Reconstruction Capabilities of the Photon Detection System of SBND

LiDINE 2025

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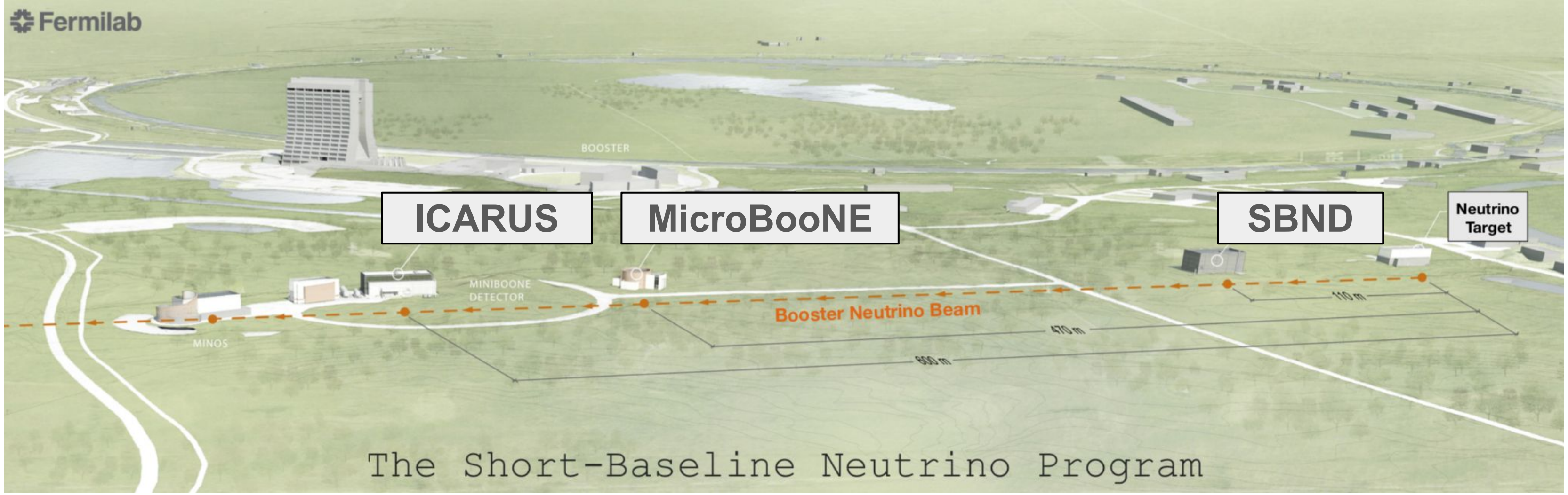
On behalf of the SBND Collaboration

Hong Kong, October 2025

UNIVERSIDAD DE GRANADA

SBN Program:

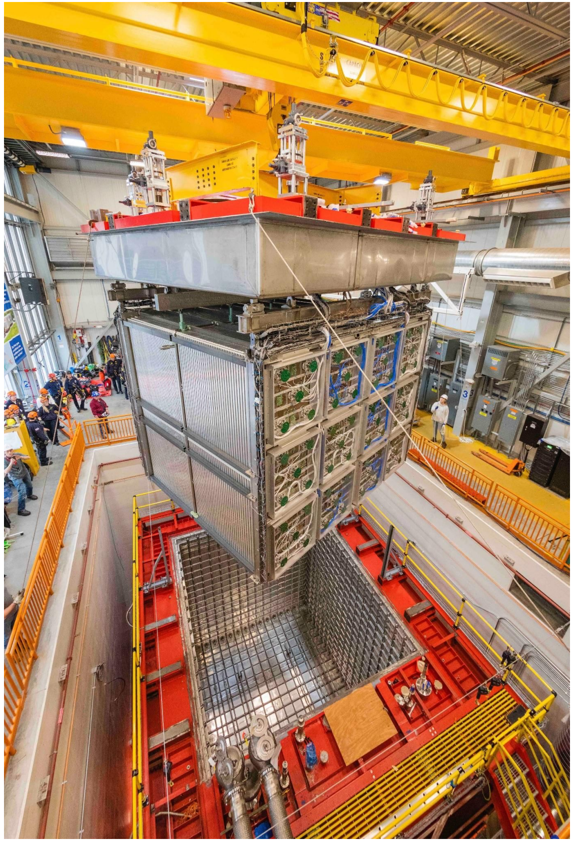


- The **S**hort **B**aseline **N**ear **D**etector (SBND) is the closest to the neutrino source of the three detectors that integrate the Short-Baseline Neutrino Program at Fermilab.
- Three detectors based on the **L**iquid **Ar**gon **T**ime **P**rojection **C**hamber (LArTPC) technology to detect neutrinos produced at the **B**ooster **N**eutrino **B**eam (BNB).
- SBN physics goal: search for light ($\Delta m^2 \sim 1eV^2$) sterile neutrino oscillations

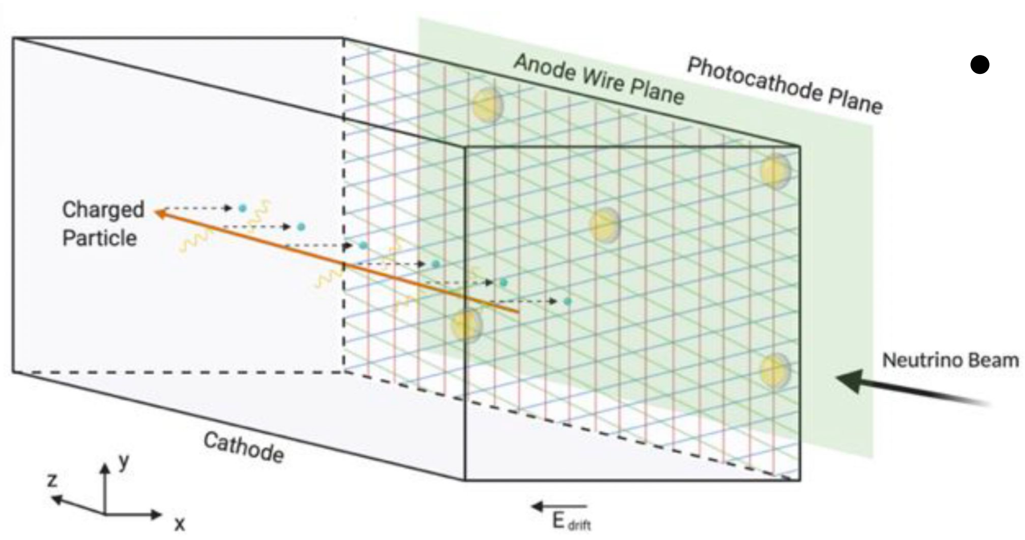
Short Baseline Neutrino Detector:

- SBND has a rich physics program:
  - Closest detector to the neutrino beam. It will characterize the unoscillated neutrino flux.
  - Will record ~2M neutrino interactions per year, allowing the study of interactions with unprecedented precision at ~1 GeV energies.
  - Other BSM searches (HNL, light dark matter…)
  - R&D for future LArTPC experiments (X-Arapuca, TPB-coated foils, WLS coated and uncoated detectors…)

- Detector operations started last year. First physics run already completed!



Liquid Argon Time Projection Chamber:



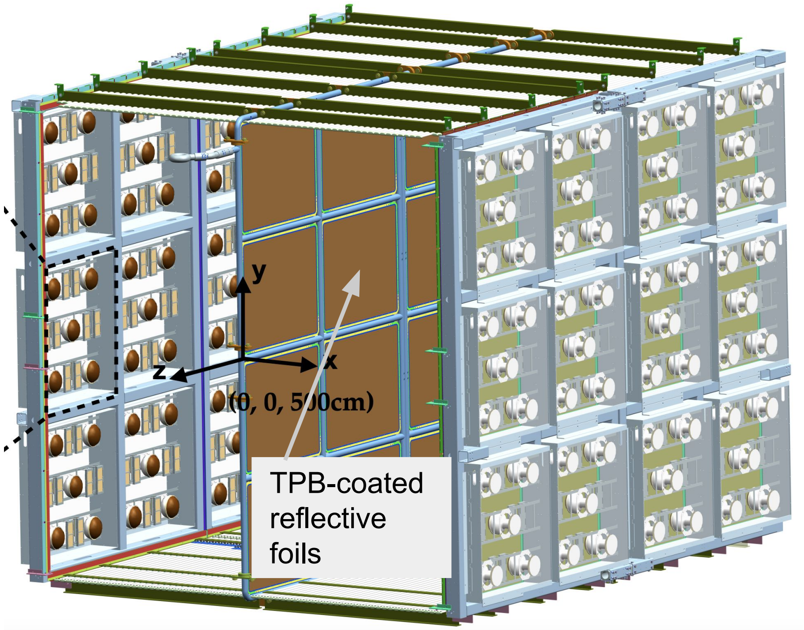
- Two complementary signals:
  - Ionization electrons: drifted through an electric field and detected at the charge readout plane.
  - Scintillation photons: detected by the photon detection system.

- Ionization signals traditionally used for calorimetric and topological reconstruction.
- Scintillation signals traditionally used for trigger purposes.

SBND Photon Detection System:

- SBND Photon Detection System (PDS) aims at maximizing the physics output that can be obtained from scintillation signals through an innovative design.

PASSIVE COMPONENTS



- Reflected foils coated with Tetra-PhenylButadiene (TPB) wavelength shifter (WLS) installed at the cathode.
  - Absorbs VUV photons and re-emits them with a visible wavelength.
- PDS sensitive to two light components:
  - Primary: VUV (main component).
  - Reflected: Visible (extra component).

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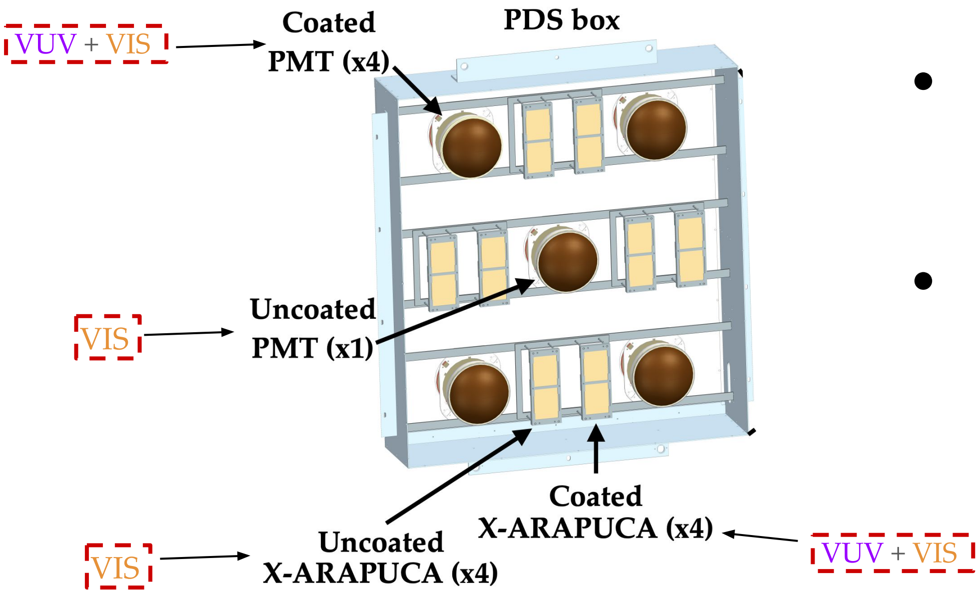

- Detection of VUV light is challenging: WLS compounds are used
- Primary system: 120 8”Hamamatsu Photomultiplier tubes (PMTs). Well know technology
- 192 X-ARAPUCAs: technology under development
    - Acts as a light trap: WLS and dichroic filters.
    - Readout by SiPMs.

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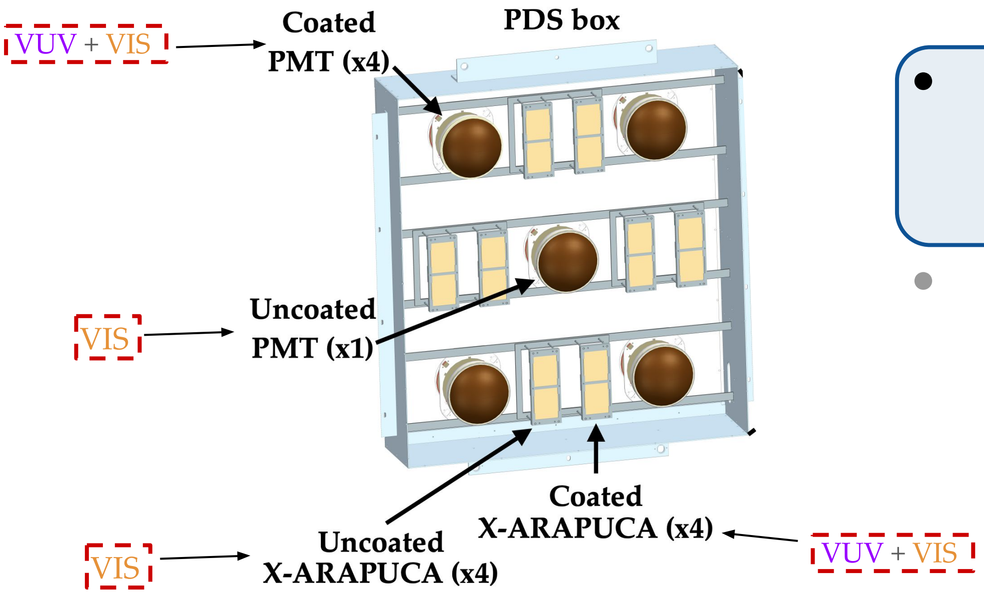

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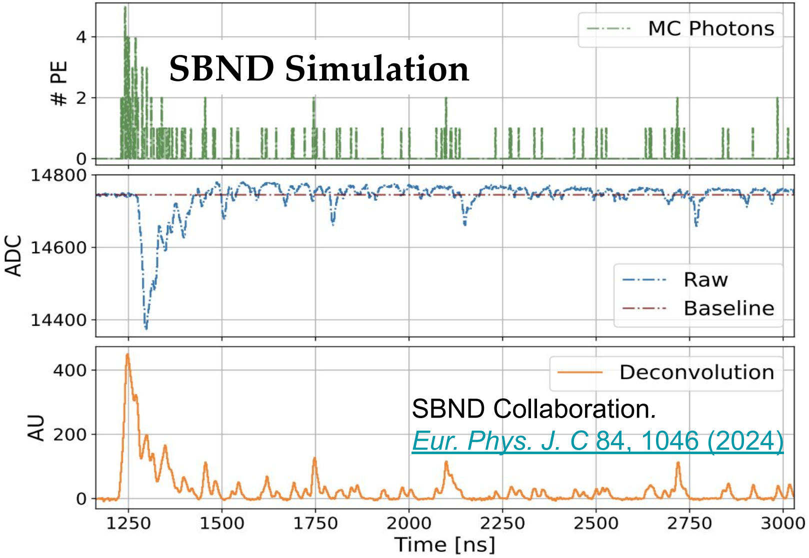
PMT Response Calibration:

- PMT bipolar waveforms call for a deconvolution-based PMT reconstruction
  - requires a channel-by-channel characterization of the Single Electron Response function.
- Characterization performed using cosmic muons



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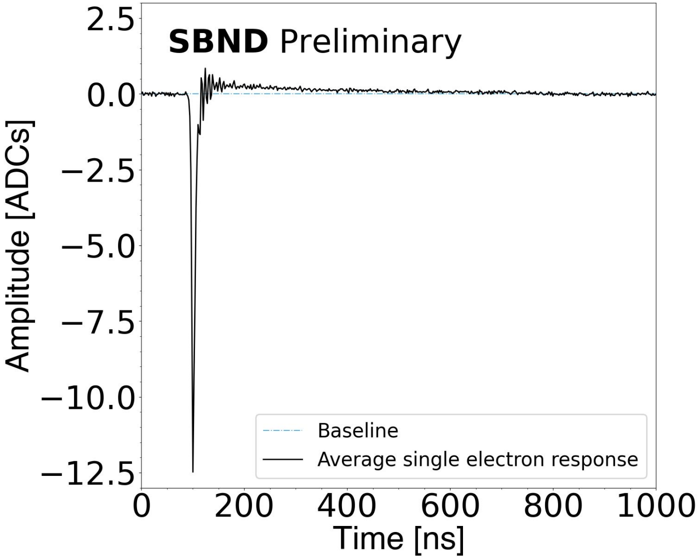
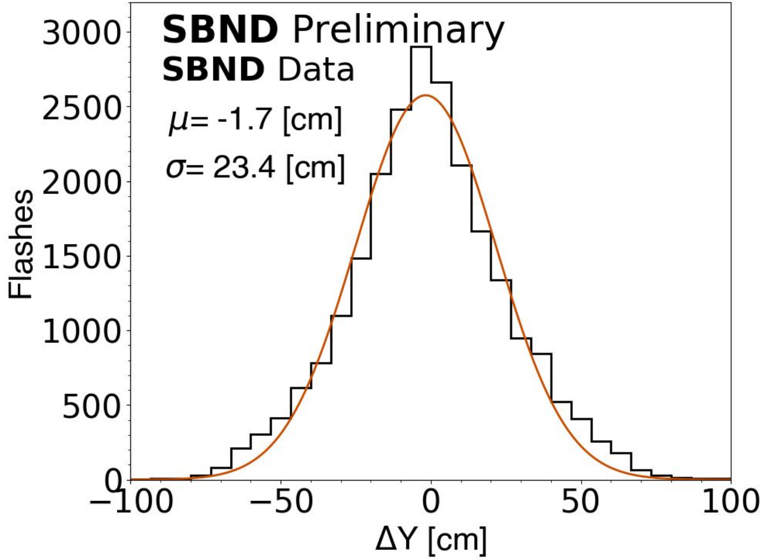
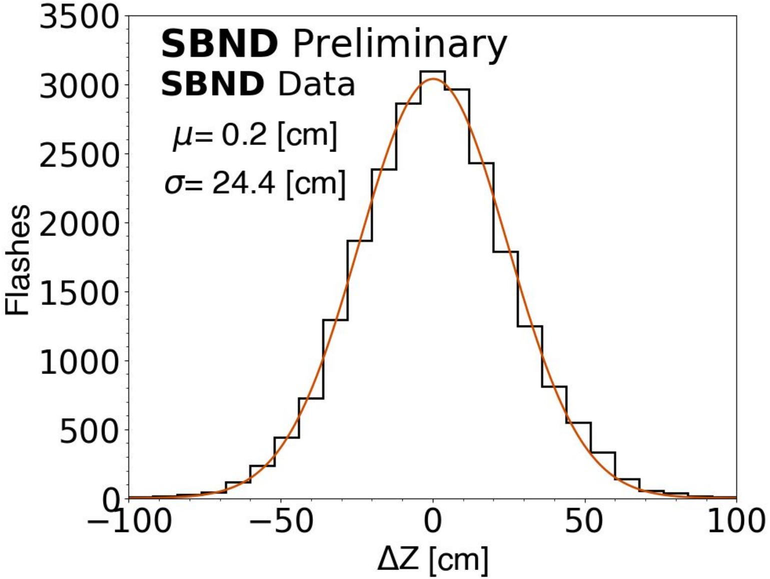


- Electronic noise also characterized channel by channel
- This step is the basis of the PMT reconstruction workflow

PMT Position Reconstruction:

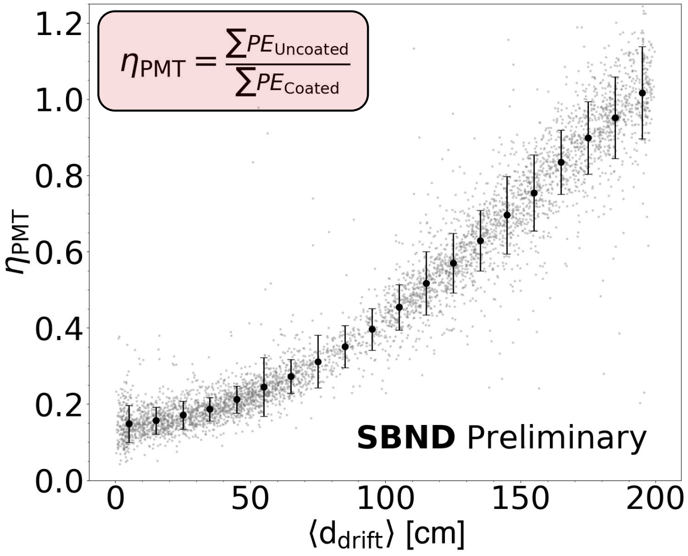
- One of the unique features of SBND's PDS is the ability of performing light-only 3D reconstruction.
- Reconstruction on the PDS plane (YZ) is performed using a barycenter-based algorithm.
  - Resolution below 25 cm for YZ reconstruction

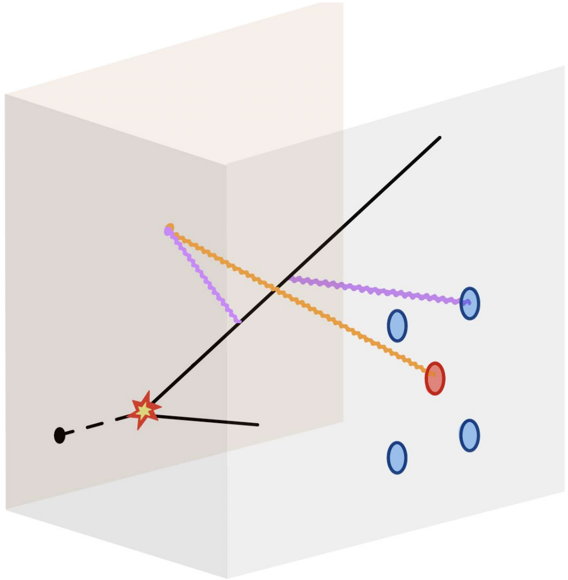




PMT Position Reconstruction:

- One of the unique features of SBND's PDS is the ability of performing light-only 3D reconstruction.
- Reconstruction on the drift coordinate based on its sensitivity to two light components.
  - $\boldsymbol{\eta}_{\mathrm{PMT}}$ is used as a proxy for the drift distance of a neutrino interaction





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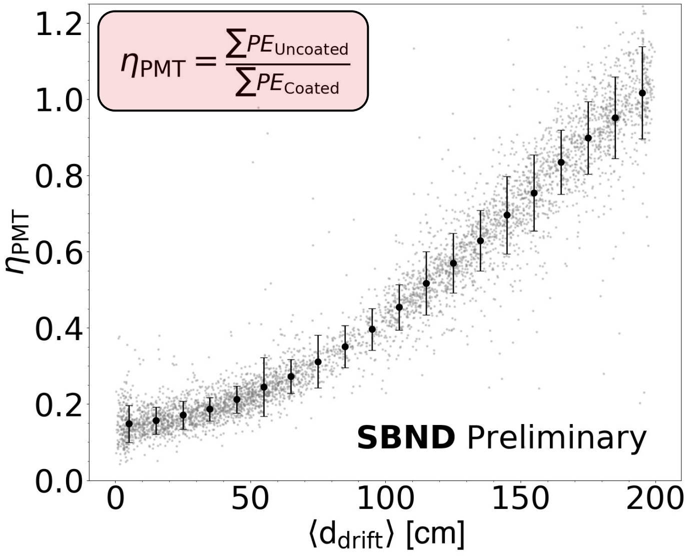
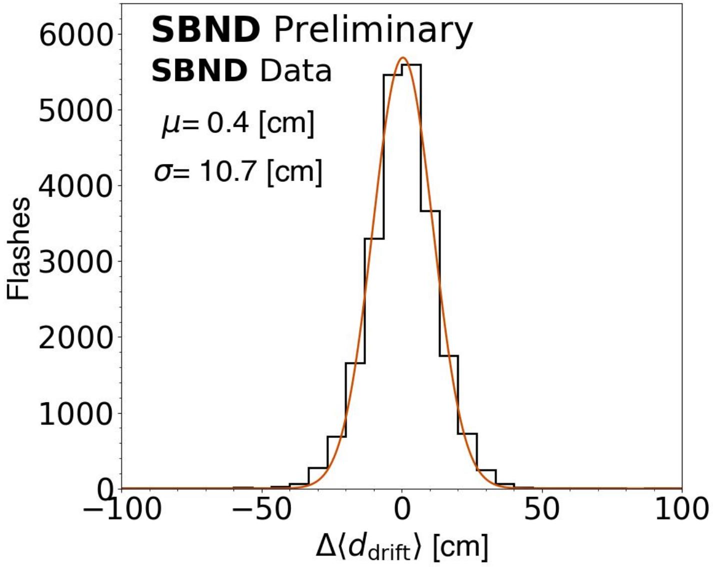
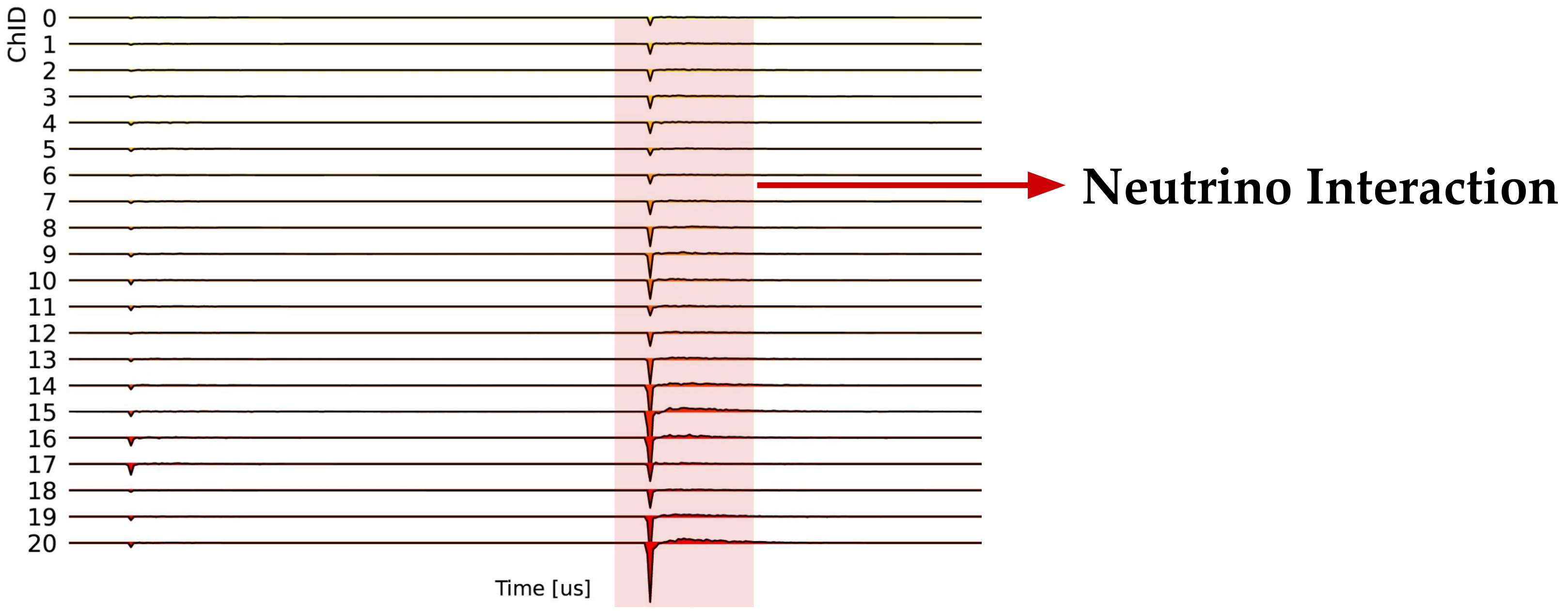




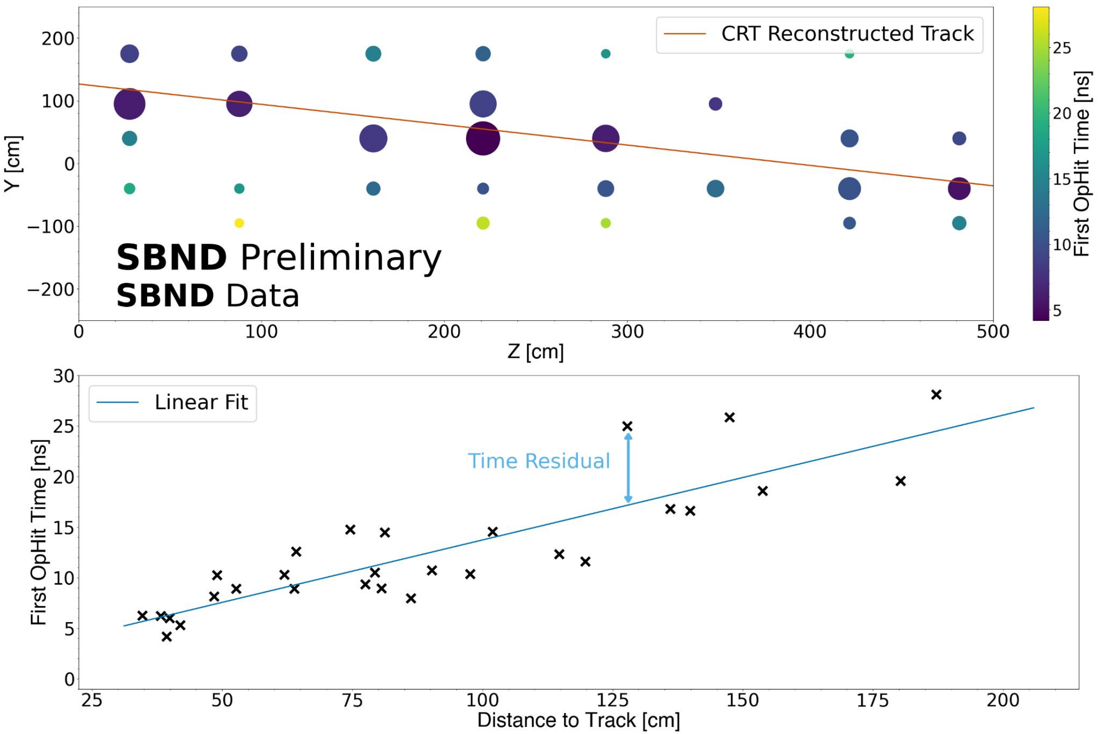
PMT Timing Reconstruction:

- Neutrino interaction time reconstruction is performed using a clustering algorithm that groups together pulses coincident in time
  - PMT to PMT alignment is paramount for precise timing reconstruction



PMT Timing Calibration:

- Relative transit time is calibrated using cosmic muons whose trajectory is tagged with the CRT system. Exploit the linear relationship of photon arrival time and distance between the PMT and the track.
  - Technique only used for coated PMTs for simplicity



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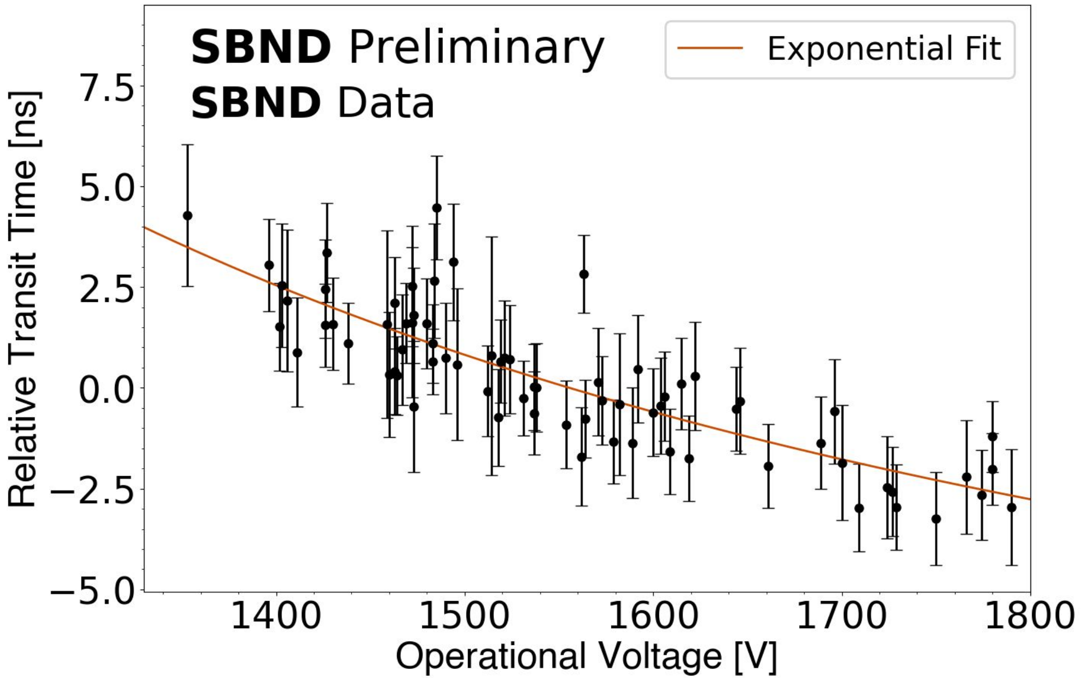
- Exponential fit is used to extrapolate the correction for uncoated PMTs



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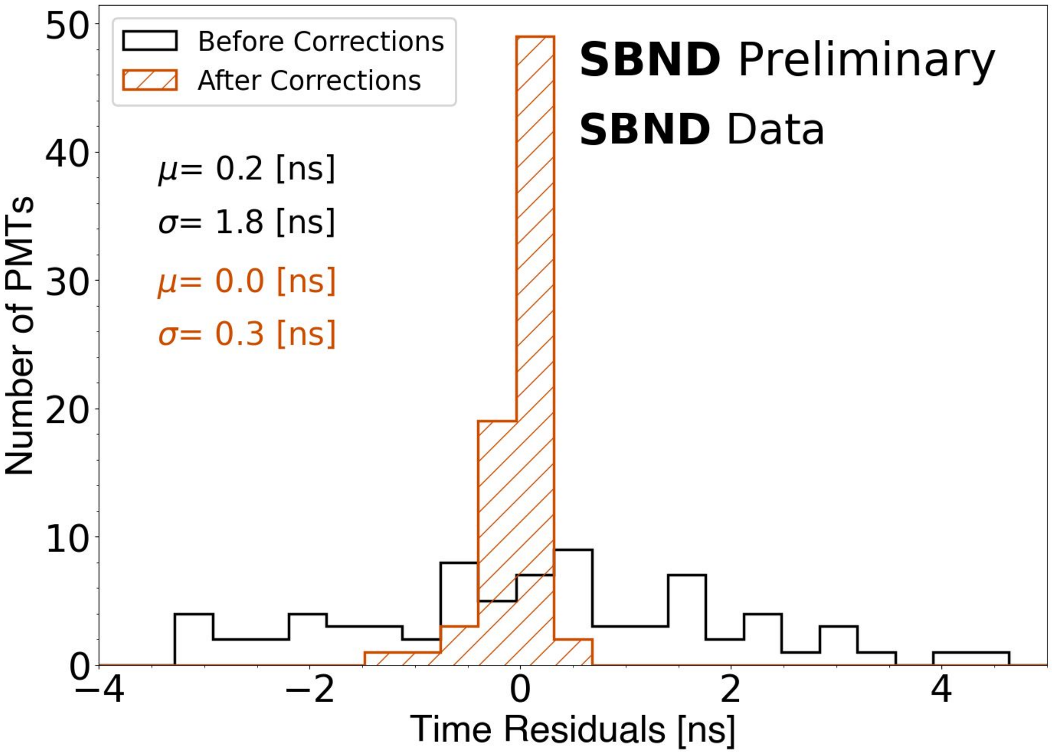
- Differences in PMT operational voltages produce ~10 ns spread in their transit time.
- Exponential fit is used to extrapolate the correction for uncoated PMTs
- Final timing inter-calibration below 1 ns



BNB Timing Reconstruction:

- The Booster Neutrino Beam (BNB) delivers proton pulses to the target. Each ~1.6 μs pulse contains 81 bunches with a spread of 1.3 ns.
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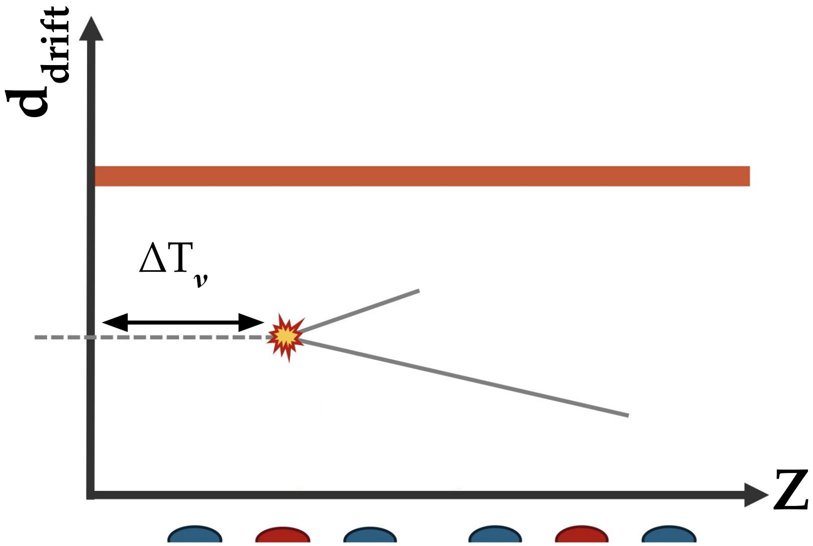
- Reconstructing the neutrino BNB bucket structure requires correcting for
  - neutrino propagation time inside the detector

    Z reconstruction $\longrightarrow$ up to 17 ns



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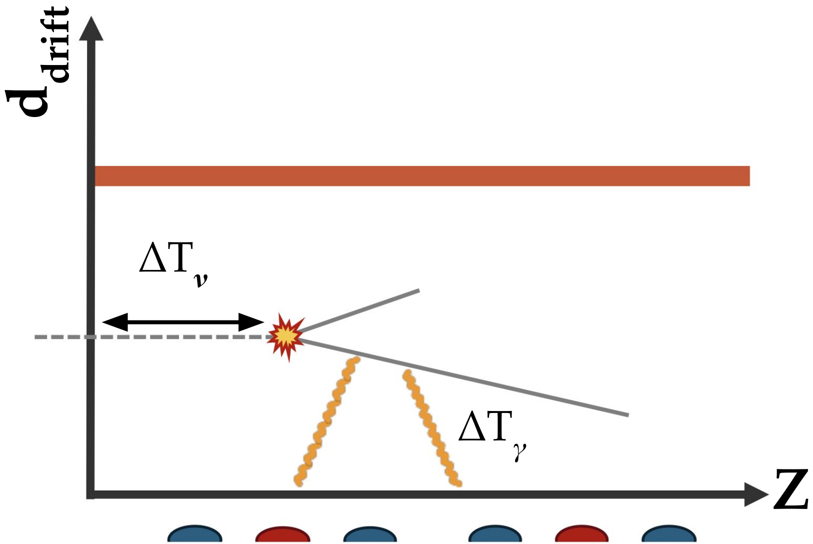
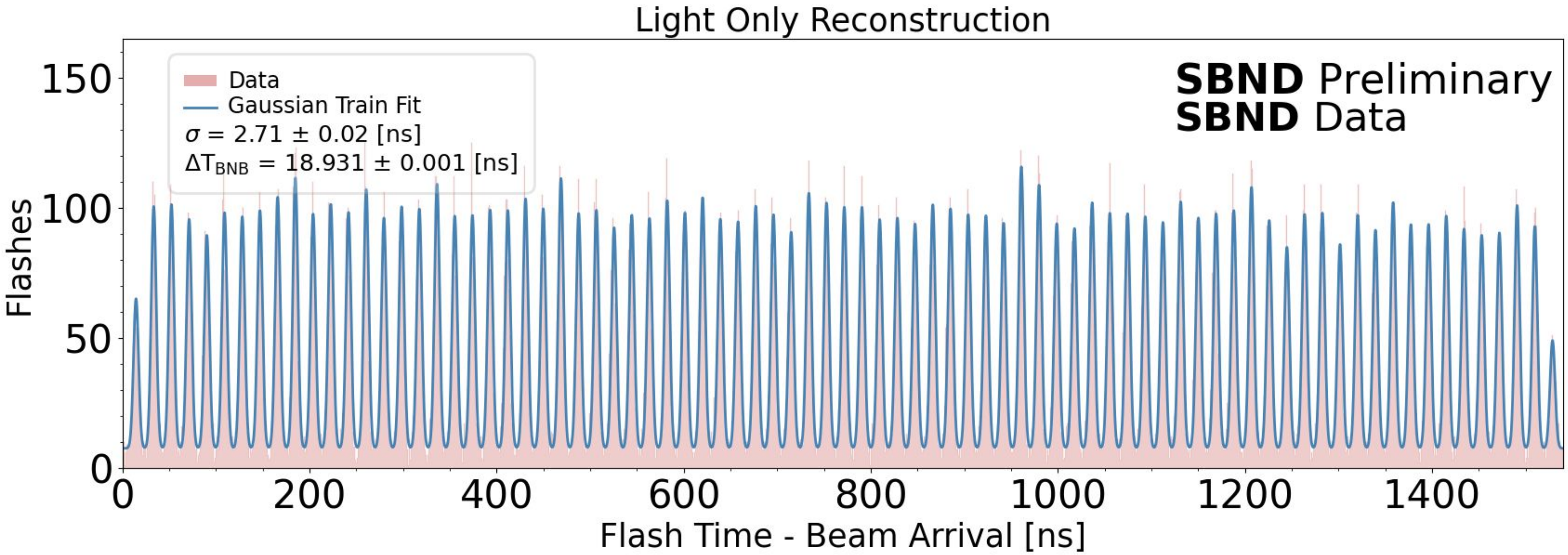
  - neutrino propagation time inside the detector
    Z reconstruction ⟶ up to 17 ns
  - light propagation time from the interaction point to the photon detectors
    X reconstruction ⟶ up to 15 ns



Light-only BNB Timing Reconstruction:

- Using light-only information the obtained resolution is $\boldsymbol{\sigma}$**=2.71±0.02 ns**.



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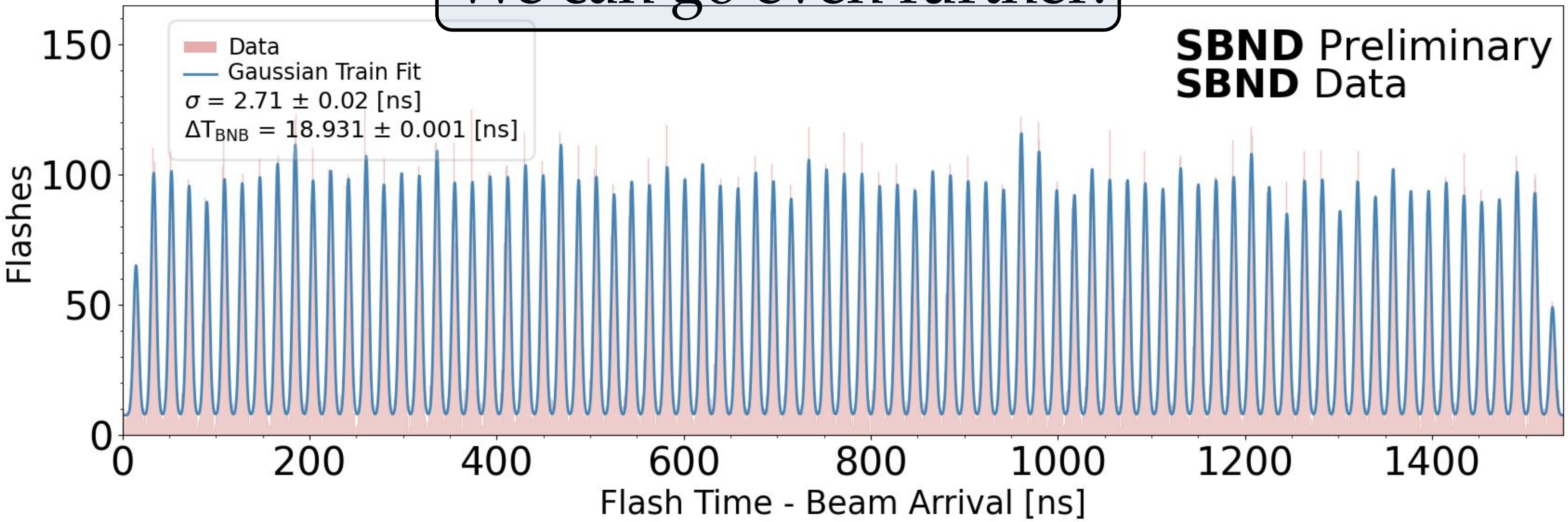
We can go even further!



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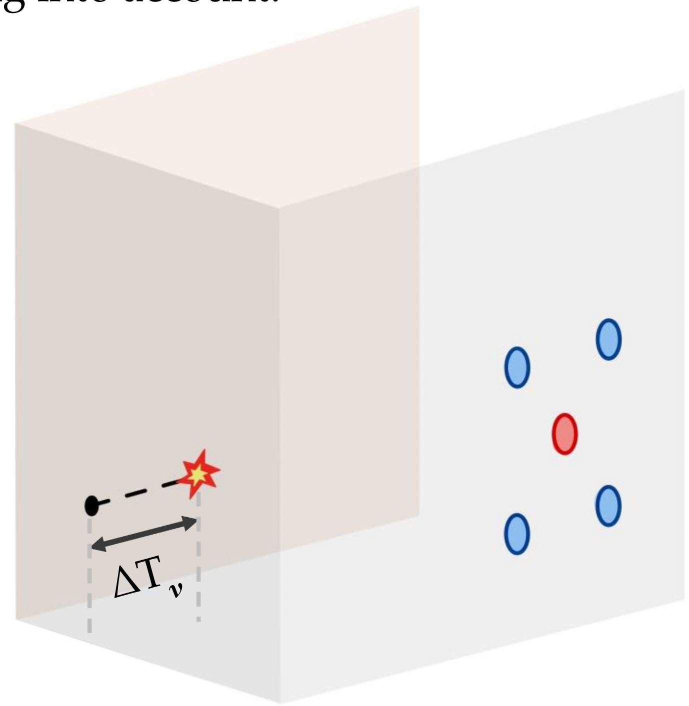

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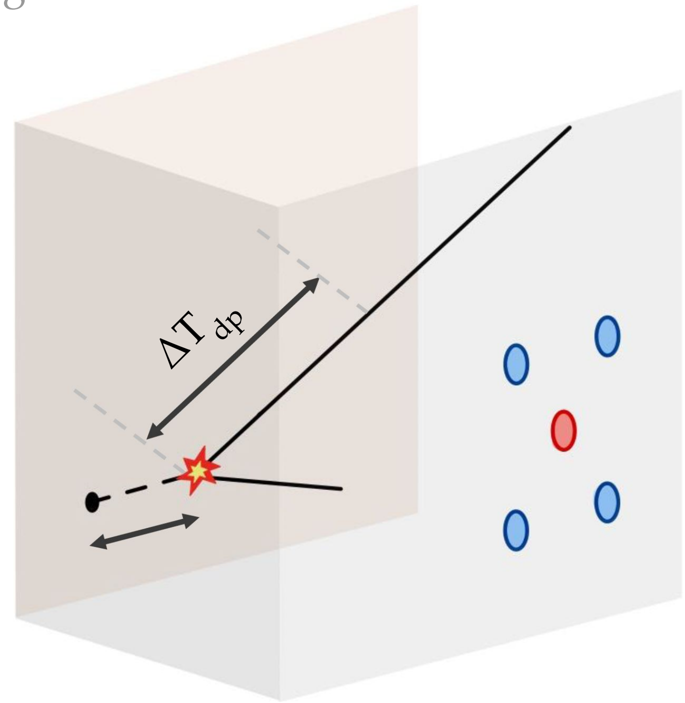

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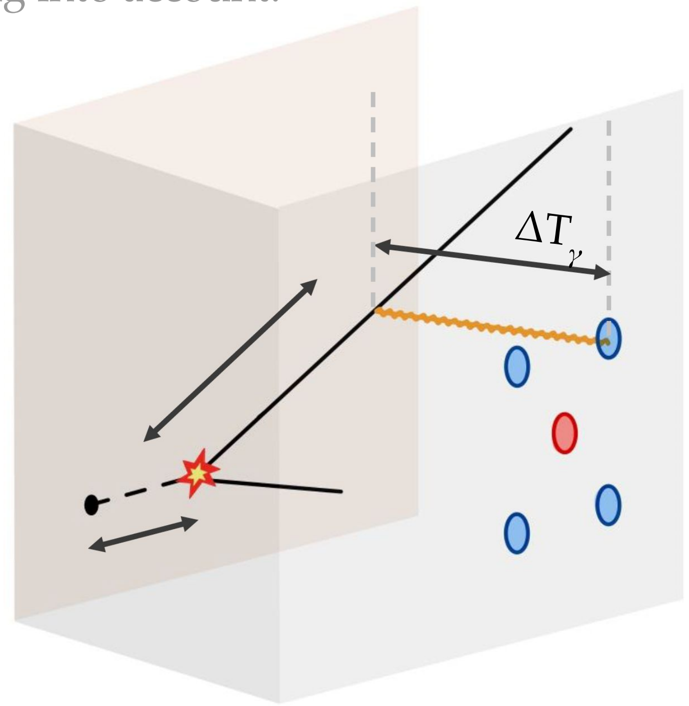
  - Light propagation from the emission point to the PMT



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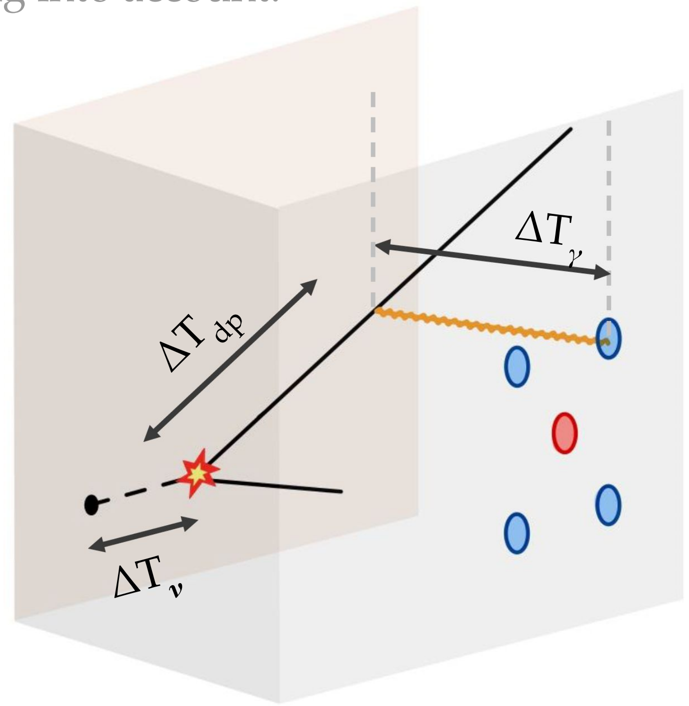
  - Each channel is corrected by the space point that minimises:

$$\Delta T = \Delta T_{\nu} + \Delta T_{dp} + \Delta T_{\gamma}$$



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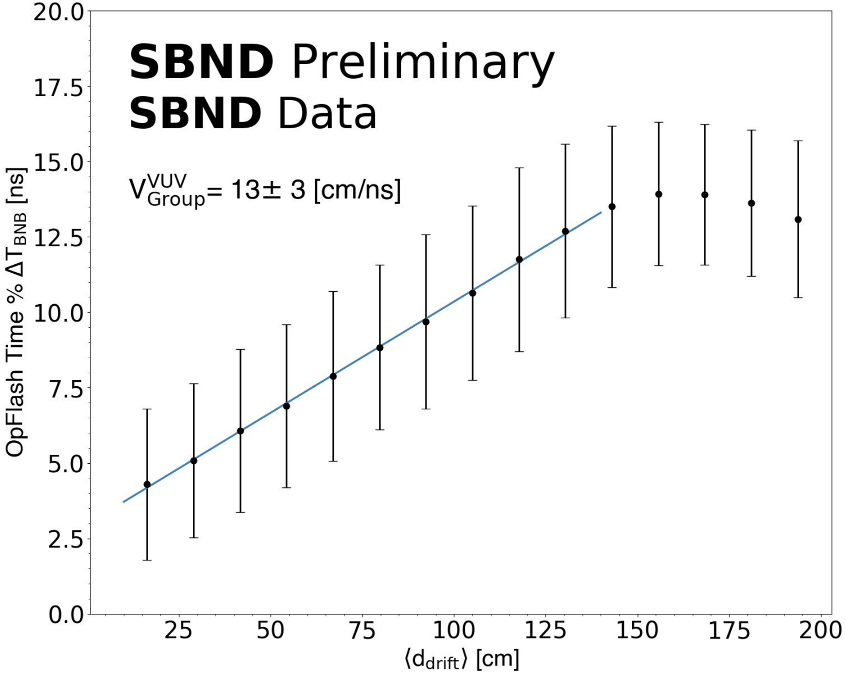
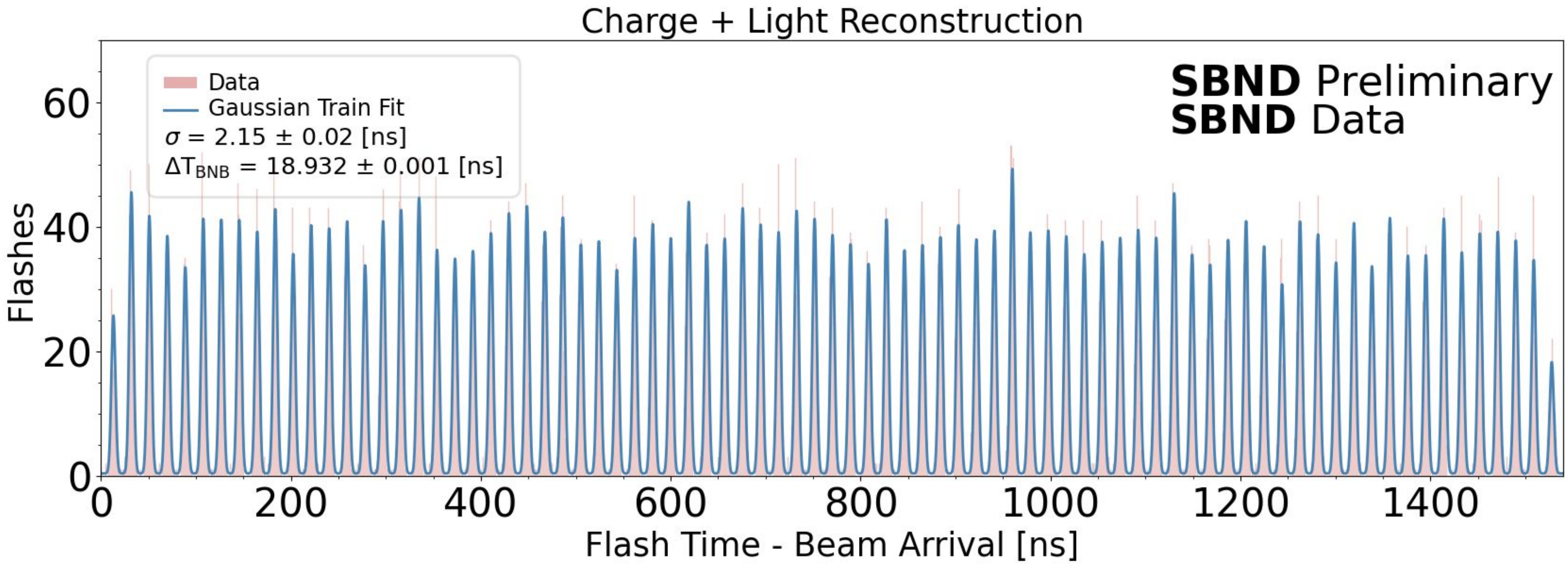
- Bonus: measuring light propagation delay as a function of drift distance provides a measure of VUV light group velocity.



Enhanced BNB Timing Reconstruction:

- Neutrino time resolution is significantly improved after including TPC-based propagation time corrections yielding a resolution **σ=2.15±0.02 ns**
- TPC used for neutrino event selection: cosmic background pedestal disappears



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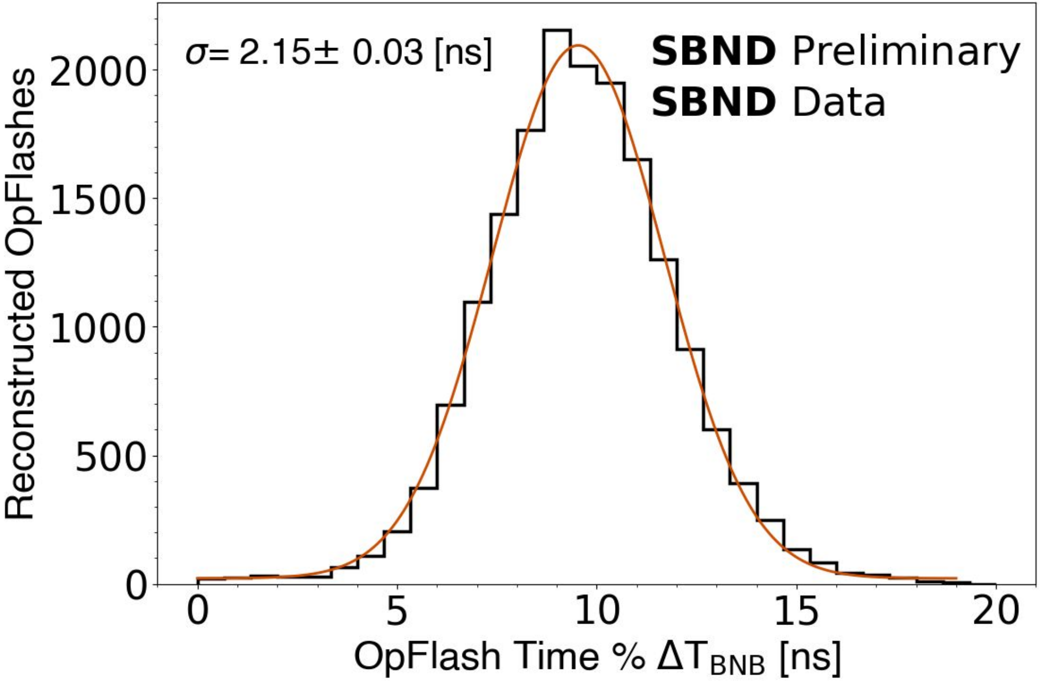
- This level of resolution enables leveraging BNB inner structure for:
  - Cosmic background rejection: selection window within bucket time
  - BSM searches: selection window between buckets to improve neutrino background rejection



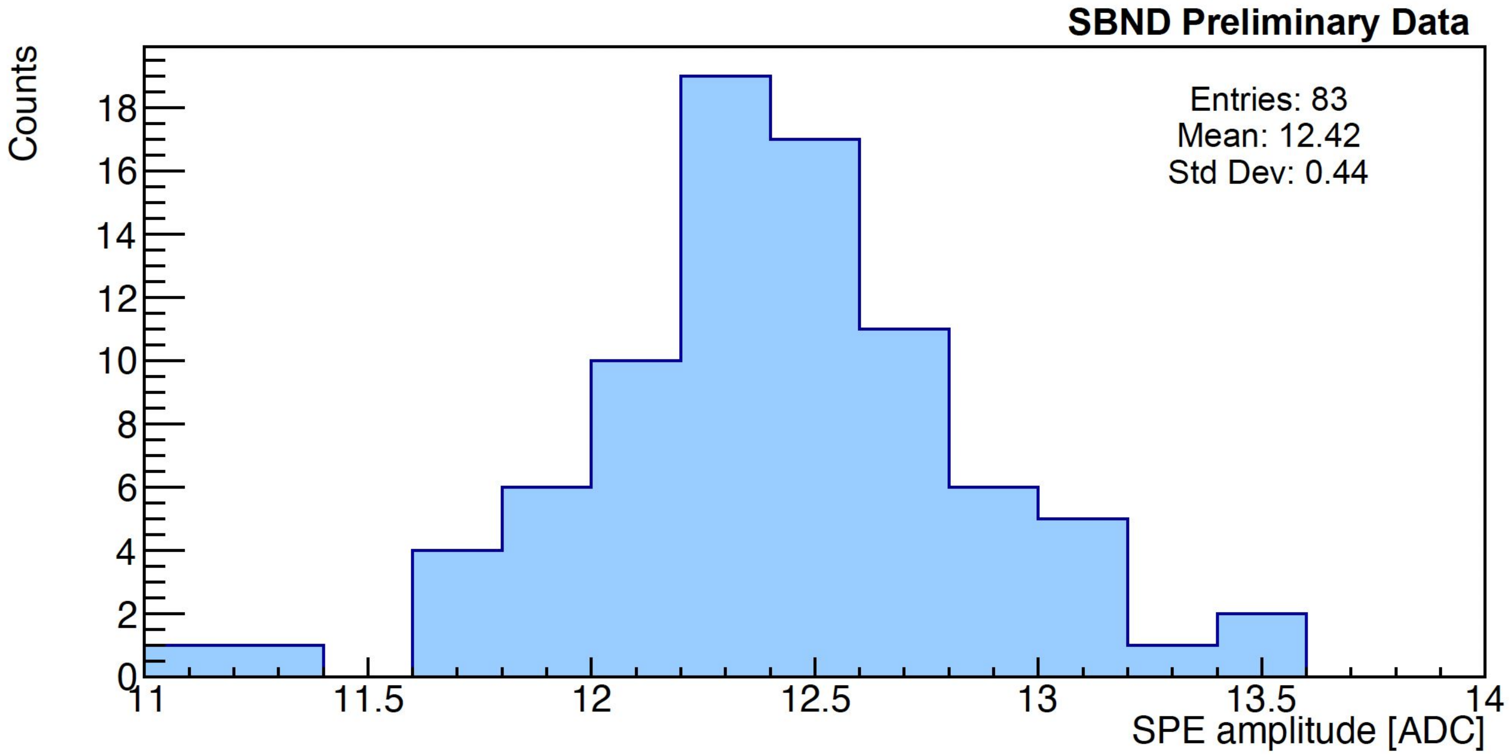
Summary:

- SBND is the LArTPC detector using the most advanced Photon Detection System so far.
- Reconstruction capabilities of such an advanced detection system have been shown in terms of
  - 3D position reconstruction (σ_Y , σ_Z < 25 cm ; σ_X < 11 cm)
  - Timing reconstruction ***O***(2ns)
- Combining TPC and PMT information timing resolution is improved allowing for
  - powerful background rejection
  - enhanced sensitivity for BSM searches
- First physics results coming soon!

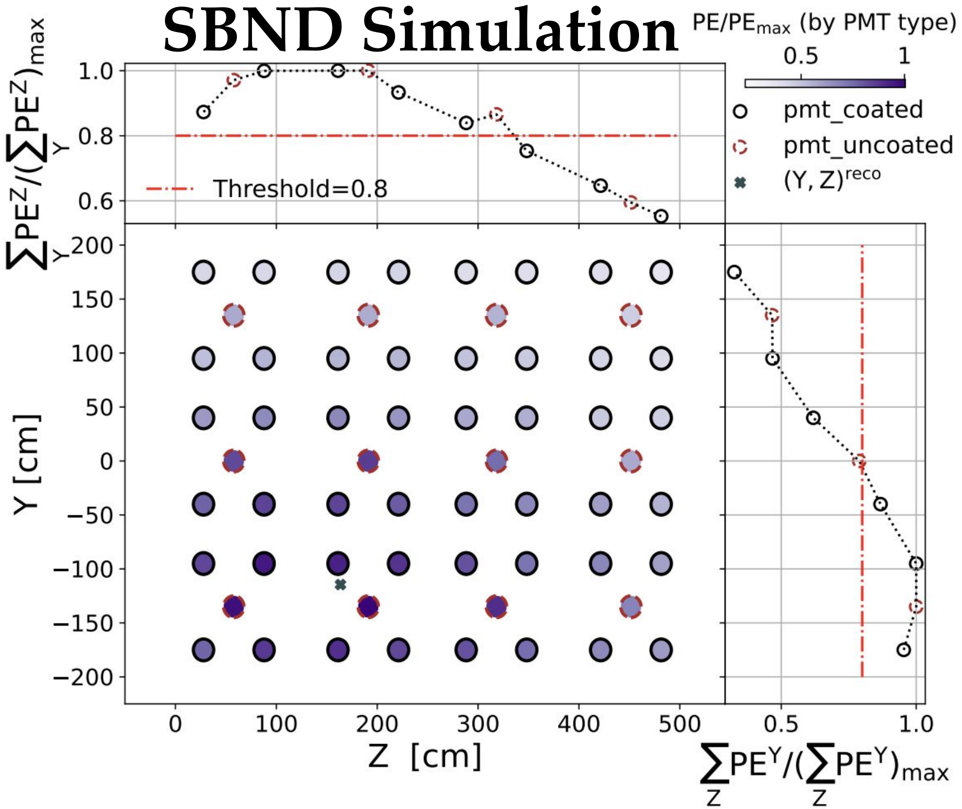
¡Gracias!

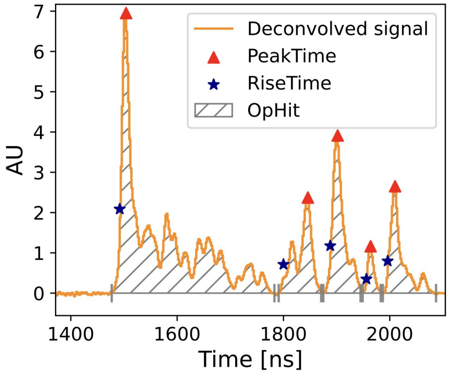
Backup

PMT Gain Equalisation:



PMT Position Reconstruction:





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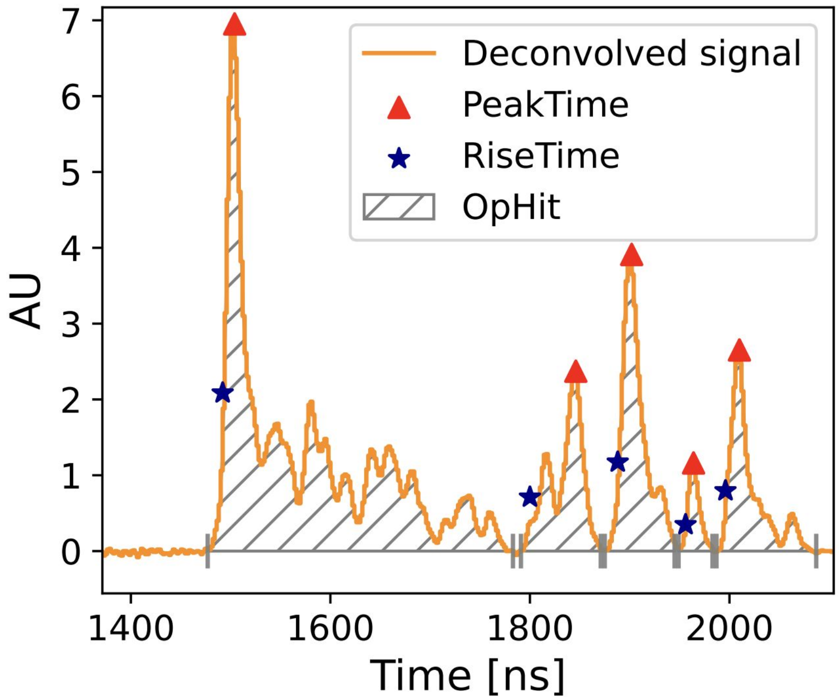
PMT Timing Reconstruction:

SBND Simulation



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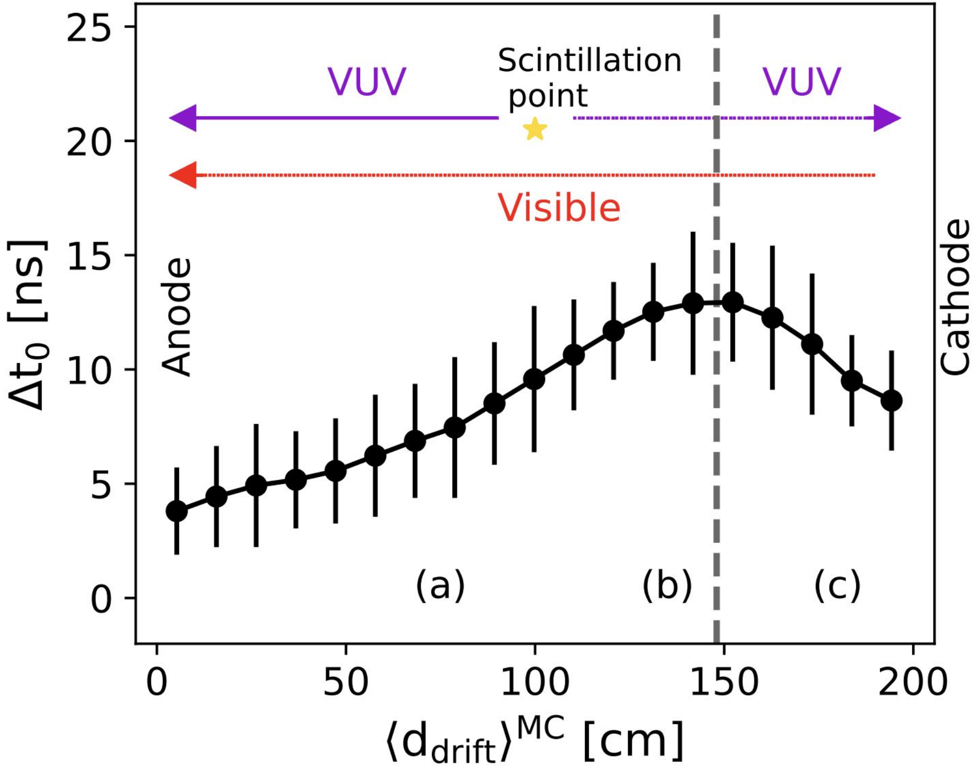
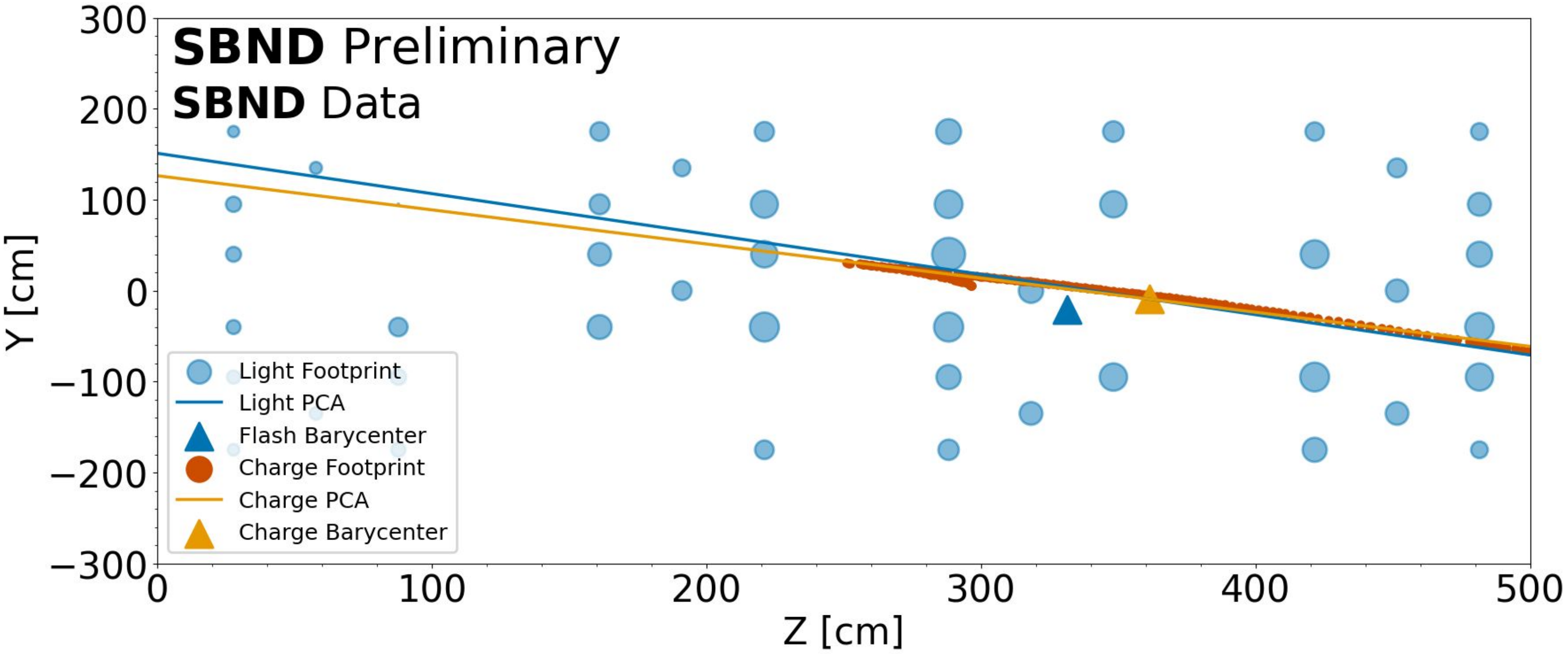
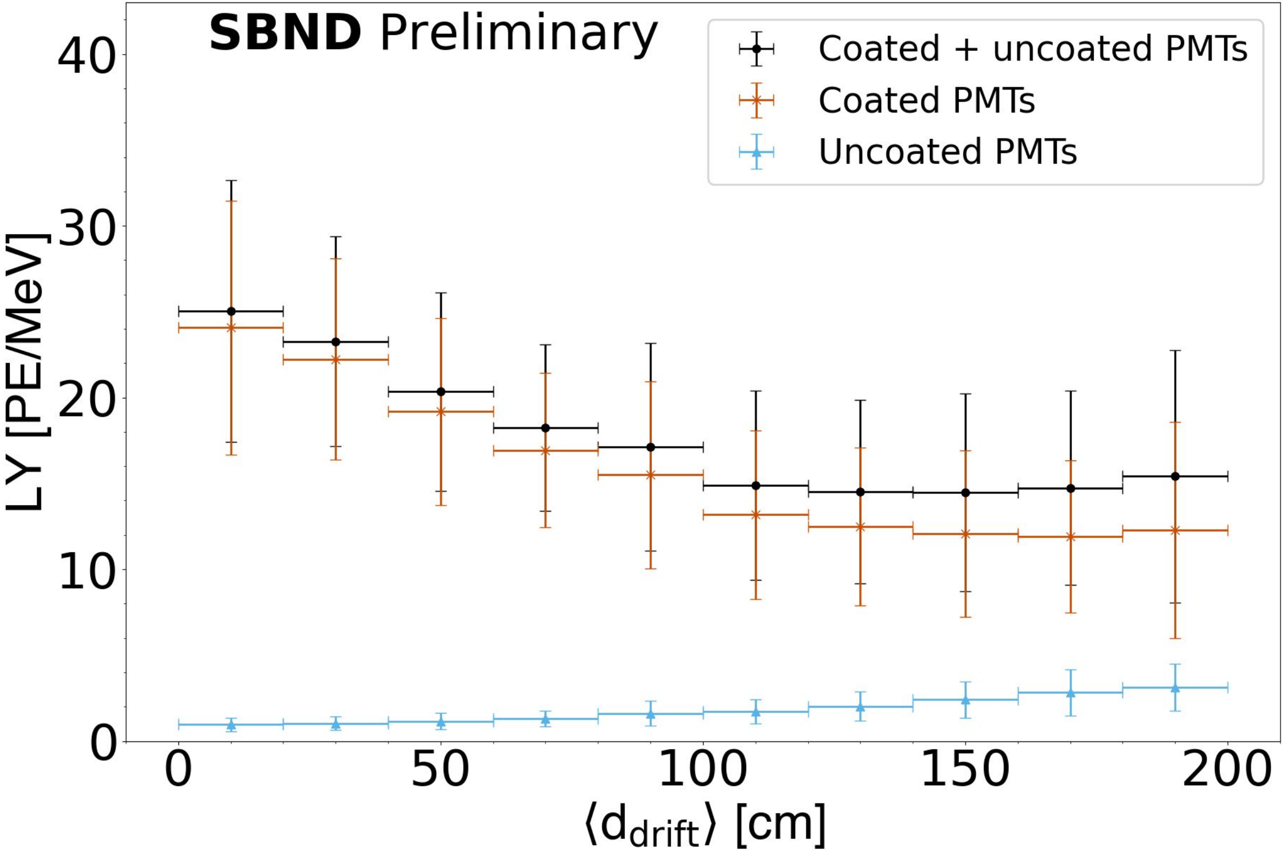
Light Propagation Time:



Charge-light matching:



Light Yield:


SBND Preliminary
Coated + uncoated PMTs
Coated PMTs
Uncoated PMTs
LY [PE/MeV]
40
30
20
10
0
0
50
100
150
200
$\langle d_{drift} \rangle$ [cm]