Development of a Simulation Framework for Spherical Proportional Counters

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25th June 2020

UNIVERSITY OF BIRMINGHAM

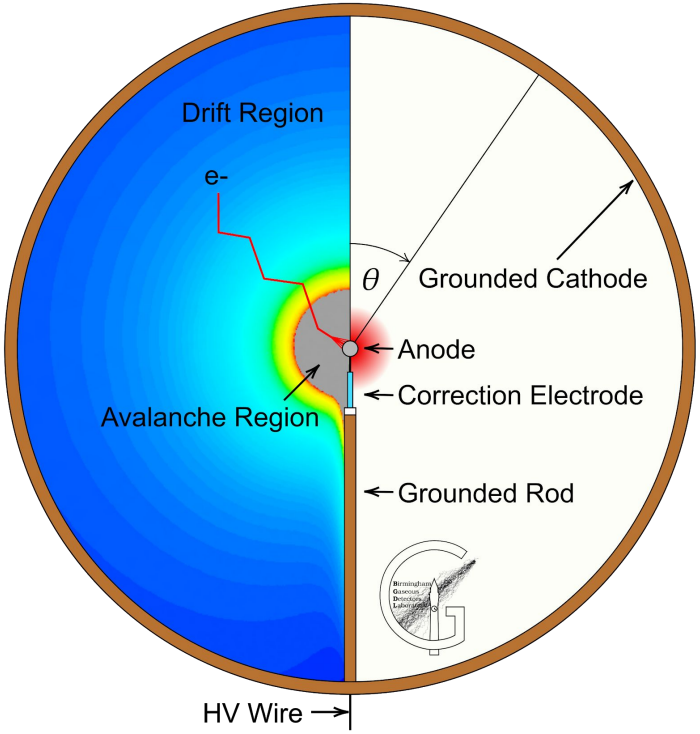
Birmingham Gaseous Detectors Laboratory

Introduction to Spherical Proportional Counters

The Spherical Proportional Counter (2008 JINST 3 P09007) is a novel gaseous detector with a range of applications

- Direct low-mass dark matter detection (NEWS-G): Astropart. Phys. 97 (2018) 54
- Neutrinoless double beta-decay (R2D2): 2018 JINST 13 P01009
- Neutron, alpha and gamma ray spectroscopy: Nucl. Instrum. Meth. A 847 (2017) 10
- Low energy neutrino physics : Nucl. Instrum. Meth. A 530 (2004) 330 Phys. Lett. B 634 (2006) 23 Phys. Rev. D 79 (2009) 113001

Review of spherical proportional counters: J. Phys. Conf. Ser. 1029 (2018) 012006



Principle of operation

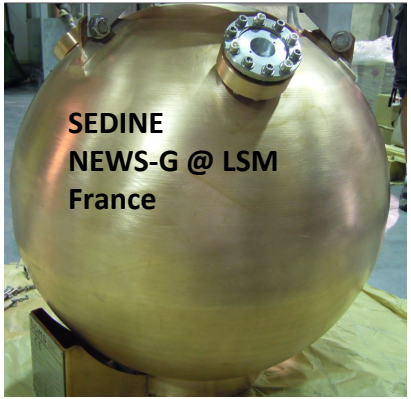
Why Spherical Proportional Counters?

Advantages of spherical shape:

- Low capacitance independent of detector size
- High pressure operation
- Maximum volume-to-surface ratio

Additional benefits:

- Simple and robust design
- Flexibility of gas mixtures
- Determination of interaction properties from pulse-shape analysis



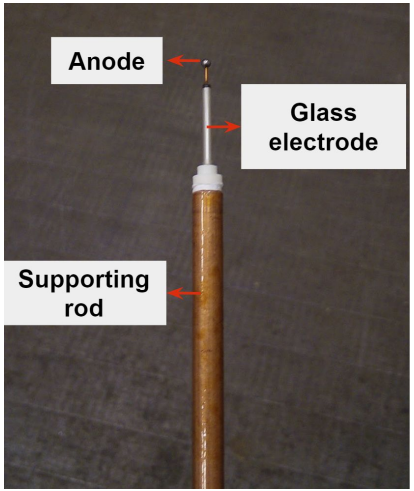
Single-Anode Sensor

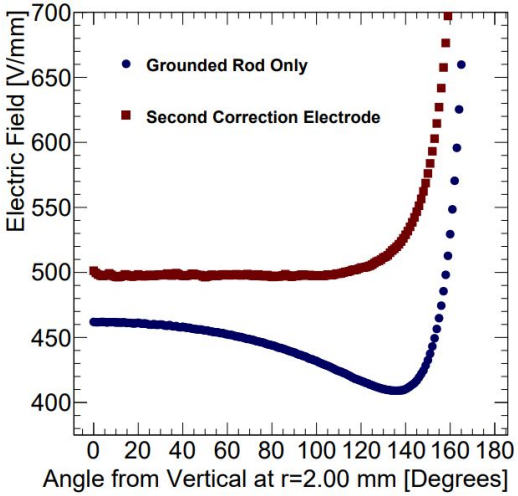
Single anode at centre of detector, supported by grounded rod

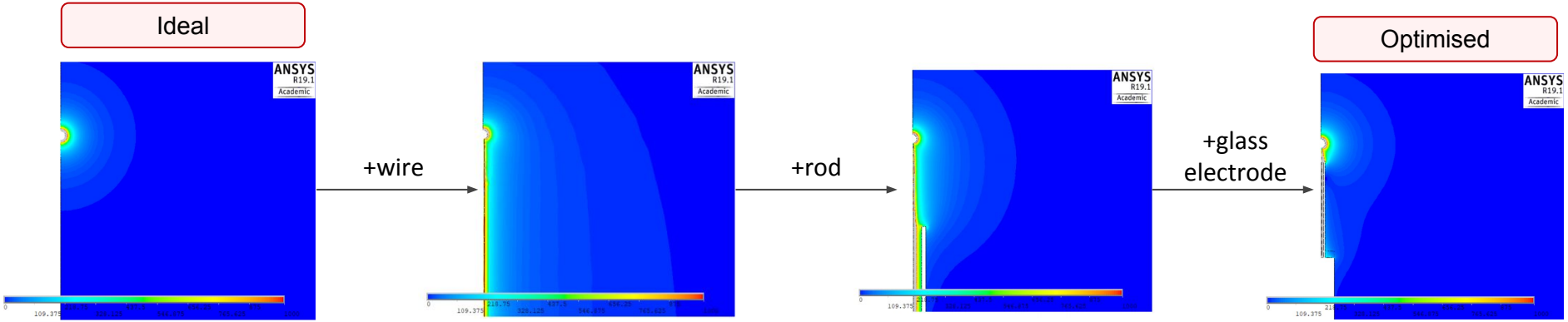
- Radial electric field $\propto 1/r^2$
- Single readout channel

Use a correction electrode to reduce distortion of the electric field by the wire and rod

- Sensor optimisation is a focus of development: [2018 JINST 13 P11006]







Multi-Anode Sensor: ACHINOS

Operation of large and high pressure detectors are a challenge with the single-anode

- Electric field in drift and avalanche regions are linked

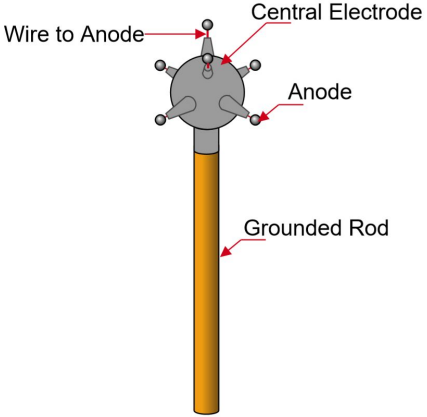
ACHINOS - Multiple anodes, placed at equal distances:
2017 JINST **12** P12031

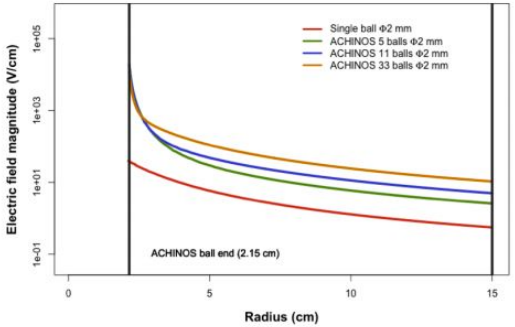
- Gain influenced by individual anode sizes
- Large-radius electric field determined by collective field of all anodes

Drift and avalanche electric fields are decoupled

Also enables individual anode read-out

- Position information of interactions





Simulation Software

Simulations are crucial for detector development

- Began development of a purely Garfield++ simulation Summer 2018
- Soon after integrated this into a Geant4 application

Use several software toolkits:

- Geant4 for the simulation of primary ionisation
- Garfield++ for the simulation of electron-ion drift and signal calculation, interfacing:
  - Heed to aid in simulating primary particle interactions
  - ANSYS, a finite-element-method software, to model the electric field
  - Magboltz to model electron transport parameters in gas mixtures

Approach was inspired by recent developments:
[Nucl. Instrum. Meth. A 935 (2019) 121]

Development of a simulation framework for spherical proportional counters

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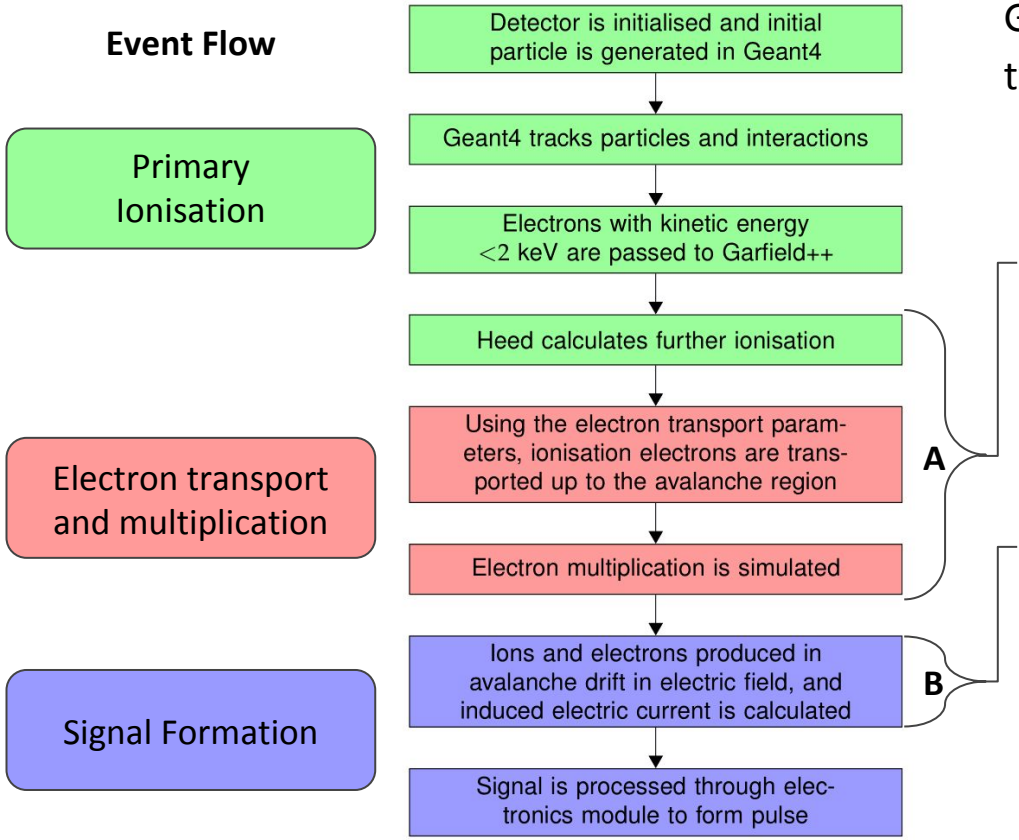
Abstract: The spherical proportional counter is a novel gaseous detector with numerous applications, including direct dark matter searches and neutron spectroscopy. The strengths of the Geant4 and Garfield++ toolkits are combined to create a simulation framework for spherical proportional counters. The interface is implemented by introducing Garfield++ classes within a Geant4 application. Simulated muon, electron, and photon signals are presented, and the effects of gas mixture composition and anode support structure on detector response are discussed.

Simulation framework discussed today:
2020 *JINST* **15** C06013

Simulation Framework: Overview



Geant4 application which interfaces Garfield++ in two stages:

A: Primary ionisation, and electron transport and multiplication

- Implemented a custom model using Geant4 physics parameterisation

B: Signal formation

- end-of-event-action method enhanced with Garfield++ functionality

Pass information from **A** to **B** using Geant4 sensitive detectors

Simulation Framework: Primary Ionisation

Event Flow

Primary Ionisation

Electron transport and multiplication

Signal Formation

Detector is initialised and initial particle is generated in Geant4

↓

Geant4 tracks particles and interactions

↓

Electrons with kinetic energy <2 keV are passed to Garfield++

↓

Heed calculates further ionisation

↓

Using the electron transport parameters, ionisation electrons are transported up to the avalanche region

↓

Electron multiplication is simulated

↓

Ions and electrons produced in avalanche drift in electric field, and induced electric current is calculated

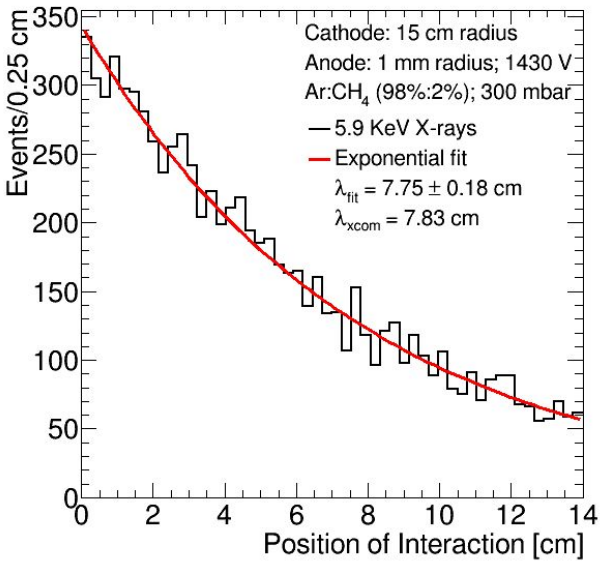
↓

Signal is processed through electronics module to form pulse

Ions handled by SRIM - Recently Added

Example: 5.9 keV X-rays from decay of ^{55}Fe

- Attenuation length in agreement with XCOM



Simulation Framework: Electron Transport and Multiplication

Event Flow

Primary Ionisation

Electron transport and multiplication

Signal Formation

Detector is initialised and initial particle is generated in Geant4

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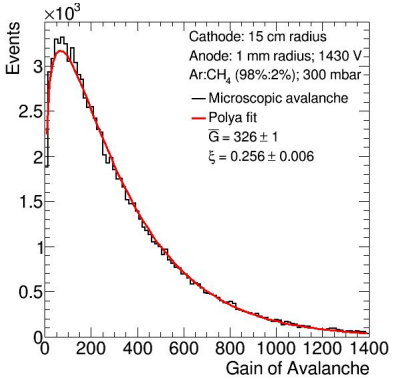
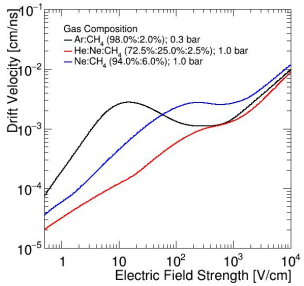
Drift of ionisation electrons:

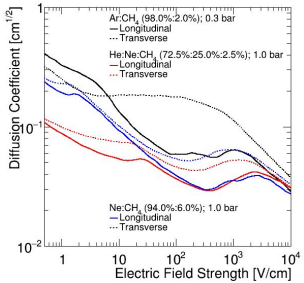
- Garfield++ Monte Carlo drift line method
- ANSYS electric field maps
- Magboltz electron transport parameters

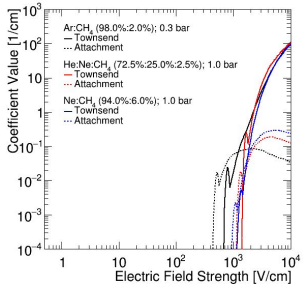
Electron multiplication:

- Garfield++ microscopic avalanche or our custom avalanche method









Simulation Framework: Signal Formation

Event Flow

Primary Ionisation

Electron transport and multiplication

Signal Formation

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Ions and electrons produced in avalanche drift in electric field, and induced electric current is calculated

↓

Signal is processed through electronics module to form pulse

Following multiplication, electron-ion pairs are transported using the Garfield++ drift line RKF method

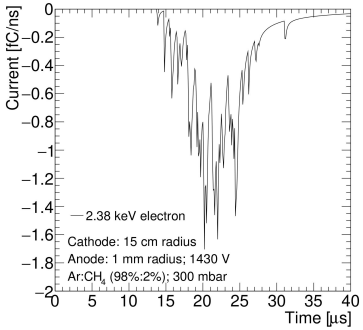
Calculate induced signal with Garfield++ sensor objects

- Shockley-Ramo theorem

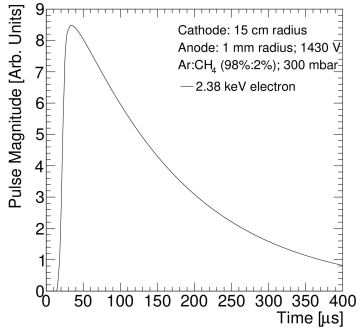
Calculate readout pulse in custom electronics module

- Applies transfer function to induced current via a fast Fourier transform

Example: simple charge sensitive amplifier with 140μs time constant



Transfer function →



Simulation Framework: Custom Electron Multiplication

Microscopic tracking models multiplication down to individual electron-atom collisions

- Most precise method, but costly to compute

Electron multiplication follows a Polya distribution:

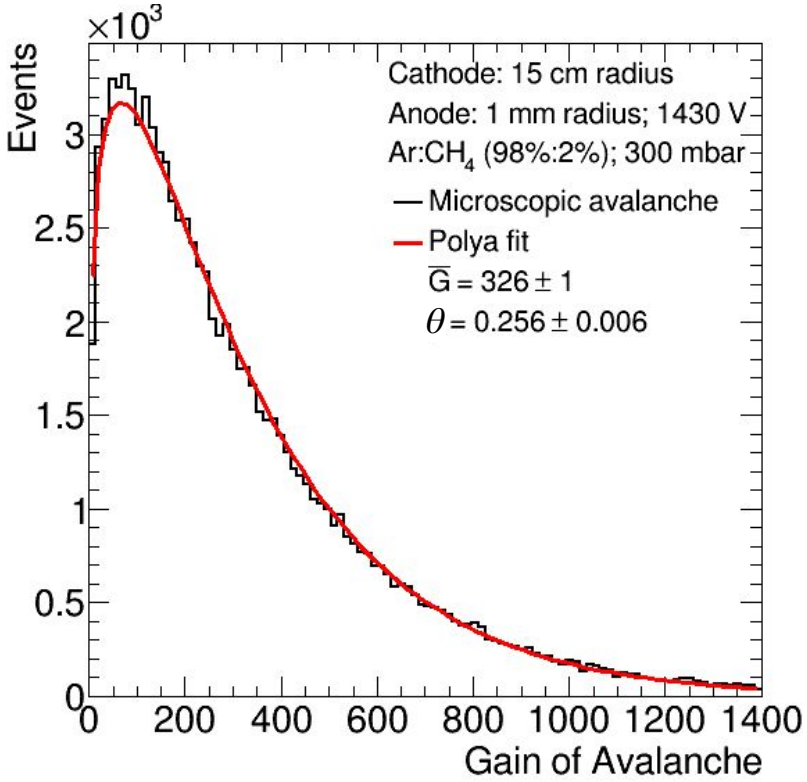
$$P\left(\frac{G}{\bar{G}}\right) = \left((1+\theta)\frac{G}{\bar{G}}\right)^{\theta} \exp\left[-(1+\theta)\frac{G}{\bar{G}}\right]$$

Parameterise gain in custom method:

- Numerically integrate effective townsend co-efficient to get $\bar{G}$

$$\bar{G} = \exp\left[\int_{\vec{r}} \left(\alpha(\mathbf{r}) - \eta(\mathbf{r})\right) d\vec{r}\right]$$

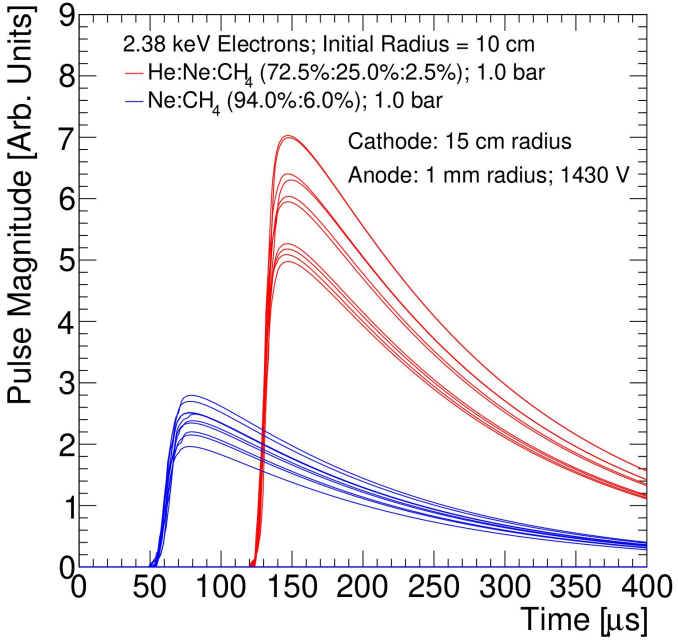
- Estimate θ using microscopic avalanche - approximately independent with position of avalanche



Application: Effect of Gas Mixture

Physics of simulation demonstrated by comparing gas mixtures:

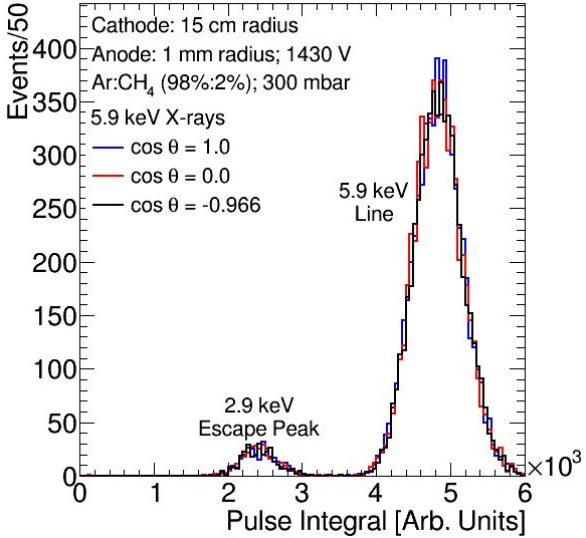
- Gain in He:Ne:CH_4 larger than that in Ne:CH_4, determined by Townsend and attachment coefficients
- Gain fluctuations shown by variation in pulse amplitude
- Differences in electron drift velocity determine start time of pulses



Application: Effect of the Anode Support Structure

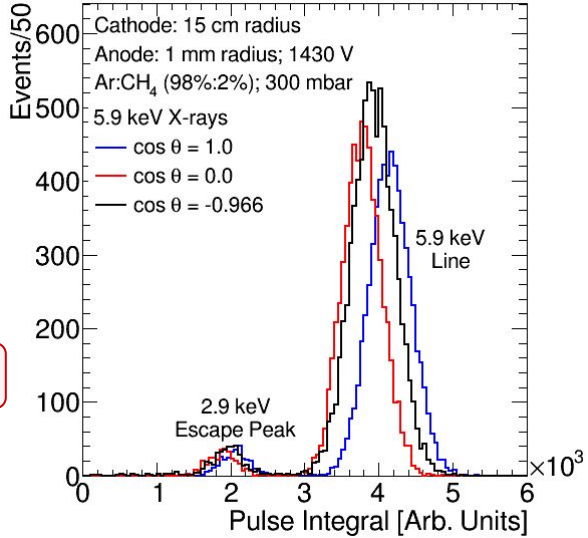
Use simulation to measure effect of anode support structure on detector response:

- Detect 5.9 keV line of ^{55}Fe and a 2.9 keV argon escape peak
- Response is homogenous with Θ for ideal electric field
- Response depends on Θ for single anode configuration



Ideal detector

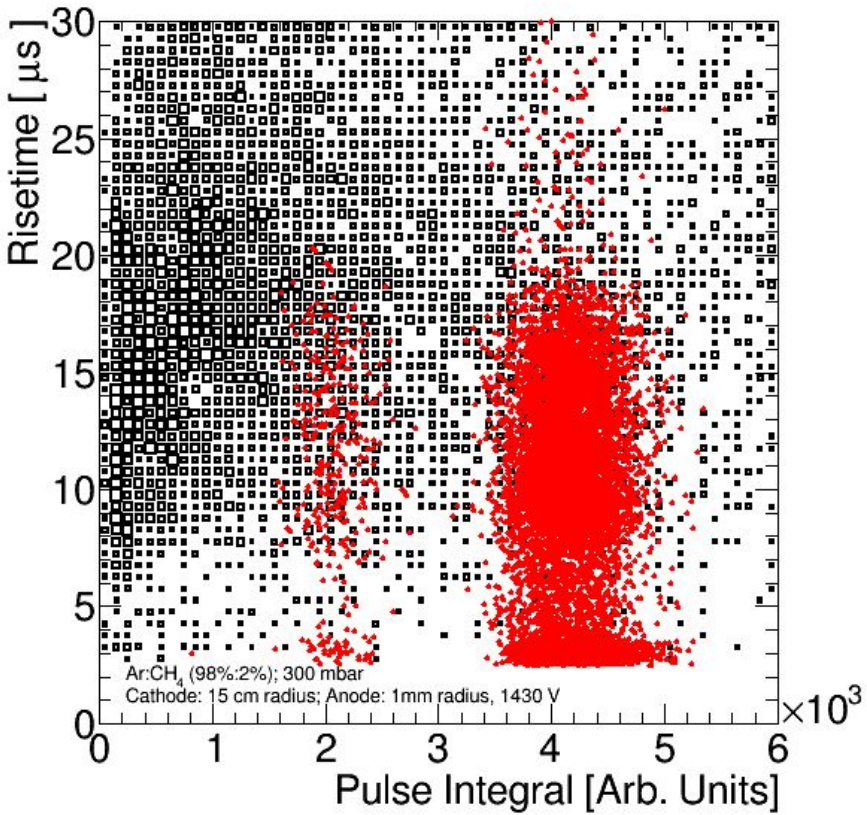
Single anode configuration



Application: Particle Identification

Simulation can be used for particle identification:

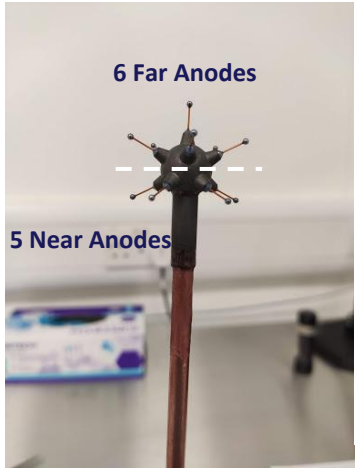
- Cosmic muons may mask interaction of ^{55}Fe X-rays
- Ionisation profiles are different - pulse-shape analysis informs selections to suppress backgrounds

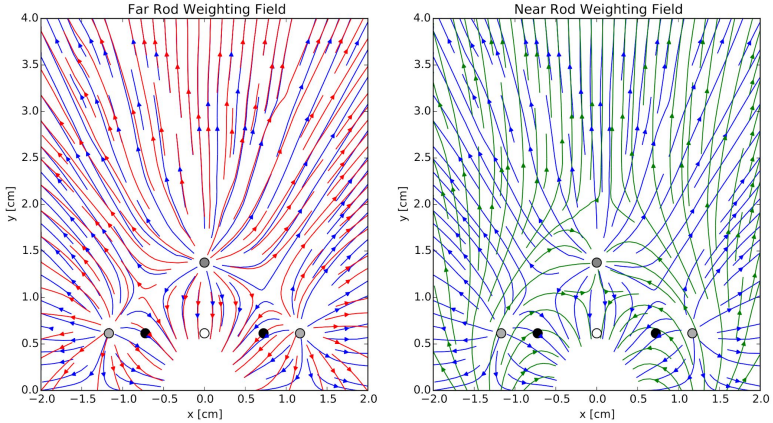


Application: ACHINOS Simulation

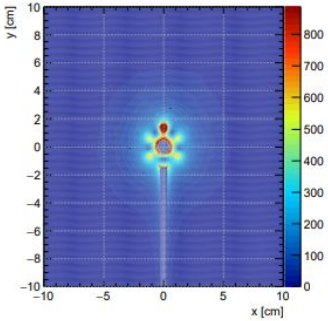
Developing ACHINOS simulation to have multiple read-outs

- Separate anodes into two hemispheres
  - 5 Anodes near the rod; 6 anodes far from rod
- Calculate two separate signals
  - One signal per hemisphere
- Calculate weighting fields with ANSYS

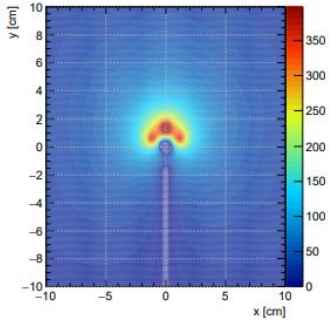




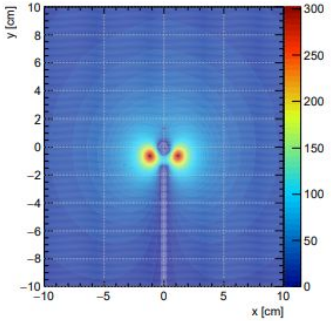
Blue: operational field lines



E-field magnitude



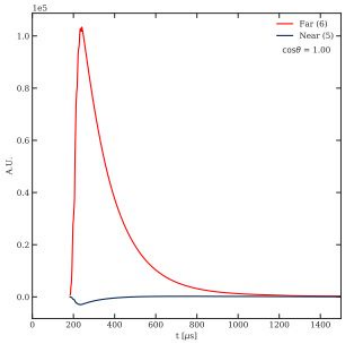
Far weighting field *V*



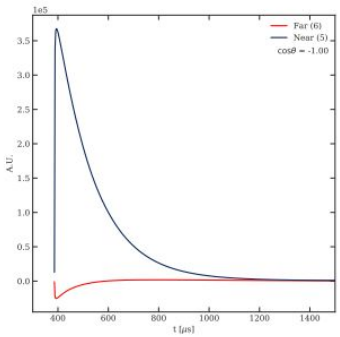
Near weighting field *V*

Application: ACHINOS Simulation

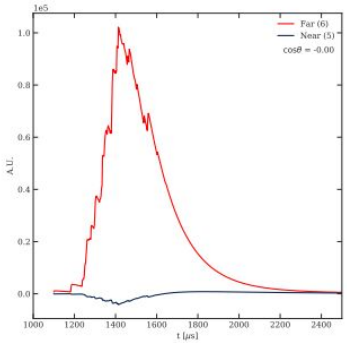
- Majority of pulse for events in hemisphere away from rod is formed on far anodes
  - Negative pulse on near anodes
- See opposite effect for events in hemisphere near bar
- Electrons produced from the side drift to far hemisphere
- Use asymmetry to discern which hemisphere the interaction occurred



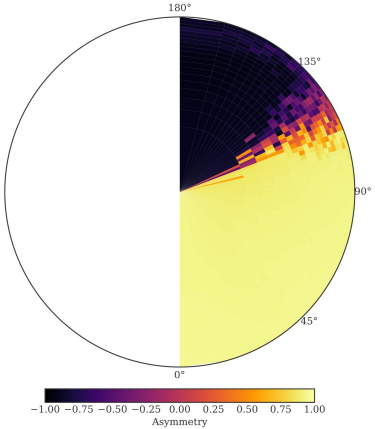
Interaction in far hemisphere



Interaction in near hemisphere



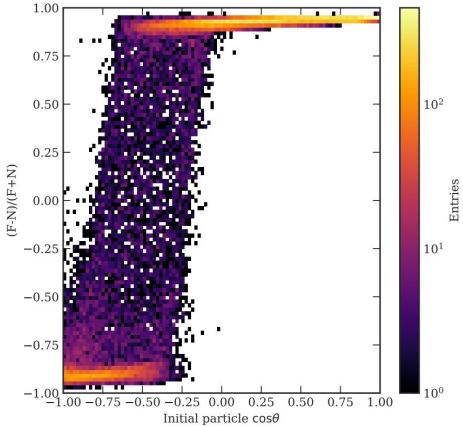
Interaction from side of detector



Pulse asymmetry:

$$A = (F - N)/(F + N)$$

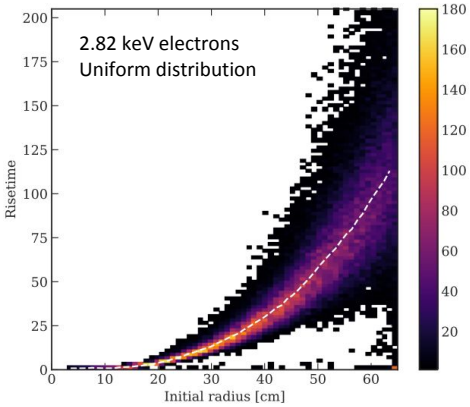
- F = amplitude of pulse on far anodes
- N = amplitude of pulse on near anodes

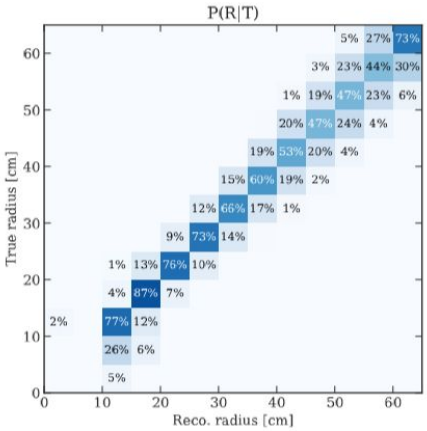


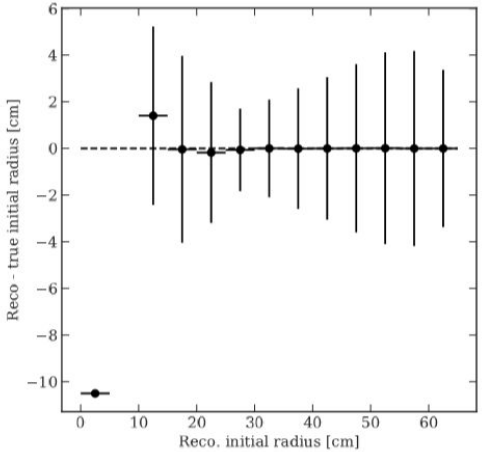
Application: Interaction Radius and Fiducialisation

Ionisation electrons produced in events at edge of detector drift longer than electrons near the centre:

- Using ACHINOS in single read-out mode, simulate 2.82 keV electrons from the decay of ^{37}Ar
- Events at large radii have increased rise-times (time for a pulse to go 10% to 90% of its amplitude)
- Use rise-time relationship to reconstruct interaction radius
- Majority of background for rare events searches originate at detector surface





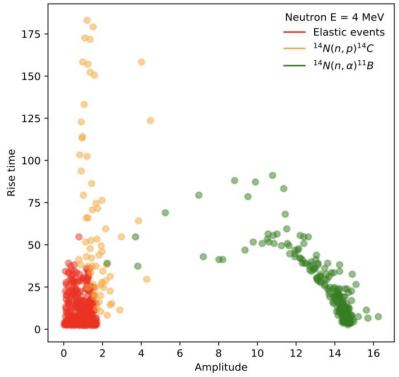


Application: Fast Neutron Spectroscopy

Neutron spectroscopy with Spherical Proportional Counter

- Use Nitrogen as gas
- $^{14}N+n \rightarrow {}^{14}C+p$ + 625 keV
- $^{14}N+n \rightarrow {}^{11}B+\alpha$ - 159 keV

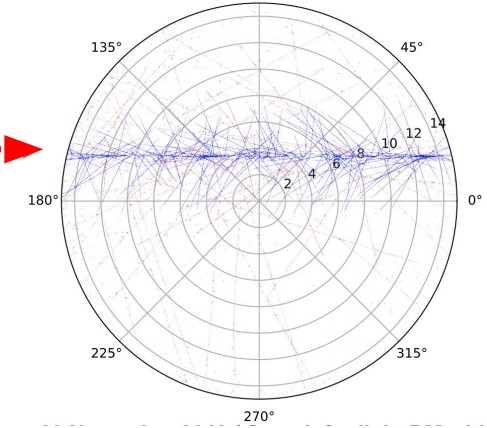
Simulation Parameters:
Ø vessel 30 cm
Nitrogen at 300 mbar
Anode Ø 2 mm

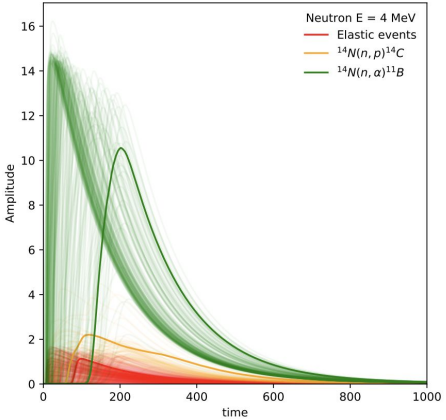


Pulse analysis

Neutron Beam

4 MeV

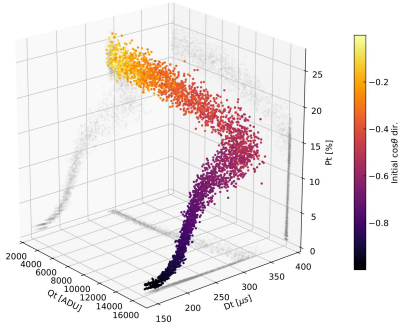


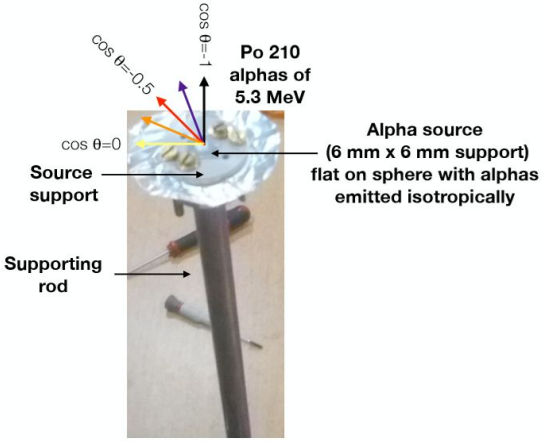


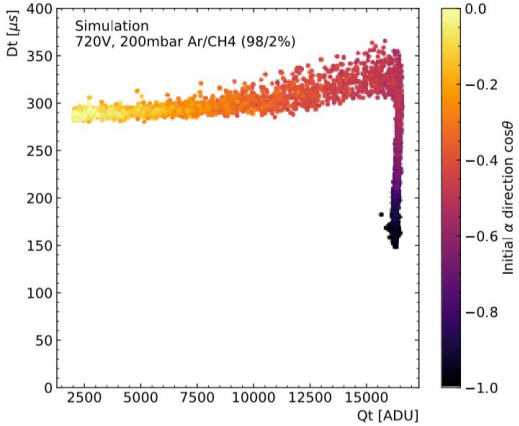
Application: R2D2 Collaboration

R2D2 (Rare Decays with Radial Detectors) collaboration (website):

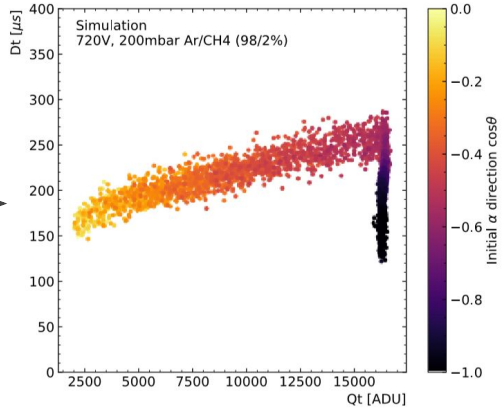
- R&D for $0\nu\beta\beta$ experiment with ^{136}Xe
- Validate detector using 5.3 MeV α-decays of ^{210}Po







Add noise



Conclusions

Developed a flexible and predictive framework for simulating spherical proportional counters

- Combines the strengths of Geant4 and Garfield++ toolkits
- Accelerates detector R&D, experimental design, and physics analysis
- Details in the recent publication: 2020 *JINST* **15** C06013

Next steps:

- Study in more detail the space charge effects
  - Preliminary studies already performed
- Apply simulation method to micropattern gaseous detectors
- Improve user interface to facilitate its wider use by the community

Thank you for the invitation to speak today - we look forward to giving updates in the future!