# Cherenkov Light at the Coherent CAPTAIN-Mills Experiment

**10 ton liquid Argon light collection detector studying neutrino and beyond Standard Model physics at Los Alamos National Lab**

✵Presenting new results!

**Hybrid Scintillation/Cherenkov Detection Workshop**
**5 June 2025**

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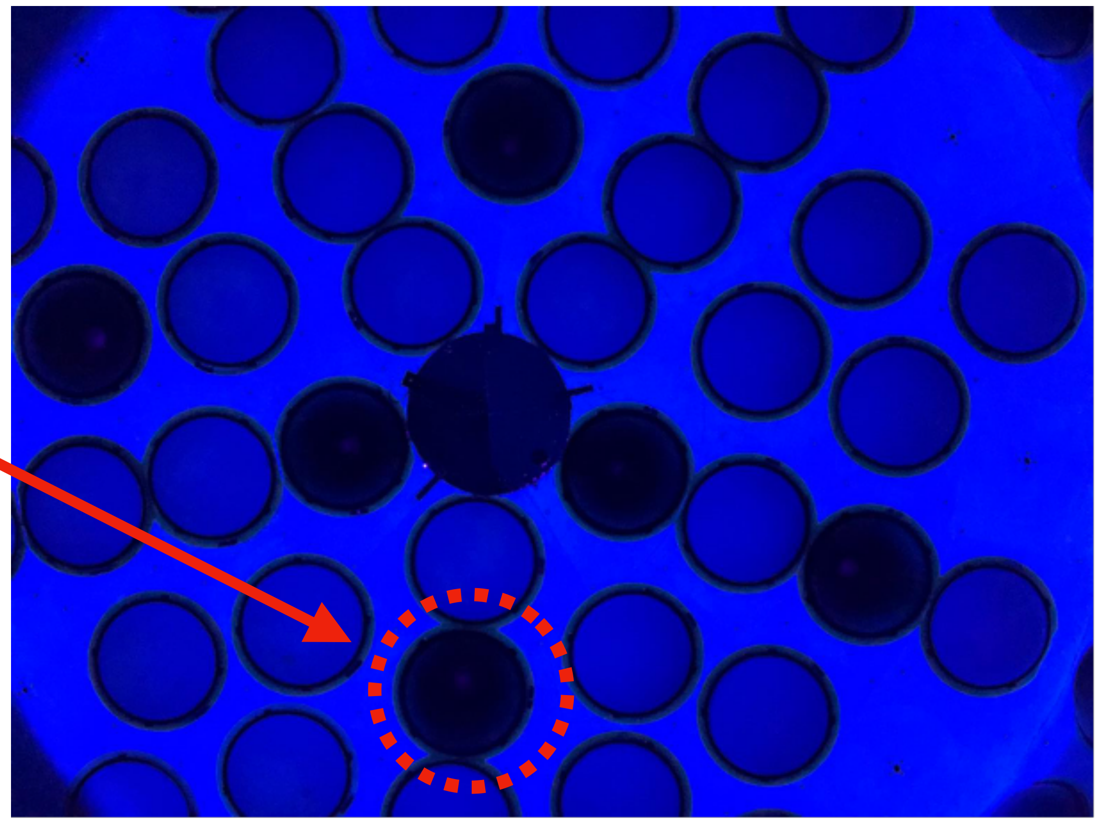
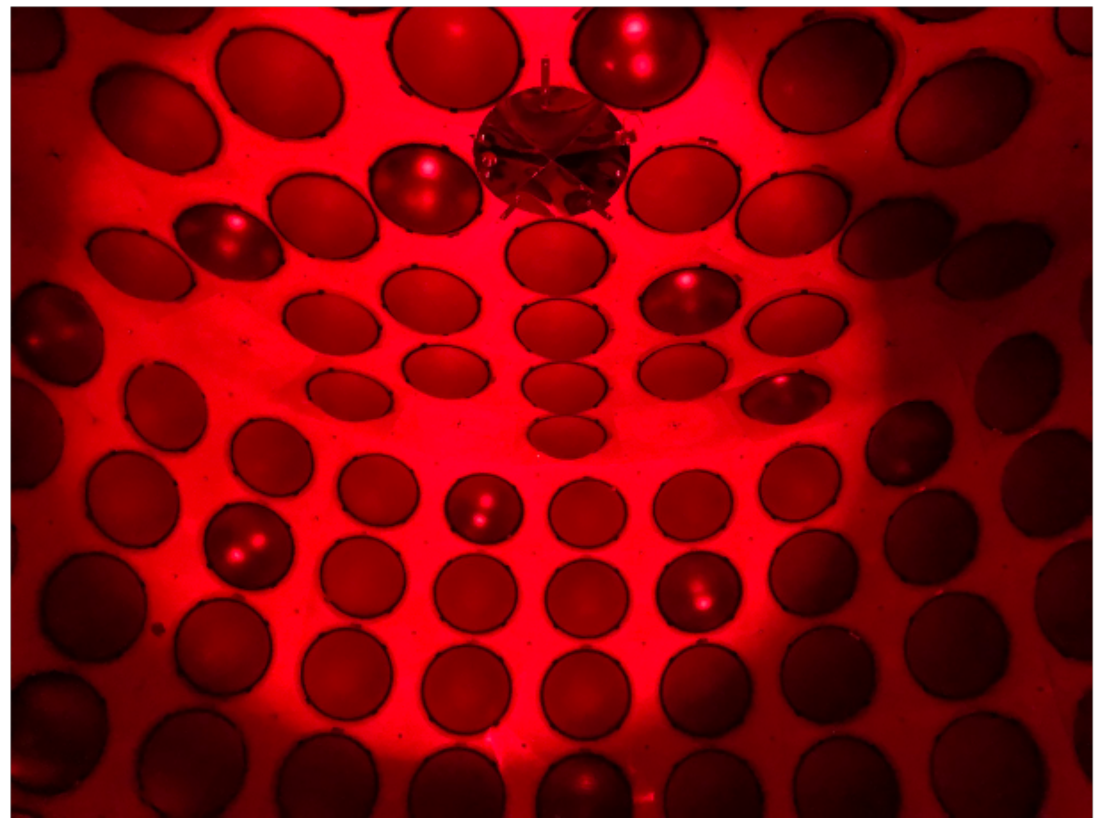
# Coherent CAPTAIN-Mills Overview

- ***Running*** 10 ton LAr light collection experiment at LANSCE (published results: here, here, here, and here)
- **7 ton active LAr volume, 200 8” PMTs, 50% photocoverage**
    - R5912 10 stage Hamamatsu cryogenic PMTs
- Walls of detector and 160 PMTs are coated in tetraphenyl butadiene (TPB) ***(40 uncoated tubes)***
- **2 ns** timing resolution from CAEN V1730 digitizers
- Energy detection range from ~100 keV to ~200 MeV







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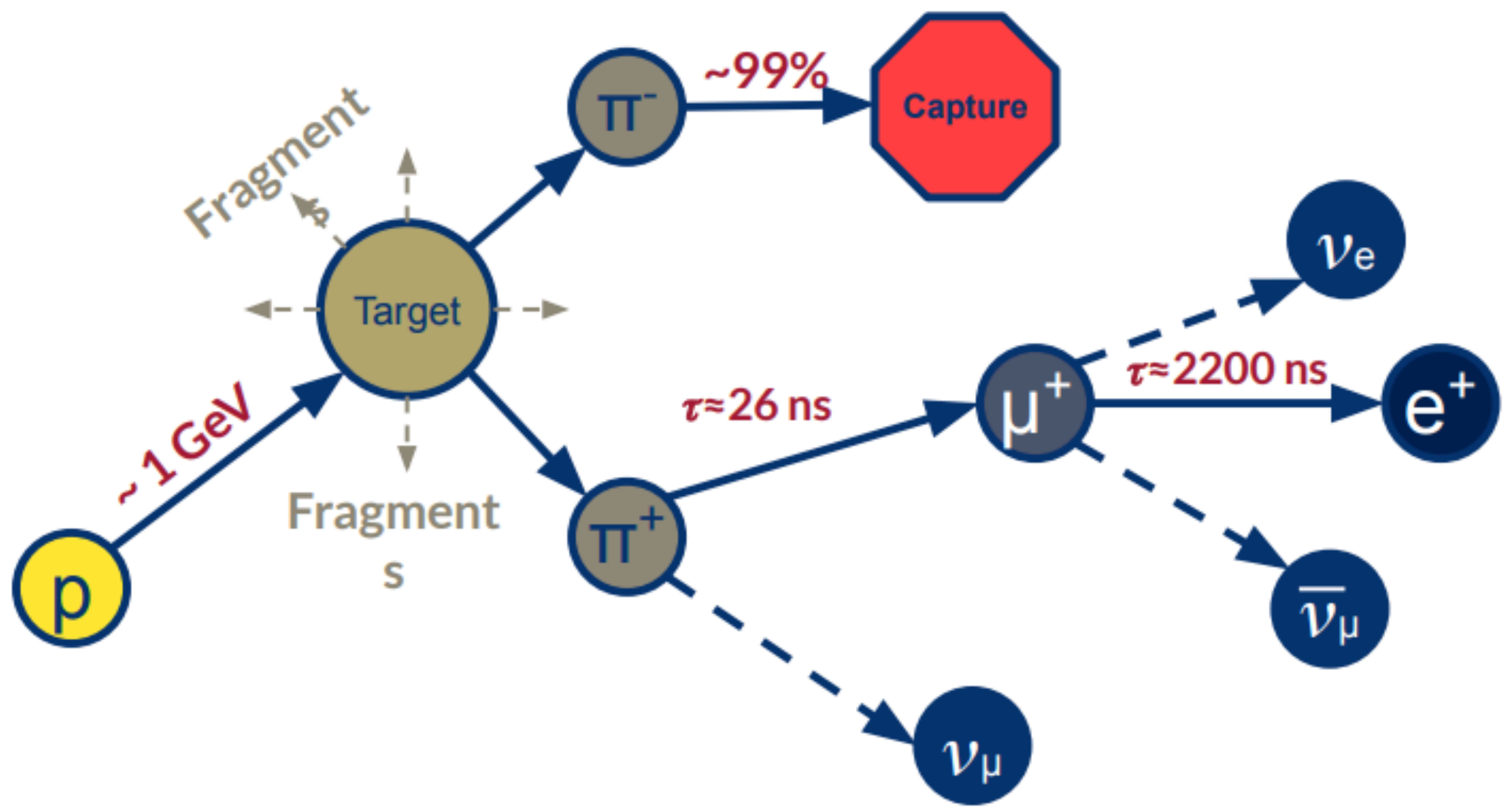
# Coherent CAPTAIN-Mills Physics Program

- 800 MeV proton beam impinges on tungsten target creating $\pi$DAR source and intense flux of electrons/photons
- Standard Model: CC$\nu_e$ cross section measurement relevant to DUNE supernovae physics
- Beyond Standard Model: MeV-scale ALPs/QCD axion, scalar mediator DM, leptophobic DM, meson portal model



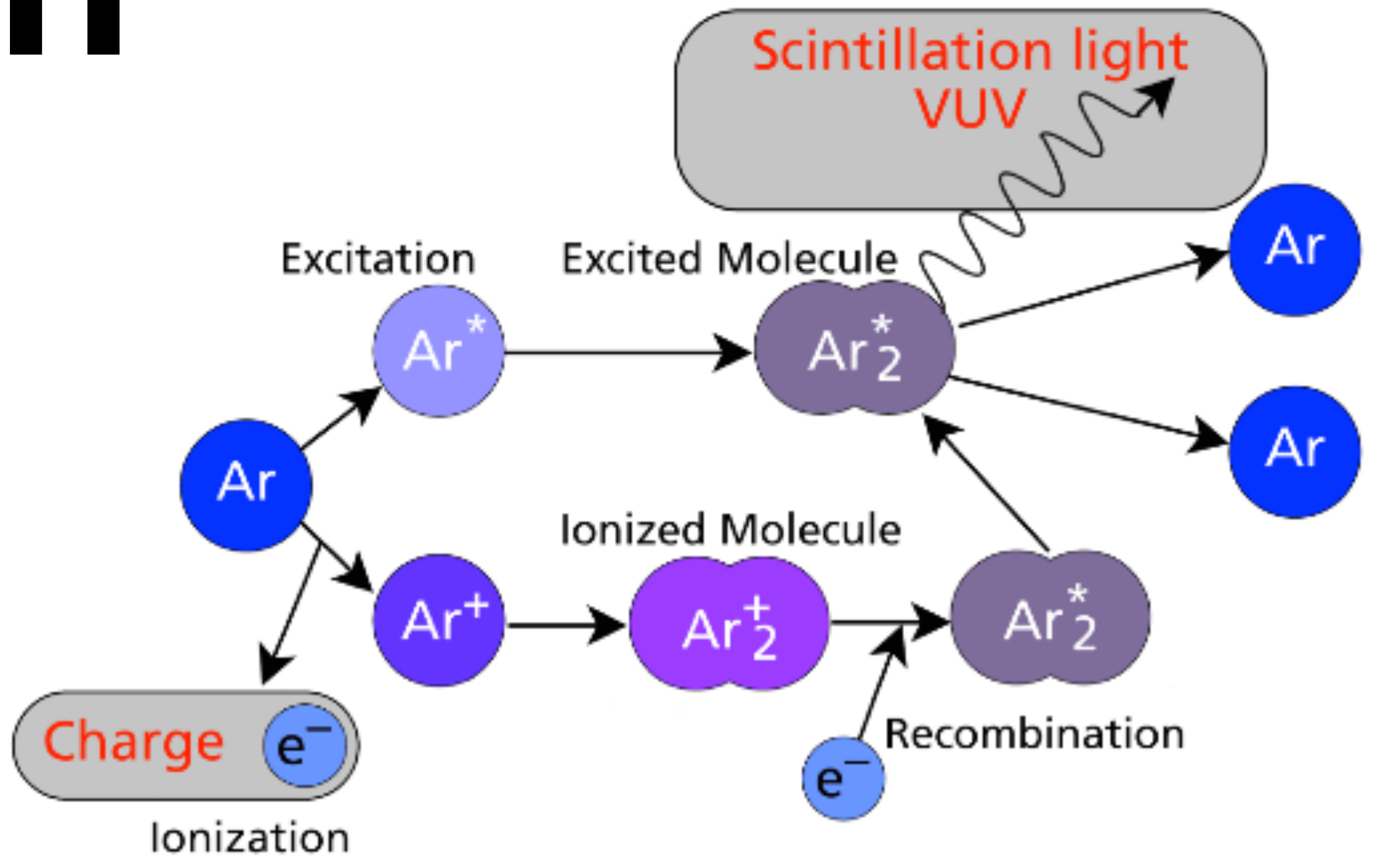
# Motivations for Cherenkov Light Separation

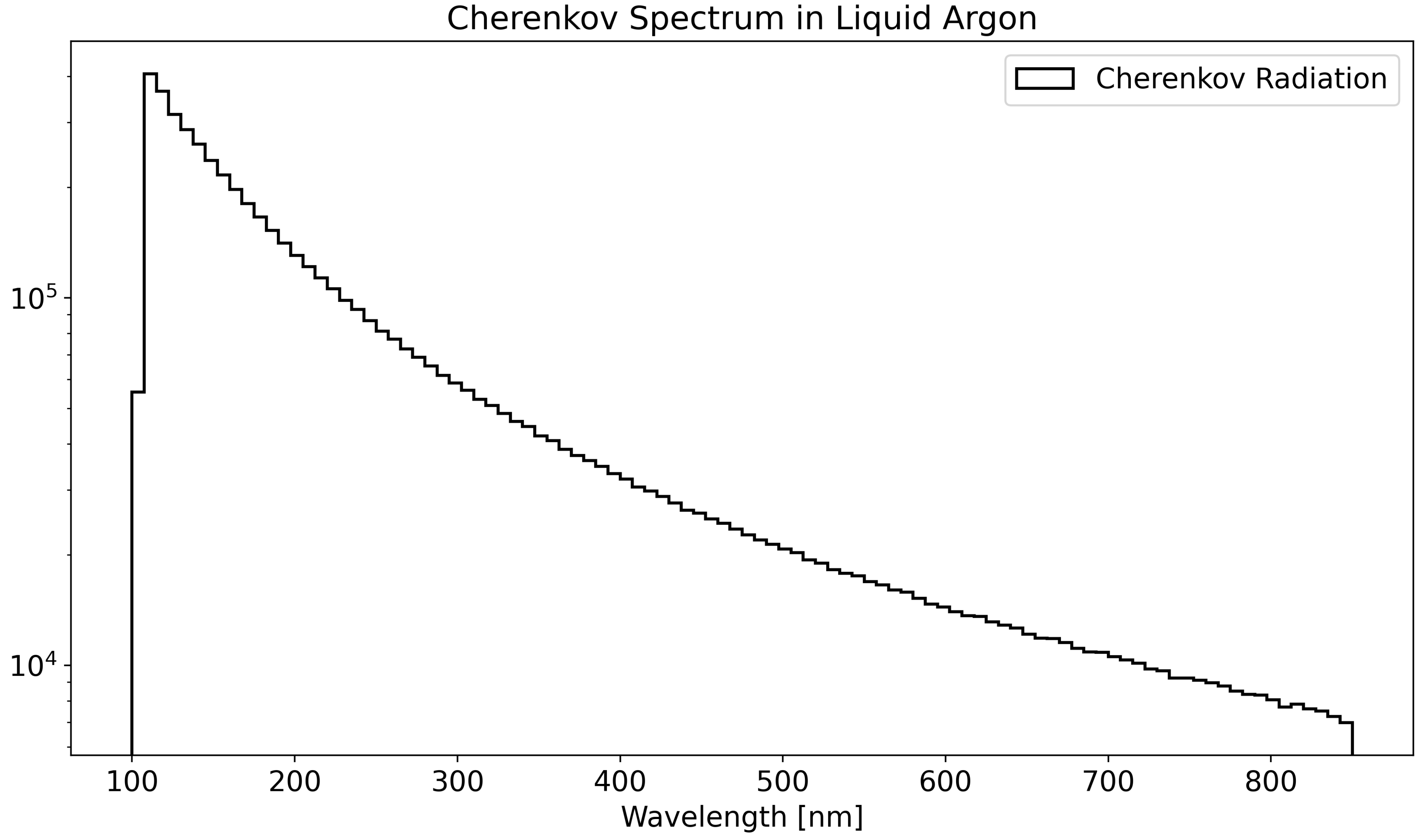
- For CCM's physics goals, we are focused on ***event-by-event identification of Cherenkov light from MeV-scale electrons***
- Being at a spallation neutron source, primary unconstrained background for EM final states are ***fast neutrons***
    - Expect only scintillation light from background
- For nuclear recoil final states, $^{39}Ar$ decays are the primary background
    - Expect Cherenkov light from only background beta decays

| Final State Signals | Electron/Photon | Nuclear Recoil |
|---|---|---|
| **Energy Range** | ~1 - 100 MeV | ~100 keV |
| **Scintillation Light** | Yes | Yes |
| **Cherenkov Light** | Yes | No |
| **Background** | Fast neutron scatters | Low energy beta decays ($^{39}Ar$) |
| **Background signal** | Scintillation light only | Scintillation and cherenkov light |

# Light Production in Liquid Argon

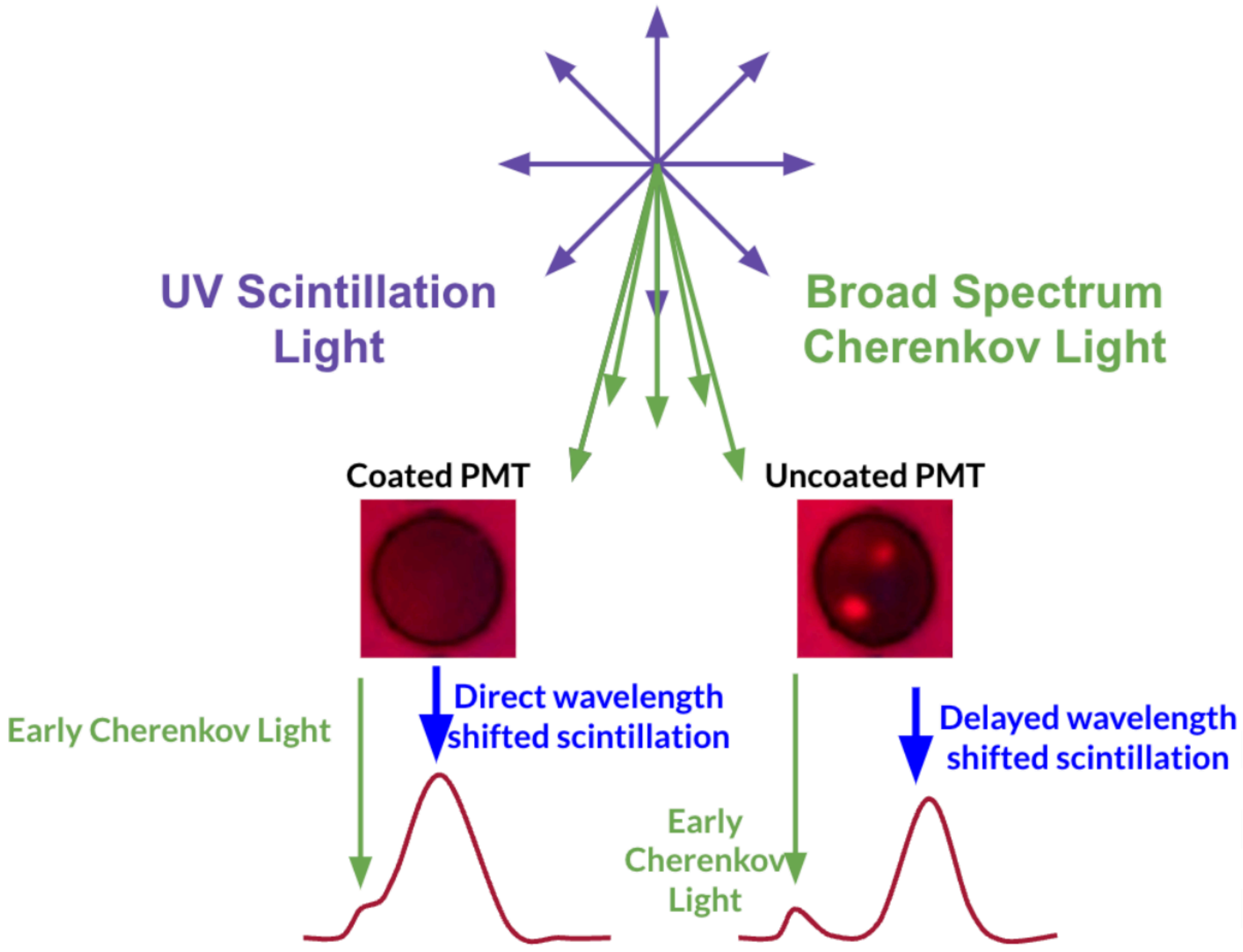
| Quality | Scintillation Light | Cherenkov Light |
|---|---|---|
| Intensity (for a MIP) | ~40,000 photons/MeV | ~ 700 photons/MeV (wavelength > 100nm) |
| Direction | Isotropic | Directional |
| Timing | Fast component (nsec) and slow component (usec) <u>measured by DEAP collaboration</u> | Prompt (psec start) |
| Photon Wavelength | Spectrum peaks at 128 nm | $dN/d\lambda \propto \lambda^{-2}$ |



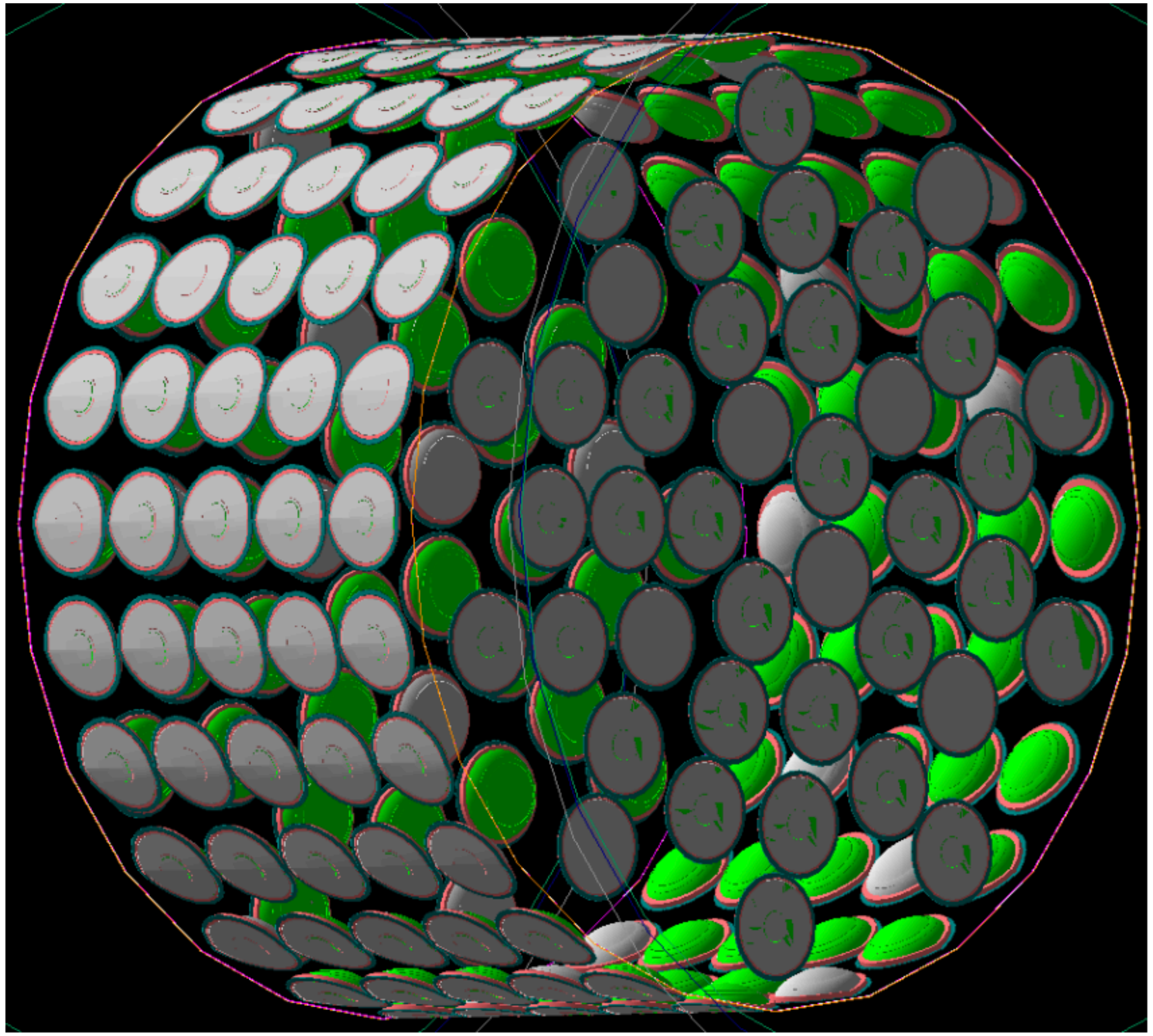
# Our Approach for Cherenkov Light Separation

- ***Uncoated PMTs*** allow for wavelength discrimination between UV scintillation light and broad spectrum Cherenkov light
- Visible Cherenkov photons detected by uncoated tubes ***before*** wavelength shifted scintillation light
- Combined with 2ns timing resolution, able to ***isolate early Cherenkov signal in uncoated PMTs***



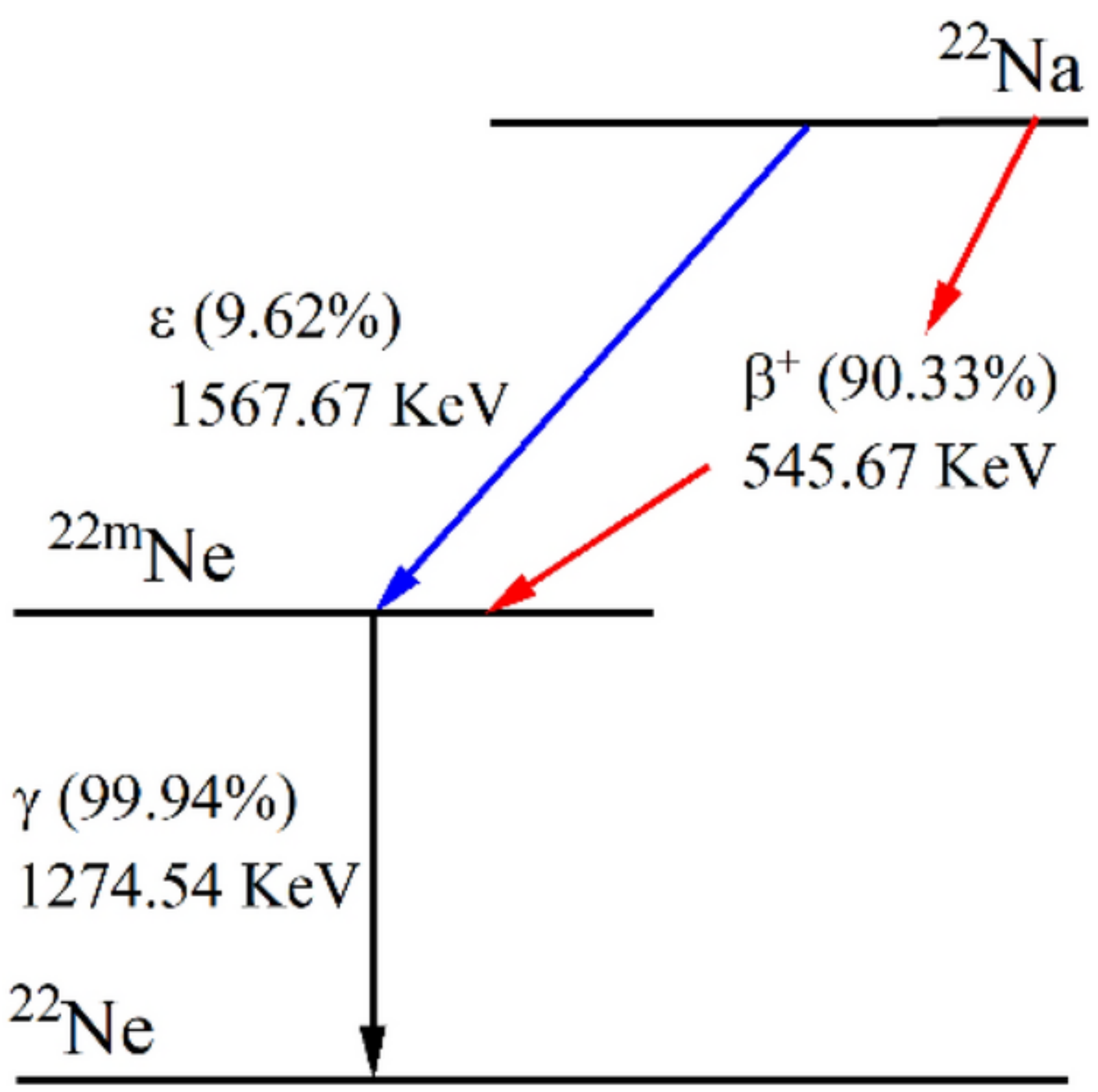
# Detector Simulation Optimization

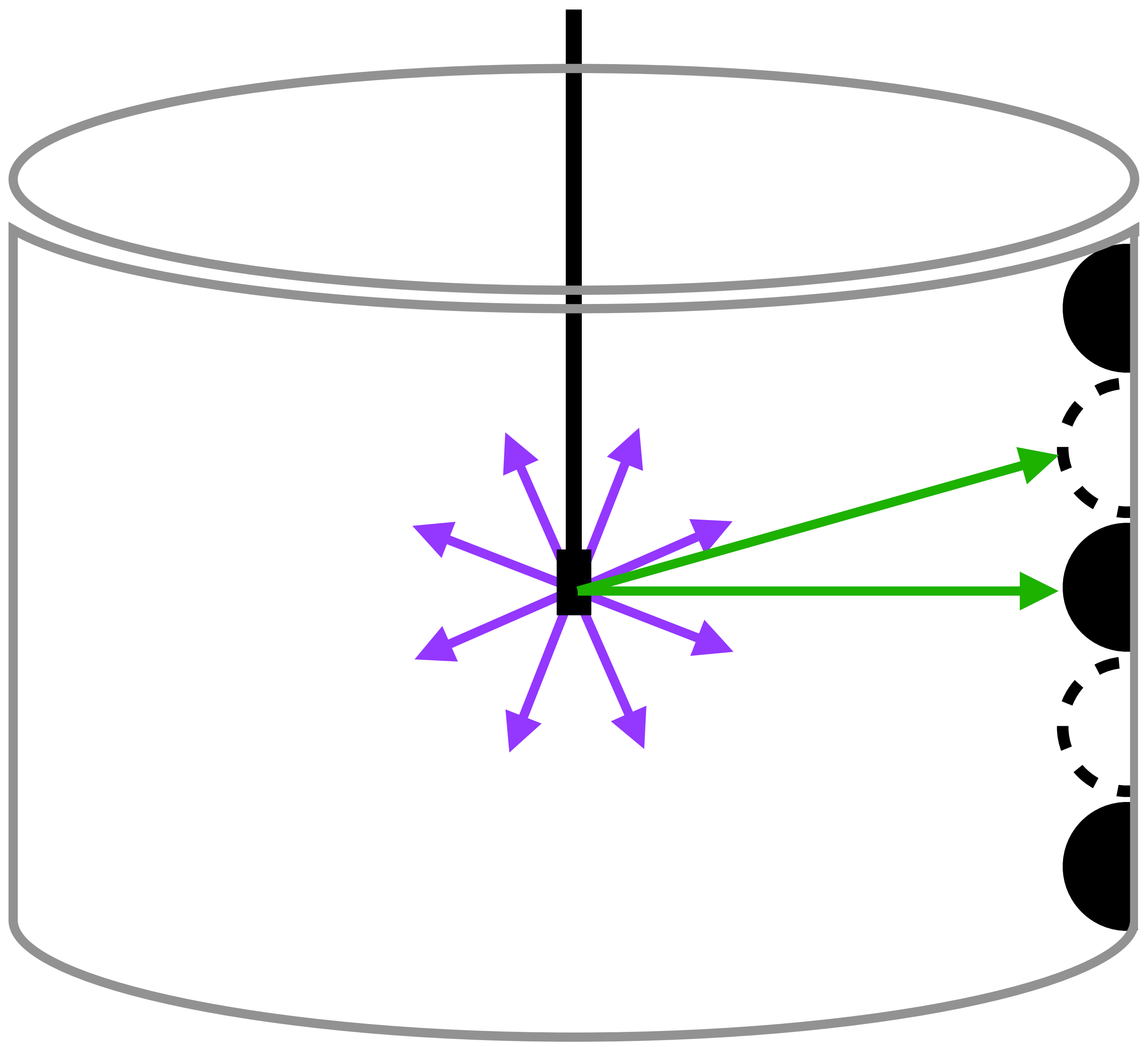
- Need a well characterized simulation for physics modeling
- Geant4 based ***differential simulation***
    - Tracking photon properties (original wavelength, distance travelled, WLS, detection wavelength and time)
    - Allows for re-weighting between different physics scenarios
- ***Minimize likelihood using automatic differentiation to fit for optical model***

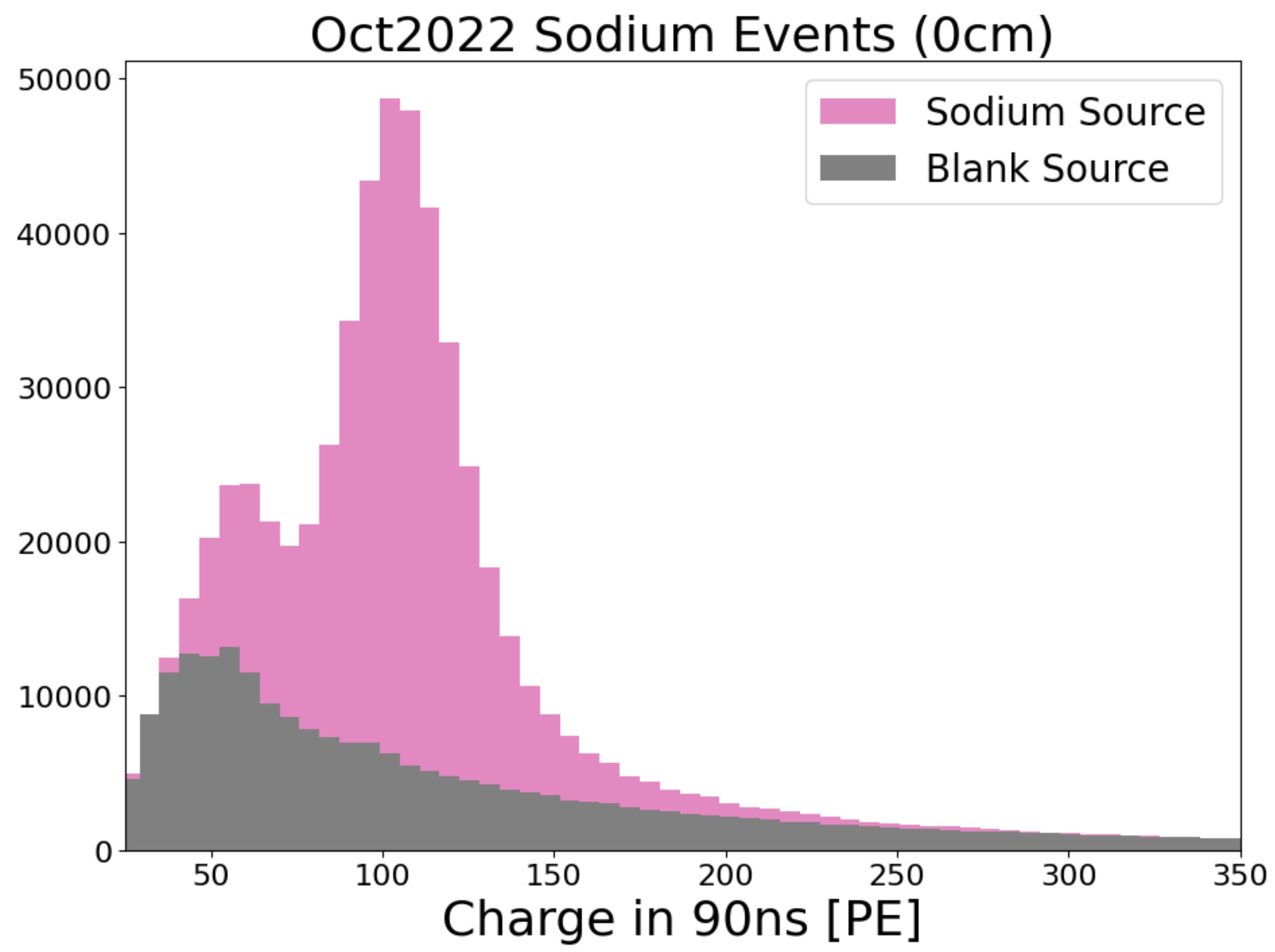


# Calibration Source

- $^{22}$Na calibration source at origin of the detector
    - Source is enclosed in stainless steel
    - Decays produce 1.275 MeV $\gamma$ and 0.546 MeV $e^+$
    - ***Expect scintillation and sub-MeV Cherenkov light from gamma interactions (Compton scatters)***
- Use accumulated data to fit for scintillation light profile and light propagation effects



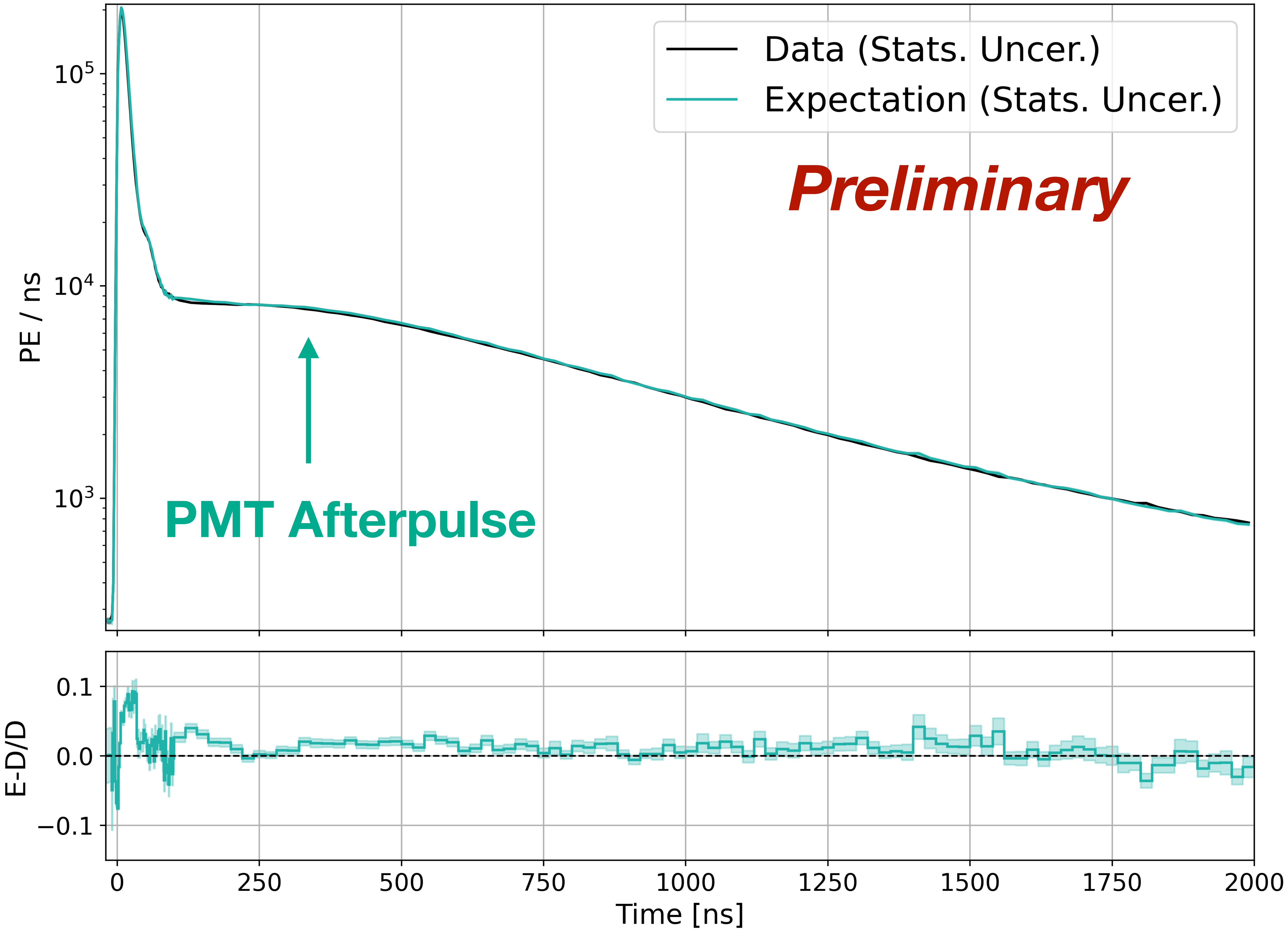


# Best Fit Scintillation Light Parameters

- Data vs expectation summed across all PMTs
- Fitting for $R_s$ ($R_t = 1.0 - R_s$), $\tau_s$, $\tau_t$
  - $R_s = 0.5$, $\tau_s = 4.34$ns, $\tau_t = 584.03$ns

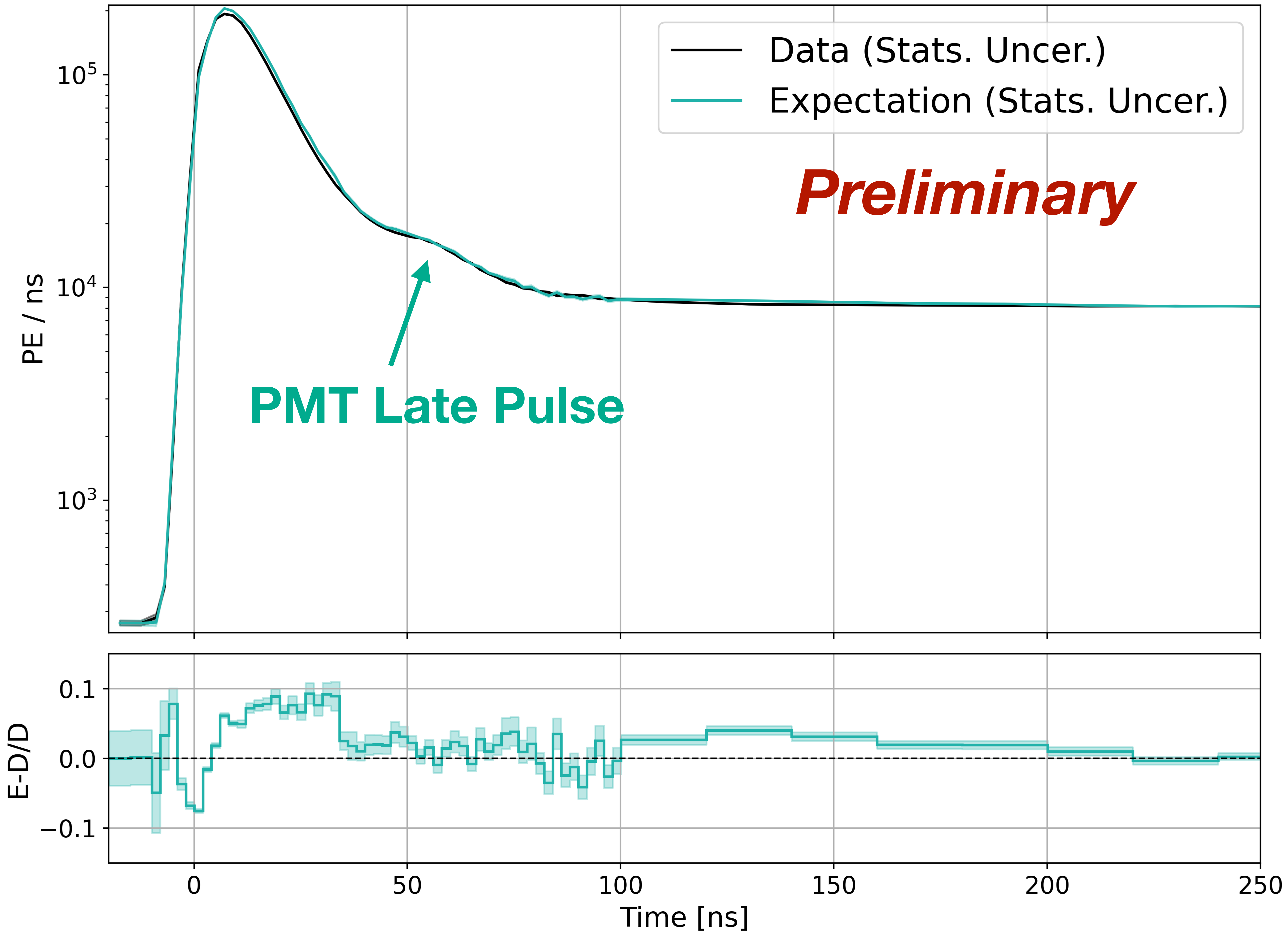
***CCM does NOT filter LAr!***

- Additionally, fit for PMT afterpulse around 300ns
- Better than 5% agreement at long time scale across all tubes



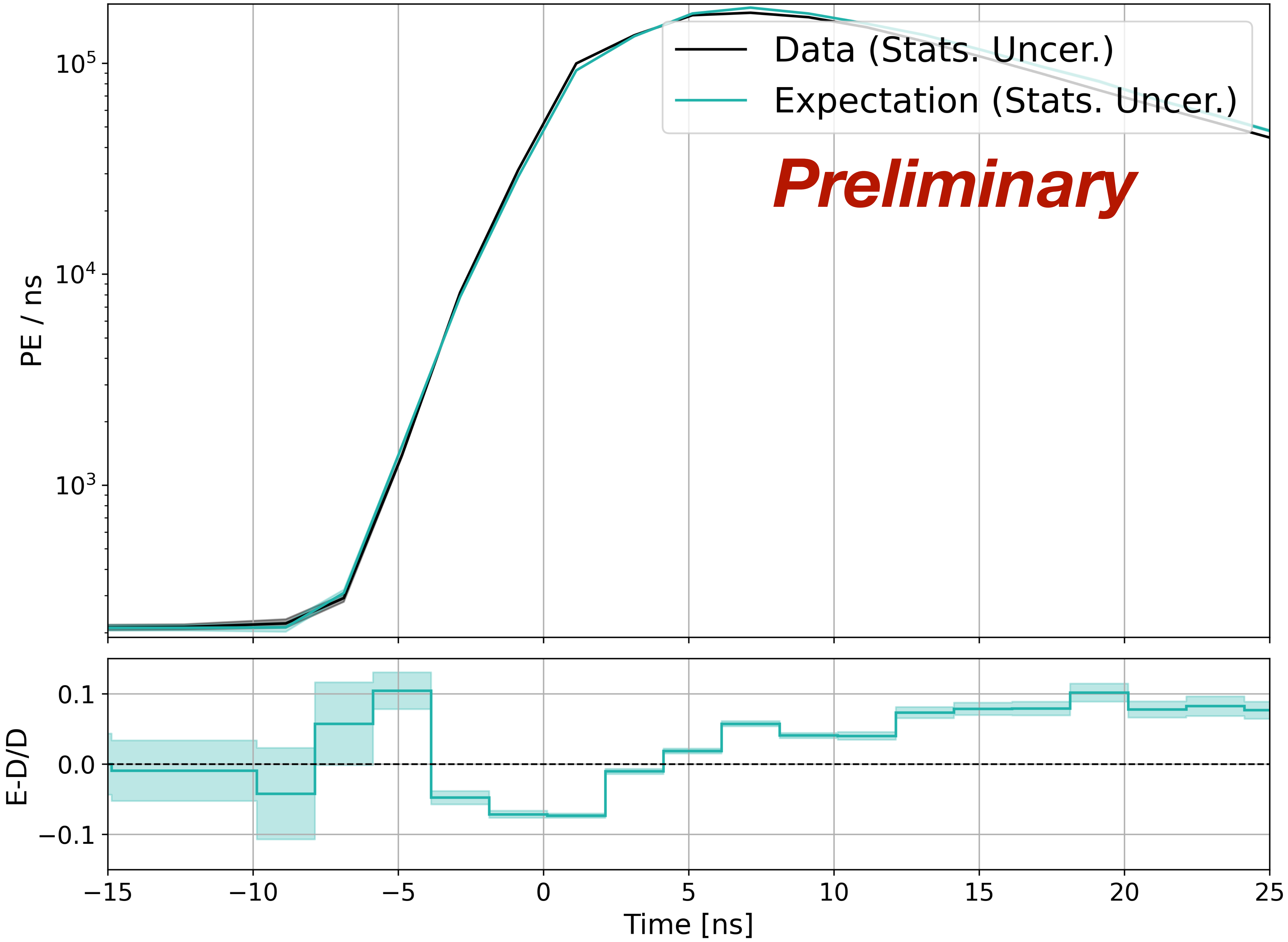
# Data vs Expectation — Medium Time Scale

- Data vs expectation summed across all PMTs
- Fit for late pulse around 50ns
- Across the entire time region, better than 10% agreement across all tubes

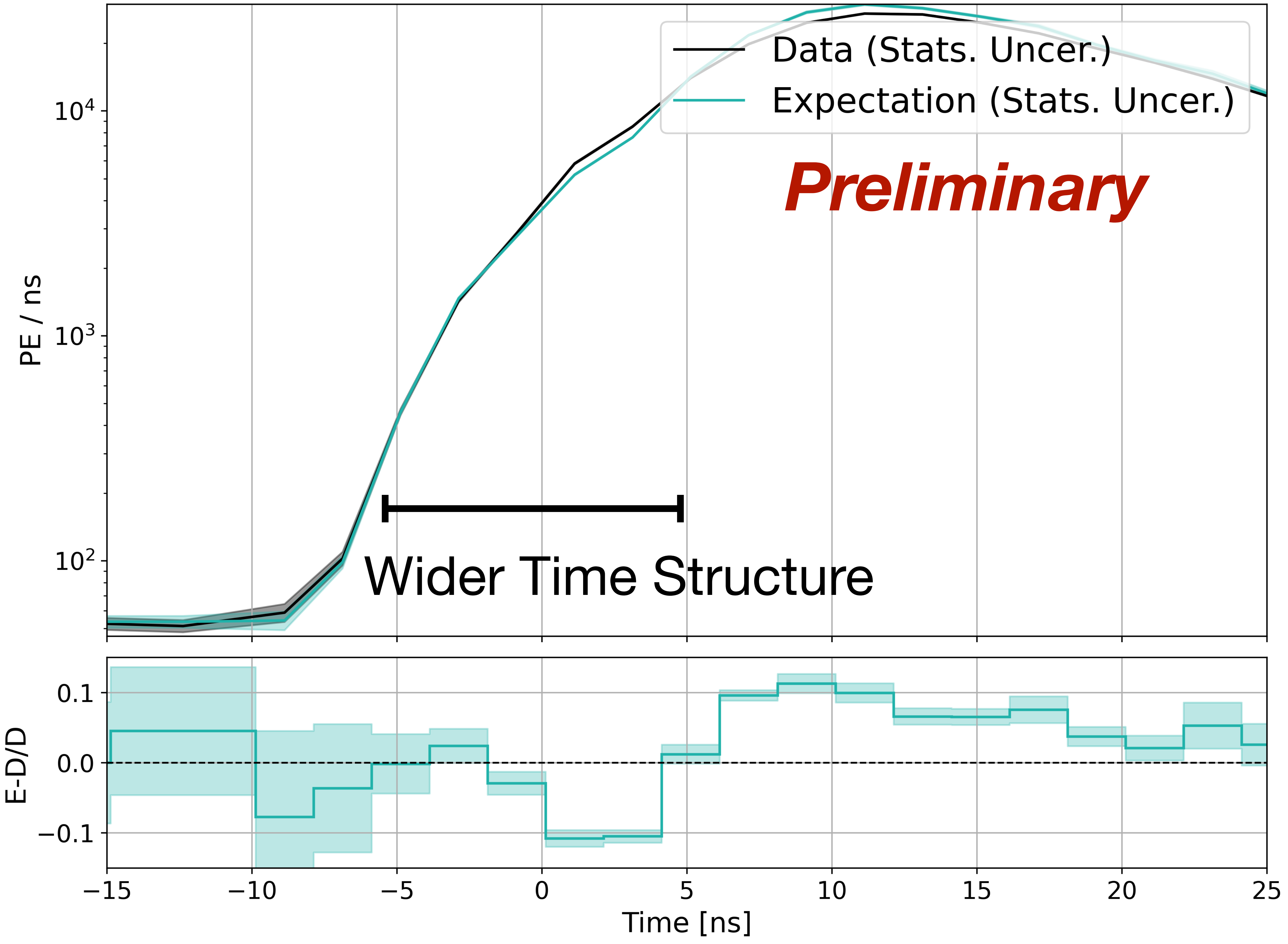


# Data vs Expectation — Short Time Scale

## Summed Coated PMTs

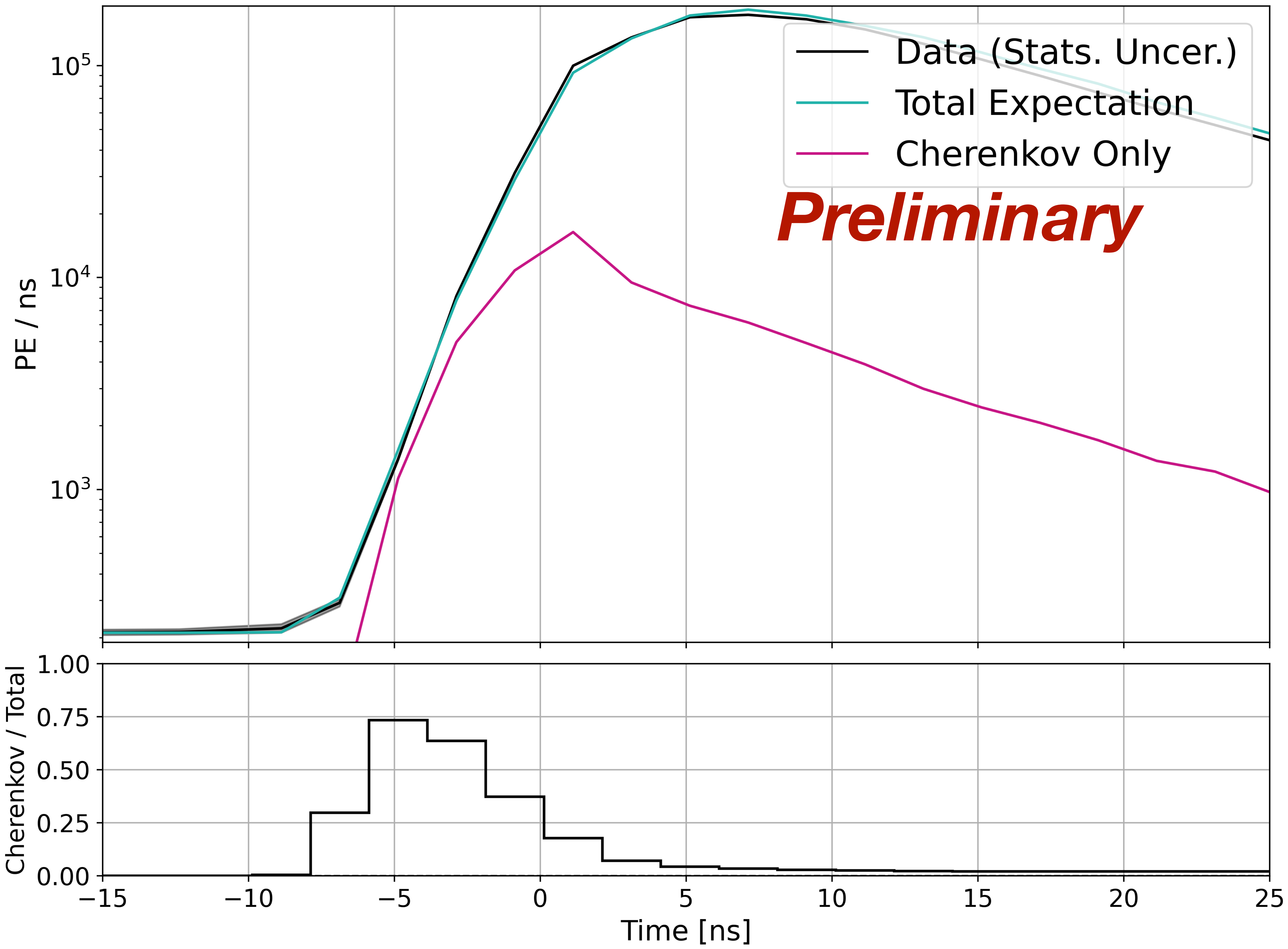



## Summed Uncoated PMTs

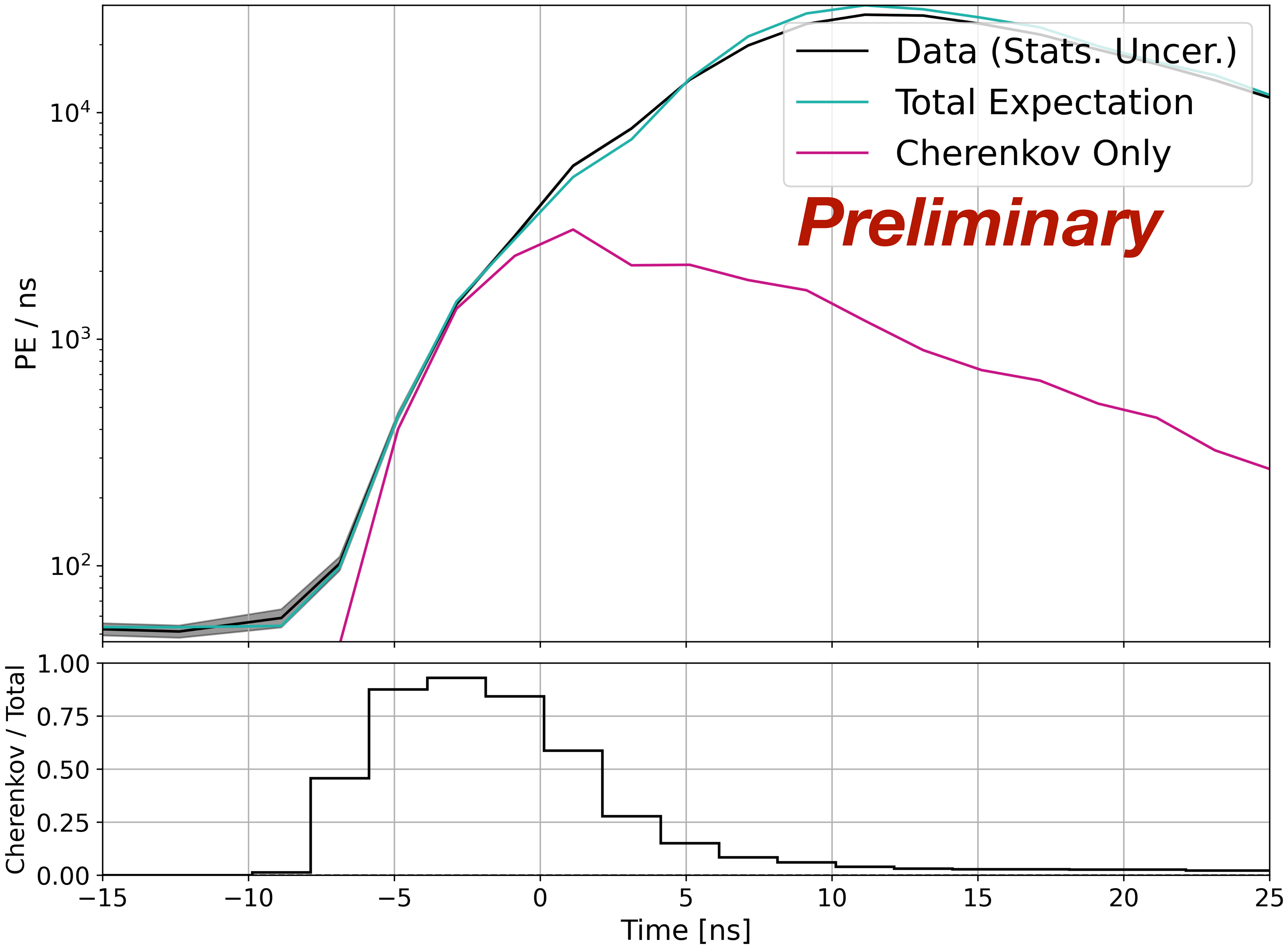


# Cherenkov Light in Expectation

## Summed Coated PMTs

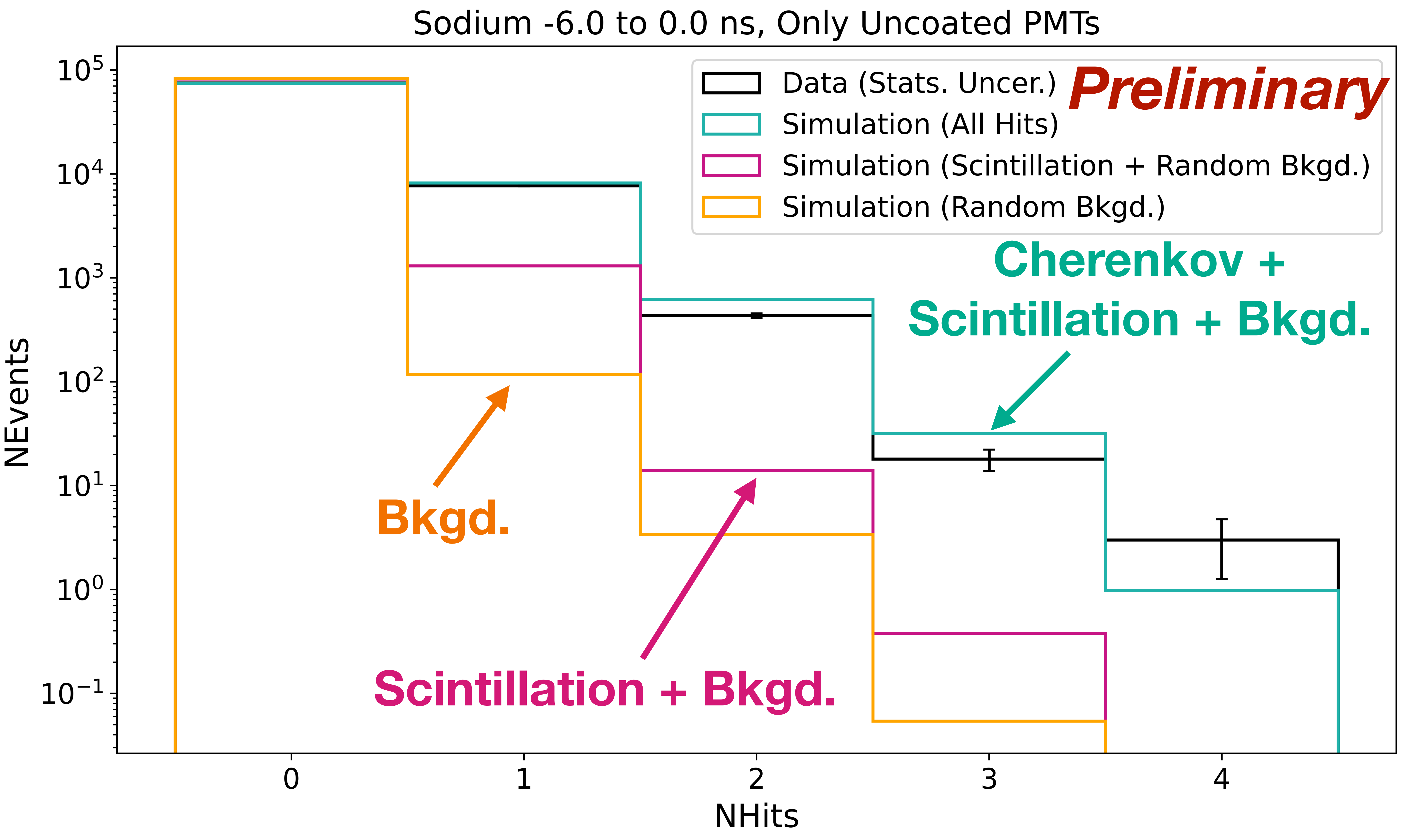



## Summed Uncoated PMTs



# NHits in Early Time Region

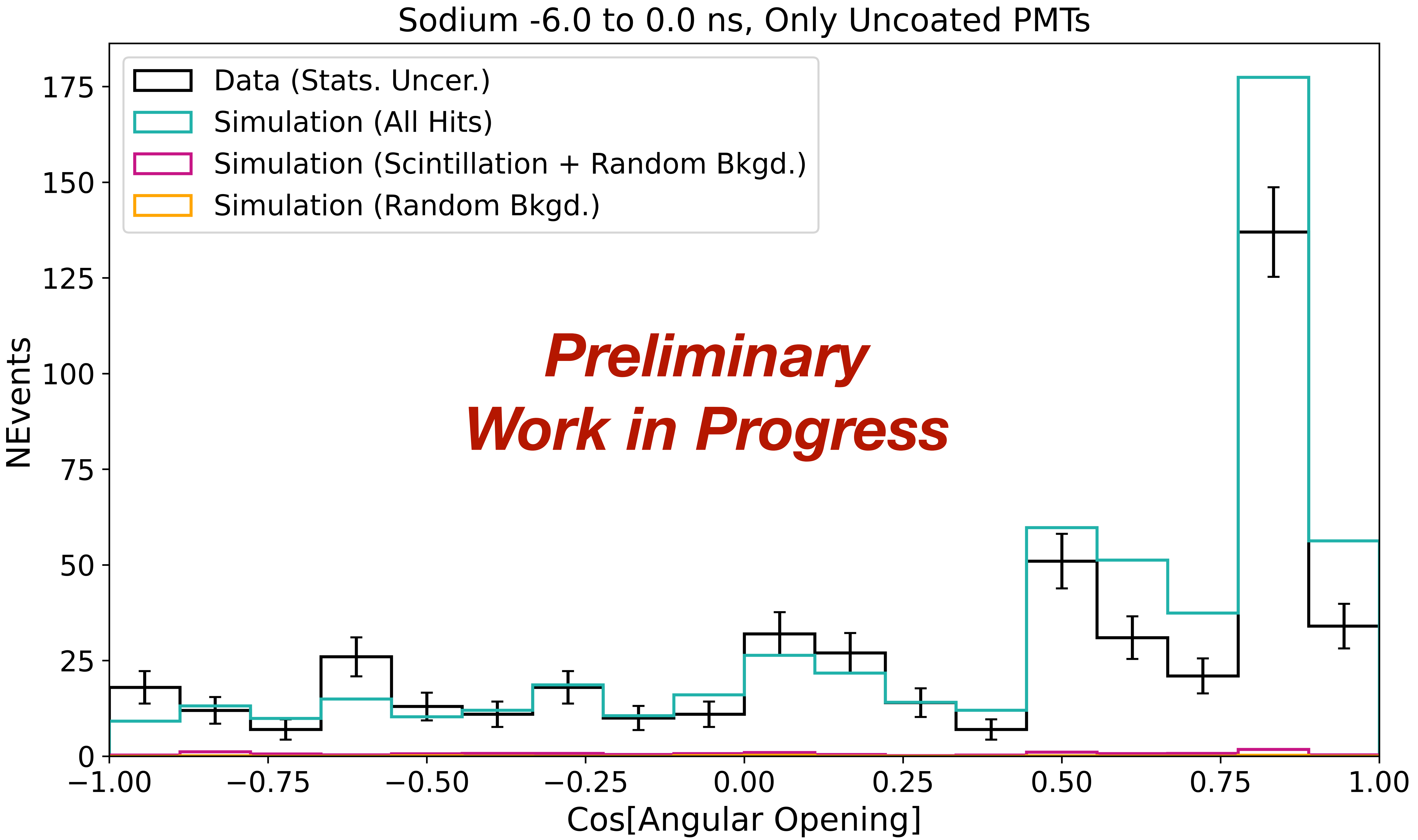
- Selecting early time region in sodium events, examine number of hits on uncoated tubes
- 10% of events in simulation and data have at least 1 hit in early region
- ***86% Cherenkov purity for one or more hit in early time region***



# Angular Distribution in Early Time Region

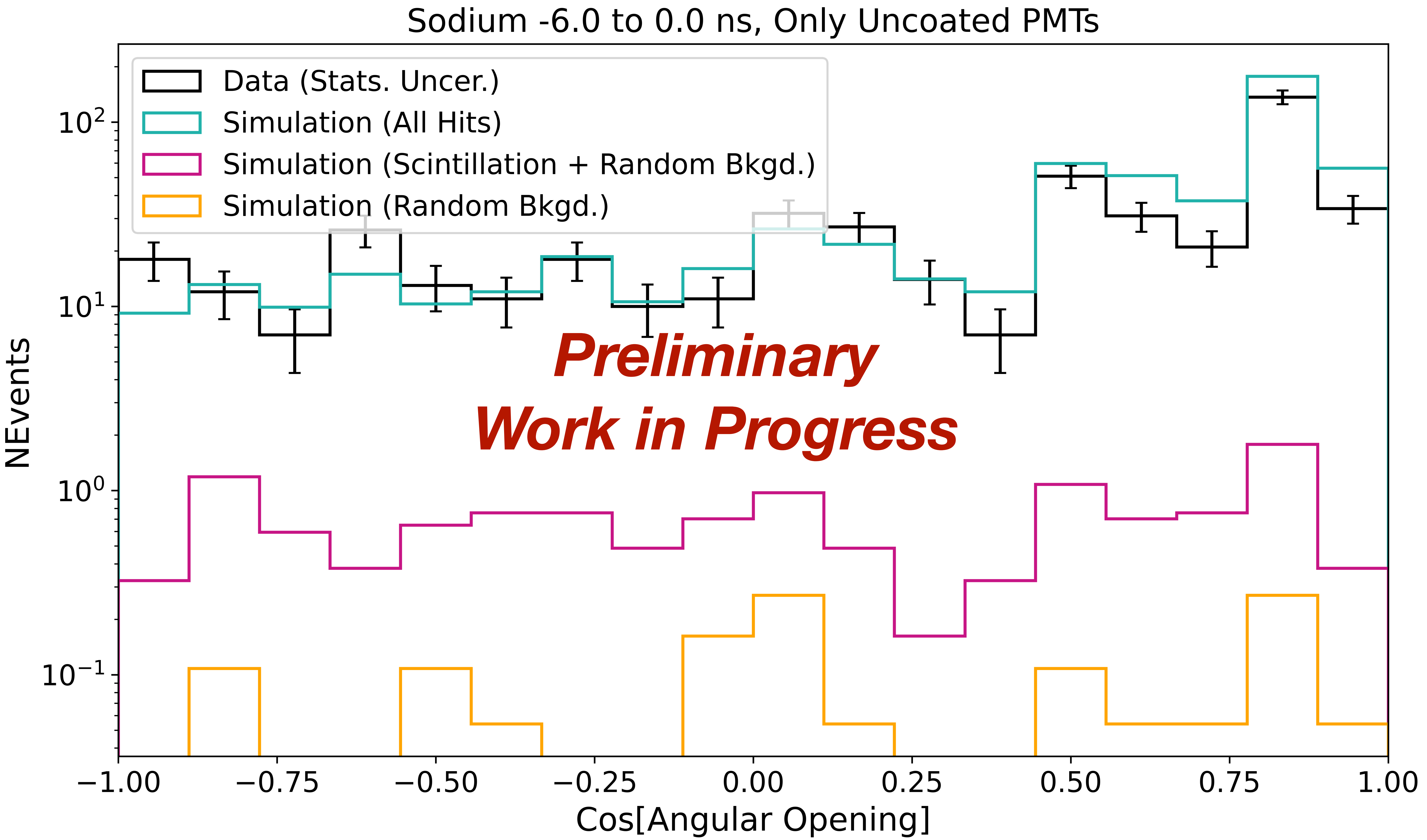
- If more than two hits in the early time region on uncoated tubes, examine the ***opening angle with the source location***

- Simulation (blue) shows directional preference similar to data



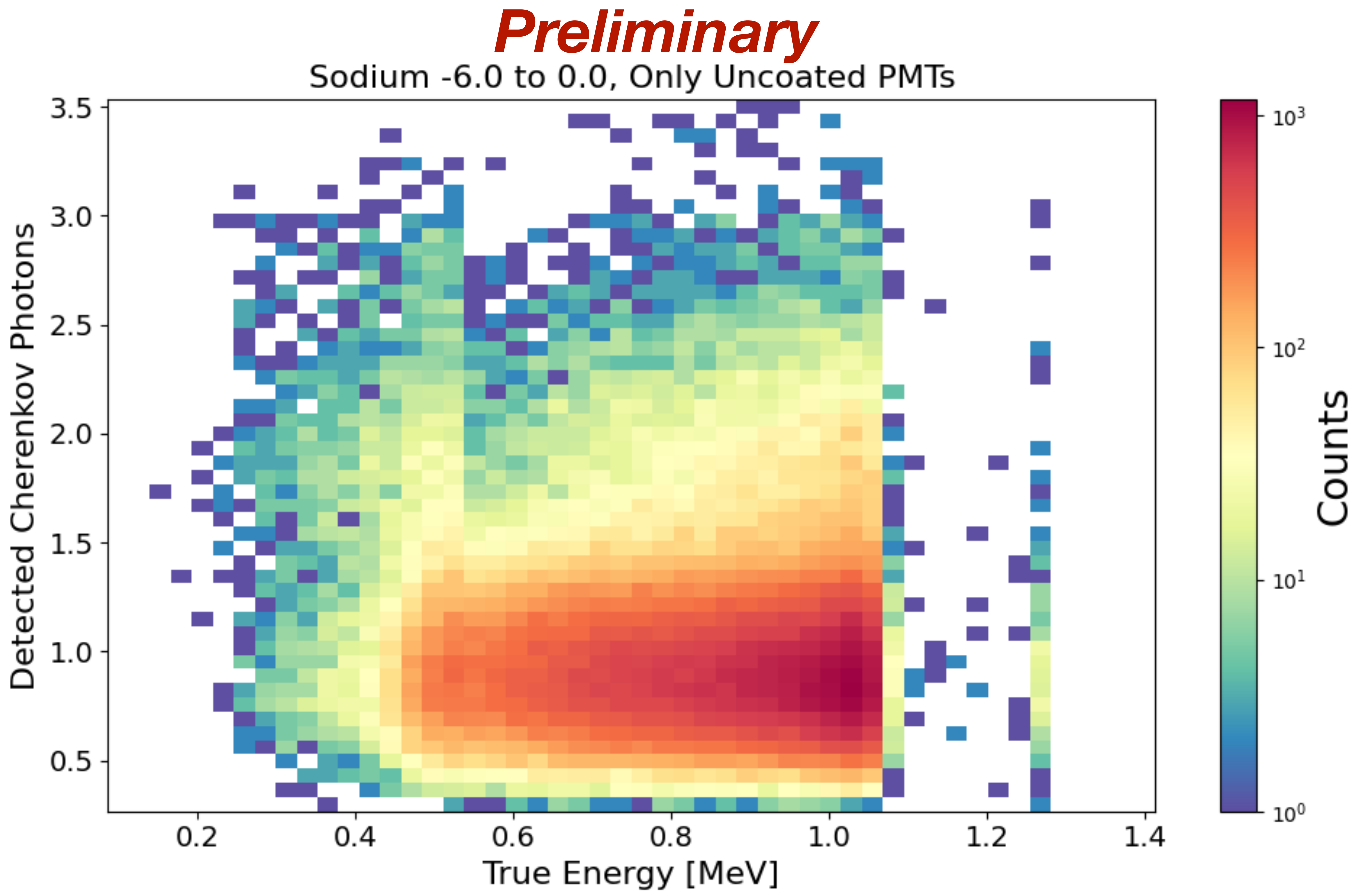
# Angular Distribution in Early Time Region

- If more than two hits in the early time region on uncoated tubes, examine the ***opening angle with the source location***
- Simulation (blue) shows directional preference similar to data
- Scintillation and random background are relatively isotropic (orange and pink)



# Electron Energy vs NCherenkov Photons

- Sodium produces 1.275 MeV and two 0.511 MeV gammas which typically Compton scatter
- Resulting electrons create both the Cherenkov and scintillation signals
- Examine the ***true energy of electron vs number of Cherenkov photons*** detected in early time region on uncoated tubes in simulation
- ***Detecting Cherenkov radiation from sub-MeV electrons in LAr on event-by-event basis***





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# Conclusion

- First event-by-event identification of Cherenkov light produced from sub-MeV electrons in LAr ***(paper in progress)!***
- Developing reconstruction to leverage Cherenkov light on event-by-event basis to allow physics searches to approach background free limit
- Ongoing study of large LAr light collection detector that can separate Cherenkov from scintillation light

# Thank you for listening!

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# Backup

# Angular Distribution in Early Time Region