(B)SM Phenomenology and Event Generators

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Looking Beyond Snowmass
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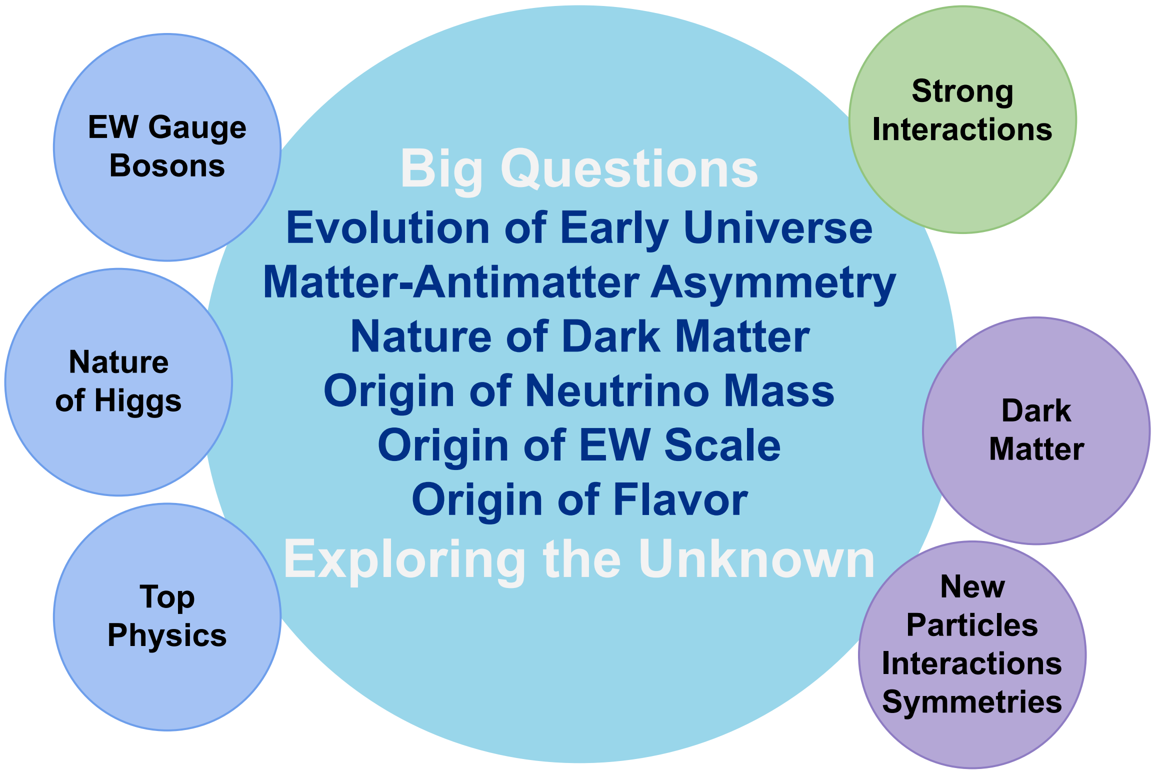
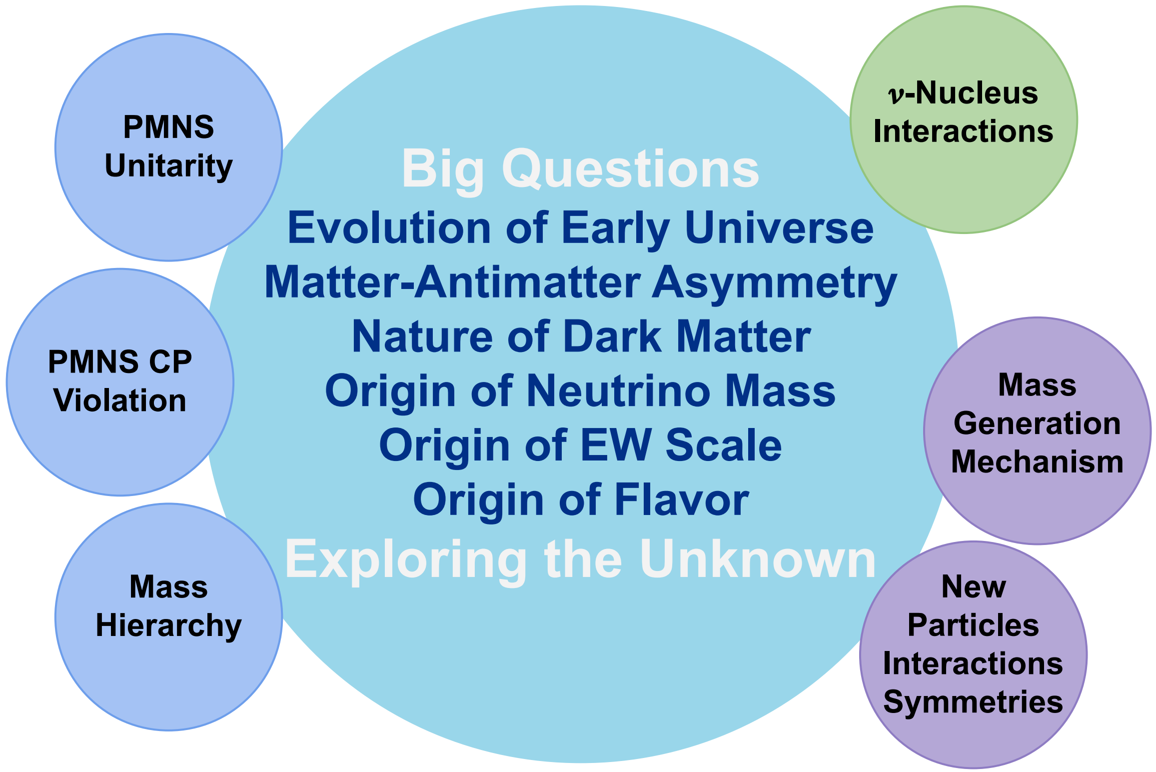
Physics at the Energy Frontier – Snowmass 2021



- What can we learn about the origin of the EW scale and the EW phase transition from an in-depth study of SM particles at colliders (HL-LHC)?
- What can we learn about the dynamics of strong interactions in different regimes?
- How can we build a complete program of BSM searches which includes both model-specific and model-independent explorations at high scales?

[Narain et al.] arXiv:2211.11084

Physics at the Neutrino Frontier – Snowmass 2021

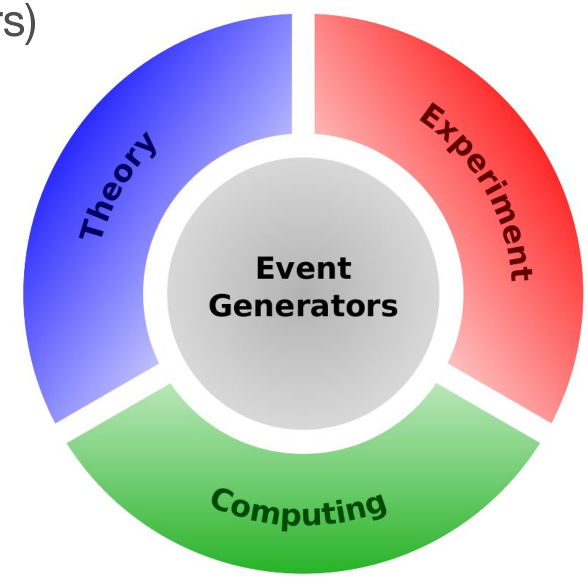


- What can we learn about the origin of the neutrino masses and the absolute mass scale from high-intensity neutrino experiments (DUNE, SBND, Project 8, $0\nu\beta\beta$)?
- Is there a source of CP violation in the lepton/neutrino sector?
- How can we exploit neutrinos as uniquely sensitive tools to probe a wide range of low-scale and/or small coupling BSM physics?

[Huber et al.] arXiv:2211.08641

Connecting Theory and Experiment

- HEP experiments rely on simulations (event generators) for design, analysis and interpretation of data
- Theory needs generators to connect to experiments
- Generators preserve the collective knowledge of high-energy particle physicists in a set of calculations and models that are implemented in publicly accessible open-source computer code (Open Science)



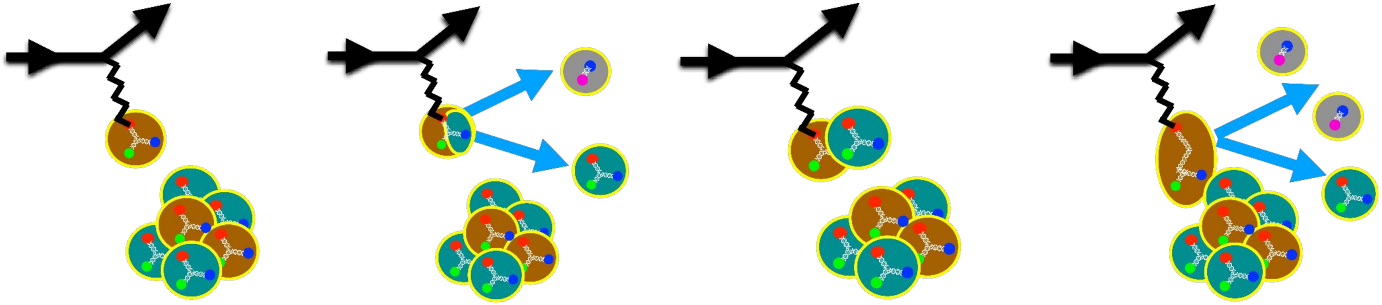


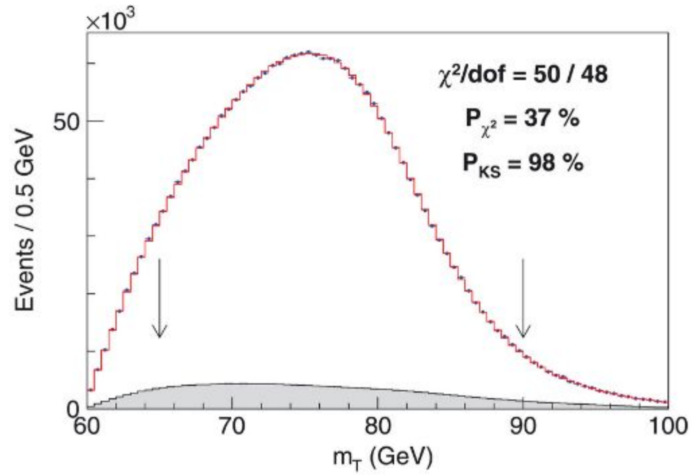
Image courtesy of M. Wagman

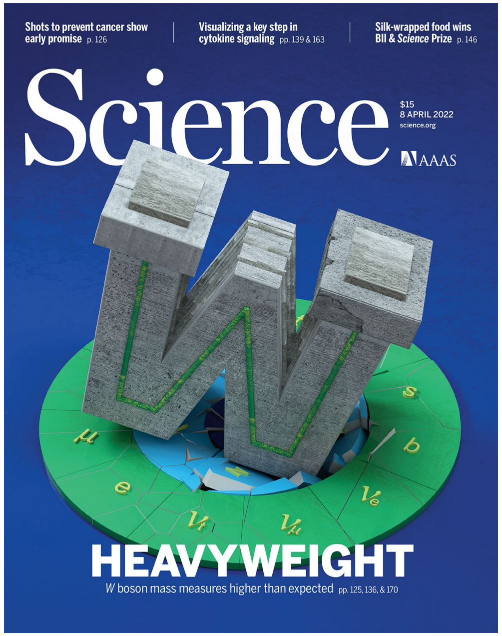
[Campbell et al.] arXiv:2203.11110

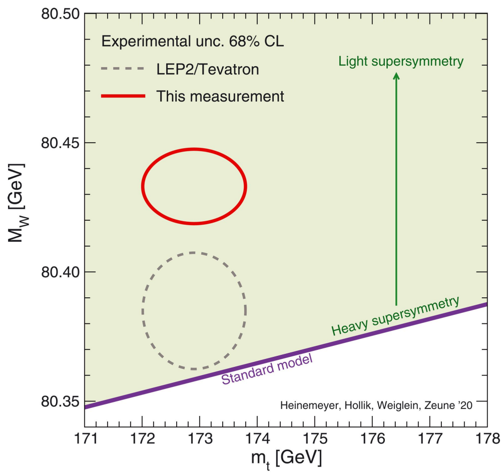
Precision Measurements at Colliders

- CDF's measurement of the W-boson mass emphasizes importance of precision calculations for extraction of SM parameters at colliders

- (B)SM interpretation of results depends on sub-permille level precision in lepton p_T spectrum







[CDF Collaboration]
Science, 376, 6589, 170-176

- Fermilab theorists provides two of the most important tools for predictions of the p_T spectrum: MCFM and ResBos

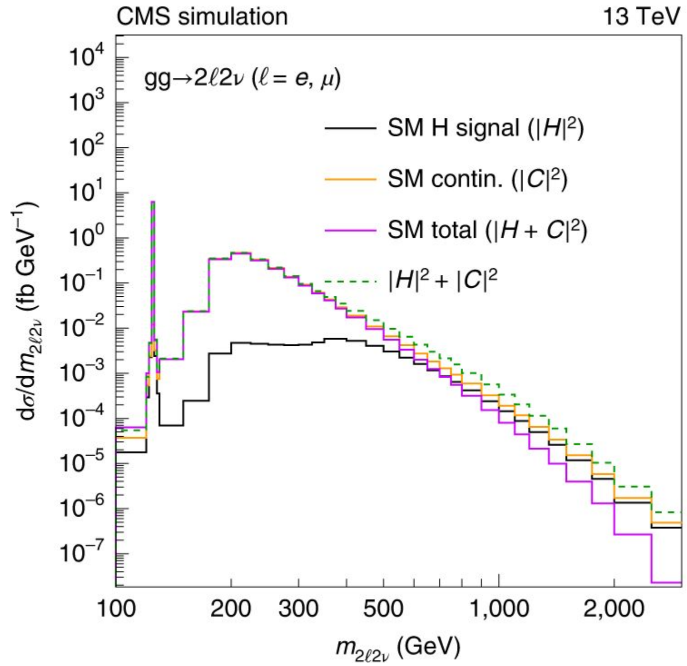
- ResBos2 – N^2LO fixed order, N^3LL resummed [Isaacson et al.]

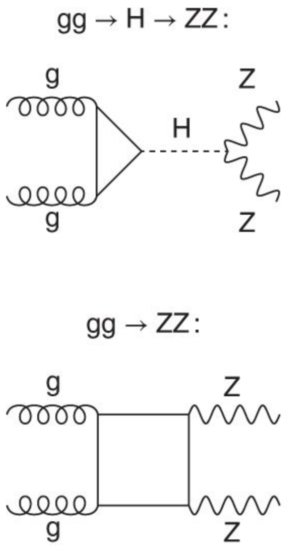
- MCFM – N^3LO fixed order, N^4LL resummed [Campbell et al.]

- Multiple methods & codes to estimate perturbative truncation error

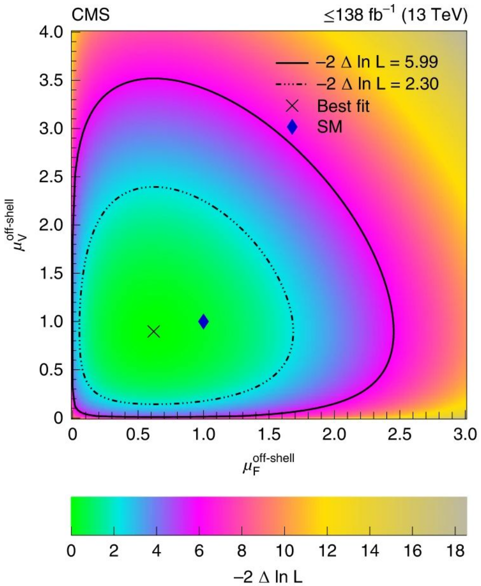
Precision Measurements at Colliders

- Recent CMS measurement of Higgs boson width a success of both experiment & theory
- Off-shell interference due to loop-induced processes with special helicity configurations - a relatively recent finding





[CMS Collaboration] Nature Physics 18 (2022) 1329



- Fermilab theorists helped establish method and developed tools for experimental analysis [Campbell,Ellis,Williams]
- Rich BSM phenomenology also in di-photon decay channel [Campbell,Carena,Harnik,Liu]
- Future bounds on width also from $\gamma\gamma$ channel [Dixon et al.]

Exploring the Unknown – The Higgs Potential

- Higgs self interaction is key to understanding of EW sector
- Measurement will require careful combination of many analyses with full HL-LHC data set
- Heavy flavor channels needed for high statistical significance e.g. via “ABCD” method

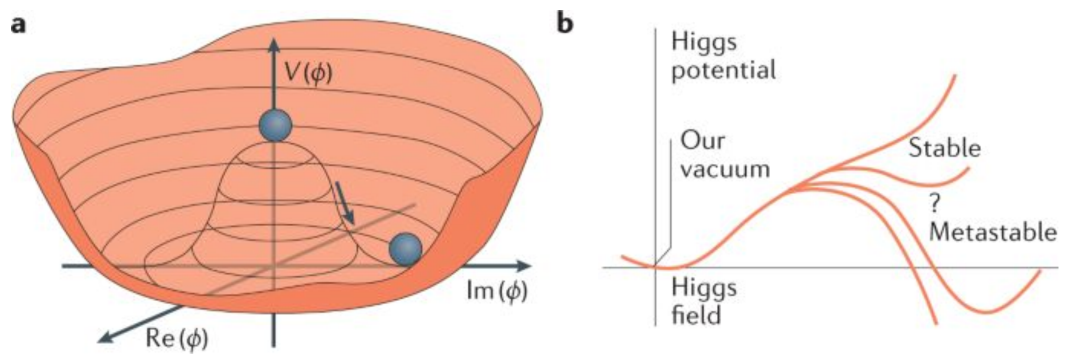
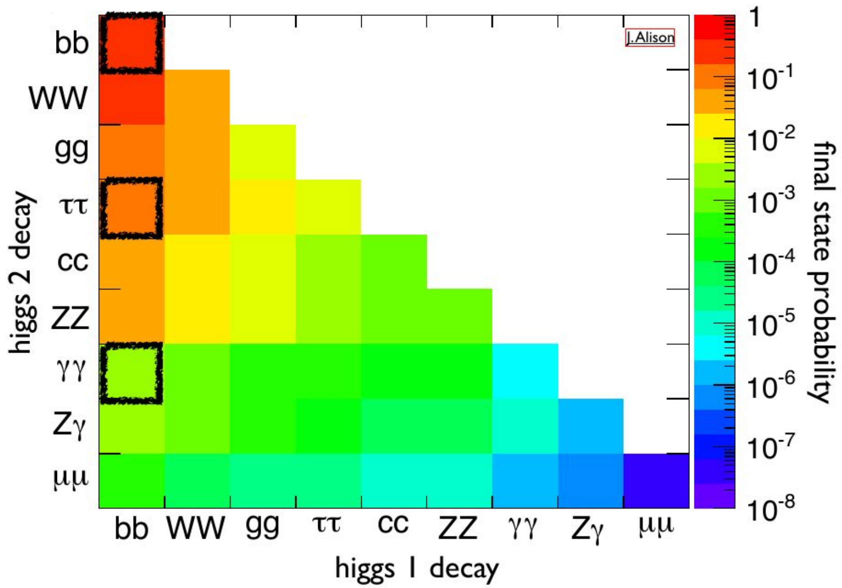
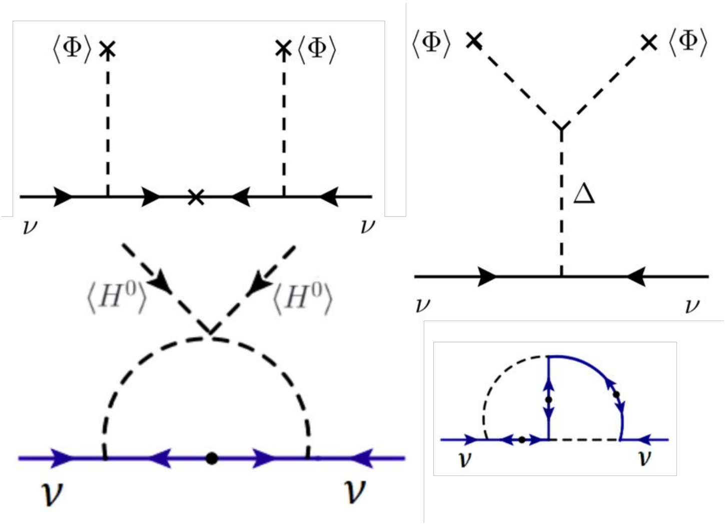


Image Credit: *Nat Rev Phys* **3**, 608–624 (2021)



- Predictions for heavy quark production as part of inclusive heavy plus light flavor jets difficult to obtain at high precision
- Multiple approaches co-developed at Fermilab & implemented in simulations
  - MCFM [Campbell et al.]
  - Sherpa [Höche et al.]
- Estimation of matching scheme uncertainties crucial for reliable extraction of triple Higgs coupling

Precision Neutrino Phenomenology



- **Mechanism of neutrino masses qualitatively different from SM charged fermions: Requires BSM**
- Realizations of the neutrino mass mechanism can live in the sub-eV up to the 10^{13} GeV scale
- Neutrino sector a promising portal to new physics scenarios

- For oscillation physics need to reconstruct incoming neutrino energy

$$\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

- Detector response depends on final state: energy, direction & type of each particle
- **To fully exploit neutrino sector, need to describe neutrino-nucleus interactions differentially: Requires simulations**
- Factorization is key to simulation

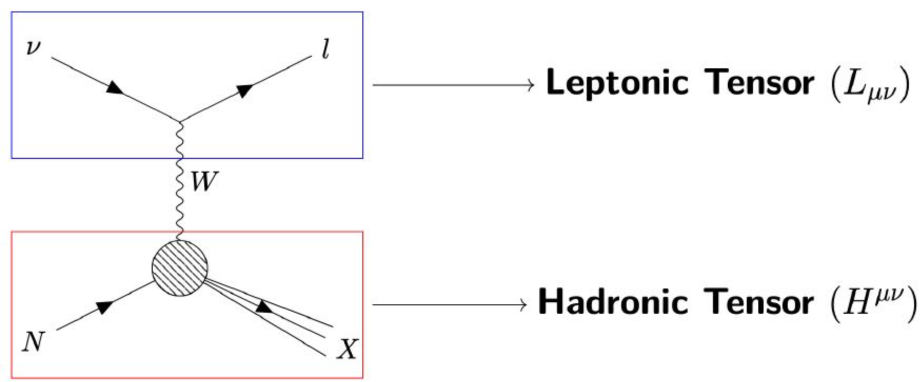
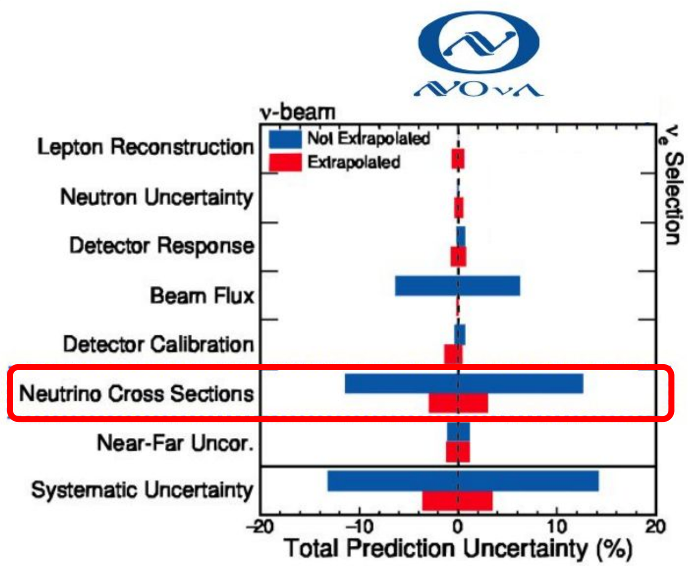


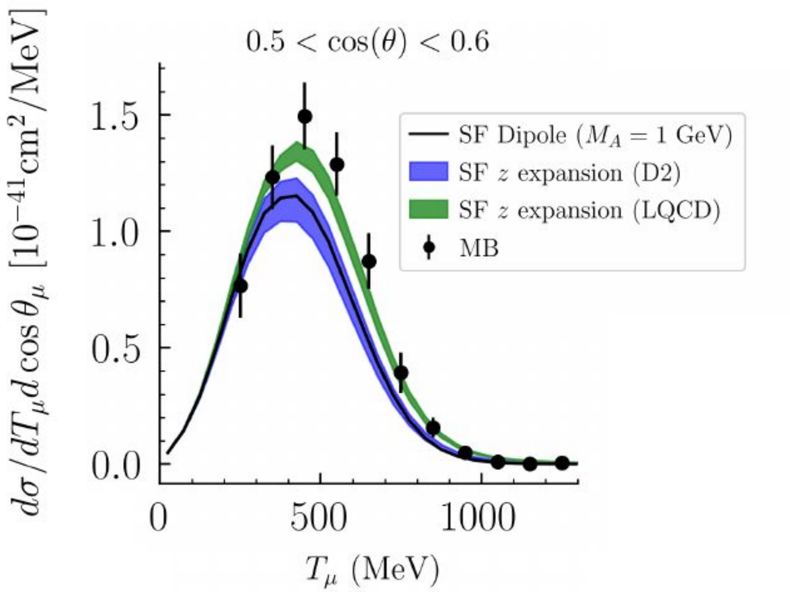
Image credit: J. Isaacson

Precision Neutrino Phenomenology

- Current uncertainty estimates of neutrino nuclear interaction modeling: 5-10%
  Mismodeling can hinder BSM searches or lead to fake anomalies [Machado et al.]

- Reaching precision goals of DUNE possible, but will require strong effort
  Must ensure continued support for simulations and background theory





[Simons et al.] arXiv:2210.02455

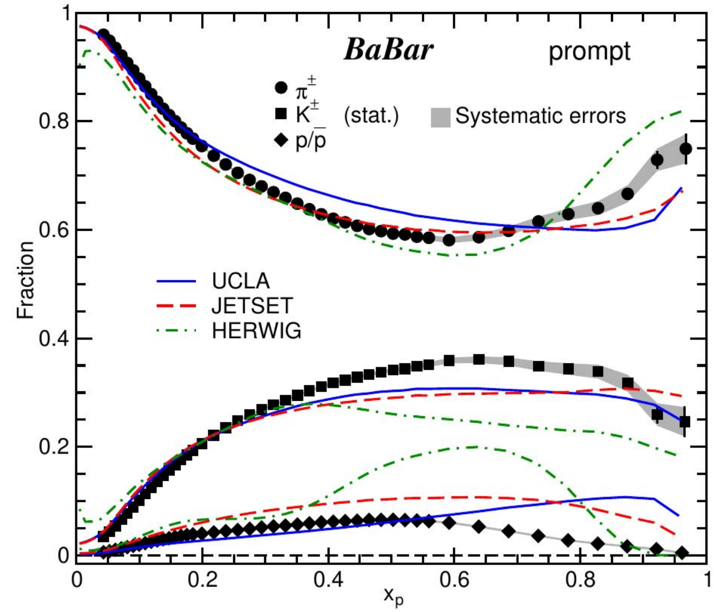
- Computation of spectral functions for neutrino-nucleus interaction [Rocco et al.]

- Collaboration between nuclear theory and lattice QCD to improve nuclear matrix elements [Rocco,Wagman et al.]

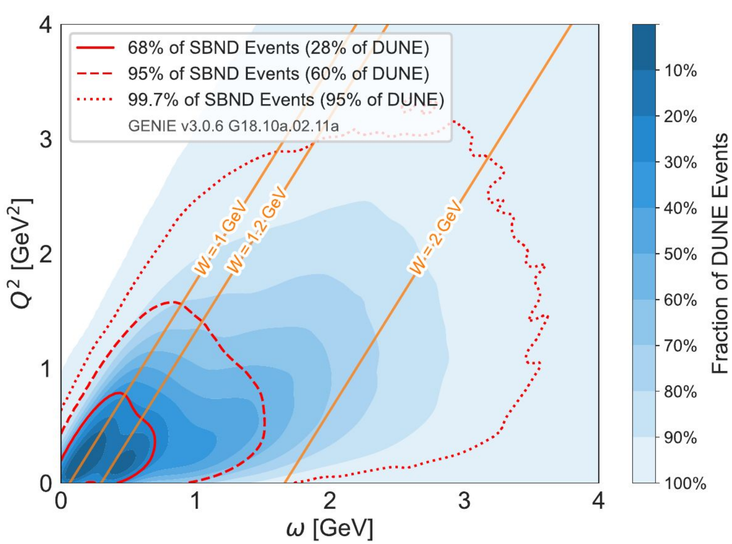
- Collaboration with experiment to include in Genie [Rocco,Steinberg et al.]

Precision Neutrino Phenomenology

- Modeling of non-perturbative parton-to-hadron transition important for detector response, especially at low particle multiplicity
- Flavor composition of jets and identified hadron production typically somewhat challenging, especially at low energy
- Must be addressed in order to reach precision goals of future colliders & neutrino experiments



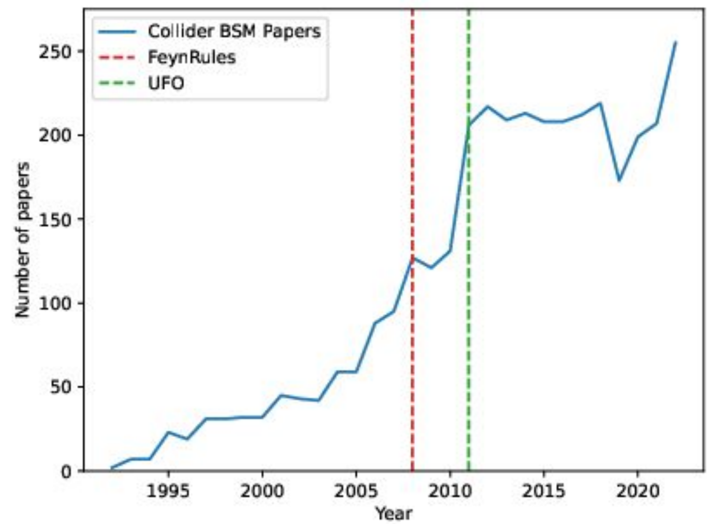
[Lees et al.] arXiv:1306.2895



- About 10% of DUNE events expected to be in DIS region → precision target for low Q^2 hadronization models of 10%
- Challenging for any existing generator
- Fermilab involved in two model developments: String [Mrenna] & Cluster [Höche]

BSM Neutrino Phenomenology

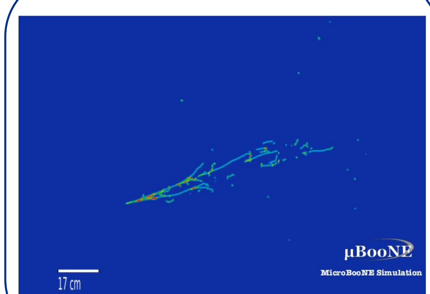
- Ideal workflow for BSM explorations: Lagrangian → Simulation → Analysis
- Enabled by developments in collider physics community (FeynRules+UFO) [Darmé et al.] arXiv:2304.09883
- If BSM only in leptonic sector, analogous solution for neutrino event generators [Isaacson et al.] arXiv:2110.15319



$$
\mathcal{L}_{\mathcal{D}} \supset \frac{m^2_{Z_{\mathcal{D}}}}{2} Z_{\mathcal{D}\mu} Z^{\mu}_{\mathcal{D}} + g_{\mathcal{D}} Z^{\mu}_{\mathcal{D}} \bar{\nu}_{\mathcal{D}} \gamma_{\mu} \nu_{\mathcal{D}} + e\epsilon \, Z^{\mu}_{\mathcal{D}} \, J^{\mathrm{em}}_{\mu} + \frac{g}{c_W} \epsilon' \, Z^{\mu}_{\mathcal{D}} \, J^{Z}_{\mu}
$$

→ Simulation → Analysis

Feynrules+UFO



Fermilab Efforts in Generator Development

- Novel neutrino event generator Achilles: Primary interaction, Cascade, BSM [Isaacson,Machado,Rocco]

- Connecting LQCD and nuclear many-body [Rocco,Wagman]

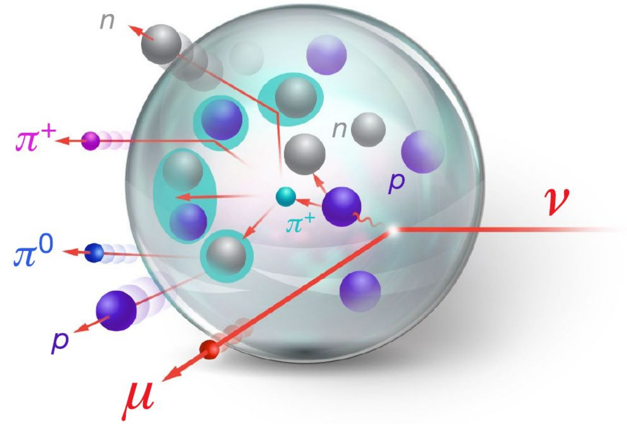
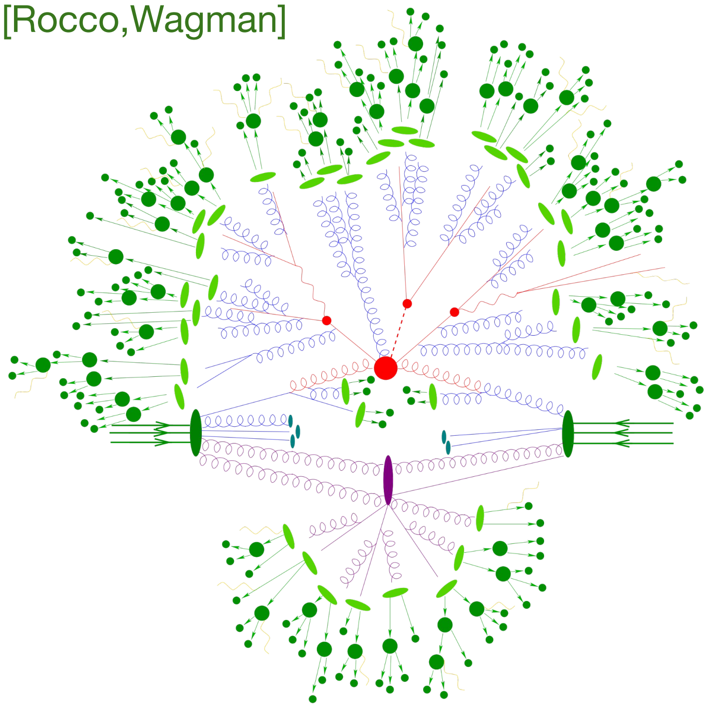


Image credit: Steven Gardiner



- General-purpose collider physics tools: Perturbation theory, resummation, hadronization modeling, QED effects [Mrenna,Höche]

- Fixed-order & resummation at highest achievable precision [Campbell,Isaacson]

Please come talk to us!

Fermilab