The Faint Particle Trigger for the IceCube Neutrino Observatory

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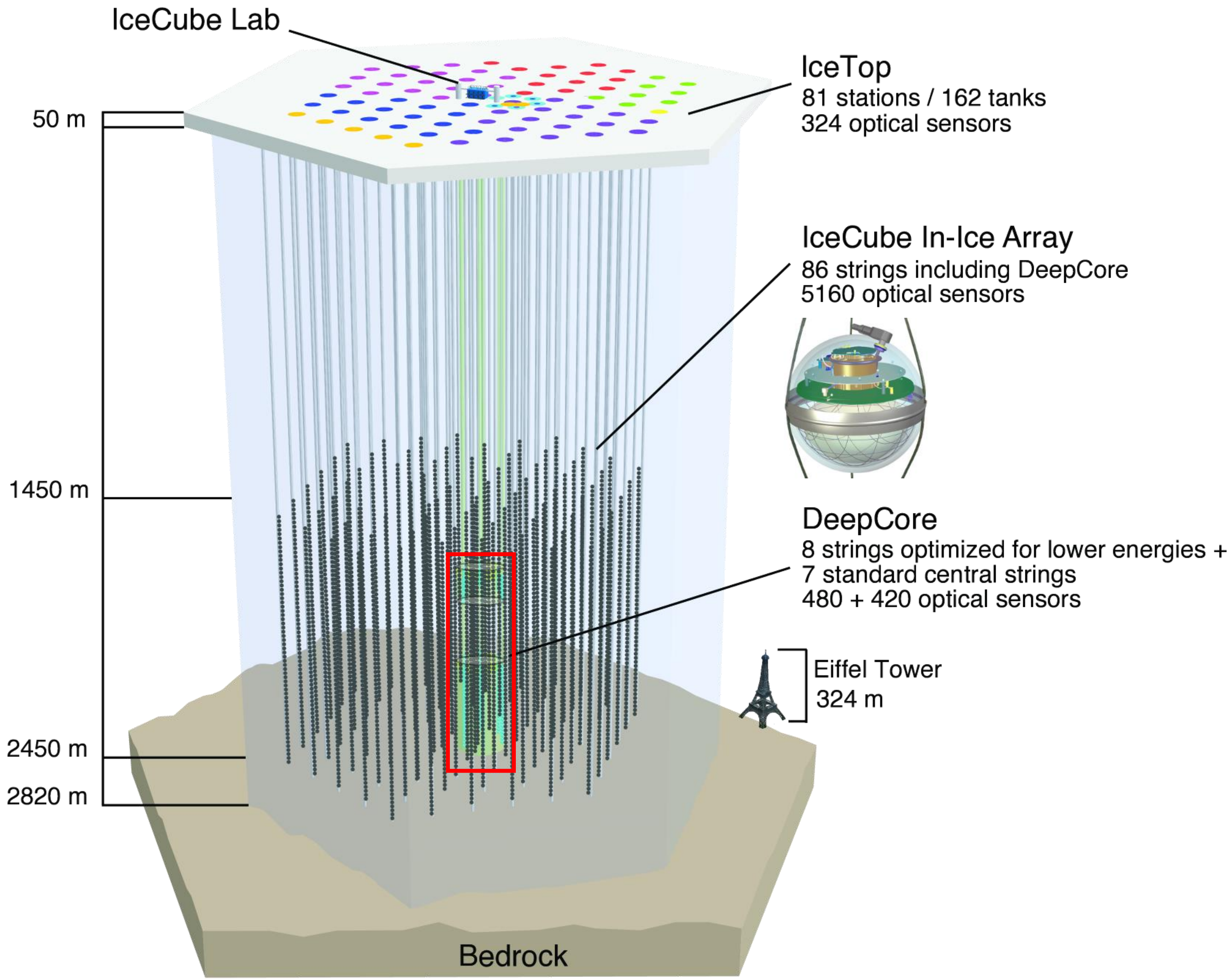
IceCube and DeepCore

- Detection of neutrinos via Cherenkov radiation of charged secondaries
- Searches for particles beyond the standard model including fractionally charged particles
- 1 km^3 of instrumented ice
- IceCube: 125 m string and 17 m PMT spacing
- DeepCore: 72 m string and 7 m PMT spacing

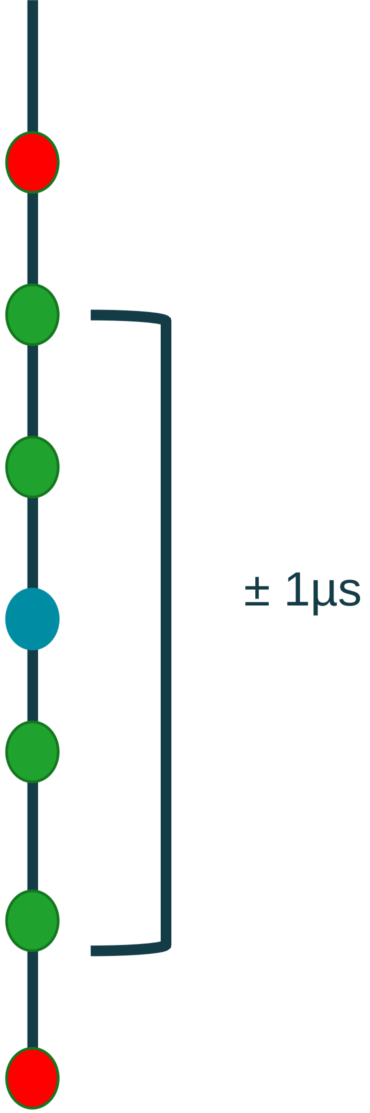


Fractionally charged particles

- Fractionally charged particles (FCPs) appear in several extensions of the standard model
- Produced Cherenkov photons, ionization, pair production and photonuclear interactions ∝ z^2
- The detector signature for FCPs are faint through going tracks
- A previous IceCube analysis searched for charges between e/3 and 2e/3
- For a charge of e/3 the triggers start to be inefficient

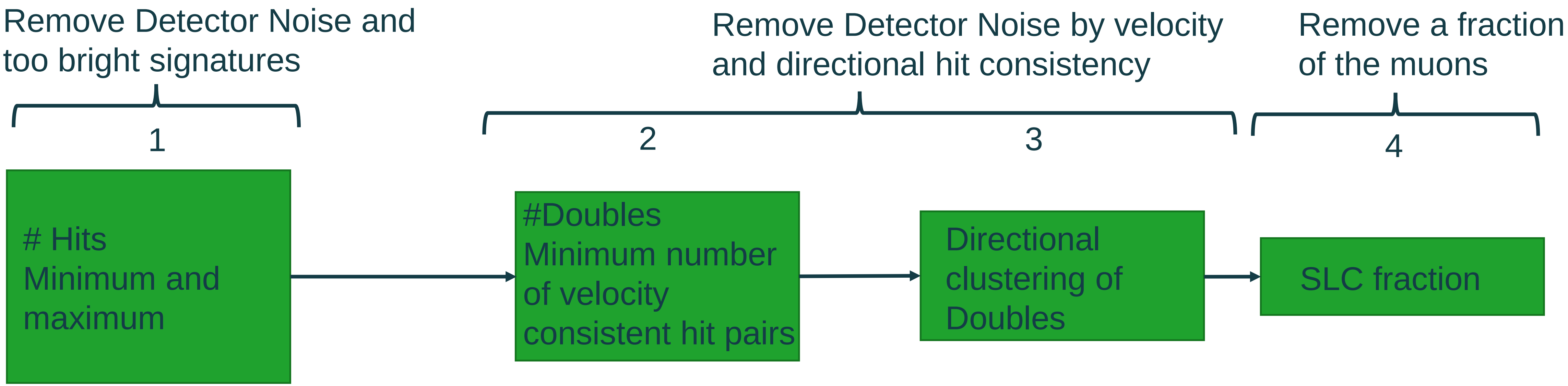
- The standard triggers work on HLC hits
  - Hard Local Coincidence (HLC): in a time frame of ± 1 µs around the hit a neighboring sensor on the same string is hit
  - Soft Local Coincidence (SLC): Single hit

- FCPs with a charge of e/3 dominantly produce SLC hits
- Built the Faint Particle Trigger (FPT) that includes SLC hits



Faint Particle Trigger structure

- FCPs dominantly produce SLC hits which are not forwarded to the standard triggers
- For the FPT all HLC and SLC hits in DeepCore are forwarded
- In a sliding time window with a size of 2500 ns four cut variables are calculated



Remove Detector Noise and too bright signatures

Remove Detector Noise by velocity and directional hit consistency

Remove a fraction of the muons

1

Hits
Minimum and maximum

2

#Doubles
Minimum number of velocity consistent hit pairs

3

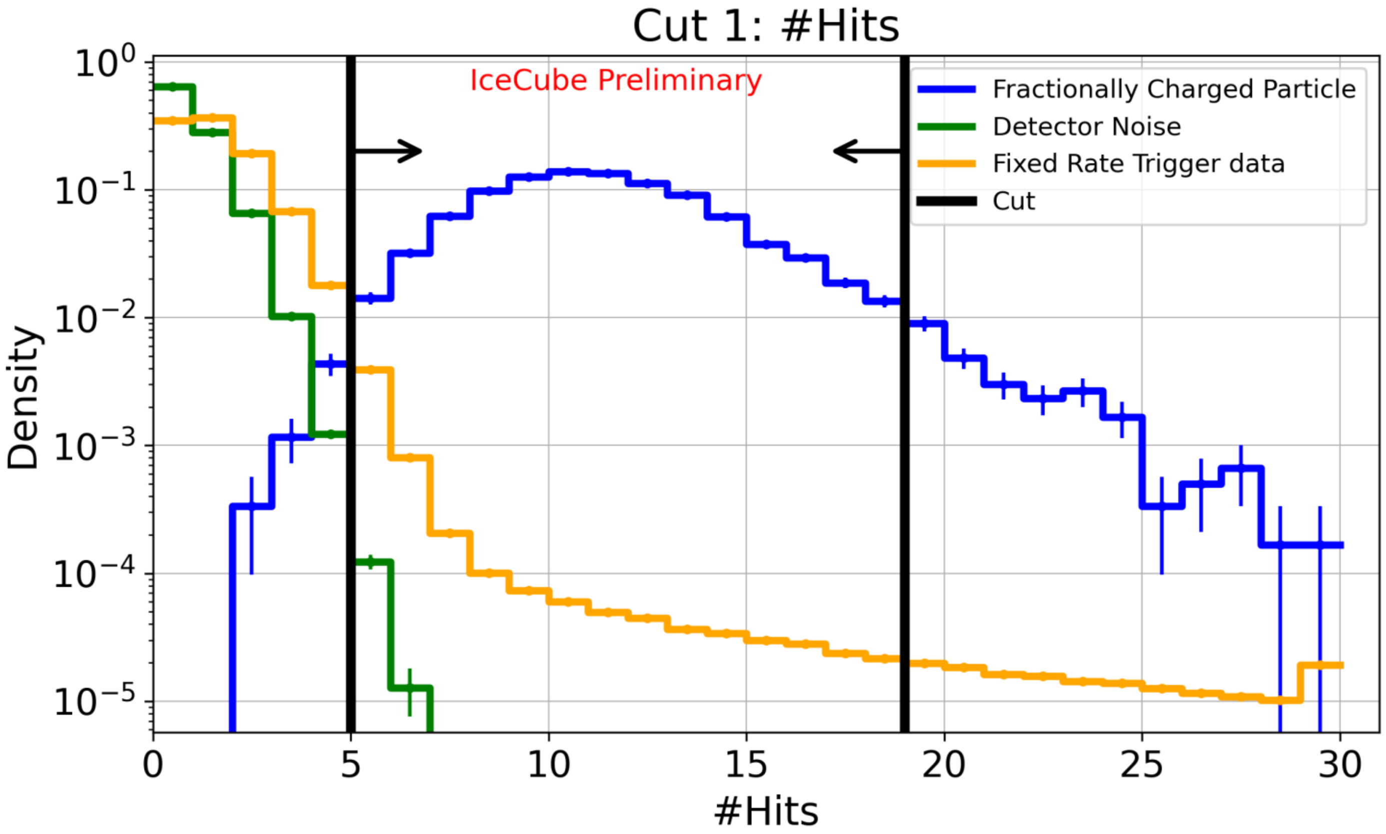
Directional clustering of Doubles

4

SLC fraction

Cut 1

- Fractionally Charged Particles (FCP) with a charge of 1/3 and a mass of 1 TeV
- Only events that produce at least 10 hits in DC
- Fixed Rate Trigger (FRT) reads out the whole detector for 10 ms every 300s
- Detector Noise simulation
  - Radioactive decay (low abundance of ^{40}K in glass spheres)
  - Correlated component
  - Thermal noise
- Detector noise produces a lower amount of hits in the time windows compared to the signal



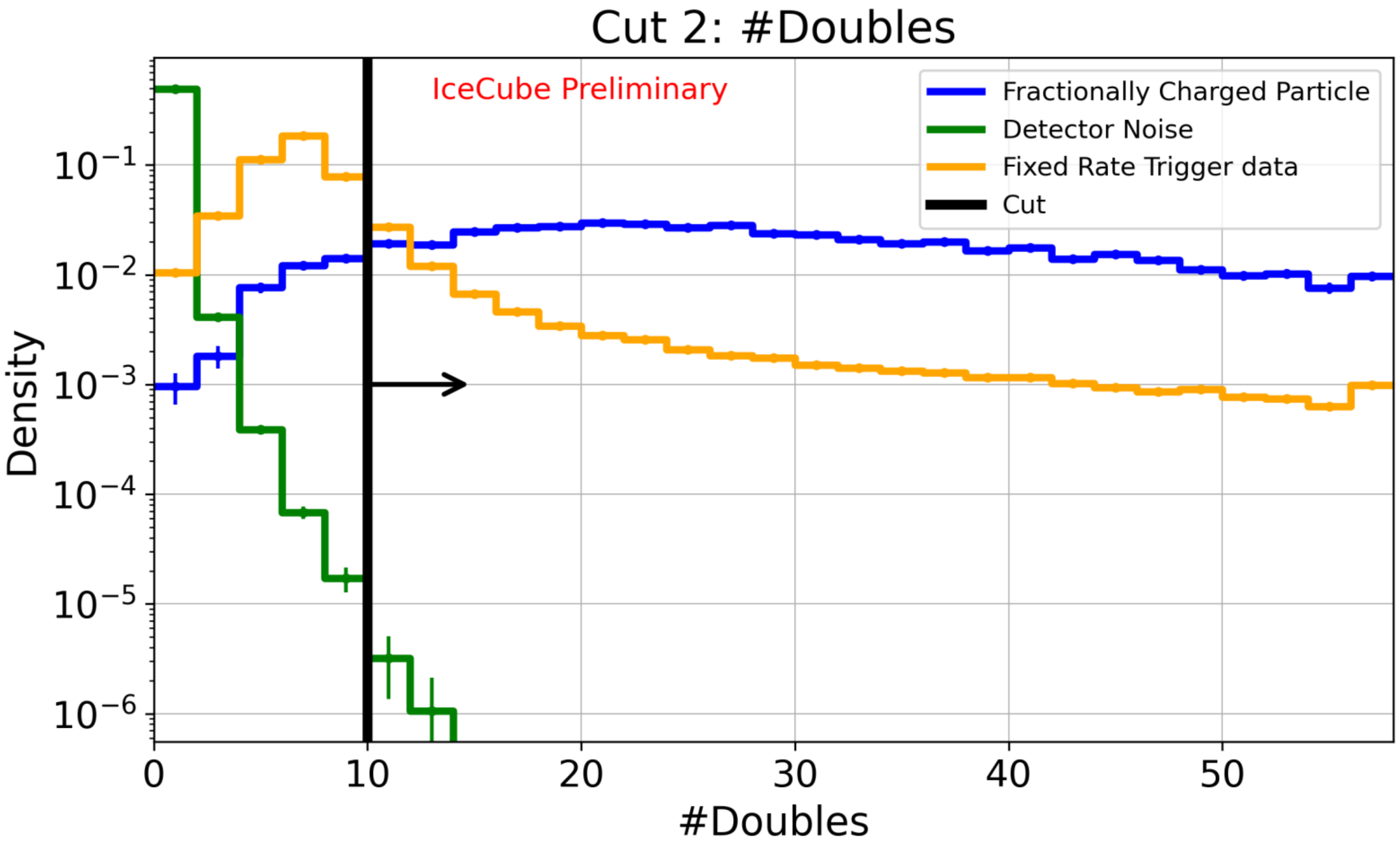
Cut 2

- Calculate the velocity of $\frac{x!}{2(x-2)!}$ hit pairs (combinations with itself and commutative ones are not calculated)

- The velocity cut interval:
  0.033 c ≤ vel ≤ 1.033 c

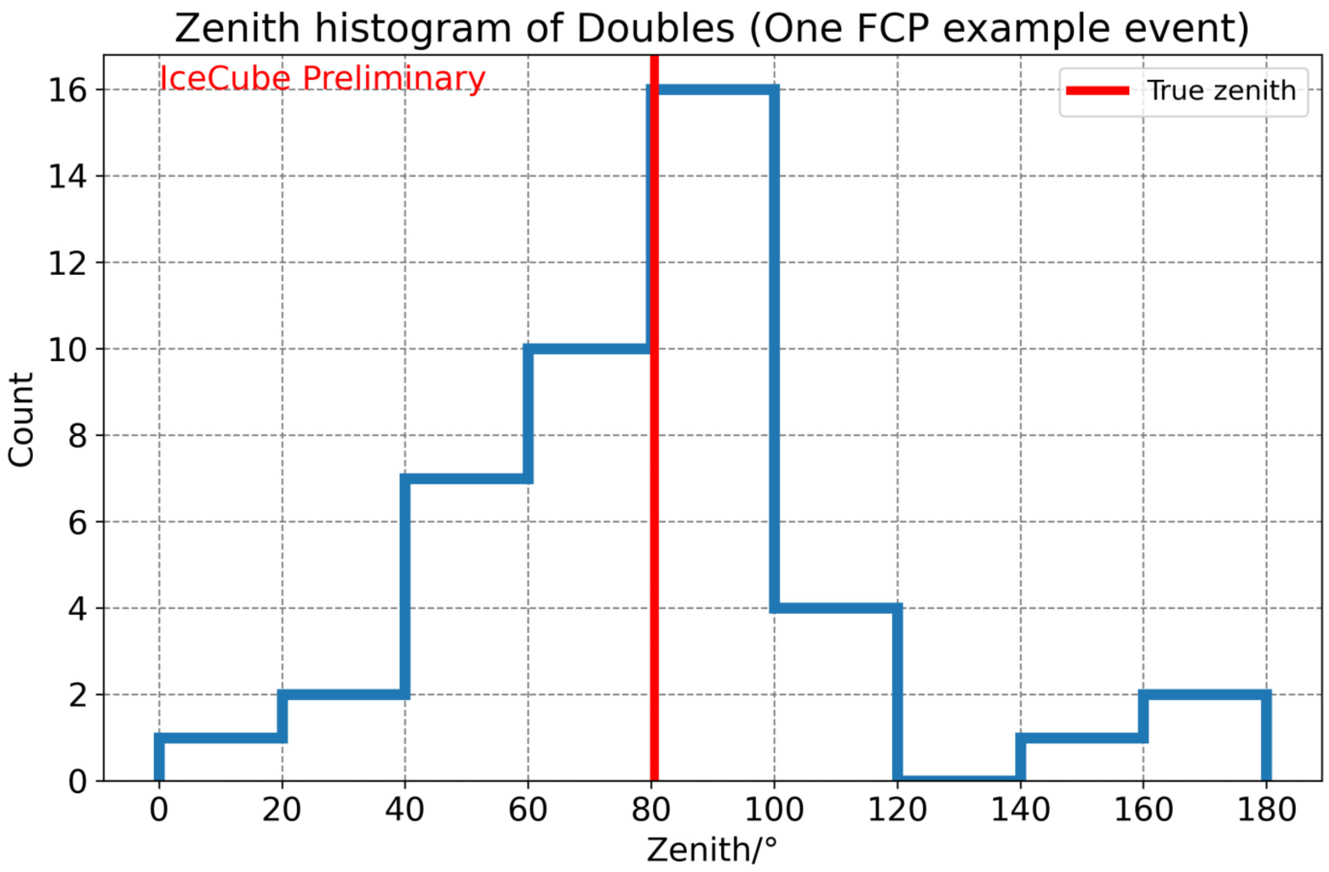
- Count the velocity consistent hit pairs (Doubles) per time window

- Detector noise clusters at lower #Doubles compared to the FCPs



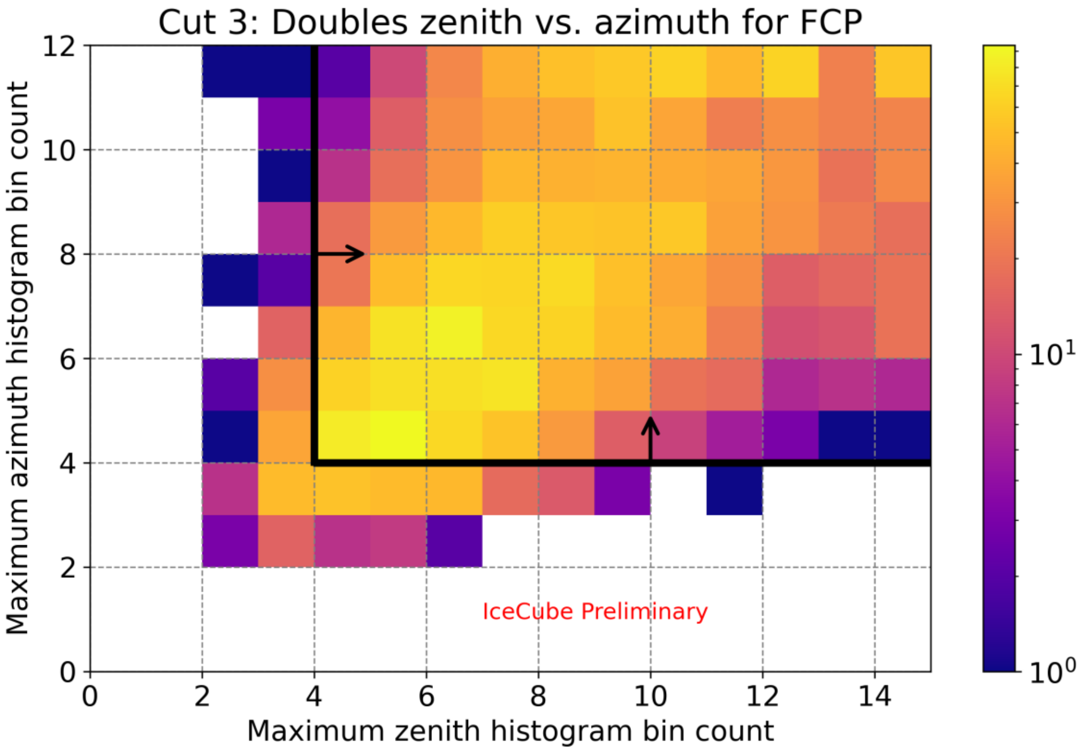
Directional clustering of Doubles

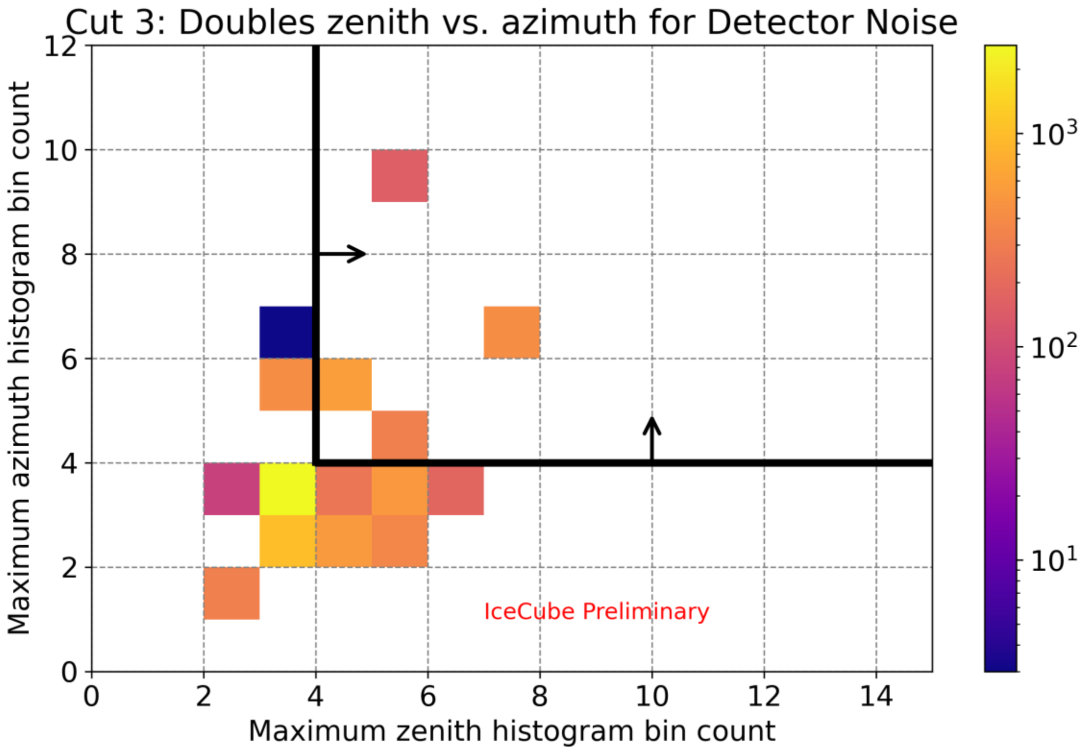
- Calculate the direction for all Doubles per time window
- For Detector Noise there should be no preferred direction
- Histogram the direction in 20° bins
- Example for one time window of a FCP event (simulated zenith 80.5°)
- Select the bin value of the bin with the maximum count



Cut 3

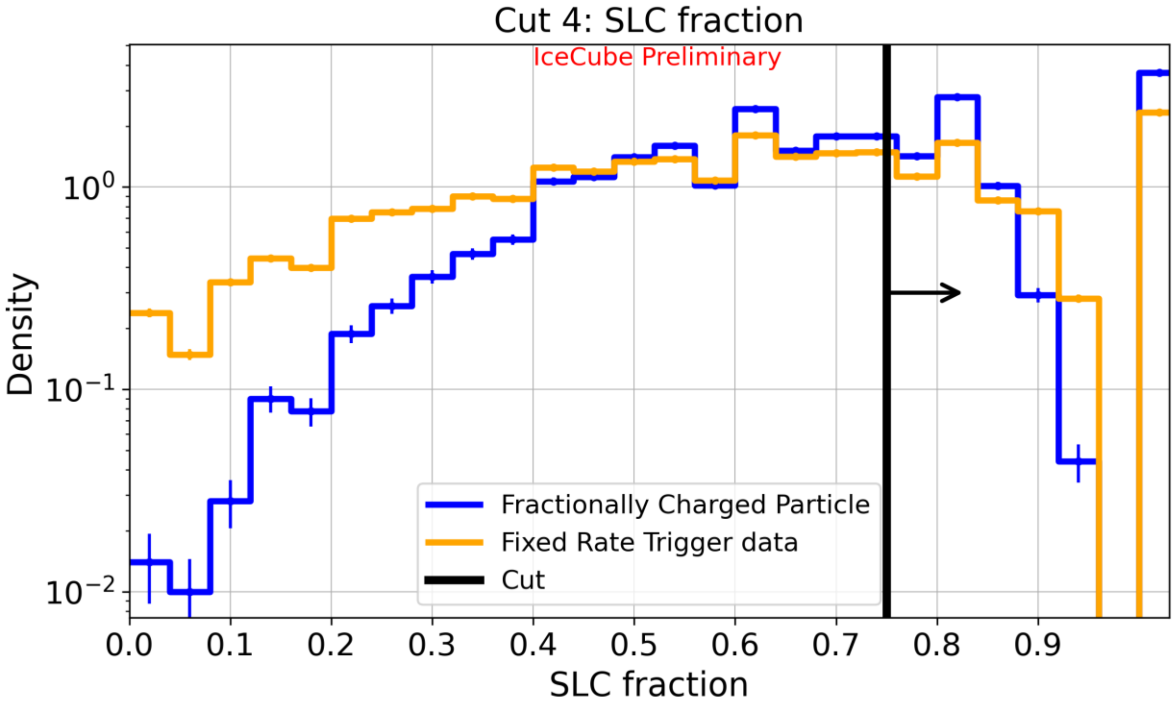
- Apply this simultaneously on the azimuth and zenith angle
- Detector Noise clusters at lower values

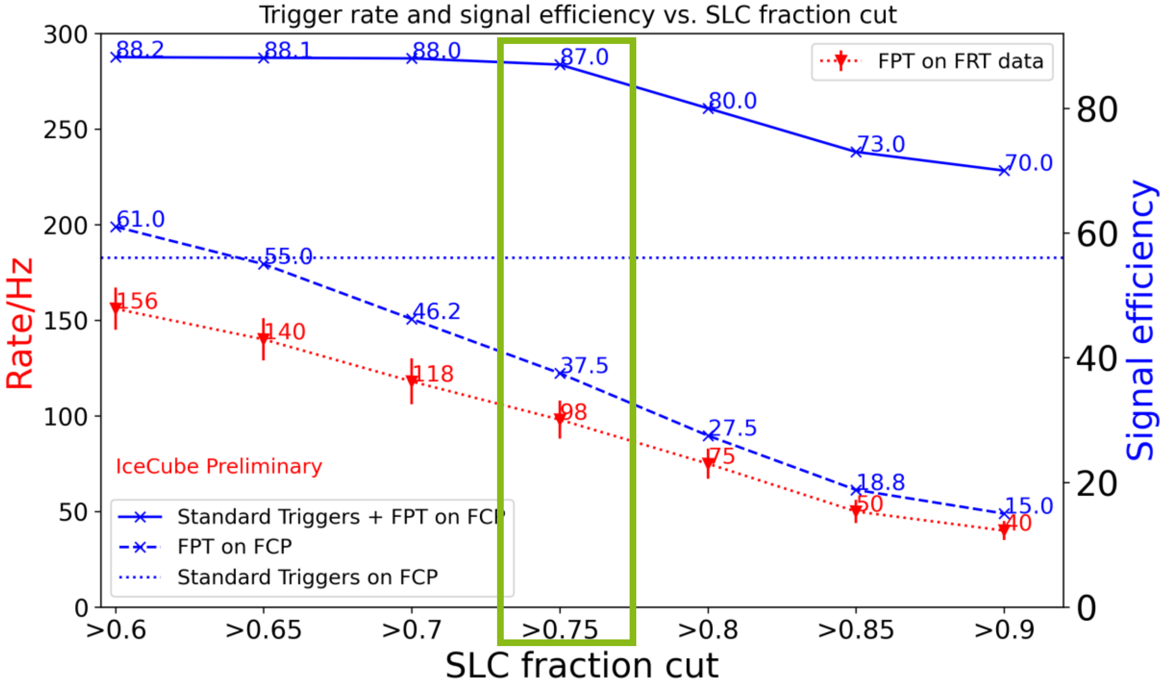




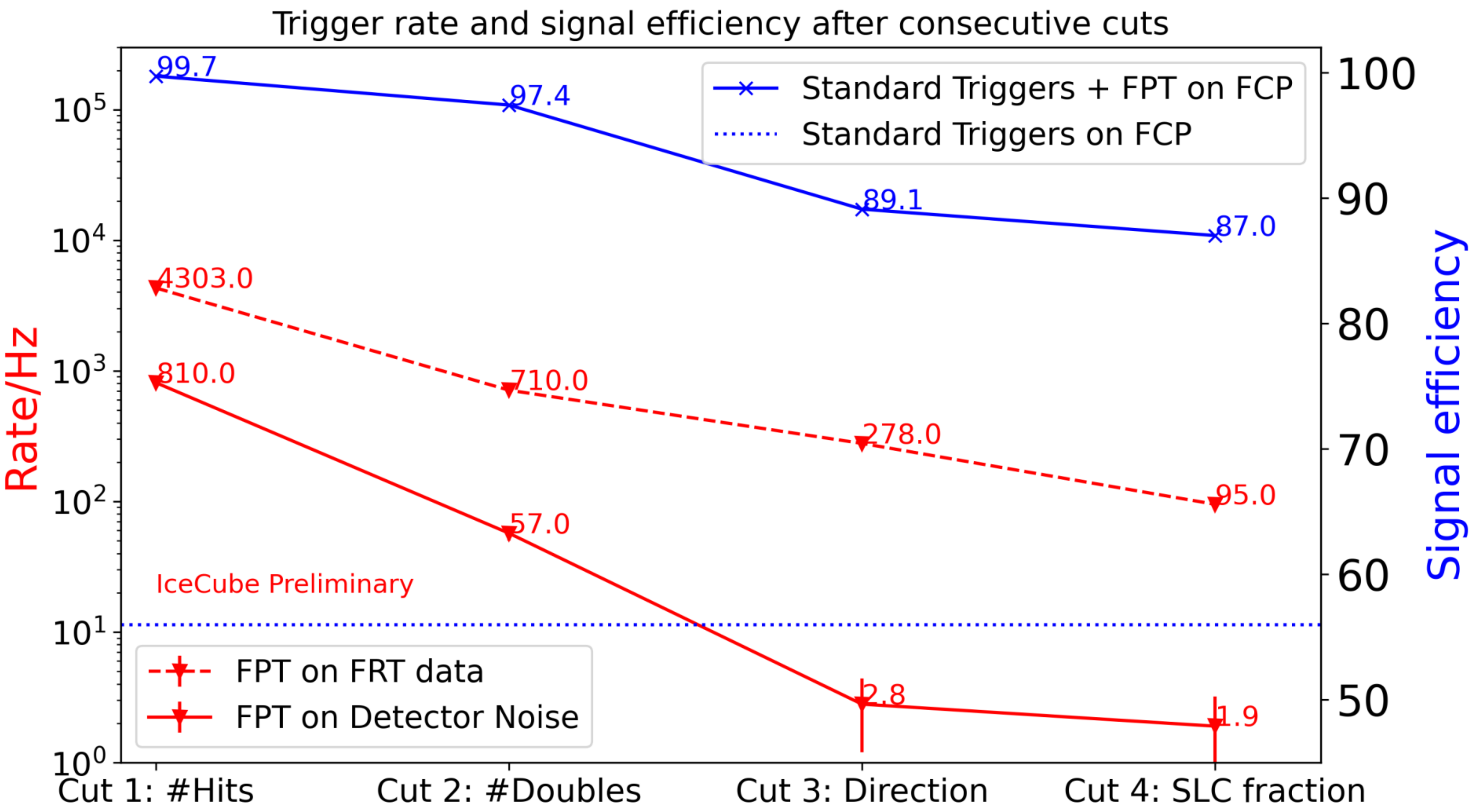
Cut 4

- Divide the number of SLC hits in the time window by the number of all hits in the time window
- Combined signal efficiency: Standard Trigger + Faint Particle Trigger
- The combined signal efficiency is “stable” up to a cut of >0.75, because additional triggered events have a high SLC fraction value and only double triggered events are lost



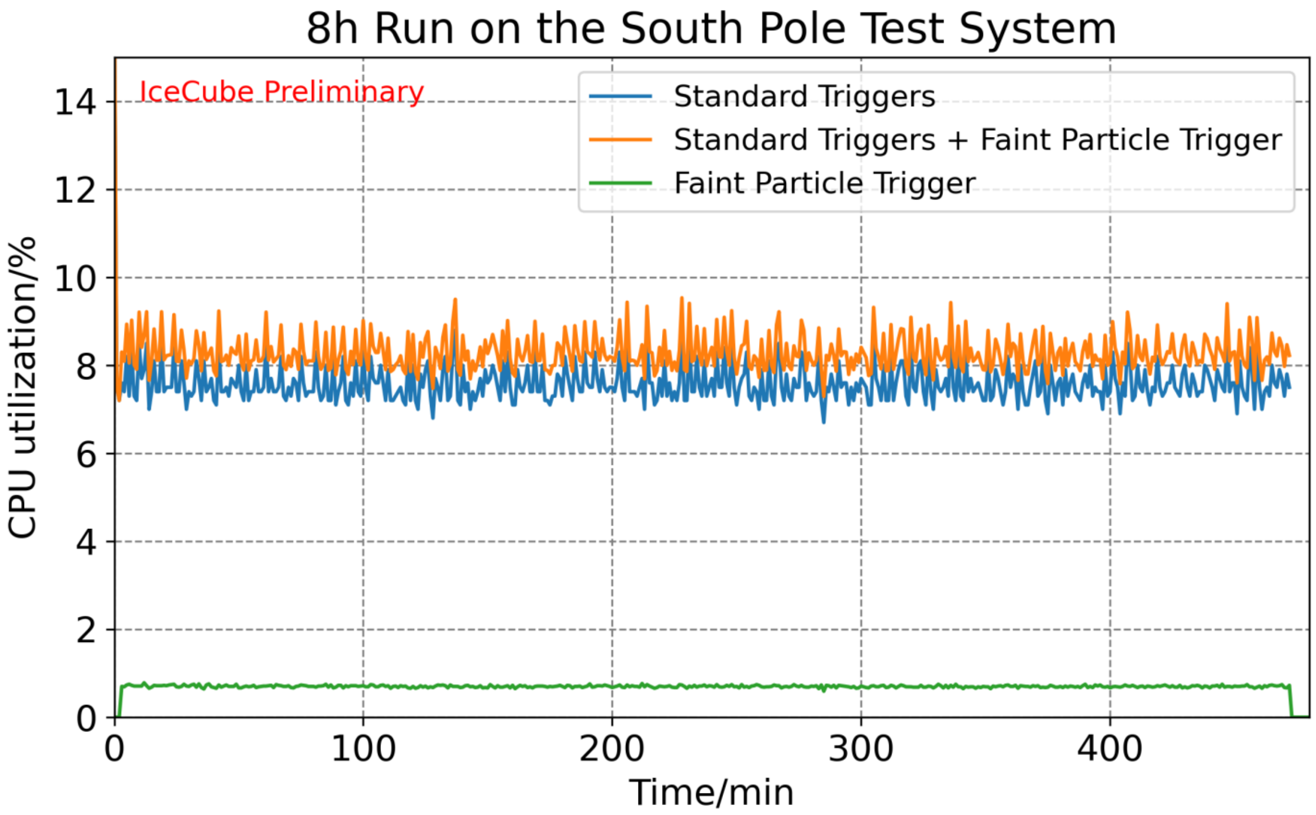


Summary Cuts 1-4



Performance and results

- Performance plot from South Pole Test System
- FPT consumes ≈ 1% of CPU utilization and produces additional ≈3.4 GB of data per day
- At the South Pole ≈ 1 TB of triggered data are saved and ≈ 100 GB of filtered data are transferred via satellite per day
- The signal efficiency for FCP is improved by a factor of ≈ 1.55 while increasing the event rate by ≈ 1.004



Trigger configuration	Signal efficiency FCP [%]	Event rate [Hz]	Additional data [GB/day]
Standard Trigger	56 ± 1	2784.0 ± 0.3	
Standard Trigger + FPT	87 ± 1	2793.9 ± 0.3	3.4

Result on low energy neutrinos

- Applied the trigger to low energy neutrino simulations in DeepCore

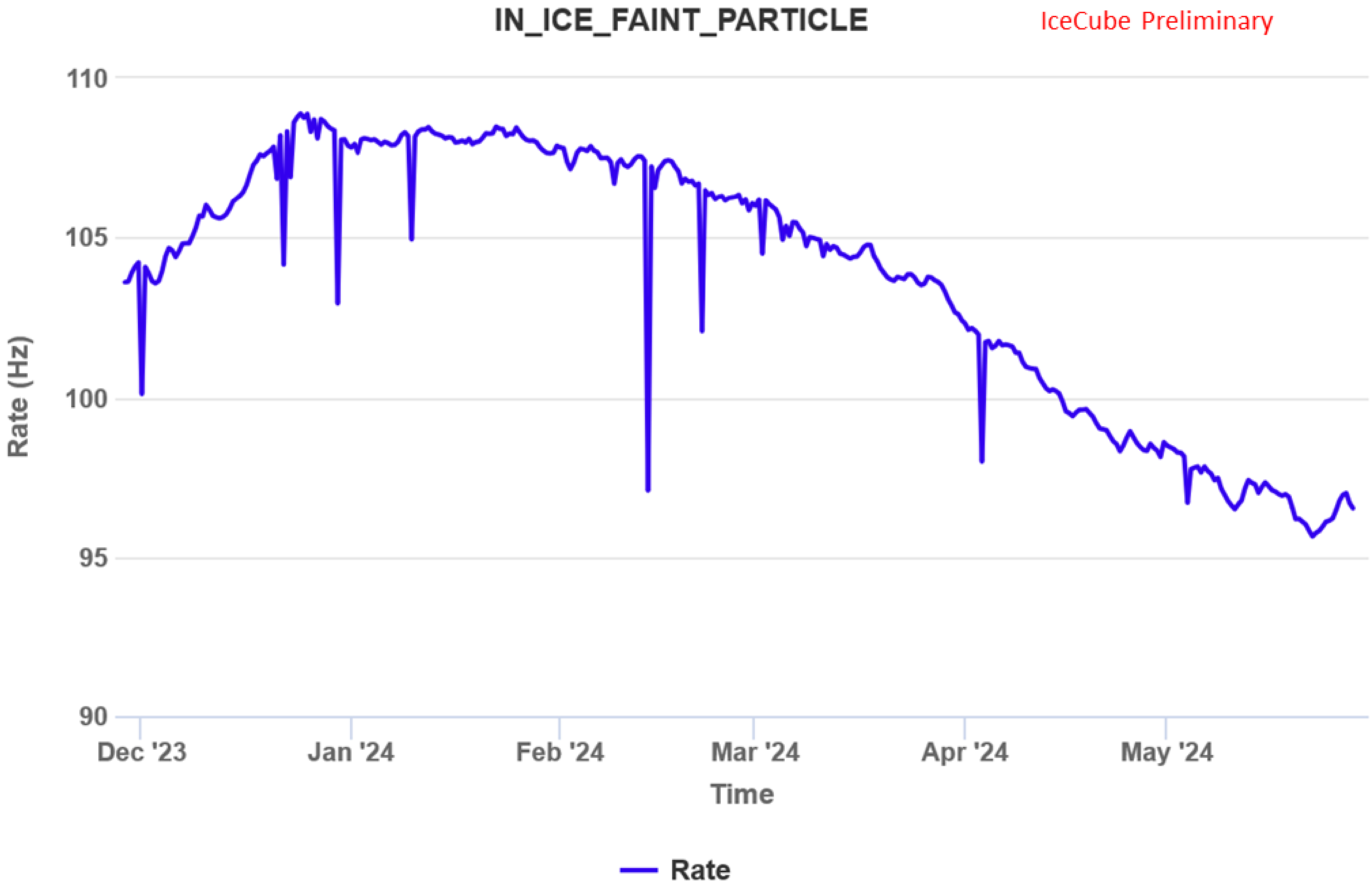
- A: 1 GeV ≤ Energy <4 GeV
- B: 4 GeV ≤ Energy <12 GeV
- C: 12 GeV ≤ Energy <100 GeV

- Analyses using low energy neutrinos will include the new events in their selections

Flavor and energy	Relative signal efficiency increase
$\nu_{e,A}$	1.11 ± 0.02
$\nu_{e,B}$	1.18 ± 0.02
$\nu_{e,C}$	1.10 ± 0.01
$\nu_{\mu,A}$	1.11 ± 0.02
$\nu_{\mu,B}$	1.15 ± 0.01
$\nu_{\tau,B}$	1.14 ± 0.02
$\nu_{\tau,B}$	1.15 ± 0.01

Trigger rate

- The FPT is online since November 28 2023
- ≈ 10% correspond to events that are only triggered by the FPT
- The trigger rate trend aligns with the trend of the main triggers
- Correlated to seasonal variations of the atmospheric temperature



Processing

- The processing of FPT events will reduce the rate by approximately one order of magnitude

- The final steps apply cleaning and reconstruction algorithms to the remaining events
  - For SLC dominated events existing cleaning algorithms had to be adjusted
  - Several cleaning methods were compared
  - Comparison of existing reconstruction algorithms and other machine learning based approaches are currently conducted

Summary

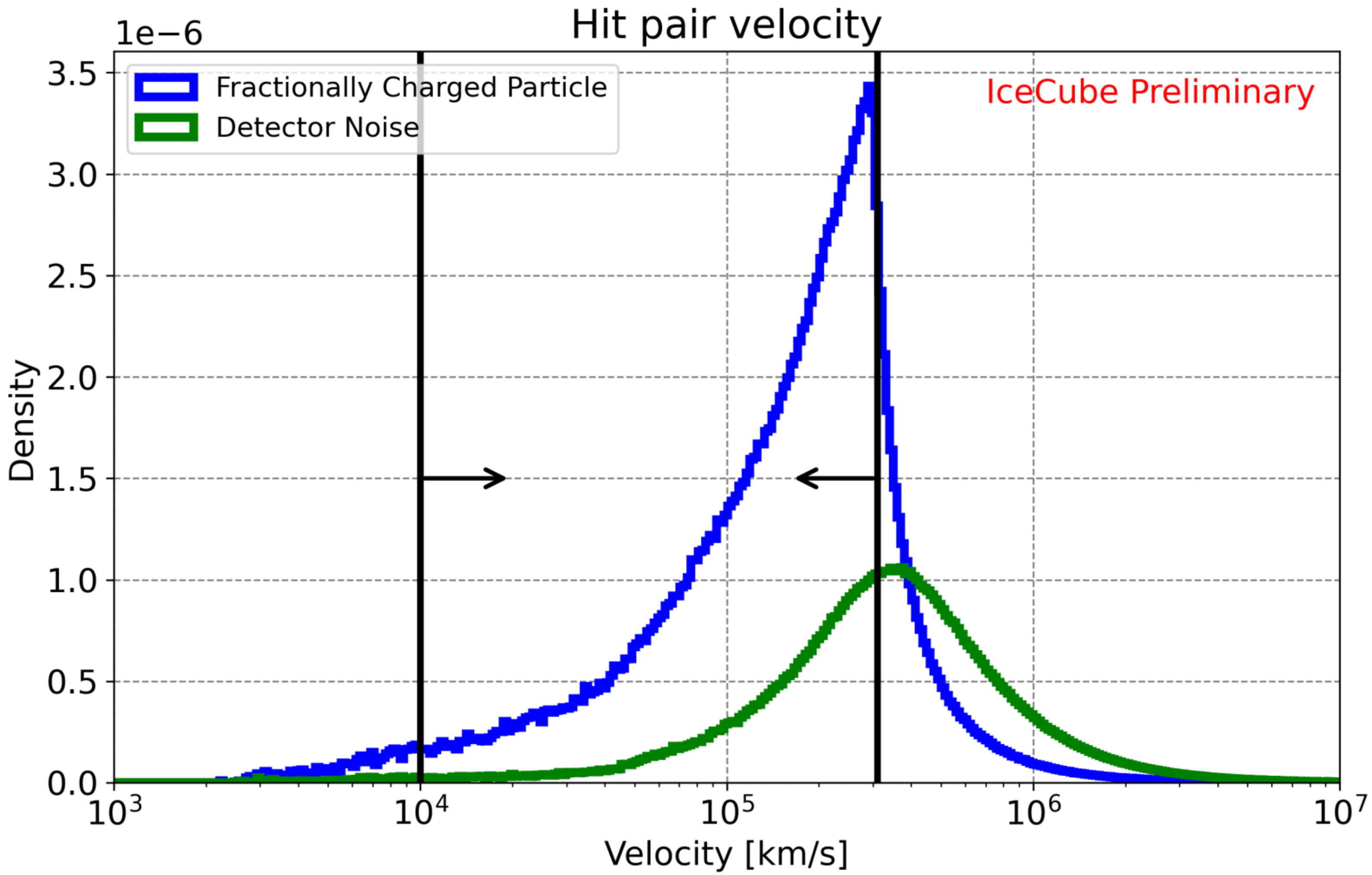
- The FPT was developed, tested and is running at South Pole since November 2023
- It significantly improves the signal efficiency for FCP while increasing the event rate by $\approx 0.5\%$
- Additional low energy neutrinos are triggered with a relative signal efficiency increase up to 1.18

Outlook

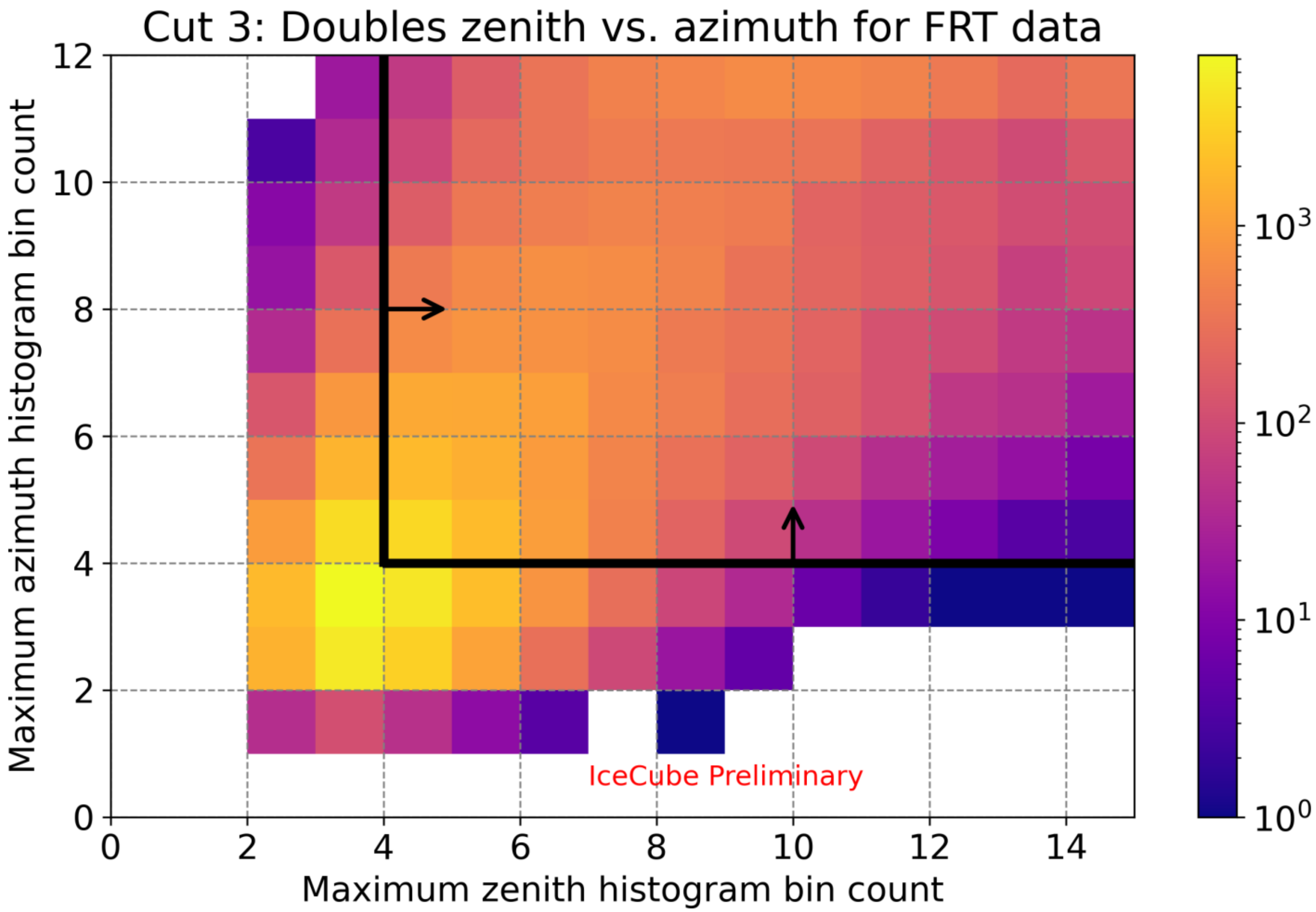
- Finalize the reconstruction algorithms for the new events
- Use new events in BSM and low energy analyses

Backup

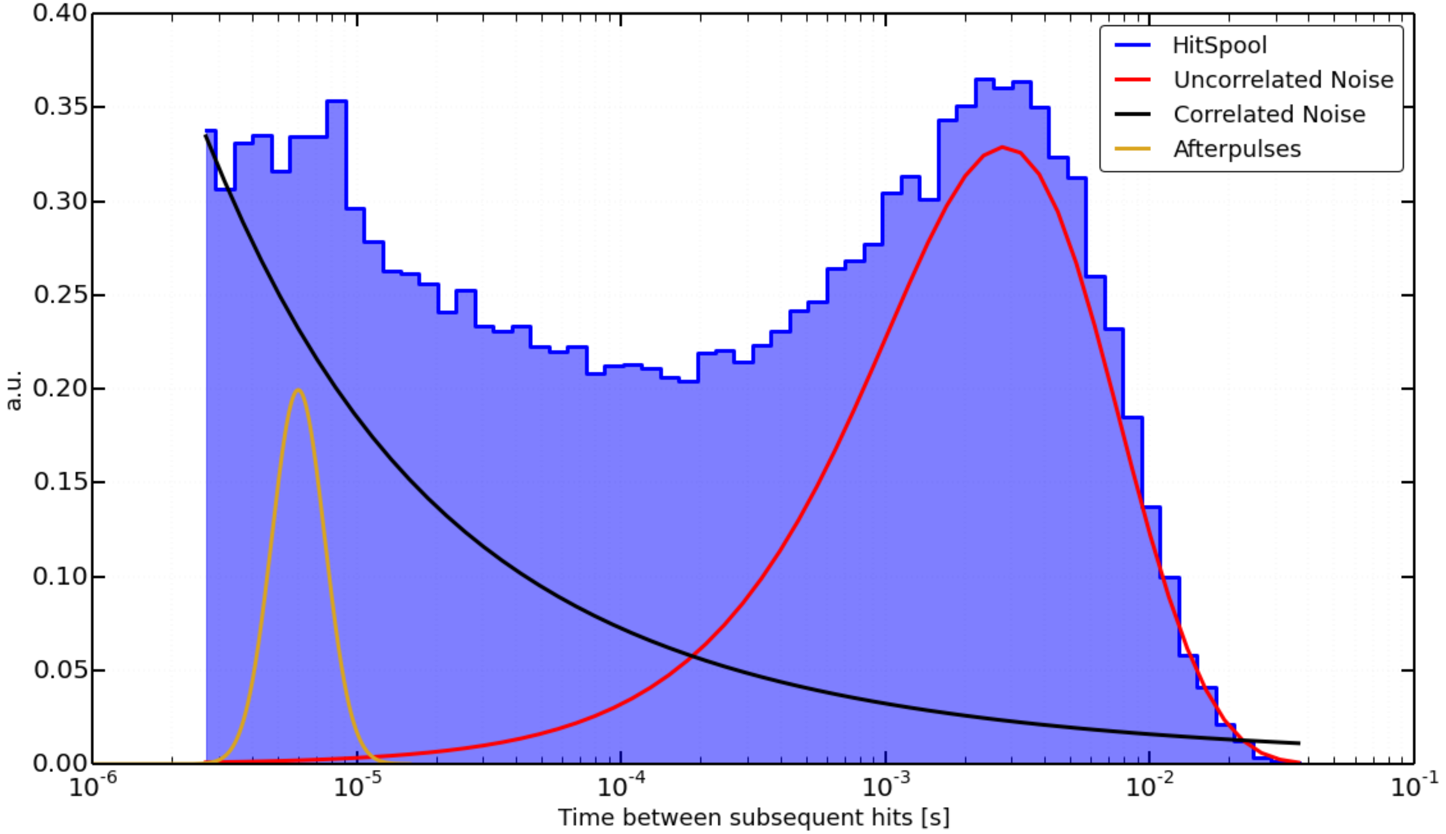
Hit pair velocity



Cut 3 for FRT data



Noise components



Noise Component	Origin	Distribution	Parameters
Afterpulses	PMT	Gaussian	$\mu = 6\,\mu\mathrm{s}$ $\sigma = 2\,\mu\mathrm{s}$
Uncorrelated	Thermal noise Radioactive Decay	Poissonian	$\lambda = \sim 250\,\mathrm{Hz}$
Correlated	Luminescence (?)	Log-normal	$\mu = -6[\log_{10}(\frac{\Delta T}{s})]$ $\sigma = 0.85[\log_{10}(\frac{\Delta T}{s})]$