Nuclear Astrophysics Experiments with HIAF

2025年9月3日至5日
Huizhou Branch, IMP
Asia/Shanghai 时区

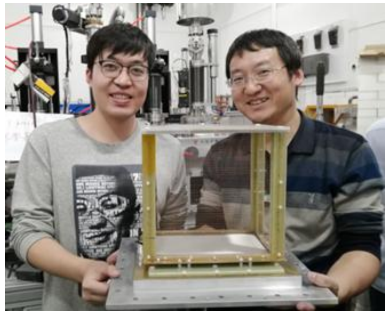
Nuclear Physics Studies with the MATE TPC

Ningtao Zhang, MATE Collaboration

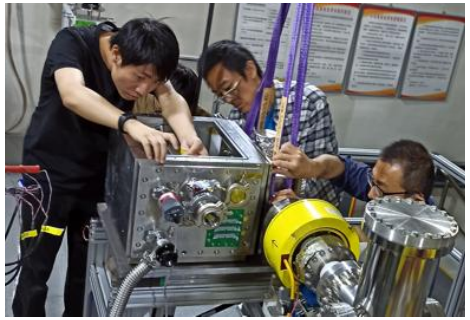
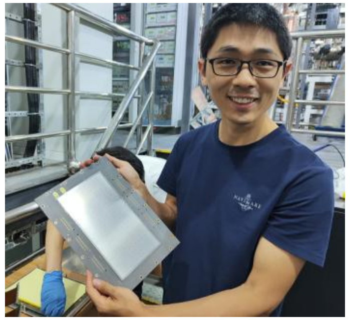
Institute of Modern Physics, Chinese Academy of Sciences

09/04, 2025

MATE TPC: *Multi-purpose Active-target Time projection chamber for nuclear Experiments*



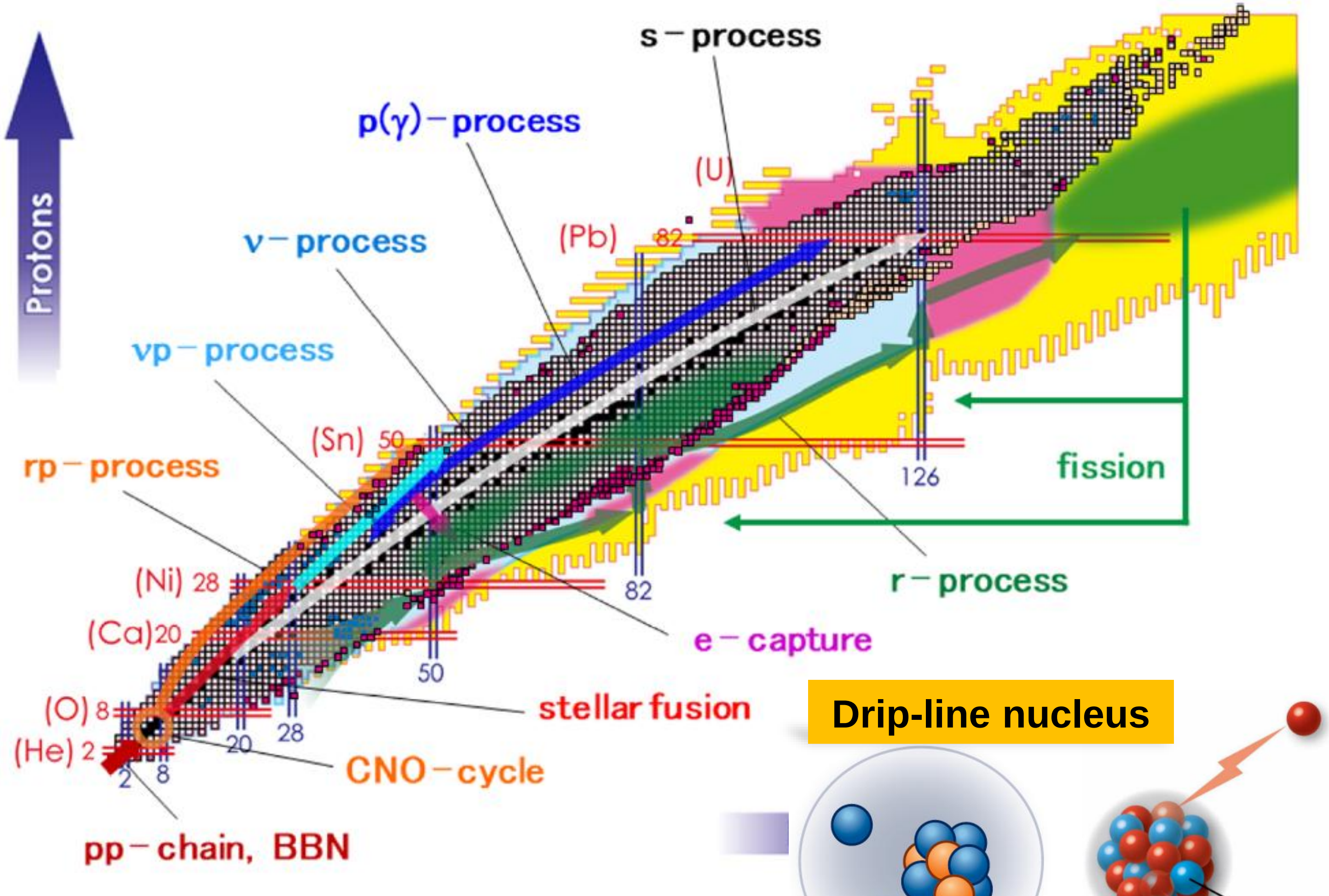


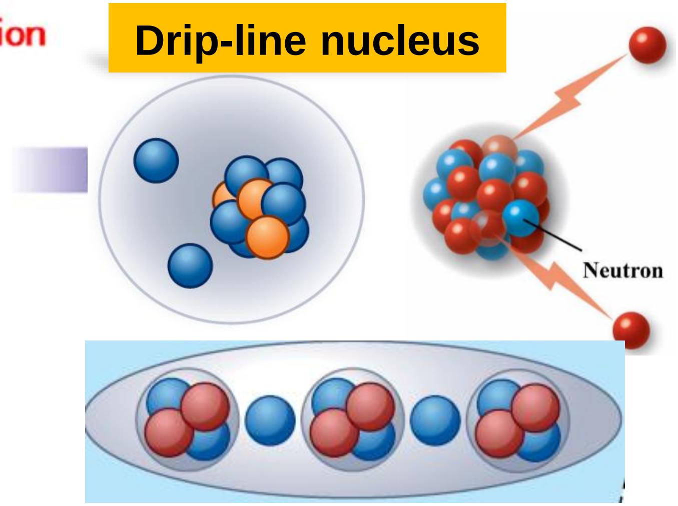
Outline

- Motivation
- Development of MATE TPC
  - pMATE→MATE→μMATE→Cylindrical MATE(under design)
- Experimental measurements
- Summary

Reaction and structure studies using TPC



Aziz *et al.*, *AAPPS Bulletin* (2021) 31



Physics motivation:

1, Direct reactions: (α,p/d), (p,α)

2, Fusion: primary beam(CC,CO,OO), neutron-rich RIB

3, Weak interaction：beta decay, (d,2p), (^{3}He,t)

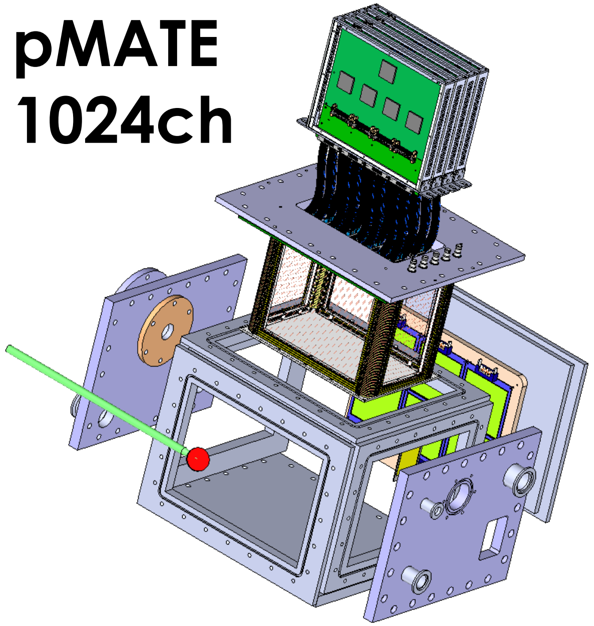
4, Fission(rprocess)：(p,p*), (p,2p)

5, Giant resonance：(p,p*), (d,d*)

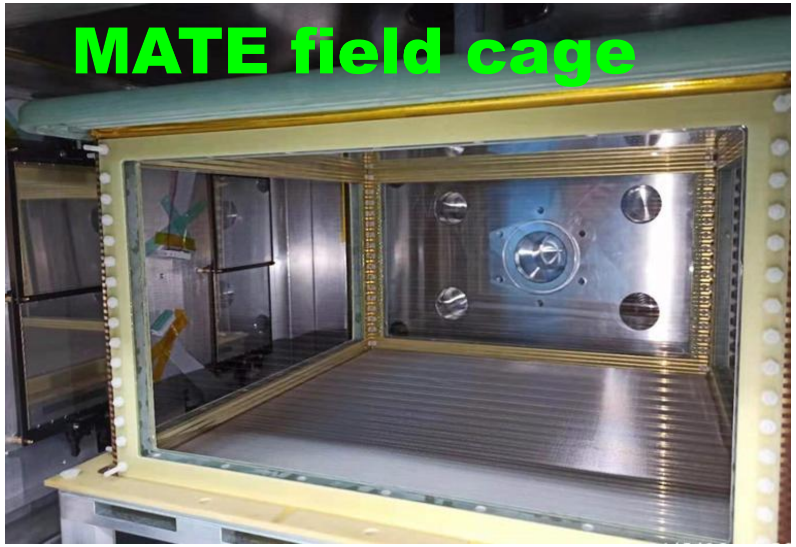
6, Nuclear structure：decay, transfer, scattering

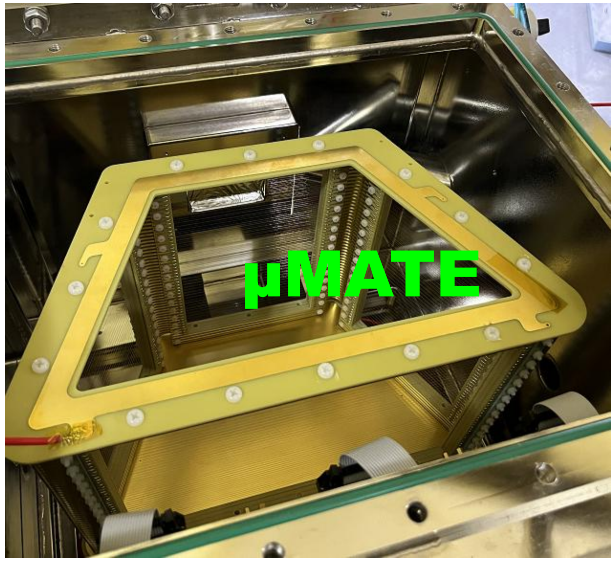
Prototype and MATE TPC: timeline

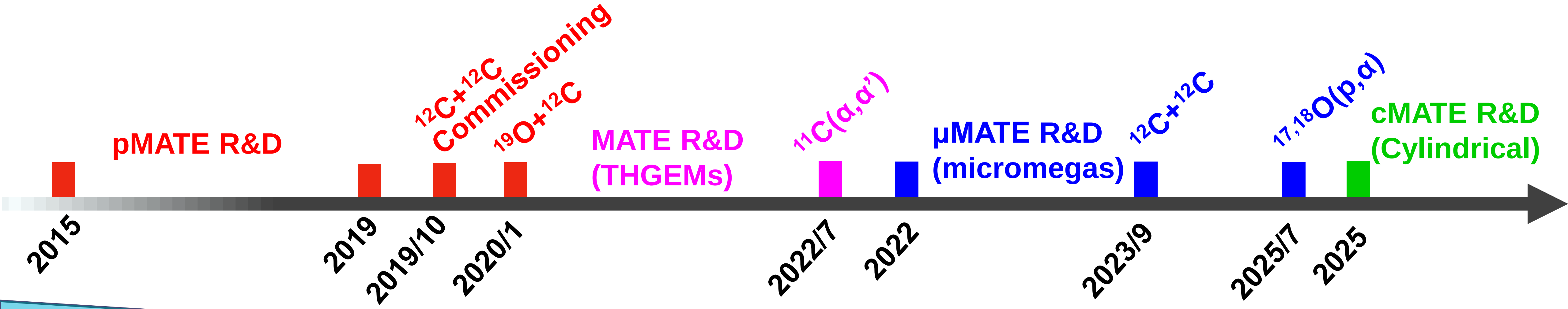
pMATE 1024ch



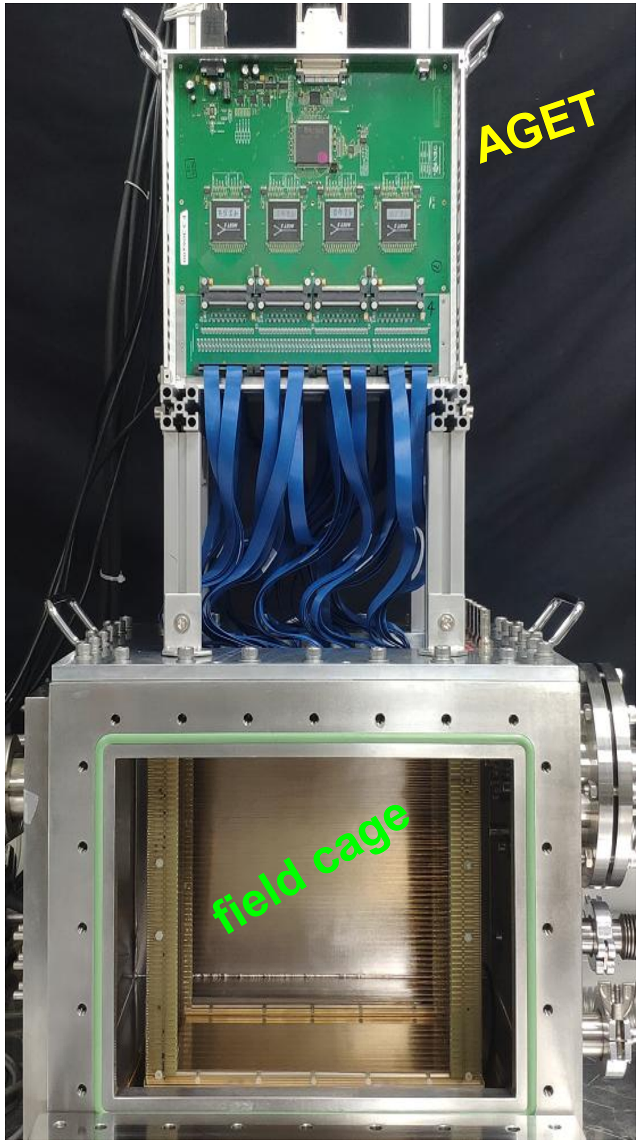
MATE 4000ch TPC

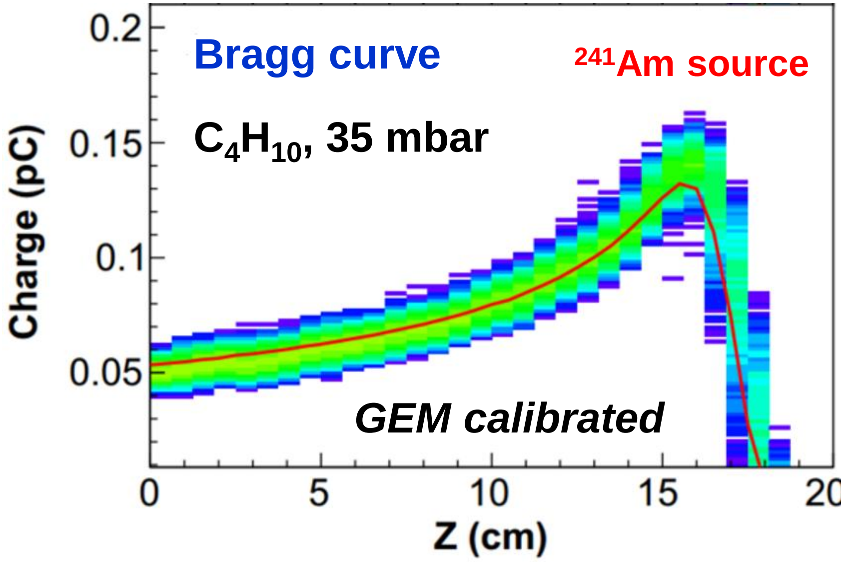




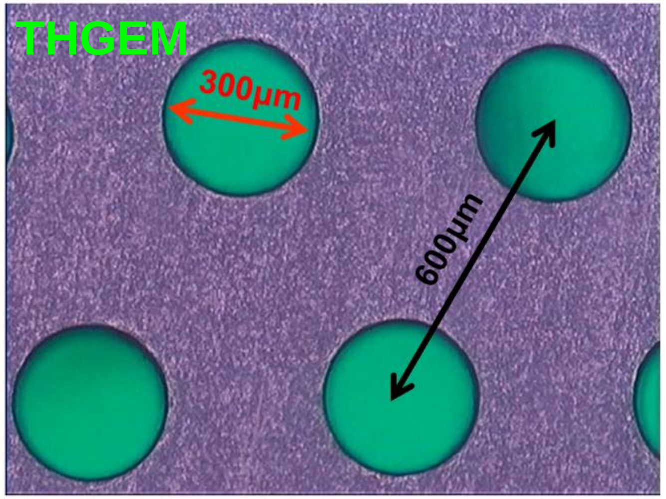


1024ch pMATE (prototype)

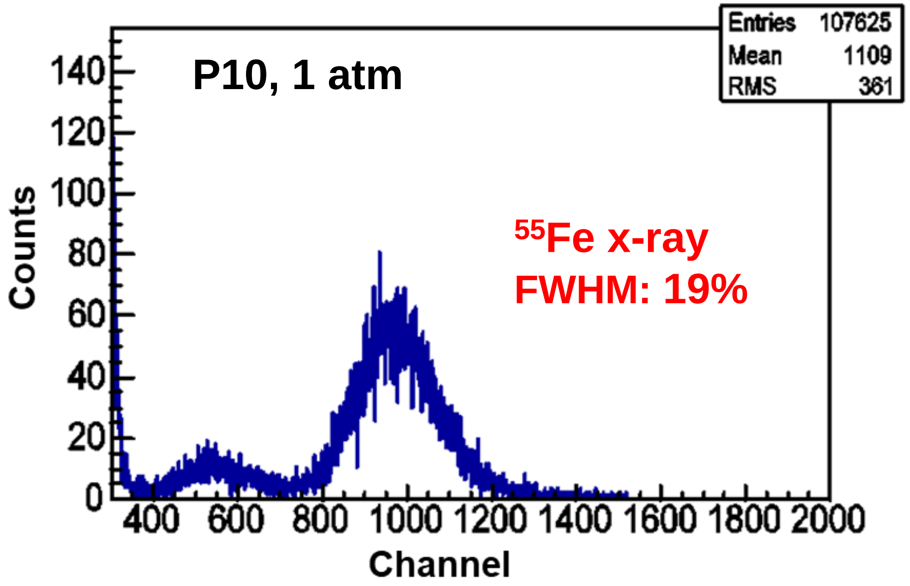




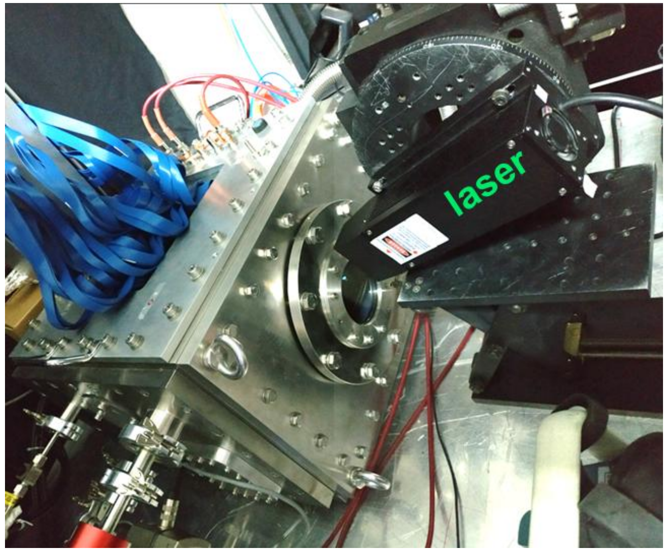
- **Active volume:**
  10cm(W)×20cm(L)×25cm(H)
- **Field cage: 3 layers of Be-Cu wires （Φ0.1mm）**
- **Double THGEMs: thickness 0.3mm**
- **Rectangular pad: 3×6mm^2, 1024 pads**



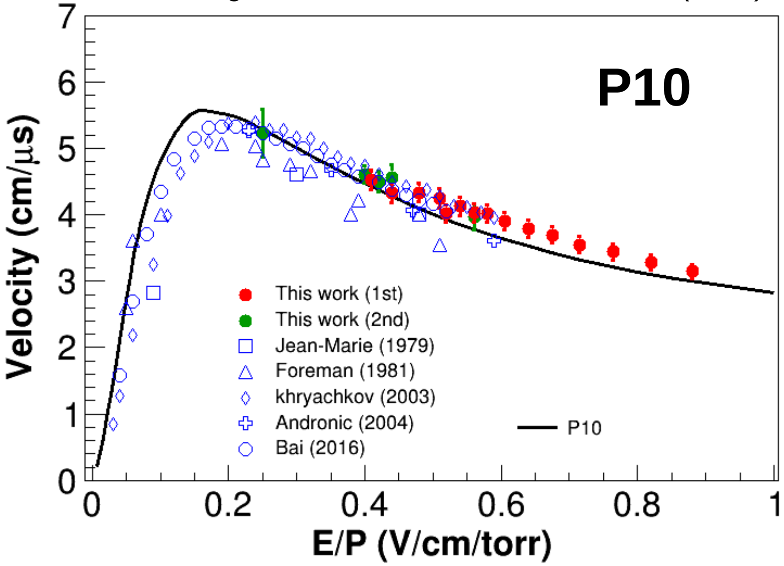
GEM by Q. Liu (UCAS)

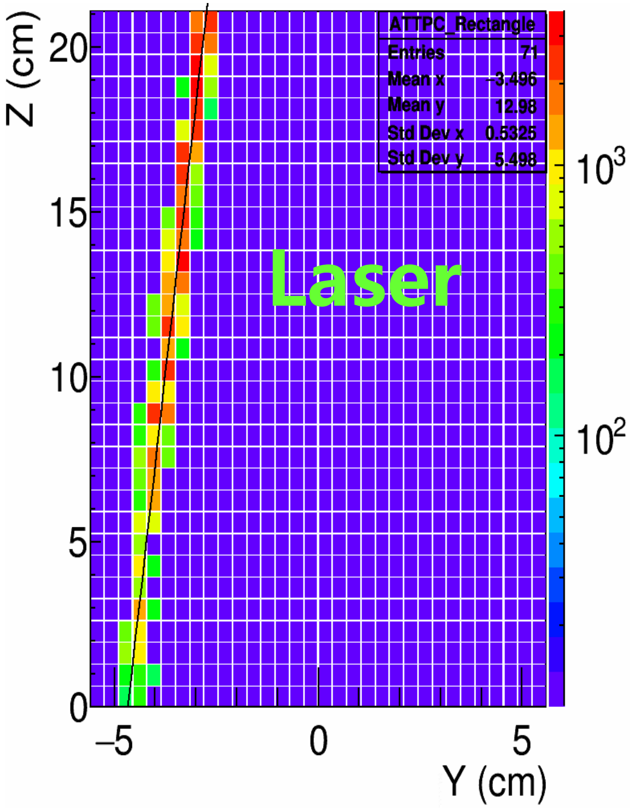


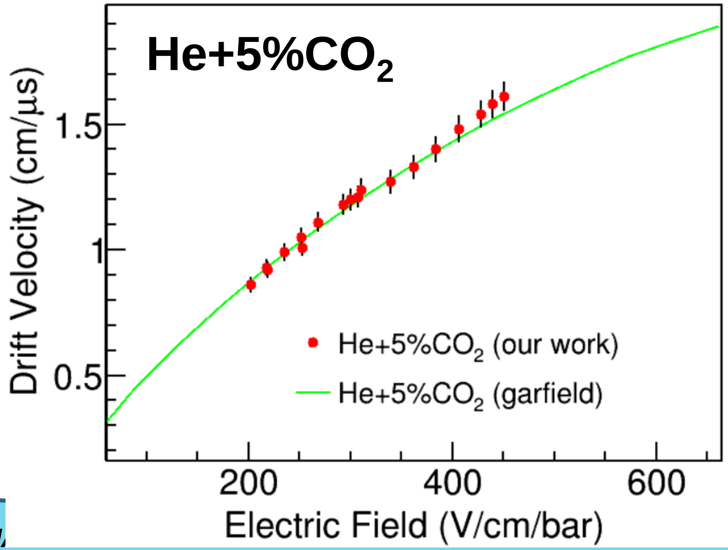
Calibration ……

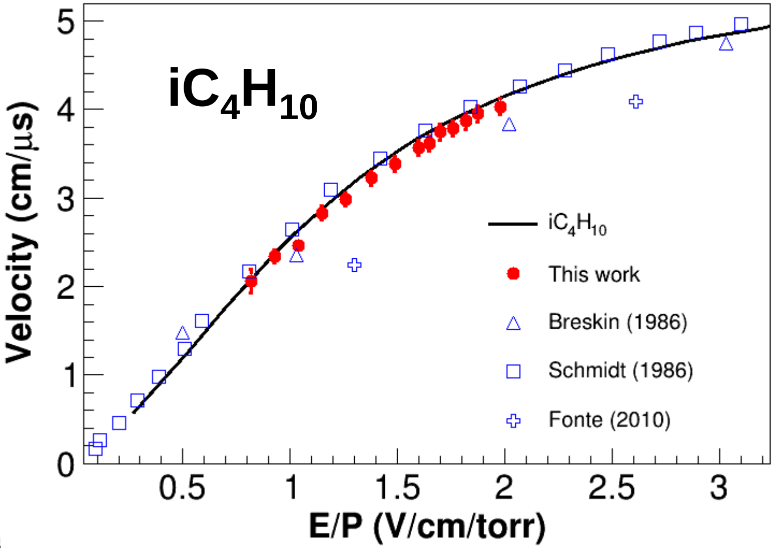


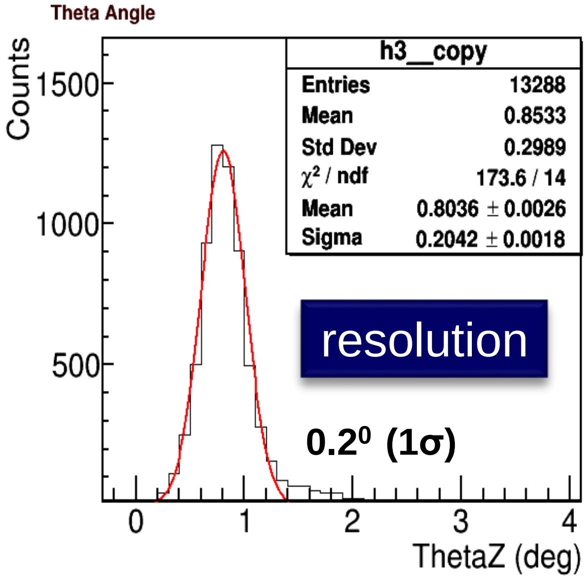
Z.C. Zhang…ZNT et al., NIMA1016, 165740(2021)*



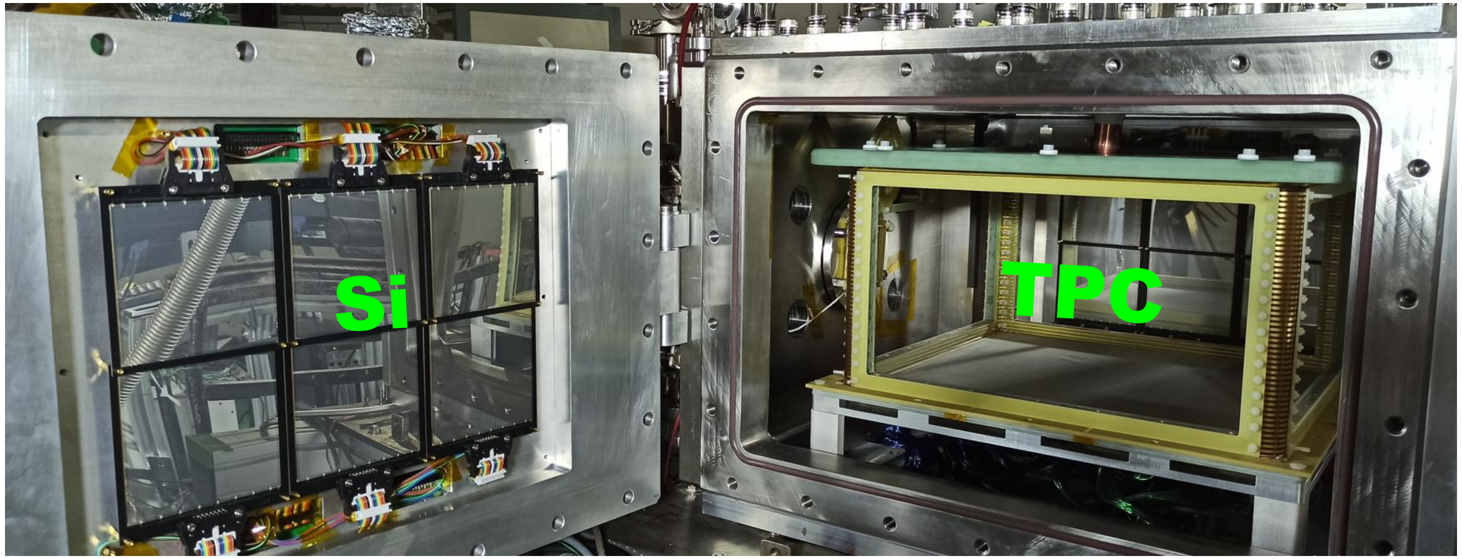








Full scale MATE-TPC

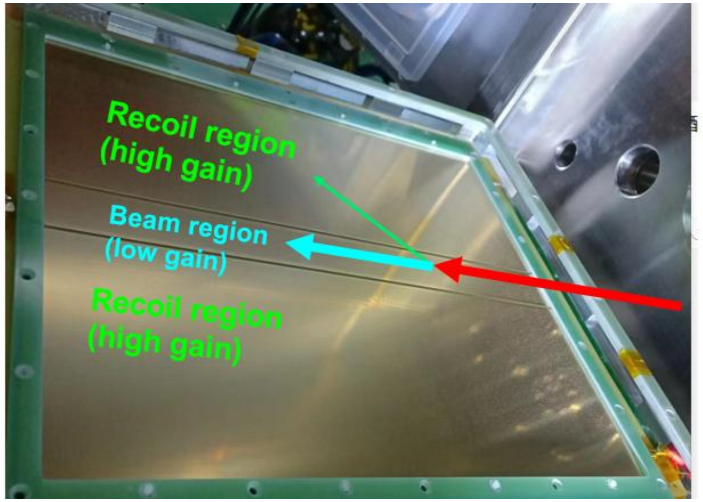


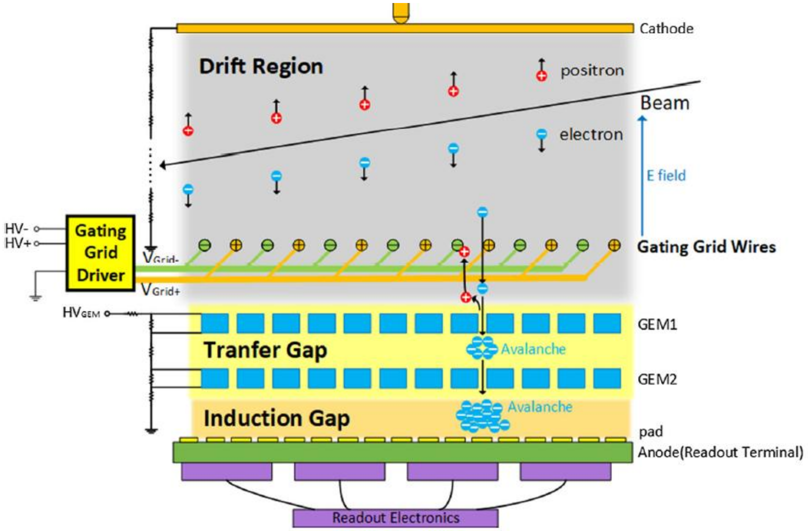
TPC

- ✓ 30x30x20(h) cm^3
- ✓ Double-layer segmented THGEM
- ✓ 3800 readout channels
- ✓ GET electronics

Si array

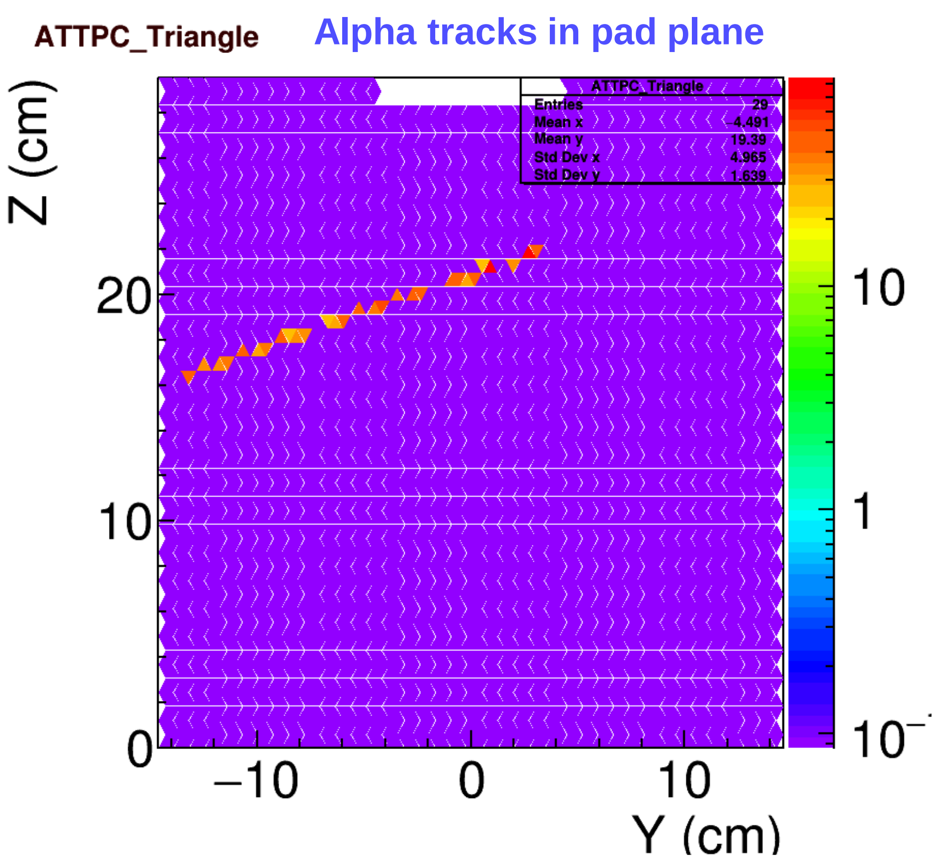
- Three silicon walls
- Sensitive area: 100×100 mm^2
- Thickness: 600 μm and 150 μm
- Angular coverage ~10%

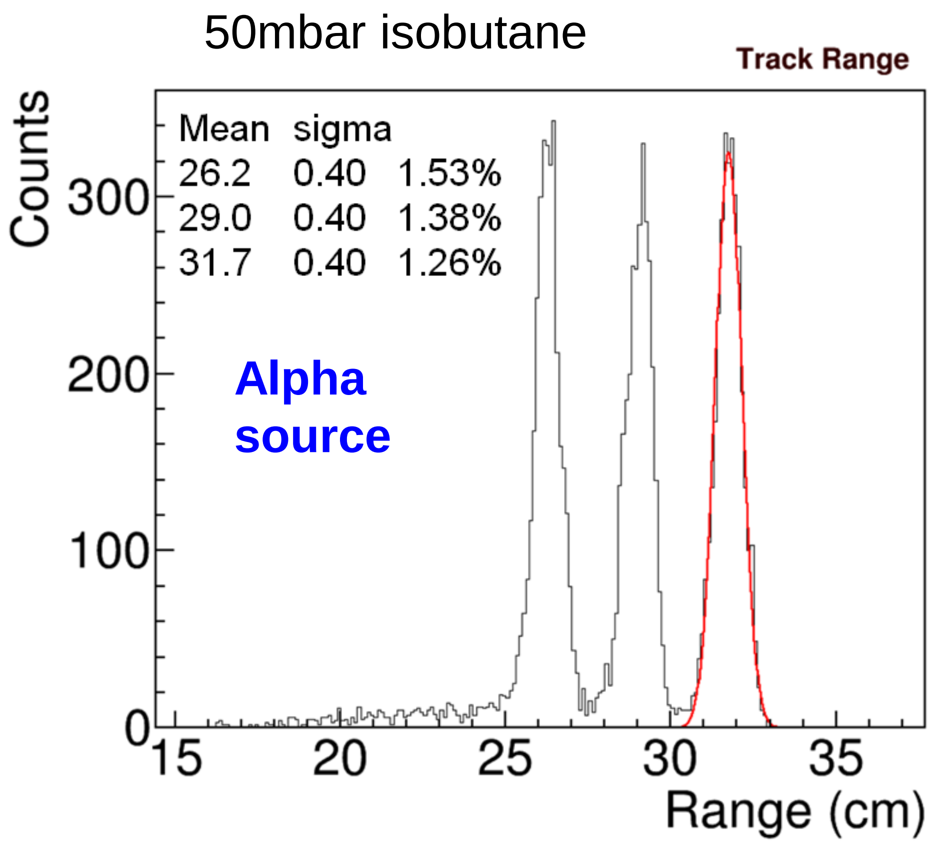




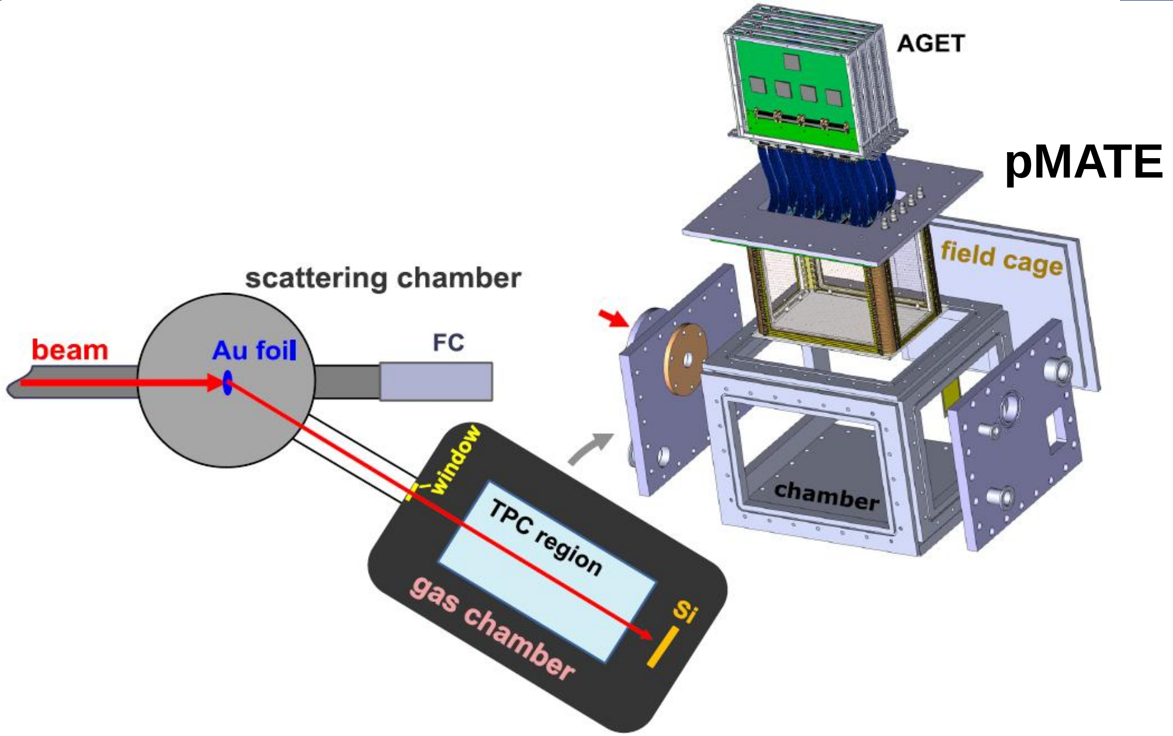
In collaboration with Prof. Ota (RCNP, CNS)

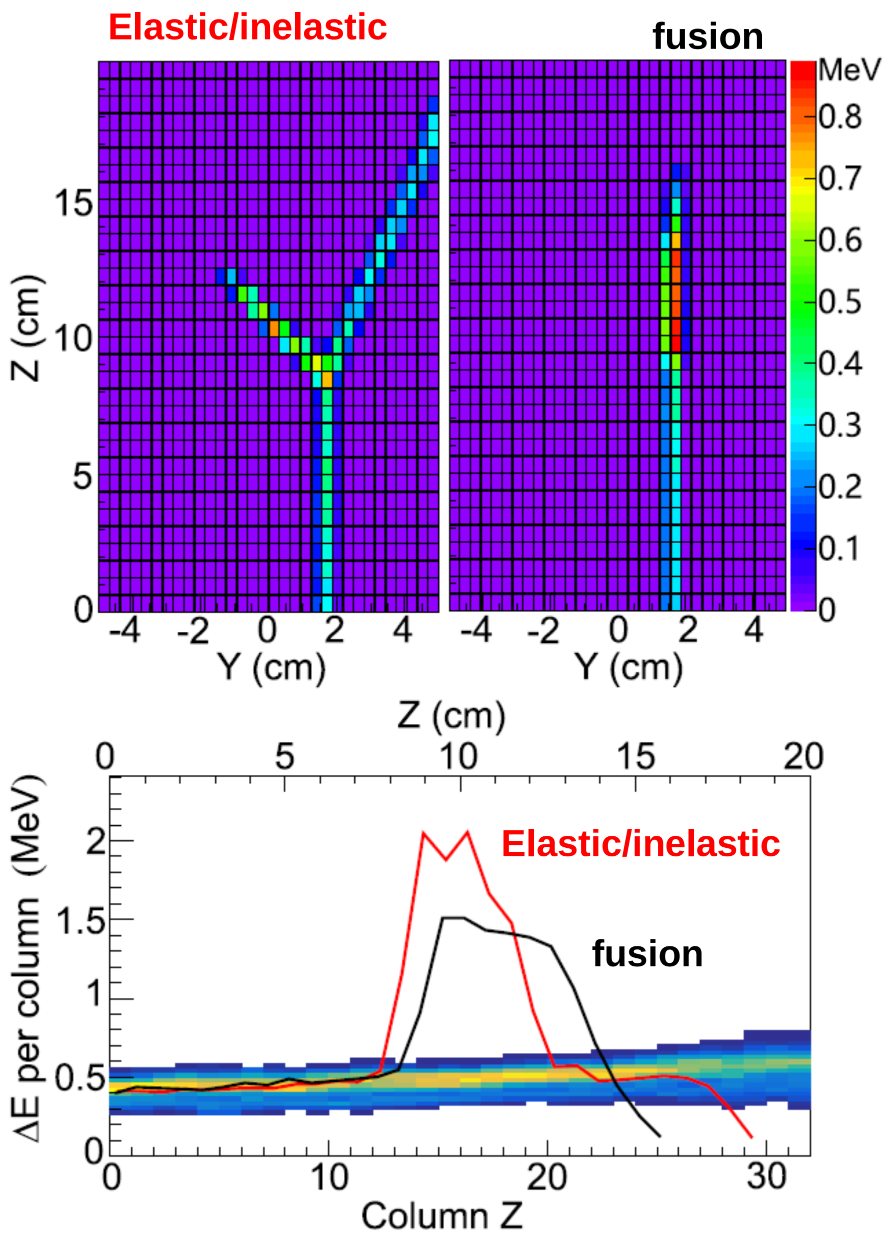
Alpha measurement by MATE





Commissioning experiment: $^{12}C+^{12}C$ fusion near coulomb barrier



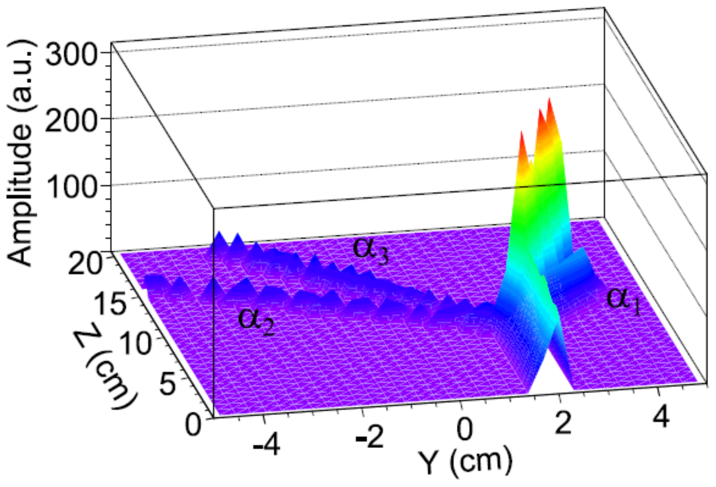


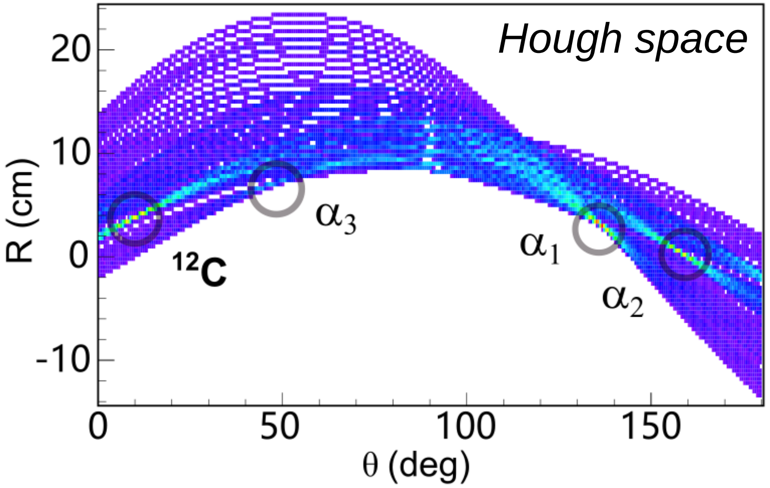
Experiments

- $^{12}C^{4+}$ **beam:** 4.9 AMeV (HIRFL, IMP)
- **TPC gas:** C_4H_{10} at 50, 100 mbar
- **Injection rate**: 200-400 cps
- **Beam time:** 31.2 hours

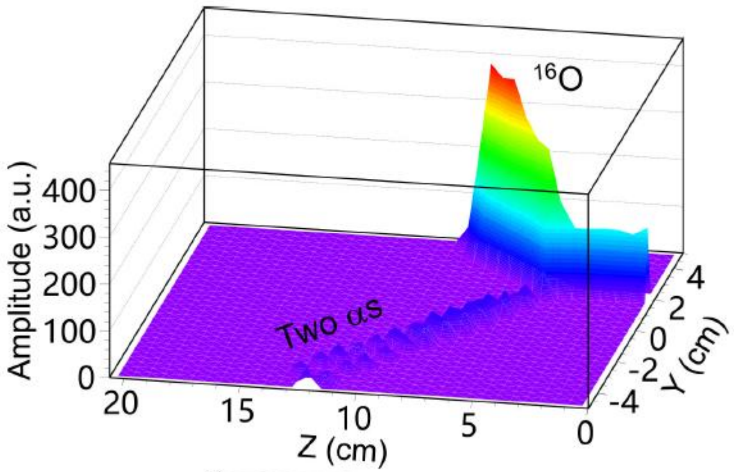
Tracking for different channels

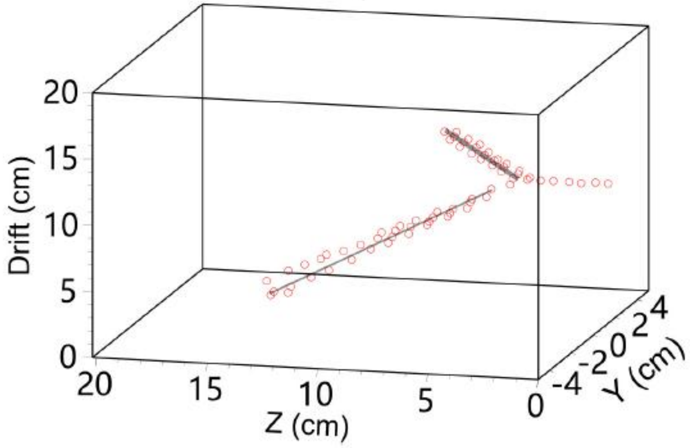
$^{12}C+^{12}C \rightarrow ^{12}C+3\alpha$



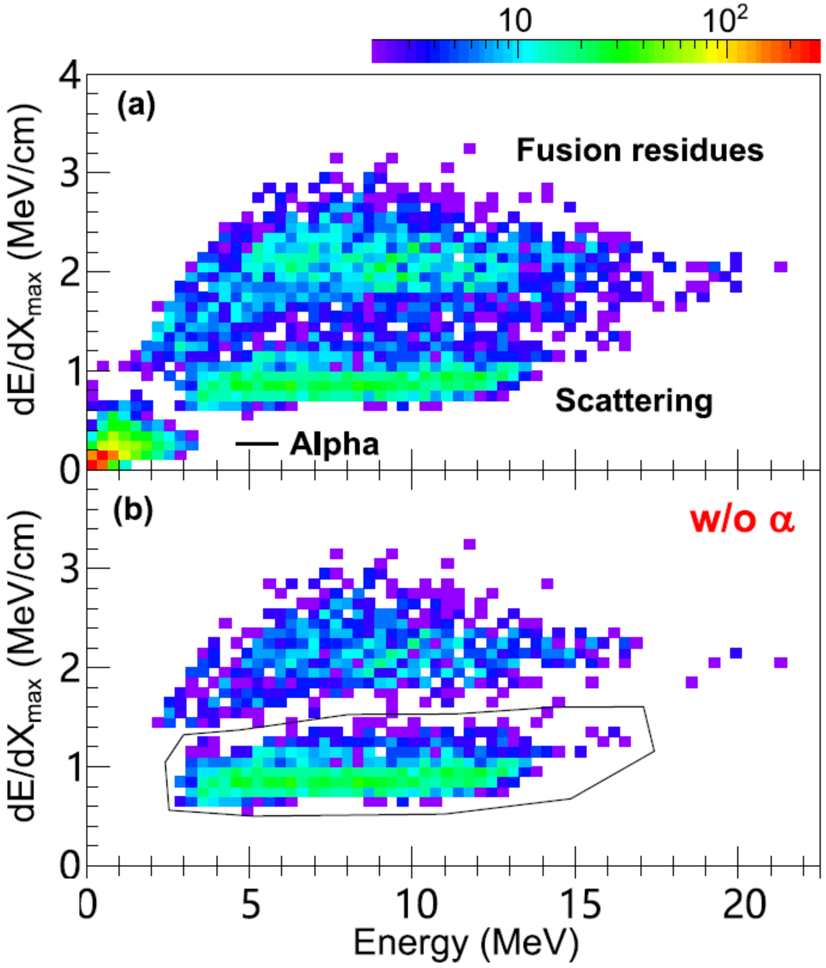


$^{12}C+^{12}C \rightarrow ^{16}C+^{8}Be(2\alpha)$



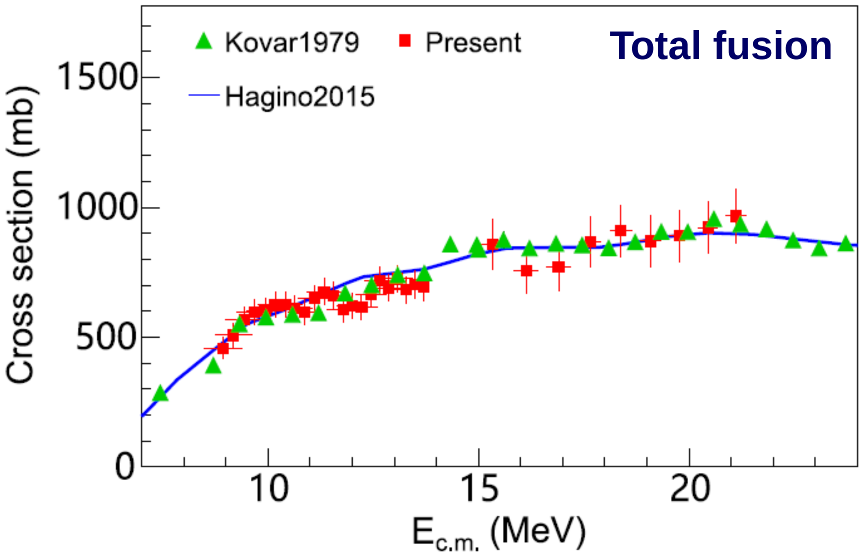


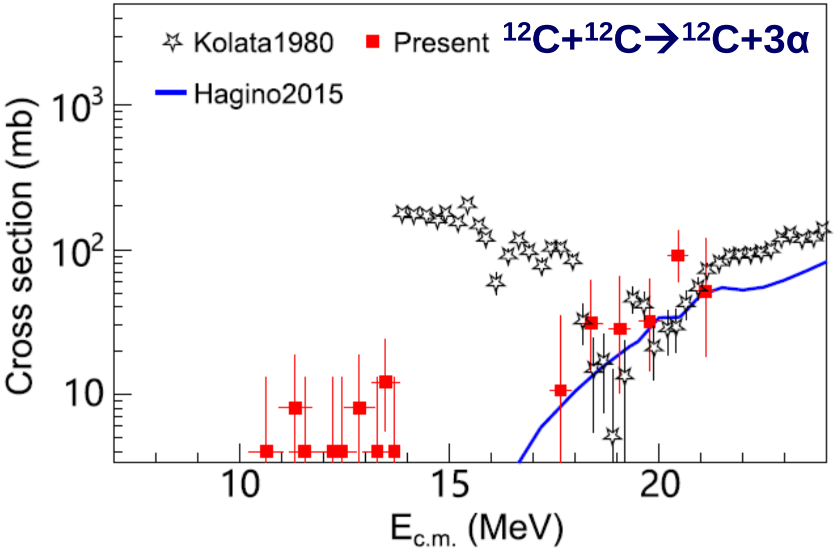
X.Y. Wang et al., CPC46, 104001(2022)



Fusion events with and without α channels

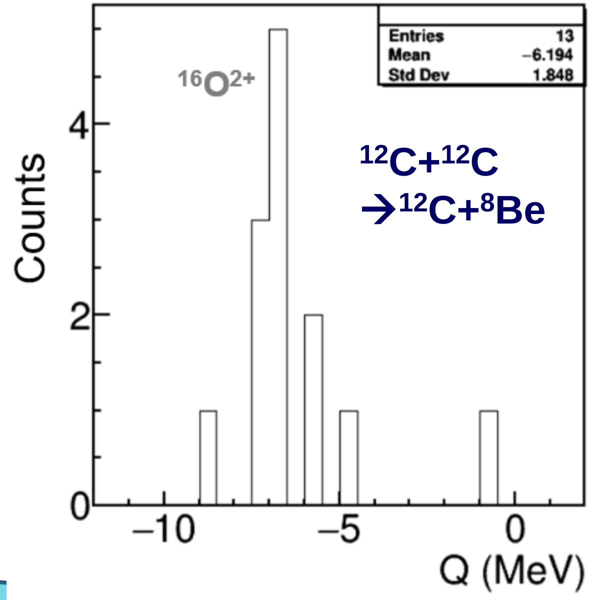
Experimental results

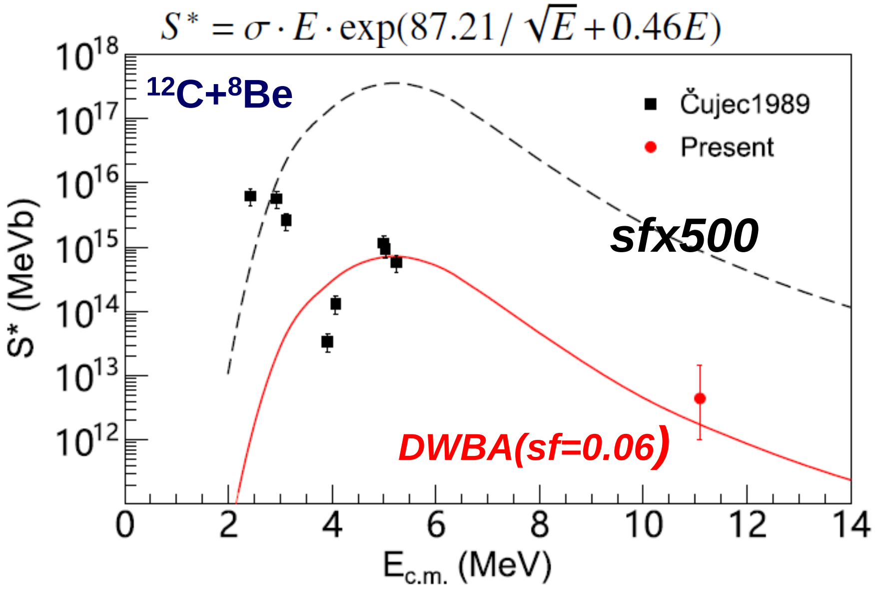




$^{12}C+^{12}C \rightarrow ^{12}O+3a$

- ✓ Consistent with statistical calculations at E_{cm}>15 MeV
- ✓ At E_{cm}<15 MeV, other mechanisms are needed

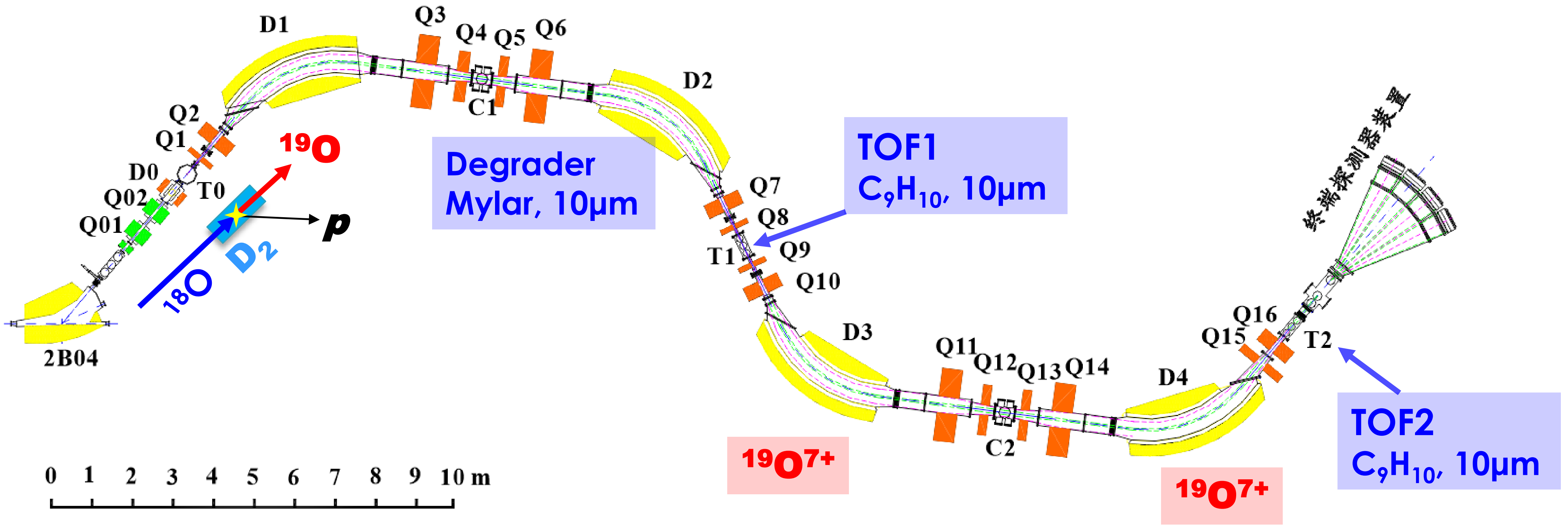




$^{12}C+^{12}C \rightarrow ^{16}O+^{8}Be$

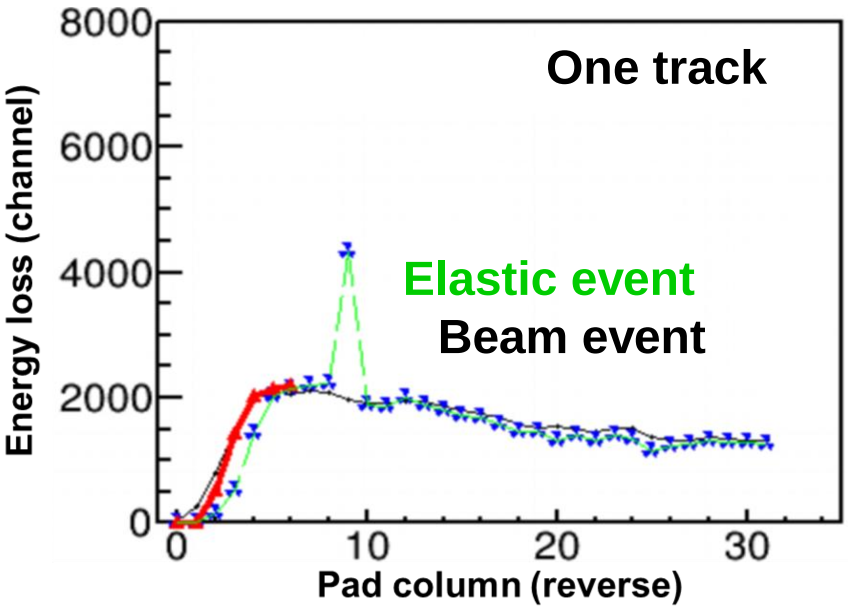
- ✓ At E_{cm}>3MeV, direct a-transfer reaction dominates
- ✓ At stellar energy(<3MeV), ^{8}Be decay can be detected by TPC

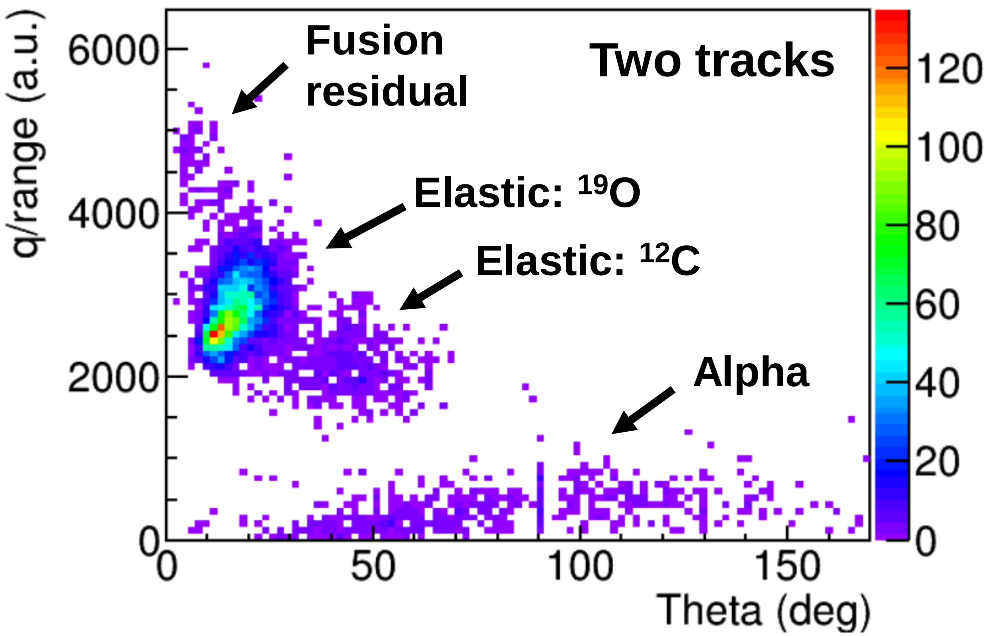
$^{19}O+^{12}C$ reaction: RIBLL beam line for ^{19}O production

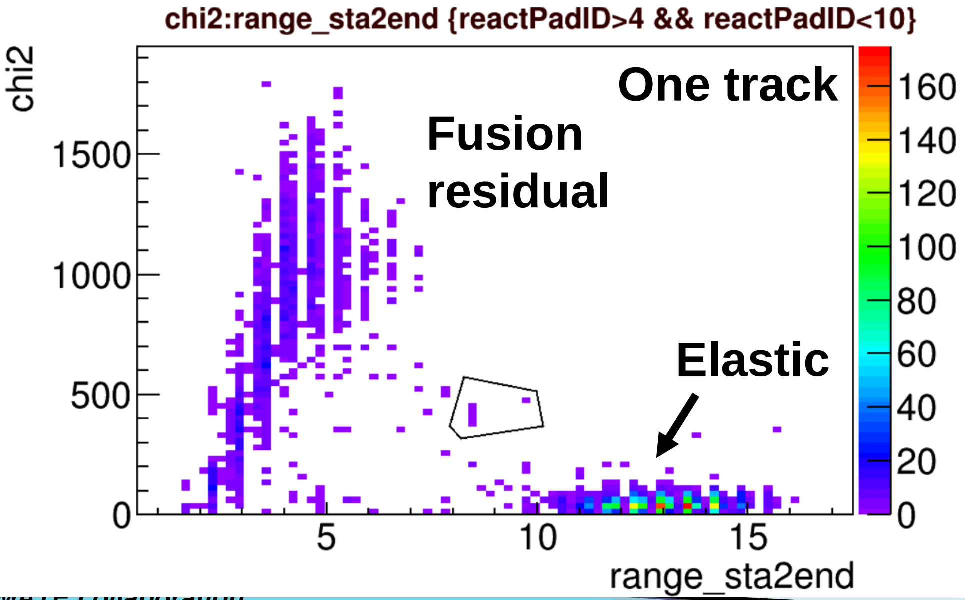


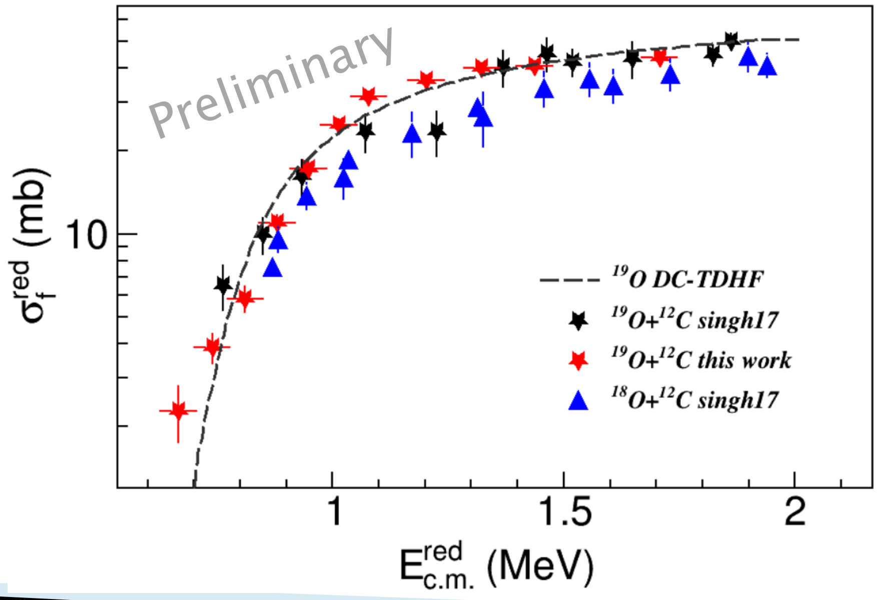
- Primary beam: $^{18}O^{8+}$, 6.17MeV/u, 260enA (HIRFL)
- Primary target: D_2 gas cooled by LN_2 at 150mbar, 500mbar
- Second beam: $^{19}O^{7+}$, 10^3-10^4 pps
  - $^{18}O(d,p)^{19}O$ reaction
  - purity upto 95%

Preliminary results









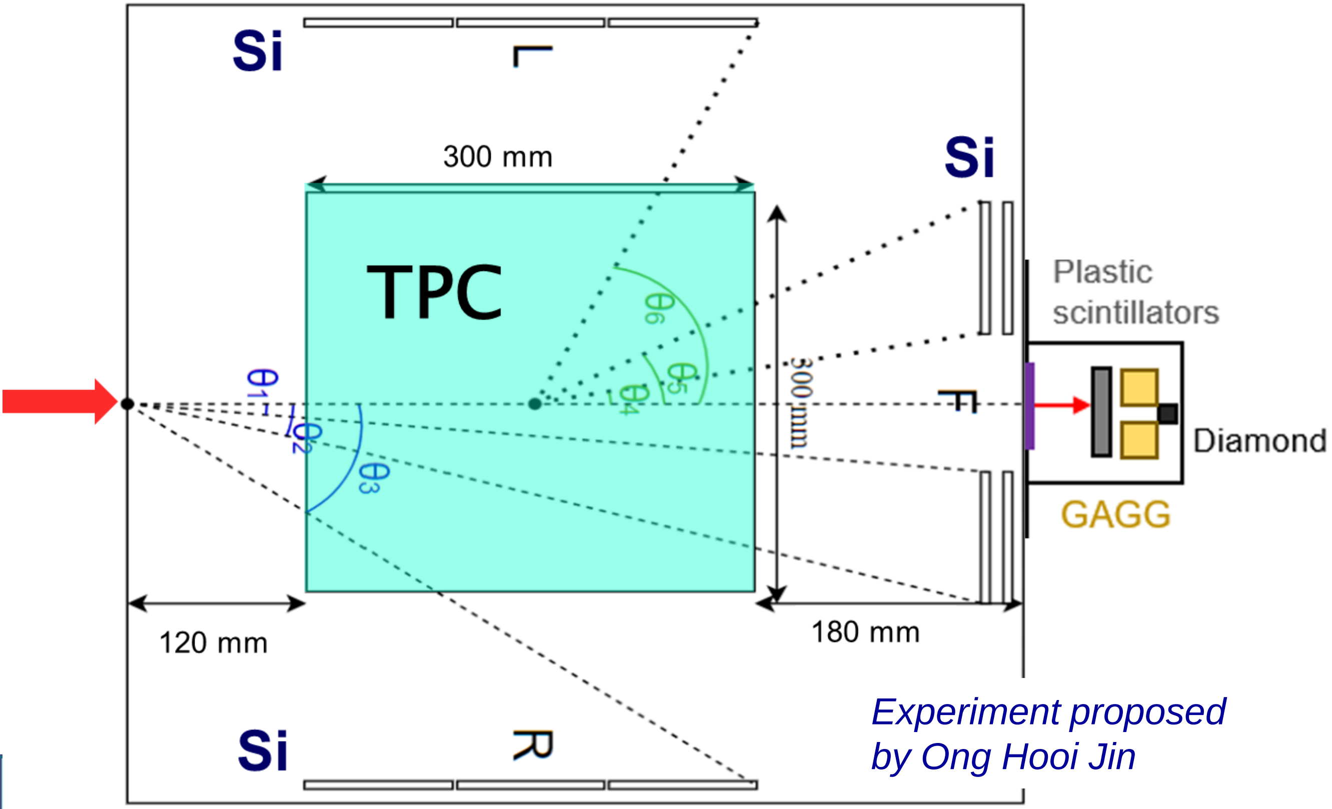
Analysis by JL Zhang, NT Zhang

Study of Z=6 subshell using $^{11}C+\alpha$ scattering

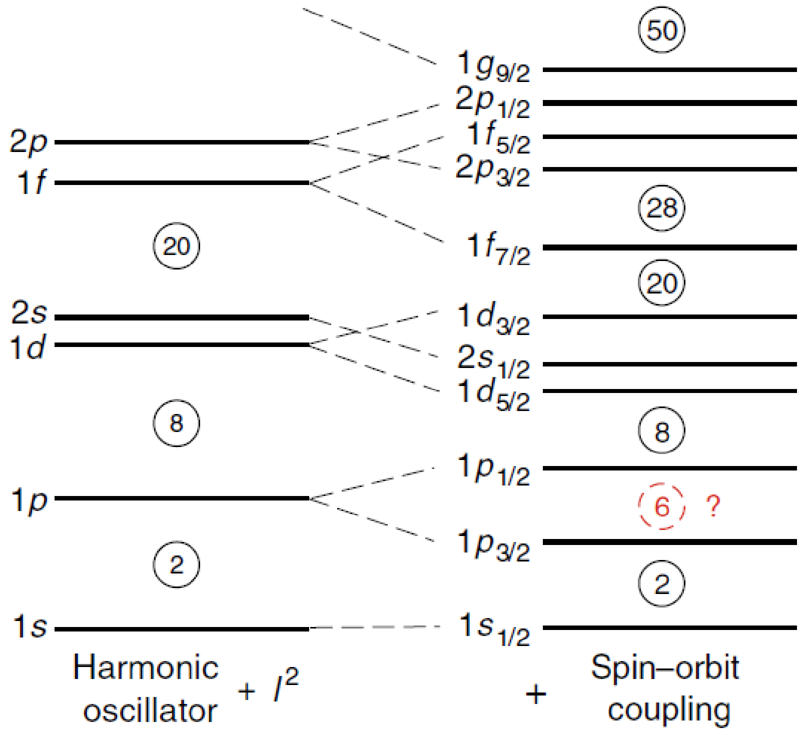
$^{11,12}C(\alpha,\alpha')$ in RIBLL

Beam injected into TPC

- ^{12}C: 75 MeV/u, ~ 10^4 pps
- **^{11}C: 55 MeV/u, ~ 10^4-10^5 pps**



Experiment proposed by Ong Hooi Jin

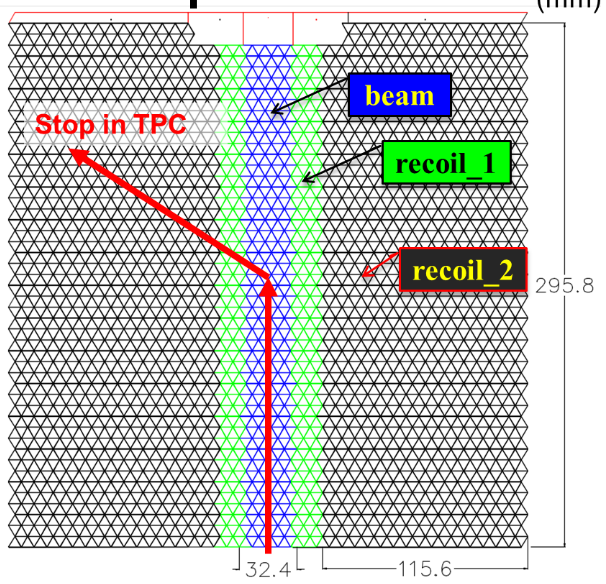


$$d\sigma/d\Omega \propto |b_n^F M_n + b_p^F M_p|^2$$

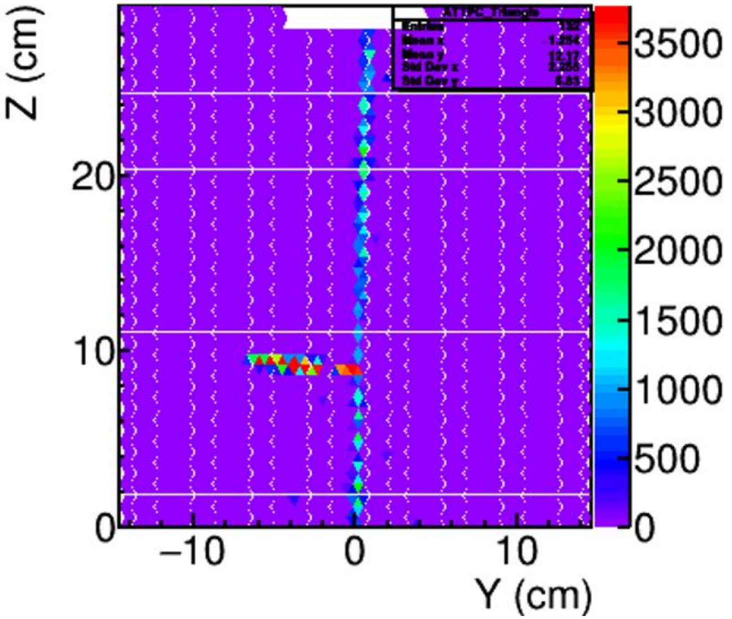
Tran et al., NC9, 1594 (2018)
Furuno et al., PRC100, 054322 (2019)

Beam rate tests and preliminary results

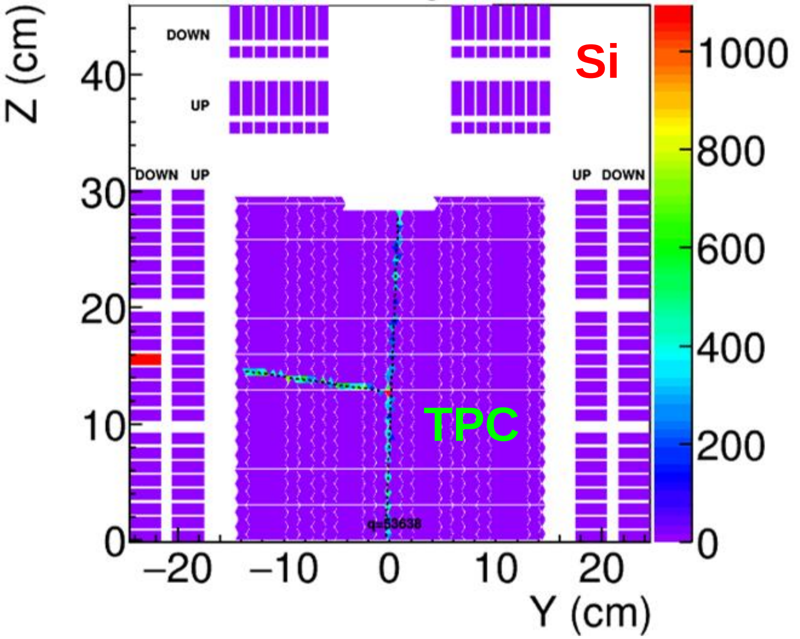
Pad map

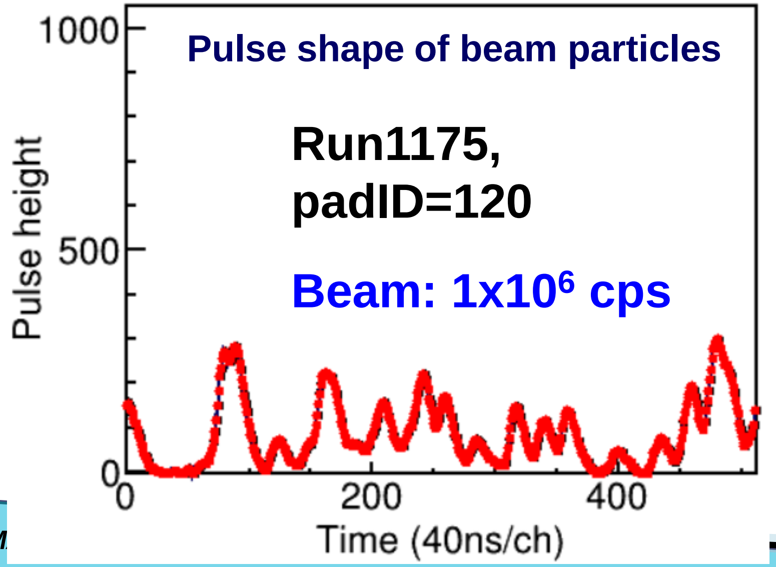


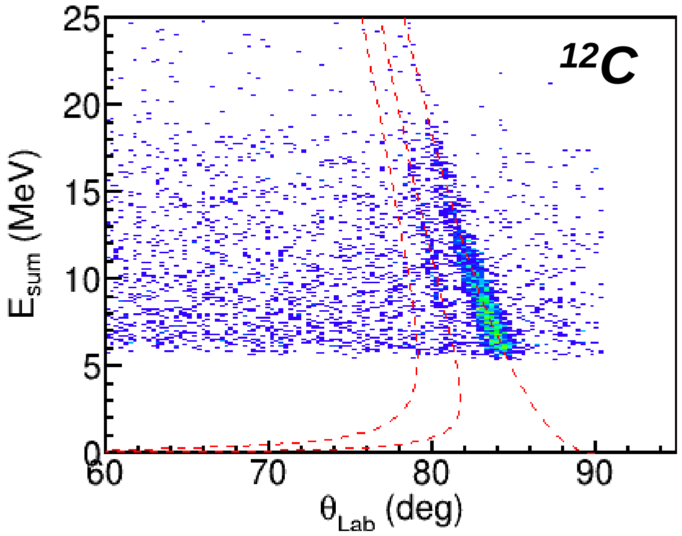
α stopped in TPC

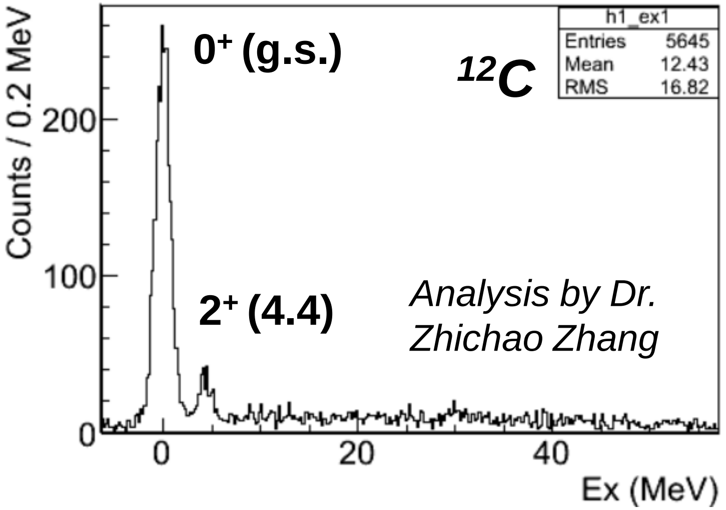


α detected by TPC+Si



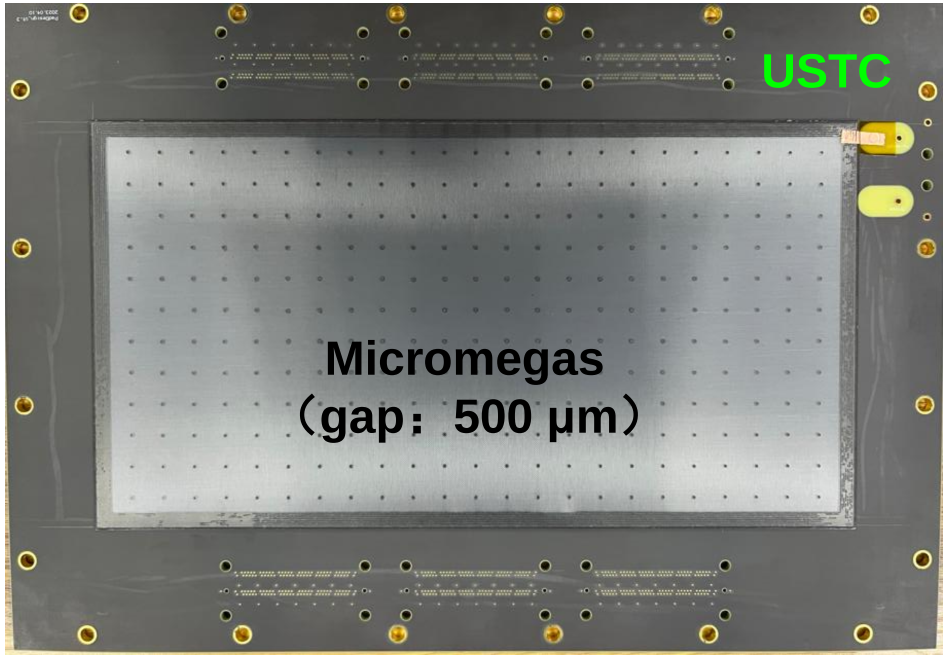


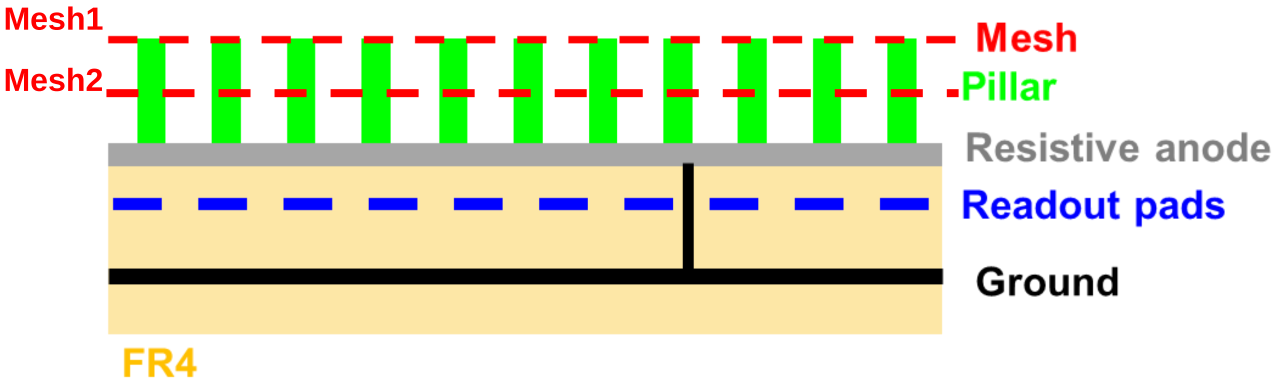




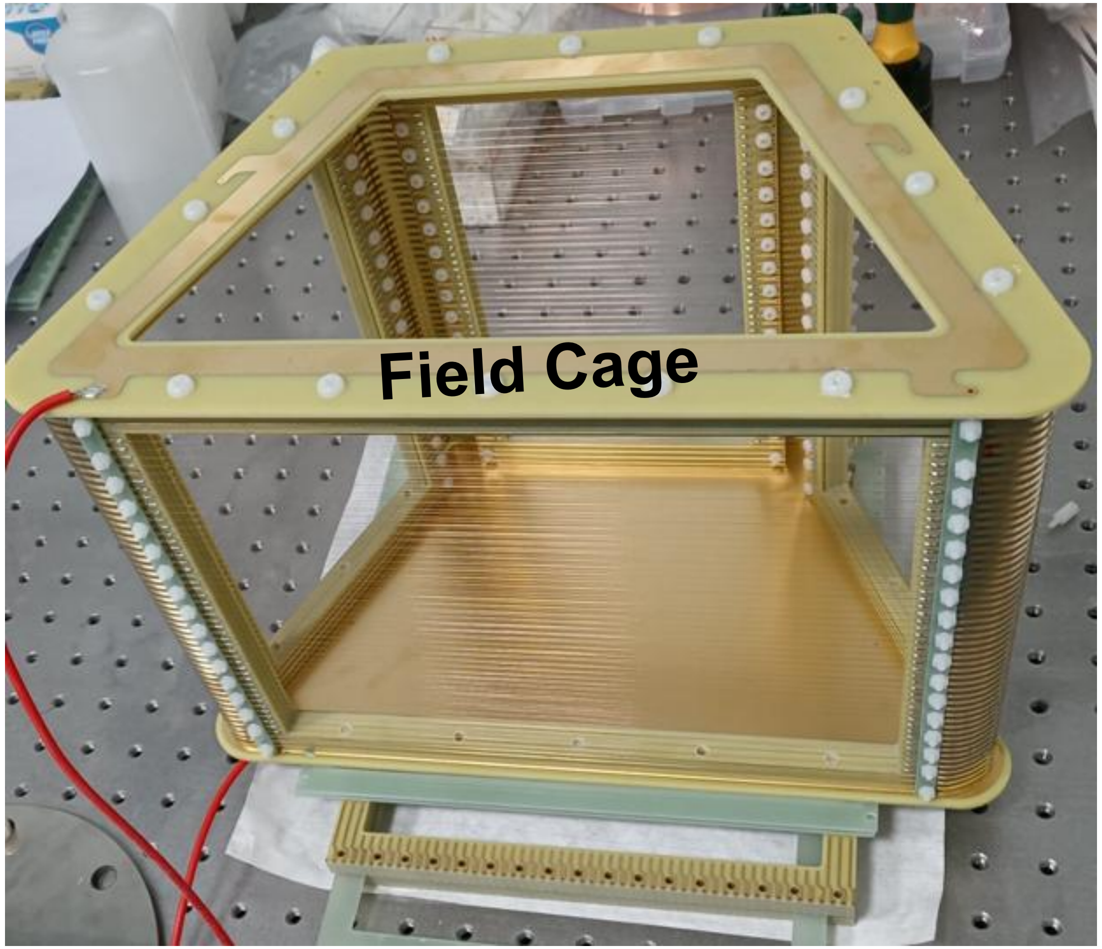
Analysis by Dr. Zhichao Zhang

Low-pressure Micromegas-based TPC (μMATE)



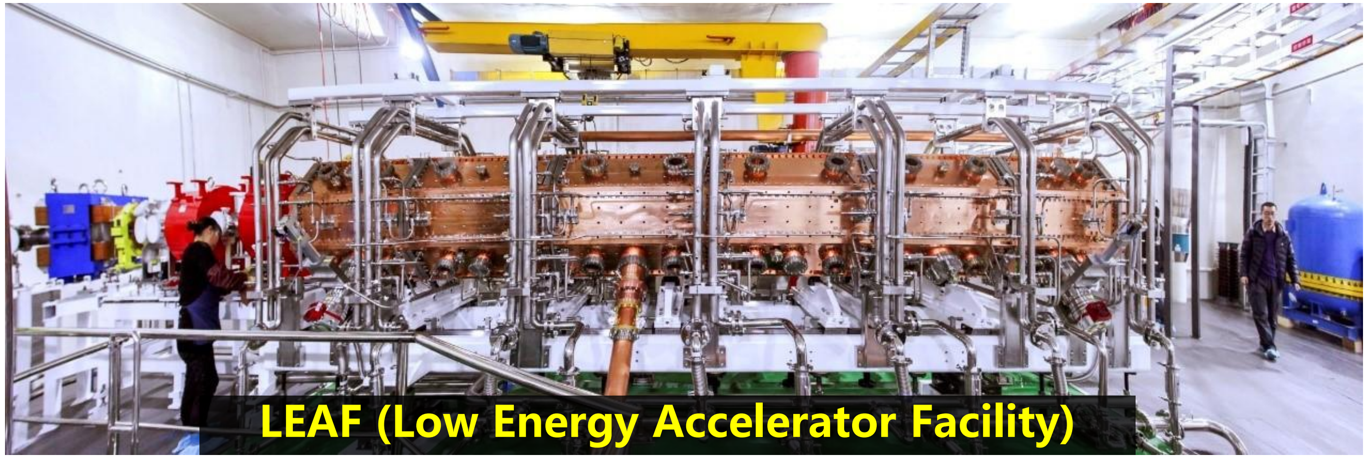


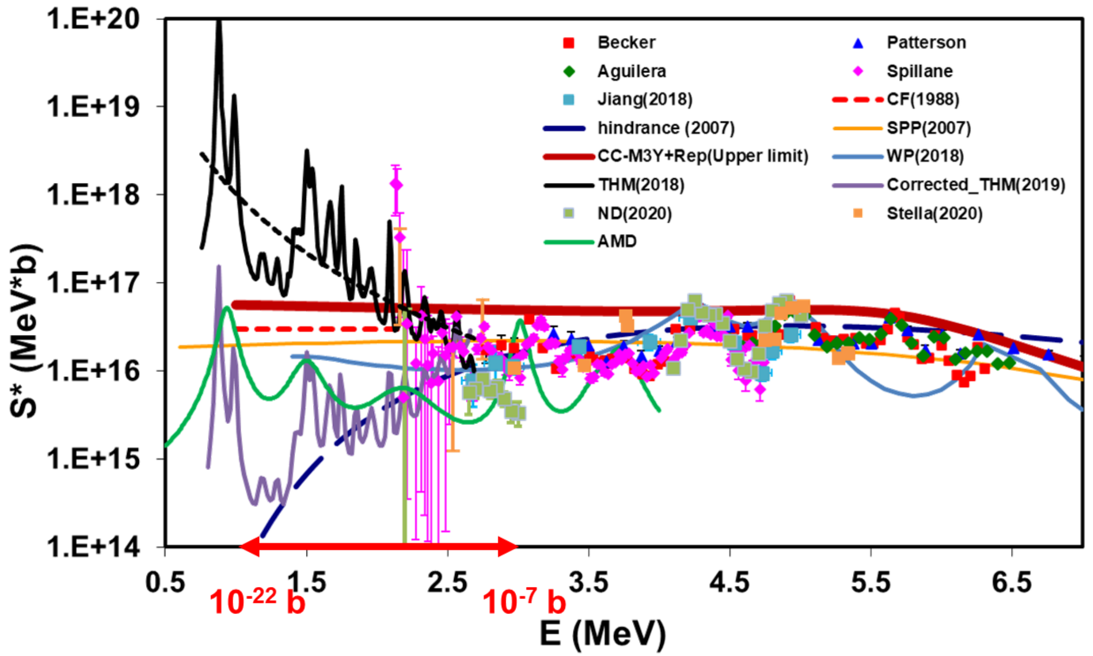
Micromegas provided by Zhiyong Zhang(USTC)*



Be used at ~70pμA experiment!

Direct measurement of $^{12}C+^{12}C$





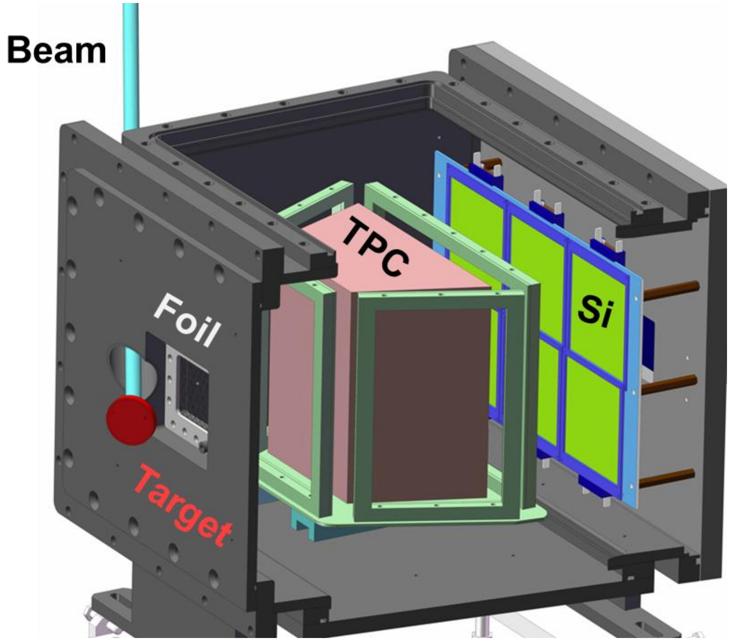
^{12}C: 0.38-0.63 MeV/u

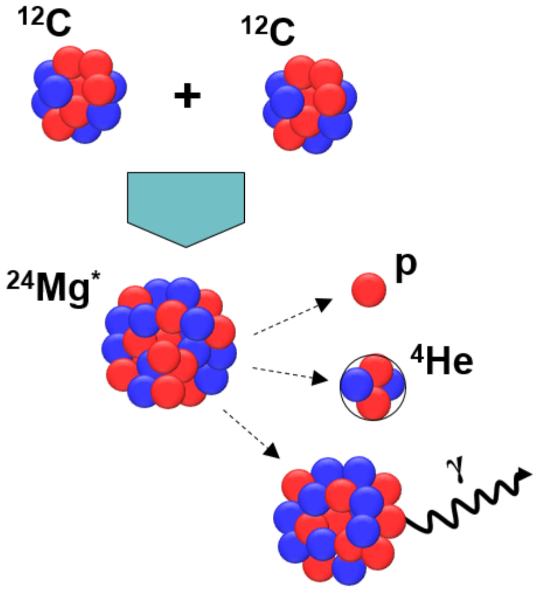
Current: upto 80 pμA

Target: thick target

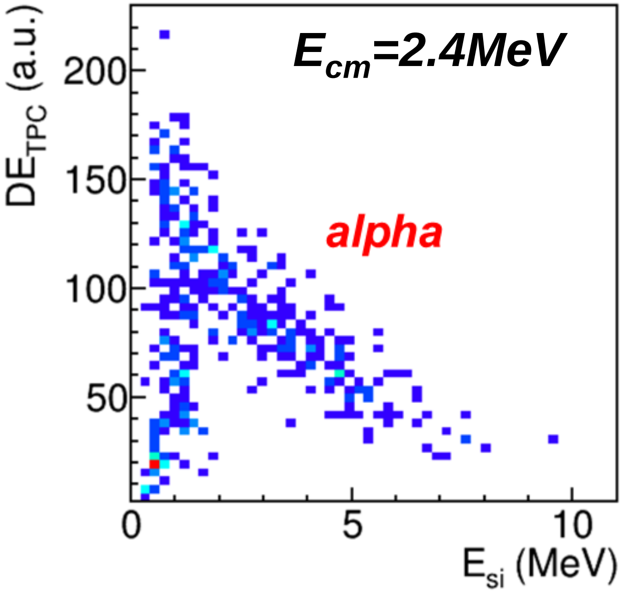
TPC gas: He mixture

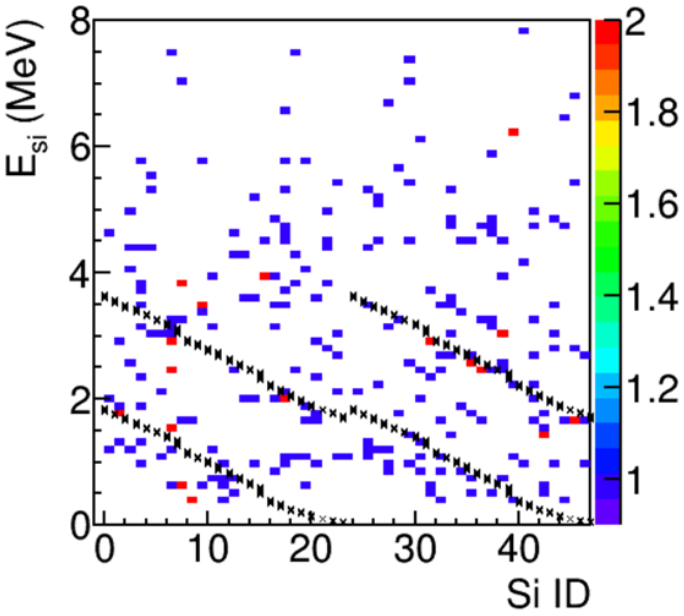
Pressure: 90-100 mbar



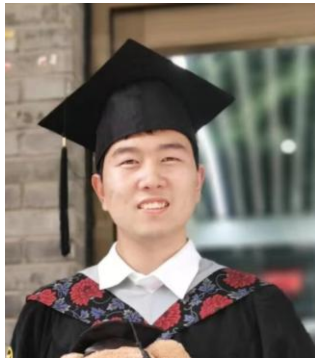


Background suppression

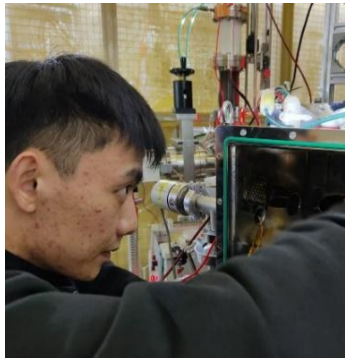


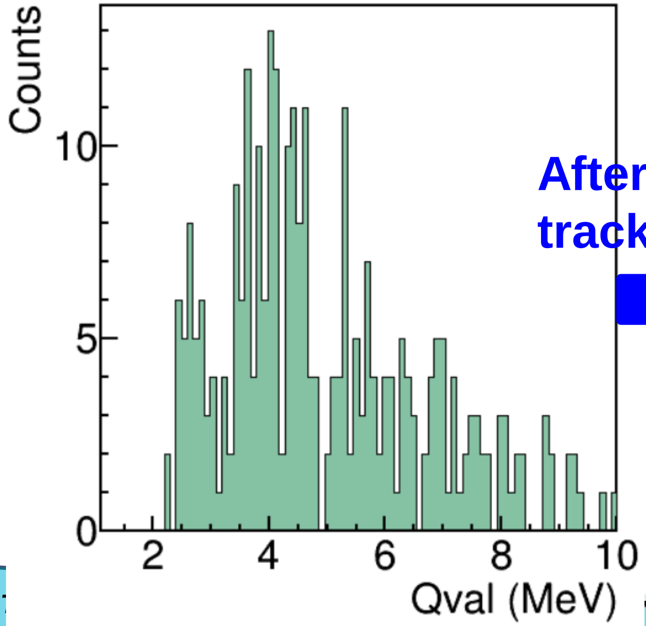


Yunzhen Li

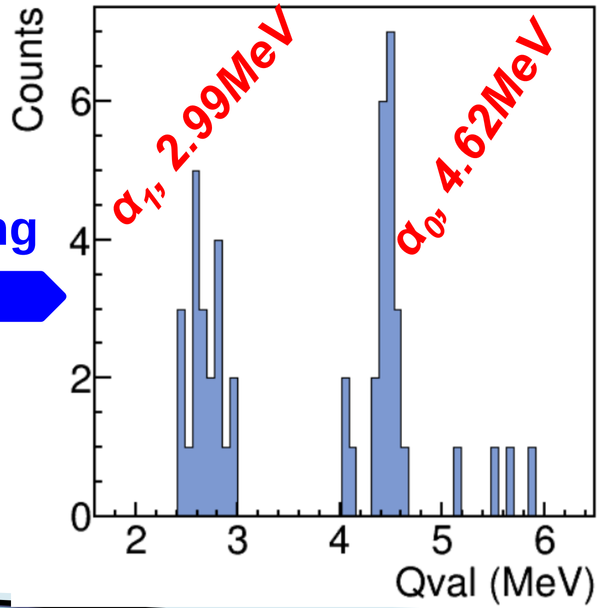


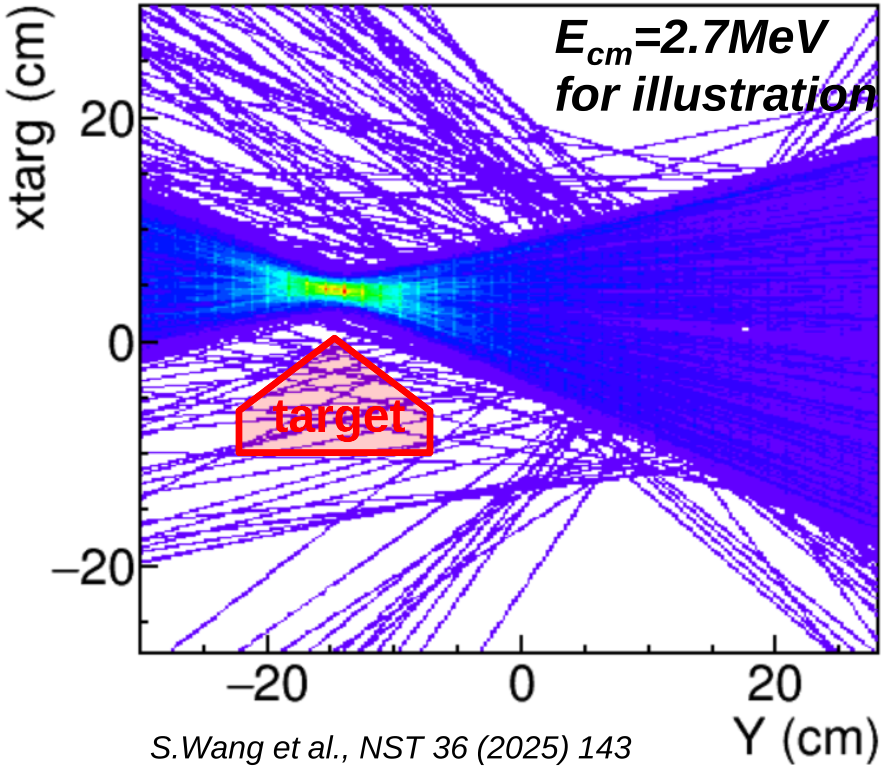
Shuo Wang





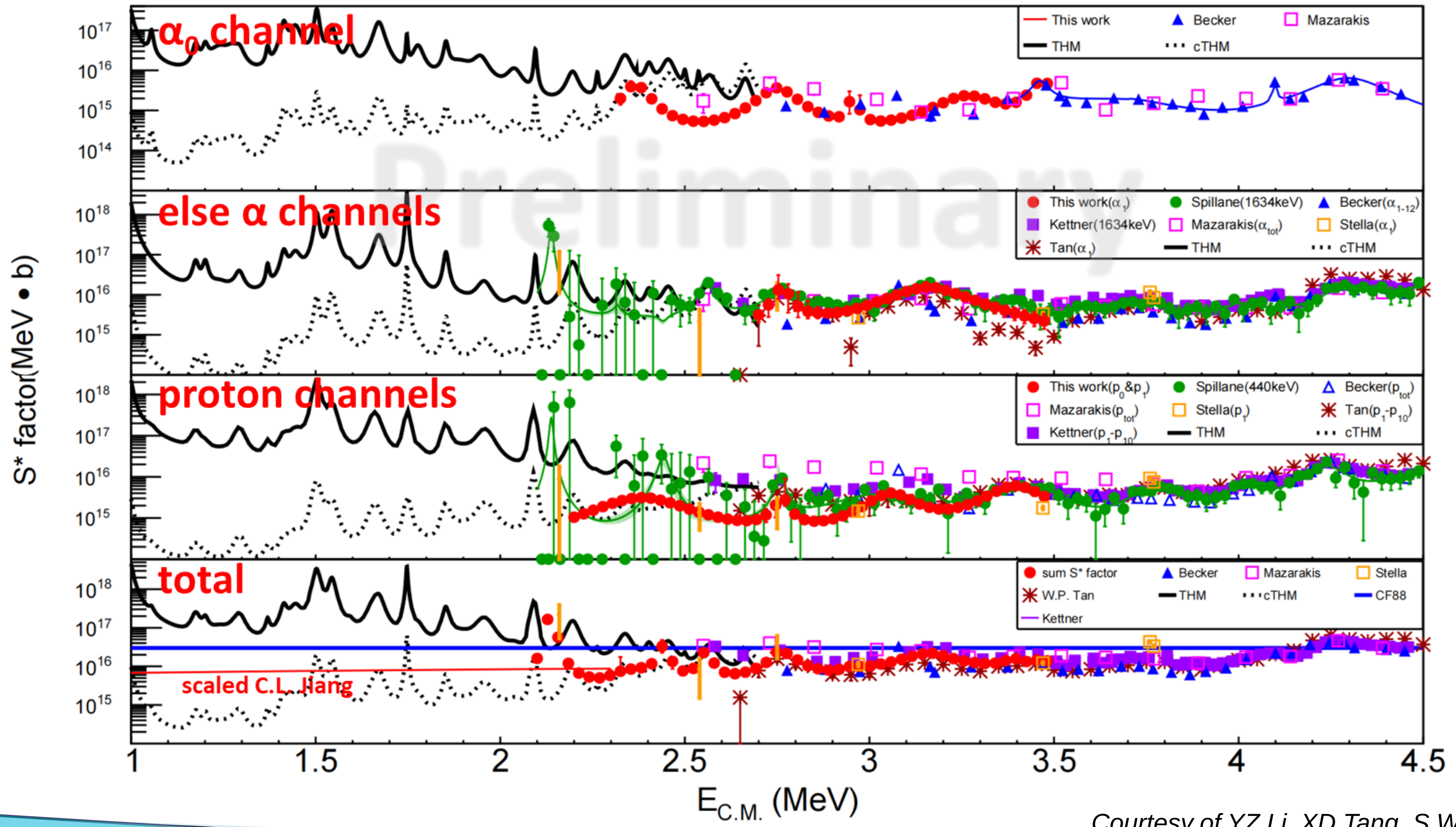
After tracking





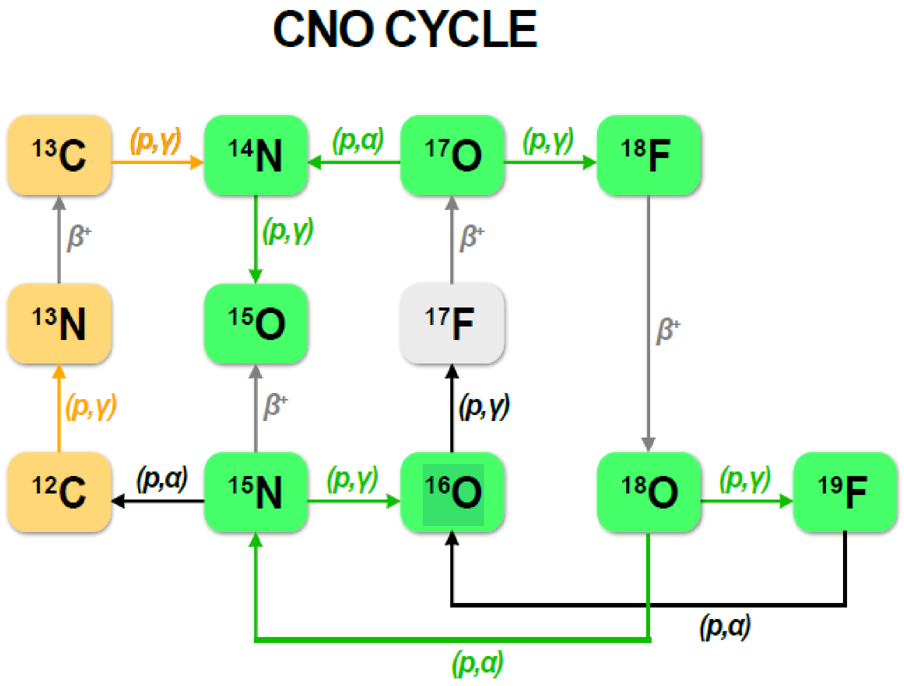
S.Wang et al., NST 36 (2025) 143

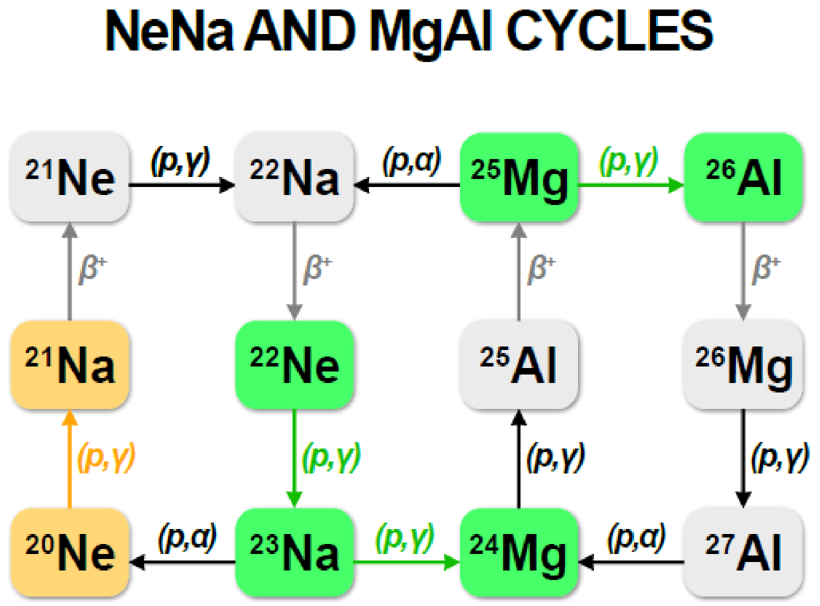
Modified S* factor (unpublished)



Courtesy of YZ Li, XD Tang, S Wang

(p,α), (α,p/d) reaction studies with high-intense primary beam



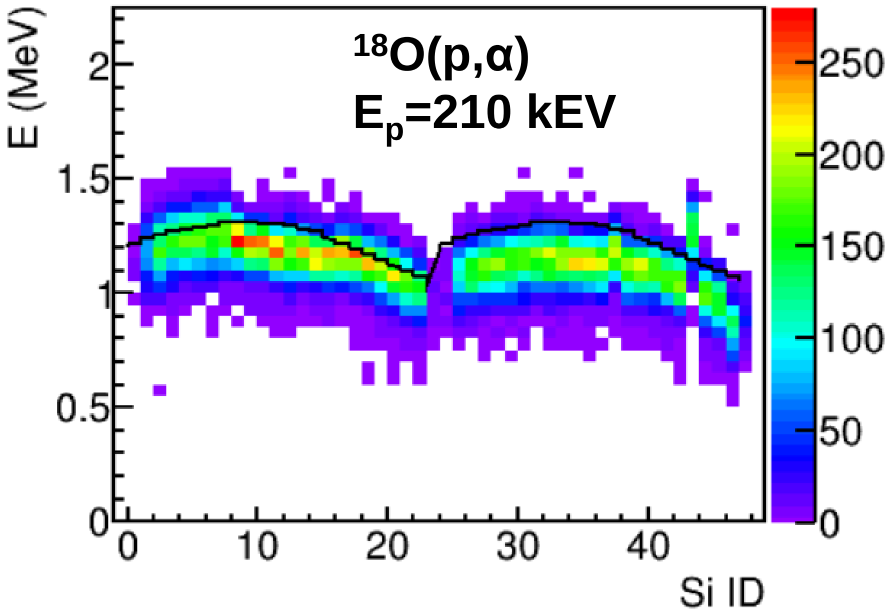


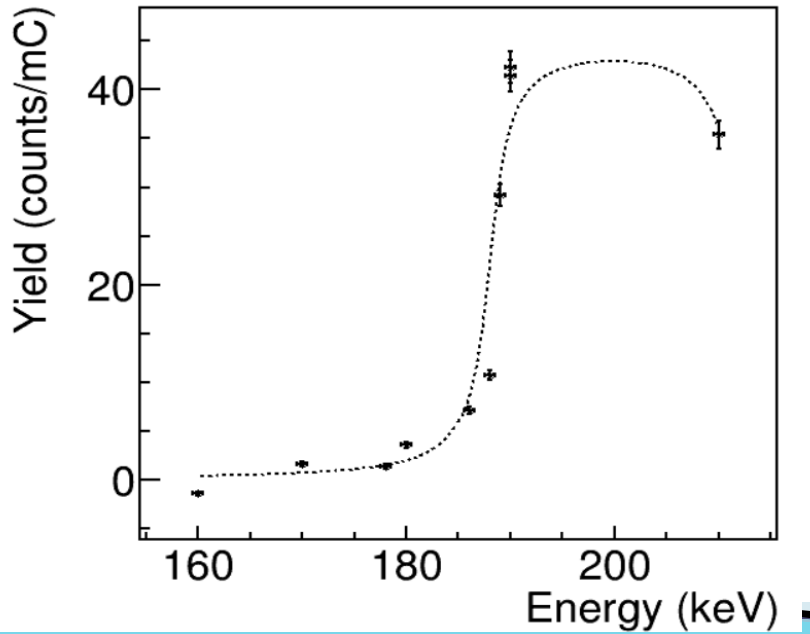
Ananna et al., Universe 2022, 8, 4.

- **Physics： ^{15}N(p,α)、^{17}O(p,α)、<u>^{18}O(p,α)</u>、^{19}F(p,α)、^{23}Na(p,α)、^{27}Al(p,α) are important closed reactions in CNO, NeNa-MgAl cycles, influence isotope ratios.**
- **High-intense accelerators: 240kV HV at IMP and JUNA-400kV HV (CJPL)**
- **Experimental methods: TPC+Si or TPC (standalone)**

Collaboration with CIAE

Some testing results





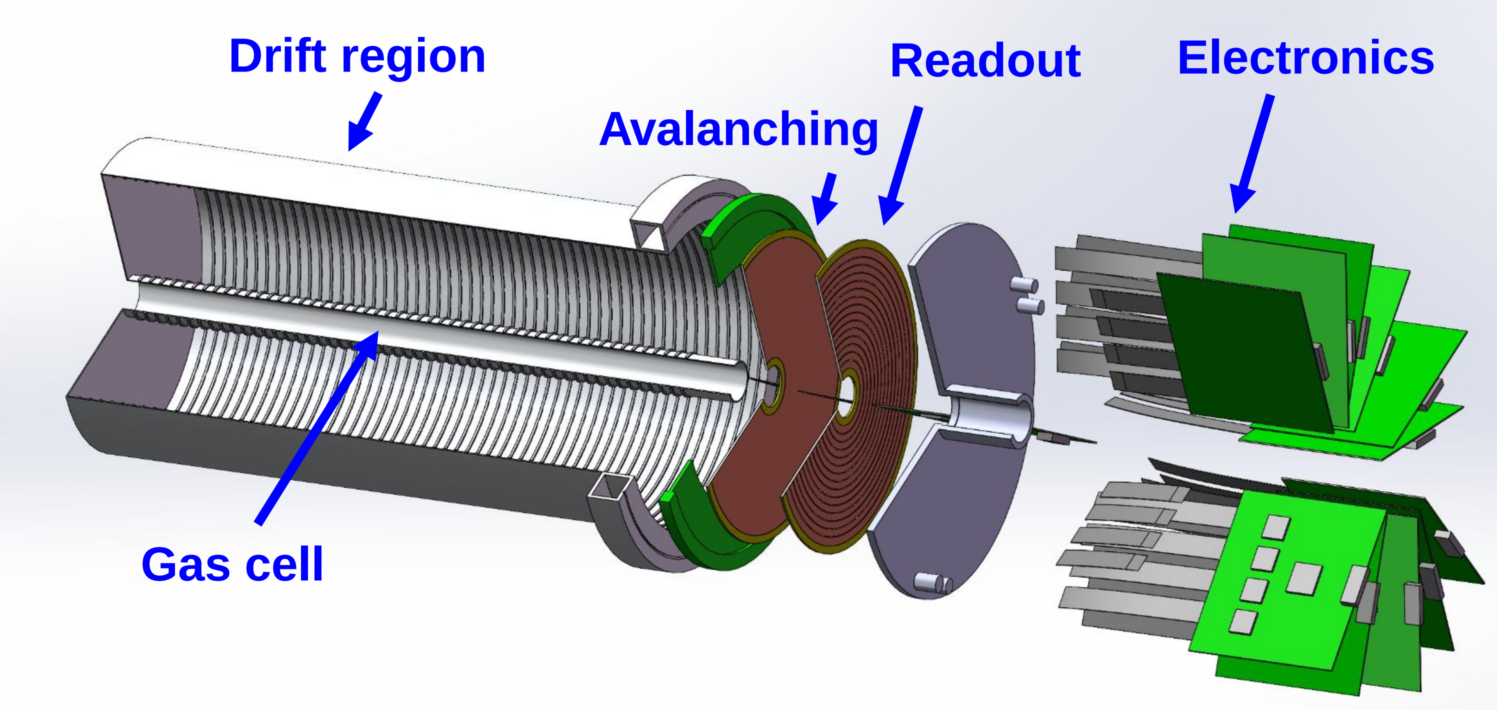
Challenges for Cr_2O_3 target

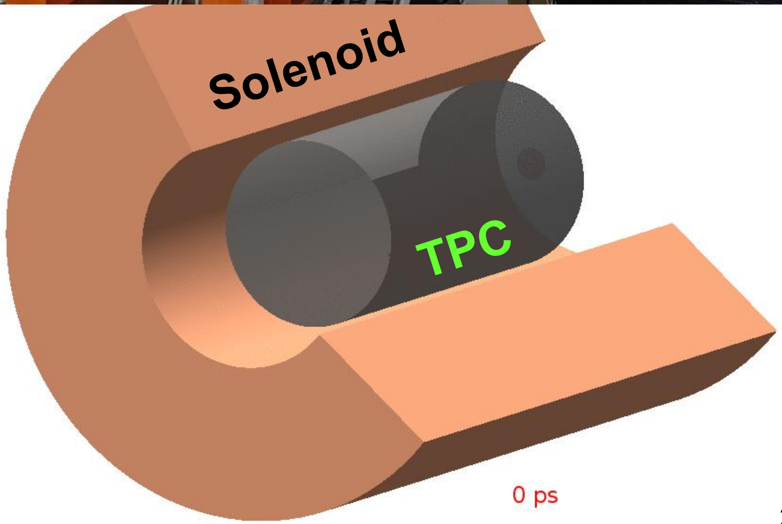
- Target stability
- $^{11}B(p,\alpha)^{8}Be$ → 3α background

AlN target

- TPC track distortion

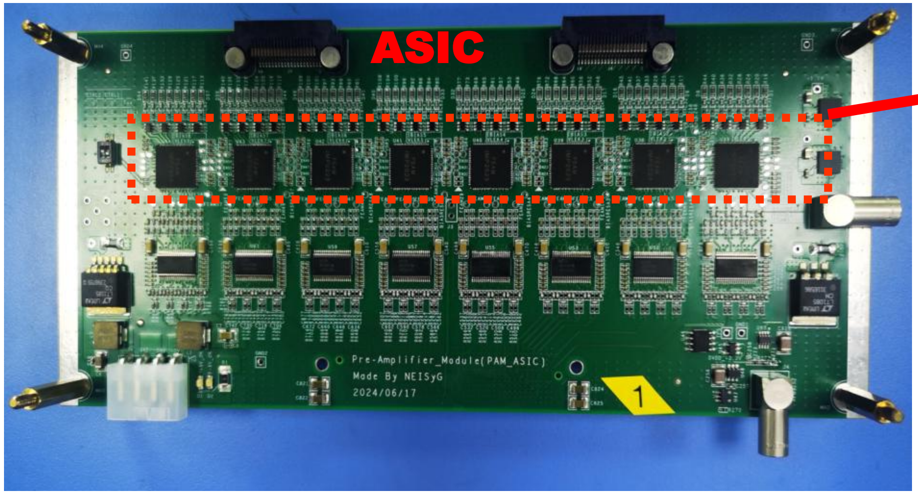
Cylindrical TPC (under design)





- Suppress delta rays in RIB experiments
- Achieve better particle identification
- Extend the measured dynamic energy range

Trigger-less electronics developed at IMP

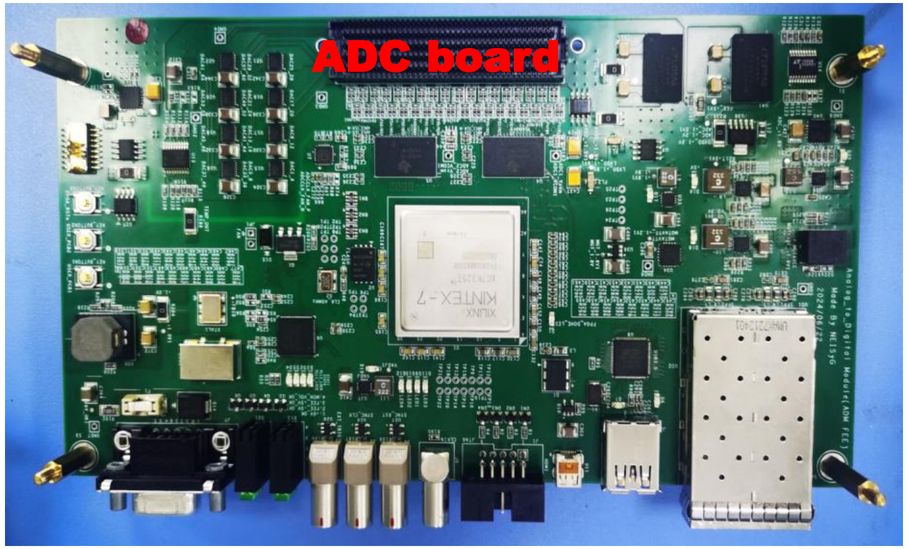


FEAM chip

FEAT chip

Parameter	Value
Gain	1mV/fC
Dynamic range	1pC
Shaping	80ns/160ns/1us
Counting rate	10KHz

Parameter	Value
Gain	8mV/fC, 4mV/fC, 1mV/fC, 0.1mV/fC
Dynamic range	125fC、1pC、2pC、10pC
Shaping	80ns / 160ns
Counting rate	1MHz

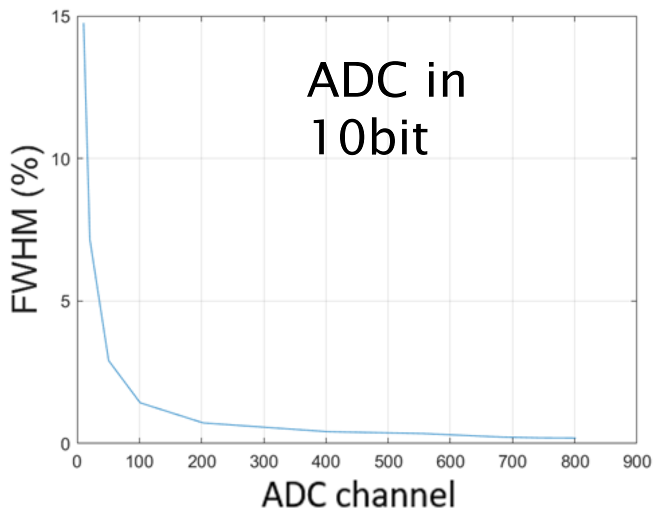


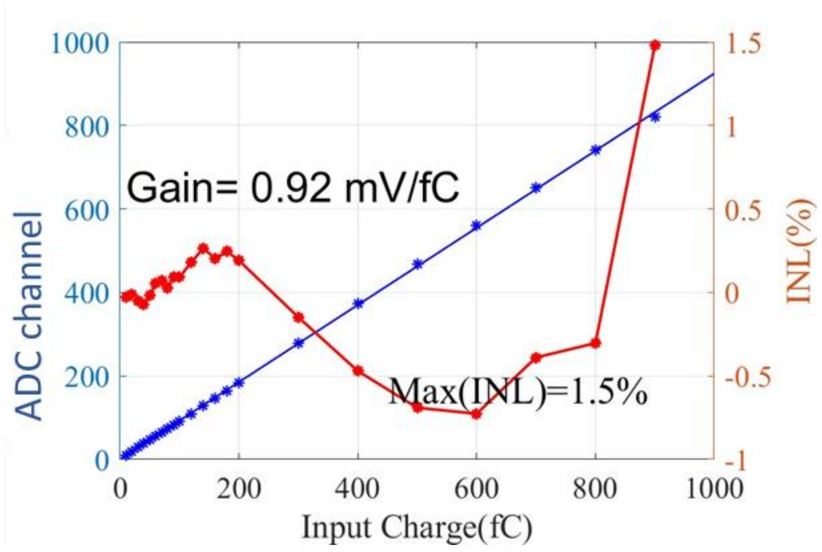
Parameter	Value
Dimension	20cm×19cm (ADC board + ASIC board)
Density	64channels / board
Sampling	40MSPS (maximum)
Resolution	10bit / 12bit
Mode	Continuous (triggerless) / external trigger / fixed rate readout(1k)
Time window	25ns-102.4μs adjustable
Data readout	Full pulse, baseline filter + zero suppression, energy + timing(ongoing)

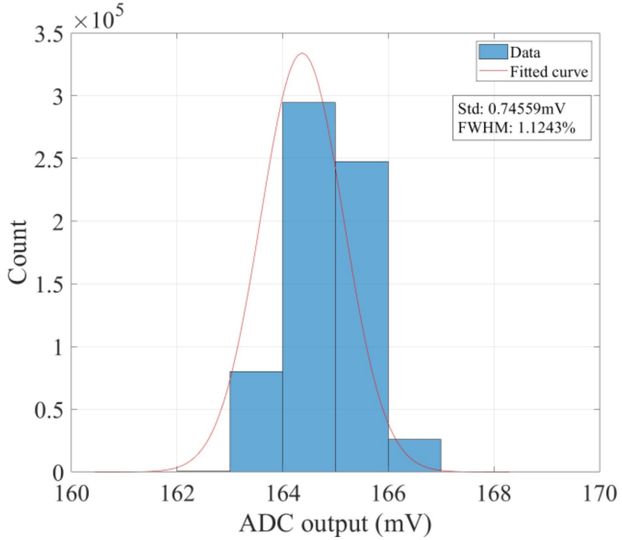
Courtesy of ZhiPeng Sun (孙志朋)

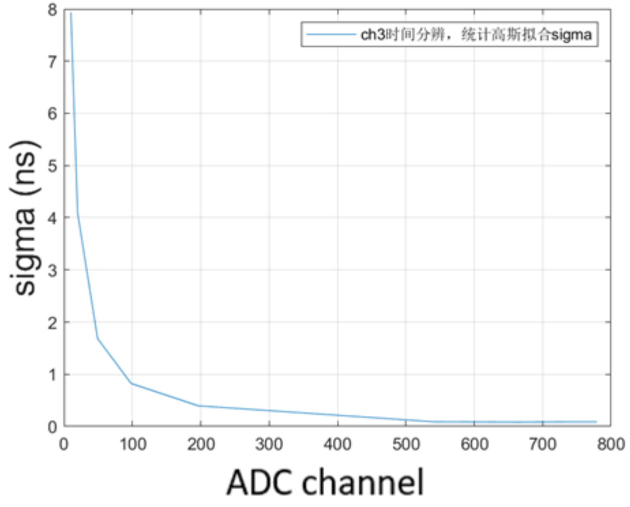
Some testing results

- Setup in test: 160ns(shape), baseline noise (σ < 1mV)
- In the dynamic range 10fC-1PC(prototype)， integral non-linearity (INL) is less than 2%
- Typical energy resolution is less than 2% (FWHM)
- Typical time resolution is around 1ns (1σ)



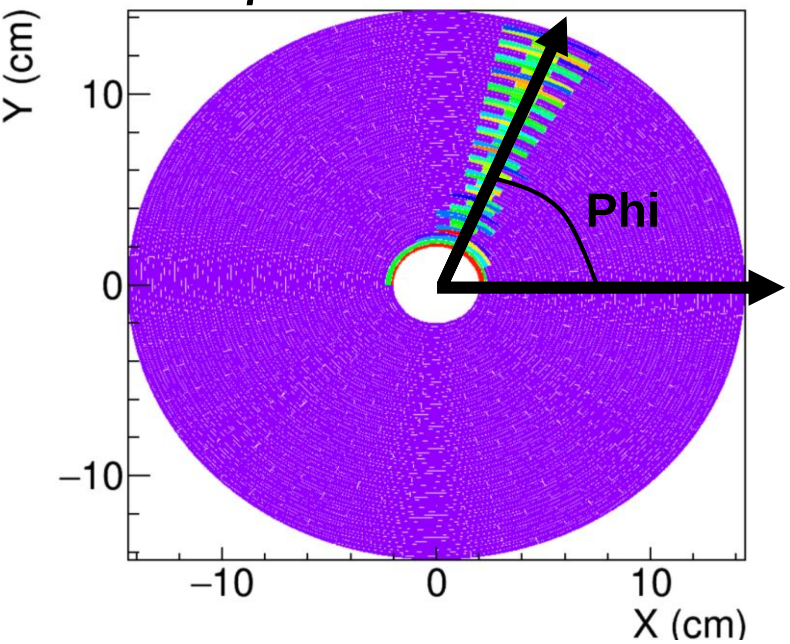




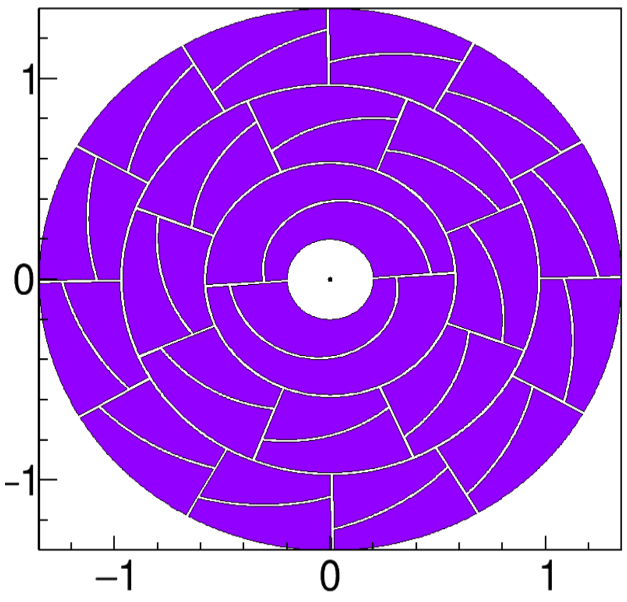


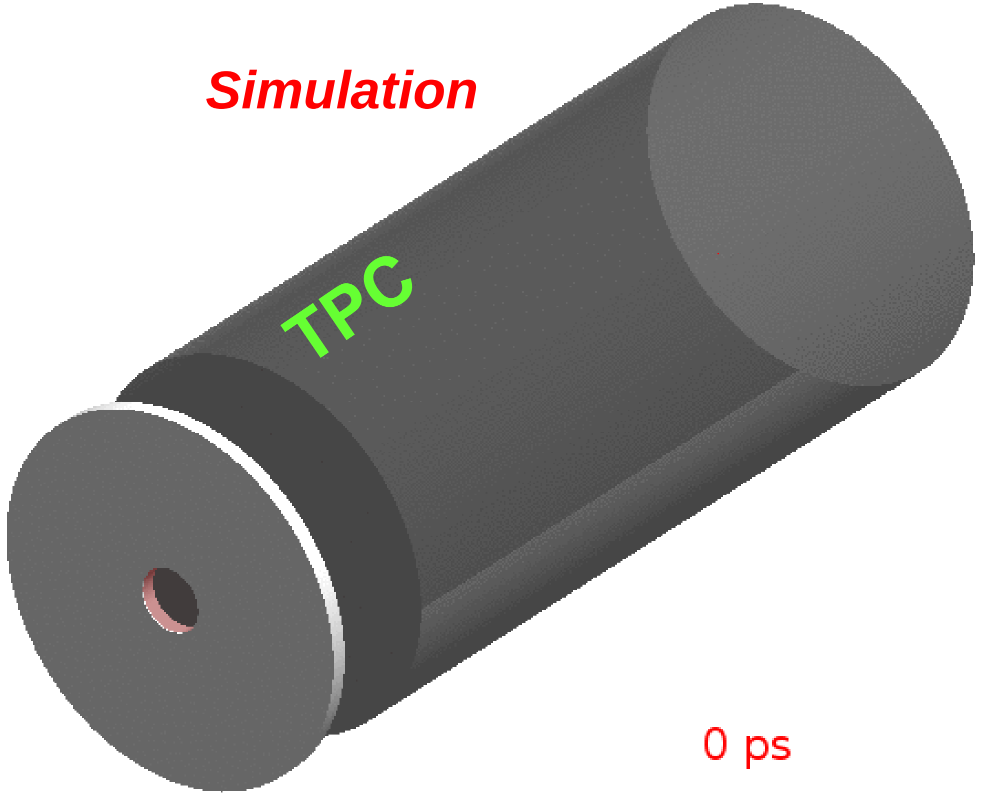
cMATE: range, angular resolution (simulation)

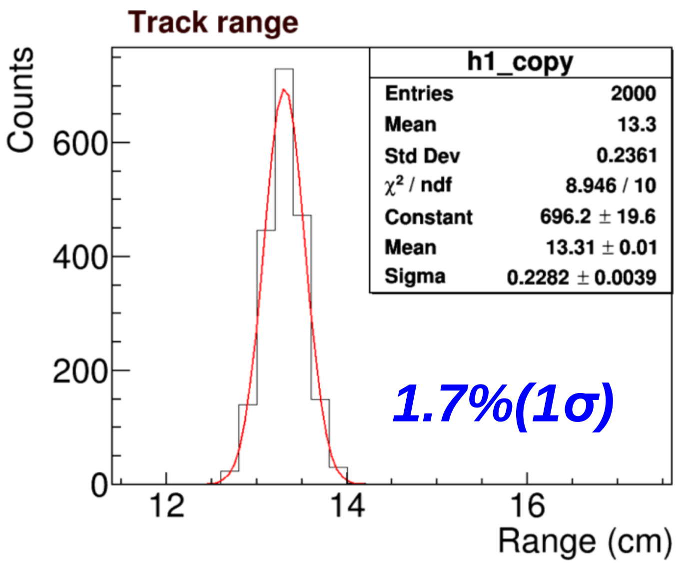
1500 pads

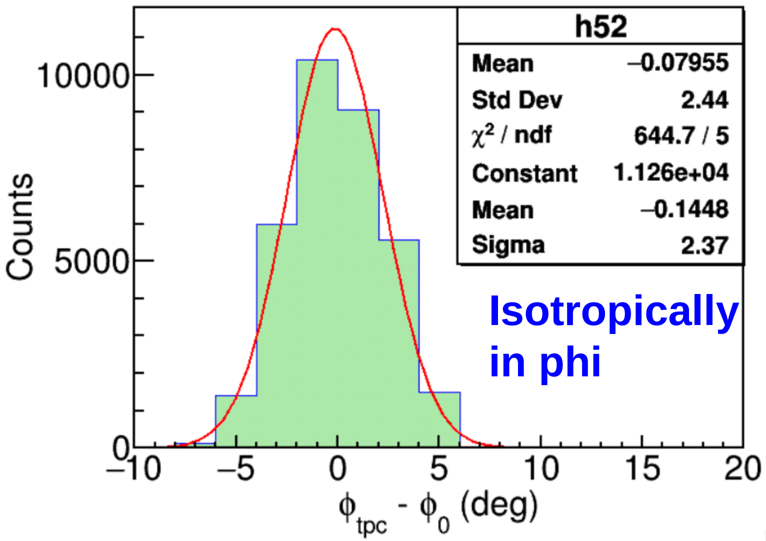


Pad geometry

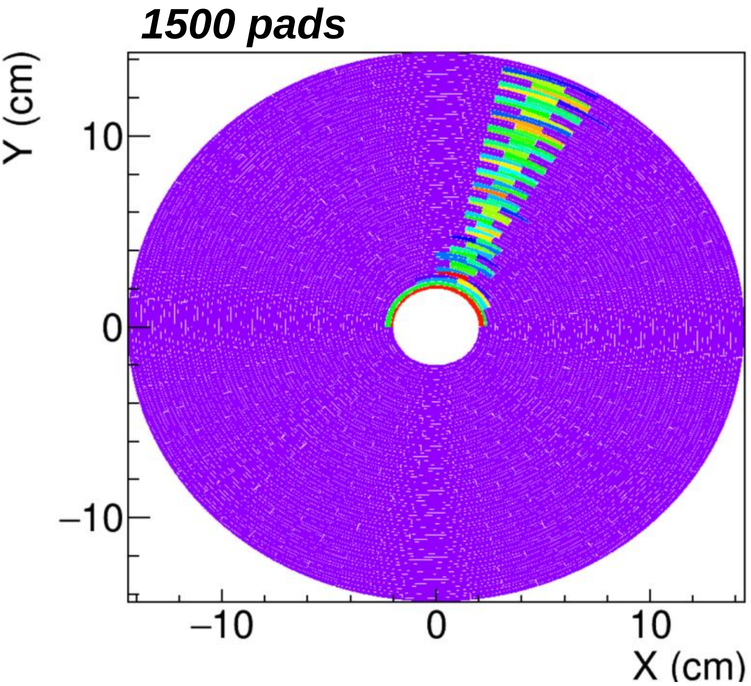


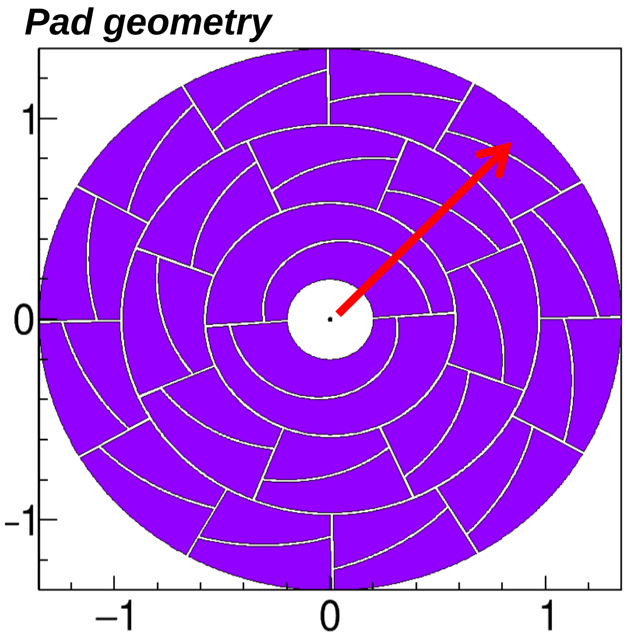


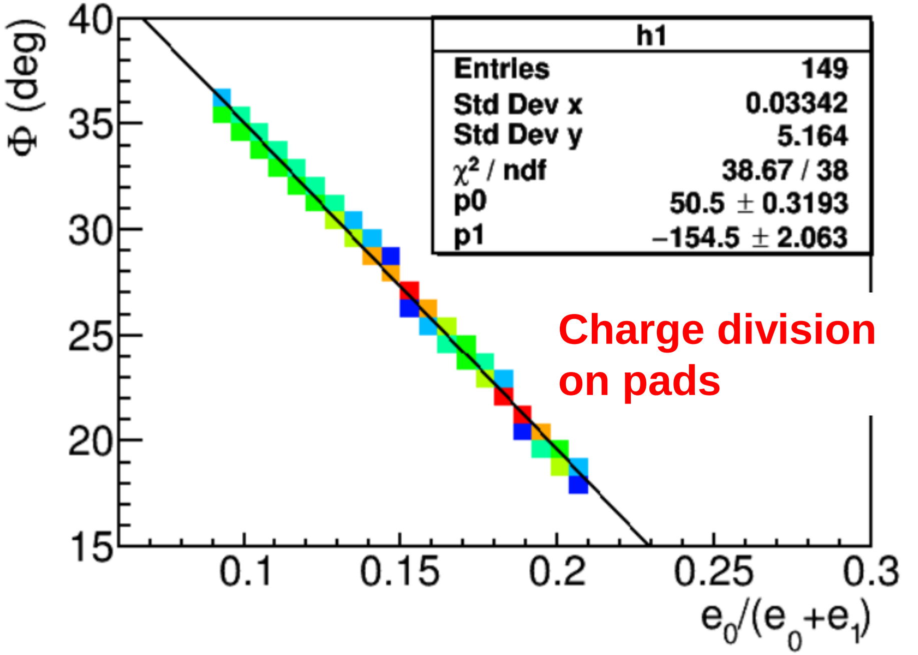


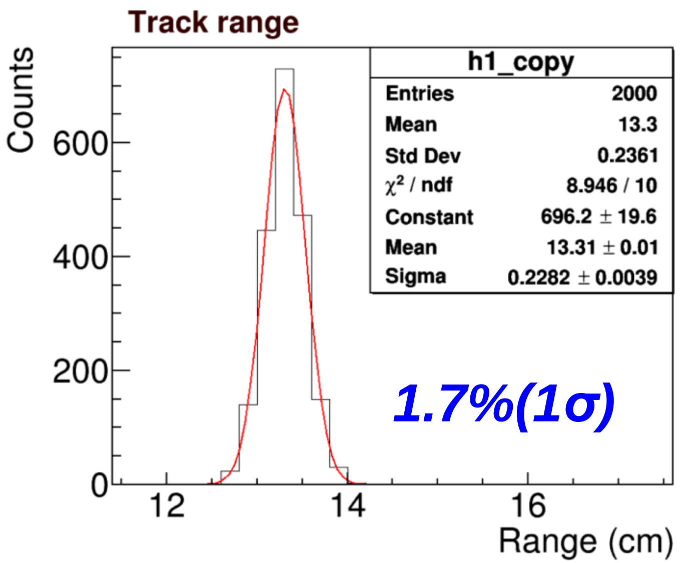


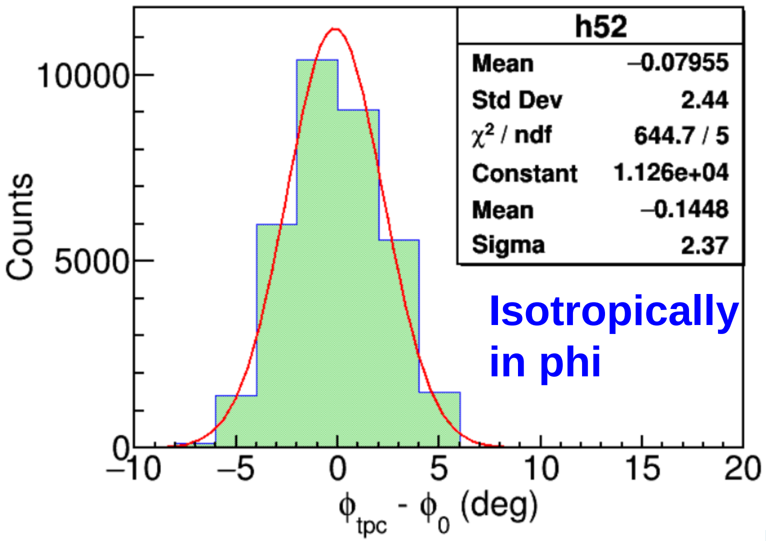
cMATE: range, angular resolution (simulation)

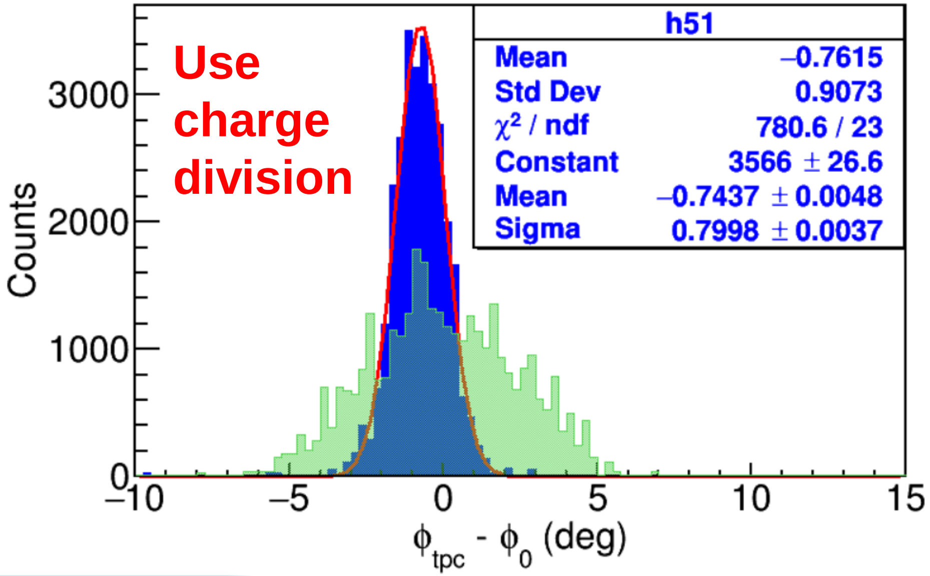




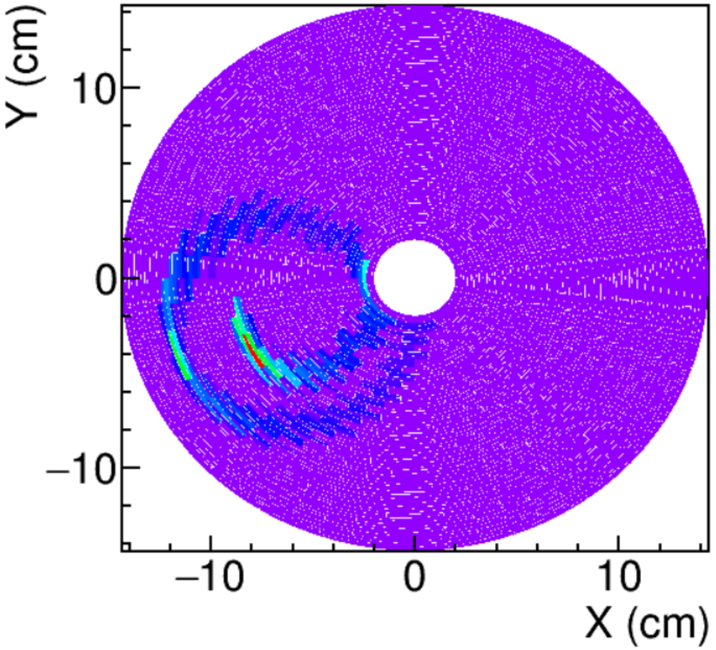


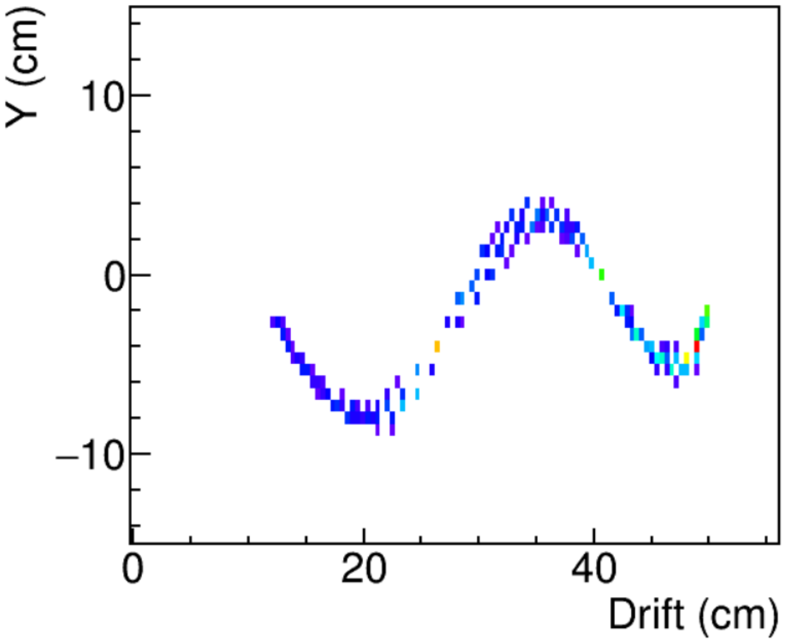


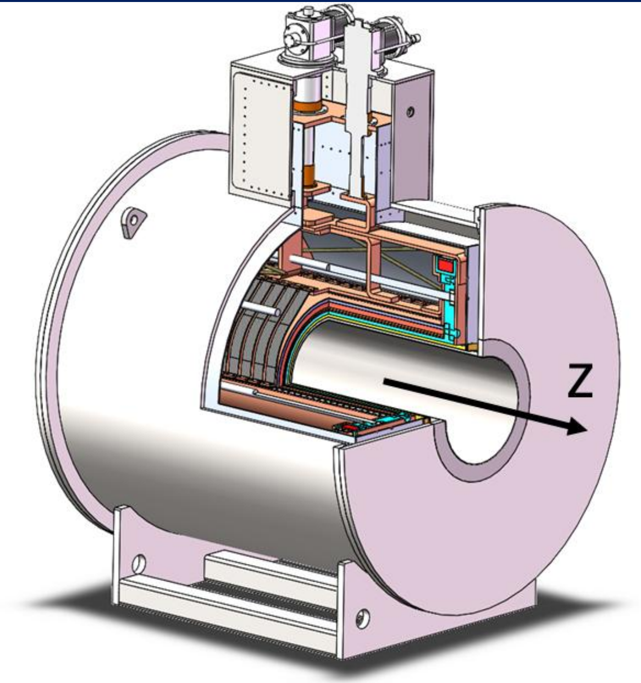


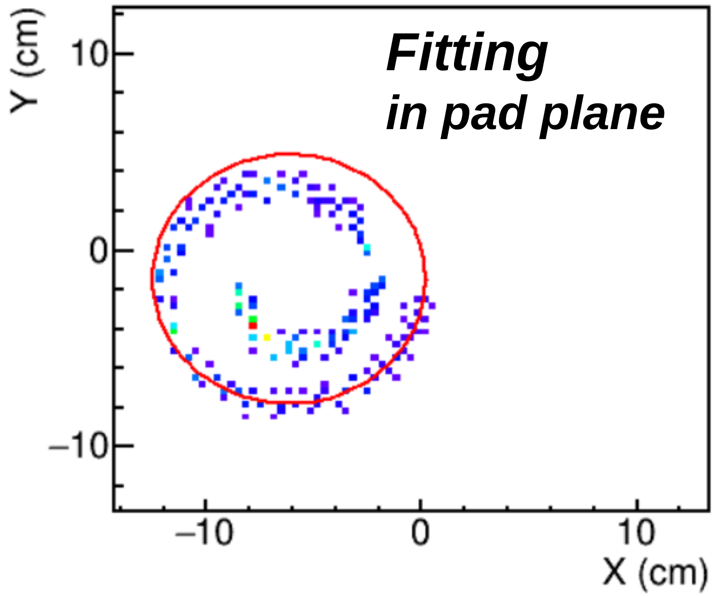


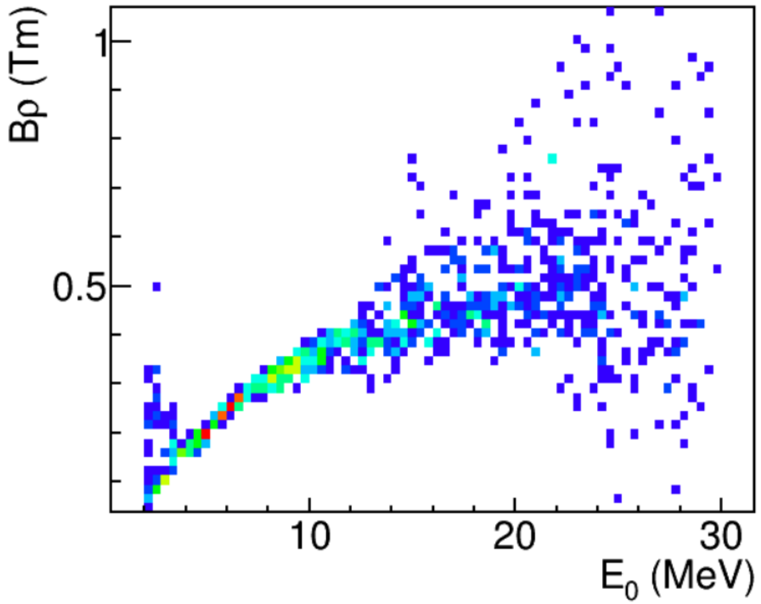
cMATE in solenoid (simulation)

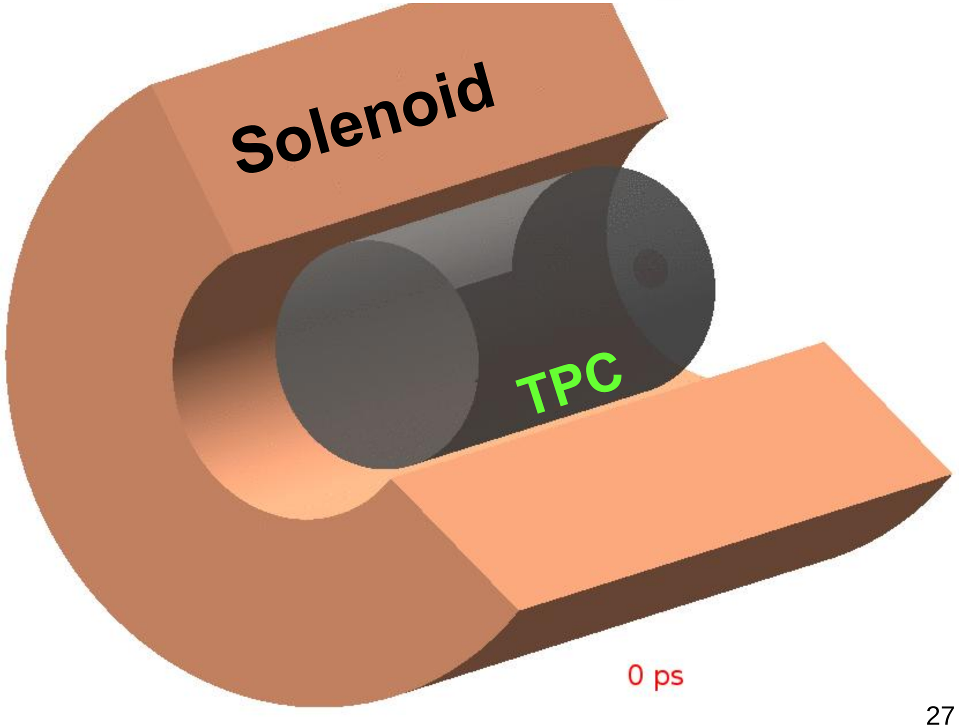












Summary

- MATE TPC detectors have been constructed
- $^{12}C+^{12}C$, $^{19}O+^{12}C$ fusion measurements with beam rate ~ 100 cps
- $^{14}N^{14}O(\alpha,p)$ (challenging at 10^5 cps), $^{11}C(\alpha,\alpha')$ (fine) measurements at 10^5 cps
- $^{12}C+^{12}C$ direct measurement at stellar energies with beam intensity ~ 70 pμA
- $^{18}O(p,\alpha)$ measurement with beam intensity of ~1 mA
- To develop Cylindrical TPC working inside solenoid (under design)