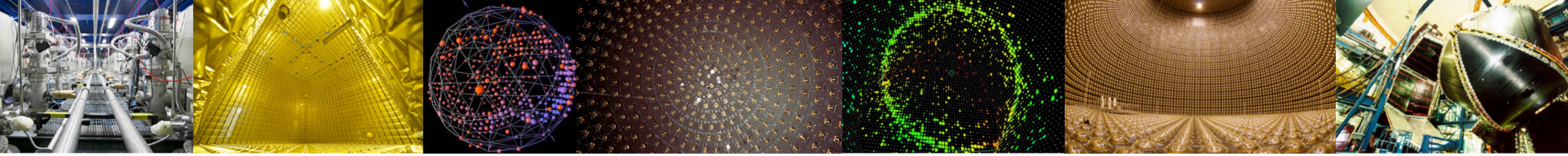
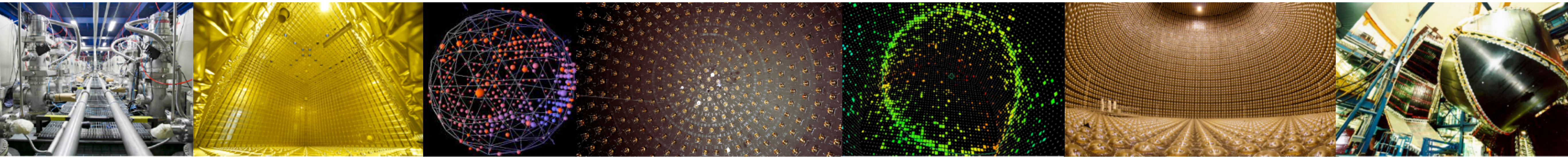
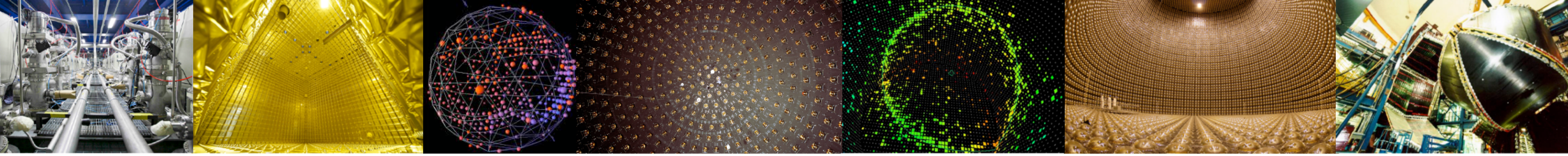


Interface between **BSM Scenarios** and **Neutrino Event Generators**

William Jay — MIT

SBN Experiment-Theory Workshop
Santa Fe, New Mexico
2-5 April 2024

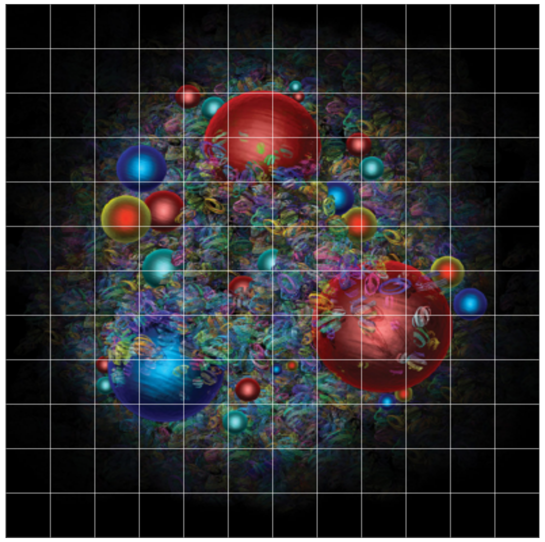




My perspective

Isaacson [WJ] et al.
***PRC* 103 (2021) 1, 015502**
[arXiv:2007.15570]

Isaacson [WJ] et al.
PRD107 (2023) 3, 033007
[arXiv:2205.06378]

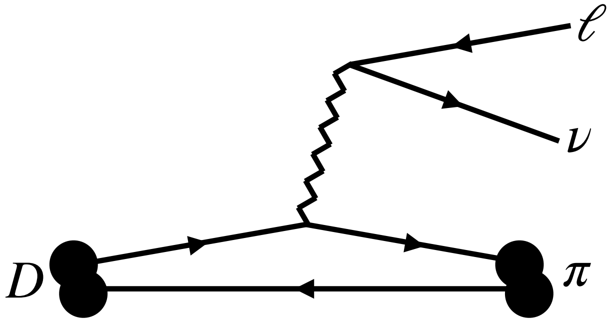


Inclusive scattering

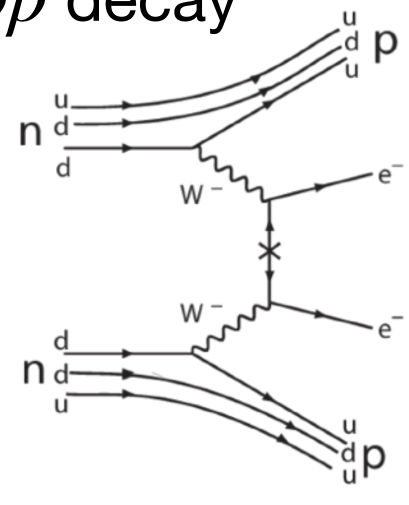
$$ep \to e'X$$

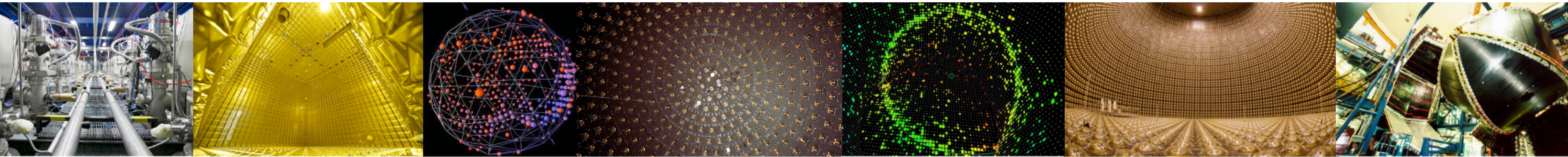
$$W^{\mu\nu} \sim \langle p | J_\mu(q) J_\nu(-q) | p \rangle$$

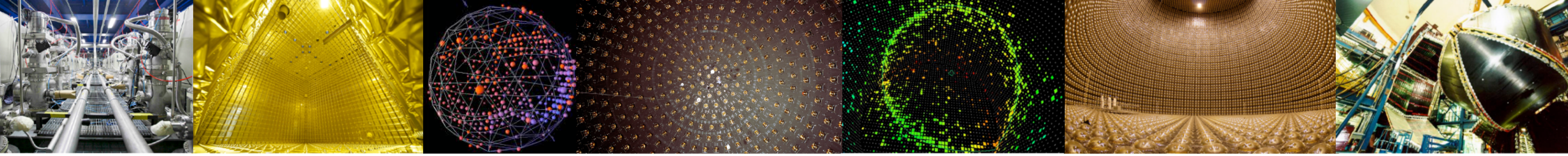
CKM Metrology



$0\nu\beta\beta$ decay





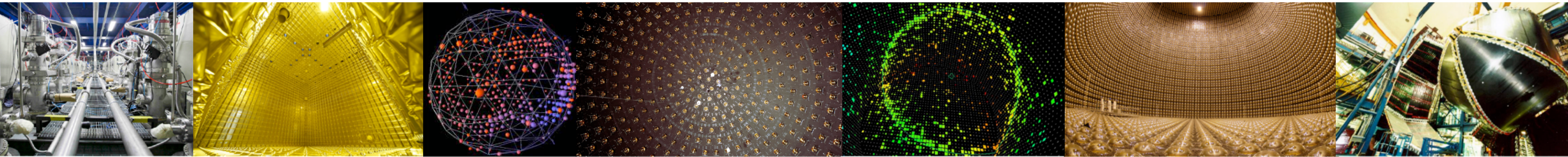


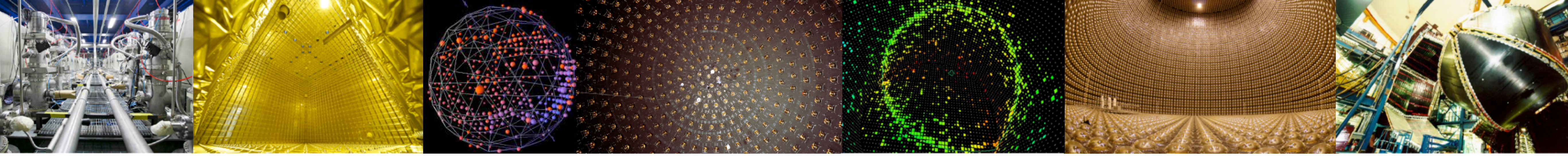
My perspective




Isaacson [WJ] et al.
PRC **103 (2021) 1, 015502**
[arXiv:2007.15570]

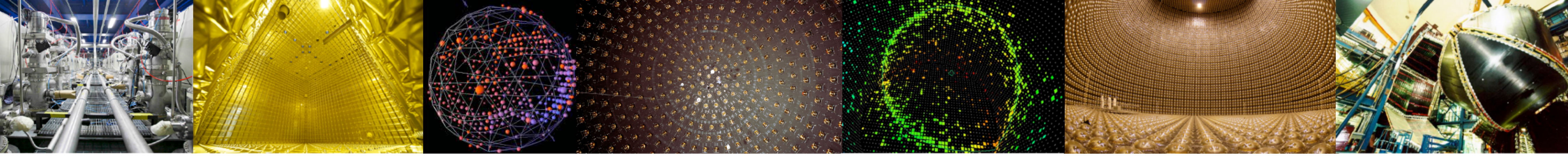
Isaacson [WJ] et al.
PRD107 (2023) 3, 033007
[arXiv:2205.06378]





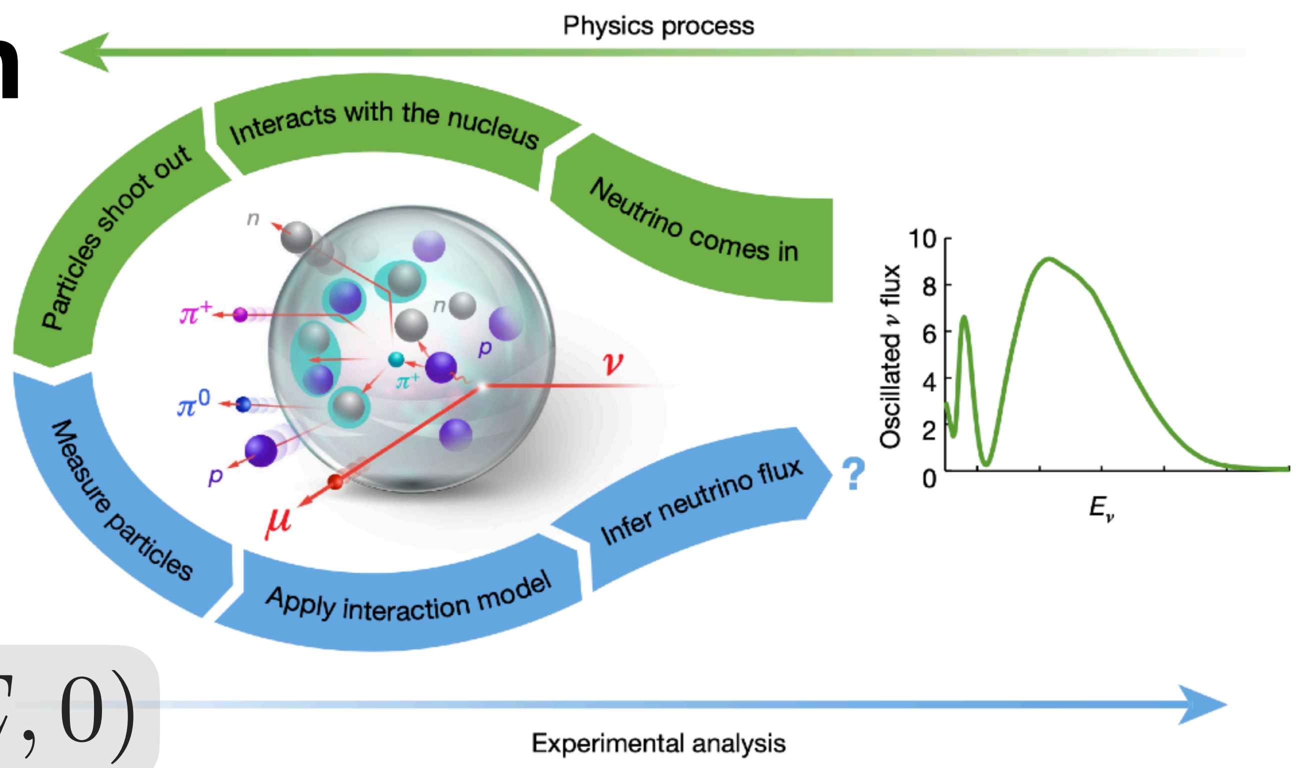
Outline

- Simulating the Standard Model
- Simulating beyond the Standard Model
- Examples
- Conclusions



Lepton Event Simulation

The hadronic grand challenge



Want: Mixing parameters, e.g, angle θ

$$P_{\nu_\mu \to \nu_e} \approx \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\Phi_e(E,L) \propto P_{\nu_\mu \to \nu_e}(E,L)\Phi_\mu(E,0)$$

Neutrino fluxes. "Measurable."

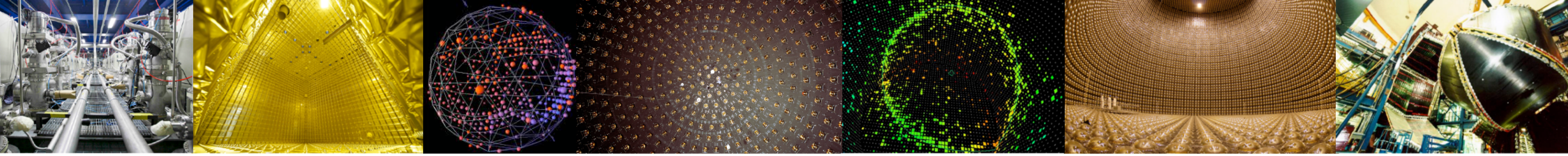
"Smearing matrix"
(Experimental + theoretical)

$$N_\alpha(E_{\rm rec},L) \propto \int dE\, \Phi_\alpha(E,L)\sigma(E) f_{\sigma_i}(E,E_{\rm rec})$$

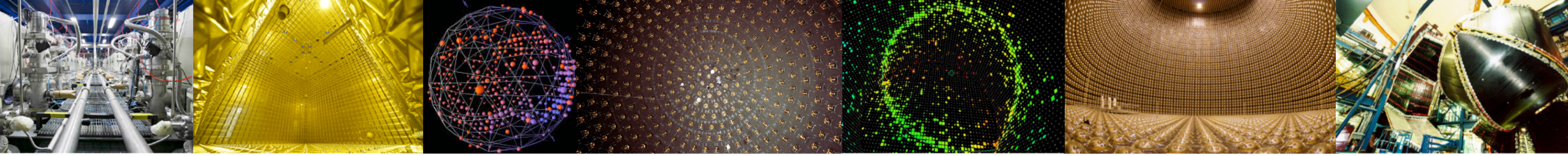
Event rate

Interaction cross section

Figure credit:
M. Khachatryan et al. (e4v)
Nature 599, 565 (2021)

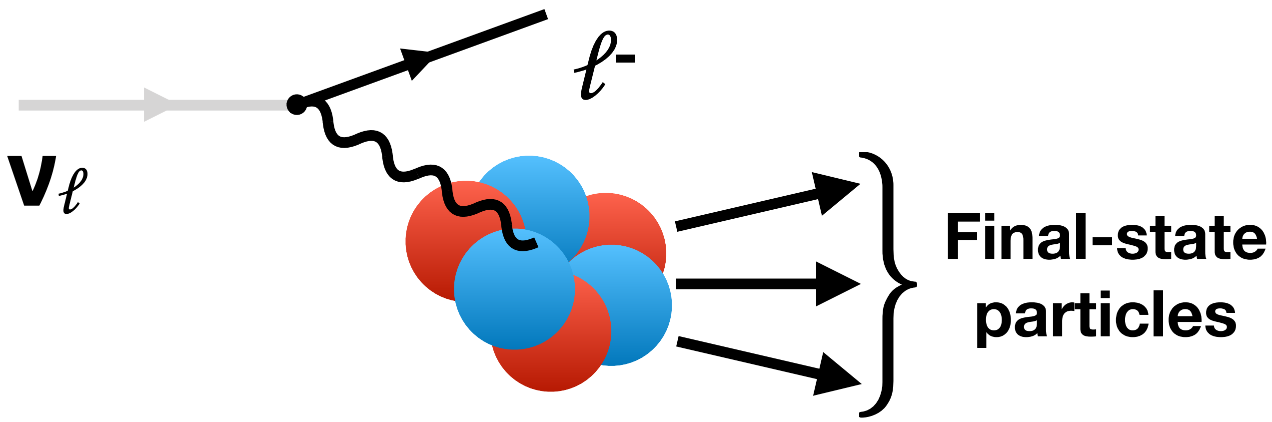


Simulating the Standard Model



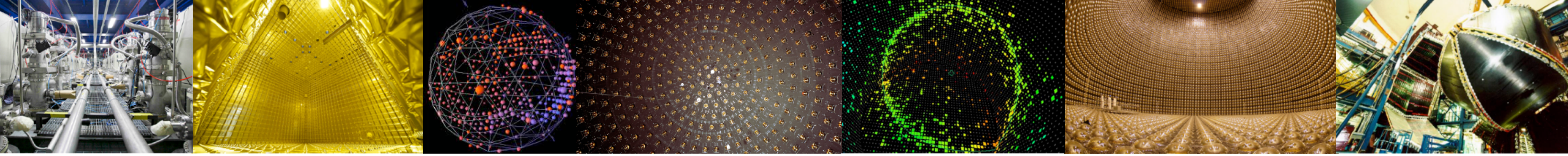
Simulating the Standard Model

Break the problem into well-defined theoretical pieces



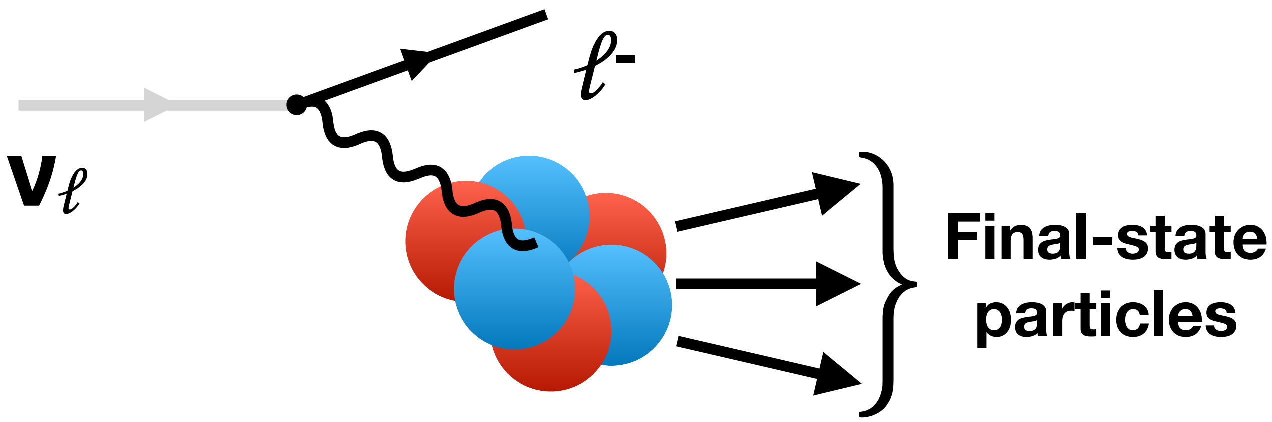
$$d\sigma = \left(\frac{1}{|v_A - v_\ell|} \frac{1}{4E_A^{\text{in}} E_\ell^{\text{in}}} \right) \times |\mathscr{M}|^2 \times \prod_f \frac{d^3 p_f}{(2\pi)^3} (2\pi)^4 \delta^4\left(k_A + k_\ell - \sum_f p_f \right)$$

$$d\sigma = (\text{flux}) \times (\text{matrix element}) \times (\text{phase space})$$



The Matrix Element

Step 1: Factorization of leptonic and hadronic physics



$$|\mathscr{M}|^2 = L_{\mu\nu}\,\frac{1}{P^2}\,W^{\mu\nu} \longrightarrow \langle\Psi_0|J^\dagger_\mu(q)|\Psi_f\rangle\langle\Psi_f|J_\nu(q)|\Psi_0\rangle$$

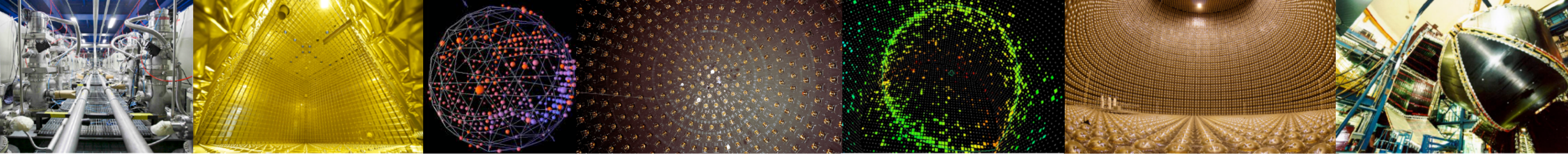
Leptonic tensor:
Calculable analytically in SM or BSM scenario.

$\Longrightarrow$ More on this later.

Hadronic tensor:
Complicated multi-scale object, encoding all the hadronic/nuclear physics

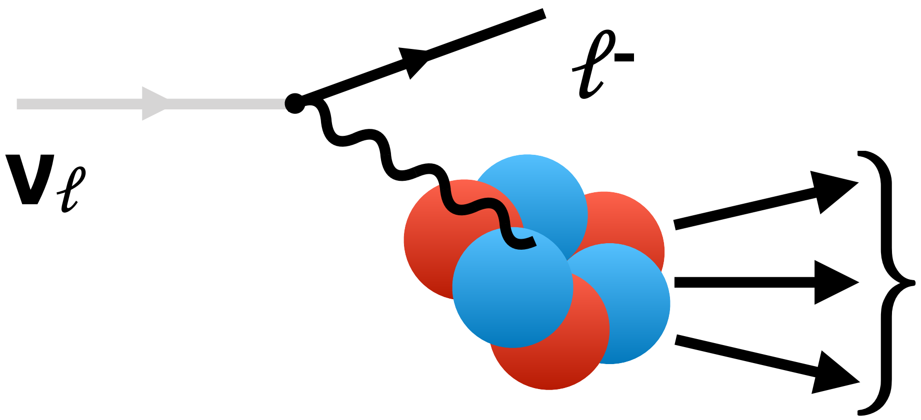
$|\Psi_0\rangle$: Initial state (say, ^{40}Ar or H_2O)

$|\Psi_f\rangle$: Final state (nuclear remnant + outgoing pions, kaons, etc…)



The Matrix Element

Step 2: Factorization of primary vertex



$\mathscr{V}$: Primary-interaction vertex

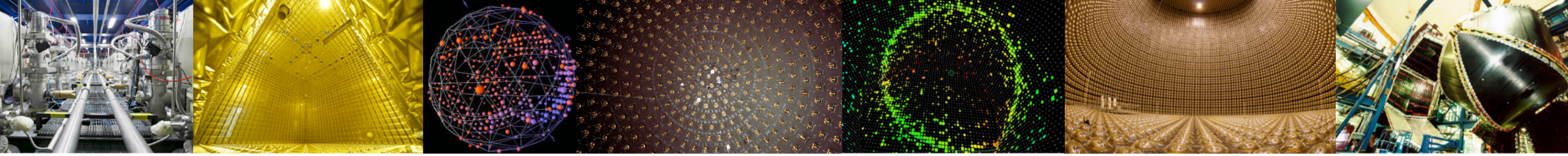
$\mathscr{P}$: Time evolution to produce observed final states

"Sum coherently over all possible intermediate states p'."
-Quantum mechanics

$$|\mathcal{M}(\{k\} \to \{p\})|^2 = \Big| \sum\!\!\!\!\!\!\int_{p'} \mathcal{V}(\{k\} \to \{p'\}) \times \mathcal{P}(\{p'\} \to \{p\}) \Big|^2$$

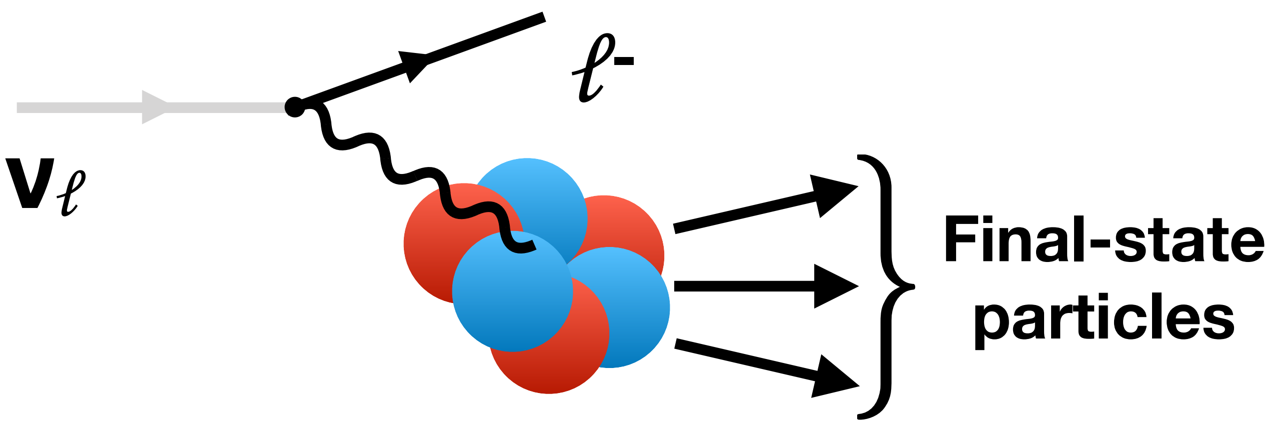
This is exact, but quite complex.

$\Longrightarrow$ **Factorize the problem.**



The Matrix Element

Step 2: Factorization of primary vertex



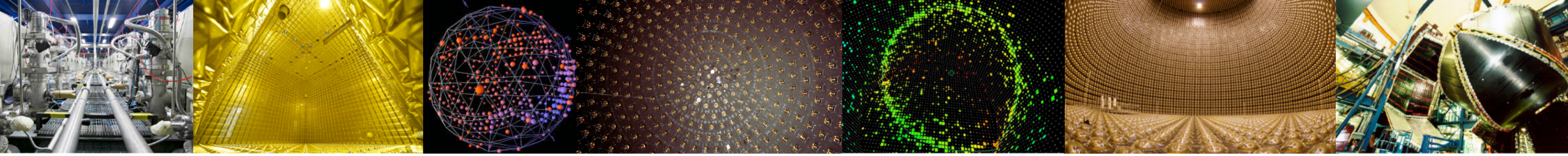
$\mathscr{V}$: Primary-interaction vertex

$\mathscr{P}$: Time evolution to produce observed final states

$$|\mathcal{M}(\{k\} \to \{p\})|^2 \simeq \sum\!\!\!\!\!\!\!\int_{p'} |\mathcal{V}(\{k\} \to \{p'\})|^2 \times |\mathcal{P}(\{p'\} \to \{p\})|^2$$

Treat the sum incoherently.
Handle constituents with theoretical care.

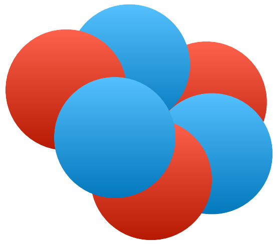
(Analogy to physics at LHC: similar to dressing hard-scattering cross sections with parton showers)



The Primary-interaction Vertex

Step 3: Choose factorization scheme and DOF

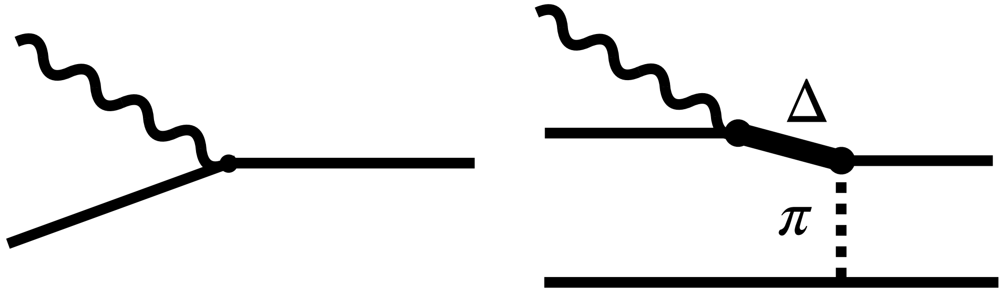
- Take nucleons as initial-state DOF



Spatial distribution from nuclear many-body theory: QMC. Quasi-exact.

- Take electroweak currents from nuclear EFT:

$$J^\mu(q) = \sum_i j_i^\mu(q) + \sum_{i<j} j_{ij}^\mu(q) + \cdots$$



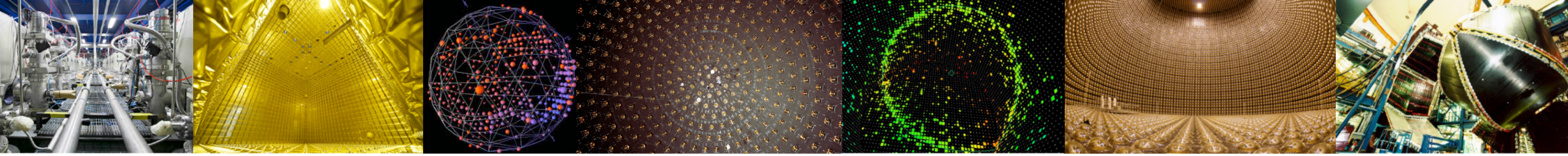
(among others)

- Choose a factorization scheme: the *impulse approximation*

$$|\Psi_f\rangle = |\mathbf{p}\rangle \otimes |\Psi_f^{A-1}\rangle$$

"For momentum transfer $|\mathbf{q}| \gtrsim 400\ \mathrm{MeV}$, external probes resolve individual nucleons."

Z. Tabrizi EFT approach to vA interactions T15:00	N. Steinberg Quasielastic, 2-body currents within many-body approaches R11:00	K. Niewczas Single- and N-nucleon knockout within many-body approaches F9:00



The Primary-interaction Vertex

Step 3: Choose factorization scheme and DOF

$$W_N^{\mu\nu} = \langle \Psi_0 | J^{\mu\dagger}(q) | \Psi_f \rangle \langle \Psi_f | J^{\nu}(q) | \Psi_0 \rangle$$

With the *impulse approximation* $|\Psi_f\rangle = |\mathbf{p}\rangle \otimes |\Psi_f^{A-1}\rangle$,

$$W_{\mathrm{N}}^{\mu\nu} \propto S_n \otimes w_n^{\mu\nu}$$

Nuclear hadronic tensor

Nuclear spectral function

(exactly calculable in nuclear many-body theory up to ~O^{16})

= "probability to find a nucleon with a given momentum inside the nucleus"

Nucleon hadronic tensor

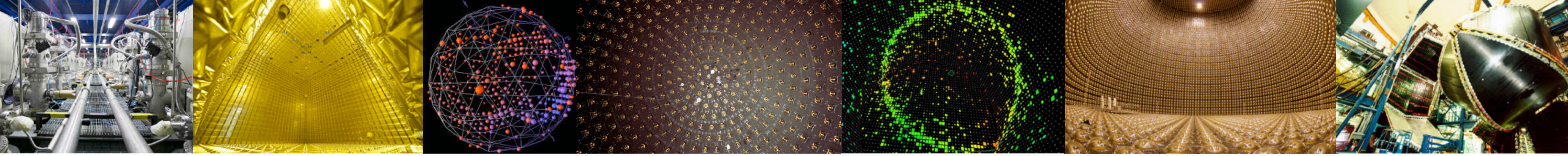
(experimentally measurable or calculable with lattice QCD)

For QE scattering:

$$w_n^{\mu\nu} \sim |\text{form factor}|^2$$

M. Wagman
Theory Uncertainties in νA interactions
W12:00

R. Gupta
Axial form factors from LQCD
Th9:00



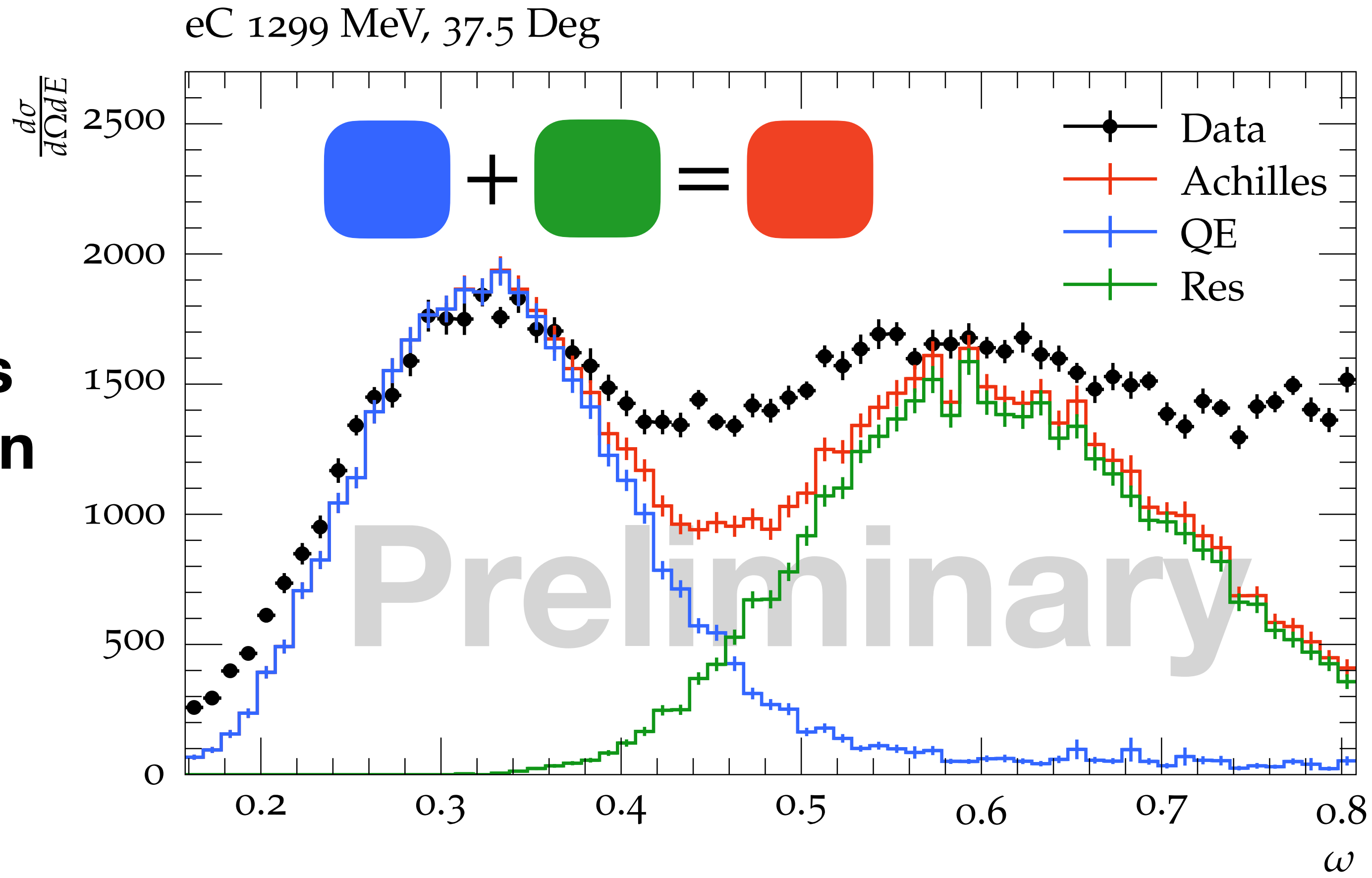
Hardonic Validation: eA-scattering

R.M. Sealock et al
Electroexcitation of the Δ(1232) in nuclei
PRL 62 (1989) 1350-1353

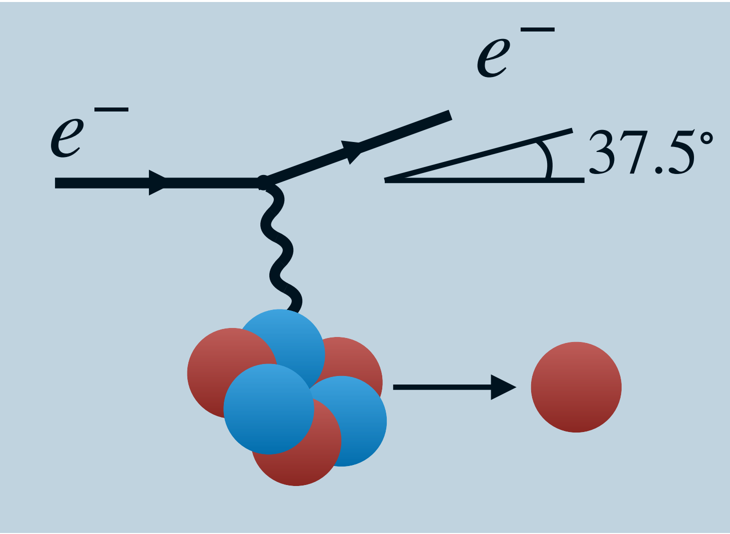
Constraining hadronic uncertainties with electron scattering

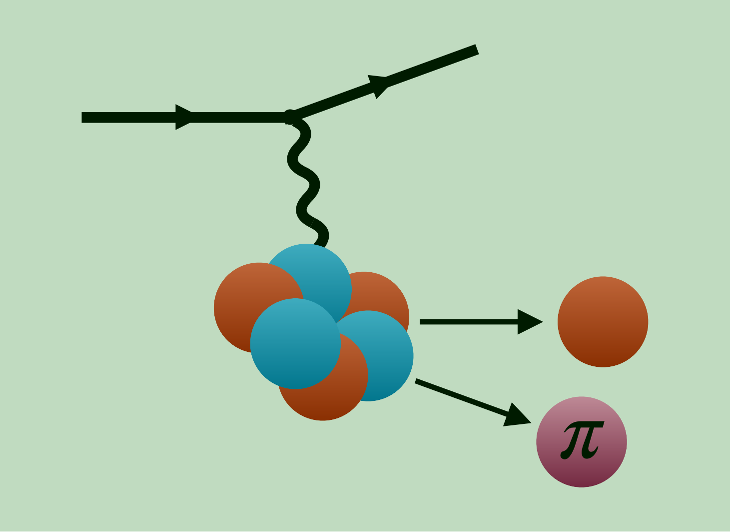
- Experimental data: $e^{12}C$ scattering at 1299 MeV, e' fixed angle $37.5°$
- **New**: Achilles now includes resonance production in dynamical coupled channel (DCC) model

Cross section

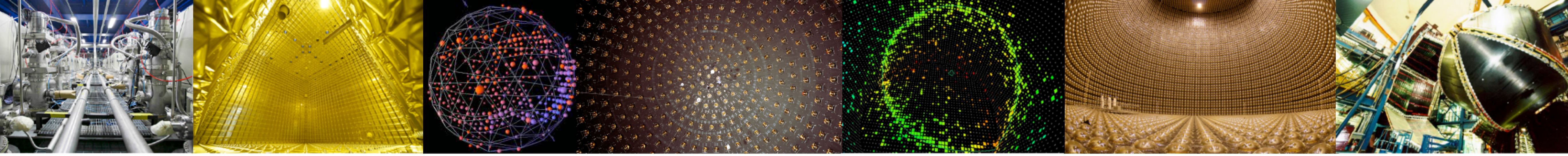


Outgoing electron energy [GeV]

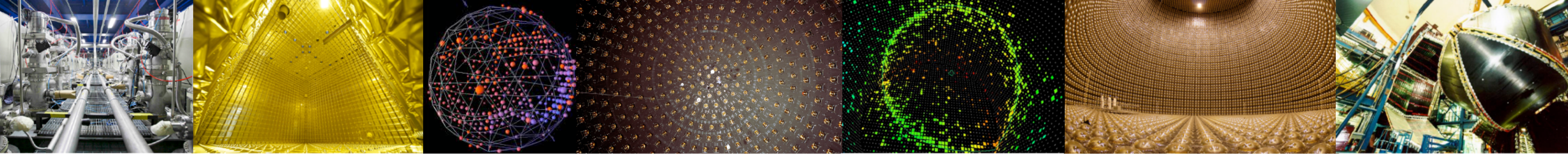




Noah Steinberg
Postdoc @ FNAL



Simulating beyond the Standard Model

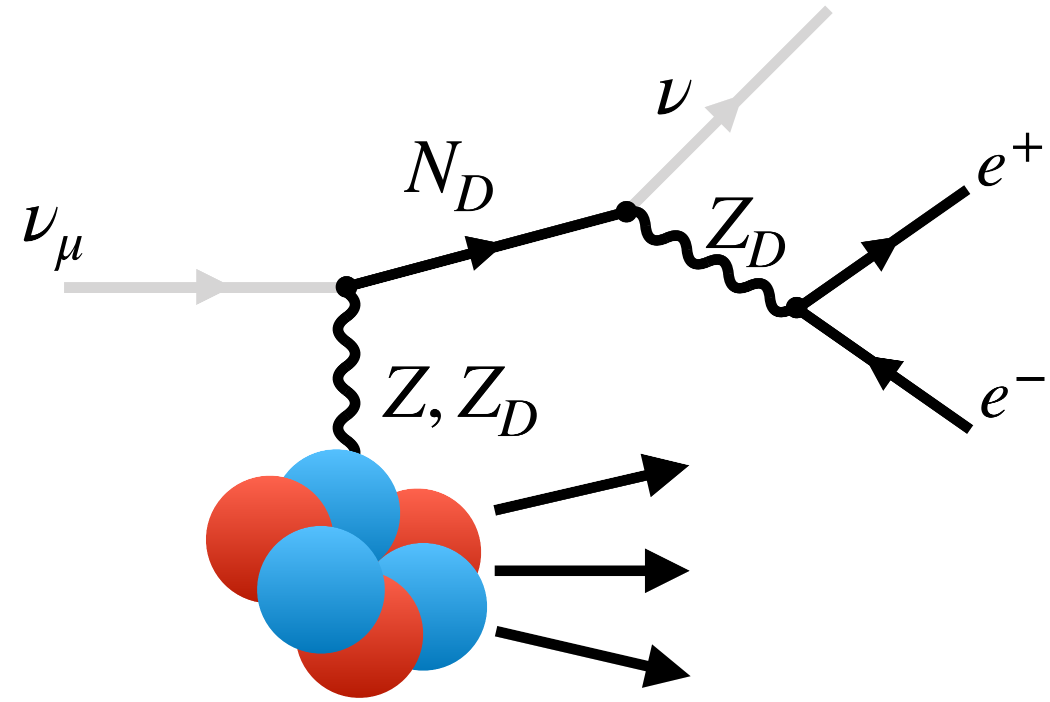


What might BSM mean?

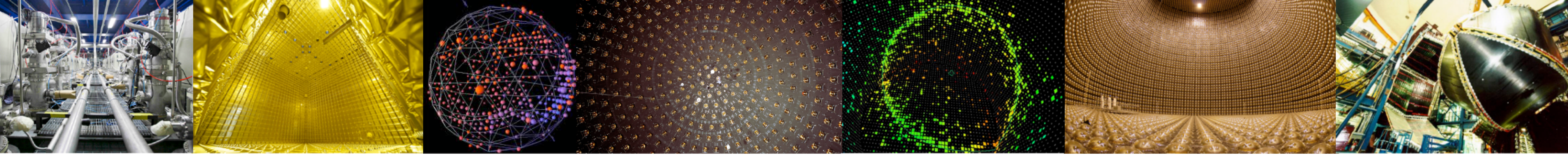
Bertuzzo, Jana, Machado, Funchal
PRL 121 (2018) 24, 241801
[arXiv:1807.09877]

For example, dark neutrino portal

- Suppose the existence of a
  - Dark neutrino N_D
  - Dark vector boson Z_D
- Suppose $m_{N_D} > m_{Z_D}$ so that $N_D \to Z_D + \nu_i$ is possible
- Suppose $m_{Z_D} < 2m_\mu$ so that Z_D decays to electrons, light neutrinos
- This setup can lead to excess low-energy electrons, e.g., in MiniBoone



Simulating these theories is important to SBN program and beyond

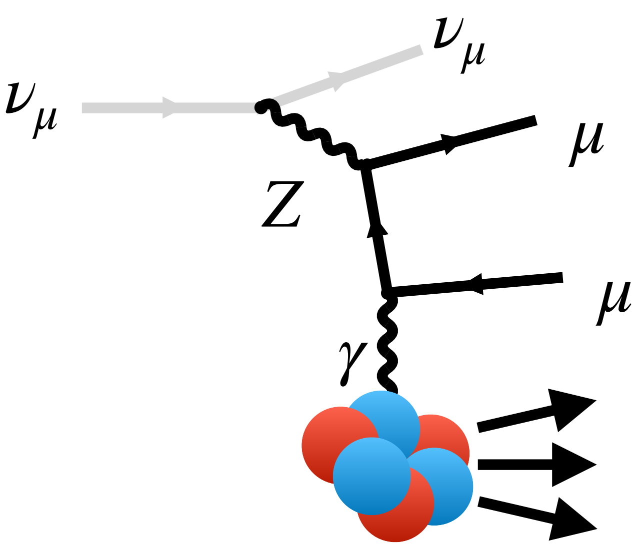


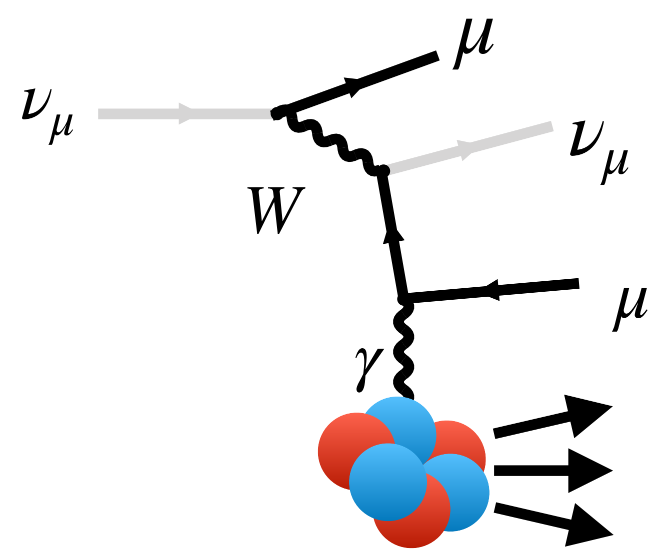
Leptonic Currents

In the SM and Beyond

SM Tridents

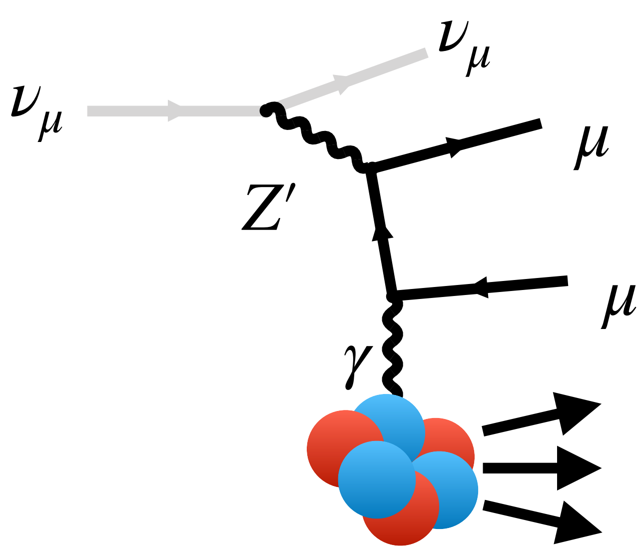
ν-induced lepton pair production

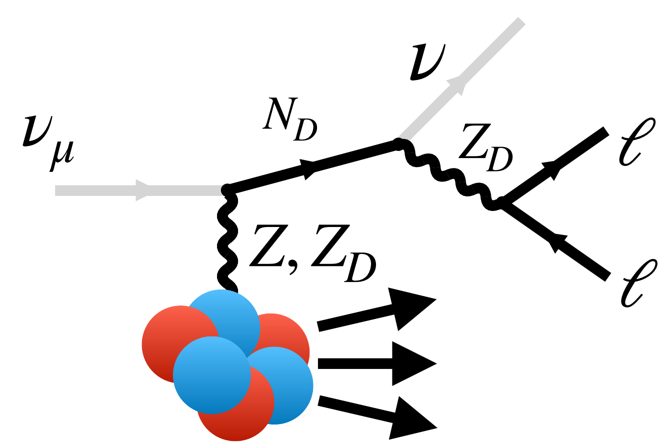


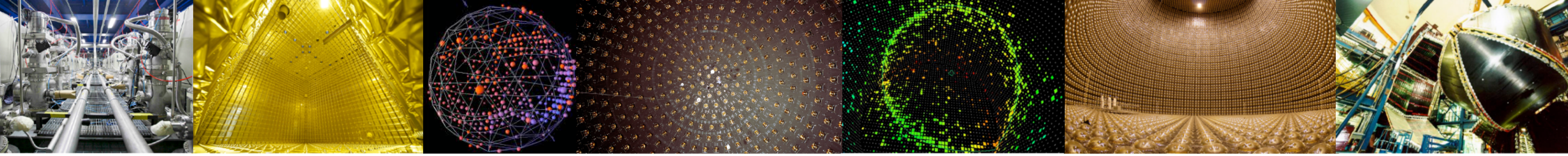


BSM Scenarios

Z', dark neutrino portal, etc...



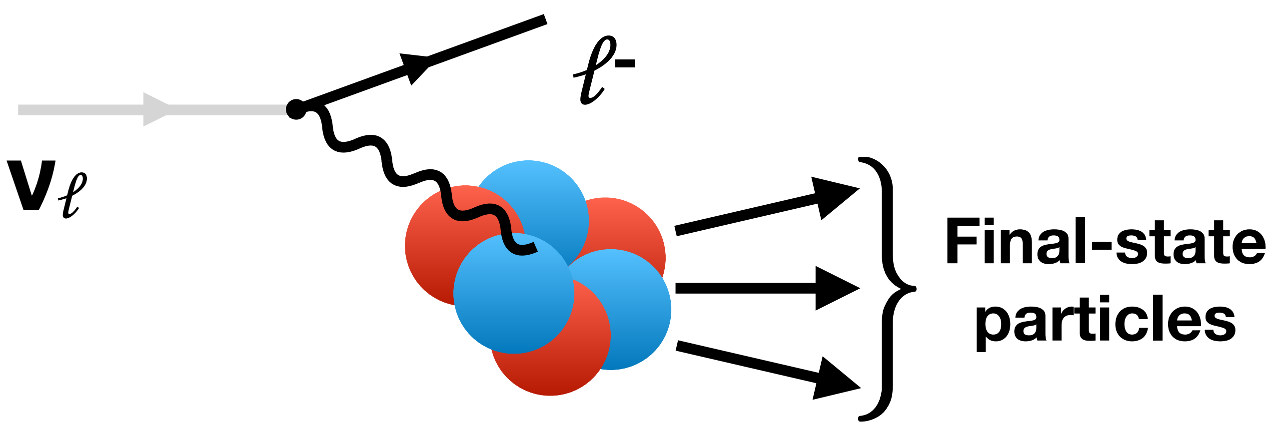




Leptonic Currents

In the SM and Beyond

$$|\mathscr{M}|^2 \propto L_{\mu\nu} \frac{1}{P^2} W^{\mu\nu}$$

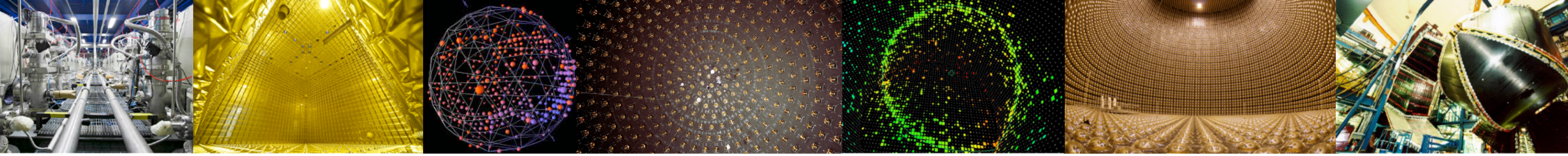


Ex: Charged-current scattering (unpolarized nucleus) in SM

$$L_{\mu\nu} = 2\left(p'_\mu p_\nu + p_\mu p'_\nu - p' \cdot p g_{\mu\nu} - i\epsilon_{\mu\nu\rho\alpha} p^\alpha p'^\beta\right)$$

Factorization of $|\mathscr{M}|^2$ becomes unwieldy for several gauge bosons (γ, Z, Z')

$$d\sigma = L^{(\gamma\gamma)}_{\mu\nu} W^{(\gamma\gamma)\mu\nu} + L^{(\gamma Z)}_{\mu\nu} W^{(\gamma Z)\mu\nu} + L^{(Z\gamma)}_{\mu\nu} W^{(Z\gamma)\mu\nu} + \ldots$$



Automatic Amplitudes

In the SM and Beyond

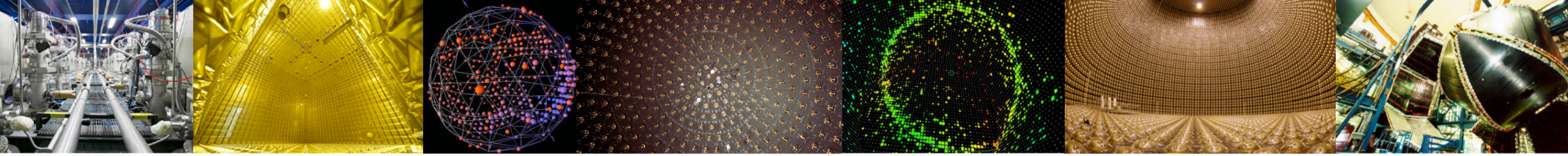
- Factorize the amplitude into products of currents

$$\mathscr{M} = \sum_i L_\mu^{(i)} W^{(i)\mu}$$

- Automate construction of the leptonic current in SM, BSM

- Build cross section from amplitudes

$$d\sigma \sim \Big| \sum_i L_\mu^{(i)} W^{(i)\mu} \Big|^2$$



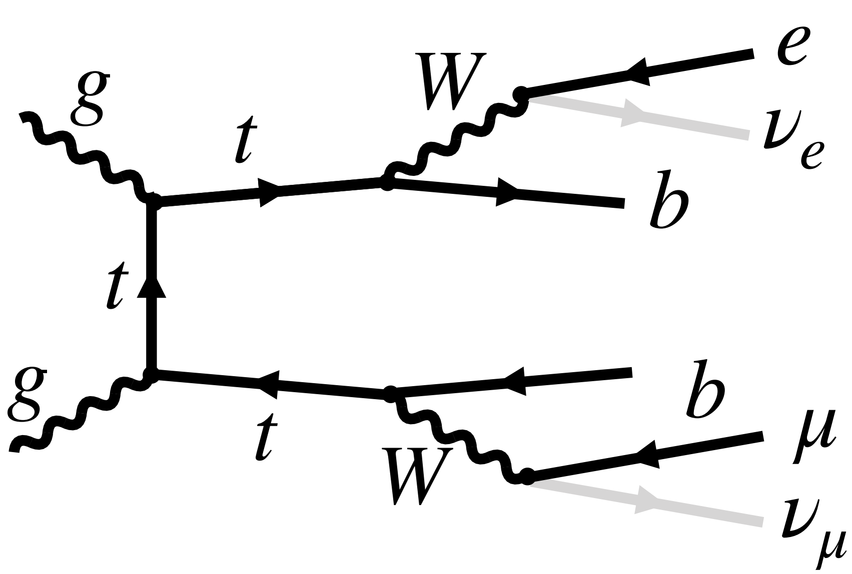
Automatic Amplitudes

In the SM and Beyond

Berends and Giele
Nucl.Phys.B 306 (1988) 759-808
S. Höche et al.
Eur.Phys.J.C 75 (2015
[arXiv:1412.6478]

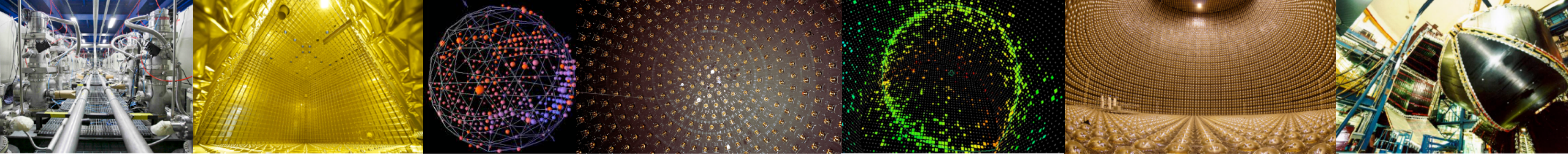
Context: $t\bar{t}$ production at LHC

$$gg \to t\bar{t} \to b\bar{b}e\nu_e\mu\nu_\mu$$



Keys for success

1. Automatic generation of tree-level amplitudes
2. Preservation of spin correlations in heavy decay cascades
3. Automatic generation of n-body phase space



Automatic Leptonic Currents

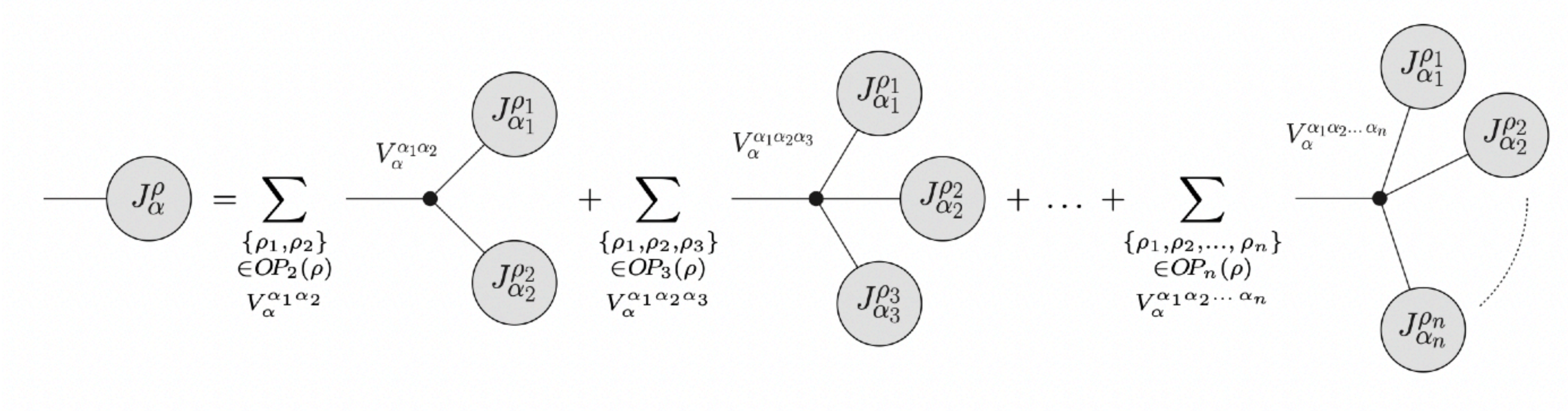
Berends and Giele
Nucl.Phys.B 306 (1988) 759-808

S. Höche et al.
Eur.Phys.J.C 75 (2015)
[arXiv:1412.6478]

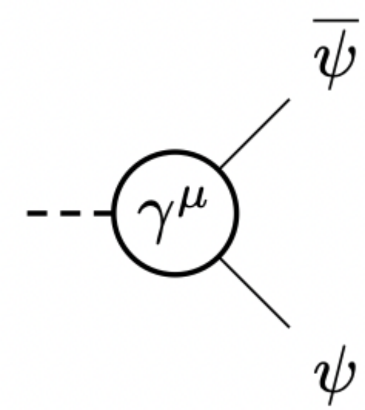
J. Isaacson et al.
PRD 105 (2022) 9, 096006
[arXiv:2110.15319]

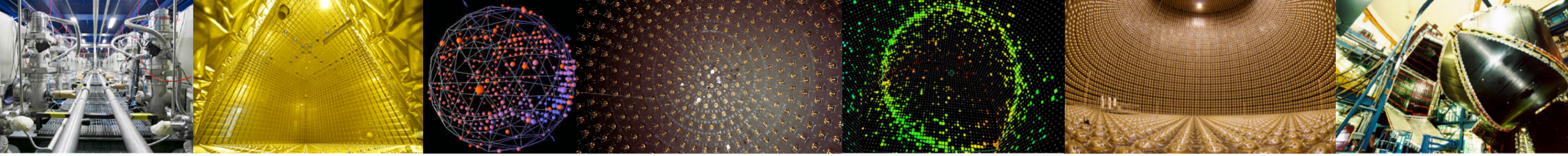
In the SM and Beyond

- Recursive definition for (off-shell) currents:
  - $(\text{current}) = \big(\text{propagator}\big) \times \sum (\text{vertex}) \times \big(\text{sub-currents}\big)$



- Example: $(\gamma^\mu)_{ab}\overline{\psi}_a\psi_b \quad = \quad \mu$





Automatic Leptonic Currents

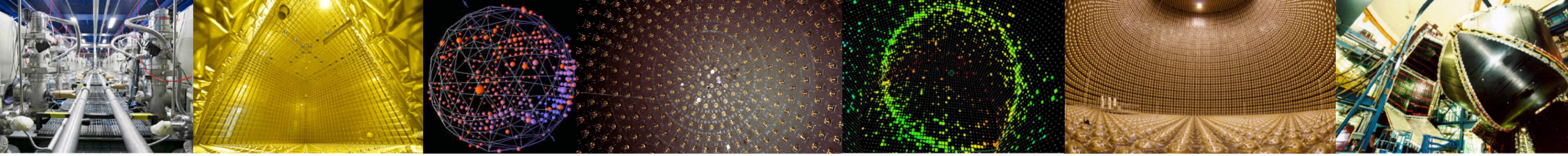
Berends and Giele
Nucl.Phys.B 306 (1988) 759-808

S. Höche et al.
Eur.Phys.J.C 75 (2015)
[arXiv:1412.6478]

J. Isaacson et al.
PRD 105 (2022) 9, 096006
[arXiv:2110.15319]

Leptonic limitations (current Achilles implementation)

- Scalar, spin-1/2, or spin-1 particles
  - Spin $> 1 \implies$ Write down/implement relevant external states and propagators
- Spin-1 probes of nucleus
  - Spin $\neq 1 \implies$ Expand nuclear model with relevant form factors
- Color-singlet particles
  - Color-charged particles: breaks assumed description via hadronic DOF at low energies
  - Most (all?) realistic BSM models are neutral under QCD



Preserving spin correlations

In the SM and Beyond

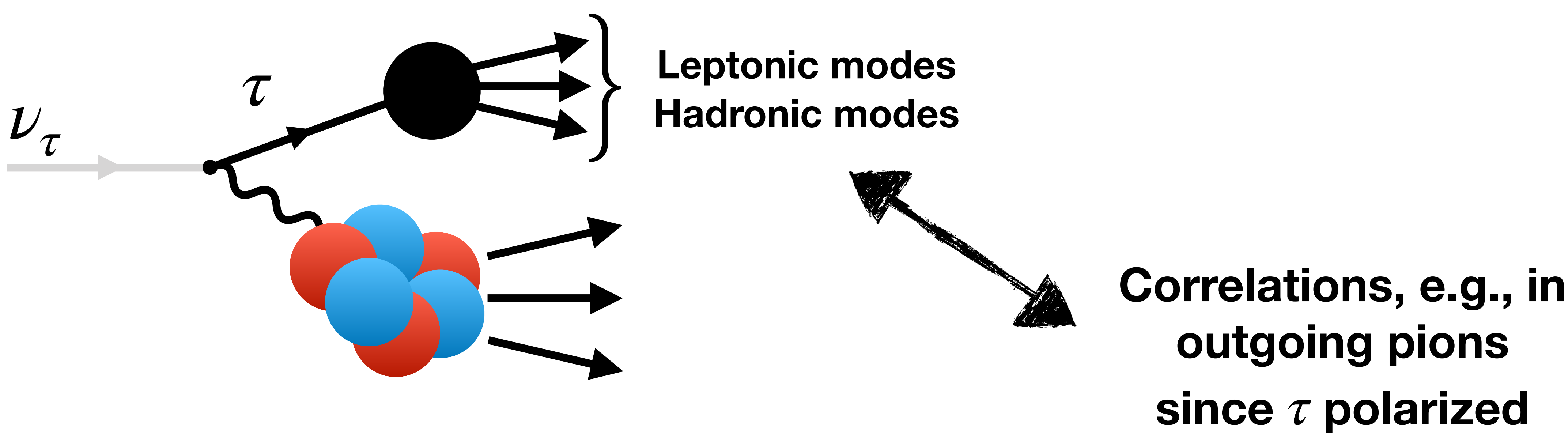
J. Collins
Nucl.Phys.B 304 (1988)794-804

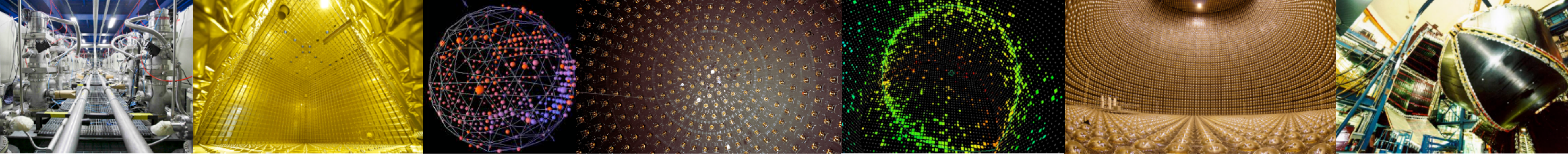
S. Höche et al.
Eur.Phys.J.C 75 (2015)
[arXiv:1412.6478]

P. Richardson
JHEP 11 (2001) 029
[arXiv:hep-ph/0110108]

J. Isaacson et al.
PRD 105 (2022) 9, 096006
[arXiv:2110.15319]

- Examples:
  - Top-quark decays in LHC physics
  - τ decays in neutrino scattering





Preserving spin correlations

In the SM and Beyond

J. Collins
Nucl.Phys.B 304 (1988)794-804

S. Höche et al.
Eur.Phys.J.C 75 (2015)
[arXiv:1412.6478]

P. Richardson
JHEP 11 (2001) 029
[arXiv:hep-ph/0110108]

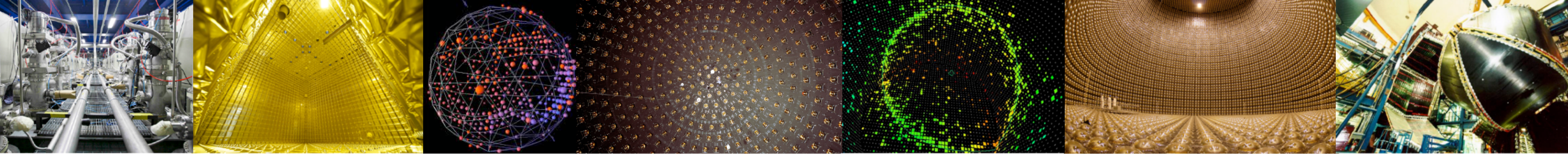
J. Isaacson et al.
PRD 105 (2022) 9, 096006
[arXiv:2110.15319]

- Big idea: Momenta are generated according to

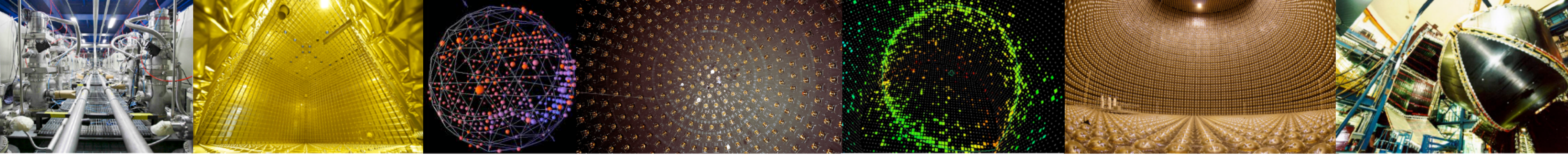
$$\left(\rho^1_{\kappa_1\kappa_1'}\rho^2_{\kappa_2\kappa_2'}\right) \times \left(\mathscr{M}_{\kappa_1\kappa_2;\lambda_1\cdots\lambda_n}\mathscr{M}^*_{\kappa_1'\kappa_2';\lambda_1'\cdots\lambda_n'}\right) \times \prod_i D^i_{\lambda_i,\lambda_i'}$$

Incoming spin-density matrices — **(Amplitude)²** — **Outgoing-particle decay matrix**

- Decay unstable particles randomly
- Develop chain of decays until final particles are stable
- Recursively determine outgoing-particle decay matrix, constrained by conservation of probability



Examples



Neutrino tridents $\nu_\mu {}^{12}C \to \nu_\mu e^+ e^- X$

Isaacson et al.
PRD 105 (2022) 9, 096006
[arXiv:2110.15319]

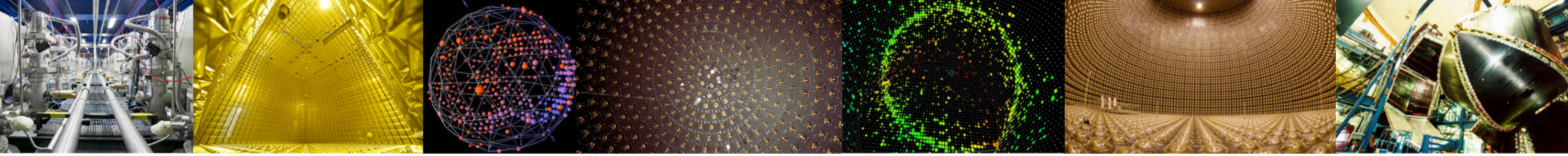
Example of the pipeline using Achilles

Motivation:

- Proof-of-concept involving interference between interactions with γ, Z.
- Proof-of-concept for generic BSM interface
- Important background for BSM explanations of the MiniBooNE excess.
- Demonstrate uses of tools developed by LHC event generation community: Sherpa, Comix, FeynRules, UFO files

Results

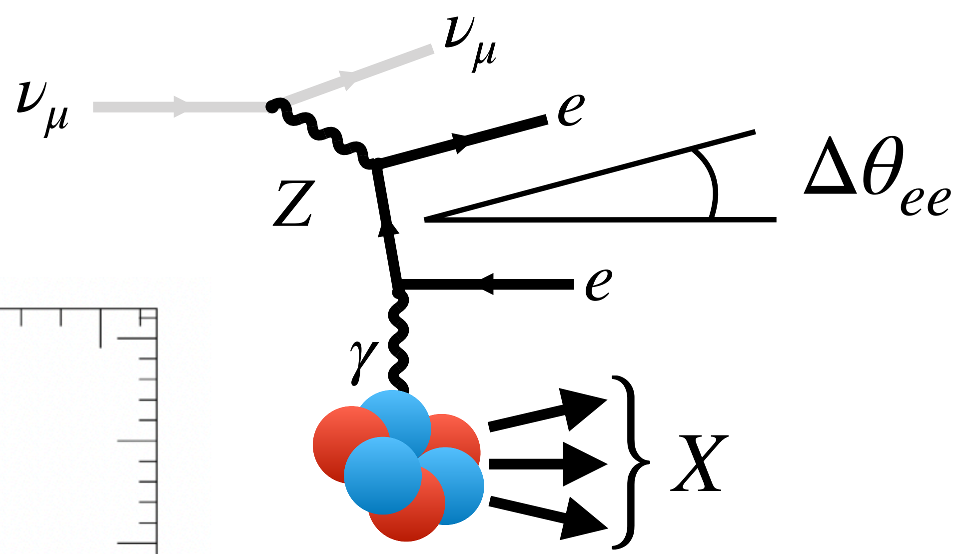
- First fully differential results for trident production in the quasielastic region



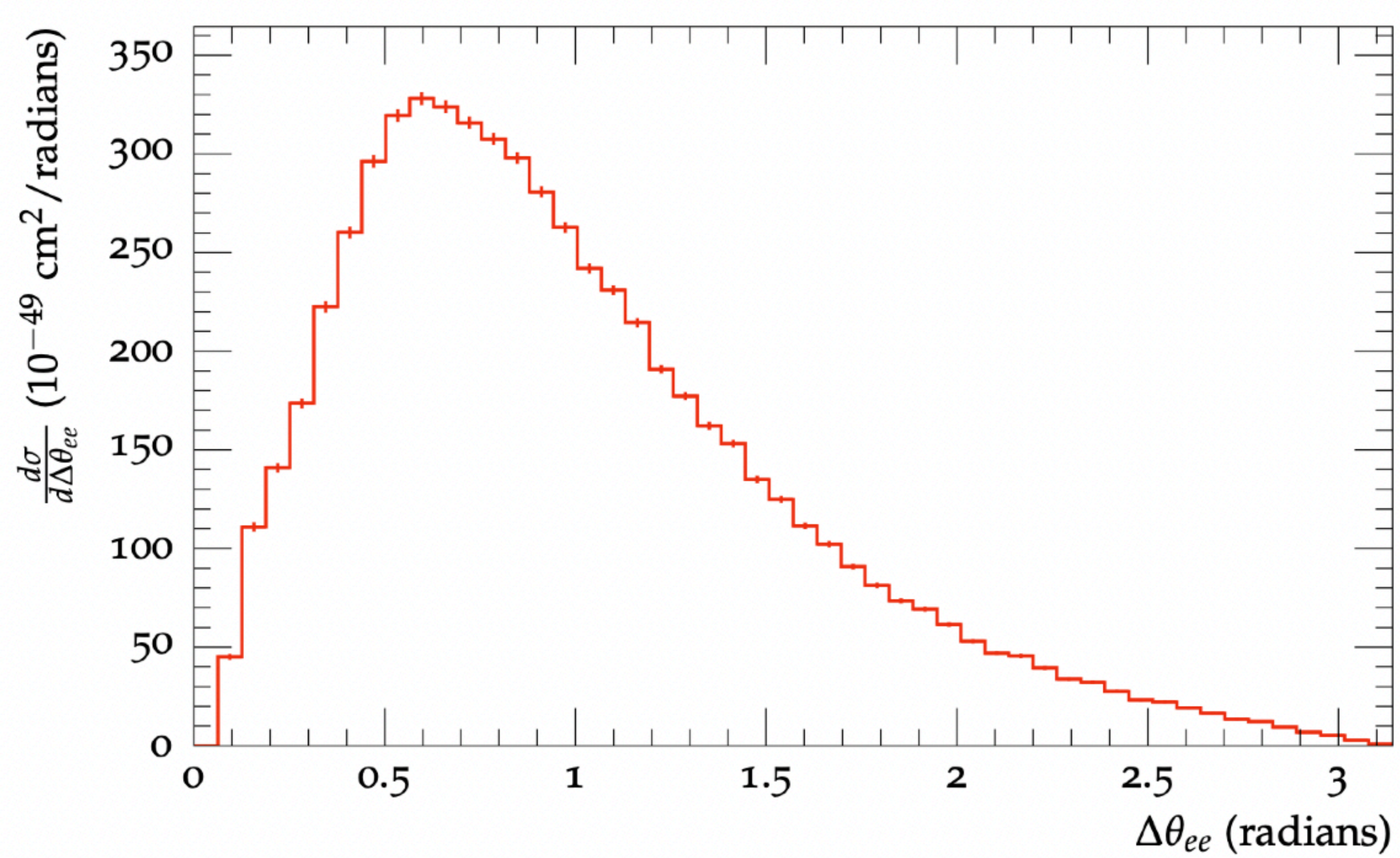
Neutrino tridents $\nu_\mu {}^{12}C \to \nu_\mu e^+ e^- X$

Isaacson et al.
PRD 105 (2022) 9, 096006
[arXiv:2110.15319]

Example of the pipeline using Achilles

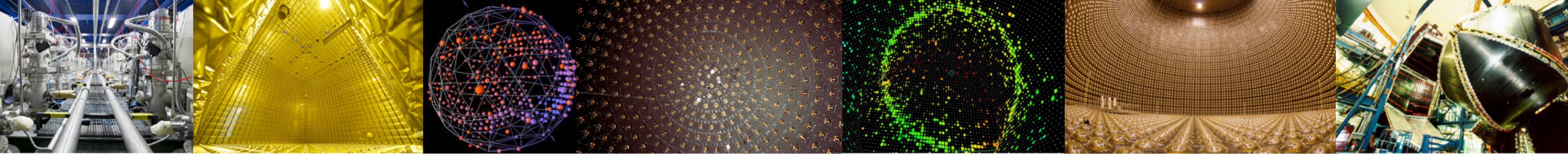


Cross section



Electron opening angle

Paper also reports energy distributions for outgoing electrons



Correlated τ decays

Example of the pipeline using Achilles

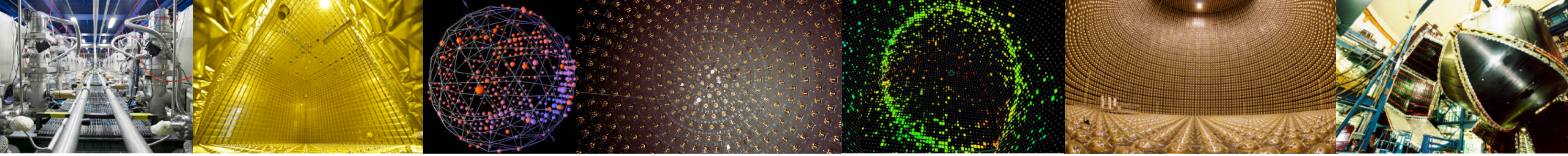
Isaacson et al.
PRD 108 (2023) 9, 093004
[arXiv:2303.08104]

Motivation:

- DUNE: $\mathcal{O}(100s)$ ν_τ events / year
- Polarized $\tau \Longrightarrow$ final-state correlations
- Standard Model predicts:
    - τ polarization perpendicular to the lepton-scattering plane *vanishes*
    - τ polarization components within the lepton-scattering plane do <u>not</u> vanish
- Other generators have often treated ν_τ interactions as for $\nu_e, \nu_\mu \rightarrow$ “outgoing τ as LH only”

Results

- First fully differential predictions for ν_τ scattering at DUNE energies, including all spin correlations and all τ decay channels
- Calculated using generic interface between Achilles and Sherpa
- Correlations between production and decay are *automatically* maintained



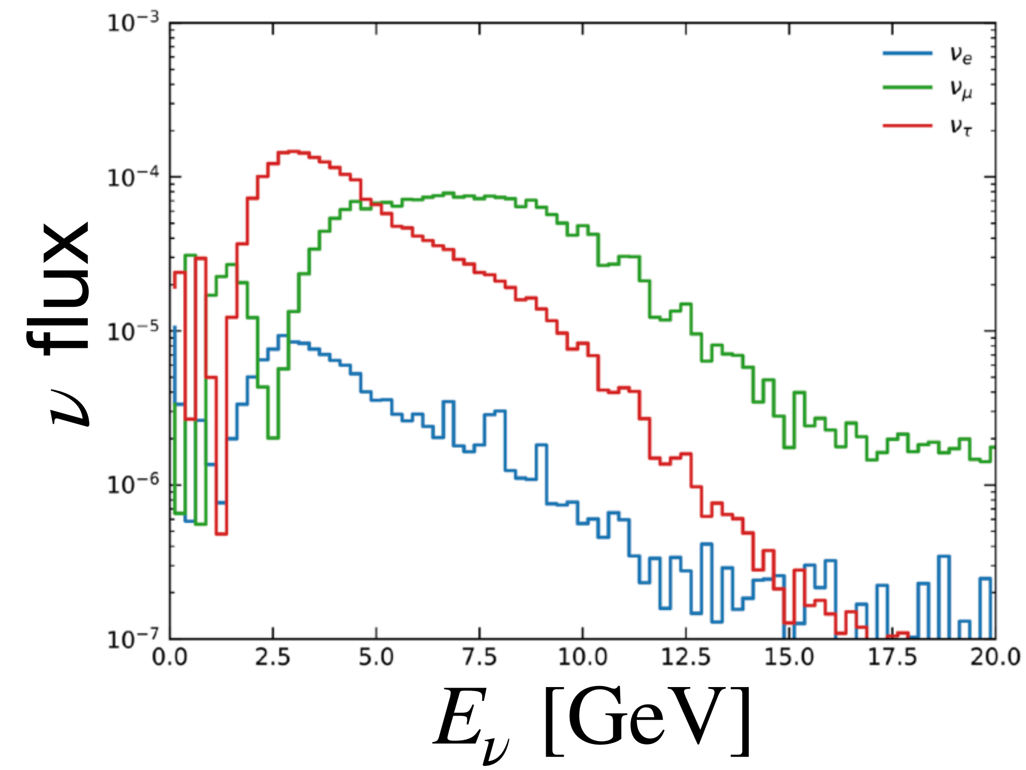
Correlated τ decays

Example of the pipeline using Achilles

Isaacson et al.
PRD 108 (2023) 9, 093004
[arXiv:2303.08104]

Momentum Fraction Distributions

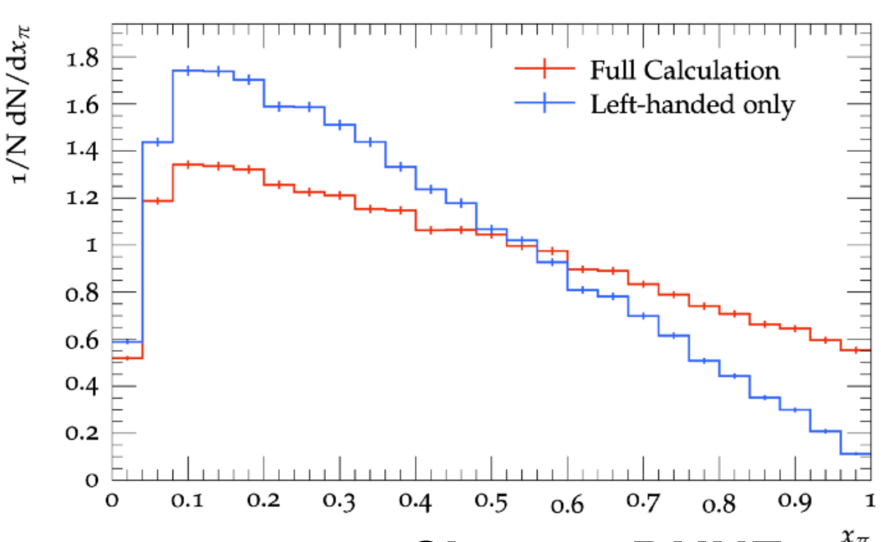
- Benchmarking done against analytic results in collinear ($p_\tau \to \infty$) limit, monochromatic beams
- Final results calculated using realistic DUNE fluxes



$$\frac{1}{N}\frac{dN}{dx_i}$$

Momentum fraction

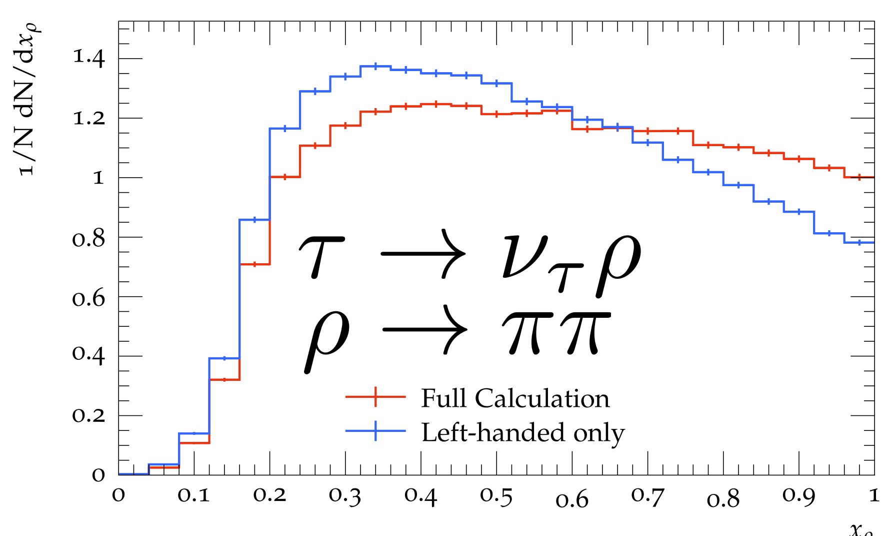
$x_i = E_i / E_\tau$



x_π

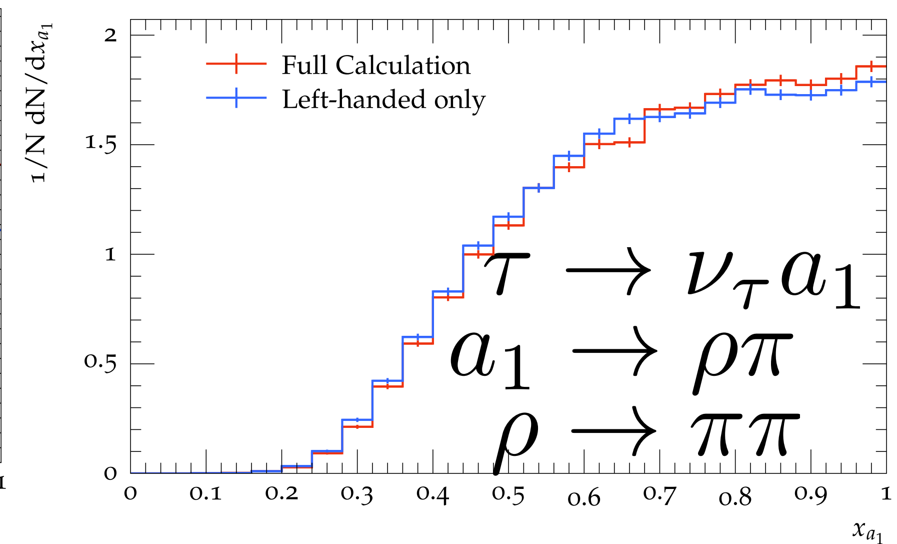
Clean at DUNE

$\mathscr{B}(1\pi) \sim 10\,\%$

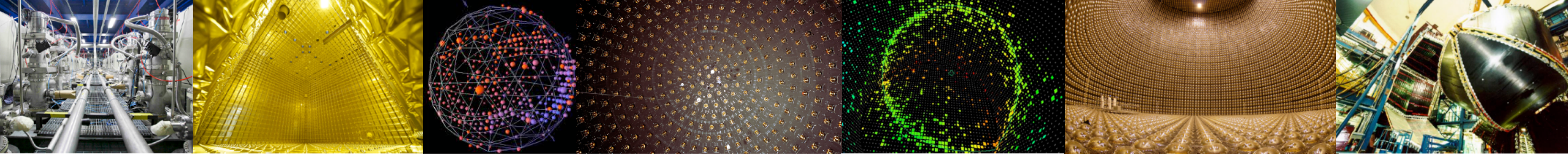


x_ρ

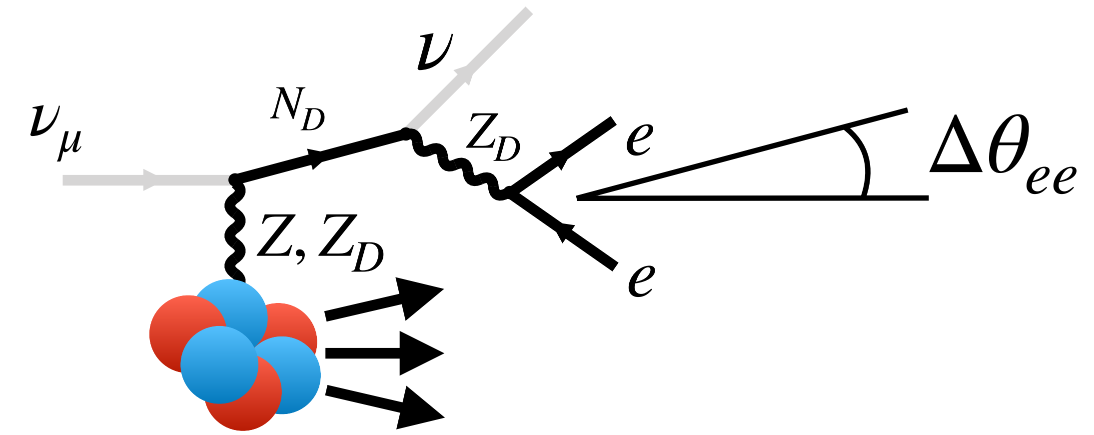
$\mathscr{B}(2\pi) \sim 25\,\%$



x_{a_1}

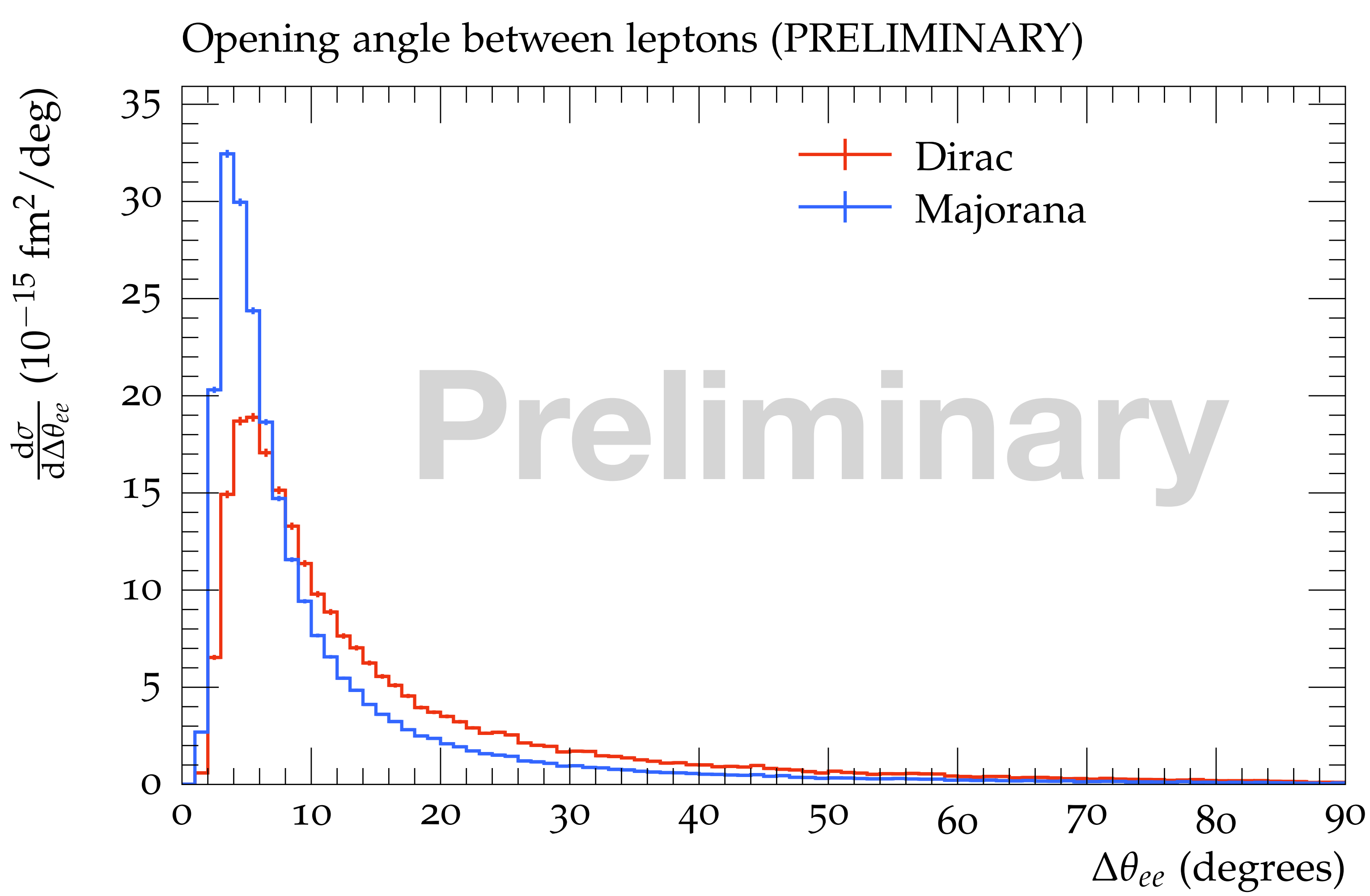


Neutrino Dark Sector



Example of the pipeline using Achilles

- Simulation of full phase space including spin correlations
- Allows for separation of Dirac and Majorana cases



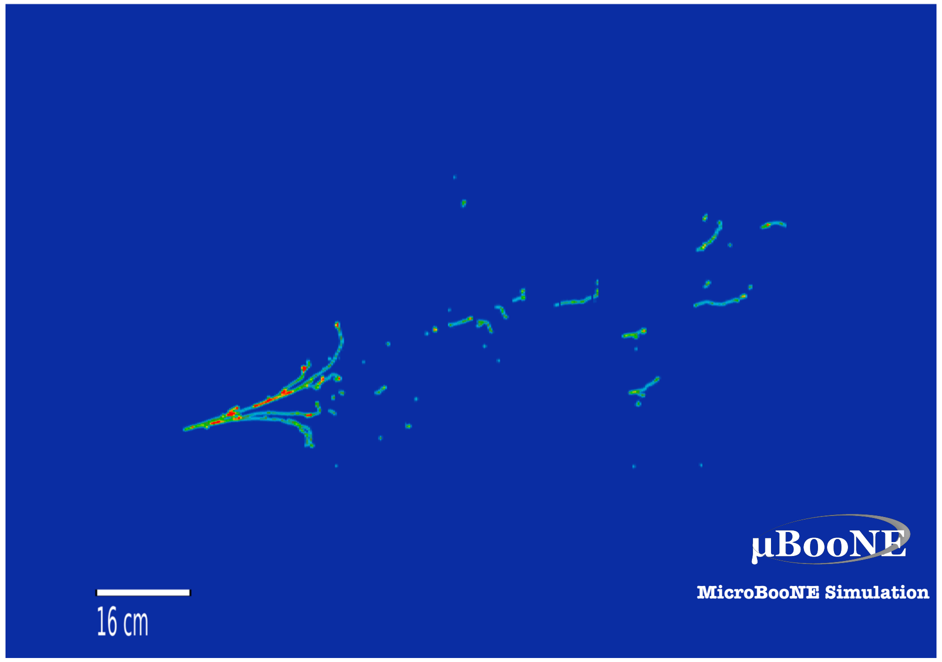
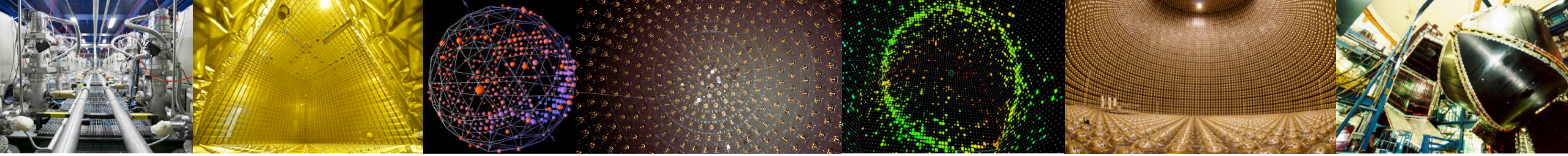
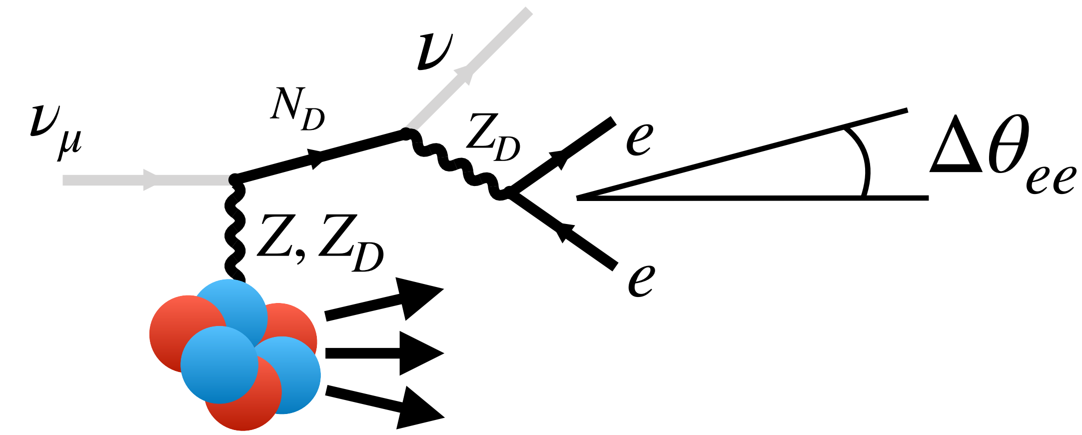


Image courtesy MicroBooNE using Achilles

Bertuzzo, Jana, Machado, Funchal
PRL 121 (2018) 24, 241801
[arXiv:1807.09877]

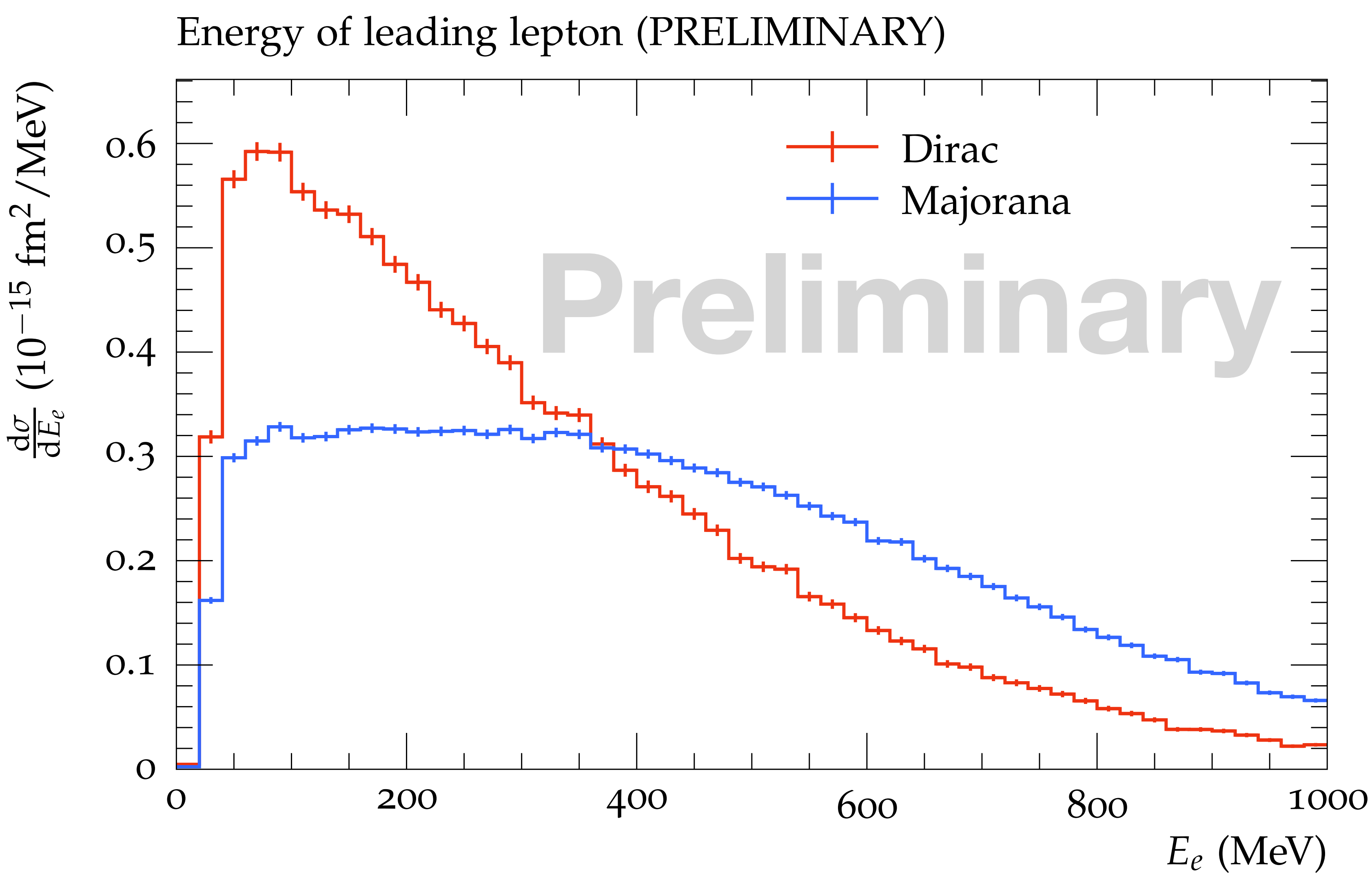


Neutrino Dark Sector



Example of the pipeline using Achilles

- Simulation of full phase space including spin correlations
- Allows for separation of Dirac and Majorana cases



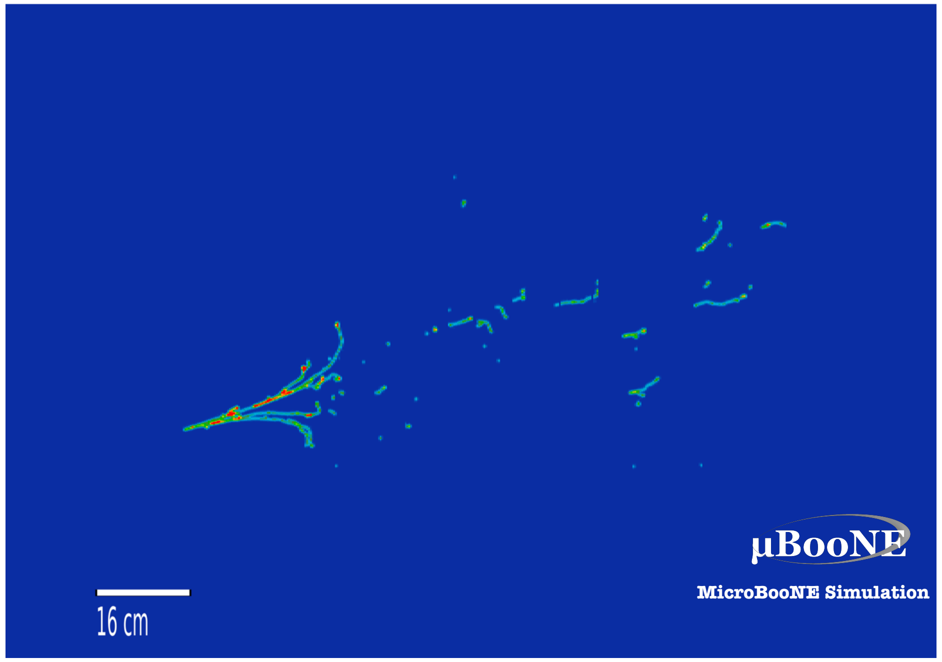
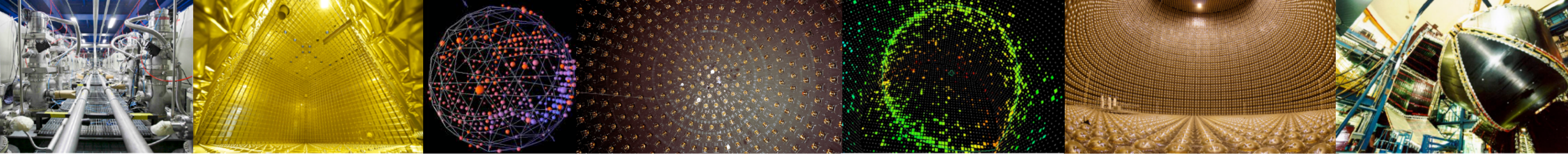


Image courtesy MicroBooNE using Achilles

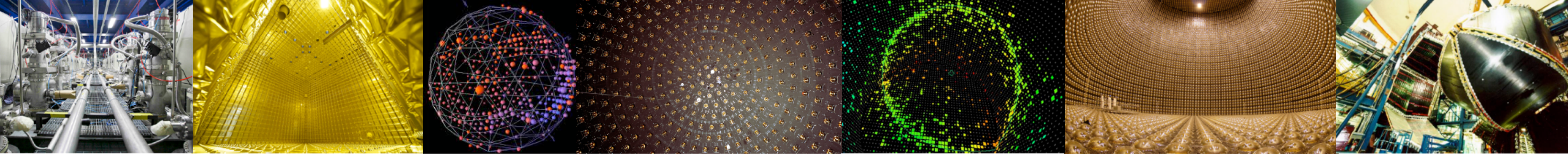
Bertuzzo, Jana, Machado, Funchal
PRL 121 (2018) 24, 241801
[arXiv:1807.09877]



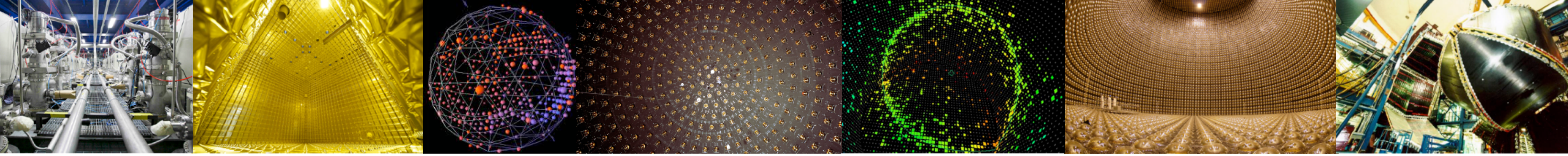
Summary / Conclusions

Standardizing for Success

- **Leptonic currents**
    - SM and BSM models have many interactions
    - Leverage existing implementations (e.g., Sherpa, Comix)
    - Ensures common definition (e.g., of a BSM model) across generators
- **Hadronic currents**
    - νA scattering involves many hadronic/nuclear inputs
    - Desirable to constrain as many “moving pieces” as possible using LQCD, *ab initio* nuclear many-body theory
- **Hadronic modeling inevitable in some areas**
    - Must be able to quantify uncertainty from “reasonable” variations
    - E.g., in situ parameter variation for uncertainty in primary-interaction vertex
    - Mention connections to vector of weights in NuHepMC standard
- **Goal**: rapid iteration of comparisons between predictions from different generators



Backup



Hadronic currents

From *ab initio* nuclear theory and lattice QCD

$$W^\mu = \langle \psi_f^A \,|\, J^\mu(q) \,|\, \psi_0^A \rangle$$

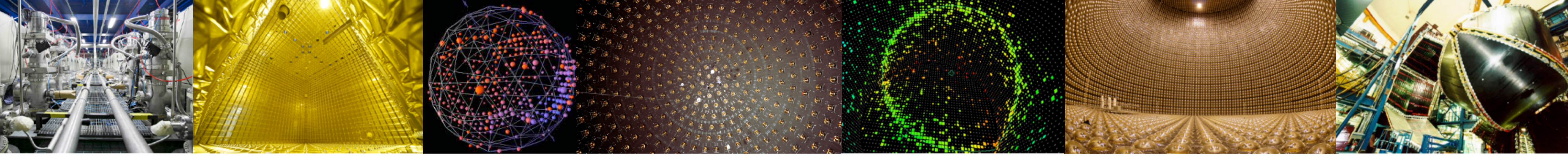
$$\to \sum_{k,i} \left[\langle \psi_f^{A-1} | \otimes \langle k | \right] | \psi_0^A \rangle \times \langle p + q \,|\, j_i^\mu(q) \,|\, k \rangle$$

Overlap with final nuclear state in impulse approximation

- Spectral function $\sim |\,\text{overlap}\,|^2$
- Calculable in *ab initio* nuclear many-body theory

Single-nucleon form factor

- Calculable in LQCD
- LQCD calculations are quickly approaching full systematic control



Achilles: Comparison to experiment

PRD 107 (2023) 3, 033007 [arXiv:2205.06378]

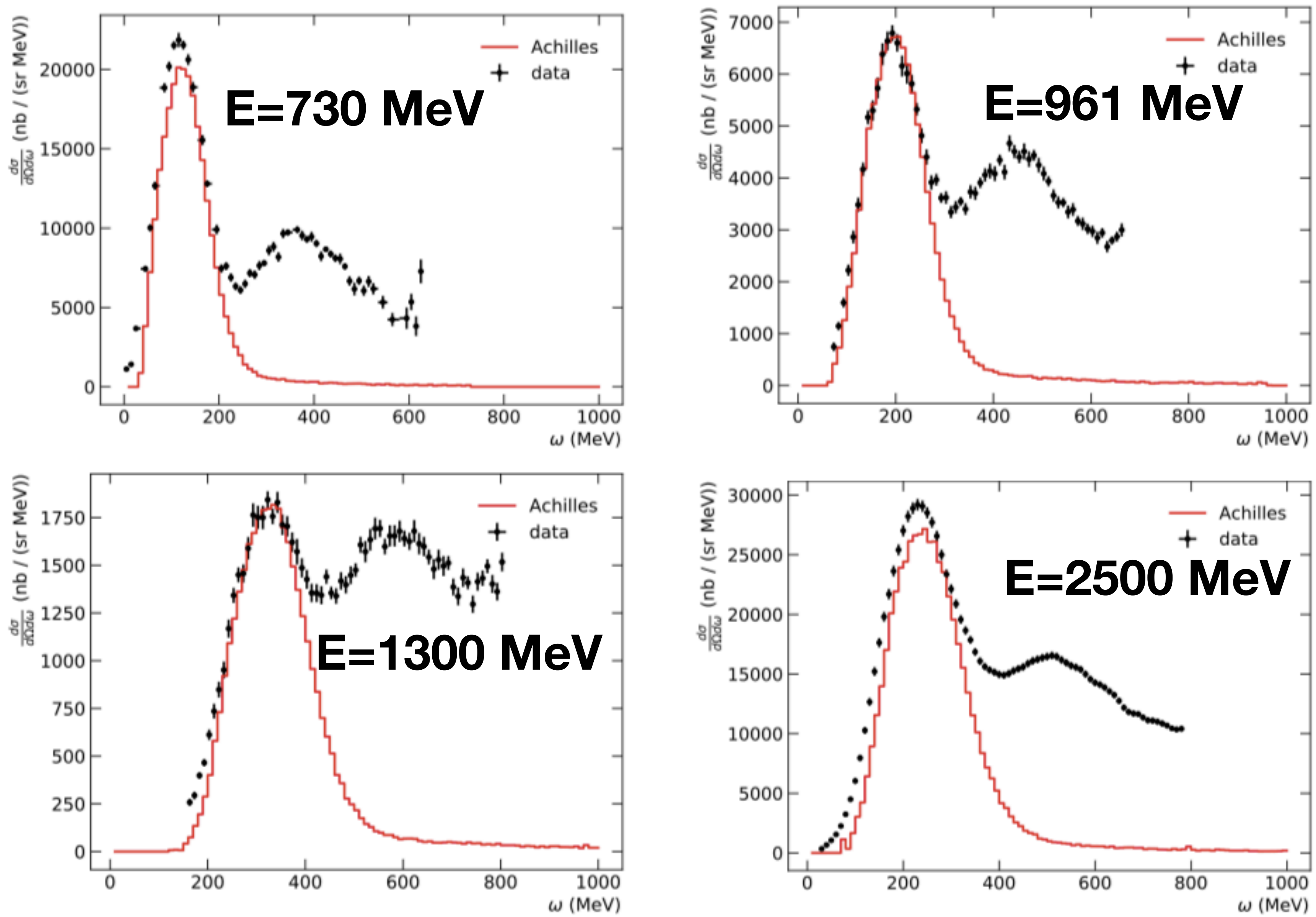
J. S. O'Connell *et al.*, Phys. Rev. C **35**, 1063 (1987).
R. M. Sealock *et al.*, Phys. Rev. Lett. **62**, 1350 (1989).
D. Zeller, Investigation of the structure of the C-12 nucleus by high-energy electron scattering, Other thesis, Karlsruhe University, 1973.

Inclusive eC hadronic cross section

$$\frac{d\sigma}{d\Omega d\omega}$$

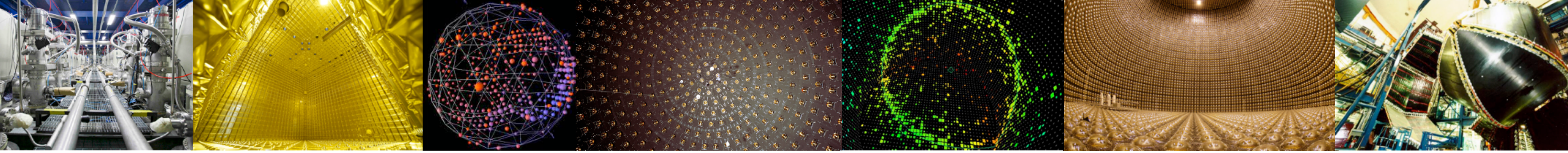
Fixed outgoing electron angle $\theta = 37^\circ$ to match experimental settings

Differential in outgoing electron energy ω



Beyond firsts peak: Neglected MEC and resonance contributions

Good agreement = Validation of initial model for QE interaction



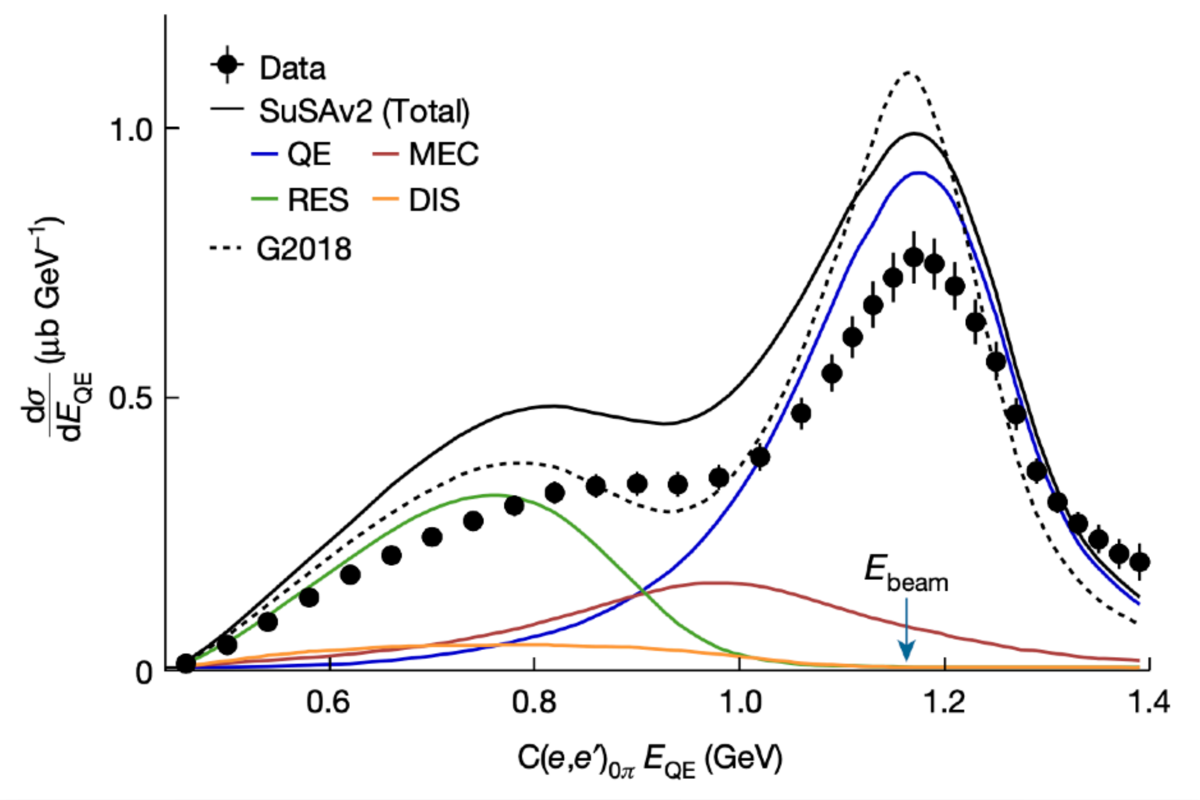
Achilles: Comparison to experiment

PRD 107 (2023) 3, 033007 [arXiv:2205.06378]

CLAS and $e4\nu$ collaborations
Nature 599 (2021) 7886, 565-570

- **Inclusive e-C hadronic cross section**
- **Analysis by $e4\nu$ to mimic kinematic setup for QE νA scattering**

$$E_{\rm QE} = \frac{2m_N\epsilon + 2m_N E_\ell - m_\ell^2}{2\left(m_N - E_\ell + p_\ell \cos\theta_\ell\right)}$$



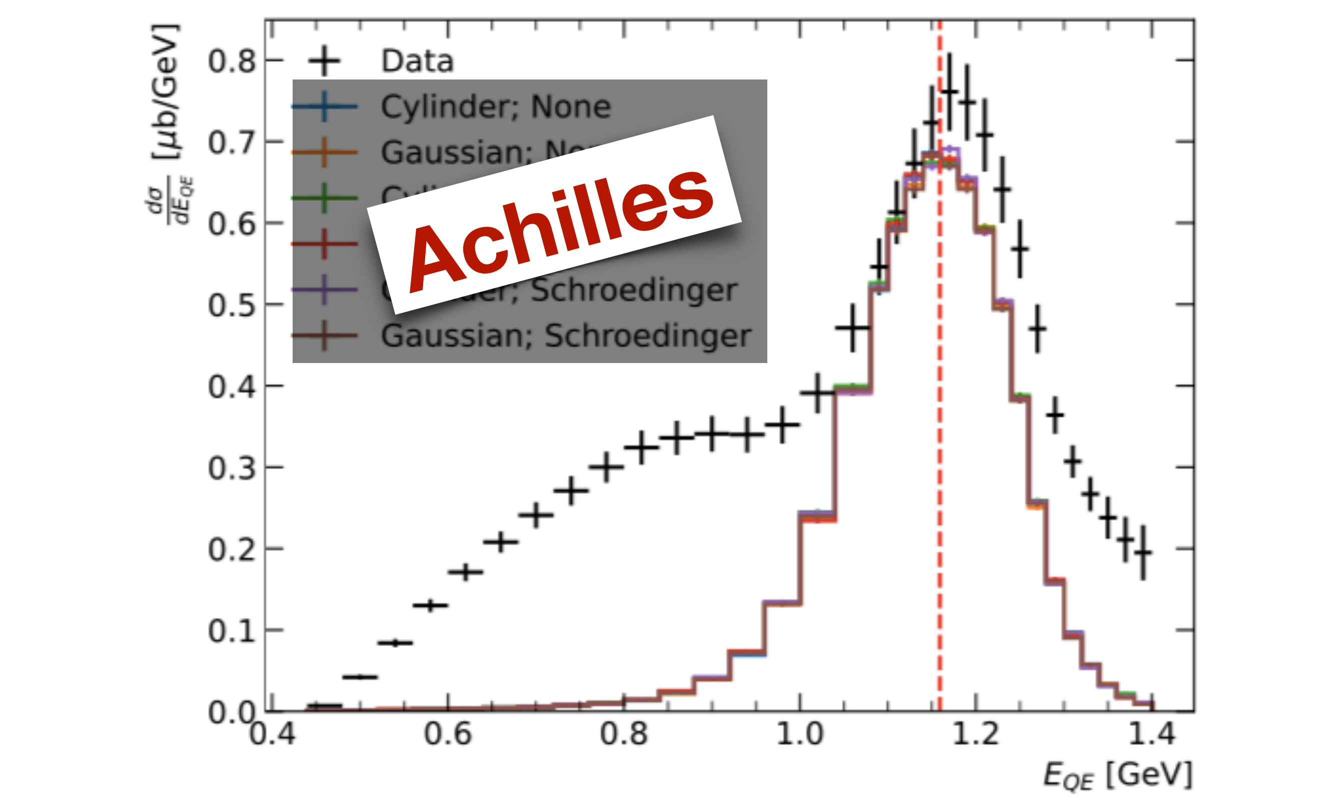
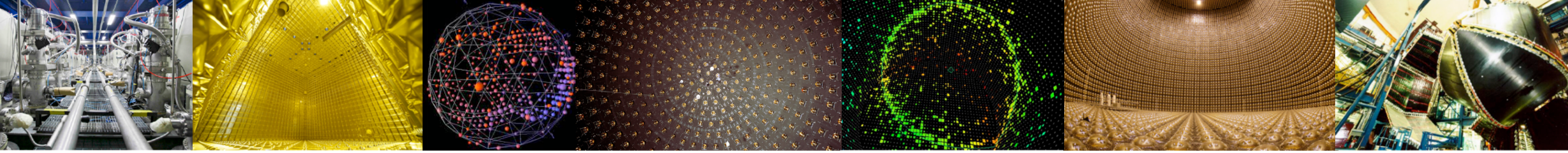


FIG. 4: Comparison of the quasielastic energy reconstructed for an electron beam of 1159 MeV. Data is taken from Ref. [69]. The definition of E_{QE} can be found in Eq. 31. The red dashed vertical line marks the true beam energy.

- **Low E_{QE} : MEC and resonance contributions**
- **High E_{QE} : interference effects (neglected)**



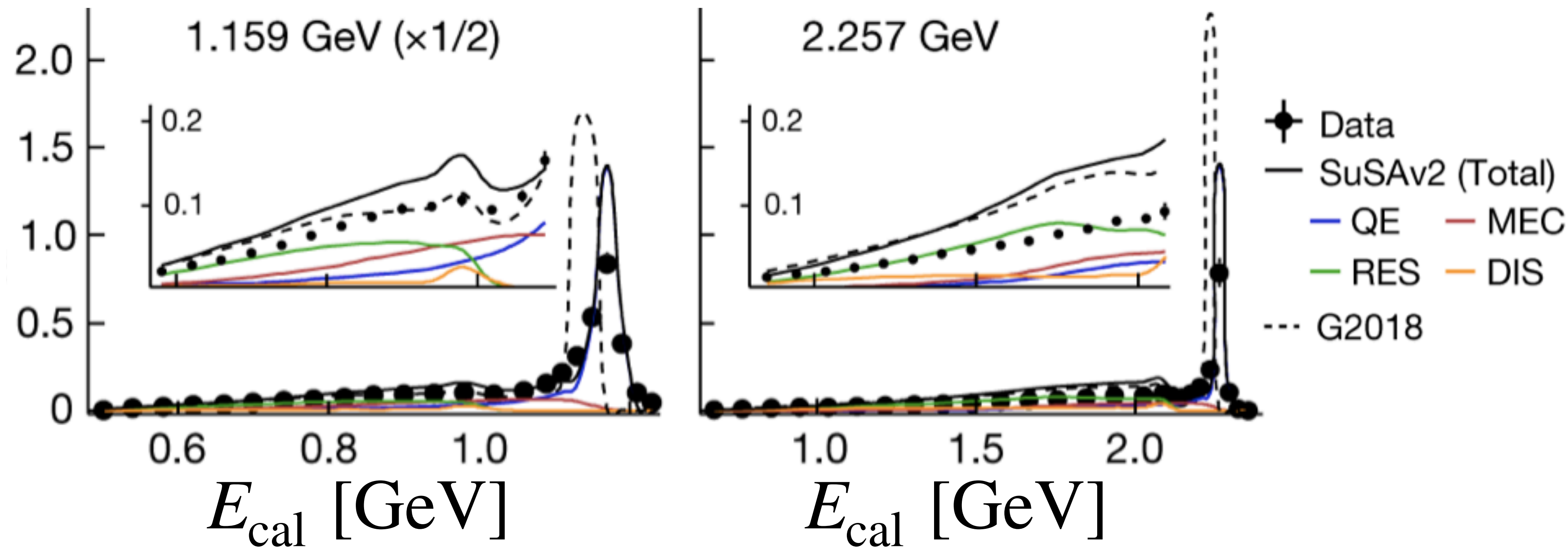
Achilles: Comparison to experiment

PRD 107 (2023) 3, 033007 [arXiv:2205.06378]

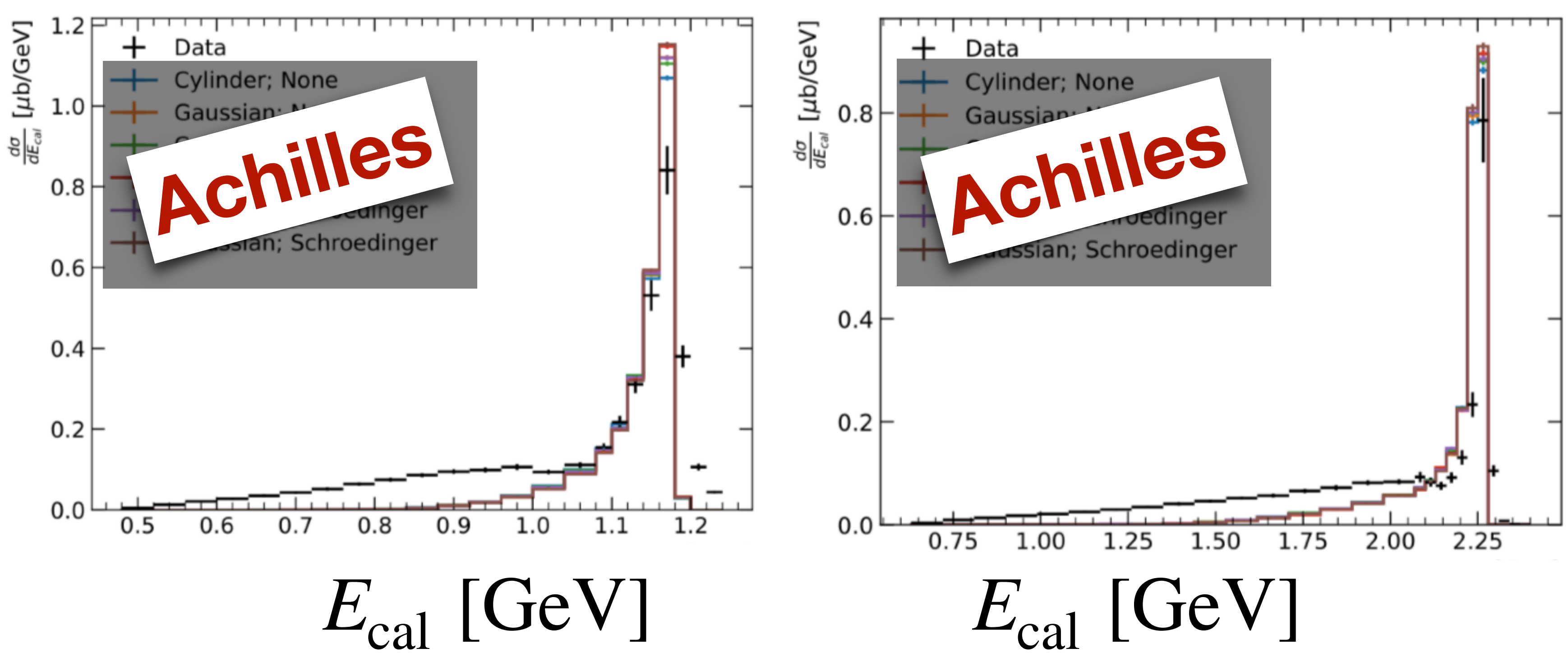
CLAS and $e4\nu$ collaborations
Nature 599 (2021) 7886, 565-570

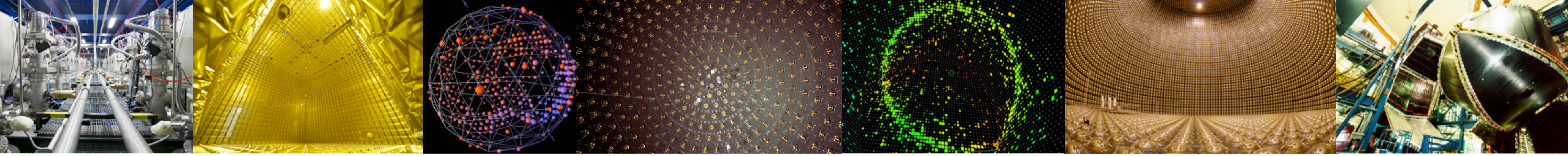
E_{cal} = "Calorimetric energy" = "sum of final-state energies"

Data + simulation from $e4\nu$ paper $\frac{d\sigma}{dE_{cal}}$



Same $e4\nu$ data vs Achilles $\frac{d\sigma}{dE_{cal}}$



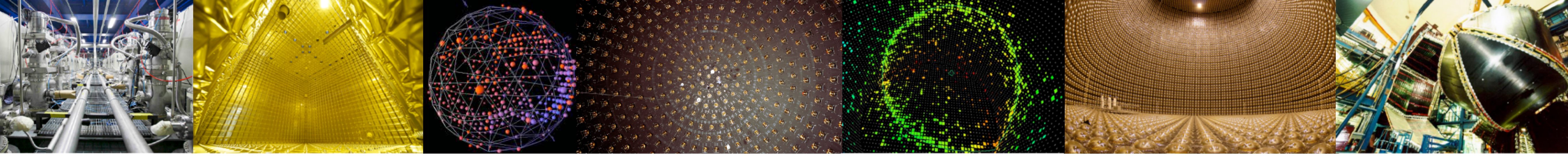


Achilles Intranuclear Cascade (INC)

$$|\mathcal{M}(\{k\} \to \{p\})|^2 \simeq \sum\!\!\!\!\!\!\!\int_{p'} |\mathcal{V}(\{k\} \to \{p'\})|^2 \times |\mathcal{P}(\{p'\} \to \{p\})|^2$$

The quantum mechanical scattering model:

- Utilizes measured NN cross sections, e.g., from from SAID database with GEANT4 or NASA parameterization
- Scatters probabilistically according to the impact parameter: $P(b) = \exp(-\pi b^2/\sigma)$
  - ☑ $\lambda^{-1} = \rho\sigma$ for the mean free path λ
  - ☑ Total probability integrates to the cross section σ
- Incorporates Pauli blocking and formation zone to constrain possible scatterings



Achilles Intranuclear Cascade (INC)

$$|\mathcal{M}(\{k\} \to \{p\})|^2 \simeq \sum\!\!\!\!\!\!\!\int_{p'} |\mathcal{V}(\{k\} \to \{p'\})|^2 \times |\mathcal{P}(\{p'\} \to \{p\})|^2$$

Classical propagation in the background nucleus creates an effective optical potential which induces two effects:

1. Short-distance: $$\frac{d\sigma}{d\Omega} \longrightarrow \left(\frac{d\sigma}{d\Omega}\right)_{\text{in medium}}$$

   (In-medium corrections to NN interactions)

2. Long-distance: $$\dot{\mathbf{p}} = -\partial_{\mathbf{q}} H \quad \dot{\mathbf{q}} = +\partial_{\mathbf{p}} H$$

   (Classical evolution in background potential)