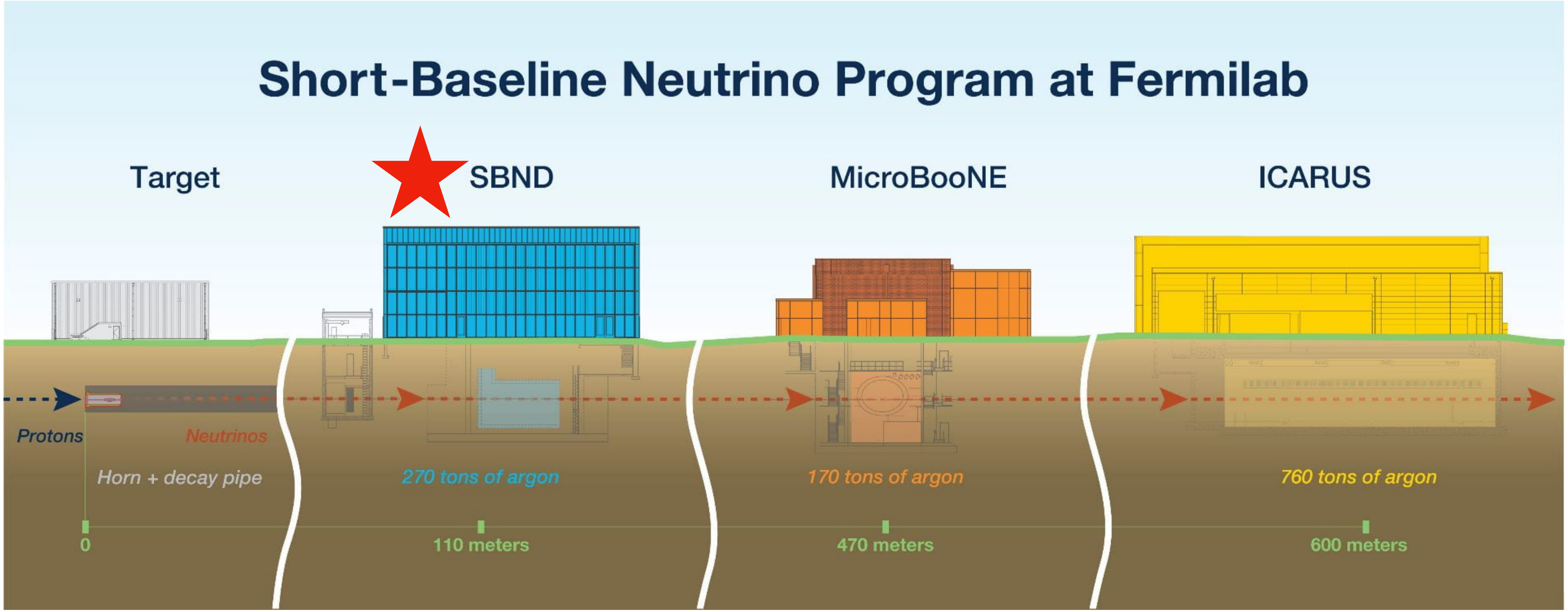
Wire-Cell in SBND

Lynn Tung & Ewerton Belchior on behalf of SBND Wire-Cell Team

Wire-Cell 2nd Reconstruction Summit
Brookhaven National Laboratory
April 11, 2024

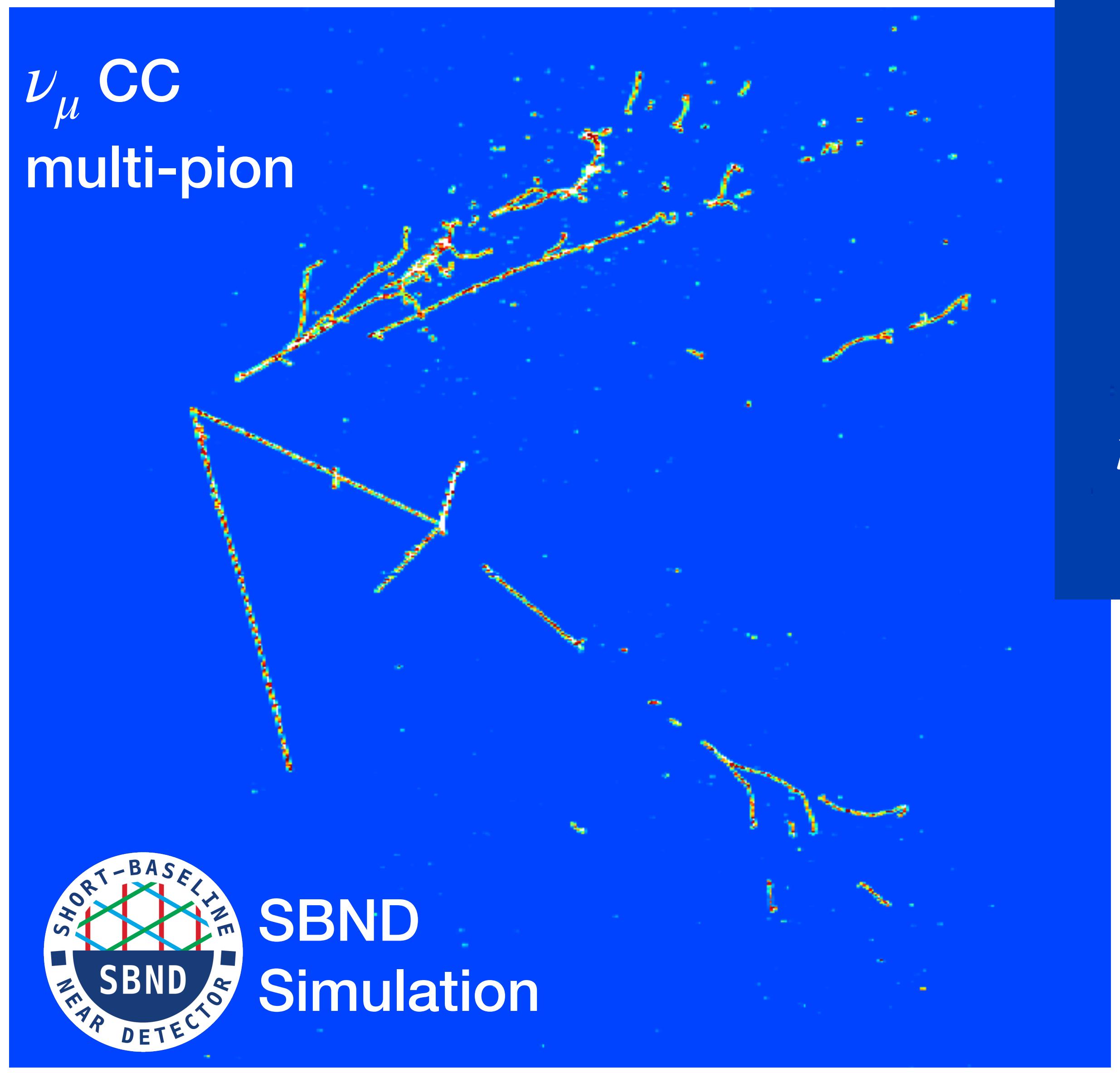
Outline

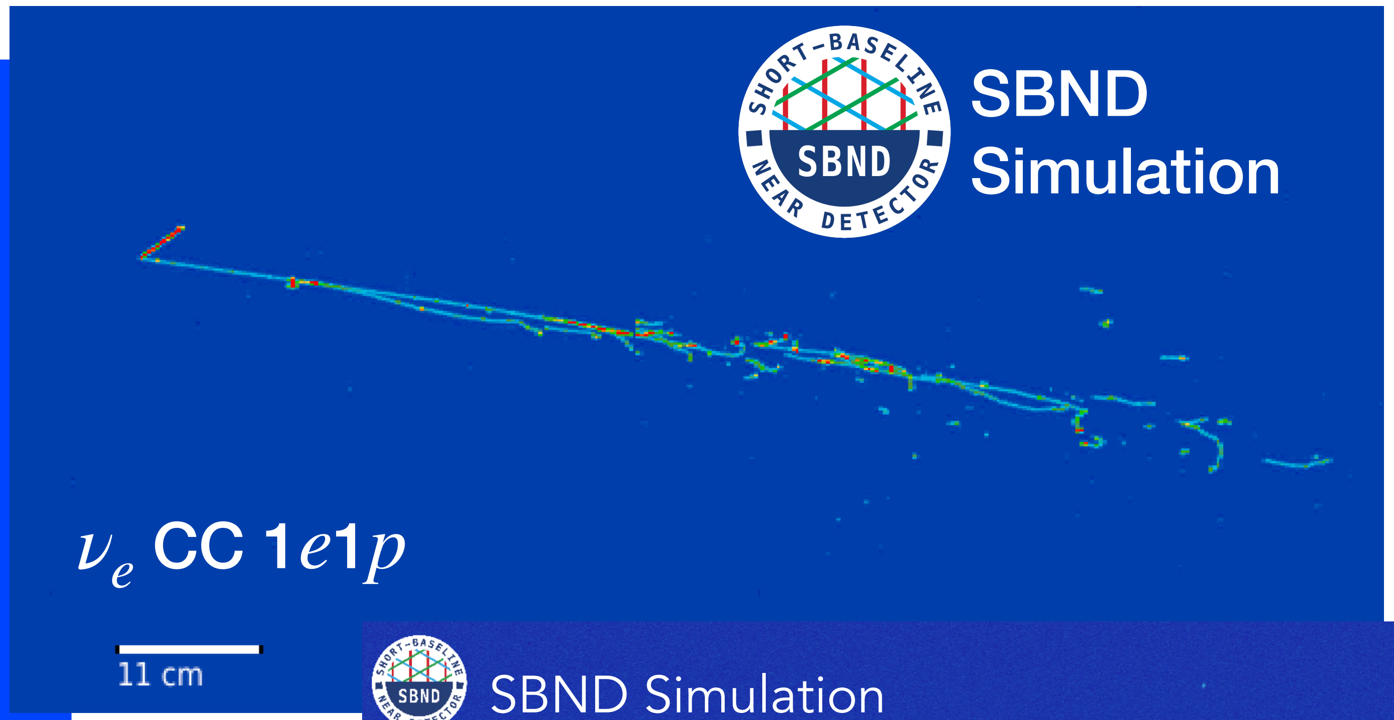
- SBND overview
    - detector, status, and physics capabilities
- Wire-Cell Signal Processing in SBND
- Wire-Cell 3D Imaging in SBND
- Wire-Cell in SBND current status, workflow, and experiment needs

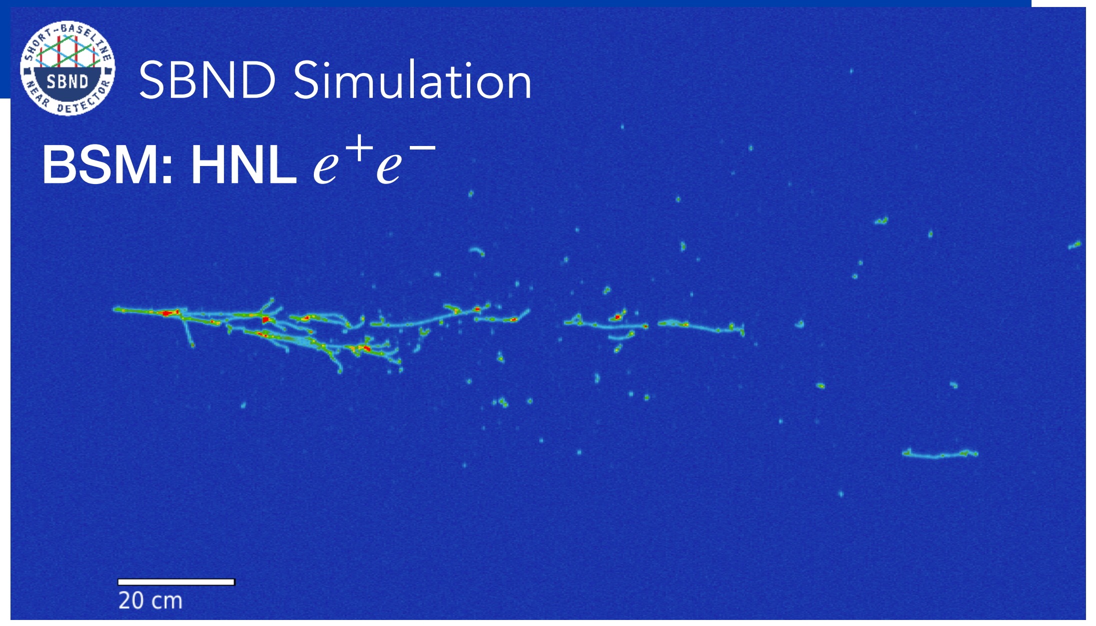


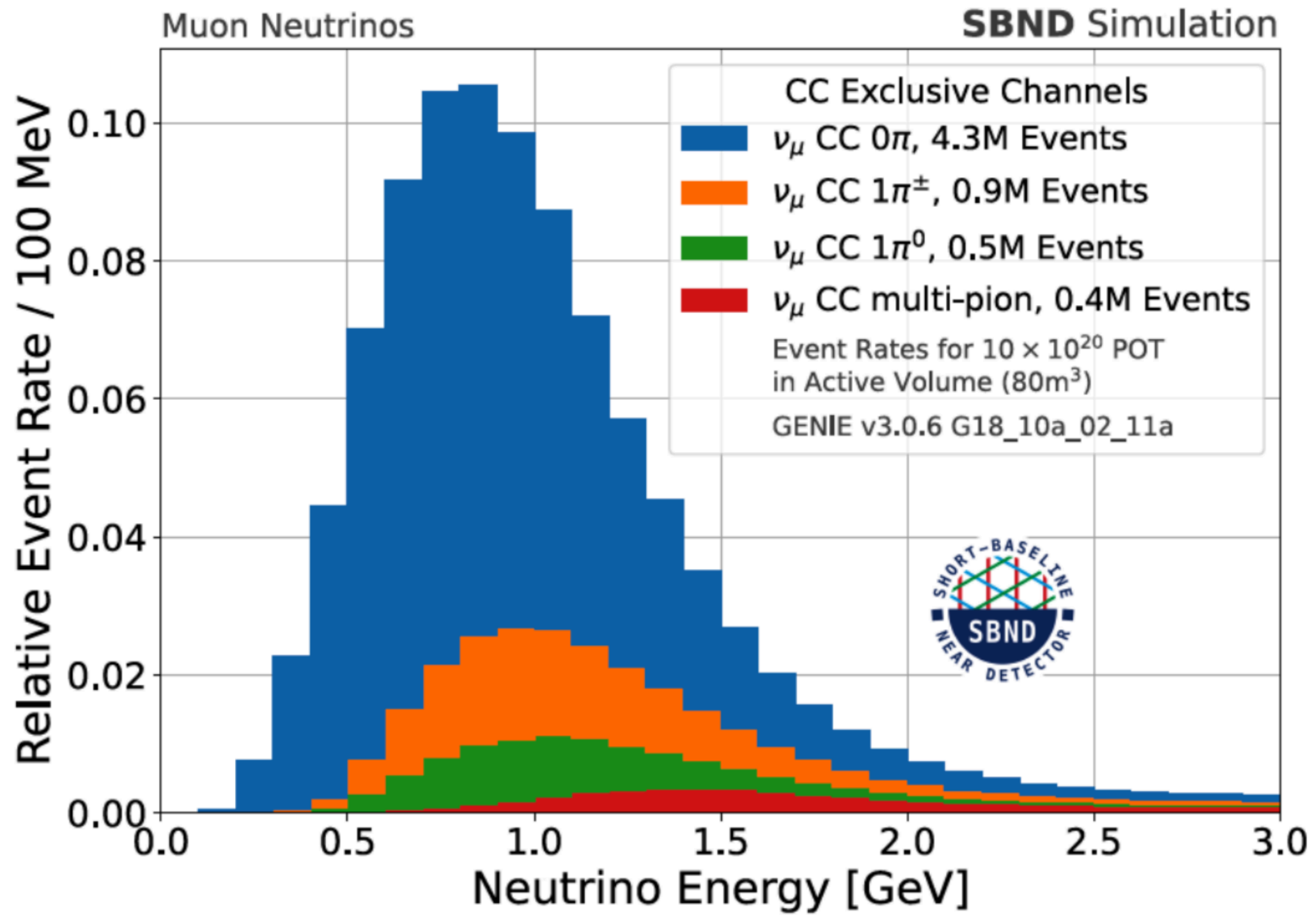
- SBND is the near detector of the Short-Baseline Neutrino Program, situated on the Booster Neutrino Beam (BNB)

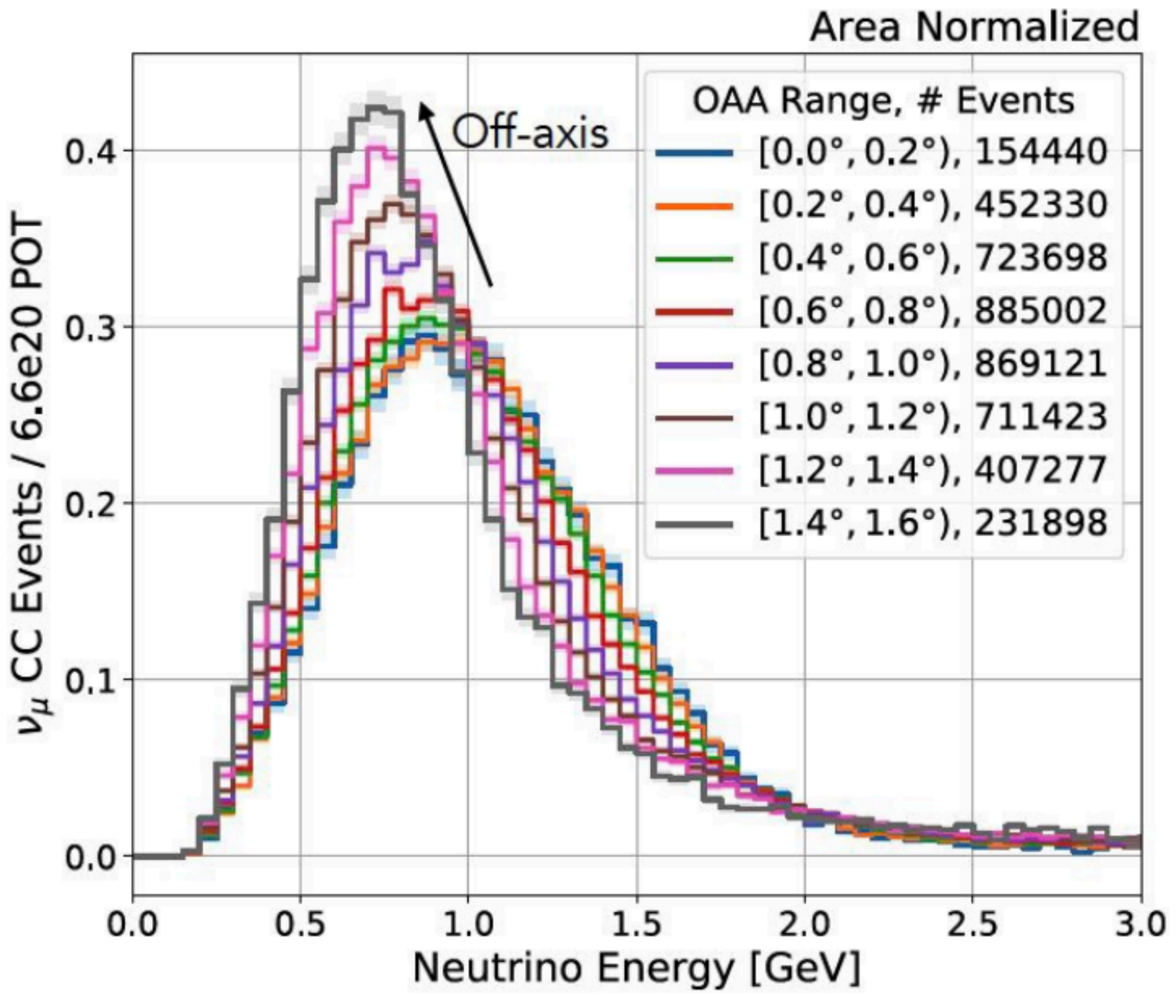
SBND Physics Program





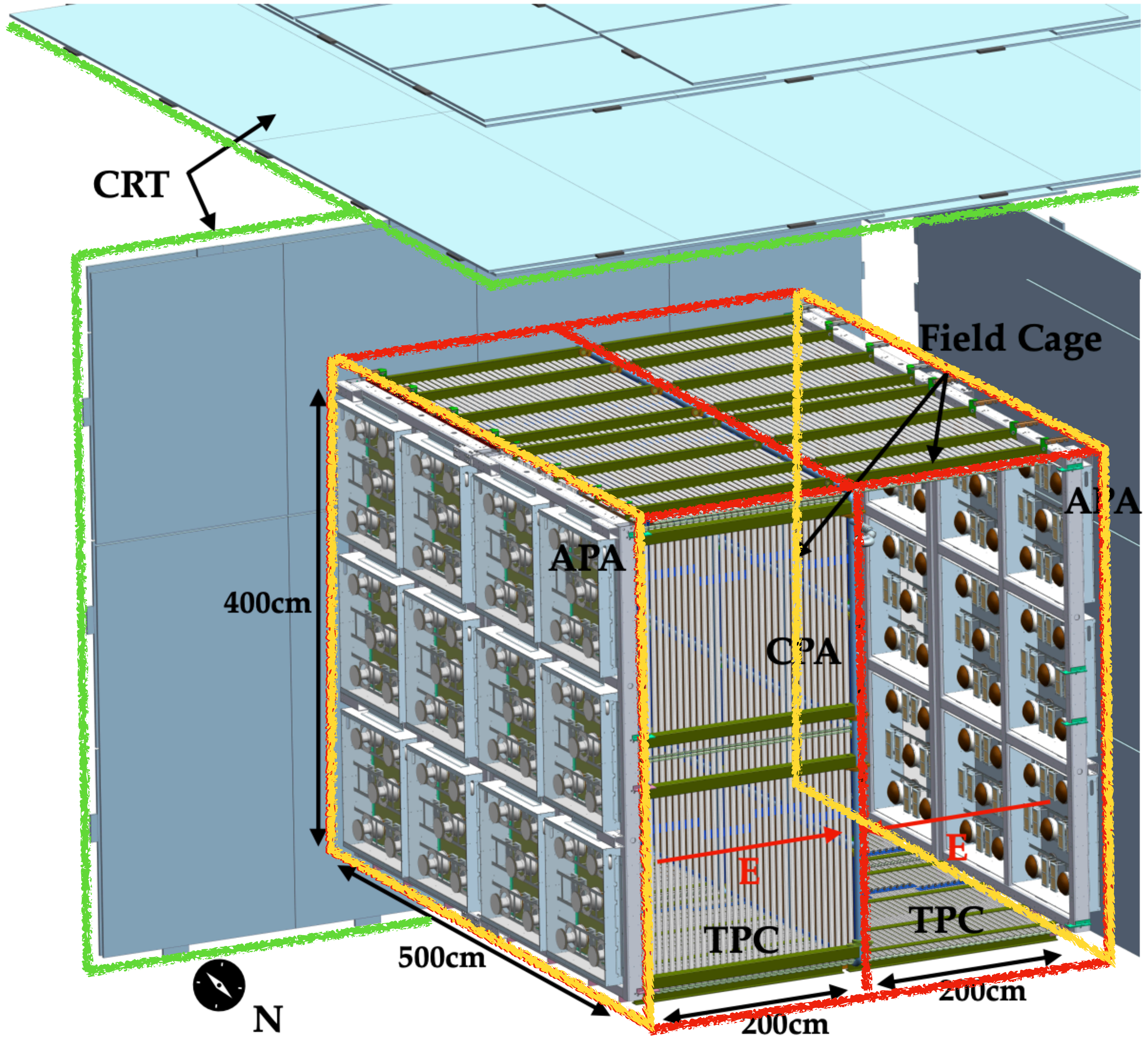






- **SBND will record the largest dataset of of neutrino-Argon interactions to date**
- **neutrino-nucleus interactions**
  - mature early data analyses: CC ν_μ inclusive, CC ν_e inclusive, CC $\nu_\mu 1p0\pi$ (stay tuned for this summer!)
  - SBND PRISM (off-axis flux effect)
- **beyond the standard model scenarios**
  - HNLs, dark neutrinos, light dark matter, many more…
- **neutrino oscillations**
  - near detector to constrain systematic uncertainties for oscillation analyses

SBND Detector

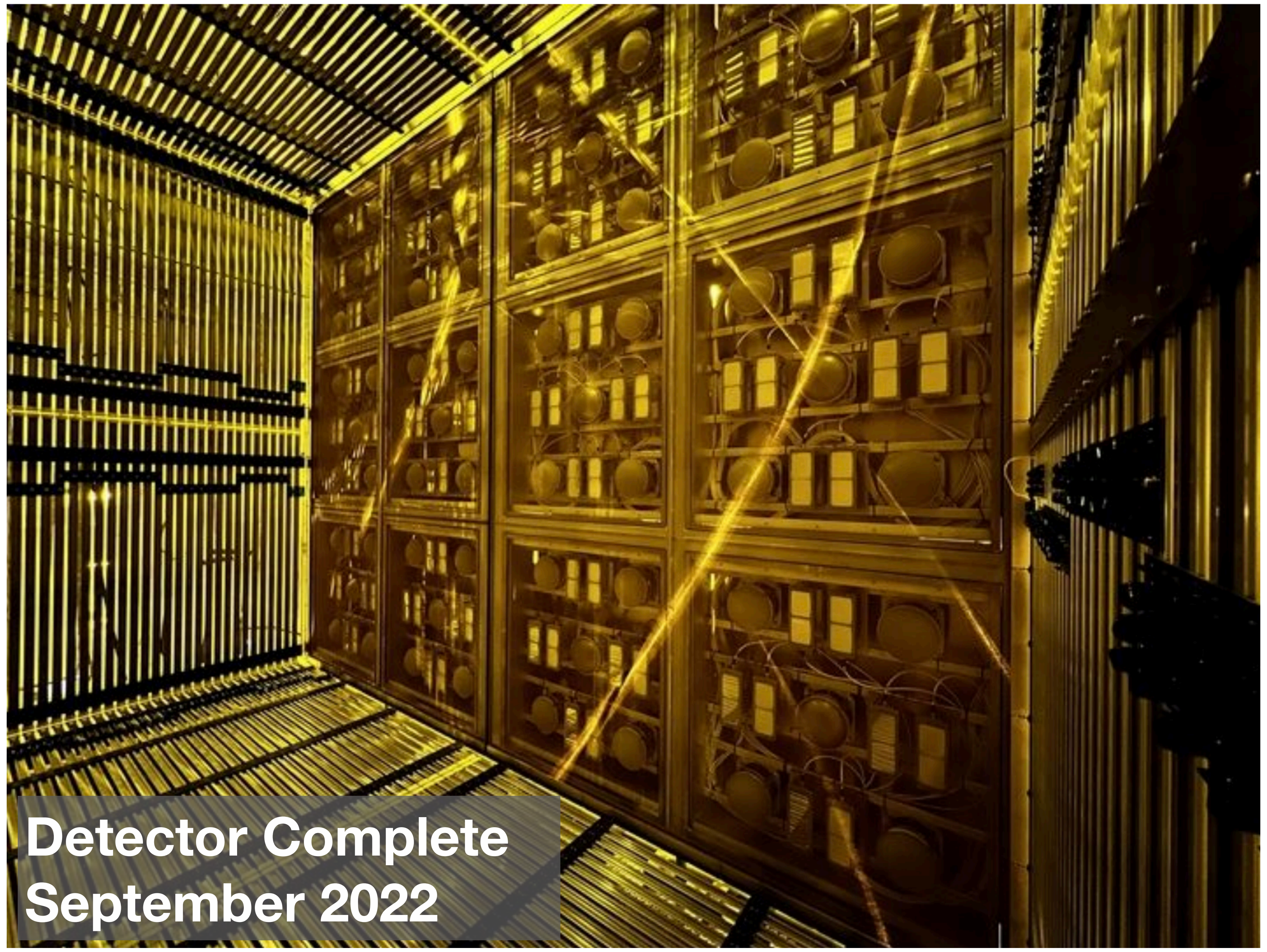


*north, east, bottom CRT panels not pictured

- Liquid Argon Time Projection Chambers (2 drift volumes)
- Photon Detection System (PDS)
  - outfitted with *312* photo-detectors (120 PMTs and 192 X-ARAPUCAs)
  - TPB-coated reflective cathode
  - can see both visible and VUV light
- Cosmic Ray Tagger (CRT)
  - a total of 7 CRT planes for full coverage around the SBND detector

SBND Status

- currently commissioning the detector!



Detector Complete
September 2022

Detector Move to ND building
December 2022

Detector Lowered into Cryostat
April 2023

LAr Fill Complete
March 2024

Wire-Cell in SBND

- Wire-Cell *Prototype*, or WCP, was originally developed alongside the needs of MicroBooNE

- Wire-Cell *Toolkit*, or WCT, is under active development and has integration in SBND, ProtoDUNE (SP, HD, VD), and ICARUS

- SBND in particular has ushered in several novel studies and features:

  - further DNN ROI development, implementation soon (Mun's talk yesterday!)

  - **signal processing *optimization* and comprehensive validation**

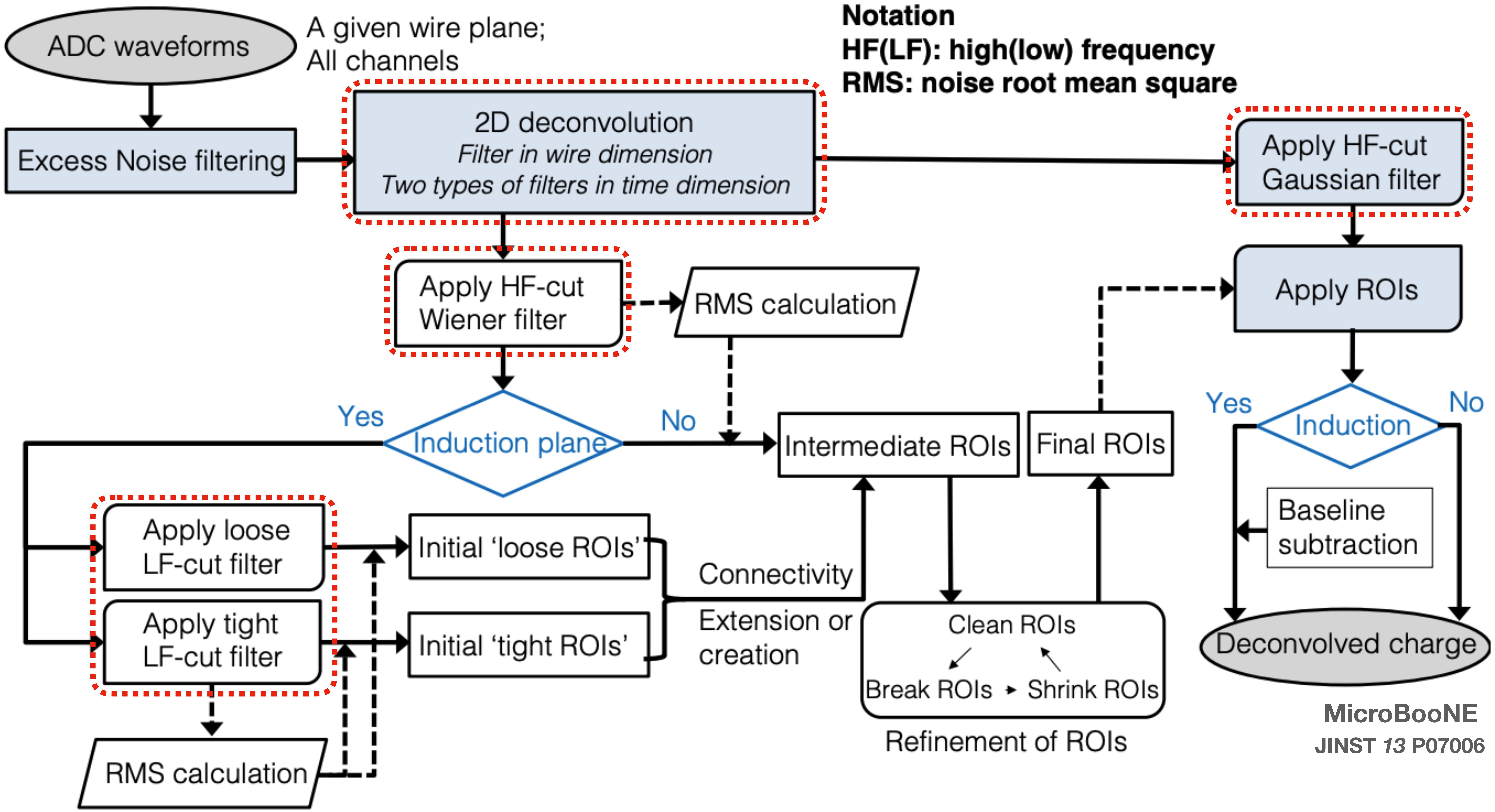
  - **3D imaging implementation and validation**

  - more to come!

Signal Processing in SBND

Optimization

→ filters we optimized

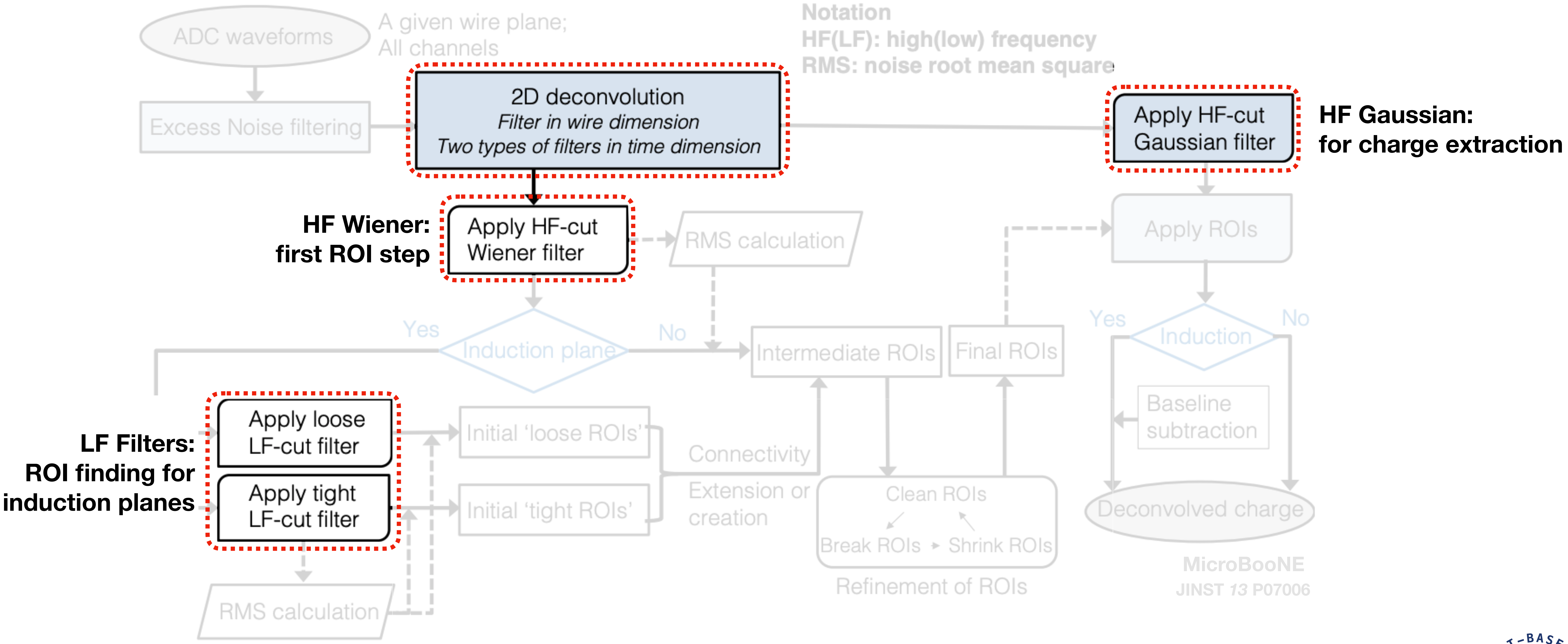


MicroBooNE
JINST *13* P07006

Signal Processing in SBND

Optimization

→ filters we optimized



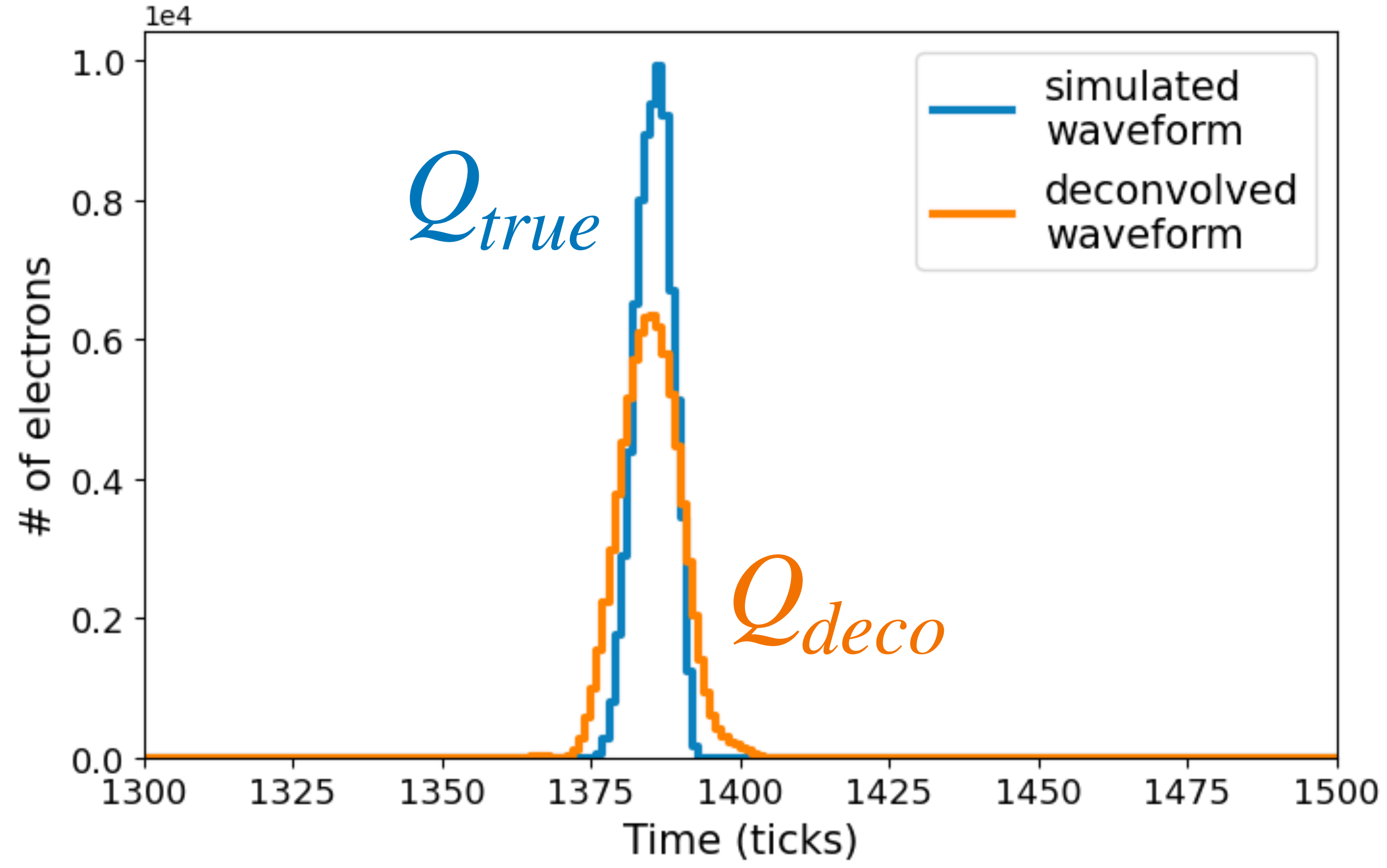
Signal Processing in SBND

Optimization

$$\text{performance metric} \equiv \frac{Q_{deco} - Q_{true}}{Q_{true}}$$

$Q_{true} \equiv$ sum of true charge on the wires

$Q_{deco} \equiv$ sum of deconvolved charge



- optimization and performance metric: *integrated* deconvolved charge vs. *integrated* simulated charge

Signal Processing in SBND

Optimization

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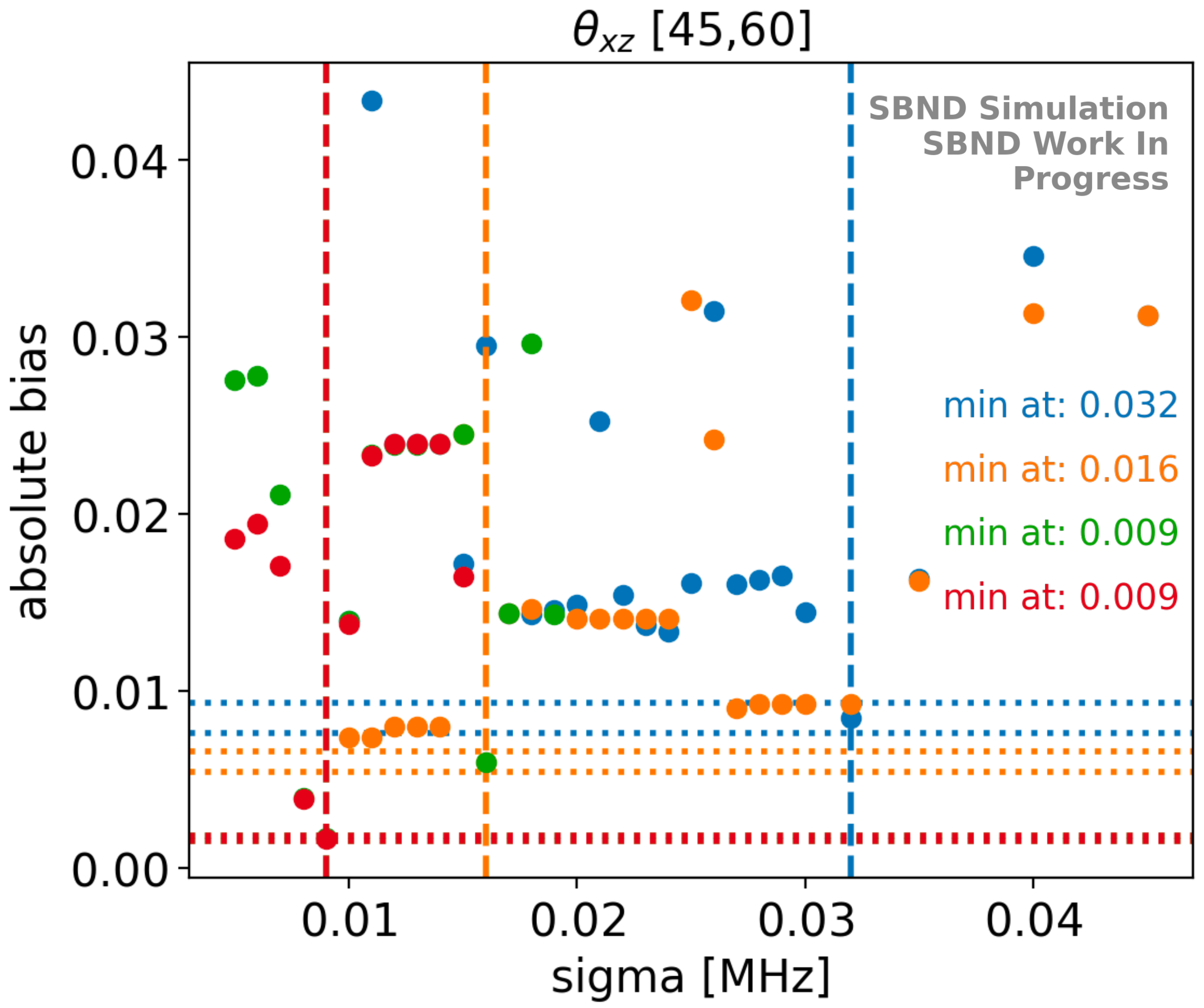
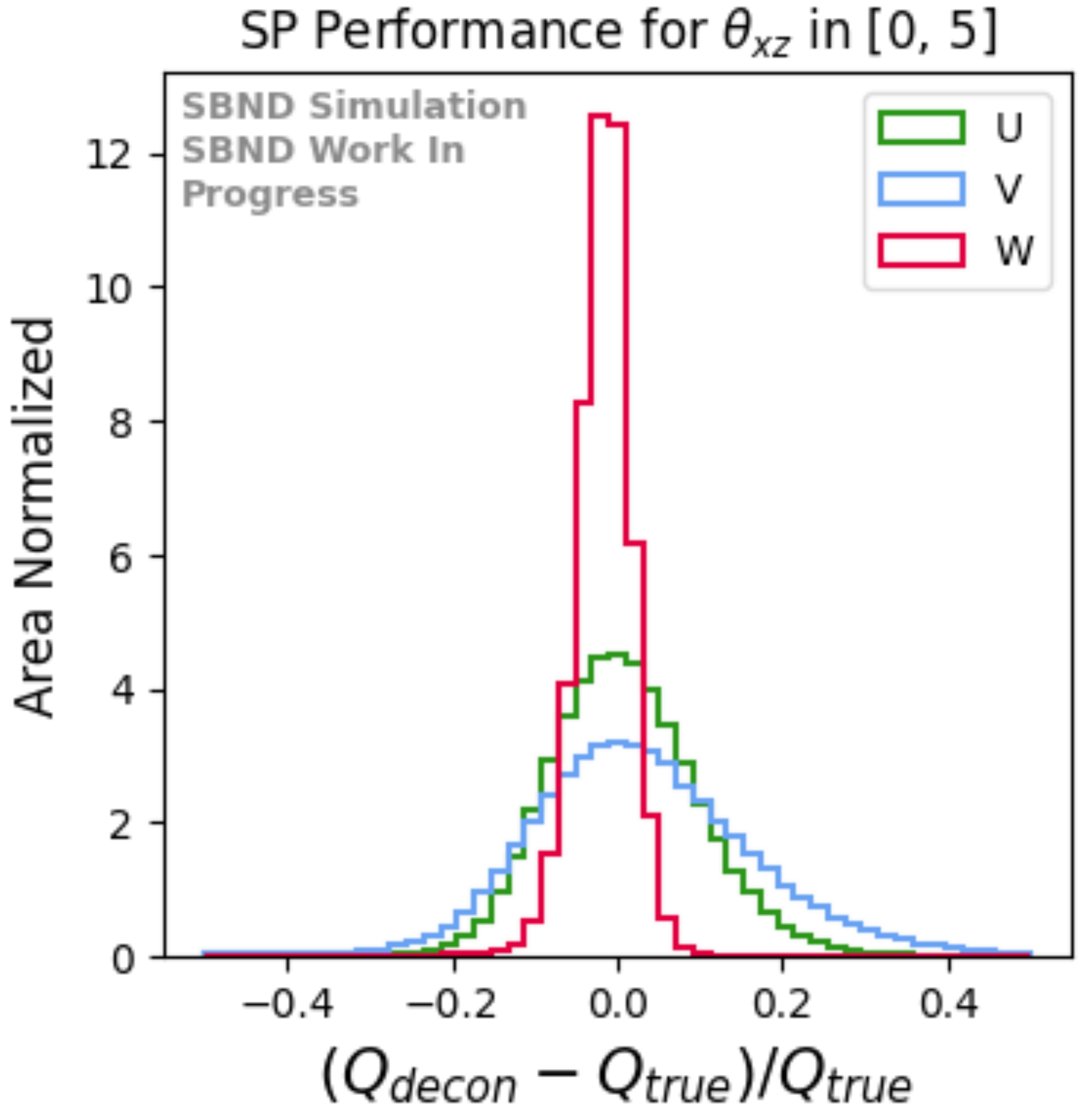


- optimization and performance metric: *integrated* deconvolved charge vs. *integrated* simulated charge
  - for optimization, we performed **coordinate descent** over filter parameters
  - minimize charge extraction bias and spread
    - choose filter values based on performance for all track angle ranges

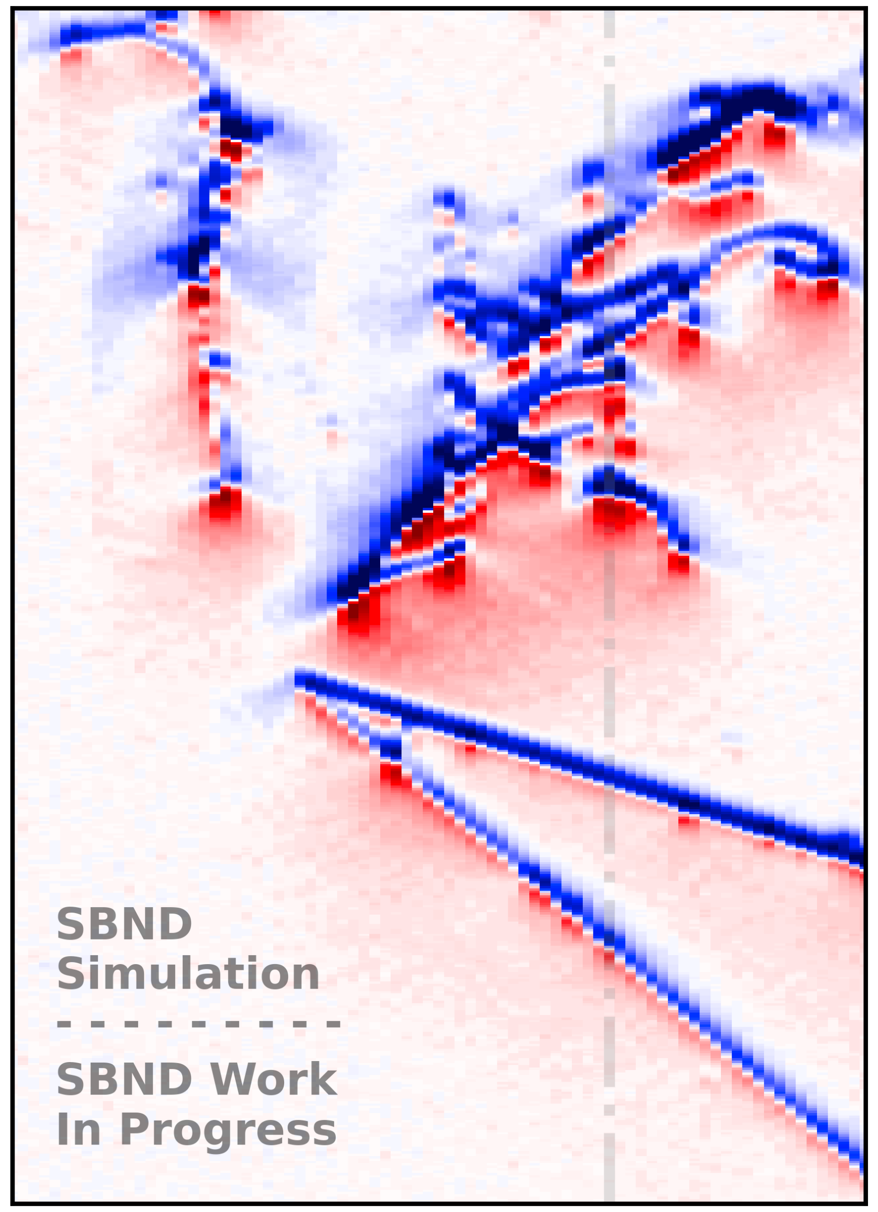


Signal Processing in SBND

Optimization

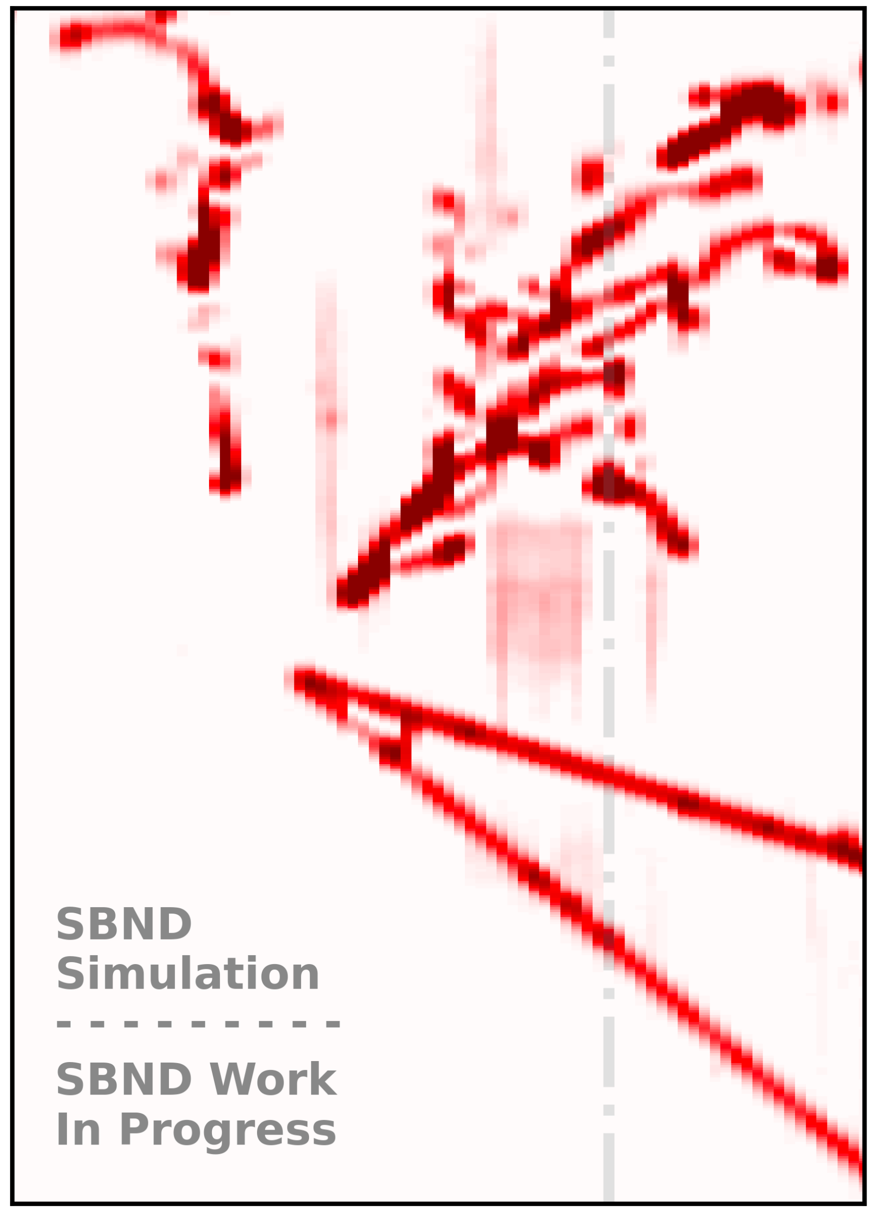
performance metric $\equiv \dfrac{Q_{deco} - Q_{true}}{Q_{true}}$

Raw Waveforms



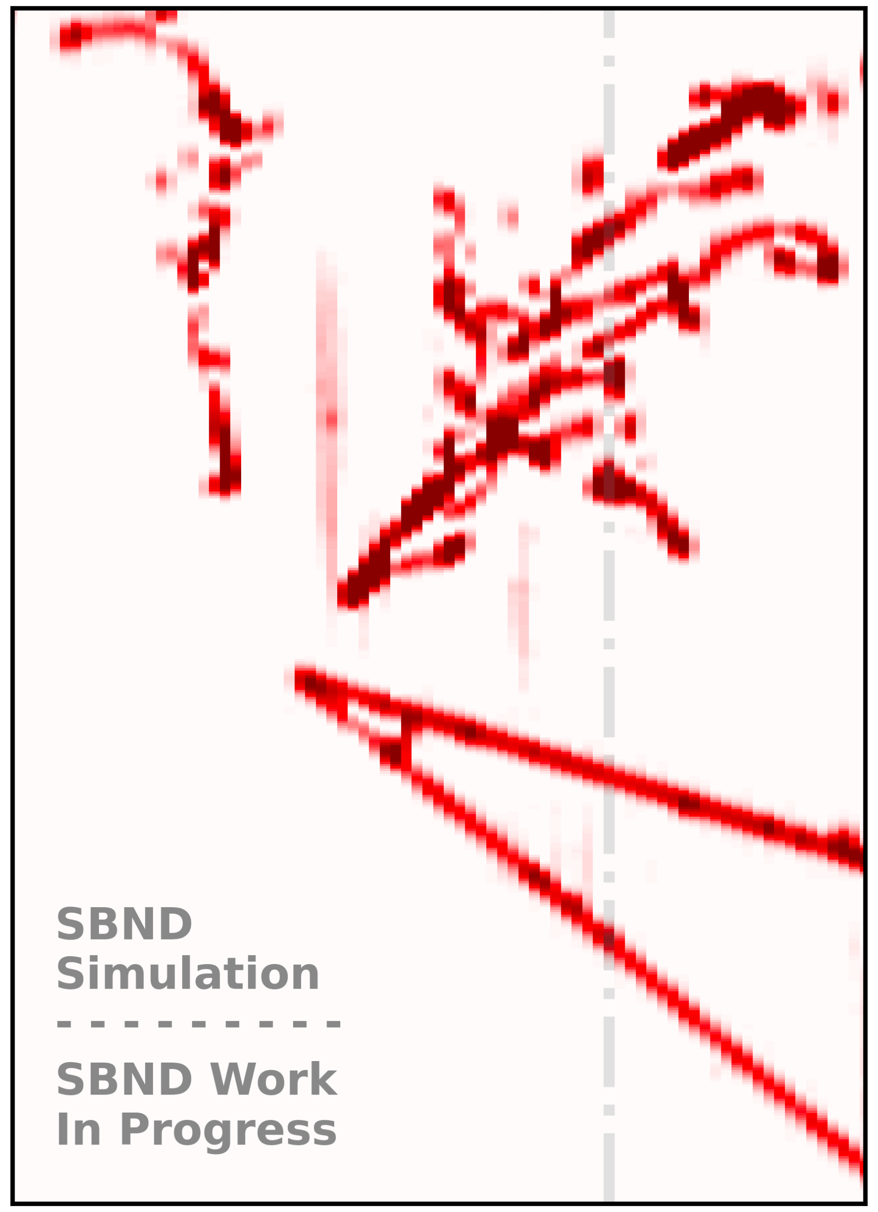
Using (default) filter values from uBooNE & ProtoDUNE

(Default) 2D Deco. + SP



***Using optimized SBND filter values**

Optimized 2D Deco. + SP



*further optimization is under development using ***DNN ROI***

see Mun's talk *yesterday for more details*

Signal Processing in SBND

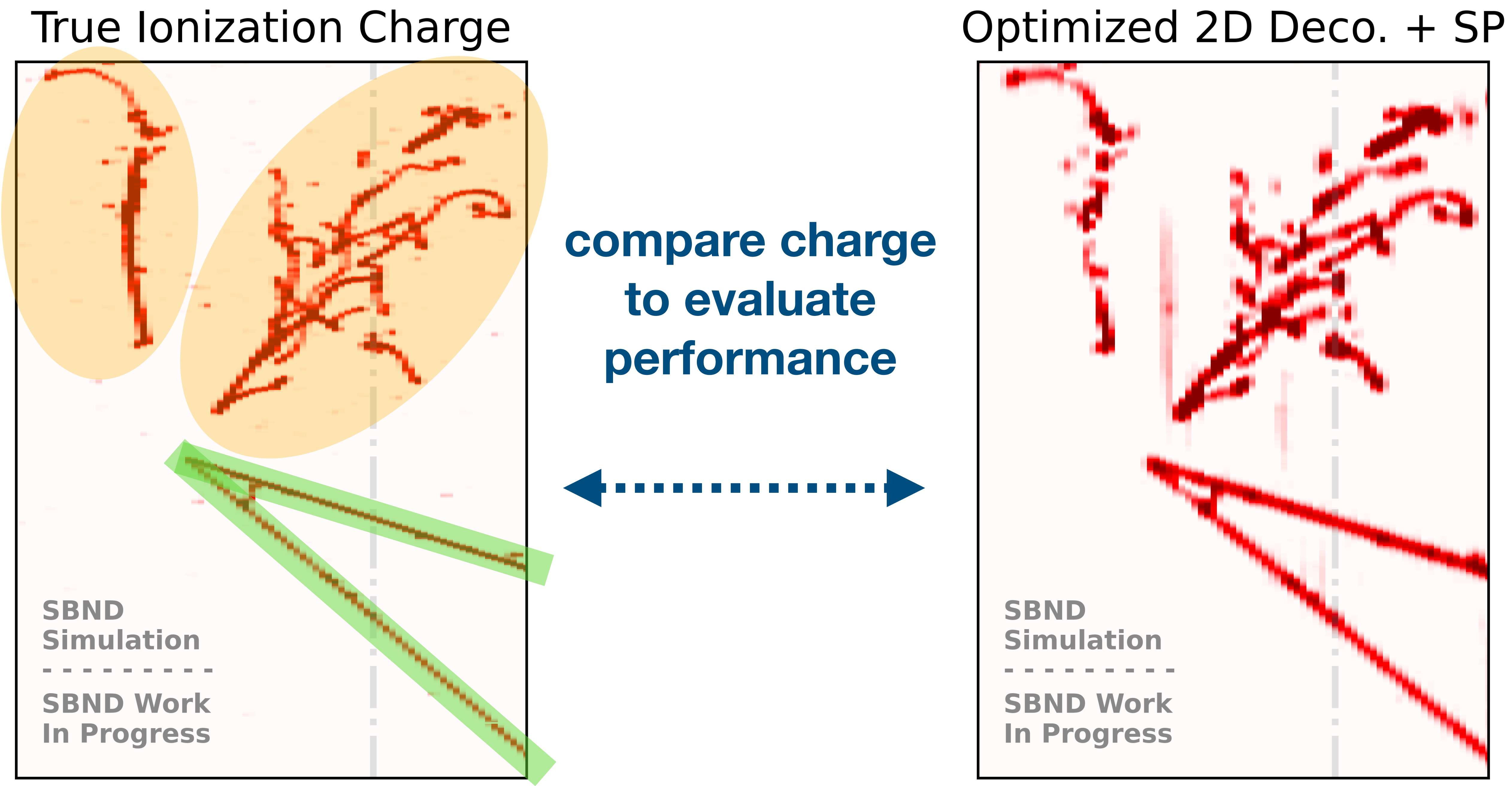
Performance

performance metric $\equiv \dfrac{Q_{deco} - Q_{true}}{Q_{true}}$

- we will use the same metric to evaluate the **signal processing performance** quantitatively

- performance evaluation is performed within *different particle types*

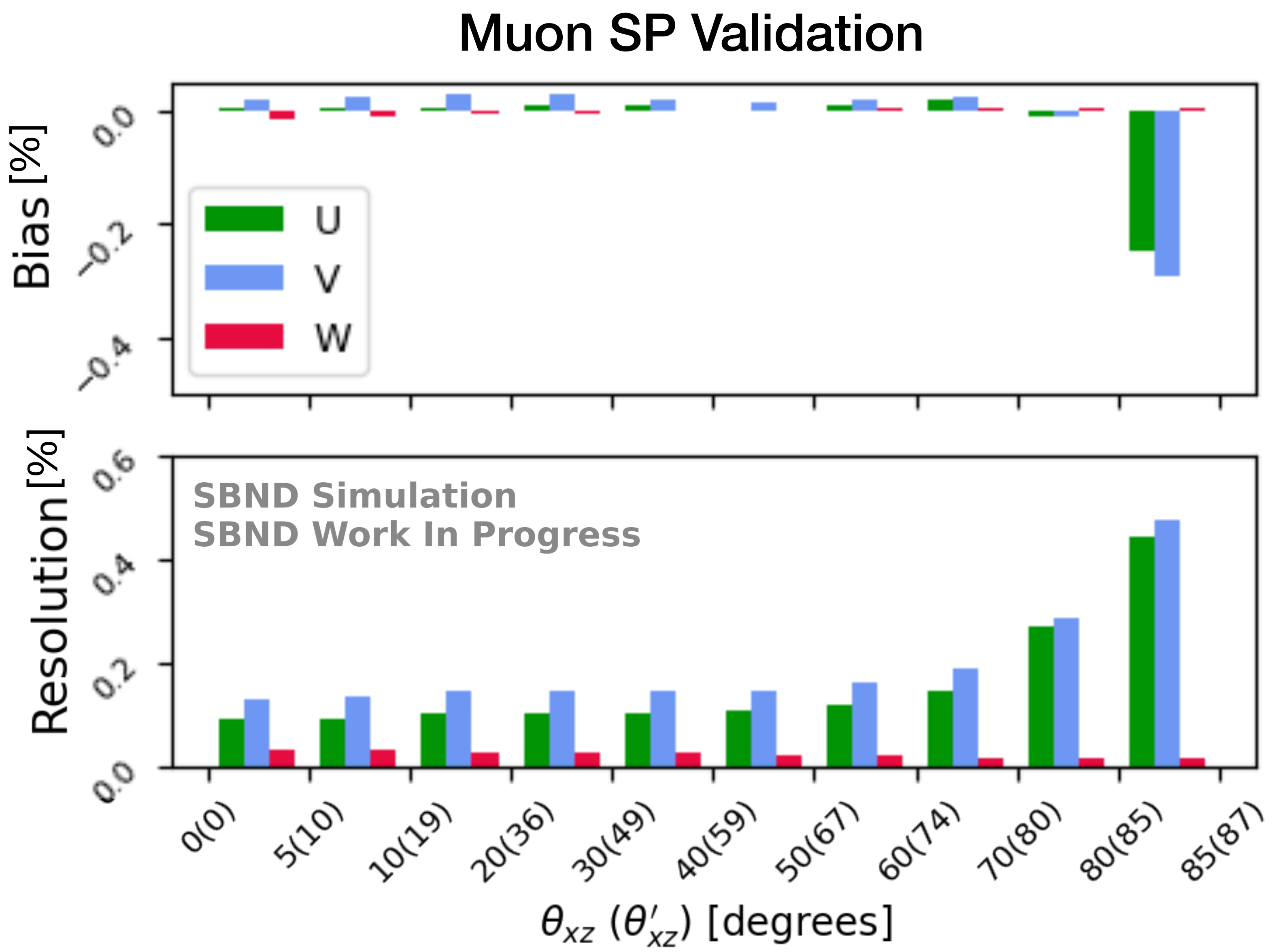
  - muons vs. protons (tracks) vs. electrons (showers)

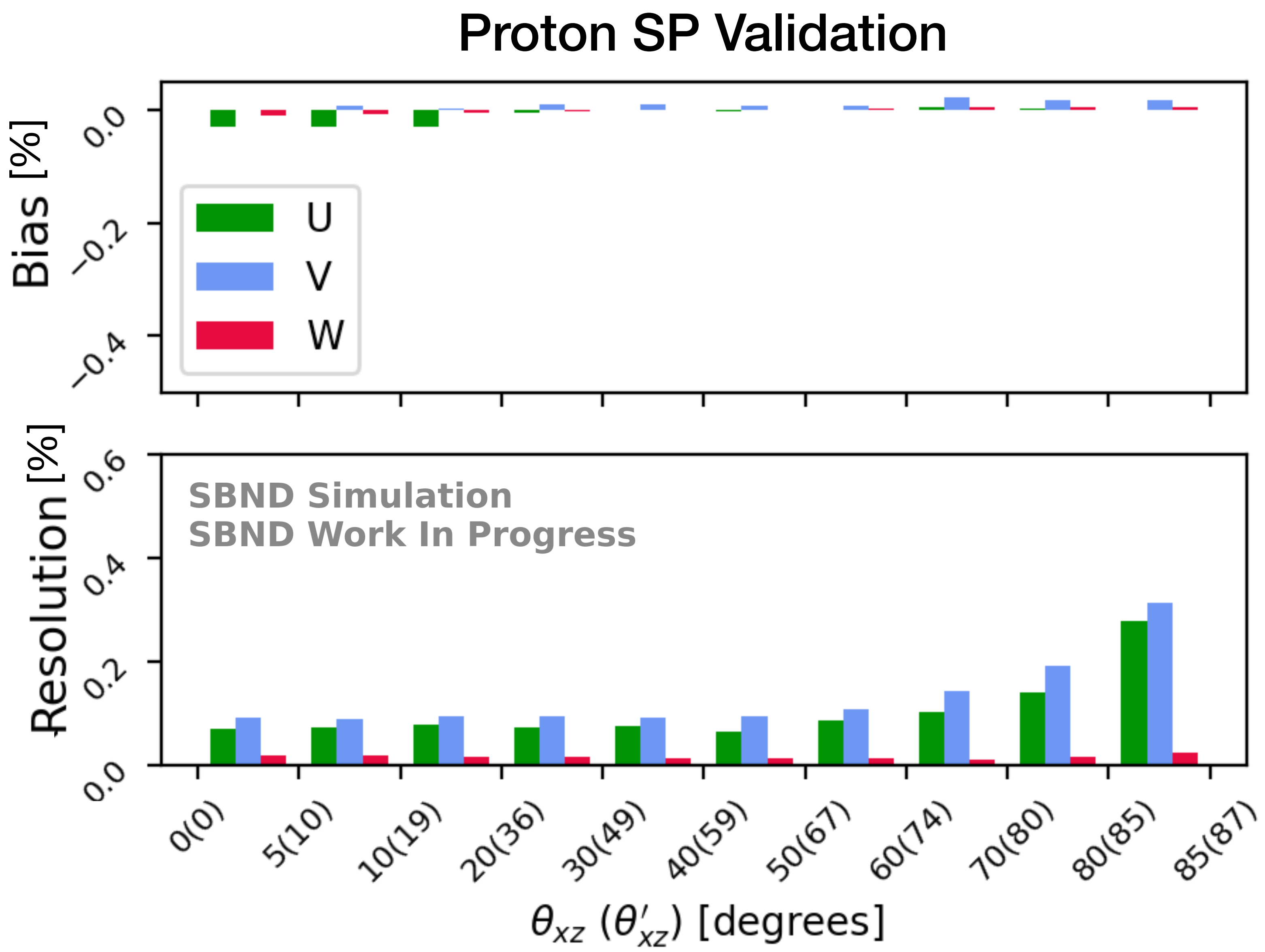


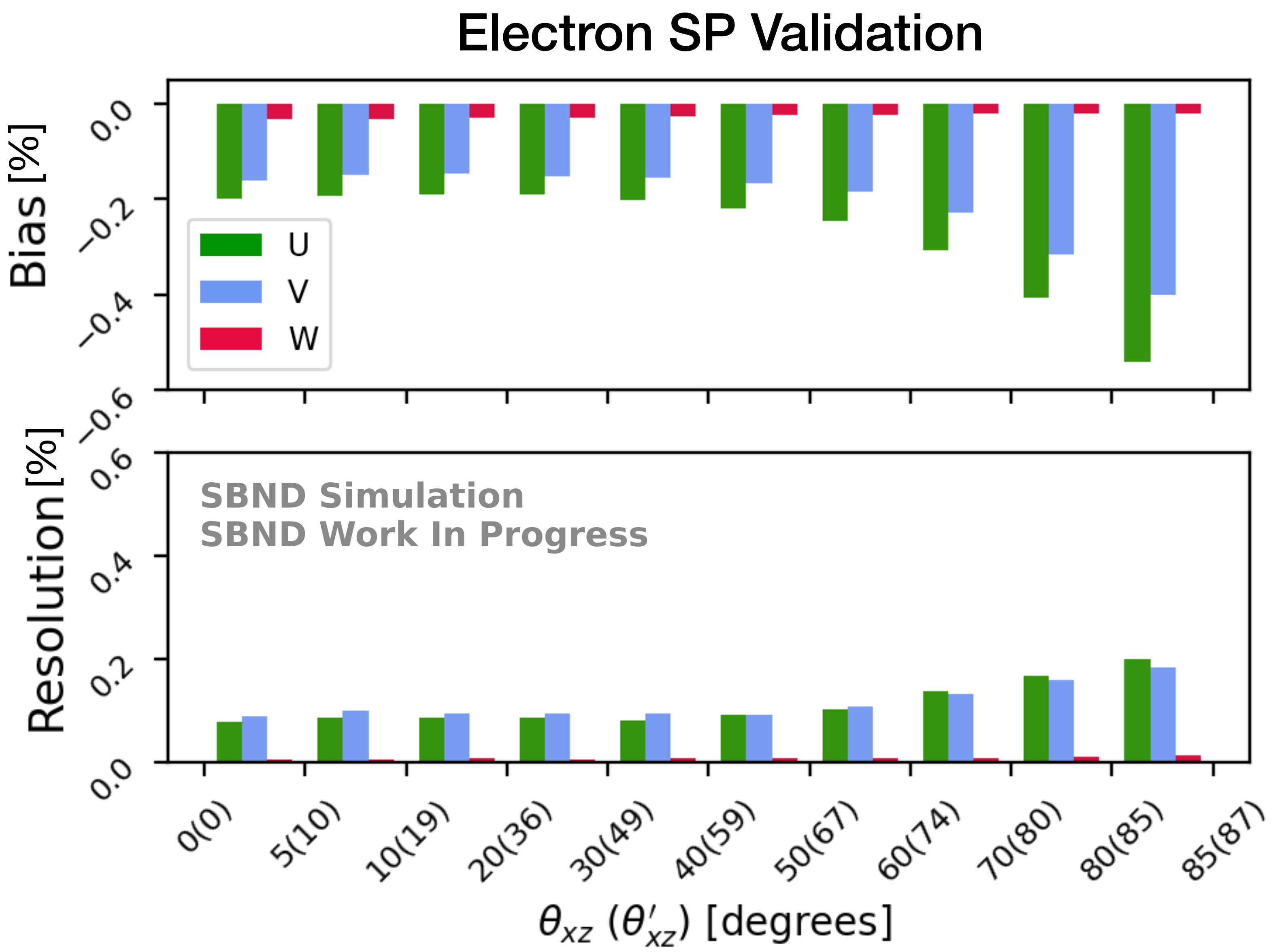
Signal Processing in SBND

Performance: All Particle Types

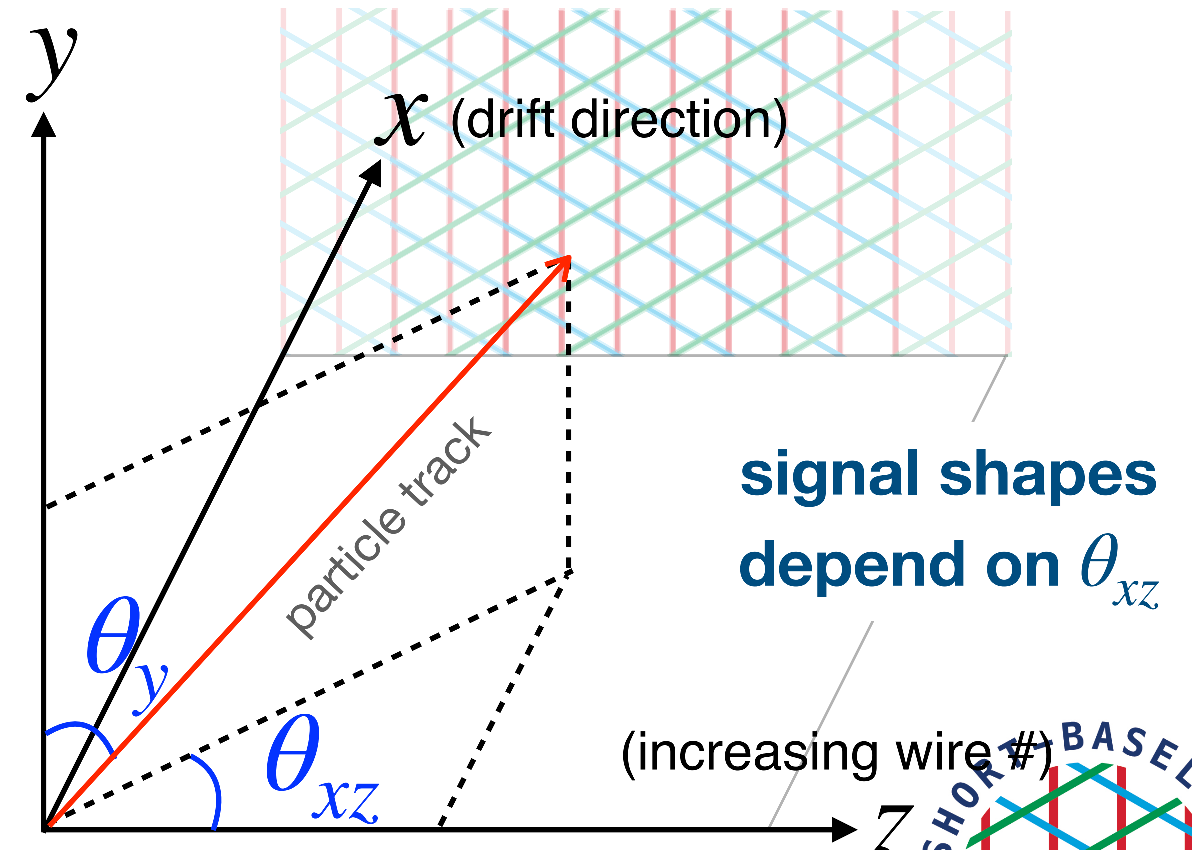
$$\text{performance metric} \equiv \frac{Q_{deco} - Q_{true}}{Q_{true}}$$







- **muons** (track-like minimizing-ionizing particles), **protons** (track-like stopping particles), and **electrons** (shower-like)
- overall, performance is good and the observed trends are expected!
- the first particle-type specific WireCell signal processing studies

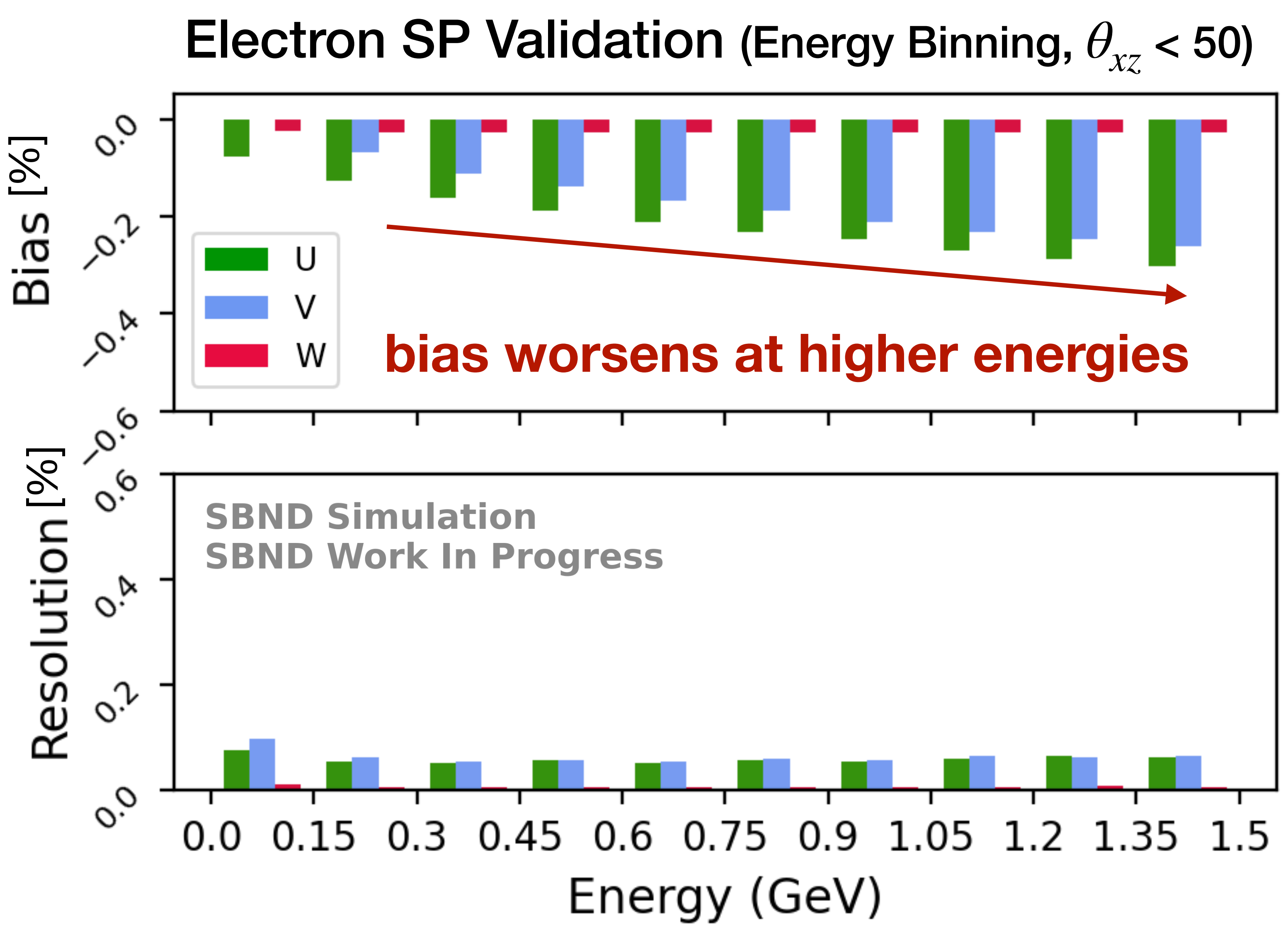


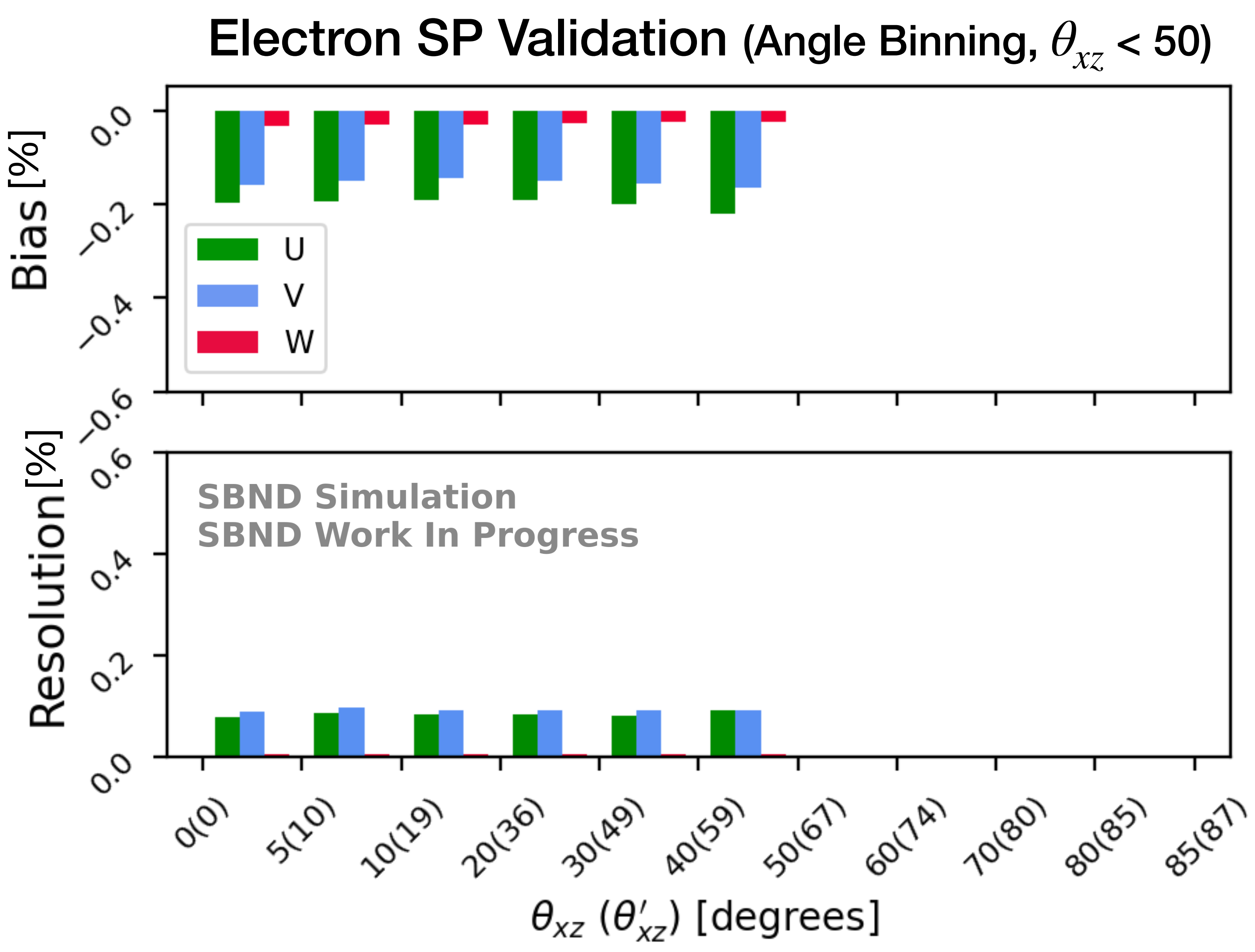
Signal Processing in SBND

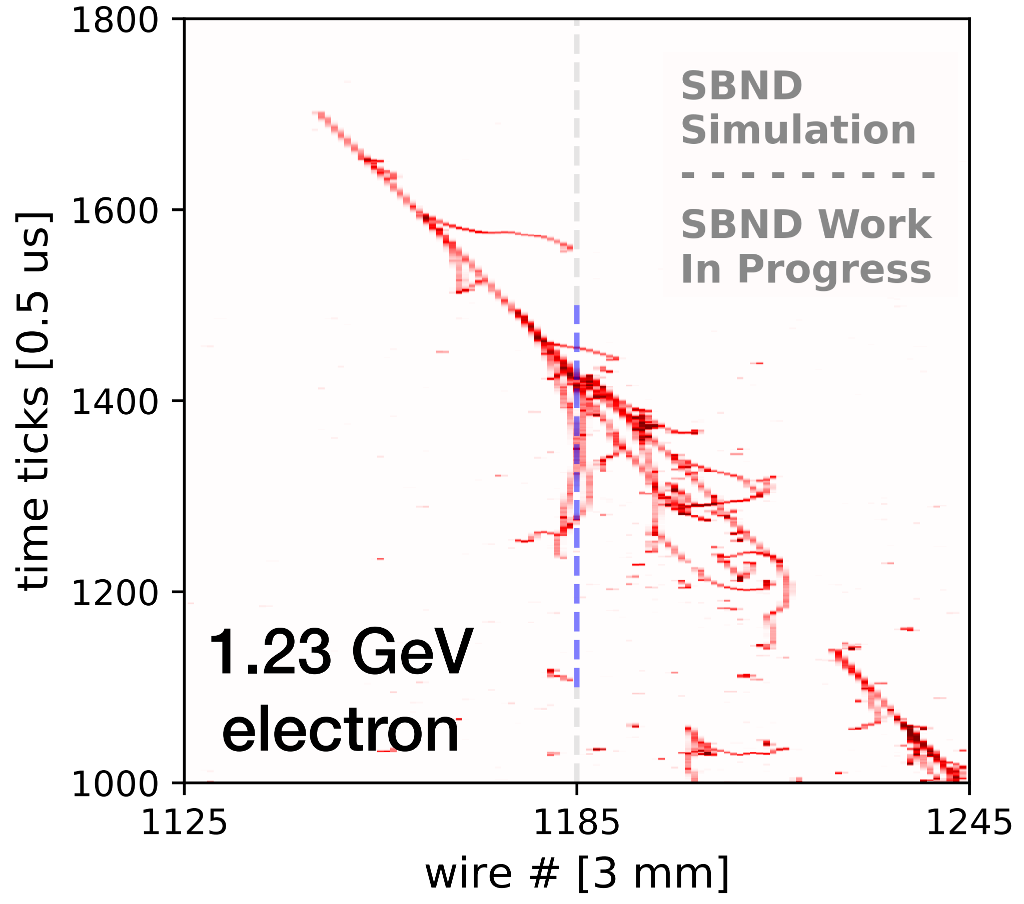
Performance: Electron case

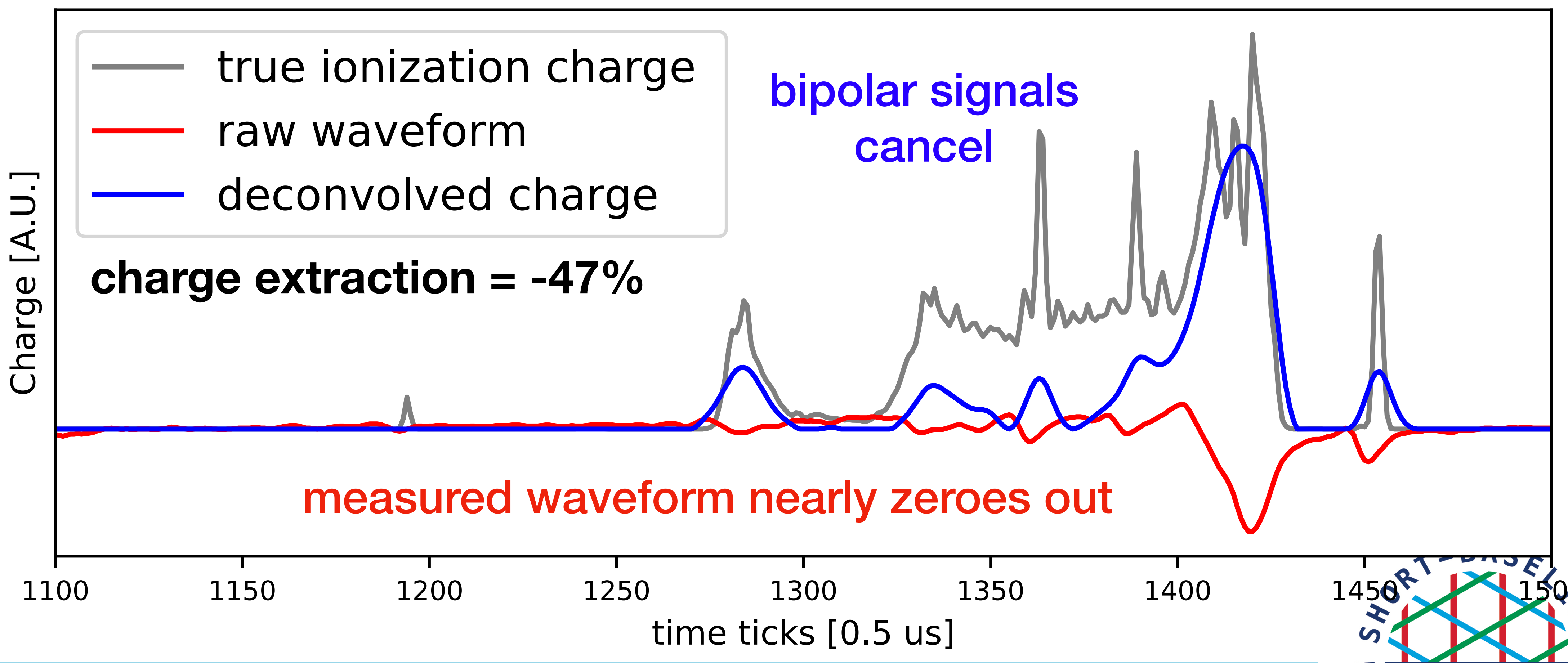
performance metric $\equiv \dfrac{Q_{deco} - Q_{true}}{Q_{true}}$

- the **bias becomes increasingly negative with increasing energy** (for induction planes)
  - resolution is stable
- at higher energies, shower topologies become more complicated
  - bipolar cancellation and prolonged tracks become more frequent



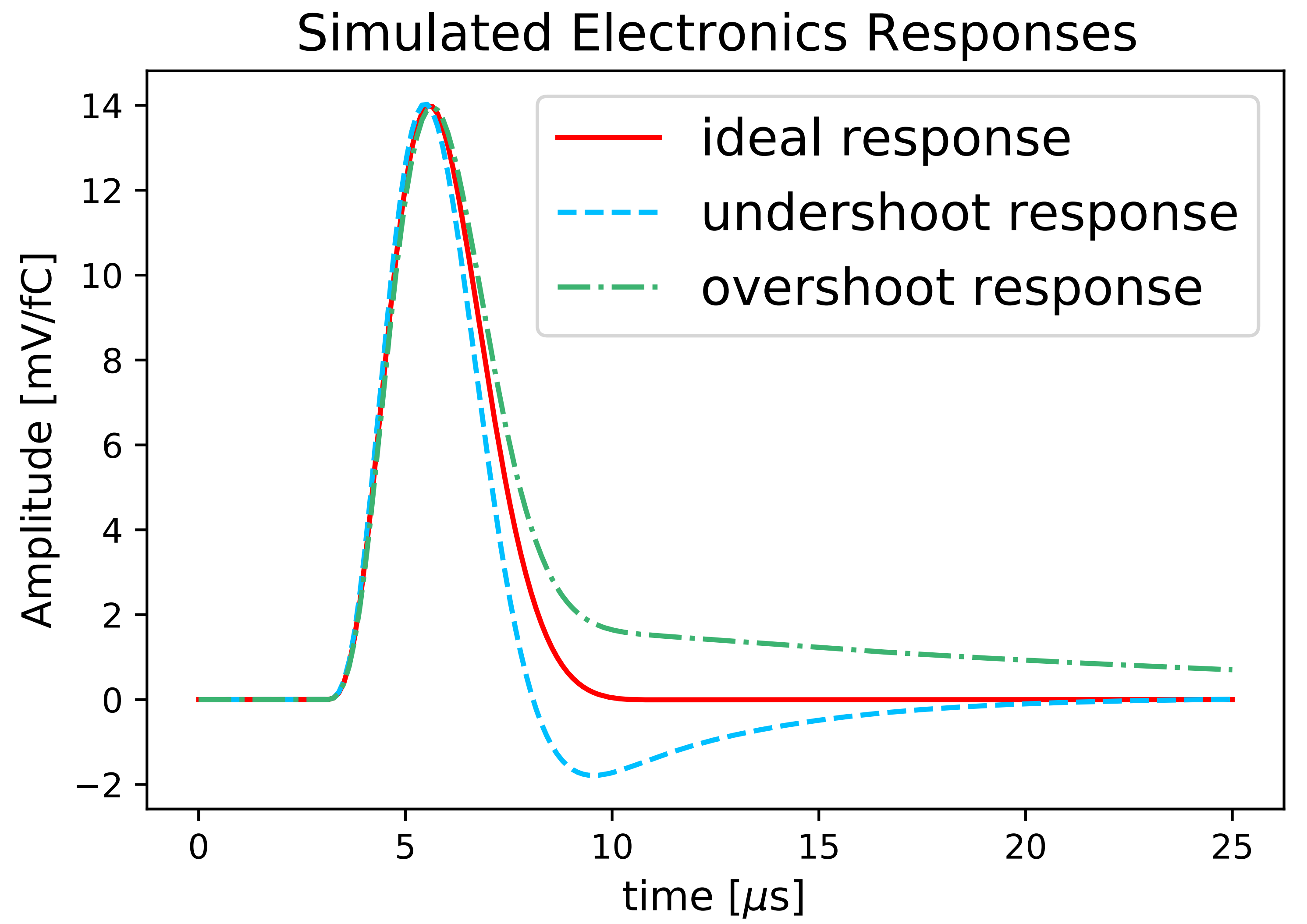


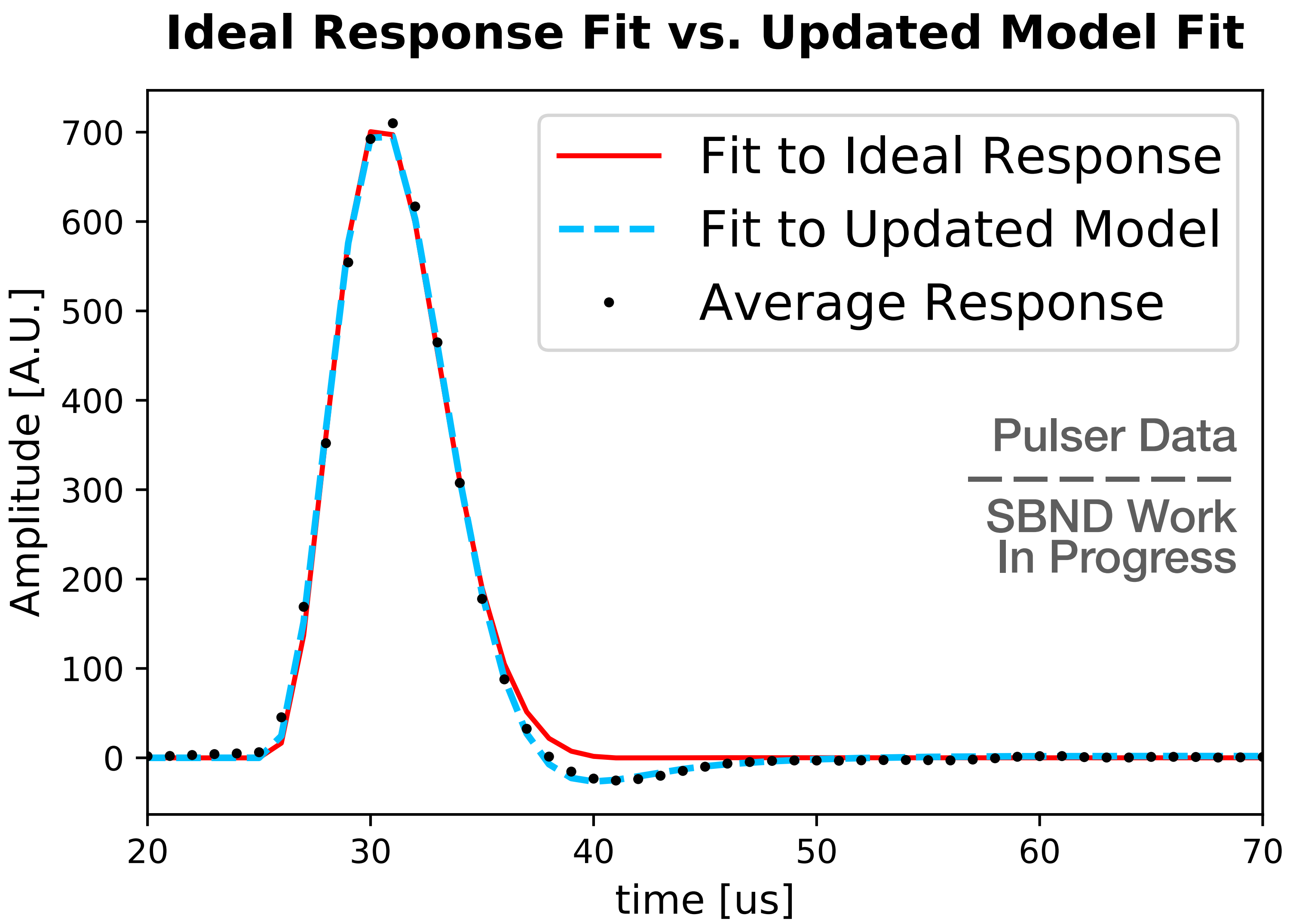




Signal Processing in SBND

Electronics Response





- electronics response (shaping, amplifying) is an important component of 2D deconvolution

$$T(s) = \frac{A_0 \cdot C_A}{(p_0 + s) \cdot (p_{i1}^2 + (p_{r1} + s)^2) \cdot (p_{i2}^2 + (p_{r2} + s)^2)},$$

ideal response (semi-Gaussian anti-aliasing filter)

- the *ideal response* does not account for effects seen in data such as **overshoot** and **undershoot**
- realistic response includes imperfect pole-zero cancellation

$$T_1(s) = T(s) \cdot \frac{(k_3 + s)(k_4 + s)}{(k_5 + s)(k_6 + s)}$$

updated response

- we are validating and implementing this updated electronics model in the SBND Calibrations workflow, working together with ProtoDUNE WireCell team

Signal Processing in SBND

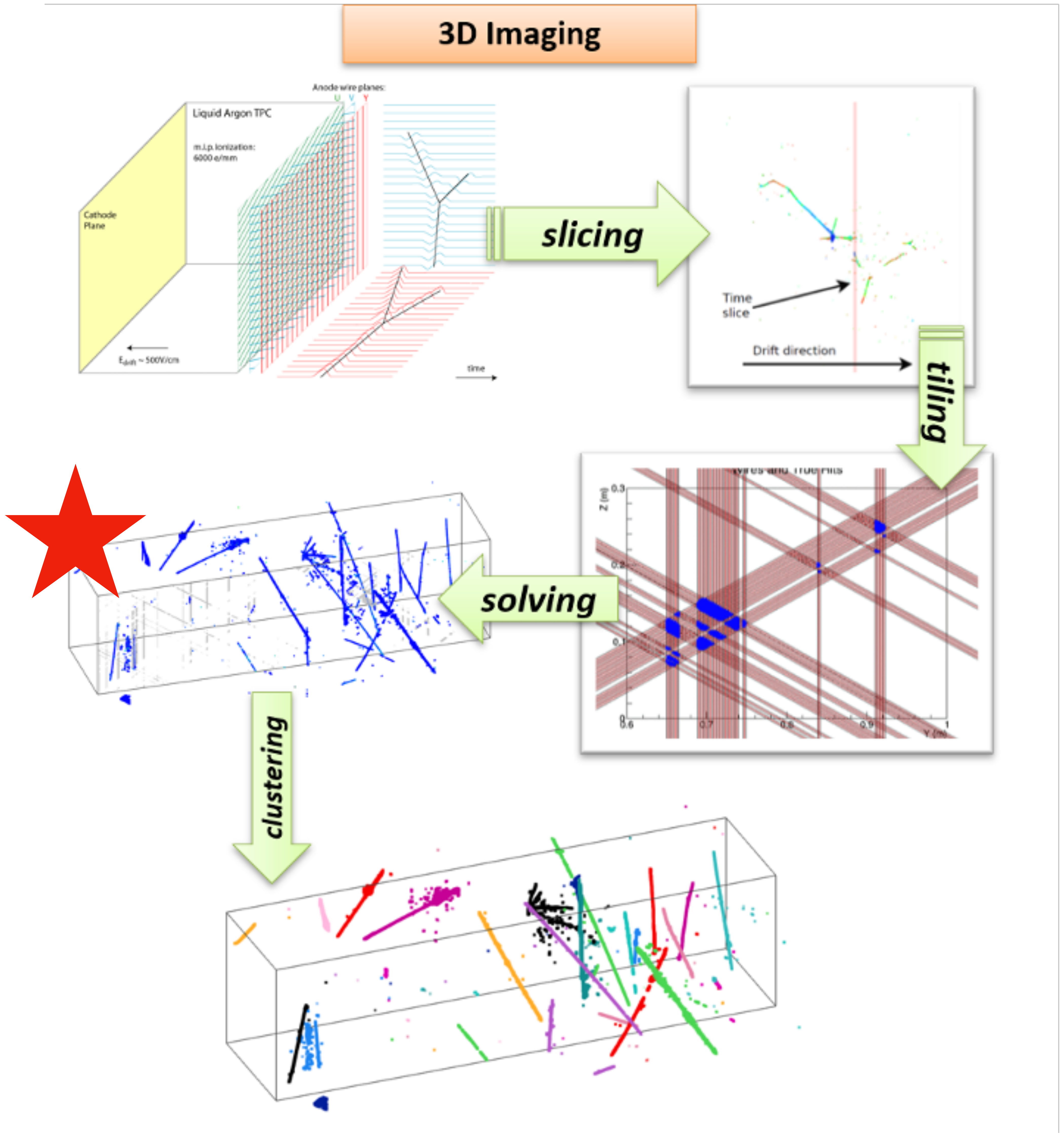
- in summary, we have:
  - (first-pass) optimized SP filter values on simulation
  - evaluated SP performance of different simulated particle types (muon, proton, electrons)
  - performed studies on the energy dependence of electron signal processing
- WireCell TPC simulation and signal processing is fully implemented and validated in the official SBND workflow!
  - WireCell Drift+SP is used by default in the next SBND production campaign
- next task… 3D imaging!

3D Imaging in SBND

- more details about imaging and reconstruction will be presented on Friday by Haiwang:

9:10 AM | **Wire-Cell Pattern Recognition and AI/ML**
Speaker: Haiwang Yu (Brookhaven National Laboratory)

- for SBND, we have reached the “charge solving” and *proto-clustering* stage in the 3D imaging workflow
    - “physics-related” clustering (clustering by particle or interaction) is still in-progress

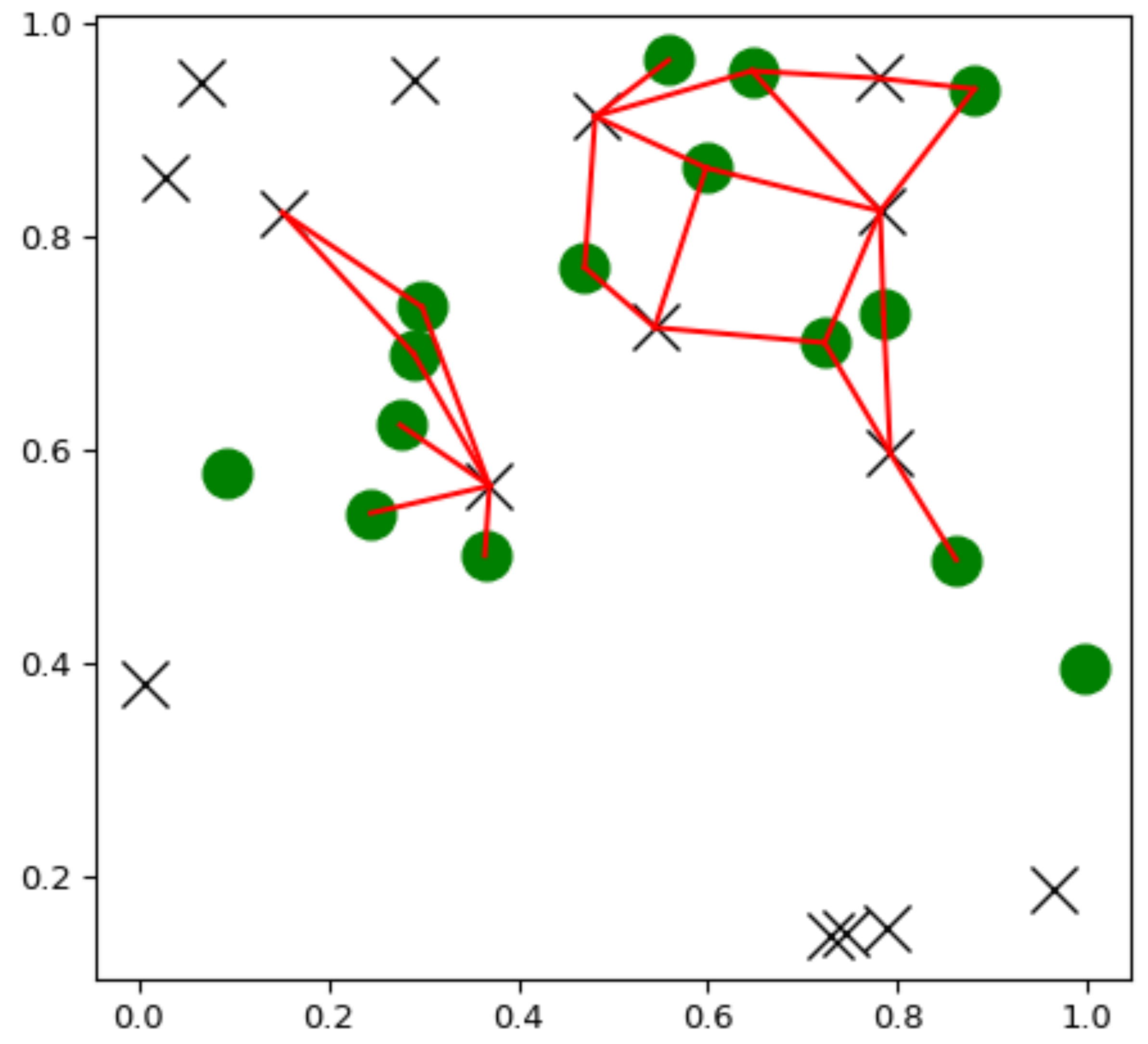


3D Imaging in SBND

Evaluation Method

- we performed *quantitative* evaluation of 3D imaging performance for the first time using: scipy.spatial.KDTree.query_ball_tree
    - matches pairs between points of two points clouds with arbitrary dimension

KDTree query_ball_tree example matching



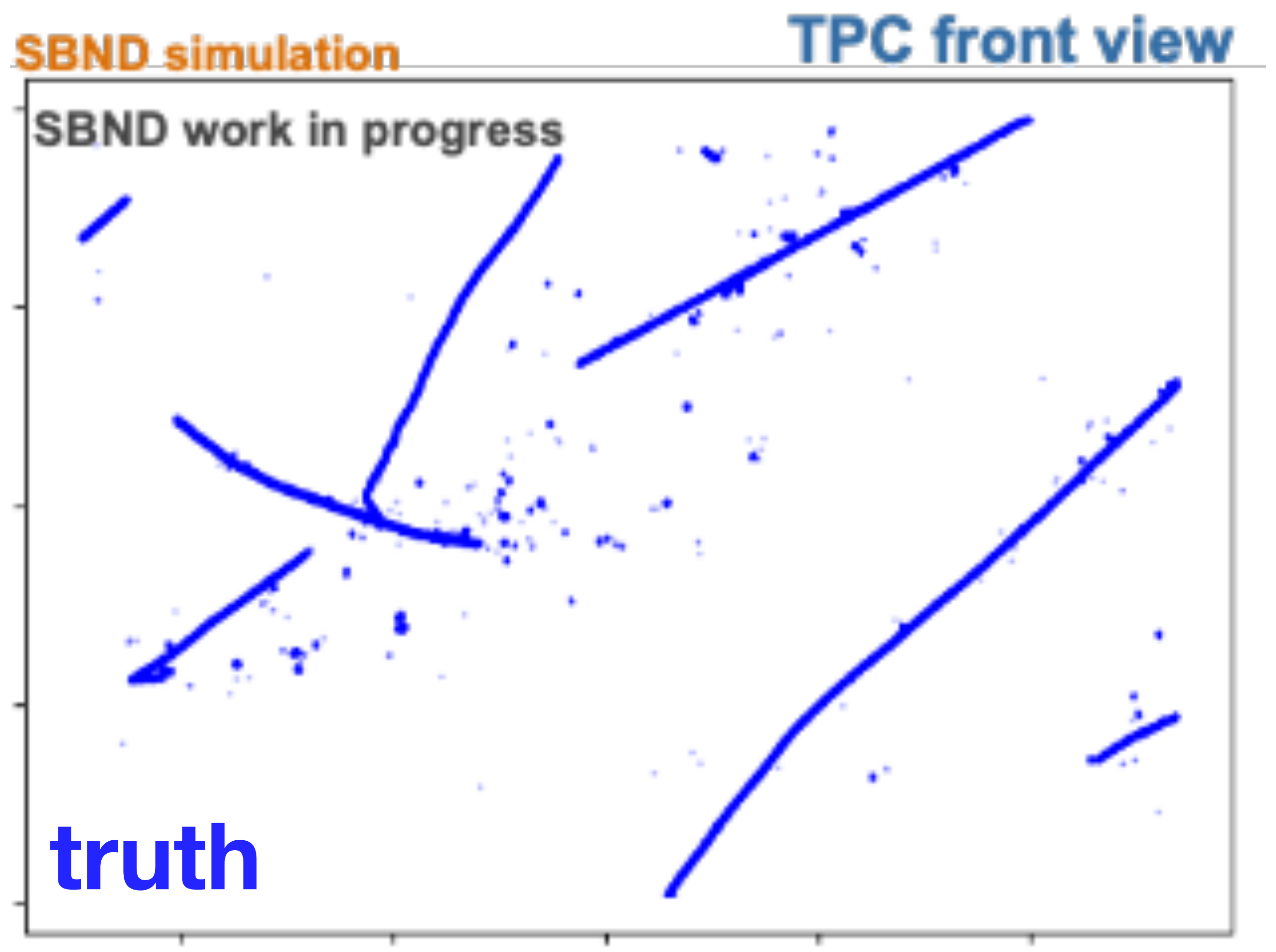
scipy documentation

- preliminary performance metrics:

$$\text{completeness} \equiv \frac{\text{true charge matched to image point}}{\text{total true charge}}$$

$$\text{purity} \equiv \frac{\text{image charge matched to true point}}{\text{total image charge}}$$

3D Imaging in SBND
Evaluation Method

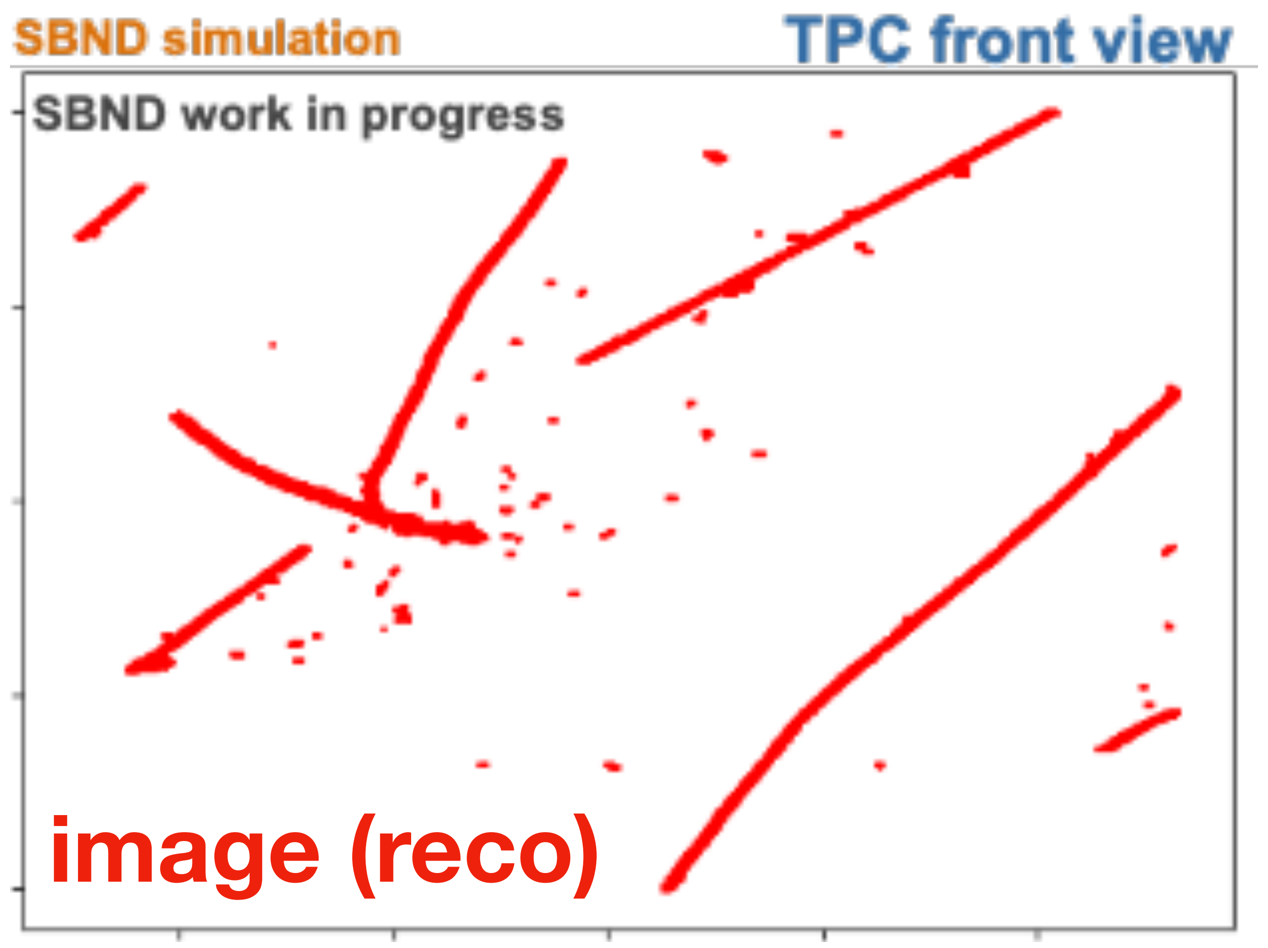


completeness

what percentage of
true charge is present
in the image?

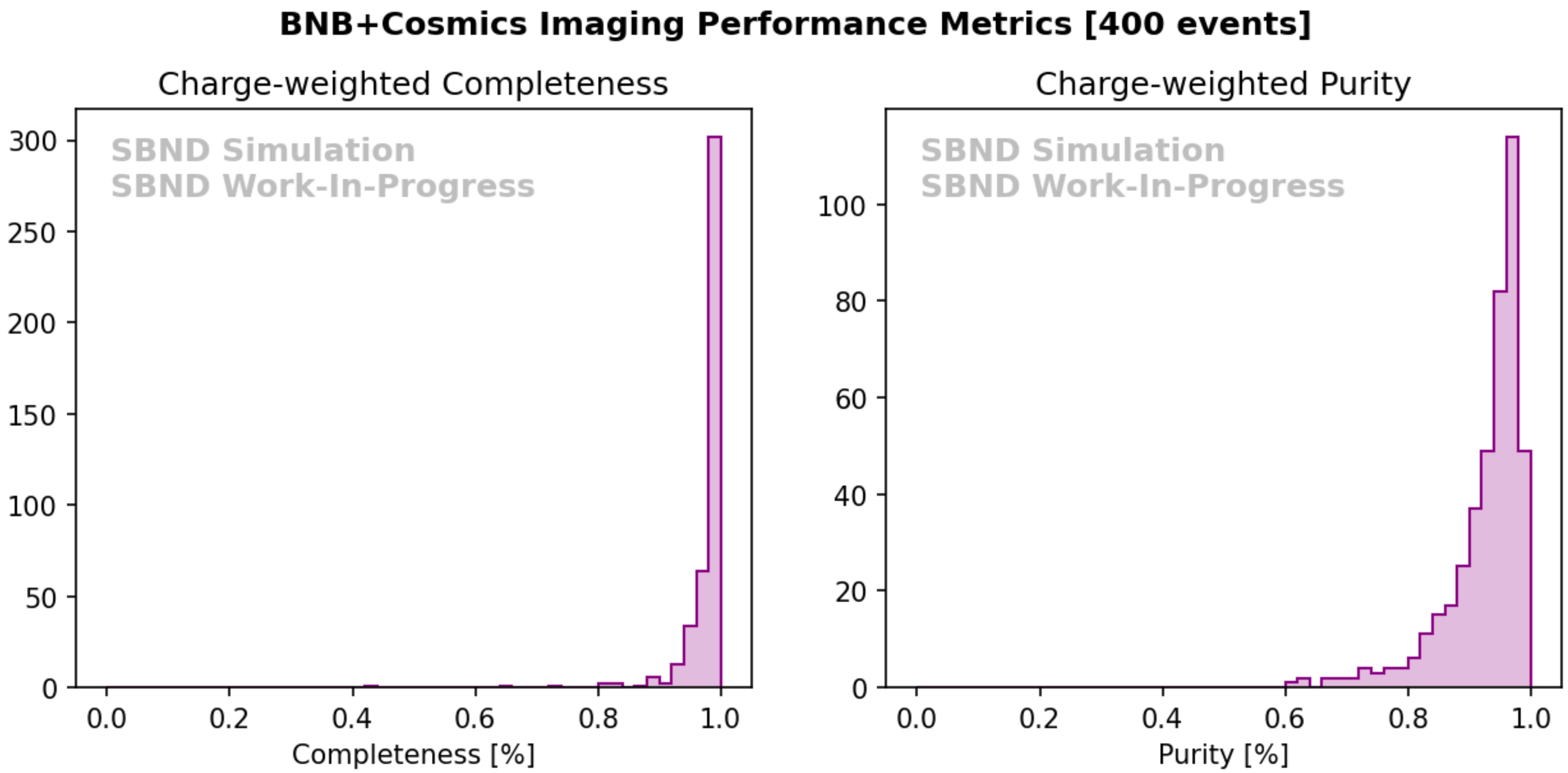
purity

what percentage of
image charge can
be associated to truth?



3D Imaging in SBND

Performance



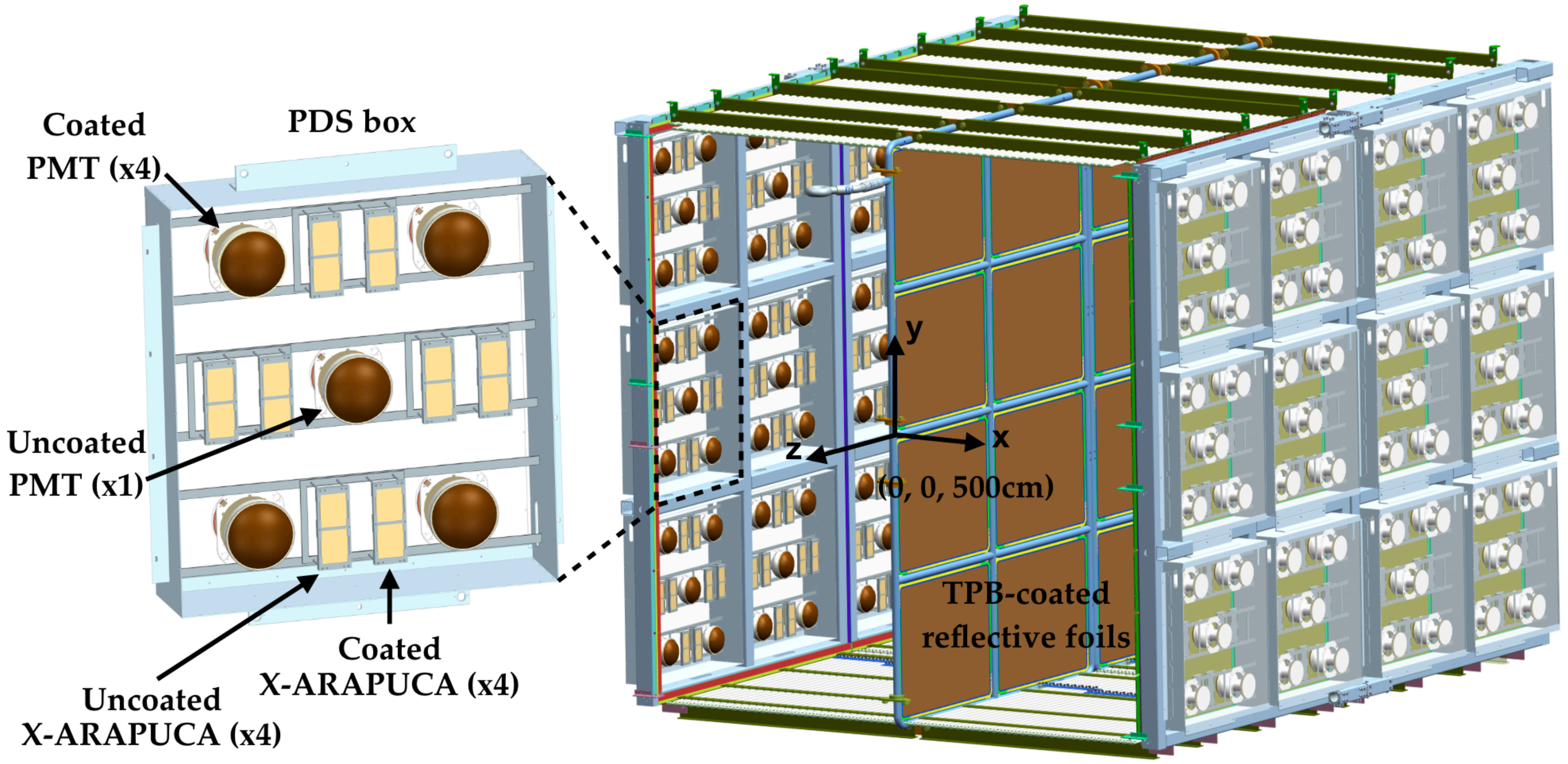
- performance on simulated neutrino+cosmic events is quite good!
- events with lower purity (<90%) can be attributed to isochronous and/or prolonged tracks, where lower performance is expected

3D Imaging in SBND

- 3D imaging (~space-point reconstruction only) has been quantitatively evaluated for SBND simulation, with very promising results
  - validation also performed for particle-gun muon and electrons, both with very good performance (>90%)
- lots of work has been done to update the 3D imaging workflow to be compatible with SBND/other LArTPC experiments
- next task… preliminary clustering + charge-light matching!
  - currently in-progress!

Charge-Light Matching in SBND

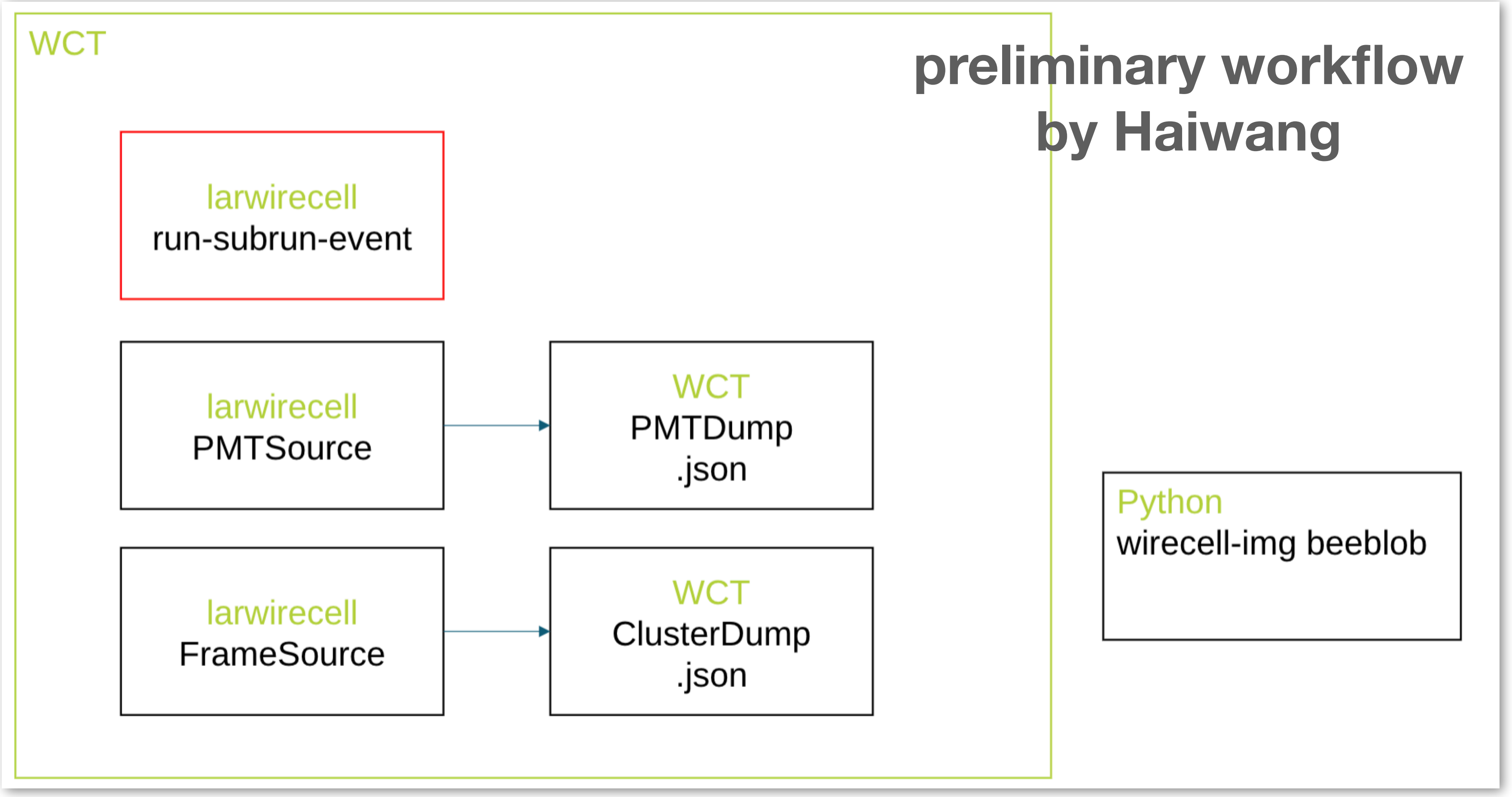
- SBND light simulation and reconstruction is very sophisticated
  - we measure and simulate both direct VUV and reflected visible light → light-only measurement of drift position!
  - uses *semi-analytical photon library* in the active volume
    [Garcia-Gamez, D., Green, P. & Szelc, A.M. Eur. Phys. J. C 81, 349 (2021)]

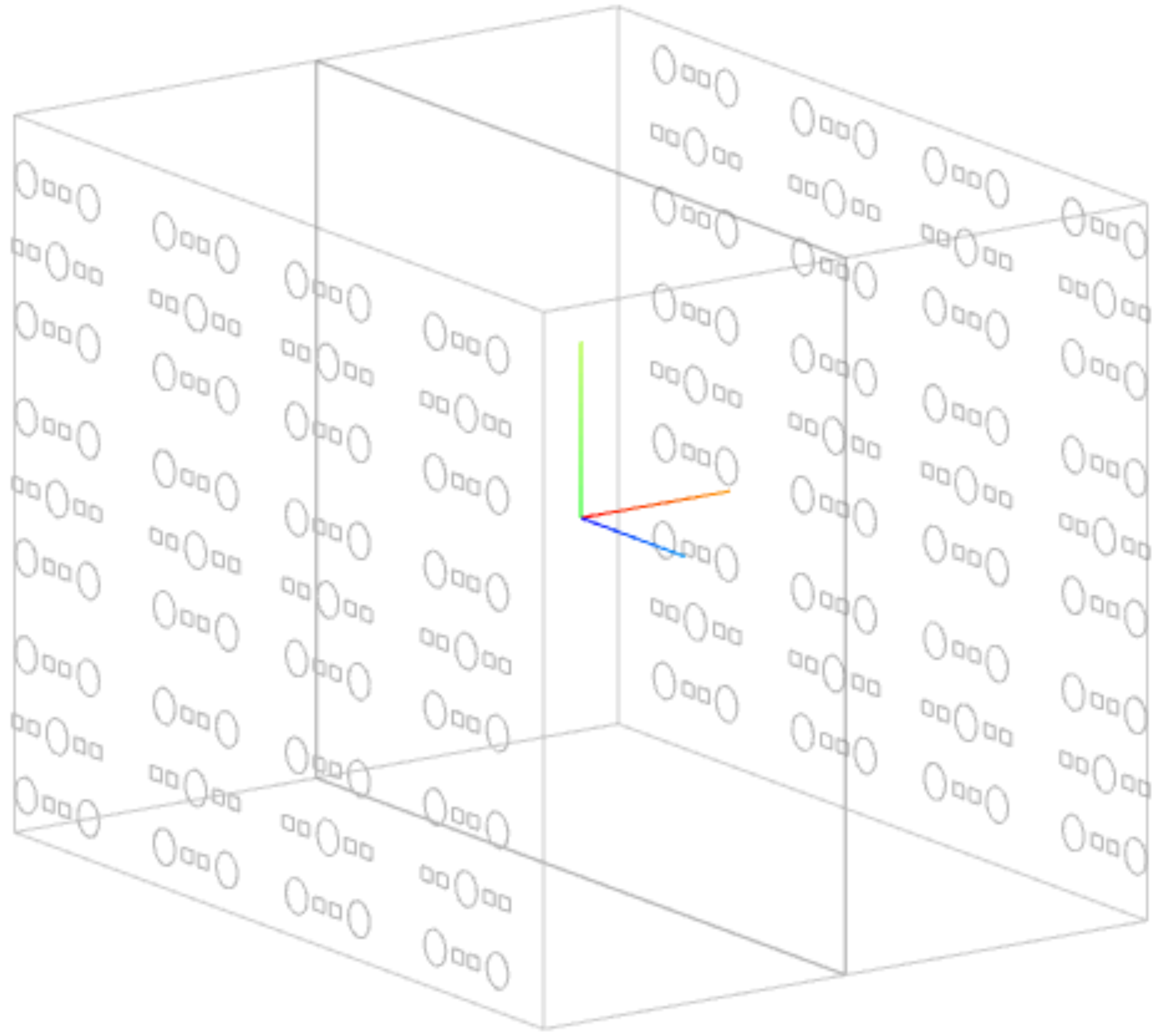


- flash-matching → χ^2 calculated for hypothesis flashes from Pandora Slices and measured flash(es) from beam spill flash(es)
  - similar in concept to Wire-Cell flash-matching
- ongoing studies on using **light calorimetry** (energy reconstruction with light)

Charge-Light Matching in SBND

- status of implementation in WireCell Toolkit (WCT)
  - **`recob::OpFlash`**es imported to WCT (thanks to Haiwang!)
  - SBND PDS geometry in BEE display (thanks to Chao!)
- challenges/work needed:
  - importing/implementing SBND's photon library
    - semi-analytic photon library calculates PE at each optical detector given (1) the energy deposit position and (2) geometry/position of optical detector
  - SBND has *two* optically-isolated TPCs
  - constraining flash-matching using higher-level light reconstruction information (such as drift position)





BEE Display w/ SBND PDS Geometry

technical integration of WCT in SBND!

- Integration initiated using WCT configurations available from different experiments;
- (Many!) configuration (jsonnet) and C++ modifications, with help of WCT experts!!
- **Successfully integrated a workflow for 2D simulation + 2D signal processing (see this talk)**. Two workflows available: single-step workflow with simulation + signal processing and separate workflow for simulation / signal processing. Both can save RawDigits.
- **3D imaging successfully integrated locally!** (upload configurations to SBND soon)
- **Extensive set of tests right after integration to make sure everything works as expected, before making it available for users in SBND!!!**

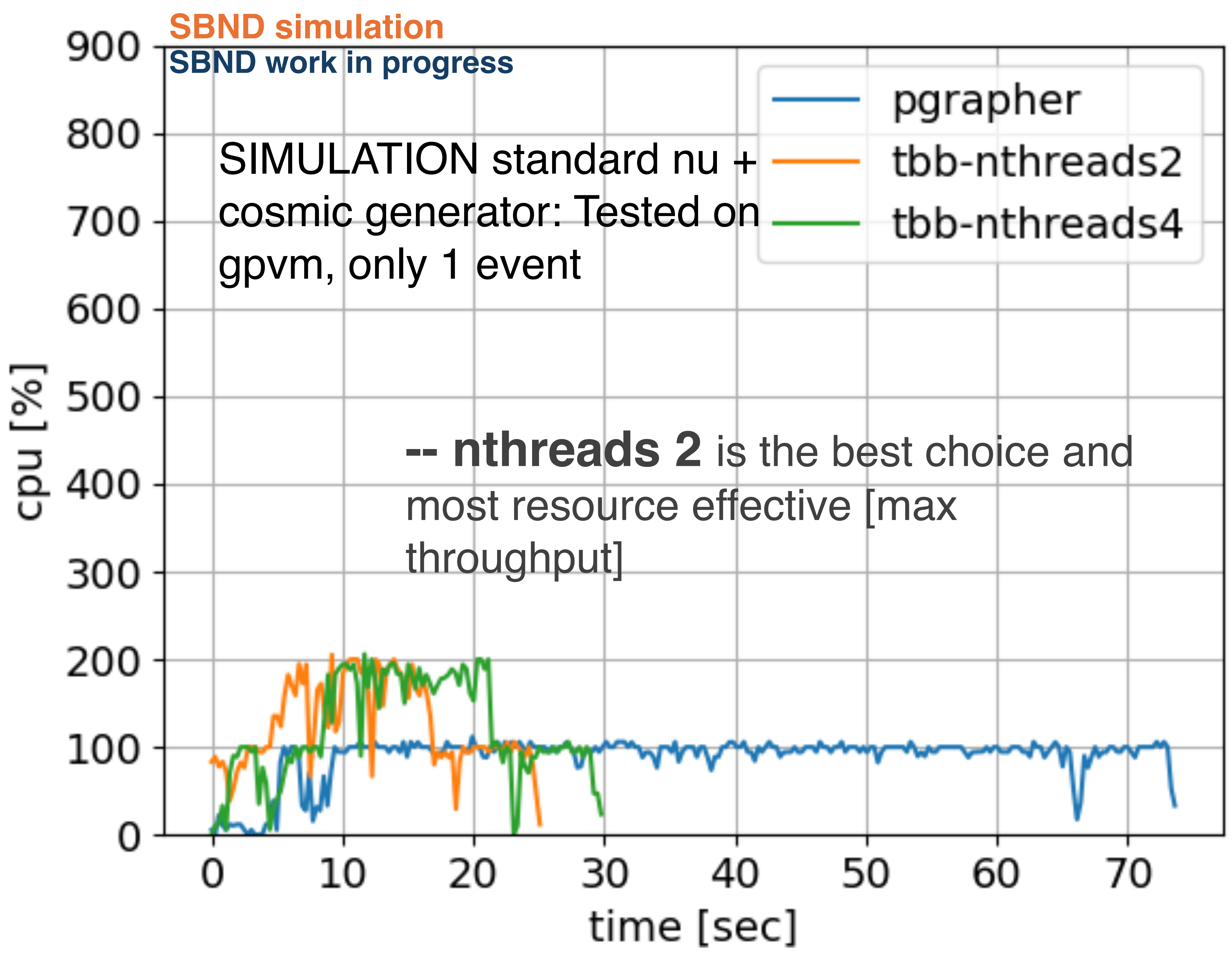
```
# Define and configure some modules to do work on each event.
# First modules are defined; they are scheduled later.
# Modules are grouped by type.
physics:
{

 producers:
 {
   rns:      { module_type: "RandomNumberSaver" }
   #daq:      @local::sbnd_simwire

   simtpc2d : {
      module_type : WireCellToolkit
      wcls_main: {
         tool_type: WCLS
         apps: ["Pgrapher"] #TbbFlow

         plugins: ["WireCellPgraph", "WireCellGen","WireCellSio","WireCellLarsoft"]

         # needs to be found via your WIRECELL_PATH
         configs: ["pgrapher/experiment/sbnd/wcls-sim-drift-simchannel-pgrapher.jsonnet"]


         # Contract note: these exact "type:name" must be used to identify
         # the configuration data structures for these components in the Jsonnet.

         inputers: ["wclsSimDepoSource:"]
         outputers: [
            "wclsSimChannelSink:postdrift",
            "wclsFrameSaver:simdigits"
         ]
```

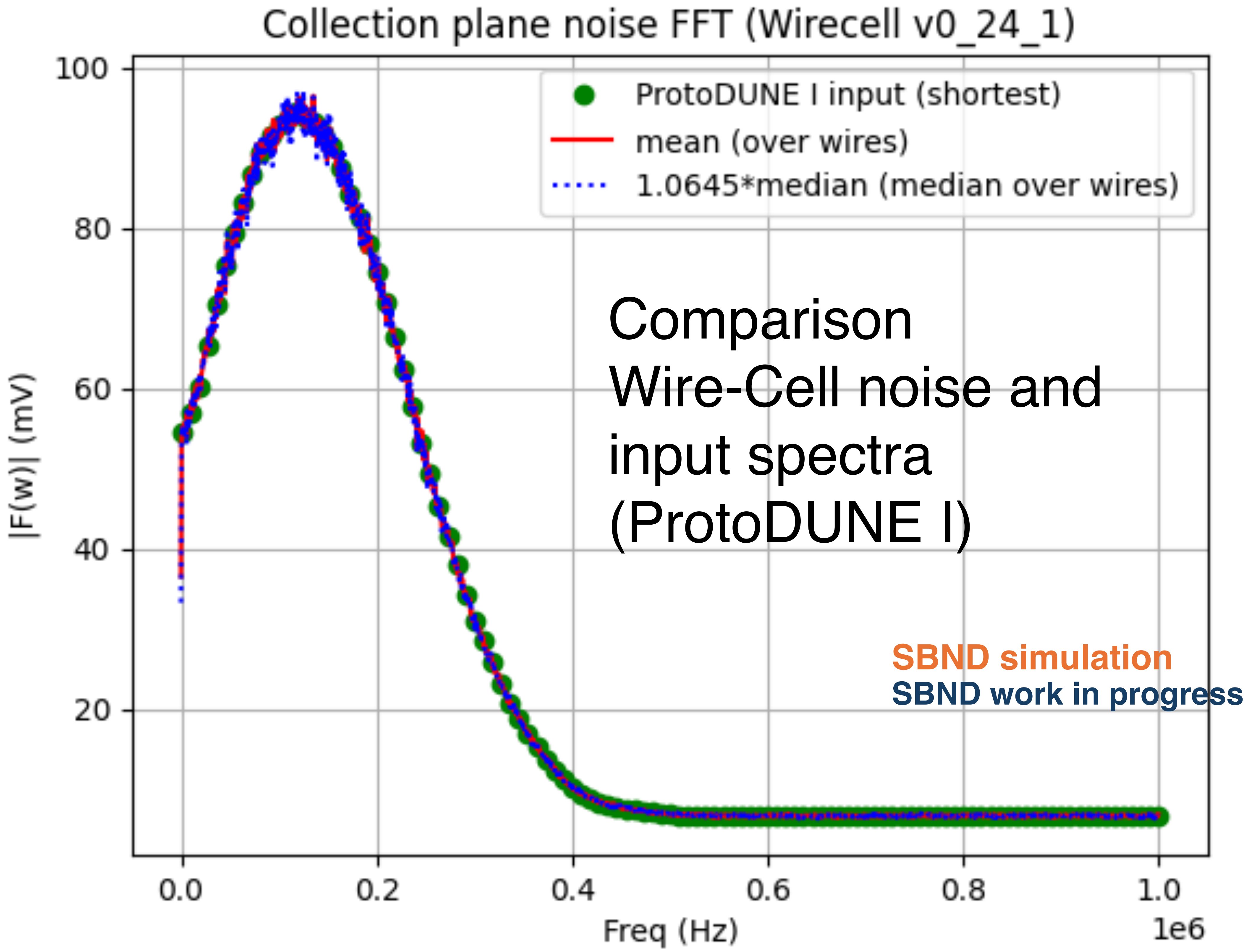
Data flow graph execution engine (Pgrapher or TbbFlow)

Wirecell modules

config jsonnet in $WIRECELL_PATH

Multi-threading and electronics noise simulation





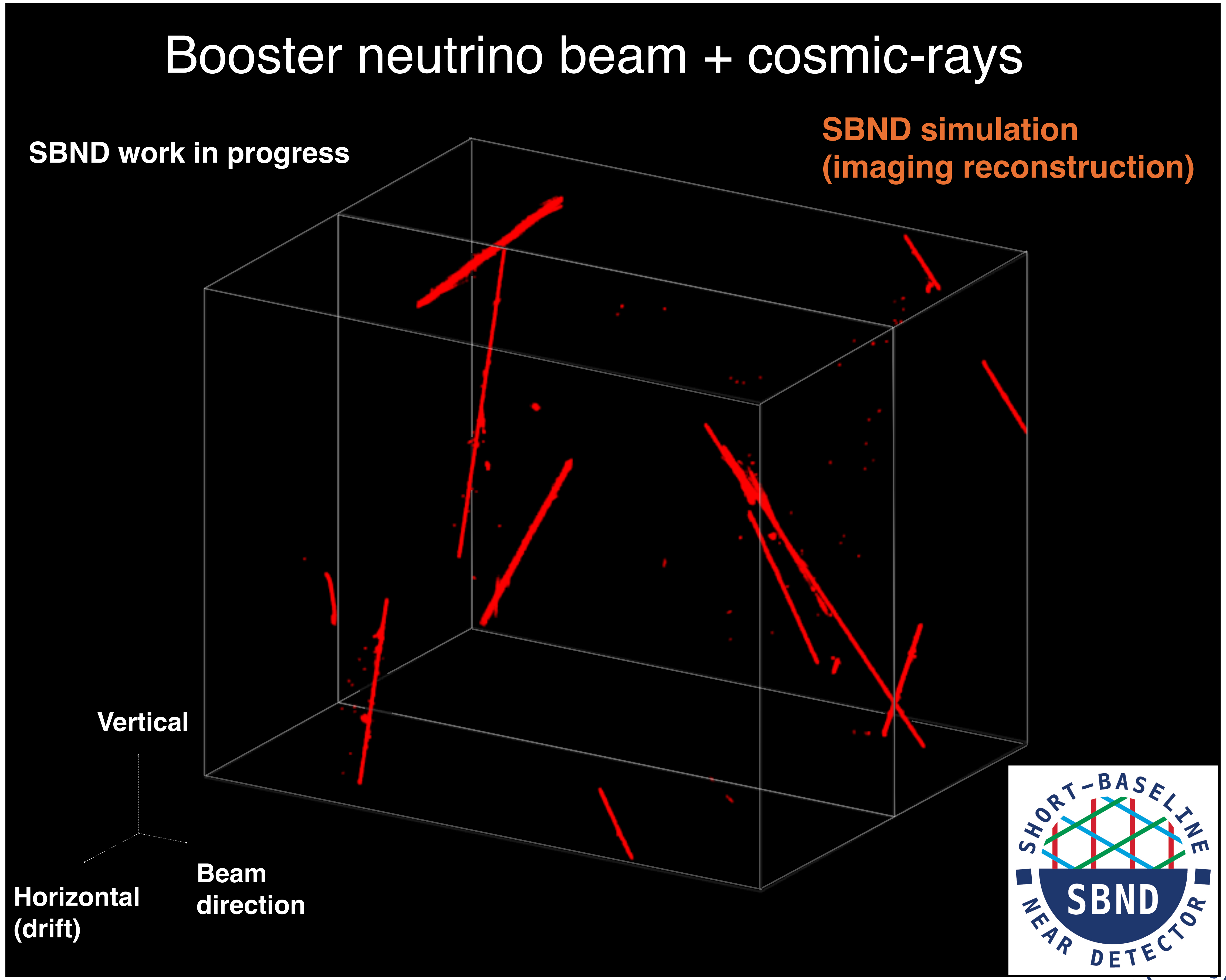
- Wirecell multi-threading extensively tested on gpvm/grid
- Shared services (thread-safe) enabled in SBND! (default were legacy services)

- WCT with electronics noise simulation in SBND (protoDUNE noise frequency spectra for now. Using SBND data soon to update!).

Integration of imaging in SBND and I/O question

- SBND final clustering – to be checked/finalized; current output data format is **.tar.gz**. (see Brett's talk). Right now we use a script to convert it to Bee display format for visualization;

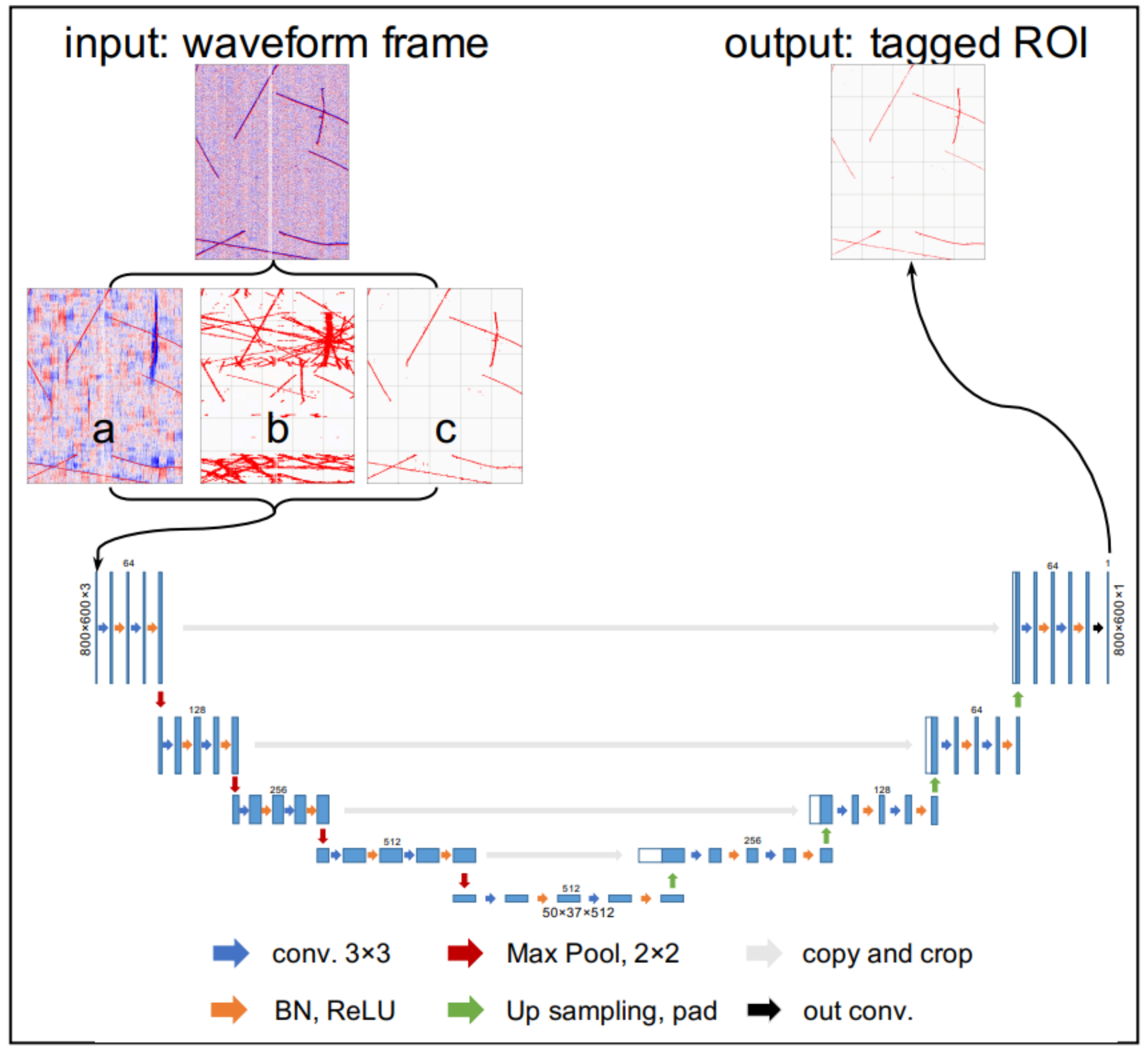
- Input to high-level reconstruction algorithms within WCT workflow (see Chao's talk), until final data product. Is there a way to have an unified data format that can be used both by larsoft and WireCell to handle those final high-level products? (see Brett's talk)



A question on DNN ROI

- DNN ROI shows better performance than traditional ROI (e.g. prolonged tracks).
- PyTorch-based implementation with multi-plane ROI matching concept. Currently implemented in WCT as as a better-performance alternative when compared to traditional ROI (traditional ROI is the current approach in SBND production workflow):
- Uses MP2/MP3/decon loose LF filter images in **time vs wire** bins as input for training and evaluation (HDF5 data format for internal WCT data handling)
- DNN ROI is a competitive approach w.r.t. traditional ROI. Is there an automated workflow w.r.t. training/validation?
- Is it possible to have a hybrid CPU/GPU usage on grid clusters? (depending on computing resources)

JINST 16 P01036



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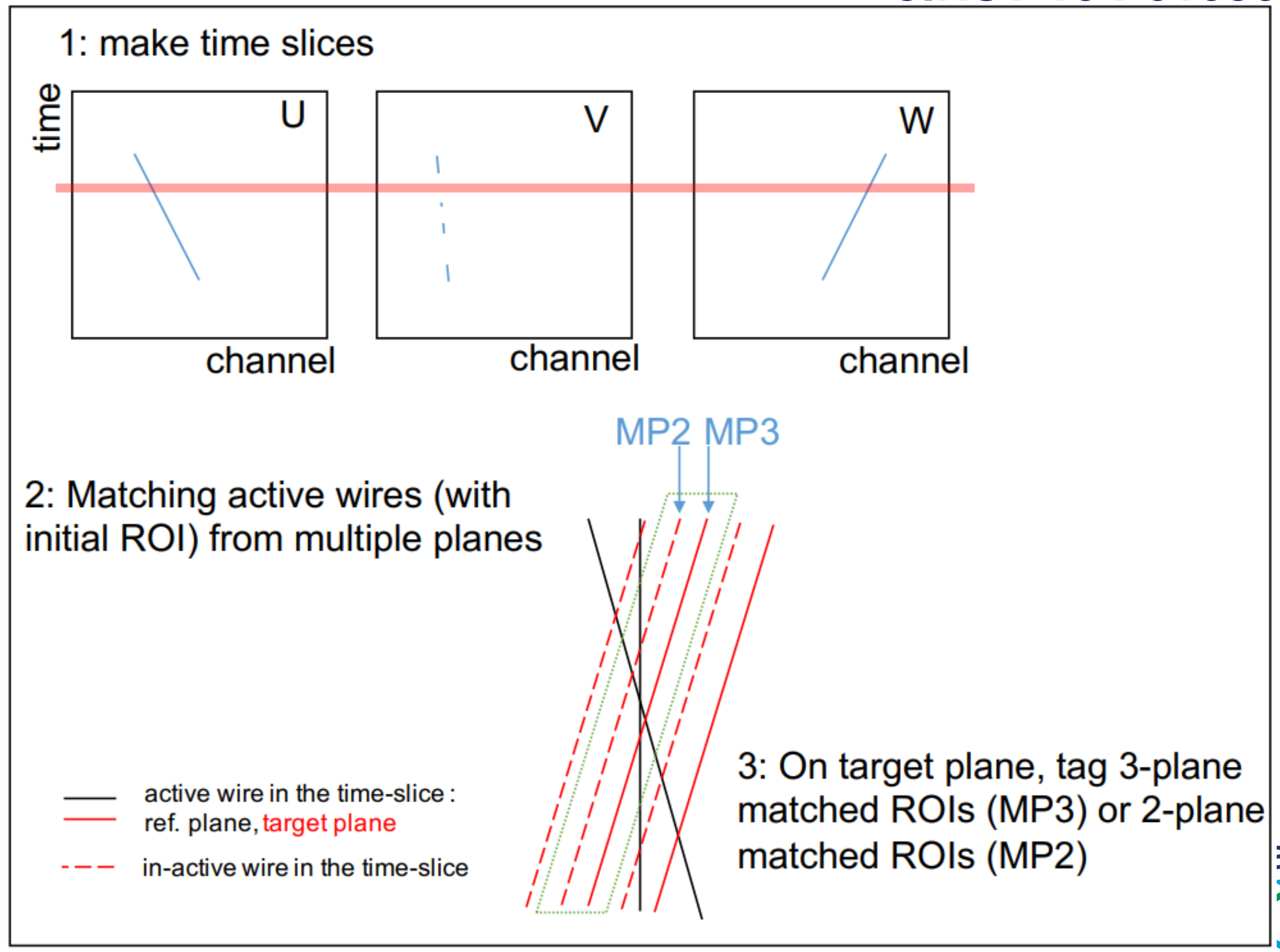

WireCell versus calibration database

- Current electronics response function has many parameters, which are currently hard-coded. Those parameters will be stored in SBND database. We expect noise filtering to need to store some info as well;

- Is it possibleto have WireCell communicating with the SBND calibration database (accessible via **ssh –K sbnd@sbnd-gateway01.fnal.gov**)? WireCell stores some data as a “jsonnet-based” internal database (e.g. chndb.jsonnet).

A question on prompt signal processing

- For prompt signal processing, it would be highly desirable to be able to execute tasks (e.g. event processing) in a parallel way;

- WireCell multi-threading engine (TbbFlow) is a powerful engine to speed up data processing, it has shown a great performance on the grid, but right now is limited by the input data stream it can read at a time (one artROOT event at a time);

- Is there a way to maximize the input data stream that WireCell signal processing workflow can read at a time? Is it possible to reduce I/O steps in this process? The current interface between larsoft and WireCell is larwirecell;

- Should we be able to have dynamic allocation of computing resources (#cores, memory) when running WireCell parallel engine (TbbFlow)?

Wire-Cell for SBN Physics

- ICARUS has been taking data since 2022, and SBND data-taking is imminent!
  - BNB $\approx$ 3.5e19 - 5.2e19 POT/month = ~300k $\nu_\mu$and 2k ν_e CC events in SBND
- very mature analyses in SBND for various channels using Pandora reco:
  - CC ν_μ inc., CC ν_e inc., CC $\nu_\mu 1e0\pi$, NC π^0, and many more
  - from informal discussions with analyzers, at minimum we need *Wire-Cell clustering, vertexing, track-shower separation*
- **where and how will Wire-Cell have the most impact for SBND Physics analyses?**
  - we need solutions for LArSoft/Pandora interface with WCT in the short-term
  - SBN/SBND will be a great testbed for potential long-term solutions

Summary

- there is major effort in SBND to develop, integrate, and validate WCT!
- in particular, we have done **additional optimization and quantitative validation** on WCT tools
- SBND's (very large) dataset could benefit enormously from Wire-Cell reconstruction, especially on the ν_e front, but it will require lots of fast-approaching work
  - an opportunity to test long-term solutions (for DUNE)!
- SBND Wire-Cell team:
  - UChicago: Lynn Tung, Mun Jung Jung, Avinay Bhat, Matt King, Dave Schmitz, Bonnie Fleming
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thank you very much!!