Reaction Studies with the Active Target Time Projection Chamber

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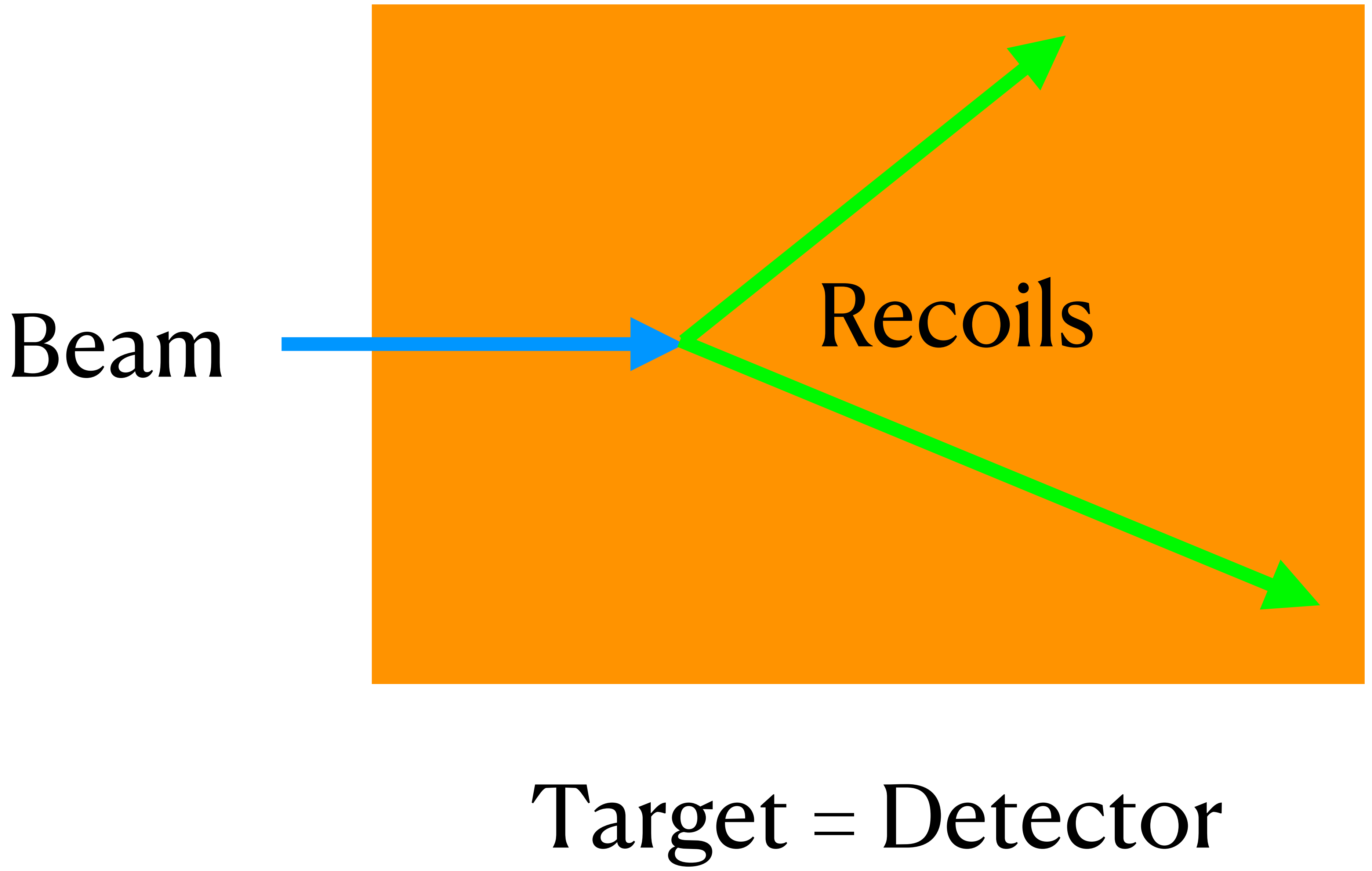
This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support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

In-beam γ-ray vs missing mass methods

- In-beam γ-ray: spectroscopy relies solely on properties of beam-like residue
  - *Inverse kinematics and high energy allow thick targets and small scattering angles → **high luminosity***
  - *Determination of partial cross sections needs to take into account **feeding** from higher energies*
  - *Lifetime of populated states cannot be to long (**isomer**)*
  - *Cross section to **ground state** cannot be directly measured (again, feeding…)*
  - *Cross section to **unbound states** difficult to measure (requires detection of emitted nucleon(s))*
- Missing mass spectroscopy in inverse kinematics: using the target-like residue
  - *Direct measurement of cross sections to populated states, **bound and unbound***
  - ***Lifetime** of populated states doesn't matter*
  - *But inverse kinematics turns from a friend into a **foe**, large ranges of energies and scattering angles*
  - *Compromise between **resolution** and target **thickness** is necessary → **low luminosity***

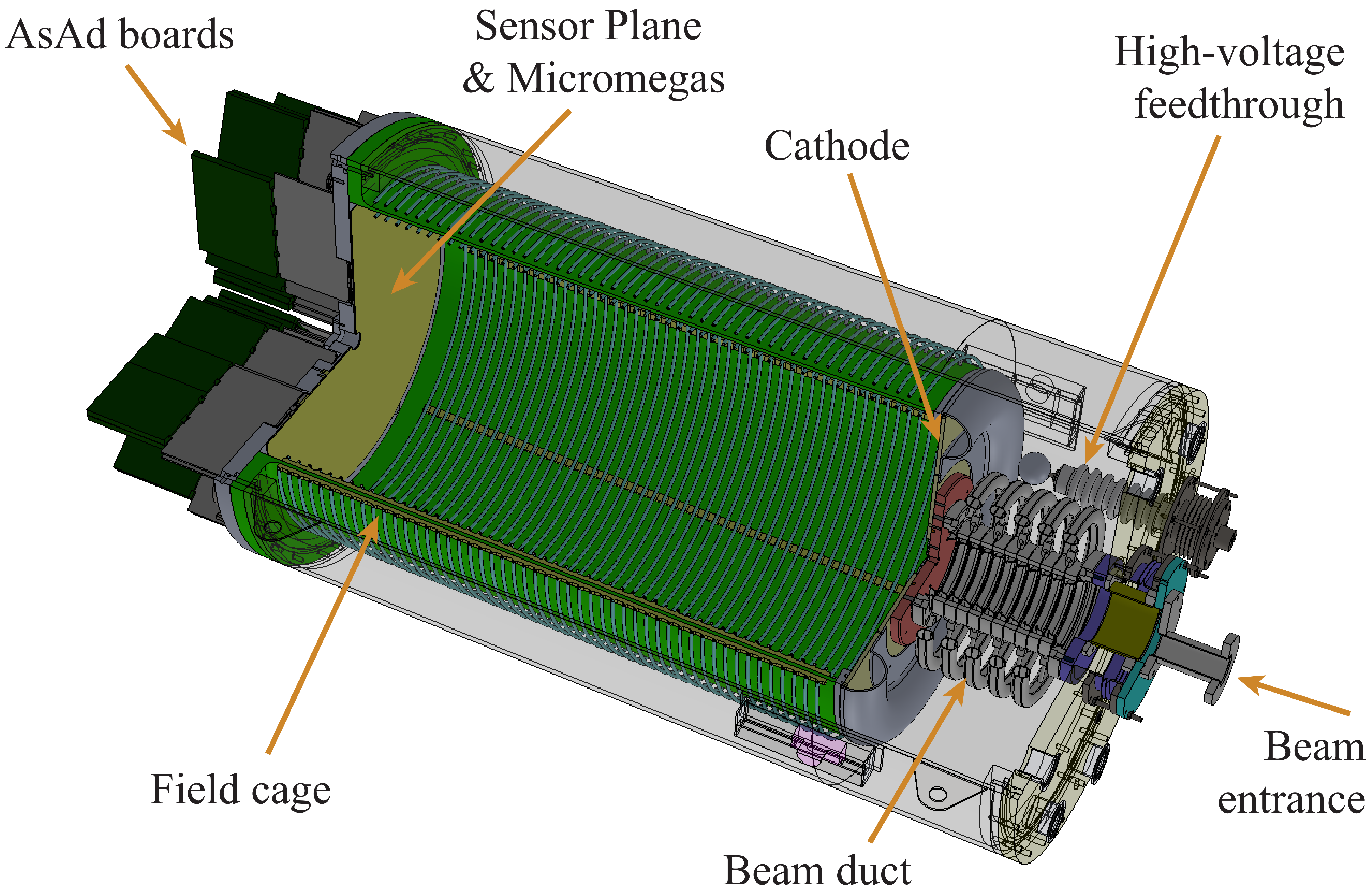
The promise of active targets

- Target thickness not constrained by energy resolution
  - *Gains of 2-3 orders of magnitude in thickness*
  - *Pure gas targets H_2, D_2 and $^{3,4}He$*
  - *Vertex and energy of each reaction measured*
- Solid angle coverage not limited by angular resolution and/or cost
  - *Detecting recoils inside target maximizes angular coverage*
  - *Geometrical efficiency close to 80%*
  - *Multiple reaction channels can be measured*
- Inverse kinematics requirements
  - *Need angular resolution < 1°*
  - *Need energy resolution < 200 keV*

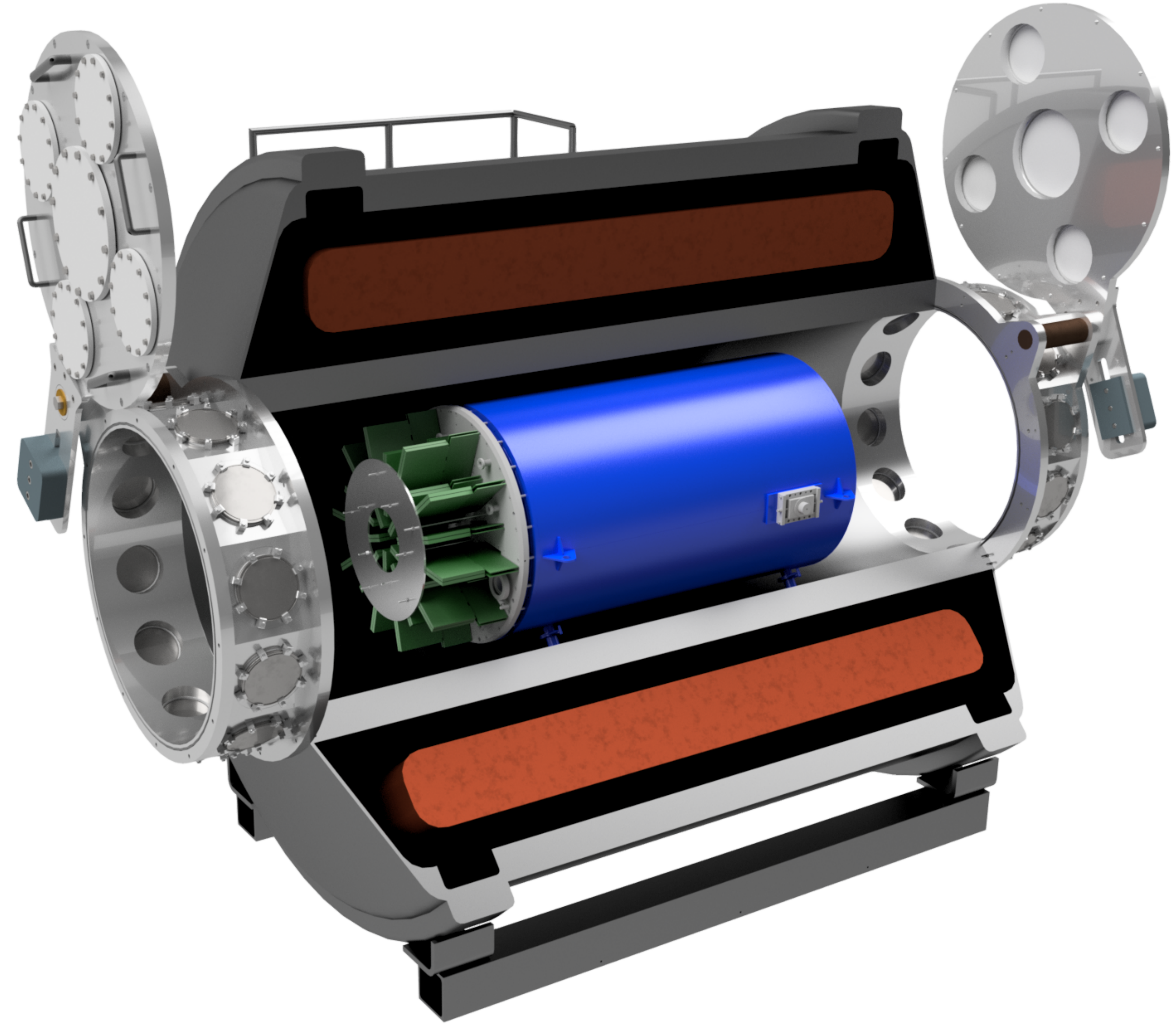


AT-TPC @ SOLARIS

Active Target Time Projection Chamber

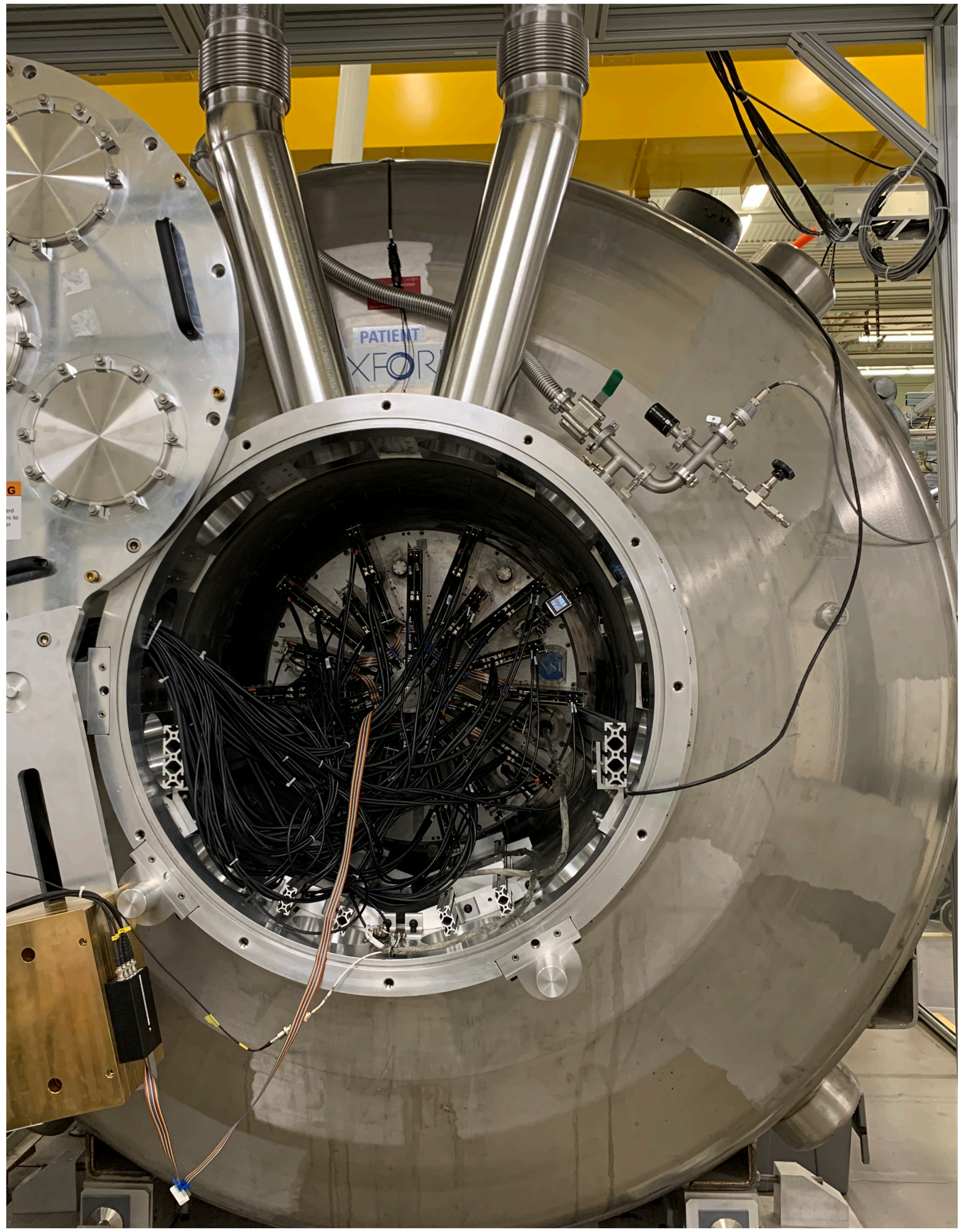


Solenoidal Spectrometer Apparatus for Reaction Studies



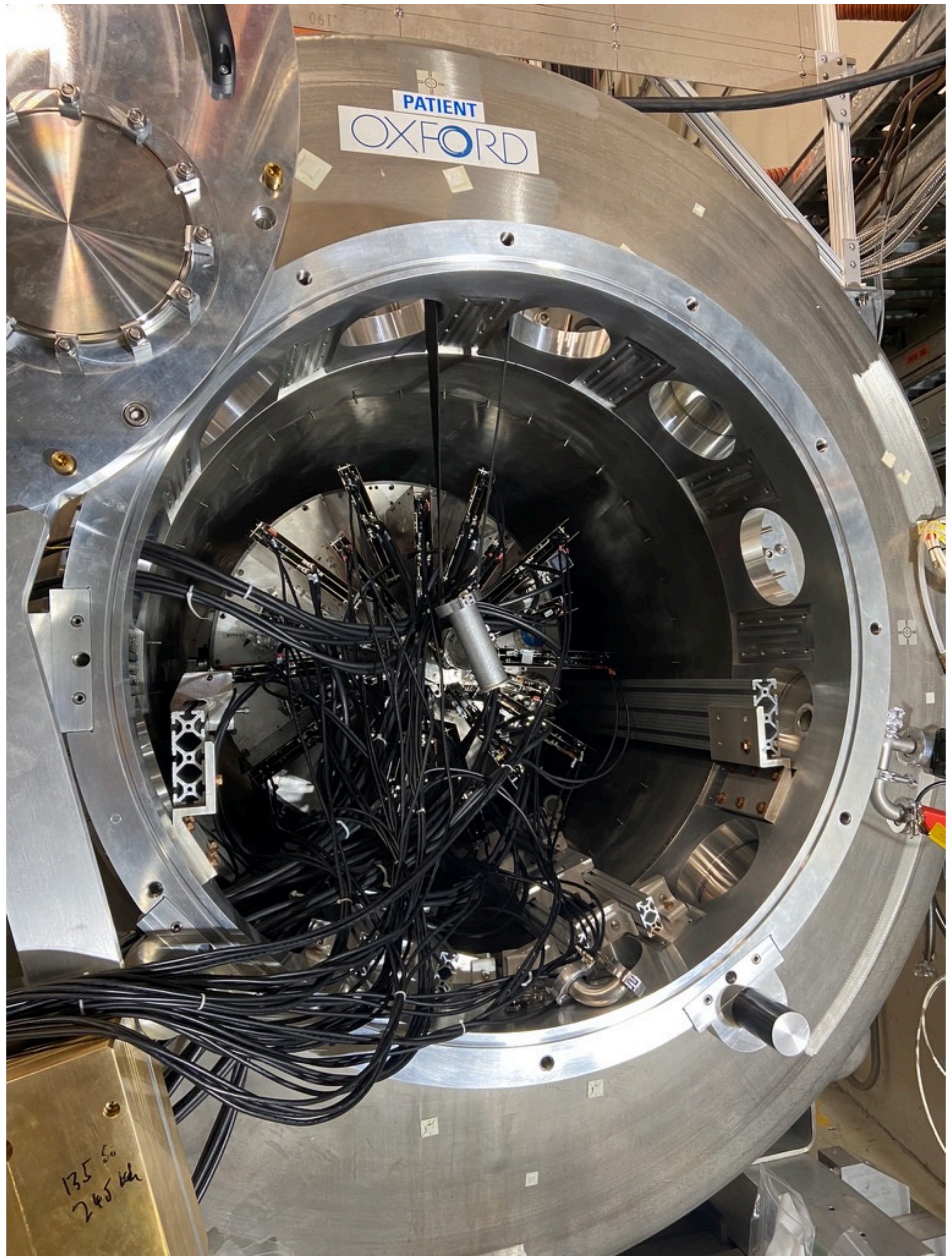
Two dual-mode solenoidal spectrometers

SOLARIS @ FRIB



- Complementarity of detector setups
  - *Si-array for > 10^4 pps*
  - *AT-TPC for < 10^4 pps*
- Complementarity of facilities
  - *FRIB + ReA6 for isotopes far from stability*
  - *ATLAS + RAISOR for isotopes ±1n ±2n*

HELIOS @ ATLAS



Scientific themes of the AT-TPC

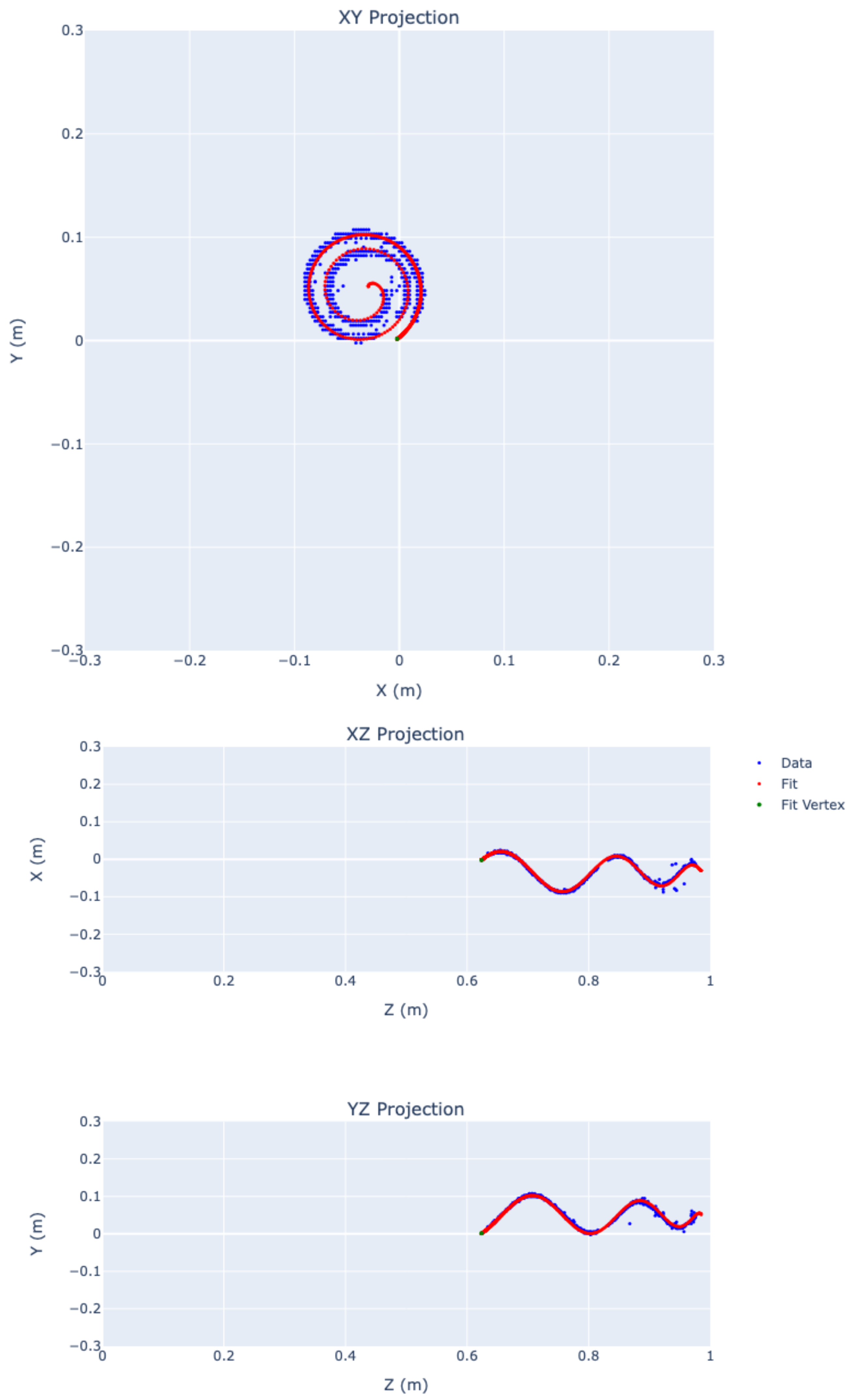
- Spectroscopy of rare nuclei using “simple” reactions in inverse kinematics
  - *Gains in luminosity of 2-3 orders of magnitude without compromising resolution*
- Study of near-threshold resonances and their decay modes using resonant scattering
  - *Invariant mass method applicable when all particles from decay are detected*
- Excitation functions of astrophysical interest reactions on unstable nuclei
  - *Beam energy loss in gas can be used to measure excitation functions*
- Collective excitations in rare nuclei
  - *SDR and GDR probed via inelastic scattering at higher energies*
- Gamov-Teller strength in the n-p direction using (d,^{2}He) charge exchange reactions
  - *Using equivalence between charge-exchange cross sections and GT strength at low momentum transfer*
- Weak β-decay branches at very low Q-values
  - *β-delayed proton emission from ^{11}Be*

Measurements performed since 2020

- Transfer reaction commissioning
  - ^{10}Be(d,p)^{11}Be, **^{10}Be(d,d')^{10}Be*** and **^{10}B(d,p)^{11}B** (2020@SOLARIS)
    - [57] by Z. Serikow on ^{11}Be (NS7 Thu 5:30)
- Resonant scattering
  - ^{16}O(α,α')^{16}O* (2021@SOLARIS)
    - Search for ^{16}O 0^+ Hoyle resonance
  - ^{10}Be(α,α')^{10}Be* (2023@SOLARIS)
    - Search for 0^+ deformed band-head resonance
- Campaign on transfer reactions (2023@HELIOS)
  - Reactions between ^{14}C and p target
  - Reactions between **^{12}Be** and **p** target
  - Reactions between ^{15}C and p, d targets
    - Quenching factors from transfer reactions
  - Reactions between **^{16}C** and p, **d**, α targets
  - Reactions between ^{7}Be and d target
    - Search for unbound resonances in ^{6}Be
- Campaign at S800 (just completed)
  - ^{32}Mg(d,^{2}He)^{32}Na
  - ^{11}Li(p,p')

New AT-TPC analysis package: Spyral

- Analysis library in Python
  - *Python: readability and "simplicity"*
  - *Scalable: parallel processing of multiple runs*
  - *Performant through use of Just-In-Time compiler Numba*
  - *Pip-installable and cross-platform*
  - *Interface with many leading analysis libraries (numpy, scipy, scikit-learn, etc)*
- Available at GitHub (https://github.com/ATTPC/Spyral) as source code or as installable Python package (https://pypi.org/project/attpc_spyral/)

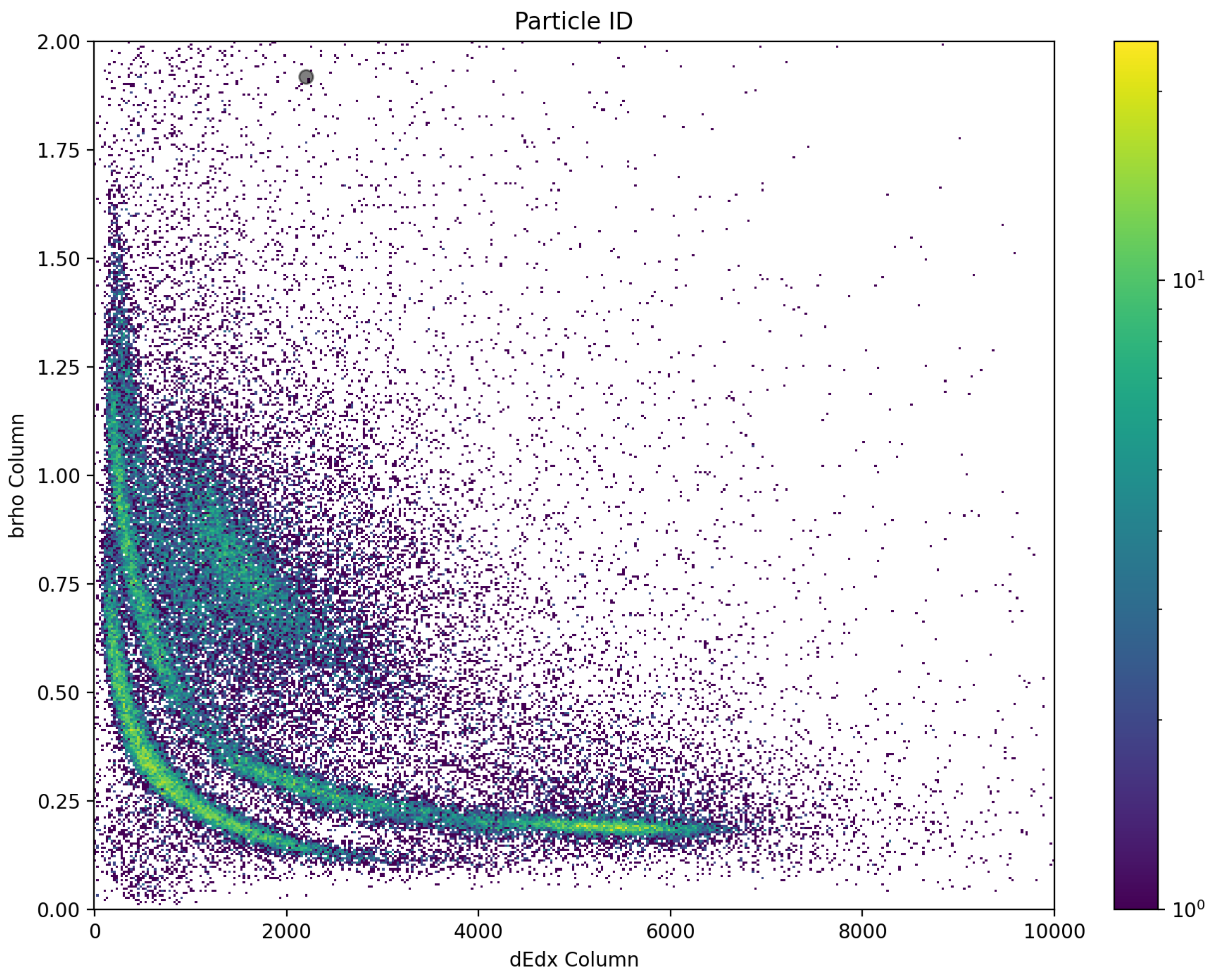


From Gordon McCann

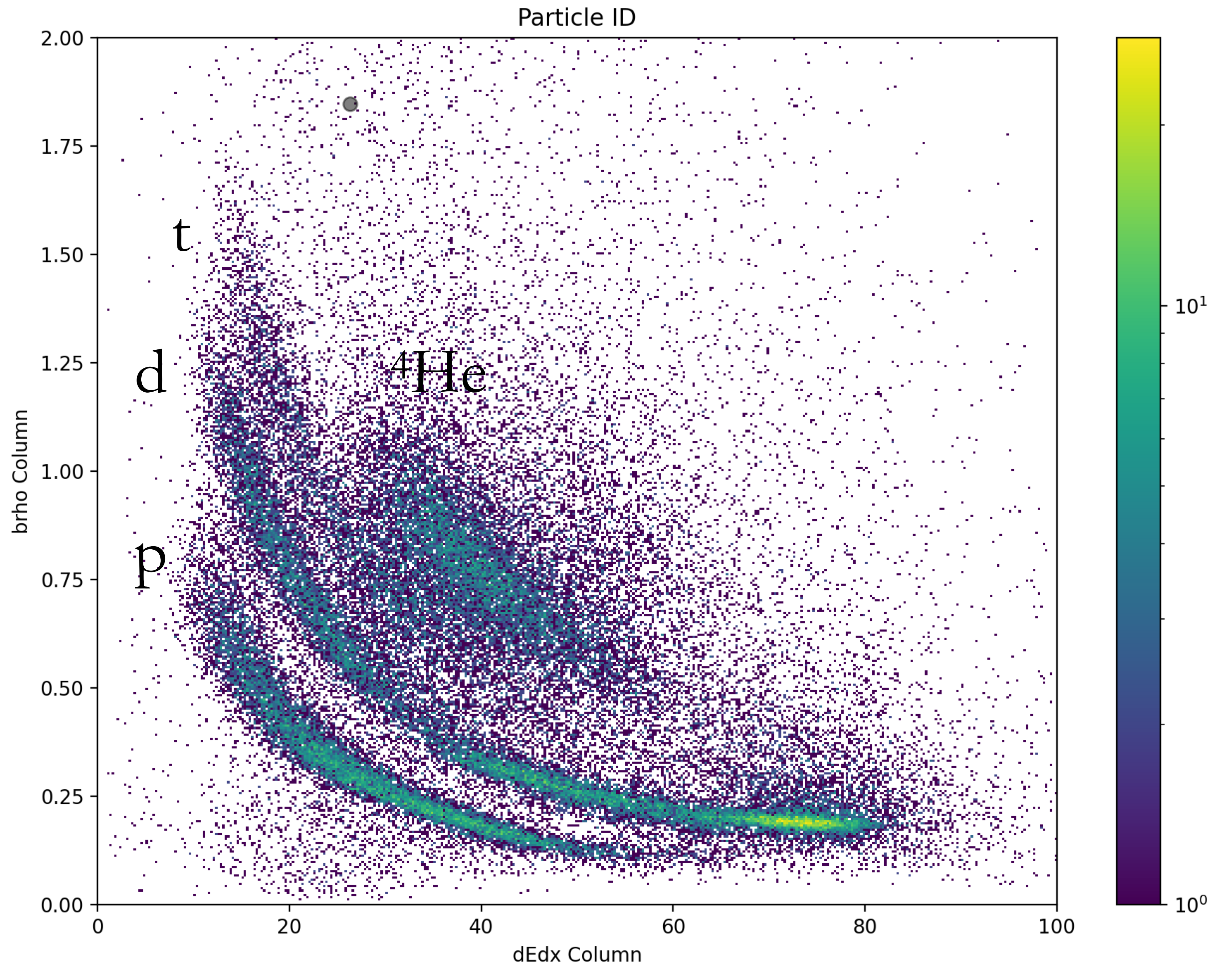
Particle identification in AT-TPC

- Magnetic rigidity
  - *From curvature of track & polar angle*
- Energy loss
  - *From charge deposited along track*
- Large dynamic range
  - *Due to inverse kinematics*
  - *Square-root representation*

Linear dE/dx



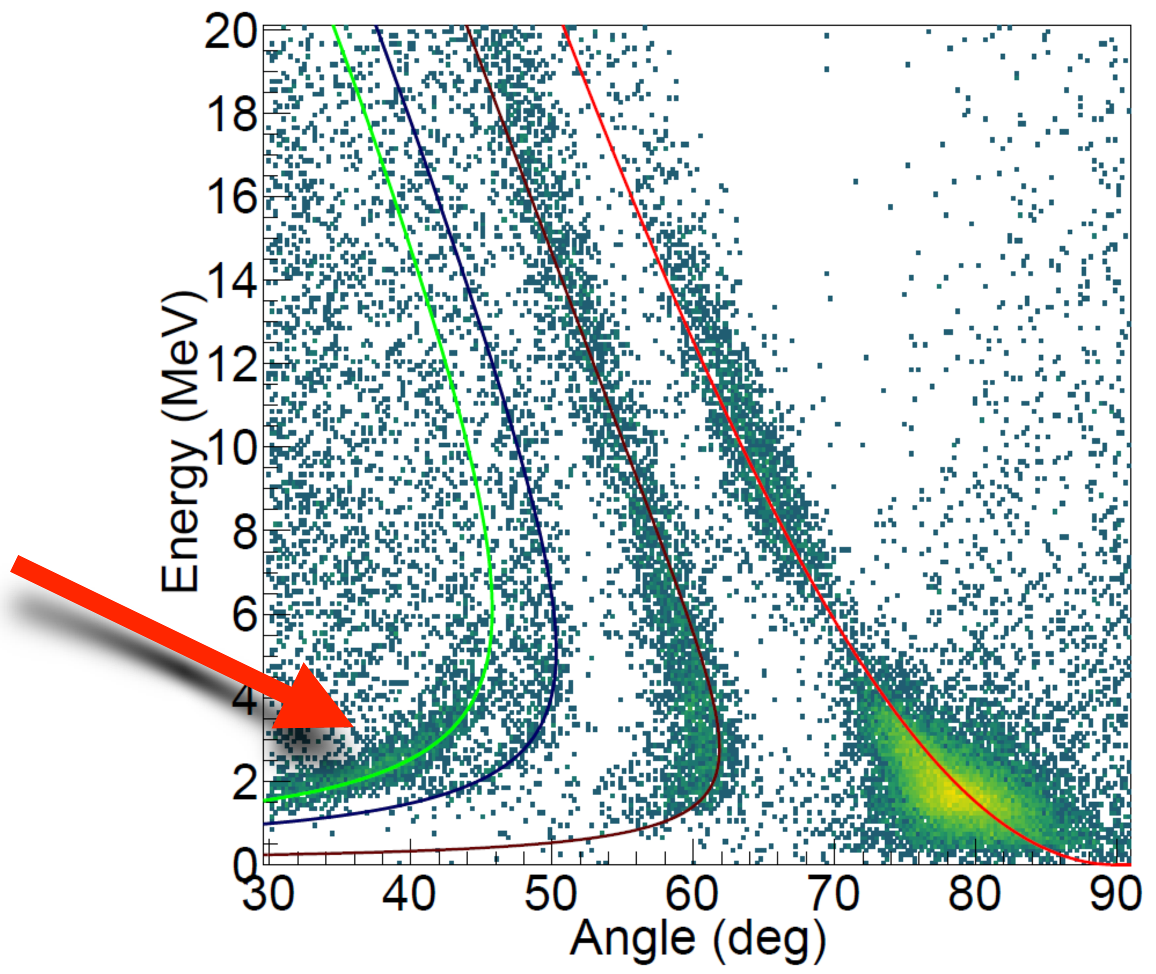
Sqrt dE/dx

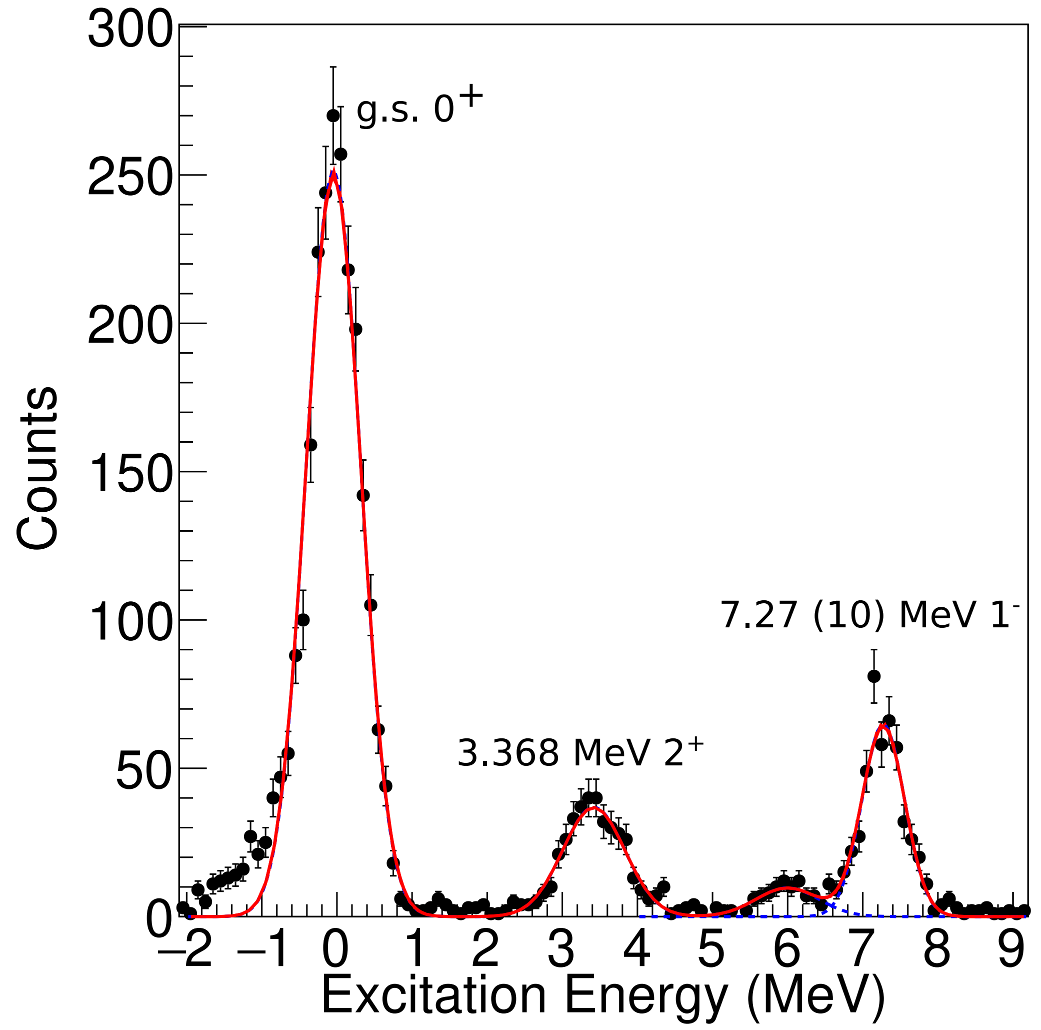


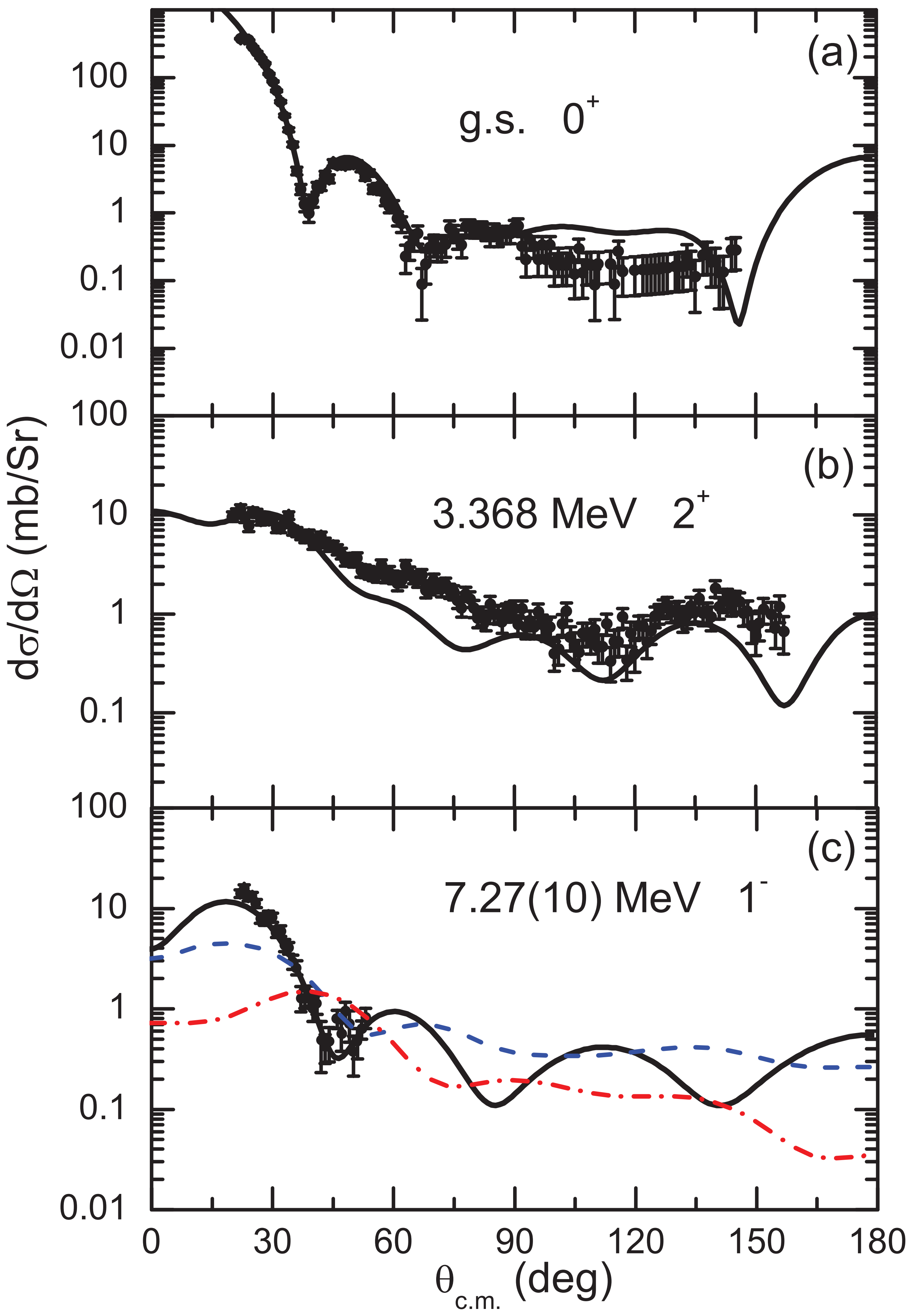
Analysis by G. McCann

Inelastic scattering $^{10}Be(d,d)^{10}Be^*$

- Isoscalar dipole resonance in ^{10}Be
  - *Observed at 7.37 MeV from ^{9}Be(d,p) as 3^-*
  - *Located near S_α (7.4 MeV)*
  - *Identified as 1^- from angular distribution*
  - *Best fit of angular distribution using dipole deformation length of δ_1=0.76 fm*
  - *Pronounced α cluster structure (5-15% of IS-EWSR)*
  - *Various theories using coupling to the continuum are able to reproduce the observed dipole strength*
- Submitted to PRL (J. Chen, Y. Ayyad et al.)

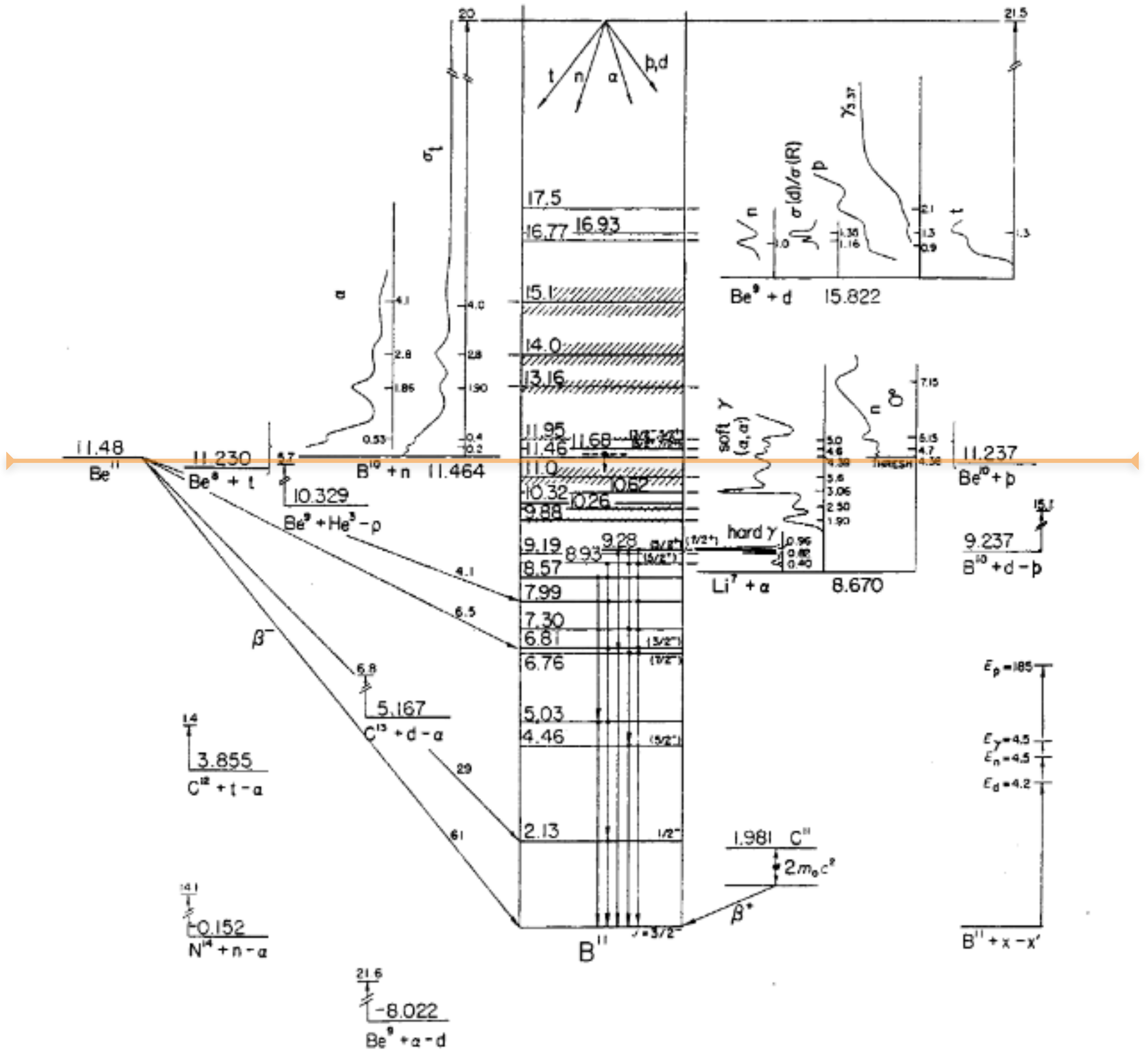




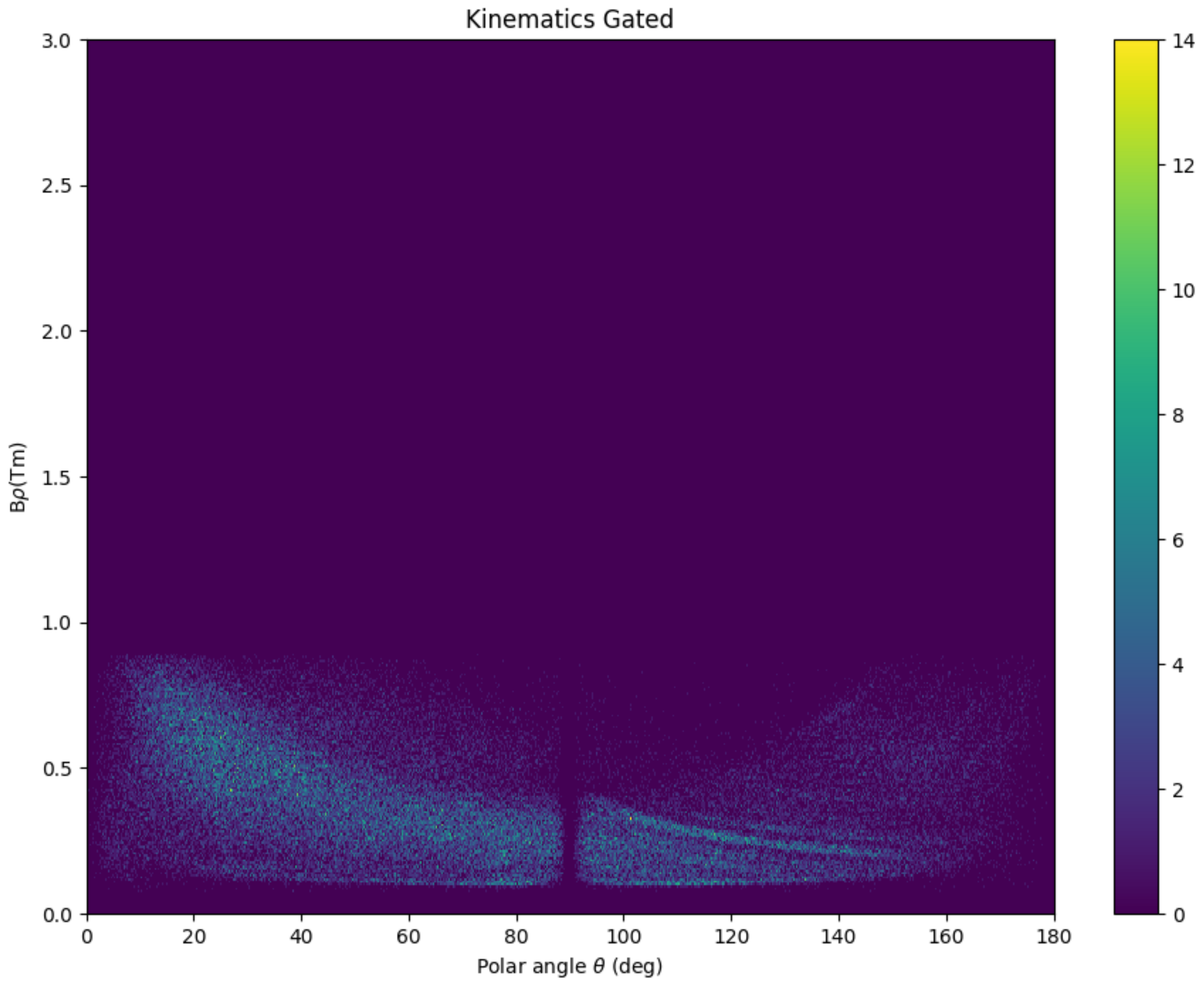


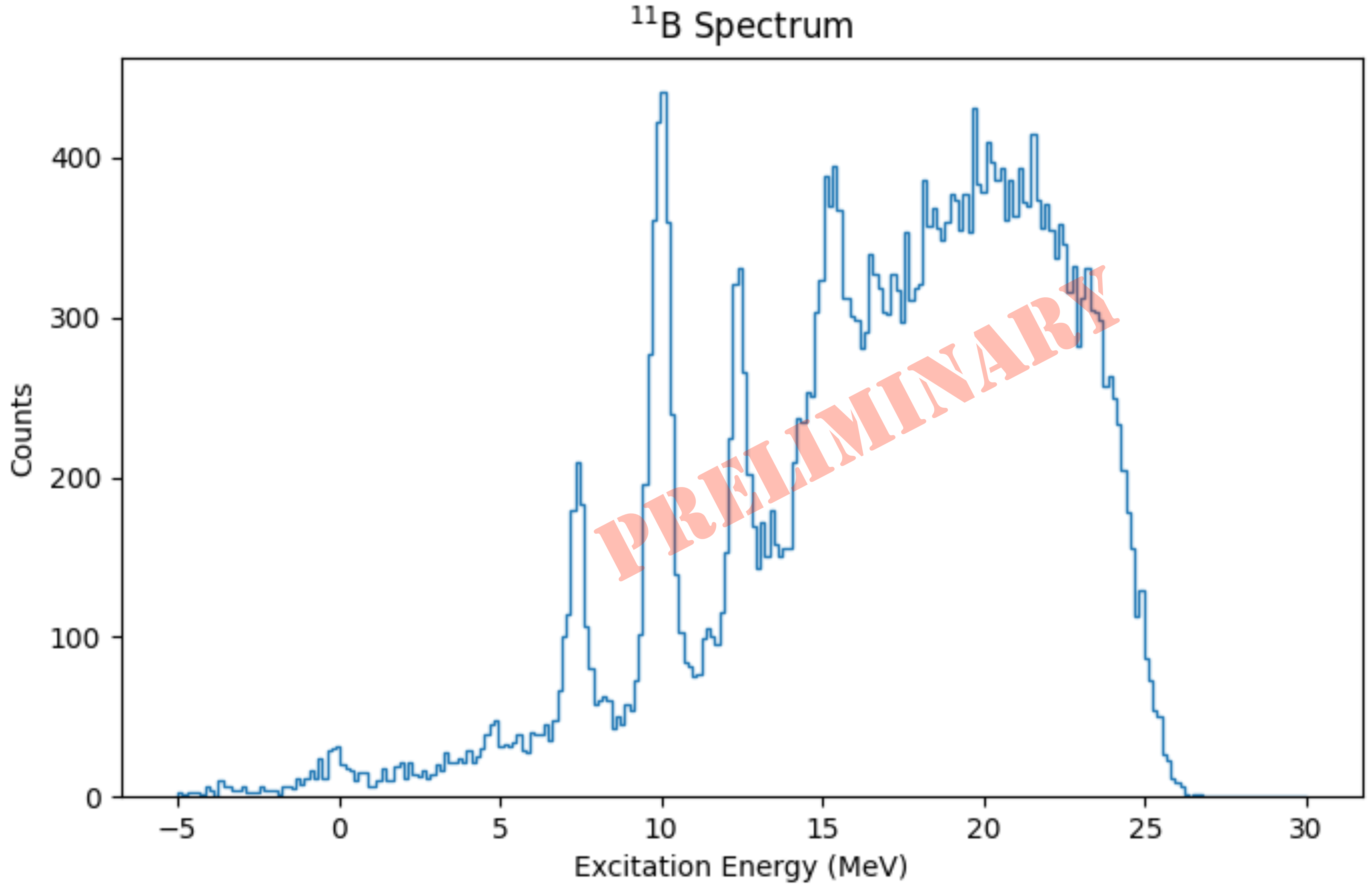
$^{10}B(d,p)^{11}B$

- ^{10}B contamination present in ^{10}Be beam
- Large Q_{value}=9.23 MeV allows population of high-lying resonances in ^{11}B
- Strong interest in resonances at around 11 MeV due to several thresholds
- β-decay proton emission of ^{11}Be
- AT-TPC is capable of measuring particle decay residues of $^{11}B^{*}$ resonances
- Branching ratios could inform on the structure of these resonances



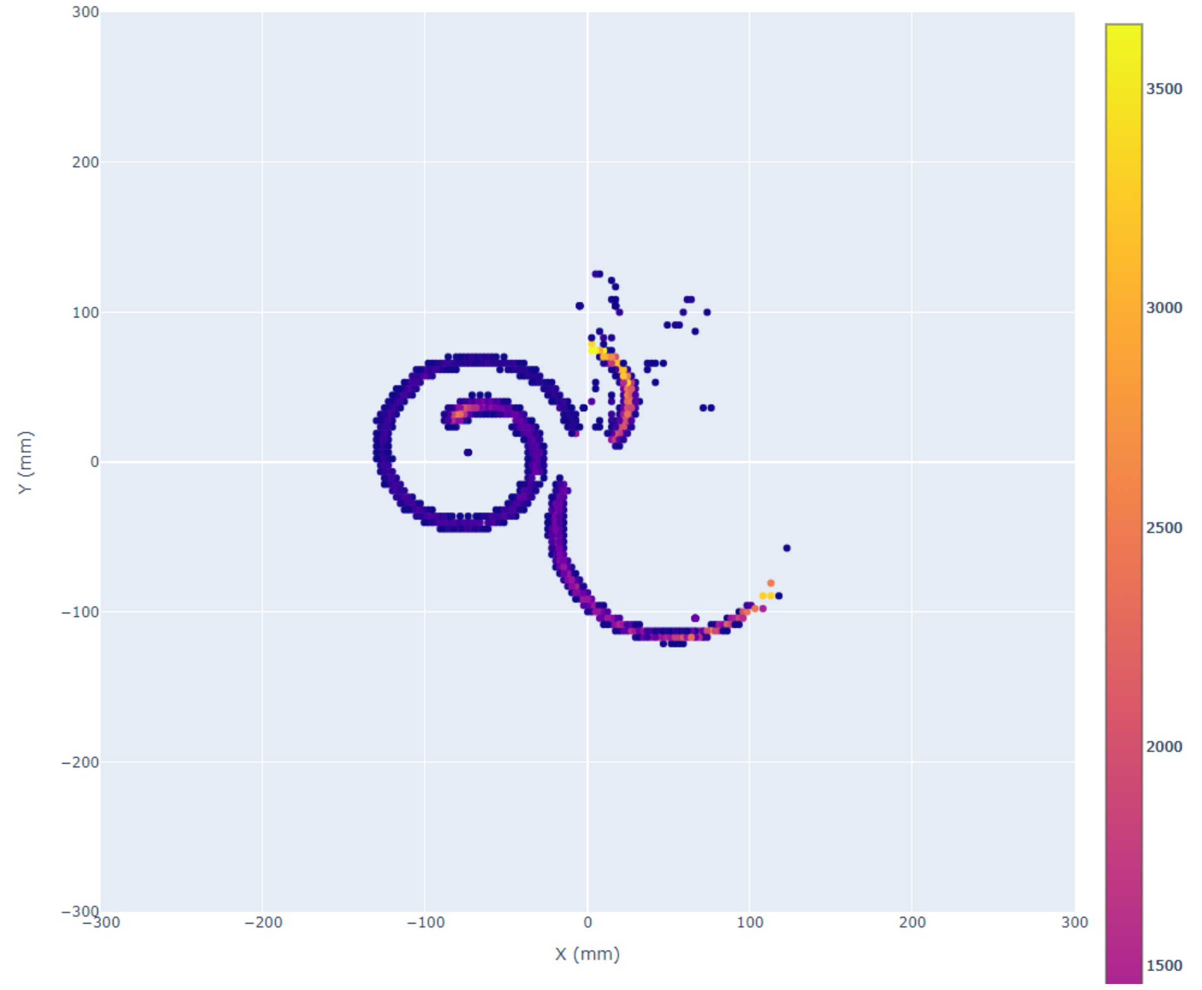
Analysis of $^{10}B(d,p)^{11}B$



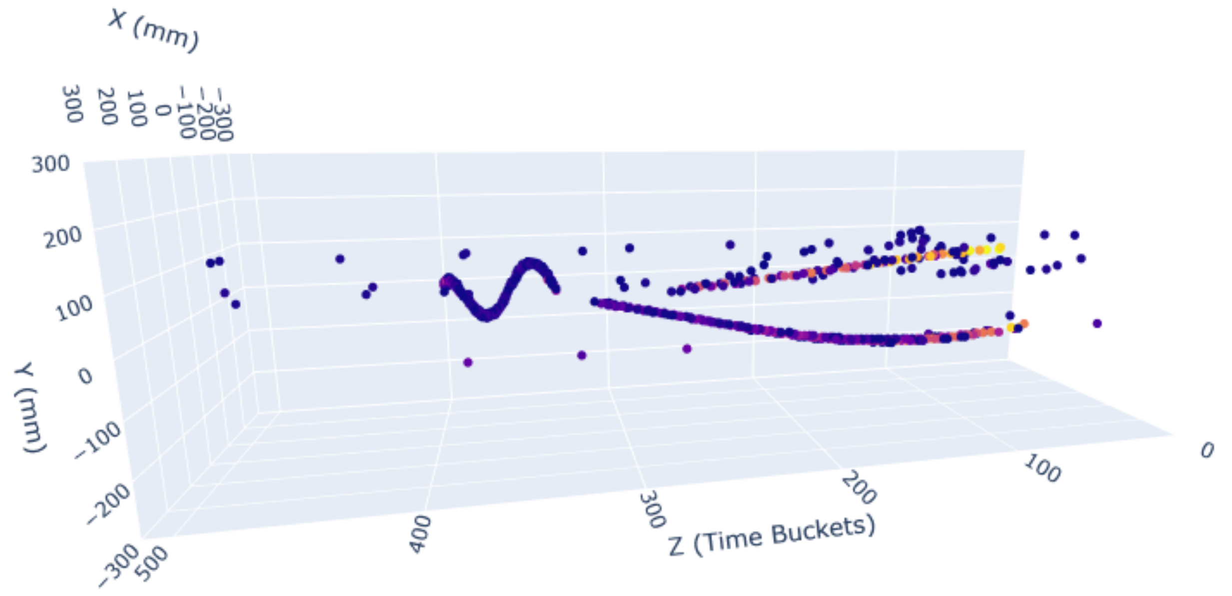


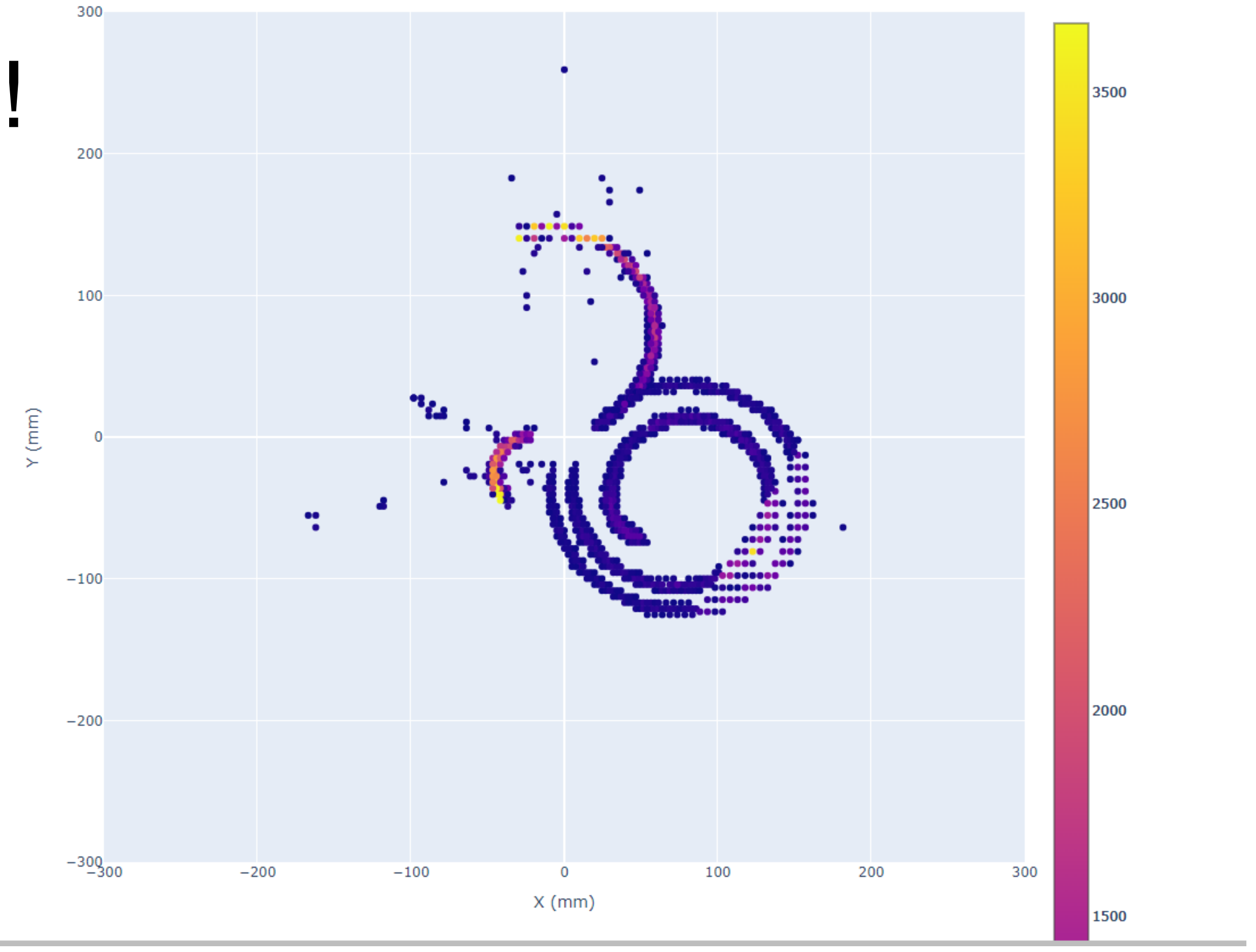
Analysis by T. Schaeffeler

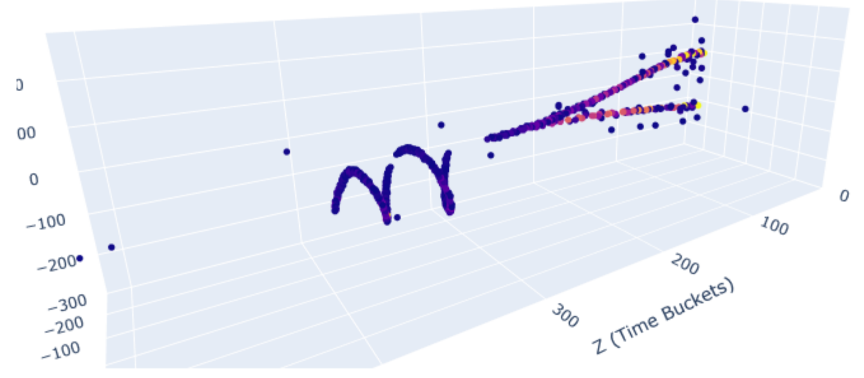
$^{10}B(d,p)^{11}B^* \rightarrow {}^{7}Li + {}^{4}He$ event from 10.6 MeV peak

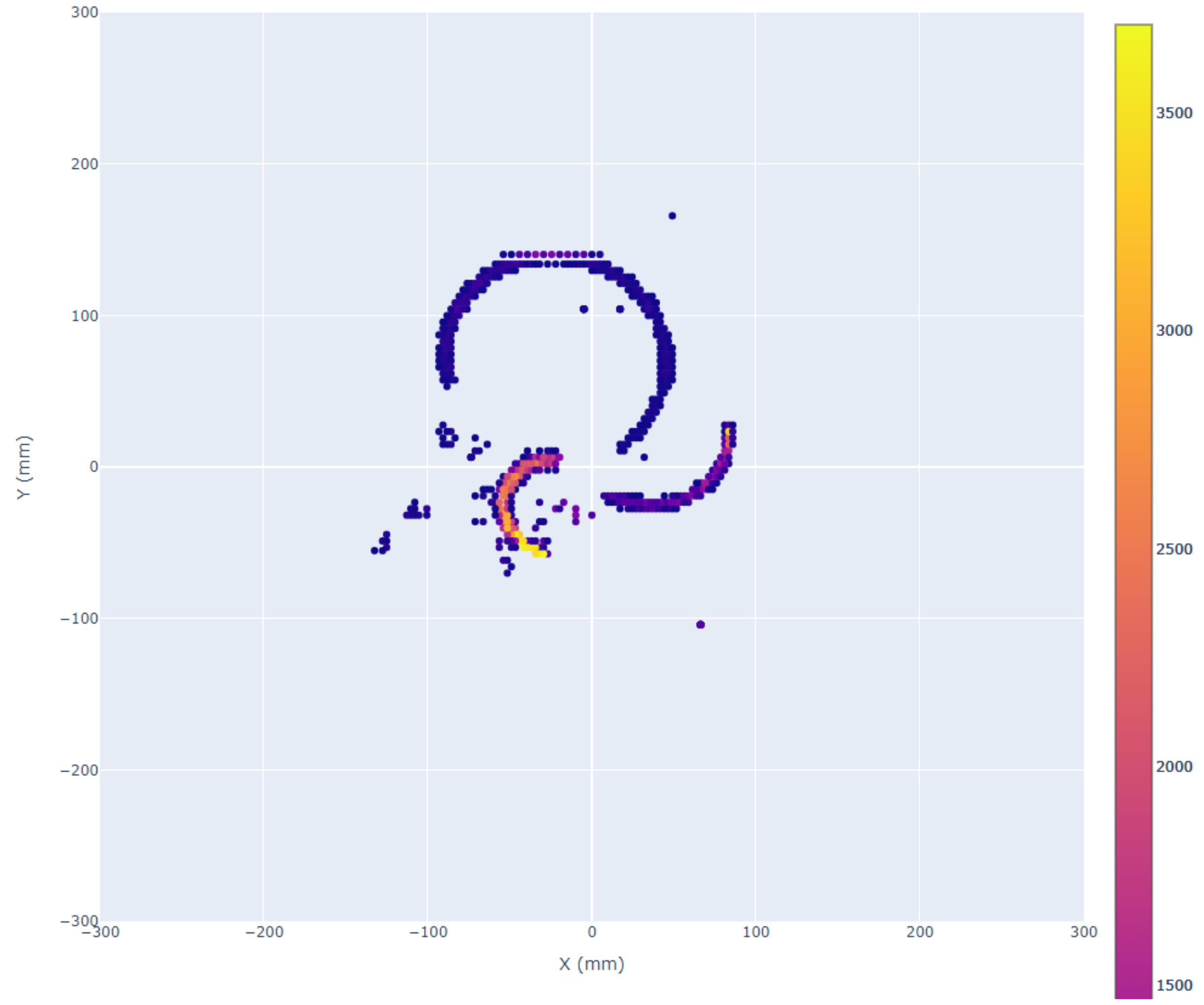


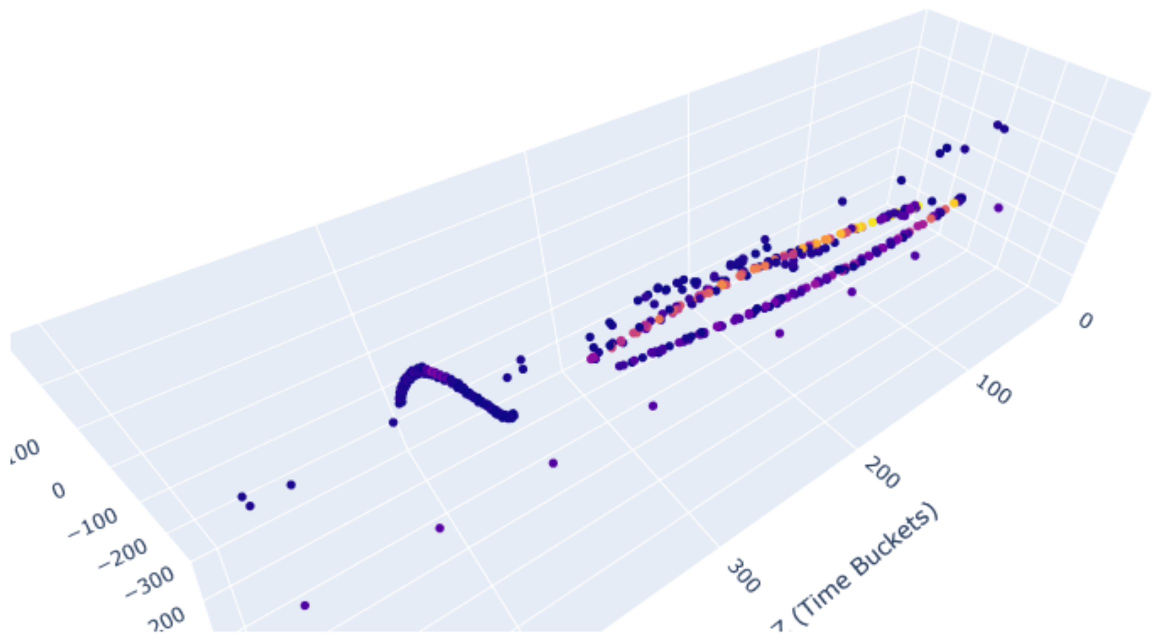
Full kinematics reconstruction!

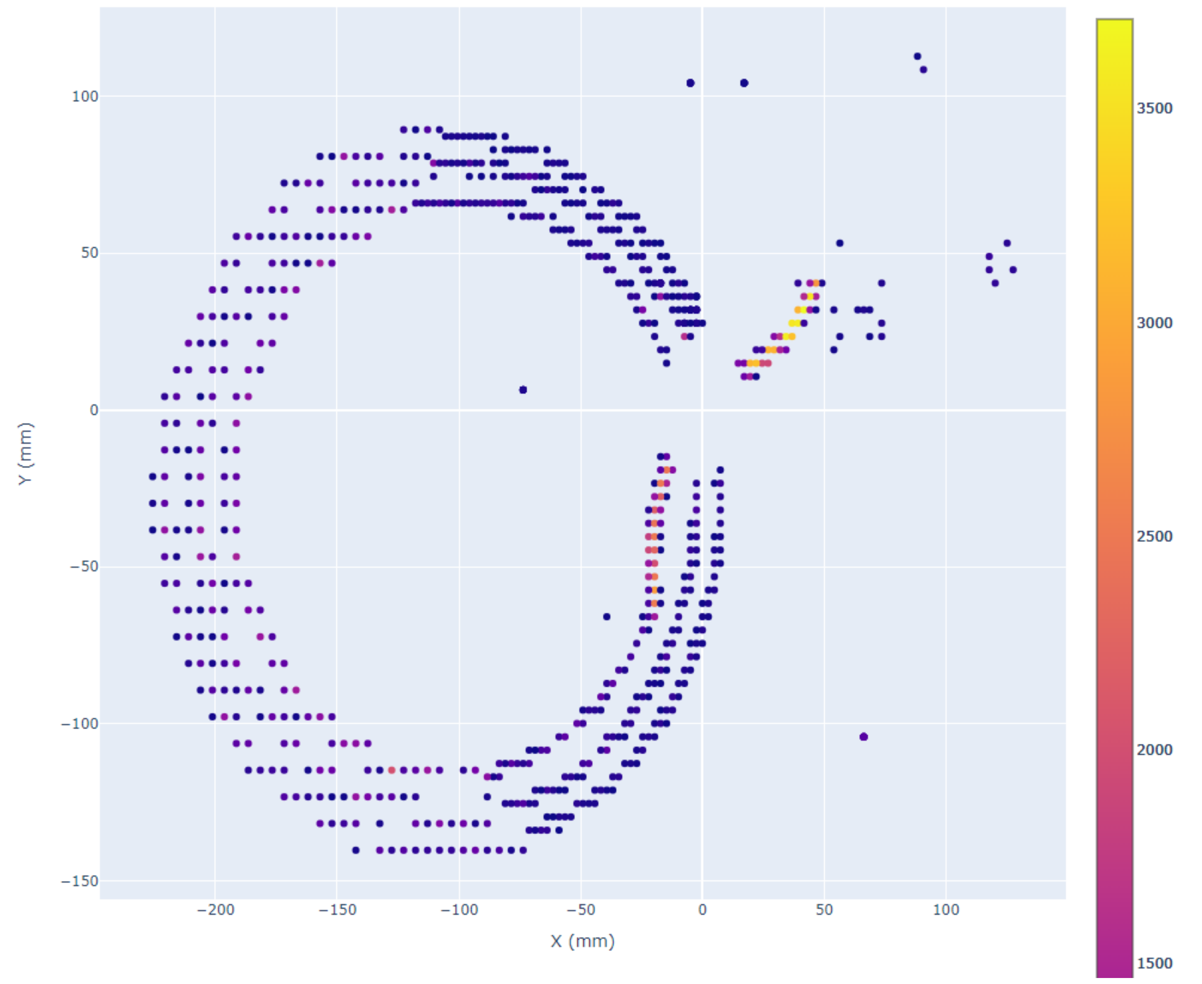


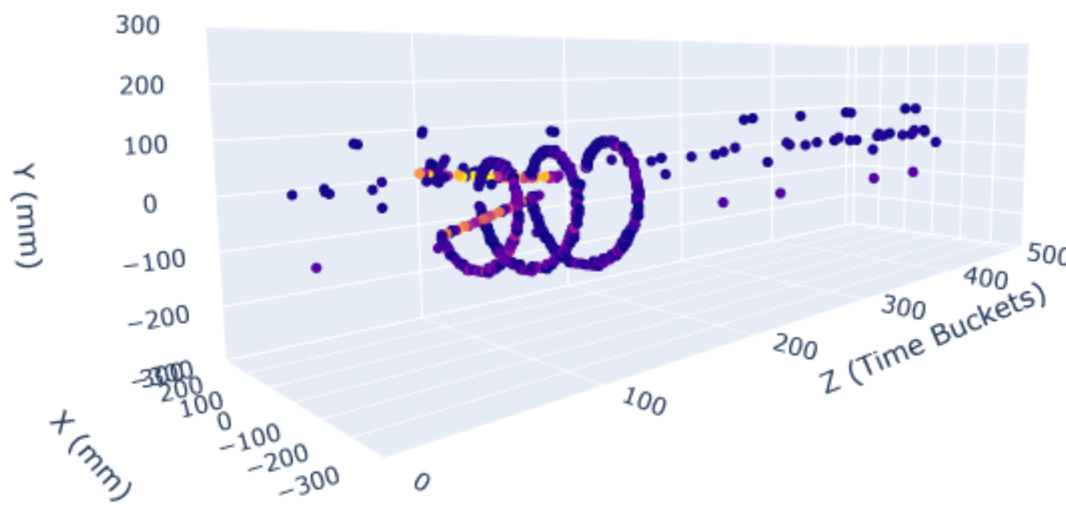








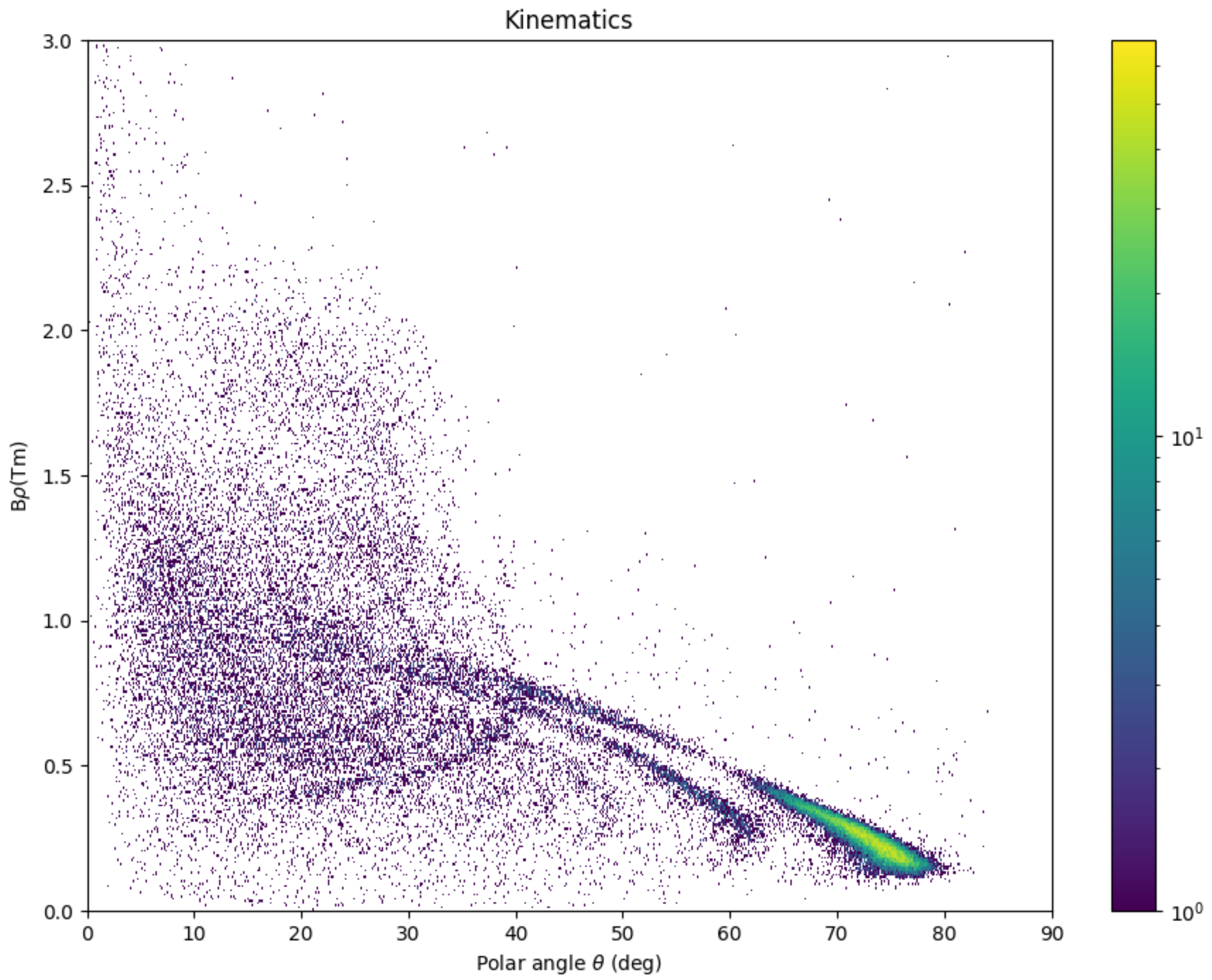




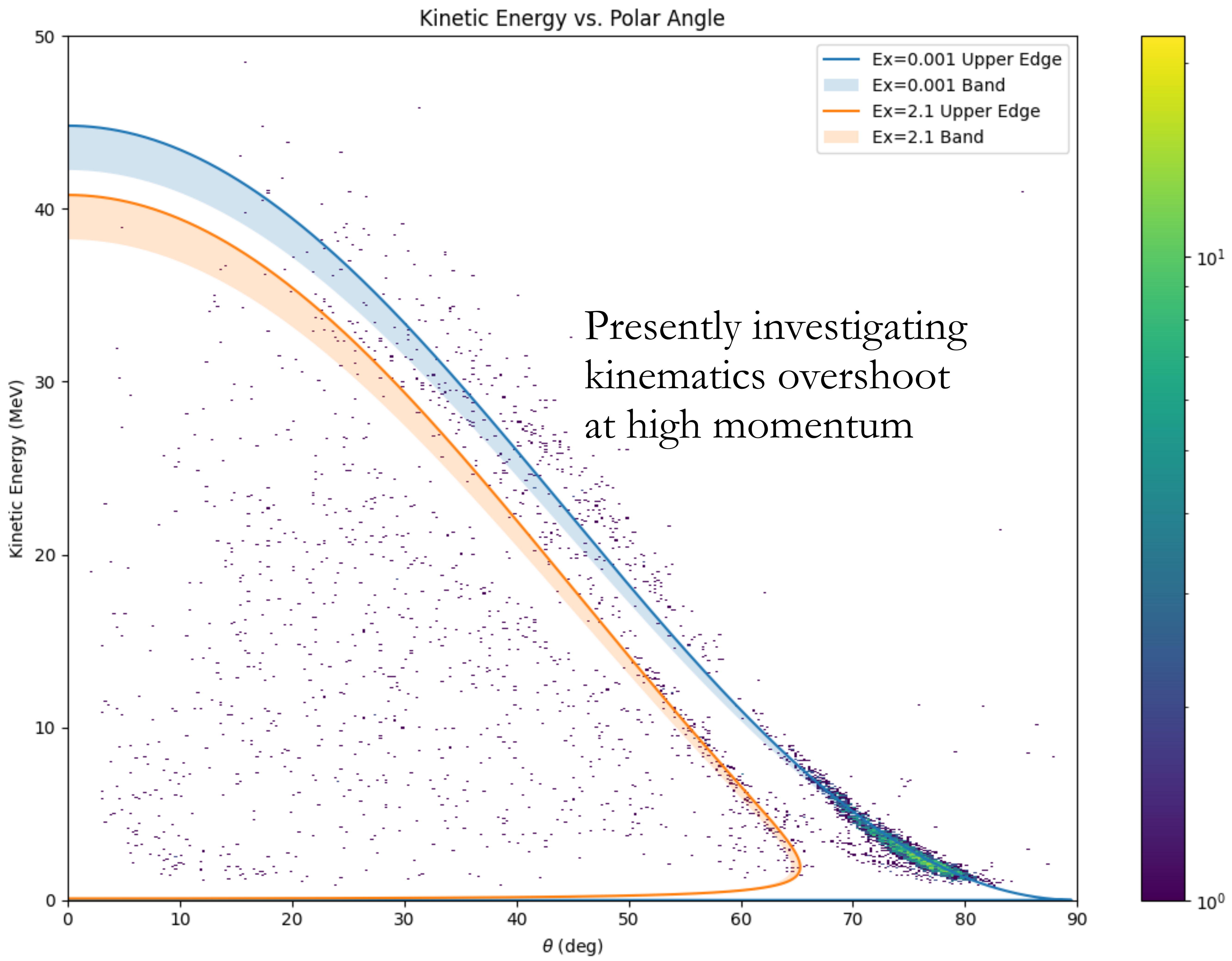
Analysis by T. Schaeffeler

^{12}Be reactions on proton target

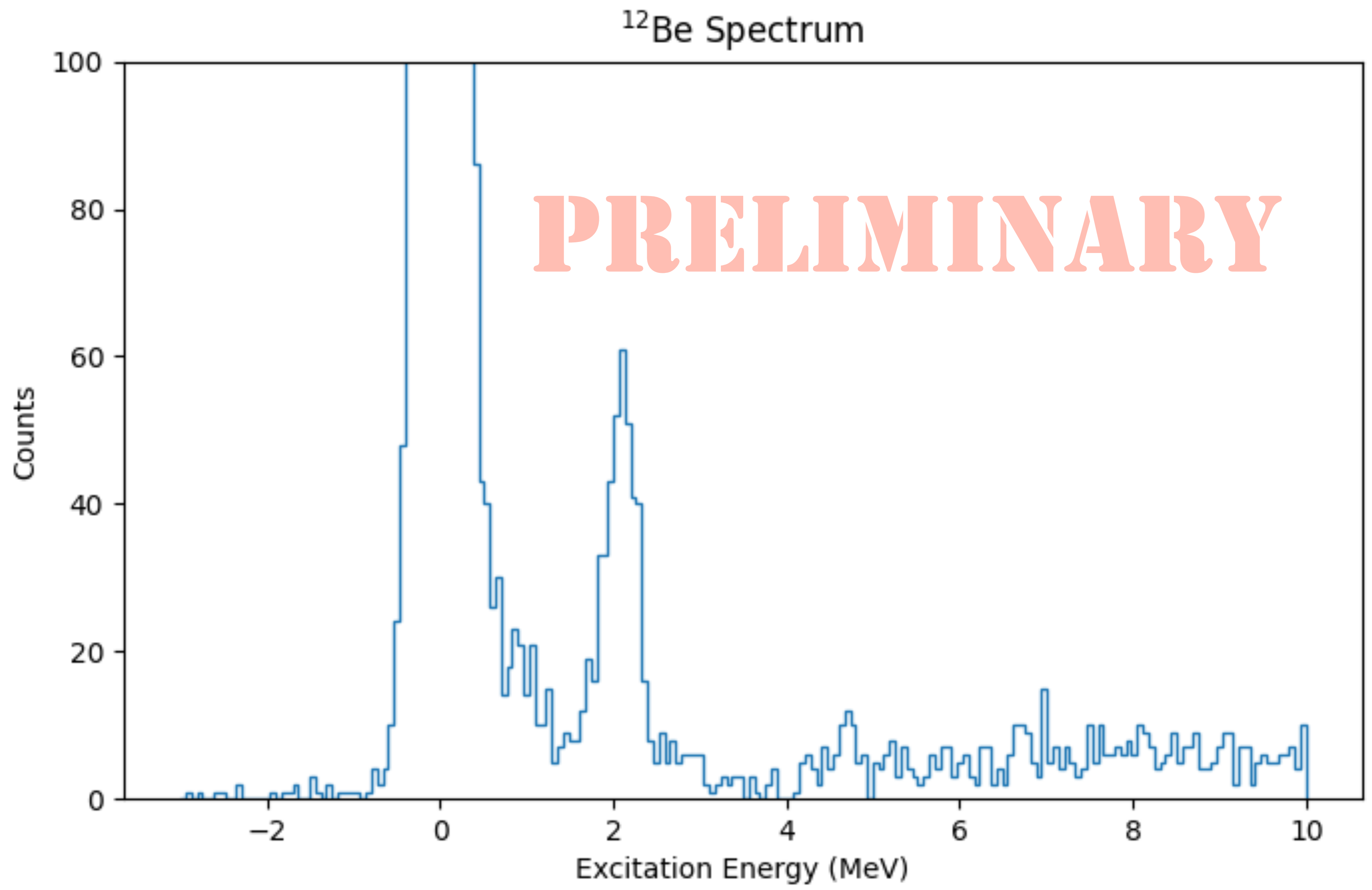
- ^{12}Be at ~12 MeV/u provided by the RAISOR separator from ATLAS ^{14}C primary beam
- **Beam intensity 100 pps**
- Pure $^{1}H_2$ target at 600 Torr
- Equivalent CH_2 target thickness (number of protons): 110 mg/cm^2
- **3 days of beam exposure**
- Pre-kinematics plot from estimation phase showing $B\rho$ versus energy loss
- Kinematics lines from elastic, inelastic, (p,d) and a hint of (p,t) reactions



^{12}Be elastic and inelastic on proton

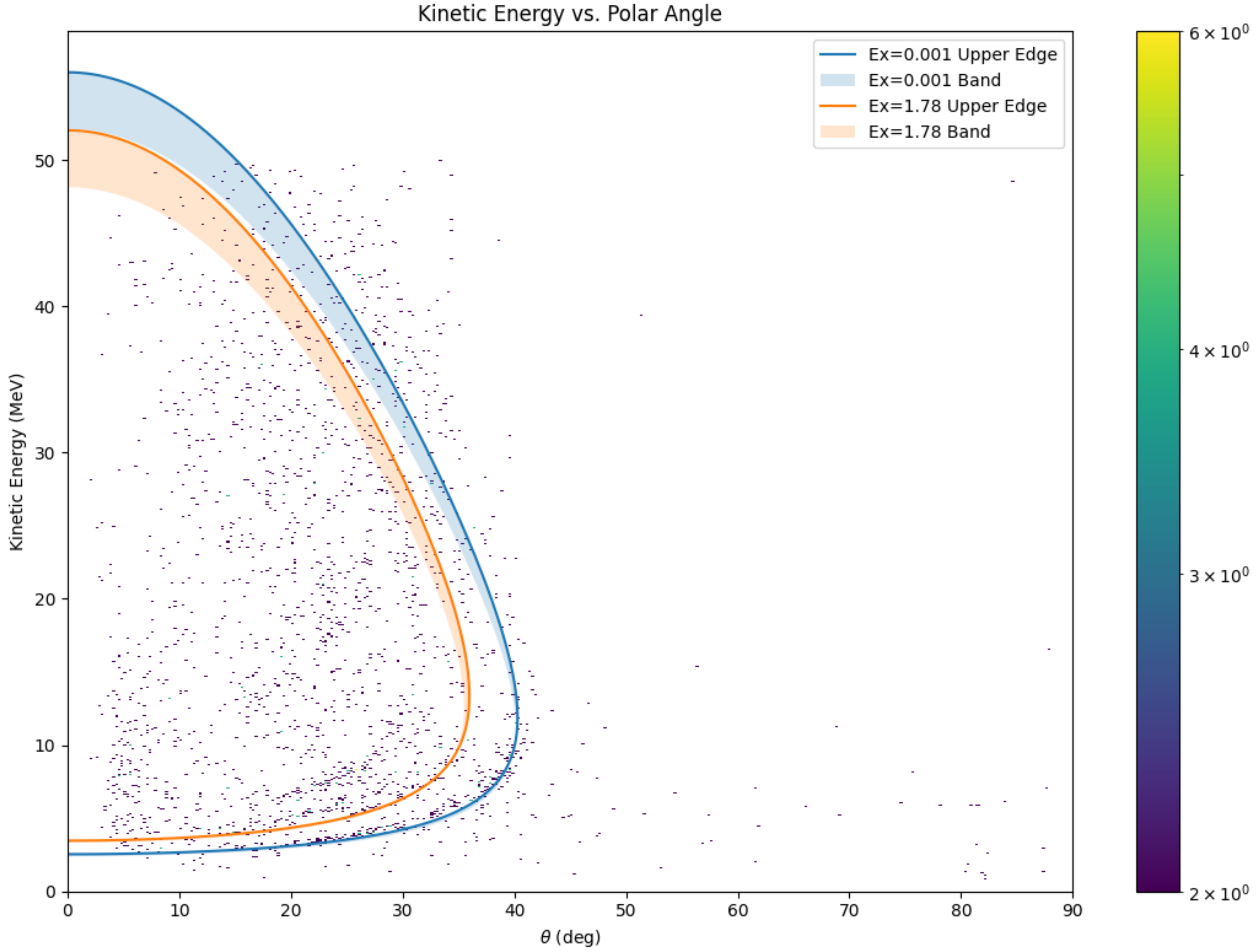


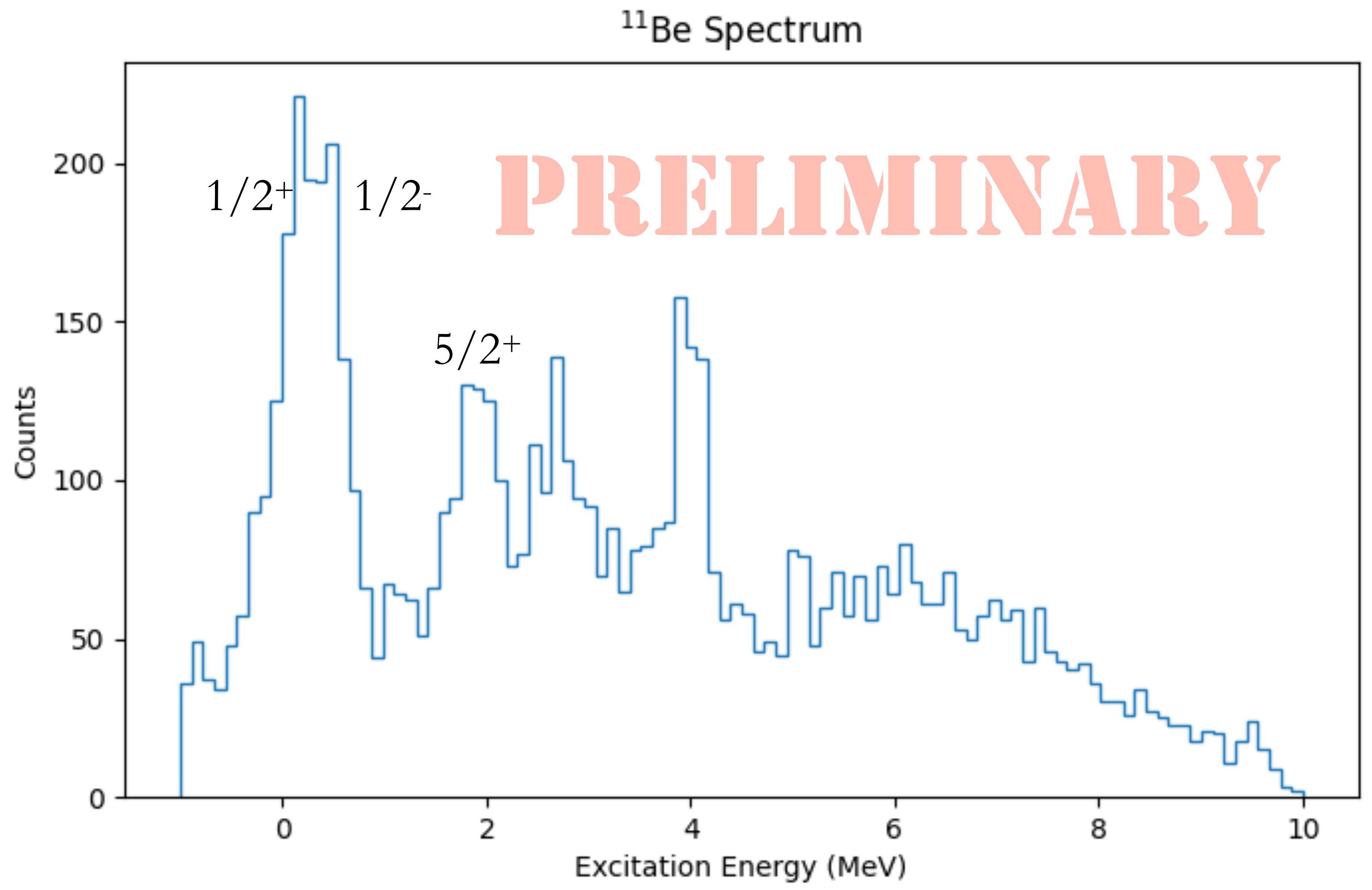
Presently investigating kinematics overshoot at high momentum



- Higher energy resonances in ^{12}Be
- Reactions on isomeric 0^+ (0.23μs)?

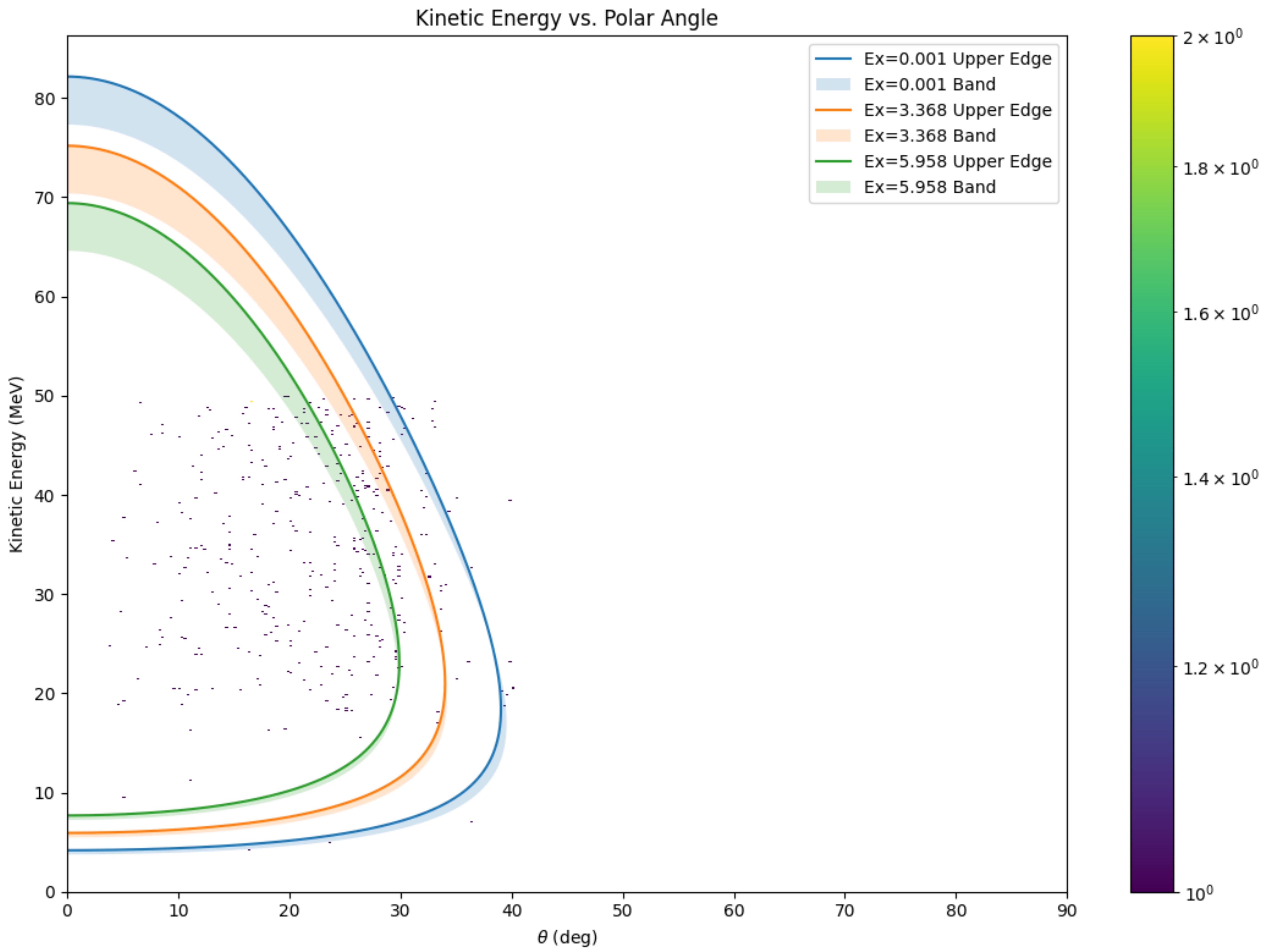
$^{12}Be(p,d)^{11}Be$



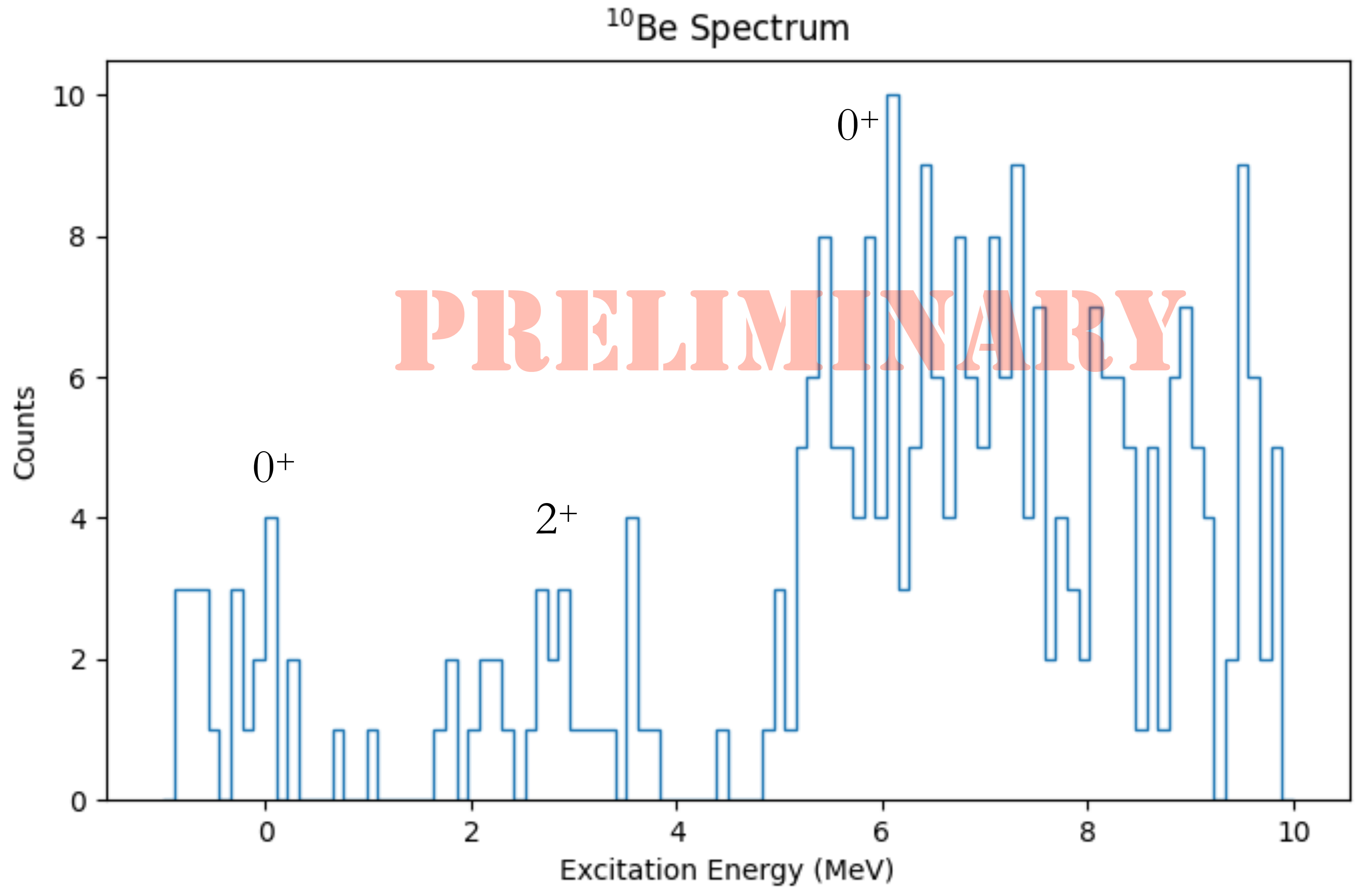


- Large cross sections to 1/2$^+$ and 1/2$^-$ bound states
- Similar reaction to ^{12}Be-1n knockout
  - *Breakdown of N=8, A. Navin et al., PRL 85, 266 (2000)*
  - *d-wave component, S. D. Pain et al., PRL 96, 032502 (2006)*
  - *Neutron-unbound resonances, W. A. Peters et al., PRC 83, 057304 (2011)*
- More details on ^{12}Be wave function from population to other unbound resonances

$^{12}Be(p,t)^{10}Be$

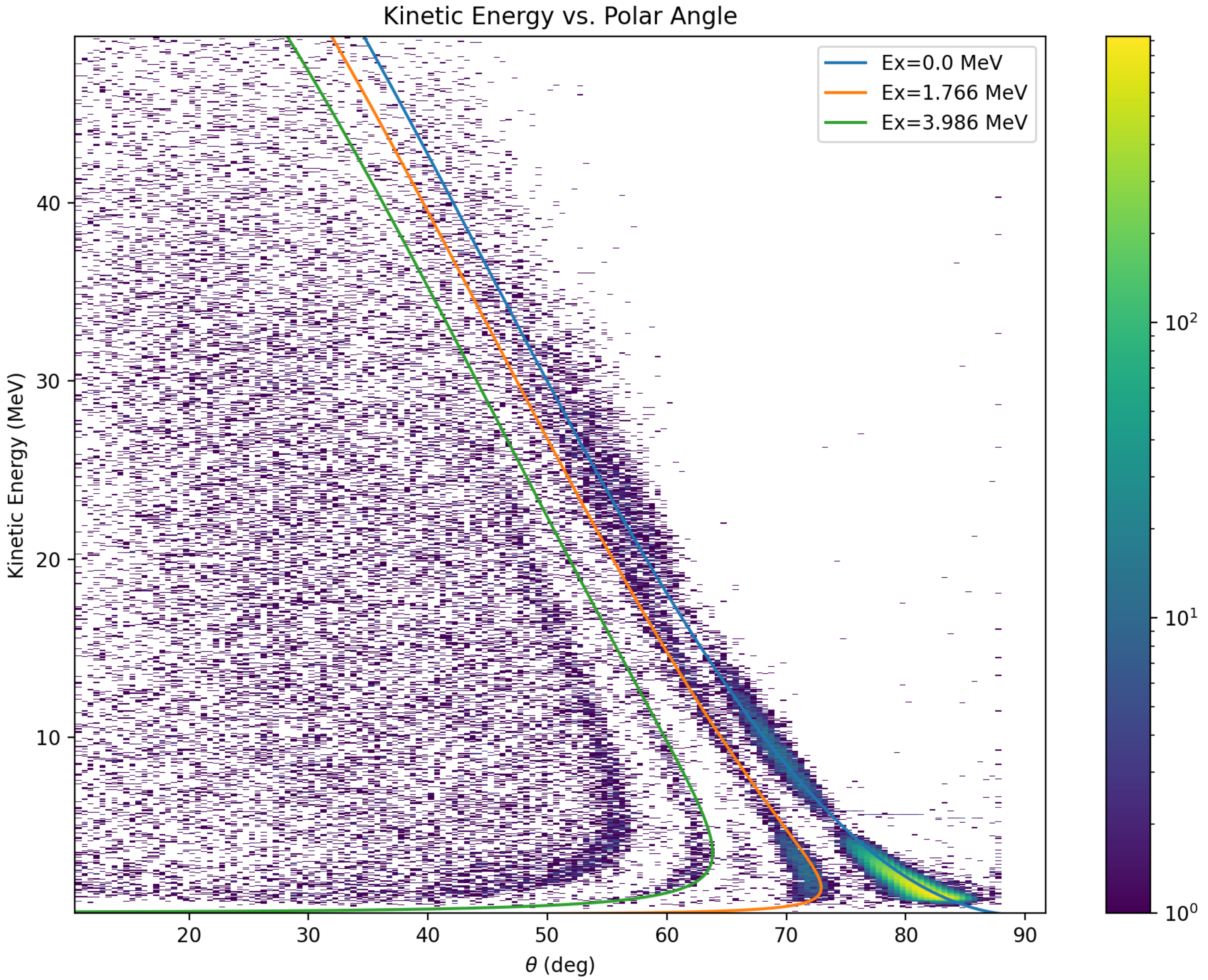


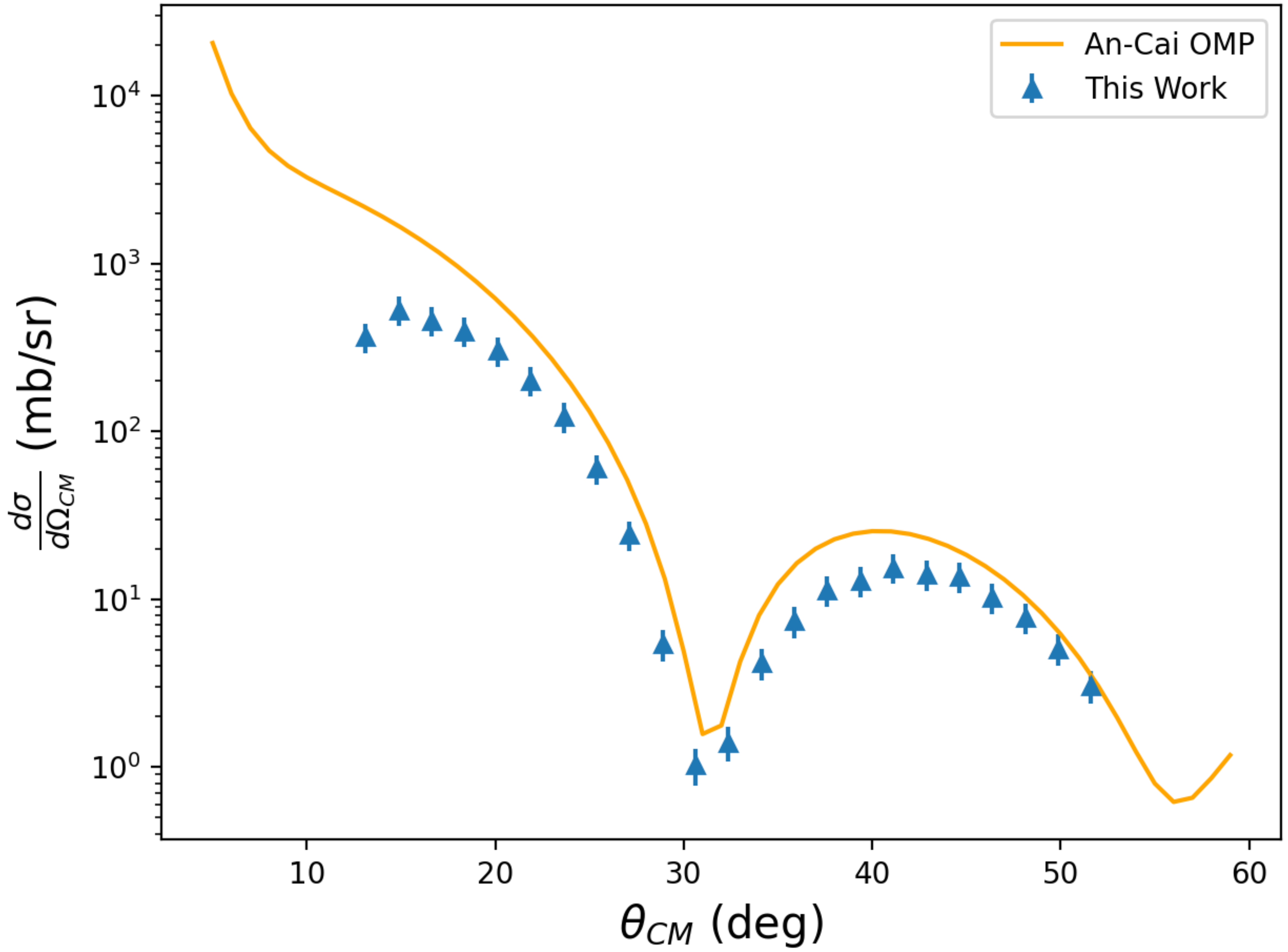
Kinetic Energy vs. Polar Angle
Ex=0.001 Upper Edge
Ex=0.001 Band
Ex=3.368 Upper Edge
Ex=3.368 Band
Ex=5.958 Upper Edge
Ex=5.958 Band
Kinetic Energy (MeV)
θ (deg)
0
10
20
30
40
50
60
70
80
90
2 × 10^0
1.8 × 10^0
1.6 × 10^0
1.4 × 10^0
1.2 × 10^0
10^0



10Be Spectrum
0+
0+
2+
PRELIMINARY
Counts
Excitation Energy (MeV)
0
2
4
6
8
10

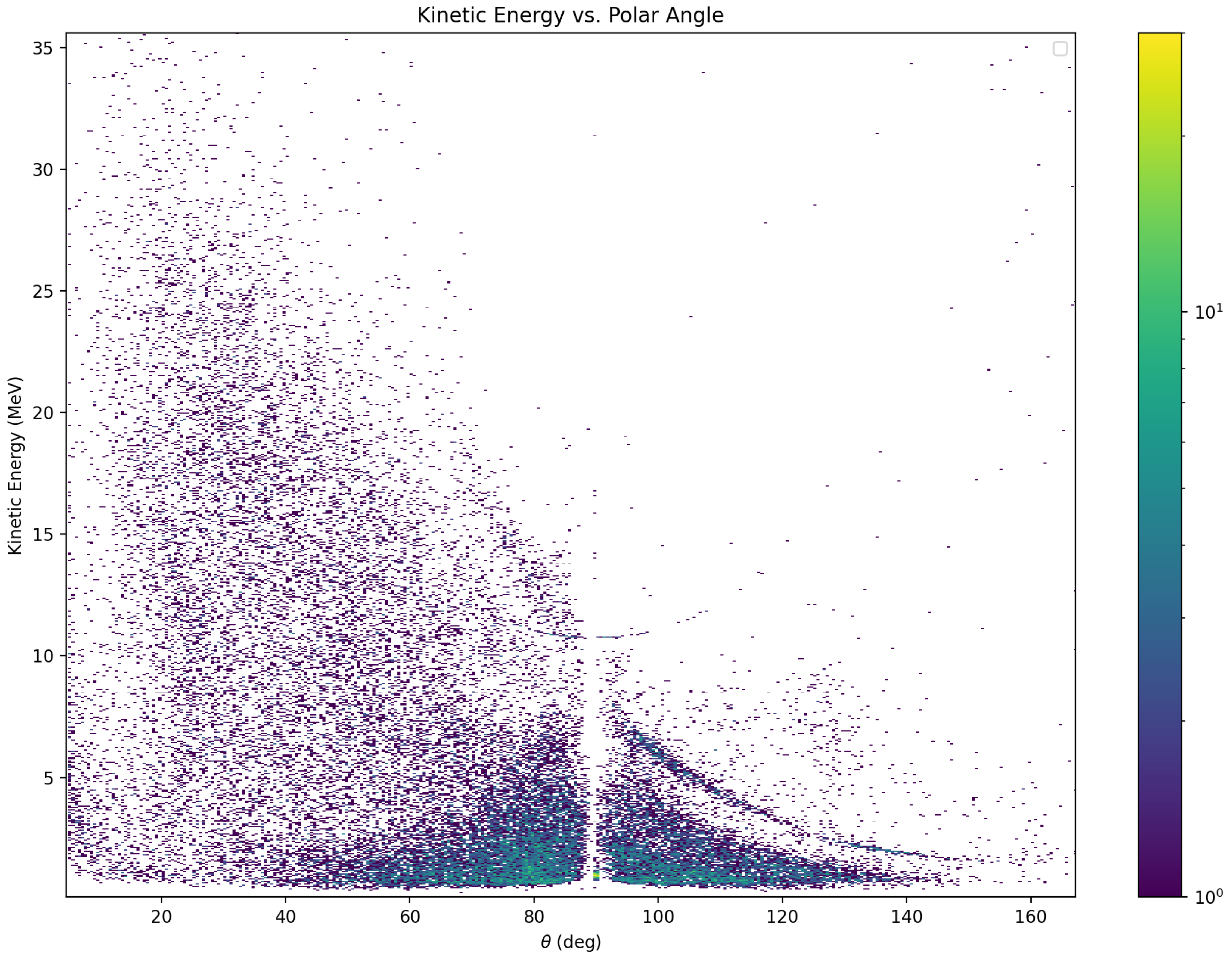
^{16}C on pure D_2 target

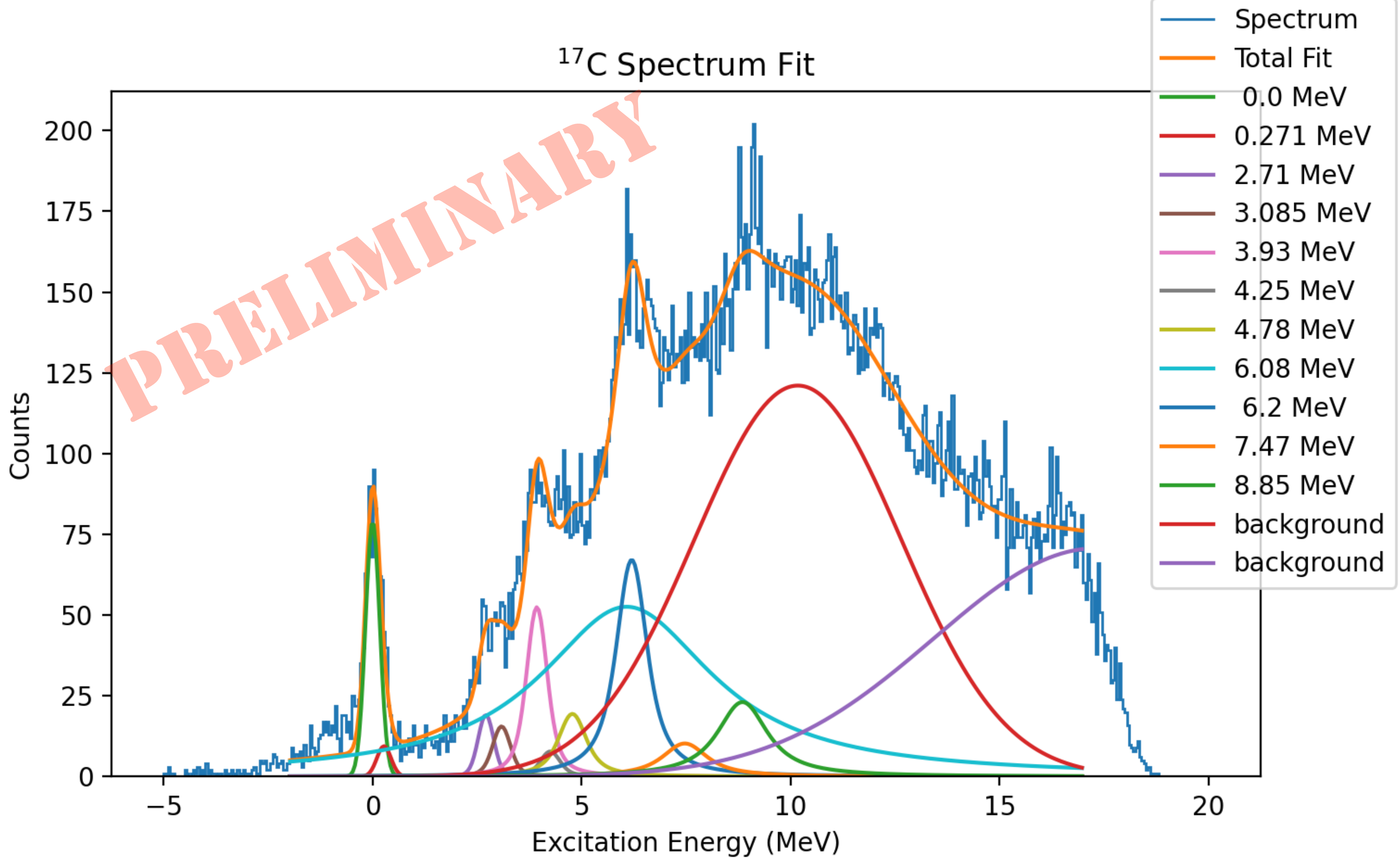




$^{16}C(d,p)^{17}C$ to bound and unbound states

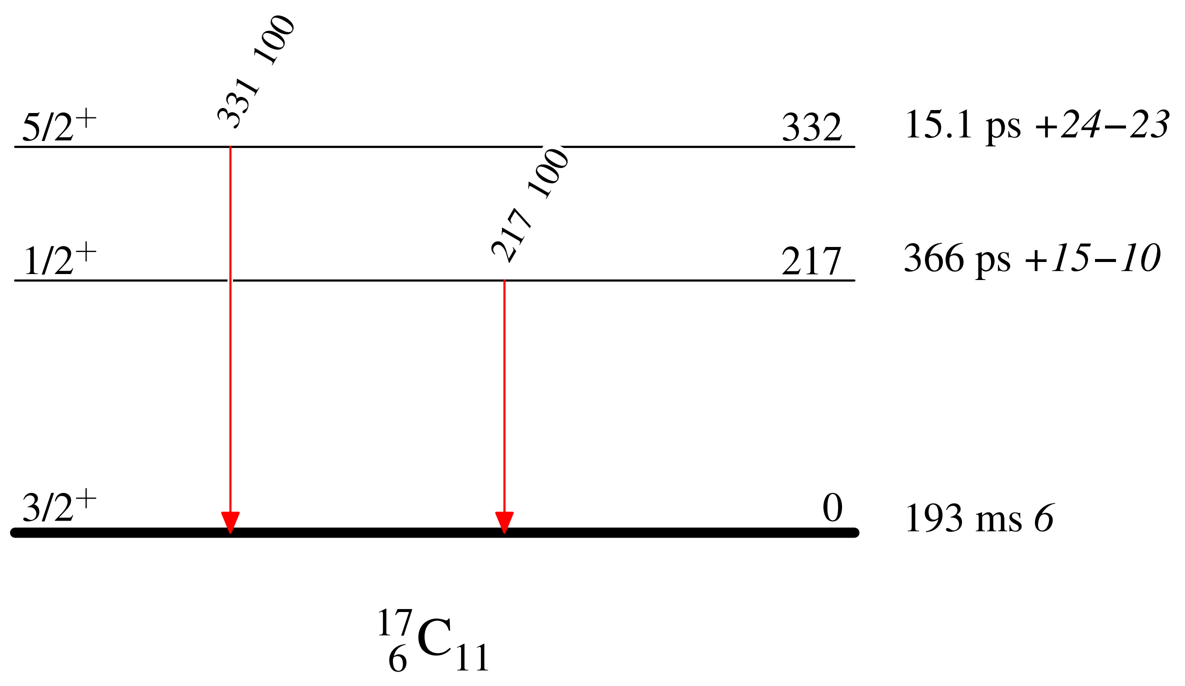
Analysis by Gordon McCann



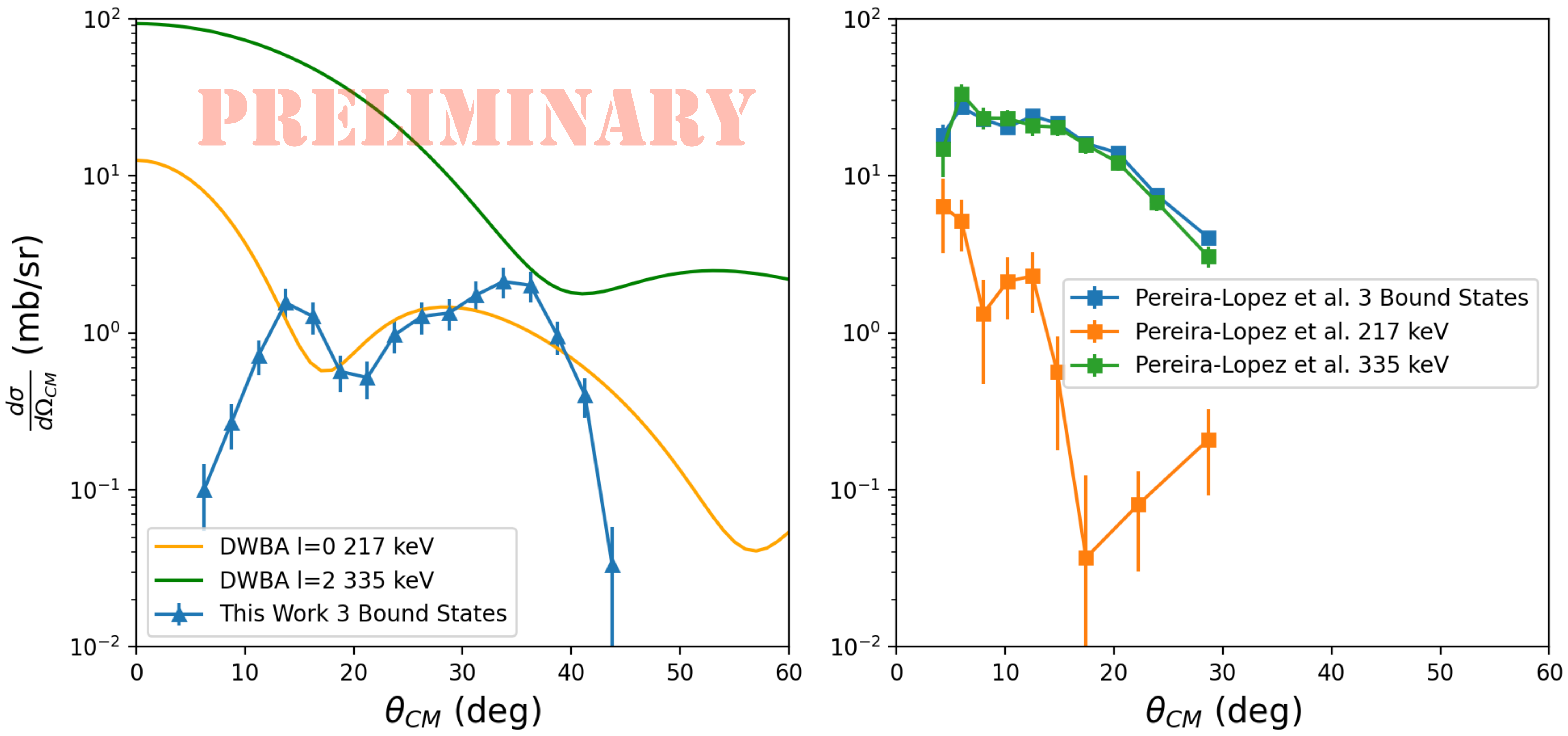


Analysis of ^{17}C bound states

- Three close-by bound states of ^{17}C
  - *Energy resolution cannot resolve*
  - *Angular distribution for all three*
  - *Matches DWBA for l=0 only*
  - *In contradiction with Pereira-López*
  - *Only halo 1/2$^+$ state ^{16}C(0$^+$)+n popula reaction*
  - *3/2$^+$ and 5/2$^+$ based on ^{16}C(2$^+$)+n*



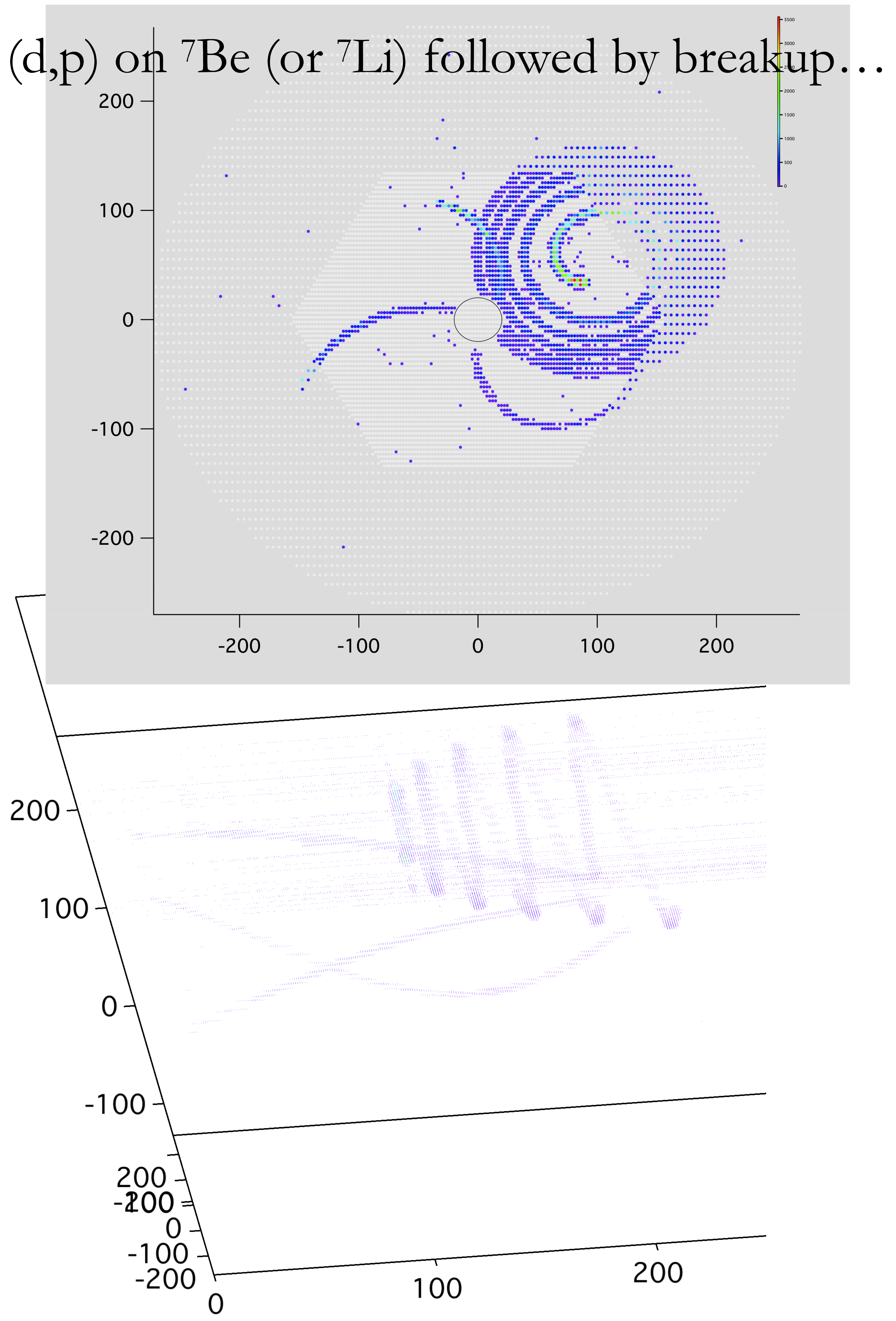
Analysis by Gordon McCann



Adapted from X. Pereira-López et al., PLB 811 (2020) 135939

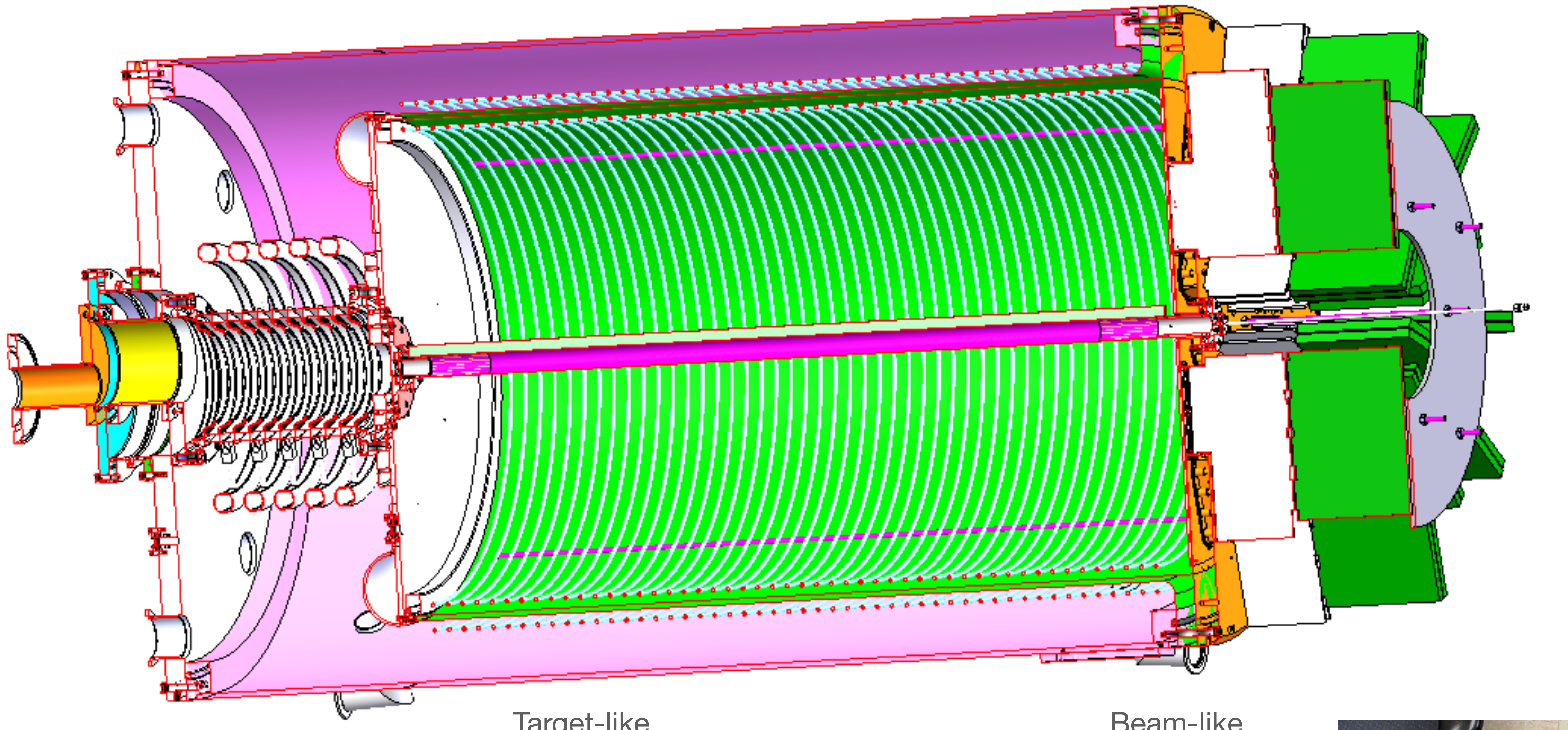
Outlook

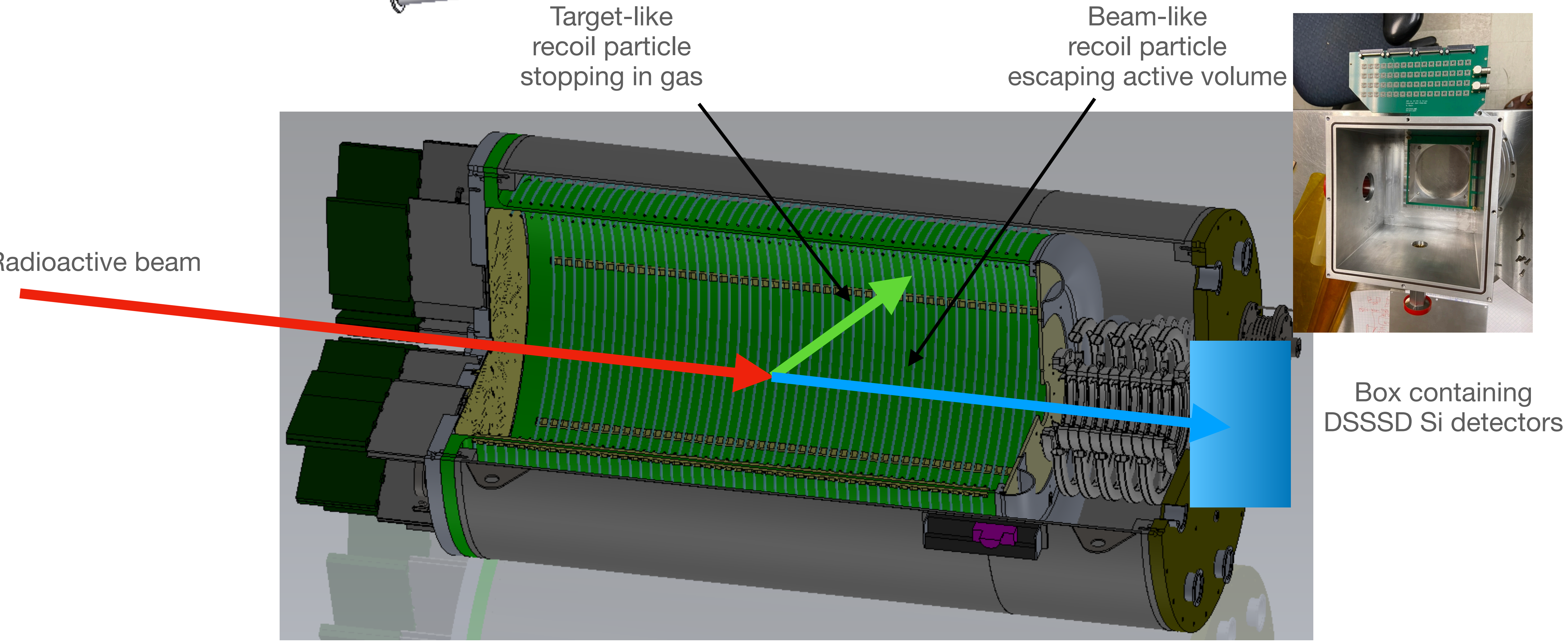
- Active targets such as the AT-TPC offer a breakthrough in measurements of Direct Reactions with Exotic Beams
  - *Luminosity gain of* ***two to three orders of magnitude*** *compared to passive targets, while retaining comparable resolutions*
  - *Transfer reaction cross sections (~ 10 mb/sr) now accessible at* ***100 pps***
  - *Solid angle coverage allows measurements of* ***full kinematics*** *of reactions (target-like and beam-like residues)*
- New avenues of exploration
  - *Missing mass spectroscopy of exotic nuclei* ***further from stability***
  - *Exploration of unbound resonances and* ***deformation*** *via rotational bands*
  - ***Effects of continuum*** *via study of unbound resonances near particle decay thresholds*



Upcoming upgrades

- Inner tube for rare gases (^{3}He)
  - *Limit cost of operation*
  - *Allow use of faster gas in detector region*
  - *Requires enough energy to punch through tube foil (12 μm polyamide)*
- Zero degree detector telescope
  - *Two DSSD Si detectors backed by CsI array*
  - *Identification of beam-like residues that scatter at small angles (~ < 10°)*
  - *Reduce pile-up using anti-coincidence with upstream ion chamber*
  - *Use AT-TPC in reverse configuration (like with S800)*





The future ahead…

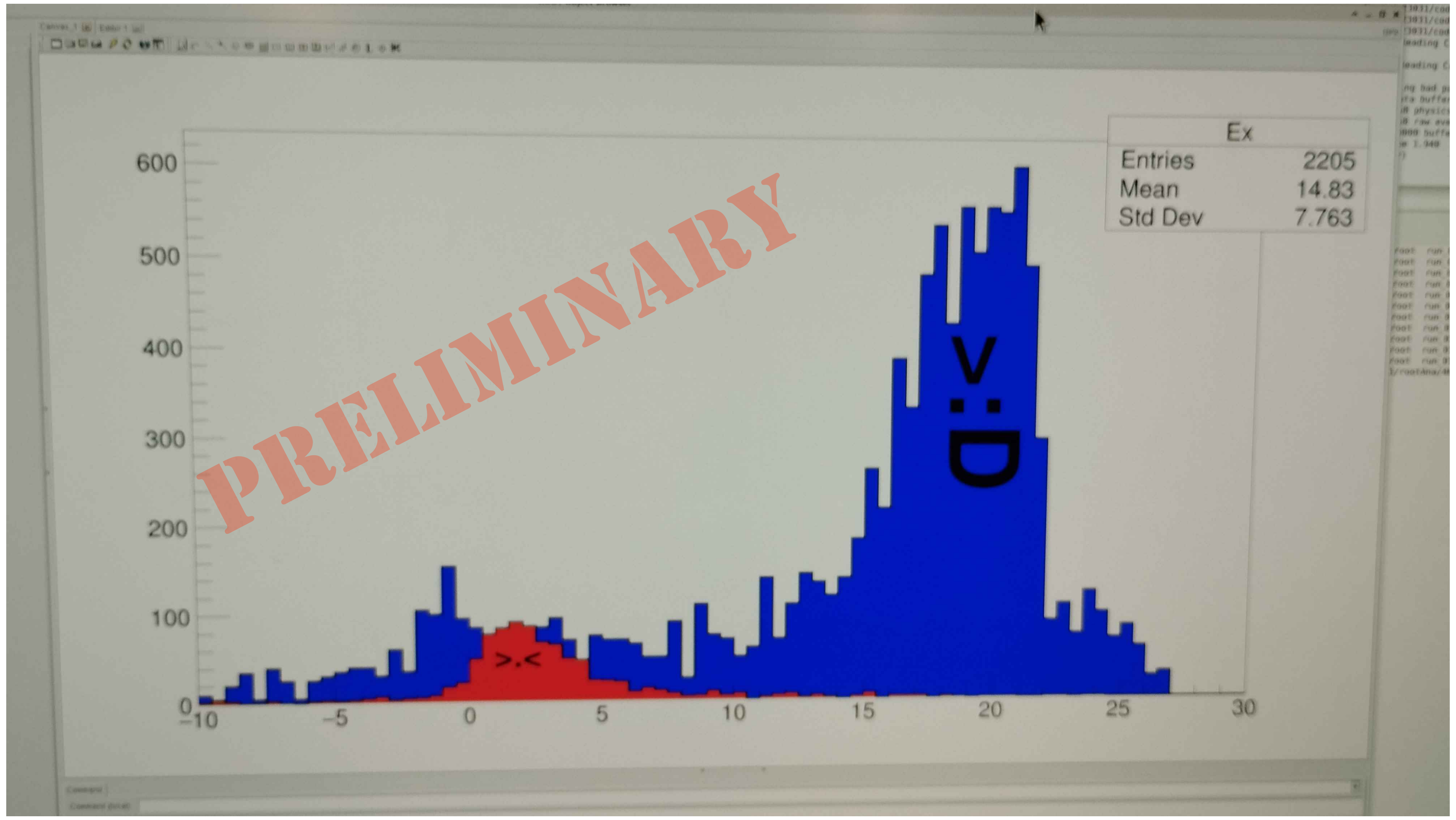
- SOLARIS experiment (Fall 2024)
  - *np pairing in ^{56}Ni via ^{56}Ni(^{3}He,p)*
- RCNP campaign (early 2025)
  - *6 experiments approved (d,^{3}He)*
  - *No magnetic field*
  - *Rely on range for PID*
  - *Zero degree DSSD telescope*
- Argonne campaign (late 2025)
  - *3 experiments approved*
  - *HELIOS solenoid*
  - *Zero degree DSSD telescope*

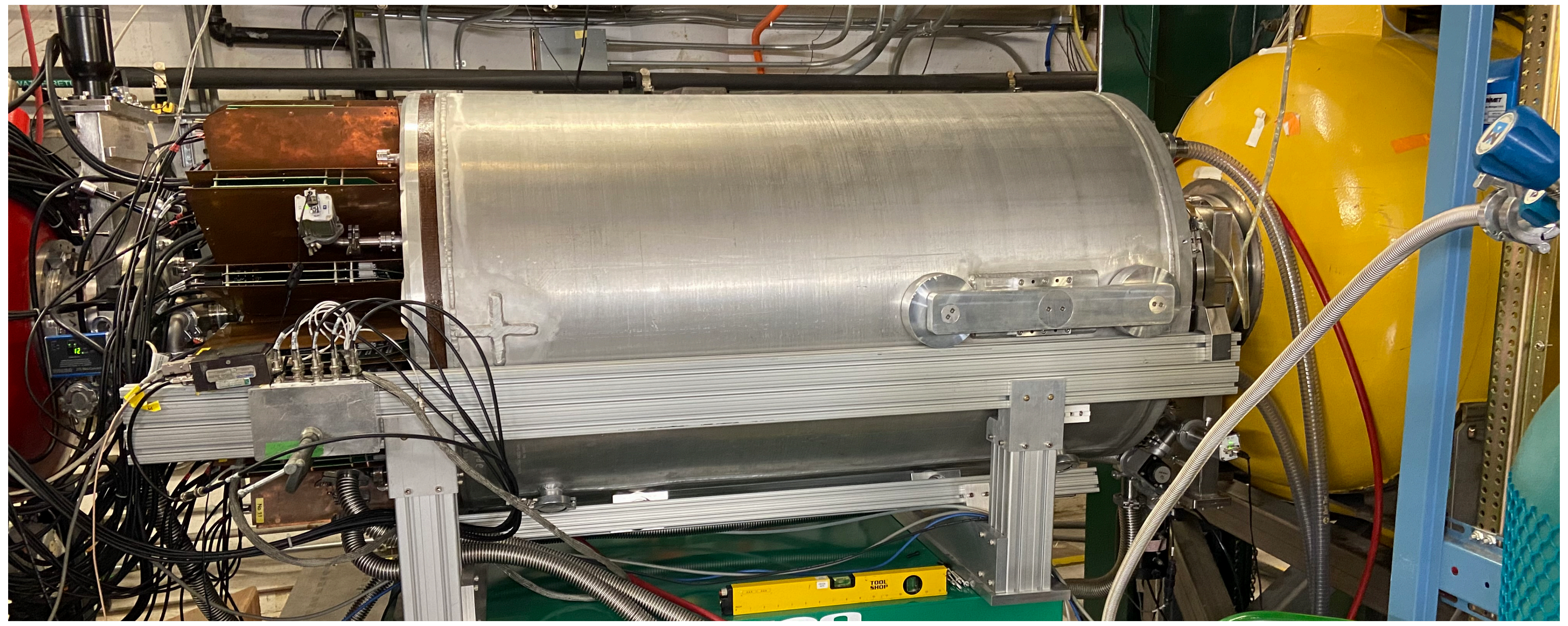
AT-TPC collaboration

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

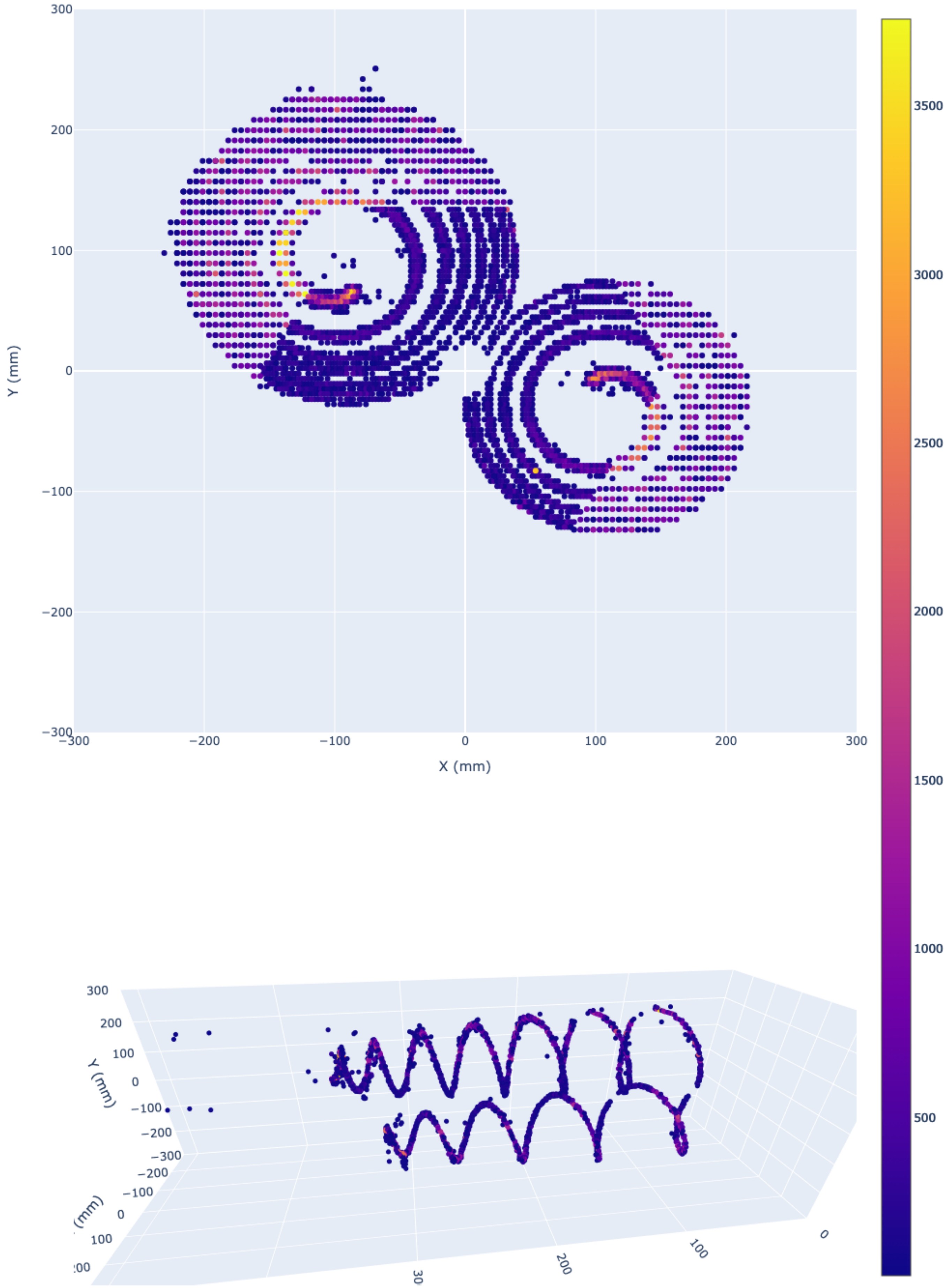
Last minute scoop!

- Measurement of SDR and GDR in ^{11}Li (Y. Ayyad)
  - *AT-TPC coupled to S800 spectrometer*
  - *FRIB ^{11}Li beam at 55 MeV/u ~ 10,000 pps*
  - *Pure H_2 and H_2+CF_4 (10%) mixtures at 600 Torr*
  - *S800 set on ^{9}Li (red) and ^{8,7}Li,^{4}He (blue)*
  - *Analysis of proton tracks stopped in gas*
  - *Cutoff of GDR due to range acceptance*
- Prior to this experiment
  - *Measurement of GT strength in N=20 Island of Inversion using ^{32}Mg, ^{33}Al(d,^{2}He) charge-exchange reaction (R. Zegers)*

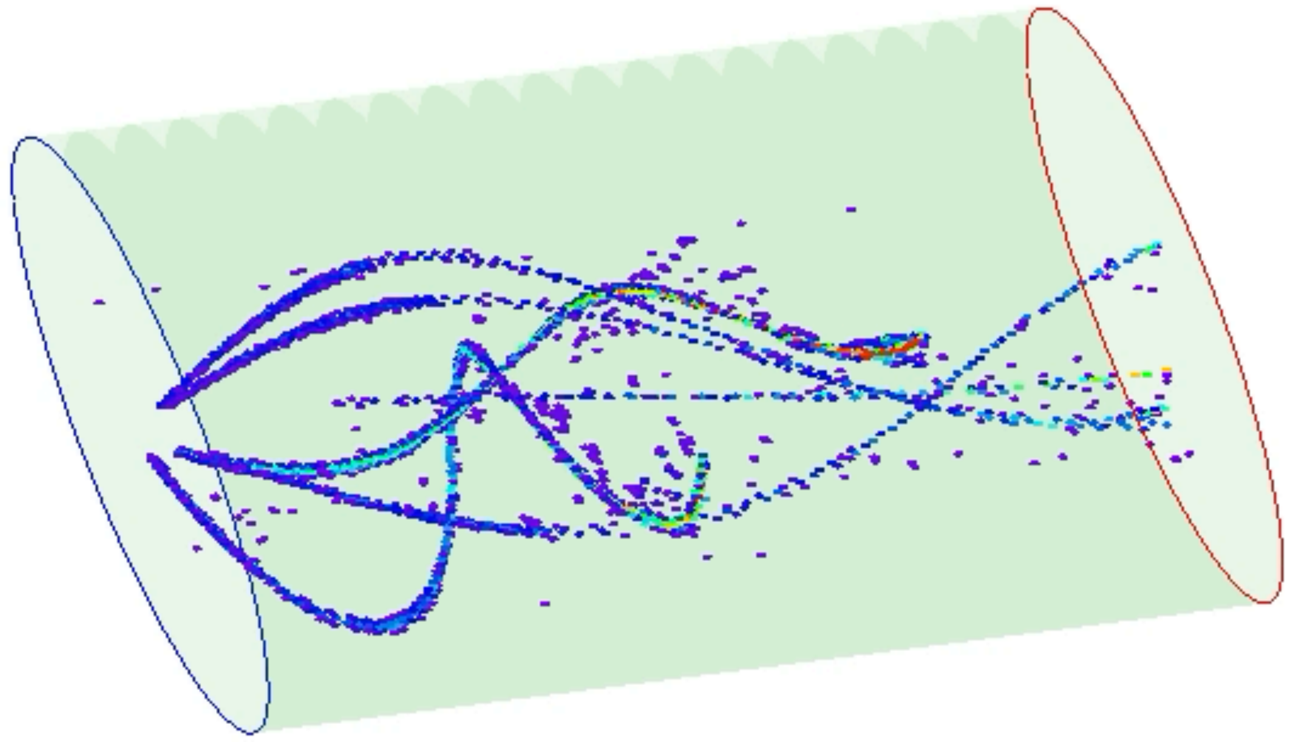


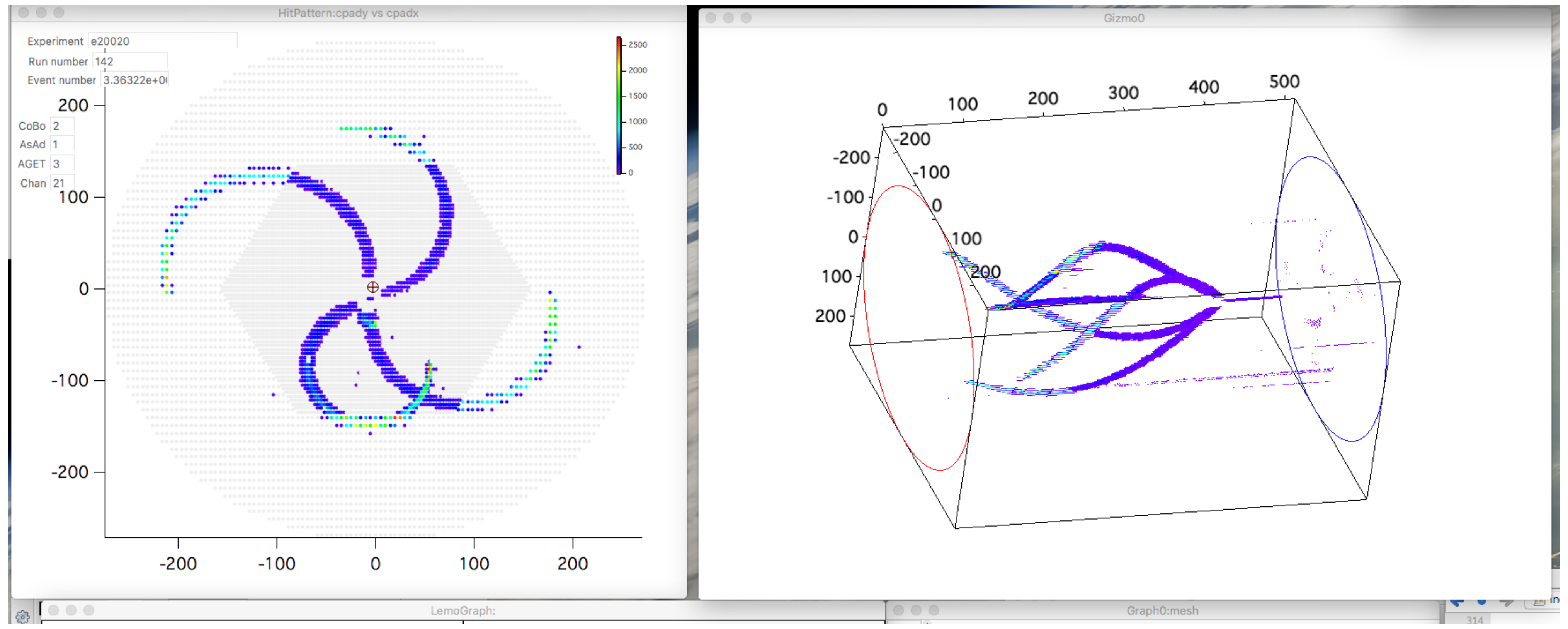


Some entertaining events...

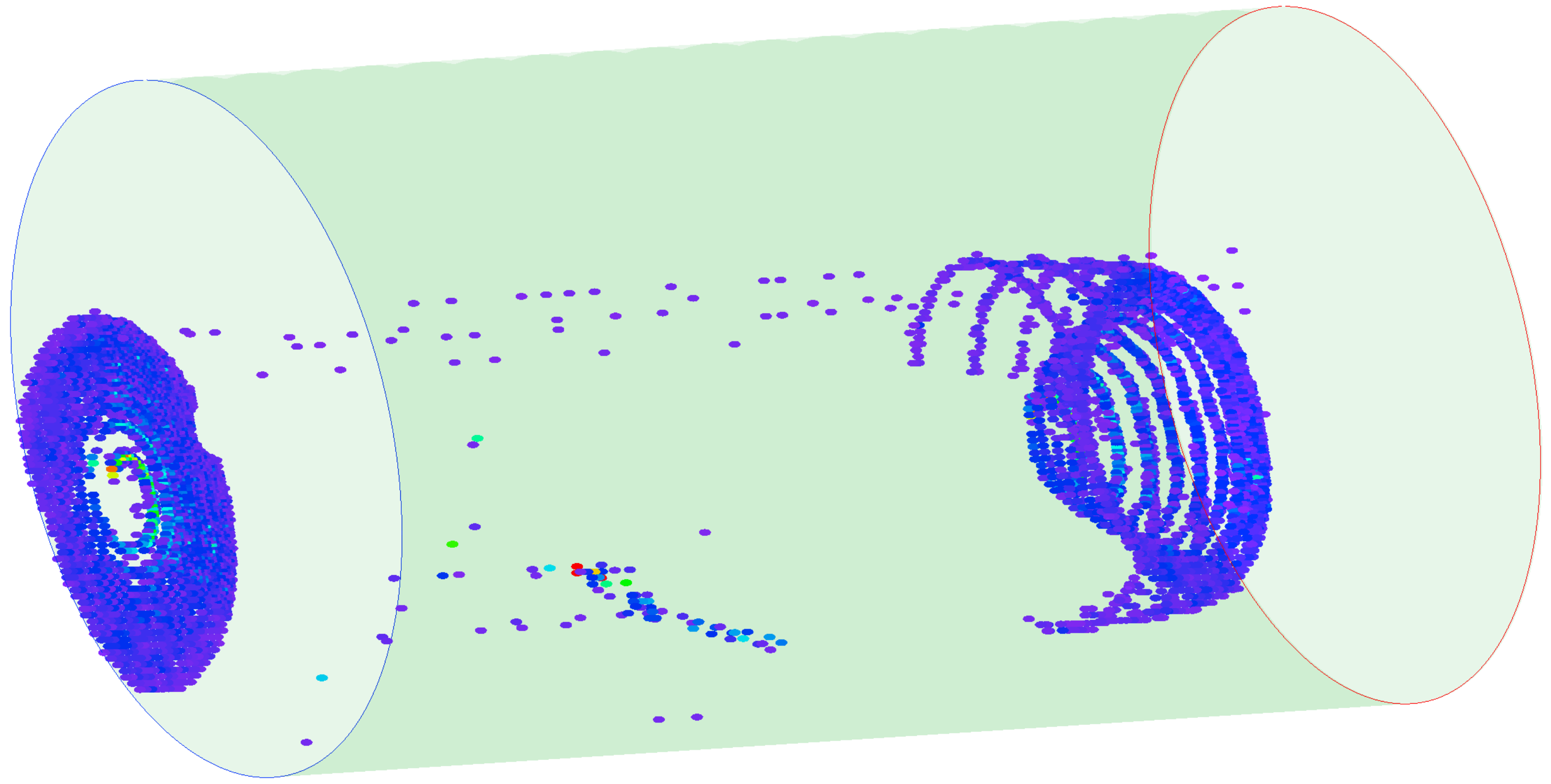


Run 33 - Event 135





Run 17 - Event 11778



Run 17 - Event 10416