



# Nu Tools for BSM: Outlook

*from my point of view as a theorist*

Pedro Machado

December, 2022



A vibrant BSM program is crucial for the future of our field

We need to start this program NOW

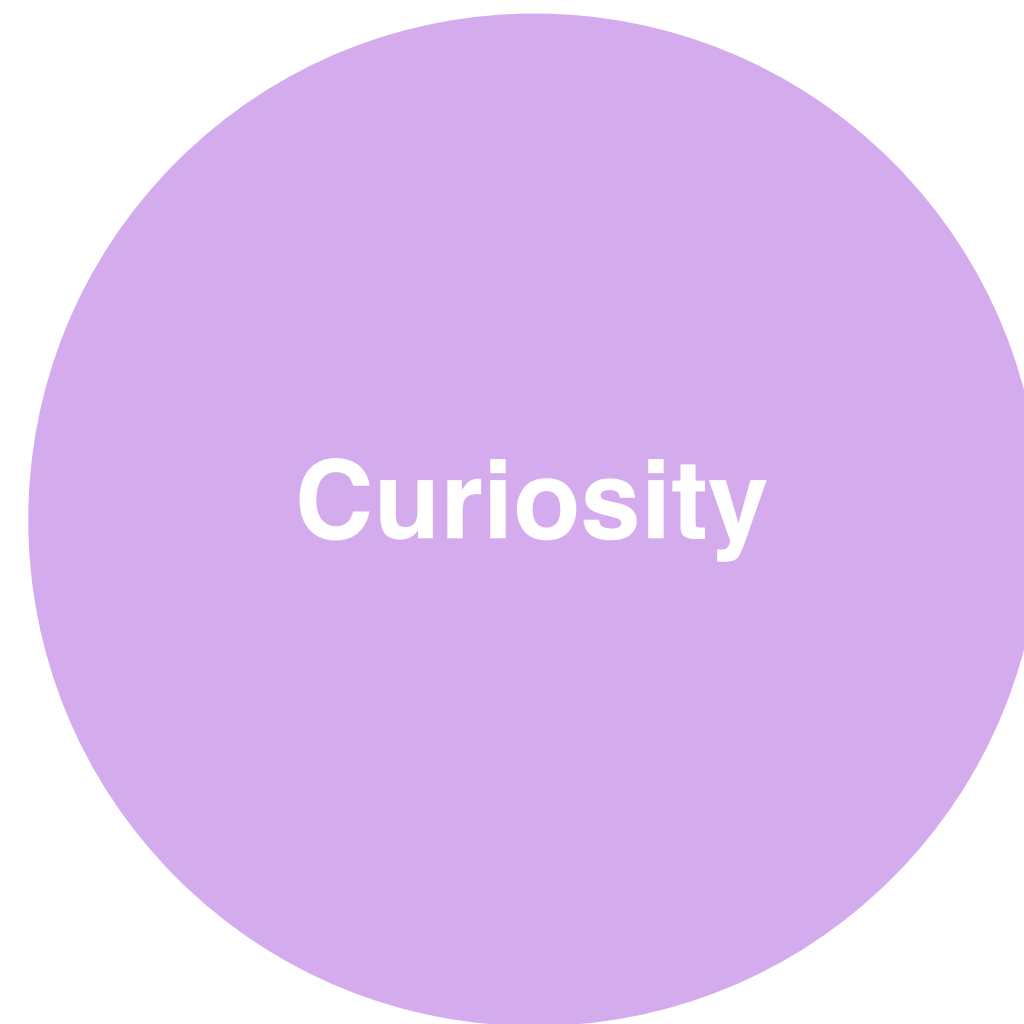
# Where is the new physics?

There are three main beacons that guide theorists



# Where is the new physics?

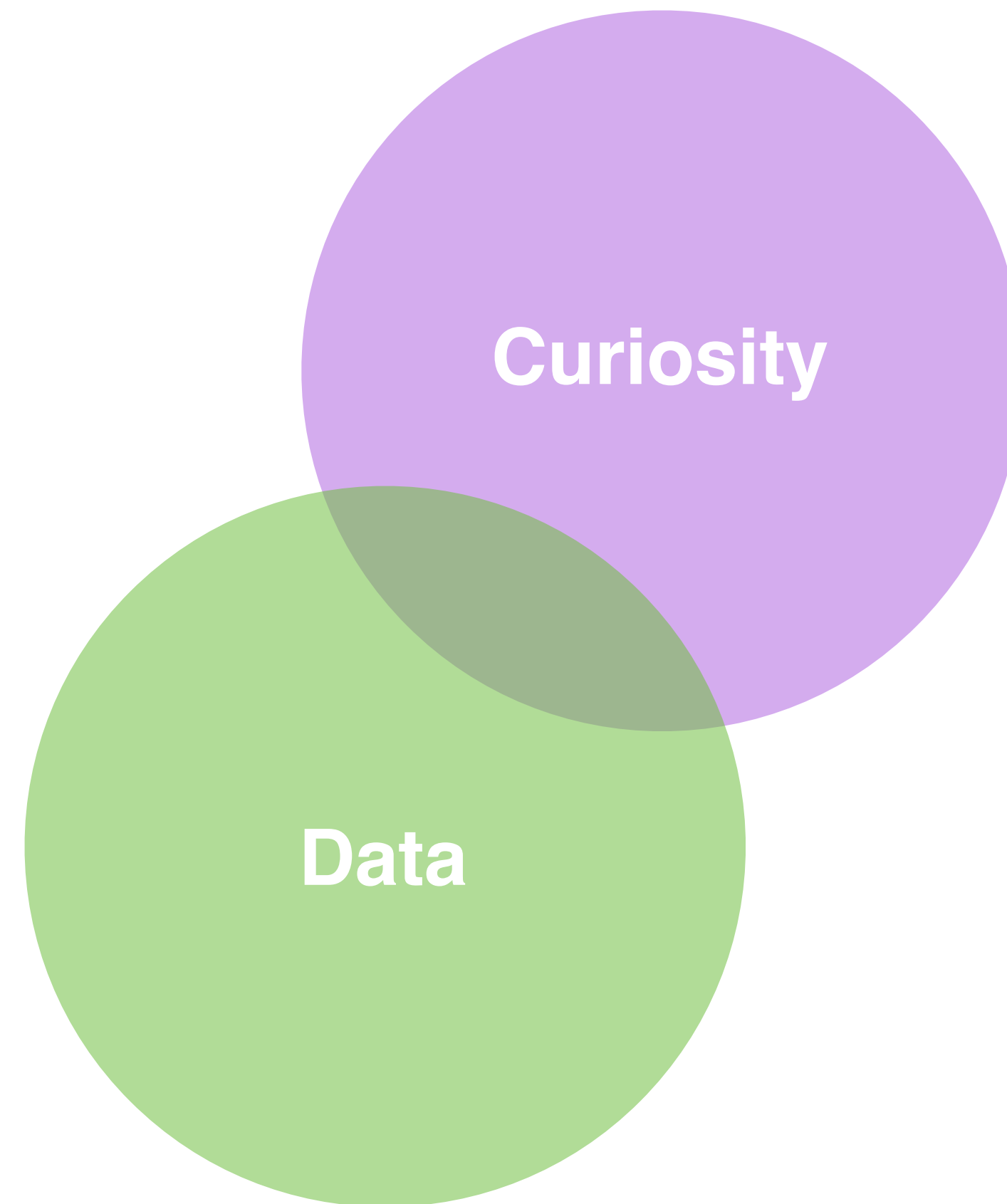
There are three main beacons that guide theorists





# Where is the new physics?

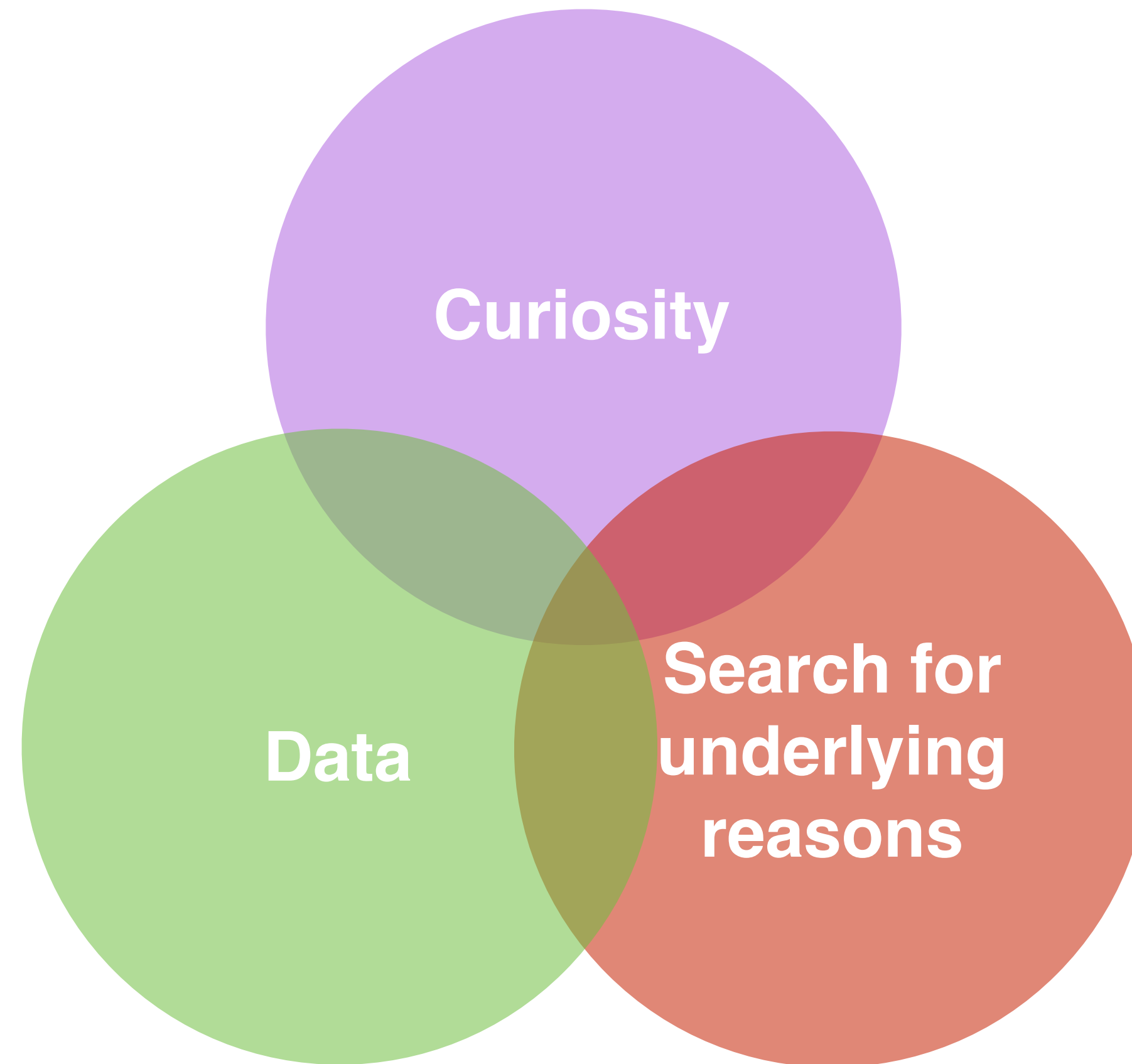
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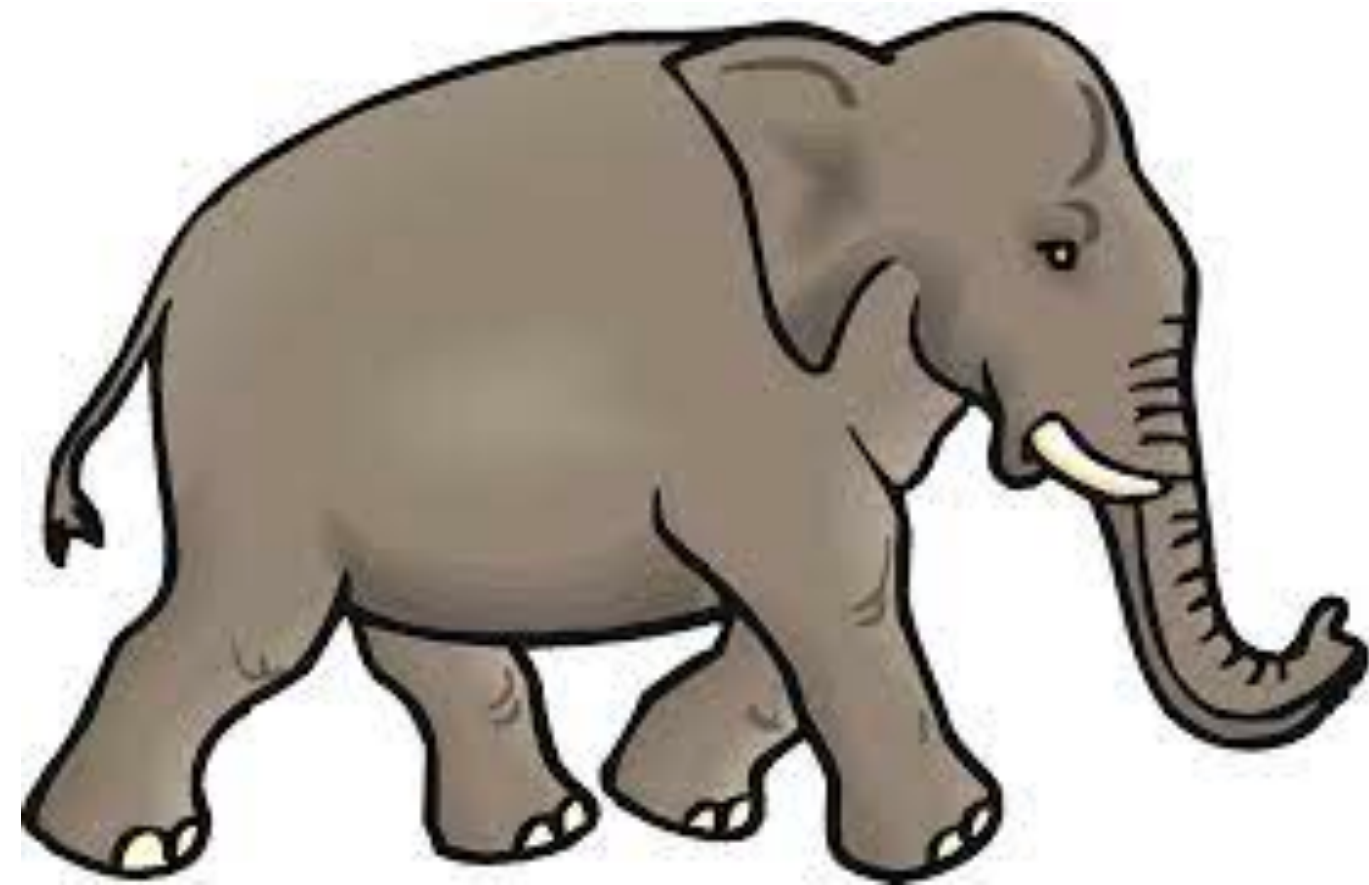


While some of our guides, like naturalness, fine tuning, unification, underlying symmetries and other concepts are still solid,  
the community is much more open to the question of  
**where is the new physics**



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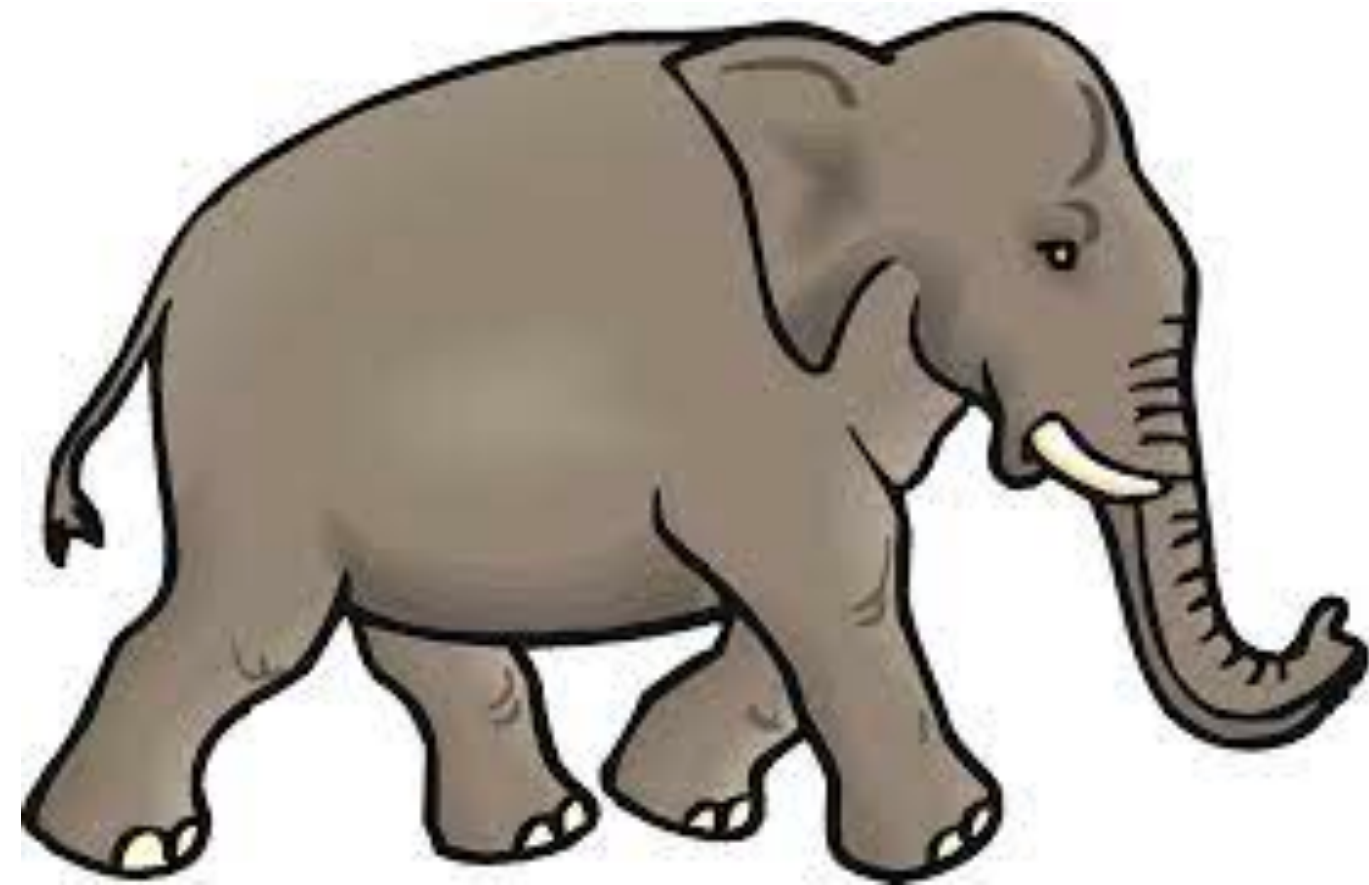
High scale new physics





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the community is much more open to the question of  
**where is the new physics**

High scale new physics



Low scale new physics



Taking a pragmatic view: there are three classes of BSM  
that can be searched in neutrino experiments

**Same signature as usual neutrinos:** sterile neutrinos, NSIs, neutrino decay, ...

**New neutrino signatures:** dark neutrinos, neutrinophilic scalars, ...

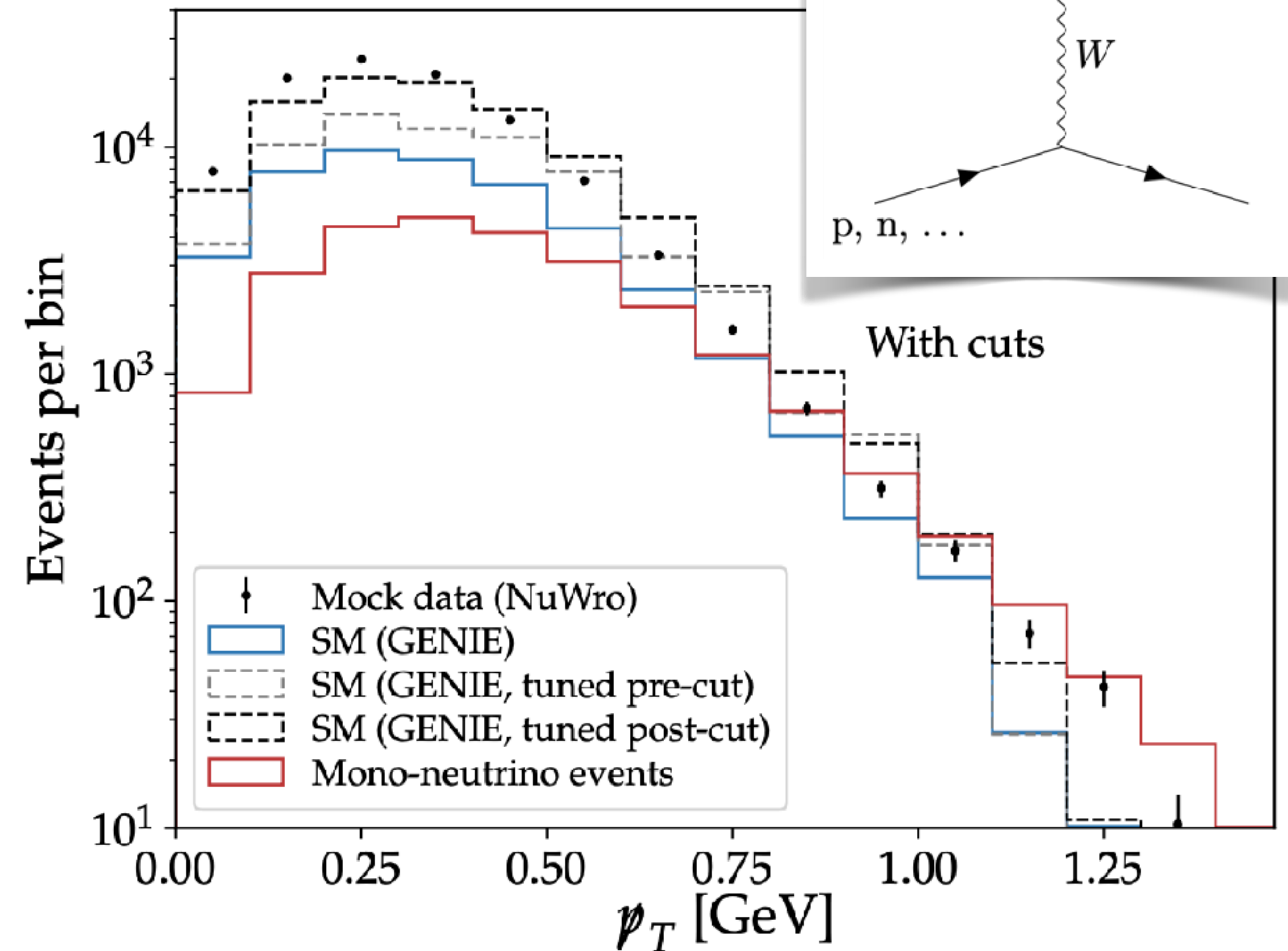
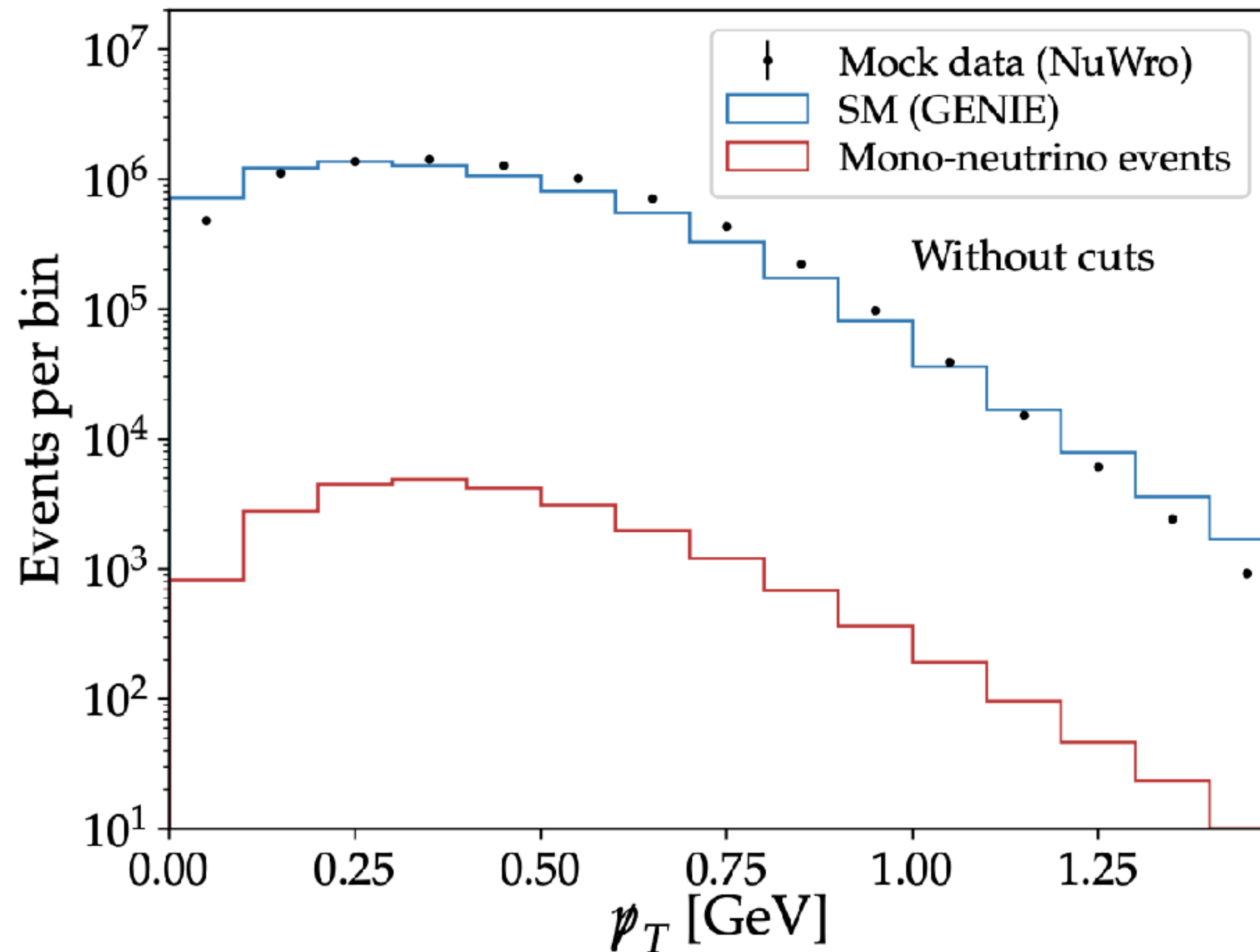
**New particles:** dark matter, heavy neutral leptons, axion-like particles, ...

Searching for different models will require overcoming different challenges

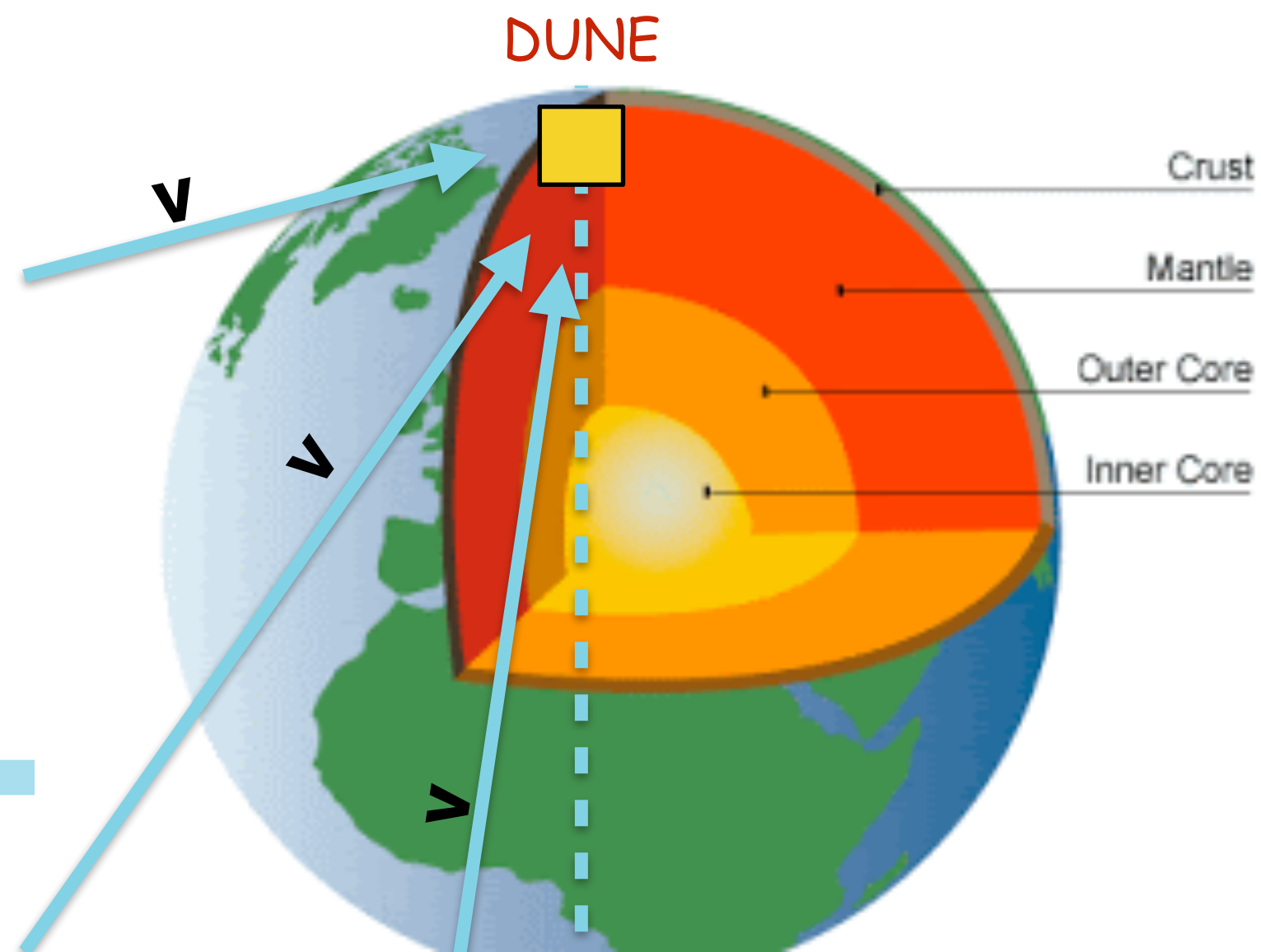
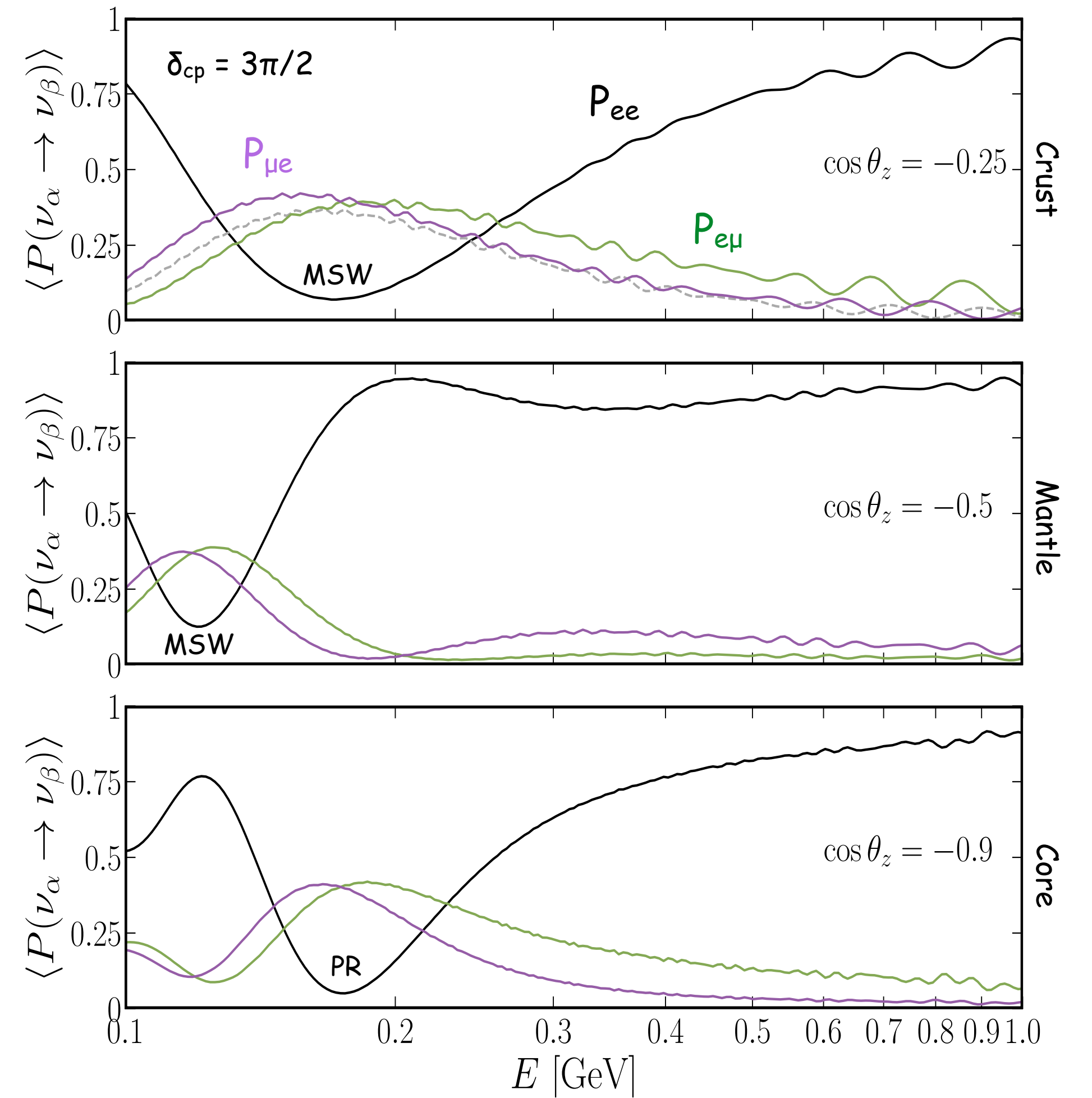
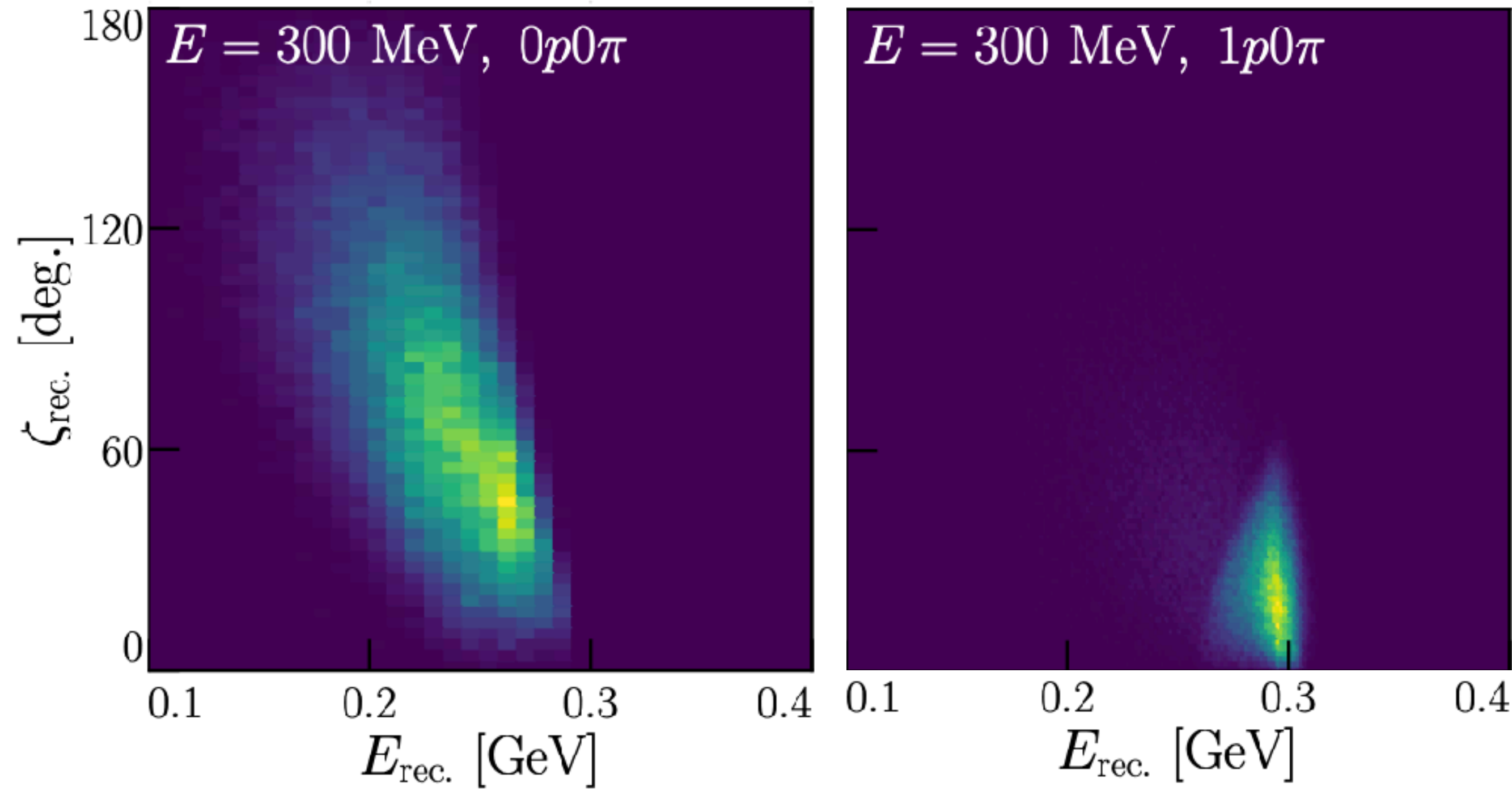
Let's look at some examples



# New signatures and BSM $\ll$ SM: $\nu$ -N interaction mis-modeling is a major challenge

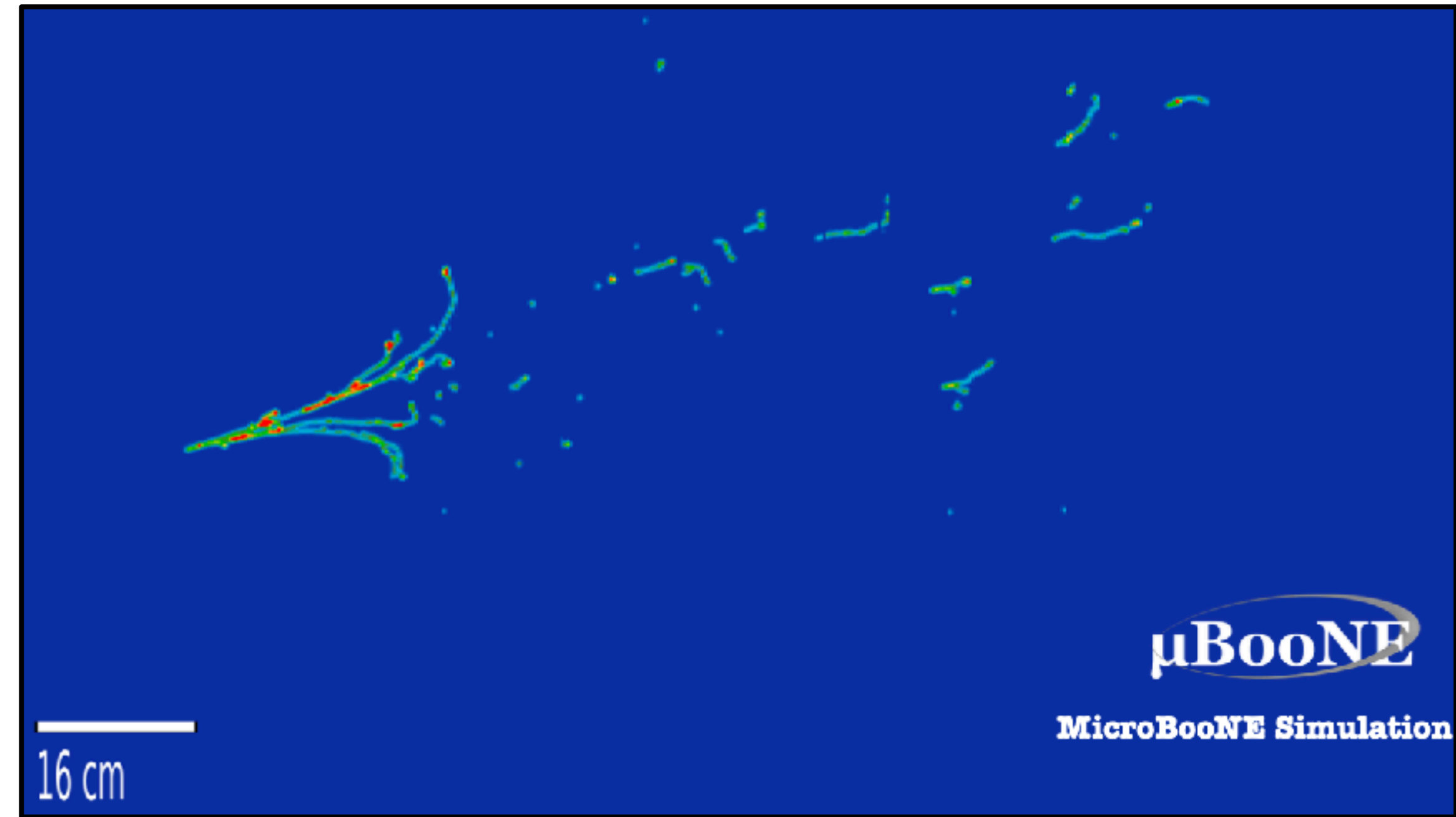
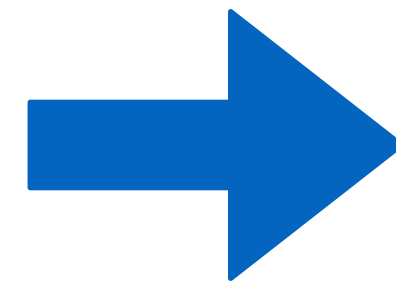
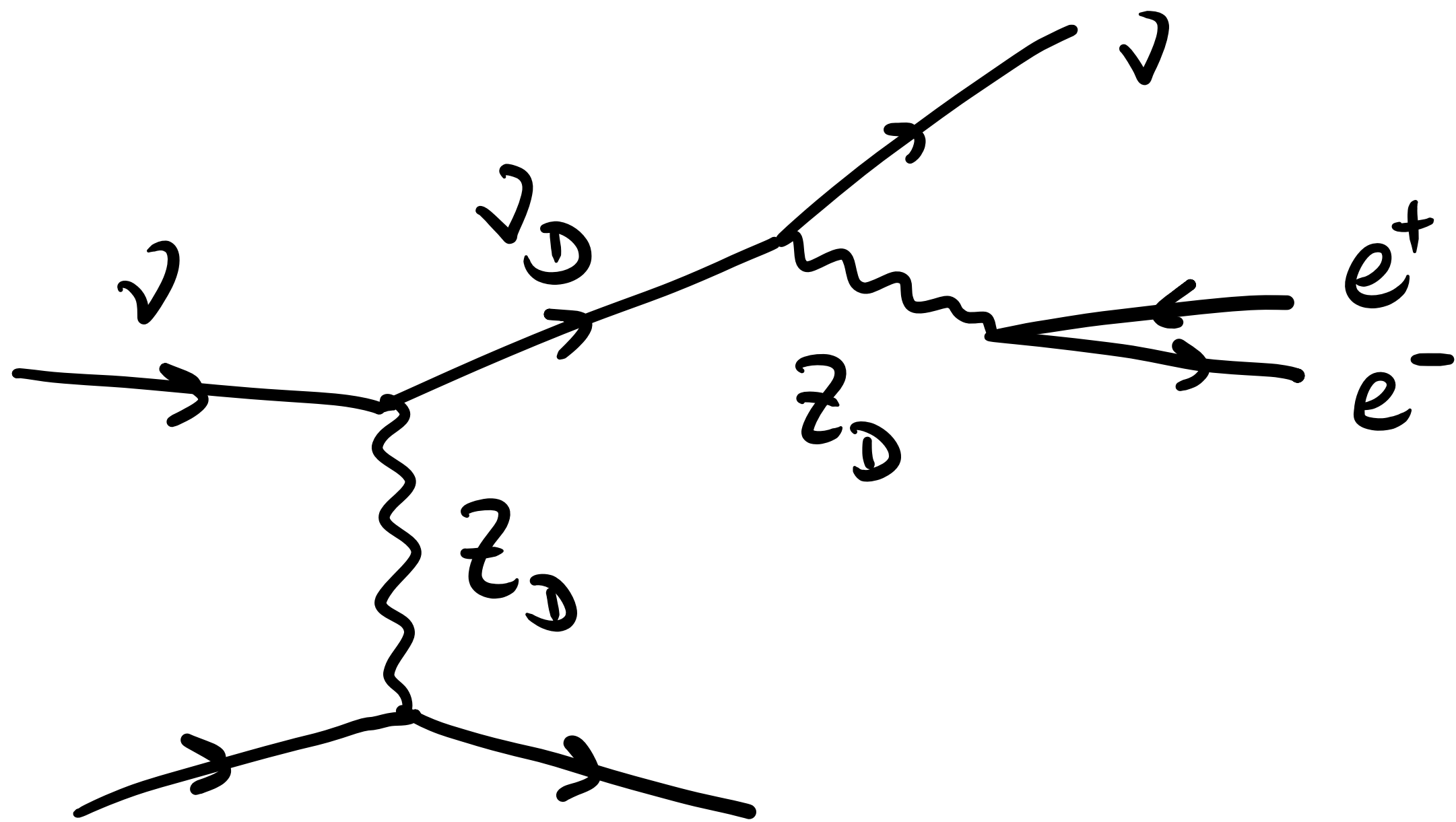


# Final state interactions are relevant for direction reconstruction

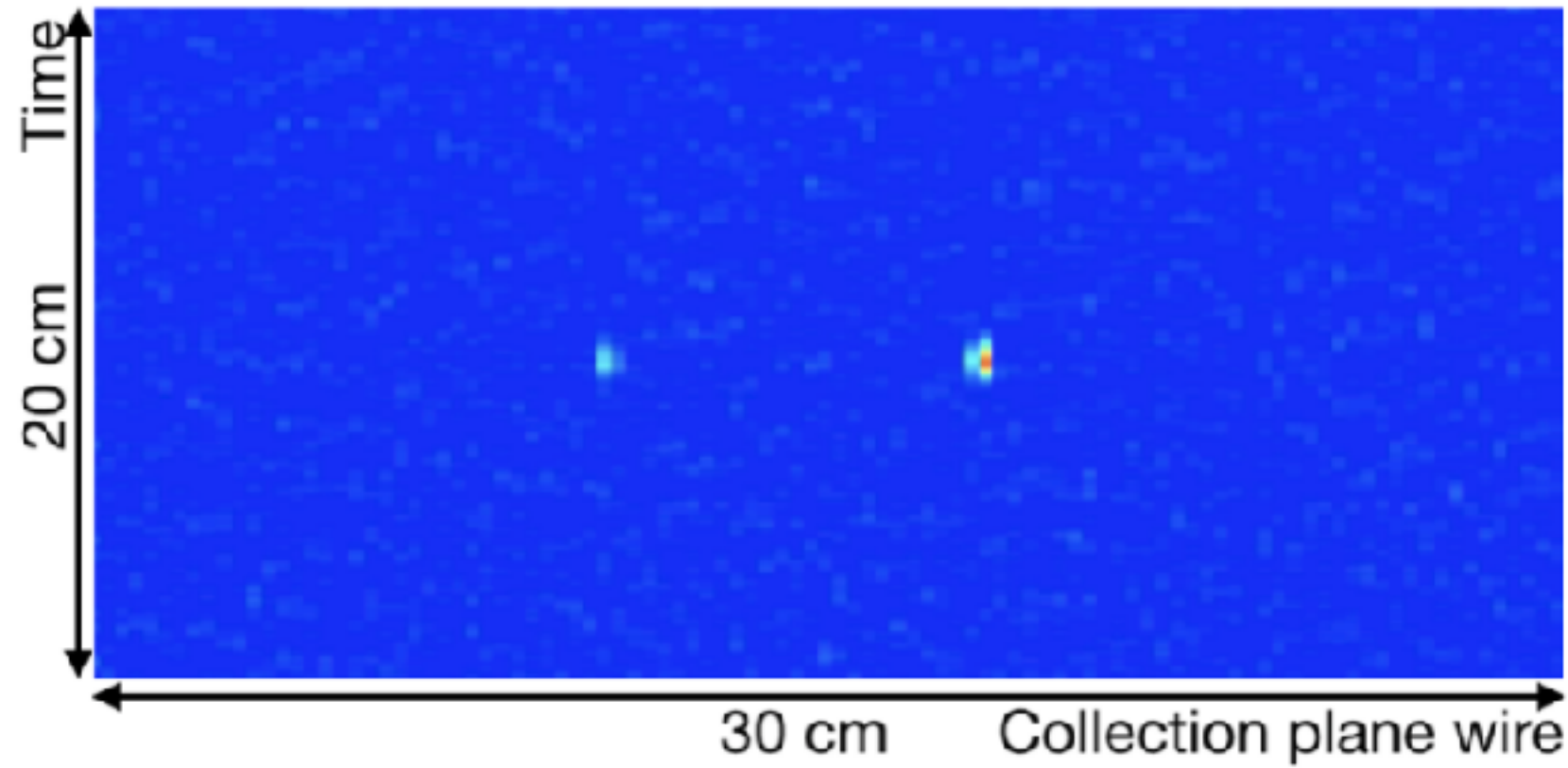




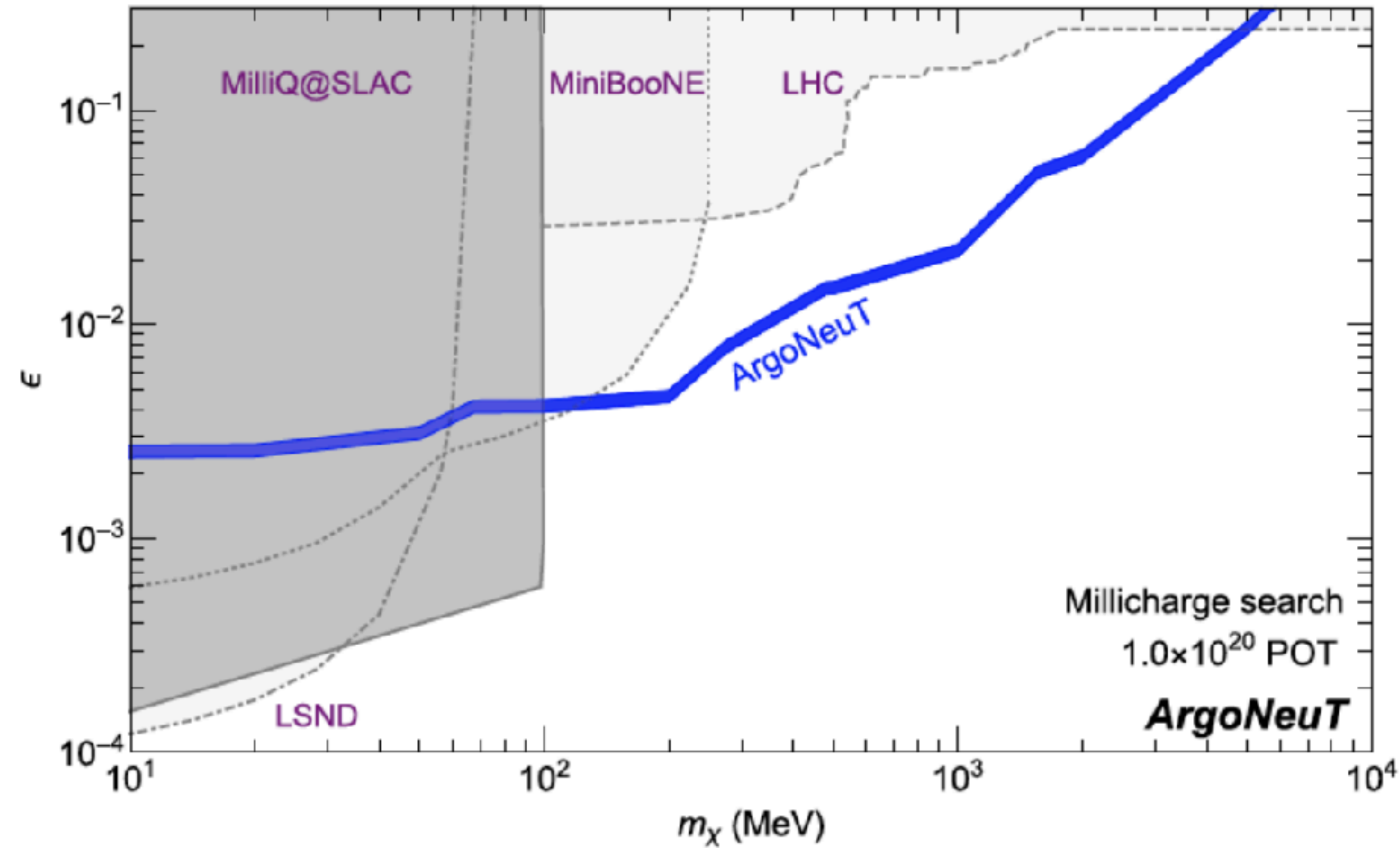
# Detector reconstruction is key



# Sometimes, we just need to be smart



ArgoNeuT Collaboration + 2 theorists (R. Harnik and Z. Liu)  
R. Acciarri et al., PRL124 131801 (2020)



**Leading constraints in unexplored parameter region!**



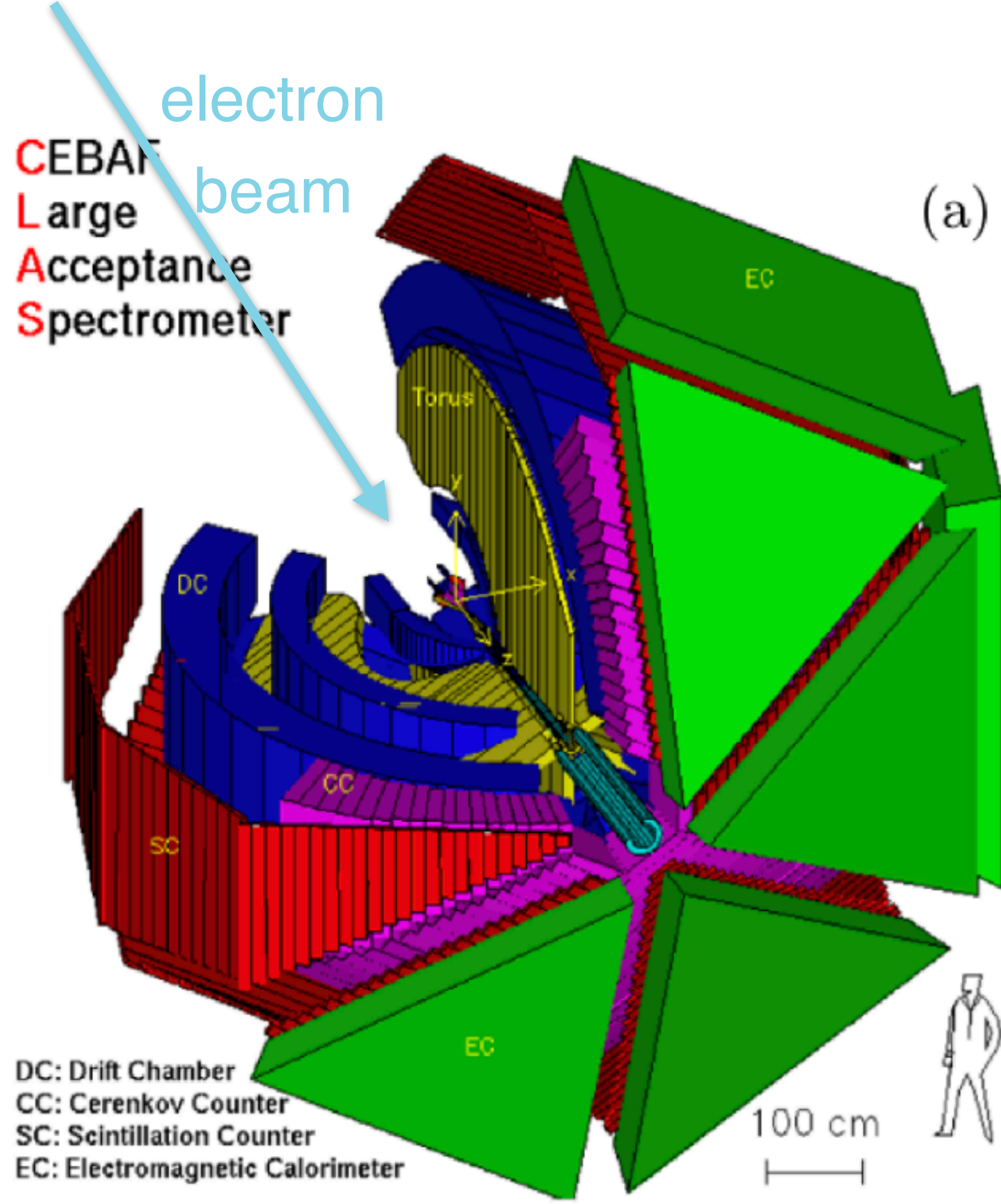
## Overall challenges

Precise description of neutrino-nucleus interaction is hard

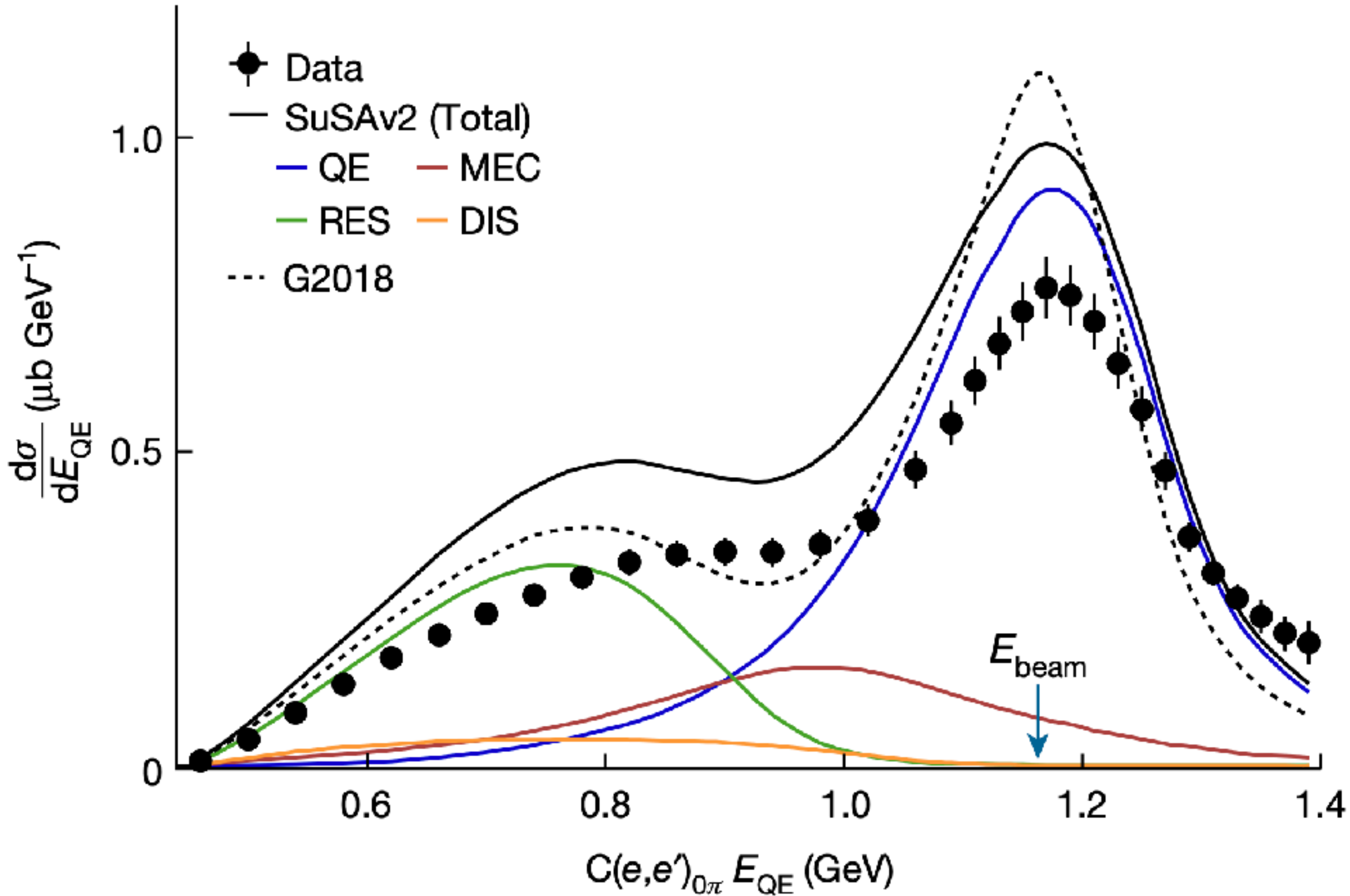
Realistic studies need heavy machinery (generators)

Leveraging detector capabilities and doing realistic analyses

# Description of neutrino-nucleus interaction is just hard



CLAS/E4v Nature 599 (2021) 7886, 565-570





```

auto otherMass = kickedPart.ID() == PID::proton() ? ParticleInfo(PID::neutron()).Mass()
: ParticleInfo(PID::proton()).Mass();

energy = otherMass*otherMass;
for(auto p : mom) energy += p*p;
std::size_t idxDiff = SIZE_MAX;
double xsecDiff = 0;
if(index_diff.size() != 0) {
    idxDiff = Random::Instance().Pick(index_diff);
    particles[idxDiff].SetMomentum(
        FourVector(mom[0], mom[1], mom[2], sqrt(energy)));

    auto p2 = particles[idxSame].Momentum();
    double fact = 1.0;
    if(m_medium == InMedium::NonRelativistic)
        fact = localNucleus -> GetPotential() -> InMediumCorrectionNonRel(p1, p2, mass, position);

    xsecDiff = GetXSec(kickedPart, particles[idxDiff])*fact;
}

double rhoSame=0.0;
double rhoDiff=0.0;
if(position < localNucleus -> Radius()) {
    //TODO: Adjust below to handle non-isosymmetric nuclei
    rhoSame = localNucleus -> Rho(position)*2*static_cast<double>(index_same.size())/static_cast<double>(particles.size());
    rhoDiff = localNucleus -> Rho(position)*2*static_cast<double>(index_diff.size())/static_cast<double>(particles.size());
}
if(rhoSame <= 0.0 && rhoDiff <= 0.0) return SIZE_MAX;
double lambda_tilde = 1.0 / (xsecSame / 10 * rhoSame + xsecDiff / 10 * rhoDiff);
double lambda = -log(Random::Instance().Uniform(0.0, 1.0))*lambda_tilde;

if(lambda > stepDistance) return SIZE_MAX;

stepDistance = lambda;
double icoice = Random::Instance().Uniform(0.0, 1.0);
if(icoice < xsecSame / (xsecSame + xsecDiff)) {
    particles[idxSame].SetPosition(kickedPart.Position());
    return idxSame;
}

particles[idxDiff].SetPosition(kickedPart.Position());
return idxDiff;
}

void Cascade::Reset() {
    kickedIdxs.resize(0);
    integrators.clear();
}

void Cascade::Evolve(nuchic::Event *event, const std::size_t &maxSteps) {
    // Set all propagating particles as kicked for the cascade
    for(size_t idx = 0; idx < event -> Hadrons().size(); ++idx) {
        if(event->Hadrons()[idx].Status() == ParticleStatus::propagating)
            SetKicked(idx);
    }

    // Run the normal cascade
    Evolve(event->CurrentNucleus(), maxSteps);
}

void Cascade::Evolve(std::shared_ptr<Nucleus> nucleus, const std::size_t &maxSteps) {
    localNucleus = nucleus;
    Particles particles = nucleus -> Nucleons();
    // Initialize symplectic integrators
    std::vector<size_t> notCaptured{};
    for(auto idx : kickedIdxs) {
        if(m_potential_prop
            && localNucleus -> GetPotential() -> Hamiltonian(particles[idx].Momentum().P(),
                particles[idx].Position().P()) < Constant::mN) {
            particles[idx].Status() = ParticleStatus::captured;
        } else {

```

**Generators are complex, requiring significant time to be developed and to incorporate new physics**

```

// Update formation zones
if(kickNuc -> InformationZone()) {
    kickNuc -> UpdateFormationZone(timeStep);
    kickNuc -> Propagate(timeStep);
    newKicked.push_back(idx);
    continue;
}

// Get allowed interactions
auto dist2 = AllowedInteractions(particles, idx);
if(dist2.size() == 0) {
    newKicked.push_back(idx);
    continue;
}

// Get interaction
auto hitIdx = Interacted(particles, *kickNuc, dist2);
if(hitIdx == SIZE_MAX) {
    newKicked.push_back(idx);
    continue;
}
Particle* hitNuc = &particles[hitIdx];

// Finalize Momentum
bool hit = FinalizeMomentum(*kickNuc, *hitNuc);
UpdateIntegrator(iox, kickNuc);

if(hit) {
    if(m_potential_prop
        && localNucleus -> GetPotential() -> Hamiltonian(kickNuc -> Momentum().P(),
            kickNuc -> Position().P()) < Constant::mN) {
        kickNuc -> Status() = ParticleStatus::captured;
    } else {
        newKicked.push_back(iox);
    }
    if(m_potential_prop
        && localNucleus -> GetPotential() -> Hamiltonian(hitNuc -> Momentum().P(),
            hitNuc -> Position().P()) < Constant::mN) {
        hitNuc -> Status() = ParticleStatus::captured;
    } else {
        newKicked.push_back(hitIdx);
        AddIntegrator(hitIdx, *hitNuc);
        hitNuc -> Status() = ParticleStatus::propagating;
    }
} else {
    newKicked.push_back(iox);
}

spdlog::debug("newKicked size = {}, {}", newKicked.size(), hit);

// Replace kicked indices with new list
kickedIdxs = newKicked;

// After step checks
Escaped(particles);
}

for(auto particle : particles) {
    if(particle.Status() == ParticleStatus::propagating) {
        std::cout << "\n";
        for(auto p : particles) spdlog::error("{} ", p);
        throw std::runtime_error("Cascade has failed. Insufficient max steps.");
    }
}

nucleus -> Nucleons() = particles;
Reset();
}

void Cascade::AddIntegrator(size_t iox, const Particle &part) {

```

# Leveraging detector capabilities and doing realistic analyses

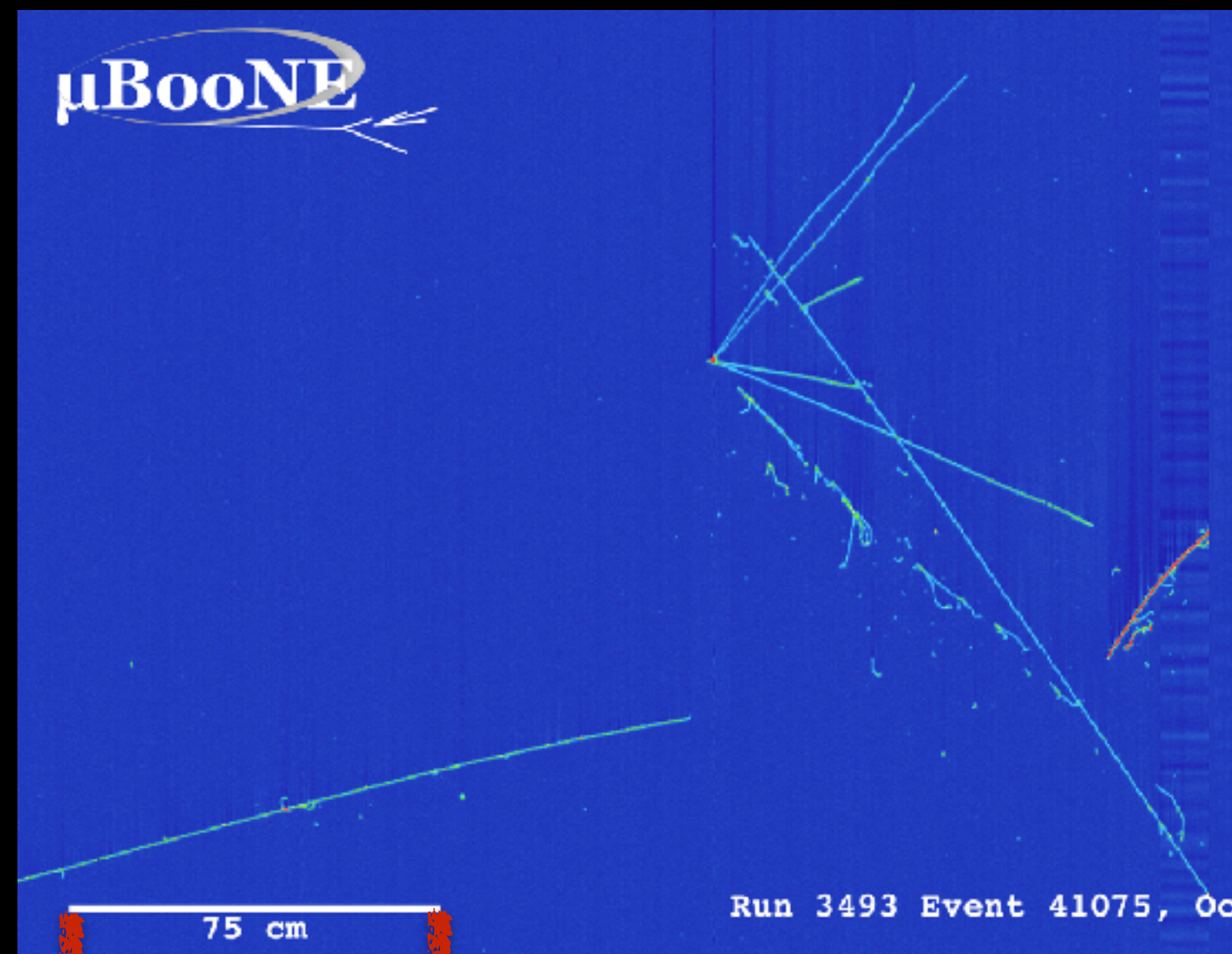
400

600

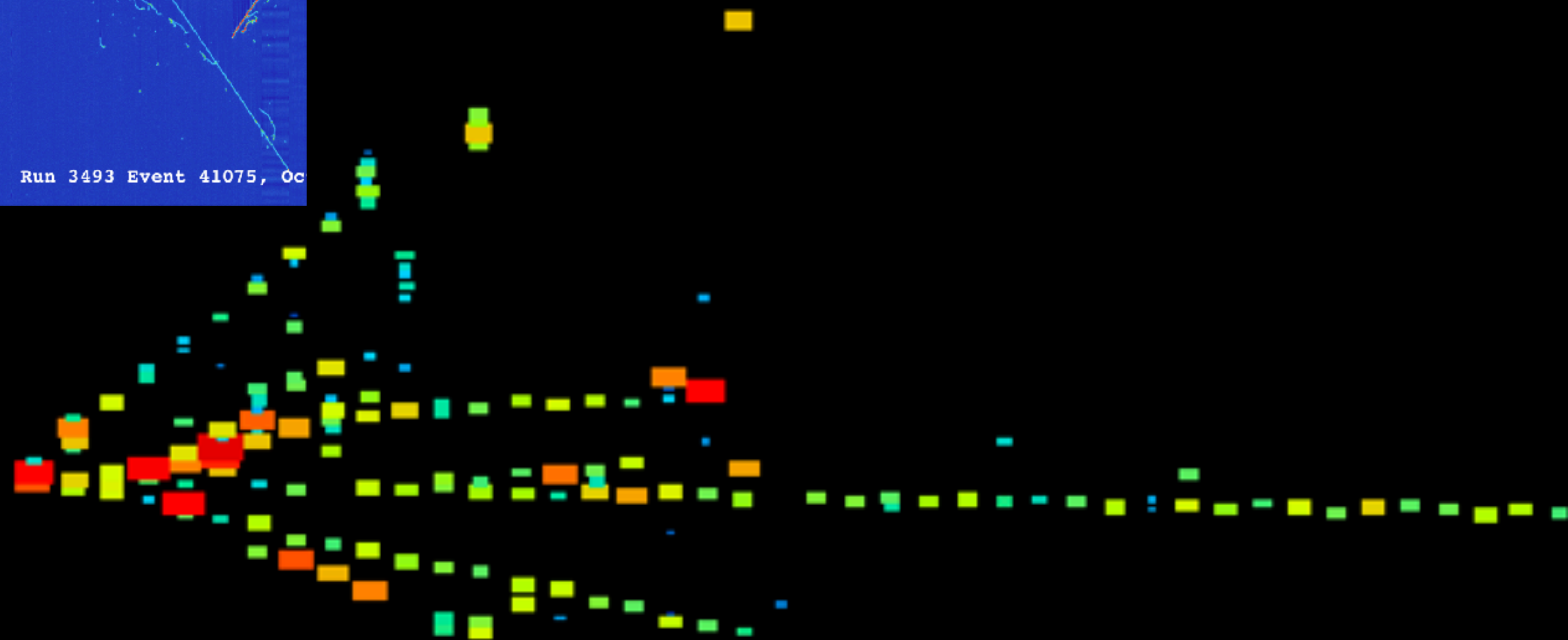
800

1000

1200



**NOvA**











What do we need to do great physics with our neutrino experiments?

The answer depends on which BSM you want to probe

**Good news: we do not need to solve all problems at once**

But there is no one size fits all

Let's come up with some wish list, but first let's get some things straight

# Hard vs. Challenging vs. Burdensome

This is my own personal definition

Hard = we don't know how to do, and it is not clear how much we will progress

Challenging = still needs a lot of work, but we will get there (to a good extent)

Burdensome = we know what to do, we just need to do it

hard

Percent-level description of neutrino-nucleus interactions

Event reconstruction

Cosmic ray rejection in SBN detectors

Electron-photon discrimination

Pile-up in DUNE ND

Particle identification

challenging

burdensome

Beam produced dark matter signal

BSM implementation on generators

Flux simulation and tracking meson momenta





# *My wish list*







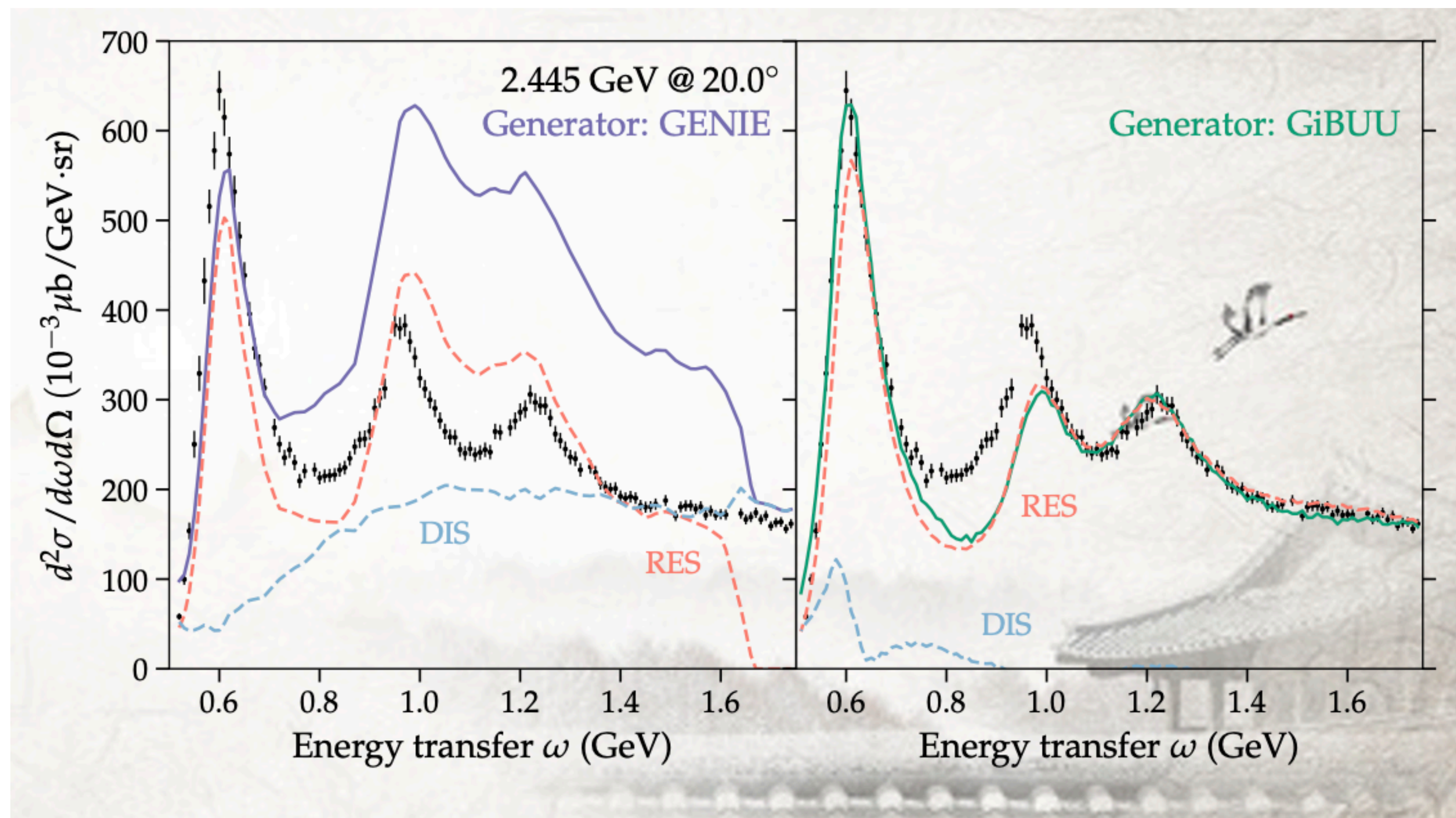
# *My wish list*



## Support generator development and theory work on neutrino-nucleus interaction physics

We need a better understanding of neutrino-nucleus interactions

This is relevant for our main goals, but even more relevant to probe light, weakly interacting physics

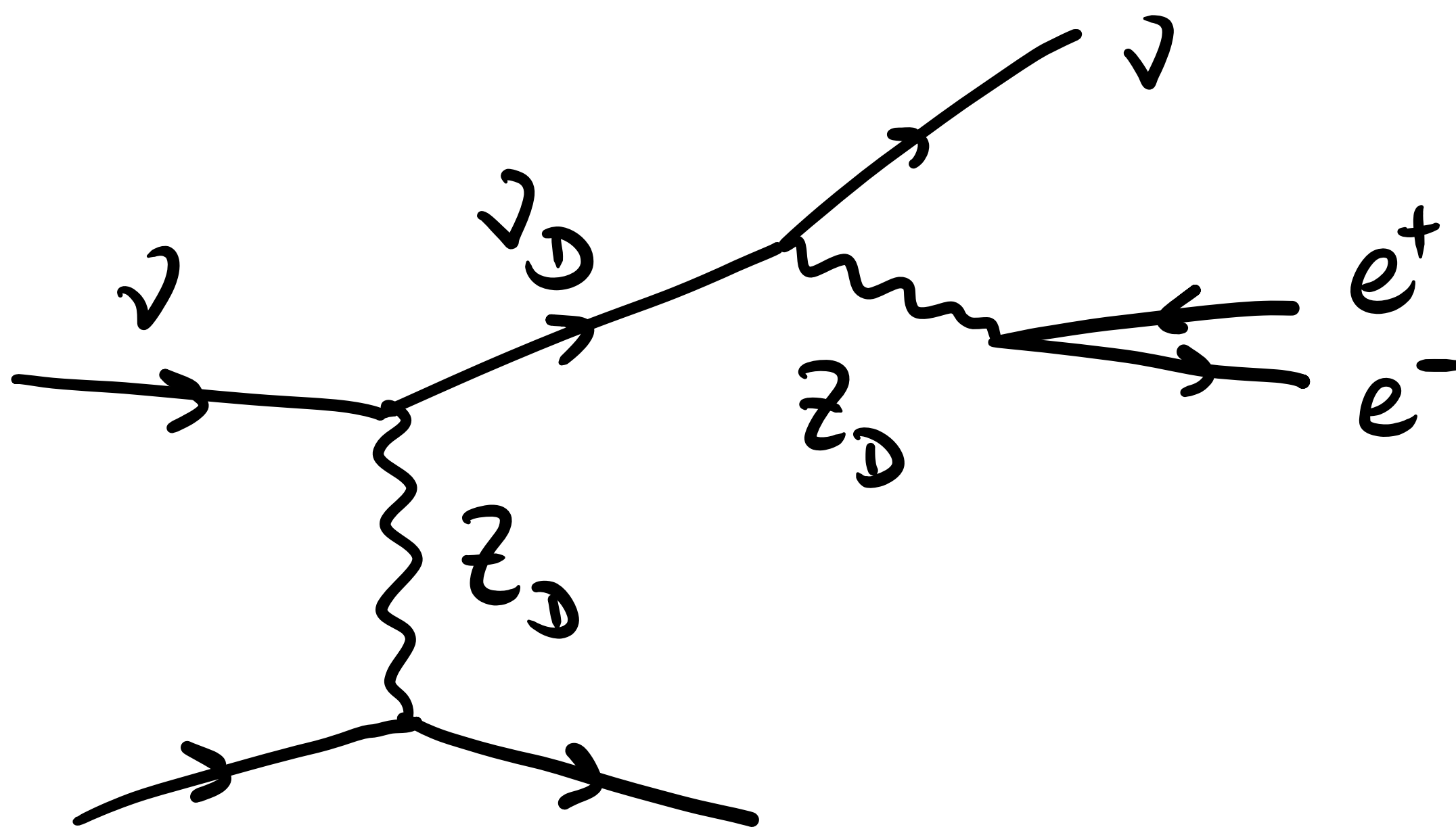




# *My wish list*



## **Make experimentalist lives easier**



Several models, however different they are, may lead to similar final states. Therefore, a single search may be useful for more than one model, or may easily be recasted/adapted to account for other scenarios



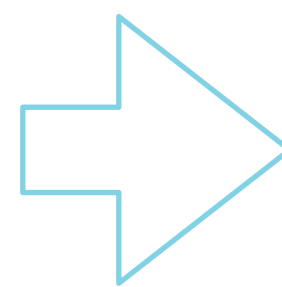
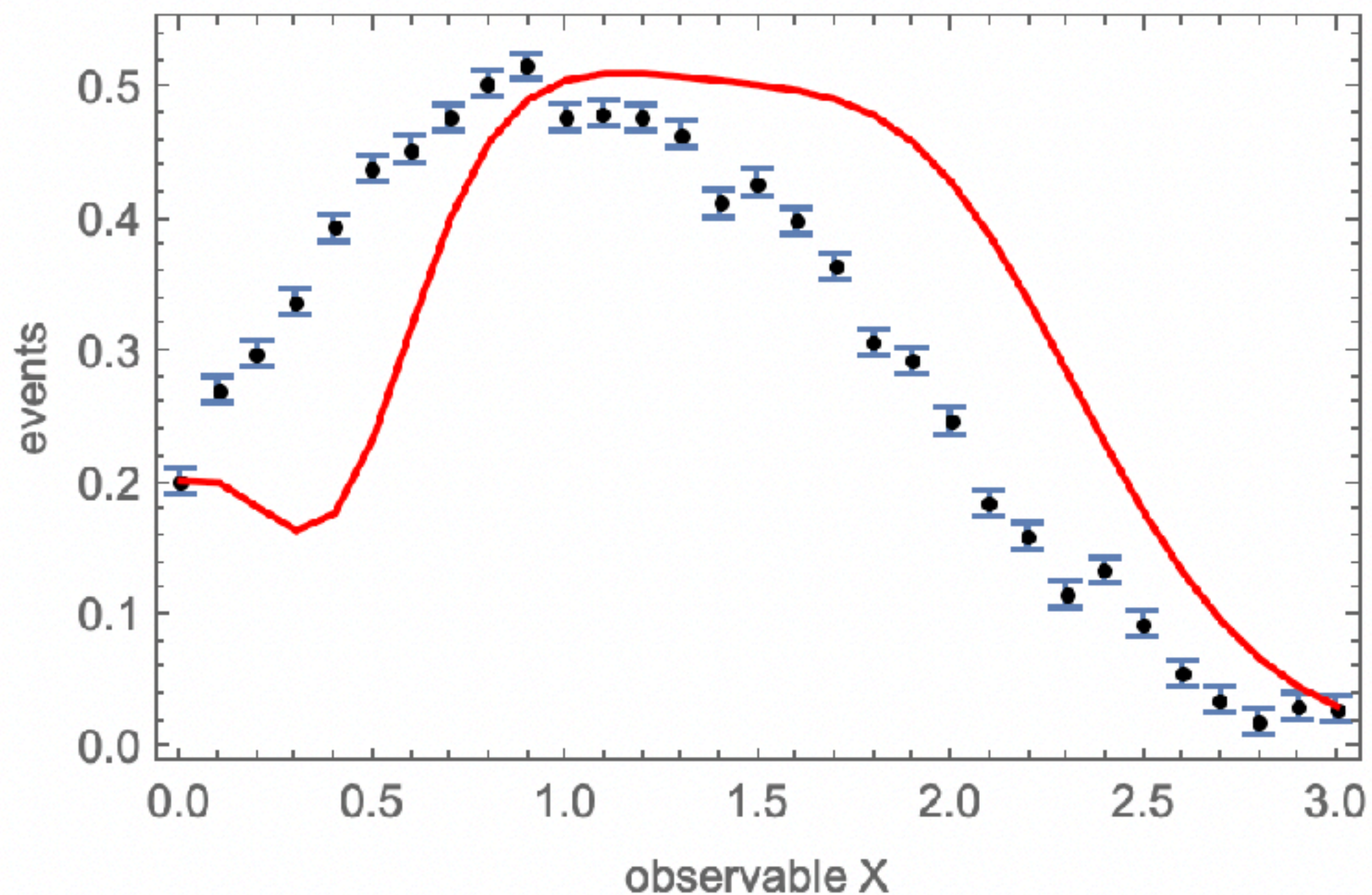


# *My wish list*

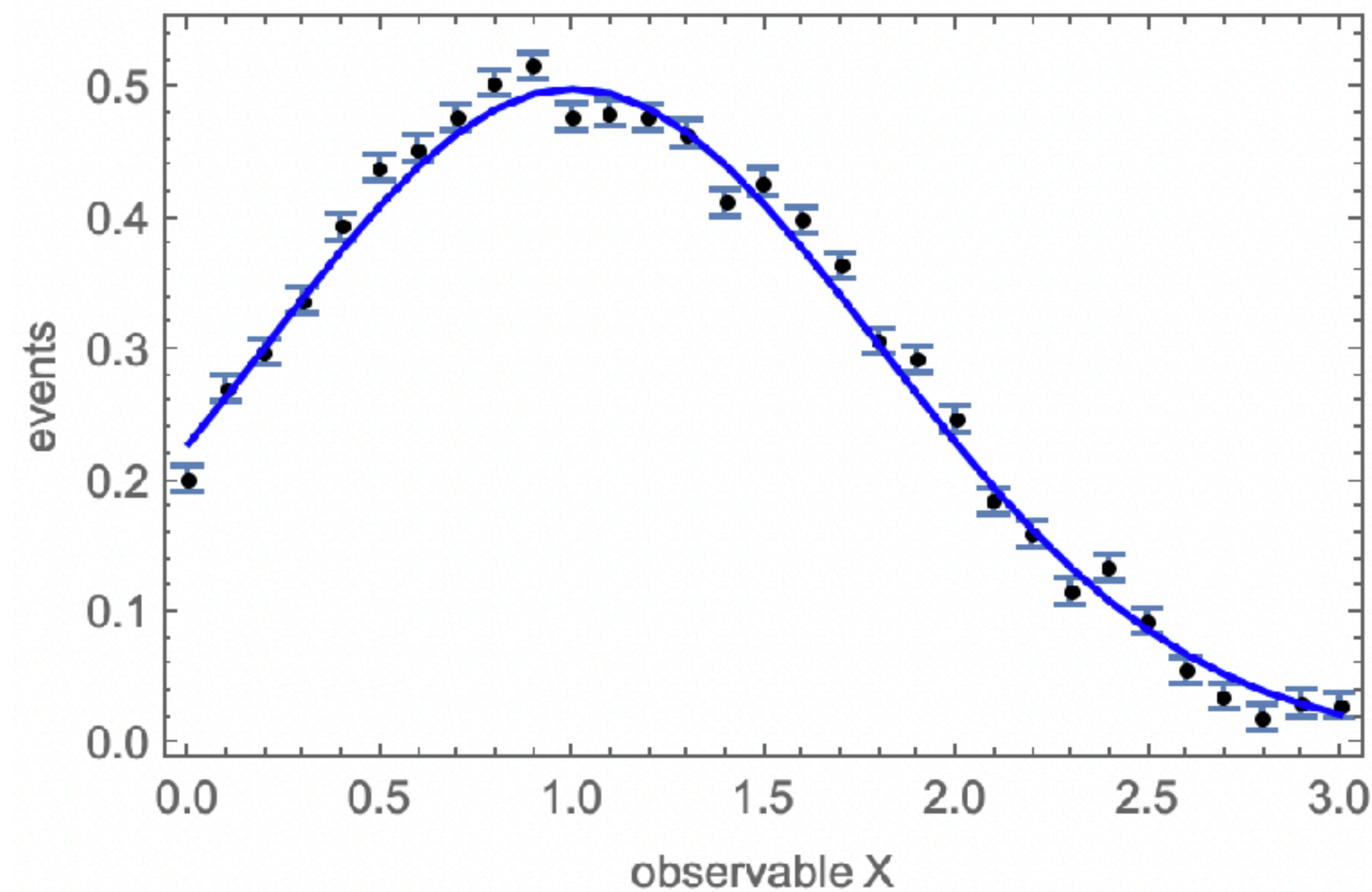


## Preserve experimental data

Today



Tomorrow



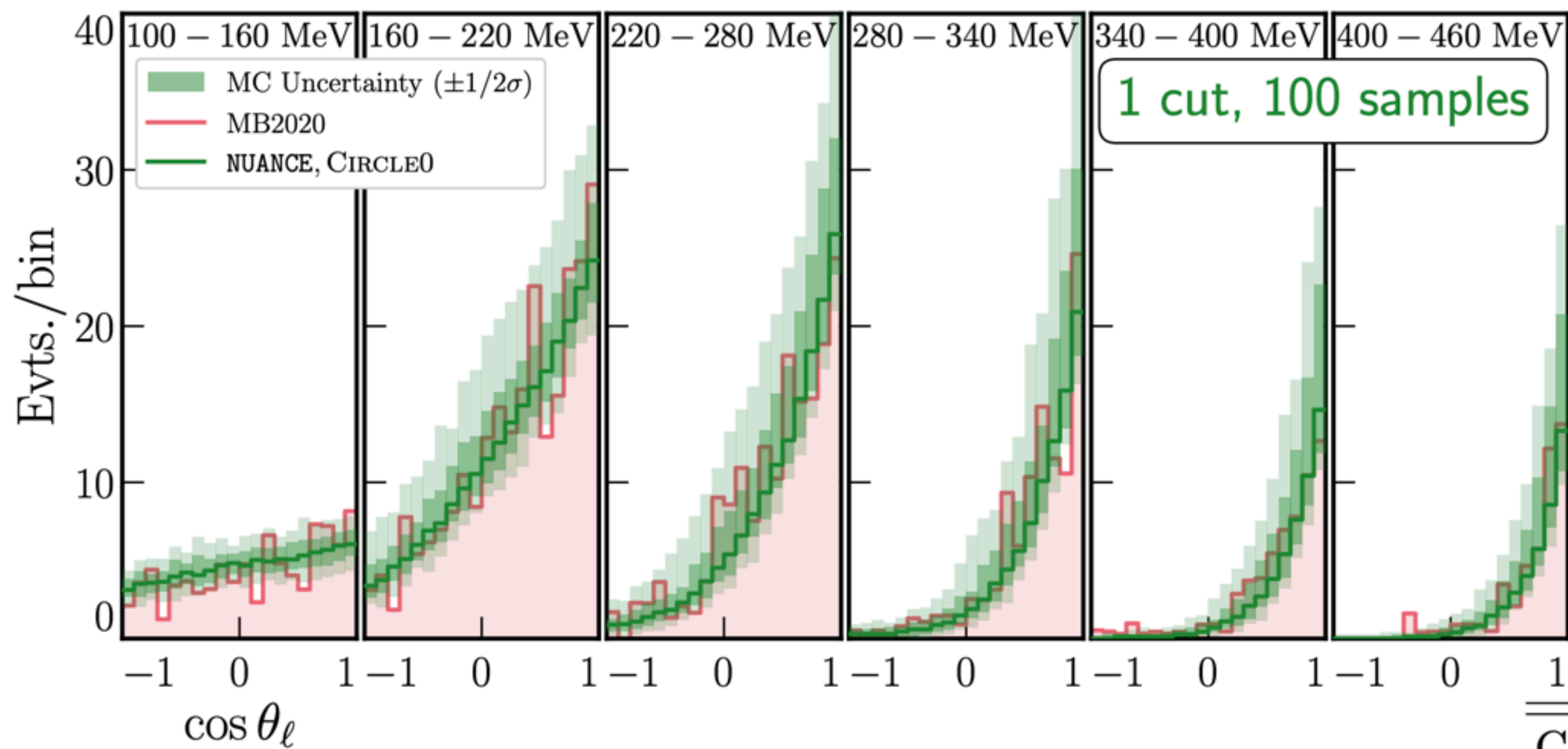




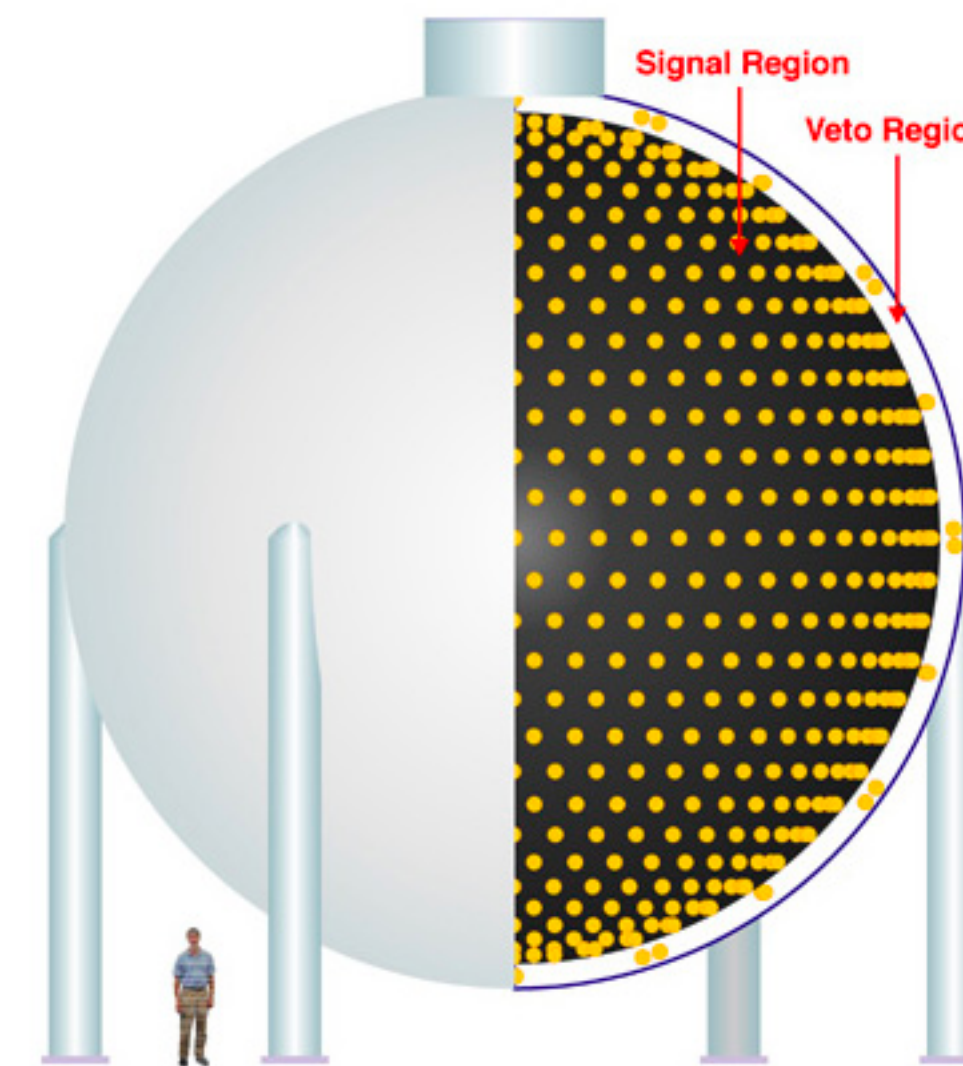
# My wish list



## Preserve experimental data



MiniBooNE Detector



Cut Prescription	NC $\pi^0$ background rate (Median $\pm 1\sigma$ range)
1 Cut, 100 Samples	
CIRCLE1	669.8 <sup>+241.3</sup> <sub>-51.8</sub>
CIRCLE0	664.3 <sup>+255.0</sup> <sub>-48.3</sub>
DIAGONAL	659.9 <sup>+266.2</sup> <sub>-48.8</sub>

Our estimate of the updated MB Significance:  $\sim 3\sigma$



# *My wish list*



**Please please please explain your analyses in a way we can reproduce them**

PS191, Physics Letters B 166, 1986

about one month. The events on tape were subsequently filtered and scanned for decay candidates using a microprocessor [8] developed to suit our requirements. The events retained for further study were a few tens. The latter were subjected to a thorough series of tests, essentially visual, to convince ourselves that they could not possibly satisfy the expected  $\nu$ -decay topology. None emerged as a credible candidate.





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MicroBooNE HPS search 2021

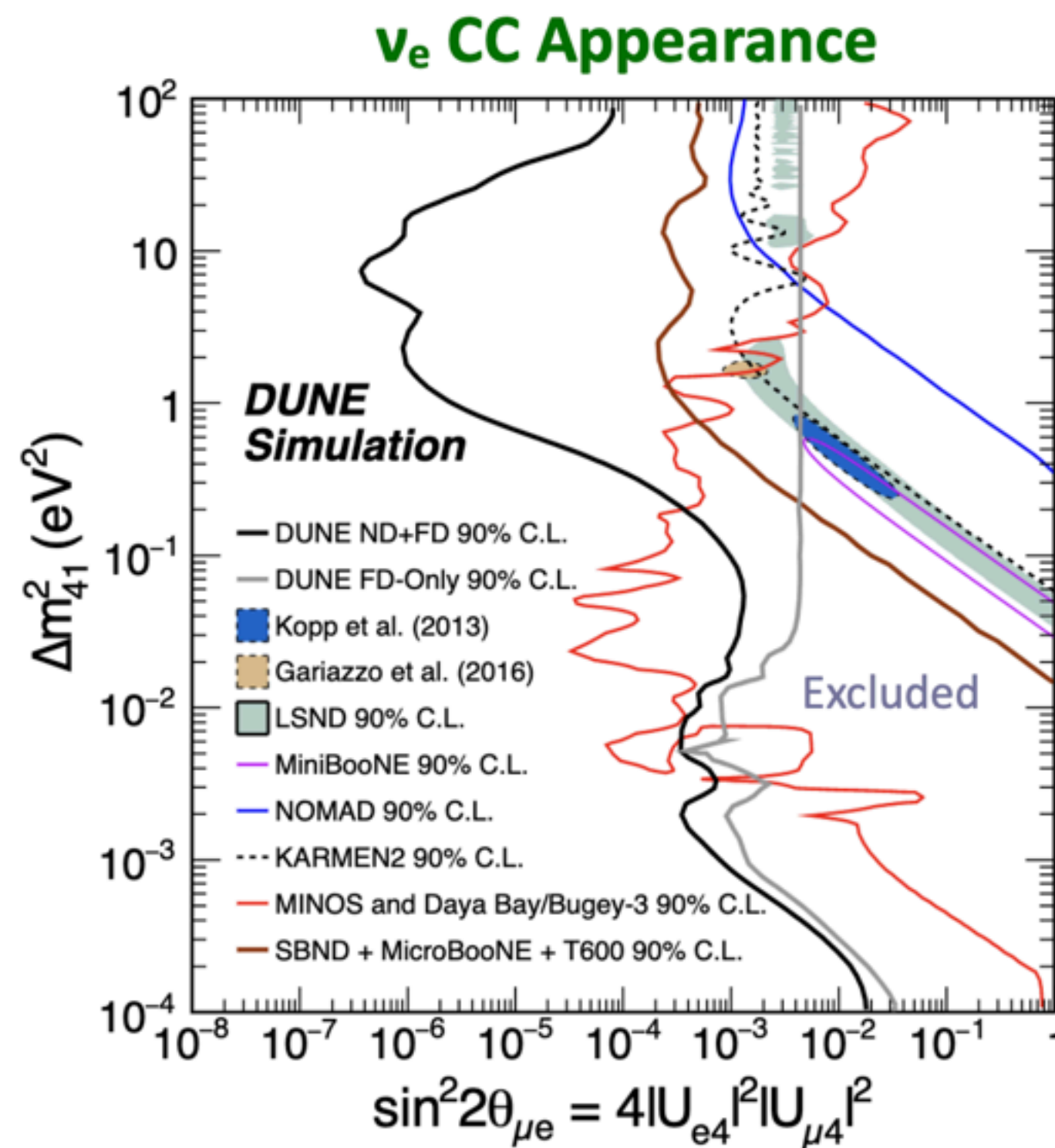
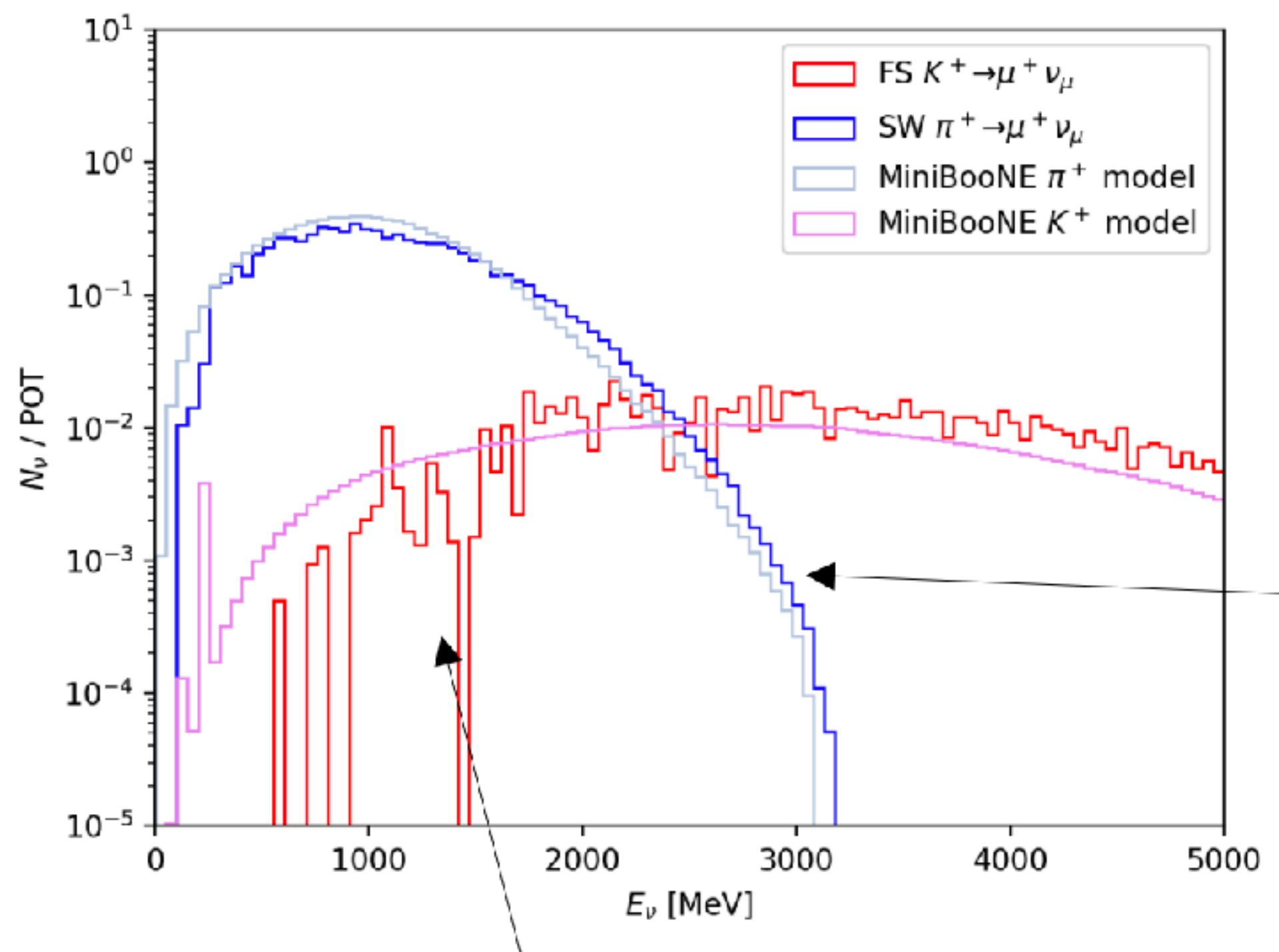
After applying the BDT selection, the number of events expected for each background contribution and for several signal definitions are shown in Table II. The table also presents the estimated signal selection efficiency. The total expected background-only prediction is  $1.9 \pm 0.8$  candidate events.



# My wish list



Make it easy to make some key information public



- Fluxes with info from mesons
- Energy reconstruction
- Covariance matrices
- Efficiencies
- Cuts
- ...





# My wish list

## Make tools publicly and easily available

The screenshot shows the Scikit-HEP website interface. On the left is a navigation menu with links for Home, Project news, Packages, User information, Developer information, Who uses Scikit-HEP?, and About. The main content area is divided into three categories:

- Particles and decays:**
  - Decay Language**: Describe and convert particle decays between digital representations.
  - Particle**: PDG particle data and identification codes.
- Fitting:**
  - Goofit**: GPU/OpenMP fitting in Python and C++. **Affiliated**
  - iminuit**: Jupyter-friendly Python interface for the Minuit2 C++ library.
  - zfit**: Scalable Pythonic fitting. **Affiliated**
- Statistics:**
  - cabinetry**: Design and steer profile likelihood fits.
  - hepstats**: Statistics tools and utilities.



## Action items:

- Create a living document with our community guidance
- Create the snapshot document of the summary of the workshop
- Mini-Workshop on data preservation/data release
  - Focus on smaller experiment
  - Involve the right people
  - Discuss in advance to arrive with a plan at the workshop
  - Invite representatives of experiments who did data preservation (IceCube, ATLAS/CMS, MINERvA, ...)
  - Wishlist for data release
  - Database for fluxes (beam lines, particles, ...)
- Start overleaf, collect wish lists, assign tasks
- Contact NTN PI and establish a network for TH+EXP+Nuc to communicate
- Topical schools/workshops?
- Neutrino Olympics?
- What have we learned from previous experiments?
- What do we want from generators?
- Categorization of models based on observables
- Fast simulation tools
- Pipeline to get experimental information
- Framework development best practices
- Timeline to accomplish action items
- Fast track from Lagrangian to observables