Spectroscopy of rare isotopes with the Active Target Time Projection Chamber

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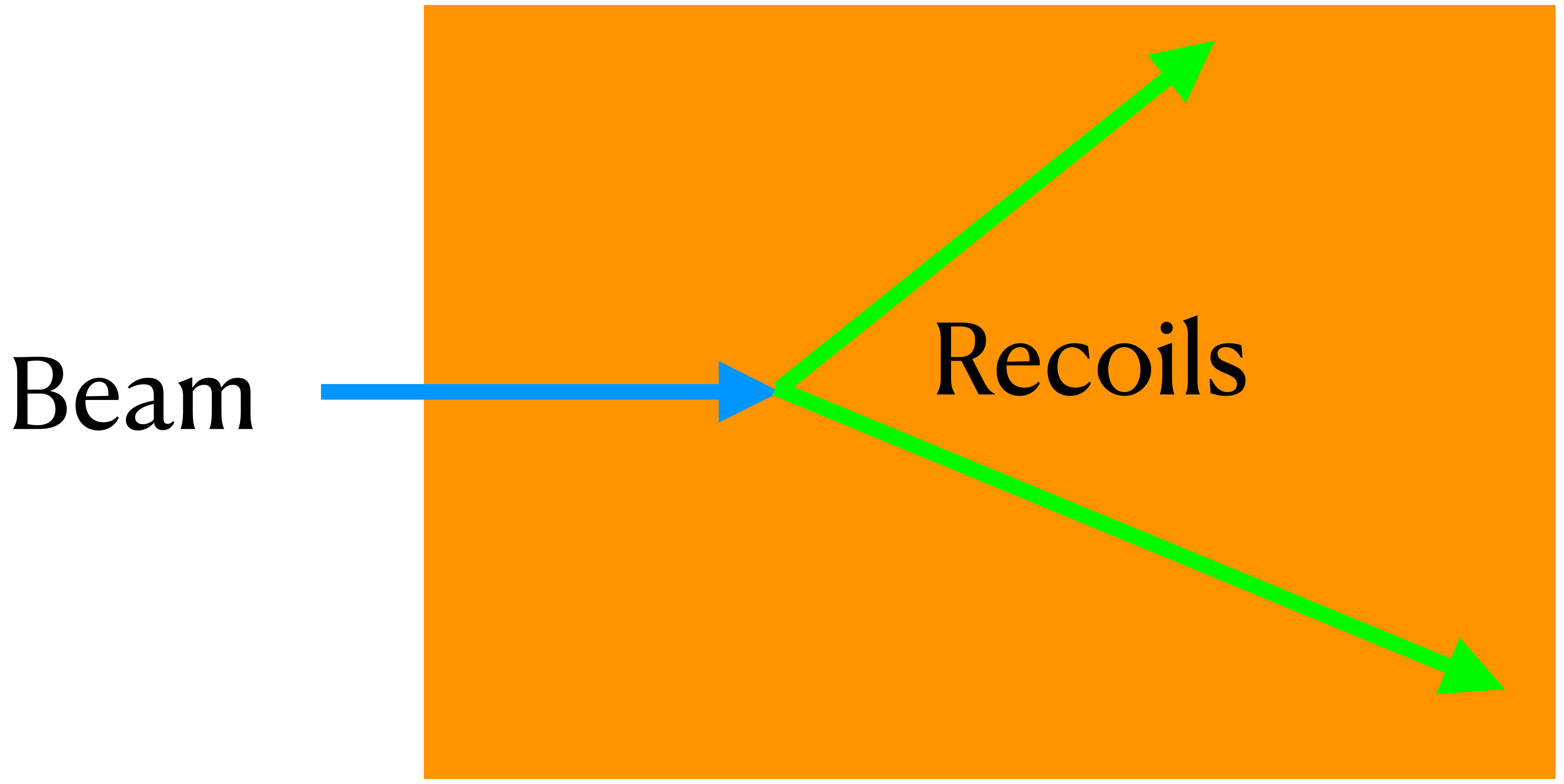
In-beam γ-ray vs missing mass methods

- 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 by up to 2 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*

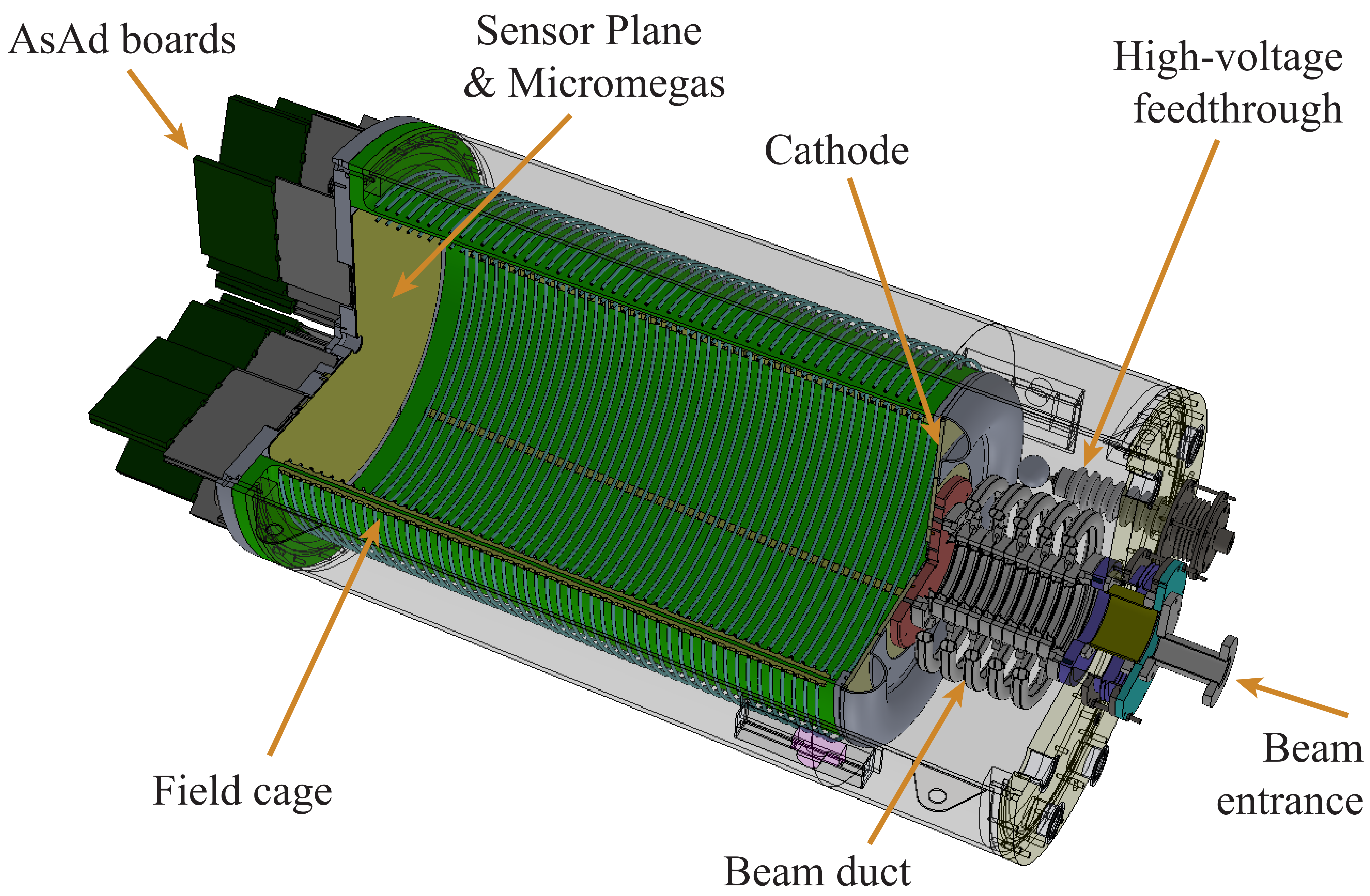


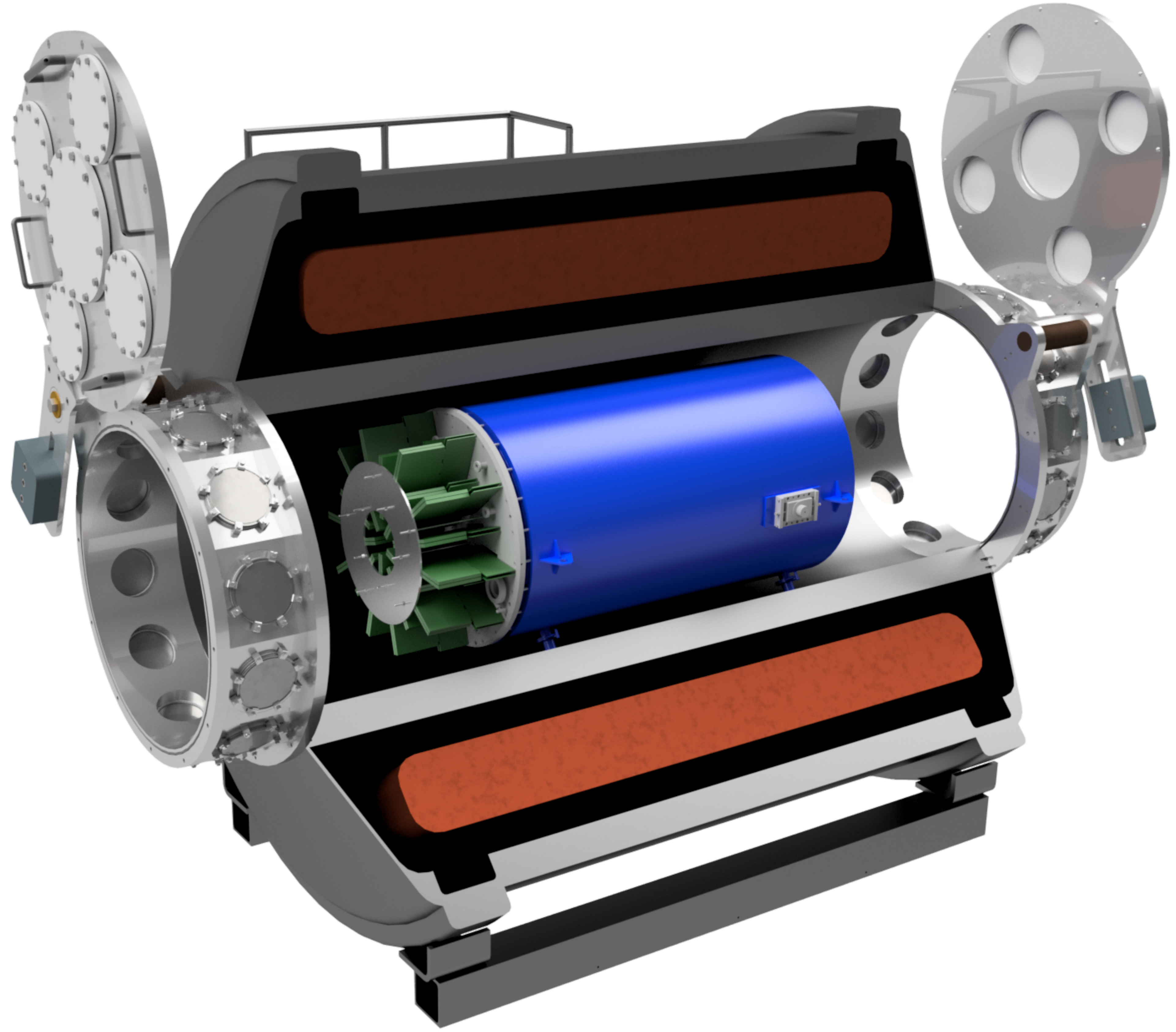
Target = Detector

AT-TPC @ SOLARIS

Active Target Time Projection Chamber

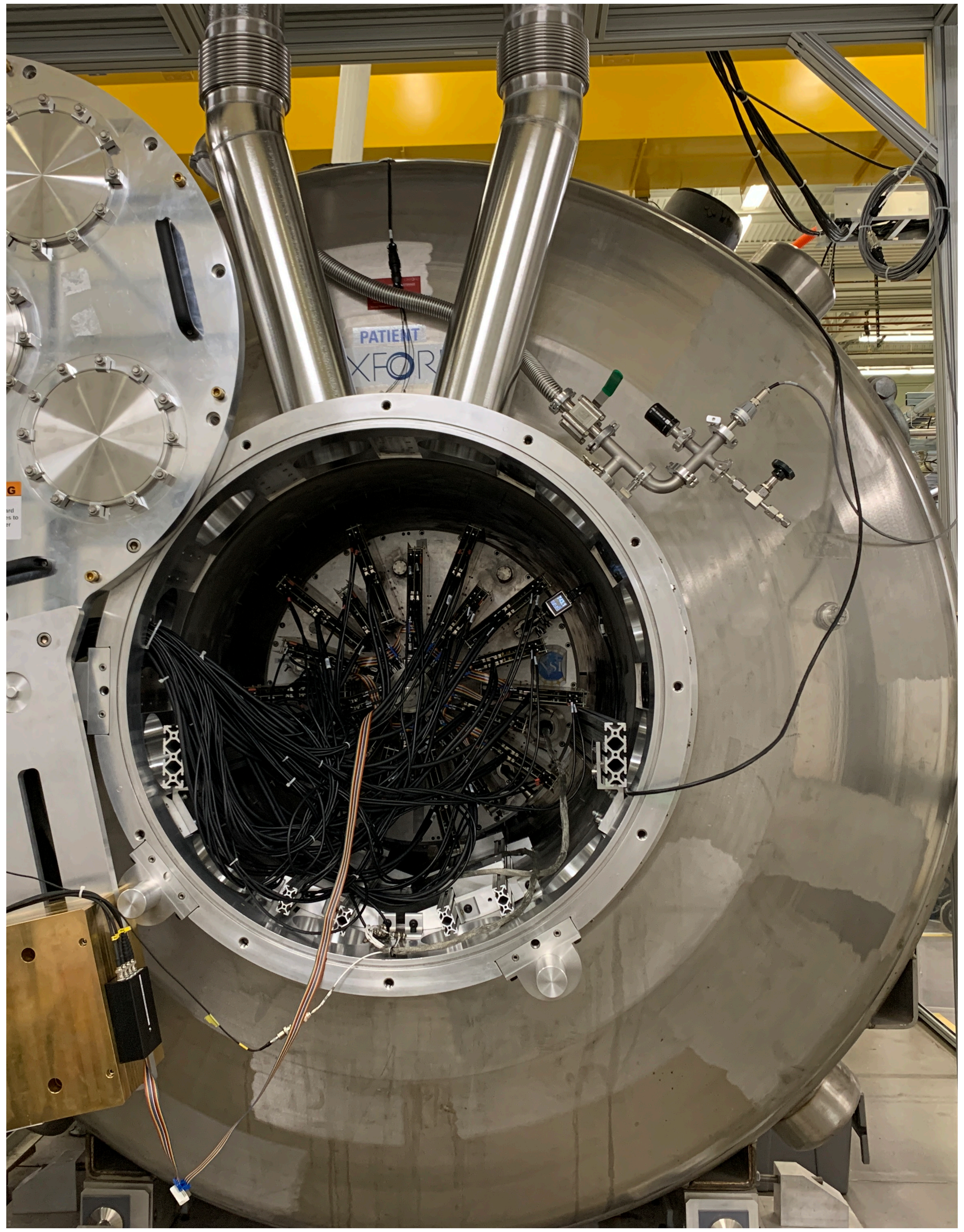
Solenoidal Spectrometer Apparatus for Reaction Studies





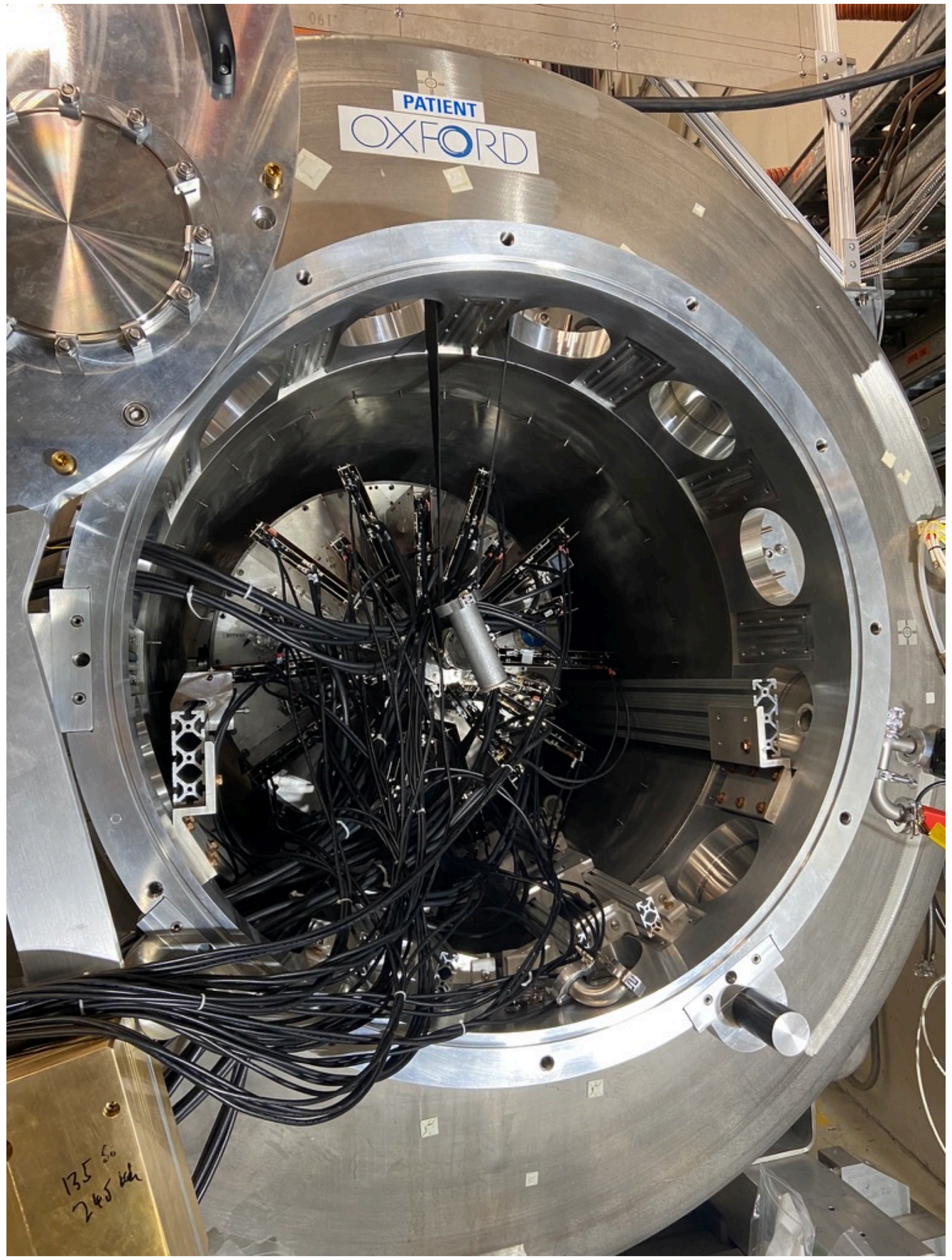
Two dual-mode solenoidal spectrometers

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

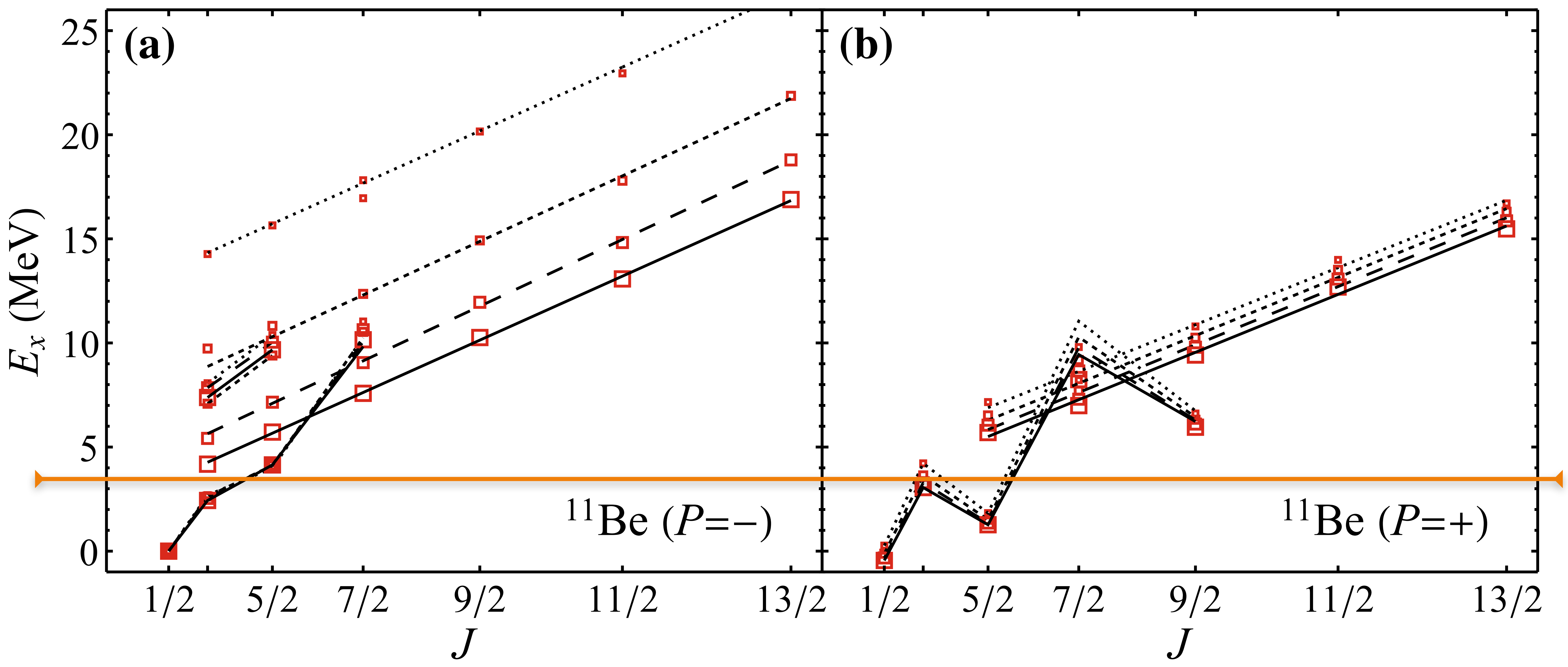


Update on performed measurements since 2020

- Transfer reaction commissioning
  - ***^{10}Be(d,p)^{11}Be***, *^{10}Be(d,d')^{10}Be* and* ***^{10}B(d,p)^{11}B*** *(2020@SOLARIS)*
    - *See talk by Jie Chen on ^{10}Be* (Thu 11:00)*
    - *See talk by Ben Kay on ^{10}B(d,p)^{11}B measured with Si-array @ HELIOS (Thu 15:20)*
- 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*
    - *See talk by Gordon McCann on ^{16}C(d,p)^{17}C (Thu 12:00)*
  - *Reactions between ^{7}Be and d target*
    - *Search for unbound resonances in ^{6}Be*
- Campaign at S800 (happening now!)

Transfer commissioning experiment: $^{10}Be(d,p)^{11}Be$

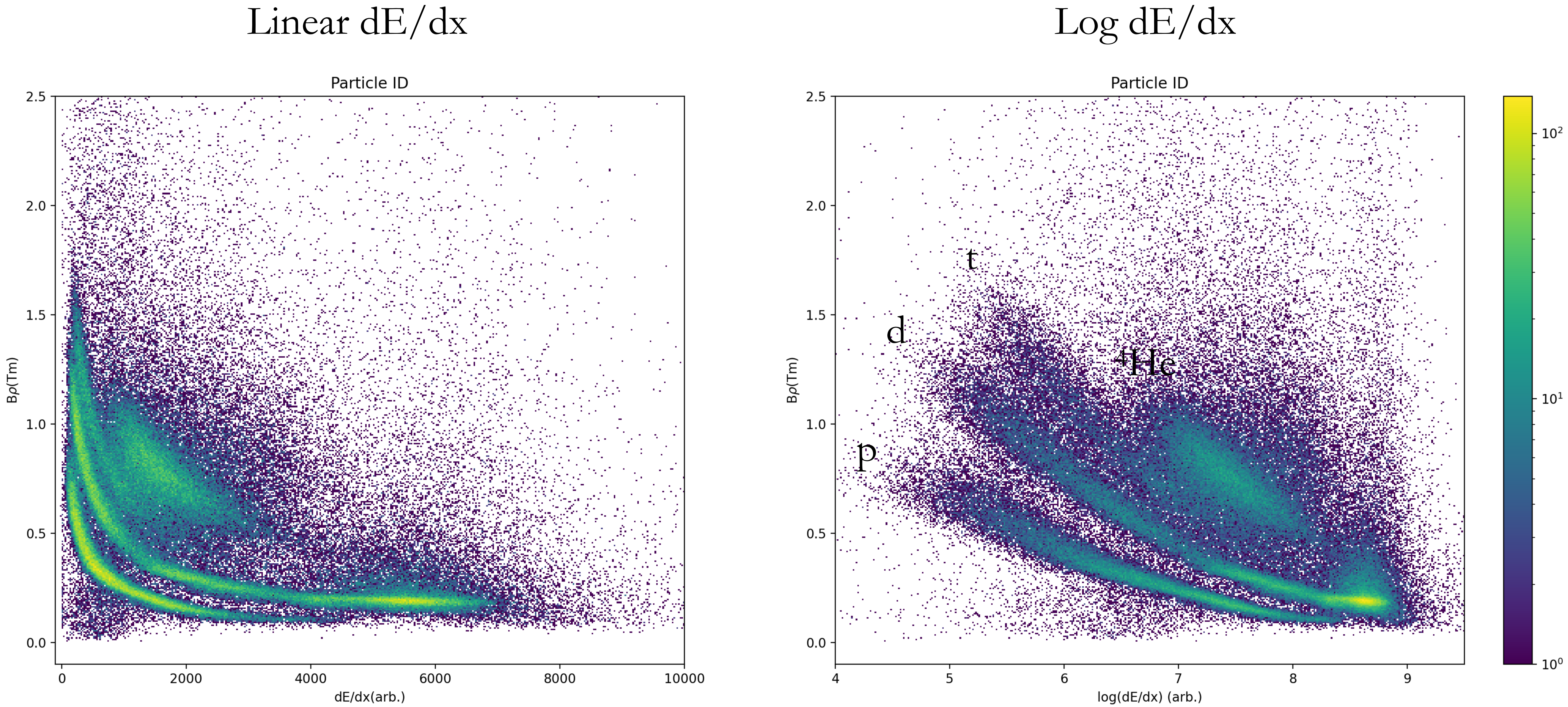
- Emergence of nuclear rotation
  - *No core SM calculations of ^{11}Be*
  - *Absolute energy convergence not reached at N_{max}=10,11*
  - *Relative energies remarkably stable, show rotational bands*
- Questions about 3/2 state around 3.4 MeV
  - *$K^P=3/2^-$ band head → $3/2^-$*
  - *$K^P=1/2^+$ band member → $3/2^+$*



Caprio, M.A. *et al.* Probing *ab initio* emergence of nuclear rotation. *Eur. Phys. J. A* **56**, 120 (2020)

Particle identification in AT-TPC

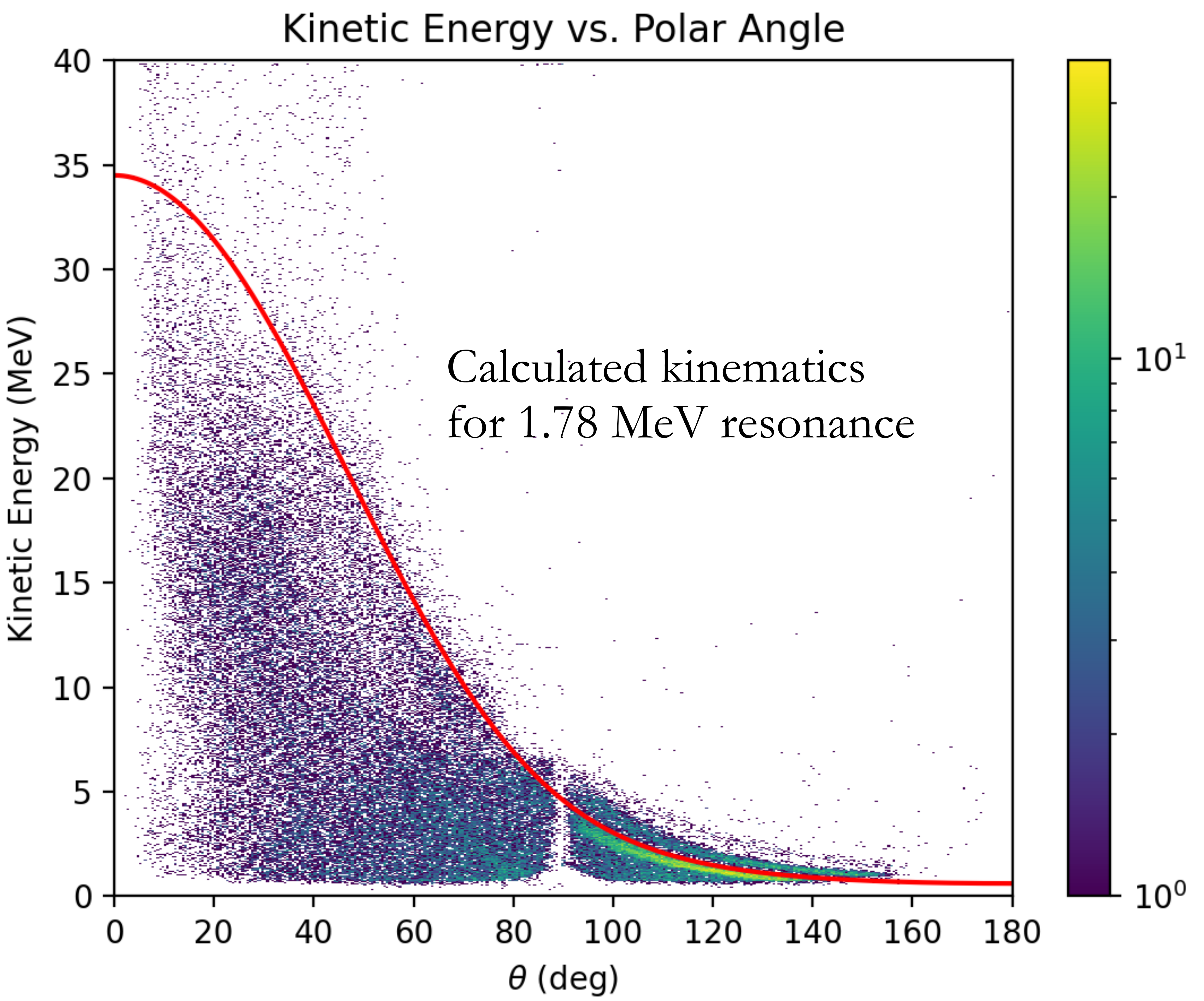
- Magnetic rigidity
  - *From curvature of track & polar angle*
- Energy loss
  - *From charge deposited along track*
- Large dynamic range
  - *Due to inverse kinematics*
  - *Logarithmic representation*



Analysis by Z. Serikow

Kinematics plot of $^{10}Be(d,p)^{11}Be$

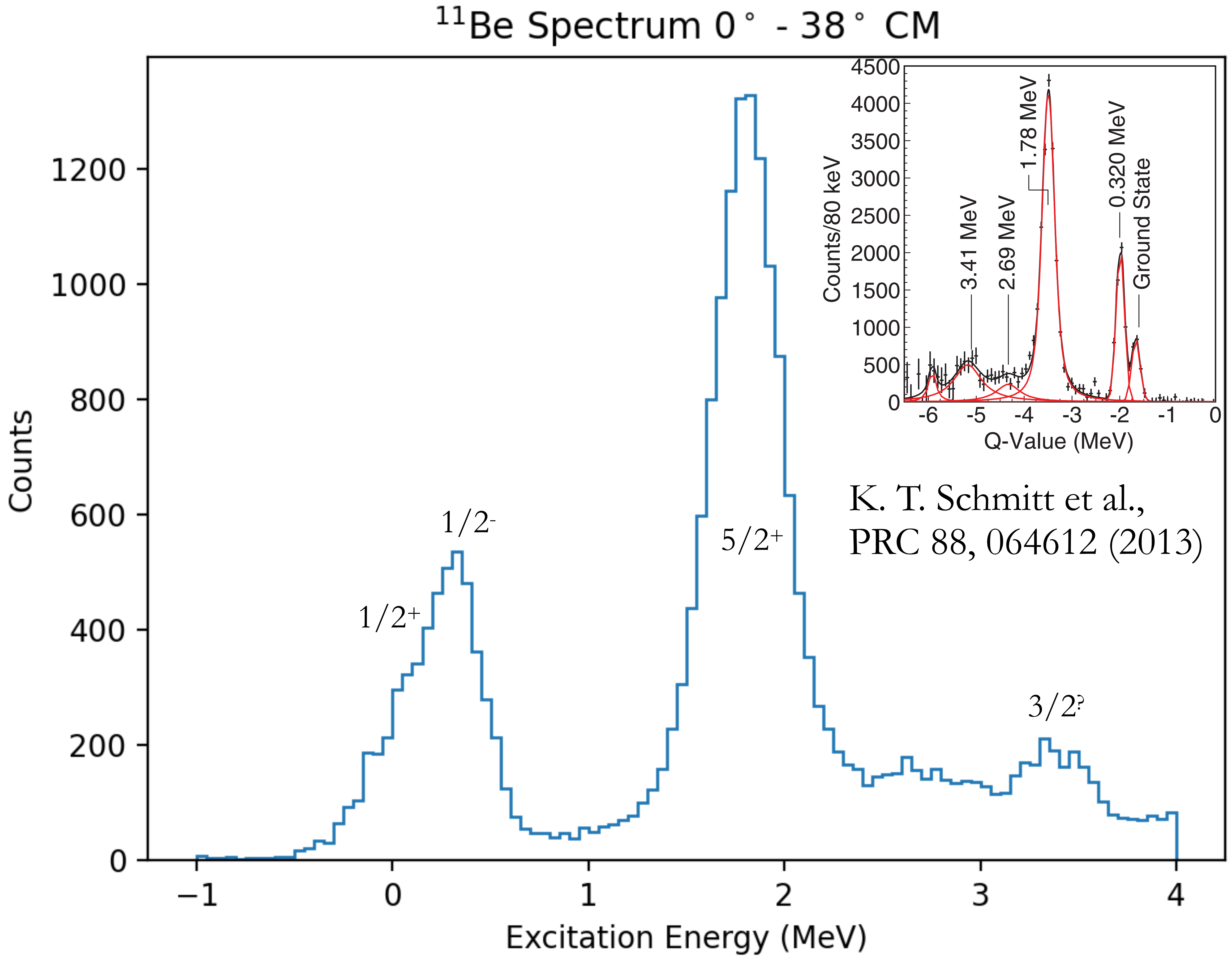
- Acceptance effects of AT-TPC
  - *Low energy cutoff at ~ 500 keV*
  - *Dependent on polar angle*
  - *Polar angle acceptance effects start at $\theta_{lab} < 20°$ and $\theta_{lab} > 160°$*
  - *Gap centered at $\theta_{lab} = 90°$ due to difficulty to analyze tracks perpendicular to beam axis*
- Resolution effects of AT-TPC
  - *Resolution degrading at higher energies*
    - *Due to limited track length at higher rigidities when target residues do not wrap around*

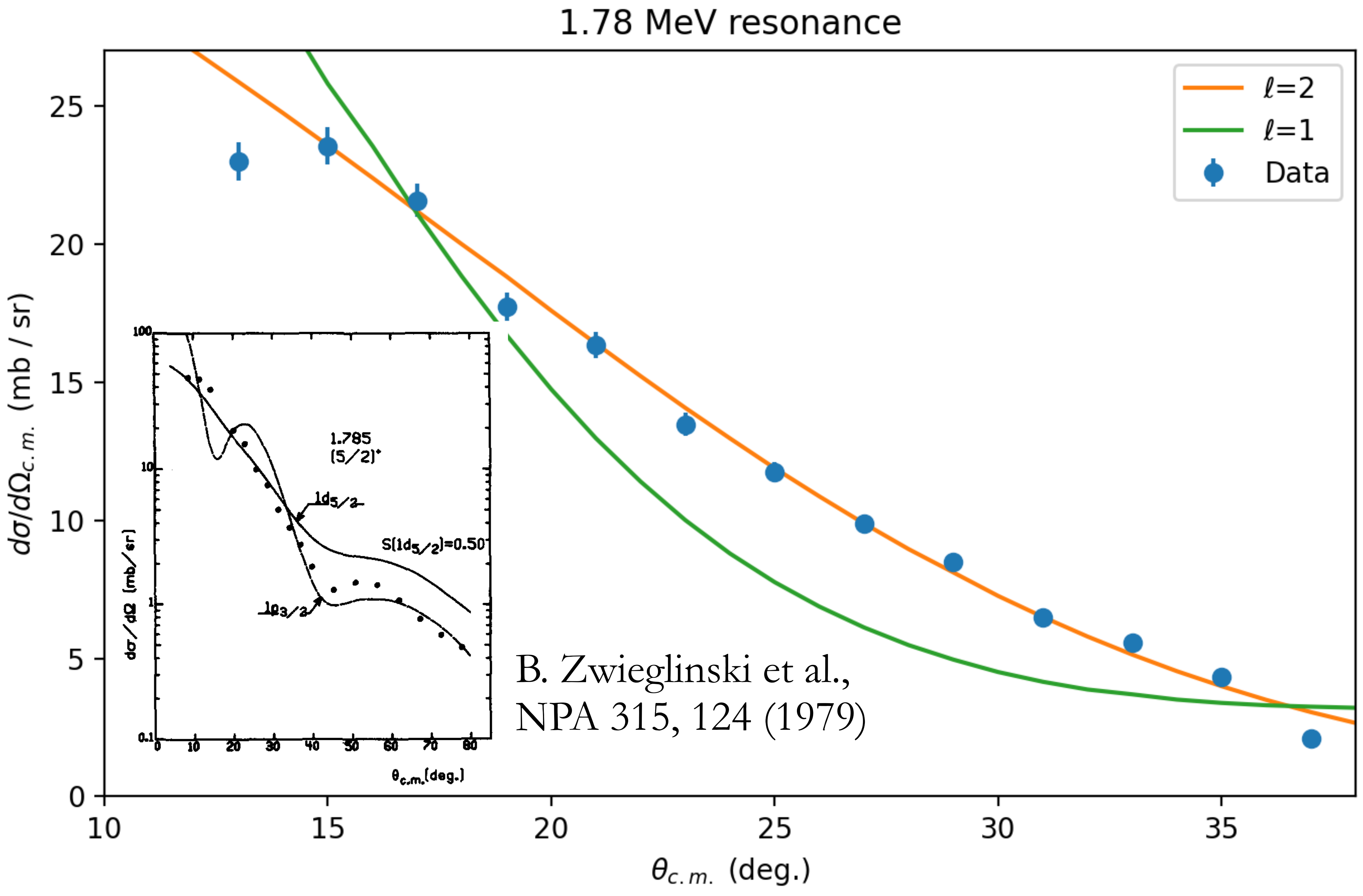


Analysis by Z. Serikow

Excitation energy spectrum and angular distributions

^{10}Be beam @ 10 MeV/u - 1000 pps / 5 days

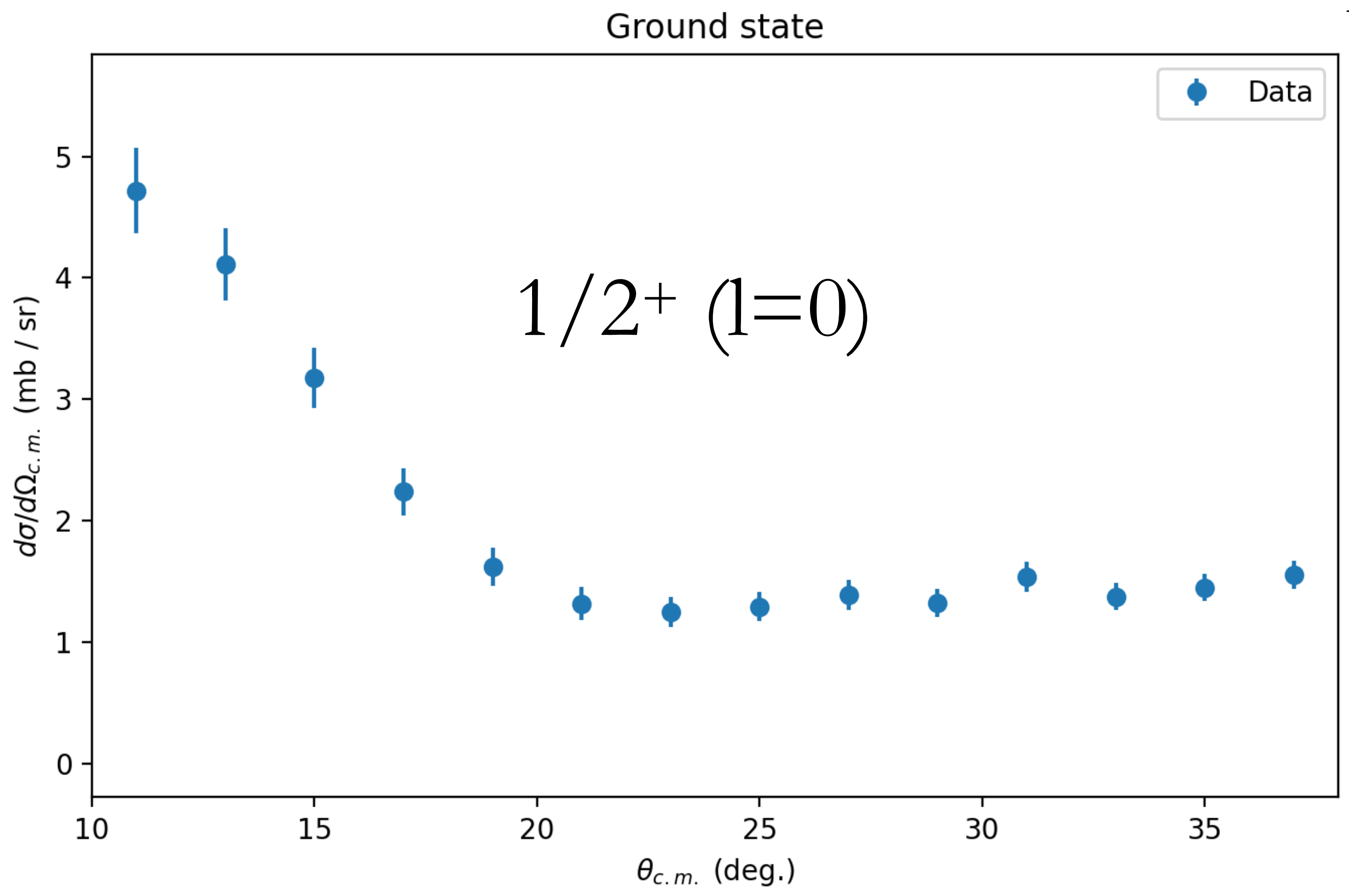


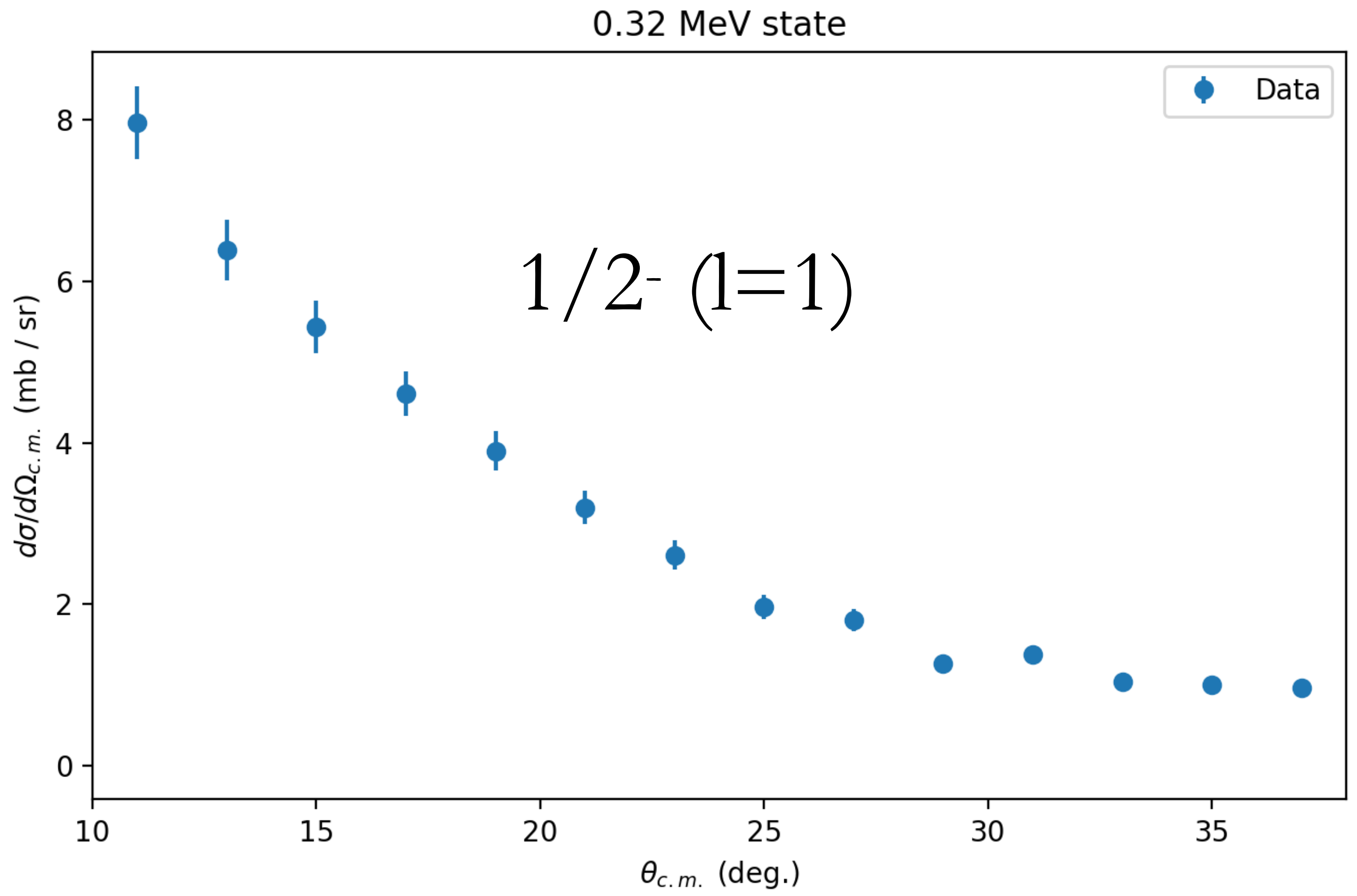


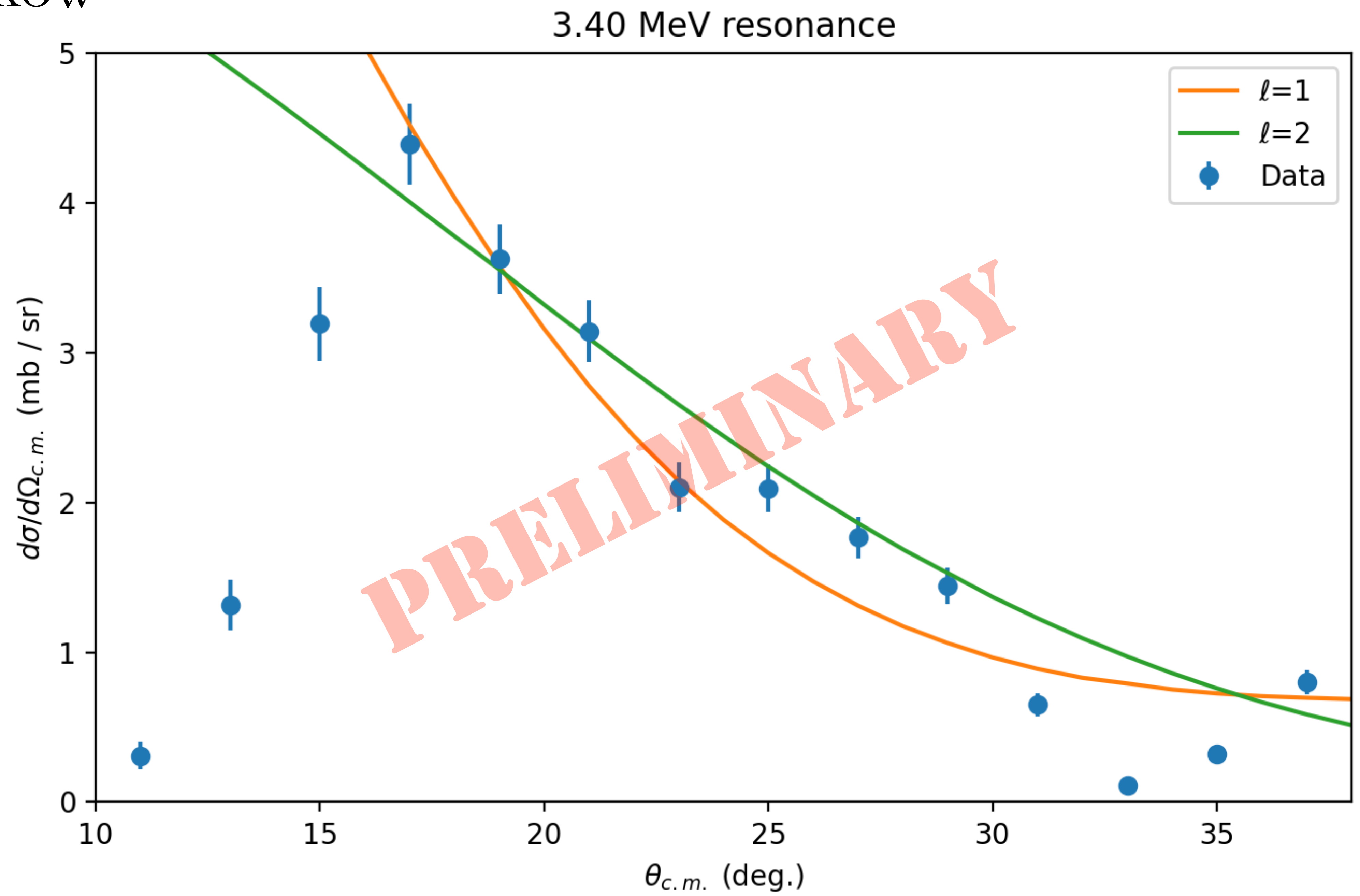
Analysis by Z. Serikow

Parity identification of 3.4 MeV resonance

Analysis by Z. Serikow



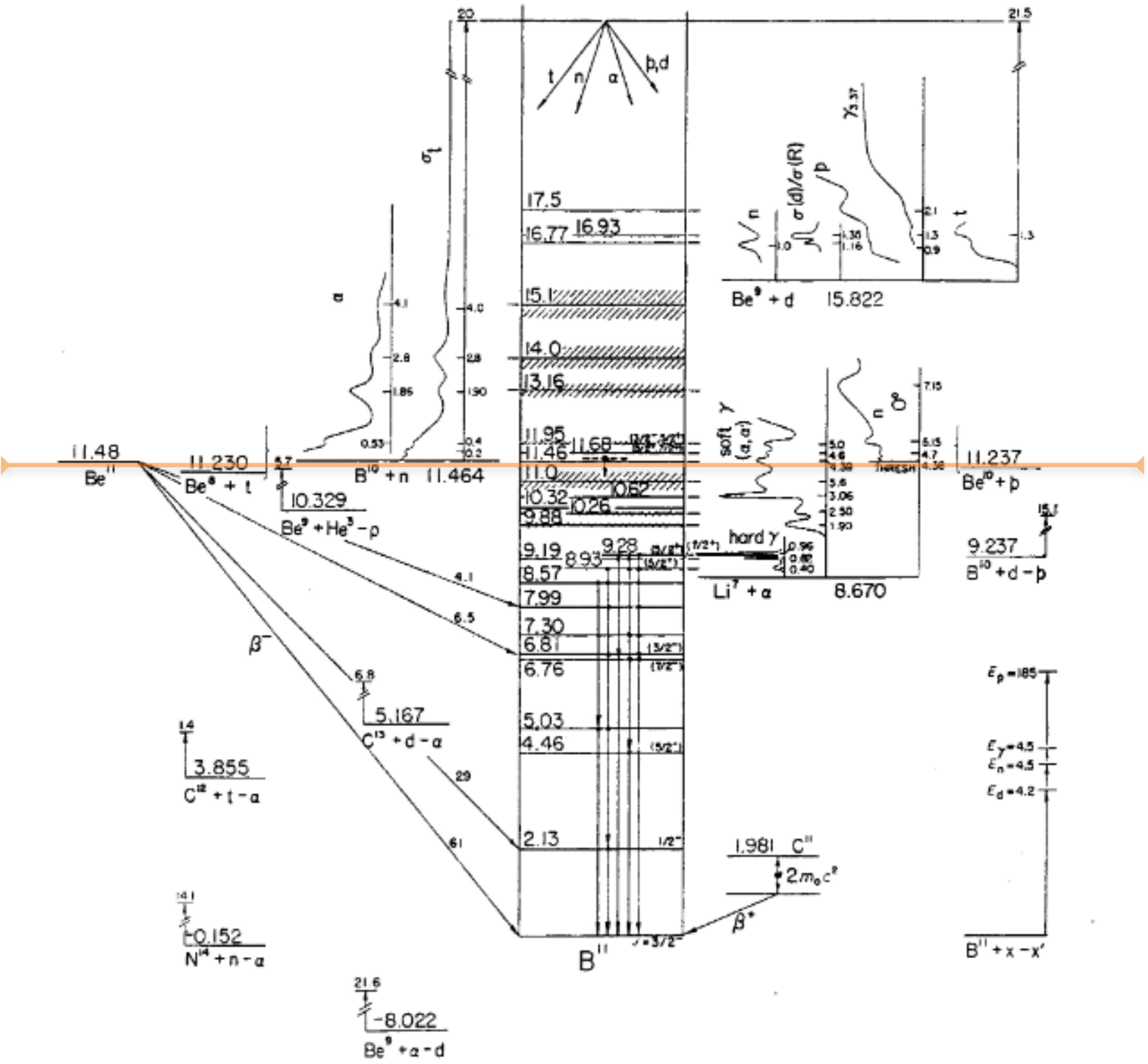




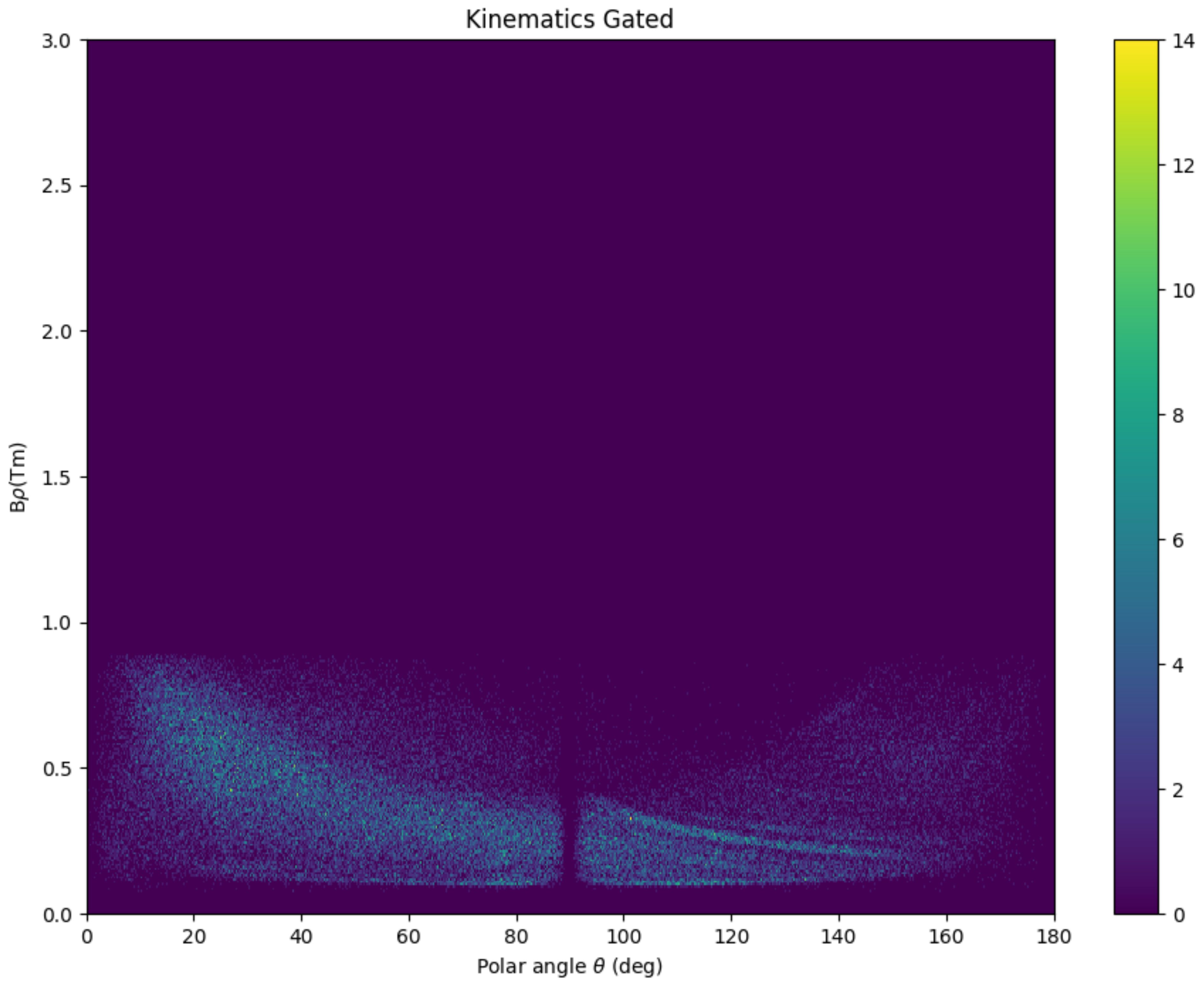
- Need to add acceptance effects from simulations to extract spectroscopic factors
- Dip around 33° corresponds to 90° effect
- Comparison to DWBA seem to indicate $3/2^+$
- This resonance would be second member of “halo” band
- Determination of $0d_{3/2}$ single-particle energy in ^{11}Be

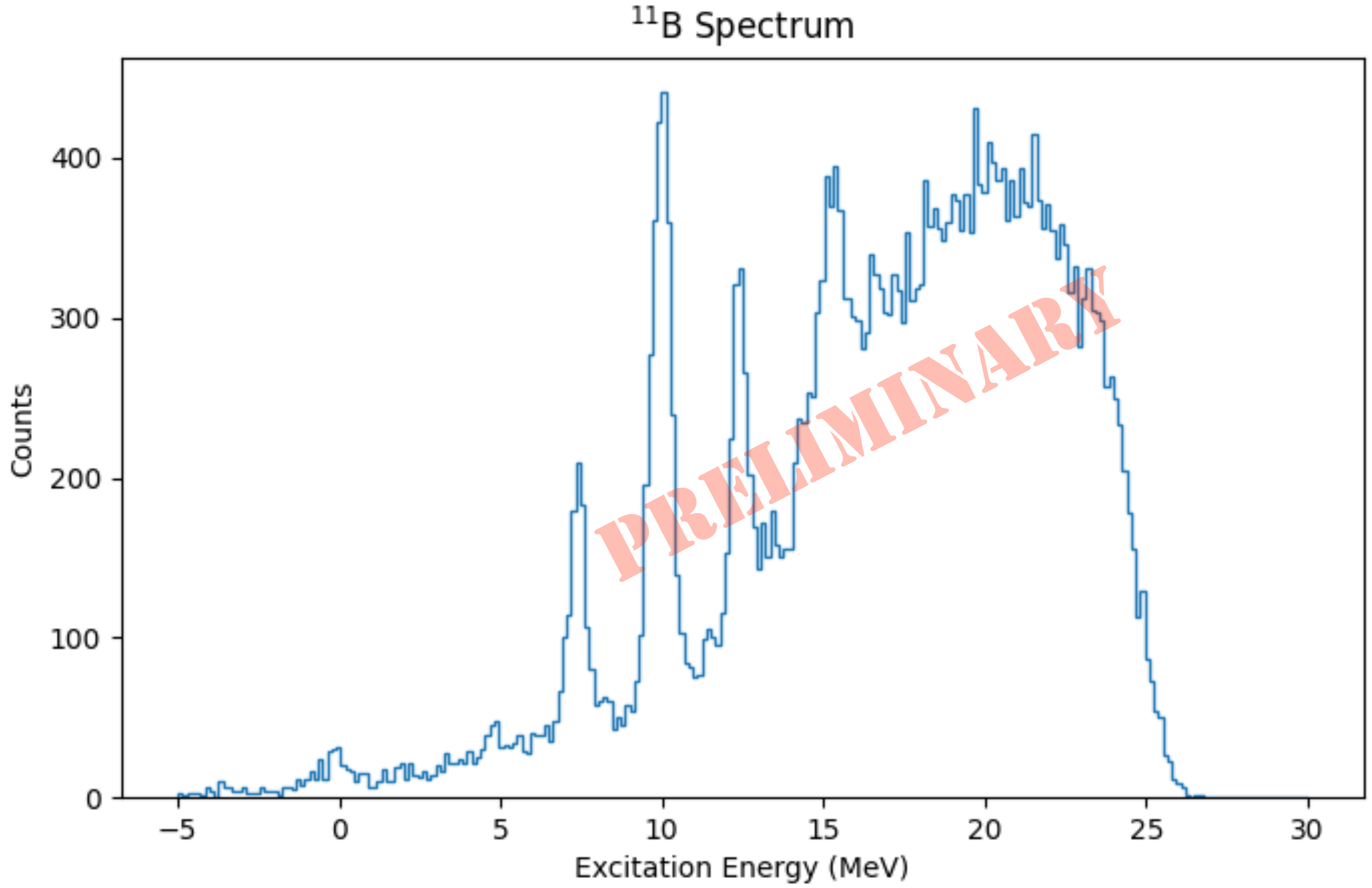
$^{10}B(d,p)^{11}B$

- ^{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
- See talk by Ben Kay on ^{10}B(d,p)^{11}B measured with Si-array @ HELIOS (Thu 15:20)



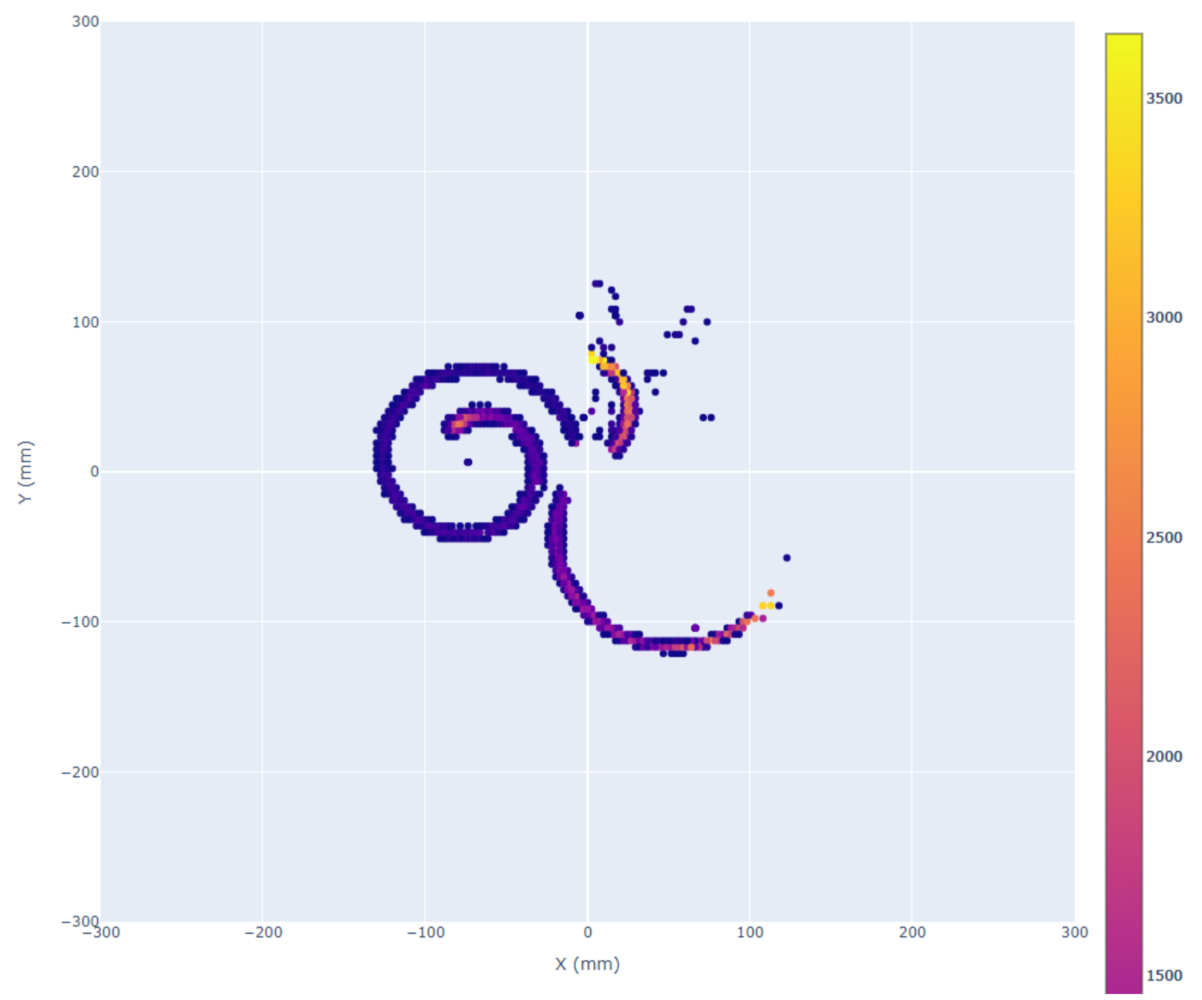
Analysis of $^{10}B(d,p)^{11}B$



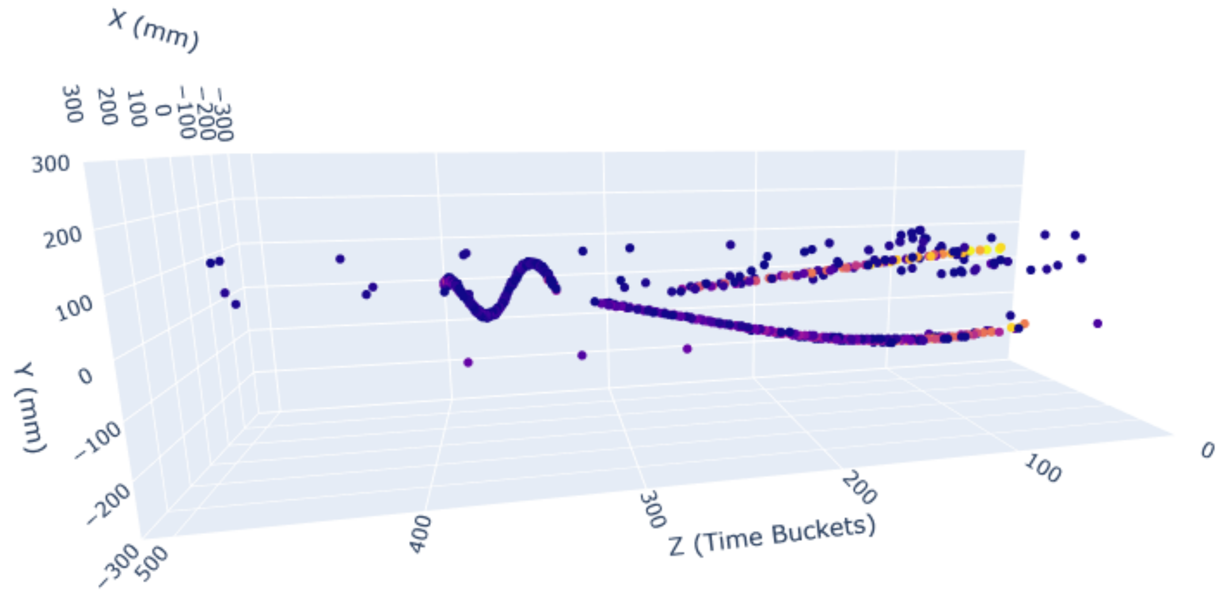


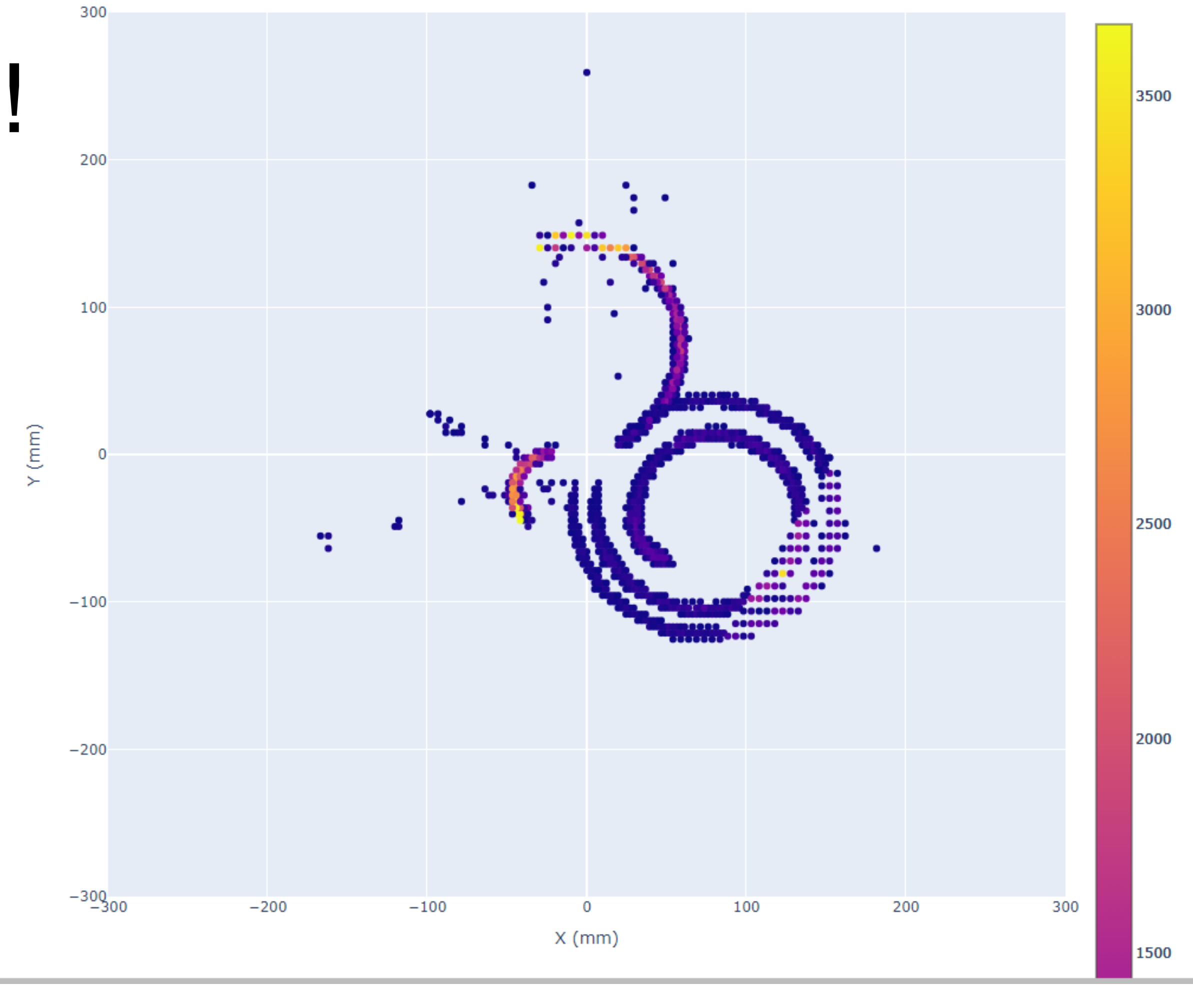
Analysis by T. Schaeffeler

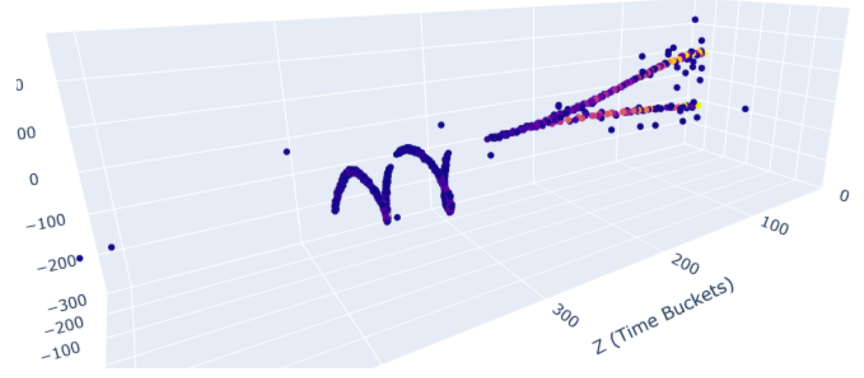
$^{10}B(d,p)^{11}B^* \rightarrow {}^{7}Li + {}^{4}He$ event from 10.6 MeV peak

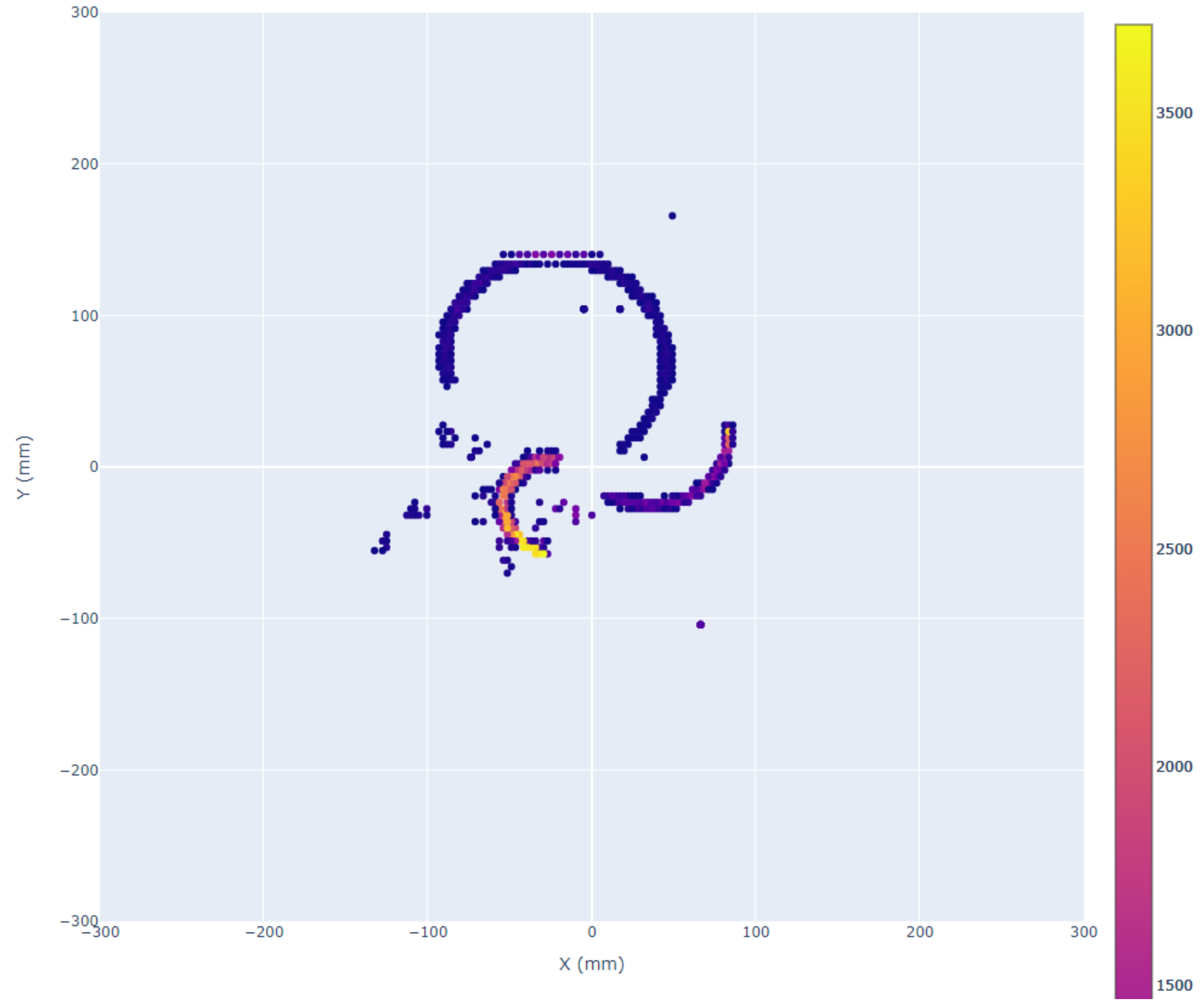


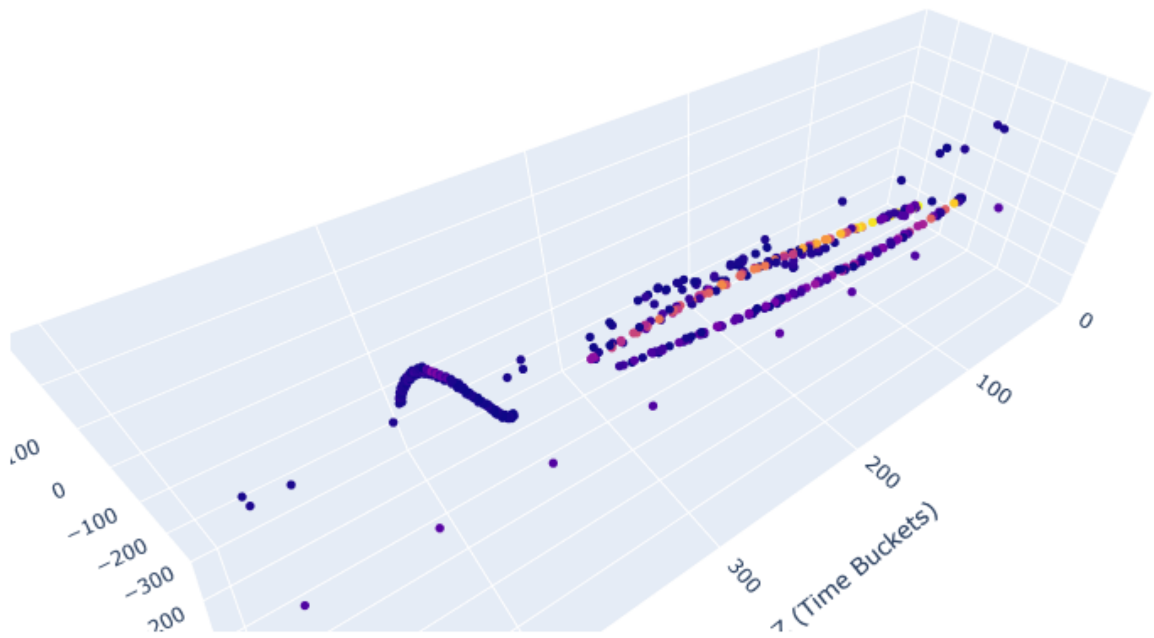
Full kinematics reconstruction!

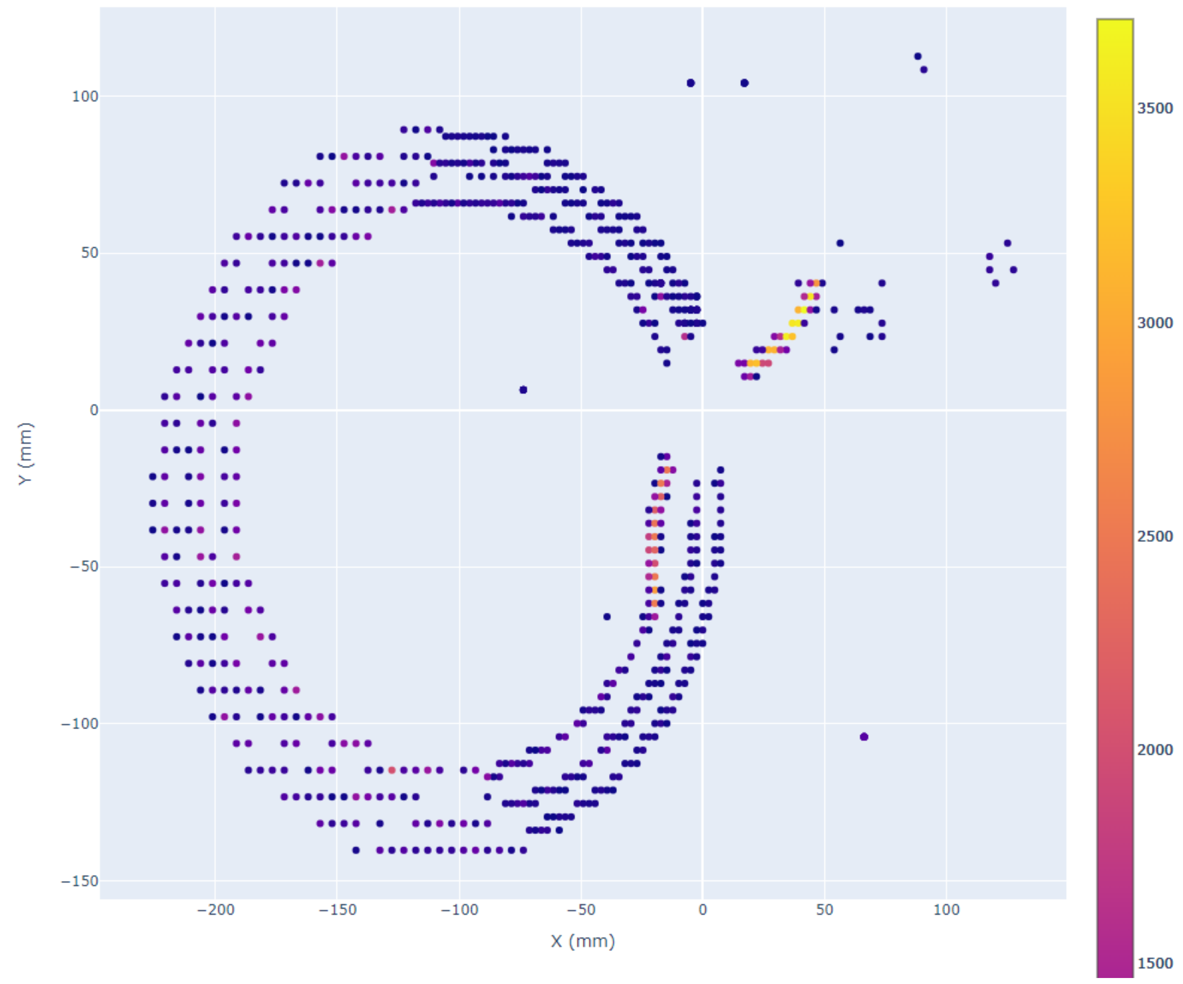


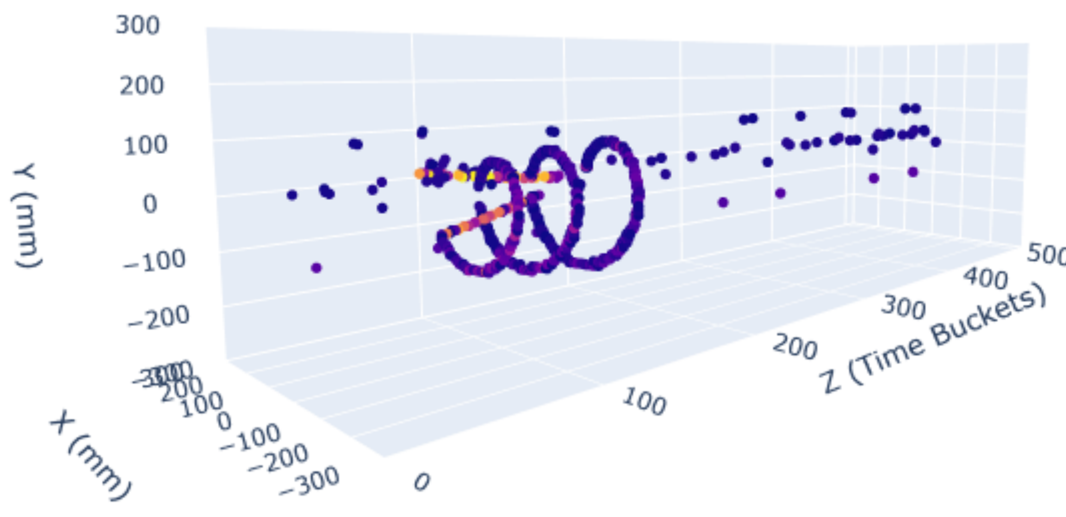








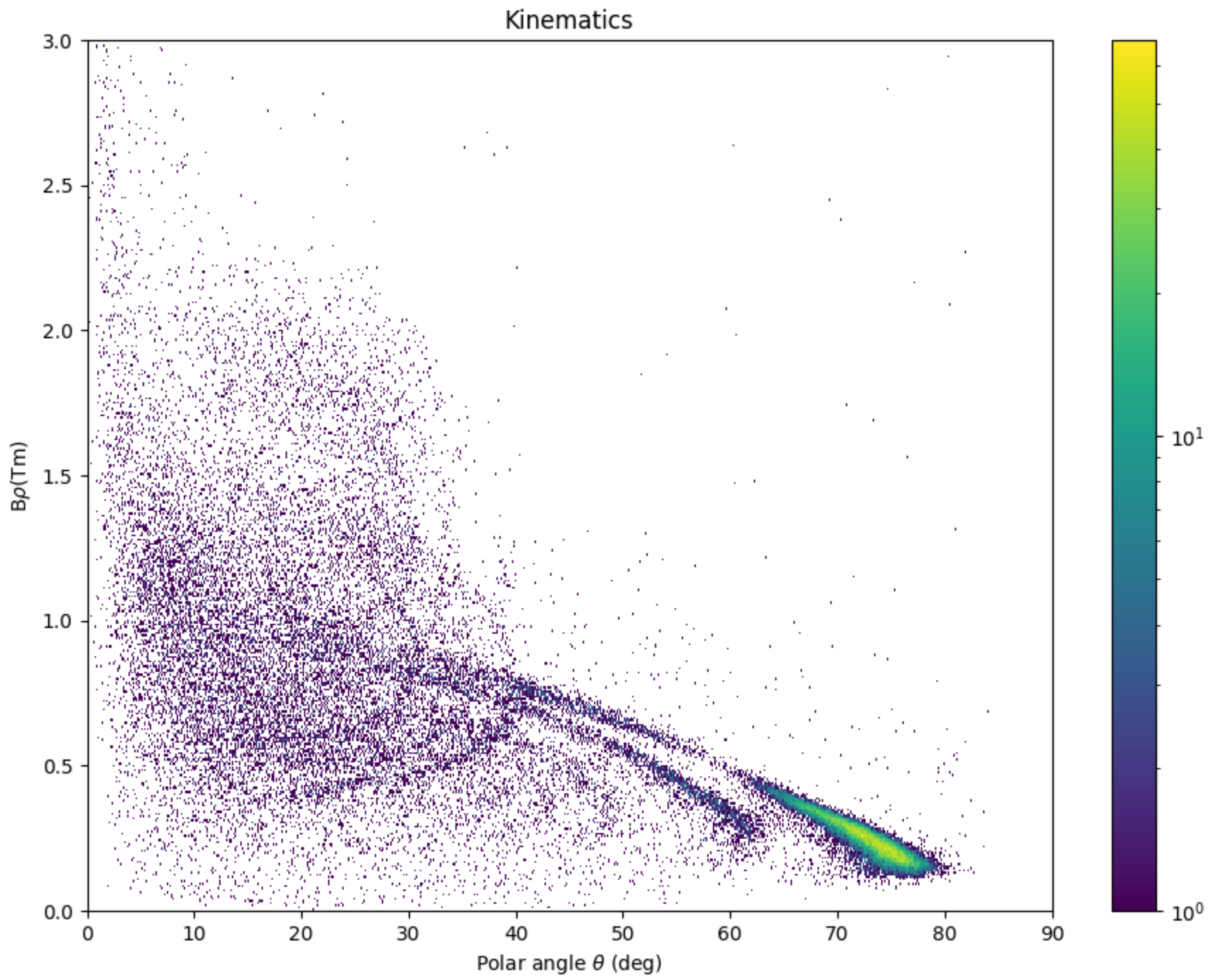




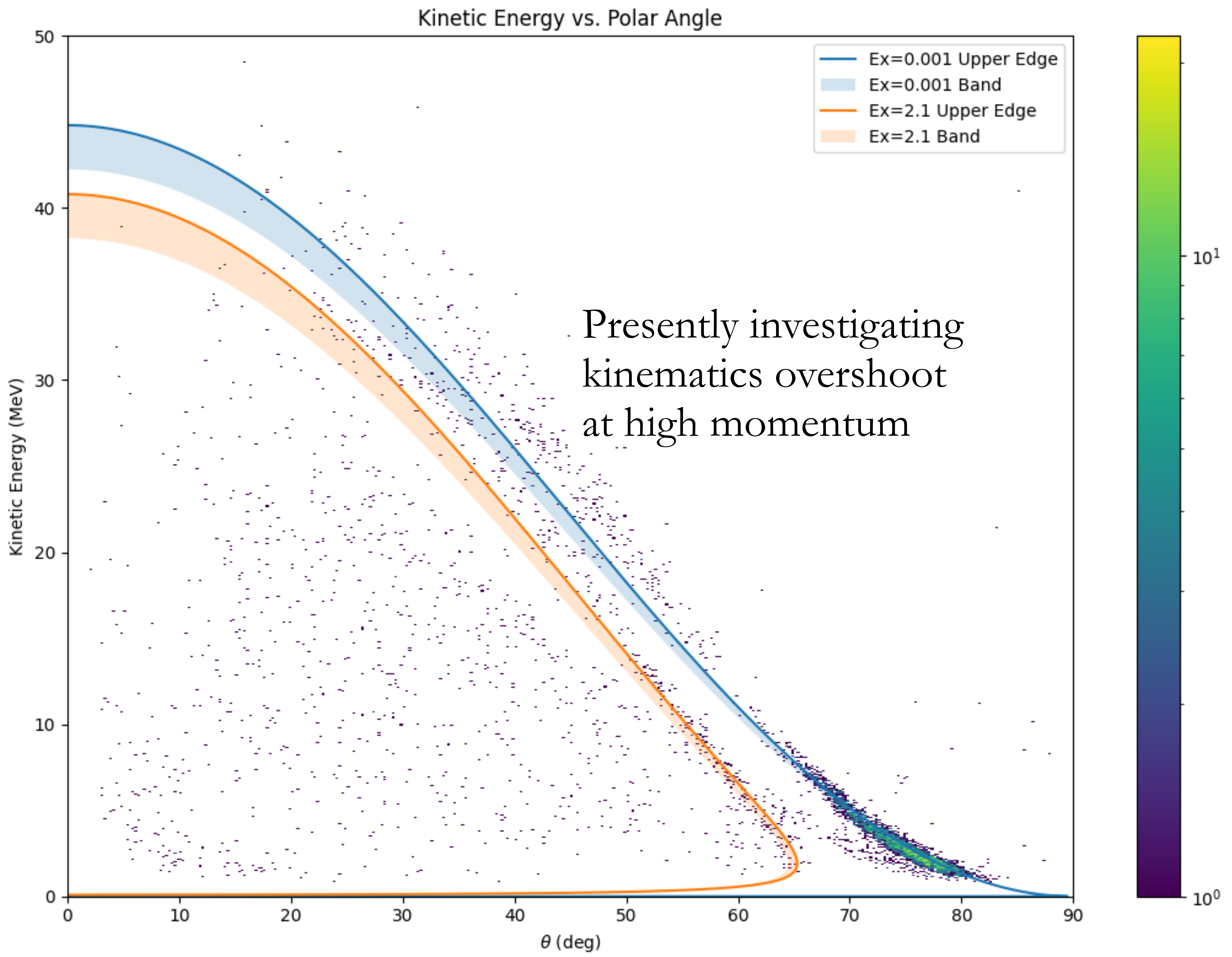
Analysis by T. Schaeffeler

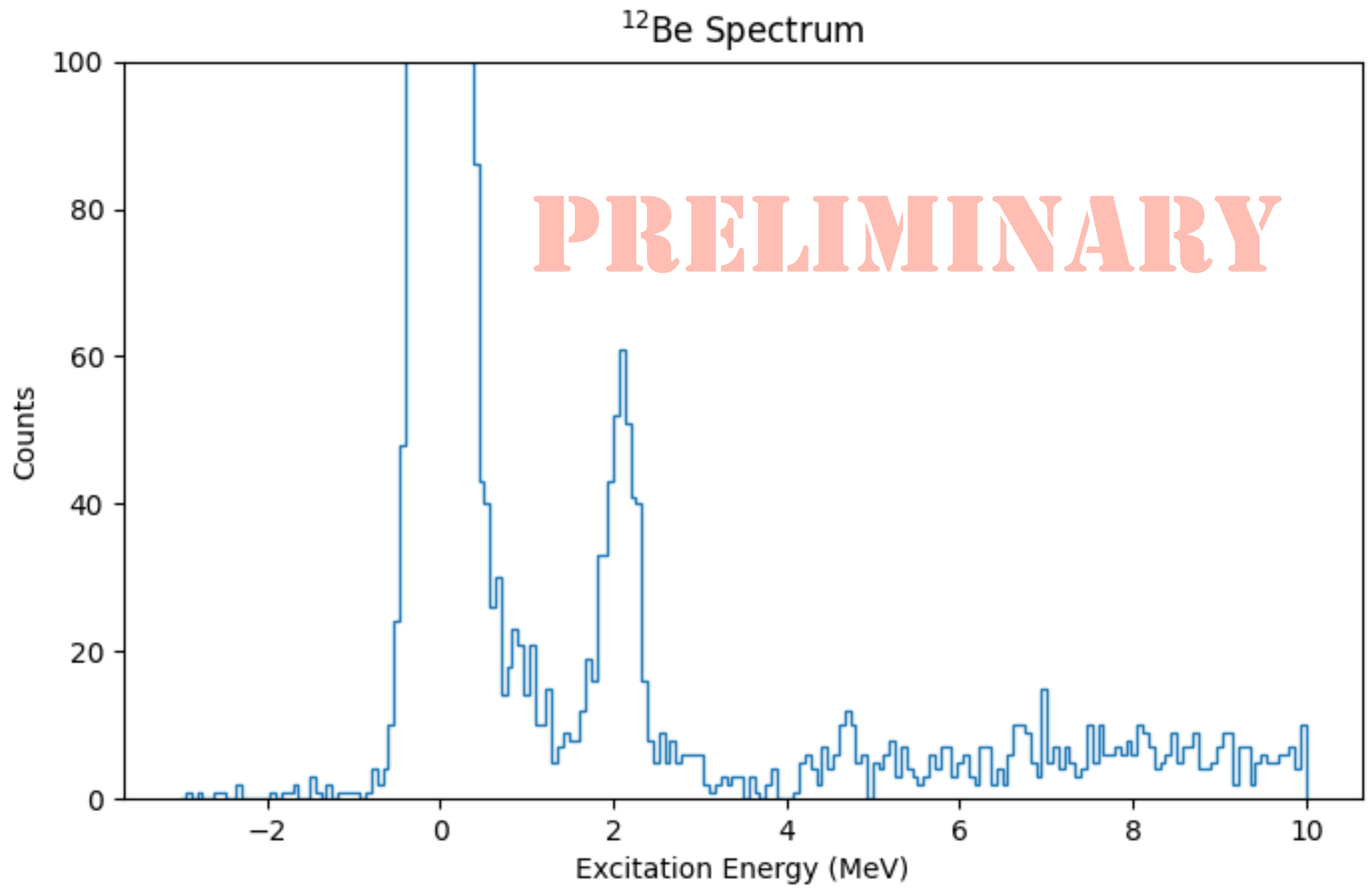
^{12}Be reactions on proton target

- ^{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 Bρ versus energy loss
- Kinematics lines from elastic, inelastic, (p,d) and a hint of (p,t) reactions



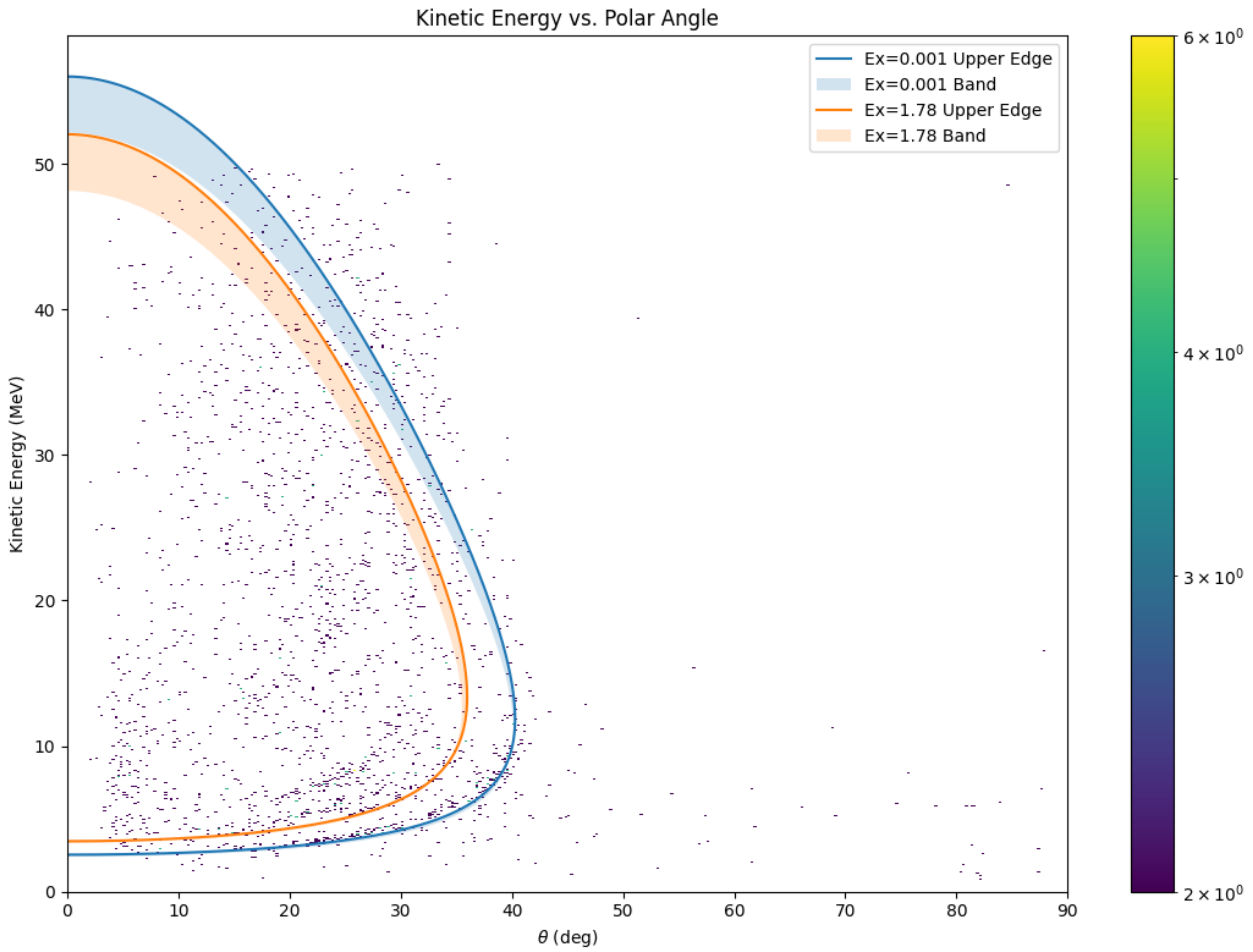
^{12}Be elastic and inelastic on proton

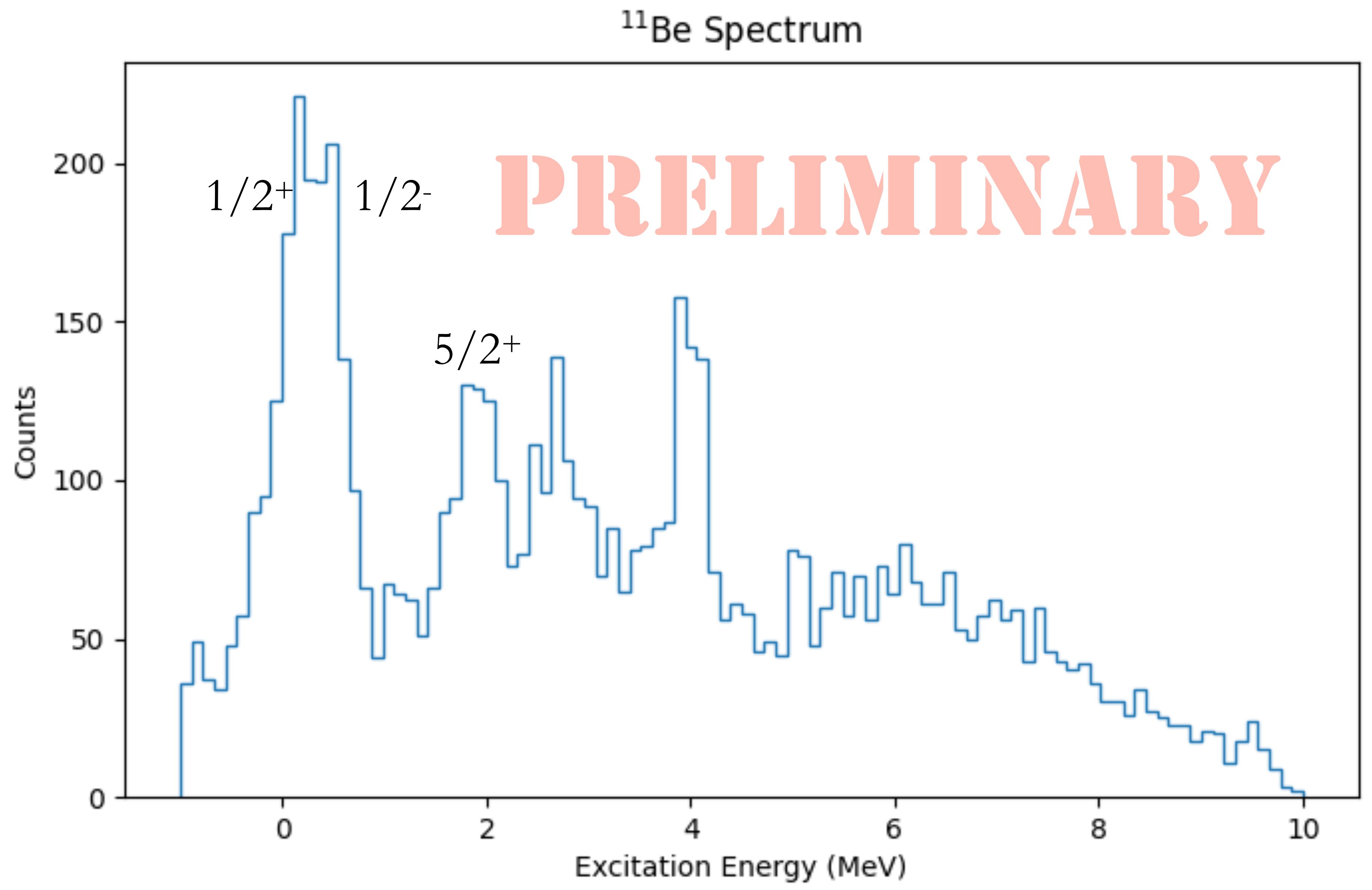




- Higher energy resonances in ^{12}Be
- Reactions on isomeric 0^+ (0.23μs)?

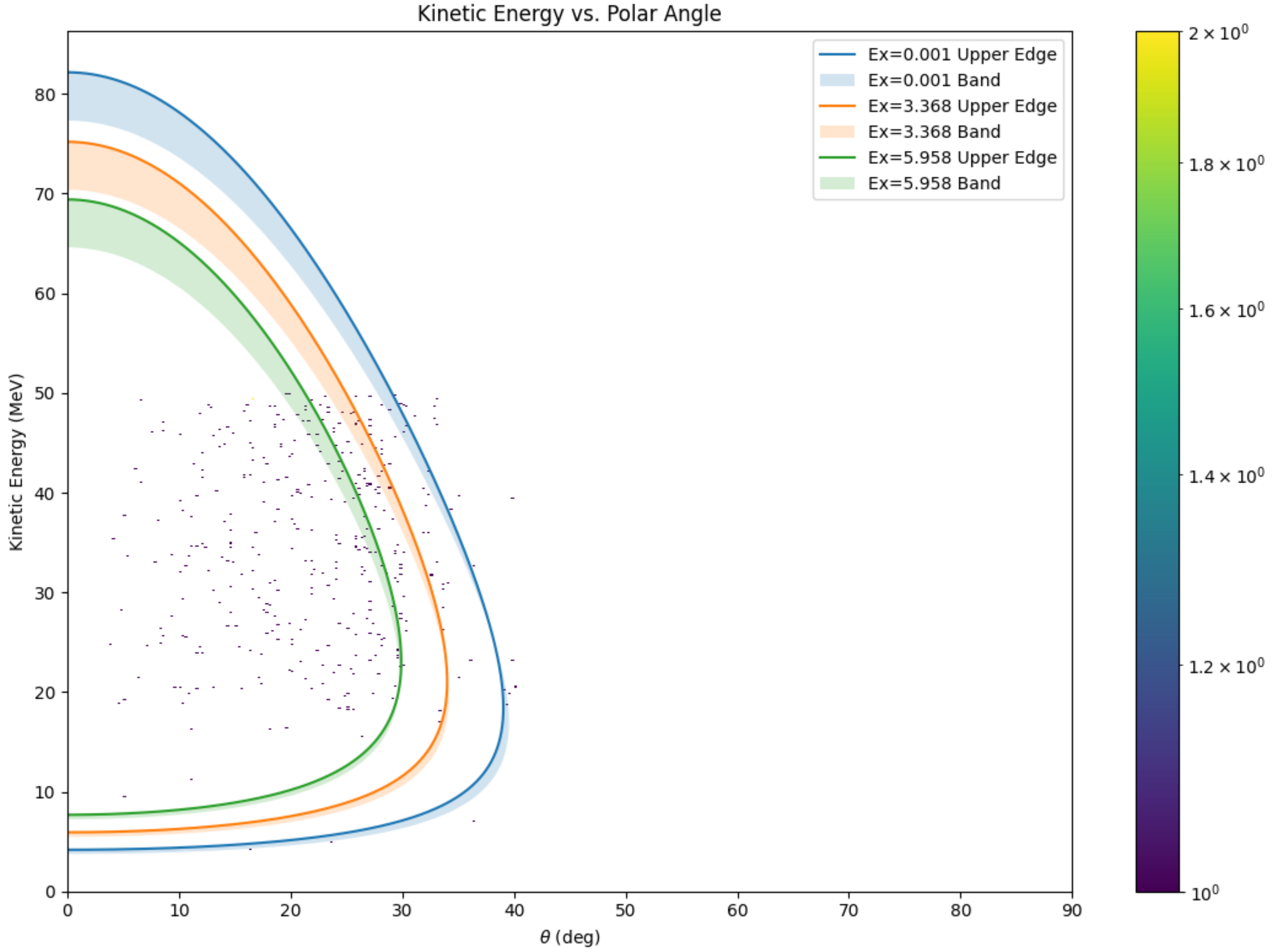
$^{12}Be(p,d)^{11}Be$

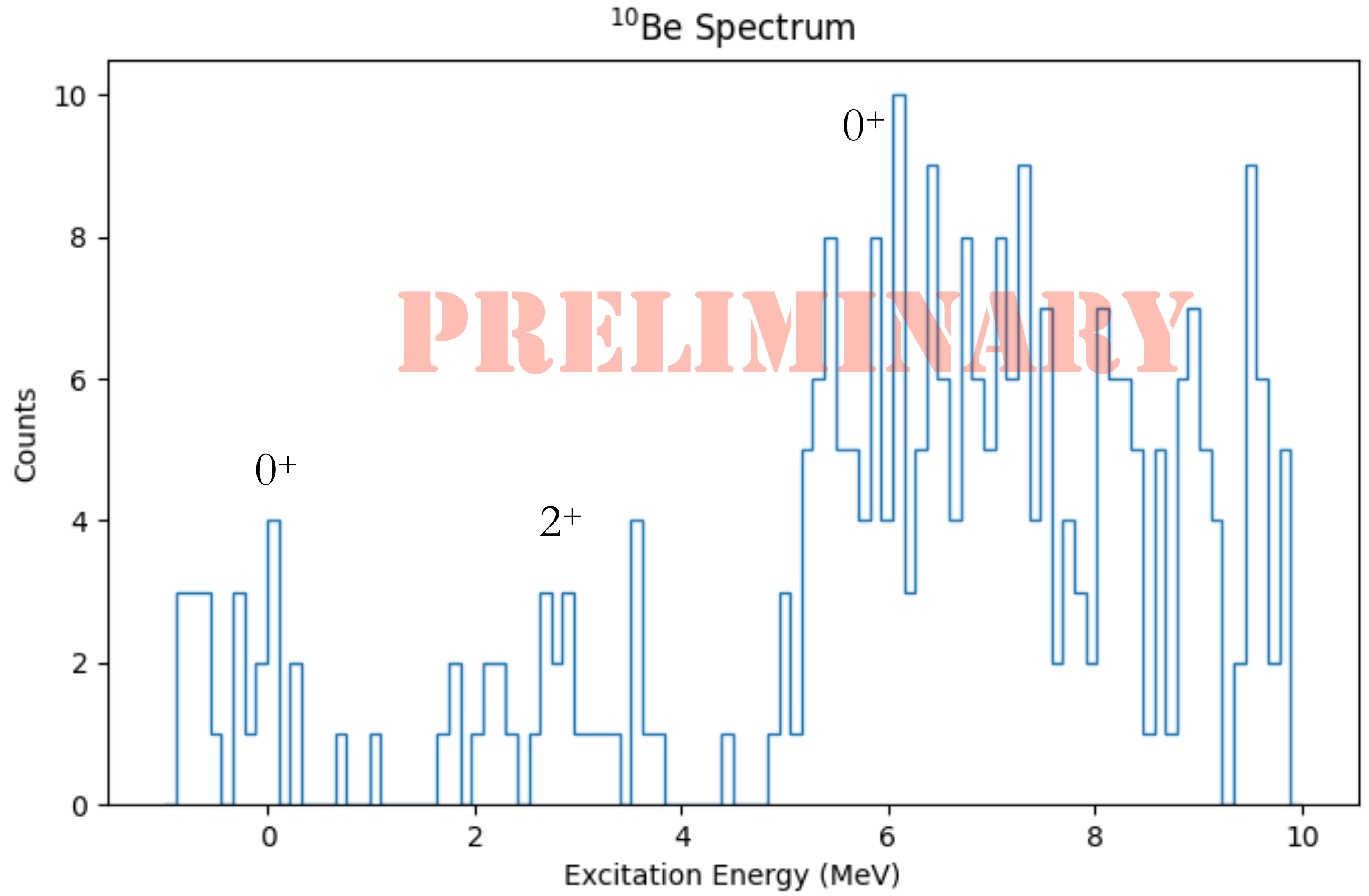




- Large cross sections to 1/2+ and 1/2- bound states
- Similar reaction to ^{12}Be-1n knockout
  - *Breakdown of N=8, A. Navin et al., PRL 85, 266 (2000)*
  - *d-wave component, S. D. Pain et al., PRL 96, 032502 (2006)*
  - *Neutron-unbound resonances, W. A. Peters et al., PRC 83, 057304 (2011)*
- More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

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

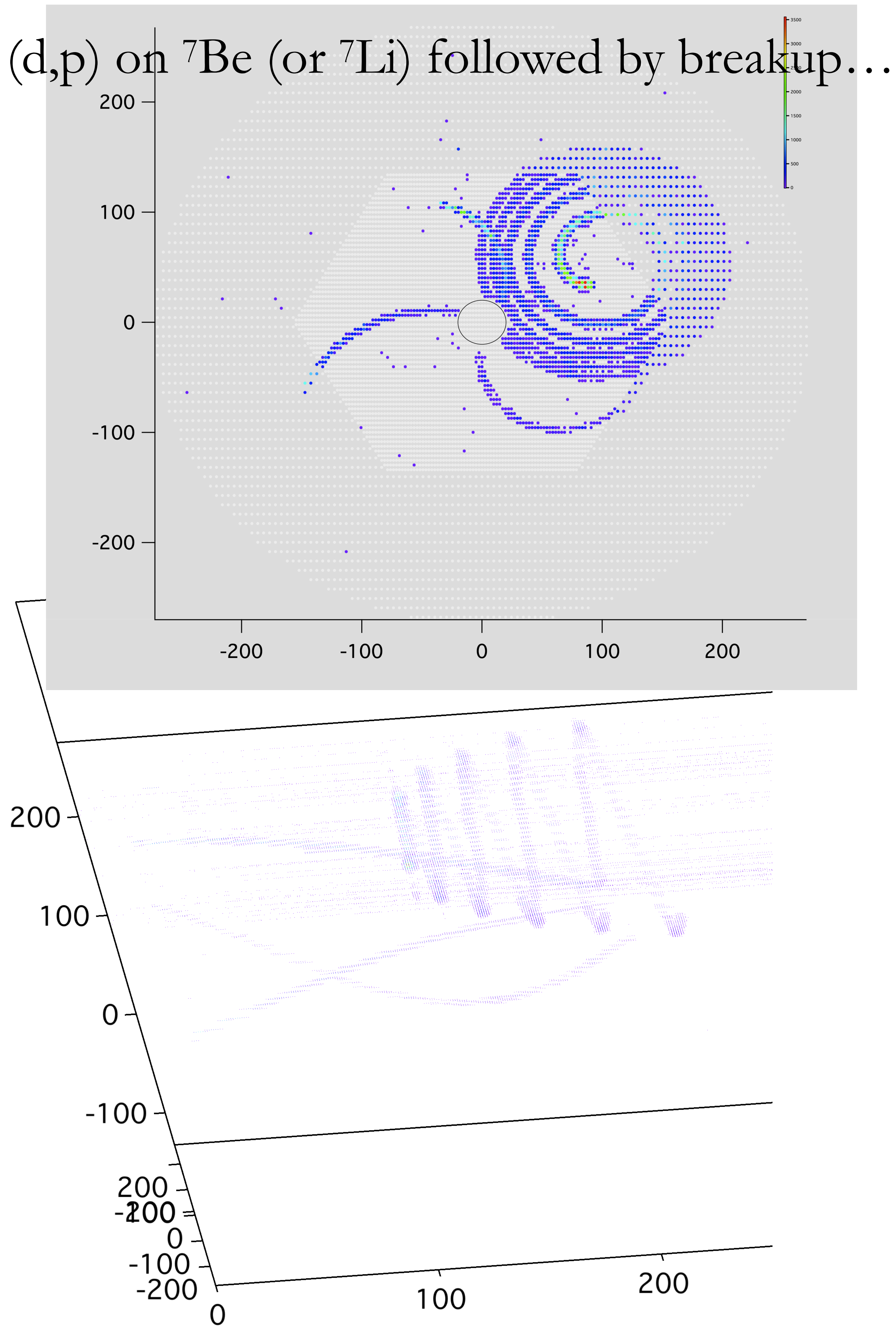




- Analysis done with **Spyral**
  - *Python based*
  - *Allows use of multi-core CPU and shared memory*
  - *Multi-platform and well documented*
  - ***See talk by G. McCann (Thu 12:00)***

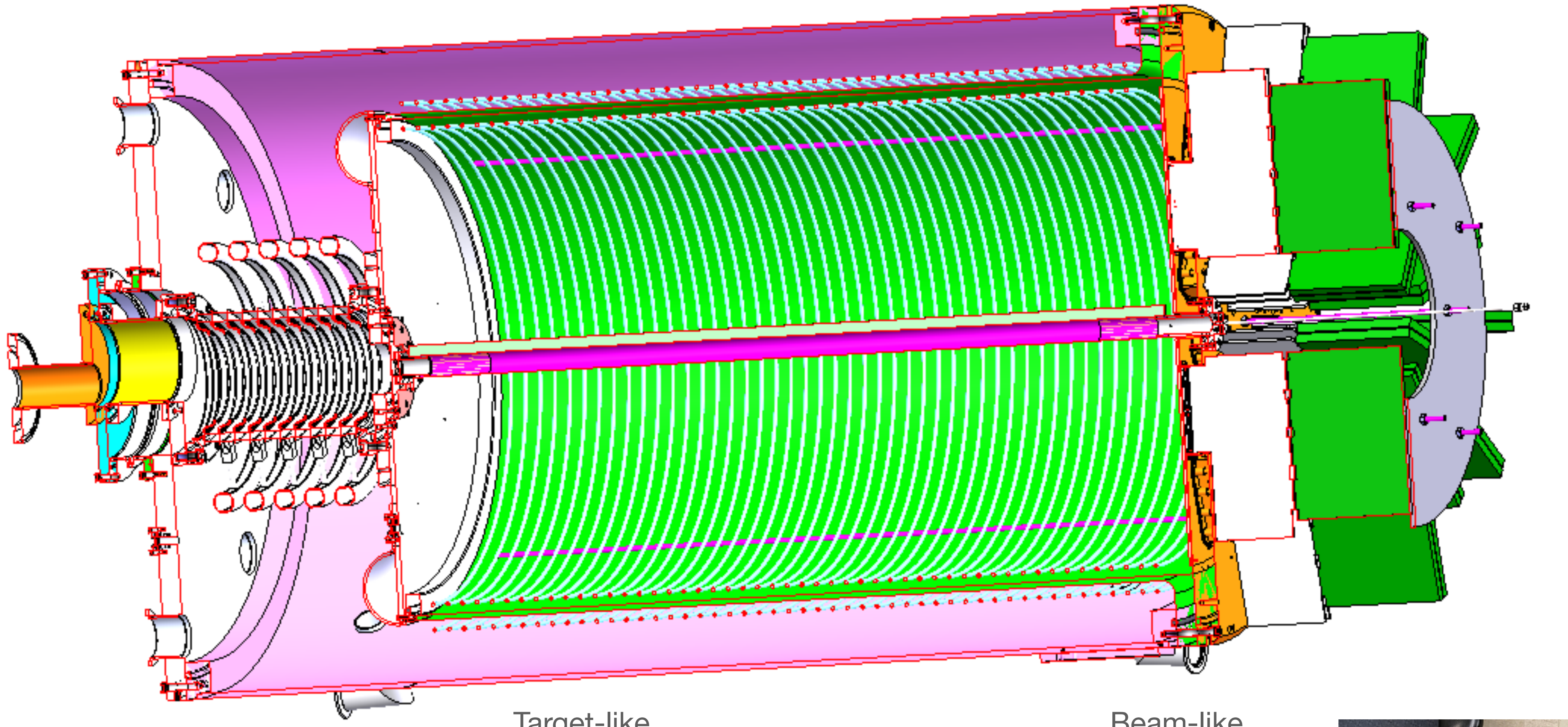
Outlook

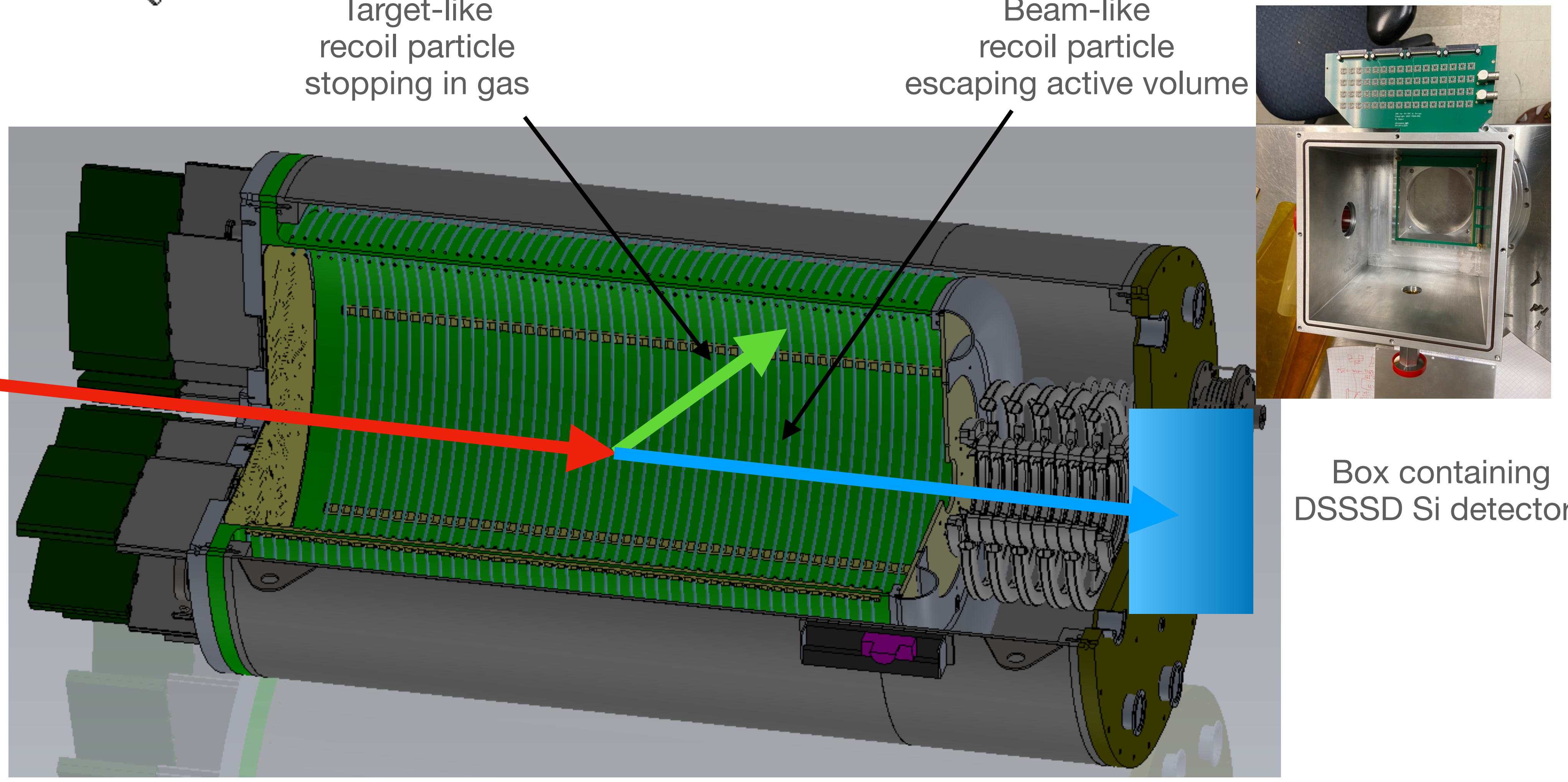
- Active targets such as the AT-TPC offer a breakthrough in measurements of Direct Reactions with Exotic Beams
  - *Luminosity gain of **two to three orders of magnitude** compared to passive targets, while retaining comparable resolutions*
  - *Transfer reaction cross sections (~ 10 mb/sr) now accessible 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)*





Upcoming experiments

- S800 campaign (happening now!)
  - *GT strength in 32Na via ^{32}Mg(d,^{2}He) Done!*
  - *PGR and GR in ^{11}Li via ^{11}Li(p,p')*
- SOLARIS experiment (Fall 2024)
  - *NP pairing in ^{56}Ni via ^{56}Ni(^{3}He,p)*
- RCNP campaign (early 2025)
  - *6 experiments approved*
- Argonne campaign (late 2025)
  - *3 experiments approved*

AT-TPC collaboration

Oak Ridge National Laboratory
Michigan State University
TRIUMF
Argonne National Laboratory
FRIB
RCNP
Morgan State University
USC Universidade de Santiago de Compostela
University of Notre Dame
SUSTech