# Track Reconstruction in the Spherical Proportional Counter

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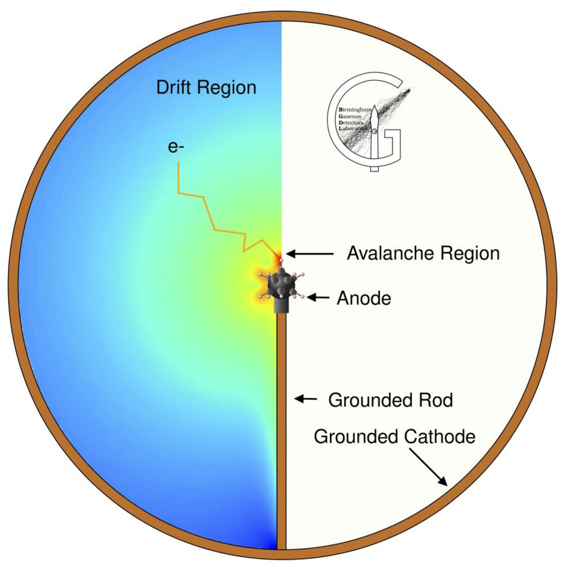
## Spherical Proportional Counters



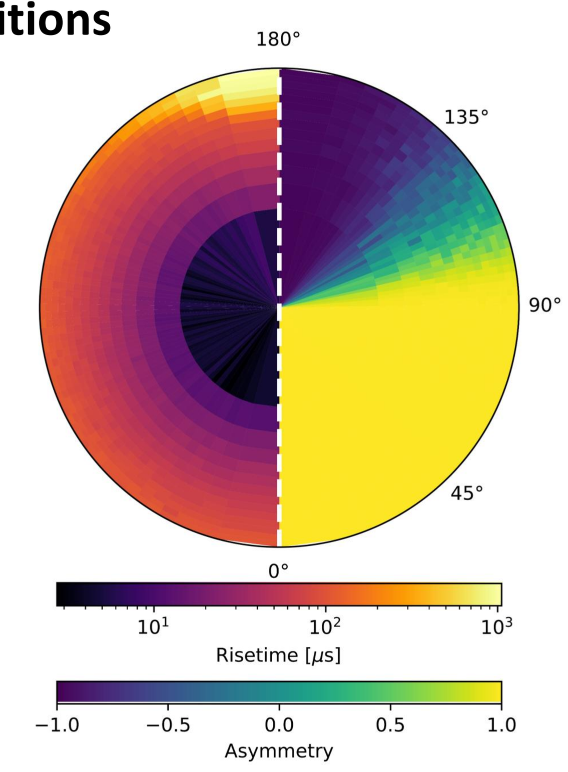

- The Spherical Proportional Counter (SPC) [1,2] is a simple and robust gaseous detector, suited to applications from fast neutron spectroscopy [3] to direct dark matter searches [4,5]
- For larger volumes and pressures, the ACHINOS multi-anode sensor was developed [6,7], decoupling the drift and avalanche fields
- Recent ACHINOS sensors allow individual anode read out [8]

### Sensitivity to Point-Like Interaction Positions

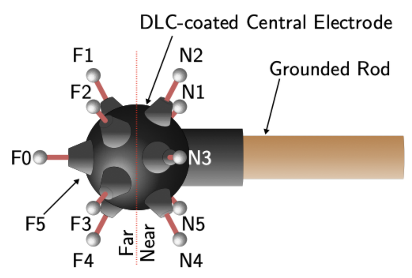
**Radius ($r$):** Pulse risetime is related to initial interaction radius via electron diffusion in the gas

**Zenith ($\cos\theta$):** Asymmetry of pulse between 'near' and 'far' anodes

**Azimuth ($\phi$):** Localisation of pulse on specific anodes




- Applies to interactions such as nuclear and electron recoil
- Aim is to expand further and reconstruct full ionisation tracks, such as from muons, exploiting individual anode readout signals and machine learning techniques
- Simulate SPC response with a combined GEANT4 and Garfield++ framework [9]:
  - Configuration: Ø30 cm SPC containing 500 mbar $Ar:CH_4$ (98%:2%) and 11-anode individual readout ACHINOS with Ø1 mm anodes biased at 1300V
  - Interactions: muons passing through the SPC uniformly distributed in position and direction, with an energy distribution following cosmic-ray muons



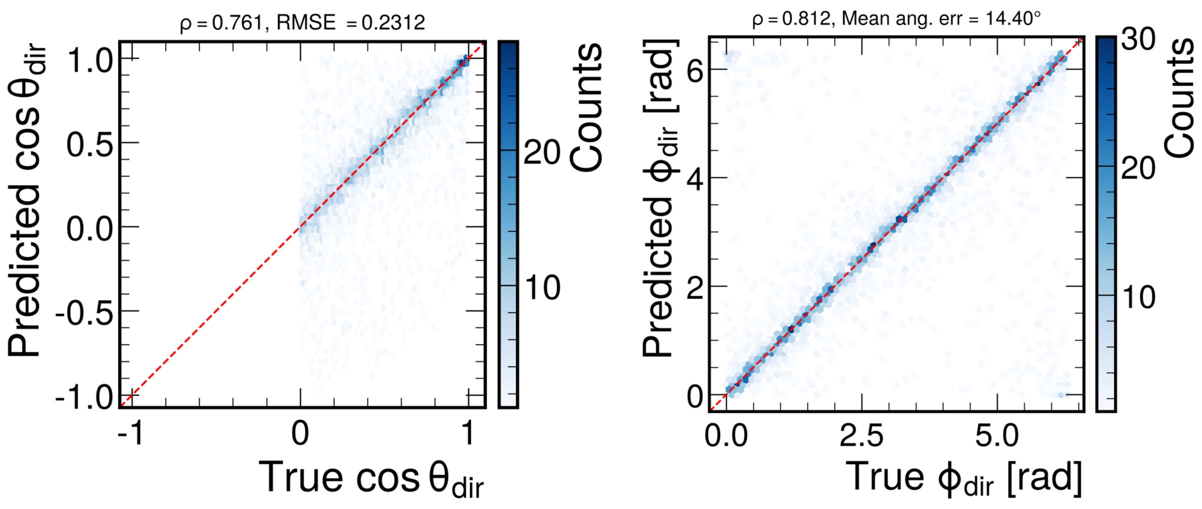

## Model Performance with $T_0$

- For externally triggered SPCs the $T_0$ of the event is known: the time at which initial ionisation occurred
- Current model reconstructs the position of closest approach within ~1.5 cm and muon axis within ~7°

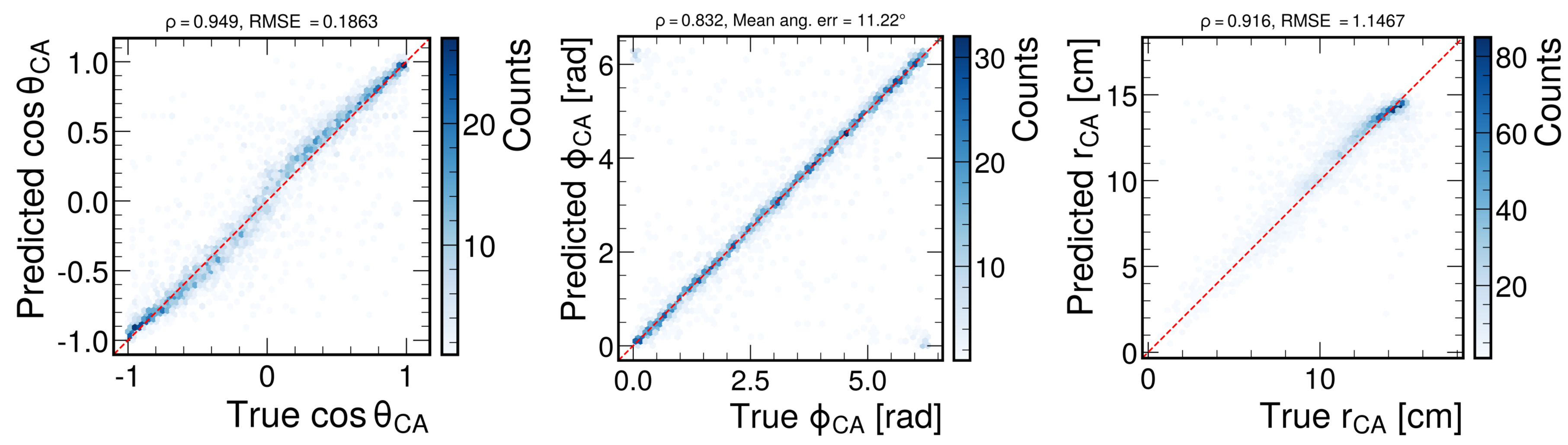
### Metrics

| Parameter | Bias | Resolution |
|---|---|---|
| $r_{CA}$ [cm] | $0.16 \pm 0.02$ | $1.14 \pm 0.05$ |
| $\cos\theta_{CA}$ | $0.012 \pm 0.003$ | $0.186 \pm 0.006$ |
| $\phi_{CA}$ [°] | $-0.2 \pm 0.4$ | $4.85 \pm 0.09$ |
| $\cos\theta_{dir}$ | $-0.008 \pm 0.004$ | $0.094 \pm 0.002$ |
| $\phi_{dir}$ [°] | $-0.3 \pm 0.5$ | $10.1 \pm 0.2$ |

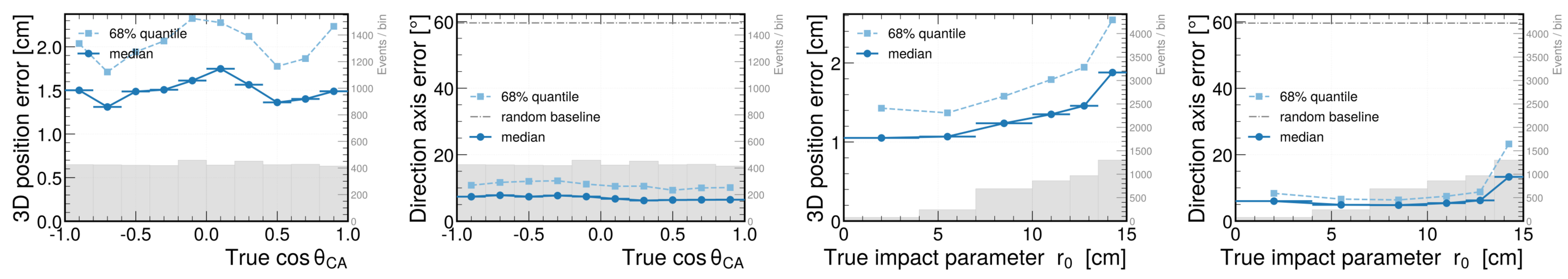
### Direction Reconstruction




### Closest Approach Position Reconstruction

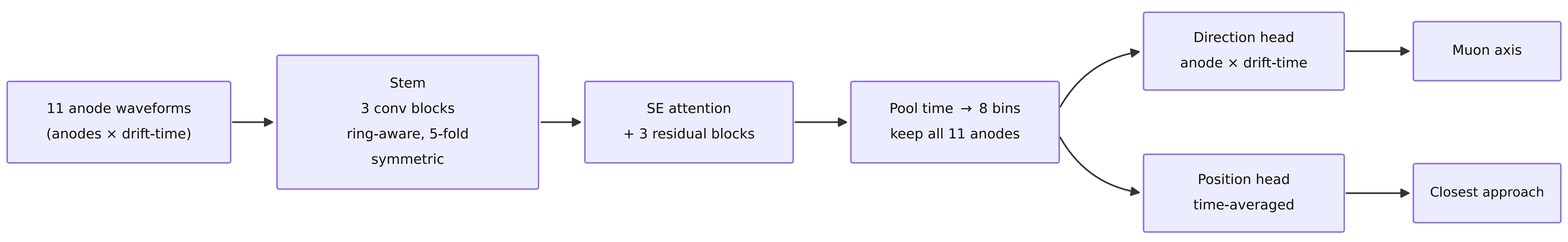



### Performance versus Closest Approach



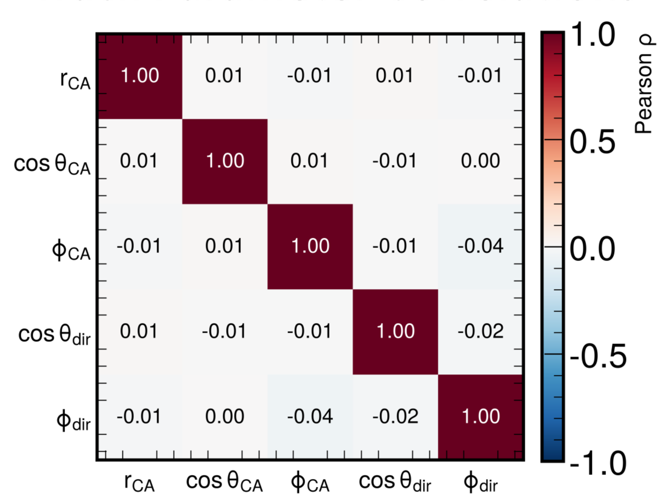

## Design of the Convolutional Neural Network

- Input: 11 anode waveforms of an event as 2D image (anodes × drift-time) accounting for readout electronics
  - Use 5-fold symmetry in $\phi$ to maximise statistics
- Convolutional neural network (CNN) with anode ring-structure-aware convolutions
  - Two separate regression heads for direction (full anode × time) vs. position (time-averaged)
  - Squeeze-Excite attention: reweights channels by importance
  - Pool to 8 drift-time bins per anode, always keep full 11 anode information

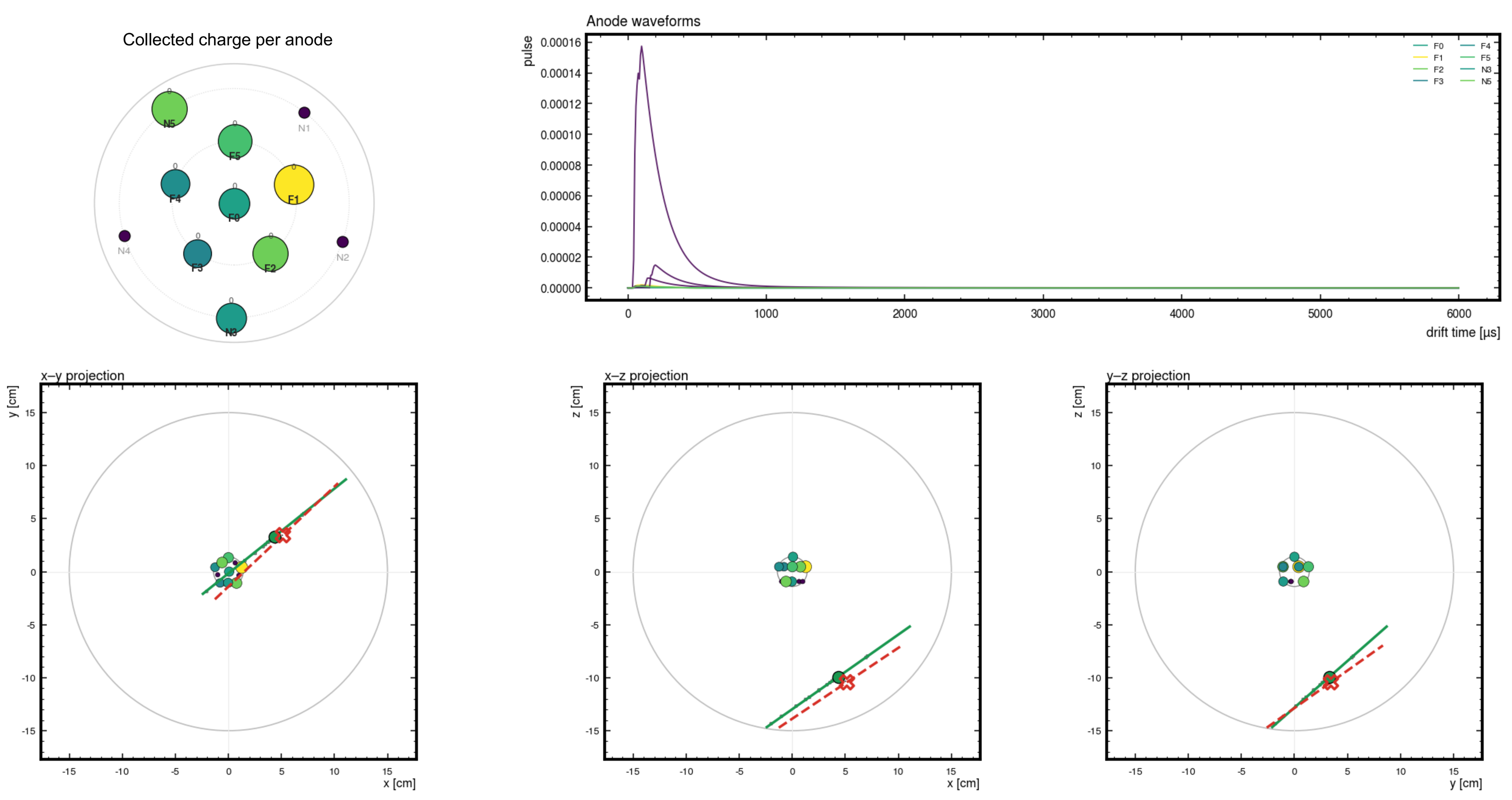



- Output: 5 parameters describing muon track
  - Muon closest approach point ($r_{CA}, \cos\theta_{CA}, \phi_{CA}$)
  - Muon axis ($\cos\theta_{dir}, \phi_{dir}$), assuming straight trajectory
- The SPC is insensitive to the orientation of the muon axis ($\boldsymbol{d} \equiv -\boldsymbol{d}$), so the CNN predicts the nematic tensor: $Q = \boldsymbol{d}\boldsymbol{d}^{\mathrm{T}} - \frac{1}{3}I$
  - Reconstructed axis is the leading eigenvector of $Q$
  - Eigenvalue separation of $Q$ gives per-event confidence estimate

### Track Parameter Correlations



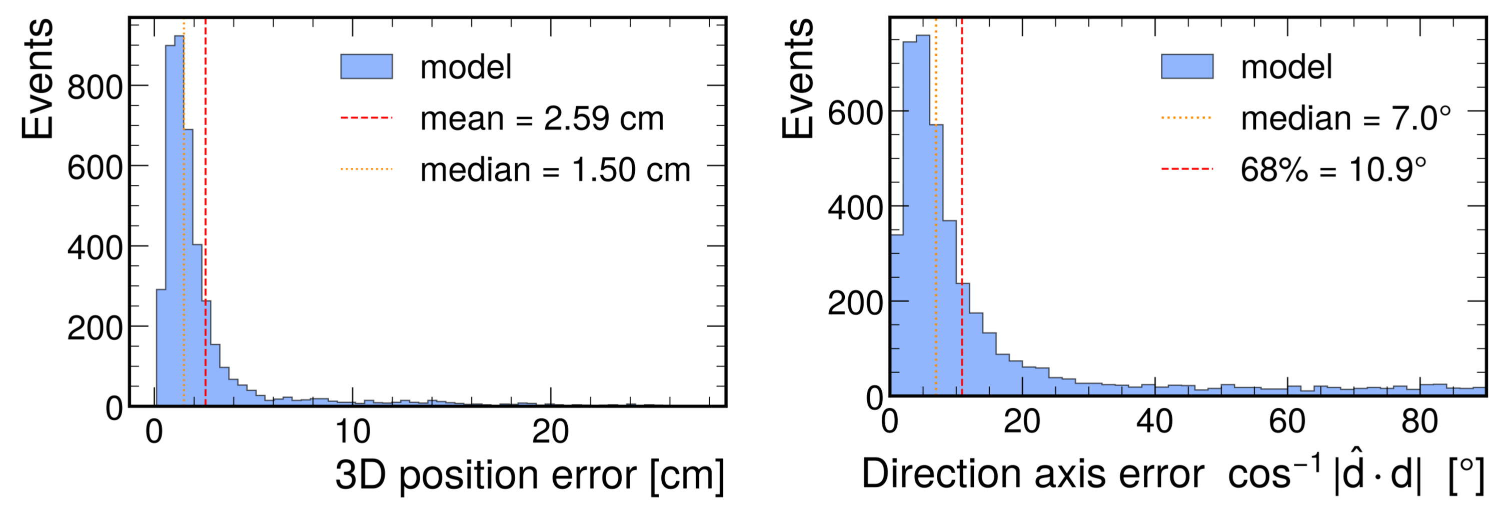

### Event Visualisation



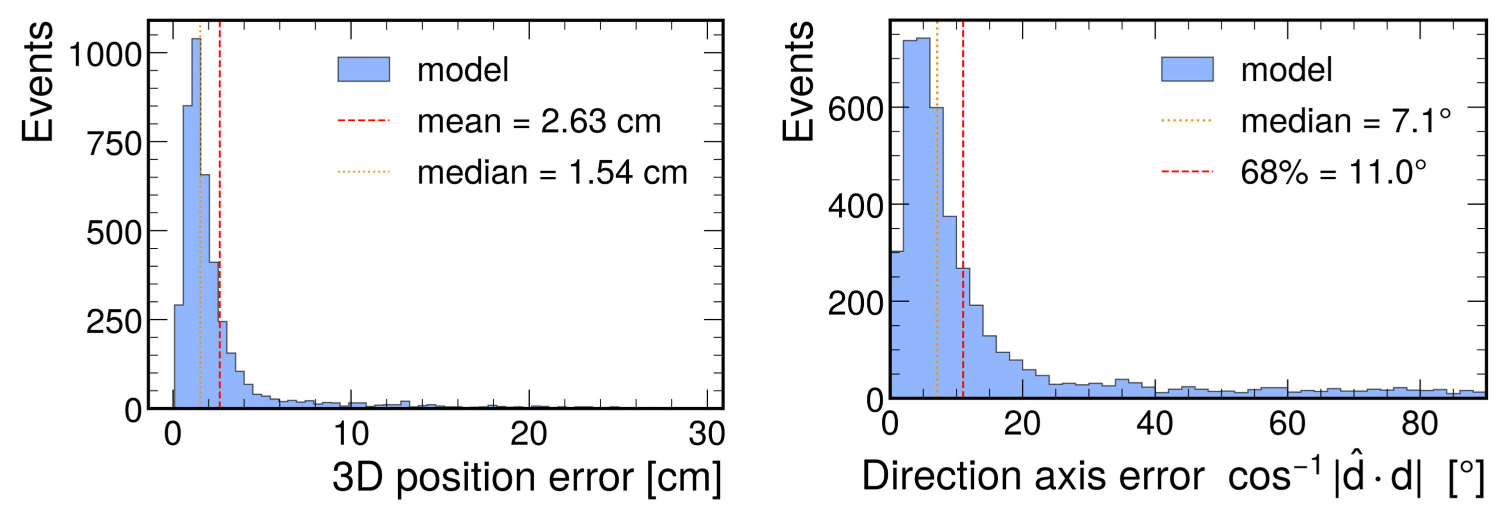

## Model Performance without $T_0$

- $T_0$ is not directly available in self-triggering SPCs, only the start time of the pulse, after electrons have already arrived at the avalanche region
- Remove knowledge of $T_0$ from the CNN by applying a uniformly distributed time shift up to 1 ms to the signals in each event
- Reconstruction of $r_{CA}$ degrades; similar performance for the other track parameters

### With $T_0$




### Without $T_0$




## Summary

- Designed a CNN architecture to reconstruct ionisation tracks in the SPC
- Model performs well in simulation for the 11-anode individual readout ACHINOS, both with and without knowledge of $T_0$

***References***

[1] I. Giomataris et al., *A novel large-volume Spherical Detector with Proportional Amplification read-out*, JINST 3 (2008) P09007

[2] I. Katsioulas et al., *A sparkless resistive glass correction electrode for the spherical proportional counter*, JINST 13 (2018) P11006

[3] I. Giomataris et al., *Neutron spectroscopy with a high-pressure nitrogen-filled spherical proportional counter*, Nucl. Instrum. Meth. A 1049 (2023) 168124

[4] Q. Arnaud et al. (NEWS-G), *First results from the NEWS-G direct dark matter search experiment at the LSM*, Astropart. Phys. 97 (2018) 54

[5] NEWS-G collaboration, *Solar Kaluza-Klein axion search with NEWS-G*, Phys. Rev. D 105 (2022) 012002

[6] A. Giganon et al., *A multiball read-out for the spherical proportional counter*, JINST 12 (2017) P12031

[7] I. Giomataris et al., *A resistive ACHINOS multi-anode structure with DLC coating for spherical proportional counters*, JINST 15 (2020) P11023

[8] D. Herd et al., *First operation of an ACHINOS-equipped spherical proportional counter with individual anode read-out*, JINST 19 (2024) P01018

[9] I. Katsioulas et al., *Development of a simulation framework for spherical proportional counters*, JINST 15 (2020) C06013

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