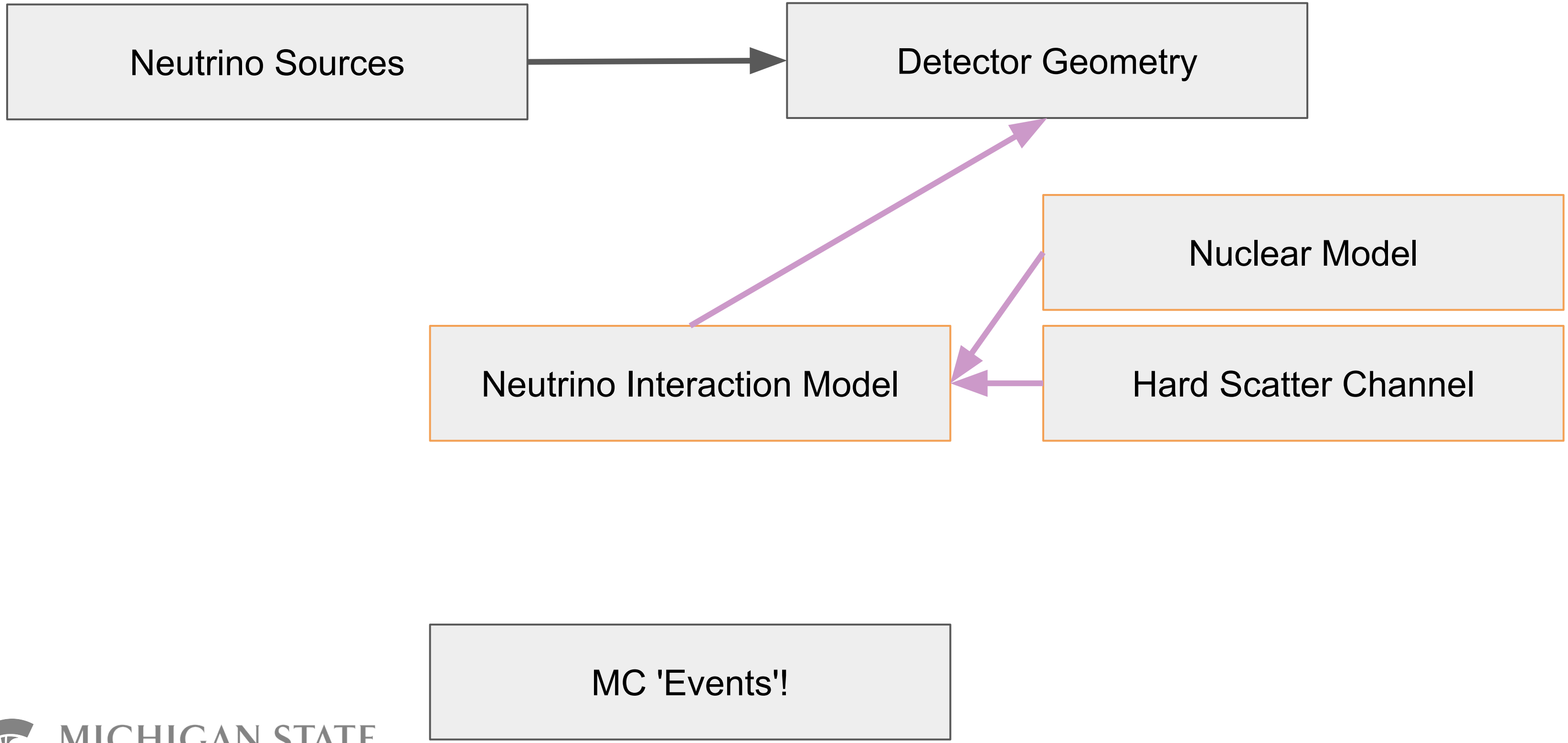

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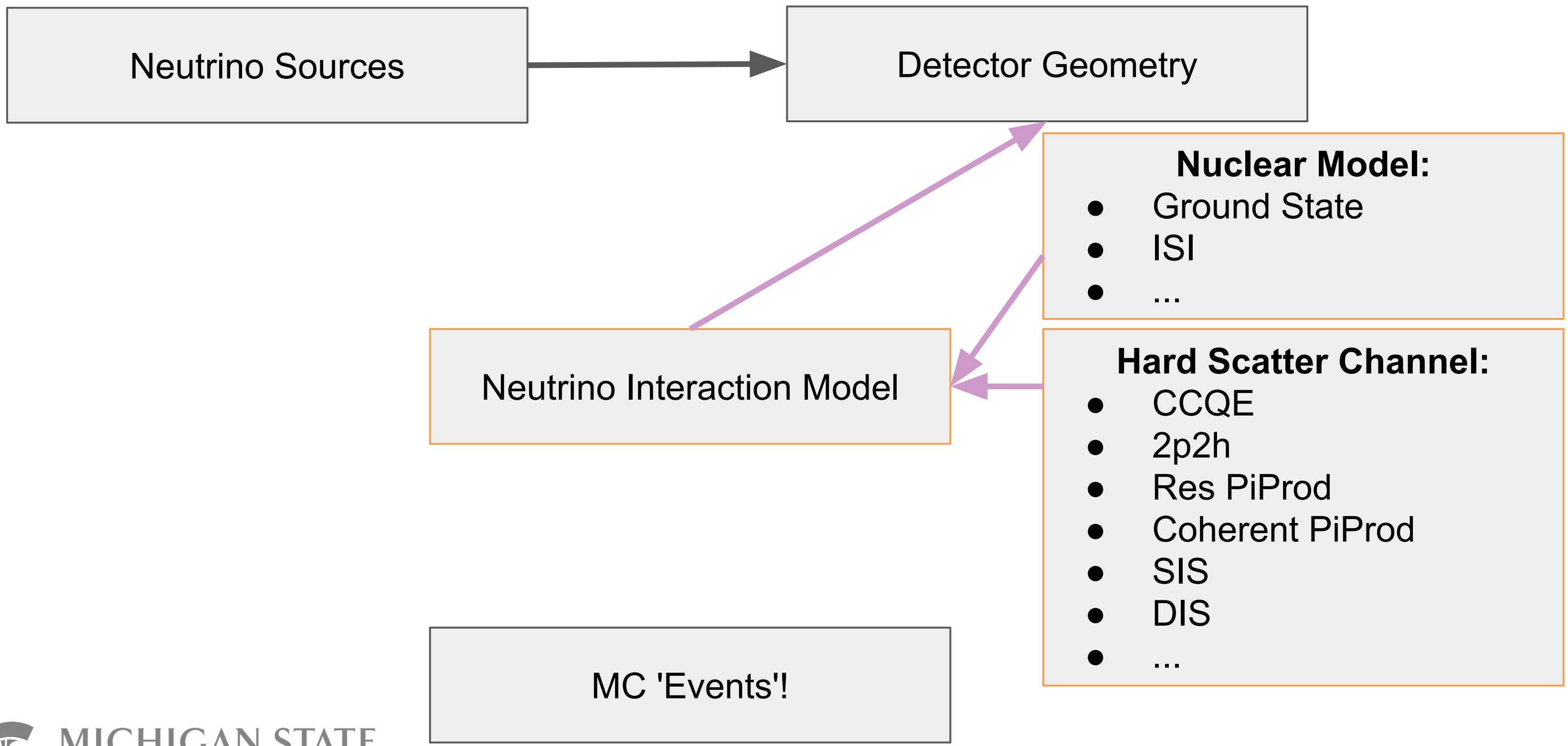
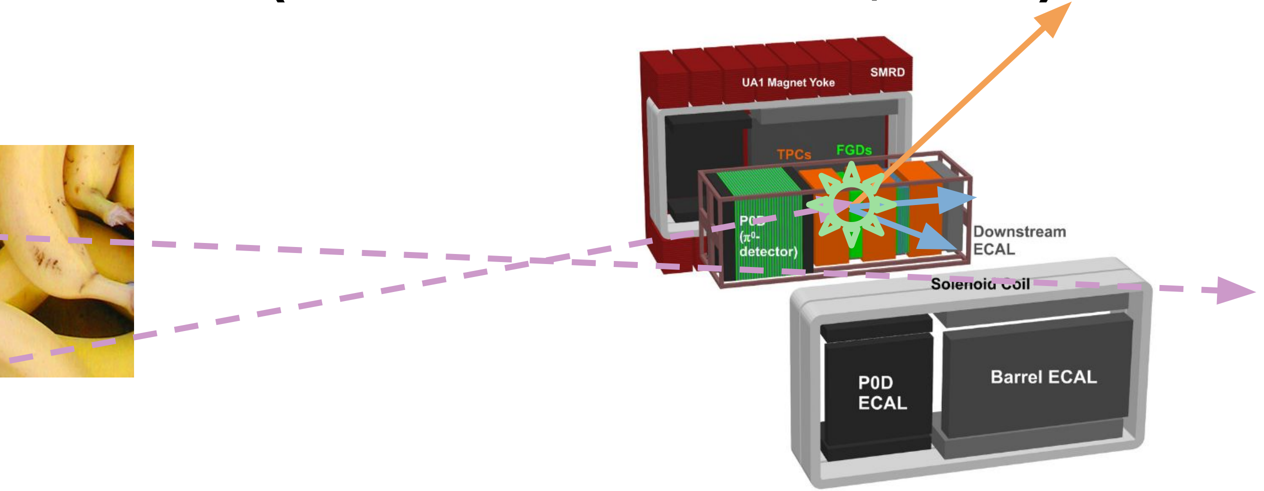


Neutrino Life-cycle

- Neutrino (species, 4-momentum) sampled from a source
- Neutrino ray is then stepped through a geometry (volumes of materials)
- Need to ask an interaction model for the probability of interaction.
- Choose whether to interact in a step
- **If interact, simulate interaction kinematics!**
- **Simulate intranuclear cascade (Final State Interactions, or FSI)**



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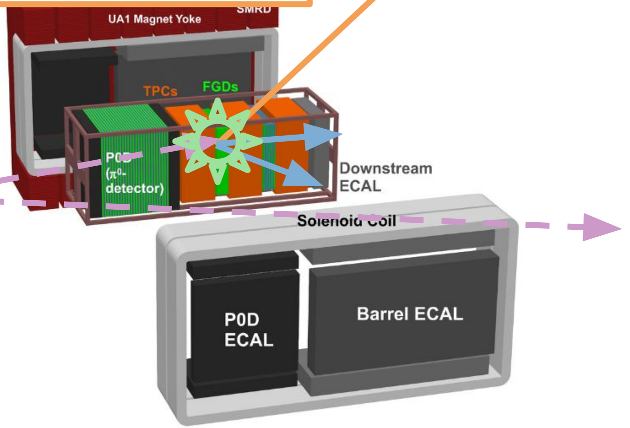
- Need to ask an interaction model for the probability of interaction.
- Choose whether to interact in a step
- **If interact**
- **Simulate** **FSI)**

This bit is often called a 'Flux/Geometry Driver(?)'
Not a particularly clear or descriptive name
I will call it a **nuint-placer**!



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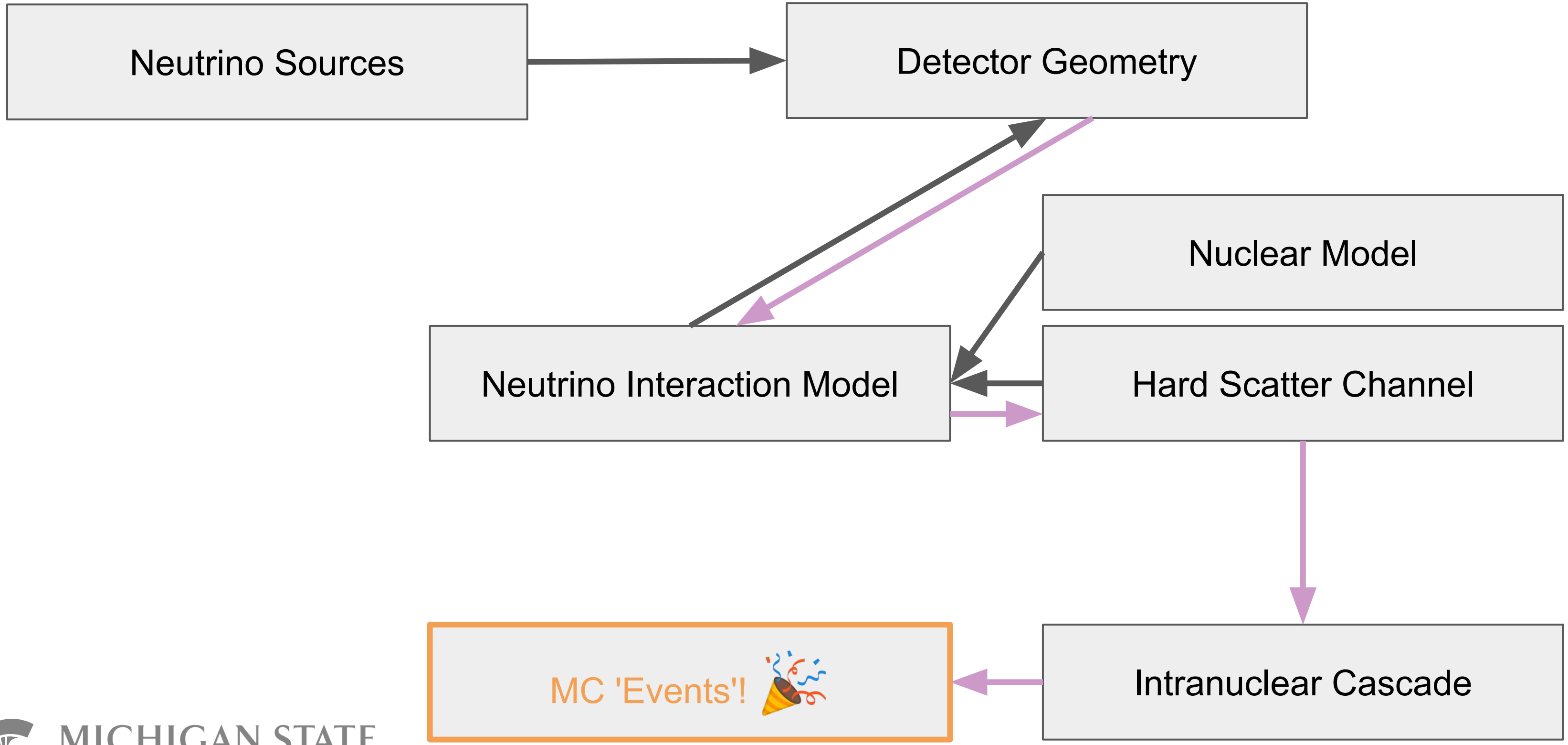
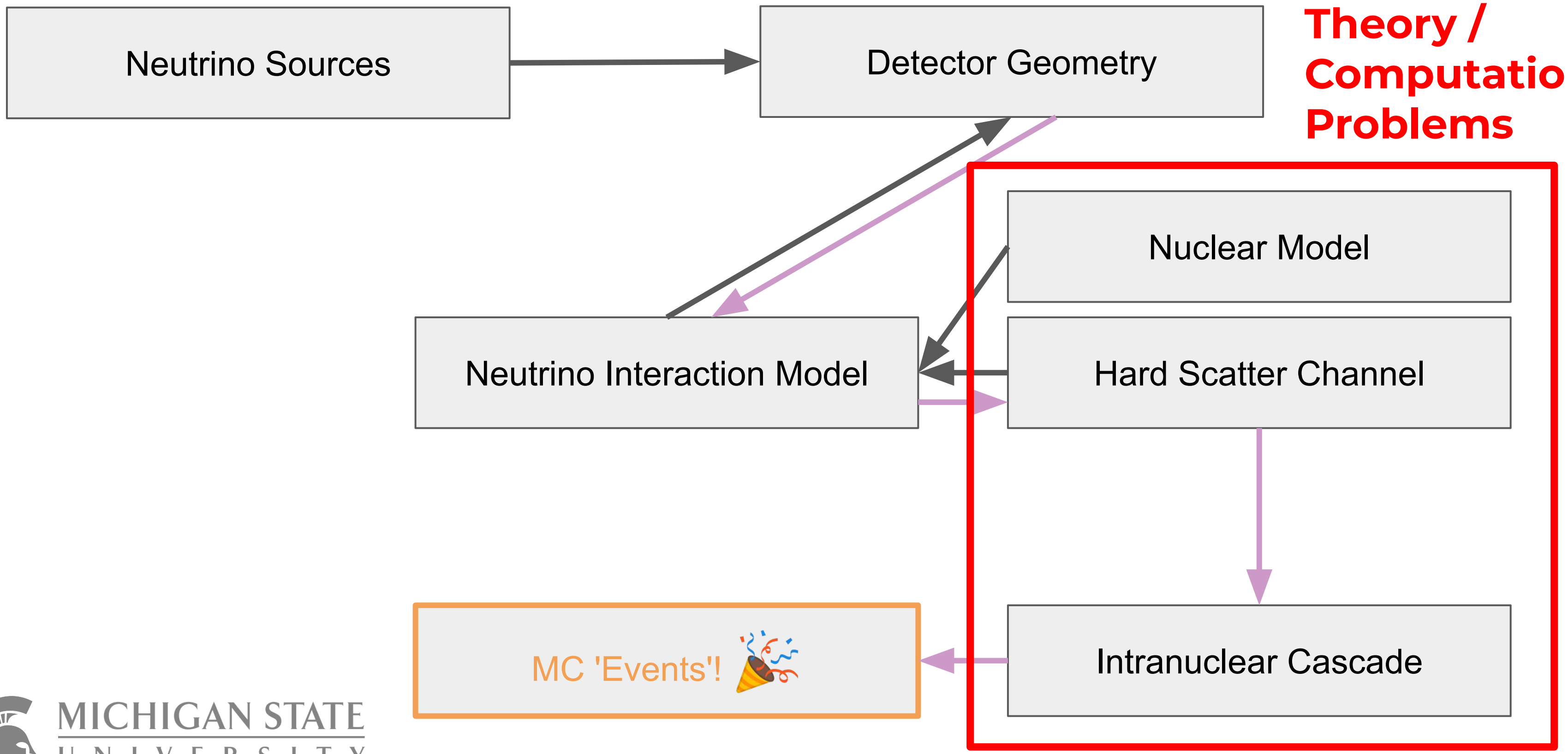


Anatomy of a Neutrino Interaction Simulation

Very difficult Theory / Computational Problems



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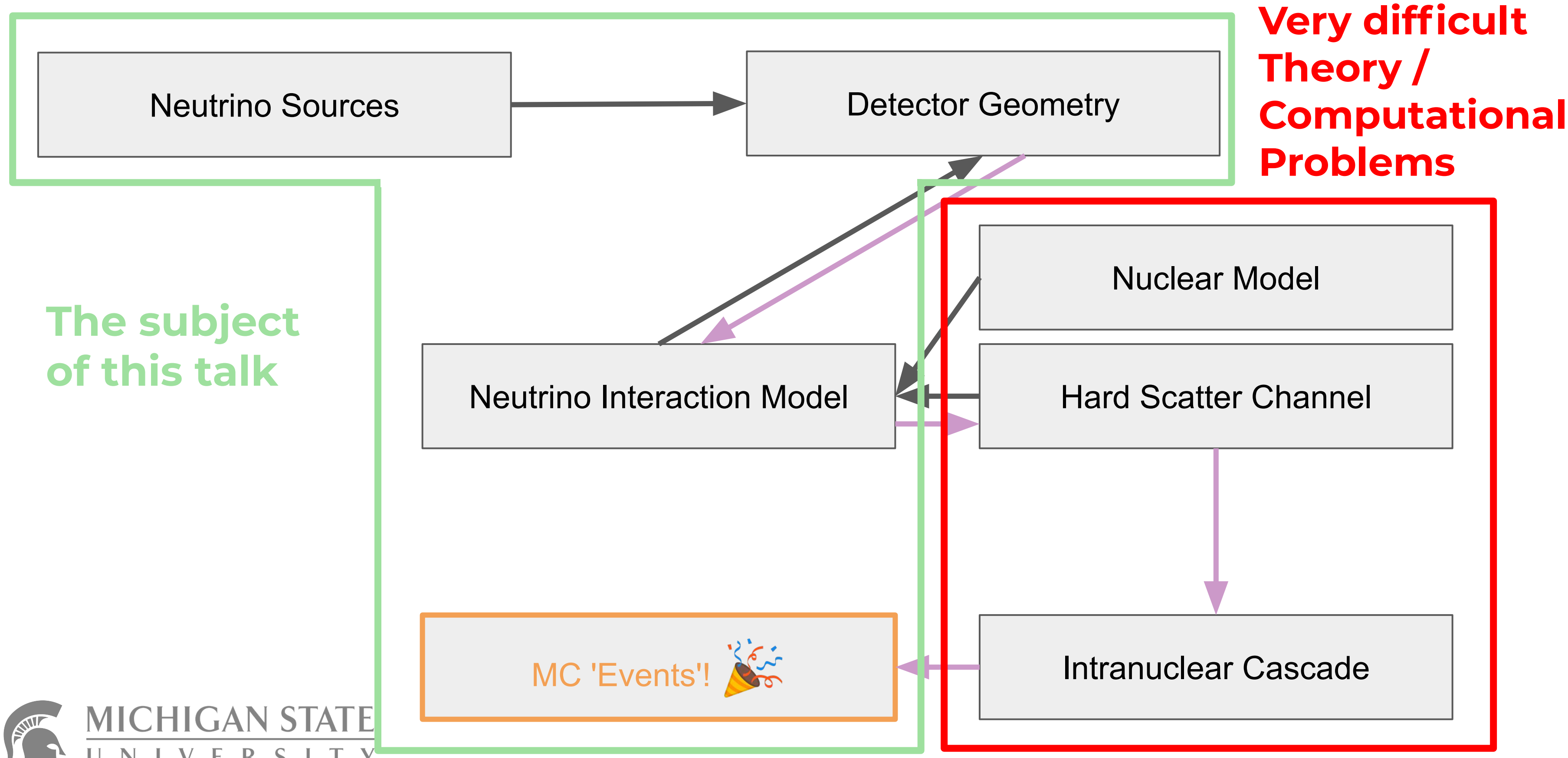

What Tools are Used by Experiments

GENIE:

- Bespoke tools for many neutrino sources (FNAL & J-PARC beams, Atmospheric, ...)
- Many, configurable interaction model components
- Includes systematic uncertainty tools

NEUT:

- *de facto* J-PARC-based experiment tool (T2K/SK)
- A number of interchangeable model components
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NuWro:

- Can simulate interactions with ROOT-based geometry
- Used for alternate model studies on T2K (and MicroBooNE).
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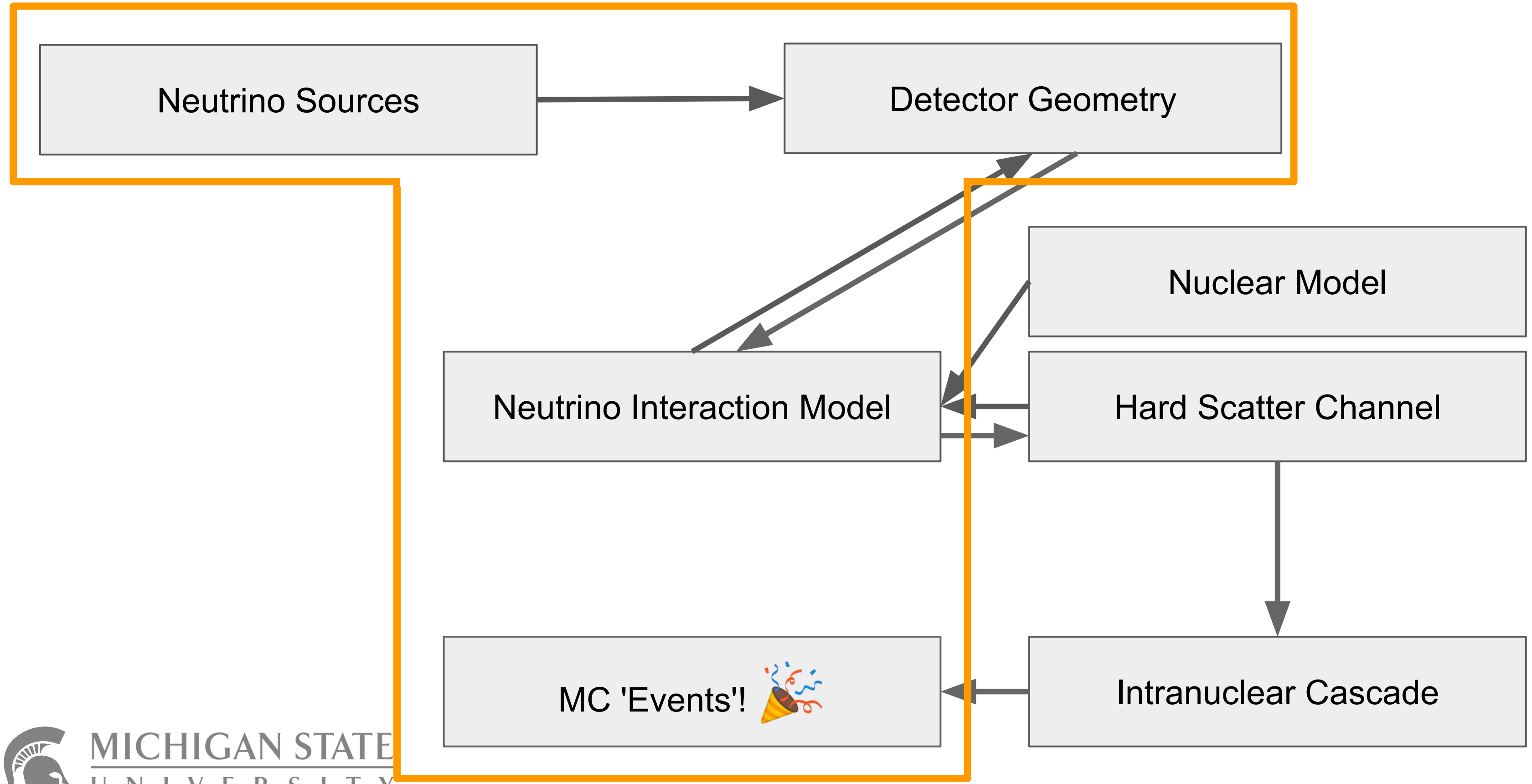
- **We do not want to write a new generator.**
- We want to be bring their solutions to the **Hard**^{tm} bits to a wider audience by building a robust, community solution to the less hard bits.
- This will also make the work of other model-building groups more accessible to current and future neutrino scattering experiments.

Vision For A Community Toolchain

- Specification and implementation of a *nuint-placer*.
- Specification and implementation of a common event format
- Specification for factorising hadronic cascade from hard-scatter
- Well defined and supported interface for integration to experimental simulations:
  - Neutrino source and detector geometry descriptions
  - To be successful, requires feedback/buy-in from experiments
- Formats that work for input-providers and output-consumers
- Provide a flexible interface for theory calculations to hook into
  - To be successful, requires buy-in from theory groups
- Factorise what can be factorised:
  - Small dedicated tools, with well defined interfaces are generally more maintainable and integrable to other software than monolithic solution.

General Considerations For Community Tools



General Considerations For Community Tools

- Development language? Additional language bindings?
  - Obvious choice is C++, is it the only reasonable choice? `rust`? `go`?
  - FORTRAN interfaces? Would Python bindings be useful?

- ROOT dependence?
  - Probably need ROOT for the geometry description: do not want to expand project scope to include custom geometry description and traversal.
  - ROOT I/O is also useful, but would like to be format-flexible.

- Validation:
  - These tools usually treated like black-boxes by everyone except their authors.
    - But they are absolutely relied upon by every aspect of an experimental analysis.

  - A key part of this new effort would be a validation suite, critically including some *a priori* validations:
    - **it is not good enough to ask** *'does it reproduced GENIE/NEUT for the same xsec?'*

Summary of Formats and Inputs/Outputs

Neutrino Source Formats:
- JNuBeam
- BNB
- NuMI
- dk2nu
- Histogram
- Atmospheric model
- ...

Detector Geometry Description:
- ROOT binary
- GEANT4 in-memory
- gdml

Neutrino Interaction Models:
- ASCII/binary tables
- Full calculation code
- For more Info see Minerba's Talk

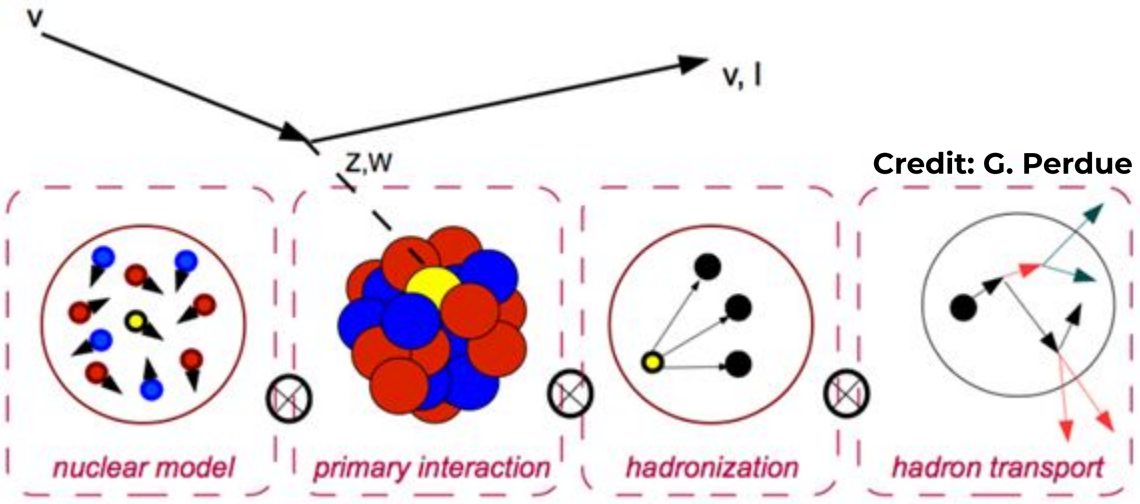
Interaction event formats:
- Each generator uses 'proprietary' ROOT TTree binary formats
- Some also have ASCII output

Flux/Geometry Considerations

- Supporting multiple formats for each of:
  - Neutrinos sources
  - Geometries
- Interfaces to models:
  - Need to request:
    - `double total_xsec(neutrino_species, energy, target_nucleus)`
    - `event generate_event(neutrino_species, energy, target_nucleus)`
  - Methods of interfacing
    - Directly linking to a defined API?
    - Other interprocess communications (named pipes, networking, MCAAS…)
- Where can we make use of existing work?
  - Separate and generalise `neutgeom`?
  - Implement all models as GENIE channels and make use of the GENIE nuint-placer?

Factorisation Considerations

- Factorisation in generator design can mean different things to different people:
    - Separating initial state nuclear model effects from the hard scatter (i.e. reducing dimensionality of integrals)
    - Separating hadronic cascade from the hard scatter
    - Separating the flux/geometry navigation from the interaction model



Credit: G. Perdue

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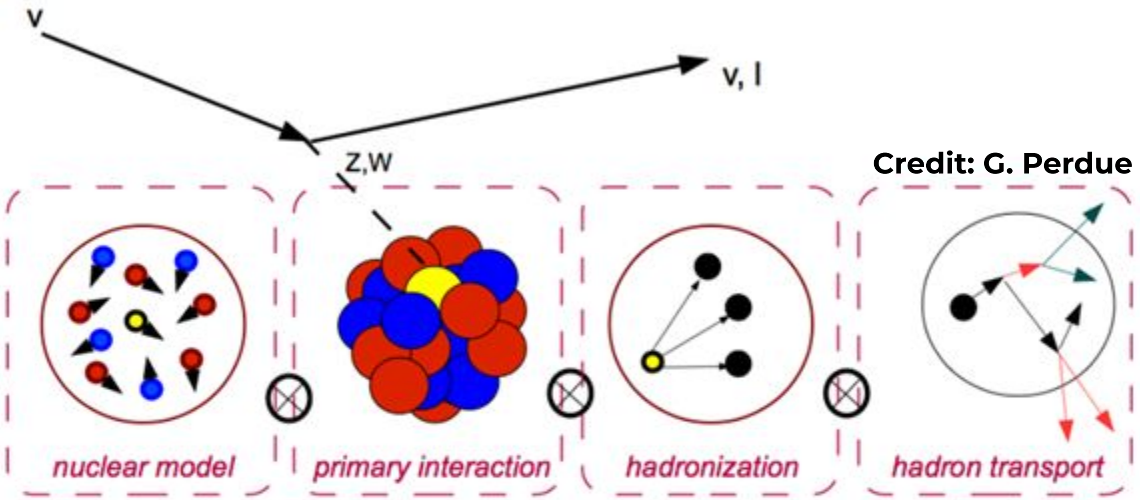

Credit: G. Perdue

Cascade Factorisation

- Factorisation of the hadronic intranuclear cascade is near-universally implemented.
  - It is not the correct thing to do in general, but it is an incredibly useful tool
- Given that it is factorised, it would useful to mix and match hard-scatter and cascade implementations.
- We plan to define an interface for separating the cascade simulation from the hard-scatter in existing generator(s)
  - GiBUU can already be run in such a mode!
- This work is closely related to/facilitated by adopting common event formats.

Common Event Format Considerations

- On-disk format?
  - ROOT? ASCII? HDF5?
- What should be defined by the format?
  - *e.g.* 'Interaction modes'? (The answer here is pretty emphatically '**no**')
- Disruption caused by a new format:
  - Should generators use it as their main output format? Or do we also provide converters?
  - Generators must be able to store enough generator-specific event information to enable systematic error propagation tools (which will not generalise).
- Maintainability:
  - Better to not 'start from scratch' if possible
  - Can we build what we need on top of a standard solution?

NuHepMC

- An example starting point designed as a set of conventions built on top of HepMC3 can be found here.
- It is built from two parts:
  - Specification that defines the neutrino-MC-specific conventions and allowed extensibility in terms of HepMC3 objects/interfaces.
  - A C++ helper library to facilitate reading/writing of HepMC3 events that respect with the spec.
- Reference implementations have been added to forks of NEUT and NUISANCE and are available for testing.
- This is not meant to be the complete solution, but a starting point for discussion and evolution.

Stretch Goal: Truth Analysis Tools

- Interaction systematic uncertainties are becoming more and more limiting to our experimental precision.
  - Tools such as GENIE-Professor, Apprentice, NUISANCE, NOvARwgt, T2KRwgt and their descendants are critical for current and next generation neutrino experiments.

- Providing 'truth analysis' tools alongside a common interaction event format will aid in the development of such tools against a common format.
  - *e.g.* `double GetQ2(event const &, units)`
  - *e.g.* `particle GetHighestMomProton(event const &, units)`
  - Such a toolkit could also include experimental contributions such as: `double MINERvA2020dpt_y(event const &, units)`

- This would come as a secondary, optional package dependent on the event format.

Planned Work

- Document the above considerations and plans to address them.
  - If you are interested, there is room for the current WG to grow, so get in touch!
- Solicit feedback and criticism from the community.
  - We want to hear as much input as possible from analysers, experts, and model-builders before committing to anything that we have designed in a small group.
- We will then draft technical specifications where relevant:
  - Total cross-section API for model/interaction-placer interface.
  - Common Event format
  - Validation suite
- Then we get to begin implementation.
- We still have time to do this work carefully before DUNE and HK
  - We have to start soon
  - Also expect to reap the benefits on current generation experiments and FNAL SBL too!

Summary

- We are looking to solve the 'easy' simulation problems very well.
  - Solve them in a way that is easily integrable into all experimental code
  - Solve them in a way where the focus is on ease of collaboration with the people working on the difficult problems.
- But to do it well is a considerable amount of work.
  - We need interest and buy-in from this community
- Buy-in in terms of:
  - Contributed specification requirements
  - Contributed development time
  - Willingness to use the tools as they become available
  - Willingness to develop models against a community agreed-upon interface
    - (But I am of the opinion this interface should be 'living' and should grow as needs change)

Dawn from the summit of Fuji-san

Thanks for listening

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