Direct Reactions studies with the AT-TPC

D. Bazin

Facility for Rare Isotope Beams

Michigan State University

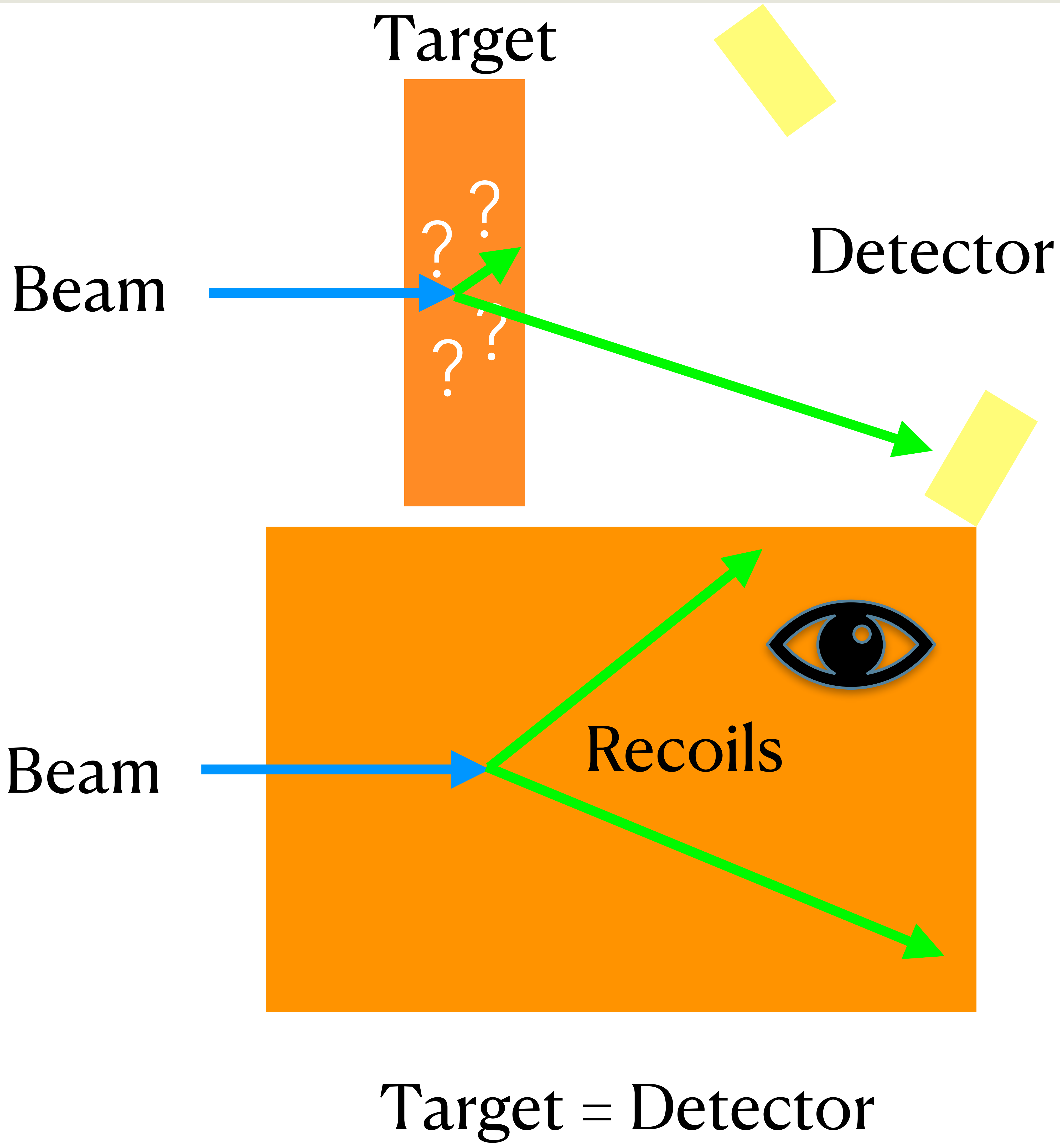
This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Outline

- Why Active Targets?
- Preliminary results from recent AT-TPC experiments
  - *0d$_{3/2}$ single-particle energy in ^{11}Be via the ^{10}Be(d,p)^{11}Be transfer reaction*
  - *Search for alpha cluster "Hoyle" state in ^{16}O via inelastic scattering on ^{4}He*
  - *Transmission mode at high energy: charge exchange (d,^{2}He) on ^{14}O*
- Outlook and gallery

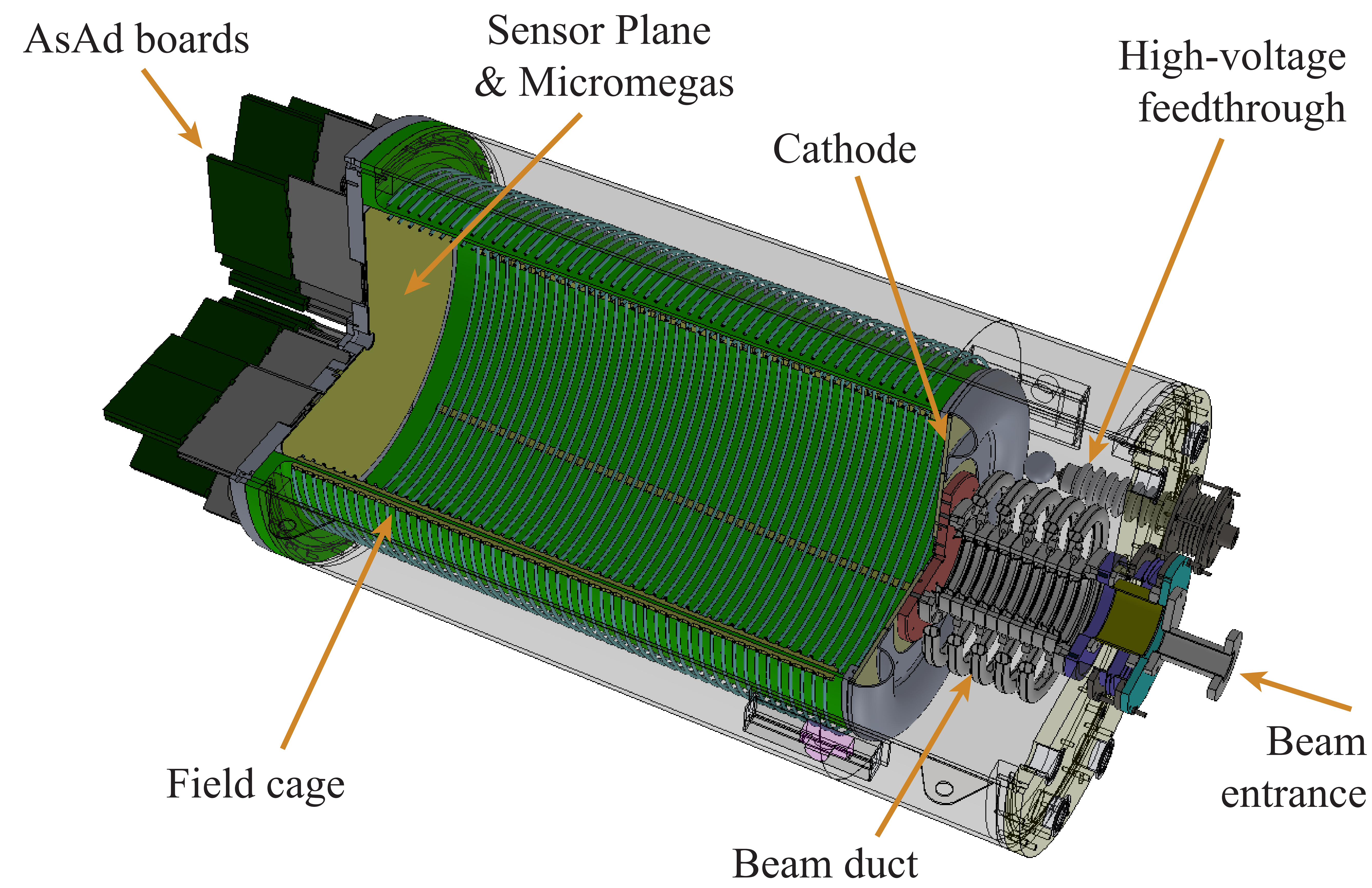
Why and when use an Active Target?

- Key experimental factors
  - *Any reaction with low energy recoils*
  - *High luminosity (3 orders of magnitude gain)*
    - *target thickness (2 orders of magnitude gain)*
    - *solid angle (1 order of magnitude gain)*
  - *No luminosity/resolution compromise*
    - *No "dead" layer of material for low energy recoils to emerge from reaction site*
    - *Vertex of reaction measured for each event, no kinematics broadening from large thickness*
    - *Resolution limited by straggling effects and track localization*

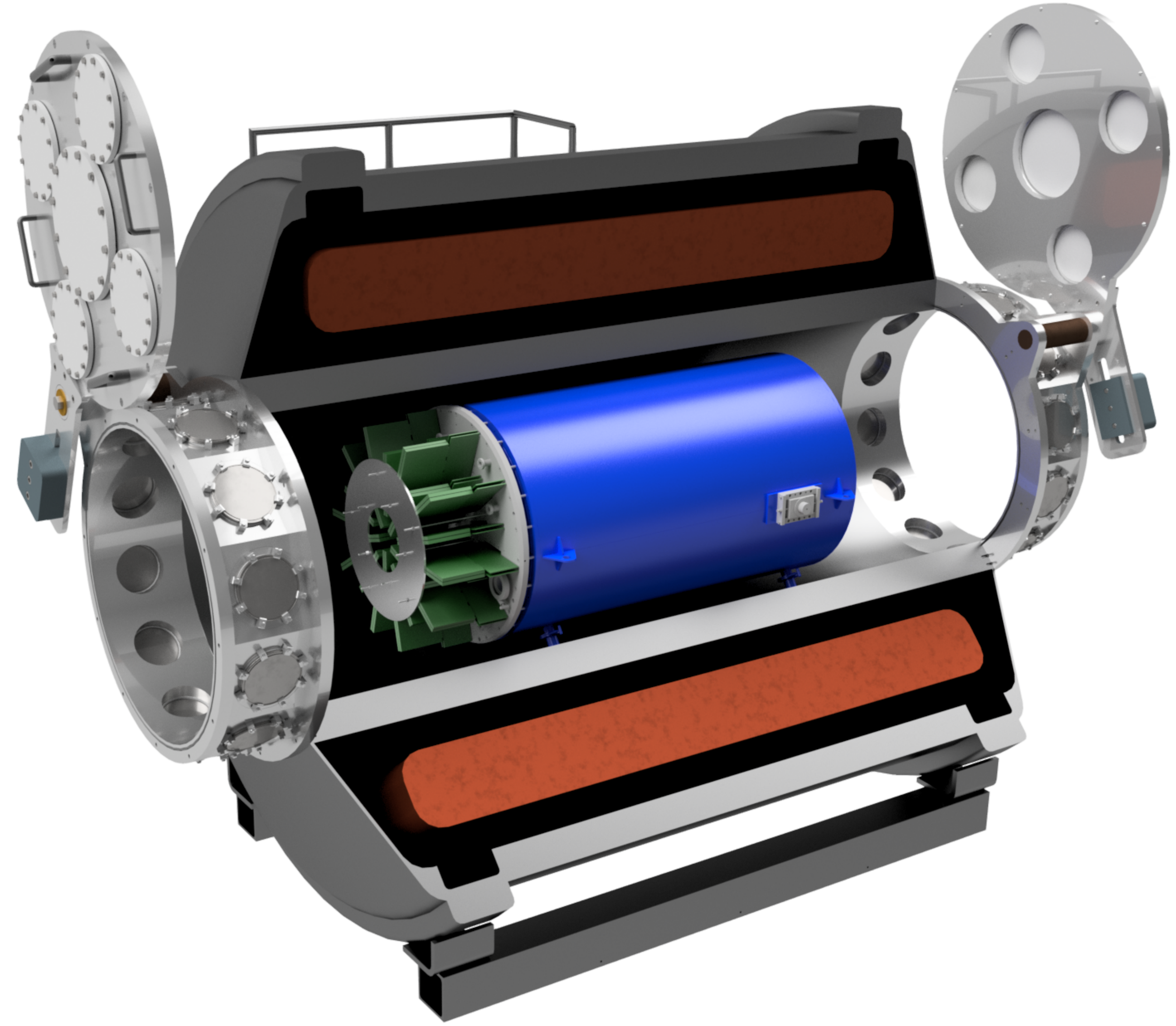


AT-TPC @ SOLARIS

Active Target Time Projection Chamber

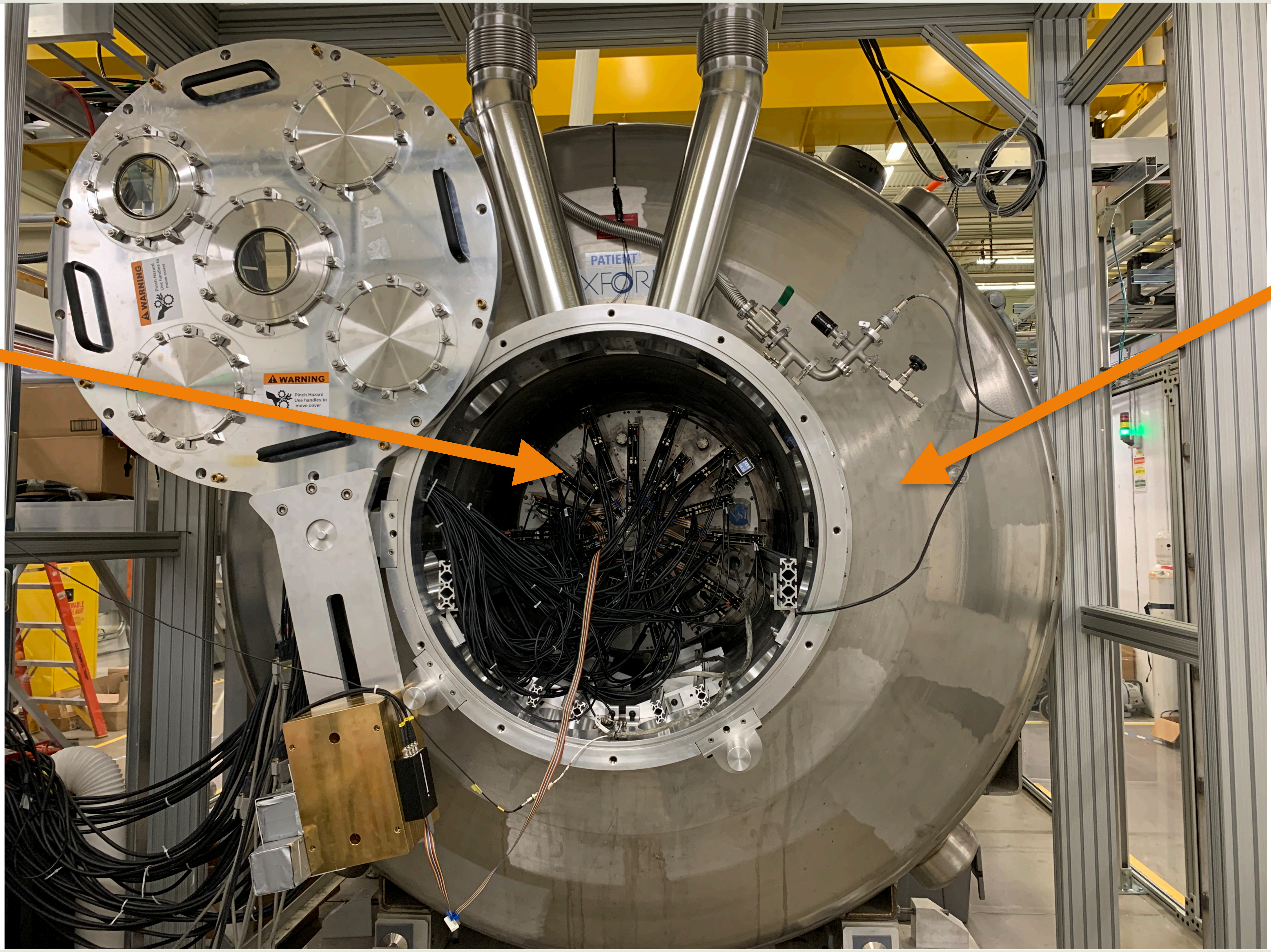


Solenoidal Spectrometer Apparatus for Reaction Studies



AT-TPC in SOLARIS

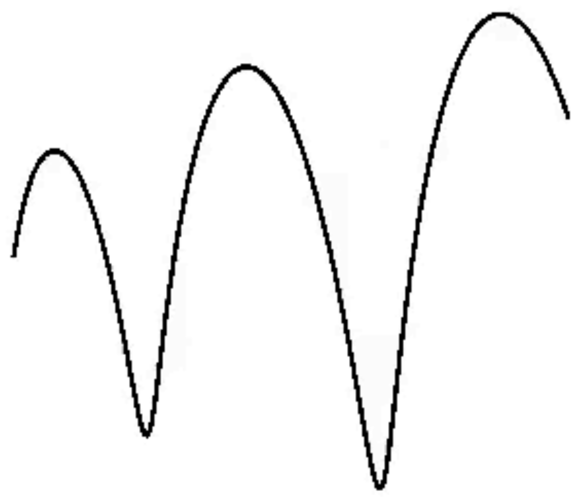
AT-TPC



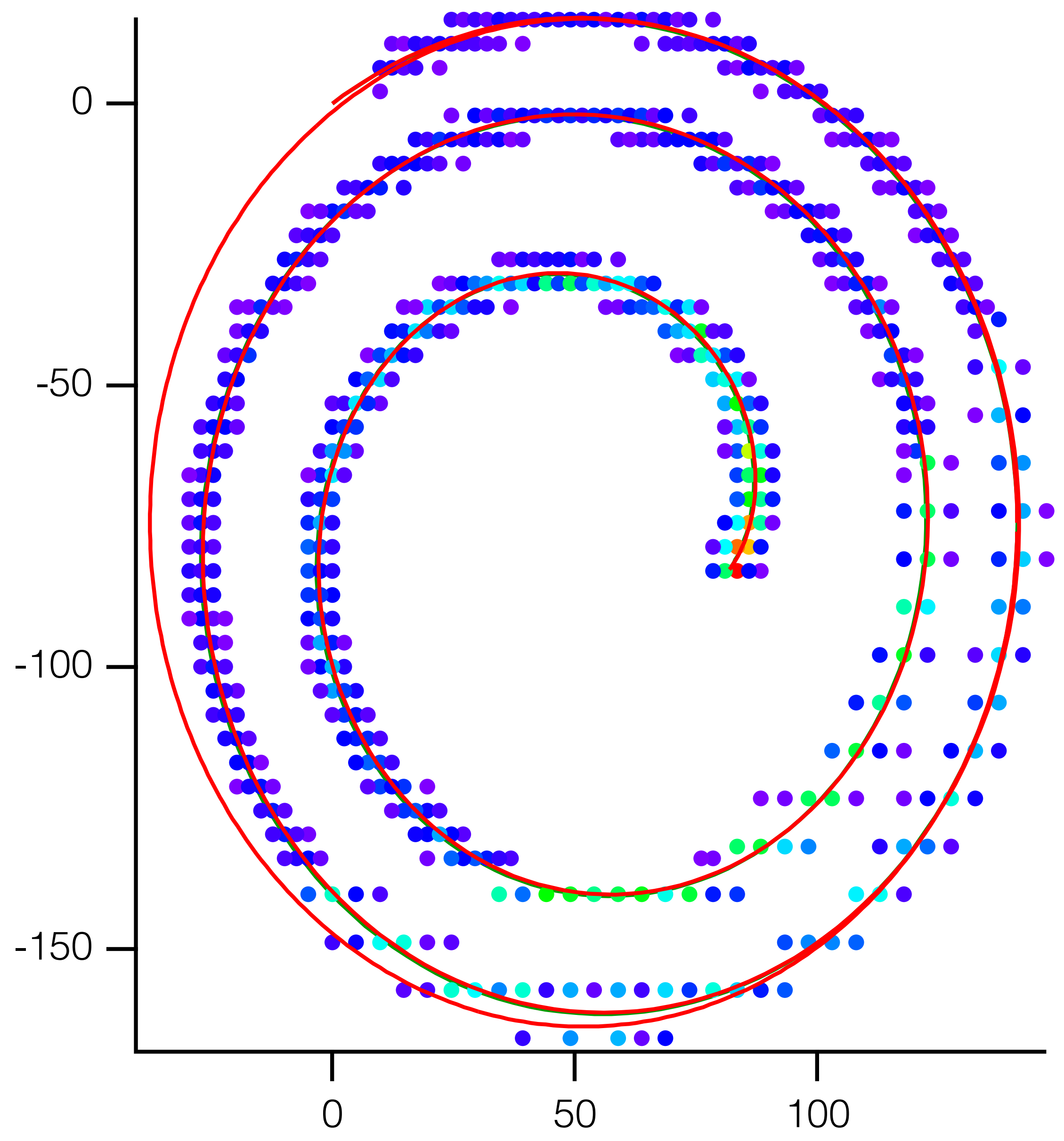
SOLARIS

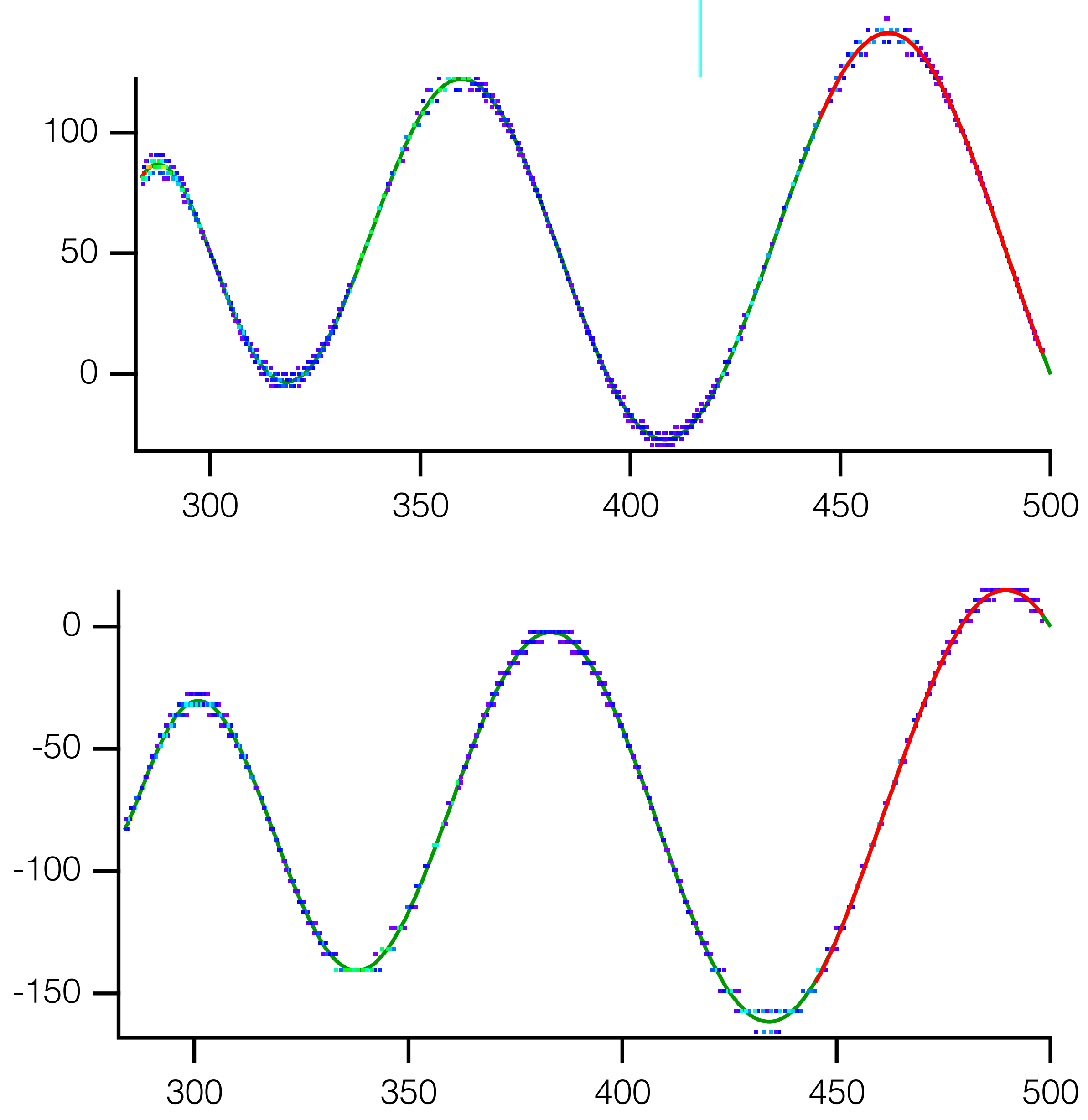
Three main challenges

- Trigger on events of interest
  - *Most "events" are beam slowing down in gas*
- Noise and electric field deformation
  - *Beam region highly ionized*
  - *Charge feedback on sensor plane*
  - *Positive ions drift very slowly (~ ms)*
- Data analysis (in magnetic field)
  - *Recoil trajectories are 3D spirals*
  - *Event classification to select reaction channel*
  - *Clustering algorithms necessary*
  - *Fitting without analytical model*



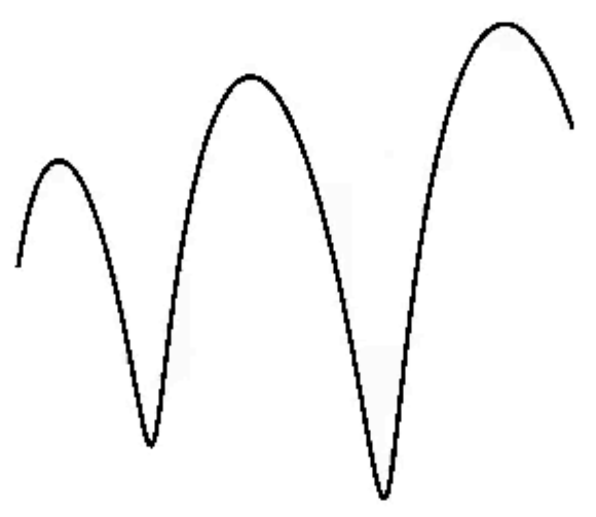
Simulated event



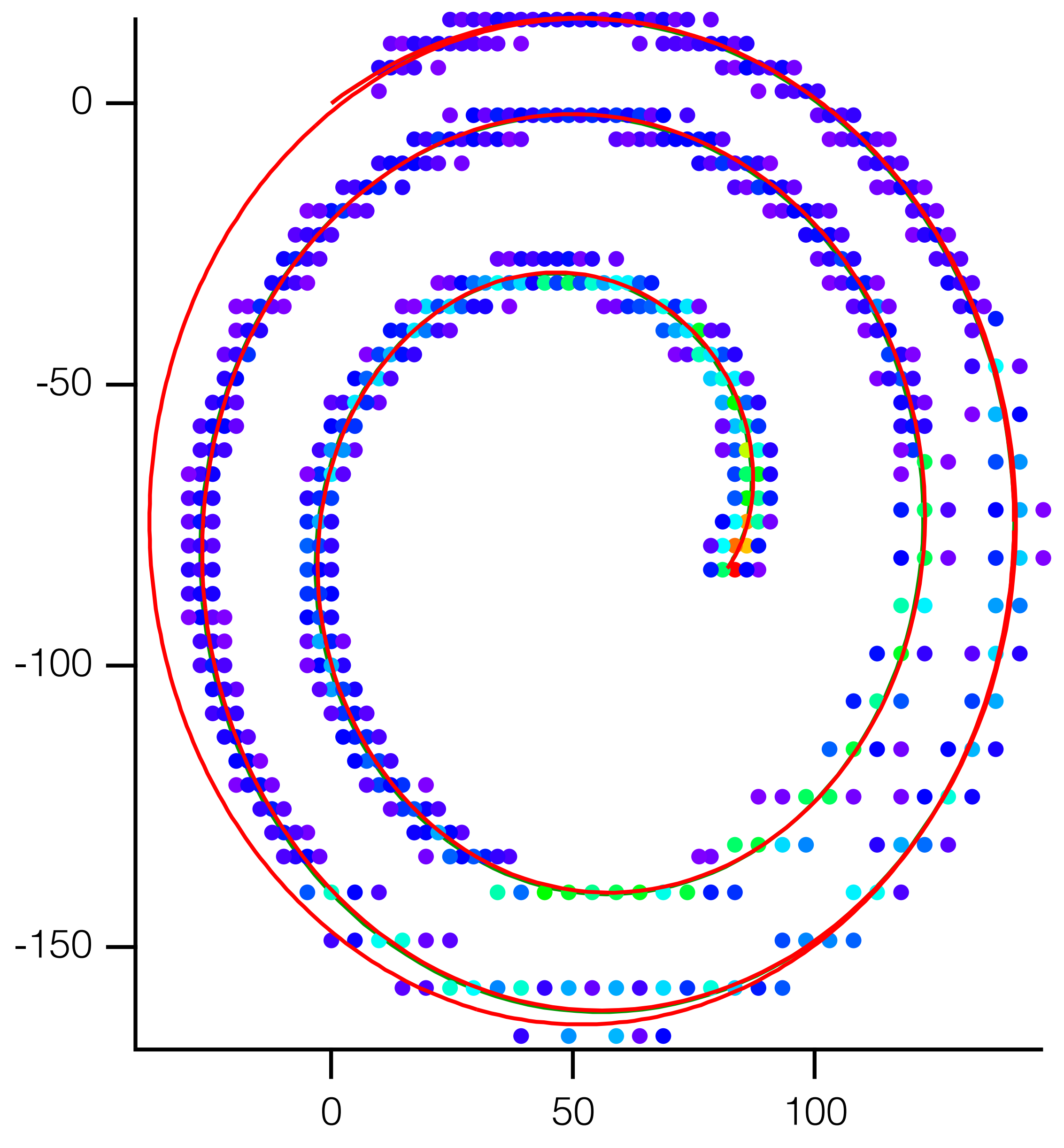


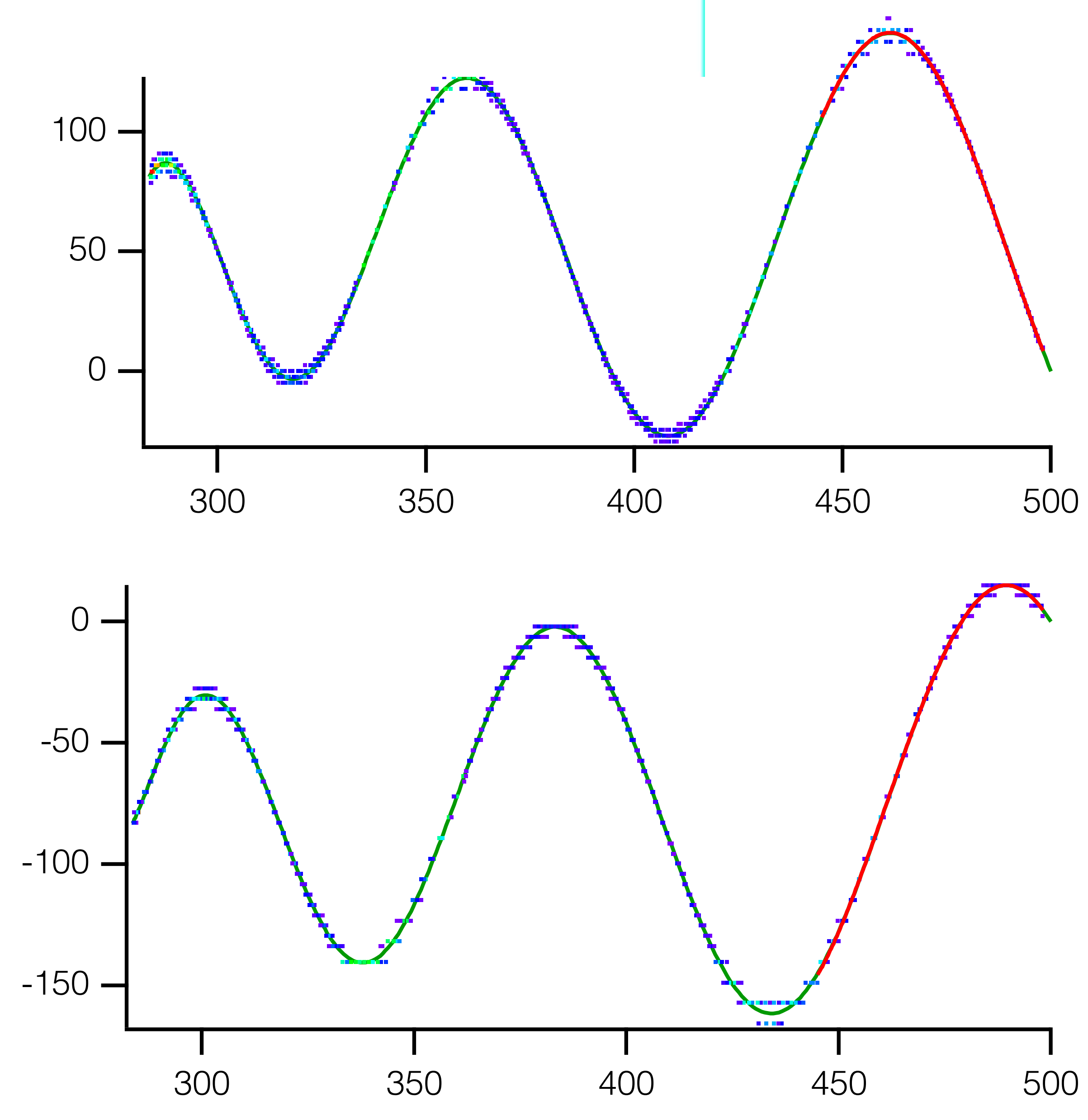
Three main challenges

- Trigger on events of interest
  - *Most "events" are beam slowing down in gas*
- Noise and electric field deformation
  - *Beam region highly ionized*
  - *Charge feedback on sensor plane*
  - *Positive ions drift very slowly (~ ms)*
- Data analysis (in magnetic field)
  - *Recoil trajectories are 3D spirals*
  - *Event classification to select reaction channel*
  - *Clustering algorithms necessary*
  - *Fitting without analytical model*



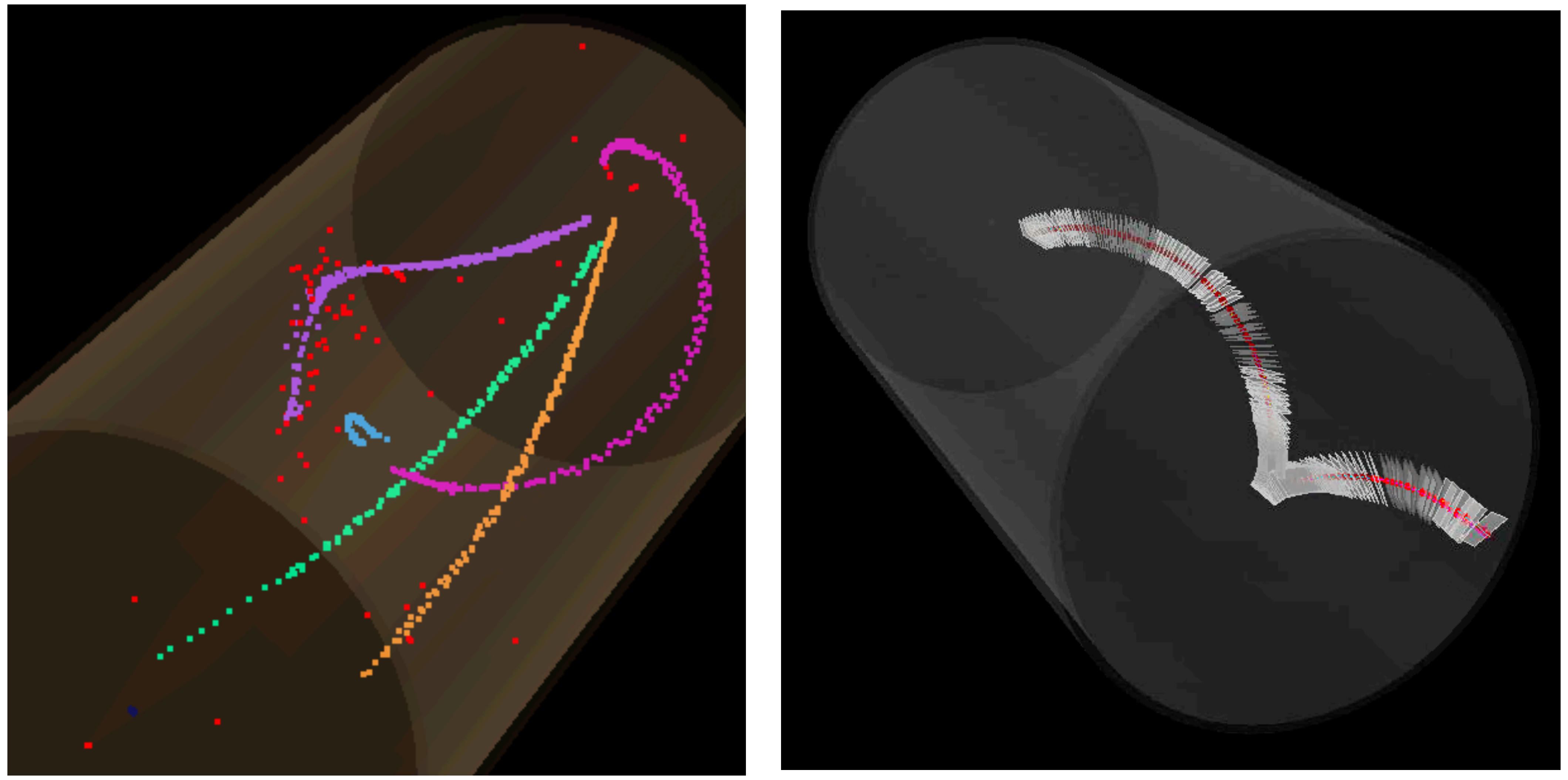
Simulated event





Analysis of AT-TPC data

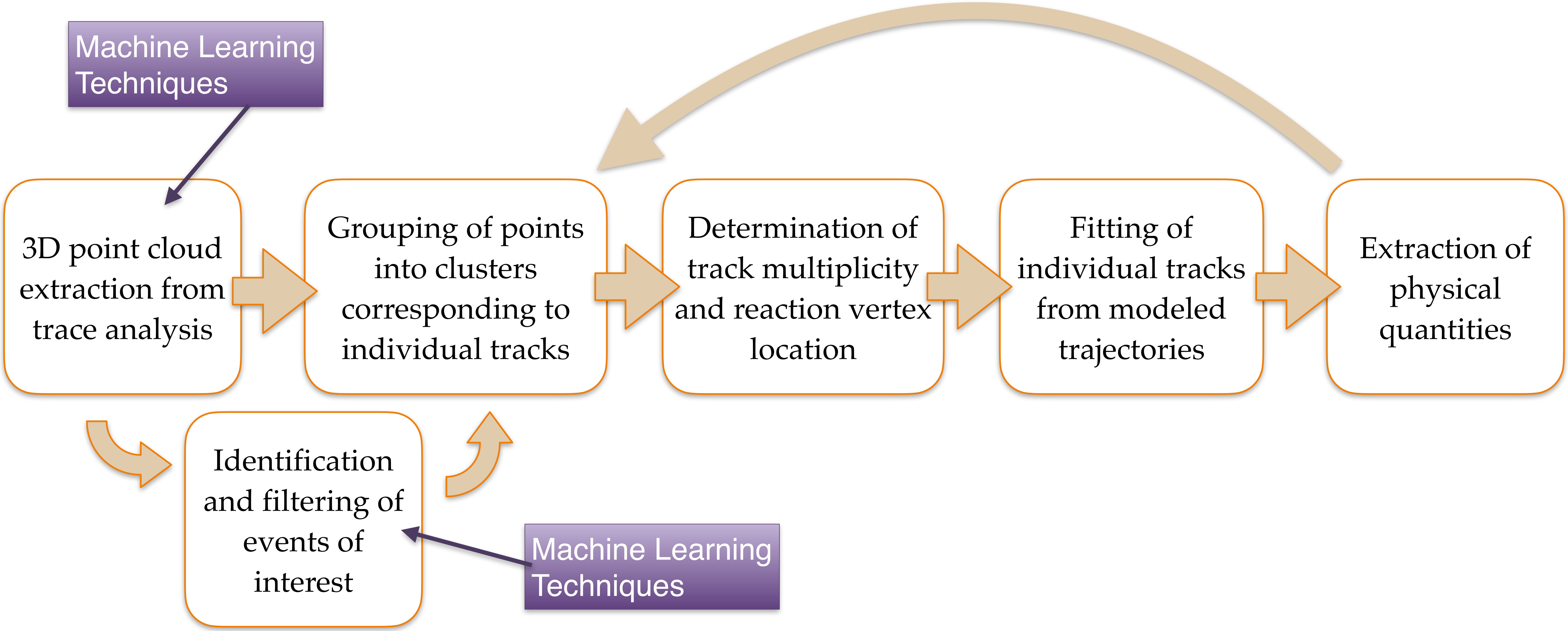
- Several challenges
  - *Large volume (traces are recorded for each pad hit)*
  - *Data reduction and clustering in tracks*
  - *Fitting of tracks and extraction of physical quantities*
  - *Event recognition and classification*
- Common effort by AT-TPC collaboration
  - *Several papers published on new methods*
  - *Tools from particle physics community not readily applicable, have to be adapted*
  - *Image processing and machine learning algorithms can help reduce the data processing time*



Analysis from ATTPCRoot (Y. Ayyad)

- *Commissioning of the Active-Target Time Projection Chamber, J. Bradt et al., NIMA 875, 65 (2017)*
- *Novel particle tracking algorithm based on the Random Sample Consensus Model for the Active Target Time Projection Chamber (AT-TPC), Y. Ayyad et al., NIMA 880, 166 (2018)*
- *Automatic trajectory recognition in Active Target Time Projection Chambers data by means of hierarchical clustering, C. Dalitz et al., Comp. Phys. Comm. 235, 159 (2019)*
- *Machine learning methods for track classification in the AT-TPC, M. P. Kuchera et al., NIMA 940, 156 (2019)*
- *Unsupervised learning for identifying events in active target experiments, R. Solli et al., NIMA 1010, 165461 (2021)*
- *Tracking algorithms for TPCs using consensus-based robust estimators, J. C. Zamora et al., NIMA 988, 164899 (2021)*

Synopsis of analysis process



Transfer reaction commissioning of AT-TPC @ SOLARIS

- Parity of 3/2 state at 3.41 MeV remains uncertain
  - *^{9}Be(t,p) and β-decay support negative parity*

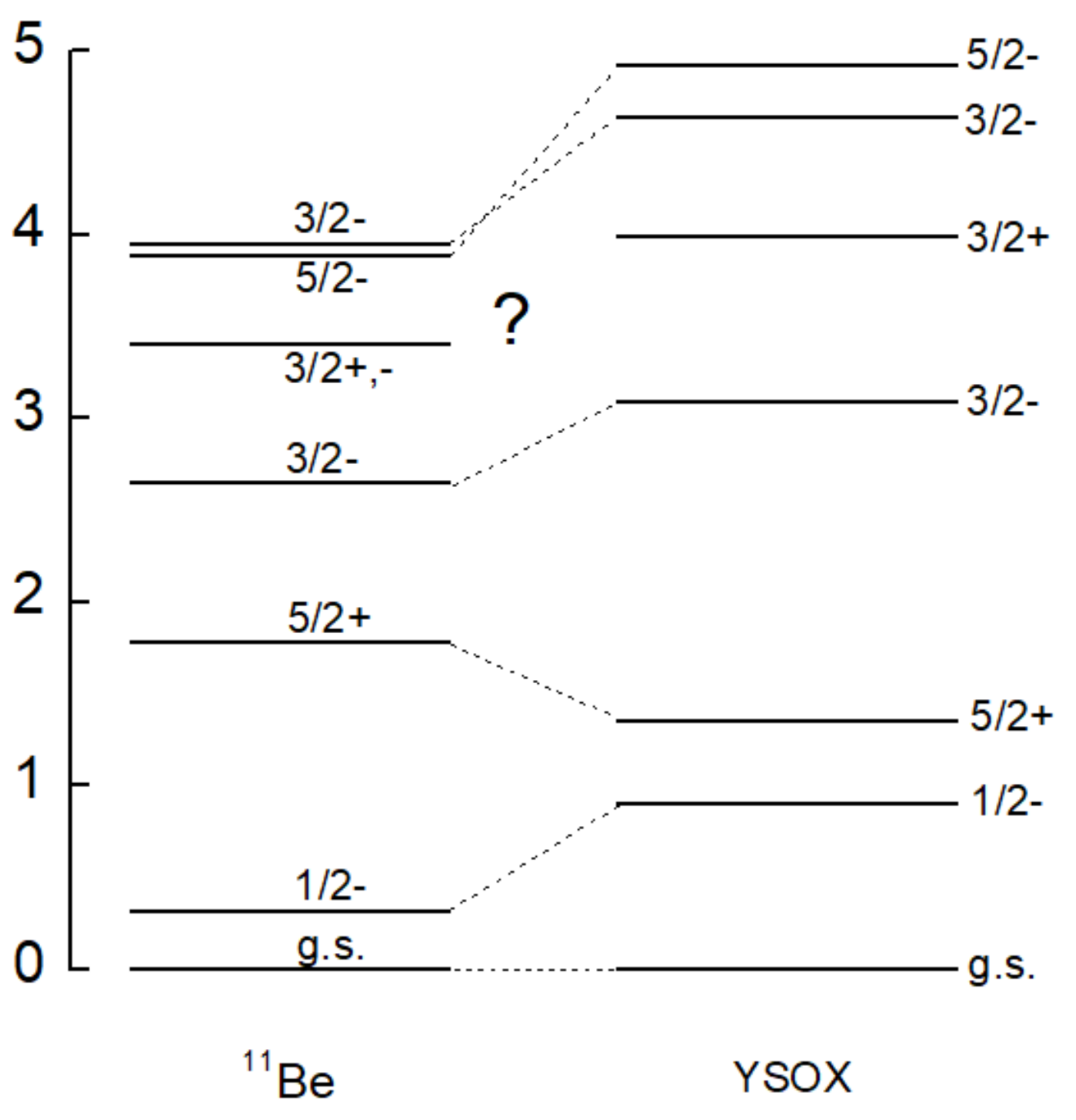
    G.-B. Liu, H.T. Fortune, Phys. Rev. C 42, 167 (1990).

    Y. Hirayama, T. Shimoda, H. Izumi, et al.,Physics Letters B 611, 239 (2005).
  - *Inelastic scattering support positive parity*

    N. Fukuda et al., Phys. Rev. C 70, 054606 (2004).
  - *Positive parity favored by ab-initio and Shell Model calculations using YSOX interaction*

    Angelo Calci, Petr Navrátil, Robert Roth, et al.,Phys. Rev. lett. 117, 242501 (2016)

    C. Yuan, T. Suzuki, T. Otsuka,et al., Phys. Rev. C 85 (2012) 064324.
  - *If confirmed positive, 3.41 MeV state would determine $0d_{3/2}$ single-particle energy in ^{11}Be*
- ^{10}Be beam from ReA6 stand alone operation



Transfer reaction commissioning of AT-TPC @ SOLARIS

- Parity of 3/2 state at 3.41 MeV remains uncertain
    - *^{9}Be(t,p) and ß-decay support negative parity*

      G.-B. Liu, H.T. Fortune, Phys. Rev. C 42, 167 (1990).

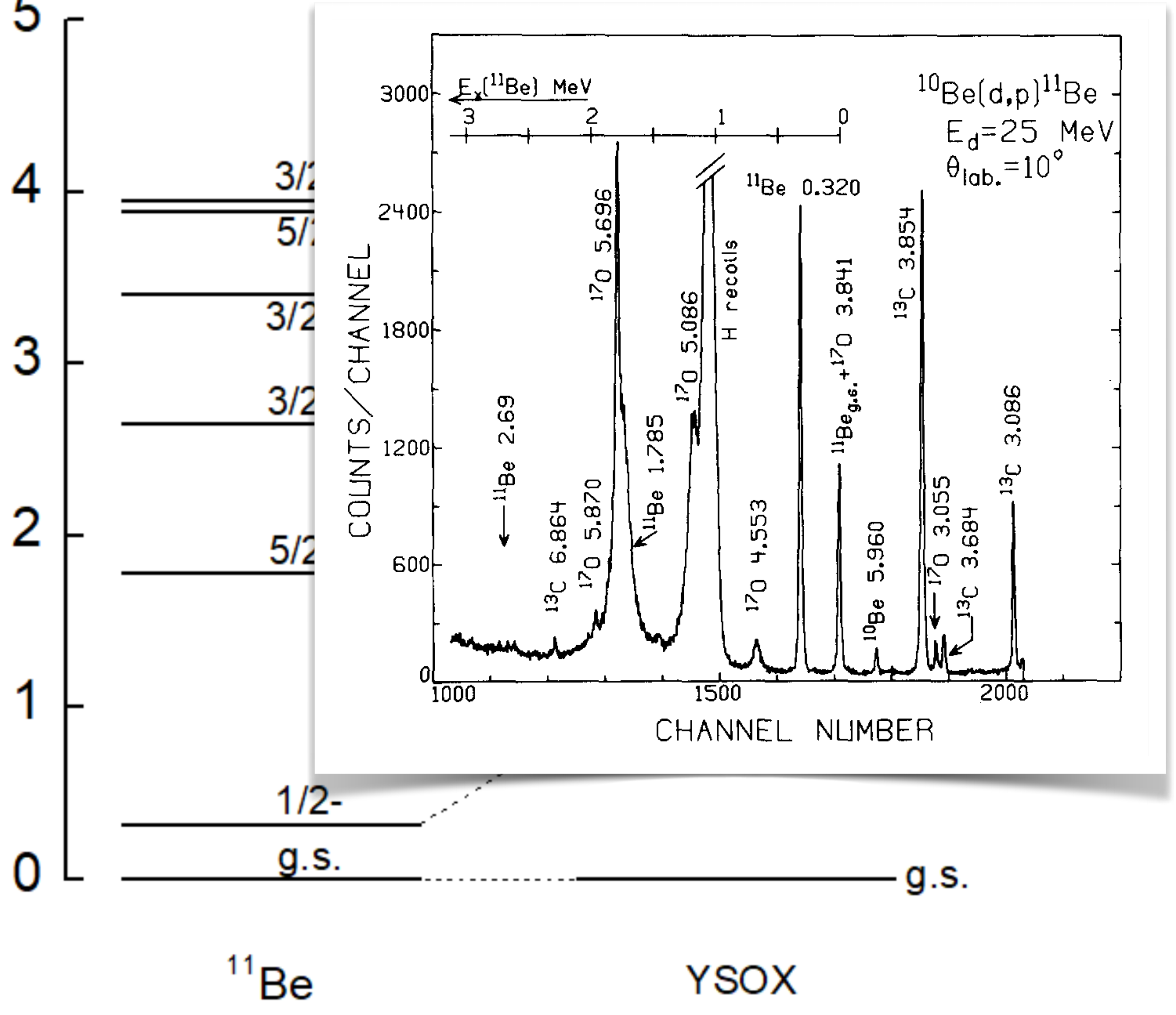
      Y. Hirayama, T. Shimoda, H. Izumi, et al.,Physics Letters B 611, 239 (2005).
    - *Inelastic scattering support positive parity*

      N. Fukuda et al., Phys. Rev. C 70, 054606 (2004).
    - *Positive parity favored by ab-initio and Shell Model calculations using YSOX interaction*

      Angelo Calci, Petr Navrátil, Robert Roth, et al.,Phys. Rev. lett. 117, 242501 (2016)

      C. Yuan, T. Suzuki, T. Otsuka,et al., Phys. Rev. C 85 (2012) 064324.
    - *If confirmed positive, 3.41 MeV state would determine $0d_{3/2}$ single-particle energy in ^{11}Be*
- ^{10}Be beam from ReA6 stand alone operation

B. Zwieglinski, W. Benenson et al., Nucl. Phys. A315, 124 (1979)



Transfer reaction commissioning of AT-TPC @ SOLARIS

- Parity of 3/2 state at 3.41 MeV remains uncertain
  - *^{9}Be(t,p) and ß-decay support negative parity*

    G.-B. Liu, H.T. Fortune, Phys. Rev. C 42, 167 (1990).

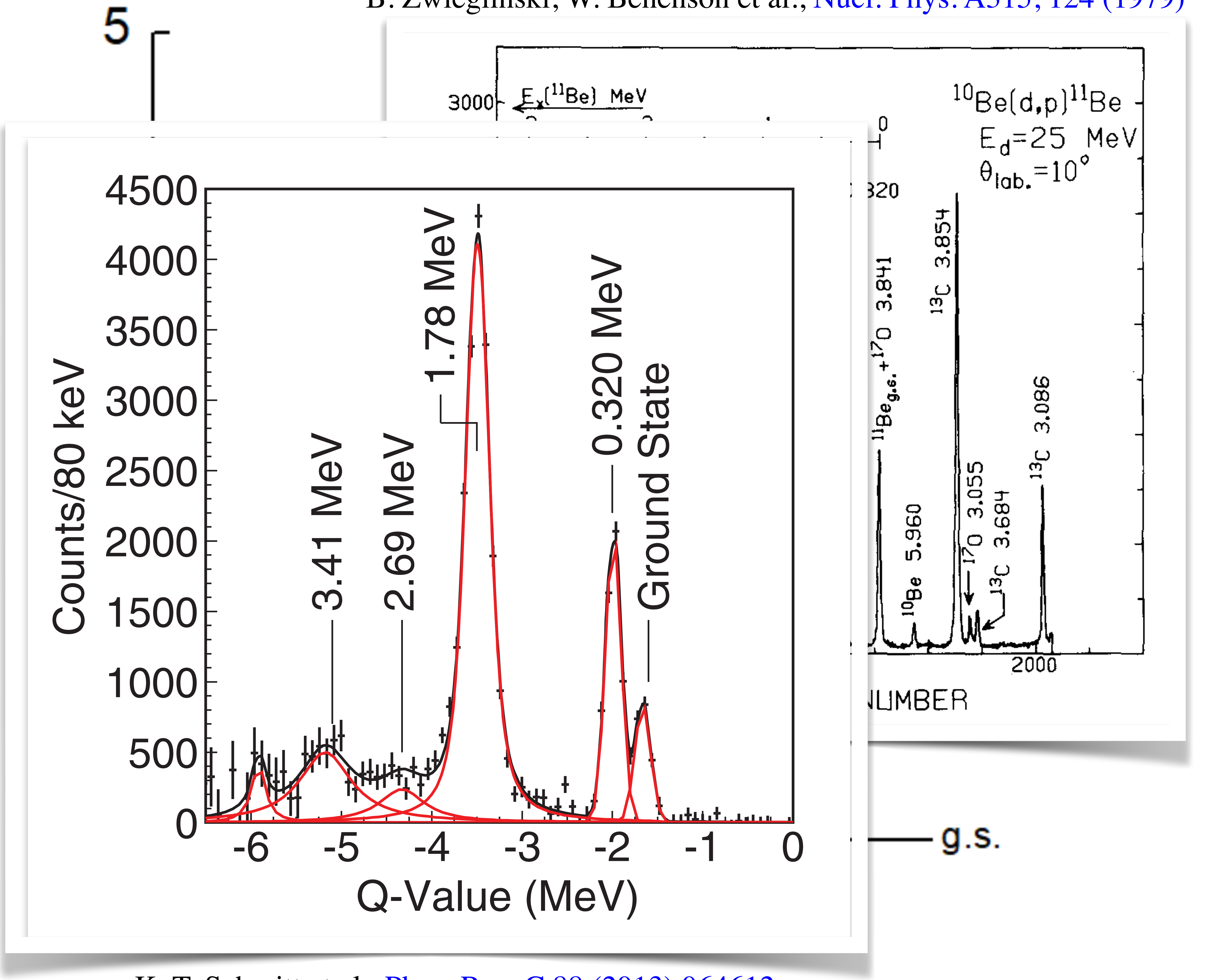
    Y. Hirayama, T. Shimoda, H. Izumi, et al.,Physics Letters B 611, 239 (2005).
  - *Inelastic scattering support positive parity*

    N. Fukuda et al., Phys. Rev. C 70, 054606 (2004).
  - *Positive parity favored by ab-initio and Shell Model calculations using YSOX interaction*

    Angelo Calci, Petr Navrátil, Robert Roth, et al.,Phys. Rev. lett. 117, 242501 (2016)

    C. Yuan, T. Suzuki, T. Otsuka,et al., Phys. Rev. C 85 (2012) 064324.
  - *If confirmed positive, 3.41 MeV state would determine $0d_{3/2}$ single-particle energy in ^{11}Be*
- ^{10}Be beam from ReA6 stand alone operation

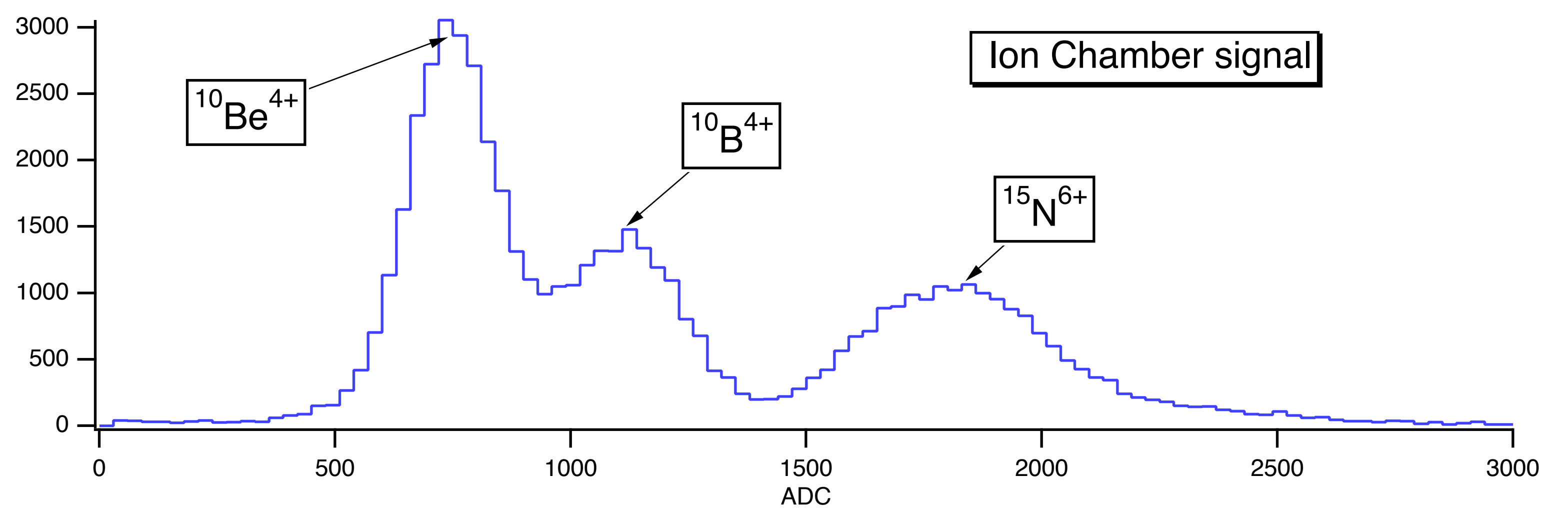
B. Zwieglinski, W. Benenson et al., Nucl. Phys. A315, 124 (1979)

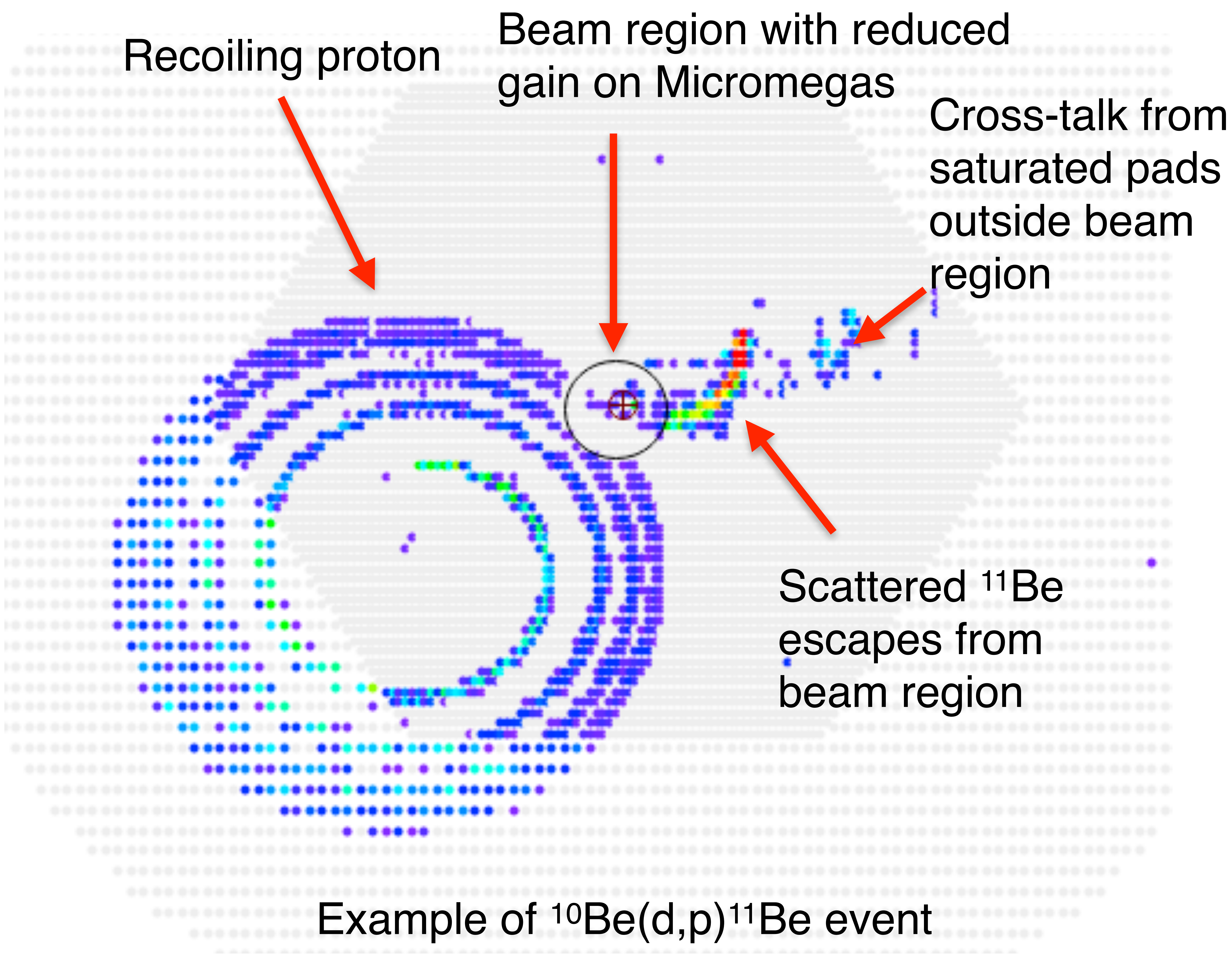


K. T. Schmitt et al., Phys. Rev. C 88 (2013) 064612.

Experimental conditions

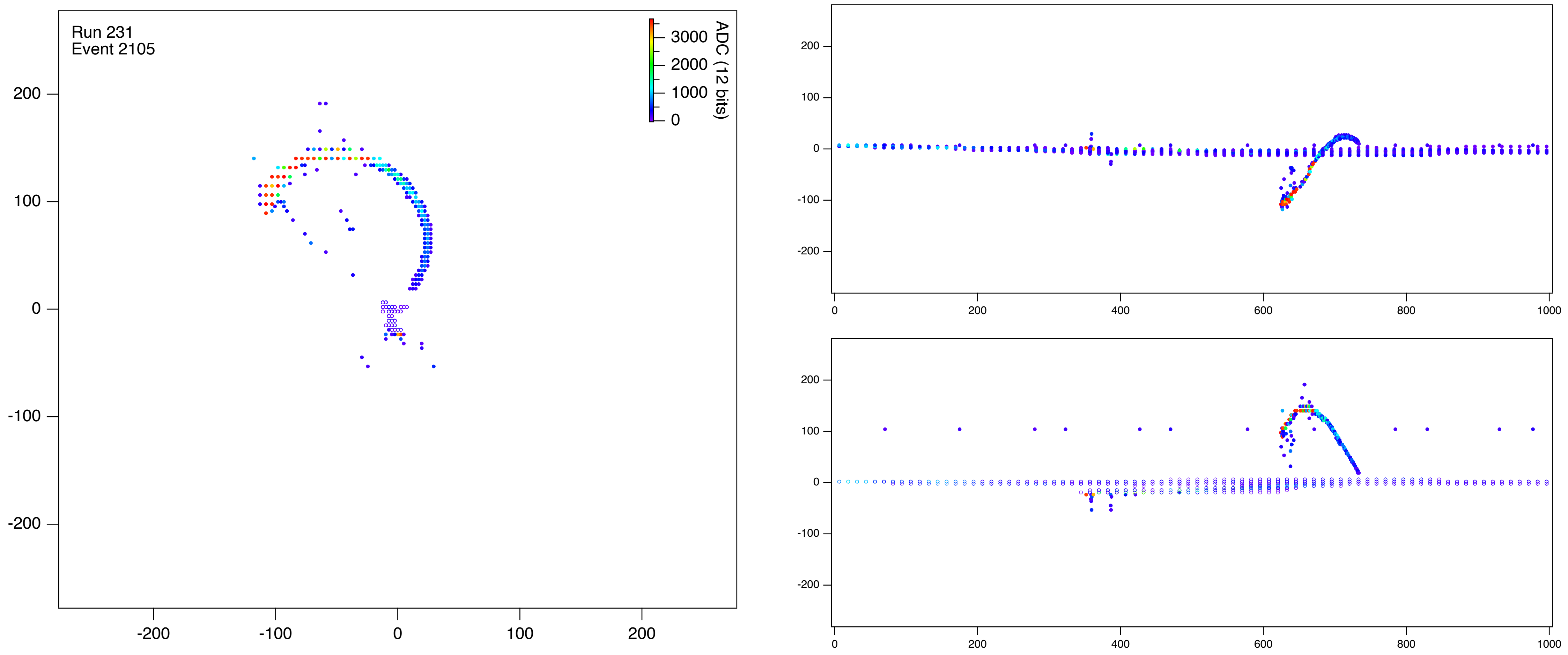
- ^{10}Be beam from ReA6 linac
  - *^{10}B and ^{15}N contaminants*
  - *9.6 MeV/u and 1,000 pps*
- AT-TPC @ SOLARIS
  - *600 Torr of D_2 gas (13 mg/cm^2)*
  - *Magnetic field 3 Tesla*
  - *Trigger on mesh signal with beam region gain suppression*

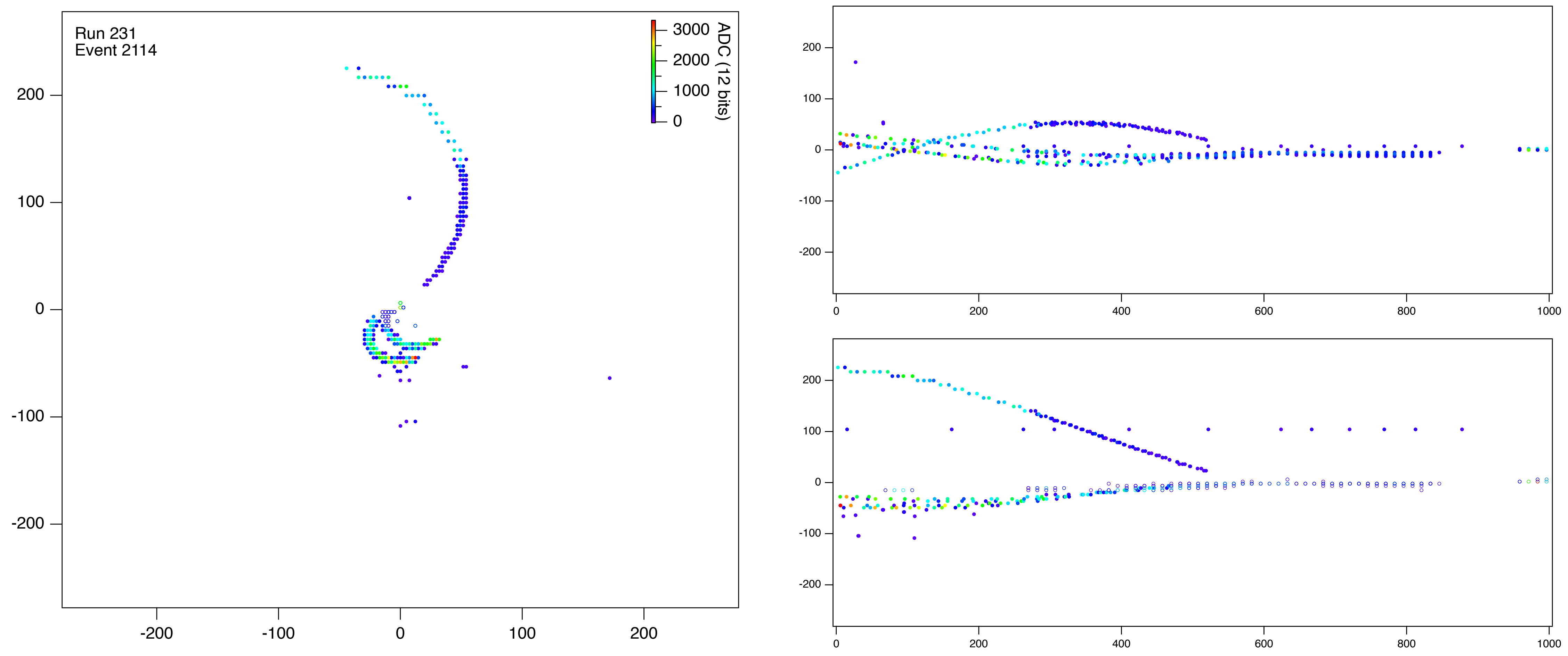


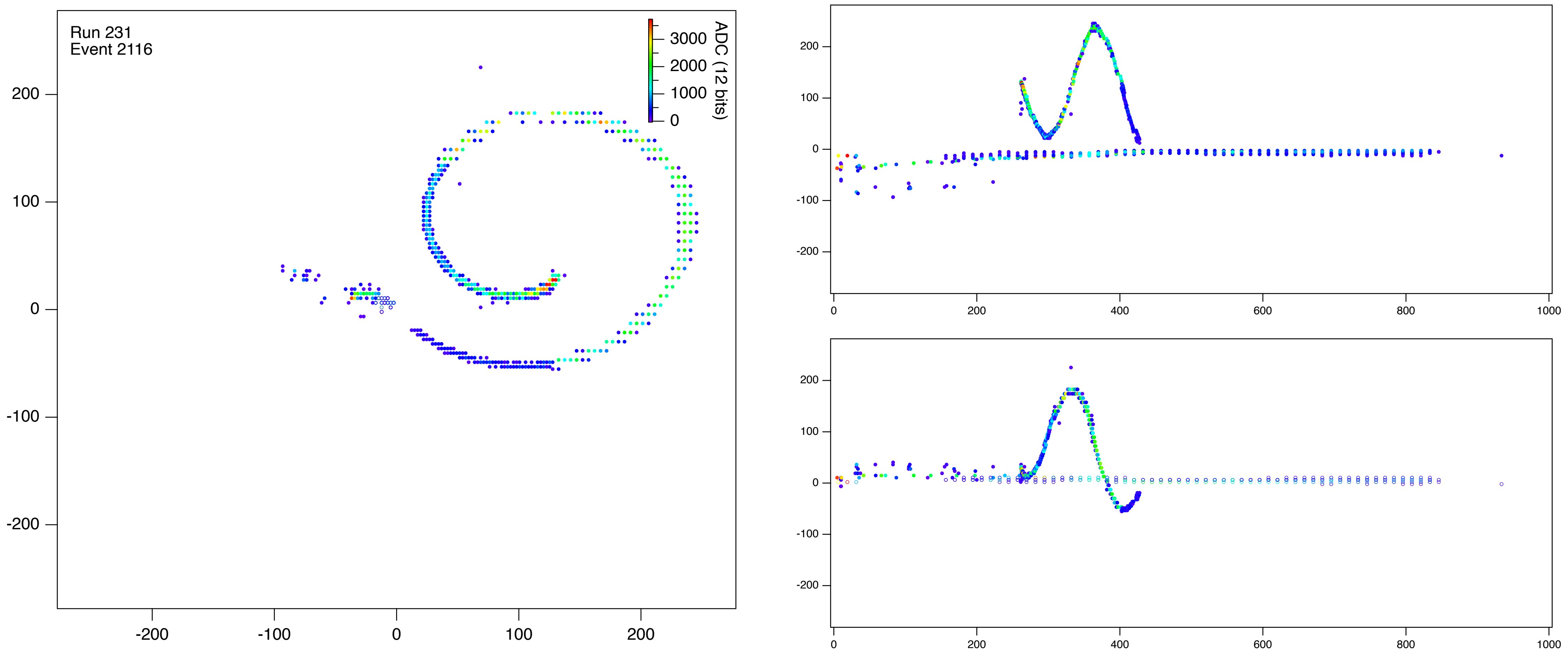


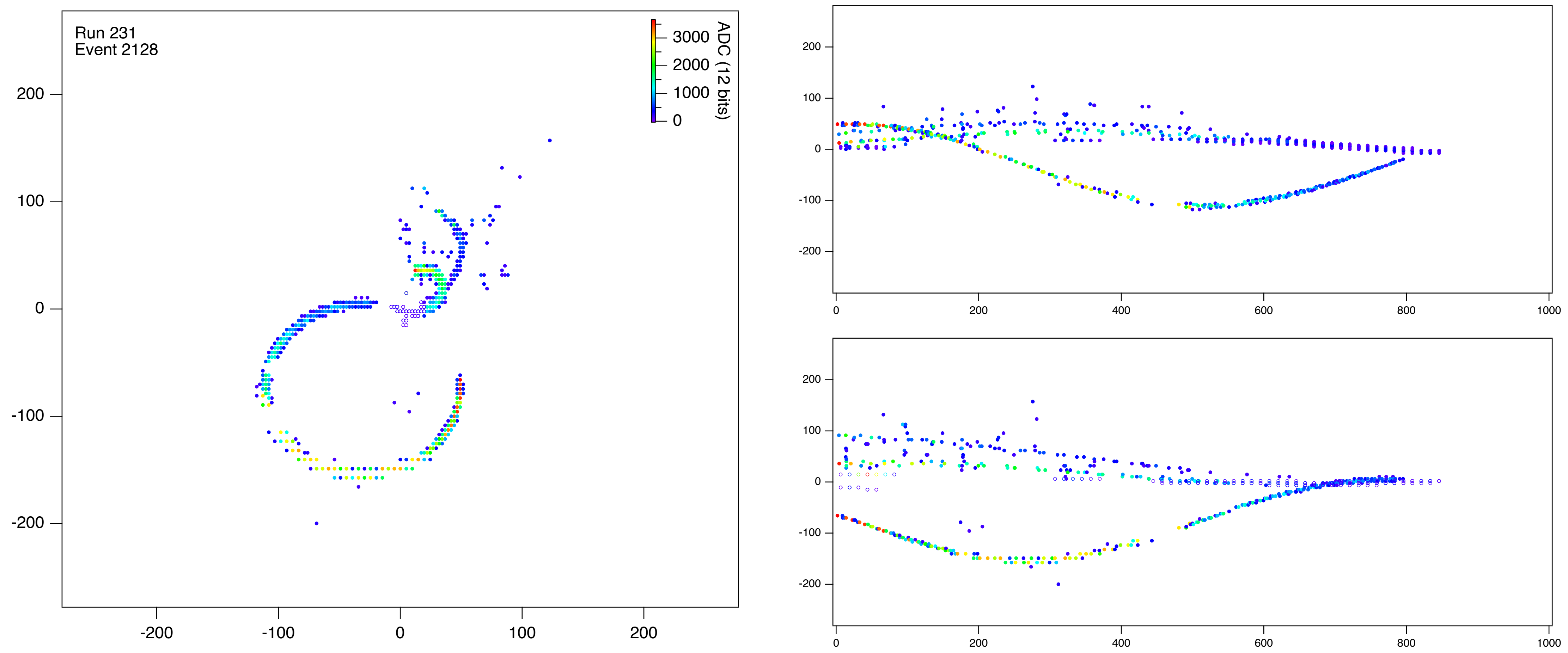
Example of ^{10}Be(d,p)^{11}Be event

Online identification of (d,d') events



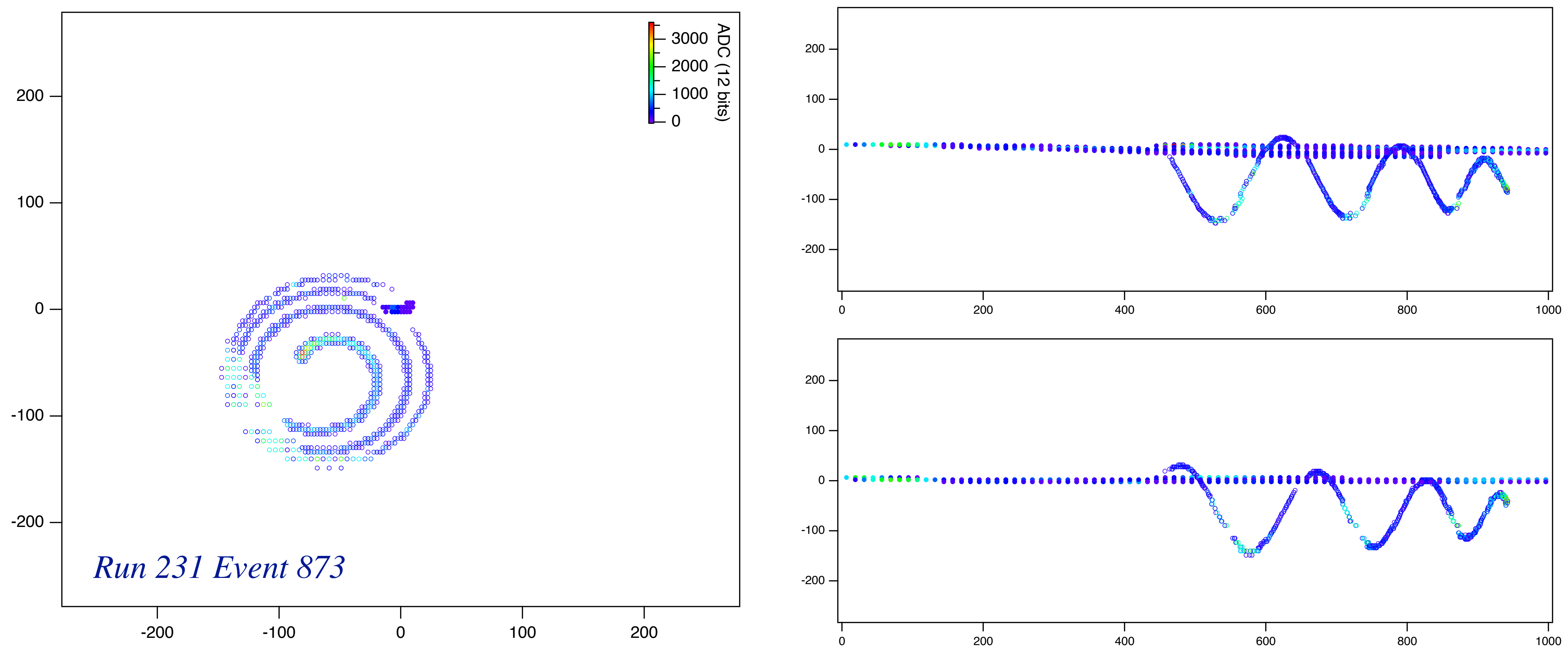


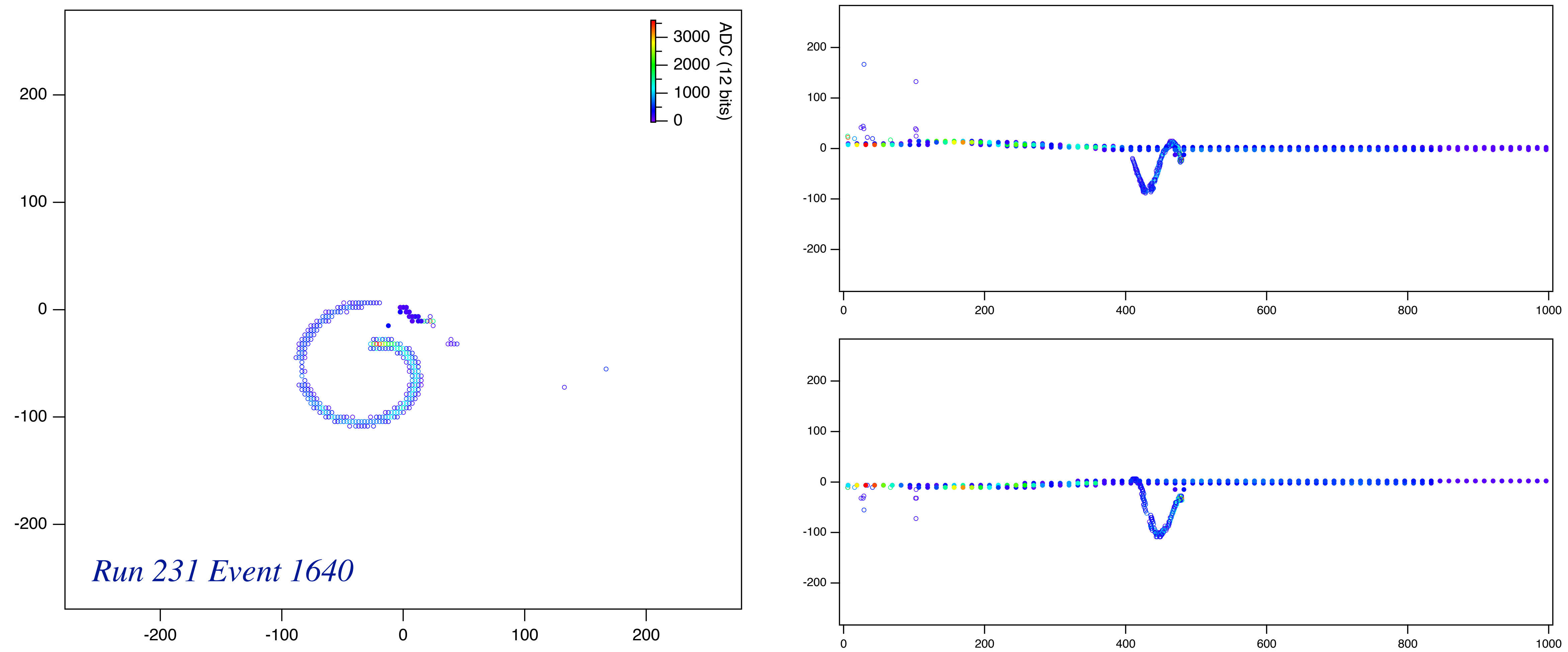


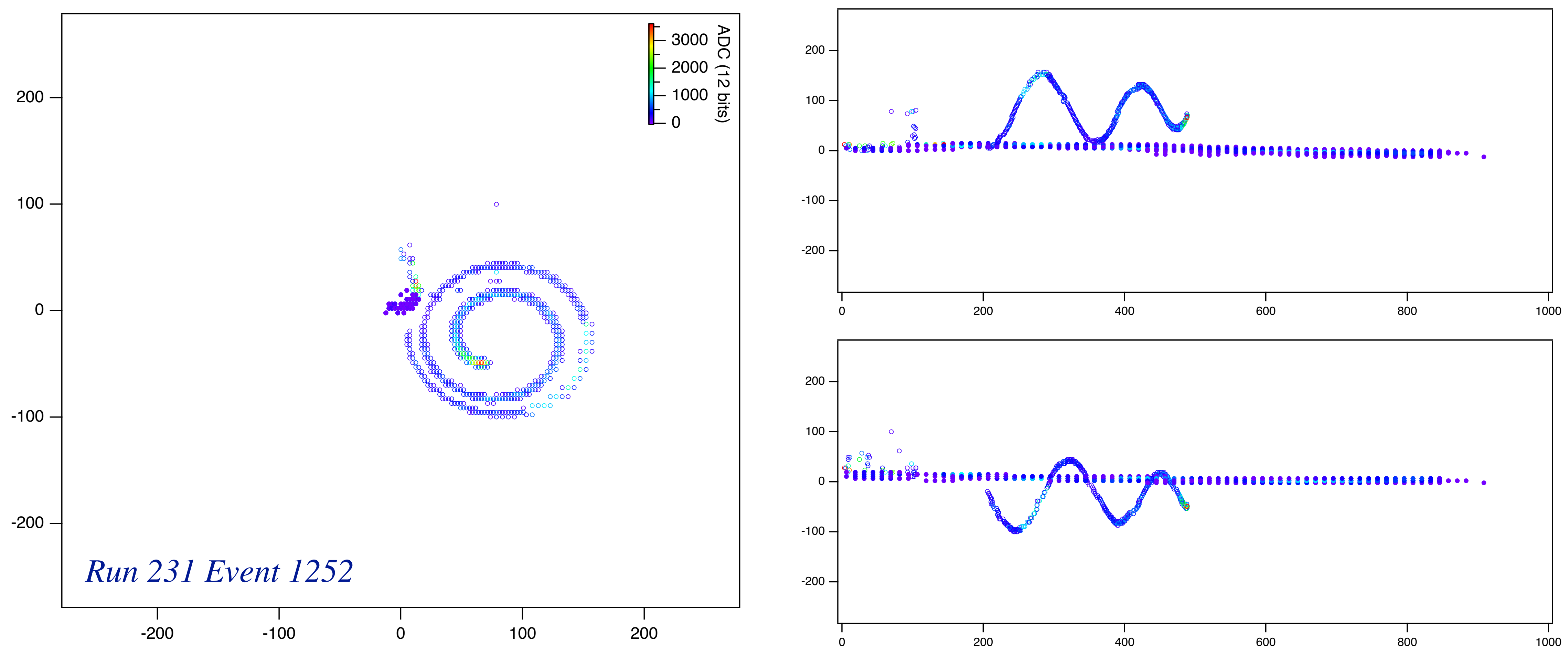


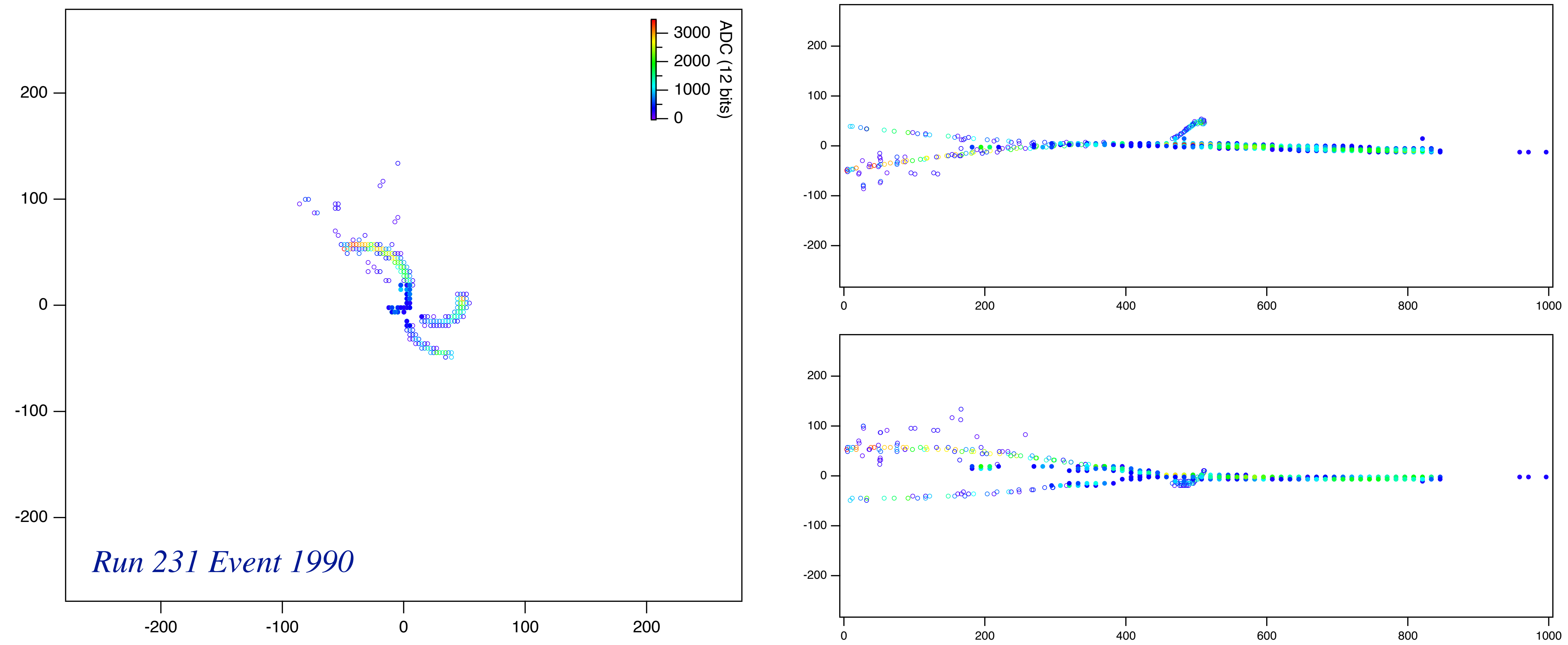
U.S. Department of Energy Office of Science
National Science Foundation
Michigan State University

Online identification of (d,p) events

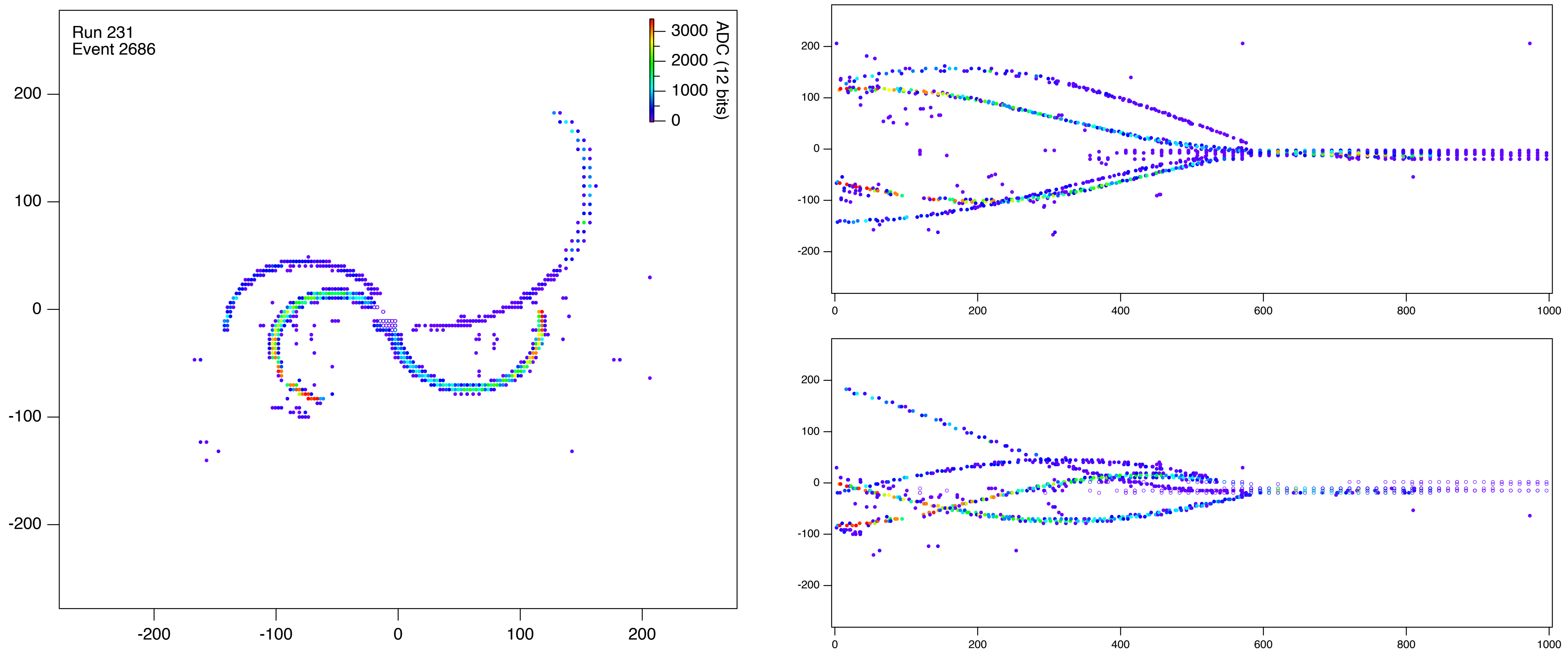


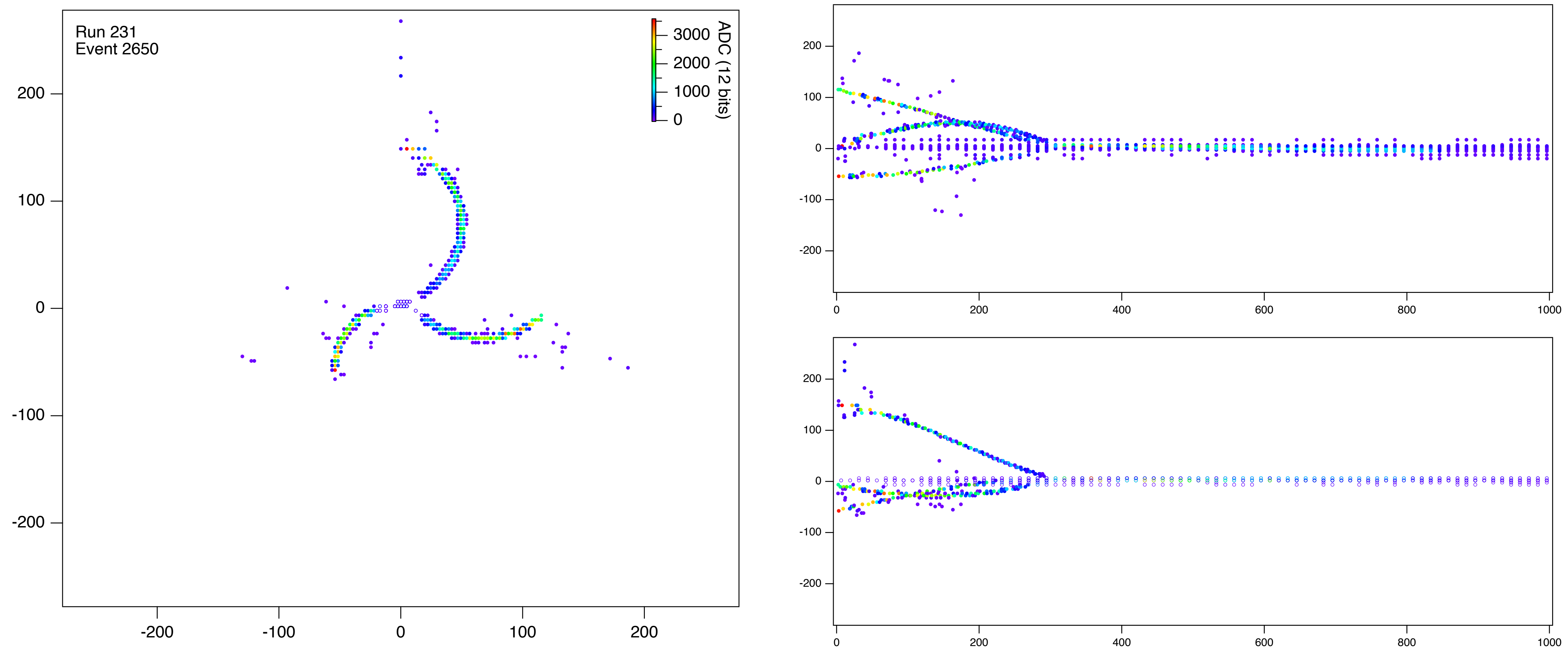


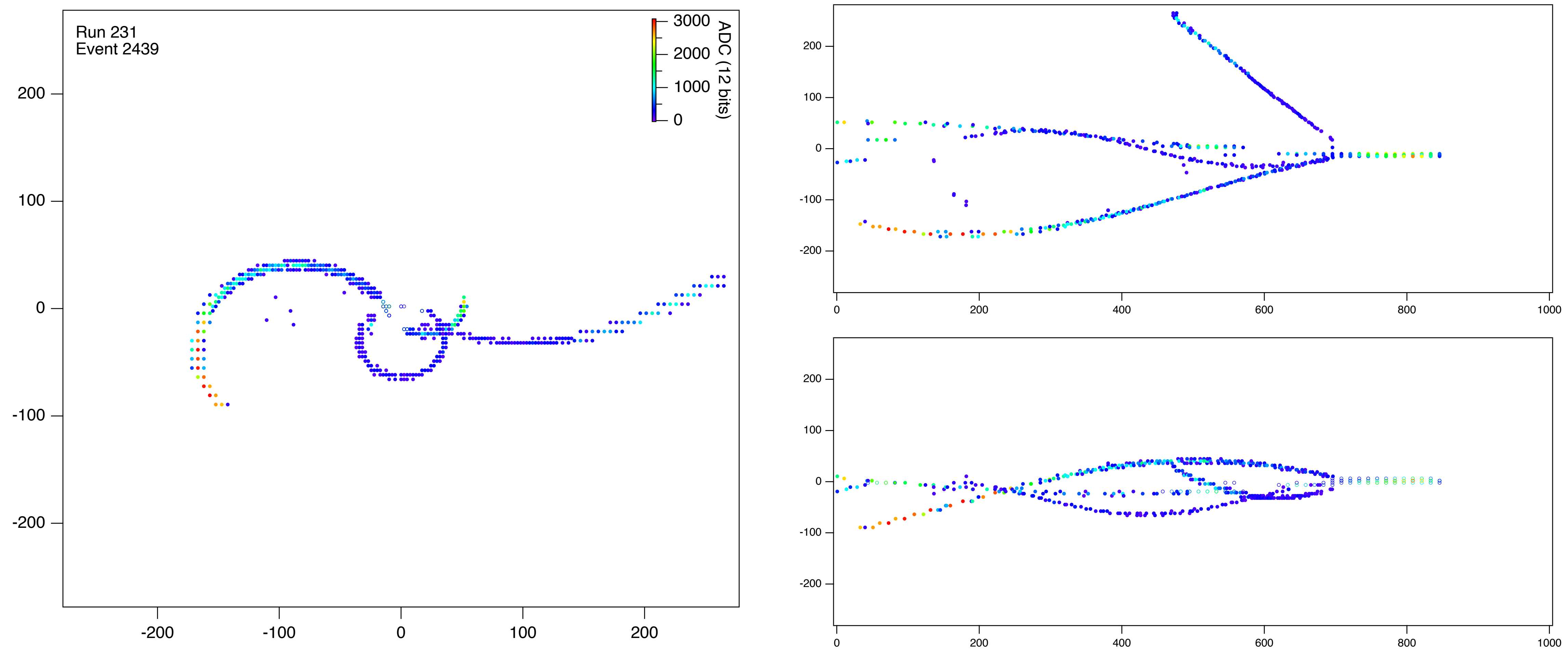


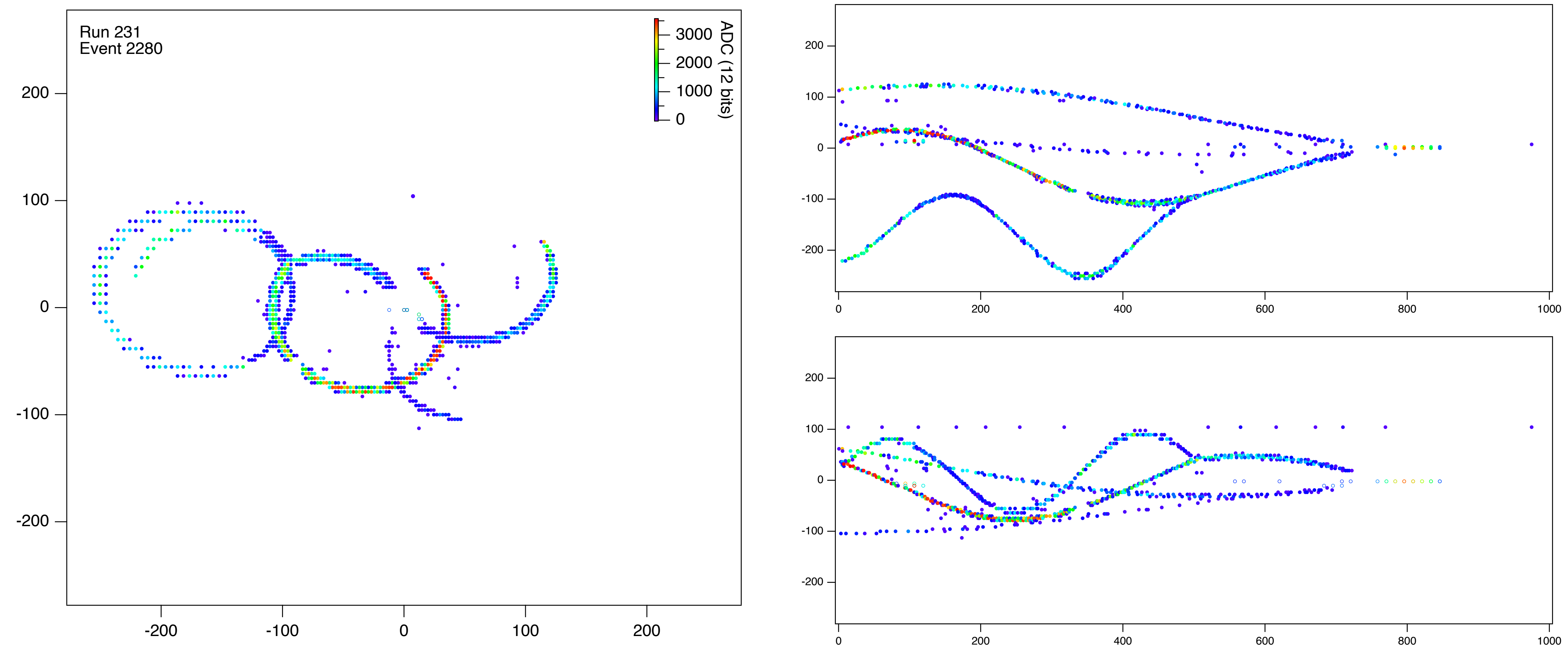


Other types of events (more central collisions)



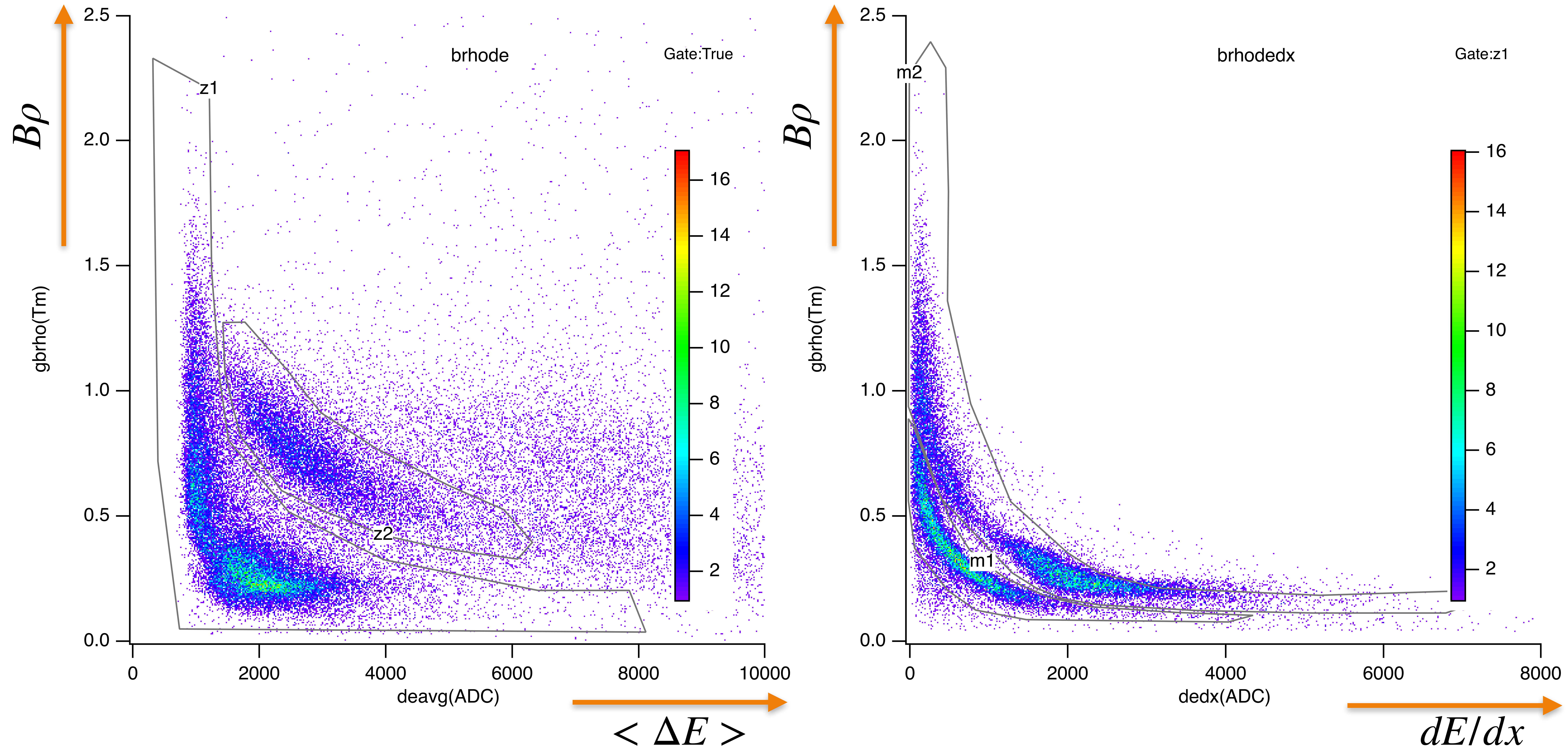




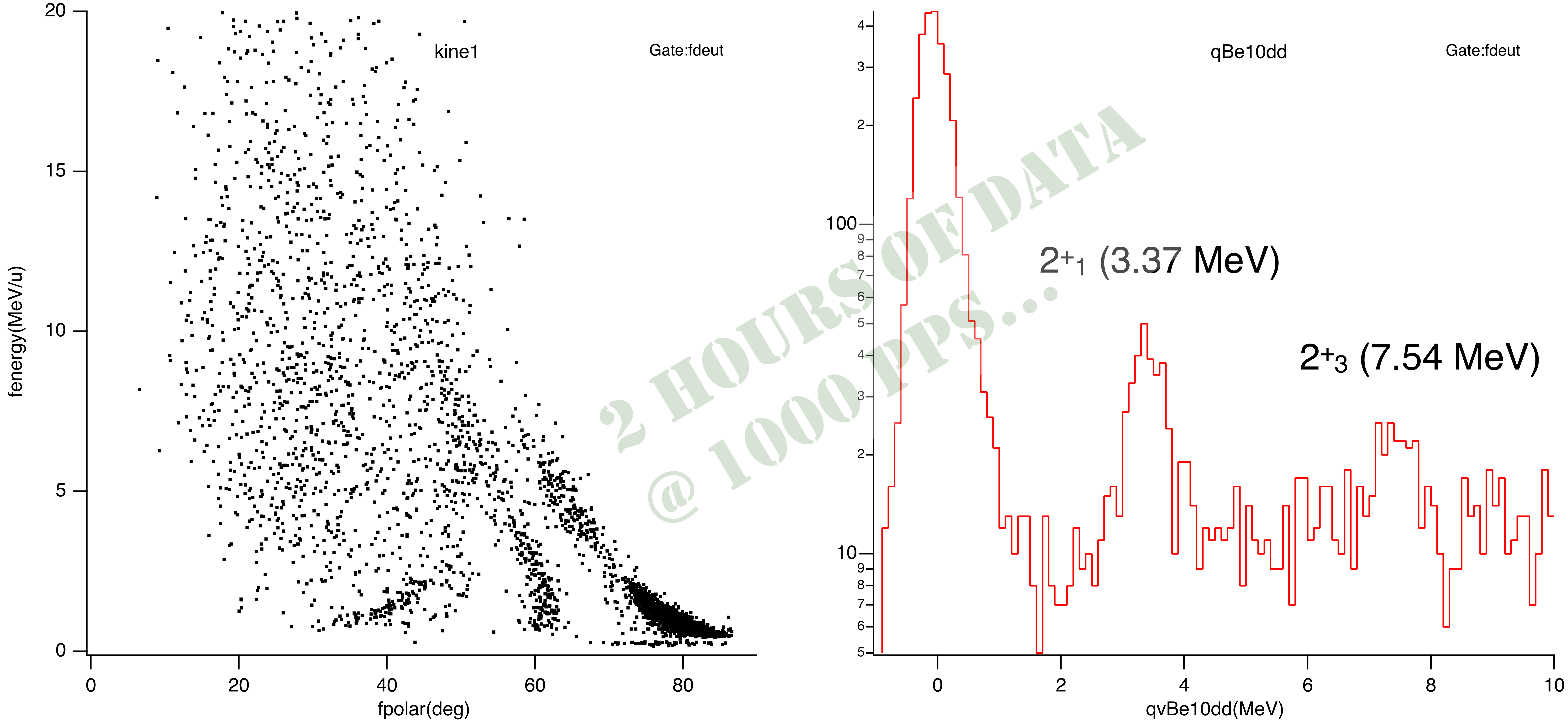


U.S. Department of Energy Office of Science
National Science Foundation
Michigan State University

Particle identification

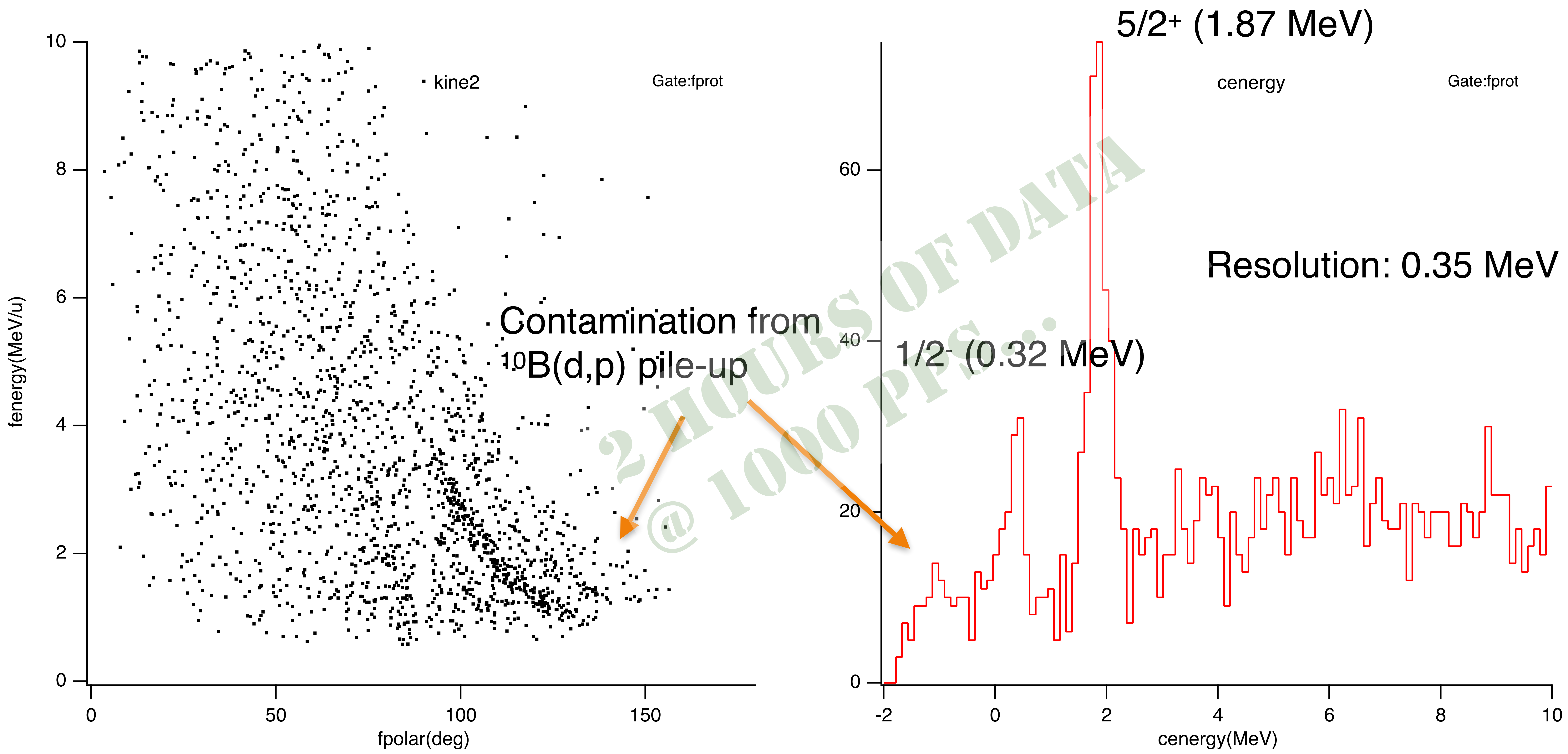


$^{10}Be(d,d)$ elastic and inelastic scattering



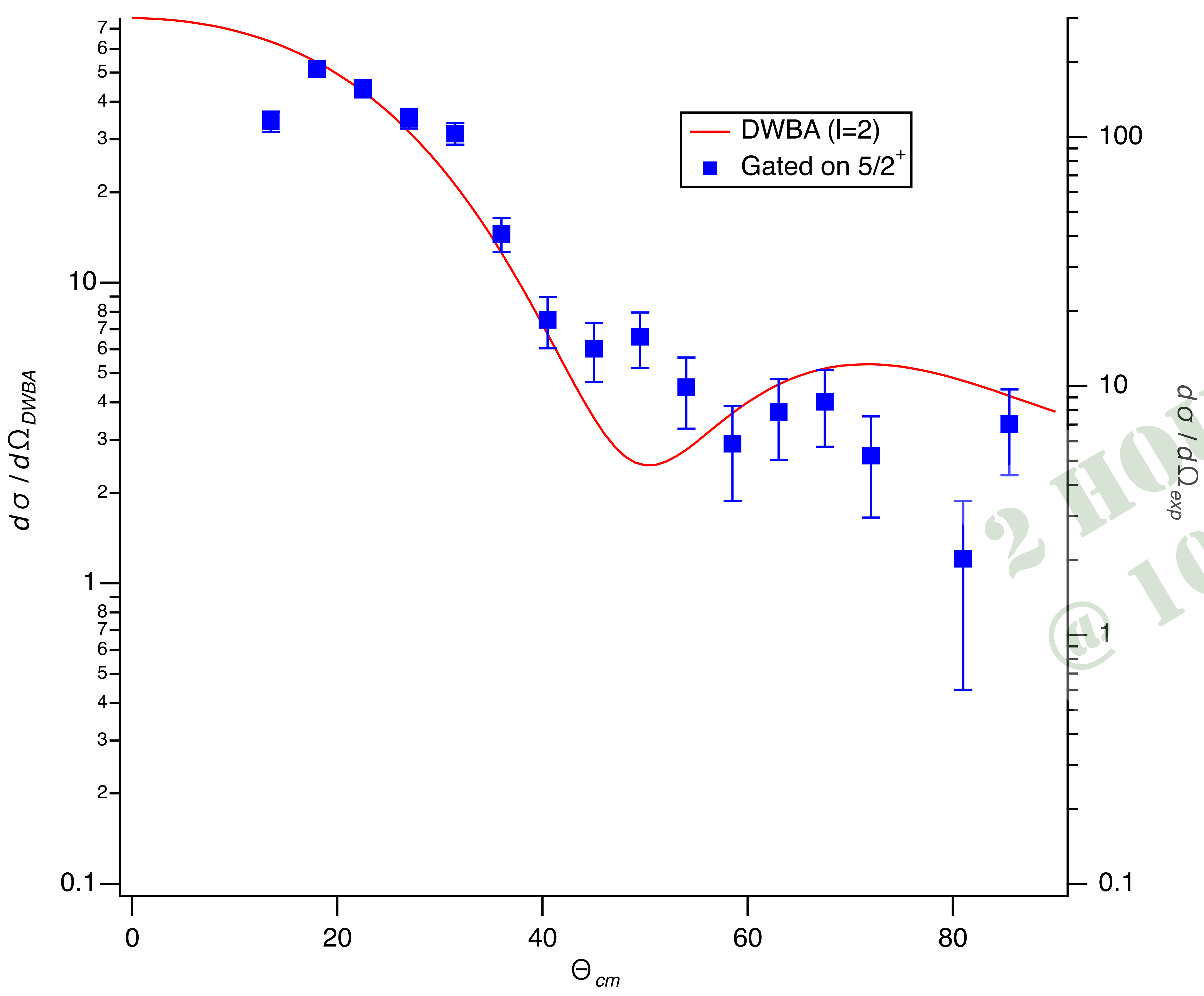
Gated on incoming ^{10}Be and scattered deuteron

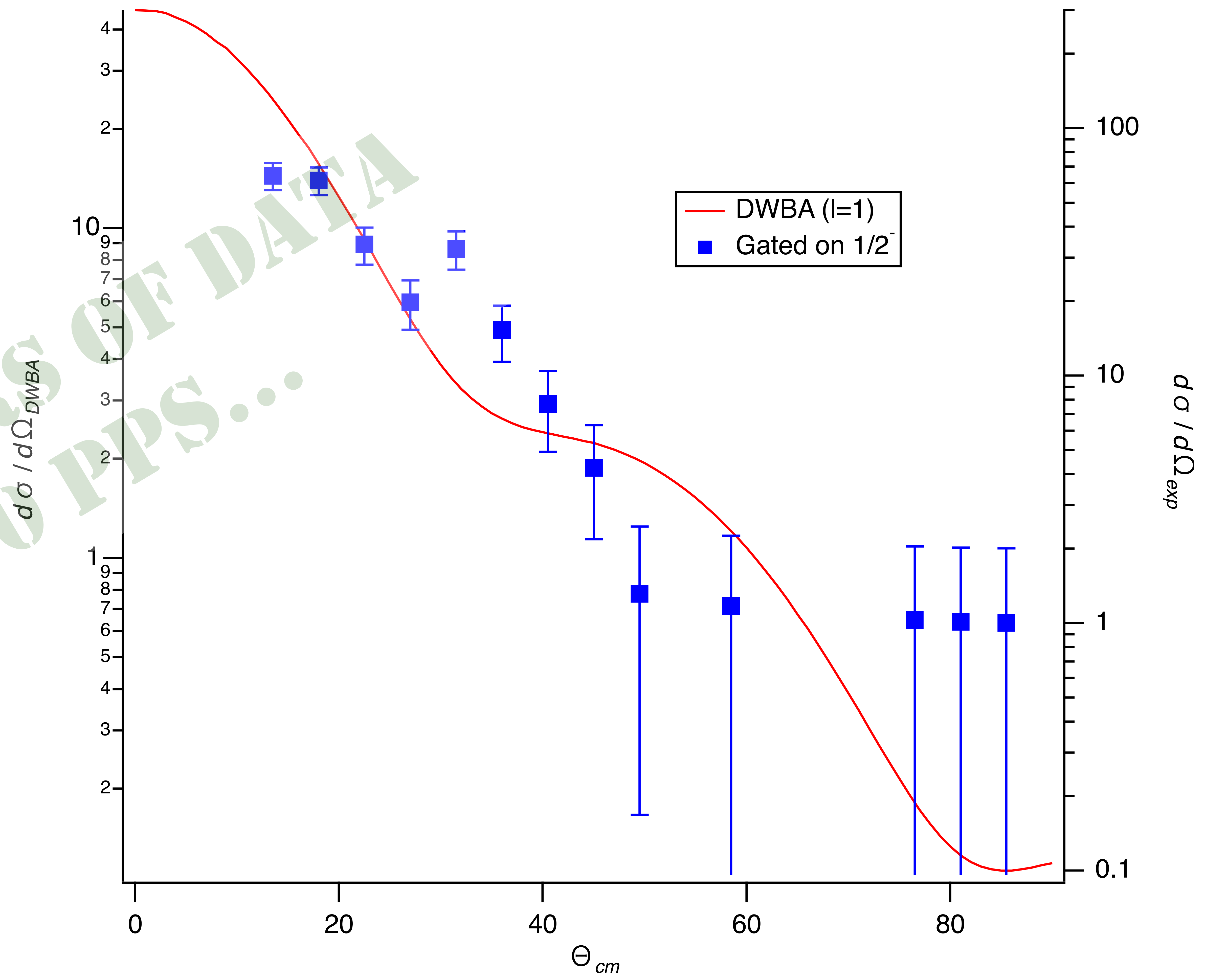
$^{10}Be(d,p)^{11}Be$ transfer



Gated on incoming ^{10}Be and scattered proton

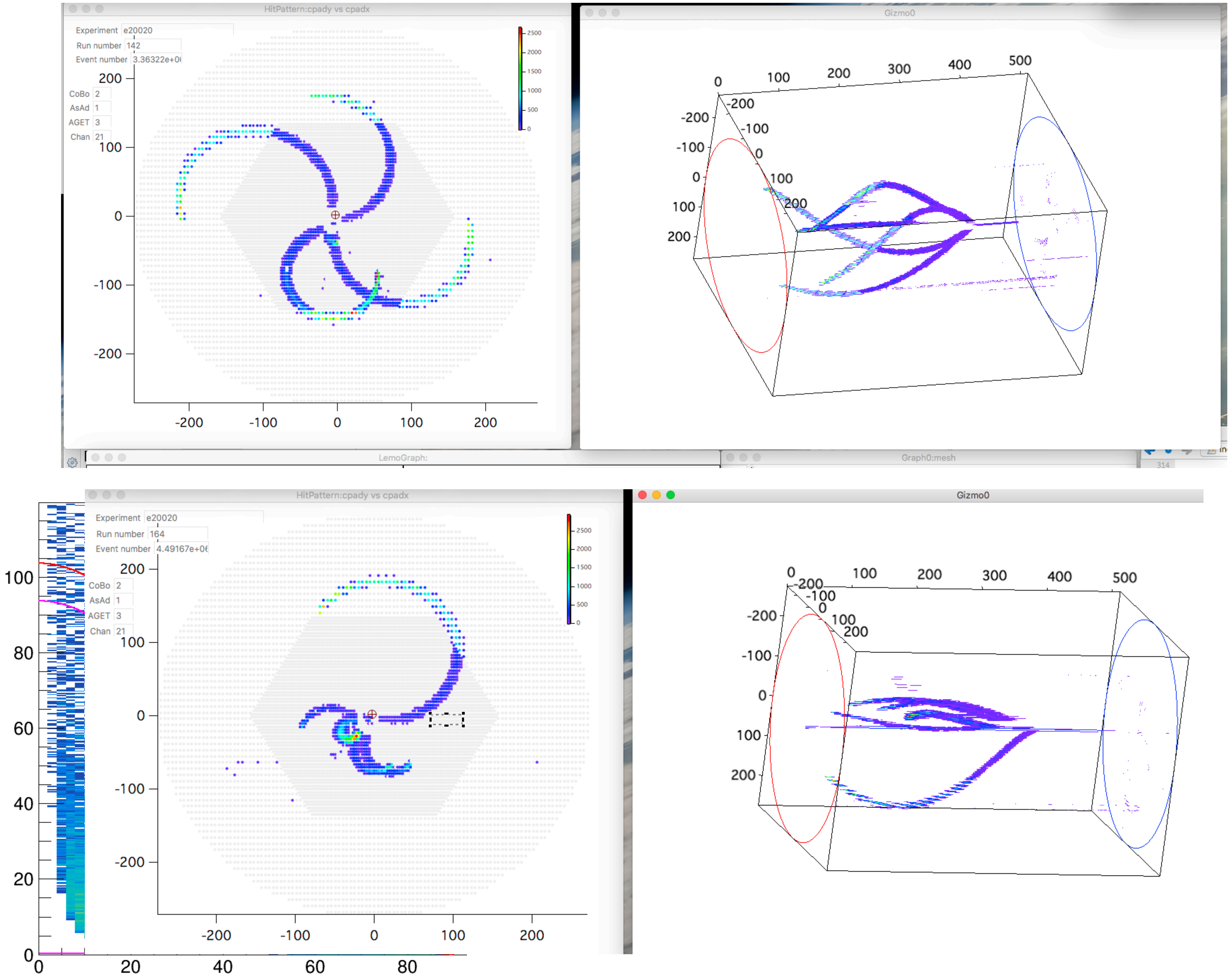
(Very preliminary) Angular distributions





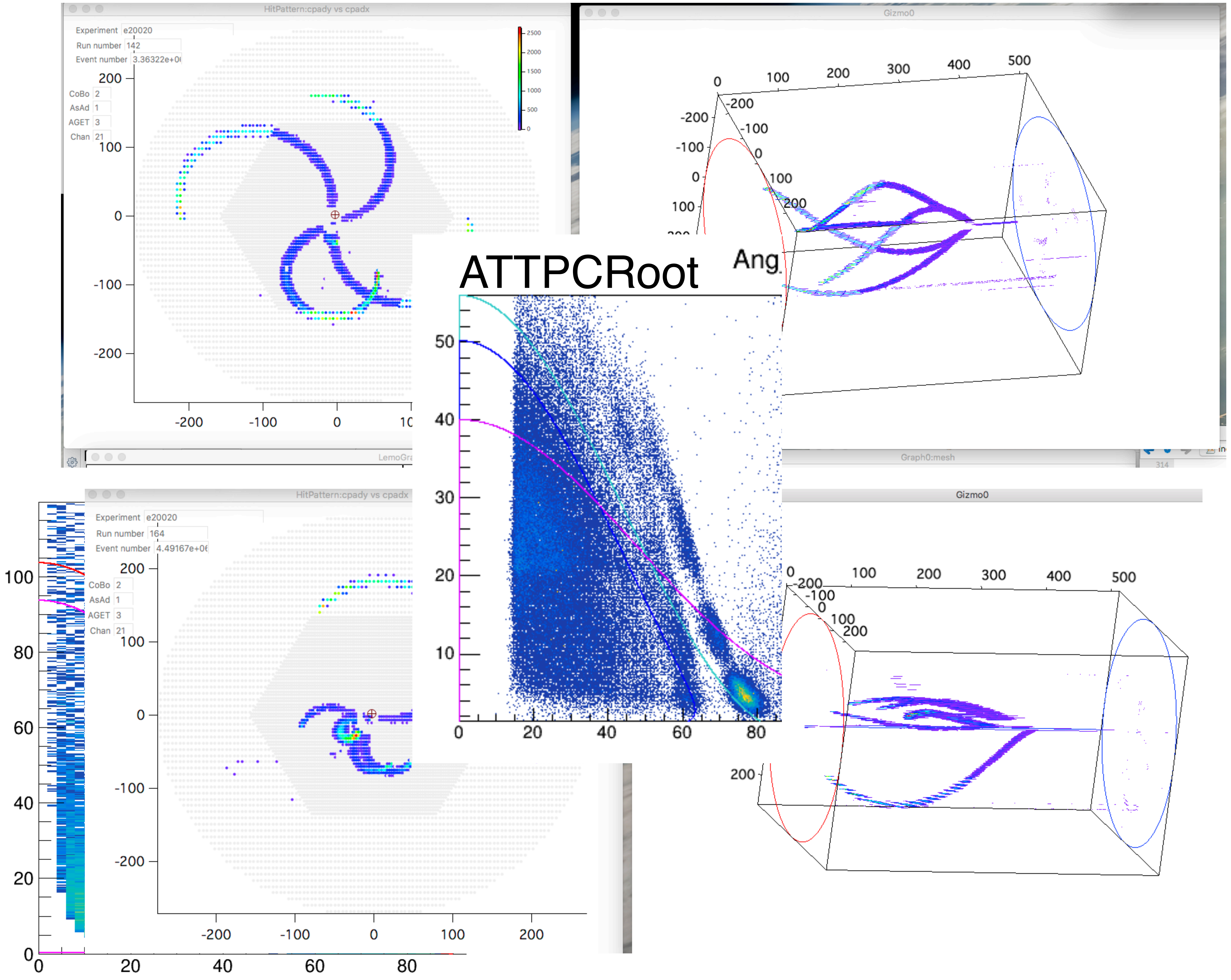
Study of α cluster states in ^{16}O

- ReA6 beam of ^{16}O at 10 MeV/u ~ 5k pps
- AT-TPC filled with 600 Torr of pure He gas
- SOLARIS solenoid set to 3 Tesla
- Trigger set on mesh signal with signal suppression in beam region (smartZAP)
- Several 5-α tracks event candidates seen online
- Ongoing analysis shows elastic and inelastic scattering
- Exploring ML techniques to filter events from track multiplicity



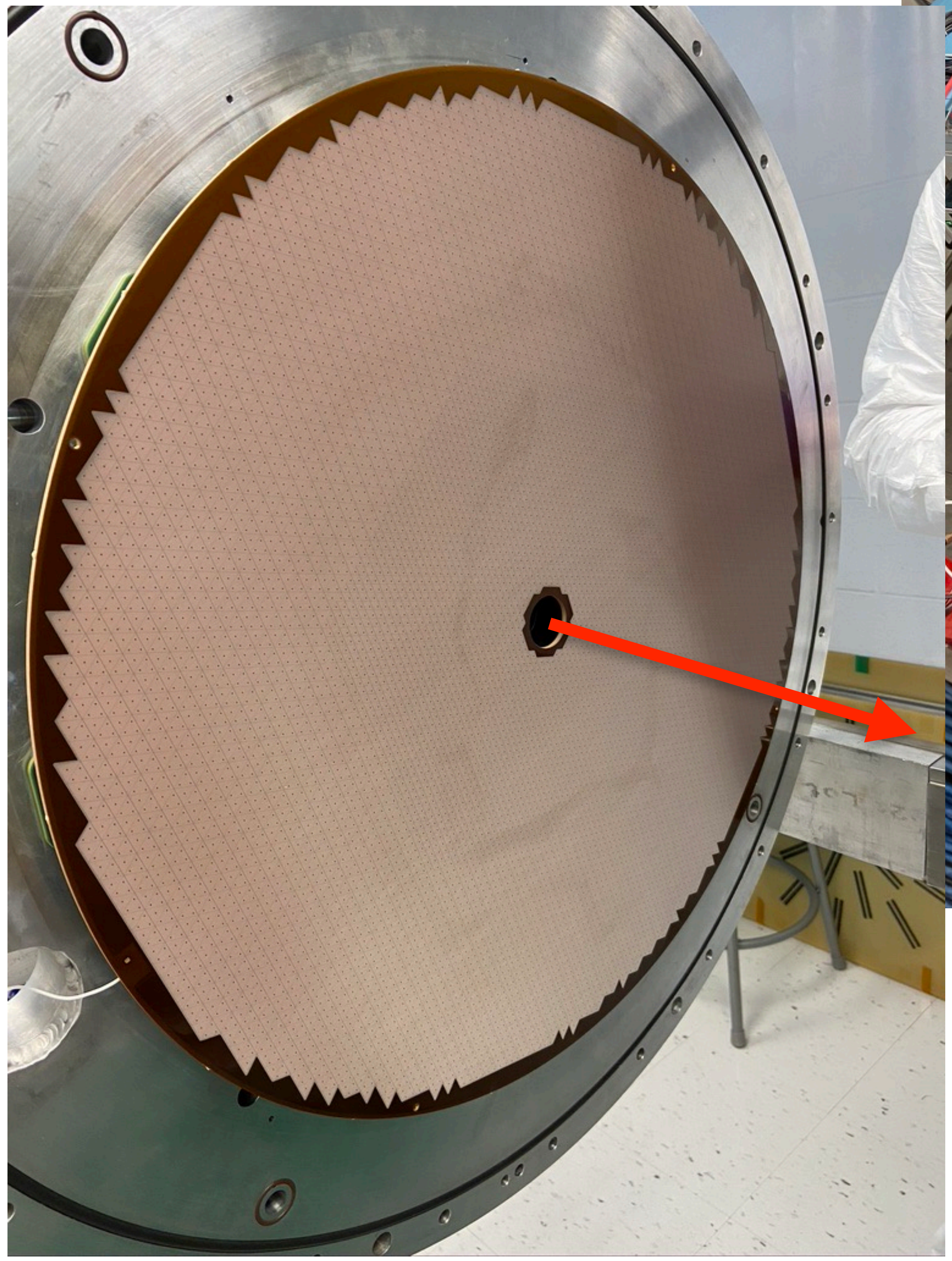
Study of α cluster states in ^{16}O

- ReA6 beam of ^{16}O at 10 MeV/u ~ 5k pps
- AT-TPC filled with 600 Torr of pure He gas
- SOLARIS solenoid set to 3 Tesla
- Trigger set on mesh signal with signal suppression in beam region (smartZAP)
- Several 5-α tracks event candidates seen online
- Ongoing analysis shows elastic and inelastic scattering
- Exploring ML techniques to filter events from track multiplicity



AT-TPC coupled to the S800

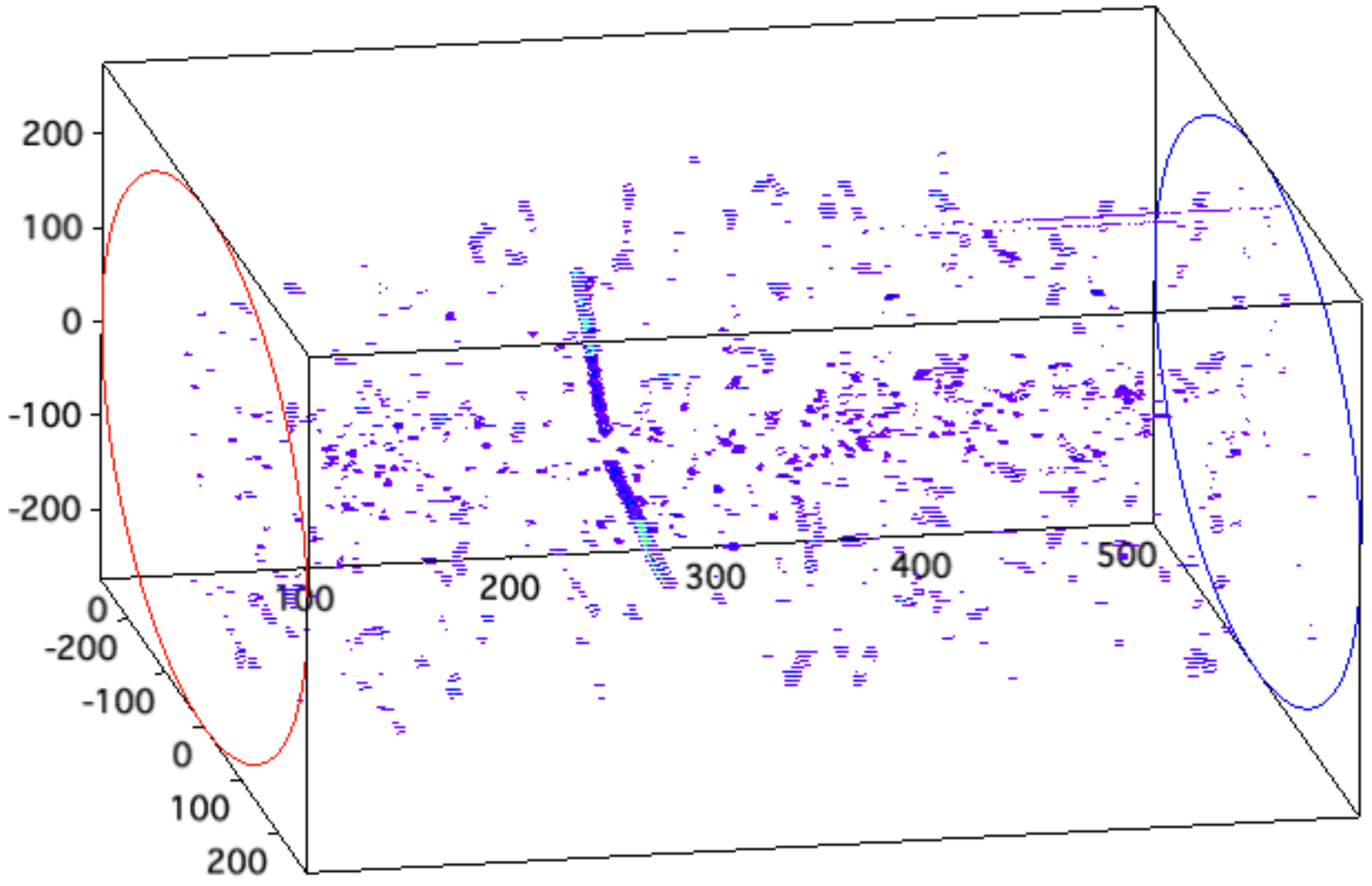
- Use redesigned pad plane with 3cm hole in the middle to let radioactive beam in active volume
- AT-TPC turned around with 4cm window on cathode end to let unreacted beam and beam residues in the S800
- Rates up to 700,000 pps inside the blind beam region were achieved during experiment e18008

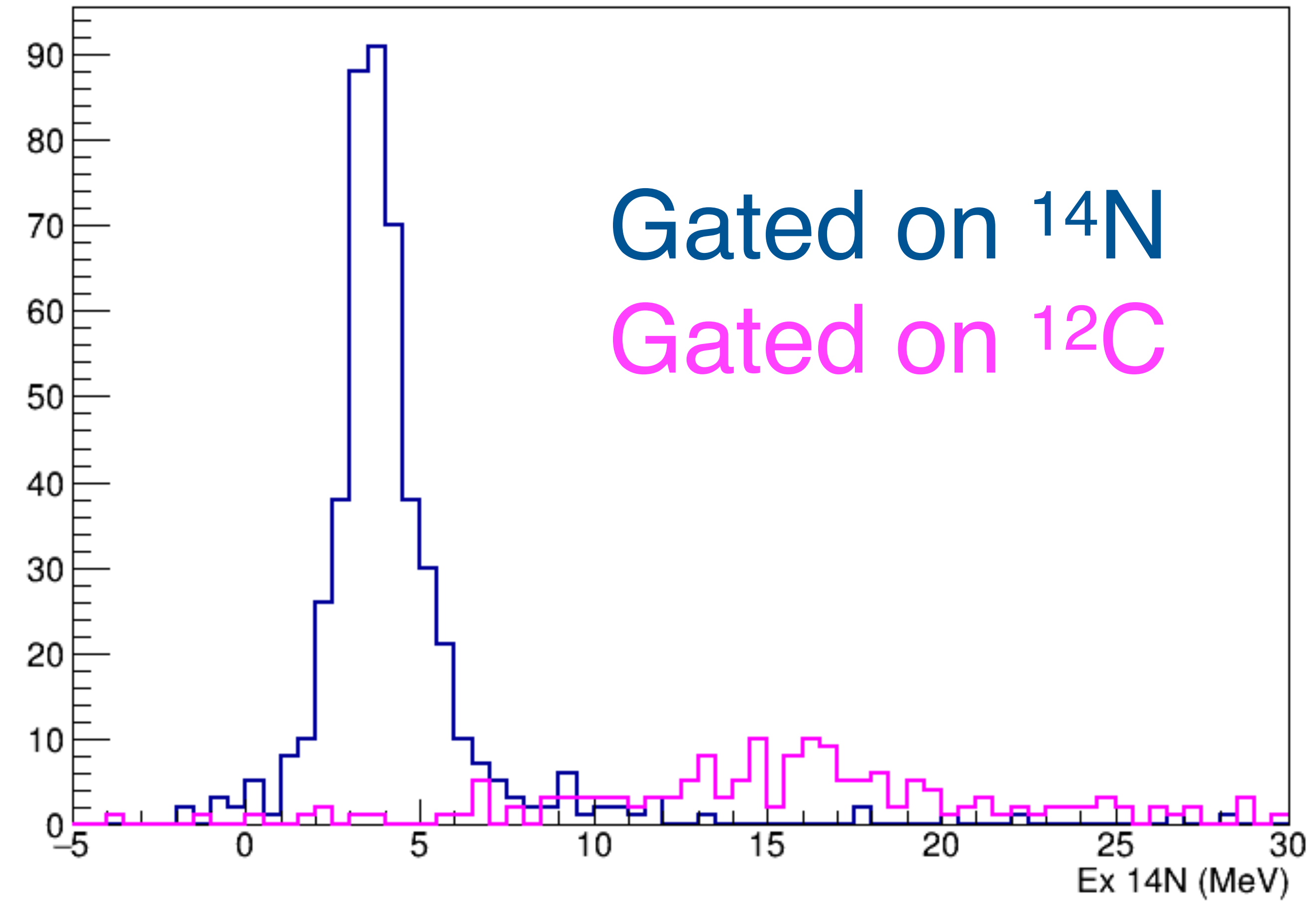


Beam
Residue
Recoil

E18008: $^{14}O(d,^{2}He)$ charge exchange

- Beam of ^{14}O at ~ 100 MeV/u
- AT-TPC filled with pure D_2 gas at 530 Torr
- Use of MTHGEM "electron preamplifier" installed on top of the Micromegas to raise gain to see proton signals
- Trigger provided by the S800
- Two-protons from ^{2}He decay clearly visible
- "Noise" tracks are actually delta electrons
- Online spectrum gated on ^{14}N residue clearly shows strong GT 1^{+} state populated
- Analysis in progress (R. Zegers group)





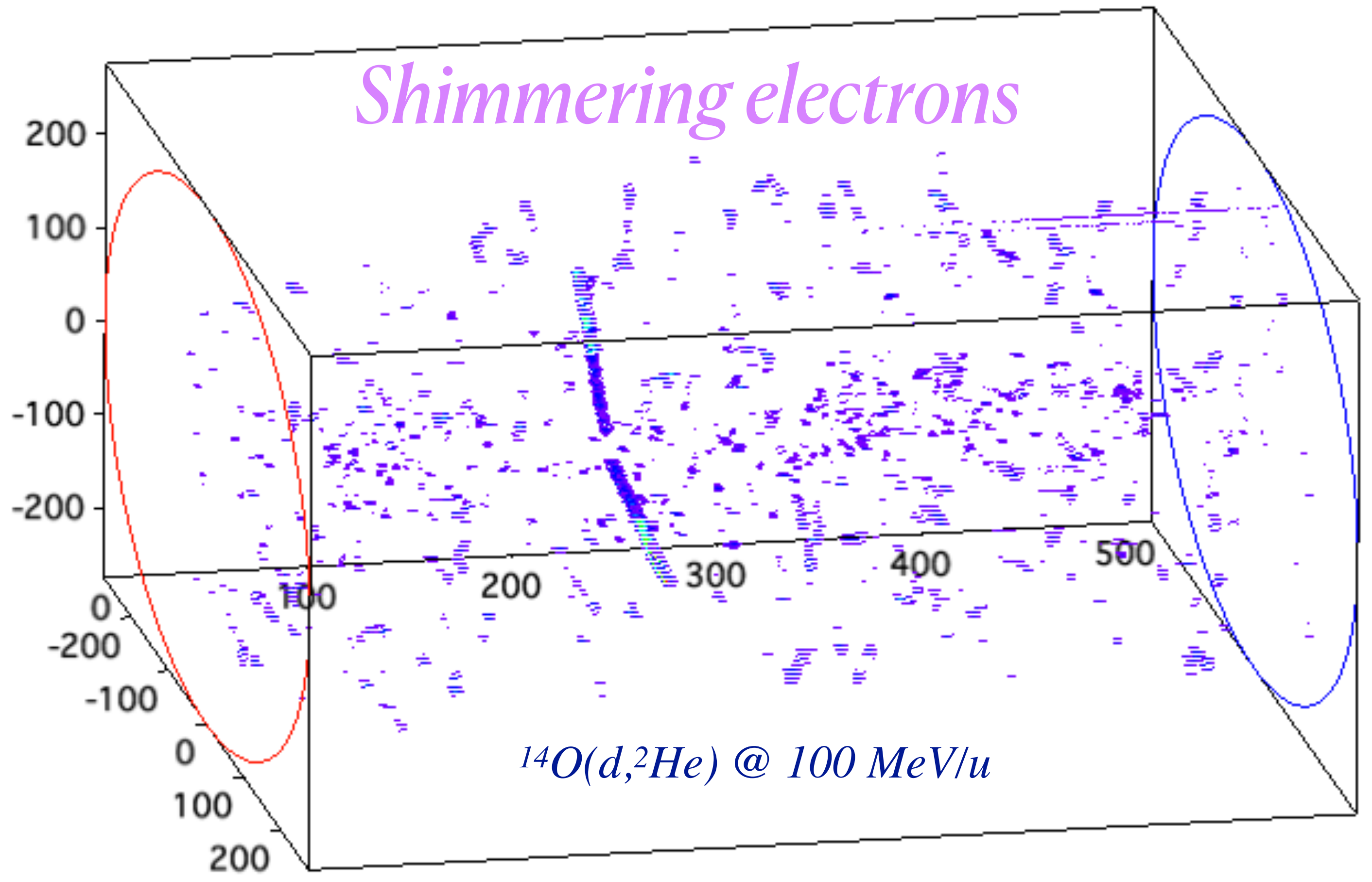
Outlook

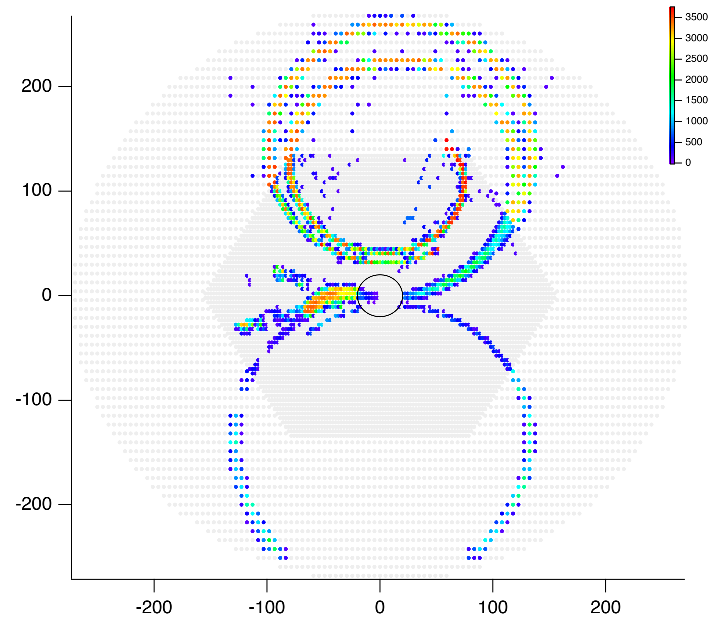
- The AT-TPC is a versatile and powerful tool to measure direct reactions with weak intensity radioactive beams
- High luminosity and good resolution can be achieved when combined with a solenoidal spectrometer such as SOLARIS
- First transfer reaction commissioning experiment on ^{10}Be(d,p)^{11}Be
    - *Preliminary resolution on Q-value: 350 keV*
    - ***Transfer reactions*** *can be performed with intensities as low as ~* ***100 pps***
- Operation of AT-TPC in transmission mode
    - *Can be coupled to spectrometer or Si-based recoil detector to measure heavy residues*
    - *Higher intensities allow to reach smaller cross sections (tested up to 700,000 pps)*

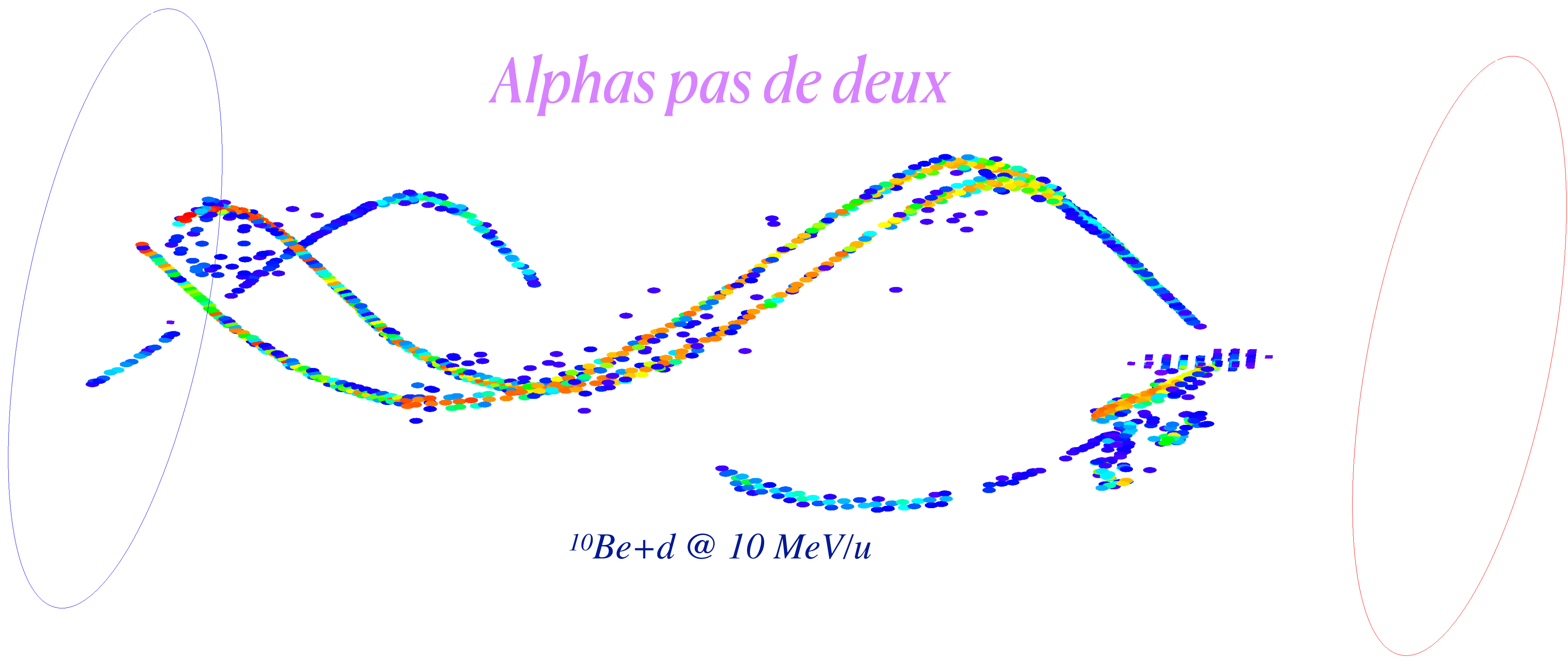
AT-TPC collaboration

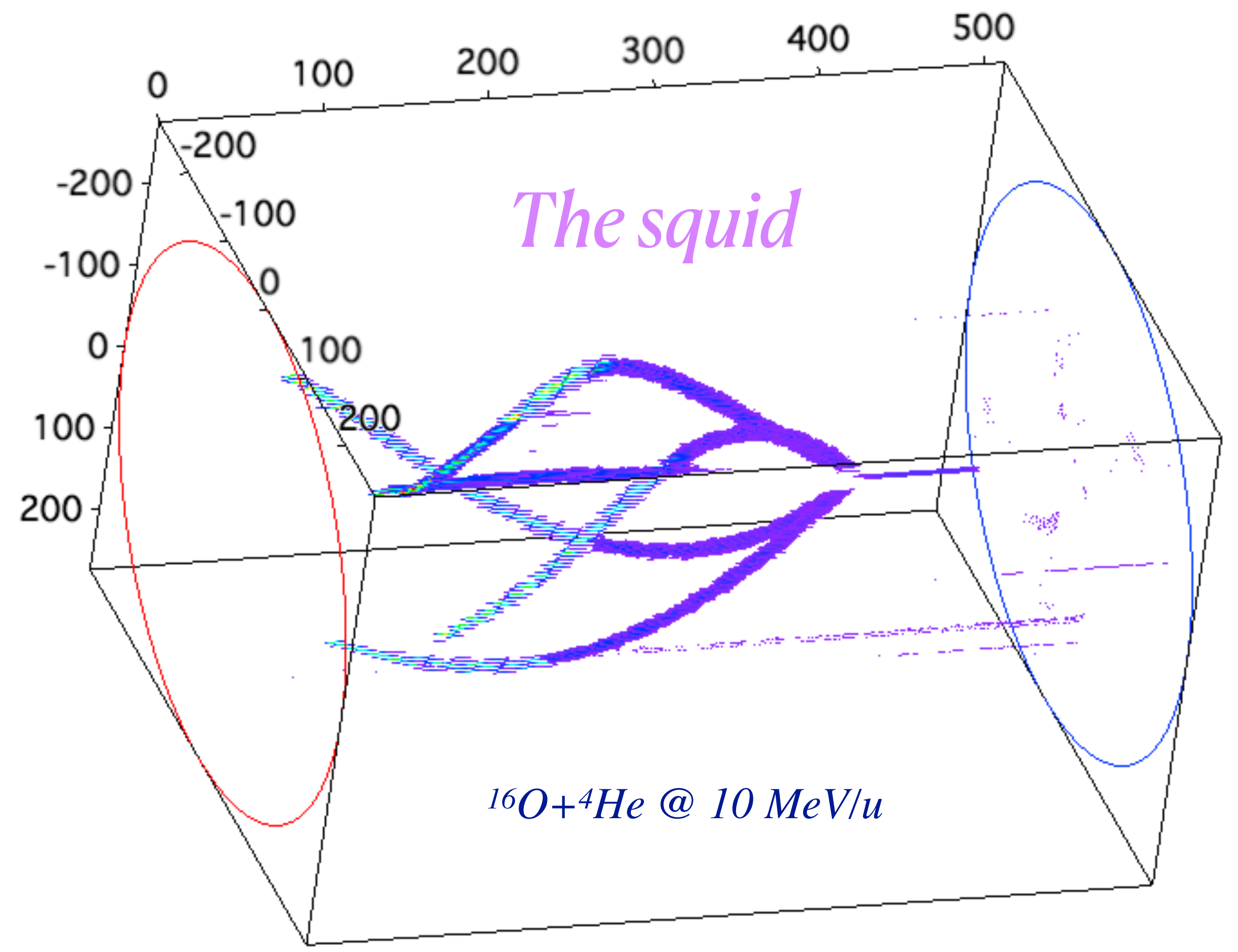
(The ^{10}Be sample was provided by the Paul Scherrer Institute)

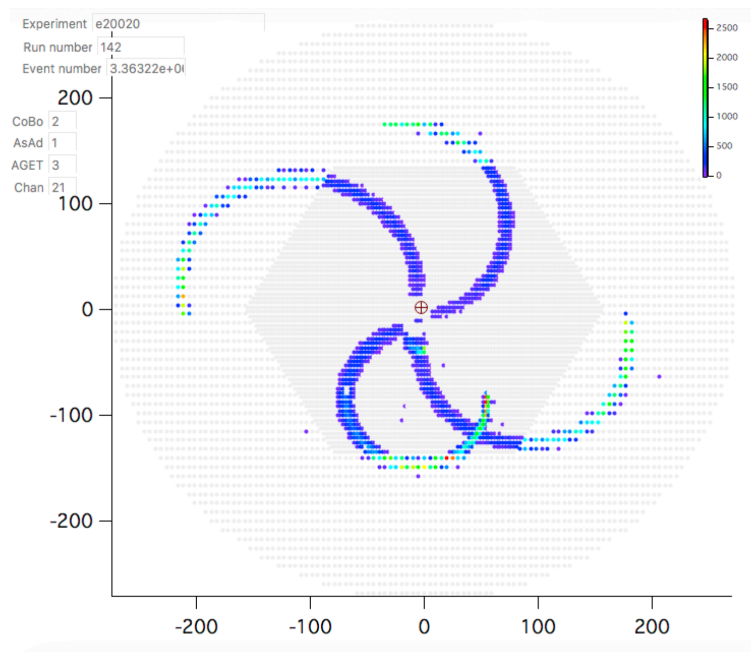
AT-TPC: an (art?) gallery

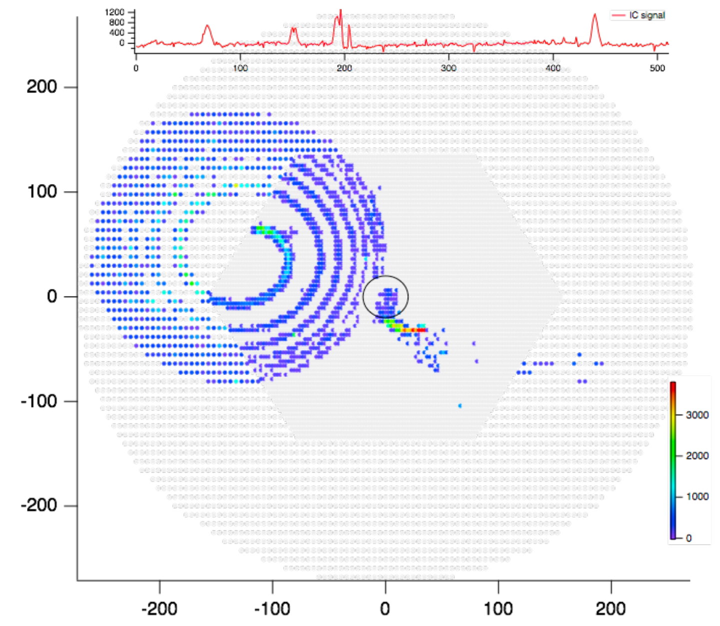


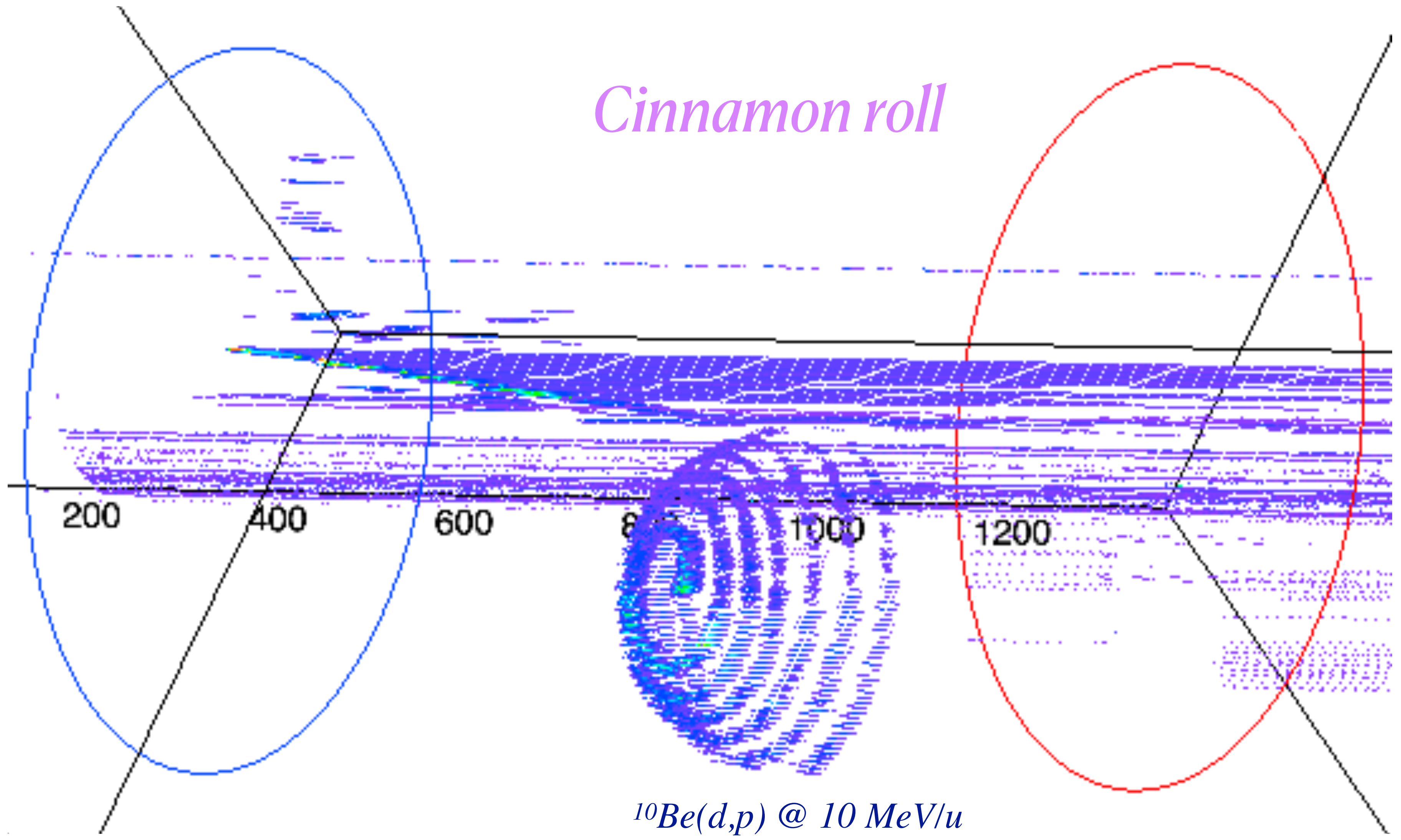












U.S. Department of Energy Office of Science
National Science Foundation
Michigan State University