Current Status of TOPTRG Work

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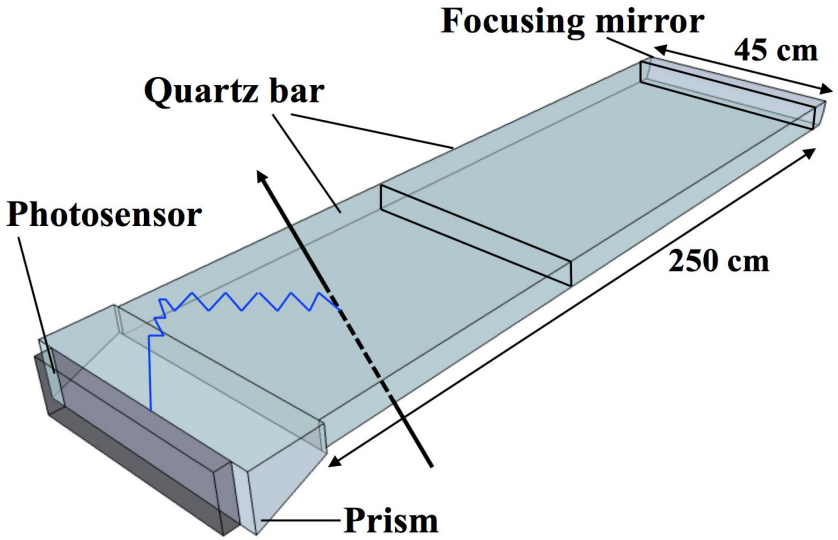
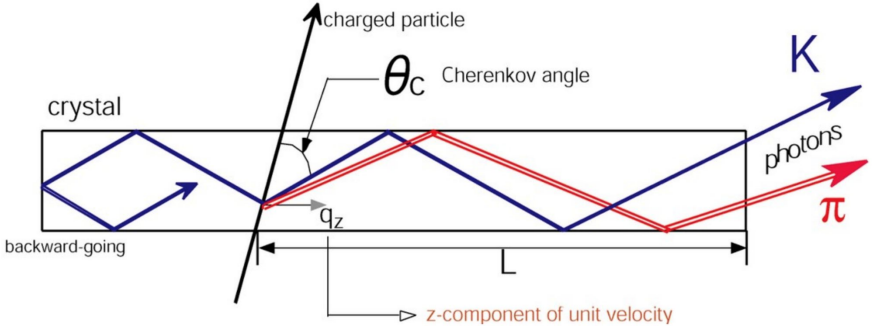
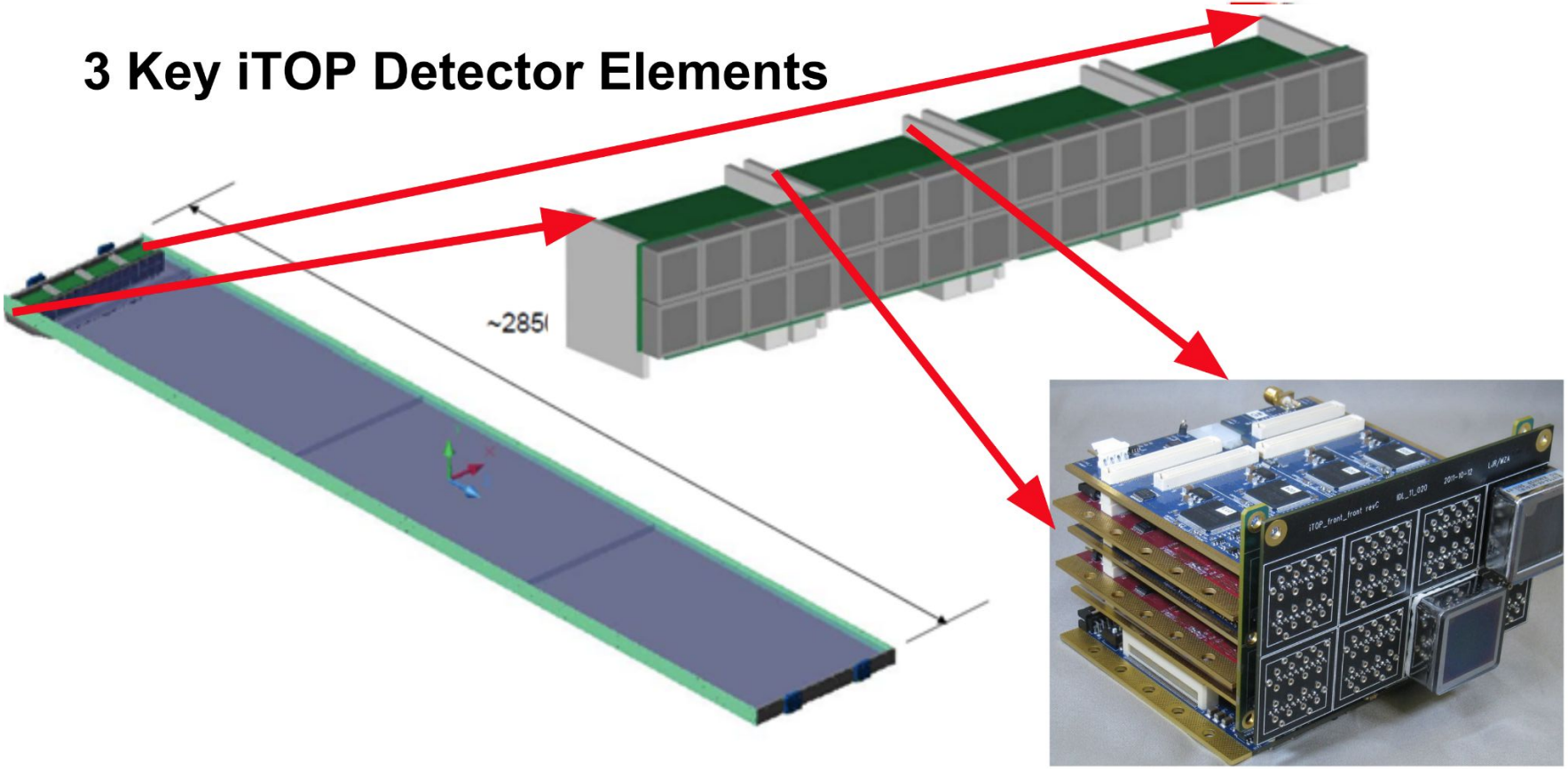
The TOP Detector

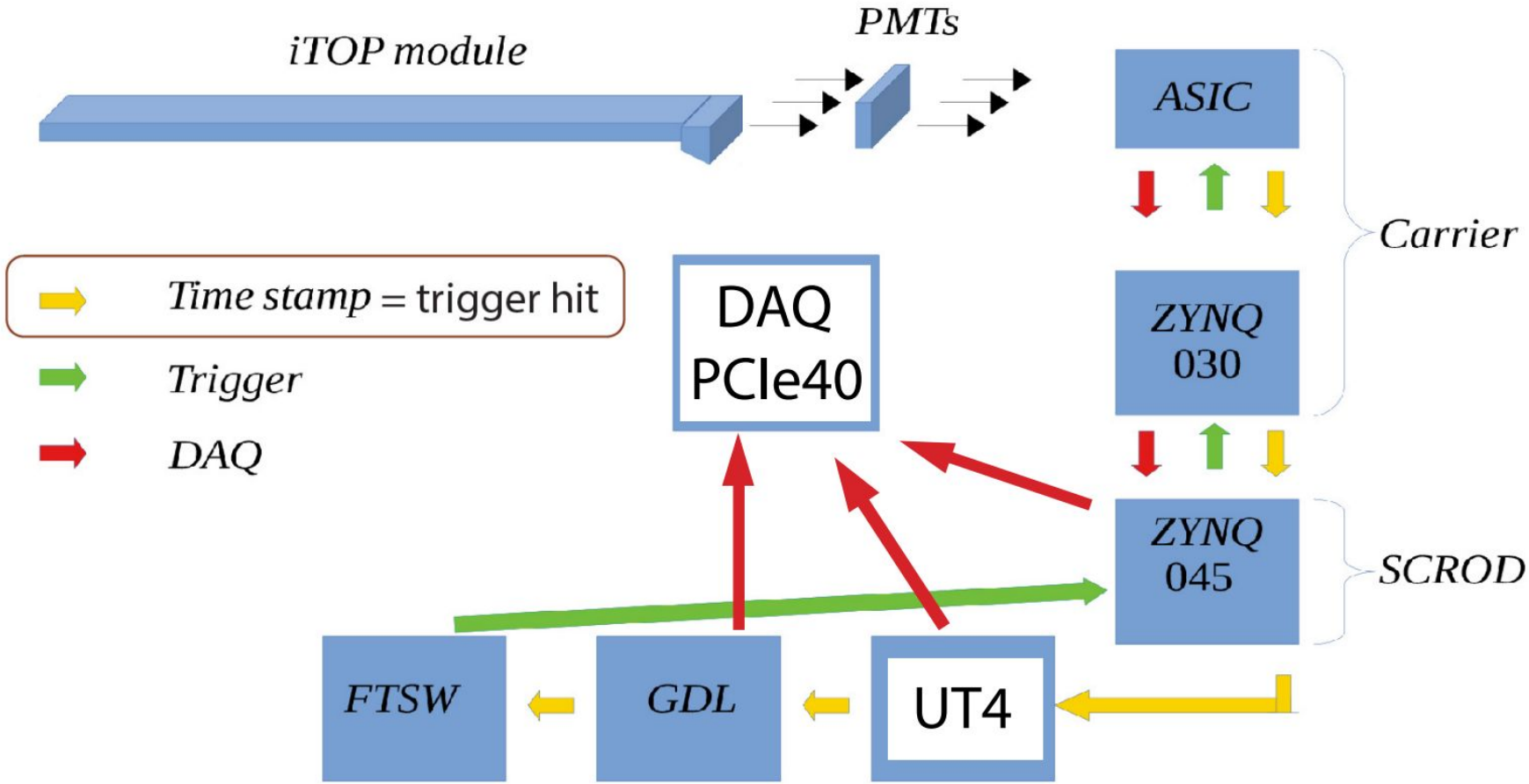




- 16 TOP bars cylindrically arranged around the beam pipe, in between the Central Drift Chamber (CDC) and the Electromagnetic Calorimeter (ECL).
- Charged particles passing a medium faster than the speed of light in the medium emit Cherenkov photons.
- For a given momentum, different particle species emit photons with different Cherenkov angles.
- Depending on where the charged particle entered the TOP bar, the arrival time of the photons will change.

3 Key iTOP Detector Elements




iTOP module
PMTs
ASIC
Carrier
Time stamp = trigger hit
Trigger
DAQ
DAQ
PCIe40
ZYNQ
030
ZYNQ
045
SCROD
FTSW
GDL
UT4

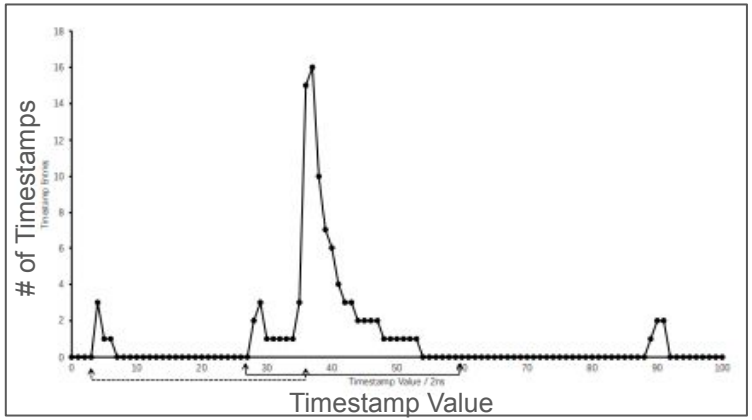
TOP Main Readout Hits

- When a photon strikes the PMT, photon waveform (prepared by the shaping circuit) is sampled by the ASIC at 2.71GHz and analog signals are stored in long capacitor arrays of the sampling circuit (this is our “oscilloscope on the chip”).
- When analog signals exceed a programmable trigger threshold, scaler values corresponding to such moments of time are streamed to UT4 as “timestamps”. These internal triggers are also stored in TOP FEE for future feature extraction.
- When the L1 signal is delivered to TOP FEE through b2tt from FTSW, we identify a region of interest (ROI) via a programmable “look back” window (“a delay”).
- Samples in the ROI are digitized and then a feature extraction is performed using this information. Each TOP main readout hit contains the time and amplitude of a single-photon waveform.

TOPTRG Waveform Readout

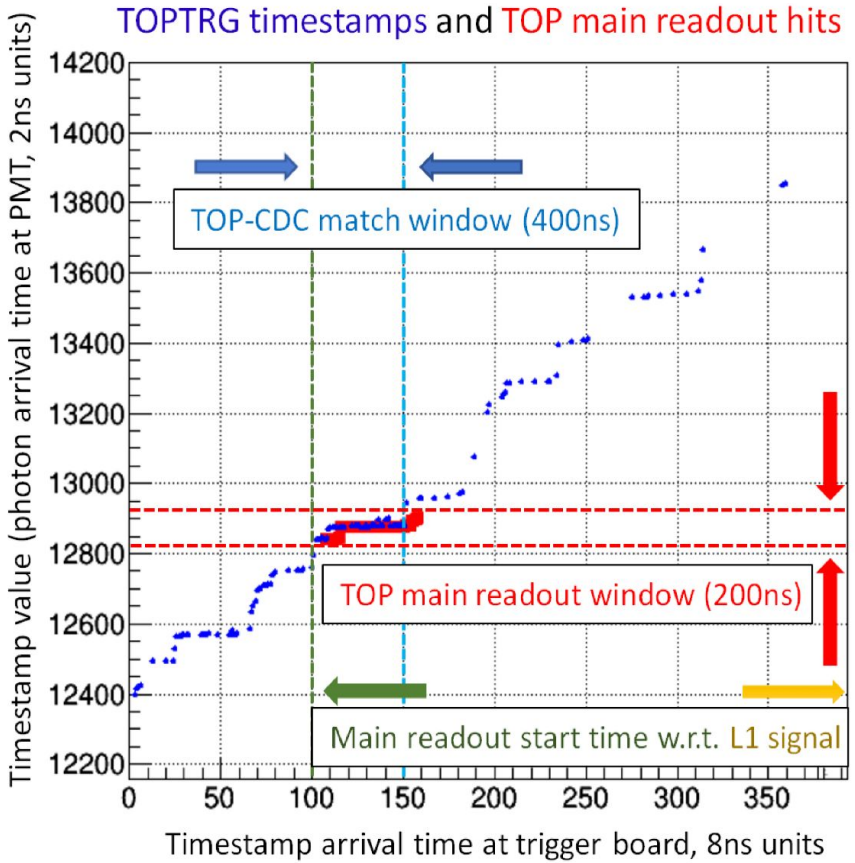
- Every 8ns, the 64 inputs from the TOP FEE are sampled by the UT4 boards.
- As TOP FEE streams timestamps to UT4, TOPTRG waveforms represent sequences of timestamps and empty clock cycles (@127MHz / 8ns).
- TOPTRG waveform readout (suppressed/prescaled by the factor of 512) represents 16 such waveforms recorded over 384 clock cycles (~3.2μs)
- A comparison between TOPTRG waveform readout and TOP main readout allows to validate TOPTRG performance and to perform a variety of calibration.
- Note that TOP main readout ROIs are only 200ns long, so we capture enough sideband in TOPTRG waveform readout to study backgrounds.

Purpose of TOPTRG



- The primary sources of L1 are ECL and CDC, however, it's always a good idea to have additional sources of timing (also, we can be especially useful for dimuon events).
- TOPTRG accumulates timing distributions of timestamps and, when the number of timestamps exceeds a certain threshold, TOPTRG makes a timing decision. GRL takes this decision into account only if it is made within ~400ns window of 2D CDC TRG info.
- Challenges: to achieve high efficiency, the thresholds need to be set low, but then we are overwhelmed by beam-related background. Timing resolution is also a problem, as we need to know where along the bar the Cherenkov photons originate from (timestamps represent the times of photons hitting the PMT).

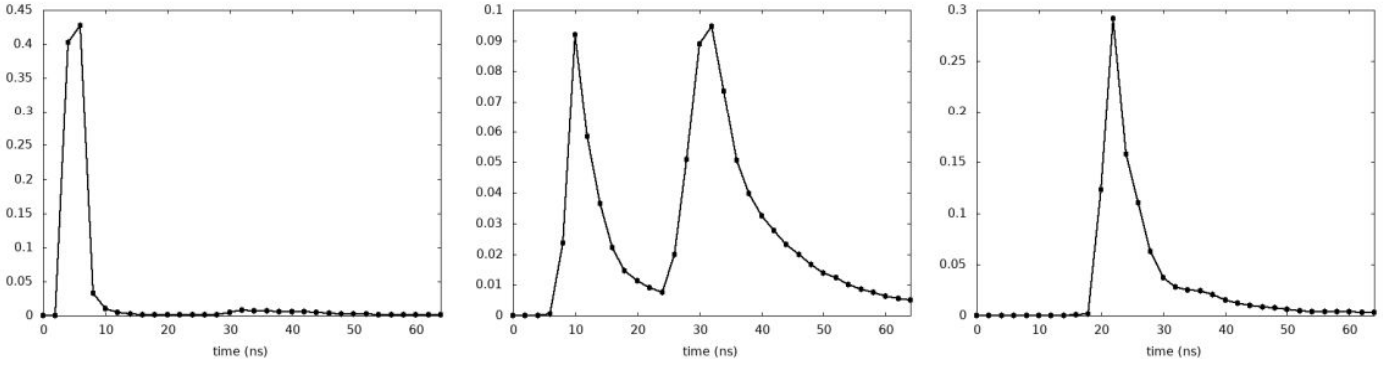
Purpose of TOPTRG



- The blue dots represent the data from TOPTRG waveform readout over 384 clock-cycles for one TOP slot.
- The red dots (blobs) represent the data from TOP main readout. The timing information is converted to the timestamp values (y-axis). The x-axis values represent would-be arrival times of the timestamps as if this information was streamed to UT4 as timestamps one by one (this x-axis information does NOT actually exist for TOP main readout hits).
- The two red dashed lines represent the width of a TOP ROI timing window (200ns).

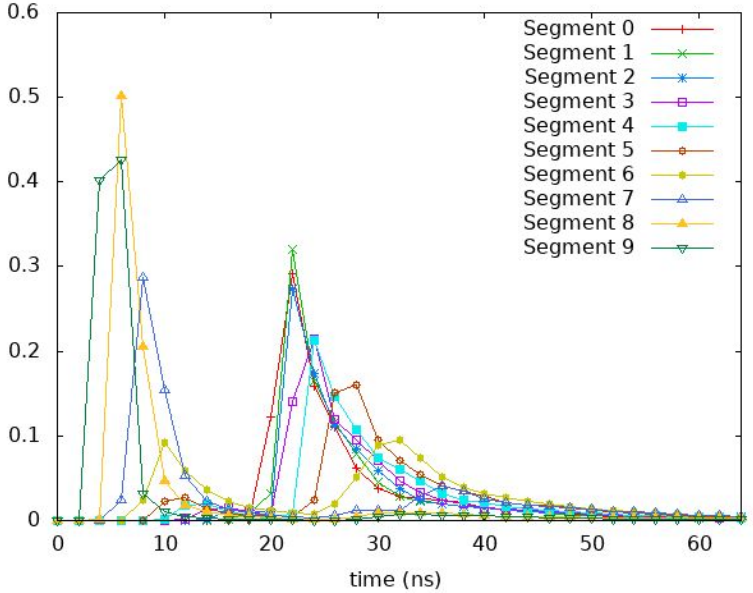
Collision Time Identification in TOPTRG

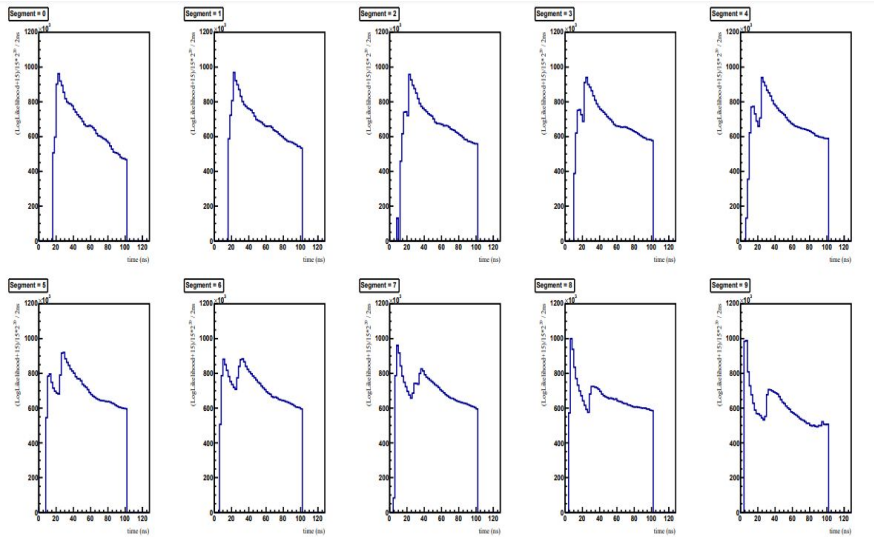
- TOP trigger firmware uses a likelihood-based approach to determine the collision time (t0) of a possible event. This is a legacy decision from a long time ago. It is being reconsidered.
- In FW, there are 10 PDFs that are stored as 10 log-likelihood LUTs. Real-time histograms of photon arrival times are compared against all 10 PDFs and the PDF with the largest log-likelihood is selected as the best match. With low statistics the discrimination power is poor.
- From the selected PDF, we can determine the most probable position the charged particle entered the bar. From the real-time histogram, we can estimate the collision time.



Probability Density Function (PDF) Matching

- PDFs were originally prepared using GEANT4 based Monte Carlo Simulation. However, these PDFs could be improved if prepared with real data (a 3D TRG tracking would be even better).
- For this project (and Wenhai's), we will use fully reconstructed events with tracks extrapolated to the TOP detector to identify the intersected module IDs and the entry positions of the charged particles along the bars.





Fully Reconstructed Events with Tracks Extrapolated to TOP

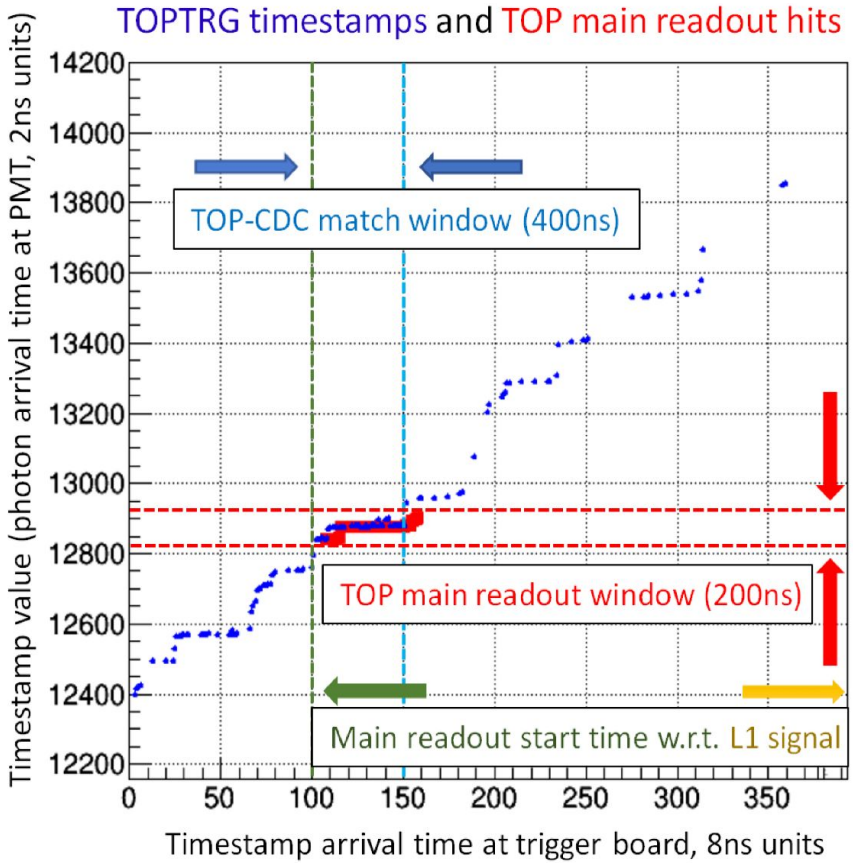
- Instead of using simulation, we will use real data (data from fully reconstructed tracks and timing information) to prepare PDFs.
- Starting with a track, a new object called TOPTrack is created. TOPTrack is an extrapolated track hit (with a pion hypothesis) to the TOP detector.

```
* Constructor from mdst track - isValid() must be checked before using the object
* @param track mdst track
* @param digitsName name of TOPDigits collection
* @param chargedStable hypothesis used in mdst track extrapolation
*/
explicit TOPTrack(const Track& track, const std::string& digitsName = "",
                  const Const::ChargedStable& chargedStable = Const::pion);
```

```
const ExtHit* exthit = trk.getExtHit();

if (exthit->getDetectorID() != myDetID) continue;
if (abs(exthit->getPdgCode()) != pdgCode) continue;

TVector3 position = exthit->getPosition();

TVector3 momentum = exthit->getMomentum();
```

- From the TOPTrack object, the module ID of the TOP bar that the track intersects can be determined.
- We can use the TRD2TTS converter to represent TOP main readout hits as trigger timestamps. Alternatively, we can use actual timestamps from UT4 TOP trigger readout.
- Using the **ExtHit** object, we obtain the track's entrance position and momentum at the TOP detector.

Machine Learning Project for Beam-Related Background



- TOPTRG timestamps (blue dots) are recorded for 384 clock-cycles.
- Comparing TOP main read out hits (red dots) and the TOPTRG timestamps, one can understand the signal region as well as the background. This is not hopeless.
- Wenhai (2nd year graduate student) is working on a machine learning/AI project to suppress background and more accurately identify the signal.

Recent Developments and Ongoing Work

1. Fiber links to TOP FEE on 8 slots were down in some exp 30 runs:
   - Caused by VME problems and idiosyncrasies in how the transceiver reference clocks were programmed via VME + system controller A7.
   - Fix: clocks are now directly programmed from VIRTEX Ultrascale FPGA (VU).

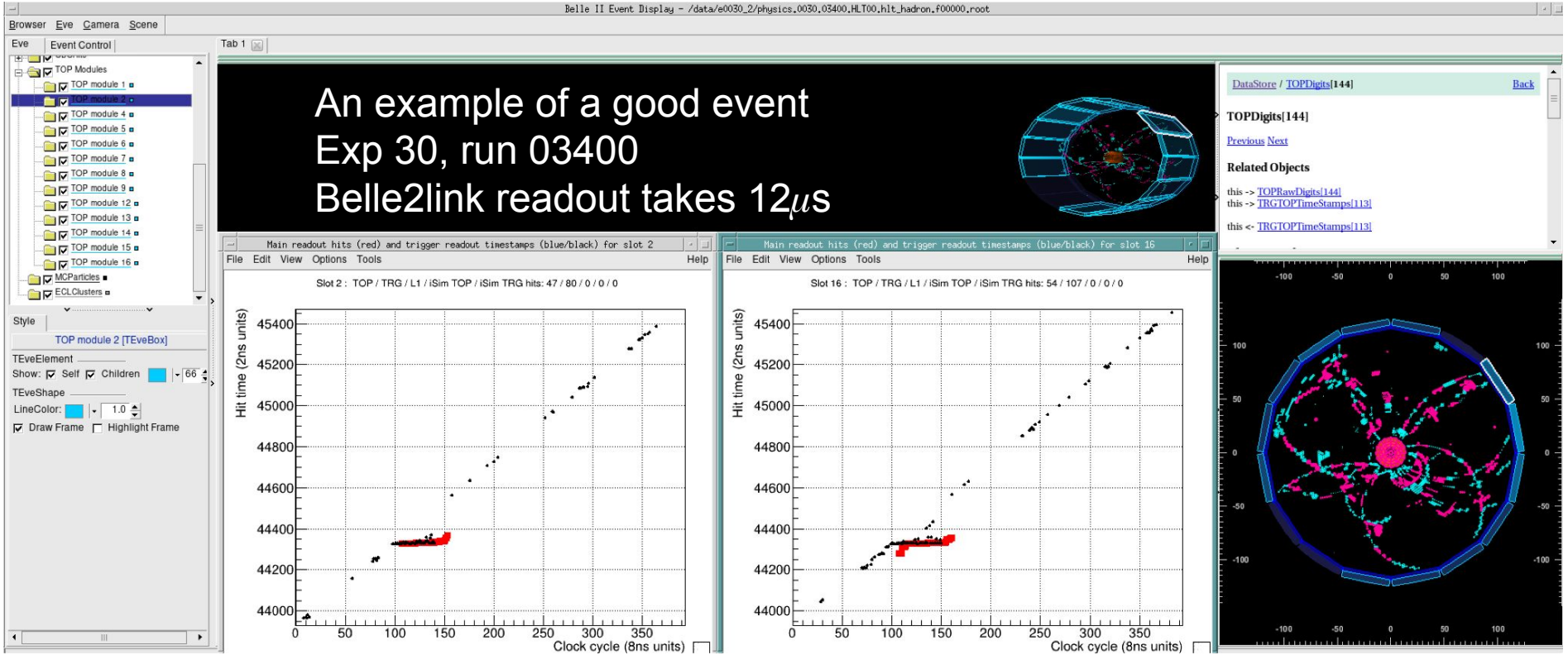
2. Missing TOPTRG Waveforms for 8 slots in some of the runs:
   - The prescale/suppression factor and look-back window (delay) come from slow-control (SLC) over VME.
   - When the VME has problems, the values could be affected, which caused some of the TOPTRG waveforms to be missing (wrong prescale was used).
   - Fix: A mechanism was put into place to prevent these problems from happening.
   - SLC needs to be improved, a DQM plot for waveform readout is needed.

Recent Developments and Ongoing Work

3. TOPTRG waveform readout and TOP main readout mismatch:

- The event number and TOPTRG event number (trg tag) did not align by 1 or 2.
- Caused by insufficient circular buffer depth for waveform readout.
    - When 2-3 L1 triggers arrived in quick succession, buffer overflow occurred before the first waveform readout sent to the DAQ via belle2link.
    - This caused the event number misalignment.
- Fix: Increased circular buffer depth to handle multiple L1 triggers in quick succession.

Inconsistencies Between TOP Main Readout and TOPTRG Waveform Readout were observed in Higher-Luminosity Runs



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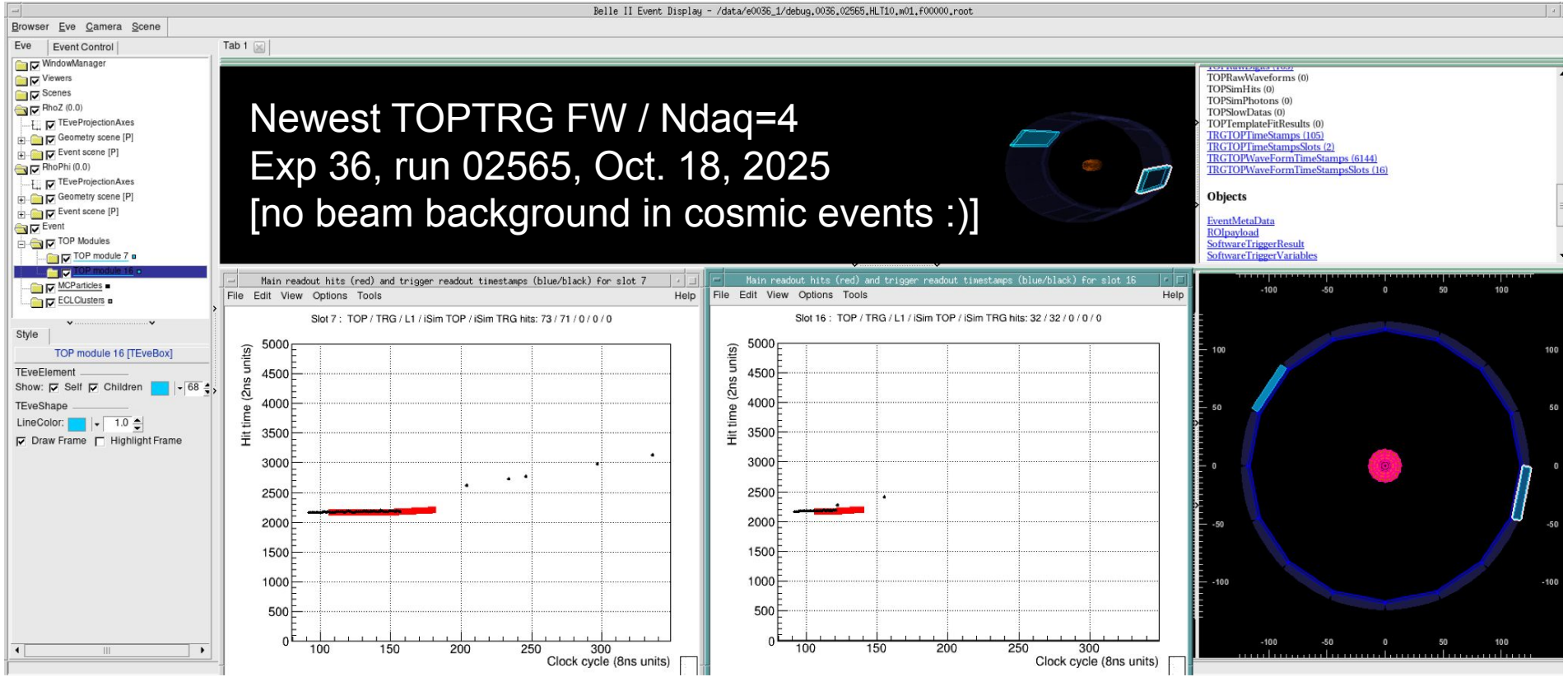

Conclusions and Future Outlook

- The analysis of exp 30 data revealed several important shortcomings
- Changes were made in TOPTRG FW, validation performed
- Ready for data taking / tested everything also with cosmic data a few days ago
- Studies of 3D tracking + a better timing algorithm based on timestamps.
- Extracting trigger PDFs from data is now possible.
- ML/AI project to suppress beam-related background could now continue also.
- Data Production request for fully reconstructed events with TOPTRG waveform readout for all discussed studies has been submitted: https://gitlab.desy.de/belle2/data-production/data/-/issues/160


Thank you for your attention!