Summary on muon reconstruction with the cone model

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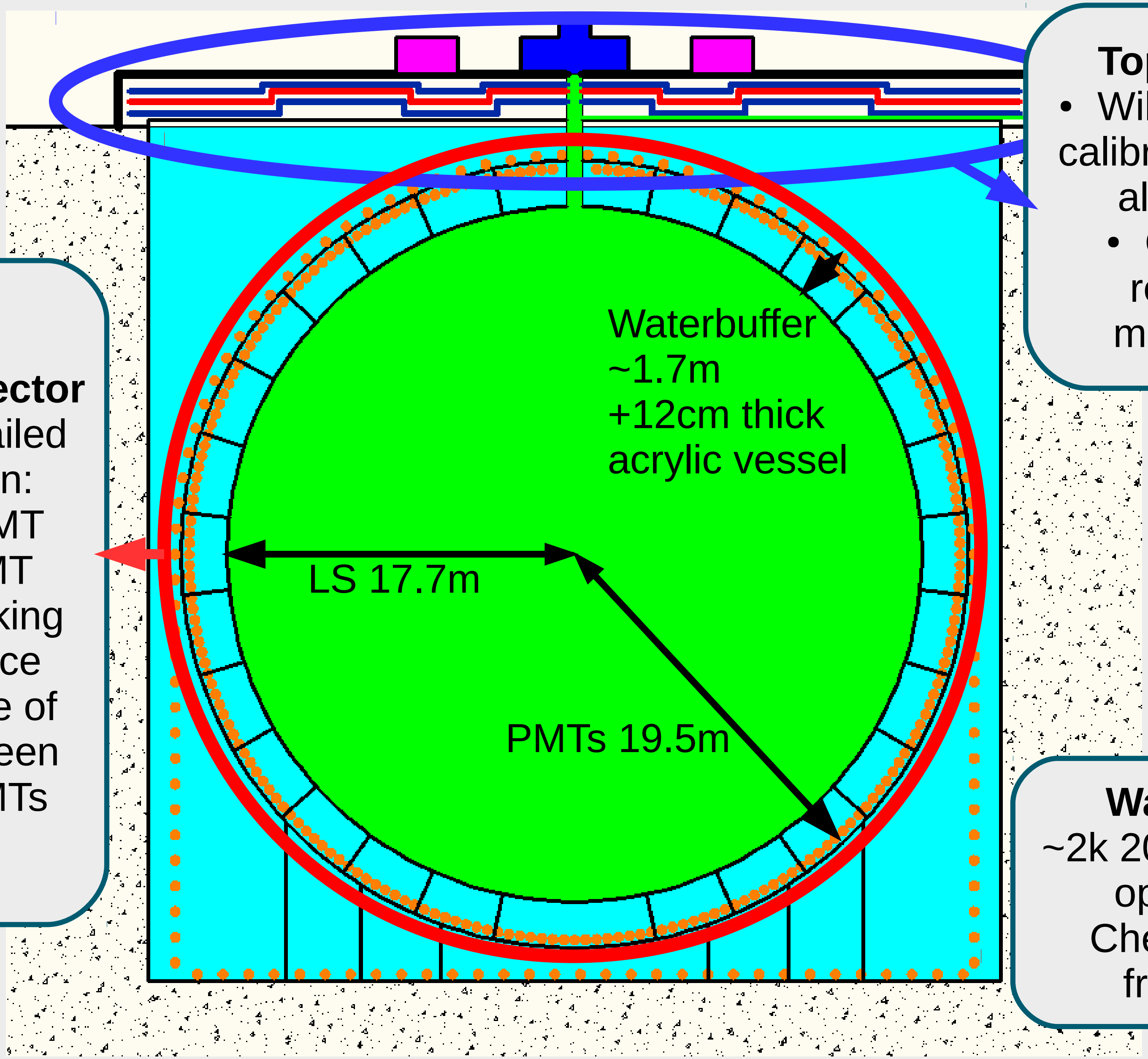
Outline

- Reminder: Tracking in liquid scintillator
  - Principle idea
  - Model & visualization
- Recent developments
  - Adaption to J17v1: Dynode- and MCP-PMTs
  - Inclusion of full electronics simulation
  - Deadtime estimation
- Summary & outlook

Perspective of a muon reconstructer

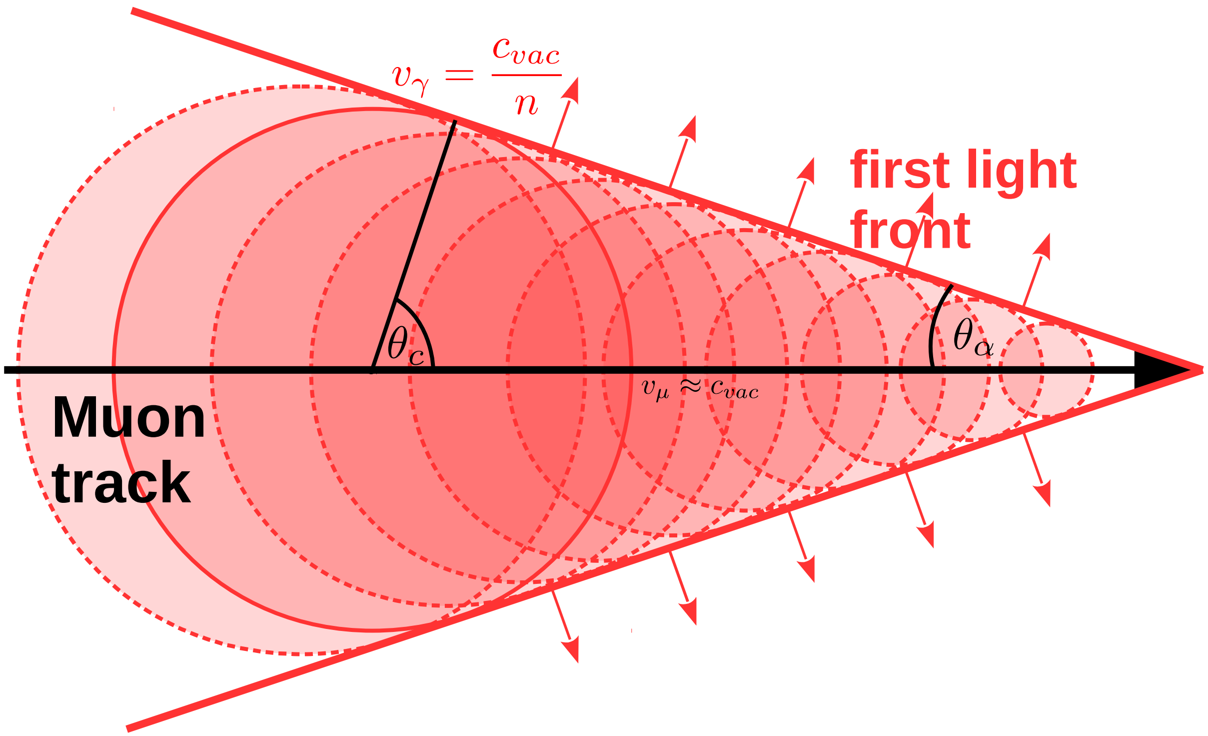


Central Detector
- Most detailed information: 18k 20'' PMT 25k 3'' PMT
- Best tracking performance
- Take care of water between LS and PMTs

Top Tracker
- Will be used to calibrate tracking algorithms
- Can also reconstruct muons in CD

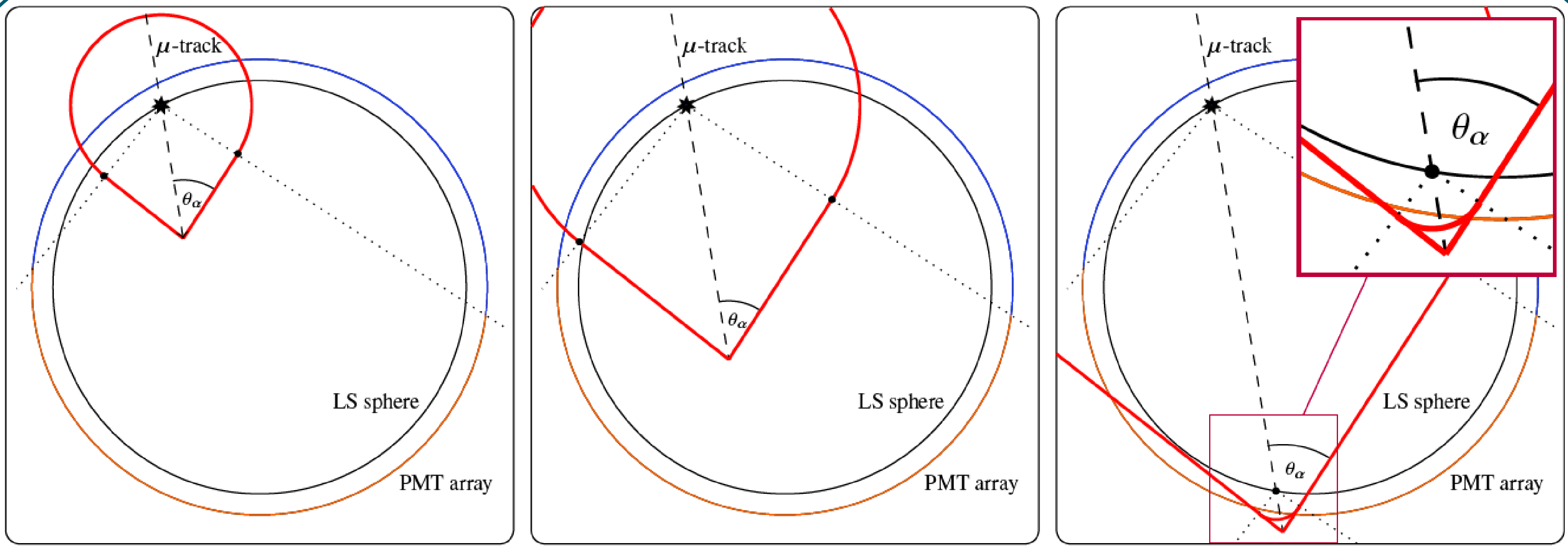
Water Pool
~2k 20'' PMT array optimized for Cherenkov light from muons

Scintillation light signal from Muons



- ***Challenge:*** Delayed, isotropic scintillation photon emissions (+Cherenkov light)
- ***Usually:*** Fit straight-line model to first-hit time pattern at PMTs
- Topology information from light propagating behind the the first-photon front
- A well understood optical model is the key to a good reconstruction

Muon tracks in JUNO
Signal evolution along a track



- **The cone** is extended by the backward sphere to model light behind the muon
- Division of array into two categories: **cone-part** and **sphere-part**
- At exit point: spherical scintillation around last point in LS + Cherenkov in waterbuffer
- Two additional signal categories:
  - **Forward sphere** for scintillation, and **Cherenkov-cone**
- In total: 4 parts weighted according to PMT orientation towards track

Likelihood implementation

$$\mathcal{L} = -2 \sum_{i=0}^{n_{PMT}} \ln f_{X_i}(\theta_{\alpha,i}; \vec{q})$$

- **Complete likelihood function** sums over all selected PMTs and calculates the probability of the opening angle θ_α under the assumption of the track hypothesis $\vec{q}$

- **Probabilities** are extracted from pre-calculated PDFs for all 4 categories (P1-P4) and weigthed according to the orientation of the PMT to the track hypothesis

$$\begin{aligned} f_{X_i}(\theta_{\alpha,i}; \vec{q}) = {} & w_2(\vec{q}) P_2(\theta_{\alpha,i}|\vec{q}) \\ & + w_3(\vec{q}) \left[w_4 P_4(\theta_{\alpha,i}|\vec{q}) + (1 - w_4(\vec{q})) P_3(\theta_{\alpha,i}|\vec{q}) \right] \\ & + (1 - w_2 - w_3) P_1(\theta_{\alpha,i}|\vec{q}). \end{aligned}$$

- **The weights** are calculated with an error function to provide a smooth transition between model categories

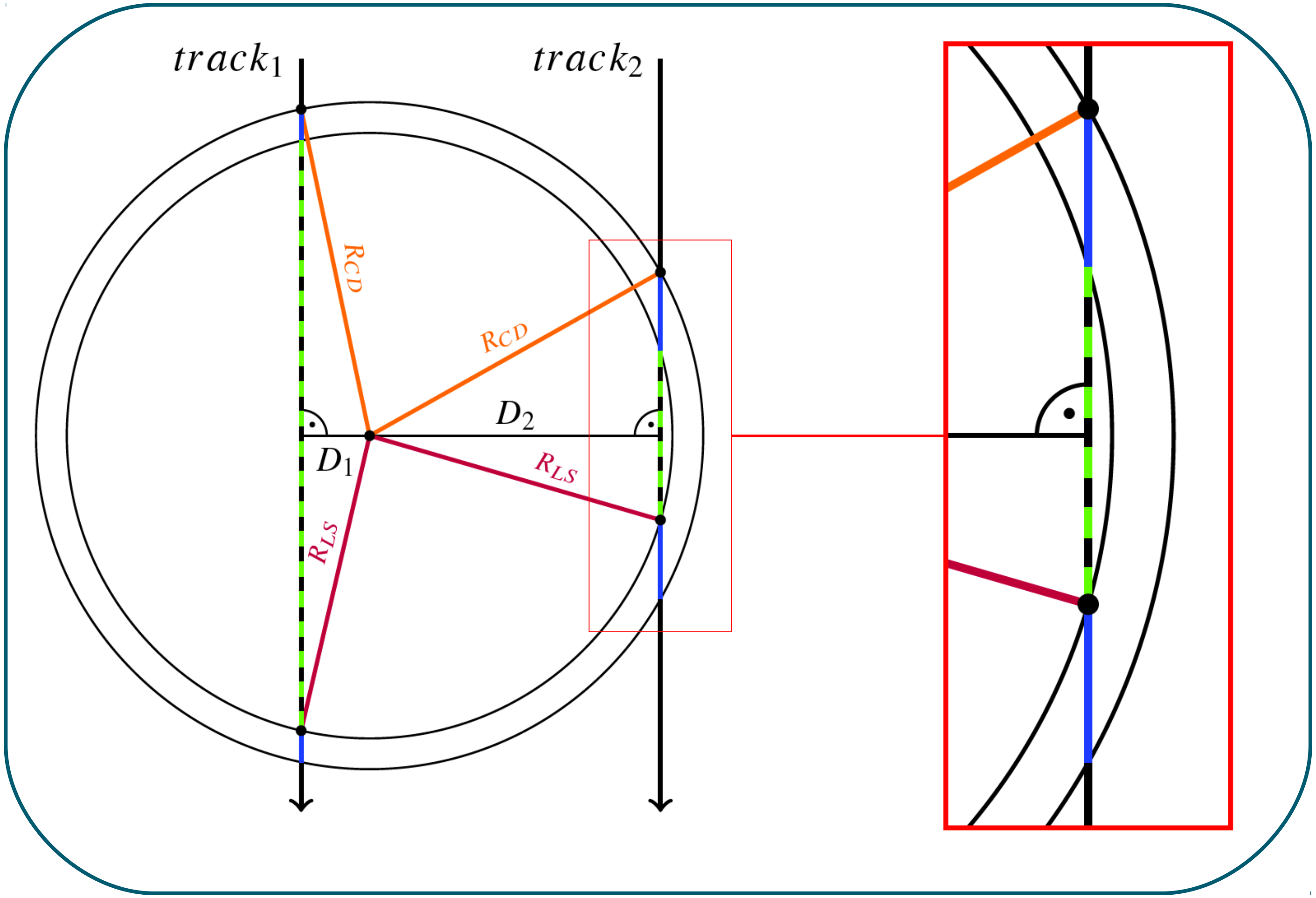
$$w_{2,i} = \frac{1}{2} \left(1 + \mathrm{erf}\left(s \cdot \Delta\phi_i\right)\right)$$

- **For example** the i-th PMT might be exactly at the transition between cone and backward sphere

  It will then receive 0.5 weight for the backward-sphere probability and 0.5 for the cone-probability

- Note that the Cherenkov-cone at the exit point is a sub-class of category 3

Symmetries in a spherical detector



- ***Minimum [D]istance from center*** is a main parameter
- With D any track's length in the liquid scintillator and the water buffer is defined

$$l_{LS} = 2\sqrt{R_{LS}^2 - D^2}$$

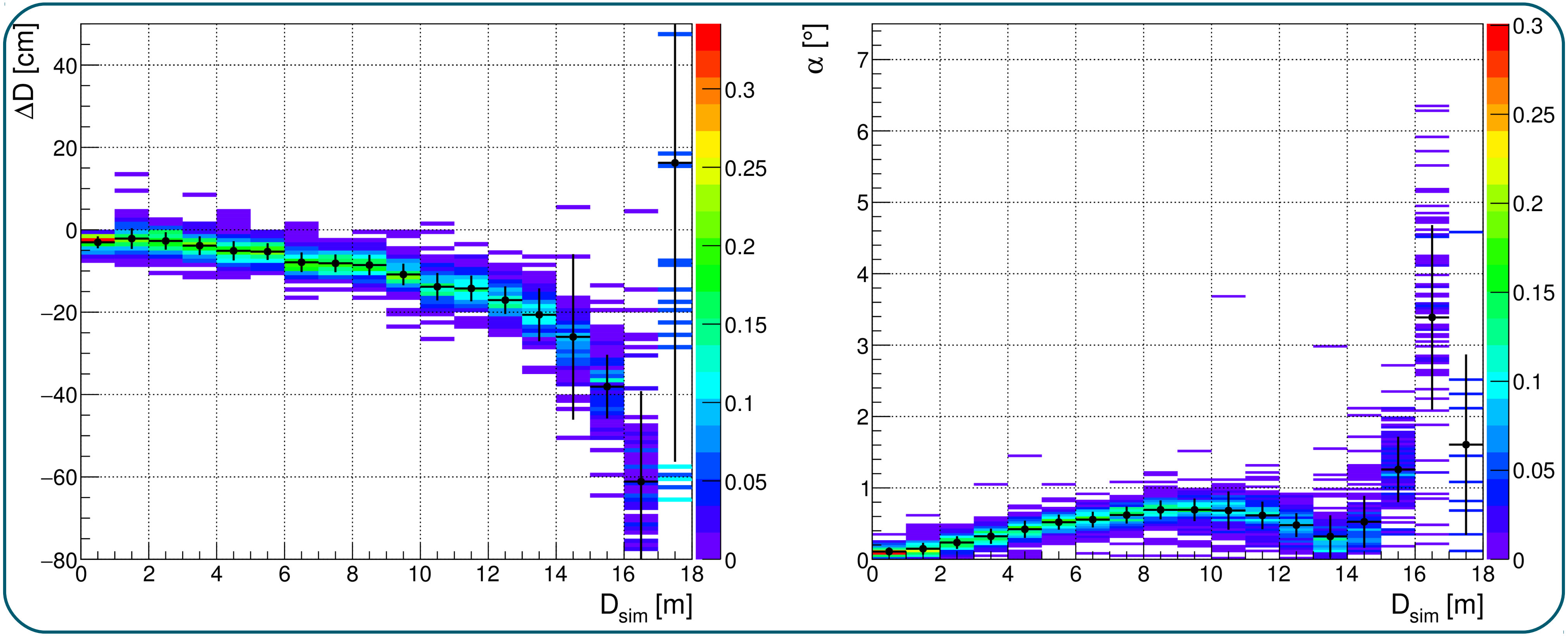
$$l_{buffer} = l_{CD} - l_{LS}$$

- Regardless of other orientation (theta, phi) the signal characteristics change mainly with D

- Tracks at the edge are harder to reconstruct due to
  - Less information (total PE)
  - Ratio of LS to water decreases
  - Very imbalanced distribution of hits on the PMT array

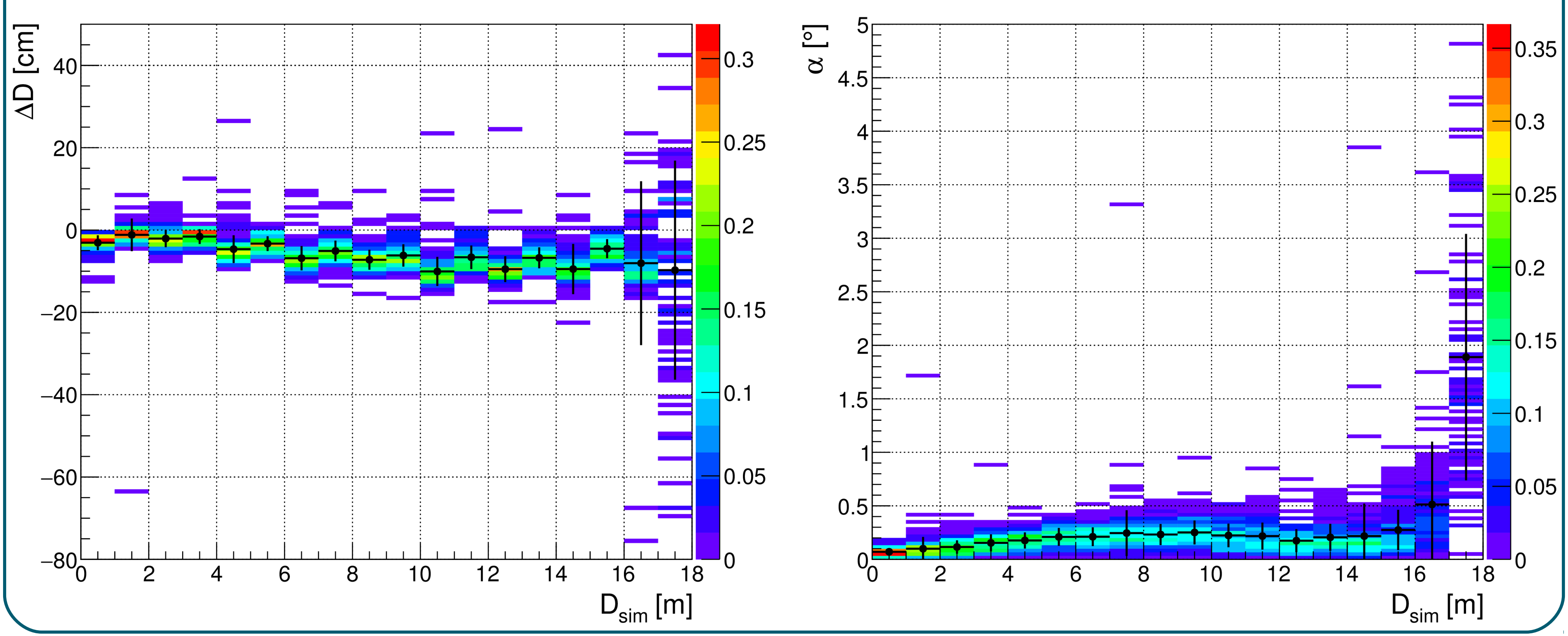
Adaption to J17v1
Two different 20-inch PMT types

- With J17v1 two different LPMT groups are distinguished:
  - 5k dynode PMTs with 3ns TTS and 13k MCP-PMTs with 12ns TTS
- Smearing hit times with gaussian and sigma from TTS, no elec sim
- LPMT system only
- Increasing bias in ΔD towards detector edge, but small spread
- at D=17m very large spread



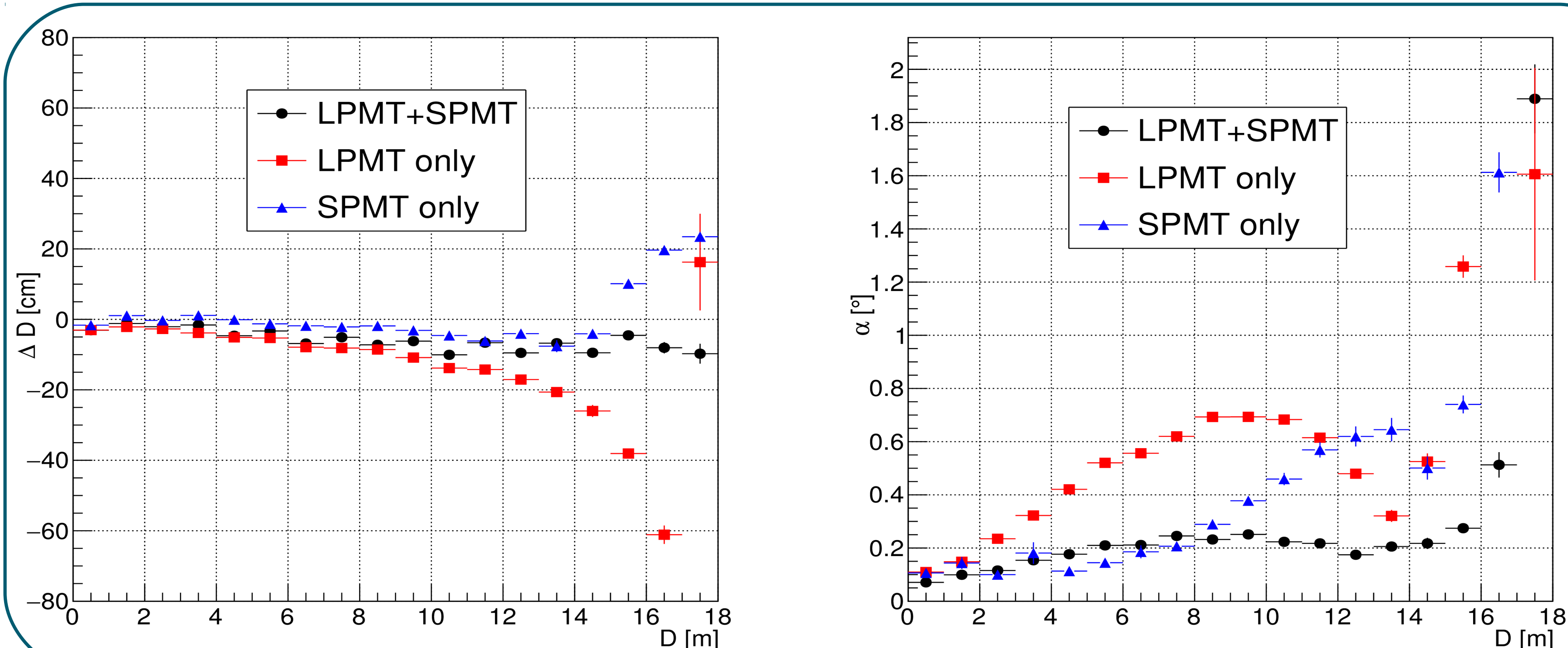
Cone method
Performance with combined PMT systems

- ***Combination of both systems*** gives best overall result
  - Small bias in ΔD still increasing for edge events
  - Spread is small and contained around mean value
  - Angular resolution better than 0.5° for largest part of the detector
  - Tracks with D>17m still have large spread



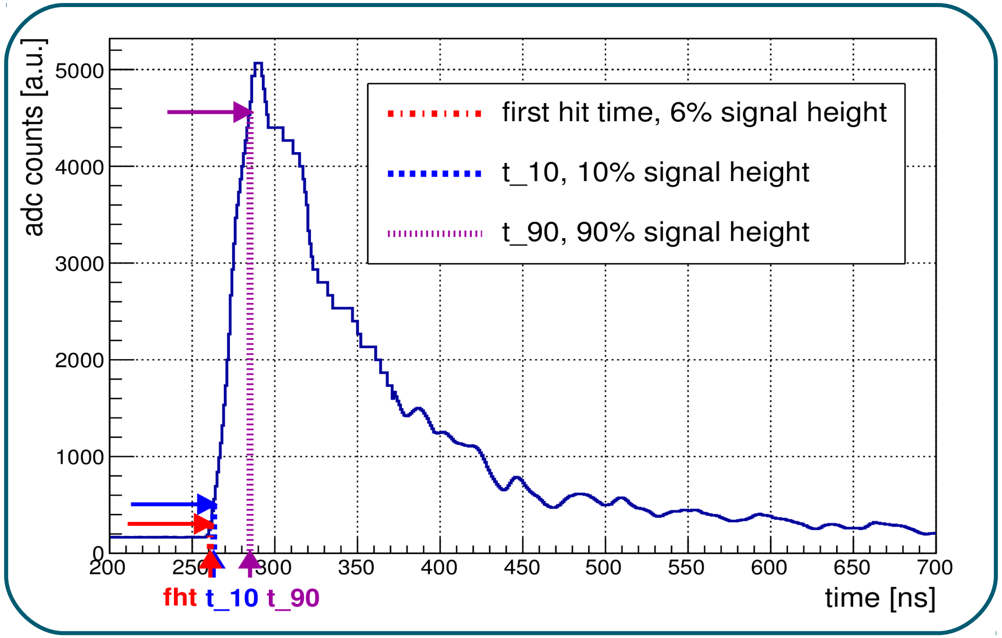
Muon Reconstruction
Comparison of PMT arrays

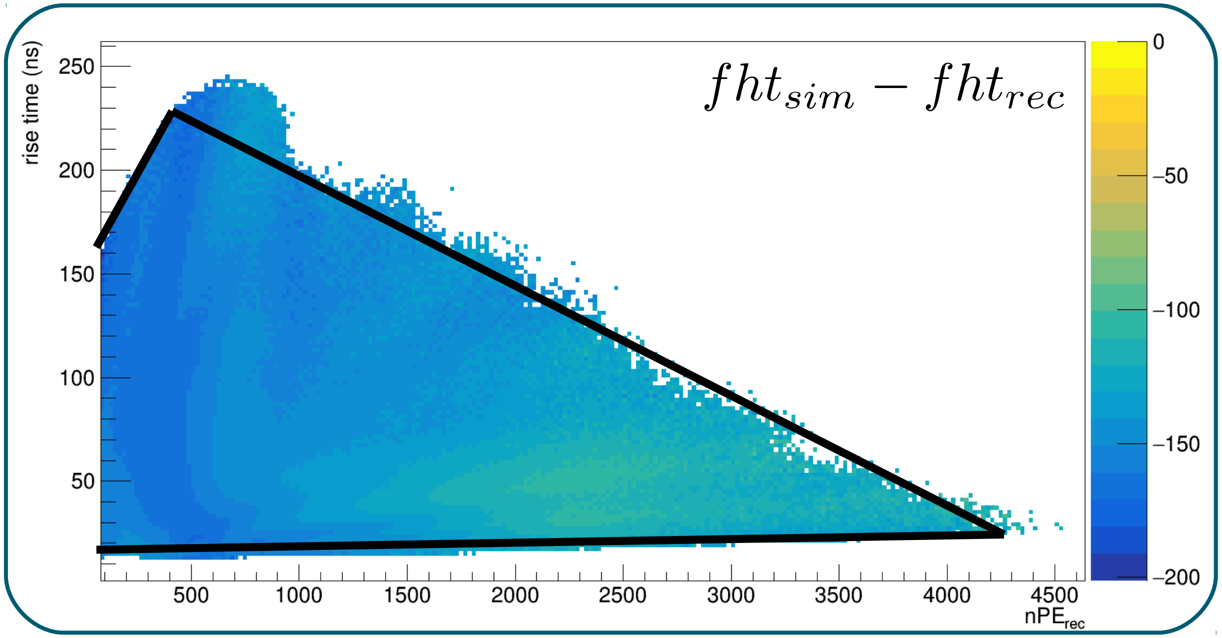
- ***SPMT*** in general perform slightly better than LPMT in this reconstruction (better timing!)
- ***Best results*** were archieved with a combination of both systems
  - Bias in ΔD seems to cancel out, stays below 10 cm
  - Angular reconstruction more stable than with isolated systems, better than 0.5° up until D=16 m



With elec sim and waveform reco

- ***Waveform reco*** works on constant fraction discrimination
- Will also extract rise time between 10% and 90% of max signal height
- Details in report by Michaela

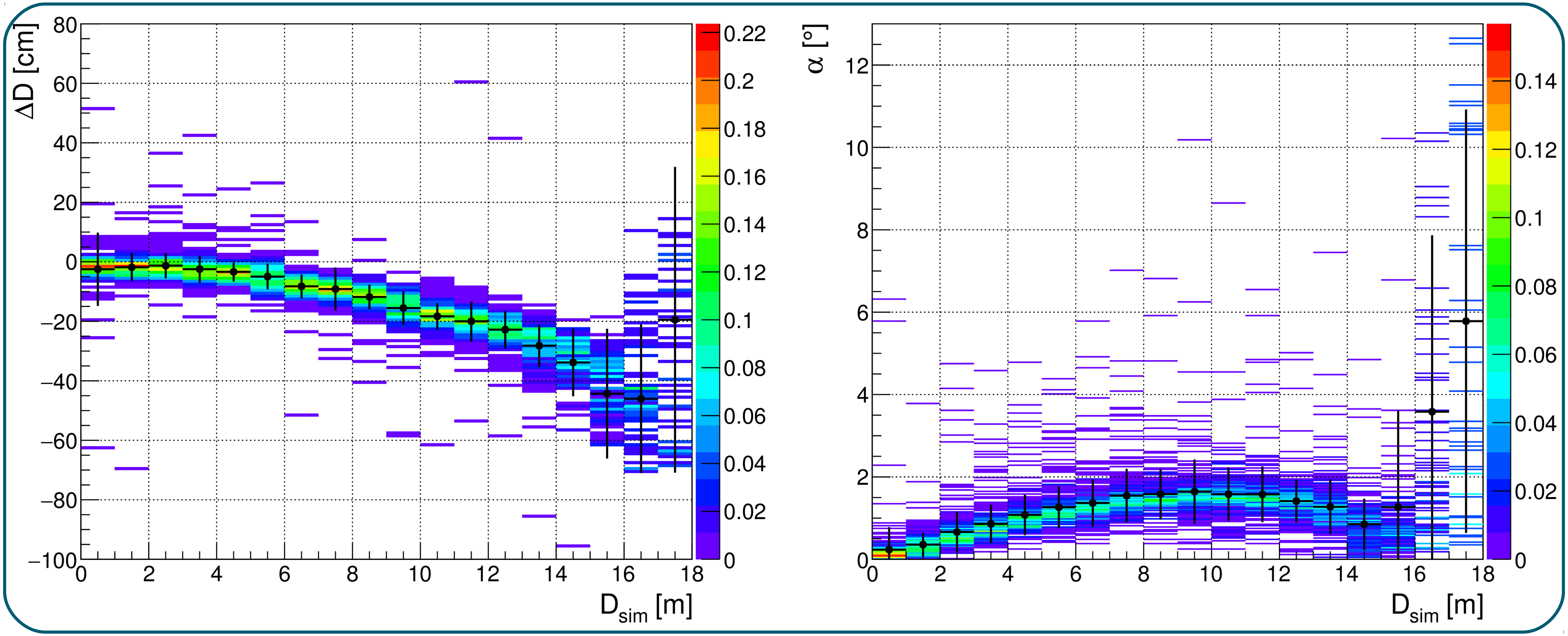




- ***2D look-up table*** in respect of reconstructed charge in nPE and waveform risetime
- Used to remove PMTs from fit selection
- Can be used to correct PMTs time shift

Results with full simulation

- Only LPMT included, because there is no elec sim for SPMT yet
- Different TTS of dynode- and MCP-PMTs included in elecsim
- Evolution of bias in ΔD the same as without elecsim, PMT selection can counter worsened hit times
- Angular reconstruction worsend by ~0.5° in regard to LPMT w/o elecsim
- Impact of full simulation can be countered with new info from waveform (rise time)



Deadtime estimation
With reconstruction imperfection

- ***Baseline veto strategy*** forsees a cylindrical veto around the muon track with radius r = 3 m for t = 1.2 s
- Muon rate 3.5/s → Several veto cylinders present at all times, overlapp possible
- Deadtime estimation with toyMC:
  - Generate muon tracks with official generator & put on global time scale according to rate
  - Evaluate vetoed&sensitve LS volume every time a new muon crosses the detector or when an old veto is released
  - Multiply volume with time until next change to get exposure
- For imperfect reconstruction: Model bias against distance from center D
  - Increase radius accordingly $r_{v,eff} = r_v + \Delta D + \sin(\alpha) l$ $\quad l = \sqrt{R_{LS}^2 - D^2}$

Veto strategy	Exposure ratio
No veto	100%
Perfect tracking	86%
ConeReco w/o elecsim	85%
ConeReco with full elecsim and waveform reco	82%

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Muon reconstruction Cone method
Summarized in Paper

- ***Cone Reconstruction*** development and results are summarized in a paper draft
- Intented to be published in JINST if approved by collaboration
- Available in DocDB2608 and Hypernews for review and general reference to the method
- Many thanks to the physics/simulation&offline group for the software-framework and feedback while development, Michaela for contributing the muon waveform reconstruction paragraph and the other muon-reconstructors for their ideas

PREPARED FOR SUBMISSION TO JINST

Muon reconstruction in JUNO with a geometrical model

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ABSTRACT: The Jiangmen Neutrino Underground Observatory (JUNO) is a 20 kton liquid scintillator detector currently under construction near Kaiping in China. The physics program focuses on the determination of the neutrino mass hierarchy with reactor anti-neutrinos. For this purpose, JUNO is located 650 m underground with a distance of 53 km to two nuclear power plants. As a result, it is exposed to a muon flux that requires a precise muon reconstruction to make a veto of cosmogenic backgrounds viable. Established muon tracking algorithms use time residuals to a track hypothesis. We developed an alternative muon tracking algorithm that utilizes the geometrical shape of the fastest light. It models the full shape of the first, direct light produced along the muon track. From the intersection with the spherical PMT array, the track parameters are extracted with a likelihood fit. The algorithm finds a selection of PMTs based on their first hit times and charges. Subsequently, it fits on timing information only. On a sample of through-going muons with a full simulation of readout electronics, we report a spatial resolution of 20 cm of distance from center and an angular resolution of 1.6° over the whole detector. Additionally, a dead time estimation is performed to measure the impact of the muon veto. With the results of the reconstruction, a loss in exposure of only 4% can be achieved compared to the case of a perfect tracking algorithm. When including only the PMT time resolution, but no further electronics simulation and waveform reconstruction the exposure loss is only 1%.

KEYWORDS: Particle tracking detectors, Neutrino detectors, Cherenkov detectors, Large detector systems for particle and astroparticle physics

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Summary & Outlook

- ***Muon reco with geometrical cone model working reliably***
  - Most aspects of signal composition included
  - Dynode and MCP-PMT differences in TTS included
  - ➔ Included model for Cherenkov light around exit point
  - SPMTs also included (Release in J17v1r1)
  - ➔ Best performance with combination of LPMT+SPMT

- ***Electronic simulation*** now also possible with new muon waveform reco package
  - Only LPMT included so far, but promising results
- ***Deadtime estimation*** gives only loss of 1% w/o electronics simulation and 4% with full elecsim and wave reco compared to perfect tracking
- ***Outlook: Compiled results into a paper***

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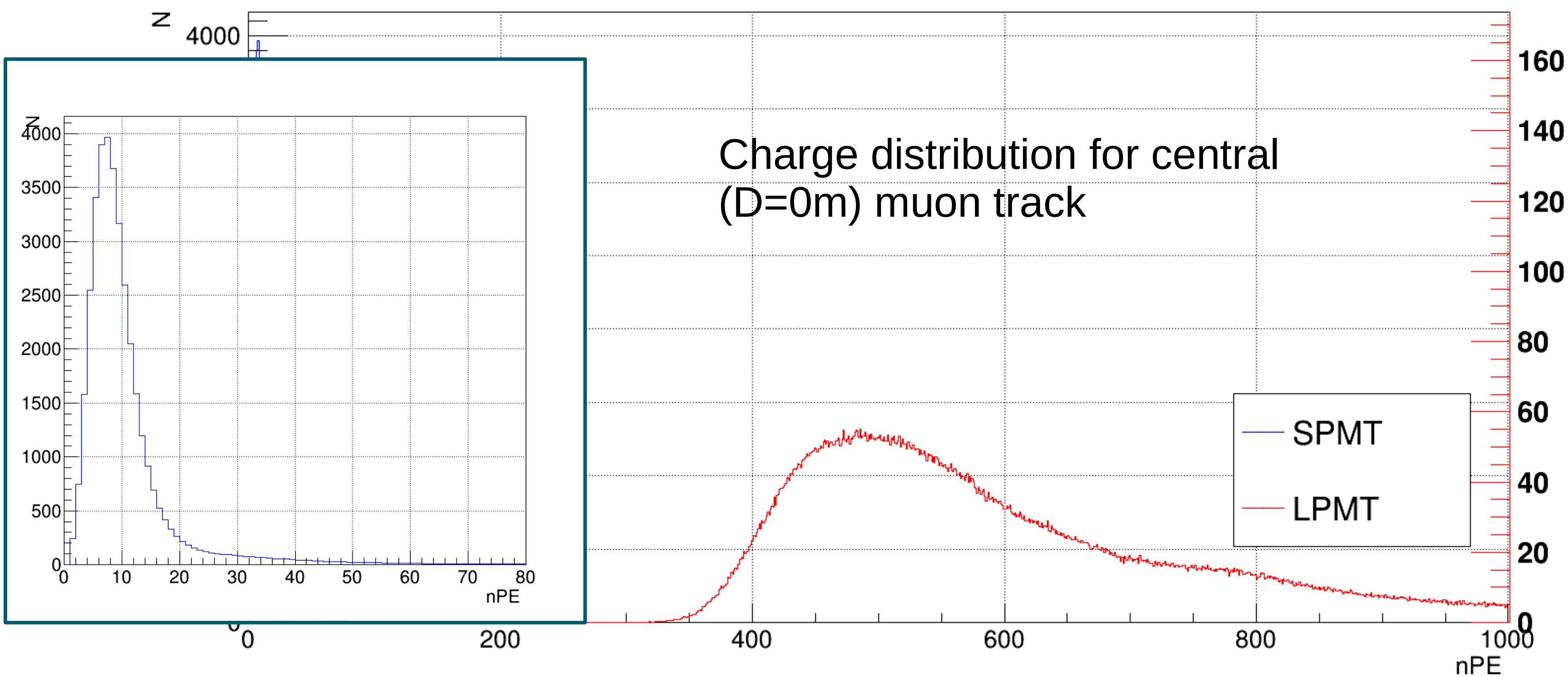
BACKUP

Small PMTs
A complementary subsystem

- ***3inch PMTs*** between the large 20inch PMTs are designed to be an aiding, complementary system → independent system to quantify systematics in LPMT measurement
- Collect much less light → lower dynamic range needed
- Available with better timing (TTS between 2.5ns and 1.0ns)



Small PMTs
Performance of the complementary system

- 25k SPMT with sigma = 1.5 ns time resolution
- Smeared hit times with gaus, no elecsim available
- Bias in increases less than with LPMT only, but larger spread around mean and in opposite direction
- Angular resolution very good (<1°) in largest part of the detector