Signal processing, tracking and MCS

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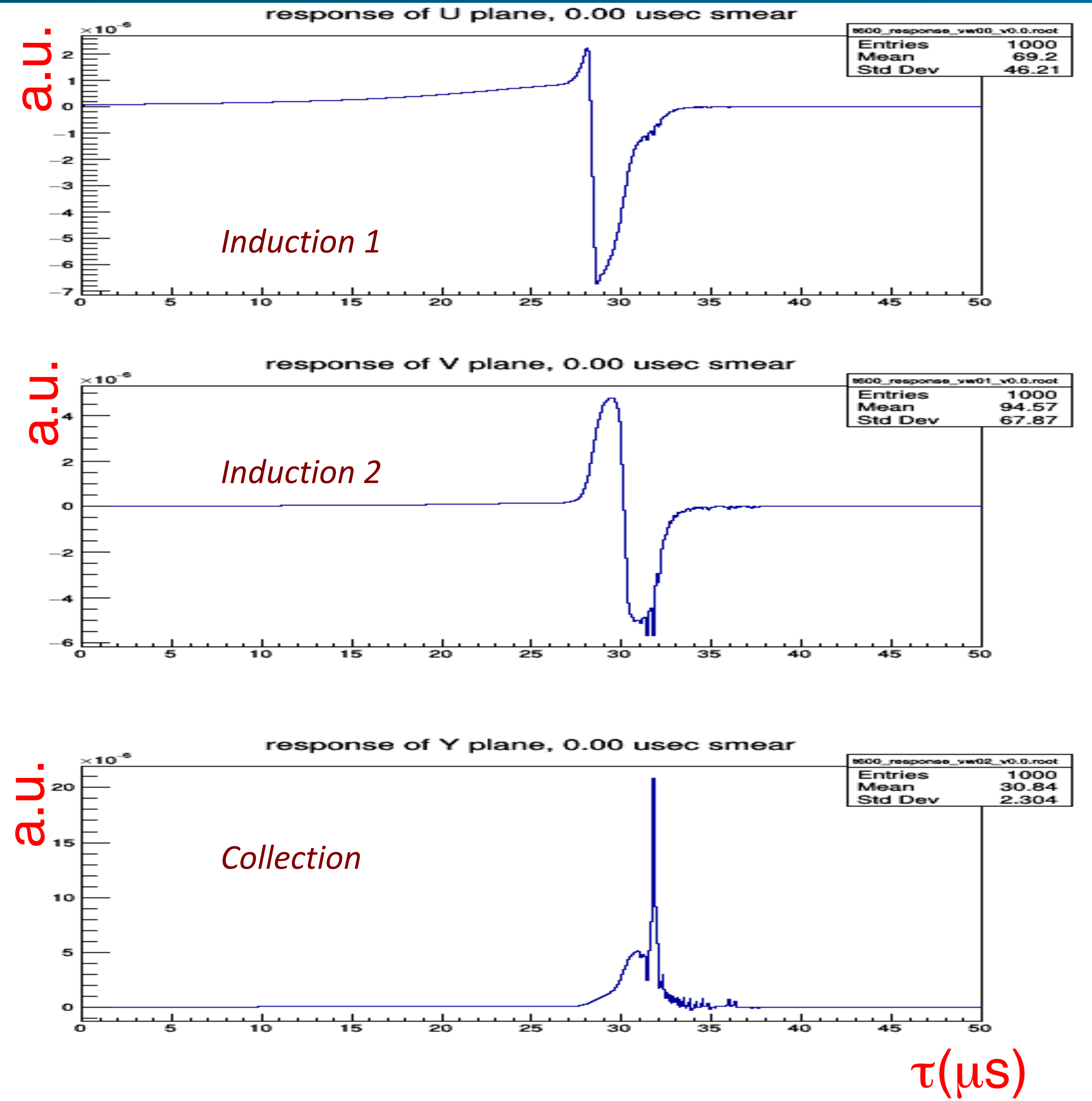
Outline

- WIRE WAVEFORM SIMULATION:
  - Ionization signal
  - Noise simulation and characterization
- SIGNAL PROCESSING:
  - Raw hit finding
  - Deconvolution and Gaussian hit finding
  - Noise filtering and mitigation
- FURTHER RECONSTRUCTION FLOW:
  - MultiTPC reconstruction structure
  - Track and shower reconstruction
  - MCS momentum measurement

ICARUS signal simulation: field response

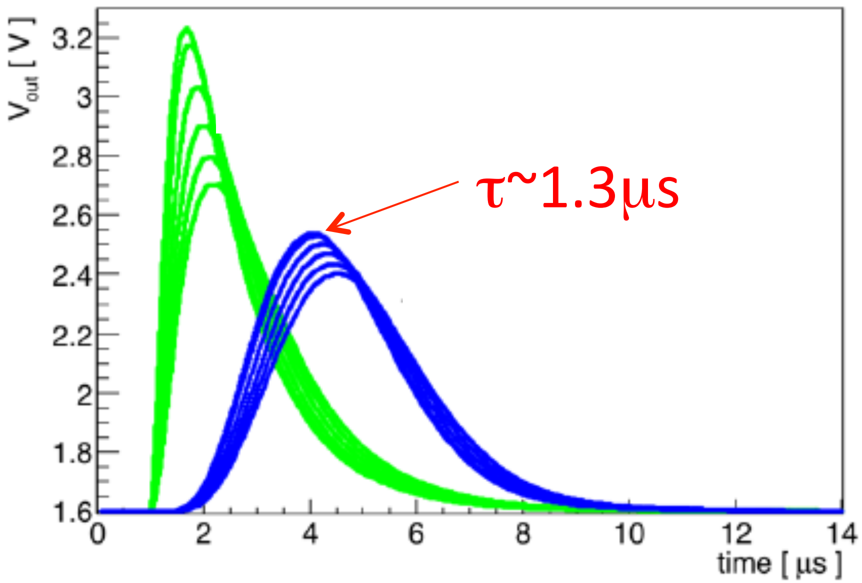
- Convolution of simulated electron current (from GEANT4) incoming on wires with response functions from drift field and readout electronics
- Field response functions (for each wire-plane) obtained by Garfield simulation (by L.Rochester)
- More detailed simulation including effects from neighboring wires will be available soon



ICARUS ionization signal simulation: electronics response

- In SBN, readout electronics is the same for all wire planes
- Electronics response function approximately modeled as ***t*exp(-t/τ)***
  - τ assumed ***1.3 μs***, from numerical approximation of response function convoluted with Bessel filter

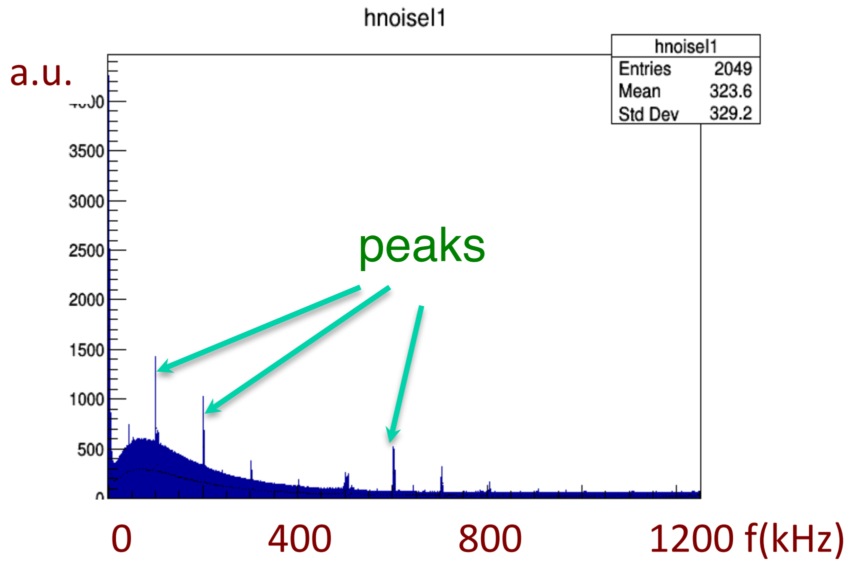
(see electronics paper **JINST 13 P12007(2018)** for details)



- Absolute normalization computed in Collection plane: gain (69.2 e-/ADC#) also taken from 50-liter TPC measurements at CERN. See paper

ICARUS wire noise simulation

- Very difficult to estimate noise condition priori, before in-situ measurements
- The standard simulation of ICARUS@SBN used noise model derived from past measurements: ICARUS@LNGS + 50-liter chamber at CERN
- Frequency spectrum from FFT of LNGS noise (in Induction 1 plane):

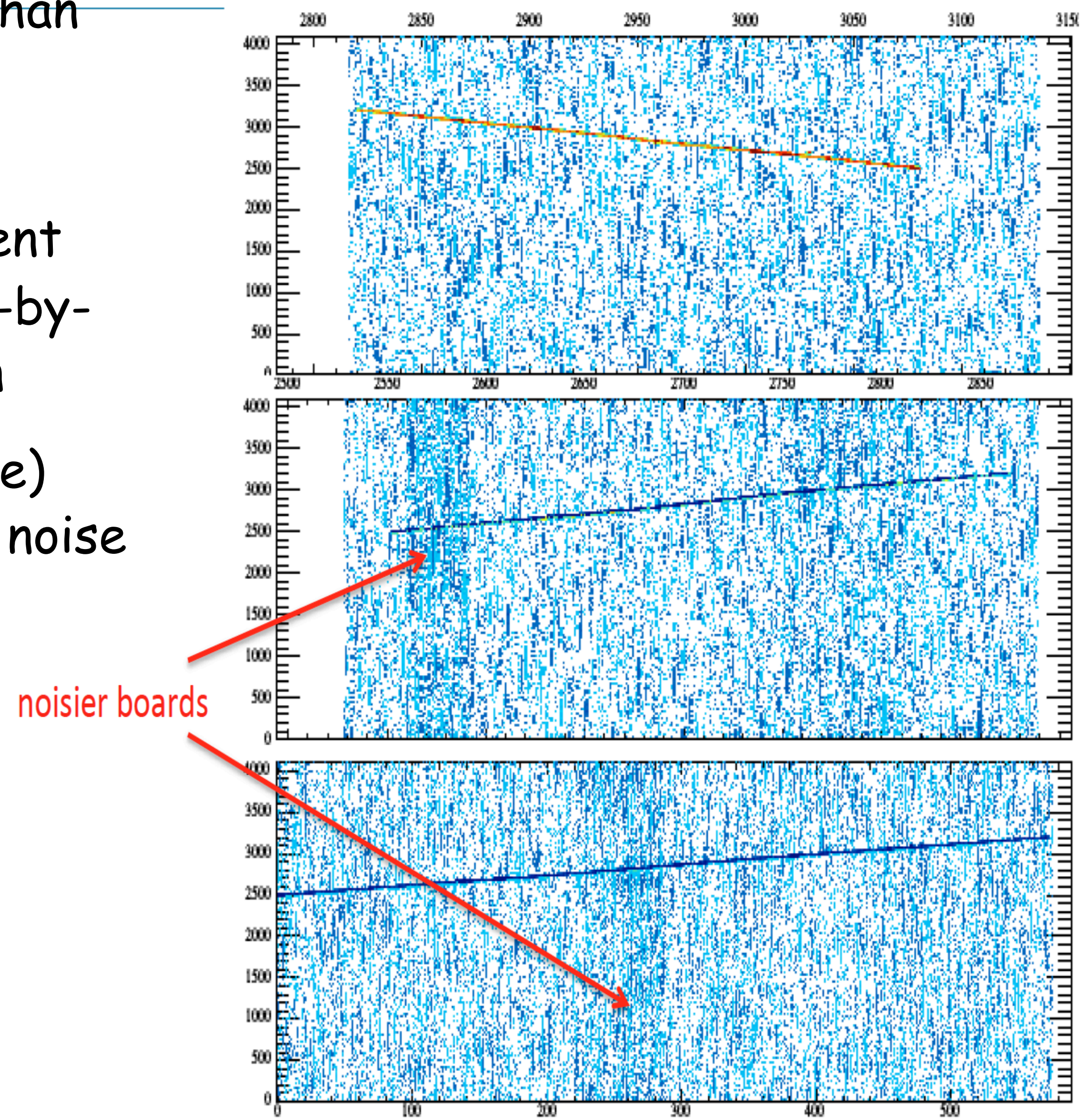


- Smooth component assumed totally uncorrelated among wires, peaks (~100 kHz harmonics) as totally correlated within a board (32 wires)
- Absolute RMS normalization (2.3 ADC#) from CERN measurements, corrected for different wire length

Example of standard signal+noise

- Coherent noise at LNGS was usually small, but comparable/higher than incoherent in a few boards
- Attempt to reproduce this variability: amplitude of coherent noise sampled randomly (board-by-board) from LNGS distribution
- Average is 0.8 ADC# (negligible) but for a few boards coherent noise can be dominant

muon MIP+standard noise



Signal to noise ratios

- Definition of physical MIP signal height may have some ambiguities:
  - Worst case (track orthogonal to wires, 3 mm deposition) vs. "typical" case (which depends on track direction)
  - Average height vs. (lower) most probable height in a Landau distribution
- Important to agree on definitions, in order to make fair comparisons
- Simulated heights in Collection and Induction-2 agree (within ~10%) with heights measured at CERN (Induction-1 was not read out there)
- Considering 3mm MIP (worst case), average height, and RMS noise of 2.3ADC#:

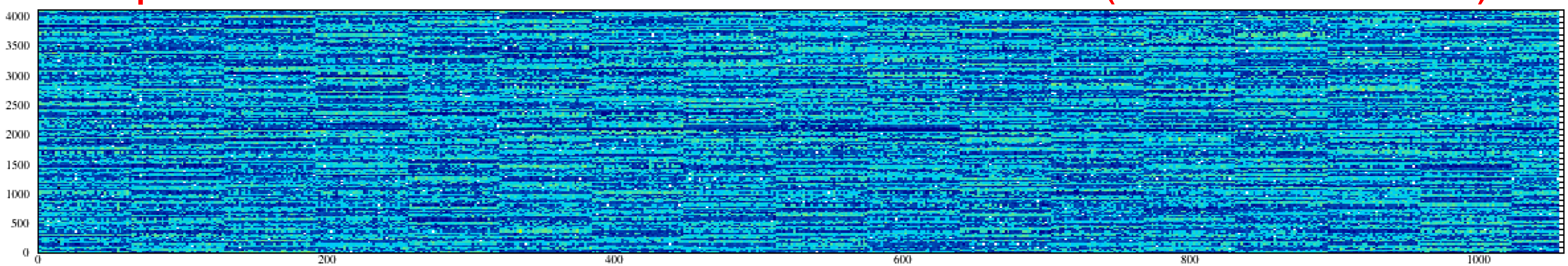
Plane	Induction-1	Induction2*	Collection
Height	~17	~11	~21
S/N	~7	~5	~9

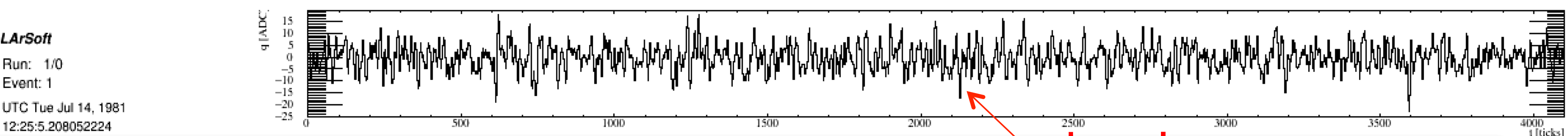
- For Induction-2 the signal is bipolar: height of one of the lobes is considered
- Integration of the signal will improve the effective S/N ratio

Simulation of SBN noise

- Noise measured in recent tests of ICARUS crates at SBN can be used as an input to simulation
- Coherent noise component identified (by averaging over a crate)
- Coherent/incoherent noises characterized independently (FFT spectrum + RMS amplitude) for each crate
- This information is fed to simulation: more realistic SBN noise can be used to compare to signals and develop/test dedicated filtering algorithms
- In the future, each crate can be simulated independently drawing from its own measured noise

Example of MIP muon in a bad induction 1 crate (RMS=5.7 ADC#)



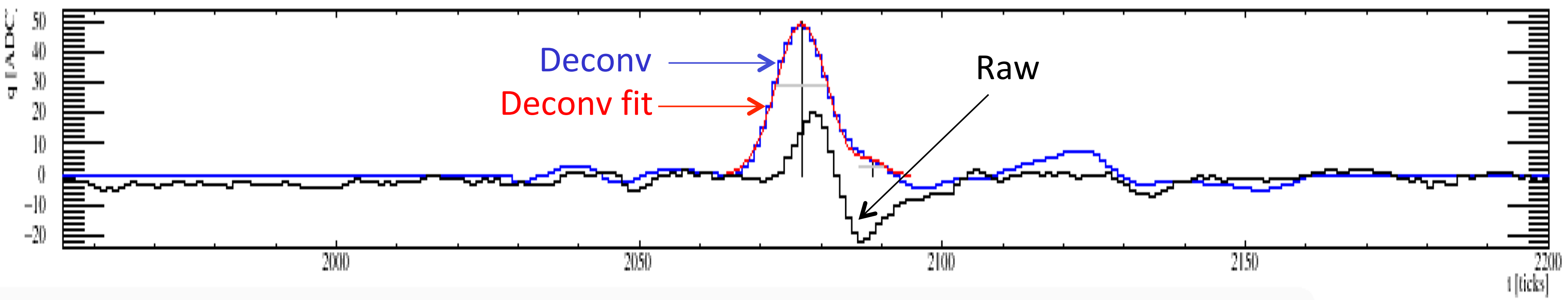


signal

Signal processing

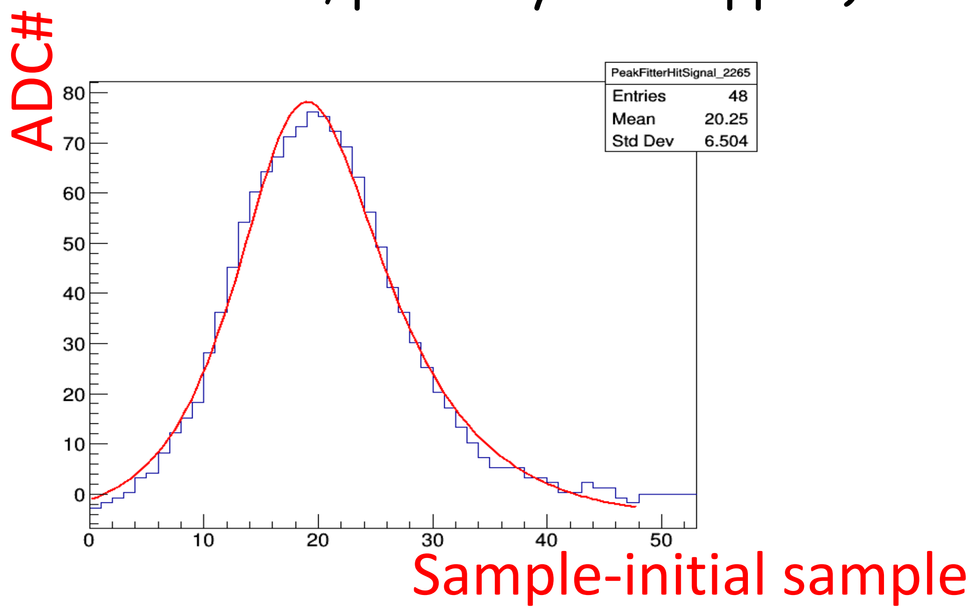
- Two different and complementary approaches are possible:
- DECONVOLUTION: response functions are inverted to (ideally) recover the intrinsical drift electron signal
  - ROI identification and hit-finding performed on deconvolved signal
  - MIP hit shape is Gaussian and independent of wire-plane
  - Used in SBND/MicroBooNE: software tools can largely be shared
- RAW (used by ICARUS@LNGS): no deconvolution takes place
  - Hit-finding directly performed on raw signal from wires
  - Different hit shapes for different wire-planes
  - Offline integration/filtering of Induction-2 signal

EXAMPLE IN INDUCTION-2 PLANE:



Raw hit finding algorithm

- Inherited from old ICARUS algorithms, ported into Larsoft
- Based on "time-over-threshold" logic, with parameters depending on wire plane
- Good performances for Collection and Induction-1 (>98% efficiency, <0.1 fake hits per wire) for "standard" noise conditions used in simulation
- In Induction-2 signal/noise ratio is lower: efficiency ~90%, ~1 fake hit per wire in the whole drift region)
- Collection fitting function fitted with double exponential: $f(t) = B + A \frac{e^{\frac{-(t-t_0)}{\tau_1}}}{1+e^{\frac{-(t-t_0)}{\tau_2}}}$
- Special fitting procedures for "long" hits (along drift coordinate) or "double" hits (several MIPs in a short time, partially overlapped)



Deconvolution

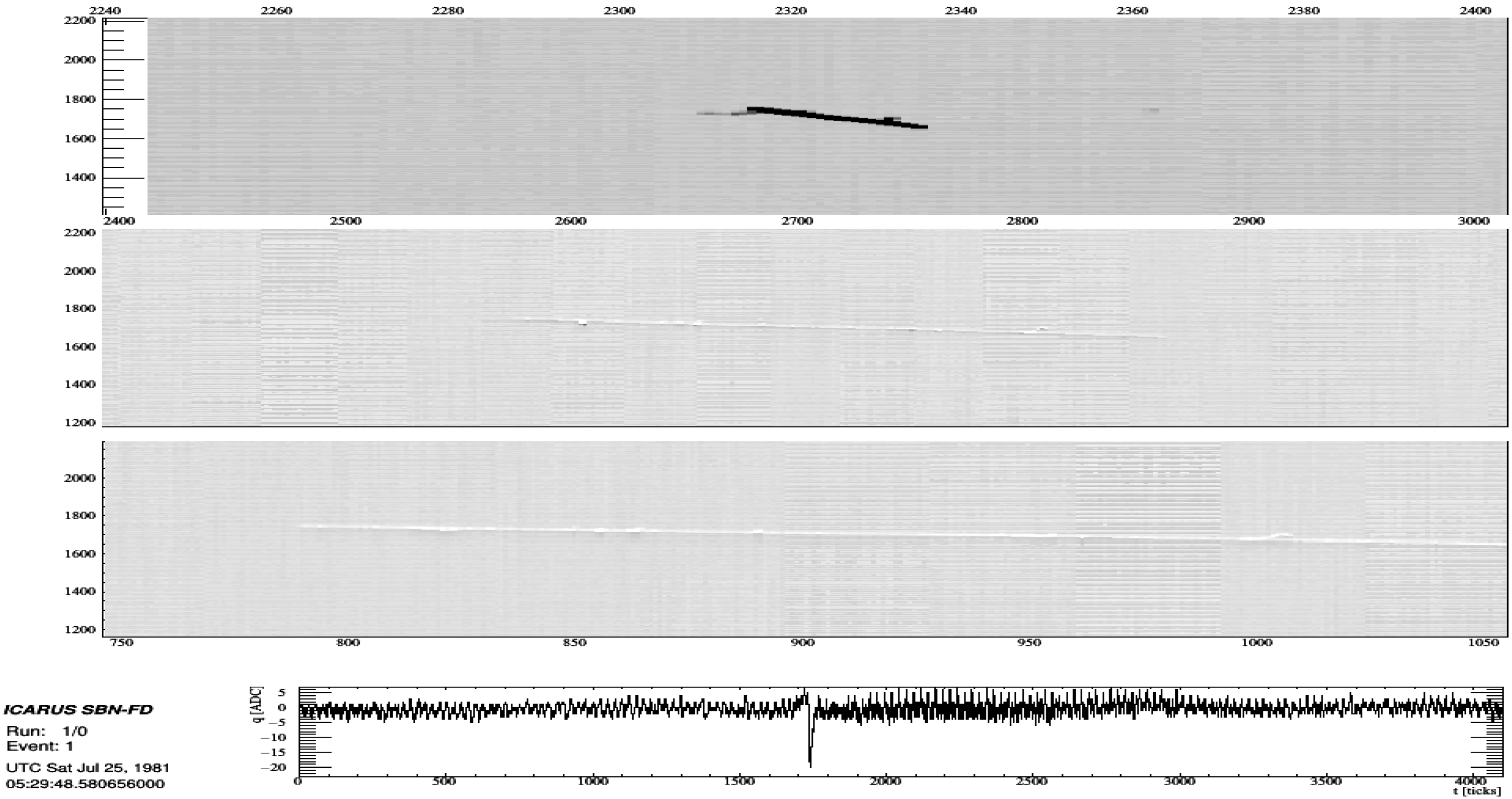
- The deconvolution algorithm:
  - Converts all raw signals (bipolar in Induction) to nominally Gaussian ones
  - Regularizes response, allowing hits from each plane to be treated as equal
- Method is to deconvolve the electronics and field response components of the signals observed on the wires (the "raw" signal):
  - Deconvolved waveforms searched for candidate peaks which are fit to one or more gaussian shapes
  - Diffusion, lifetime, recombination handled separately
  - Hit-finding efficiency comparable to raw
- Current implementation treats each wire independently and does not consider possible induced effects (due to track angles) from neighboring wires.
  - Works best for tracks with relatively shallow angles to the wire planes
  - "Good enough" for commissioning and development of reconstruction algorithms
- WireCell Team are working to integrate their toolkit into the ICARUS system which will bring 2 dimensional deconvolution in the future.

Noise Filtering

- Ported the LArSoft version of noise filtering code from MicroBooNE
  - This code was initially used by MicroBooNE until superseded by the WireCell toolkit
- Contains tools for attacking specific problems:
  - Coherent noise removal including "signal protection"
  - Incoherent oscillations
  - Channel-by-channel pedestal and rms determination per event
  - Has ability to output "ROI's" to help reduce data volume
  - Some MicroBooNE specific things not expected in ICARUS (but ready just in case)
- Code is running now as part of standard simulation/reconstruction
  - Removes the low frequency oscillation in the noise model
- Plan to use this code during the commissioning but will eventually be superseded by the WireCell noise processing toolkit once they have completed the process of adapting it to ICARUS

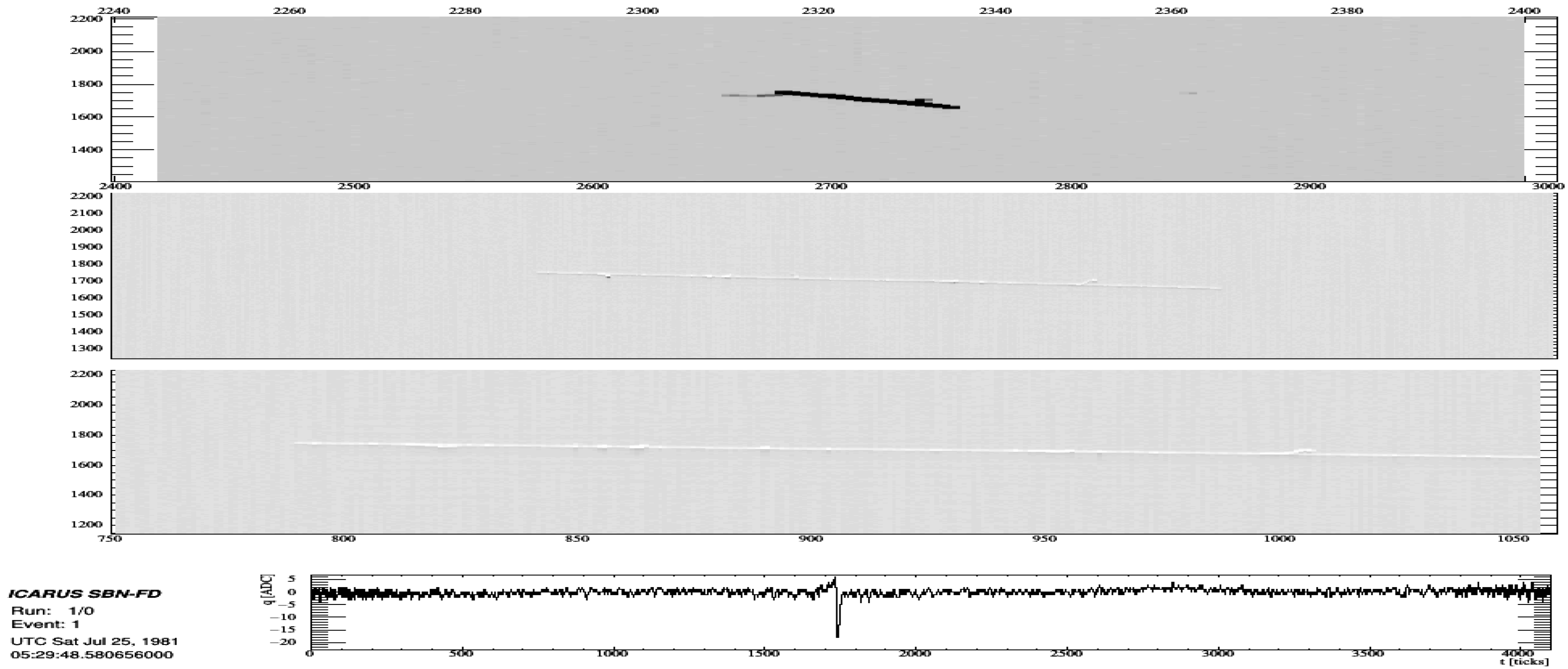
An example

WORST CASE SCENARIO: coherent noise artificially increased by a factor X



- Very large ~100 kHz coherent noise evident as a board-dependent "pattern"
- Nearly horizontal muon is hardly visible

An example (after filtering)

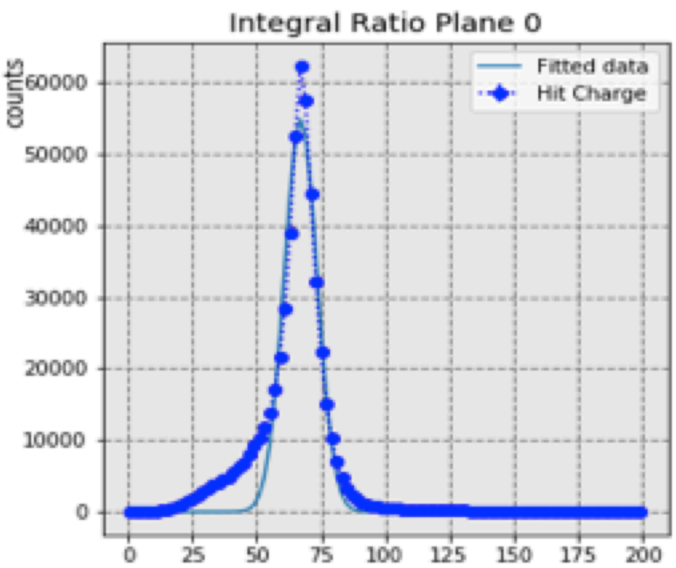


- Noise greatly reduced by subtracting median computed over 32 wires
- This would result in a significant distortion of the (nearly isochronous) signal
- Distortion is limited by identifying frequencies in the coherent noise
- Filter guarantees high hit-finding efficiency -> good track reconstruction in all views
- This is dependent on the assumption of specific frequencies in the coherent noise spectrum

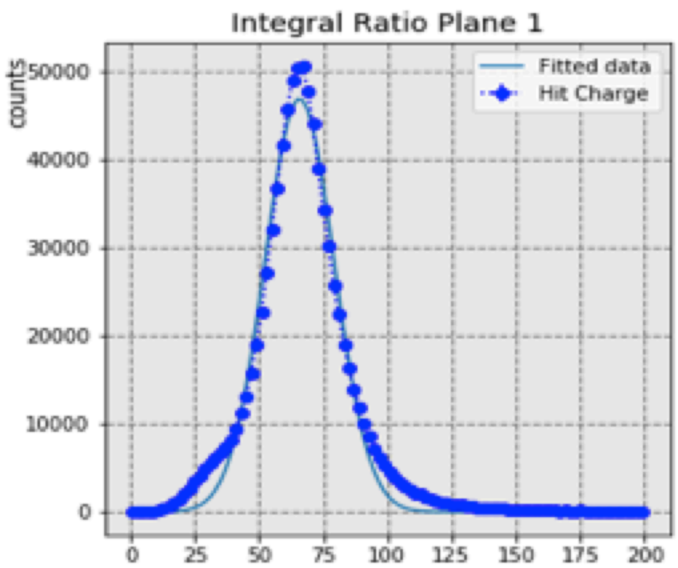
Hit area measurement

- Basic ingredient for calorimetric reconstruction (independent from detector effects like recombination, purity, diffusion)
- Two methods for area estimation: ADC sum and integral of fitting function
- Measurement validated on simulated isotropic muons: allows estimation of gain (to be compared with MC value: 67.4 electrons/ADC#)

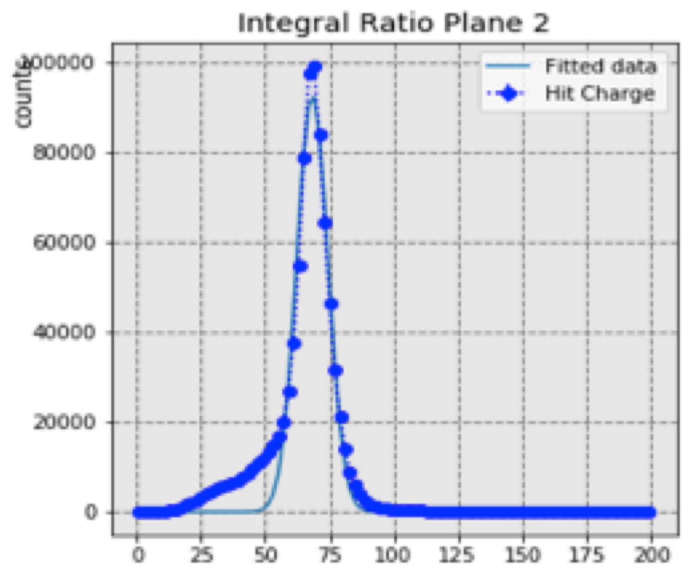
GAIN DISTRIBUTIONS FROM FIT INTEGRAL OF "DECONVOLVED" HITS:



Gain: 67.1±6.4 e-/ADC#



Gain: 65.6±13.5 e-/ADC#



Gain: 68.3±6.1 e-/ADC#

- Good average agreement in all views
- Width of distribution represents S/N ratio. Similar width for raw hits (in Collection)

Track/Shower Reconstruction

- The input are hits produced by signal processing

- To reduce noise hits (particularly from the middle induction layer), hits from each plane are combined to form SpacePoints
  - Fake hits from noise will not form valid SpacePoints and can be removed

- Resulting collection of hits are input to the Pandora framework
  - Three stages: overview, track finding, shower finding
  - Track and shower pattern recognition package
  - Returns candidate vertices for tracks/showers/particles
  - Creates particle hierarchy (PFParticles) for "connected" tracks and showers – describes structure of, for example, neutrino interactions

- Track candidates passed to track fitter to form fully fit track trajectories

- Shower candidates pass to SBN Shower reconstruction – *NEW!*

Simulation/Reconstruction Flow

- Both Simulation and Reconstruction running in "multi-TPC" mode
  - Detector simulation outputs wire waveforms (*RawDigits*) for each TPC
  - Signal Processing runs separately on each *RawDigit* collection
  - 3D (*SpacePoint*) reconstruction merges output hit collection by Cryostat
  - Pandora pattern recognition runs separately on each Cryostat hit collection
  - Goal is to help enable future parallelization of the modules to decrease clock time for running jobs
  - This also does help reduce overall memory usage

- Reconstruction runs in two job steps
  - First step performs signal processing, gauss hit production, SpacePoint formation, Pandora pattern recognition on gauss hits and PMT hit and flash reconstruction
  - Second step uses noise filtered waveforms from first step and runs the "raw hit" reconstruction, then Pandora pattern recognition on the raw hits and the CRT reconstruction

MCS momentum measurement

- Crucial for the energy reconstruction of $\nu\mu$CC interactions
- ICARUS algorithm (see paper ***JINST 12 P04010(2017)***) allowed measurement with average ~15% resolution over 0-4 GeV/c range
- Several new features w.r.t to other algorithms:
  - Event-by-event estimation of drift coordinate measurement error
  - Event-by-event optimization of segment length
  - Two estimations of deflection angle (linear fit+segment barycenter)
  - χ^2-like function comparing observed/expected deflections as a function of momentum
  - Full treatment of covariance between consecutive angle deflections
- Implementation into larsoft is being finalized
- Test on fully simulated muons and characterization of resolution as a function of track length/momentum will soon follow

Conclusions

- Signal processing tools allow basic reconstruction/visualization of TPC signals
- Simulation reproduces expected signals and noises based on measurements at ICARUS@LNGS and 50-liter chamber at CERN
- Tools are available to characterize noise from tests at SBN and feed it into simulations
- Dedicated filtering algorithms are available to reduce coherent noise
- Two complementary signal processing/hit-finding approaches (raw and deconvoluted) are available
- Assuming simulated noise levels, hit identification and area measurement capabilities are satisfying for both approaches
- Successive reconstruction tools allow pattern recognition, resulting in reconstruction of tracks and showers
- Parallelization of reconstruction flow at the single TPC level allows optimizing processing time and memory usage
- MCS momentum measuerement will soon allow detailed characterization and study of $\nu\mu$CC sample