Direct and resonant reactions with active targets

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The “art” of performing direct and resonant reactions.

Active Target Time Projection Chamber (AT-TPC) at NSCL

Recent results and perspectives

Conclusions

Direct and resonant reactions in nuclear physics

Direct reactions

$$A + a \Rightarrow B + b$$

- Small momentum transfer.
- Large impact parameter (surface).
- Cross section focused on forward direction.
- Very short time scale ($\sim 10^{-22}$ s).

- Elastic scattering: Optical potentials, density distributions.
- Inelastic scattering: Electromagnetic transitions, exotic structures and resonance modes.
- Transfer reactions: Nuclear structure, pairing.
- Charge-exchange: GT strengths, baryon resonances

Resonant reactions

$$A + a \Rightarrow C^{*} \Rightarrow B + b$$

- Going through resonances.
- Intermediate step that decays.
- Time scales can be very large ($\sim 10^{-18}$ s).
- Cross sections follow Breit-Wigner.
- Excitation function of the resonant process
- Partial width gives spectroscopic information

- Resonant (in)elastic scattering: Isobaric Analog States in the composite system. Clustering in nuclei.
- Capture reactions: Astrophysics, reactors.

Direct and resonant reactions in nuclear physics

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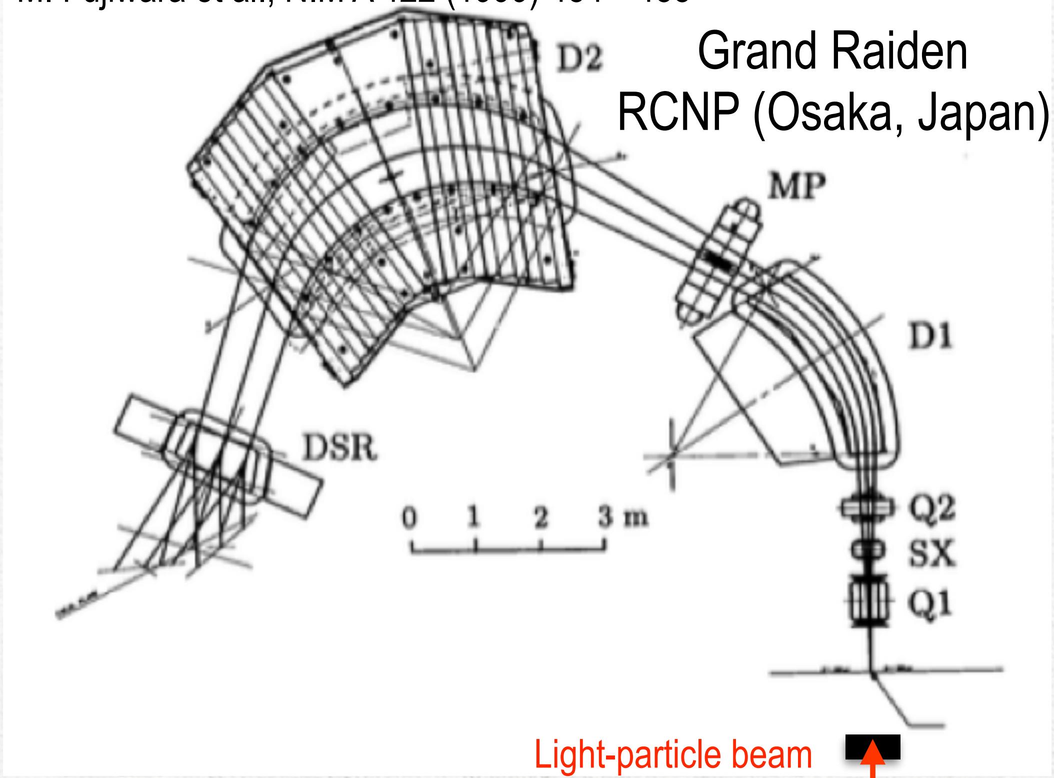
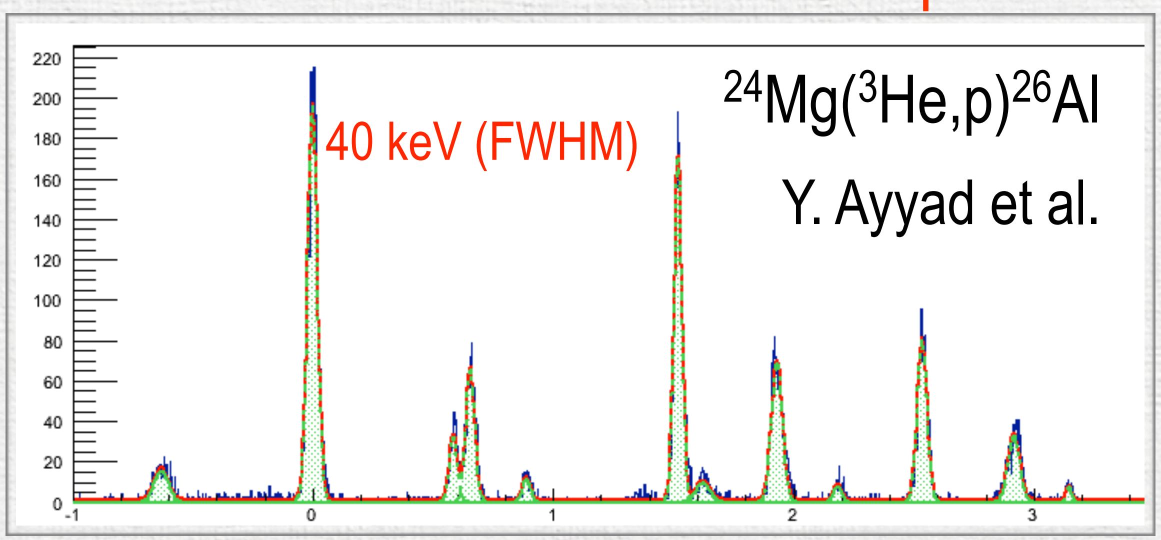
Well suited for active targets!

High resolution measurements in nuclear physics

Magnetic spectrometers

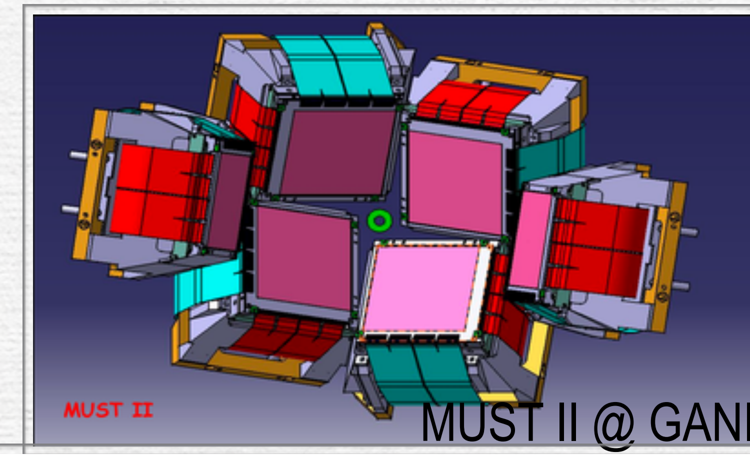
M. Fujiwara et al., NIM A 422 (1999) 484—488

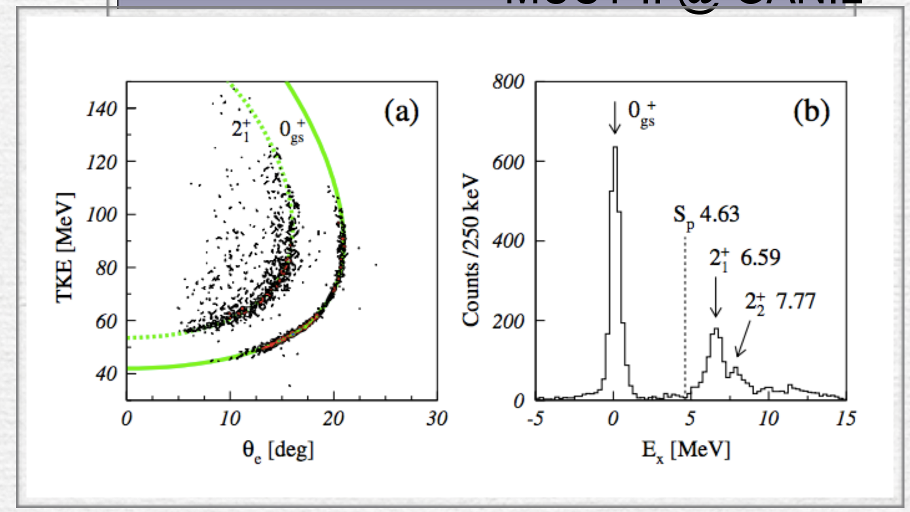


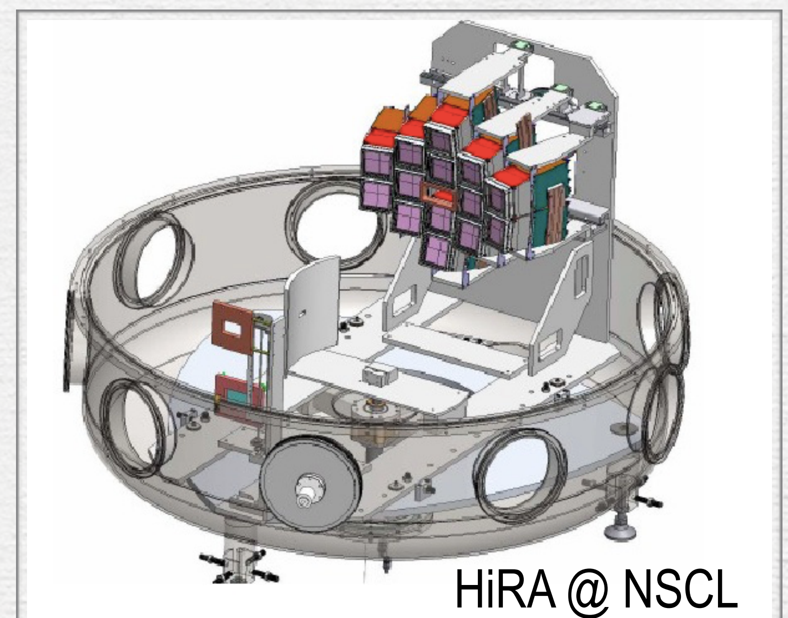


- ☑ High beam intensity
- ☑ Excellent Ex resolution
- ☐ Limited to stable/long-lived targets

Si+CsI telescopes

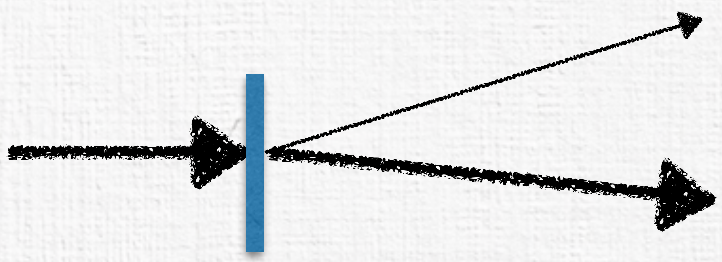




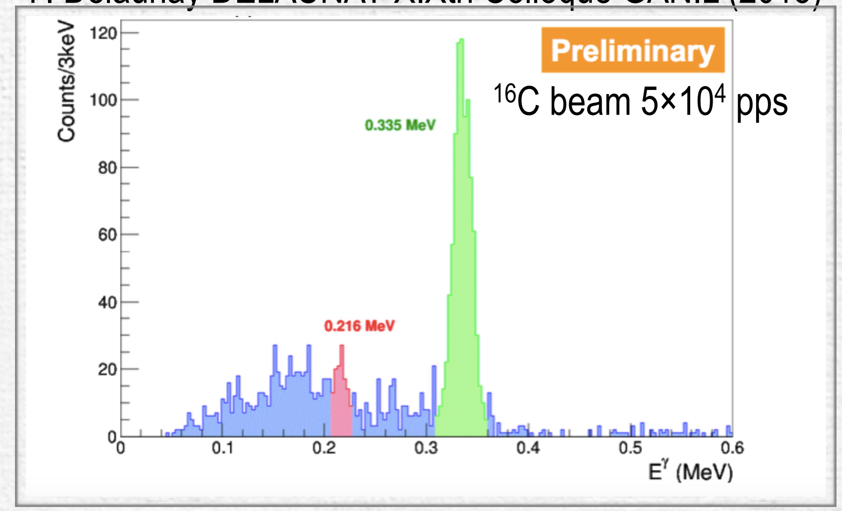


Setup configuration and trigger selection

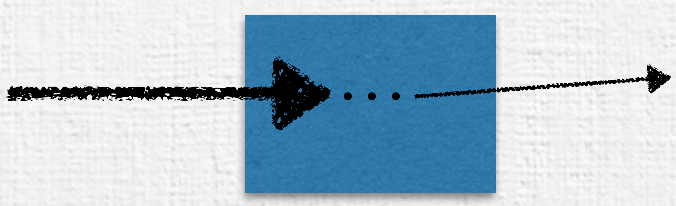
Thin CD_2 targets 0.01- 1 mg/cm^2



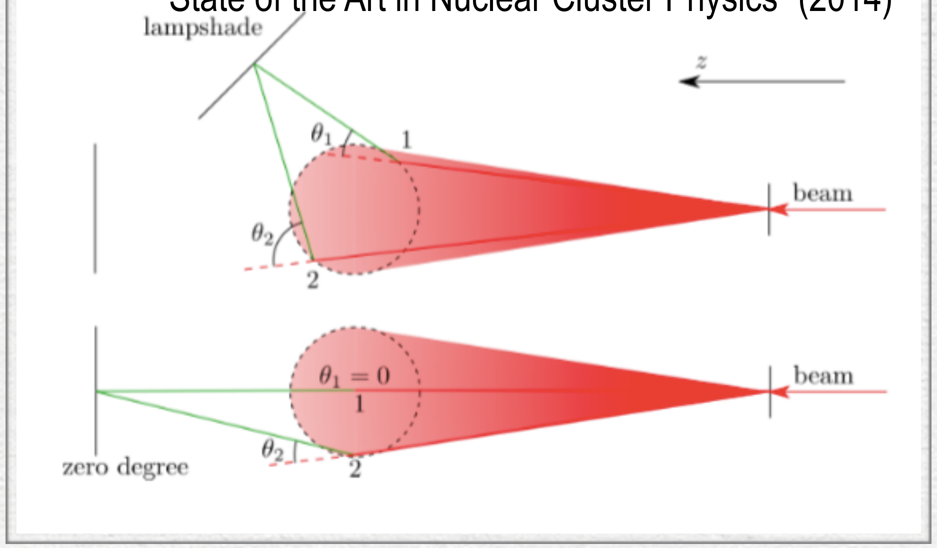
F. Delaunay DELAUNAY XIXth Colloque GANIL (2015)



Thick CH_2 8.8 mg/cm^2

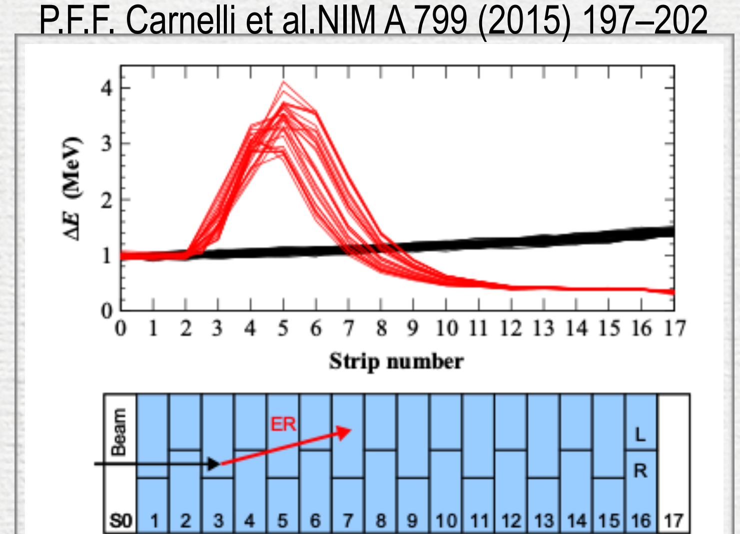


J Walshe et al., 3rd International Workshop on "State of the Art in Nuclear Cluster Physics" (2014)



"Active target" mode

P.F.F. Carnelli et al.NIM A 799 (2015) 197–202



Energy resolution in inverse kinematics

Heavy ion detected in spectrometer (3 mg/cm^2)

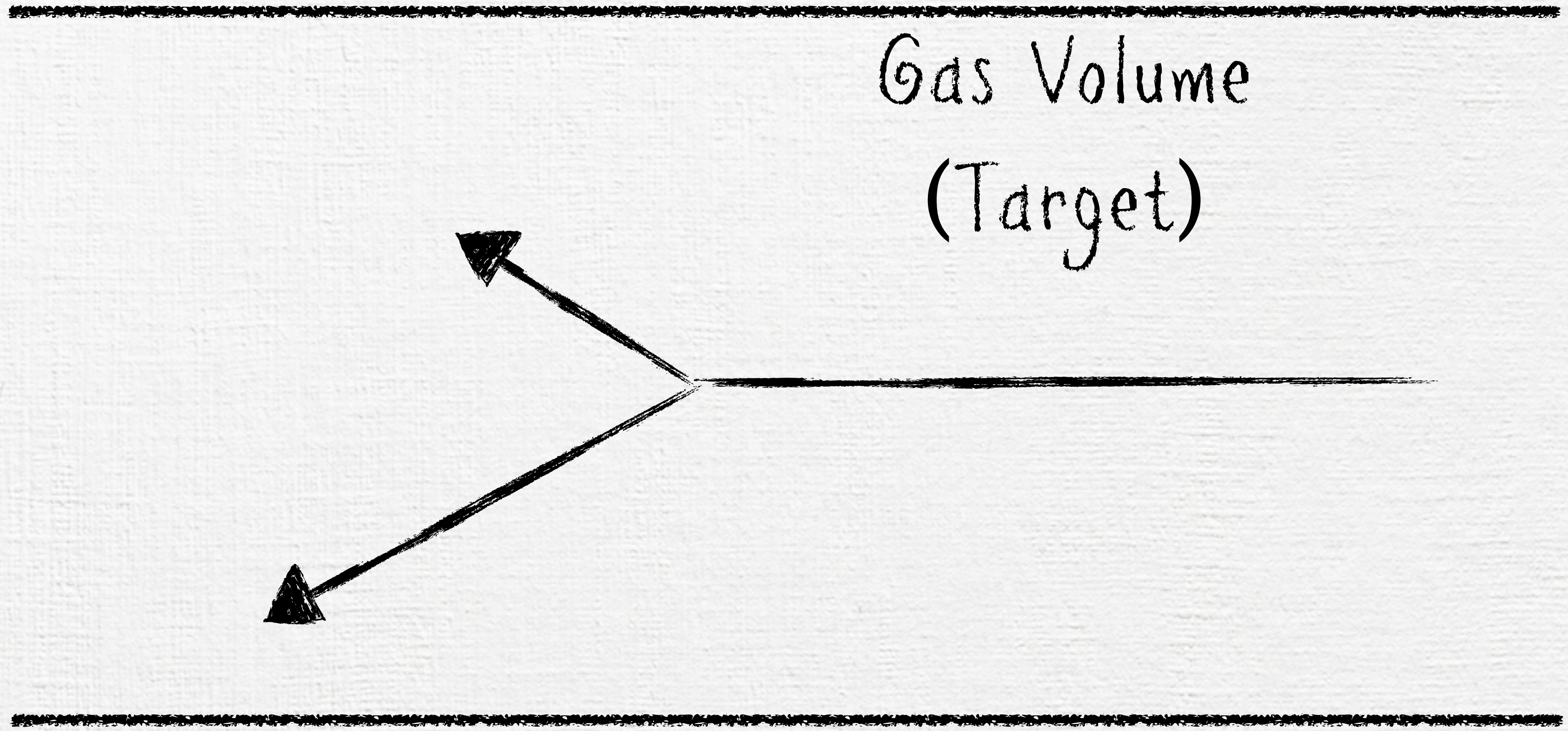
Reaction	E_i/A (MeV)	θ_{lab}	Origin of contribution					Σ_{quad}
			$\Delta\theta$	Δp	E_{stragg}	$\Theta_{1/2}$	dE/dx	
p(^{12}Be, ^{11}Be)d	30	1.07°	172	147	101	74	23	259
p(^{12}Be, ^{11}Be)d	15	1.06°	84	71	99	74	37	169
p(^{77}Kr, ^{76}Kr)d	30	0.16°	1404	811	808	723	56	1952
p(^{77}Kr, ^{76}Kr)d	10	0.10°	334	143	502	570	268	883
d(^{76}Kr, ^{77}Kr)p	10	0.21°	1140	614	2177	1859	1321	3408

Light particle detected in solid state device (3 mg/cm^2)

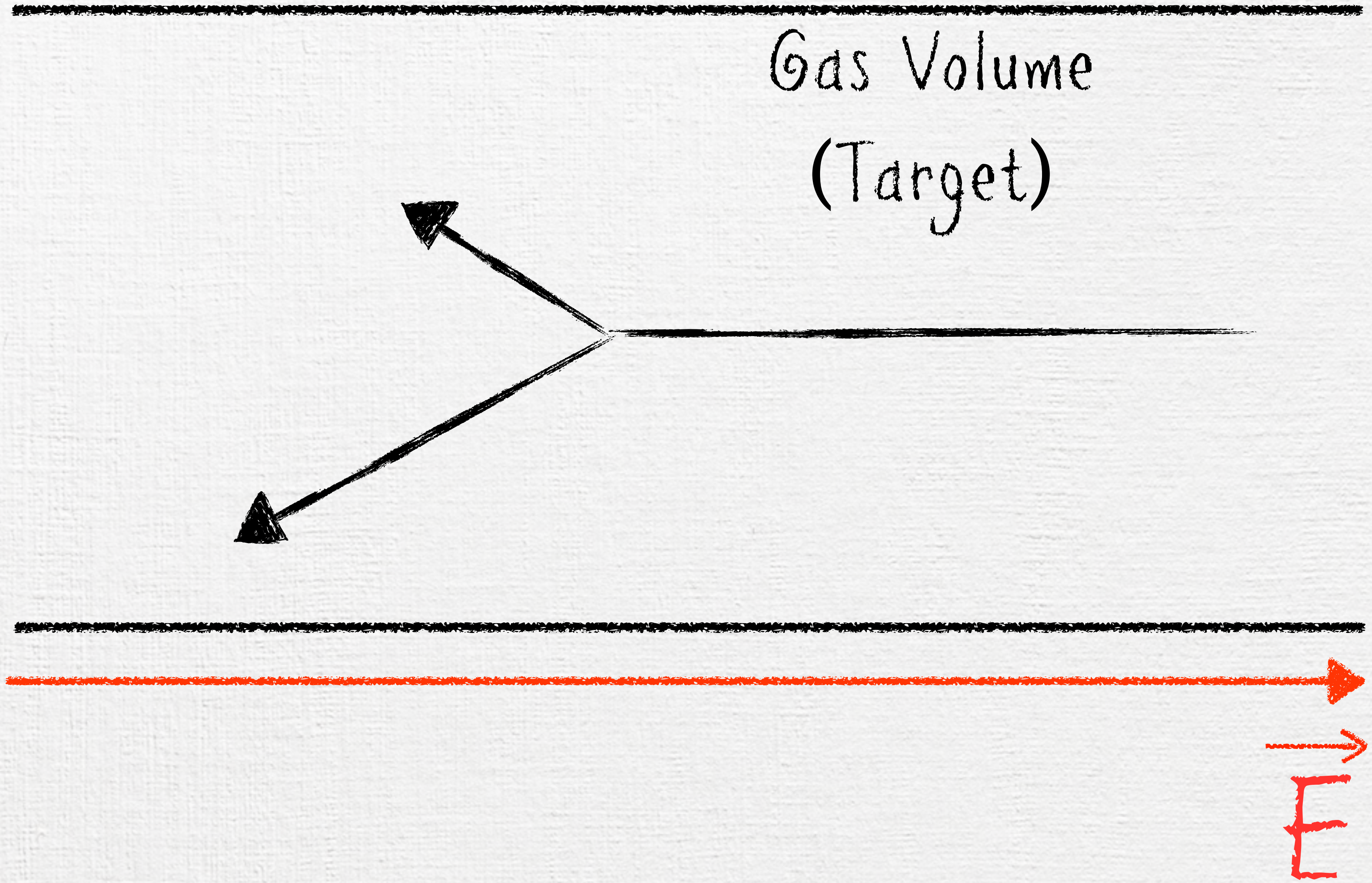
Reaction	E_i/A (MeV)	θ_{lab}	Origin of contribution					Σ_{quad}
			$\Delta\theta$	ΔE_f	ΔE_i	$\Theta_{1/2}$	dE/dx	
p(^{12}Be, d)^{11}Be	30	19.0°	136	74	114	96	649	685
p(^{12}Be, d)^{11}Be	15	17.8°	66	72	55	89	984	995
p(^{77}Kr, d)^{76}Kr	30	15.0°	124	55	64	63	186	249
p(^{77}Kr, d)^{76}Kr	10	6.0°	26	24	23	19	775	777
d(^{76}Kr, p)^{77}Kr	10	155.3°	52	93	37	60	1309	1316

J. S. Winfield et al., NIM A 396 (1997)

Active Targets for reactions with radioactive beams



Active Targets for reactions with radioactive beams



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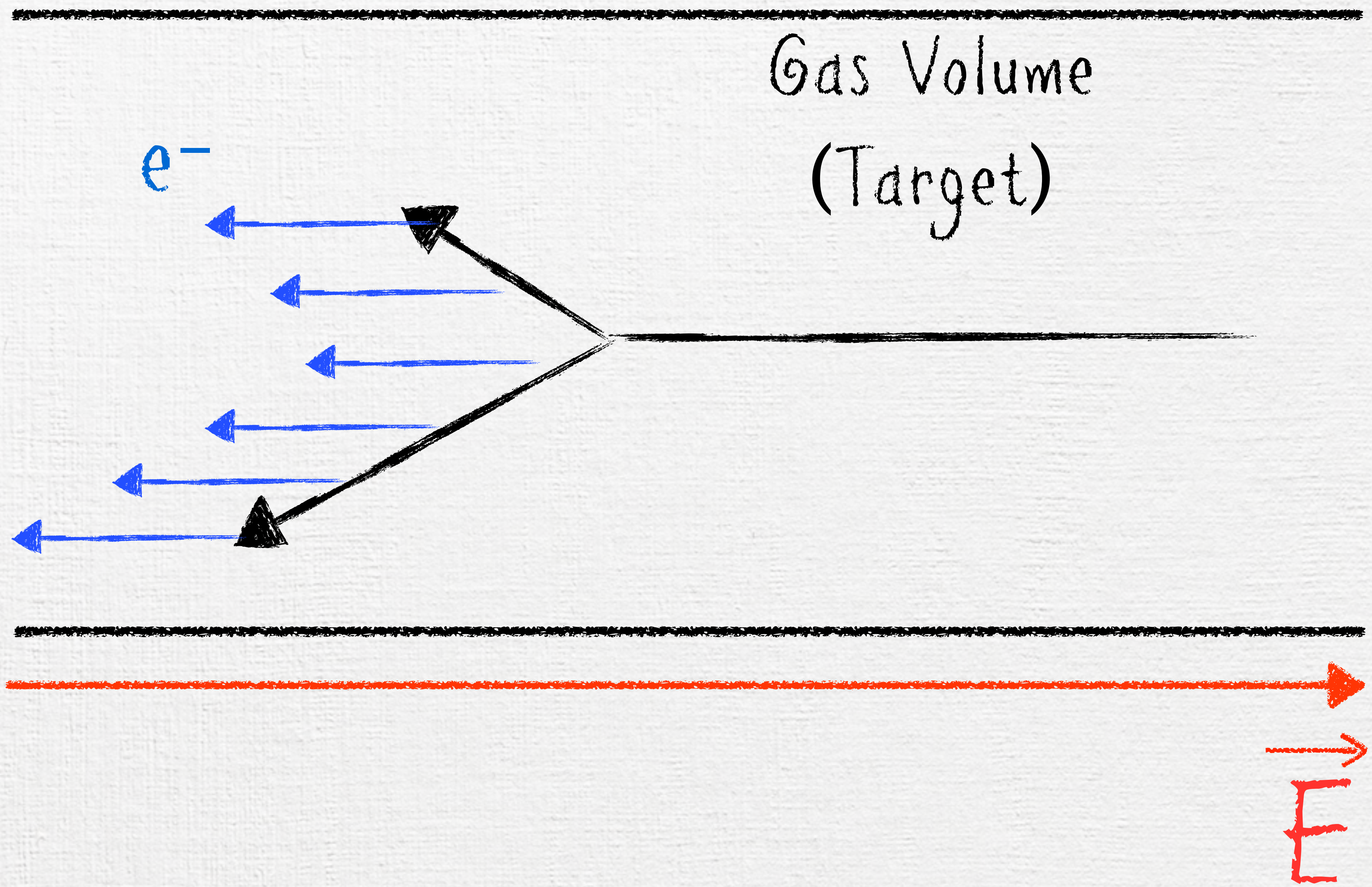

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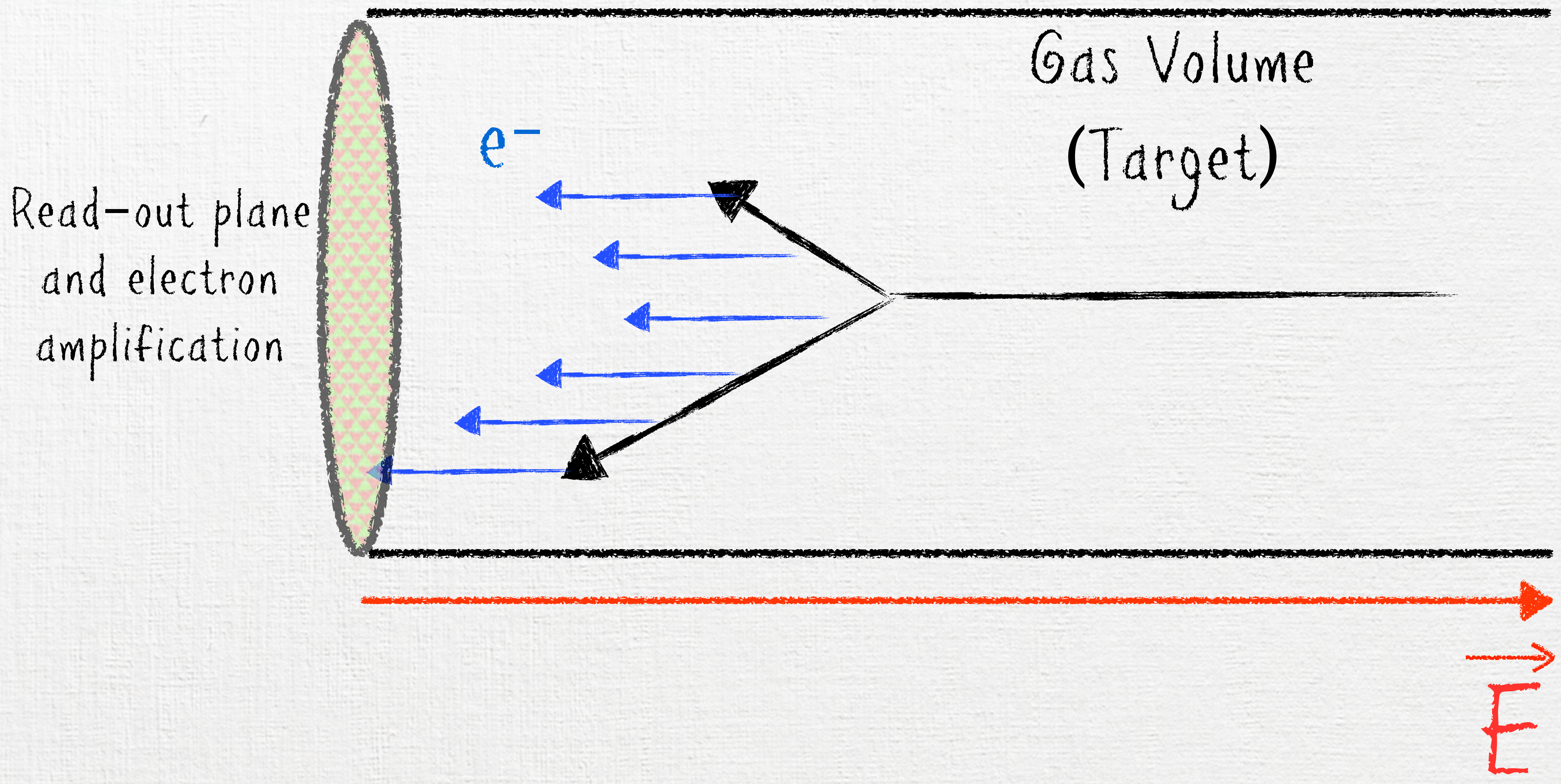

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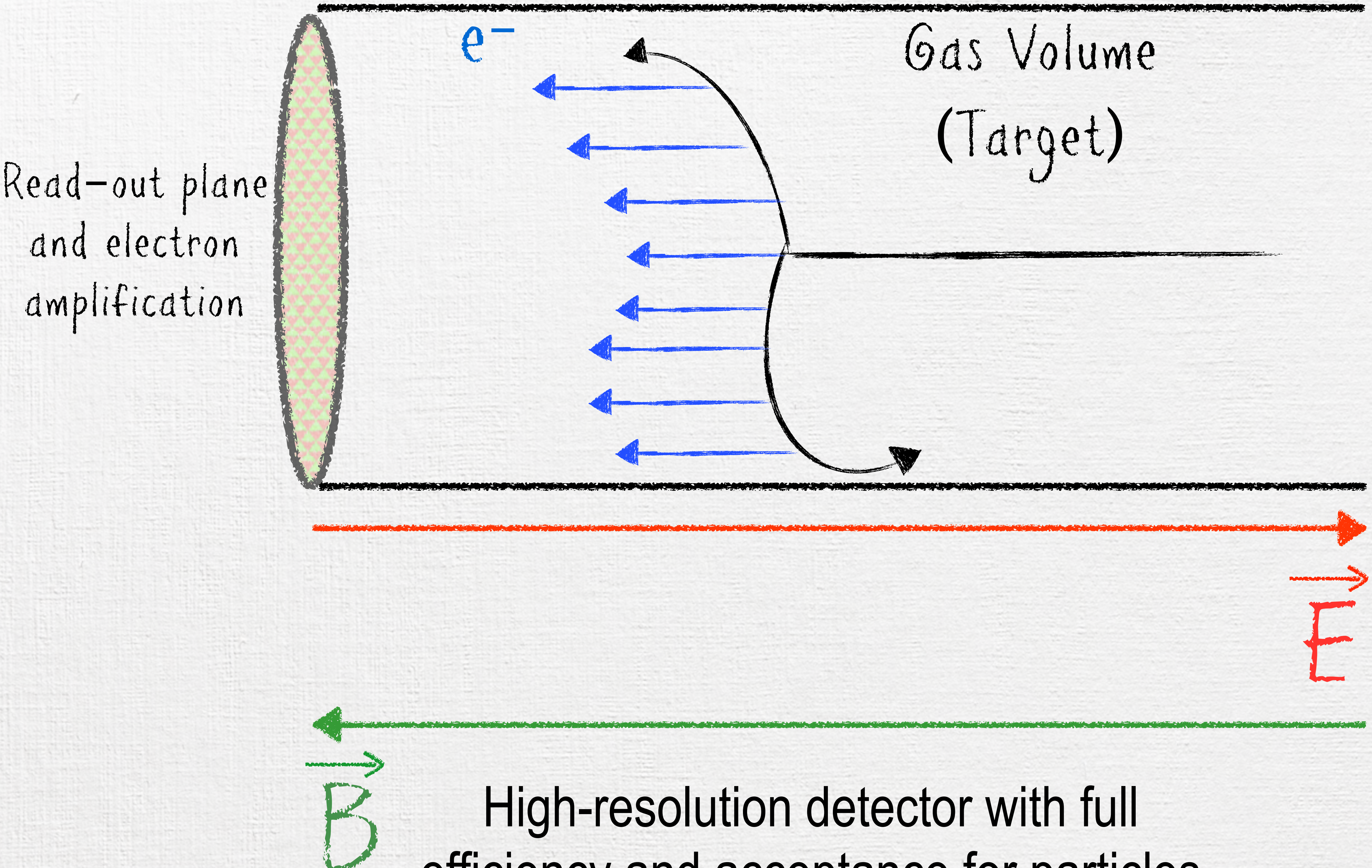


High-resolution detector with full efficiency and acceptance for particles with low recoil energy

Active Targets: An overview

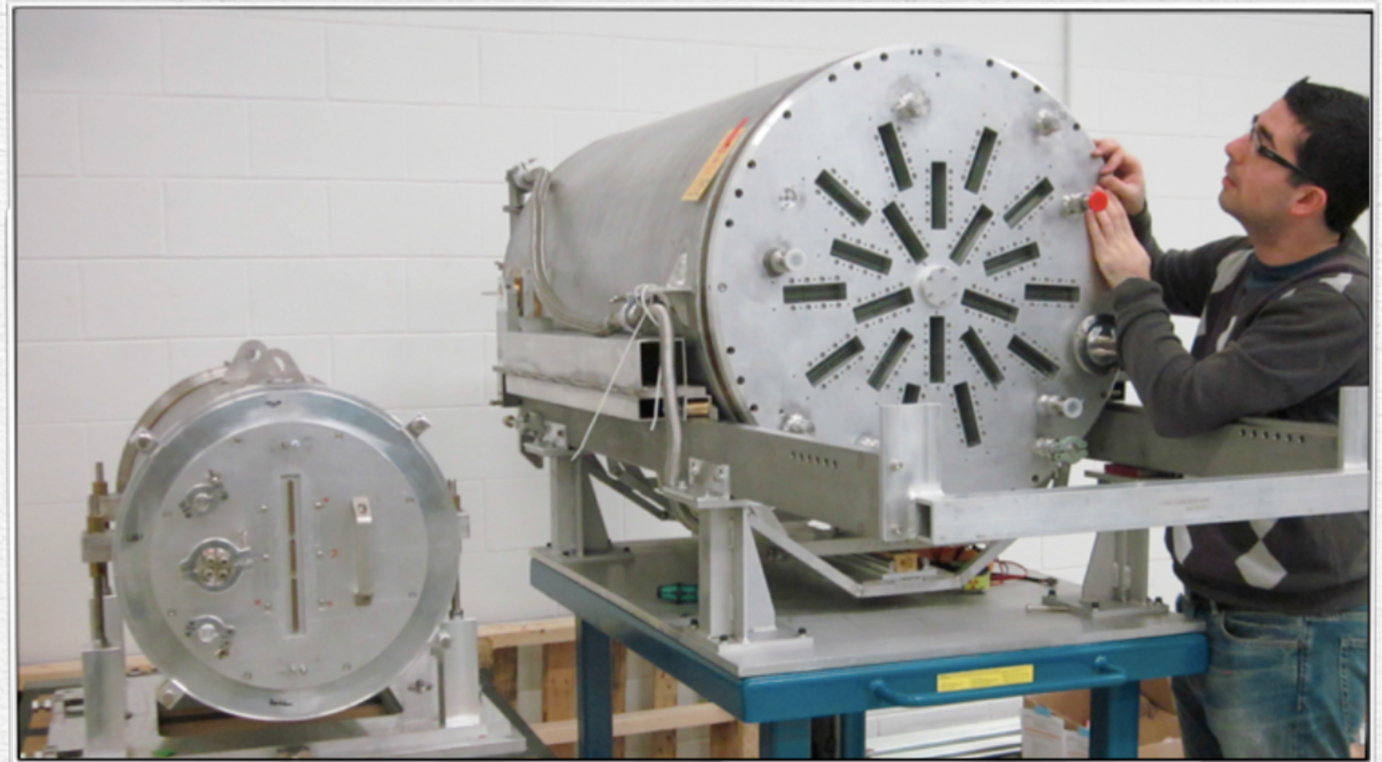
Table 1
Active targets in operation or being constructed.

Name	Lab	Gas ampl.	Volume (cm^3)	Pressure (atm)	Energy (MeV/n)	Electronics	Number of chan.	Status[a]	Ref.
Ikar	GSI	NA	$60 \cdot 20^2\pi$	10	$\gtrsim 700$	FADC	6*3	O	[6]
Maya	GANIL	Wire	$30 \cdot 28.3^2$	0.02–2	2–60	Gassiplex	1024	O	[7]
ACTAR	GANIL	μmegas	20^3	0.01–3	2–60	GET	16,000	C, P	[8]
MSTPC[b]	CNS	Wires	$70 \cdot 15 \cdot 20$[c]	<0.3	0.5–5	FADC	128	O	[9,10]
CAT	CNS	GEM	$10 \cdot 10 \cdot 25$	0.2–1	100–200	FADC	400	T	[11]
MAIKo	RNCP	μ-PIC	14^3	0.4–1	10–100	FADC	2×256	T	[12]
pAT-TPC	MSU	μmegas	$50 \cdot 12.5^2\pi$	0.01–1	1–10	GET	256	T, O	[13]
AT-TPC	FRIB	μmegas	$100 \cdot 25^2\pi$	0.01–1	1–100	GET	10,240	O	[14]
TACTIC	TRIUMF	GEM	$24 \cdot 10^2\pi$	0.25–1	1–10	FADC	48	T	[15]
ANASEN	FSU/LSU	Wires	$43 \cdot 10^2\pi$	0.1–1	1–10	ASIC	512	O	[16]
MINOS	IRFU	μmegas	6000	1	>120	Feminos	5000	O	[17]
O-TPC	TUNL	Grid	$21 \cdot 30^2$	0.1	~10	Optical CCD	$2048 \cdot 2048$ pixels	O	[18]

[a] O: operational, C: under construction, P: Project, T: test device.
[b] Two GEM versions: GEM-MSTPC (CNS) [19,20] GEM-MSTPC (KEK) [21,22].
[c] GEM-MSTPC (CNS): $23.5 \cdot 29.5 \cdot 10.0$, GEM-MSTPC (KEK): $10.0 \cdot 10.0 \cdot 10.0$.

S. Beceiro-Novo et al. / Progress in Particle and Nuclear Physics 84 (2015) 124–165

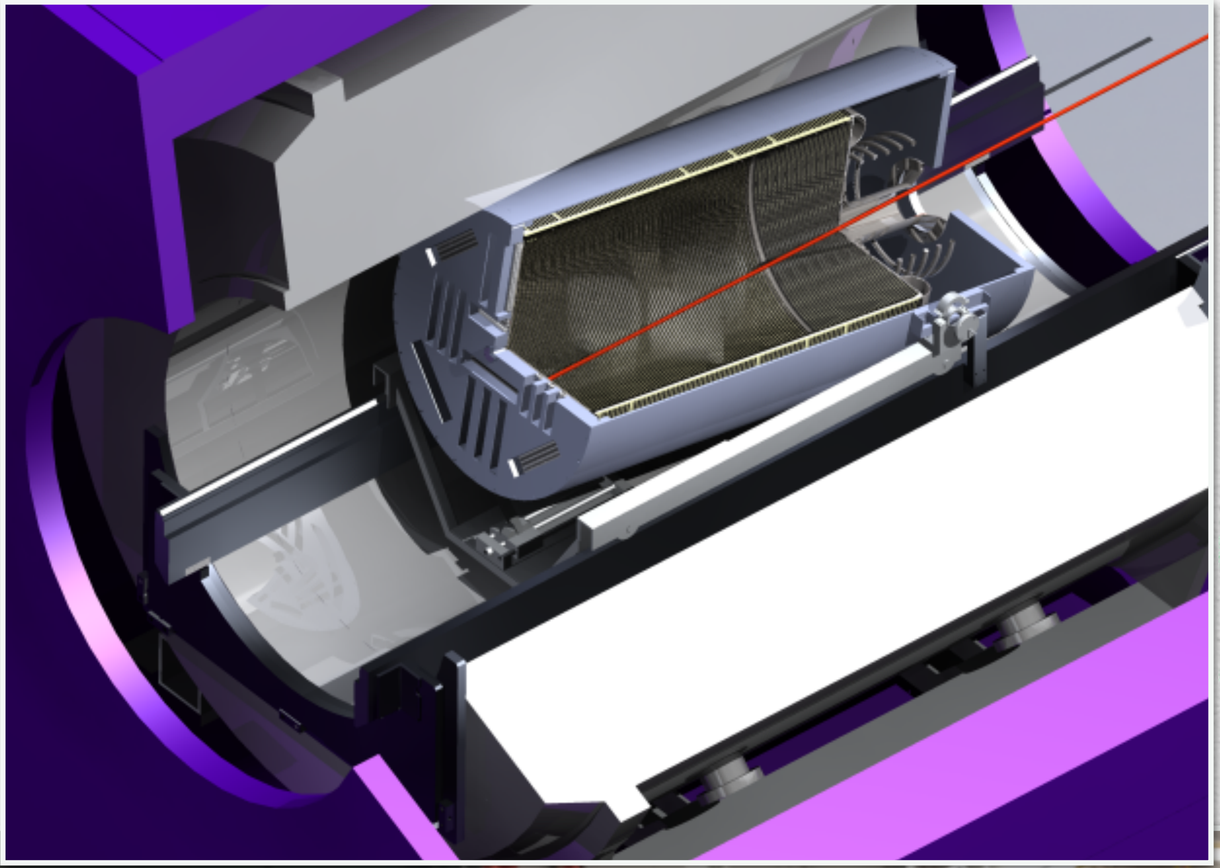
Active Target Time Projection Chamber (AT-TPC @ NSCL)

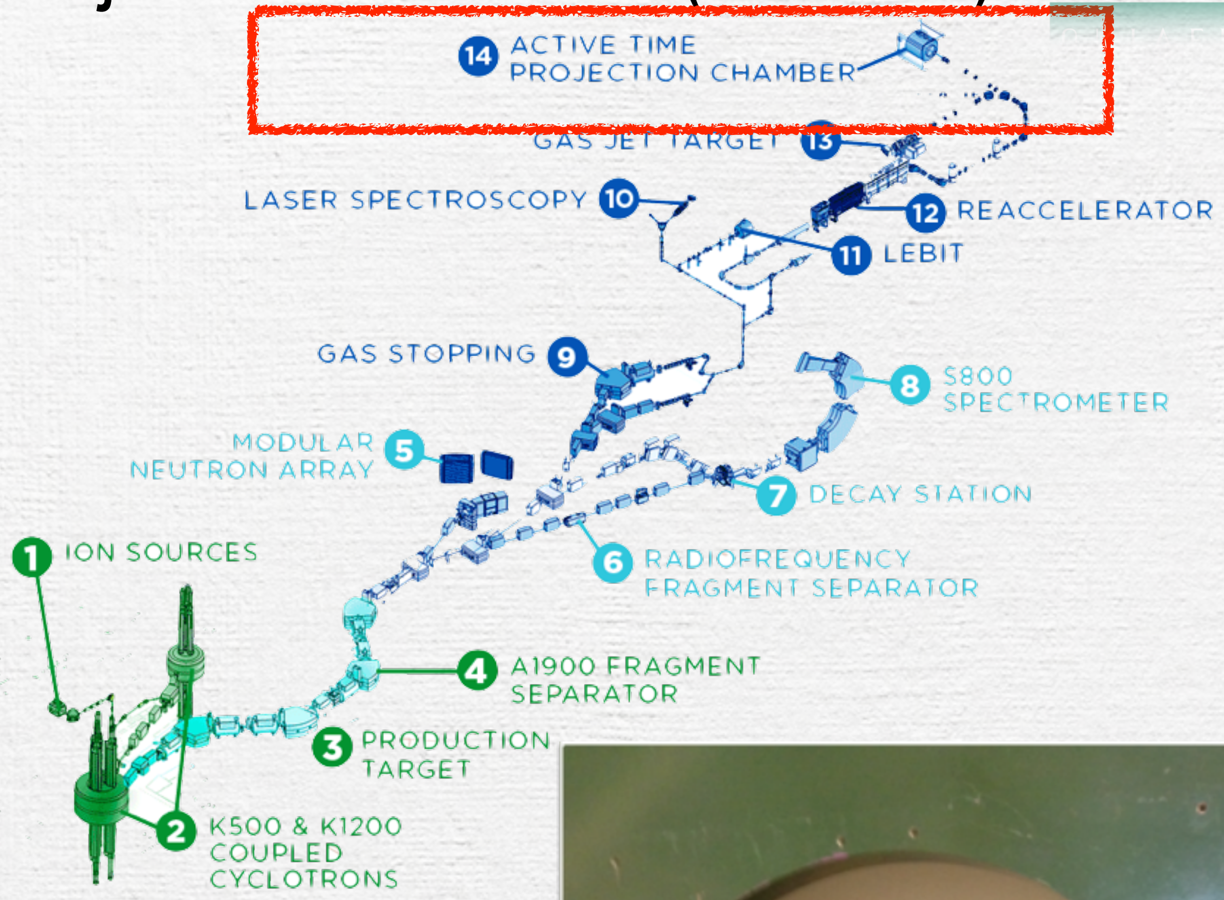


- Cylindrical-Radial type
- micromegas (+ Thick GEM) read-out
- prototype ATTPC/ ATTPC - 256/10.240 channels
- 50 cm x 12.5 cm/100 cm x 25 cm
- GET electronics (General Electronics for TPCs*)

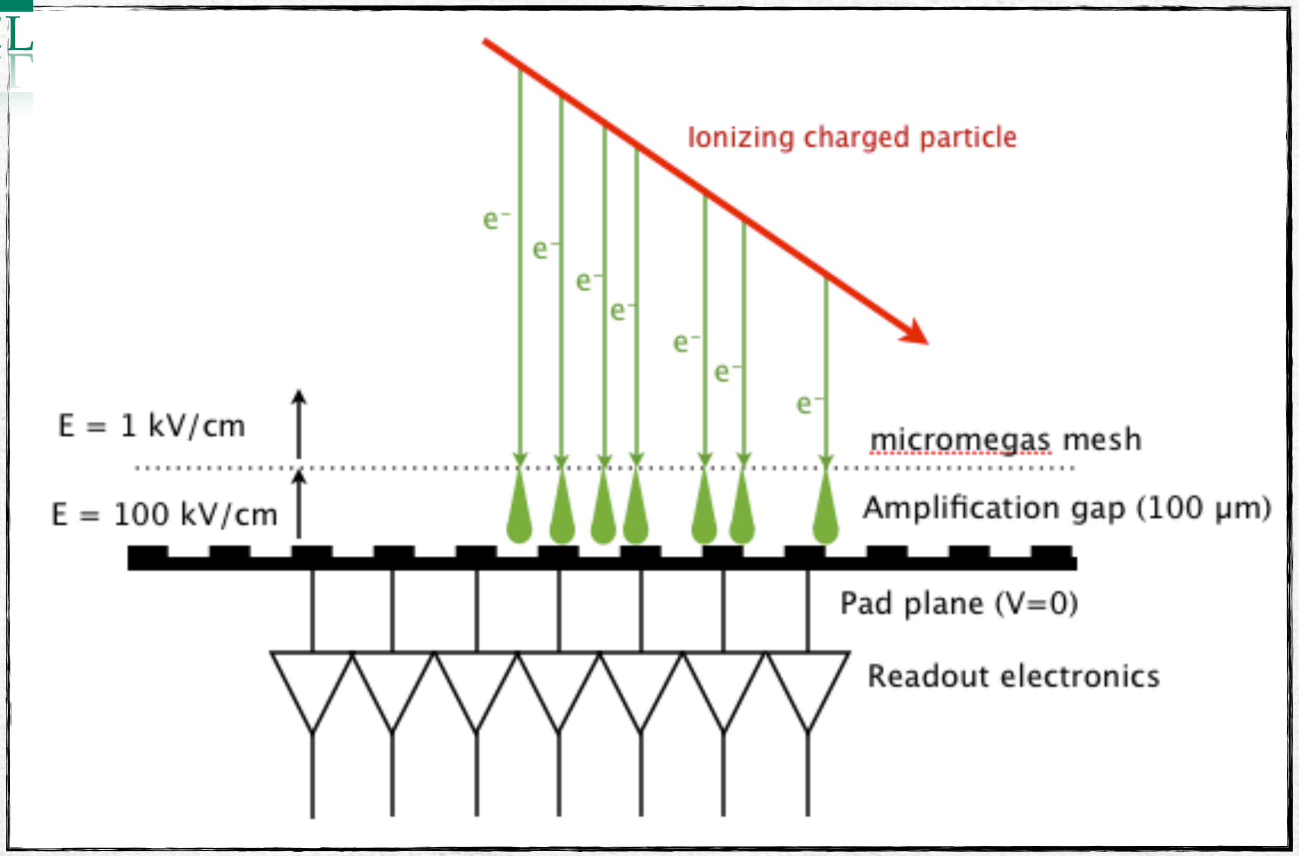
* S. Anvar et al., IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC) (IEEE, 2011) pp.745–749.

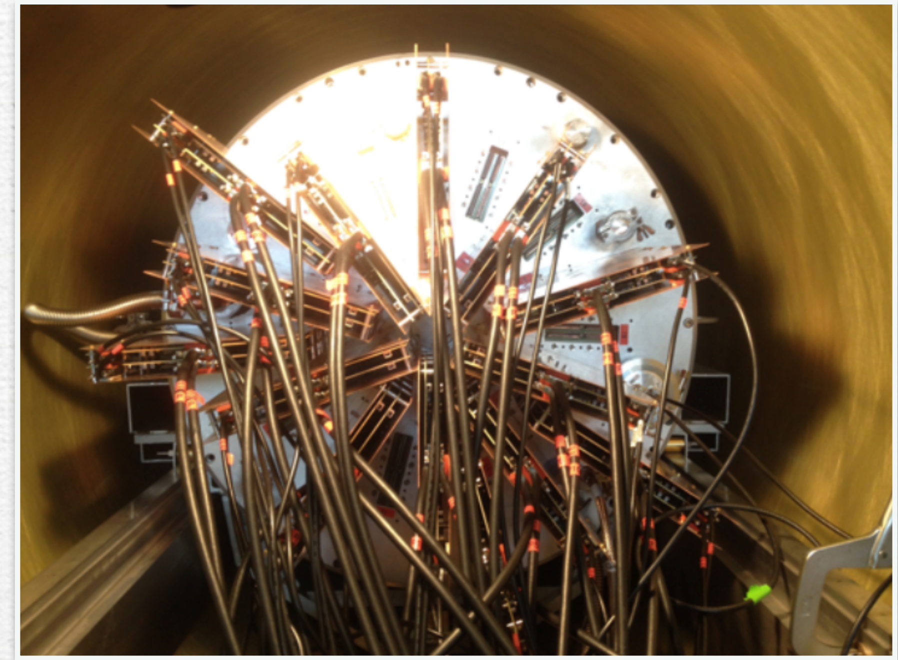
Active Target Time Projection Chamber (AT-TPC)

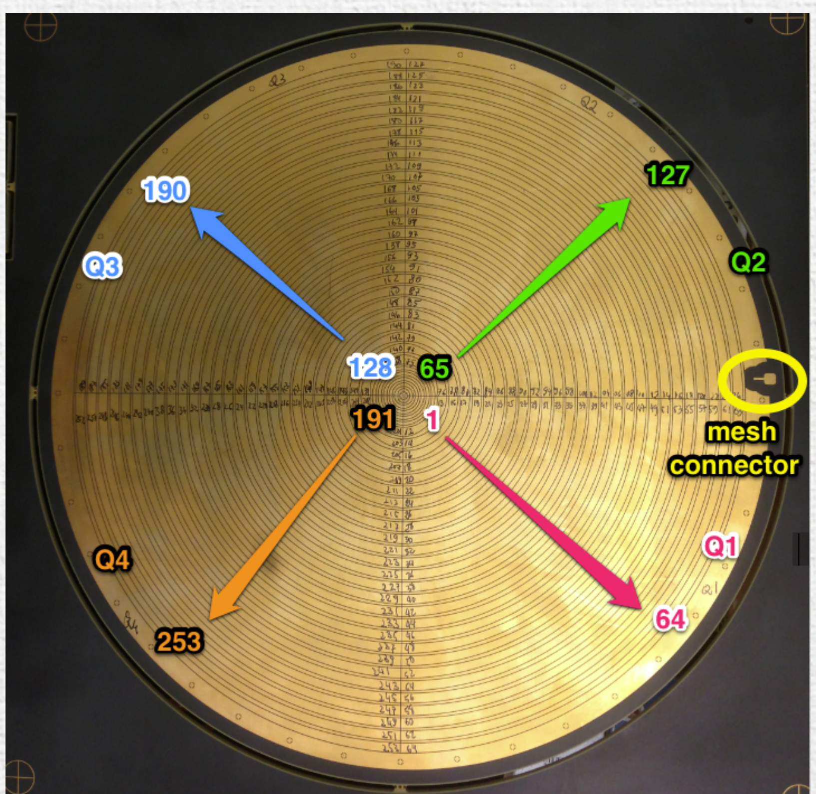




AT-TPC: Read-out and electronics







Micromegas electron amplifier

25/55 cm diameter

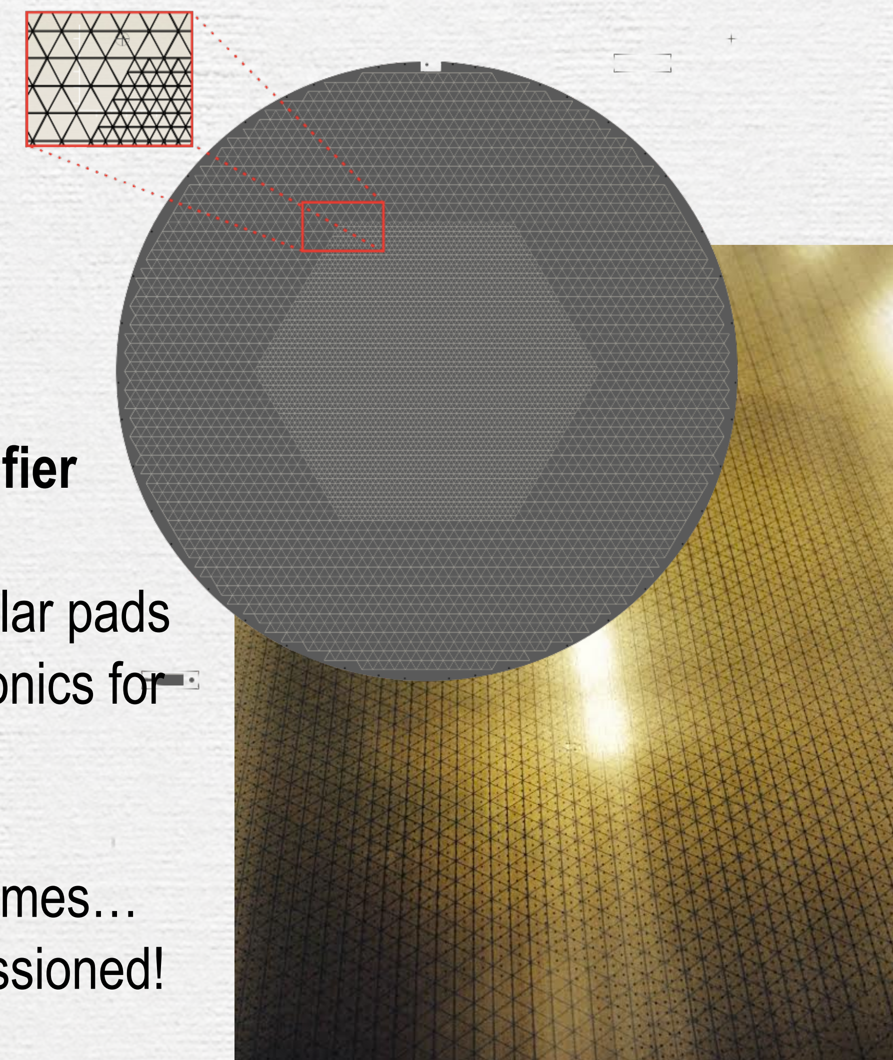
253 backgammon/10.240 triangular pads

GET electronics (General Electronics for TPCs)

Programmable trigger

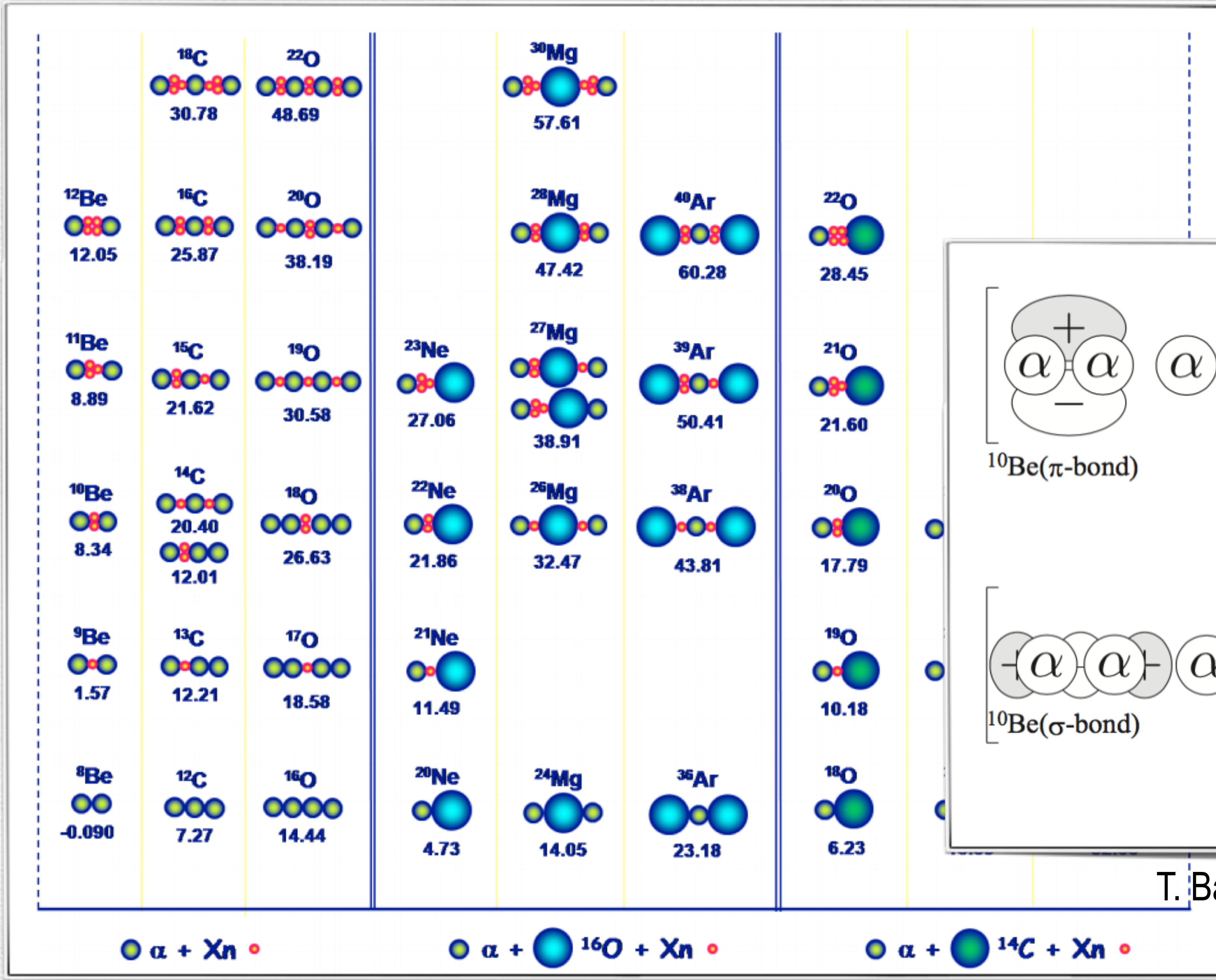
Individual thresholds, shaping times…

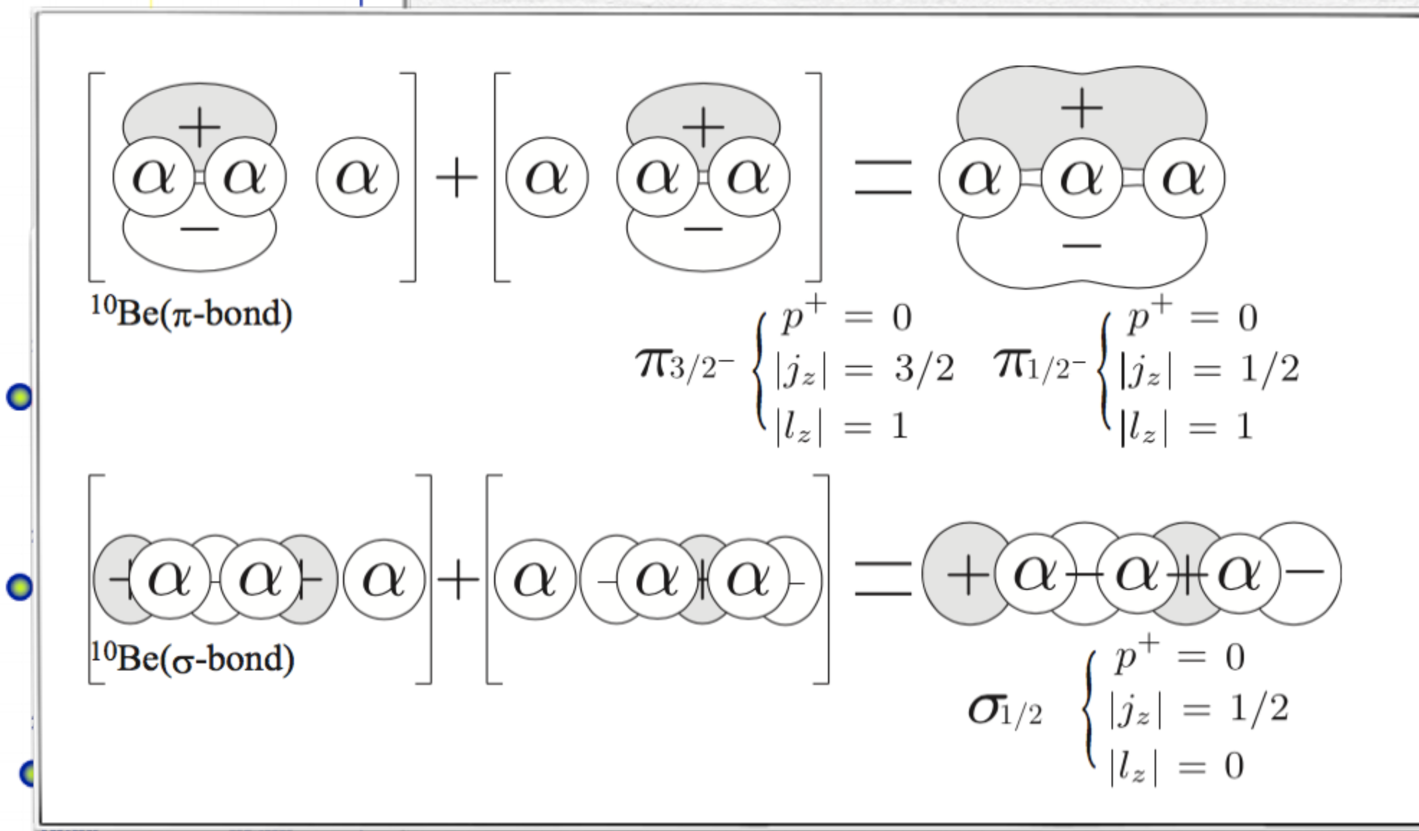
All channels successfully commissioned!



pAT-TPC: Cluster linear chain in ^{14}C

A classic: Ikeda diagram

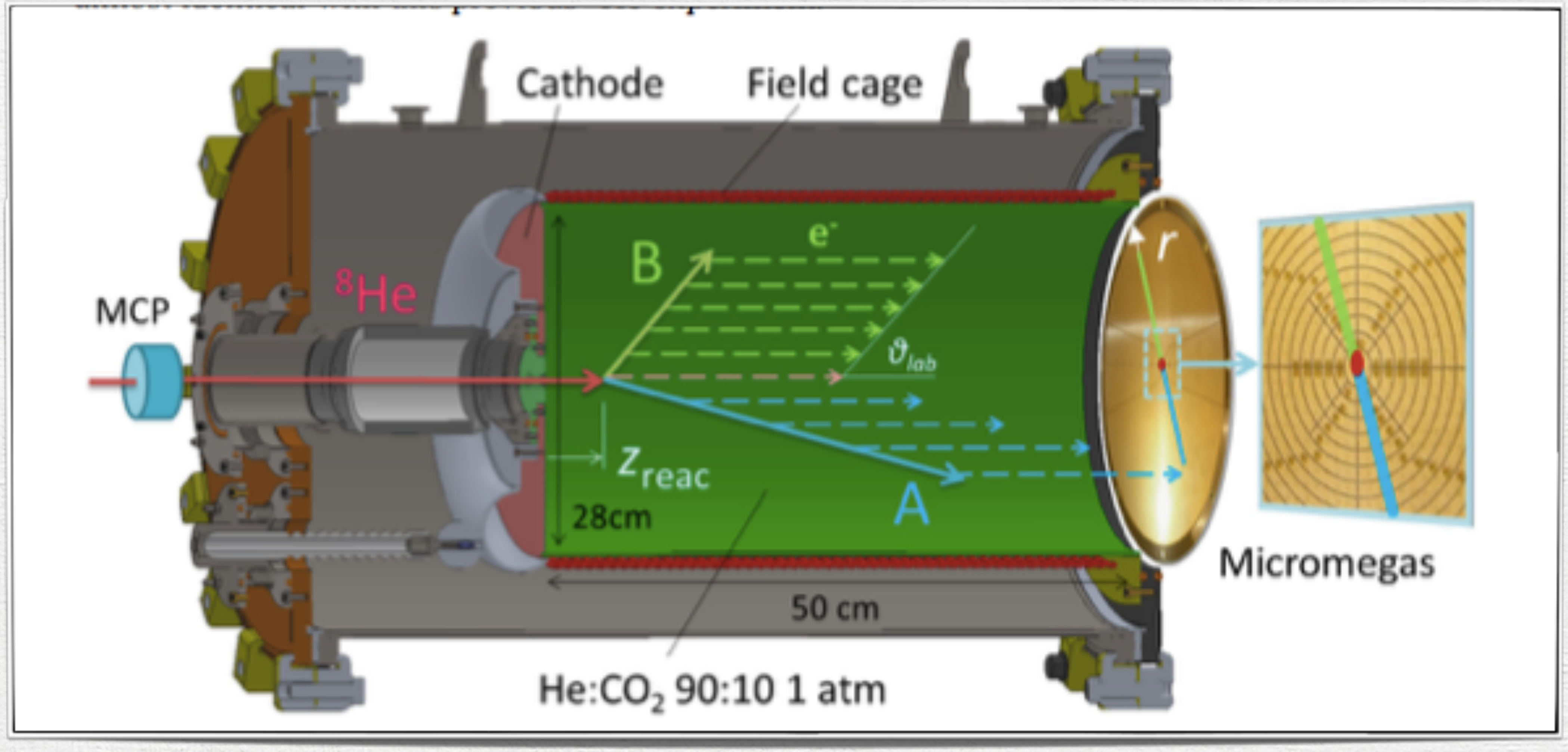




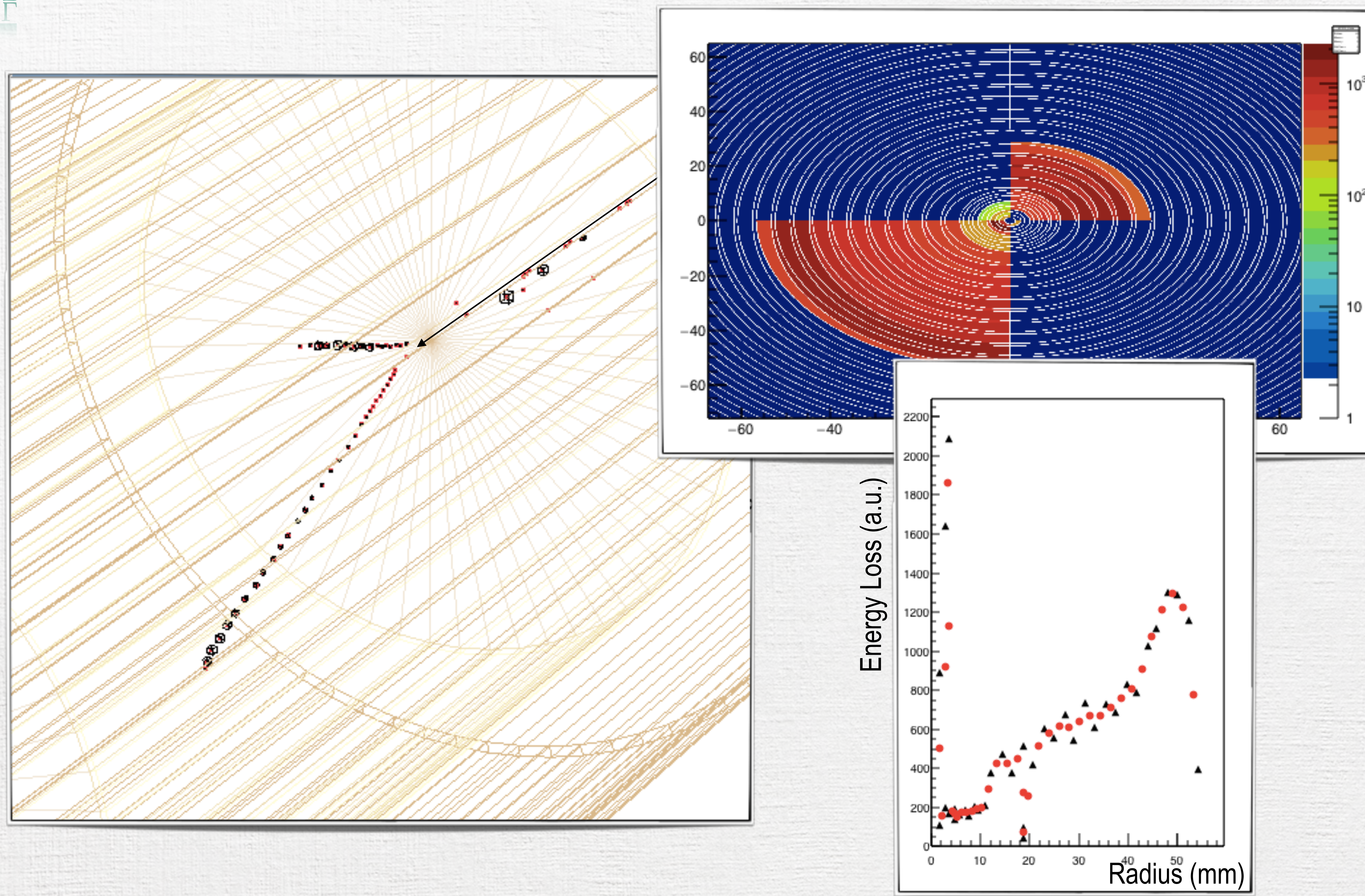
T. Baba and M. Kimura arXiv: 1605.05567v1 (May 2016)

pAT-TPC: Principle of operation

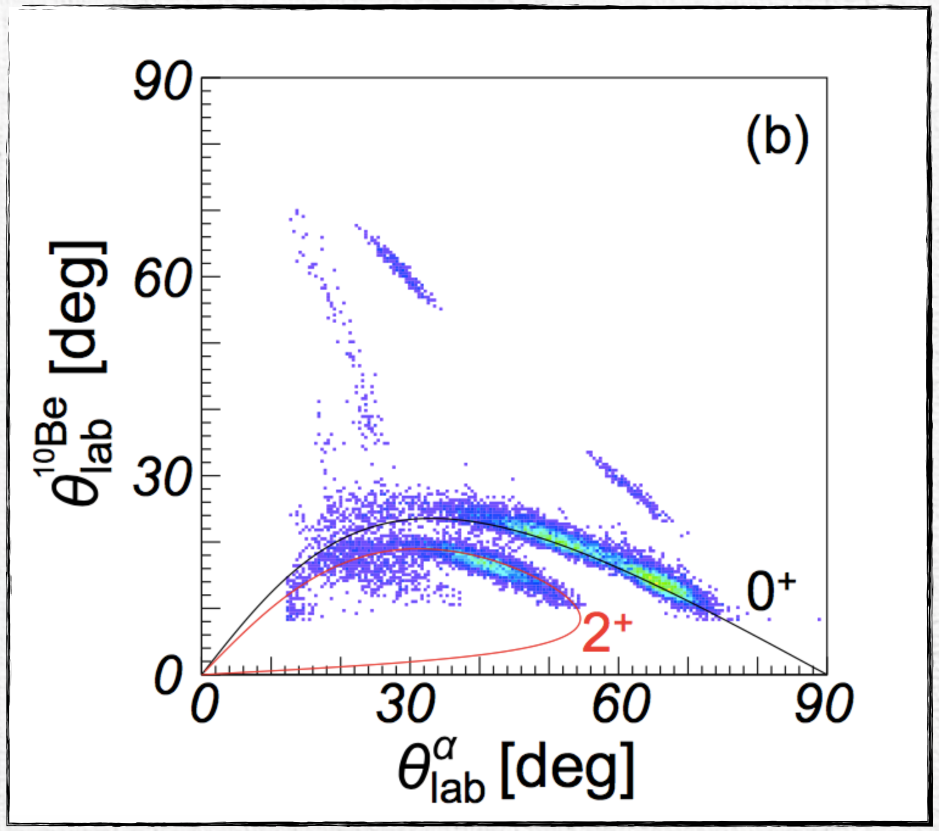
Alpha-resonant scattering on ^{10}Be



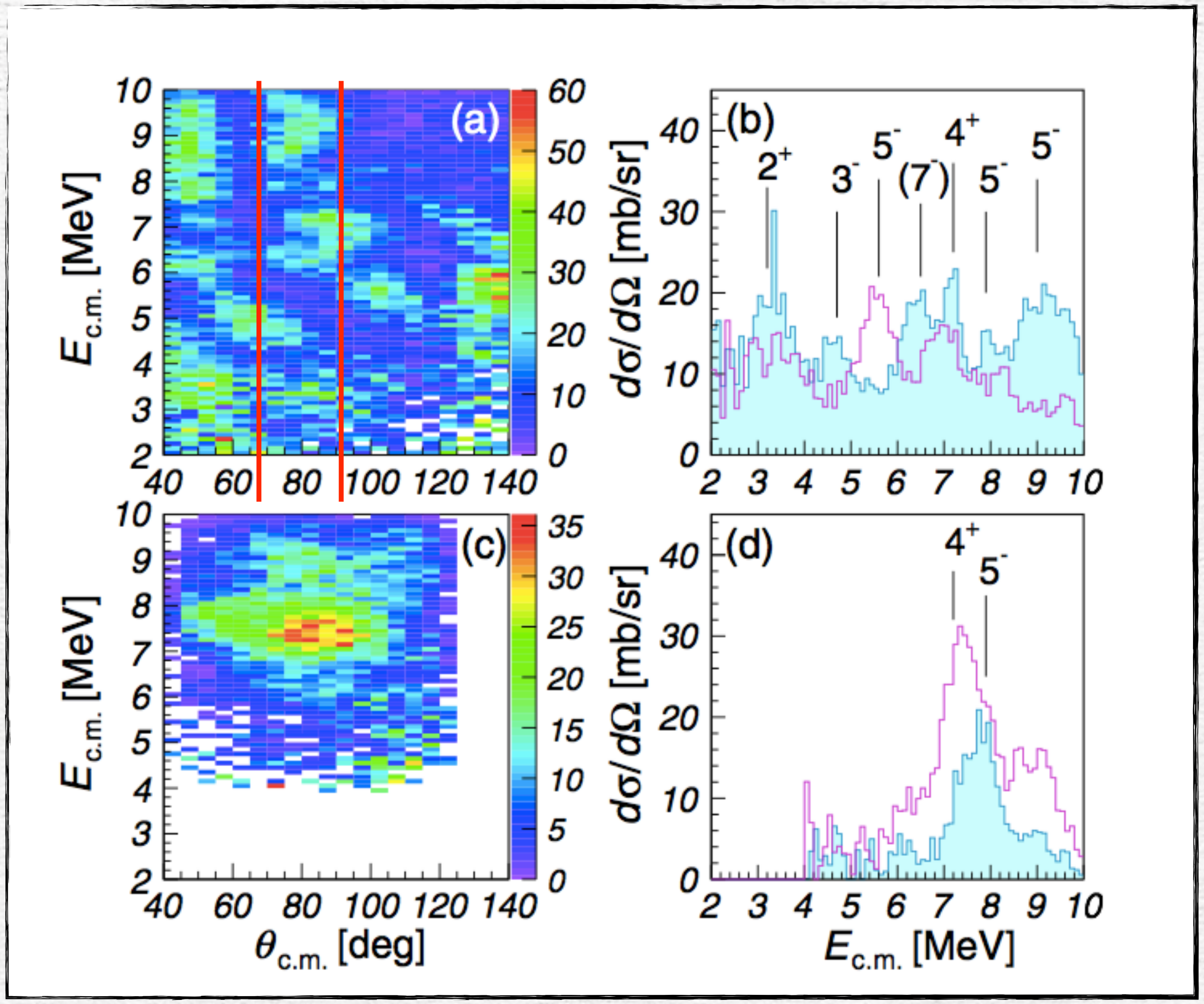
pAT-TPC: Hit pattern reconstruction



pAT-TPC: Cluster linear chain in ^{14}C



A. Fritsch et al., Phys. Rev. C 93, 014321 (2016)



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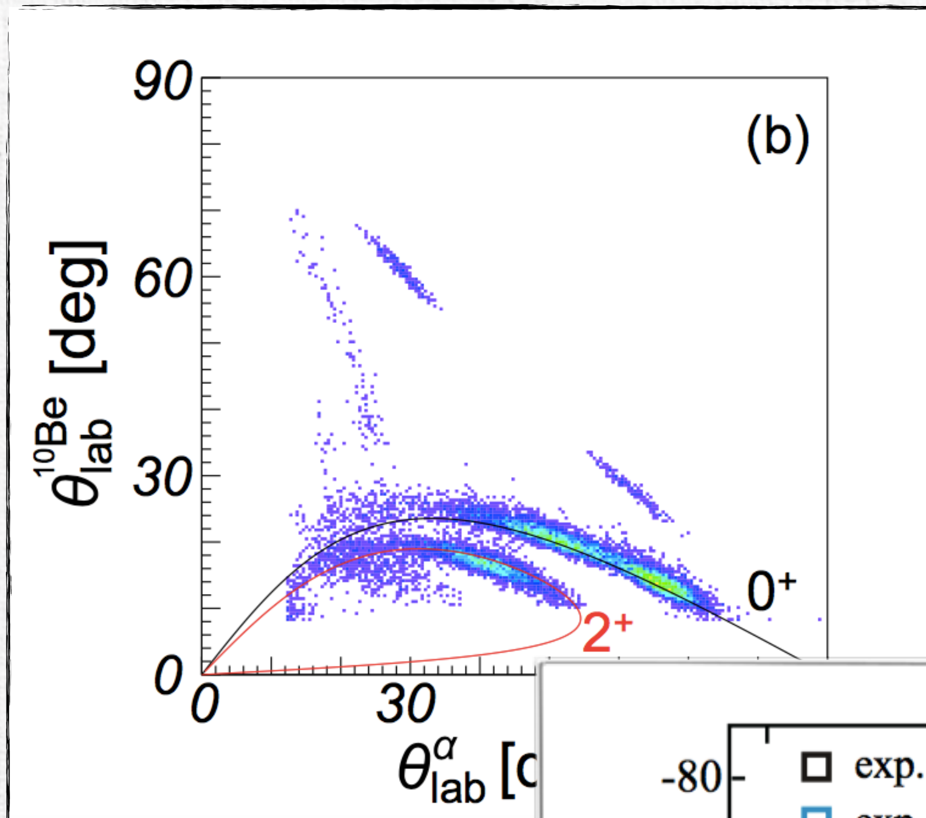
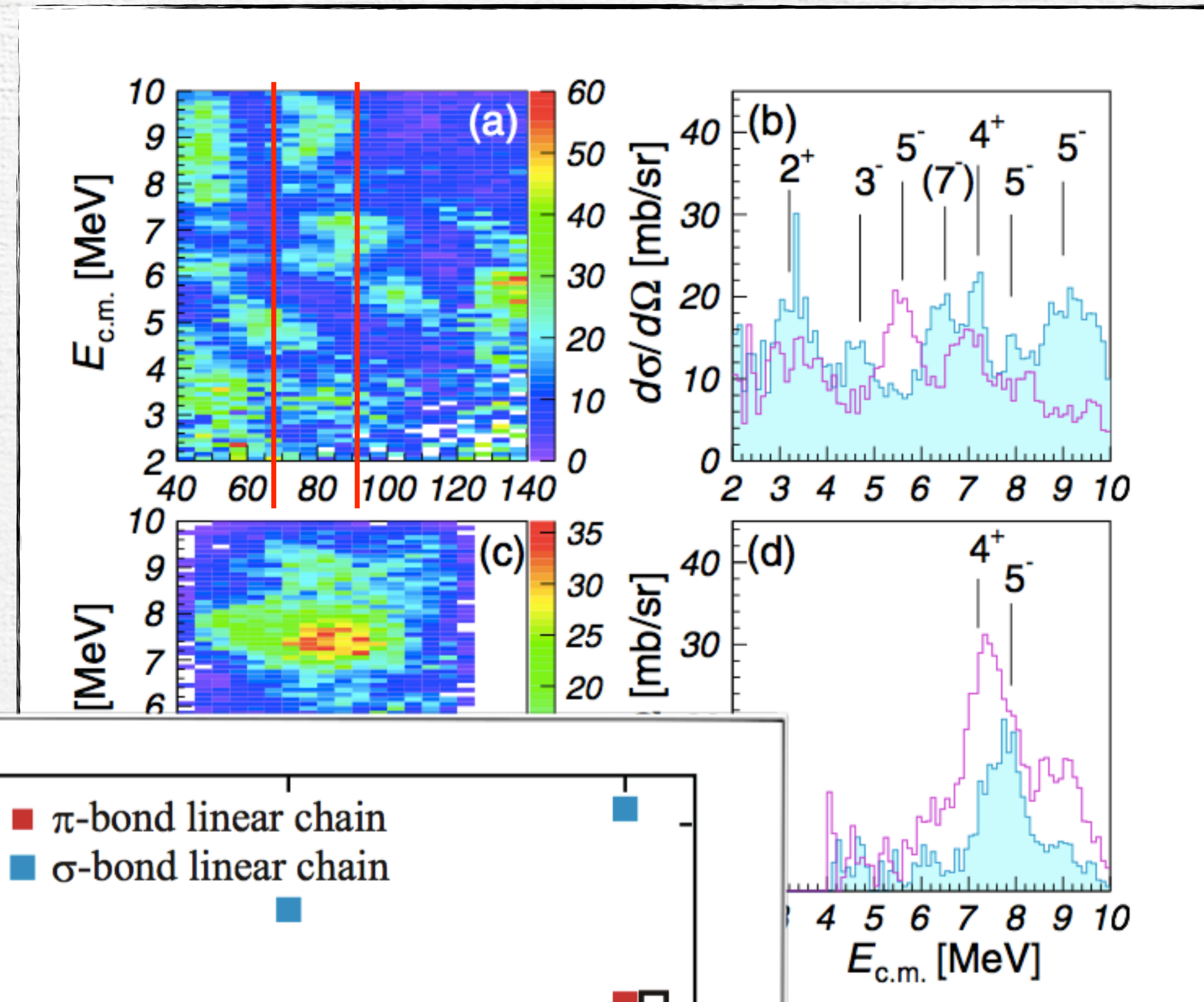
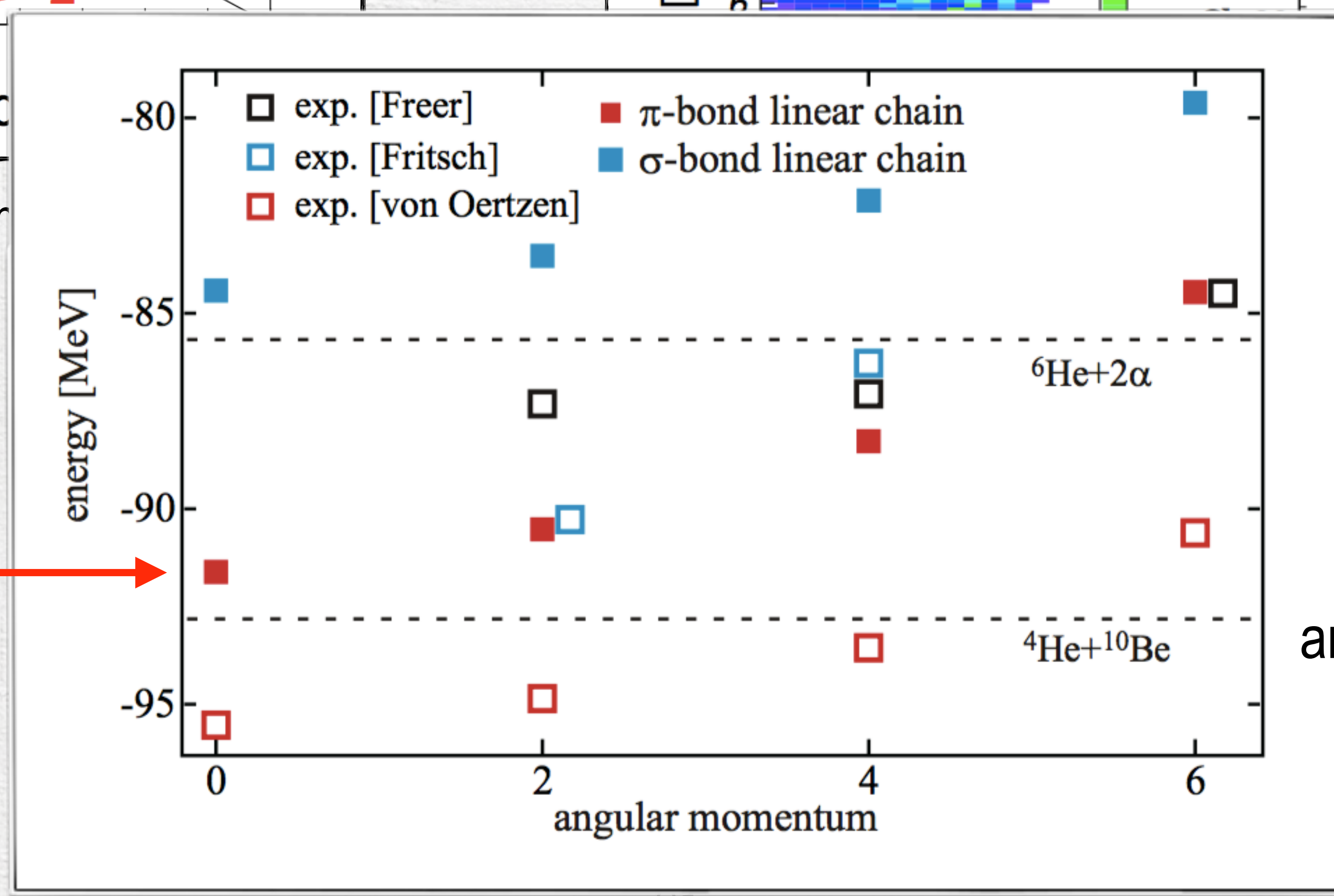


A. Fritsch et al., Ph

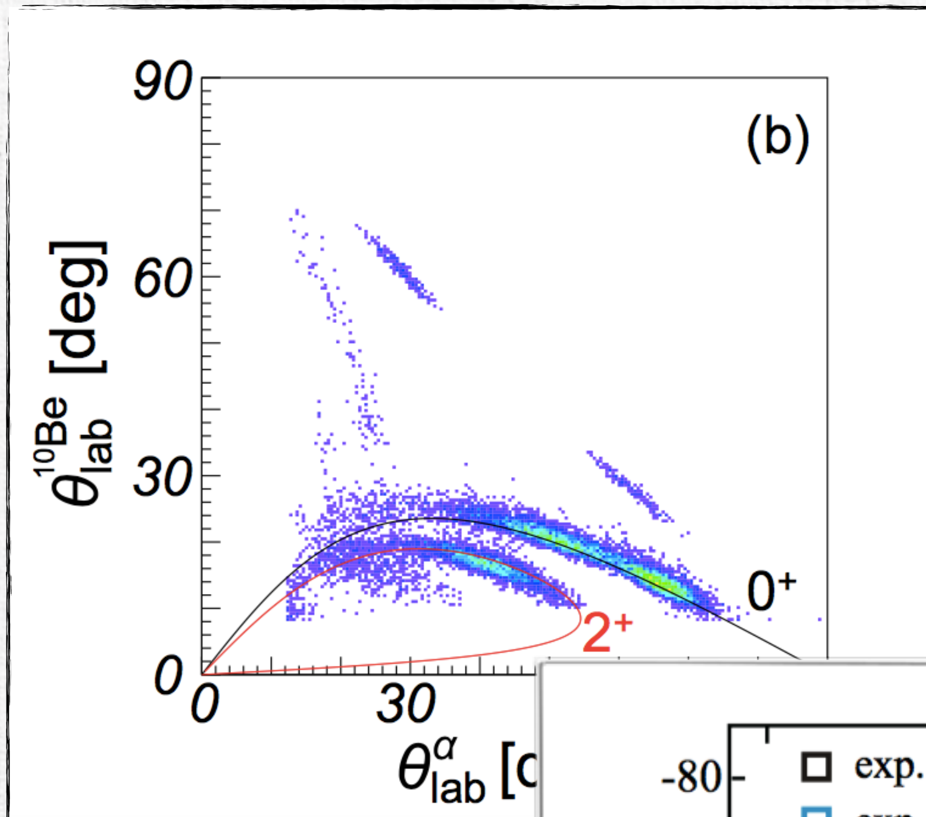




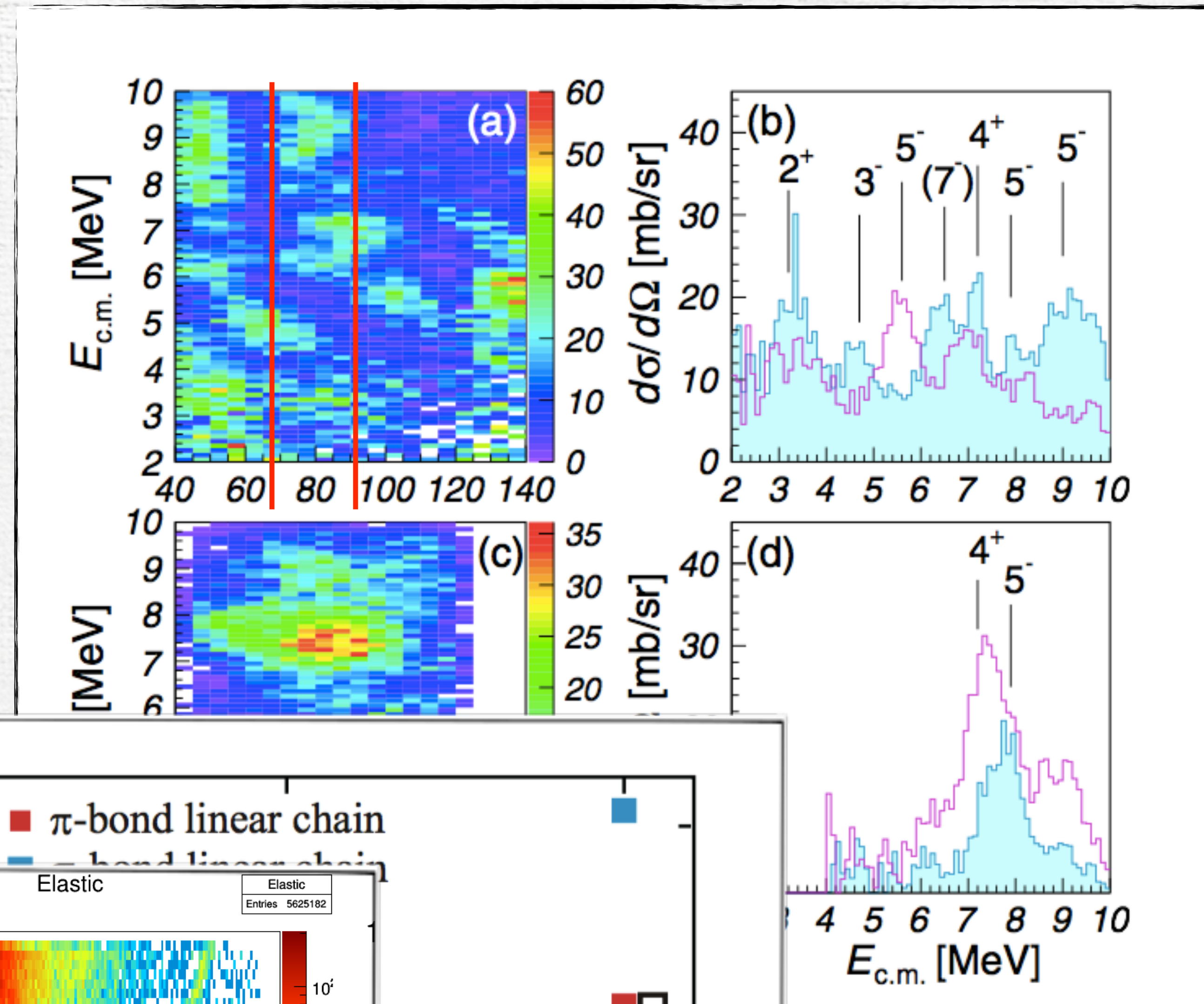
Search for 0+ →

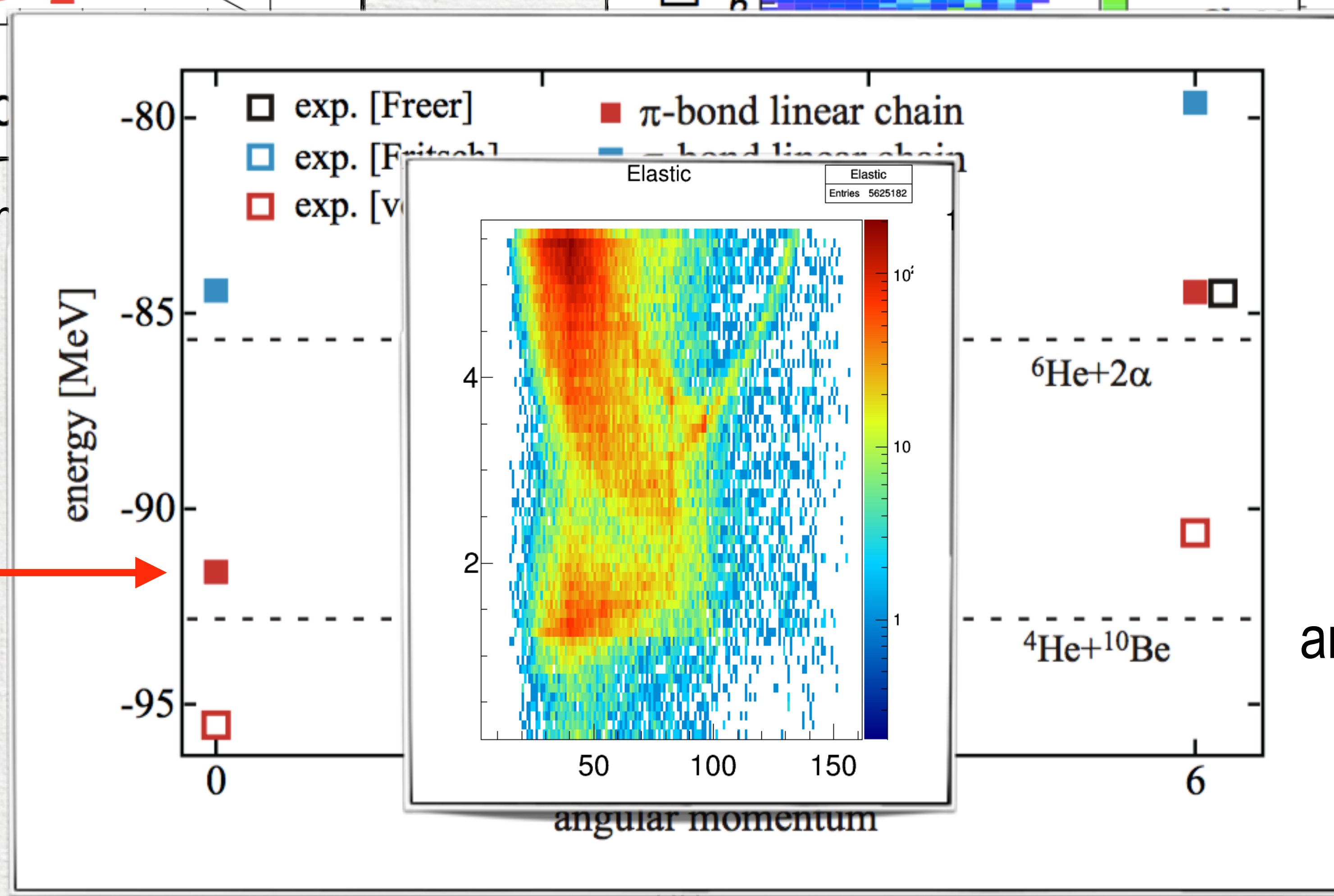
T. Baba and M. Kimura arXiv: 1605.05567v1 (May
2016)

pAT-TPC: Cluster linear chain in ^{14}C



A. Fritsch et al., Ph





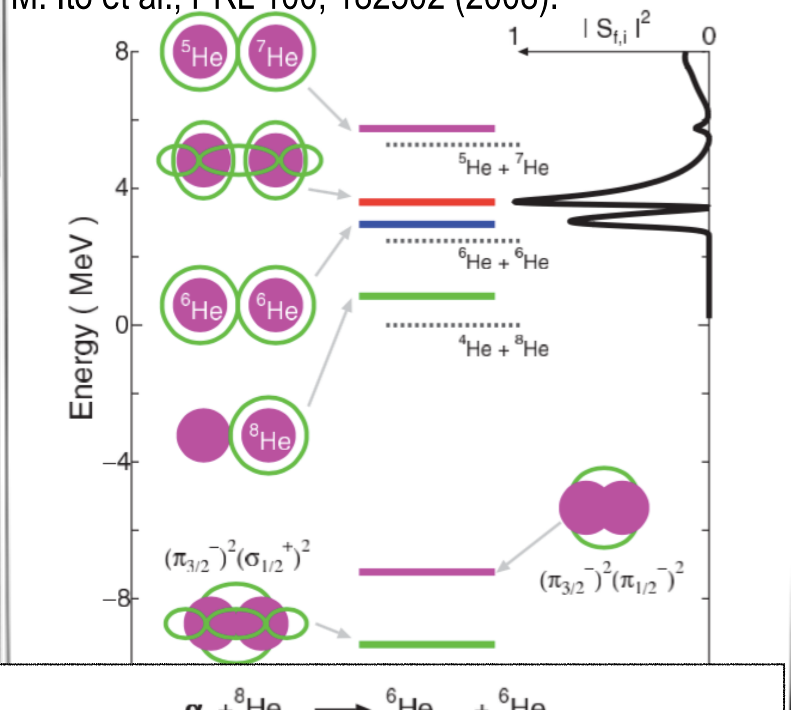
Search for 0+

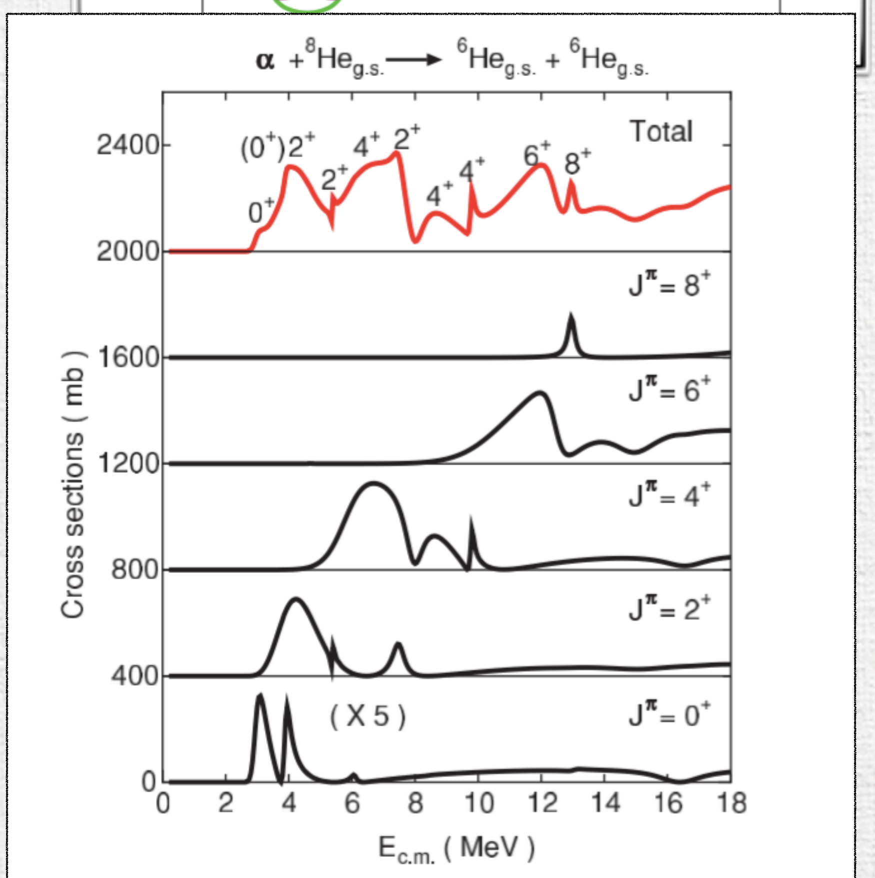
T. Baba and M. Kimura arXiv: 1605.05567v1 (May 2016)

pAT-TPC: ^{12}Be cluster states
^{8}He+^{4}He at 17 MeV @ TRIUMF (D. Suzuki)

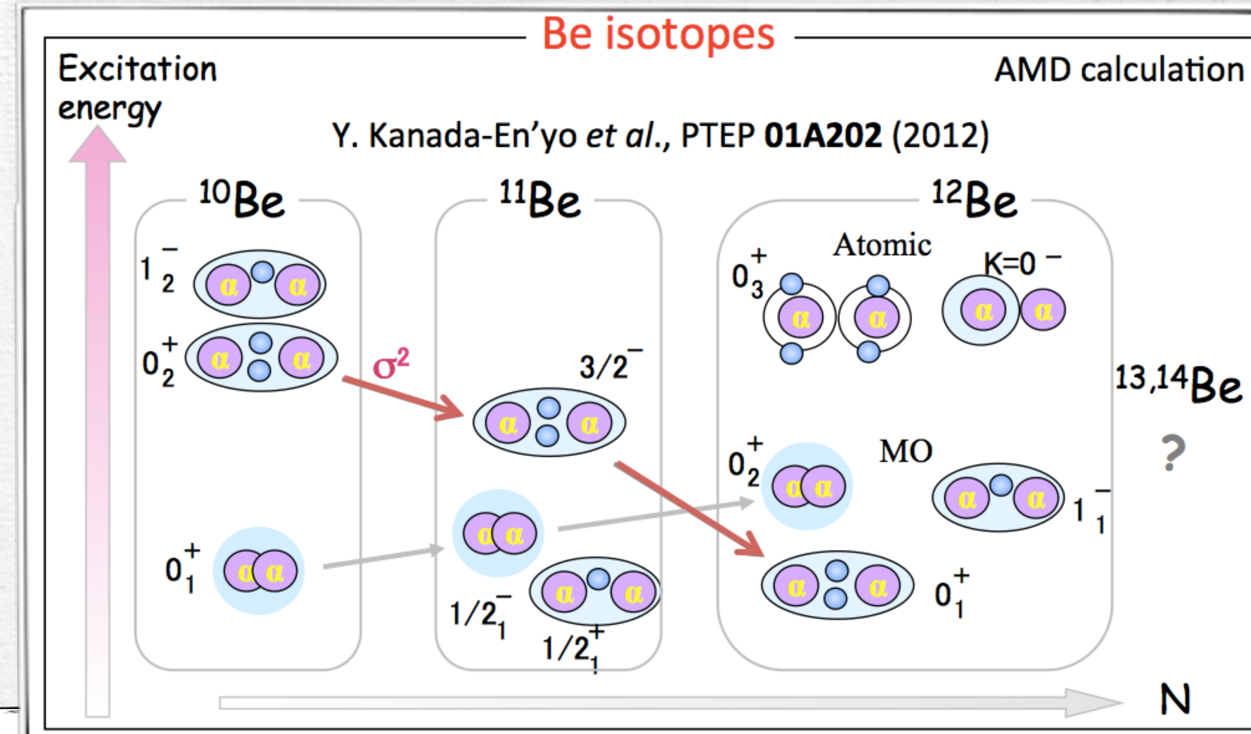
General two-center cluster approach

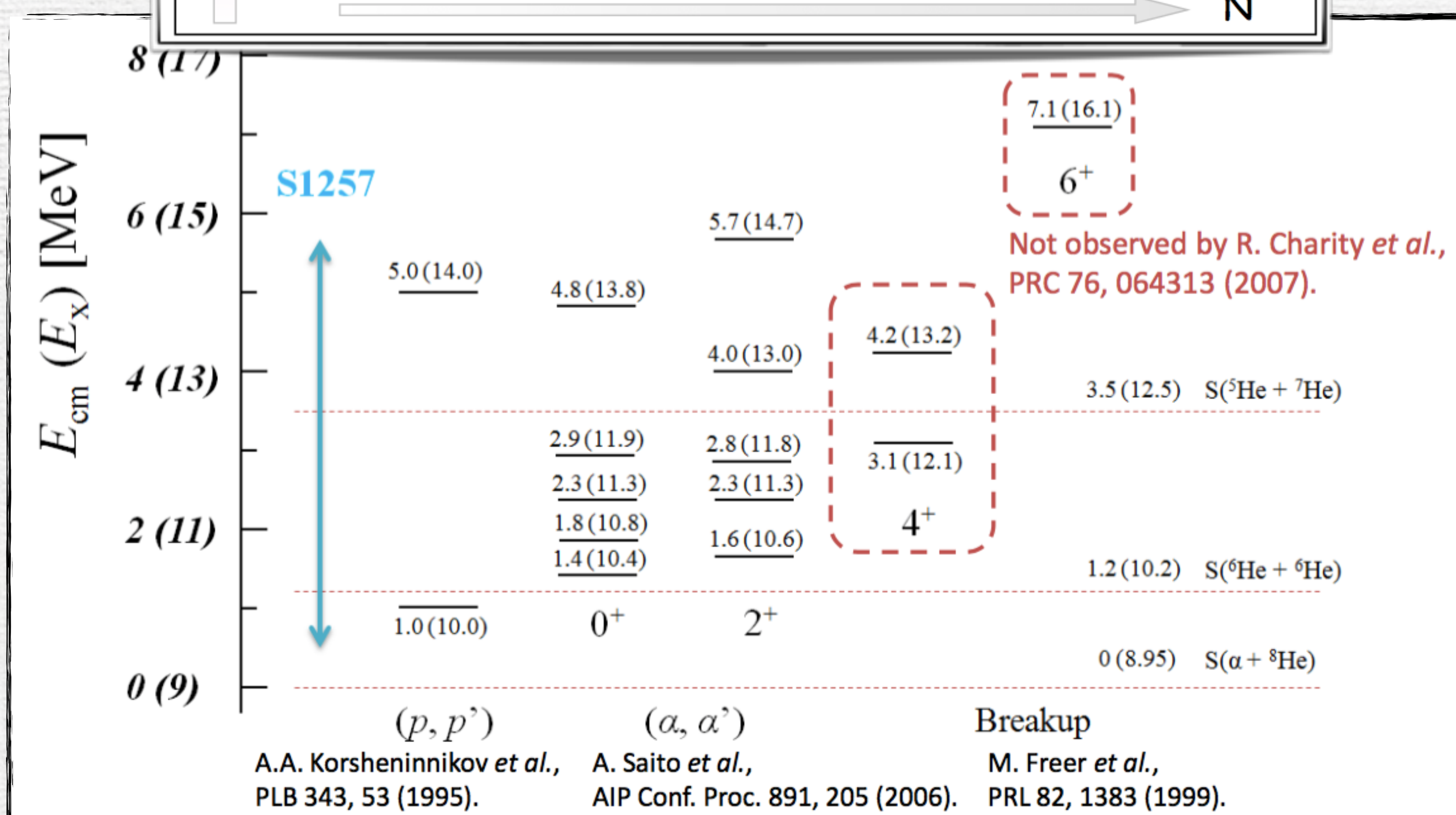
M. Ito et al., PRL 100, 182502 (2008).





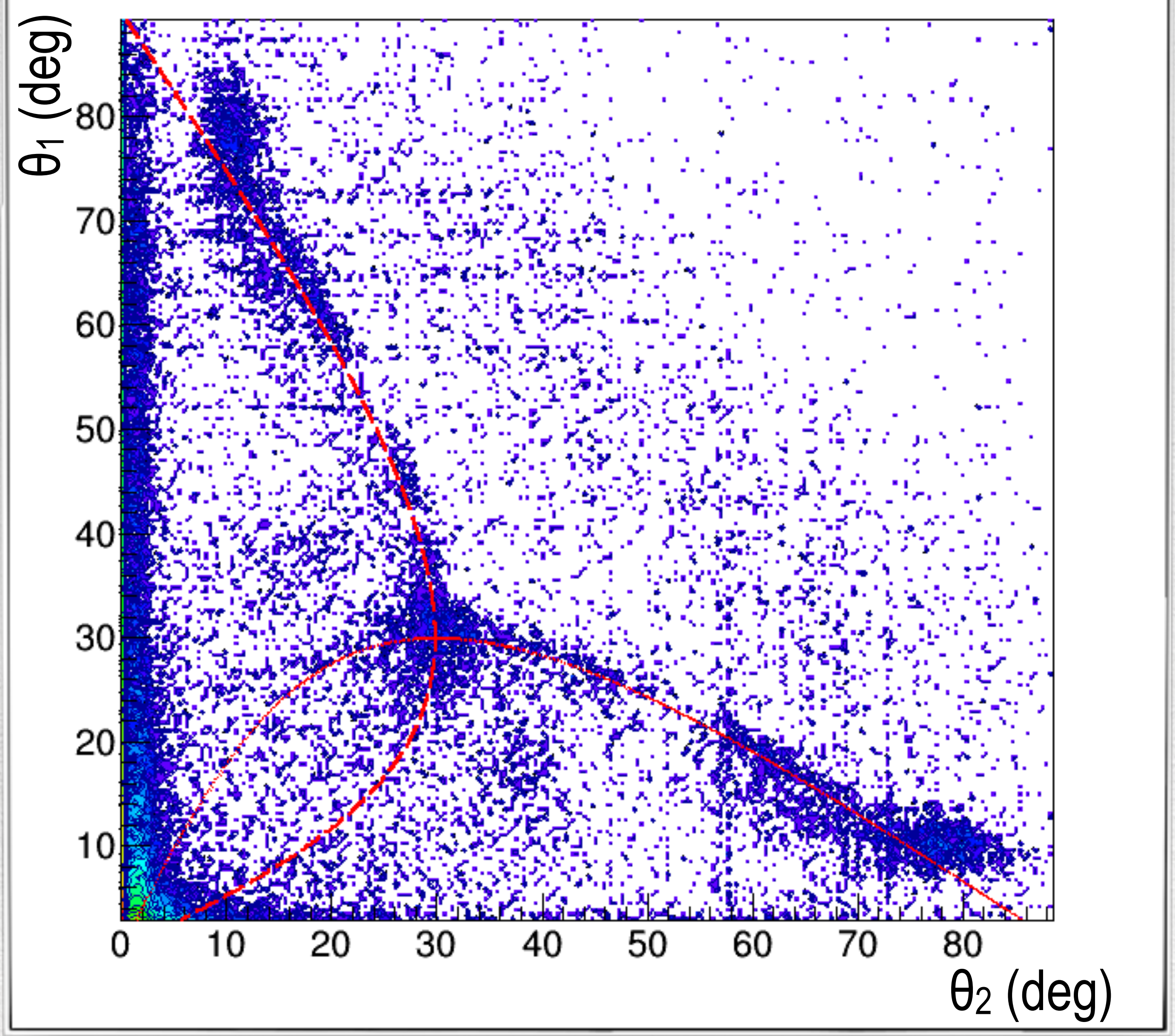
M. Ito and N. Itagaki, PRC 78, 011602(R) (2008).





Resonant α scattering to search states with large Γ_α

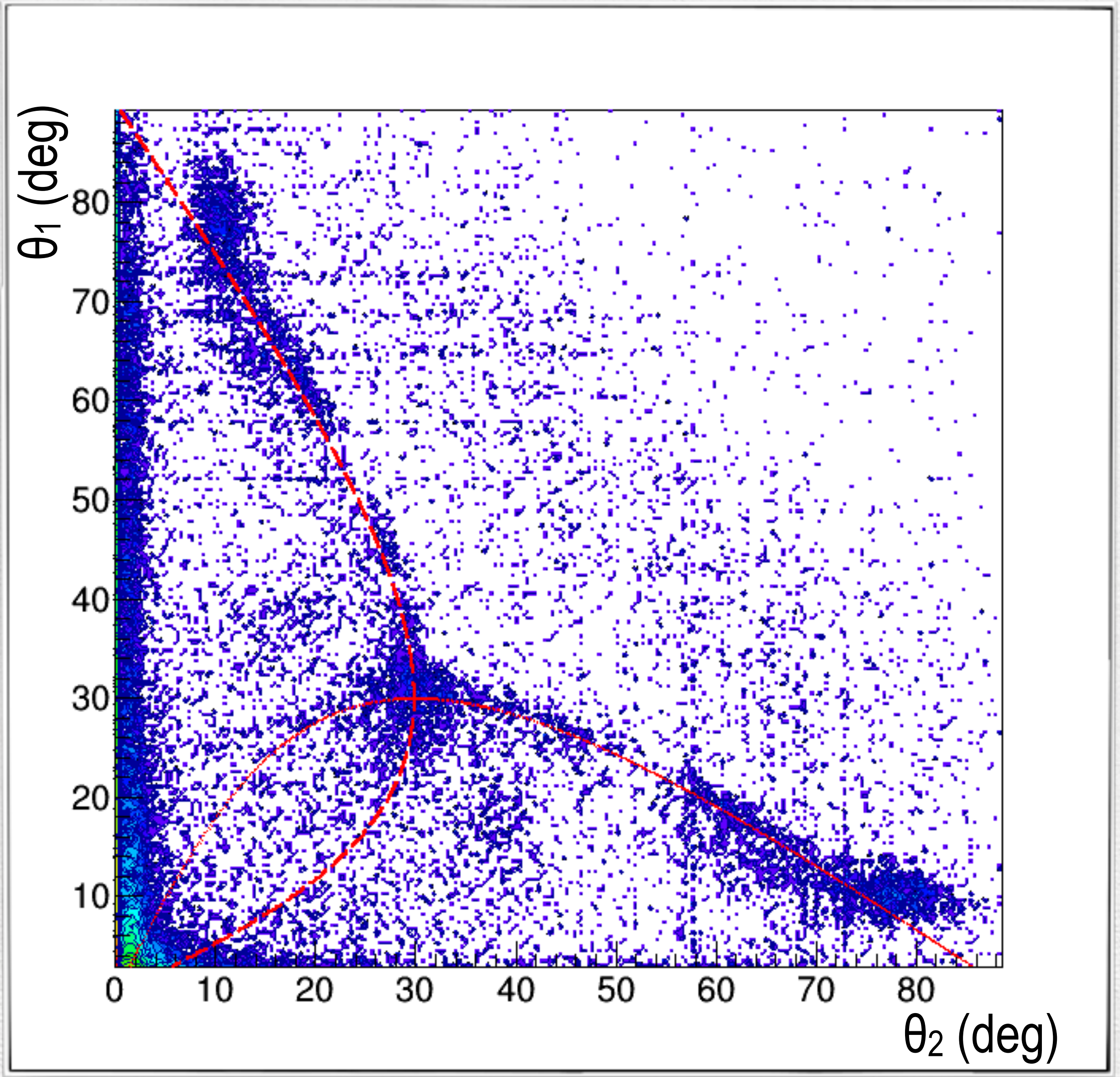
Pattern recognition algorithm for tracking

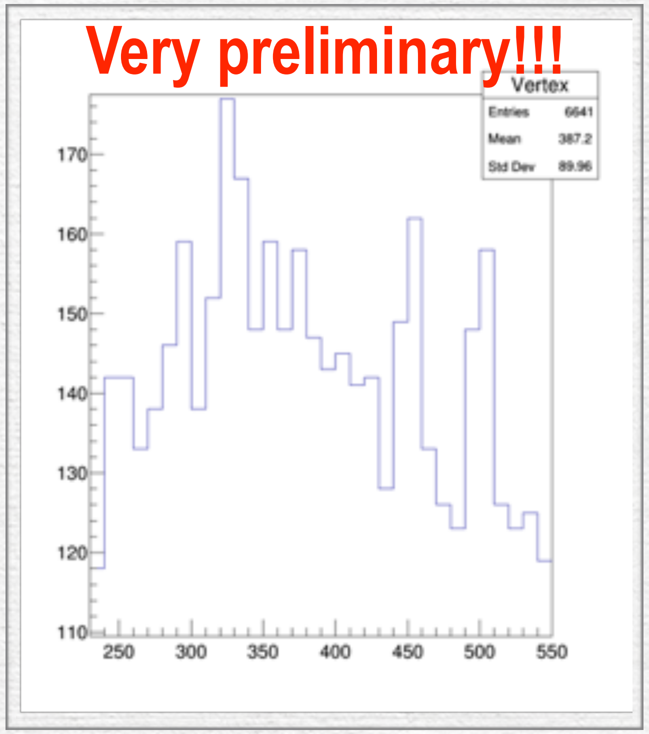


- Linear Hough space allow us to infer kinematical variables online.
- Trigger validation.
- To improve the resolution, a linear fit is needed.
- The energy of the recoil particles is extracted from the range.
- Analysis in progress, very promising!

pAT-TPC: Kinematics

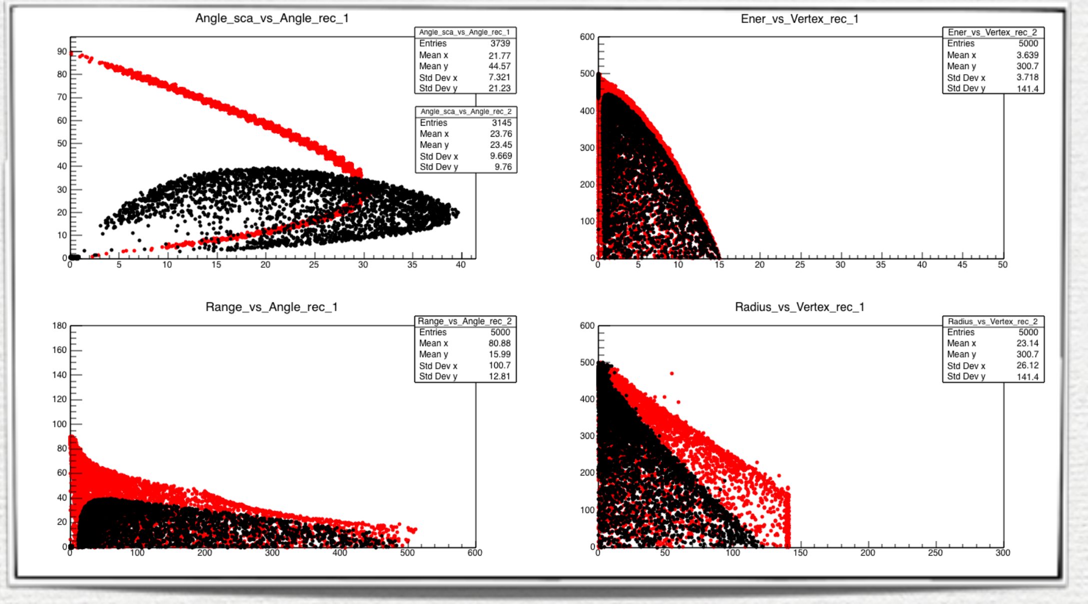
Statistics of one single run (1 hour)



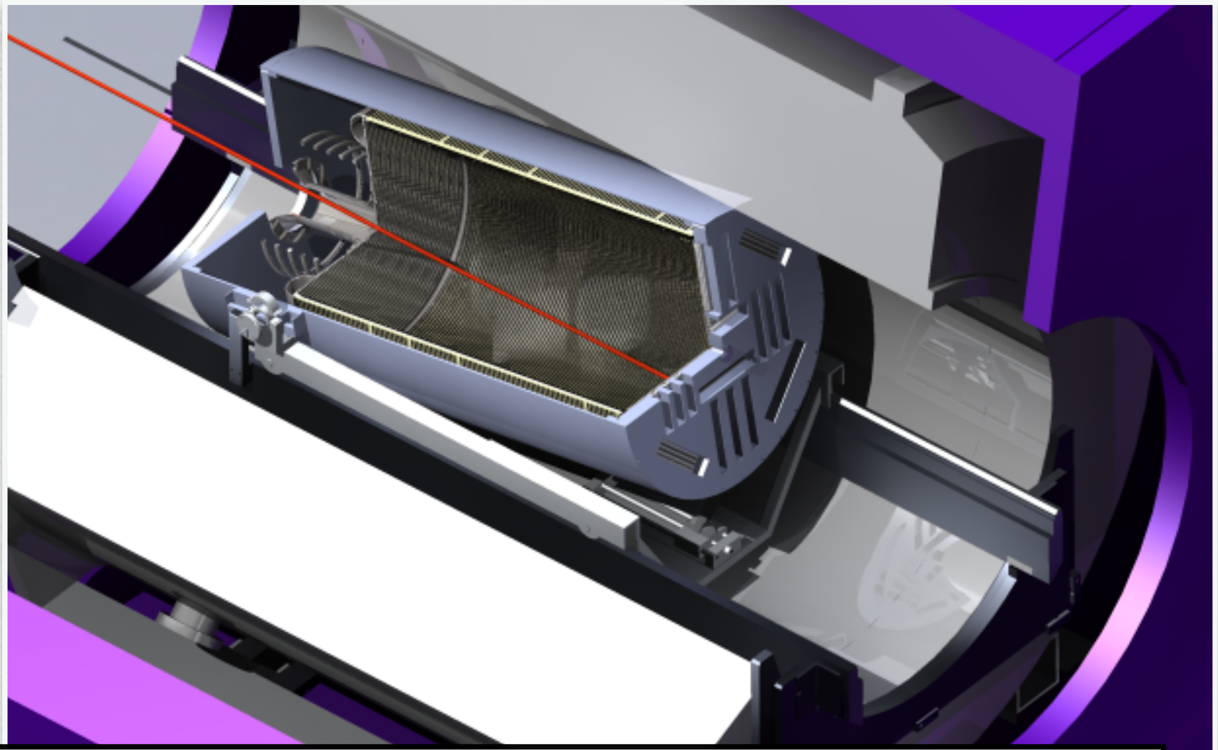


Elastic reaction : $^8He + ^4He \rightarrow ^8He + ^4He$

Transfer reaction: $^8He + ^4He \rightarrow ^6He + ^6He$

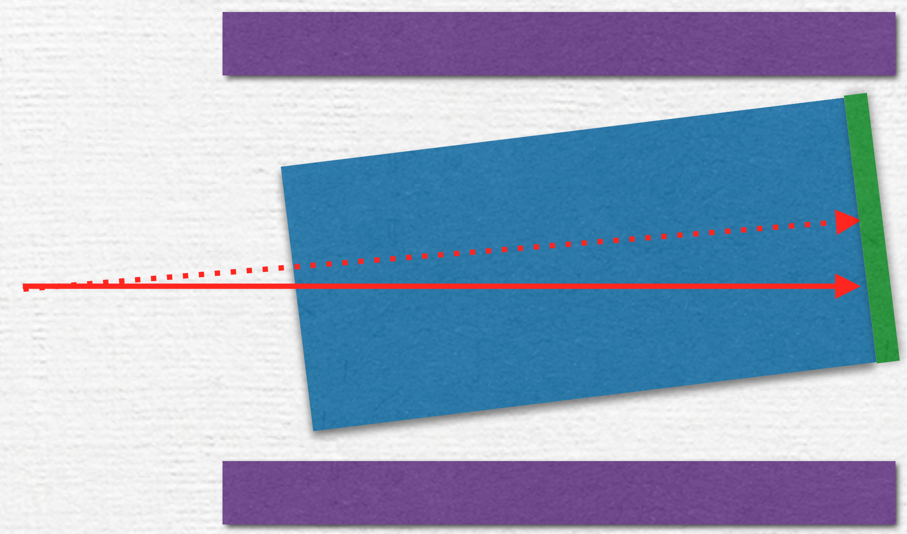


AT-TPC: Data analysis

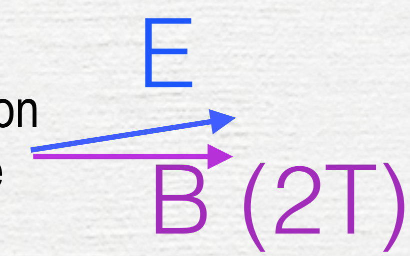


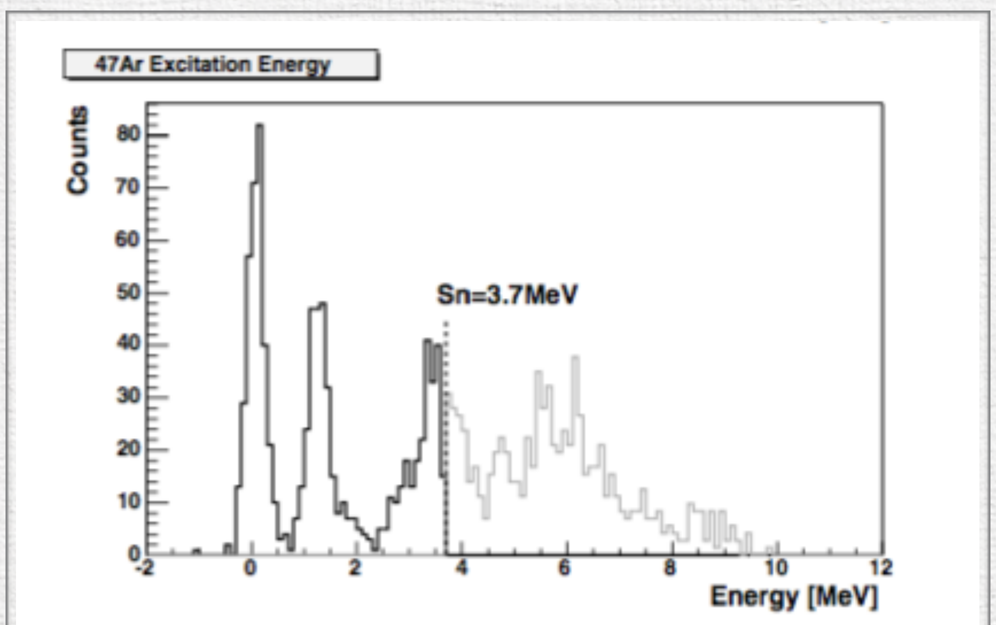
Resonant scattering of ^{46}Ar (4.5A MeV) on p (isobutane)
First ReA3 experiment with a radioactive beam (September 2015)

Detector tilted 7 degrees



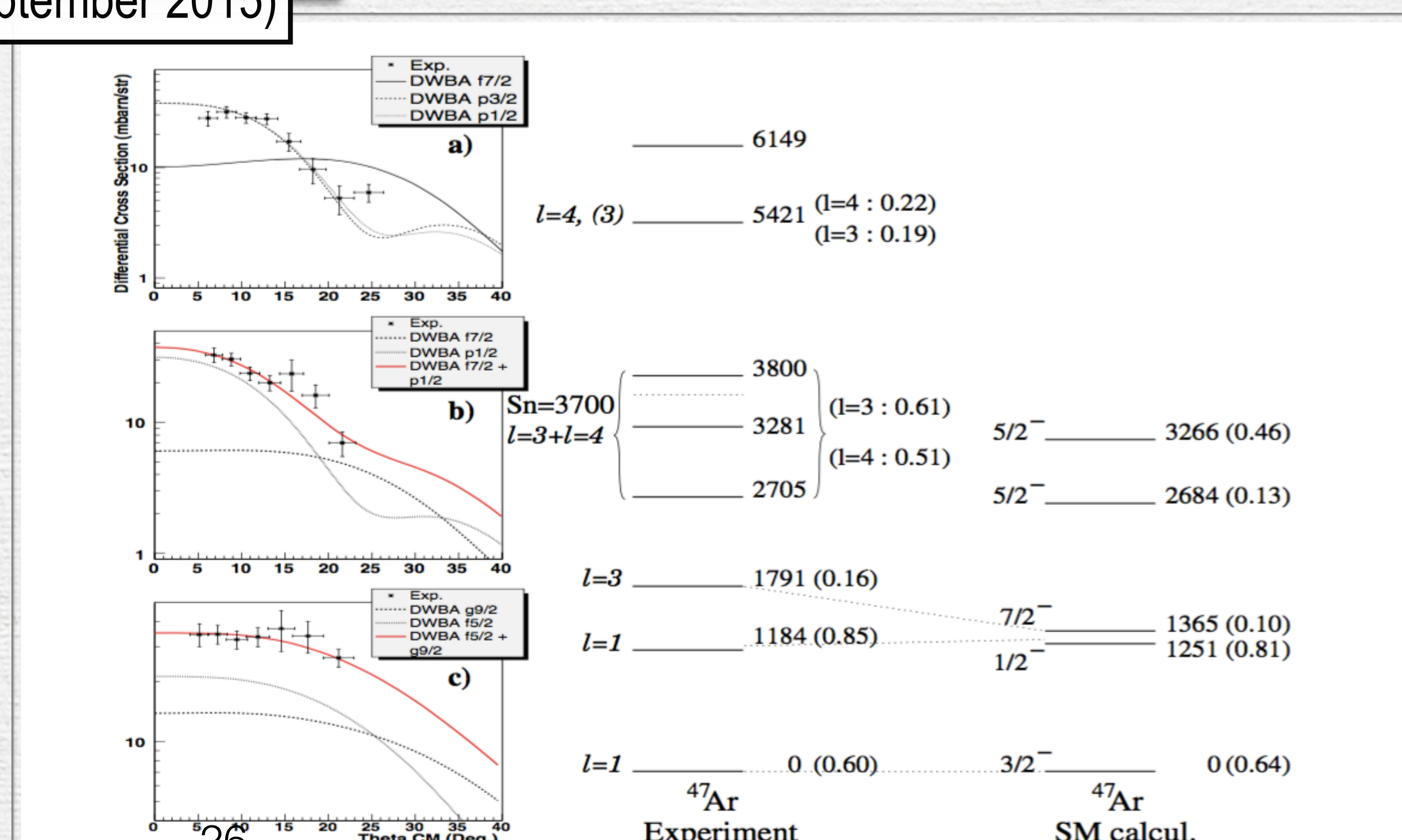
Lorentz angle: Apparent position of the beam in the pad plane



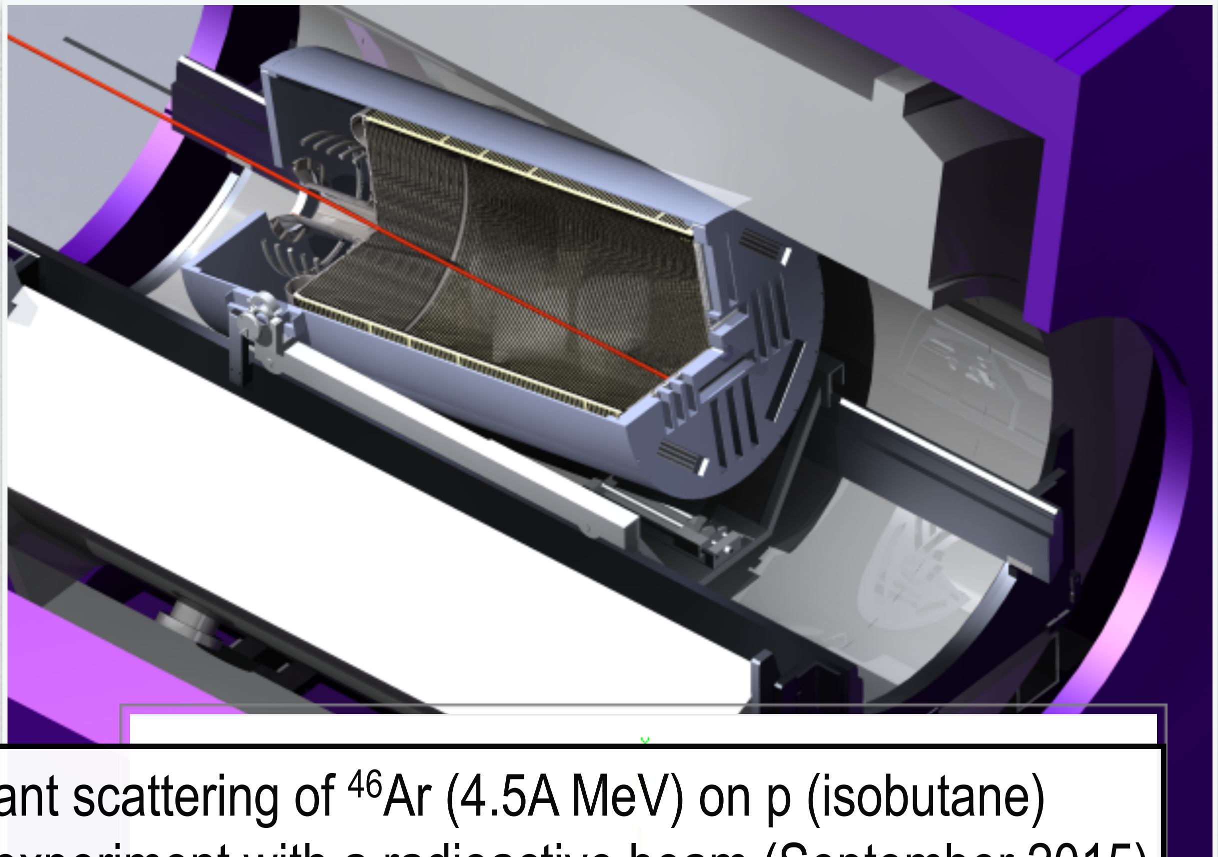


L. Gaudefroy et al.: Study of the N = 28 shell closure in the Ar isotopic chain

Eur. Phys. J. A 27, s01, 309–314 (2006)



AT-TPC: Data analysis



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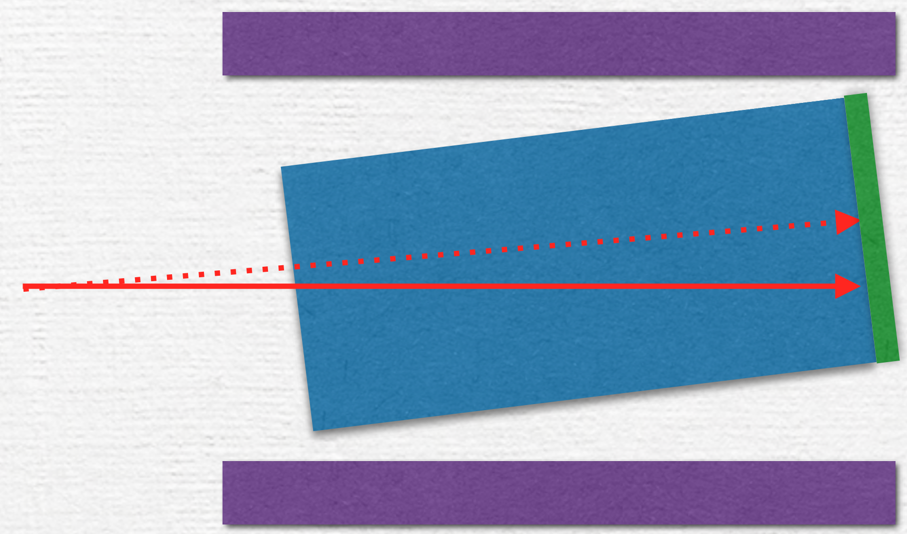
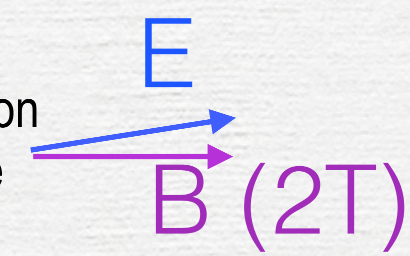
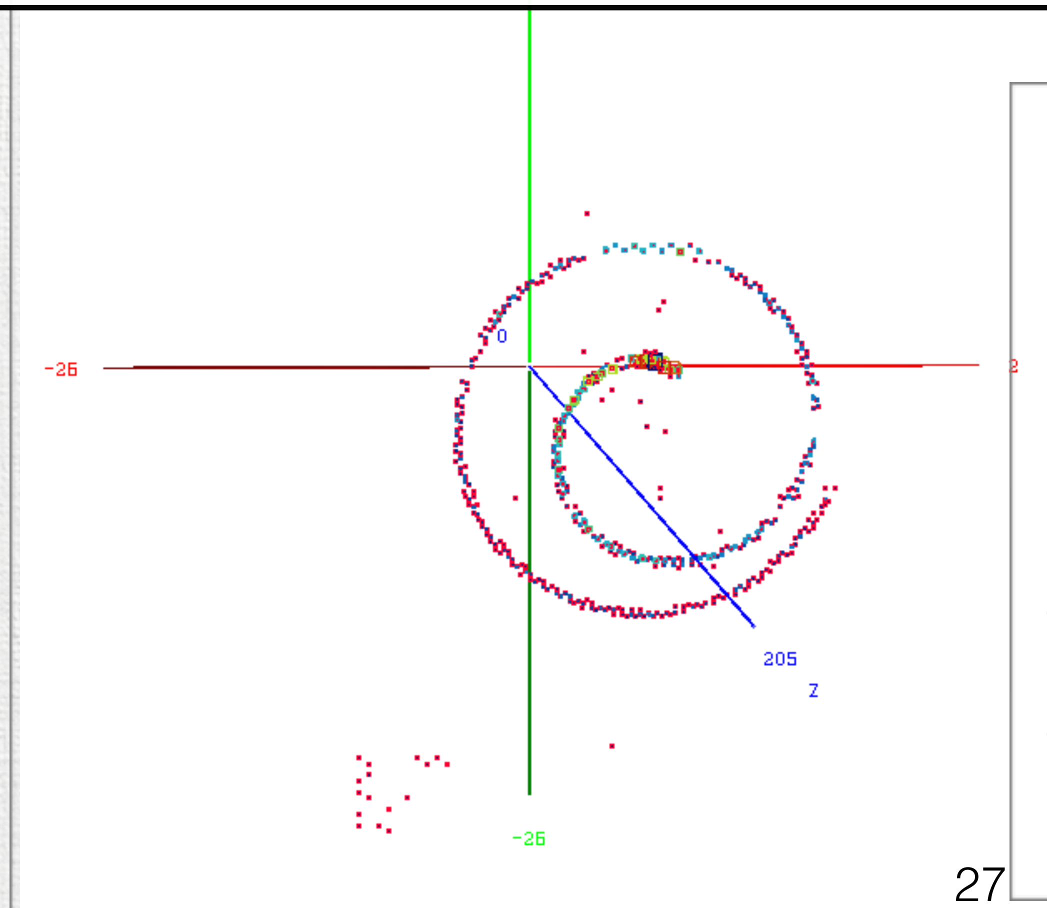
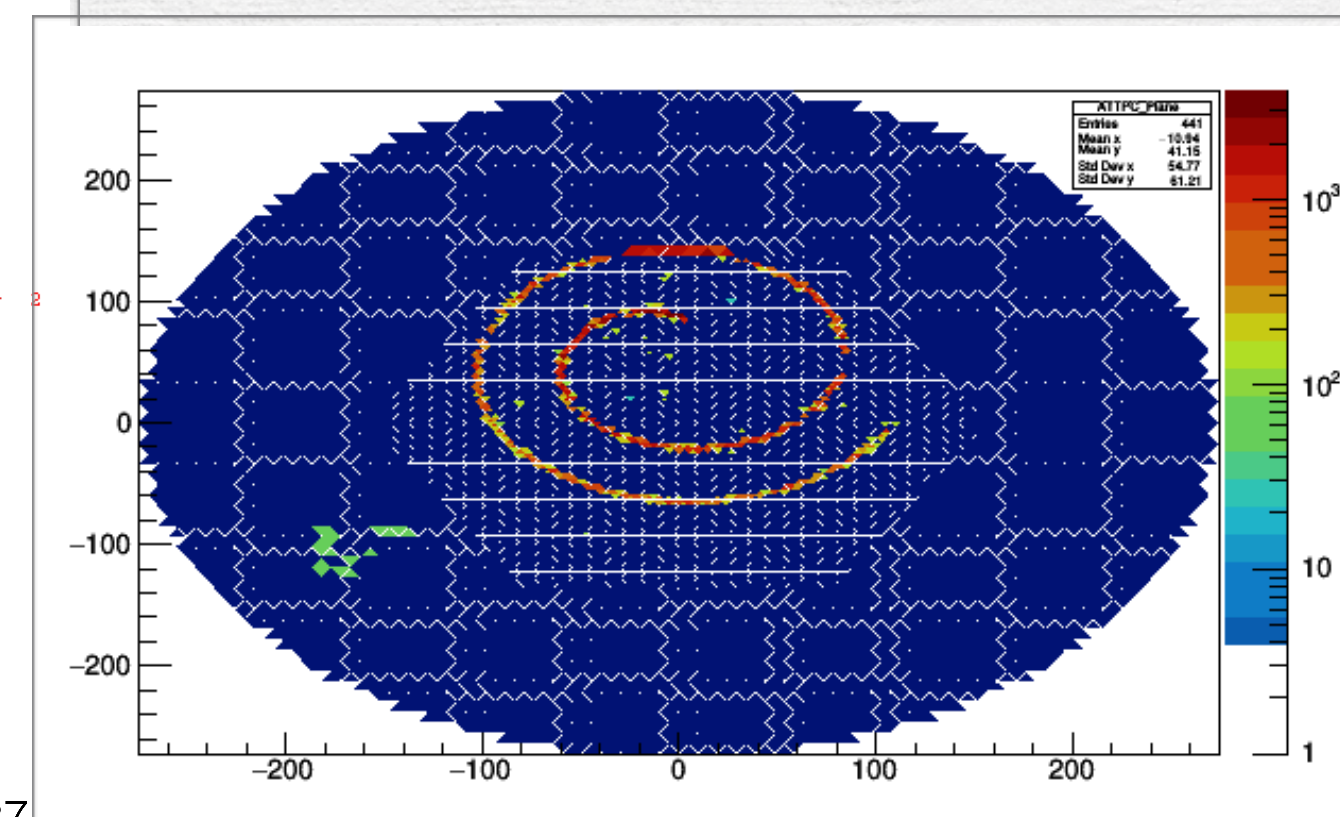


Lorentz angle: Apparent position of the beam in the pad plane

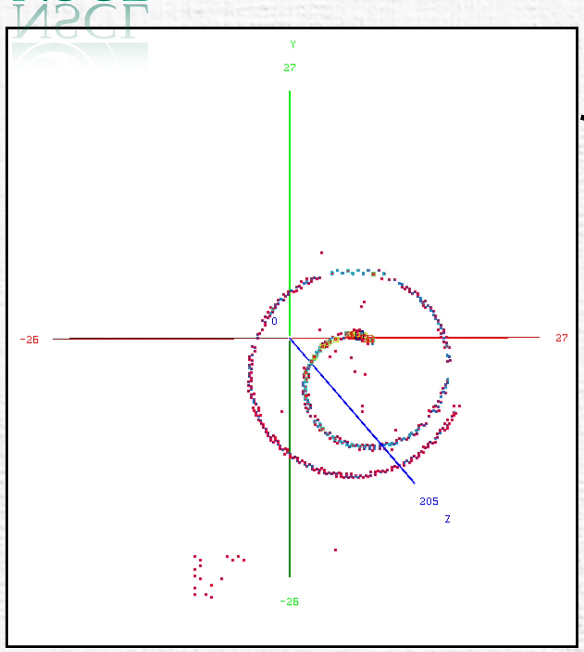


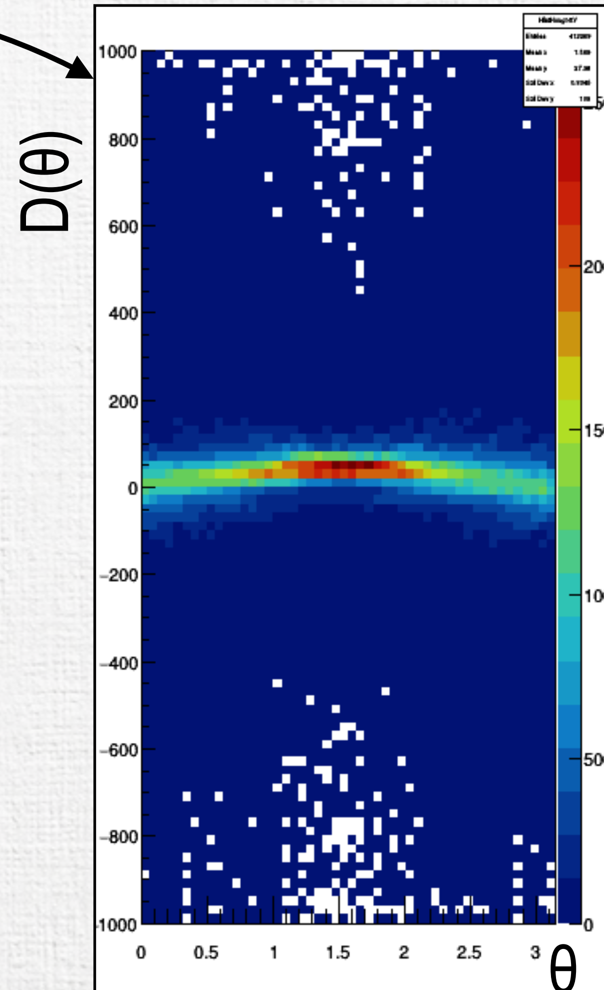


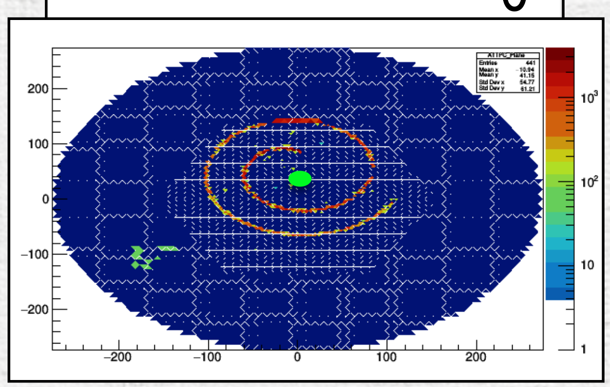


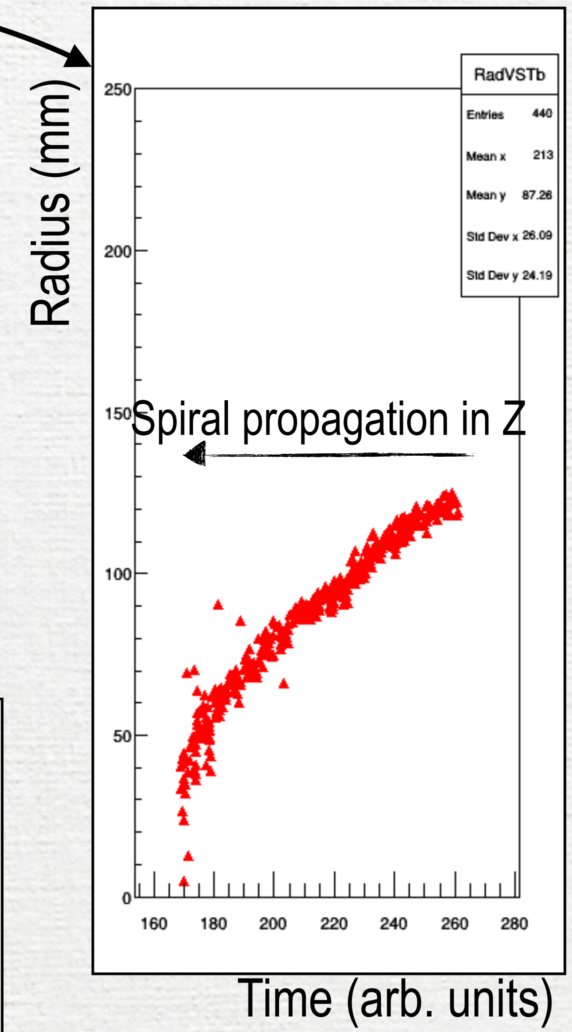
AT-TPC: Finding initial parameters

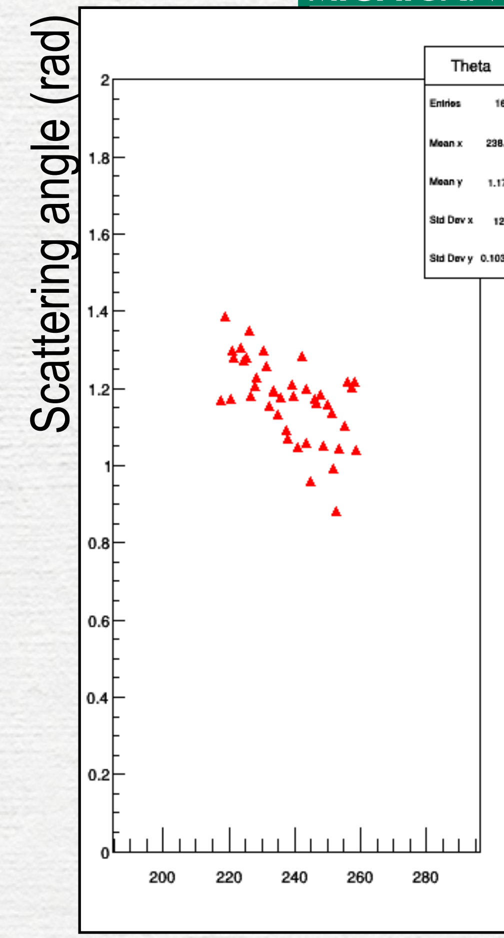
Hit Pattern

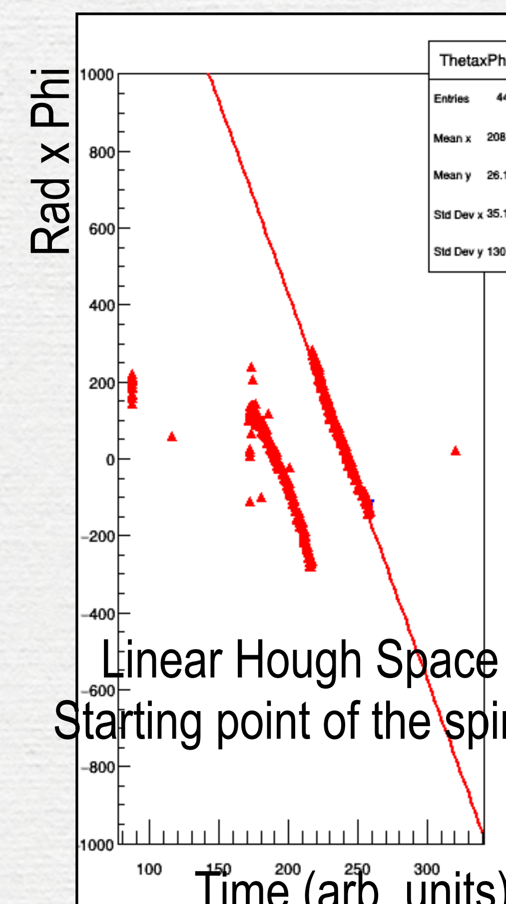




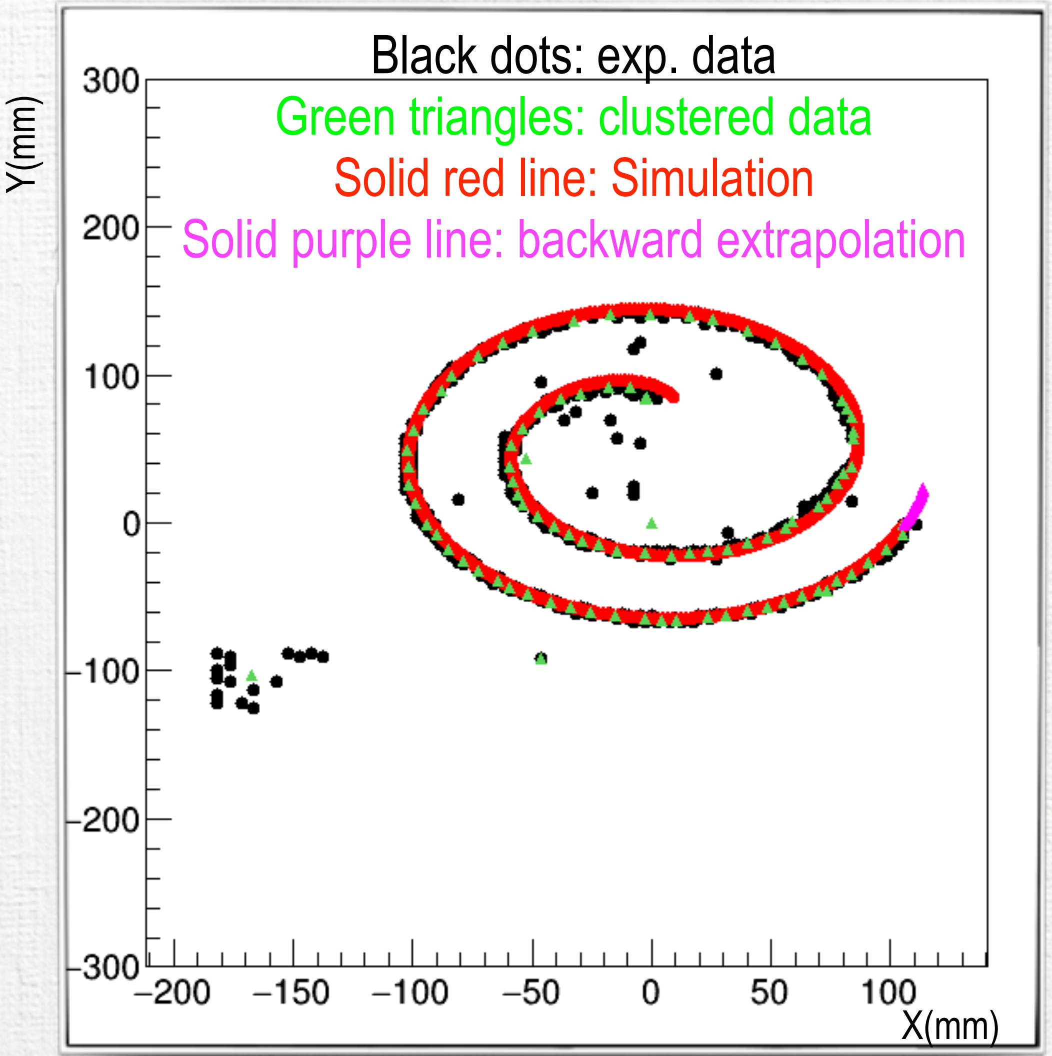


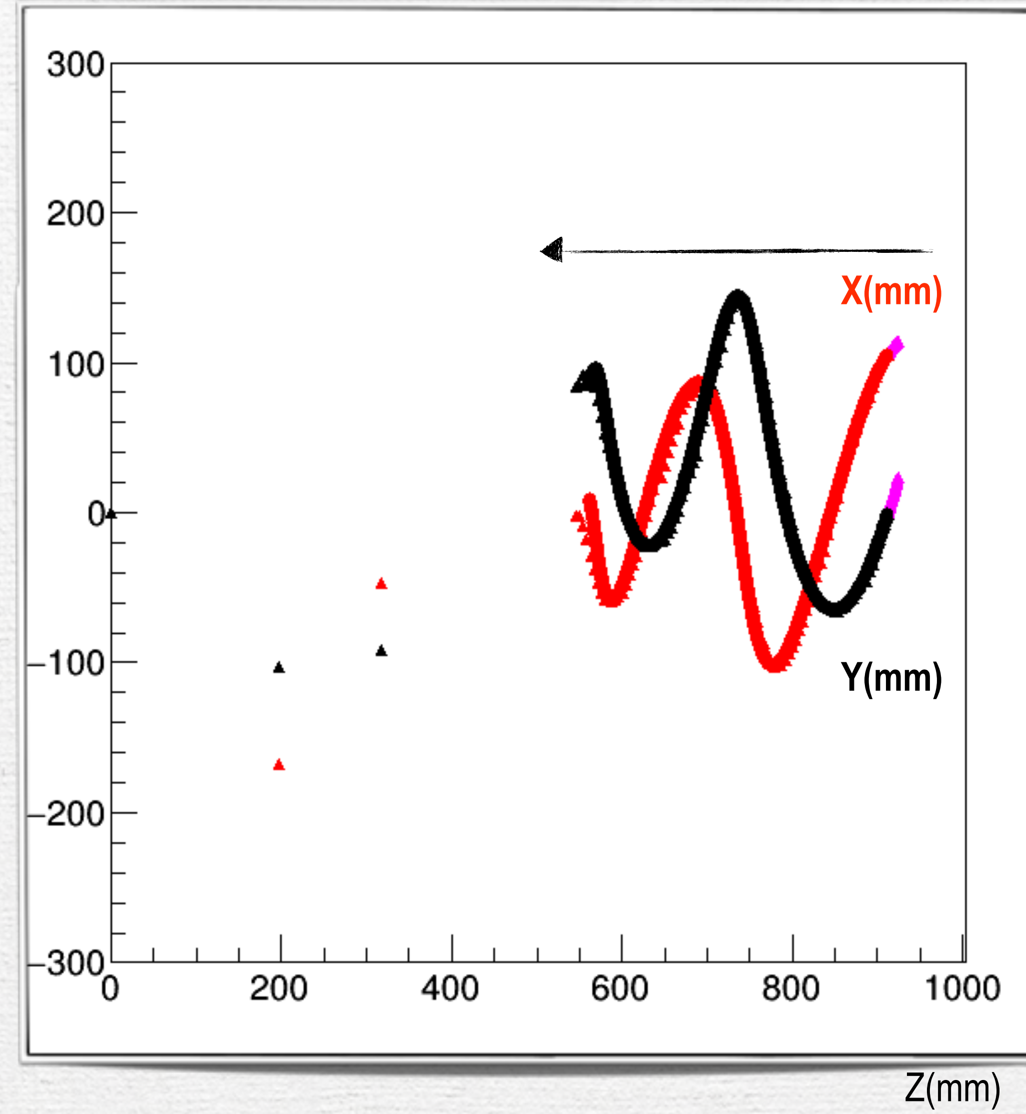


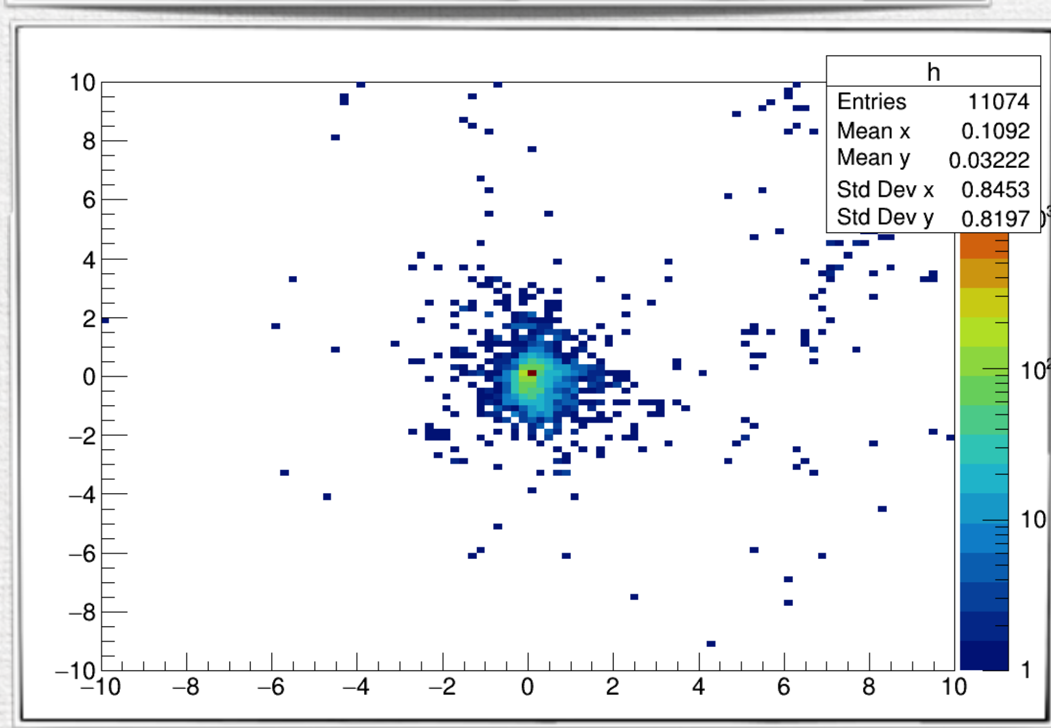


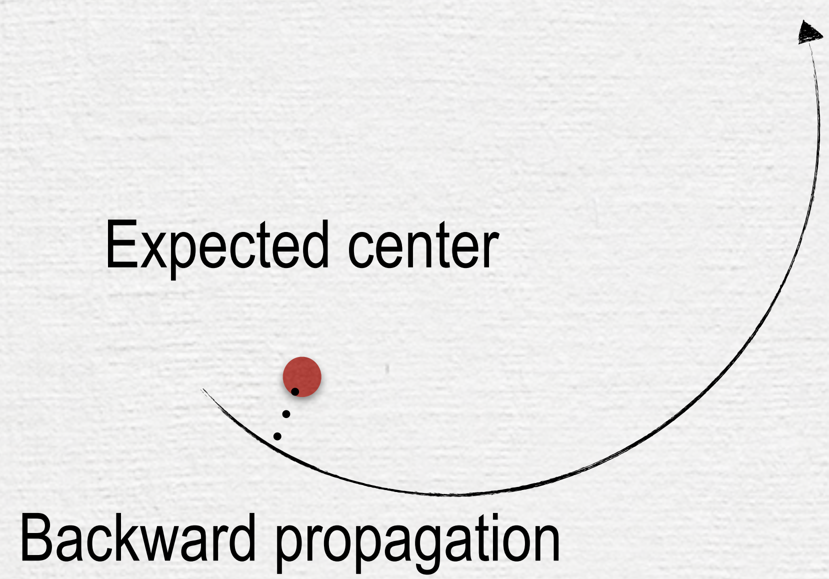


AT-TPC: Monte Carlo minimization



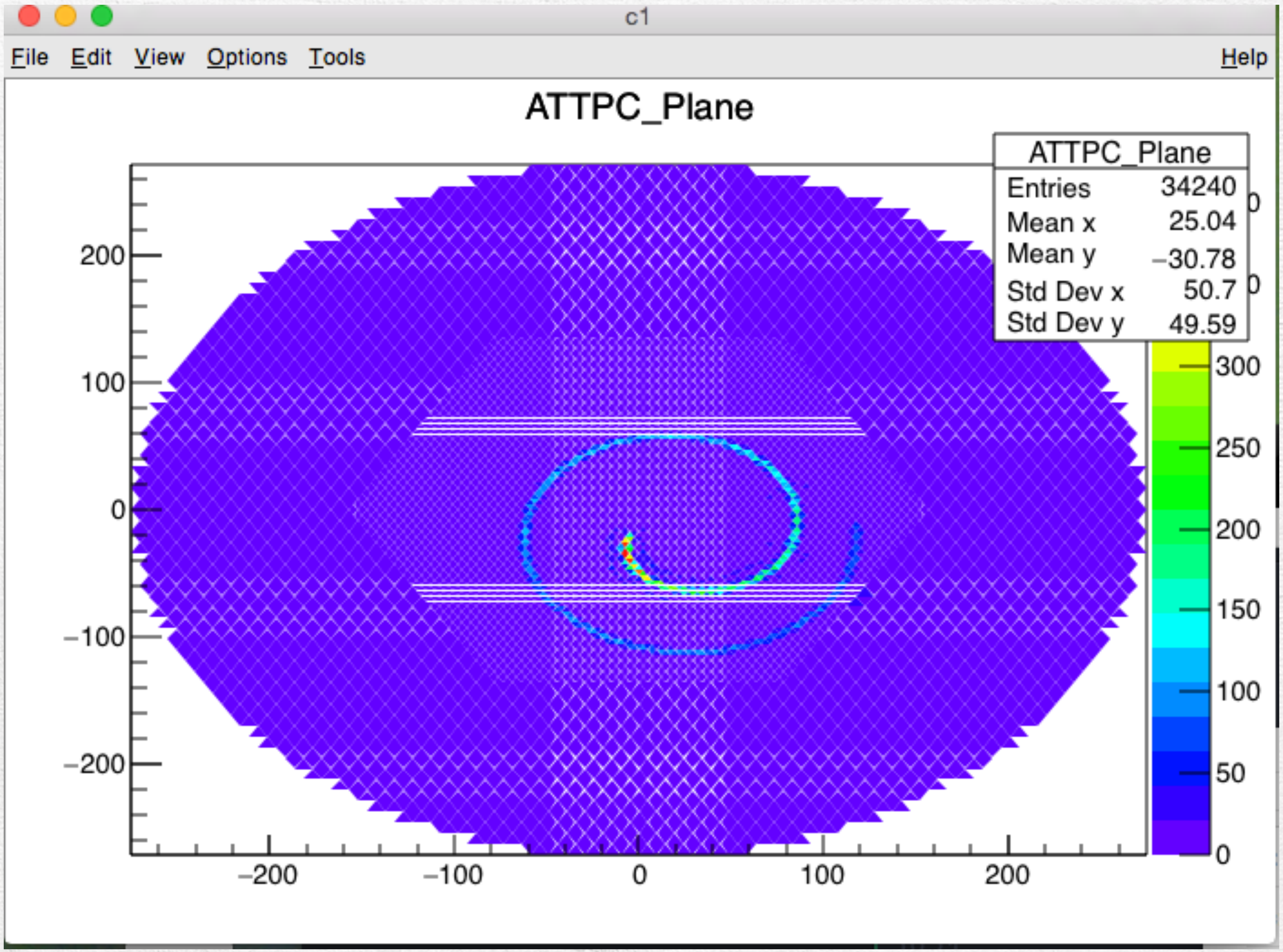






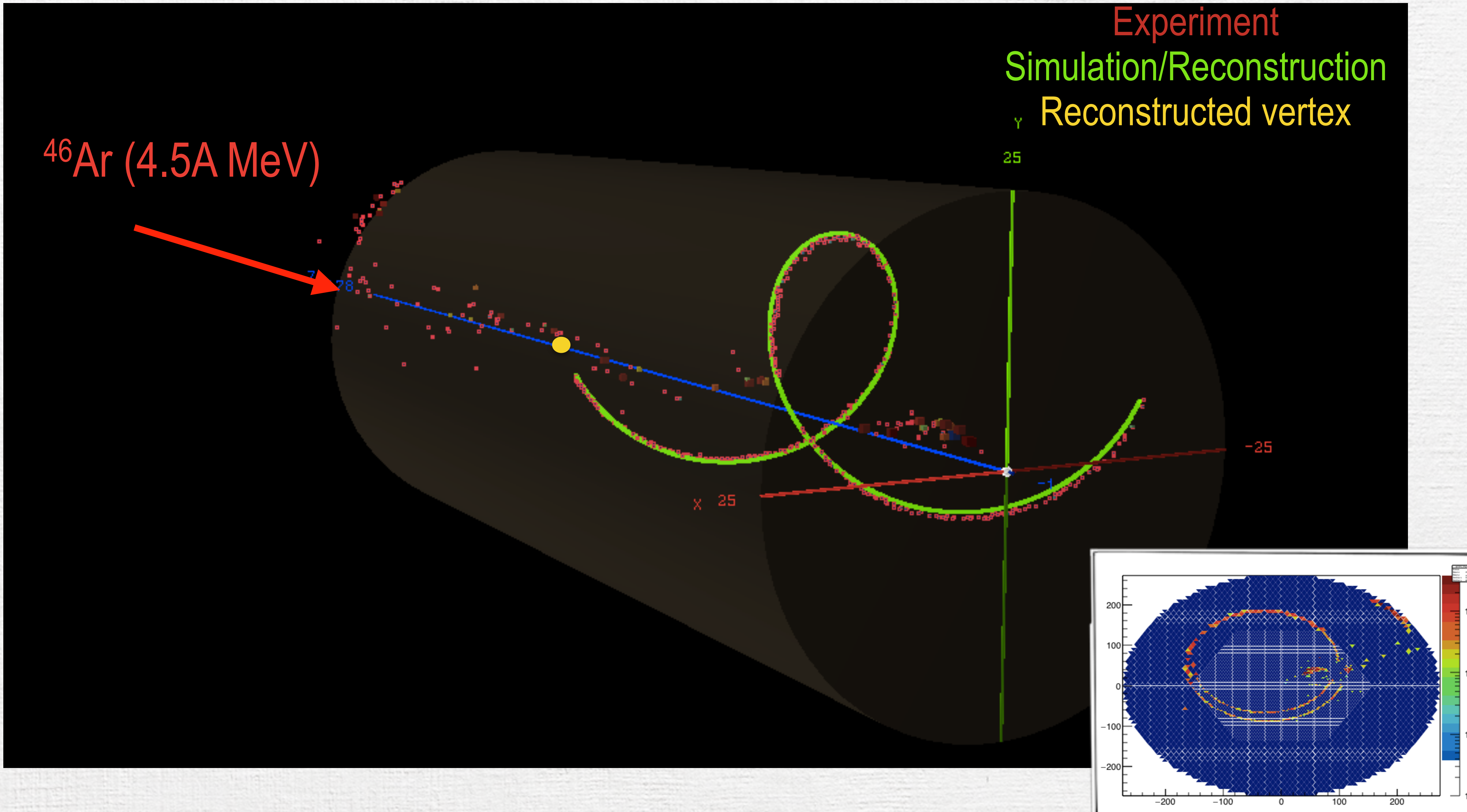
AT-TPC: Monte Carlo minimization

Toward better accuracy: MC with Energy Loss
Transversal and longitudinal straggling

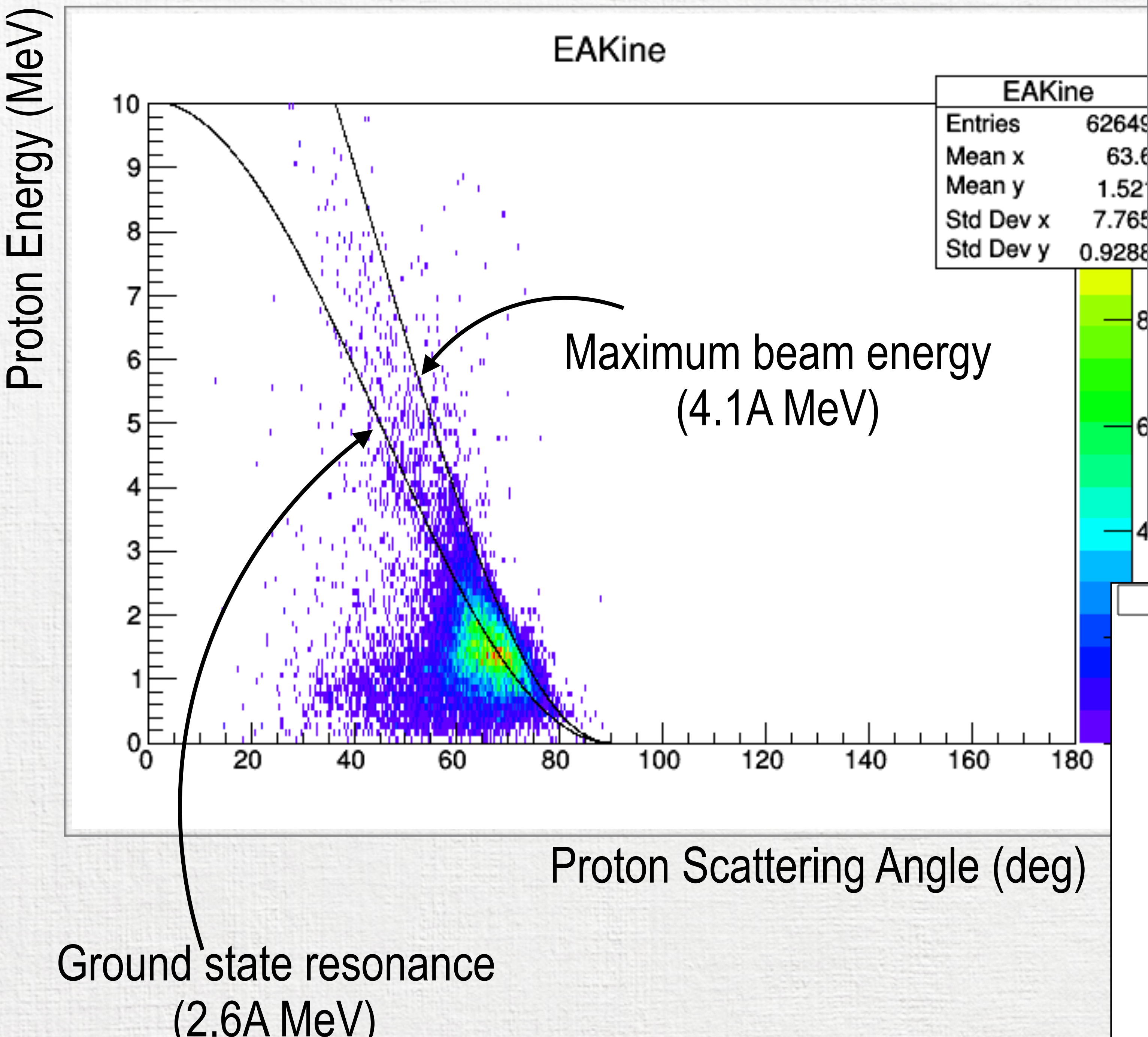


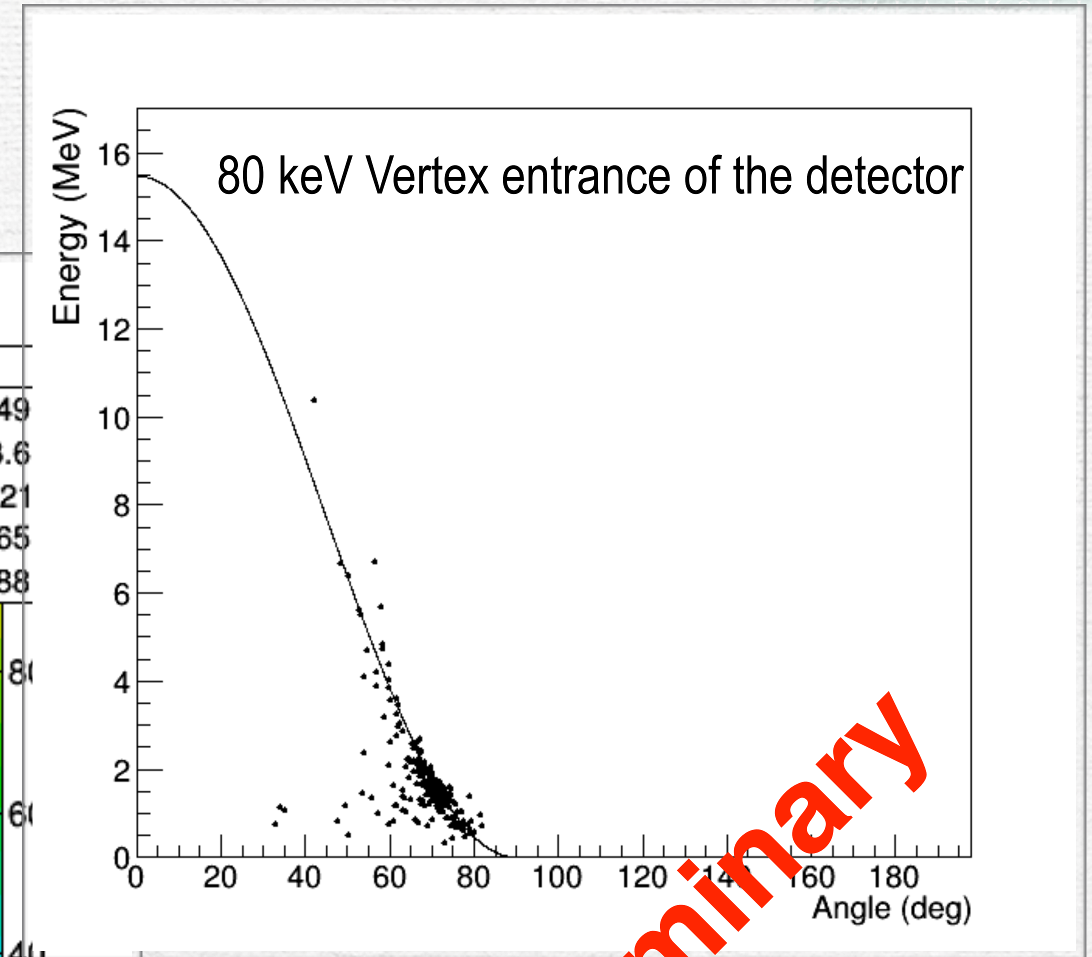
ATTPCROOT
Analysis framework

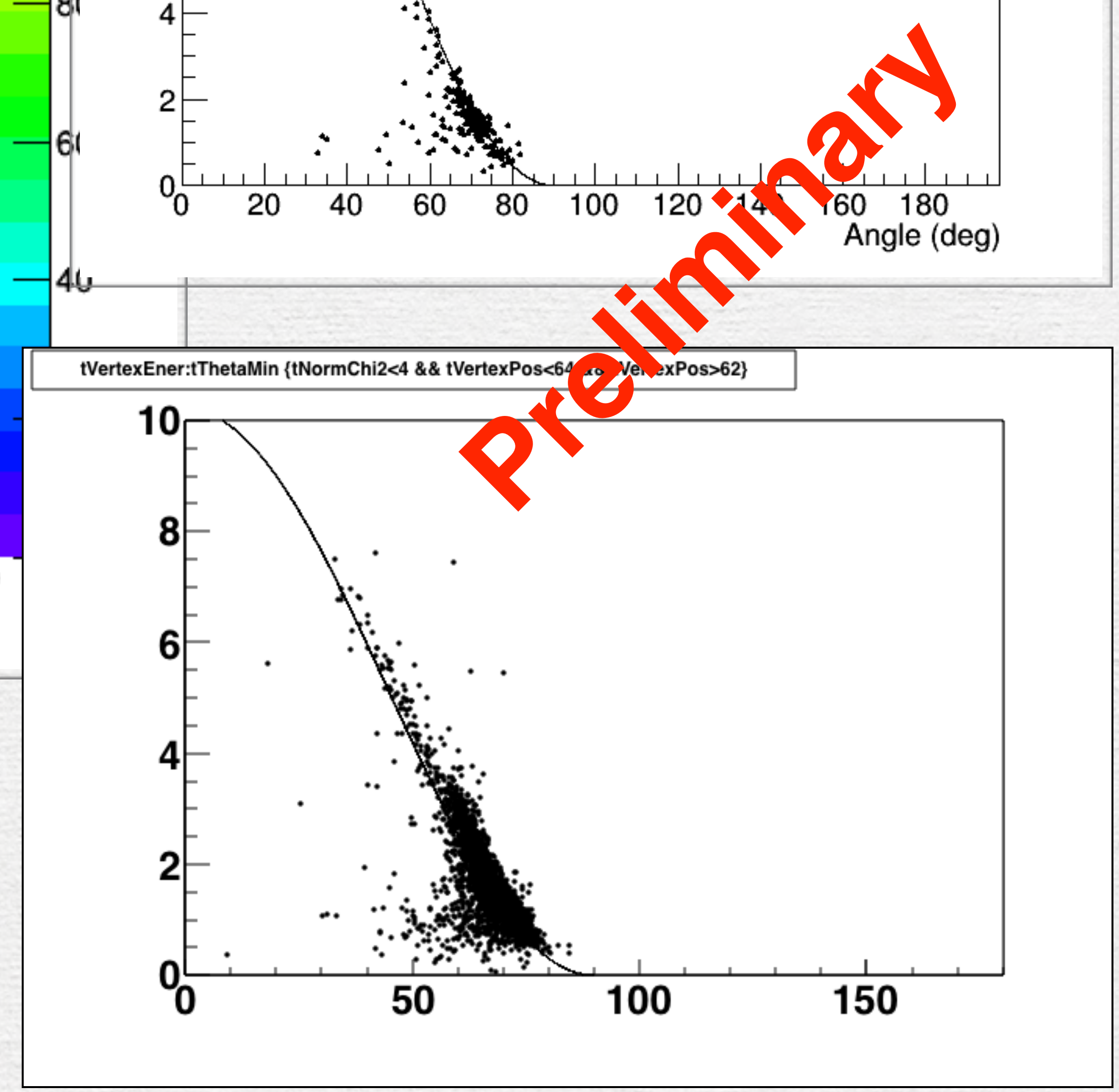
A scattering event



AT-TPC: Kinematics



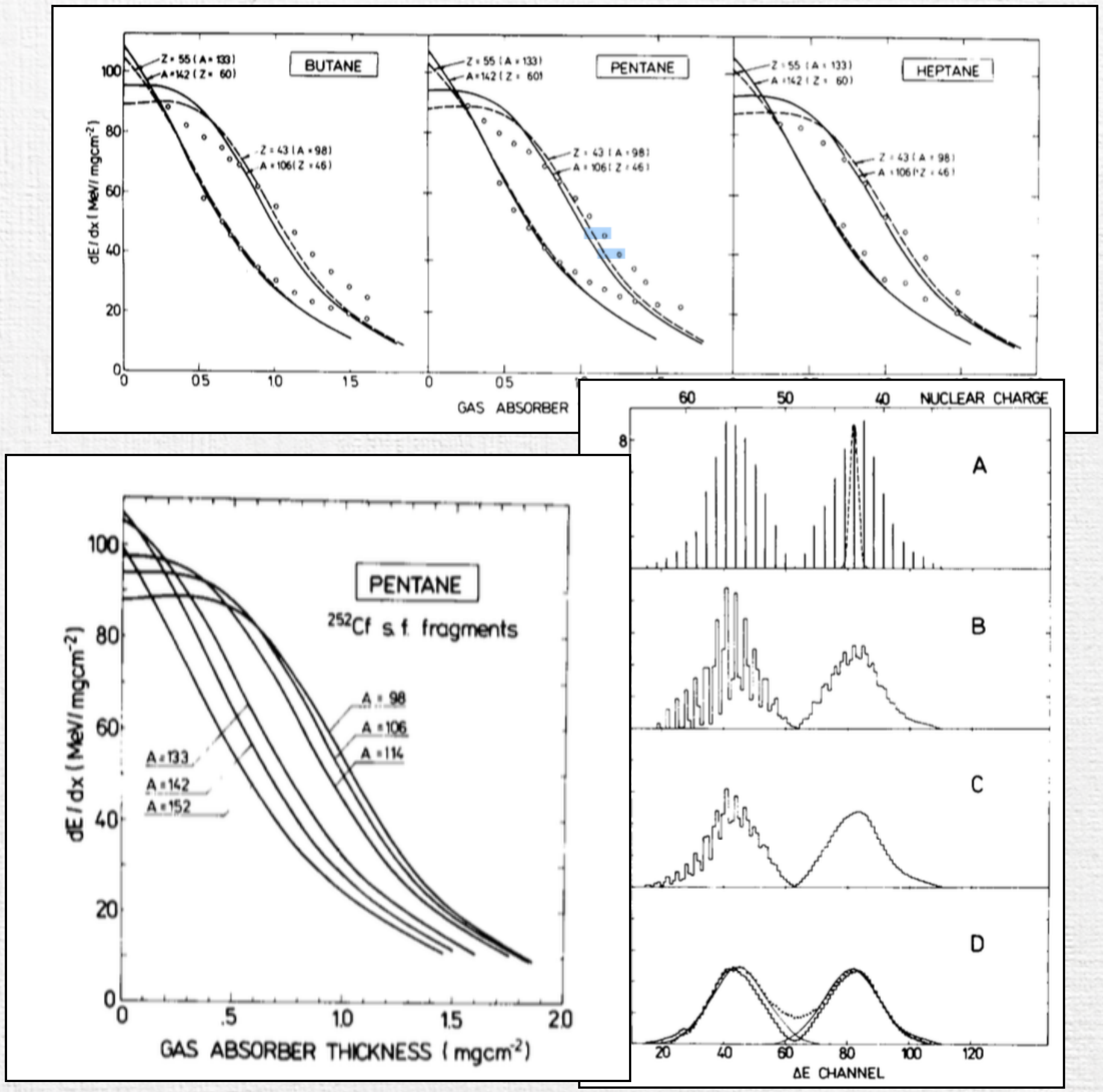




AT-TPC: Fission experiment

Fusion with neutron-rich rare isotope beams (S. Beceiro-Novo)

W. Neubert, Nucl. Instr. and Meth. A, 237, 535 (1985)



Cross sections, angular distributions, atomic number?, mass?

AT-TPC: Fission experiment

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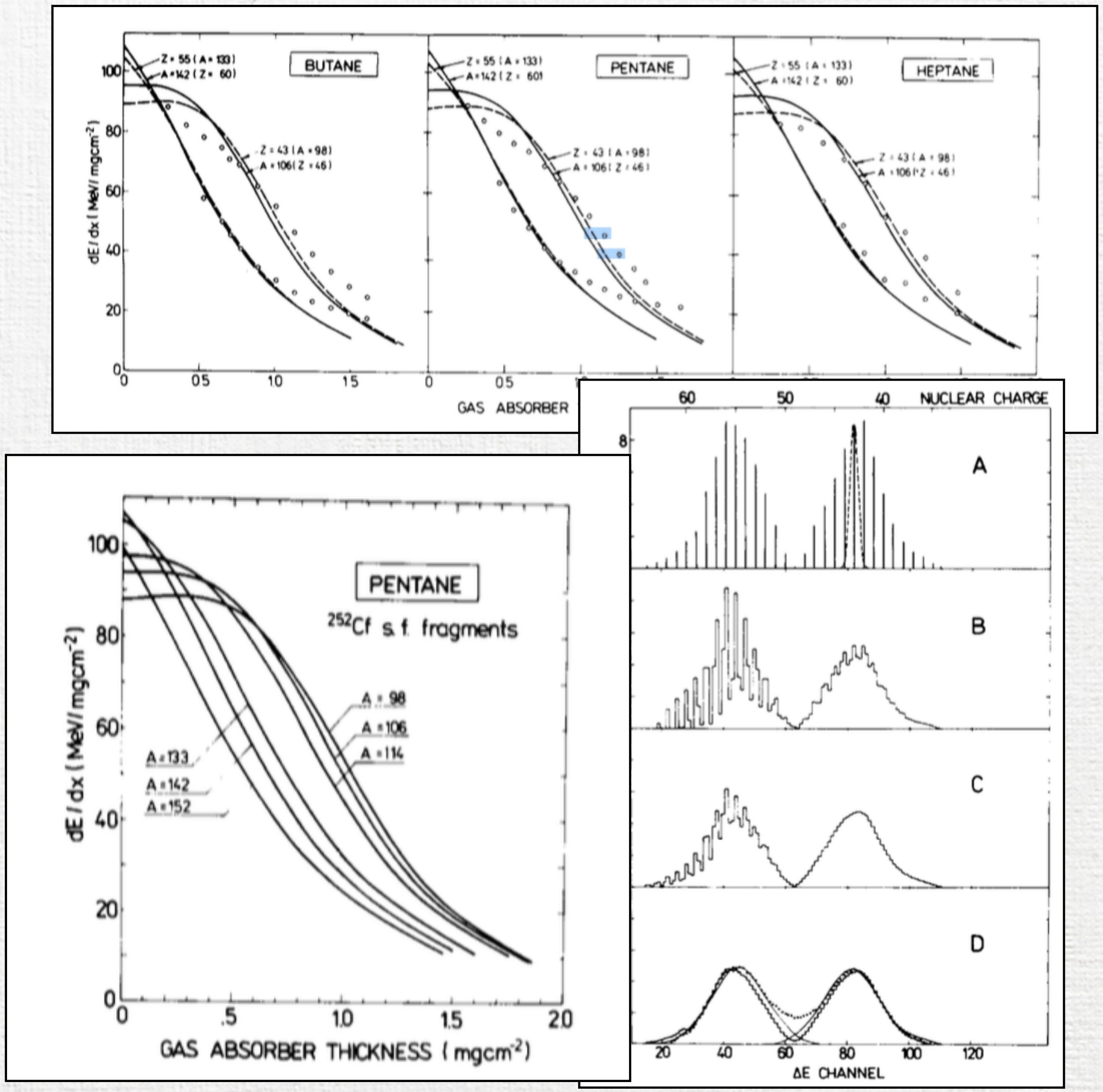
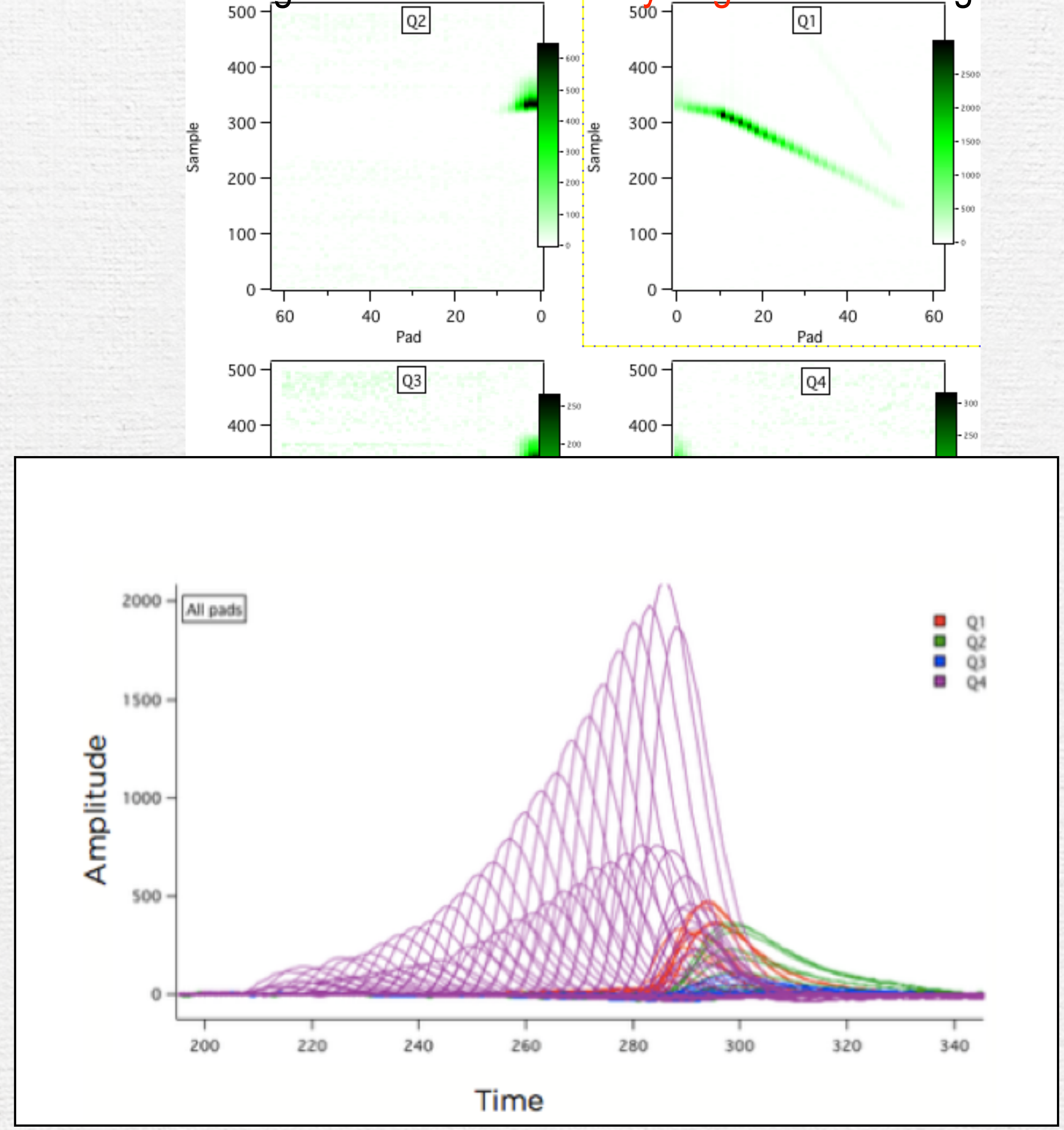


Fission fragment source + Pure hydrogen + micromegas

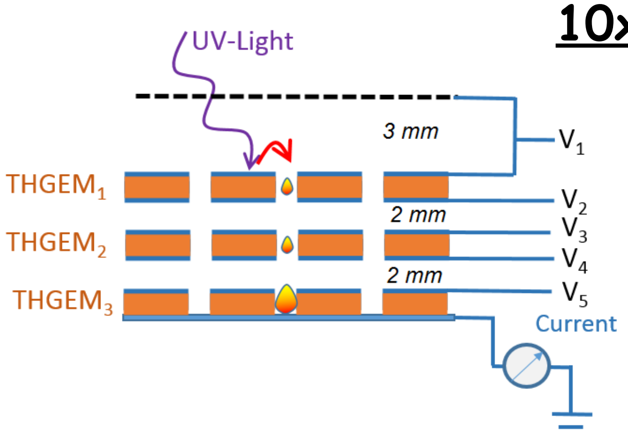


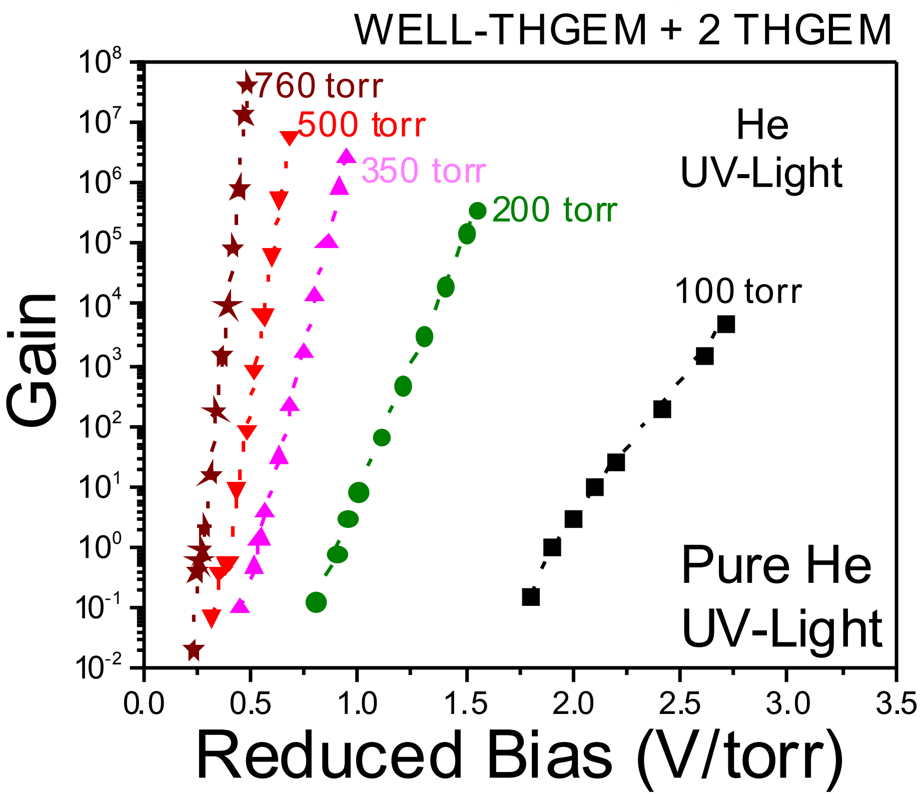
Cross sections, angular distributions, atomic number?, mass?

THGEM applications @ NSCL

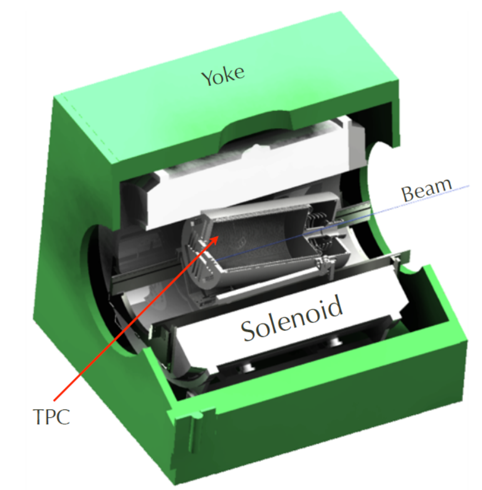
Cortesi et al. 2015 JINST 10 P02012

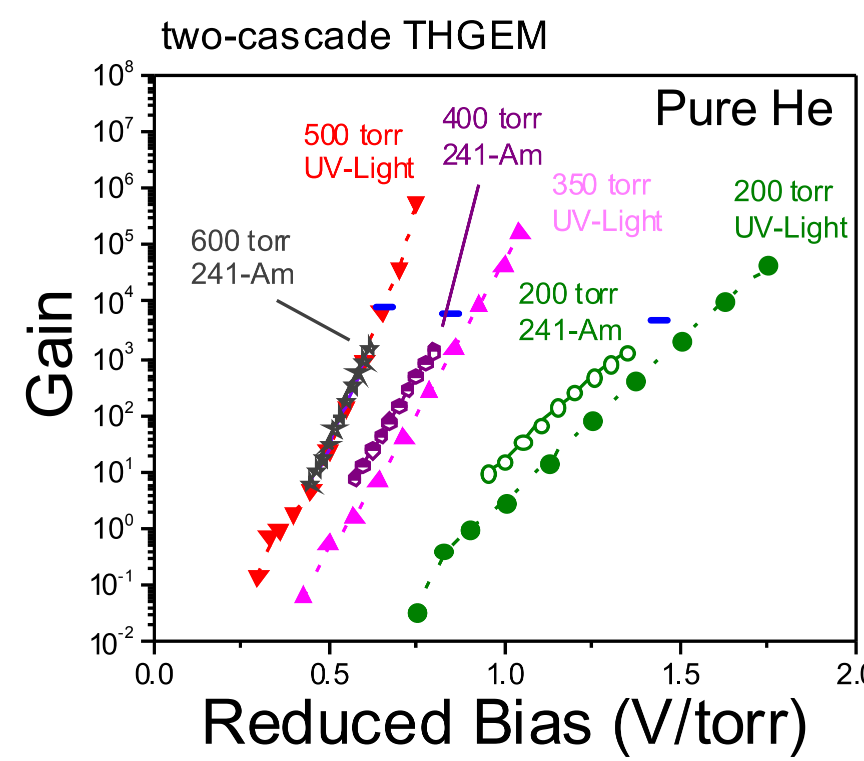
10x10cm² THGEM





Ø = 55 cm² THGEM





$Gain_{3-THGEM} > 10^6$ for p>100 torr

AT-TPC: Outlook and conclusions

- The (p)AT-TPC is a versatile detector to perform direct and resonant reactions.
- A robust framework for (p)AT-TPC data analysis is being developed. Parallelization of the code CUDA, OpenMP, MPI…Framework collaboration: MSU, TRIUMF, ND and RIKEN

Short-term future experiments:

Low and high energy reactions

- Direct measurement of a key reaction for the rp-process with the AT-TPC (Y. Ayyad and S. Beceiro-Novo, Approved, PAC39). ^{22}Mg(α,p).
- Search for cluster and molecular states in neutron-rich carbon isotopes with the AT-TPC (Y. Ayyad and T. Kawabata). ^{16}C(α,α') at 80A MeV with thick GEMs and pure helium gas.
- ^{12}Be +4He resonant scattering: Another approach (TRIUMF proposal)

And long-term prospects:

- Investigate the most exotic species in the carbon chain: ^{18}C, ^{20}C… exotic α-condensates…
- np-pairing in N=Z exotic nuclei using (^{3}He,p) reactions
- Collaboration between NSCL, RIKEN and RCNP (Osaka)

Acknowledgements

ATTPC Collaboration

NSCL: D. Bazin, S. Beceiro-Novo, J. Bradt, L. Carpenter, M. Cortesi, M. Kuchera, W. Lynch, W. Mittig, J. Yurkon

Notre Dame: T. Ahn

RIKEN: D. Suzuki

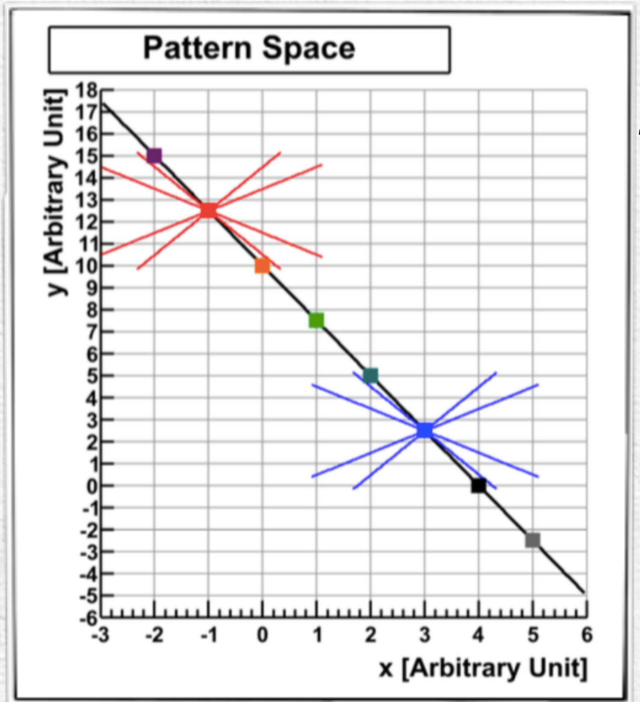
TRIUMF: R. Kanungo, M. Holl

Thank you for your attention!

pAT-TPC: Pattern recognition

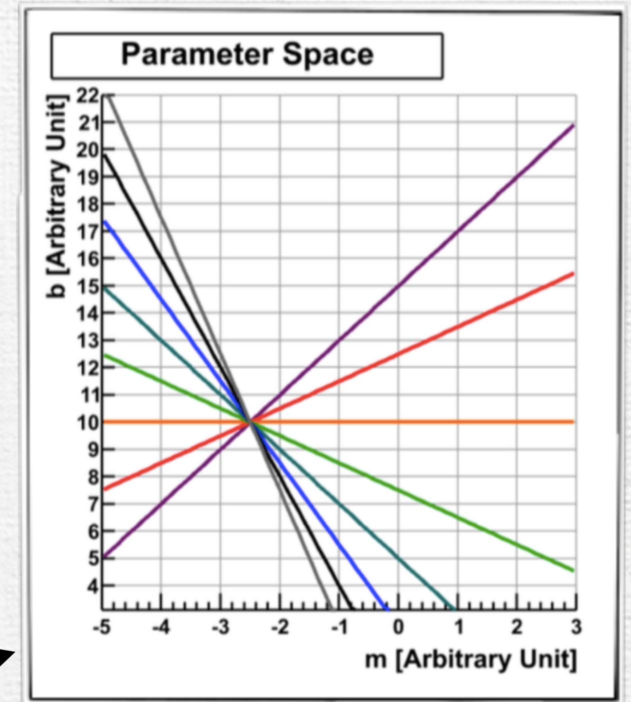
Find an efficient way to deal with what the trigger missed and analyze straight tracks

1) Hough Space Line equation

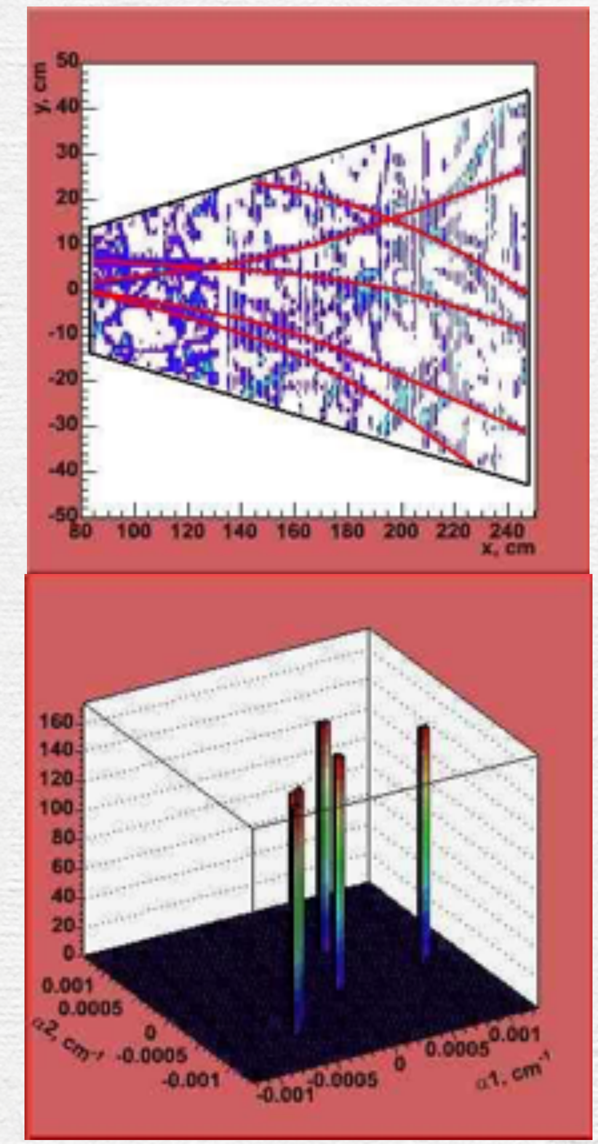


$$y(x) = mx + b$$

$$b(m) = y - mx.$$

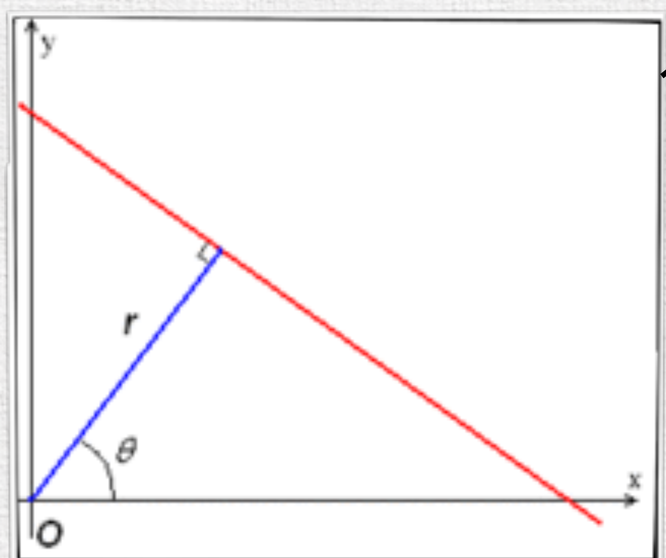


Sector of ALICE TPC @CERN



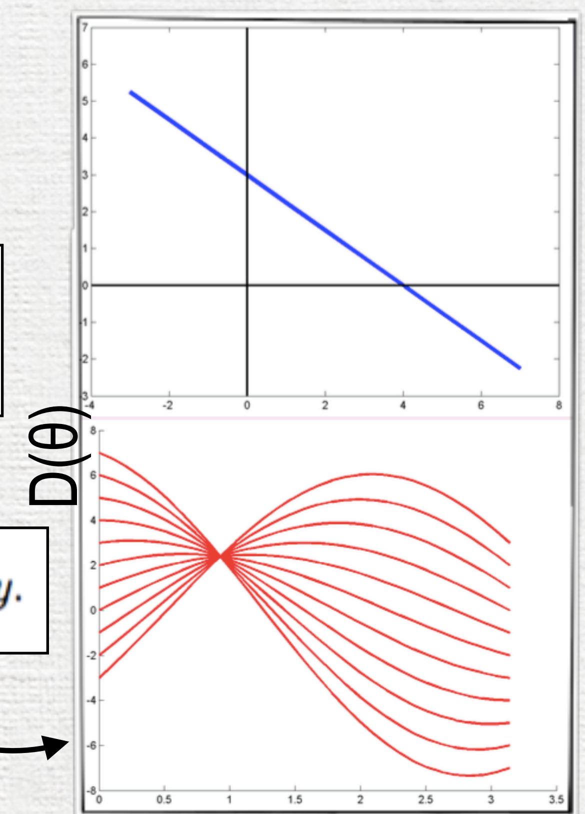
C. Cheshkov NIM A 566 (2006) 35–39

2) Normal form of a line



$$y(x) = -\frac{\cos\theta}{\sin\theta}x + \frac{d_0}{\sin\theta}.$$

$$d_0(\theta) = \cos\theta \cdot x + \sin\theta \cdot y.$$



θ

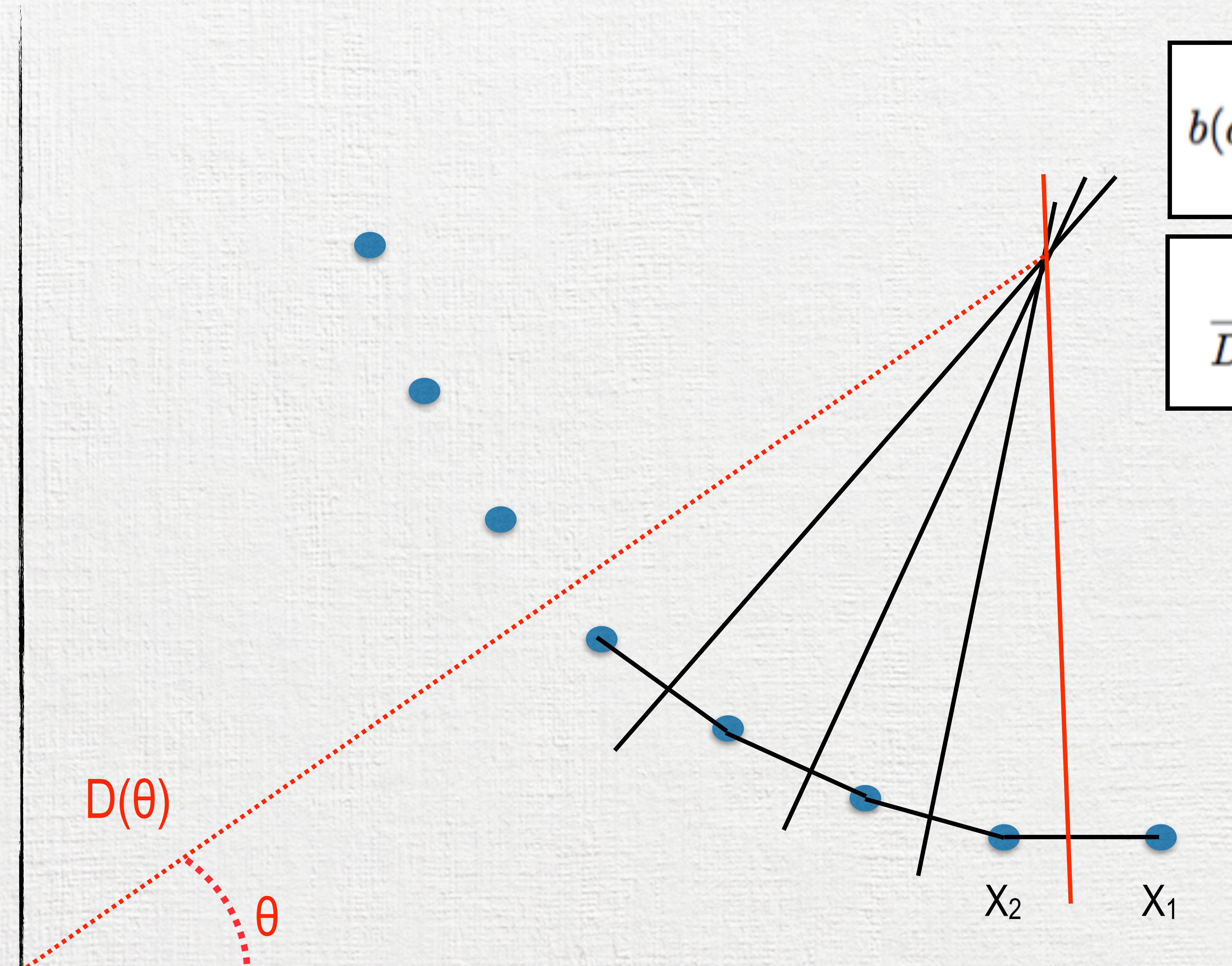
AT-TPC: Pattern recognition

Hough Space for Circles

$$R^2 = (x - x_C)^2 + (y - y_C)^2$$

3-dimensional accumulation matrix

Computationally expensive! Find all possible circles with a given R

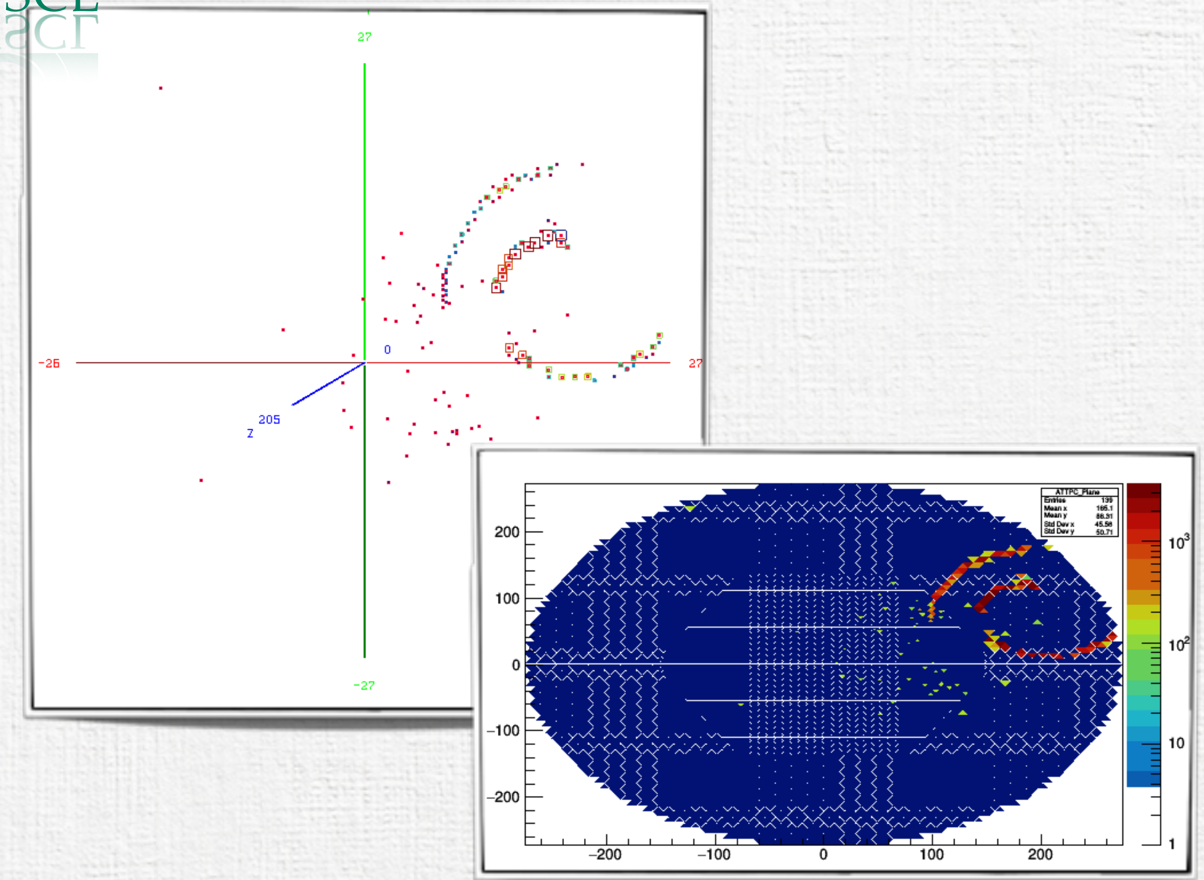


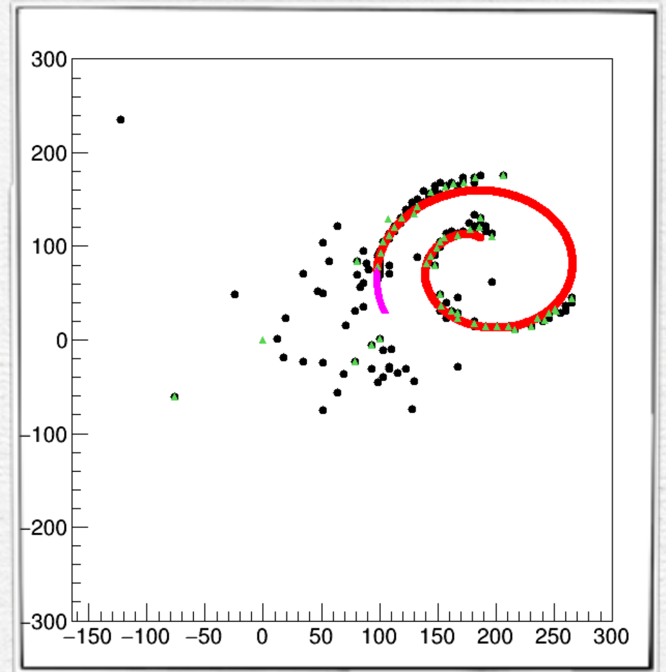
$$b(a) = \frac{x_2 - x_1}{y_1 - y_2} a + \frac{1}{2} \frac{(y_1^2 - y_2^2) + (x_1^2 - x_2^2)}{y_1 - y_2}$$

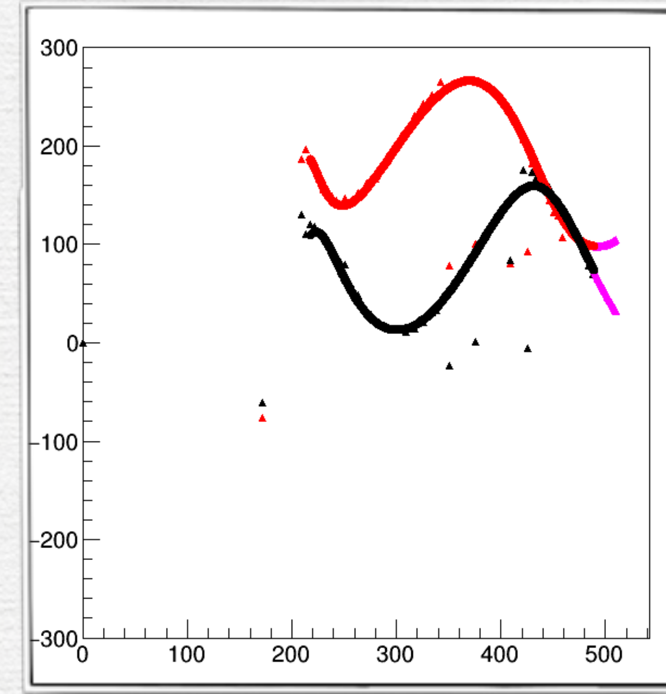
$$\frac{1}{D(\theta)} = 2 \cdot \frac{(y_1 - y_2)\sin\theta + (x_1 - x_2)\cos\theta}{(y_1^2 - y_2^2) + (x_1^2 - x_2^2)}$$

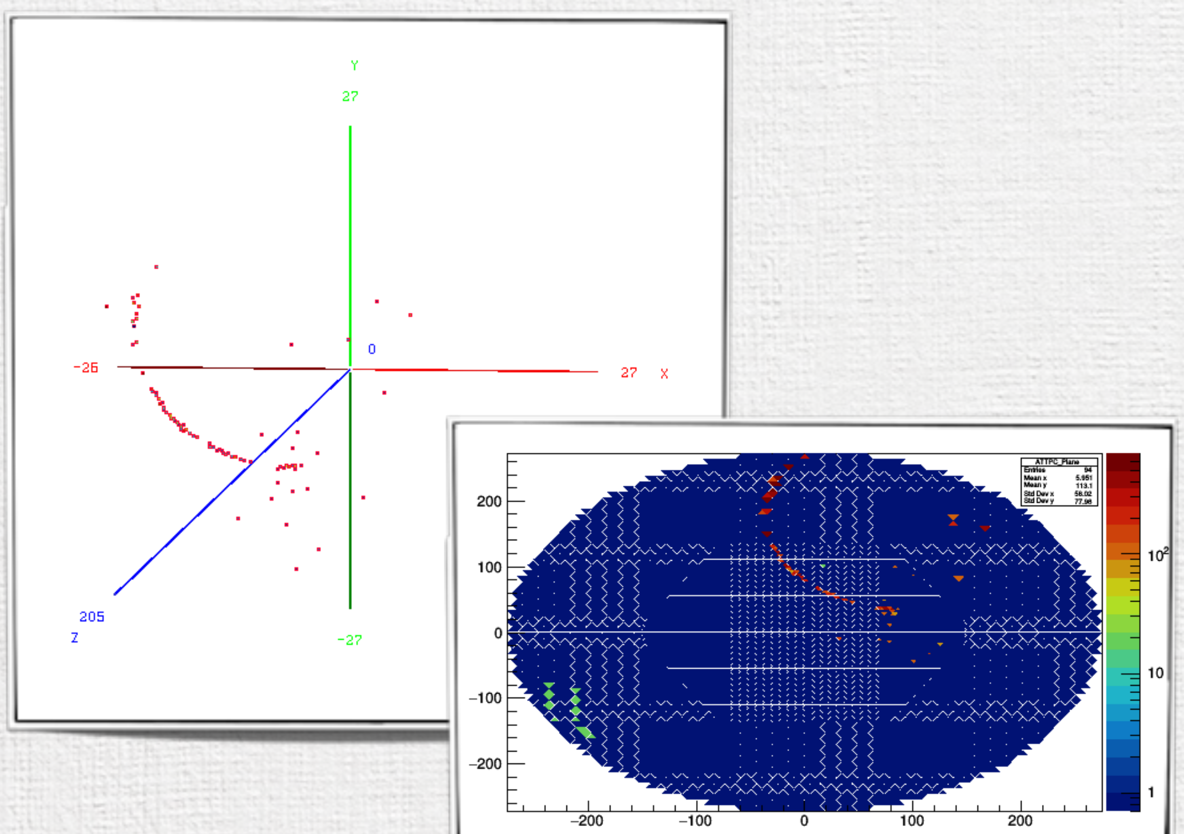
$$R = \sqrt{(a - x_{\text{hit}})^2 + (b - y_{\text{hit}})^2}.$$

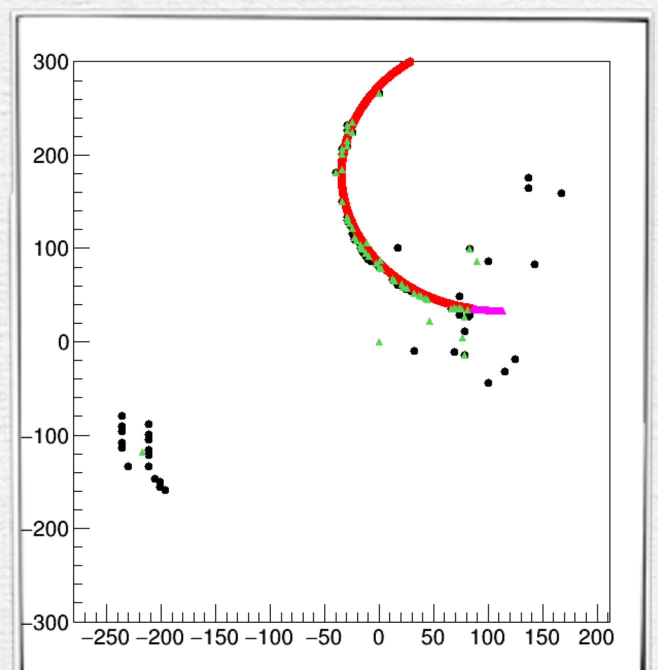
AT-TPC: Robust algorithm

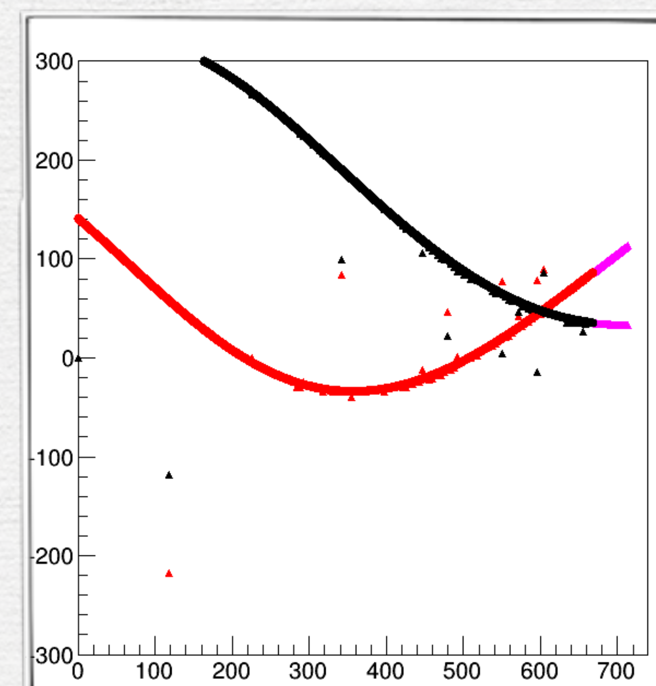


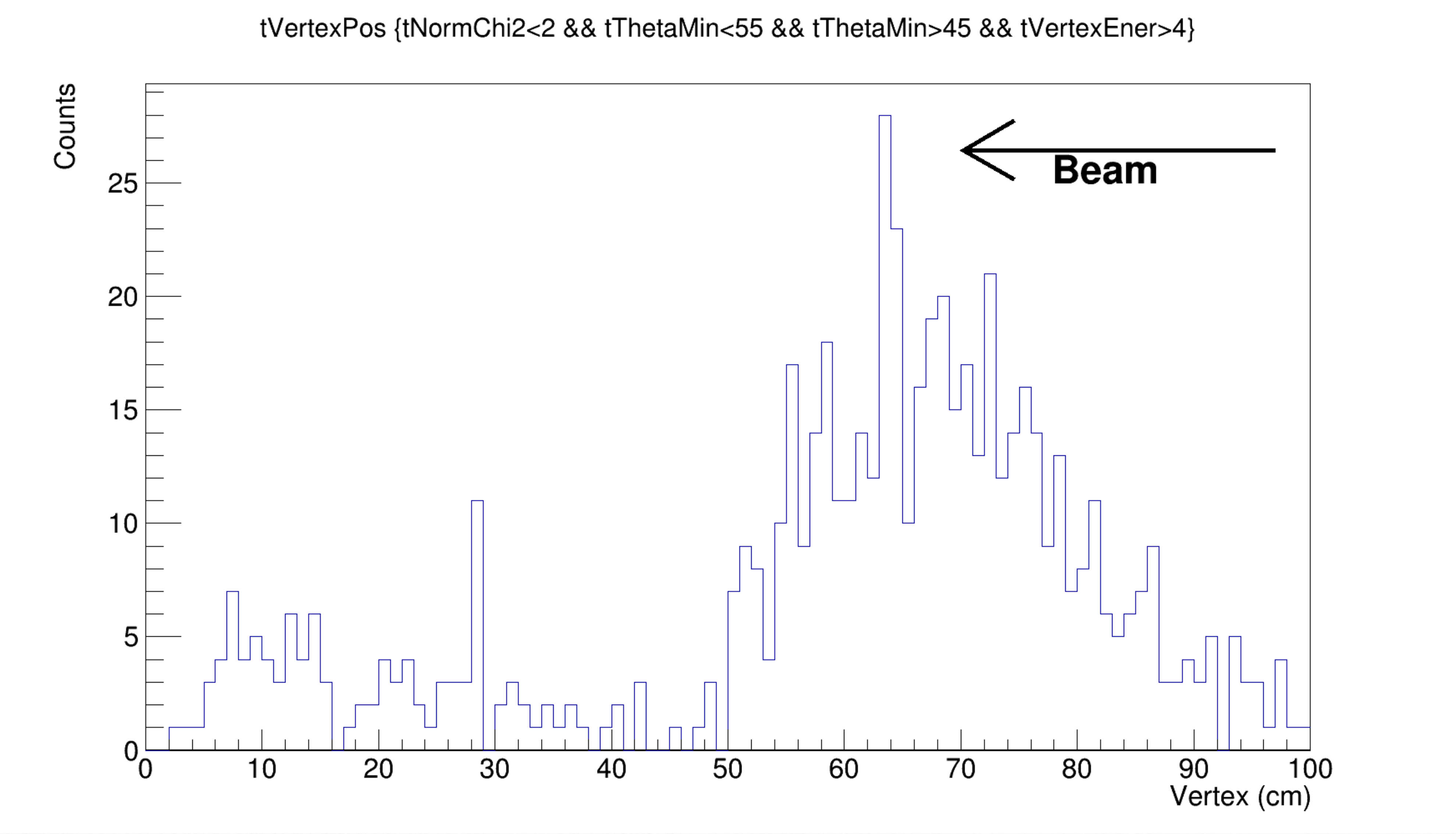








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Counts
25
20
15
10
5
0
0
10
20
30
40
50
60
70
80
90
100
Vertex (cm)
Beam