Using lasers to optimize densities and temperatures of plasmas for Nuclear Physics

M. Barbarino, Ph.d. student Texas A&M, USA

INTRODUCTION:

Create energetic ion beams under specific physical conditions, i.e. temperature, density, collective acceleration, etc., for basic nuclear science and applications.

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CONCLUSIONS

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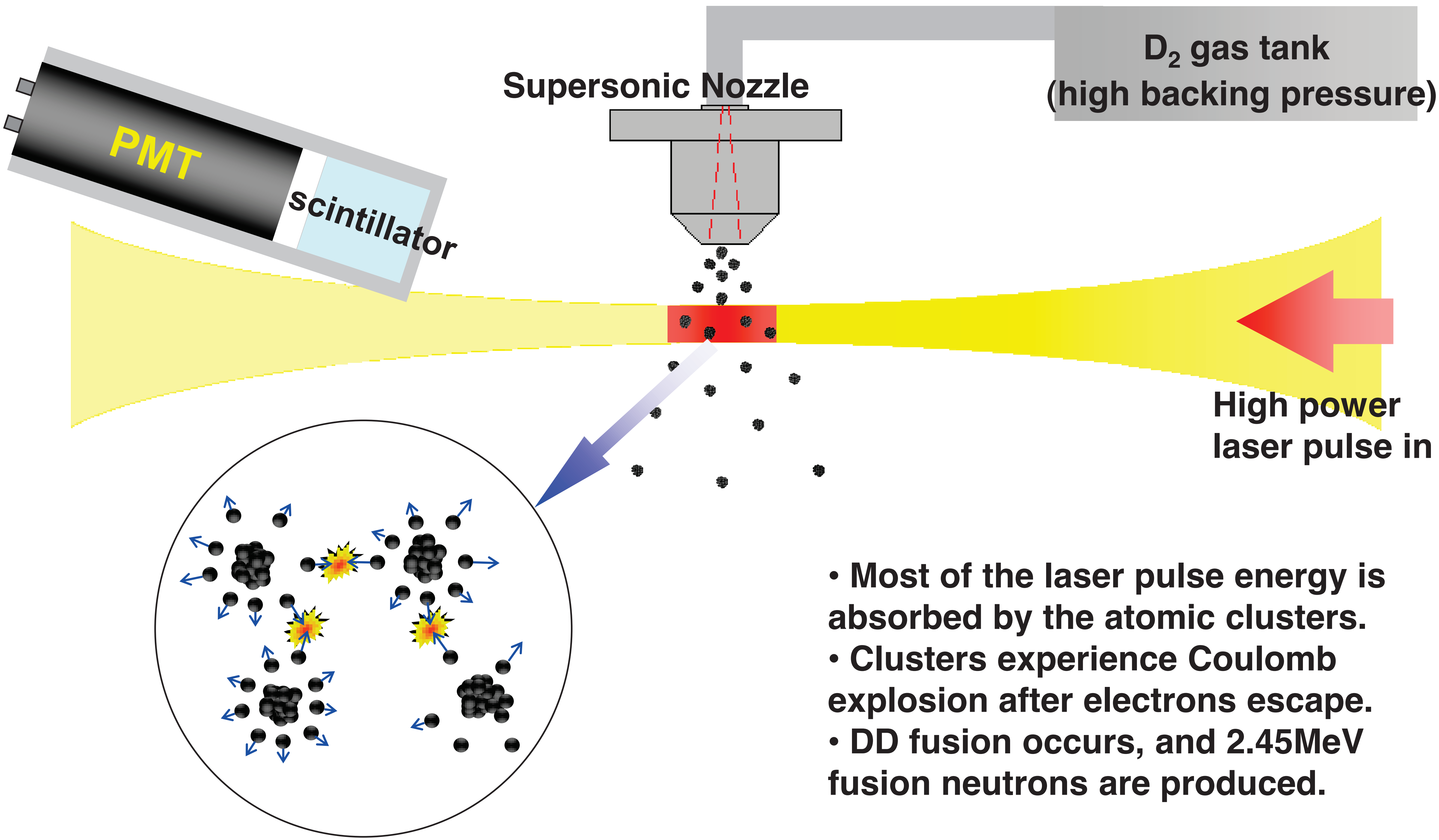
High power laser can be used to generate neutrons from the fusion reaction

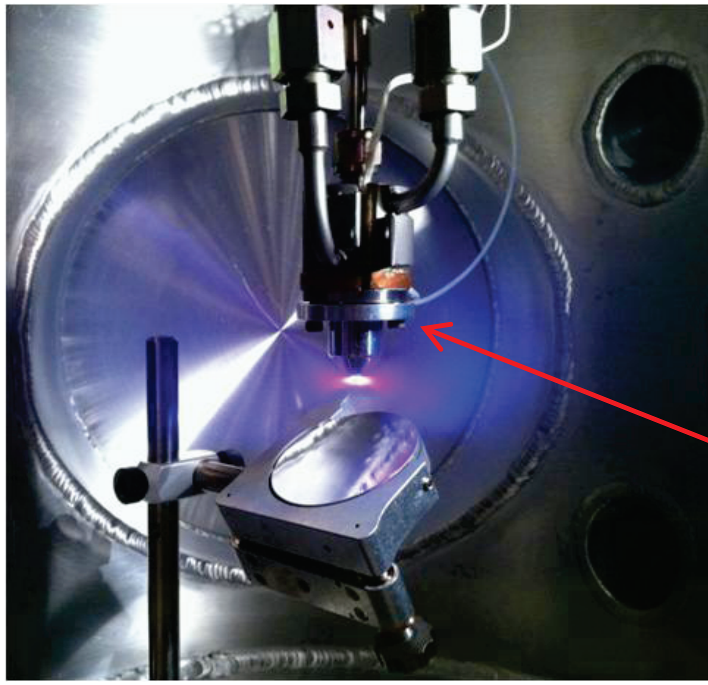
Nuclear fusion from laser-cluster interaction

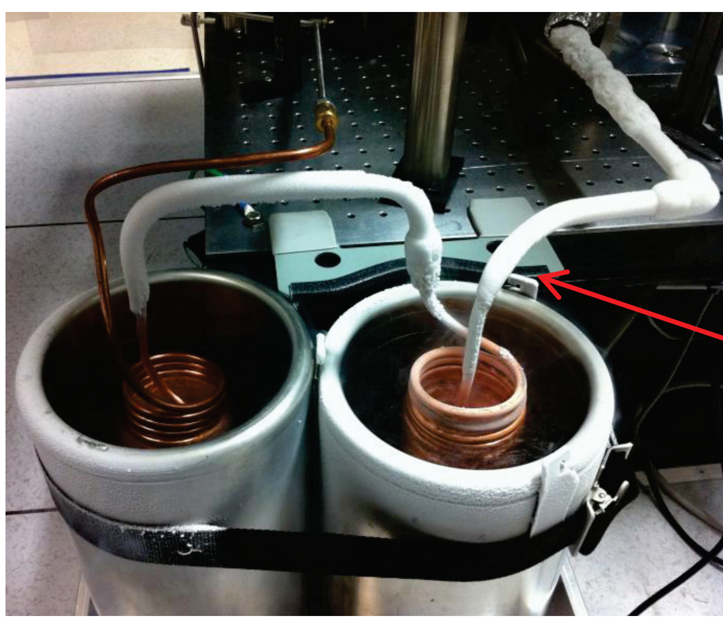


- Most of the laser pulse energy is absorbed by the atomic clusters.
- Clusters experience Coulomb explosion after electrons escape.
- DD fusion occurs, and 2.45MeV fusion neutrons are produced.

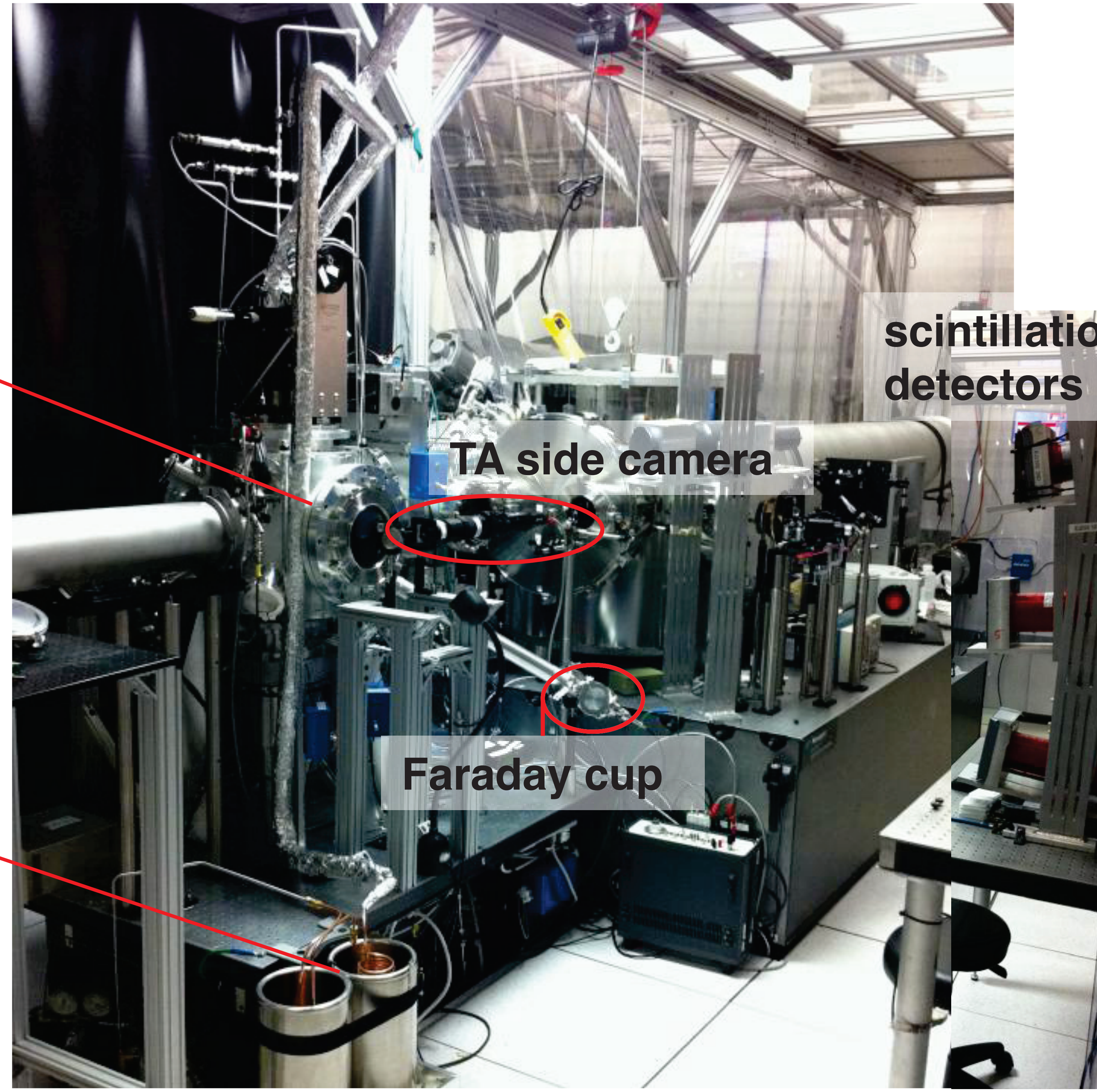
fusion experiments on the Texas Petawatt

Target area of the Texas Petawatt for the cluster fusion experiment





LN2 cooling line



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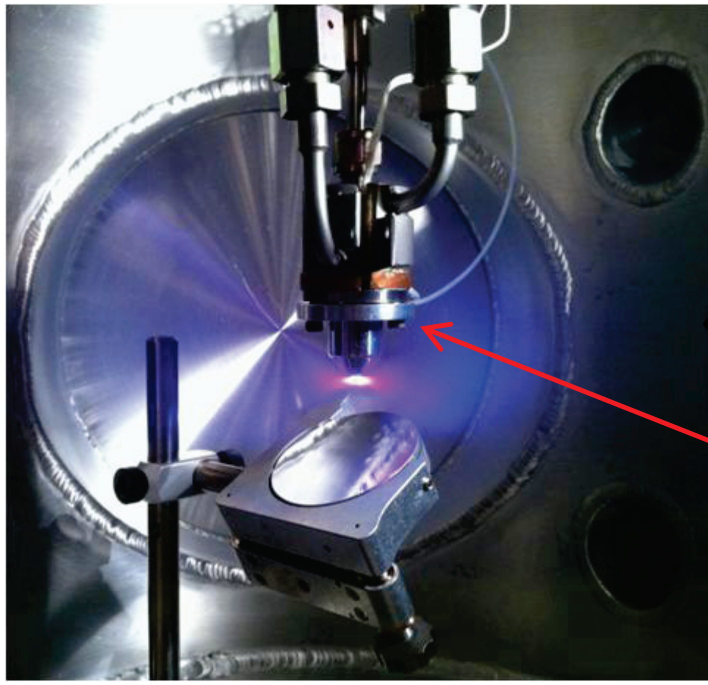

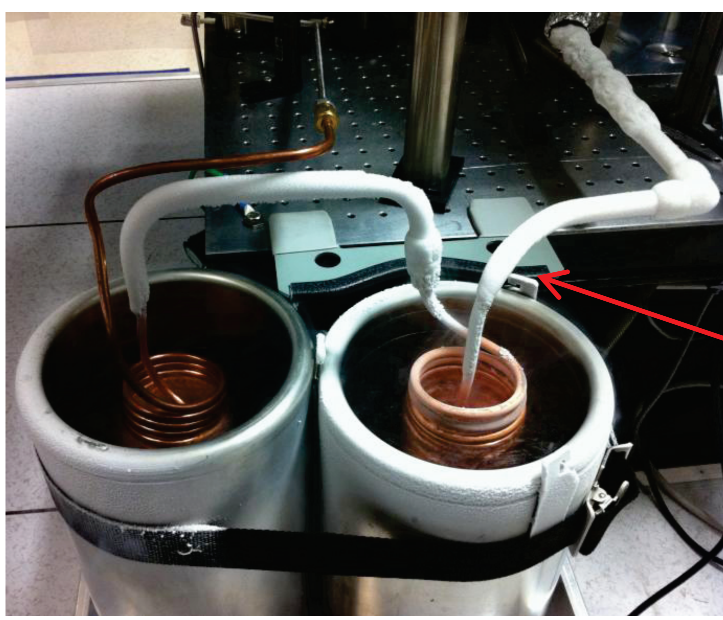

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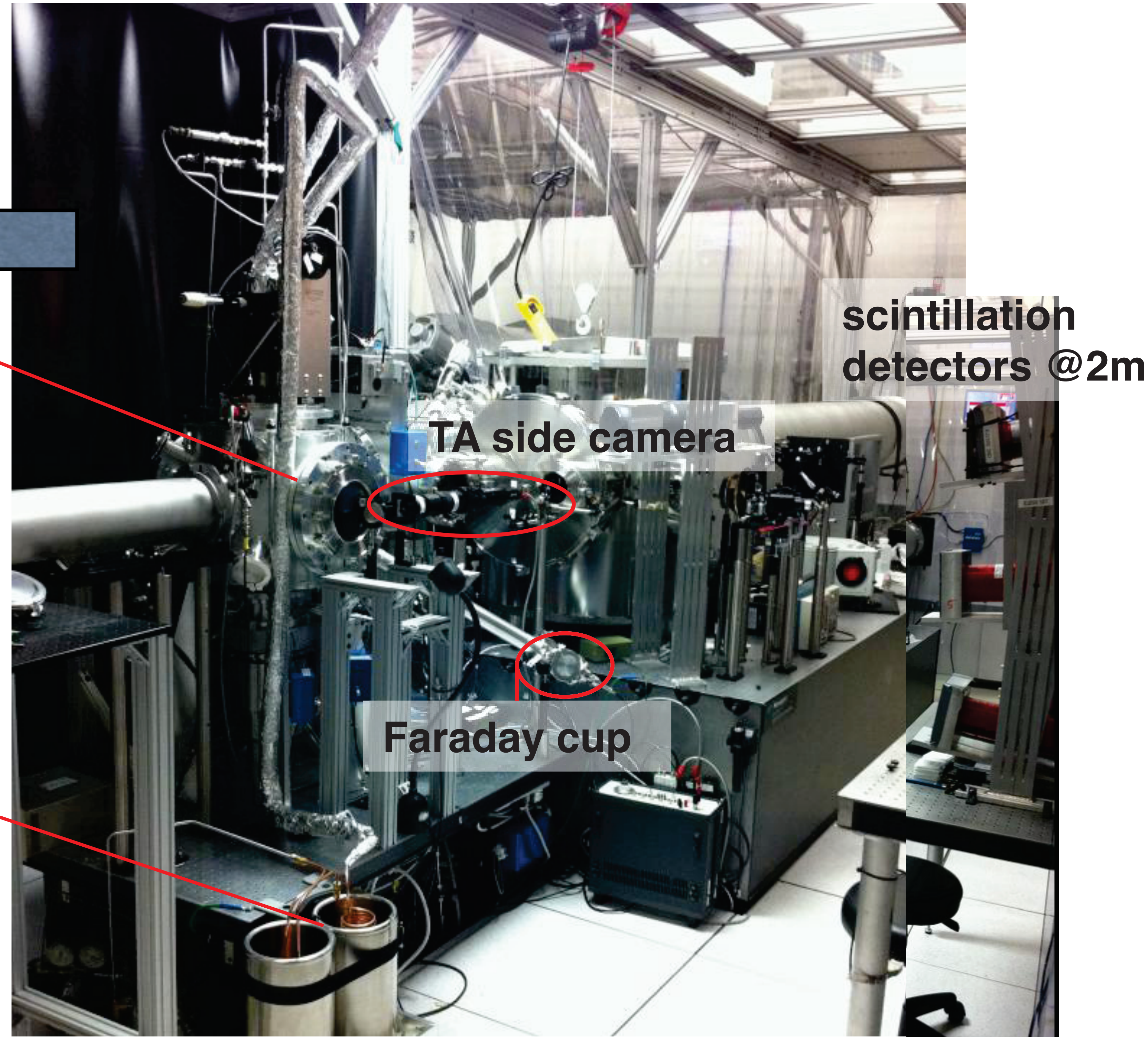

Temperature Measurements of Fusion Plasmas Produced by Petawatt-Laser-Irradiated $D_2 - {}^3He$ or $CD_4 - {}^3He$ Clustering Gases

W. Bang,[1,*] M. Barbui,[2] A. Bonasera,[2,3] G. Dyer,[1] H. J. Quevedo,[1] K. Hagel,[2] K. Schmidt,[2] F. Consoli,[4] R. De Angelis,[4] P. Andreoli,[4] E. Gaul,[1] A. C. Bernstein,[1] M. Donovan,[1] M. Barbarino,[2] S. Kimura,[3] M. Mazzocco,[5] J. Sura,[6] J. B. Natowitz,[2] and T. Ditmire[1]

[1]*Center for High Energy Density Science, C1510, University of Texas at Austin, Austin, Texas 78712, USA*
[2]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
[3]*LNS-INFN, Via S. Sofia 64, 95123 Catania, Italy*
[4]*Associazione Euratom-ENEA sulla Fusione, via E. Fermi 45, CP 65-00044 Frascati (Rome), Italy*
[5]*Physics Department, University of Padova and INFN, I-35131 Padova, Italy*
[6]*Heavy Ions Laboratory, University of Warsaw, ul. Pasteura 5a, 02-093 Warszawa, Poland*
(Received 25 February 2013; published 30 July 2013)

Two different methods have been employed to determine the plasma temperature in a laser-cluster fusion experiment on the Texas Petawatt laser. In the first, the temperature was derived from time-of-flight data of deuterium ions ejected from exploding D_2 or CD_4 clusters. In the second, the temperature was measured from the ratio of the rates of two different nuclear fusion reactions occurring in the plasma at the same time: $D(d, {}^3He)n$ and ${}^3He(d, p){}^4He$. The temperatures determined by these two methods agree well, which indicates that (i) the ion energy distribution is not significantly distorted when ions travel in the disassembling plasma; (ii) the kinetic energy of deuterium ions, especially the "hottest part" responsible for nuclear fusion, is well described by a near-Maxwellian distribution.

DOI: 10.1103/PhysRevLett.111.055002 PACS numbers: 52.50.Jm, 25.45.−z, 36.40.Wa

Nuclear fusion from explosions of laser-heated clusters has been an active research topic for over a decade [1–11]. Researchers have used explosions of cryogenically cooled deuterium (D_2) cluster targets or near-room-temperature deuterated methane cluster plasmas produced by the irradiation of a clustering gas jet by 150 fs petawatt peak power laser pulses. We find that the effective ion temperature produced can be in excess of 25 keV.

Measurement of the Plasma Astrophysical *S* Factor for the ^{3}He(^{2}H, *p*)^{4}He Reaction in Exploding Molecular Clusters

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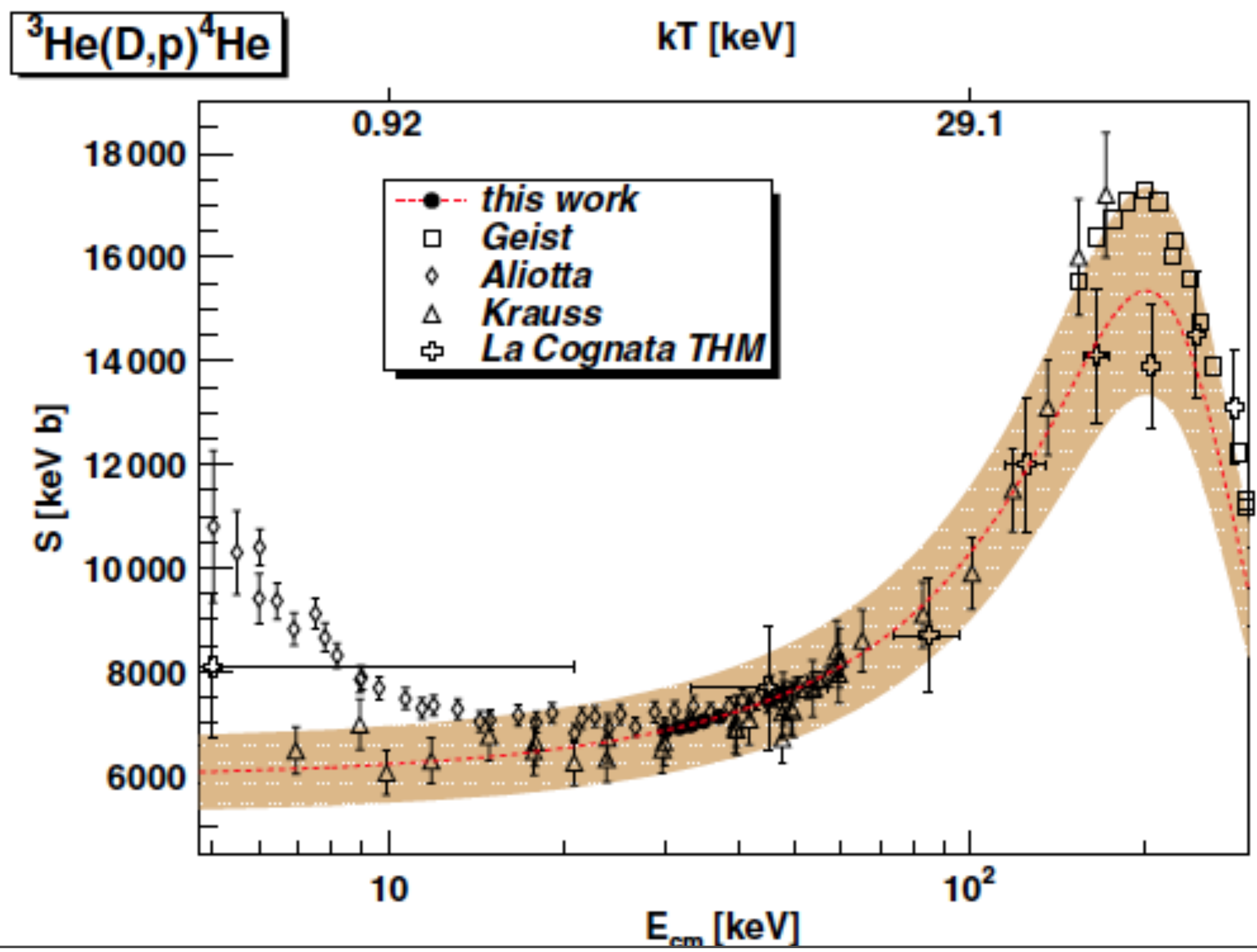

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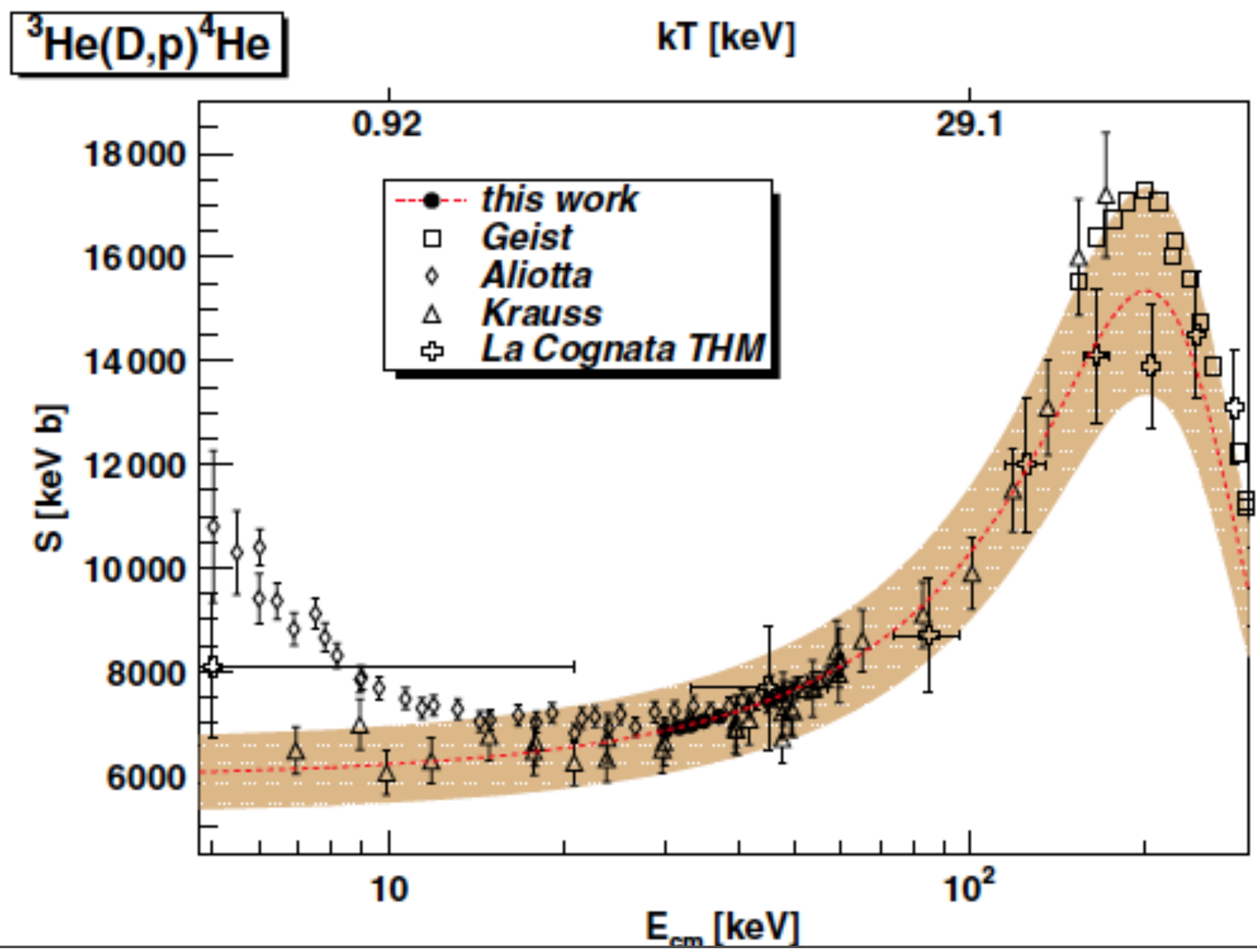

UT-Petawatt laser

100-200 J in 150-200 fs

$D+^3He$

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ABC-ENEA laser

2 beams -100 J in 3 ns

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We are trying to study fusion reaction on heavier systems but with less powerful lasers!!

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"..we do not because it is easy but because it is hard!" (J.F.K.)

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"..that is what we have available nowadays."

EXPERIMENTS LAYOUT

- Two laser beams collide onto ***solids*** ^{11}B target with different geometries
- During the experiment, a total of 10 Faraday cups were employed to collect data at different angles.

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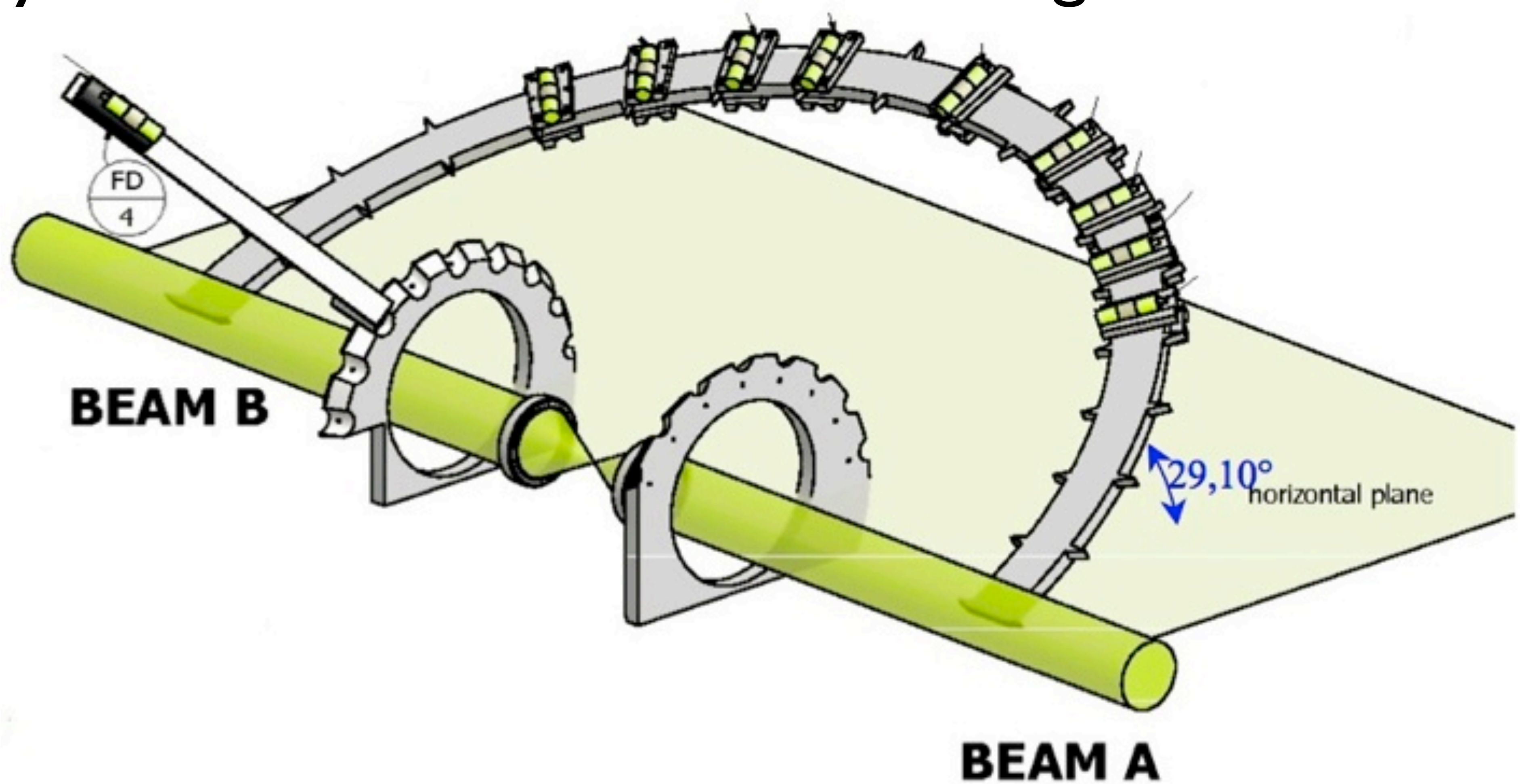

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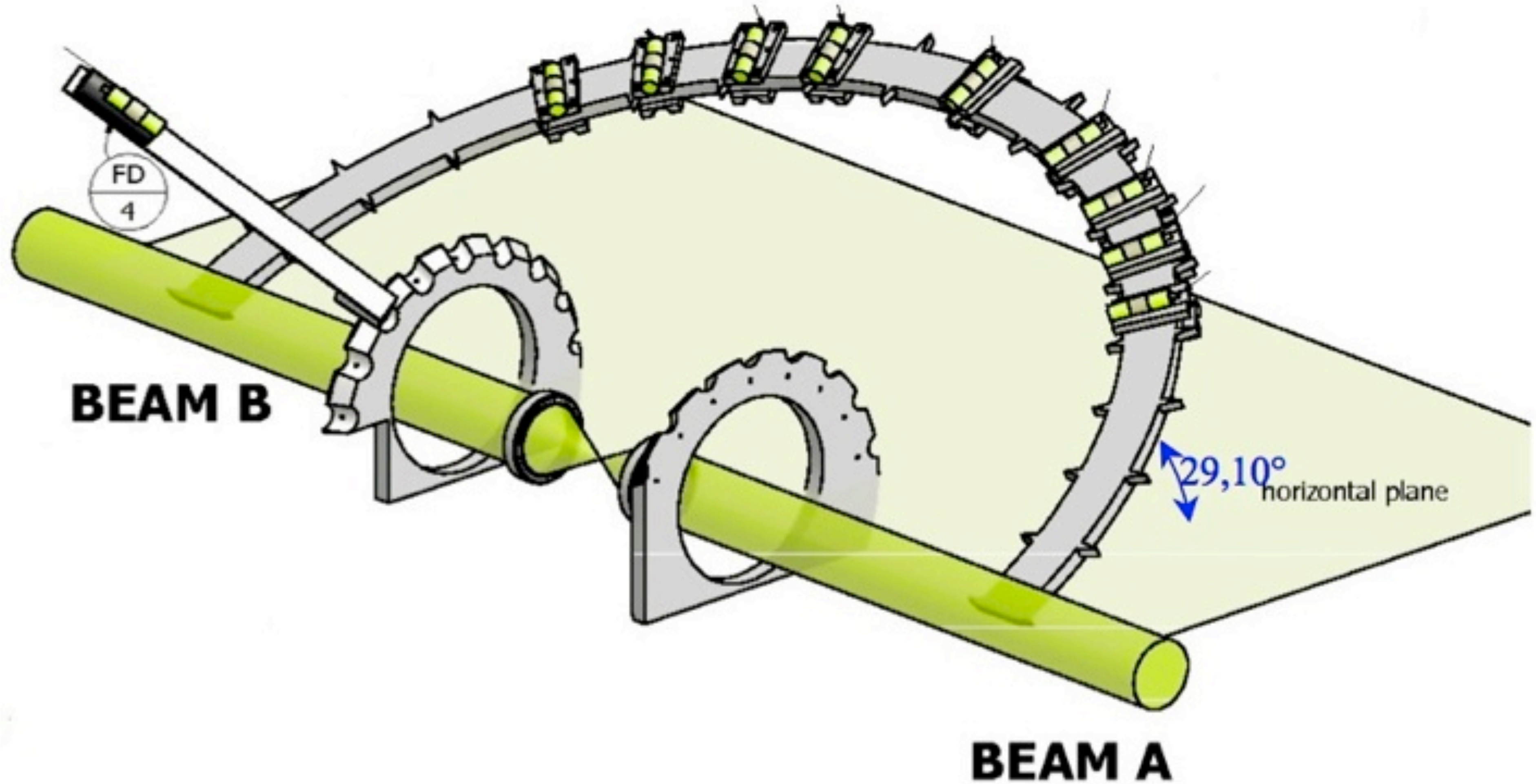
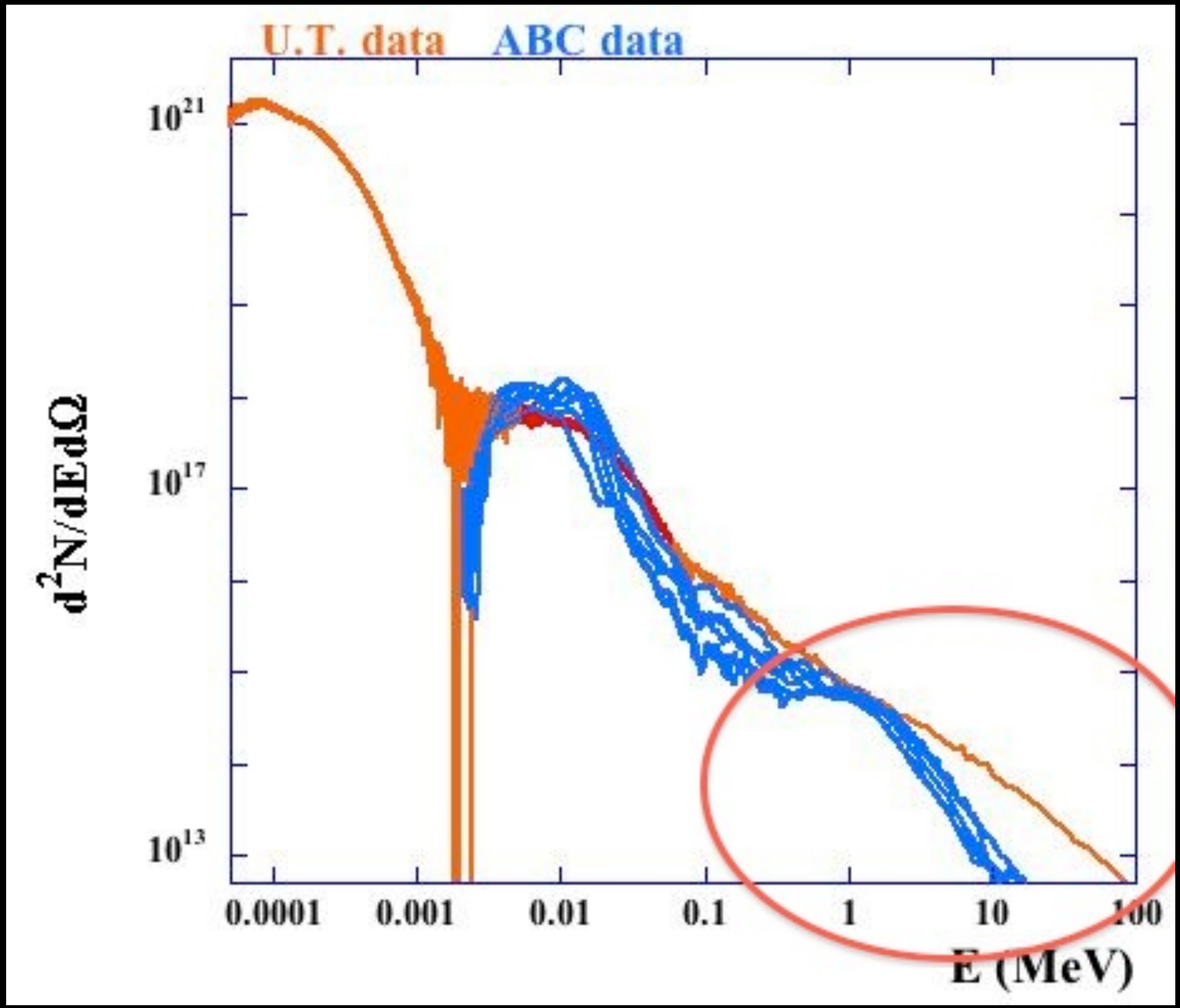
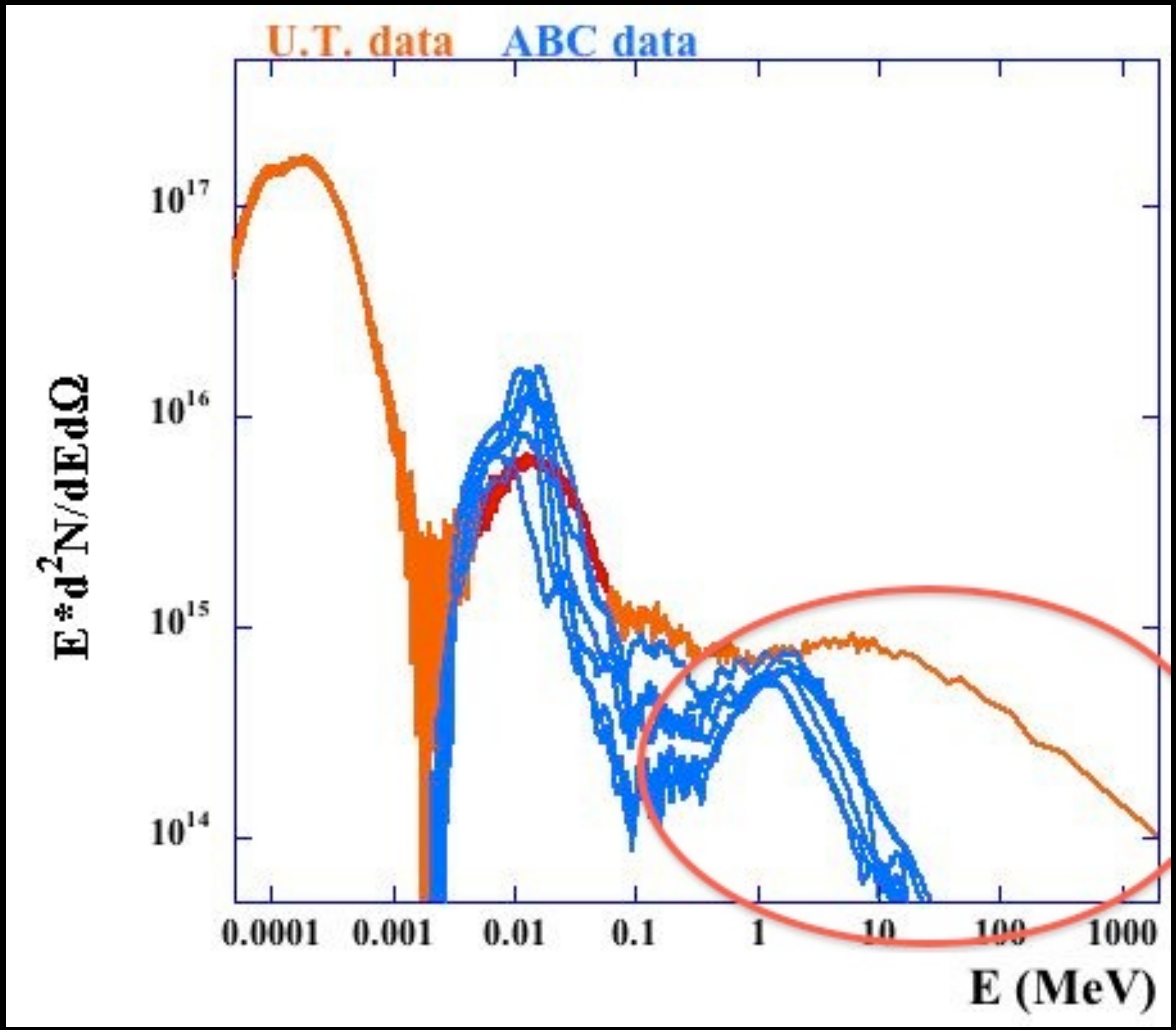


HERE BORON ATOMS ONLY!

ABC - U.T. DATA COMPARISON





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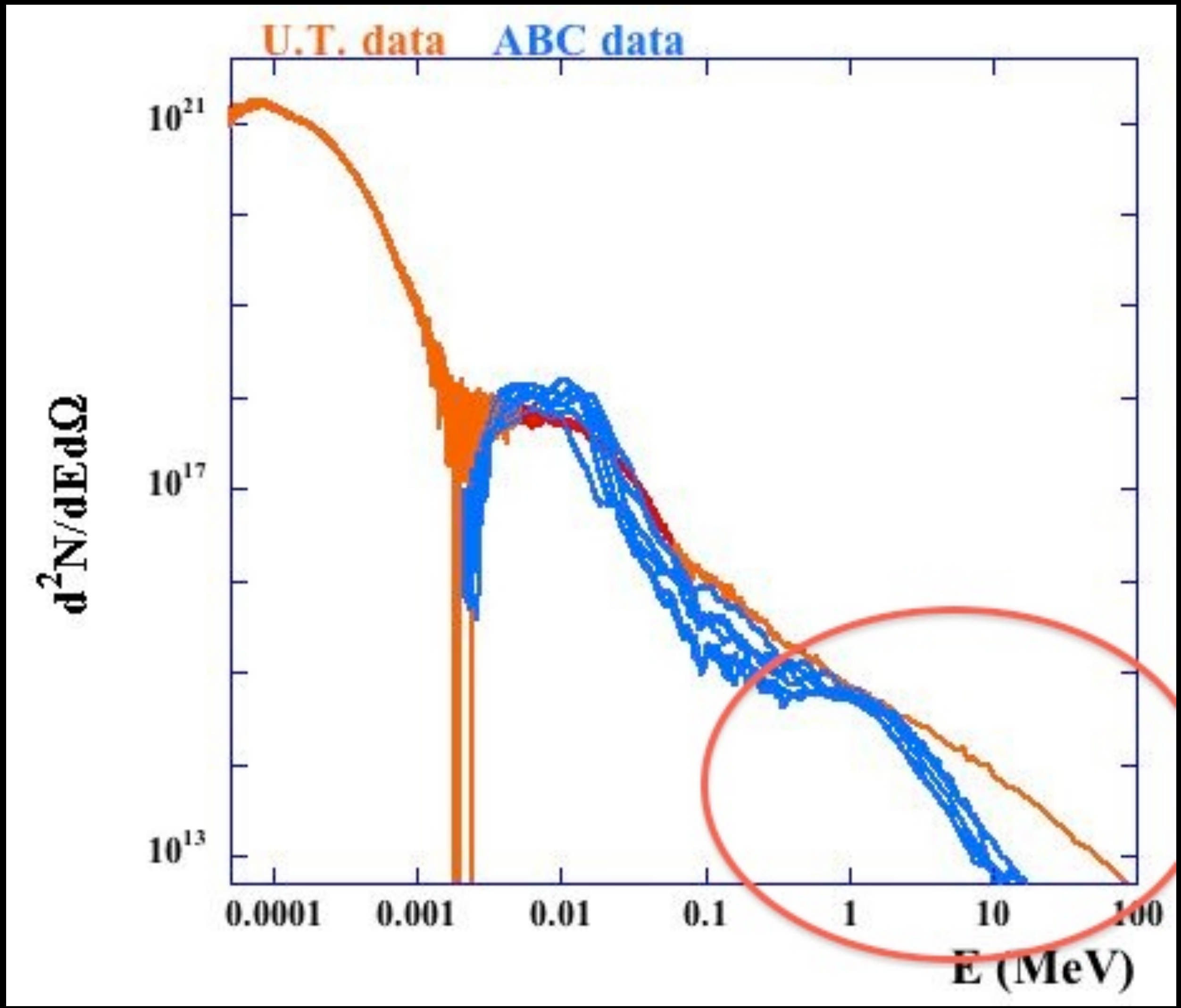

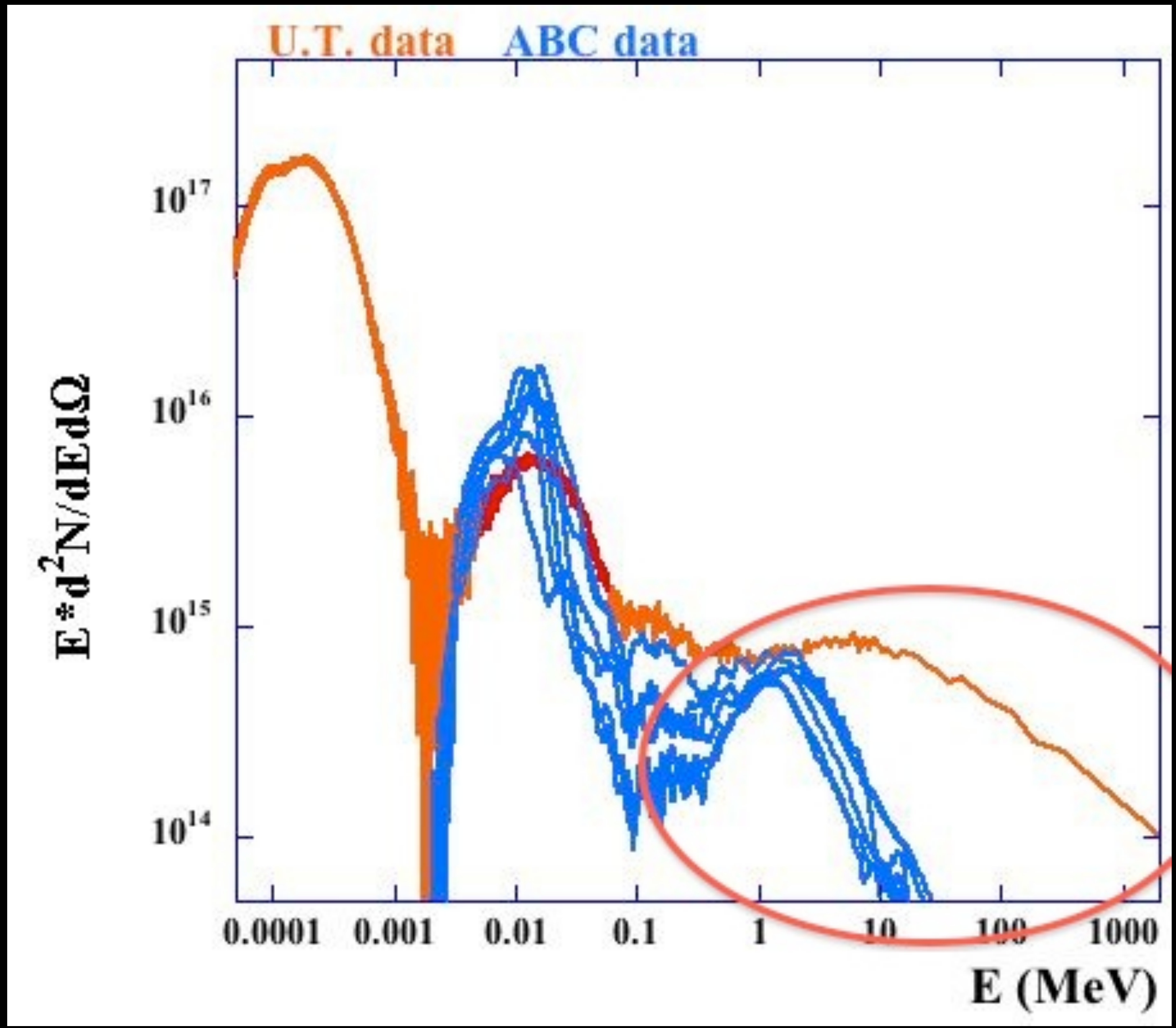

Experiments at ABC show less electromagnetic noise!

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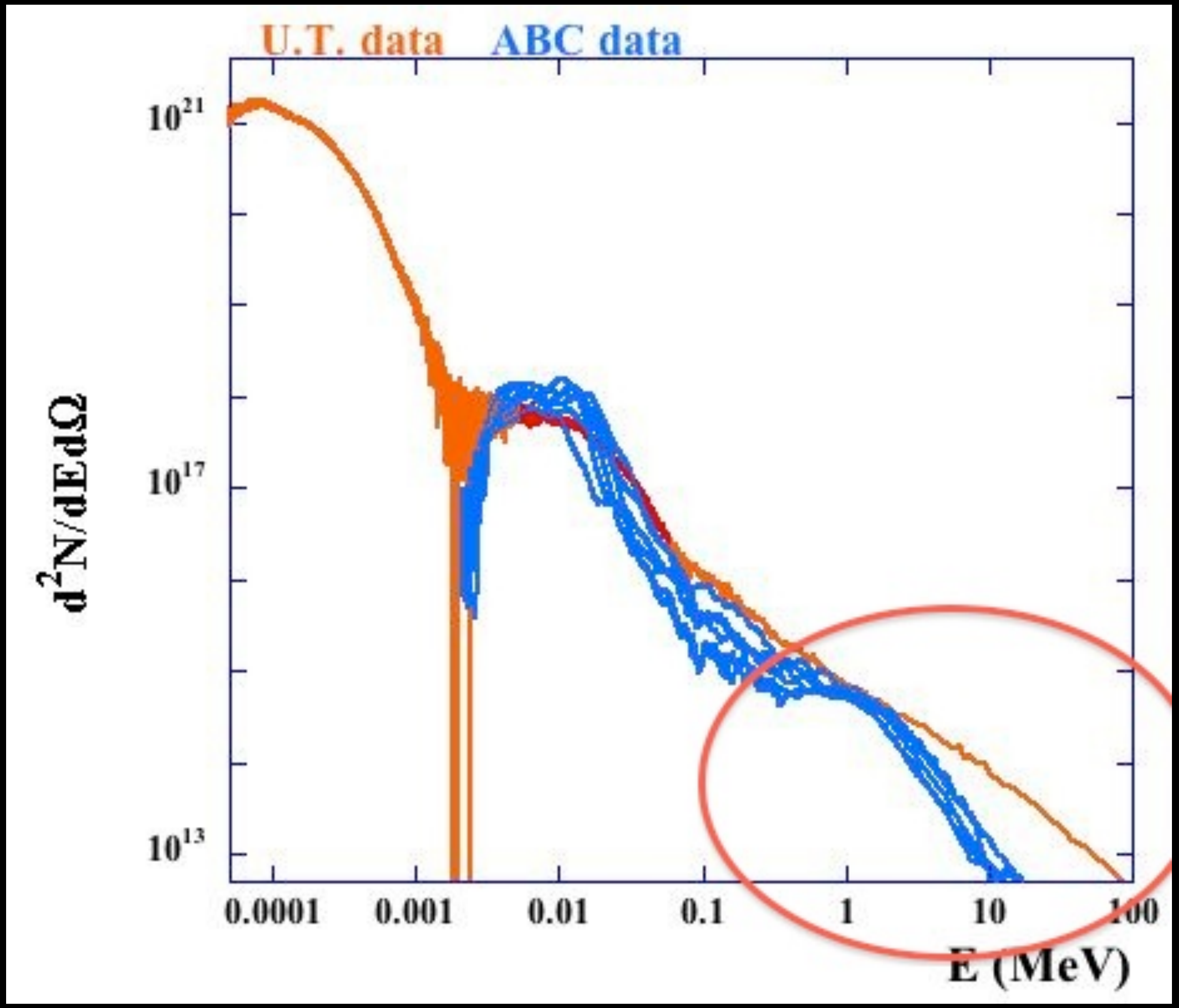

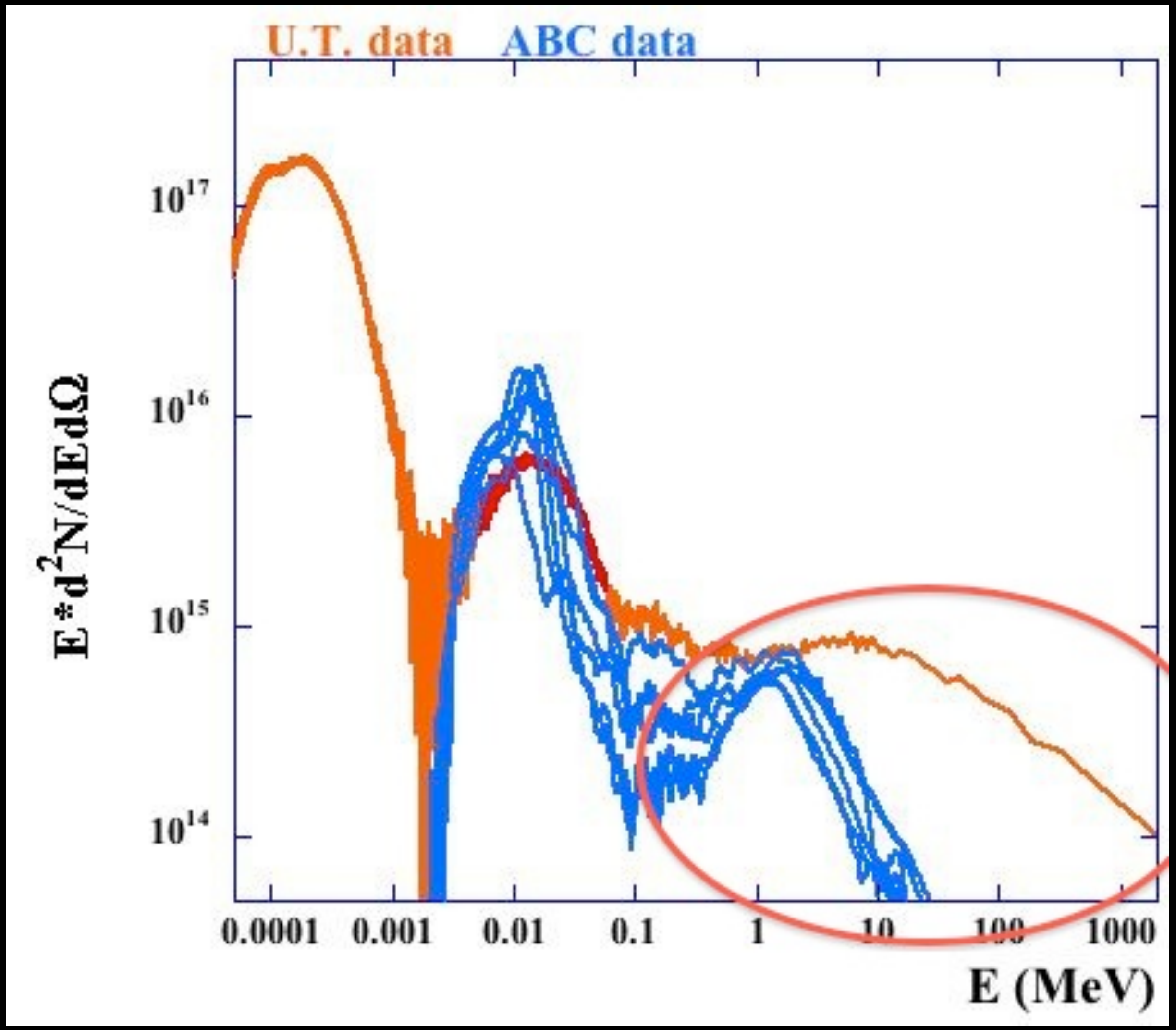

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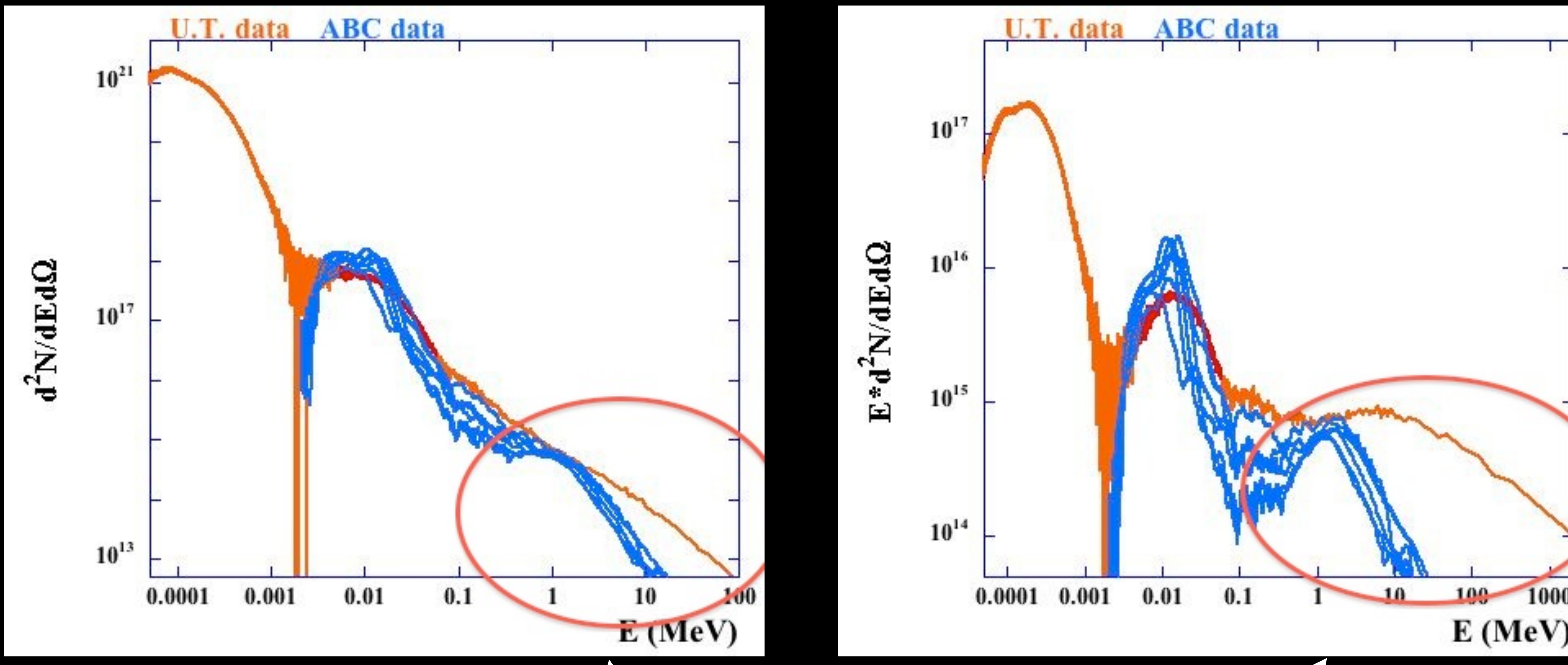

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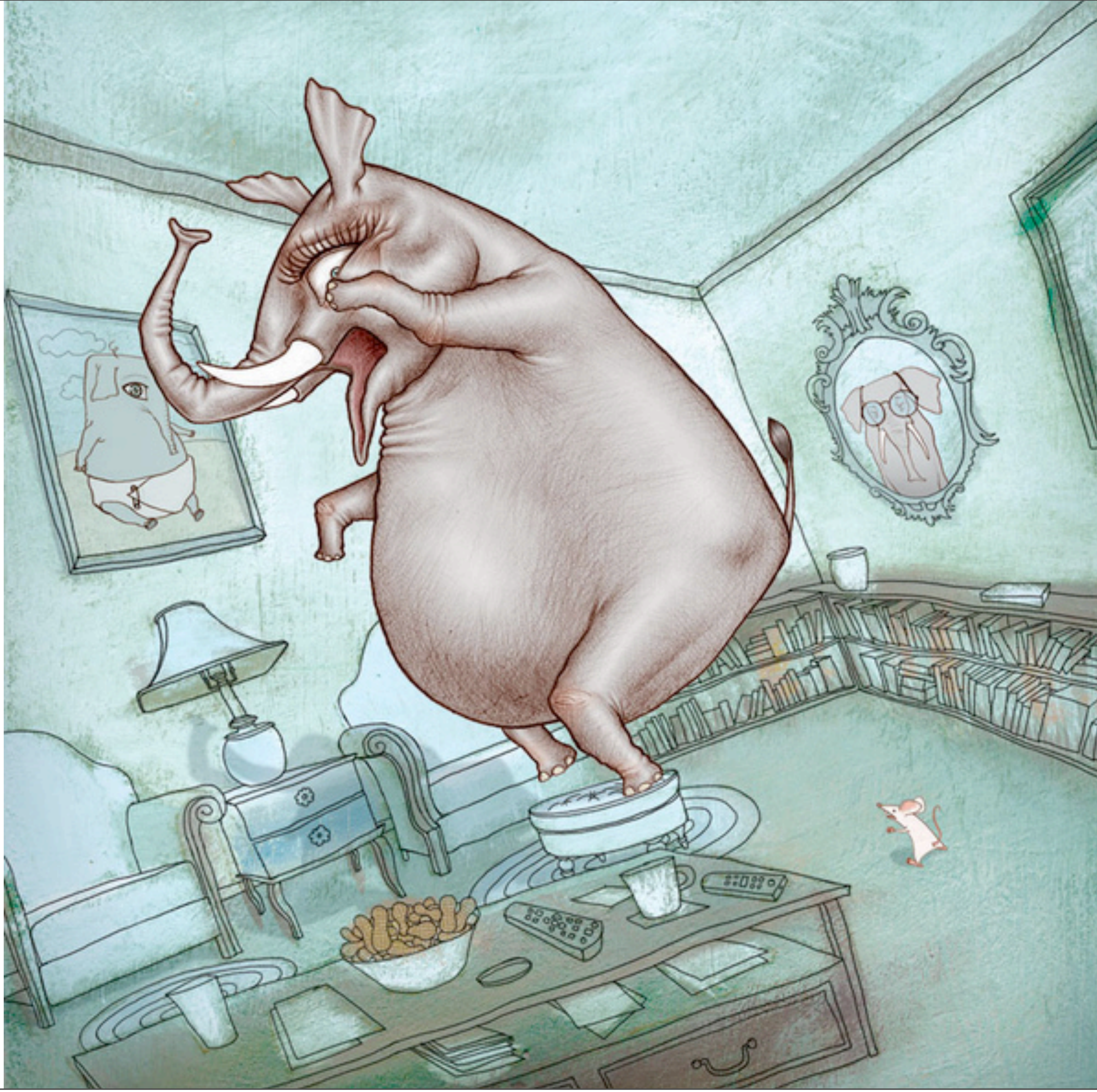


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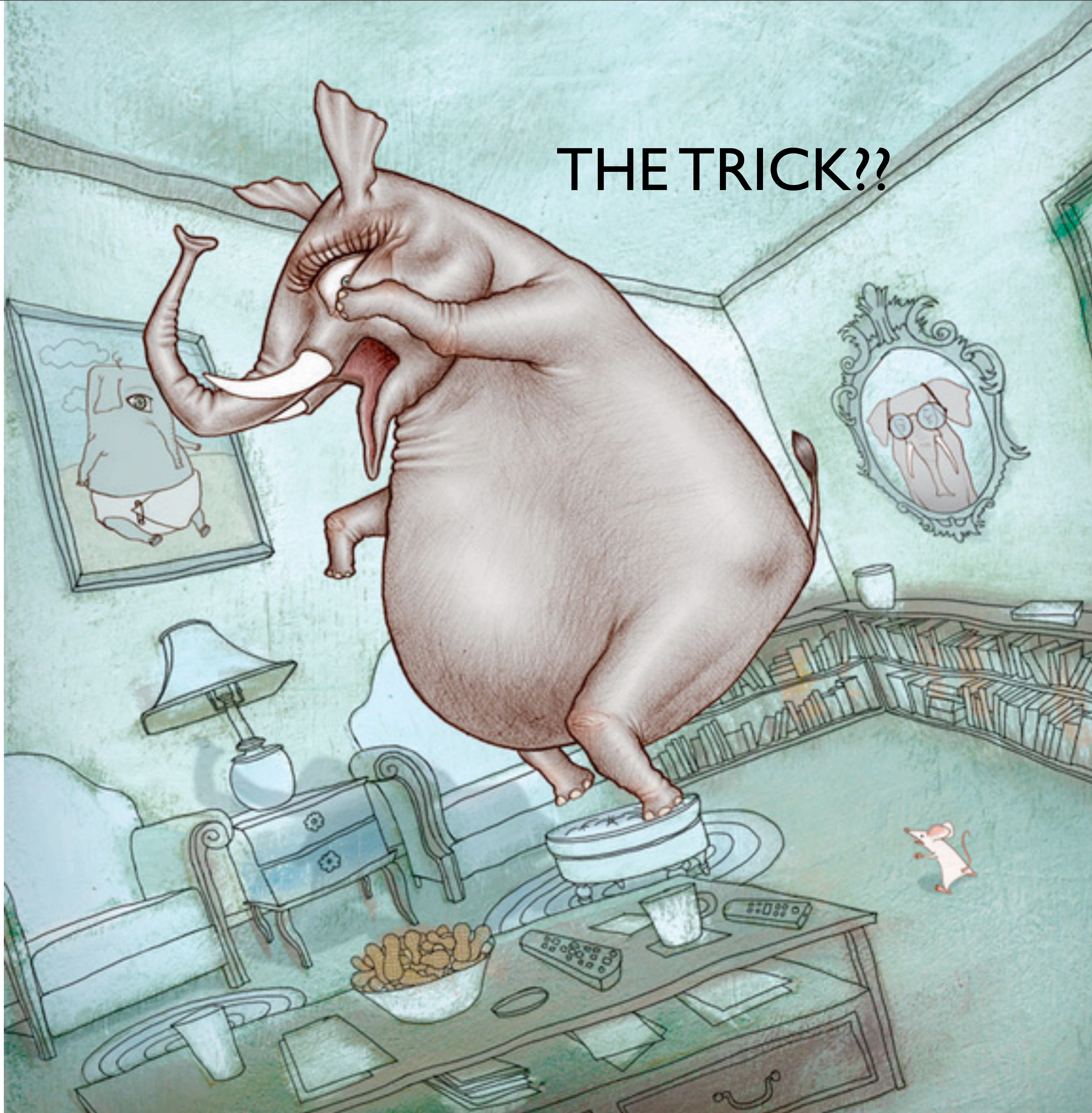
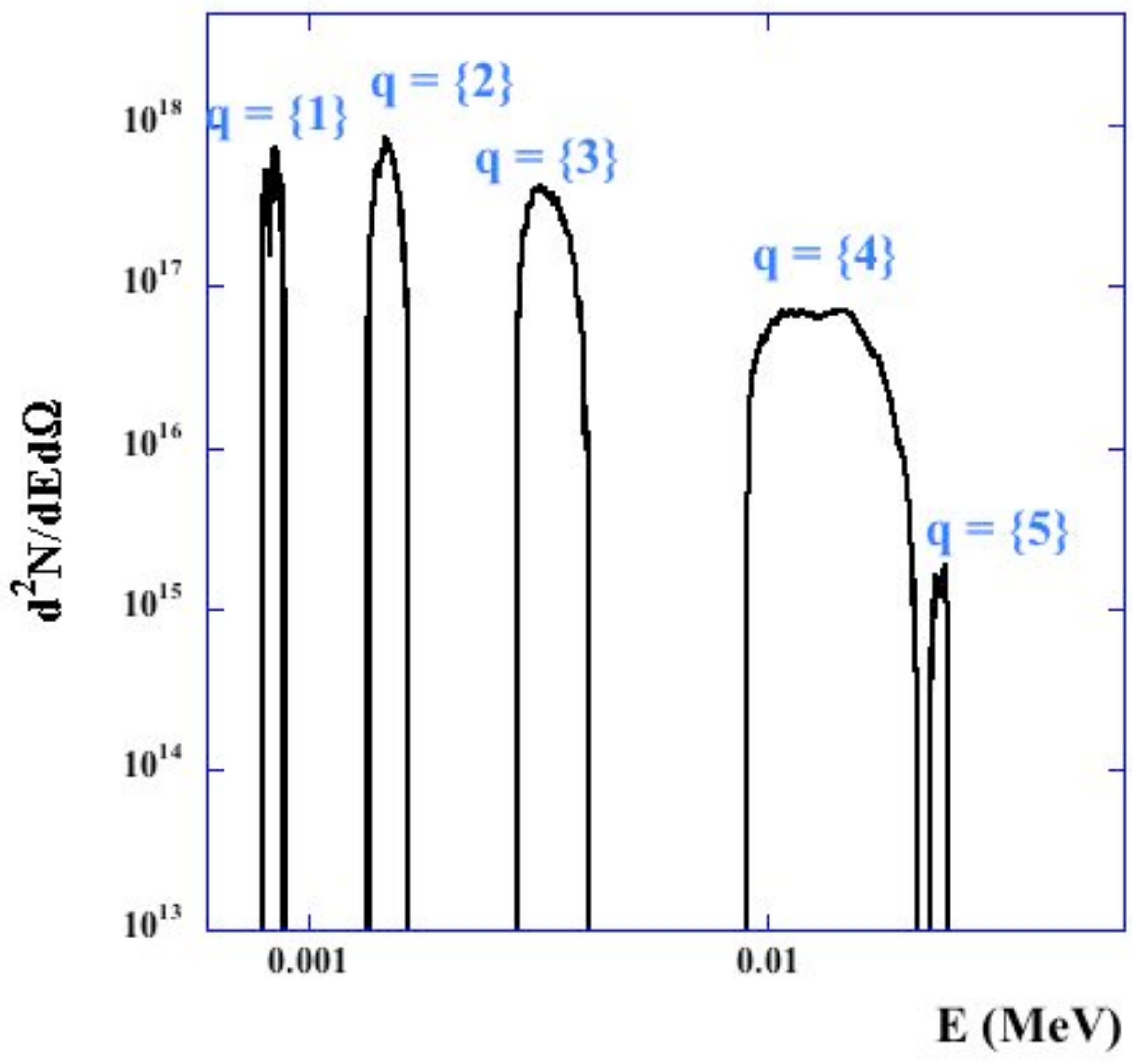
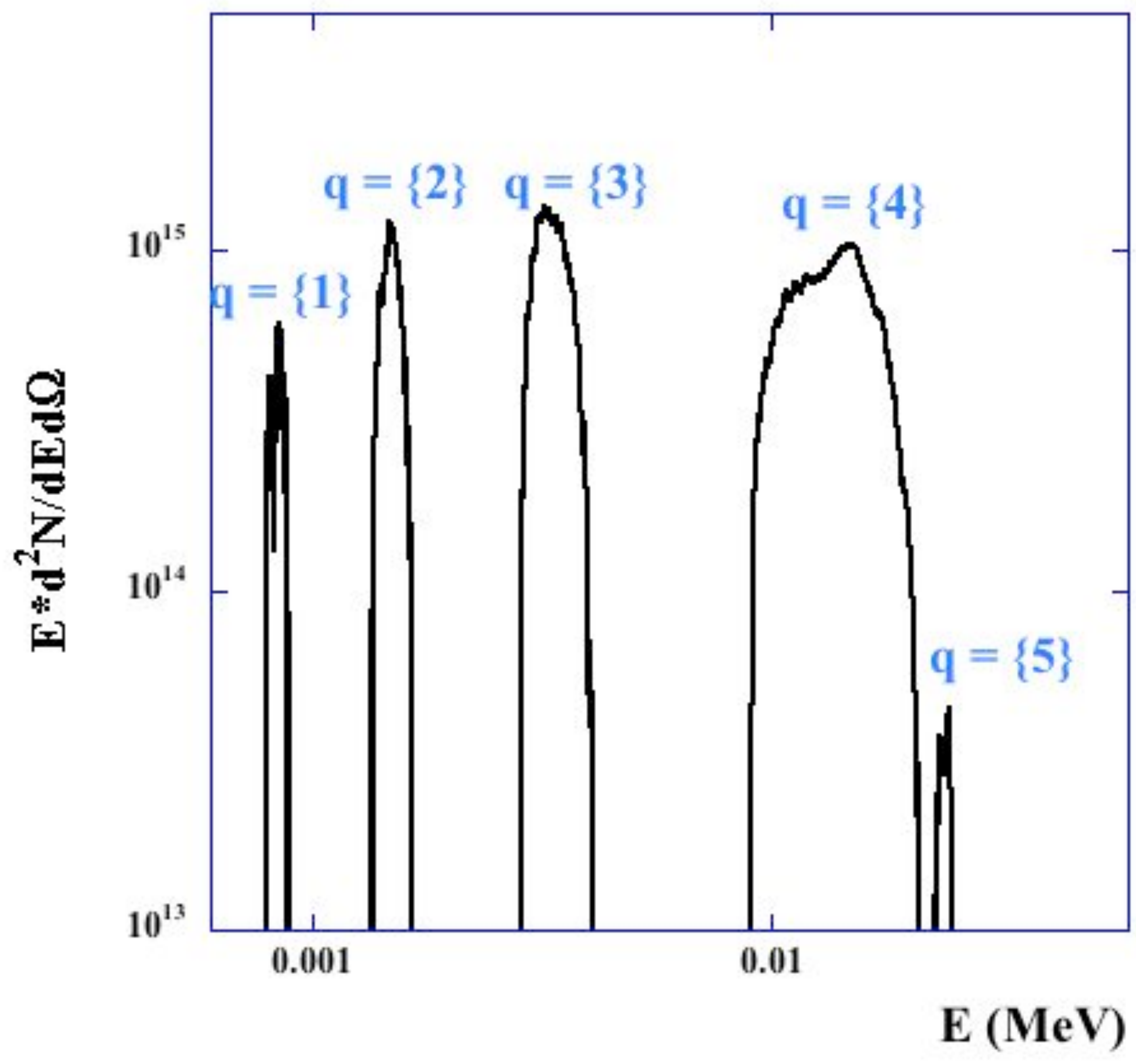


PRODUCT OF ITALY
Frascati
Denominazione di Origine Controllata
Secco
From the picturesque hills surrounding the Frascati area in central Italy. A dry and creamy light Italian white with Crisp & Refreshing flavours

DATA ANALYSIS

FARADAY CUP at 72.75°

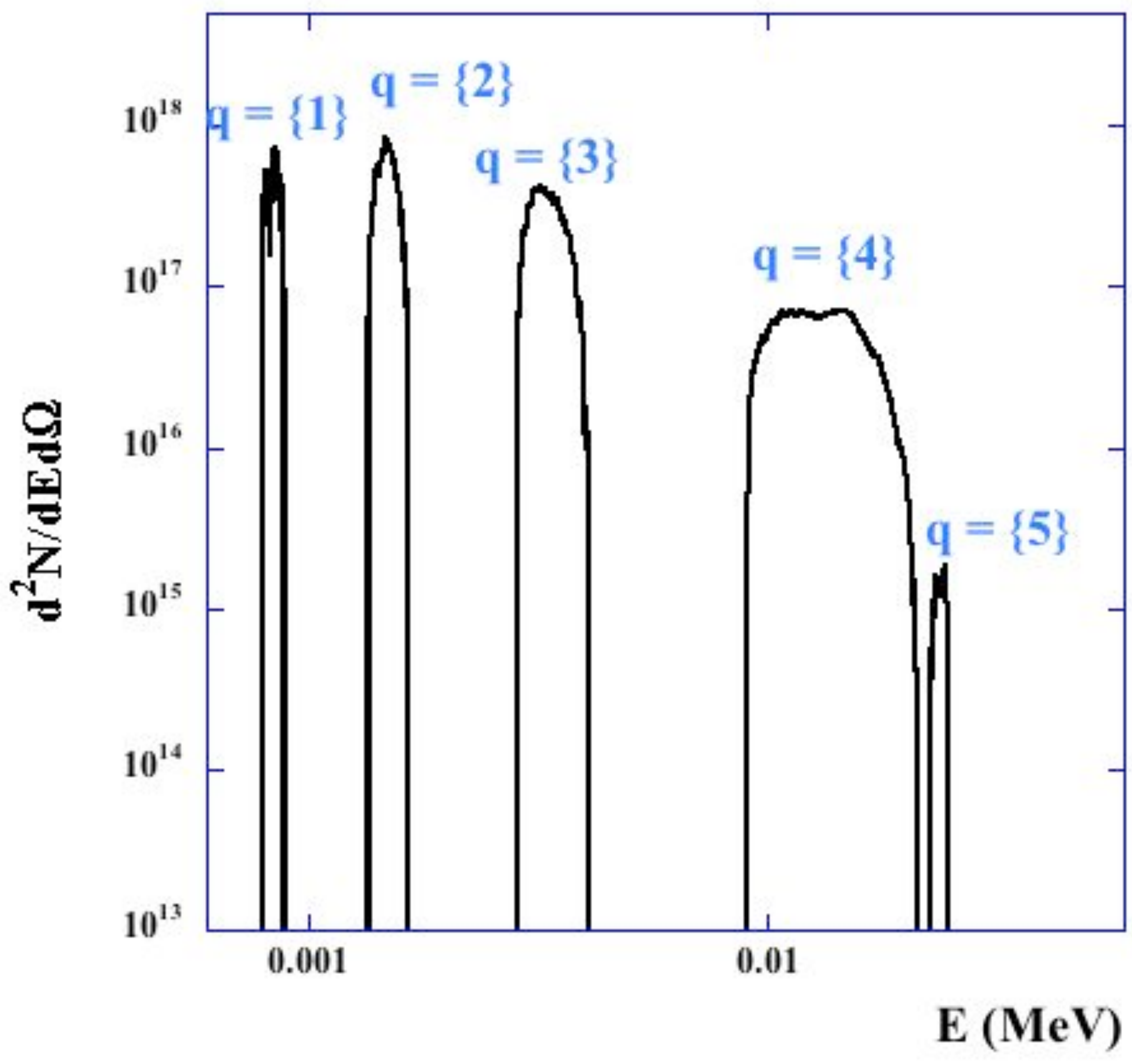


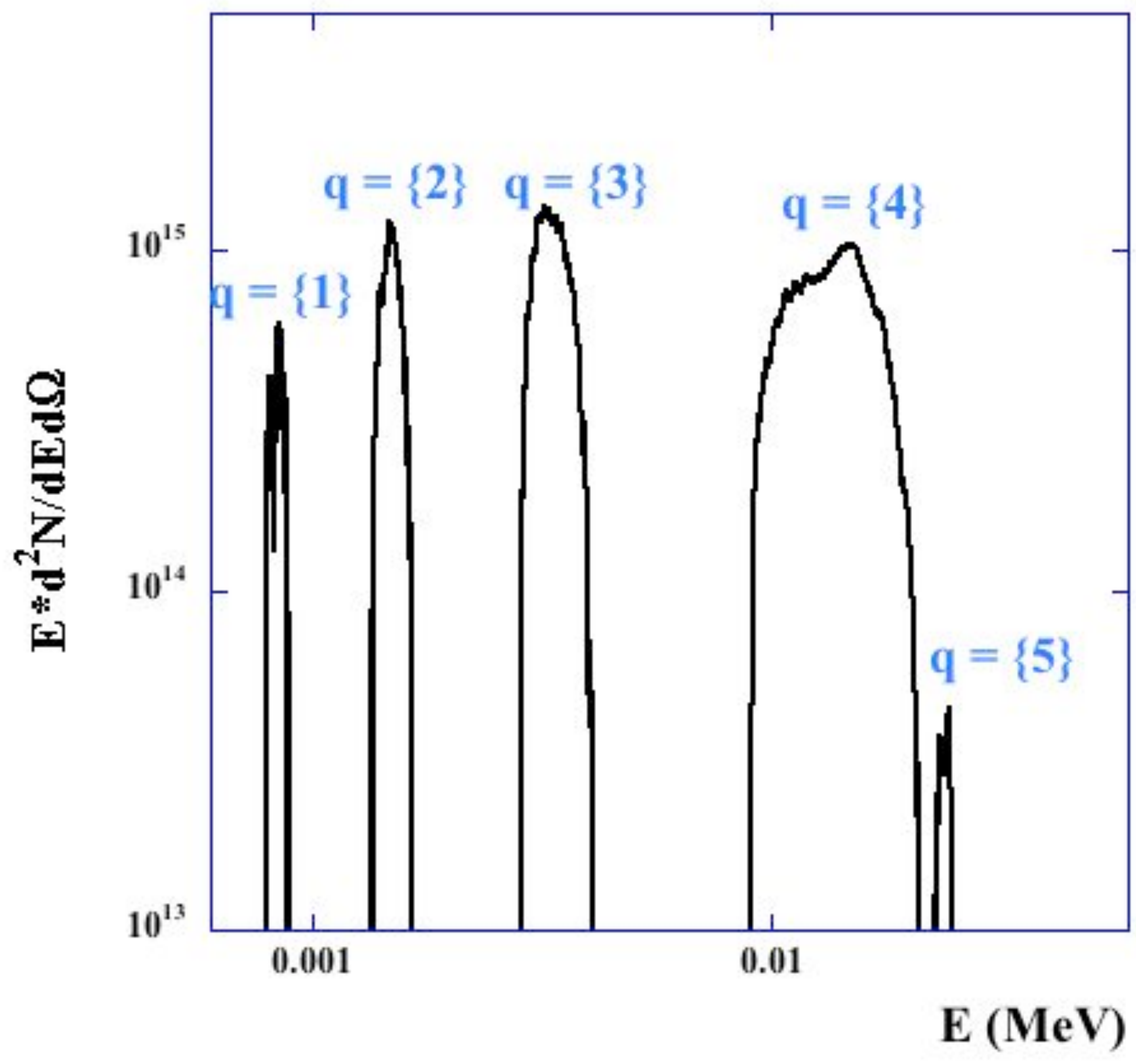


DATA ANALYSIS

FARADAY CUP at 72.75°

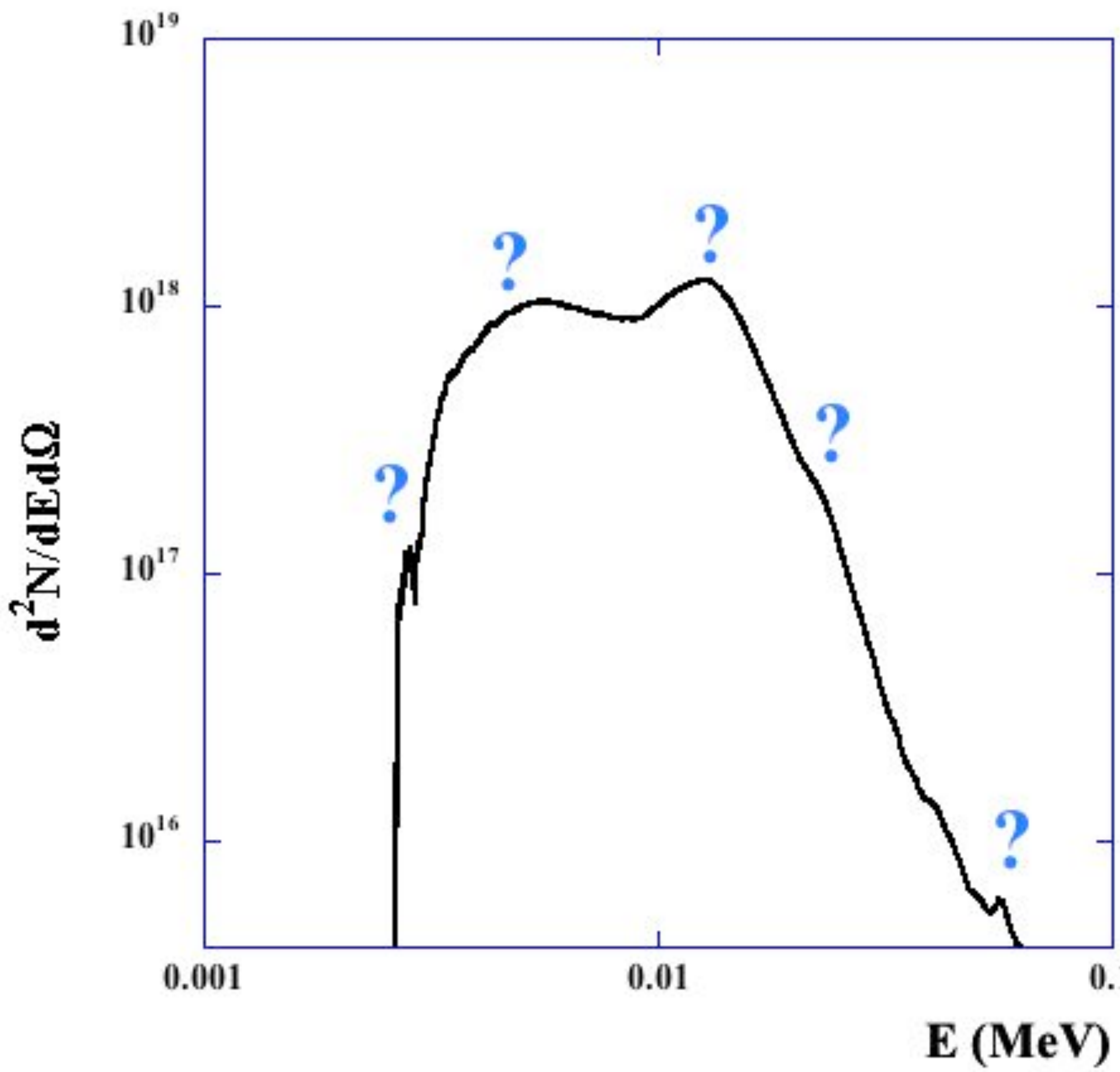
EASY

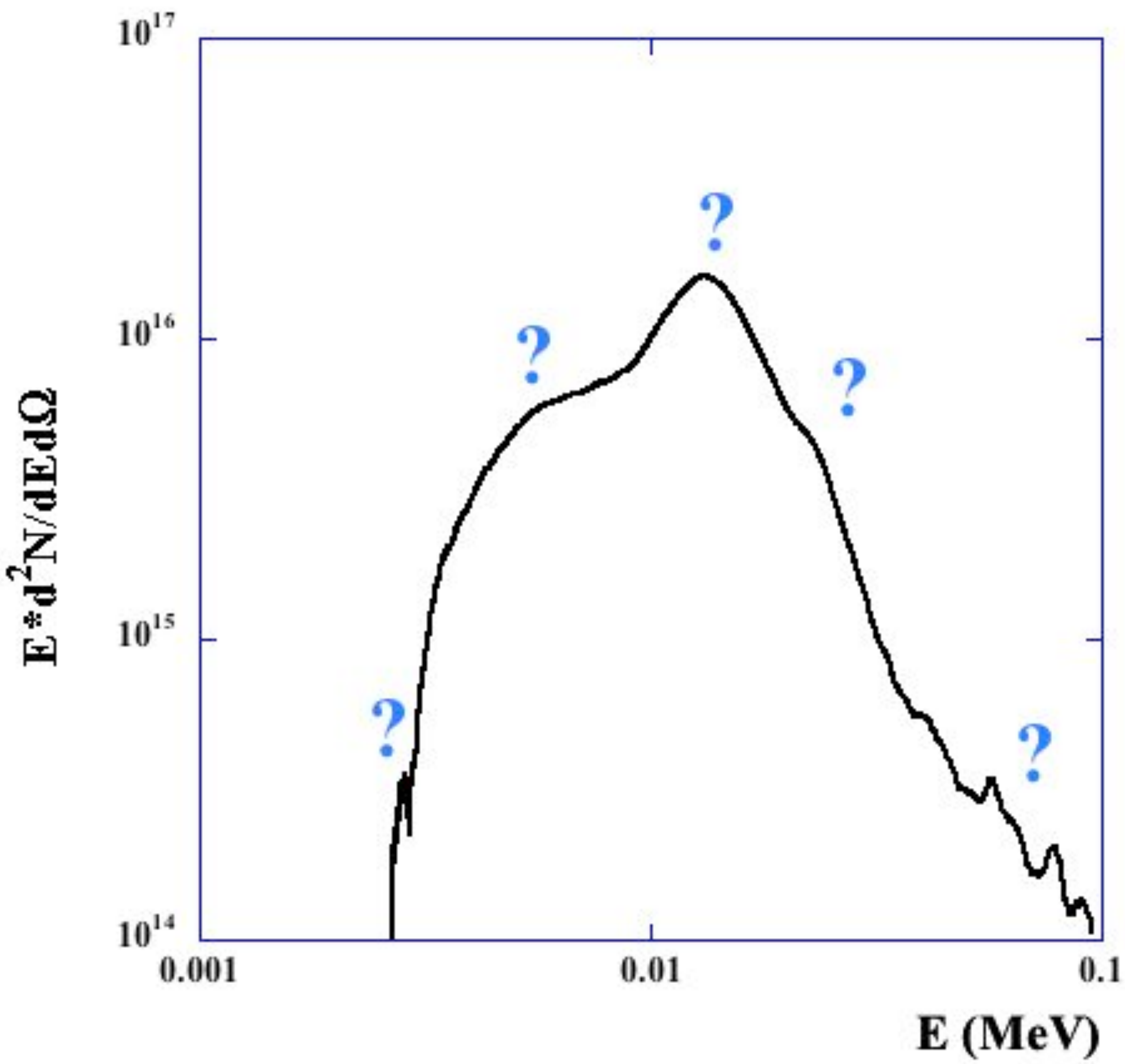




DATA ANALYSIS

FARADAY CUP at 127.5°

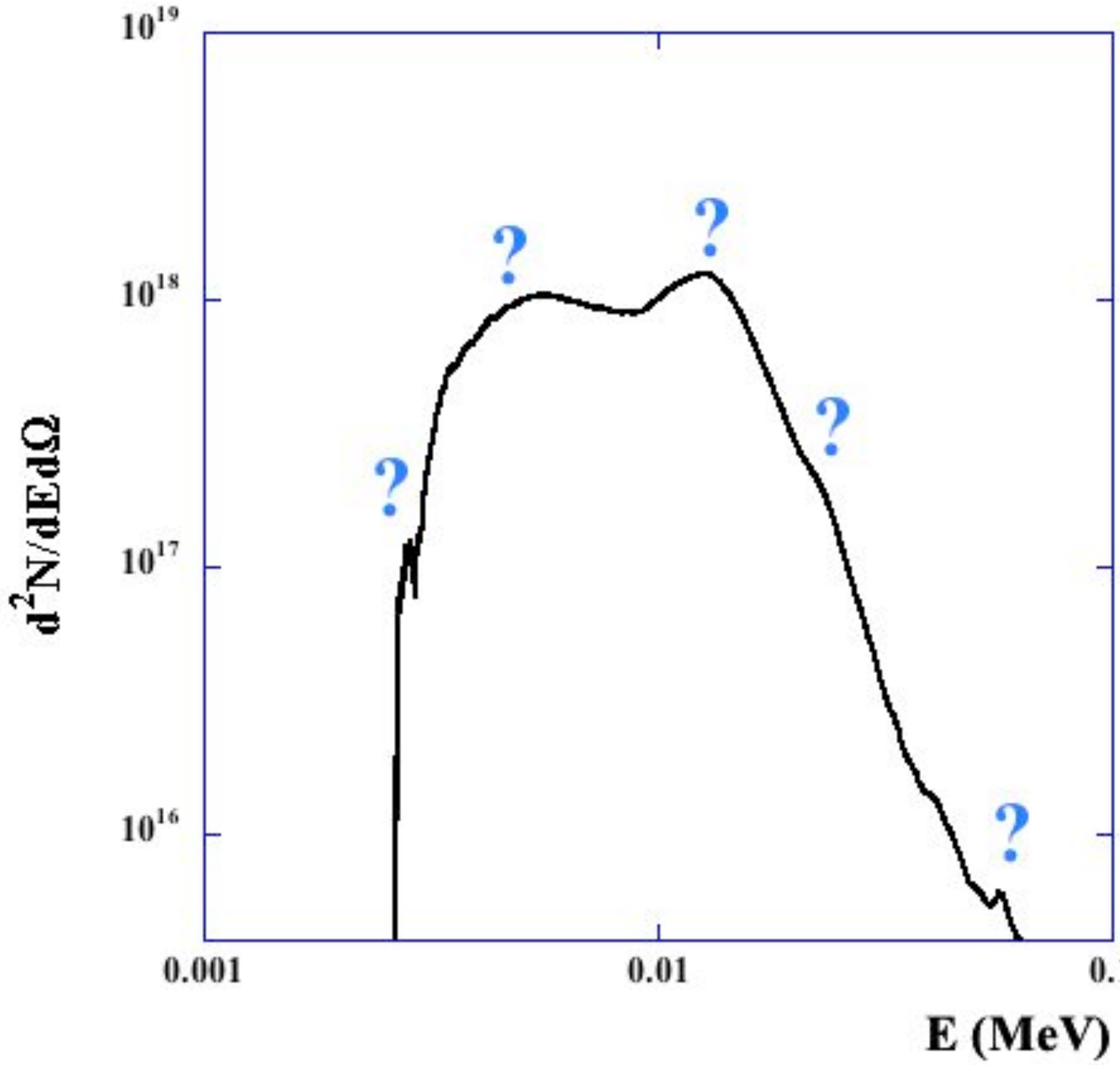


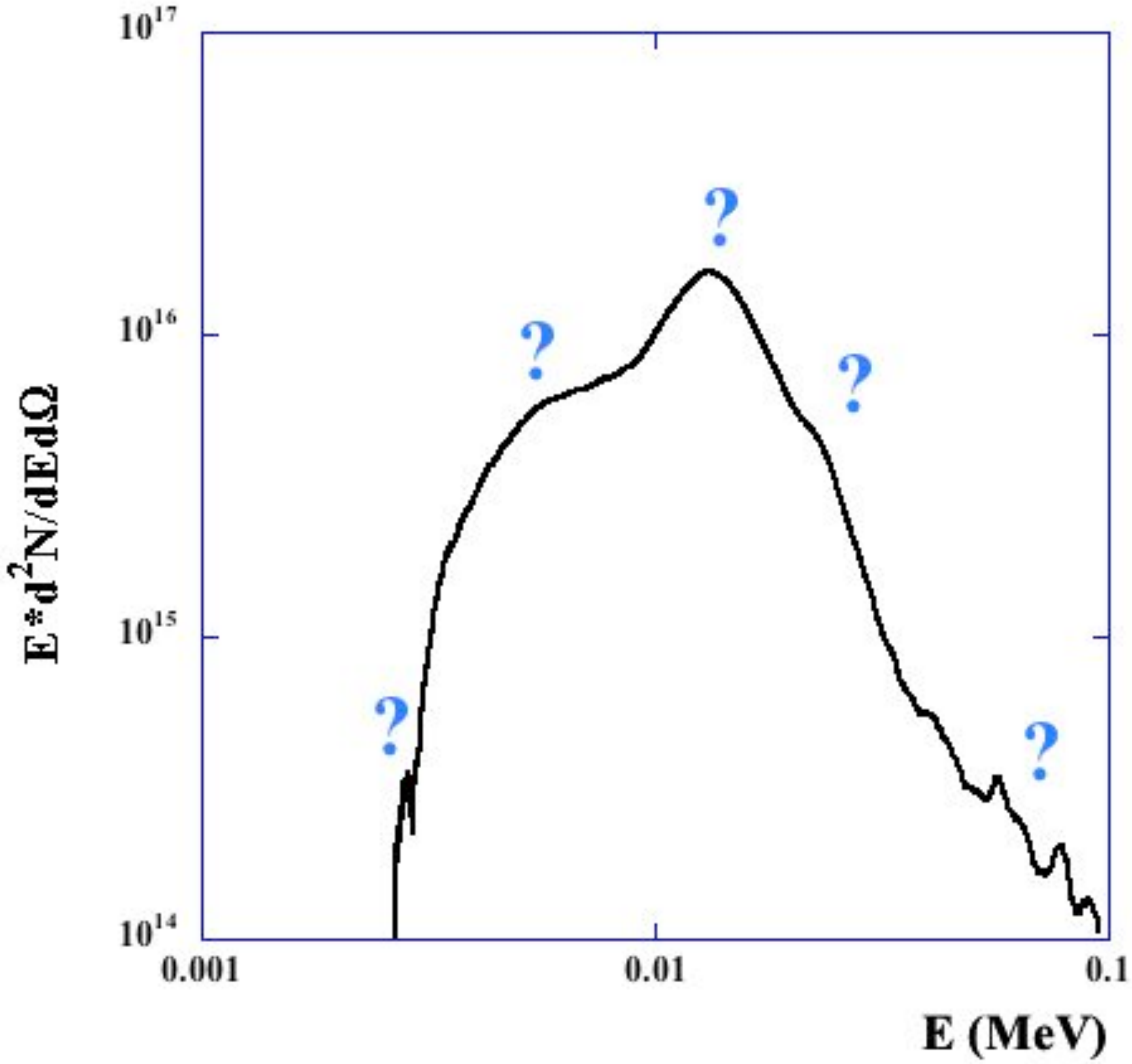


DATA ANALYSIS

FARADAY CUP at 127.5°

MORE
COMPLICATED





ENERGY MOMENTS
DATA ANALYSIS

MAXWELL DISTRIBUTION

$$\frac{d^2N}{dE\,d\Omega} = \frac{c}{T^{\frac{3}{2}}} \left(\frac{m}{2}\right)^{\frac{1}{2}} v \quad e^{-\frac{mv^2}{2T}} = \frac{c}{T^{\frac{3}{2}}} \quad E^{\frac{1}{2}} \quad e^{-\frac{E}{T}}$$

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assuming that particles experience an accelerating potential E_c:

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$$E \Rightarrow \quad (E - E_c)$$

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i.e. electrons are stripped by the laser and the ions accelerate due to repulsive Coulomb

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$$\frac{d^2N_{E_{(n)}}}{dEd\Omega} = \frac{c}{T^{\frac{3}{2}}} E^n \left(E - E_c\right)^{\frac{1}{2}} \quad e^{-\frac{(E-E_c)}{T}}$$

ENERGY MOMENTS
DATA ANALYSIS

WITH MAXIMA AT:

ENERGY MOMENTS
DATA ANALYSIS

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ENERGY MOMENTS
DATA ANALYSIS

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$$E_{(n)\max} = \frac{1}{2}\left[\frac{2n+1}{2}T + E_c \pm \sqrt{\left(\frac{2n+1}{2}T + E_c\right)^2 - 4nTE_c} \right]$$

$$\frac{d^2 N_{E_{(n)\max}}}{dE\,d\Omega} = \frac{c}{T^{\frac{3}{2}}} \times E^n_{(n)\max} \left(E_{(n)\max} - E_c\right)^{\frac{1}{2}} e^{-\frac{\left(E_{(n)\max}-E_c\right)}{T}}$$

THUS, TOTAL ENERGY:

ENERGY MOMENTS
DATA ANALYSIS

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THUS, TOTAL ENERGY:

$$\langle E \rangle = \frac{4\pi}{q} \times \left(\frac{dN}{d\Omega} E_c + \frac{3}{2}\frac{dN}{d\Omega} T \right)$$

ENERGY MOMENTS

SPECIAL CASES

ENERGY MOMENTS
SPECIAL CASES

#1

ENERGY MOMENTS
SPECIAL CASES

#1 $T \to 0 \quad \Rightarrow \quad E_{(n)\max} = E_c$

ENERGY MOMENTS

SPECIAL CASES

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#2

ENERGY MOMENTS
SPECIAL CASES

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#2 $E_c = 0 \quad \Rightarrow \quad E_{(n)\max} = \frac{2n+1}{2} T$

$$\Rightarrow \frac{d^2 N_{E_{(n)\max}}}{dE d\Omega} = \frac{c}{T^{\frac{3}{2}}} \times \left(\frac{2n+1}{2} T \right)^n \left(\frac{2n+1}{2} T \right)^{\frac{1}{2}} e^{-\frac{2n+1}{2}}$$

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SPECIAL CASES

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ENERGY MOMENTS
SPECIAL CASES

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#3

$$\frac{2n+1}{2} T + E_c >> 4nTE_c \quad \Rightarrow \quad E_{(n)\max} \cong \frac{2n+1}{2} T + E_c$$

$$\Rightarrow \quad \frac{d^2 N_{E_{(n)}}}{dE d\Omega} = \frac{c}{T^{\frac{3}{2}}} \times \left(\frac{2n+1}{2} T + E_c \right)^n \left(\frac{2n+1}{2} T \right)^{\frac{1}{2}} e^{-\frac{2n+1}{2}}$$

DATA ANALYSIS

Looking for the maxima can be easier than fitting complicated distributions!

72.75°

q=5

$$E_{(n)\max} = \frac{1}{2}\left[\frac{2n+1}{2}T + E_c \pm \sqrt{\left(\frac{2n+1}{2}T + E_c\right)^2 - 4nTE_c}\right]$$

$$\frac{d^2N_{E_{(n)\max}}}{dEd\Omega} = \frac{4\pi \times \frac{dN}{d\Omega}}{2(\pi T)^{\frac{3}{2}}} \times E^n_{(n)\max} \left(E_{(n)\max} - E_c\right)^{\frac{1}{2}} e^{-\frac{\left(E_{(n)\max}-E_c\right)}{T}}$$

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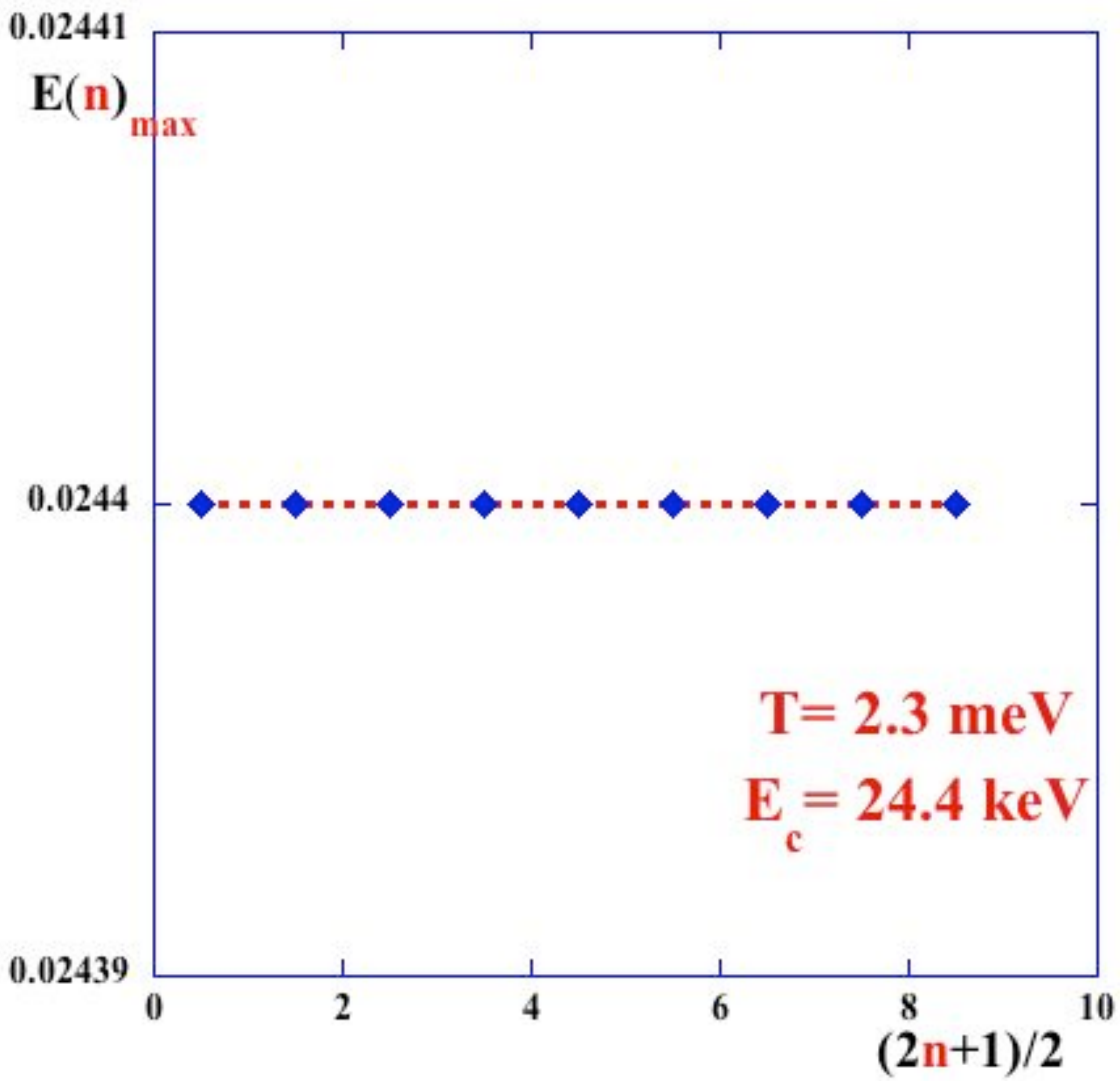

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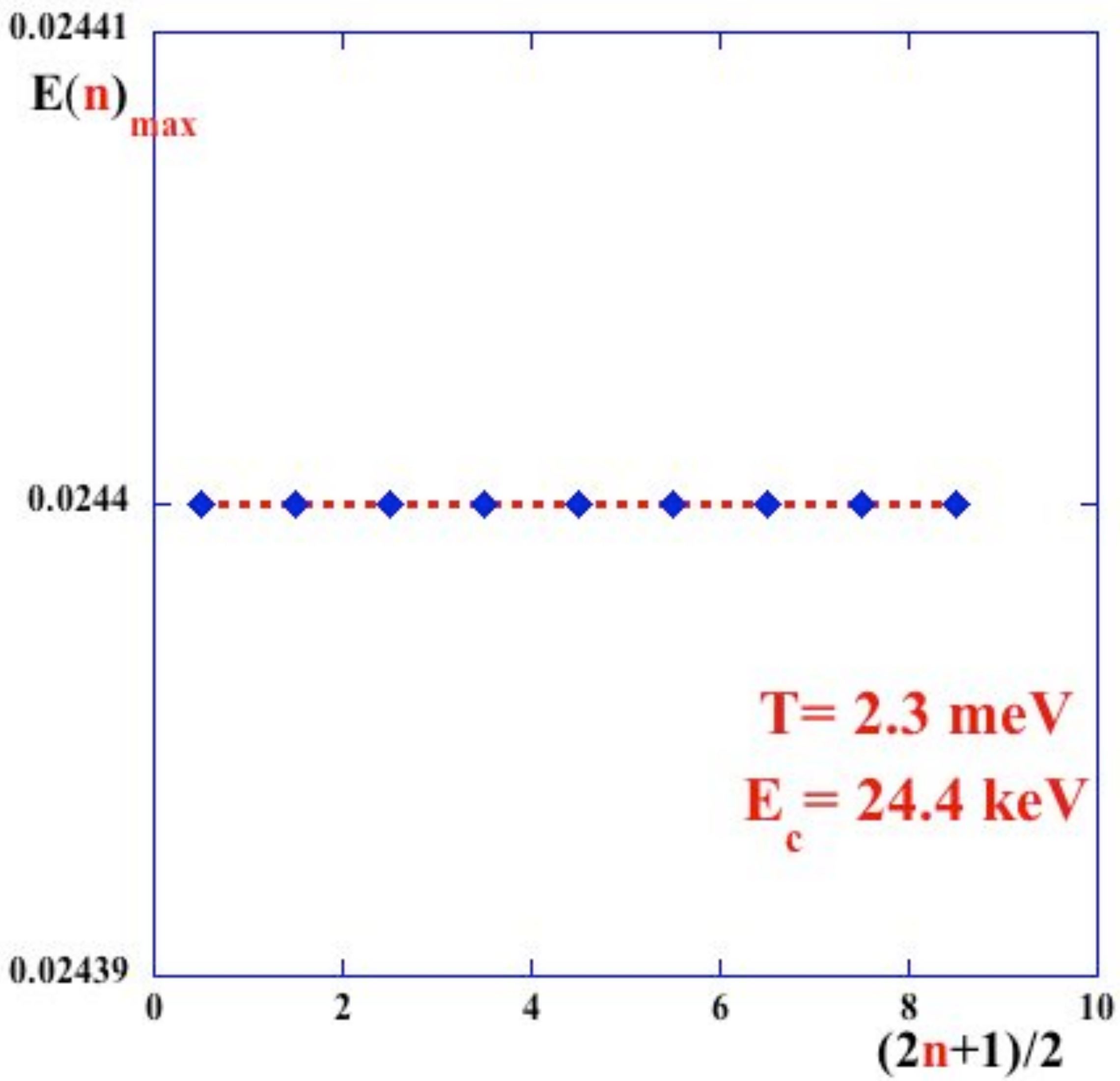

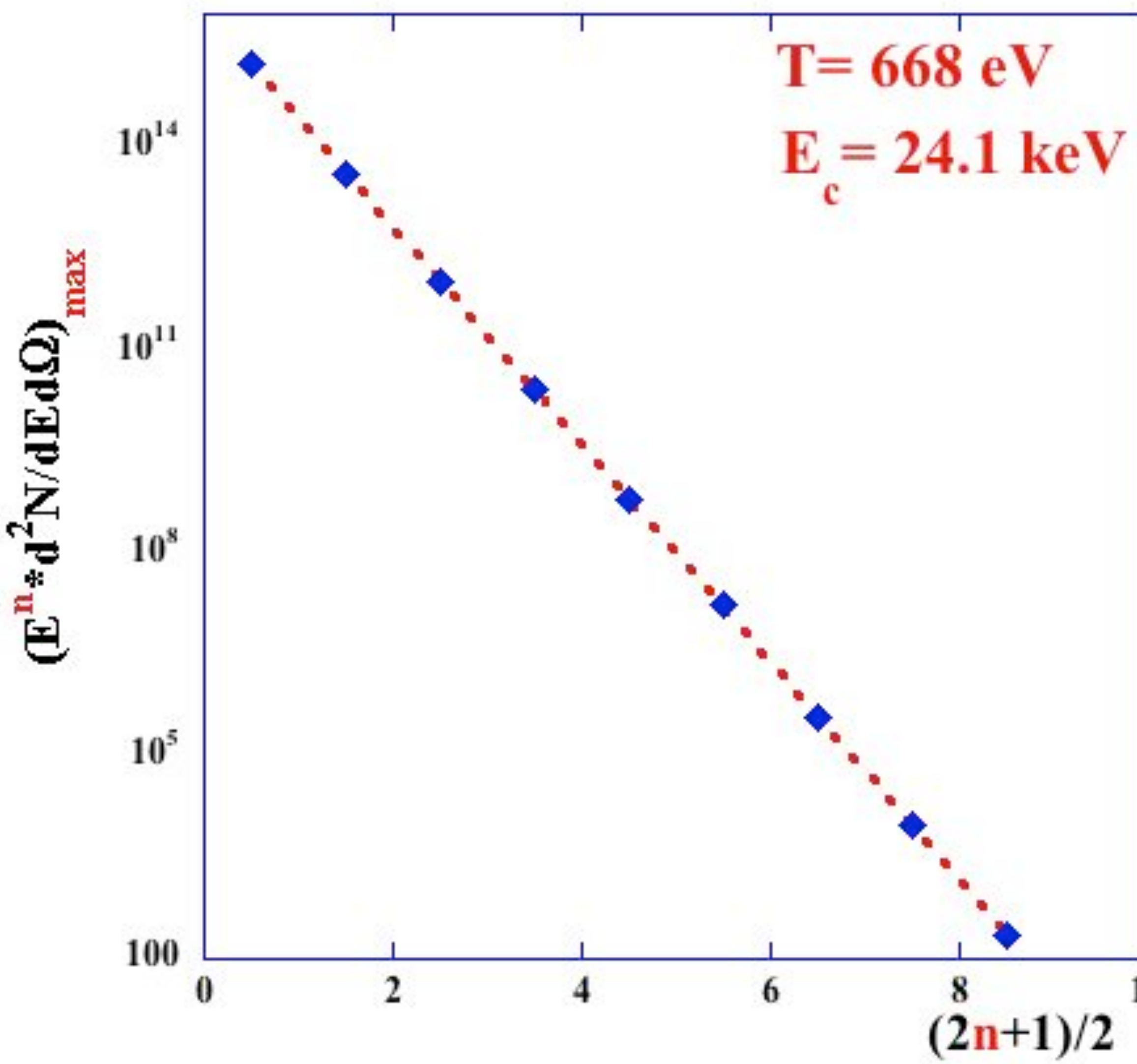

DATA ANALYSIS

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61.75°

q=3

$$E_{(n)\max} = \frac{1}{2}\left[\frac{2n+1}{2}T + E_c \pm \sqrt{\left(\frac{2n+1}{2}T + E_c\right)^2 - 4nTE_c}\right]$$

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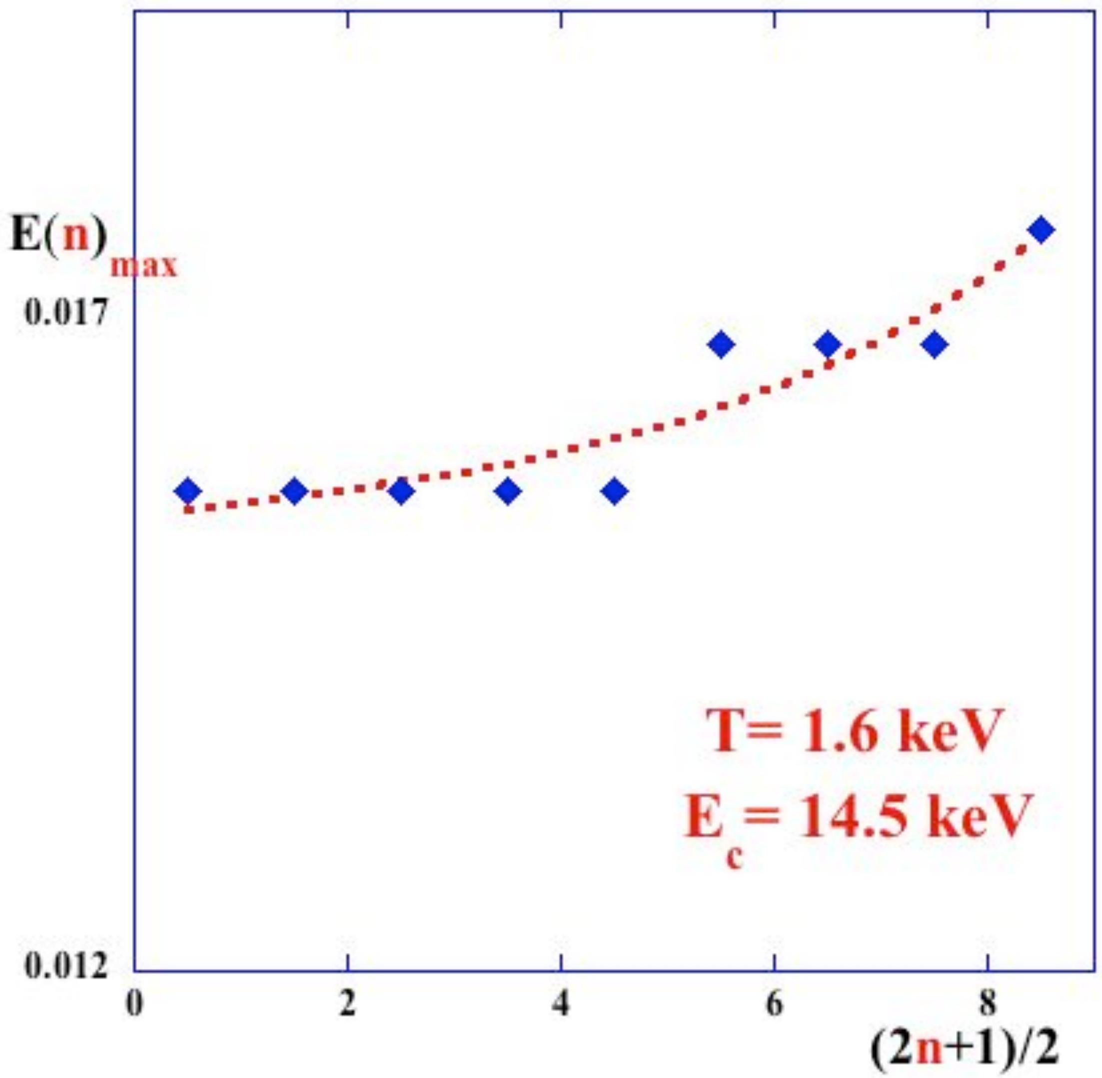
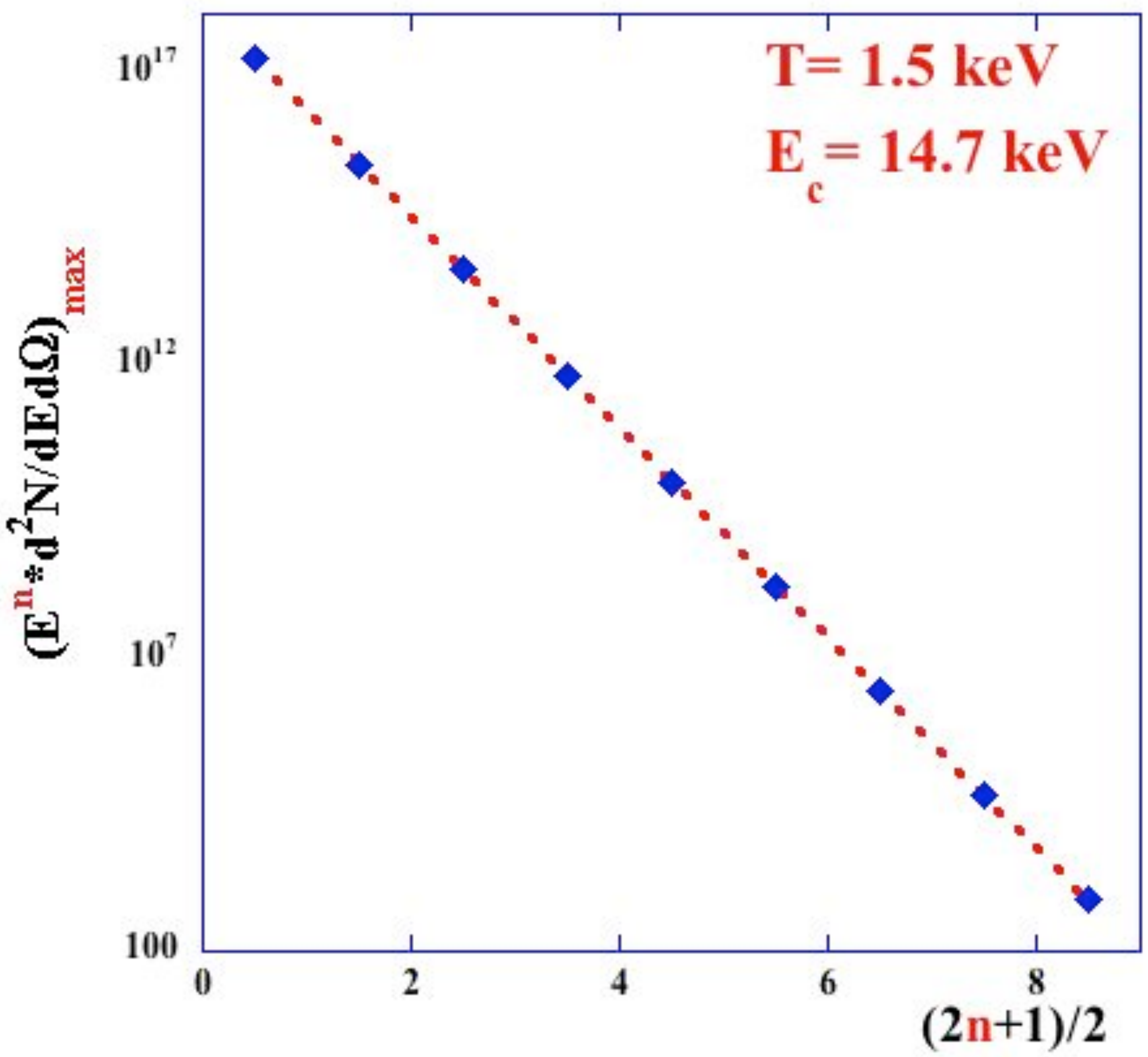
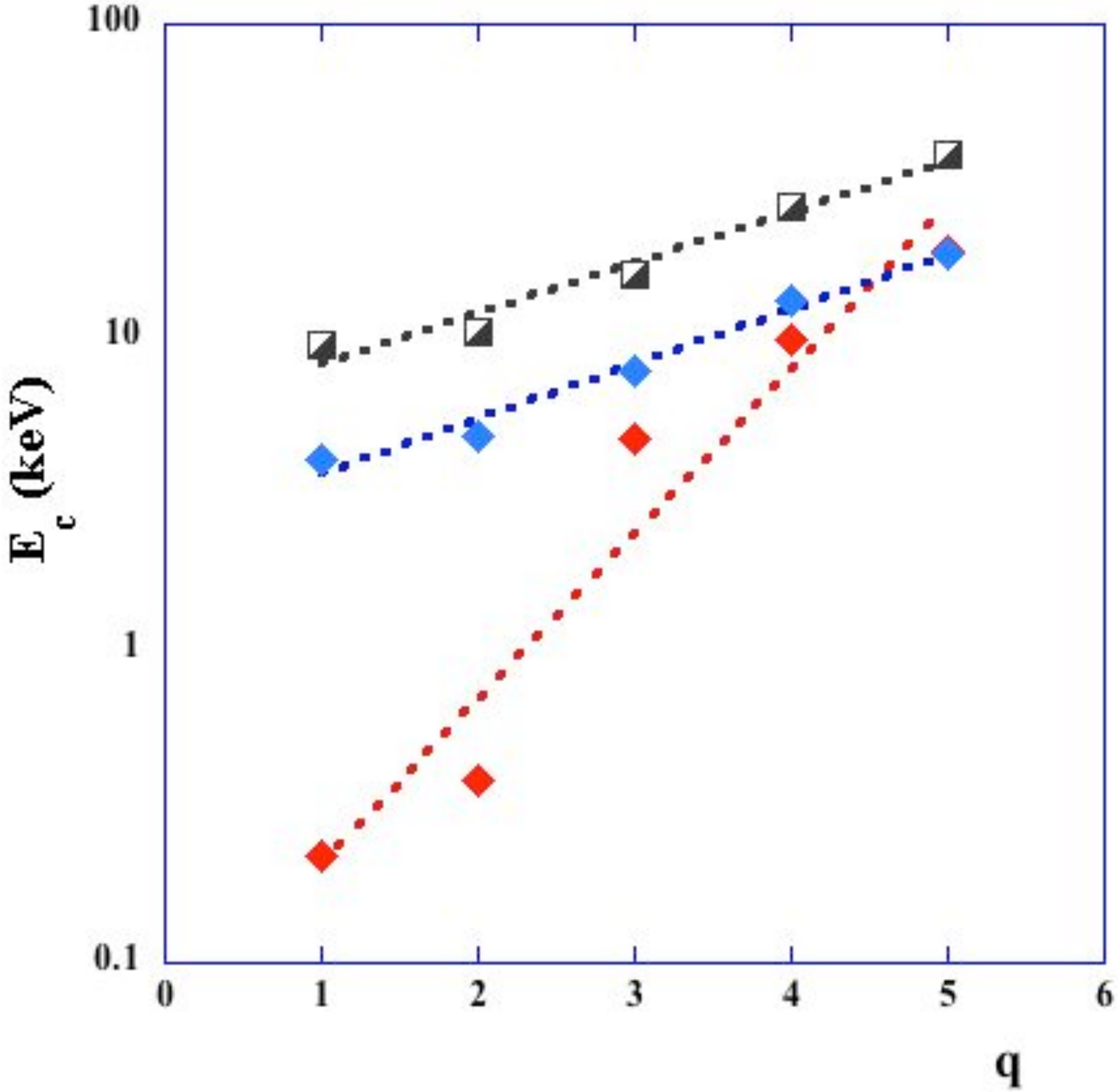




DATA ANALYSIS

For different laser energies and target geometries



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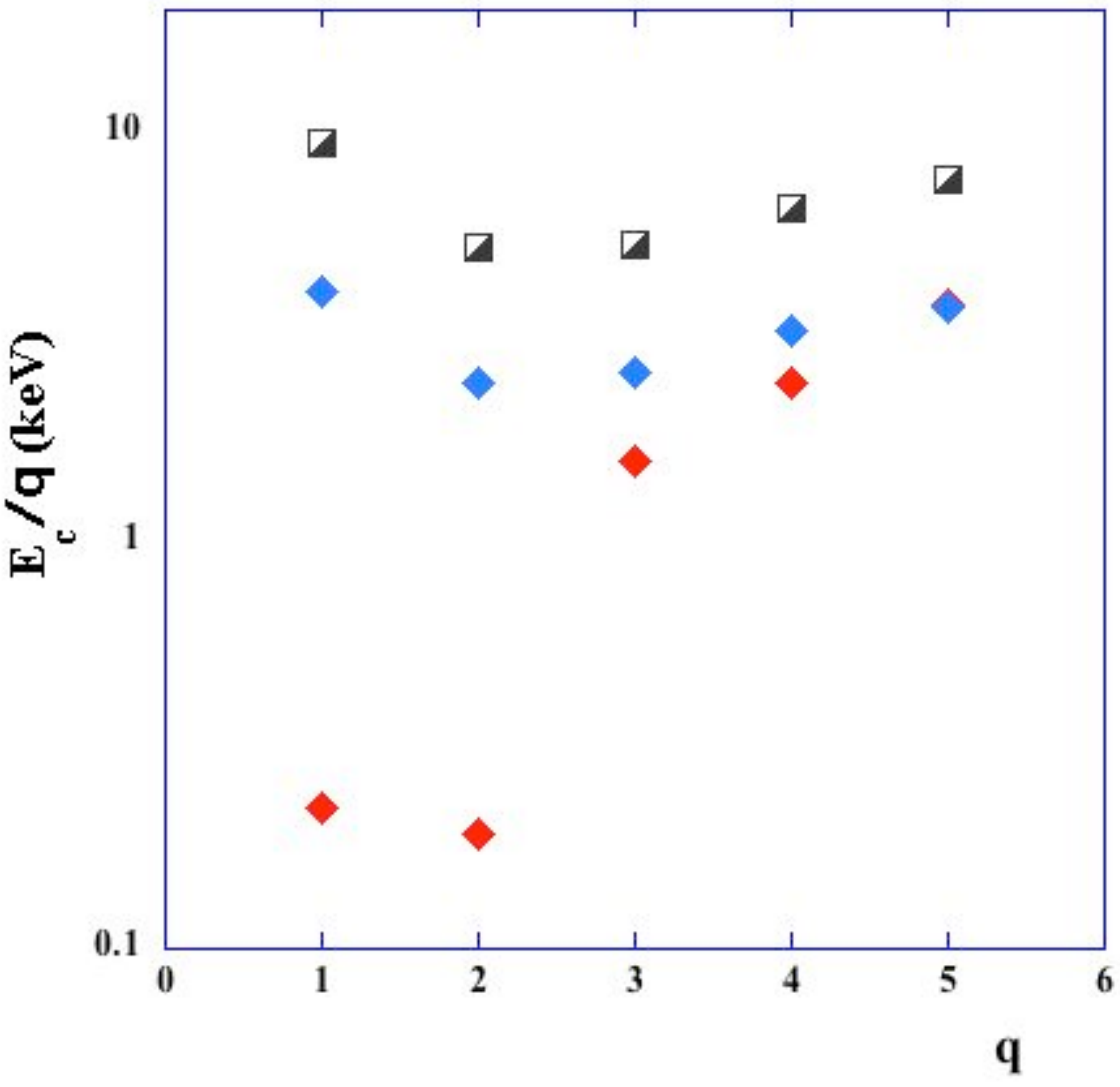

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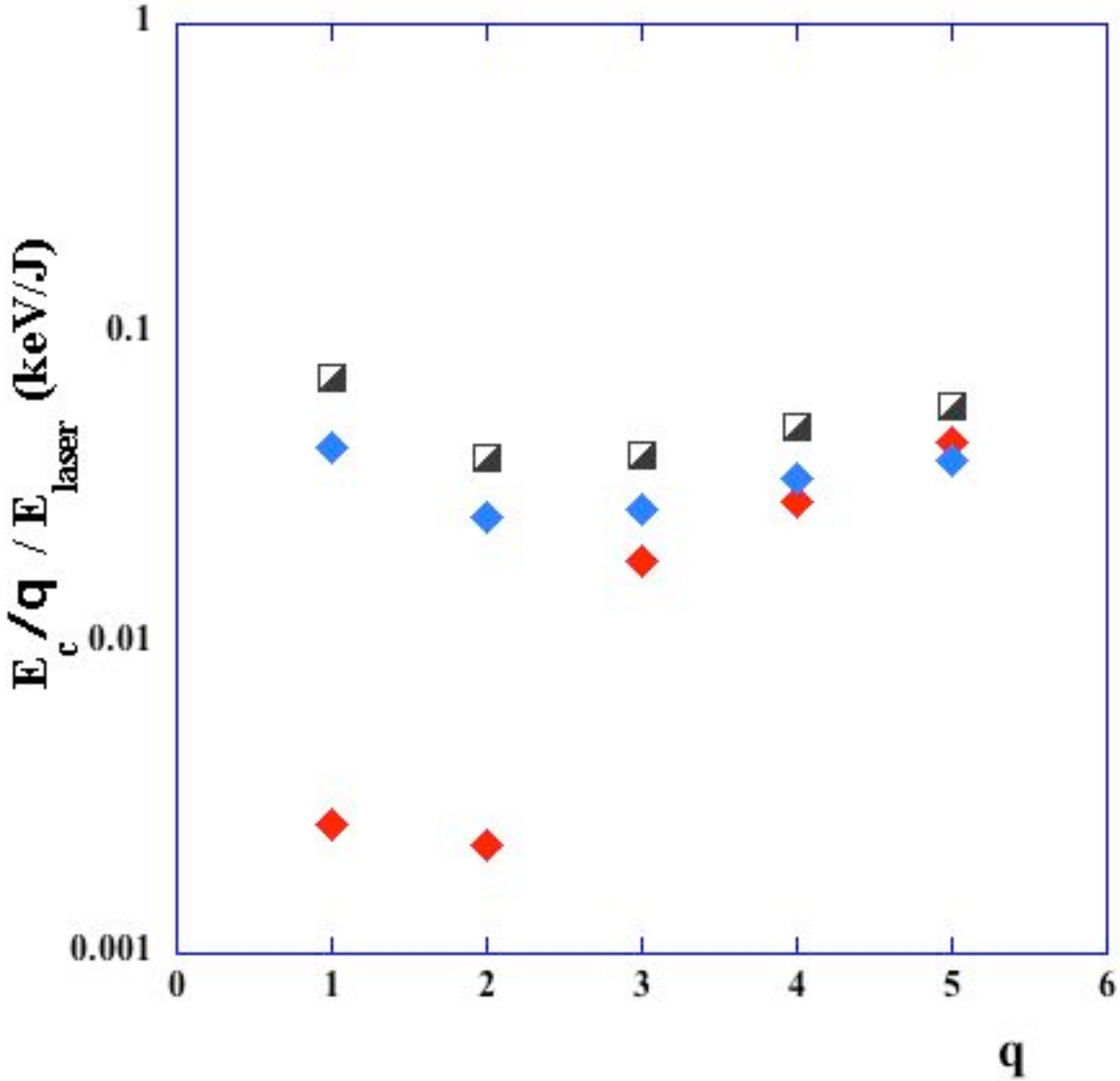

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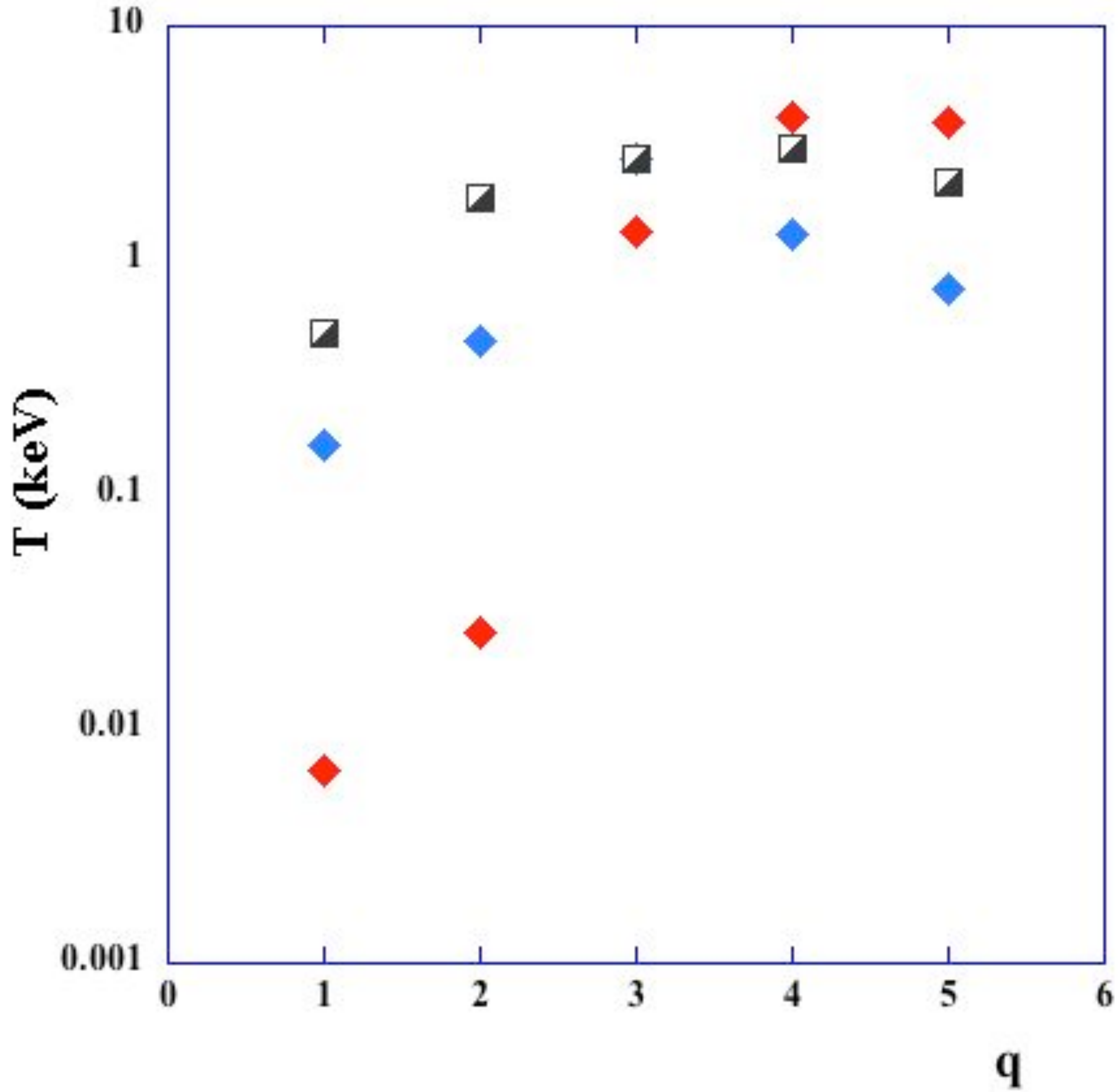

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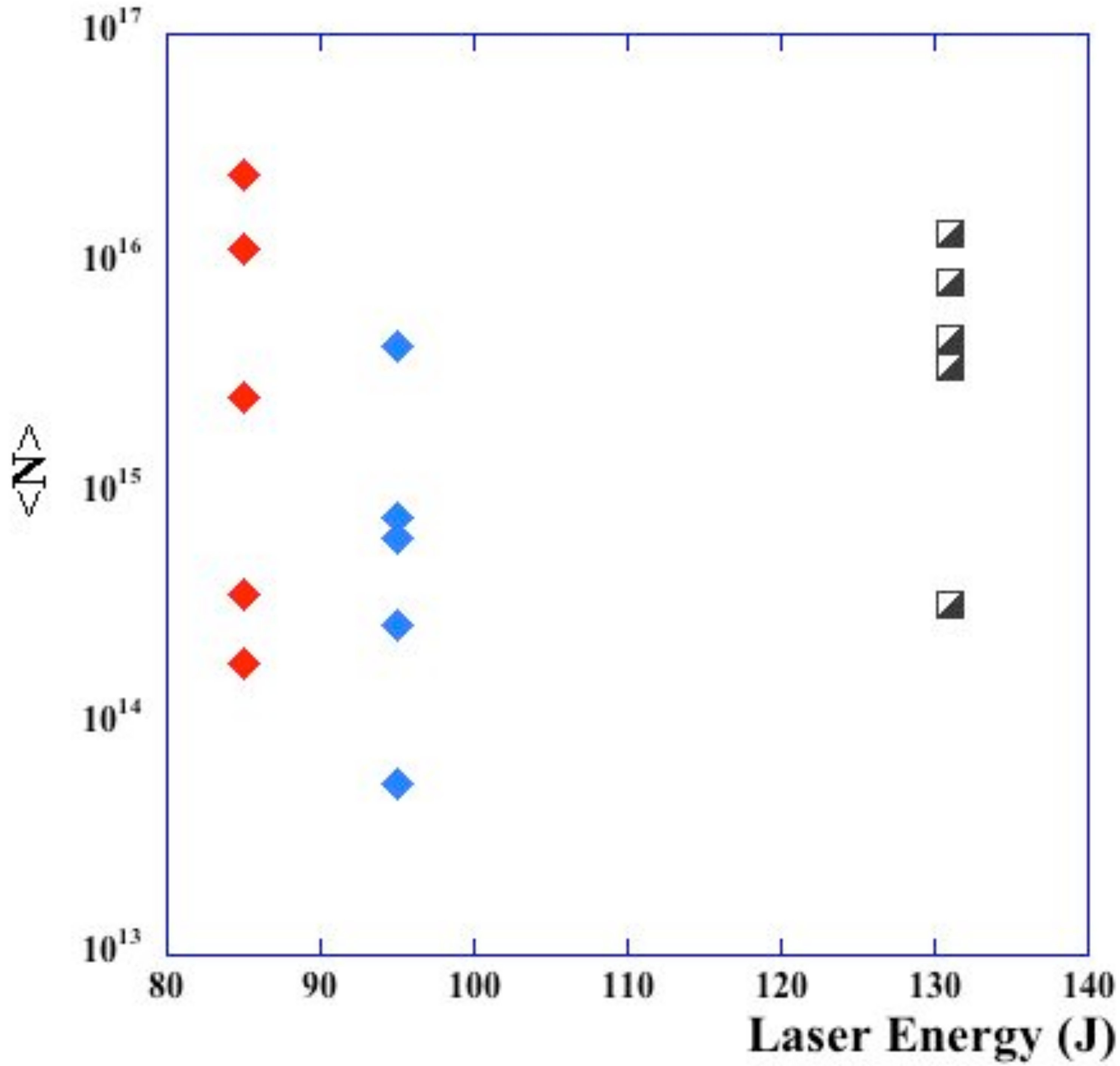
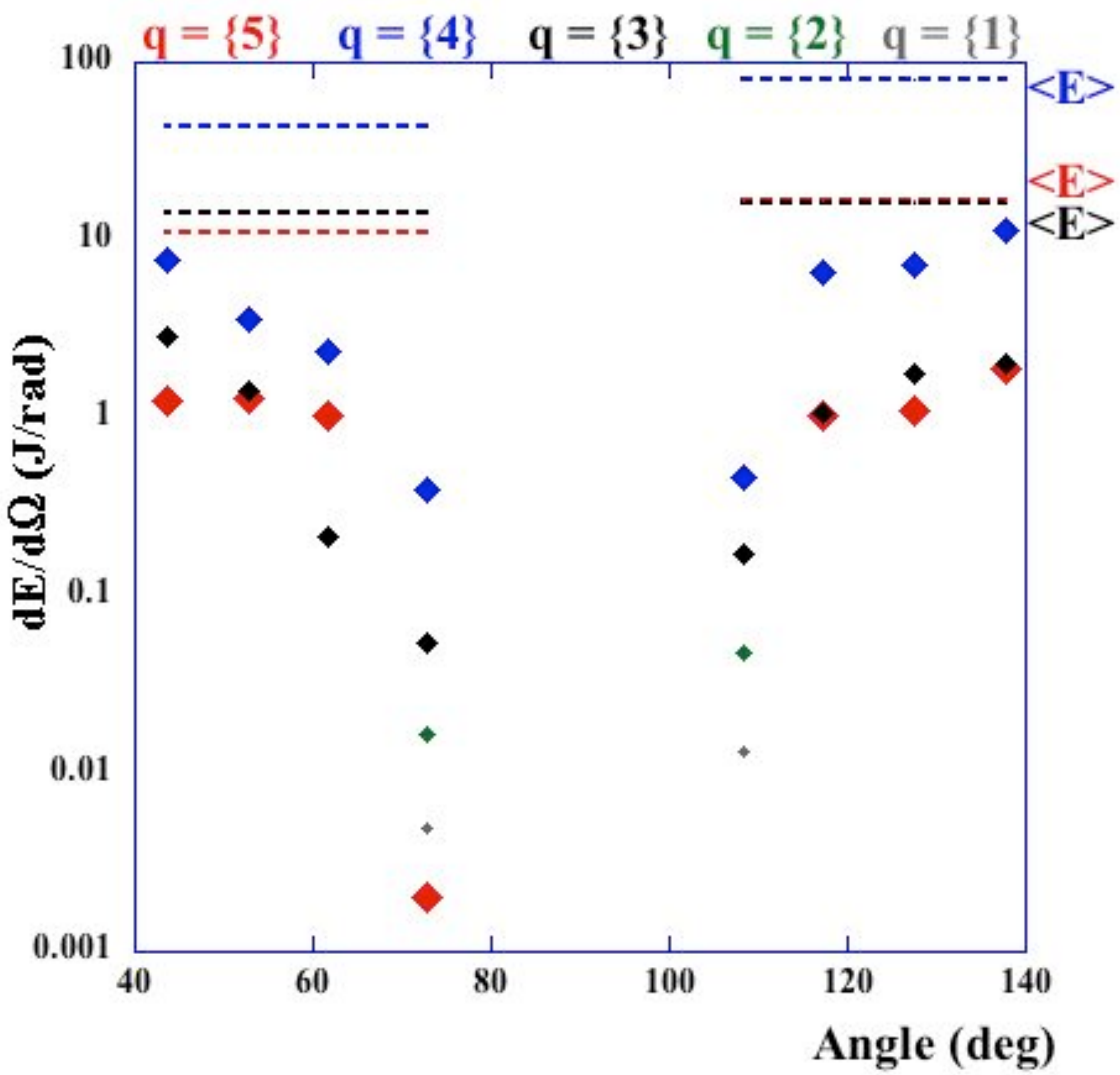


DATA ANALYSIS

The two lasers have

different energies output



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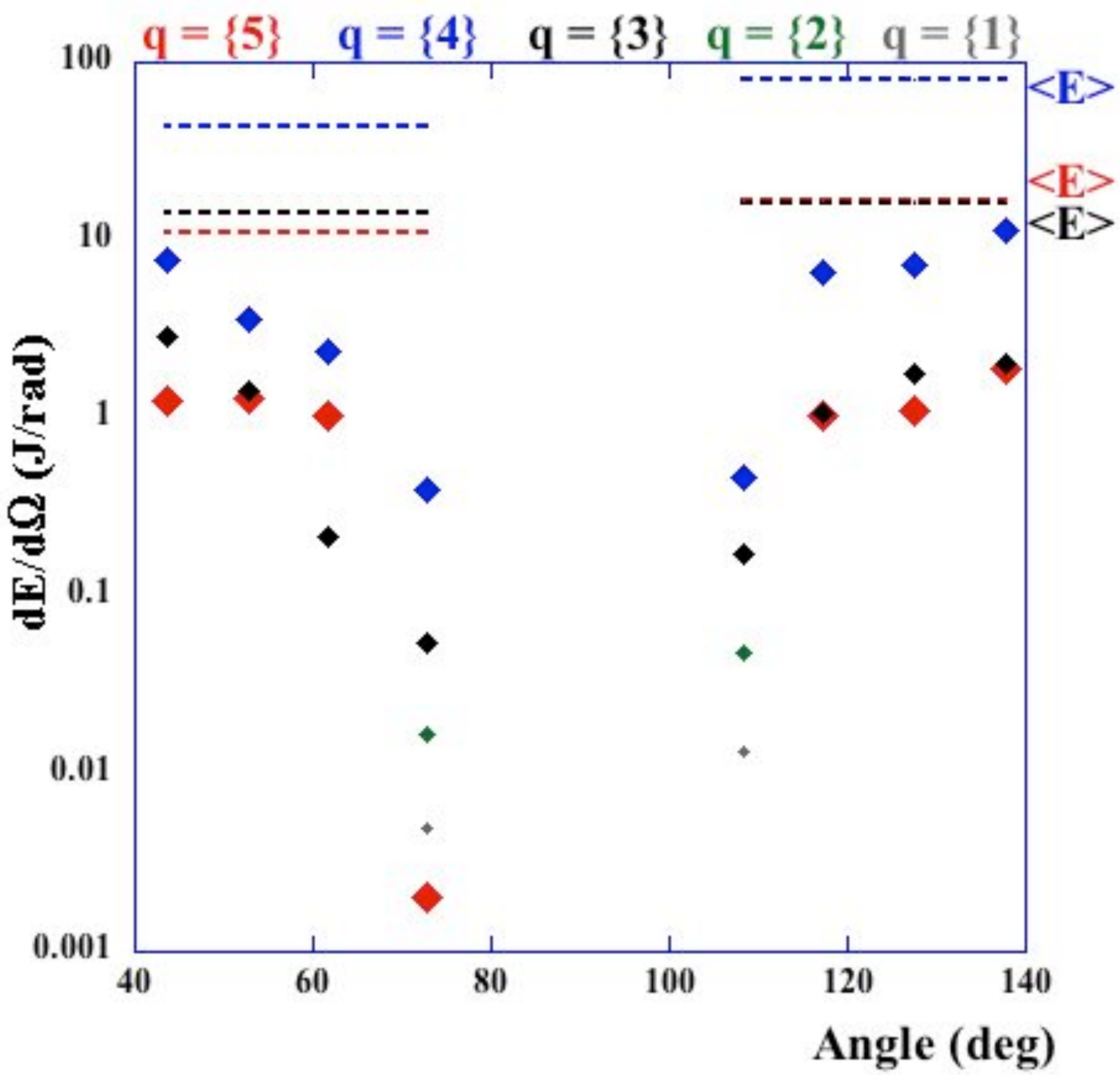

DIFFERENT

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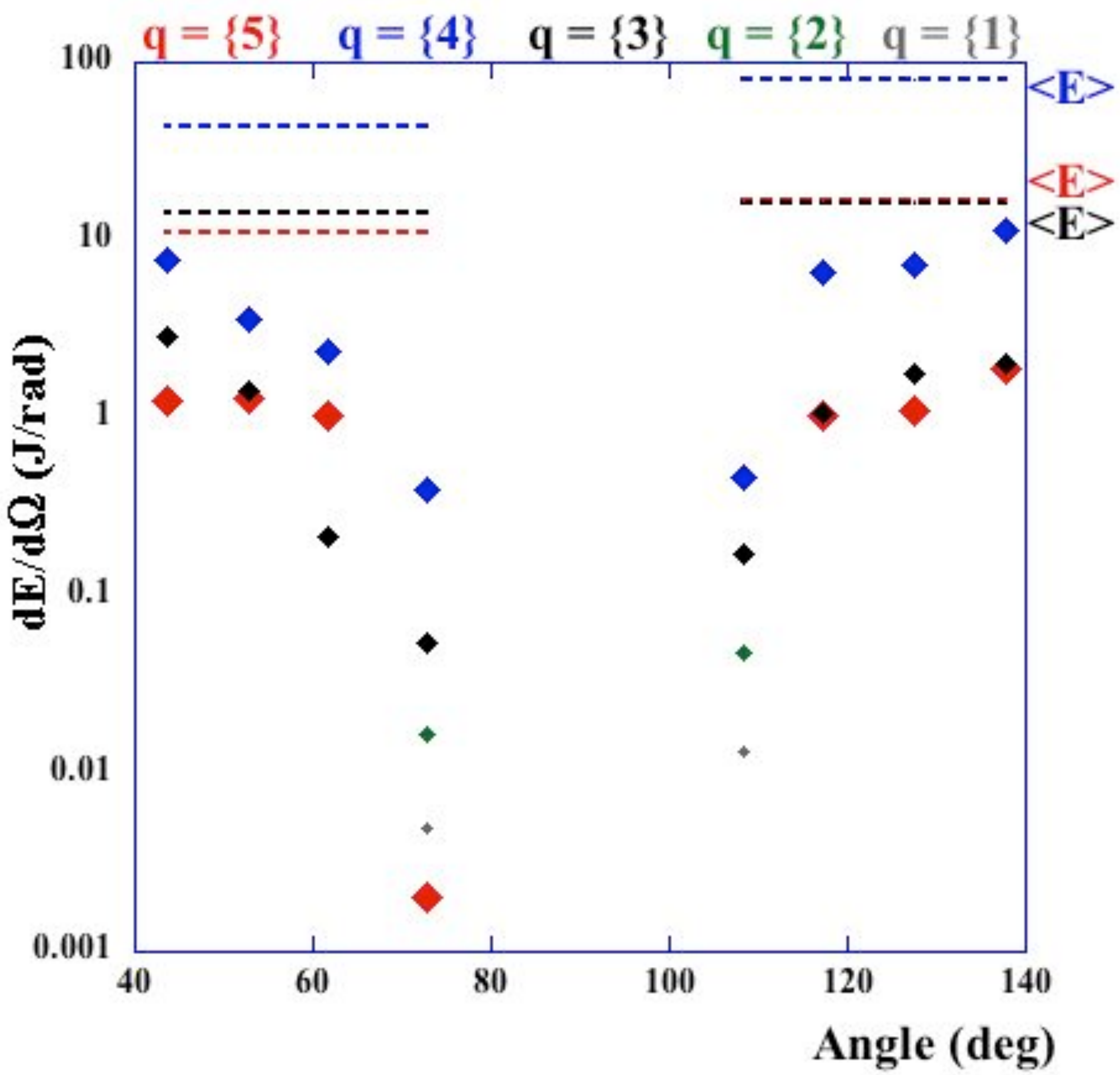
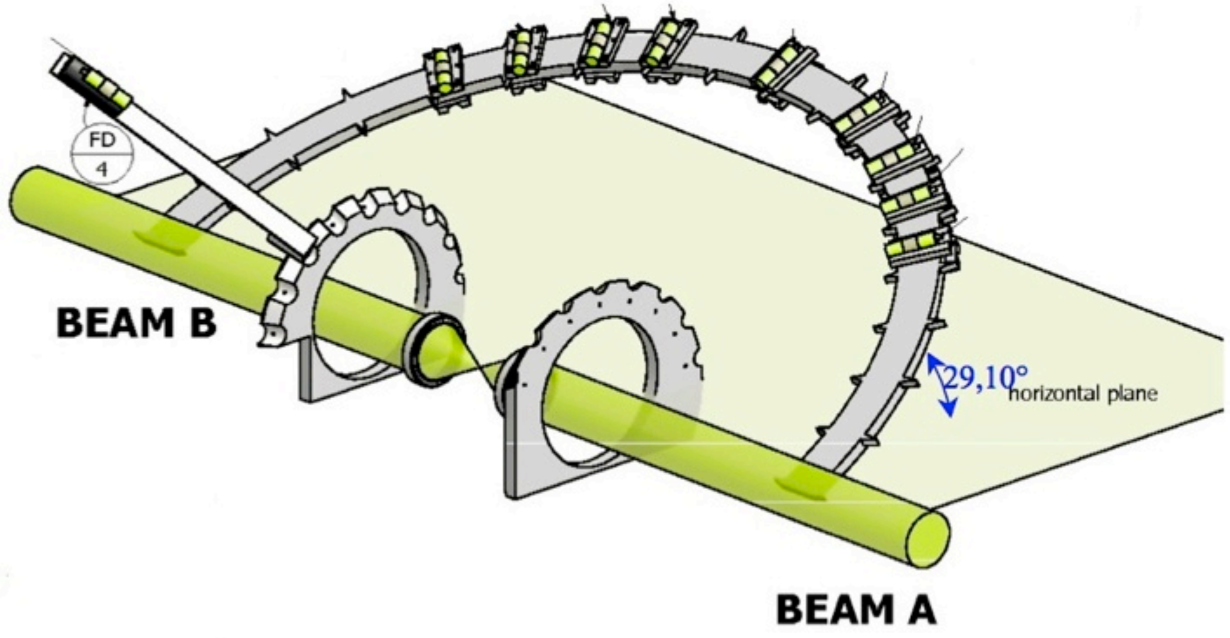


DIFFERENT ION ENERGIES



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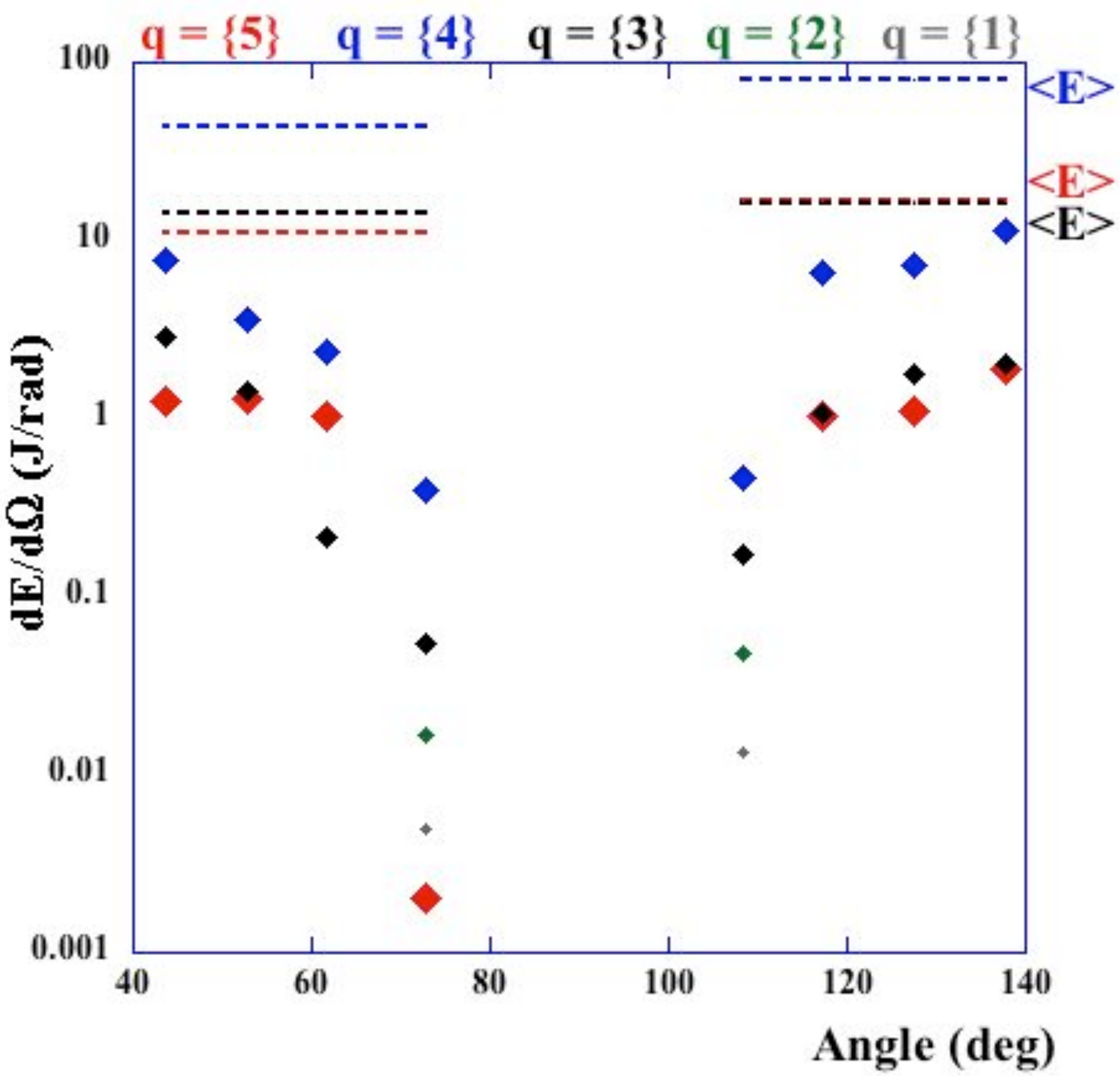

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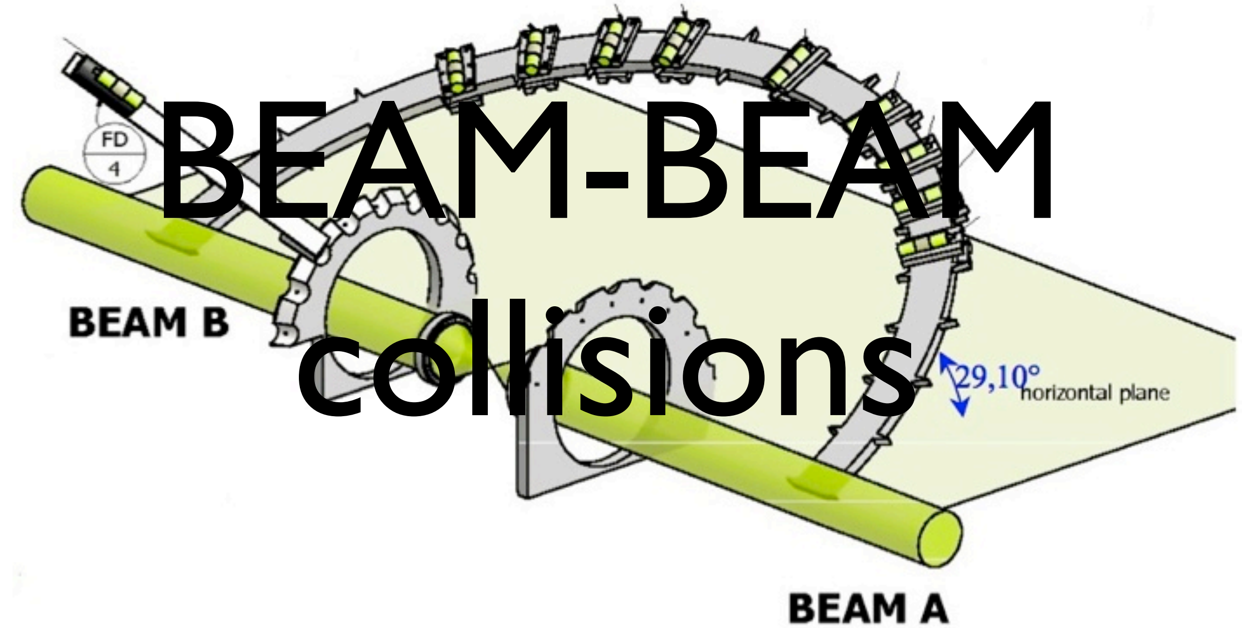

BEAM-BEAM
collisions

DATA ANALYSIS

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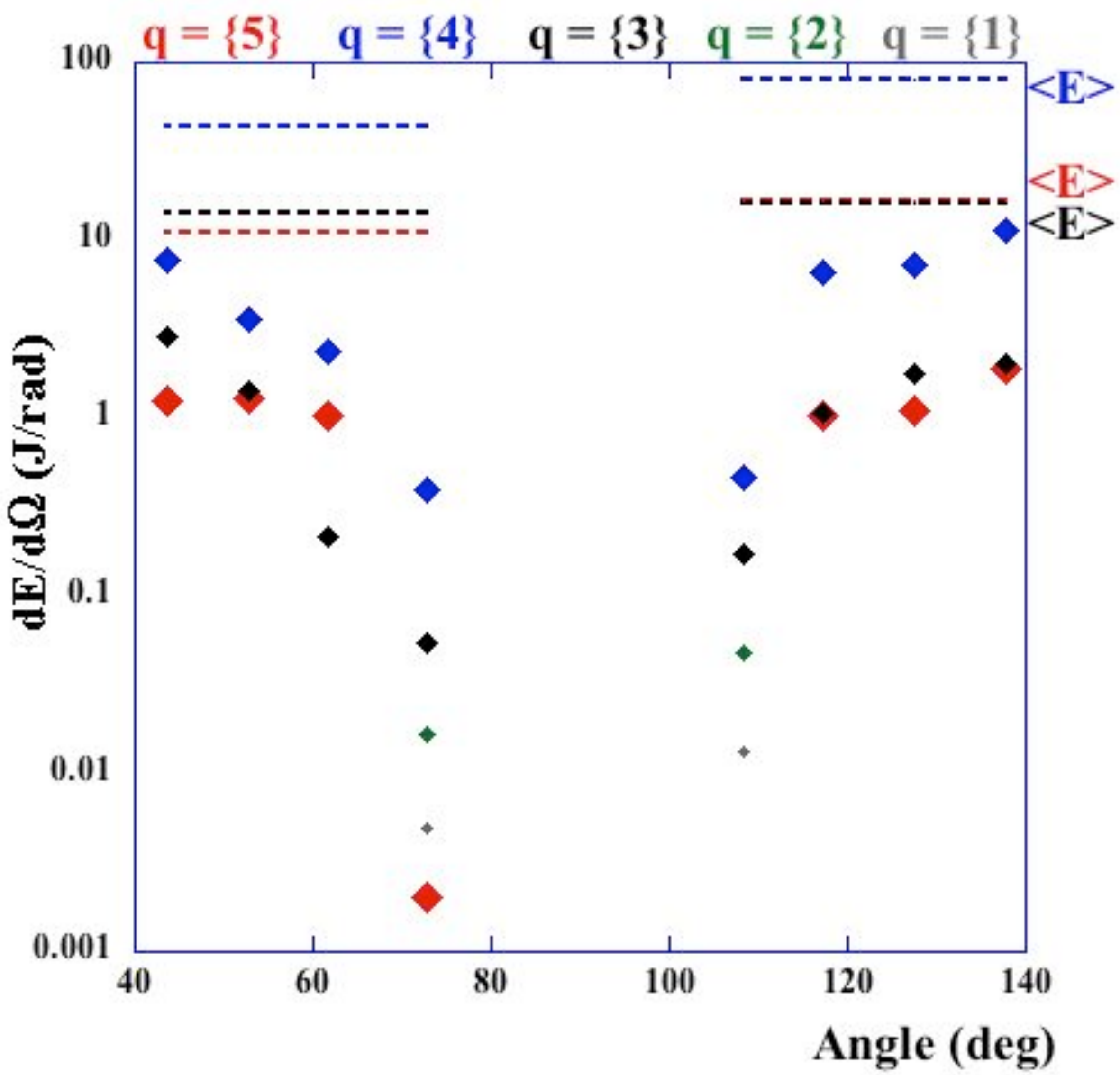

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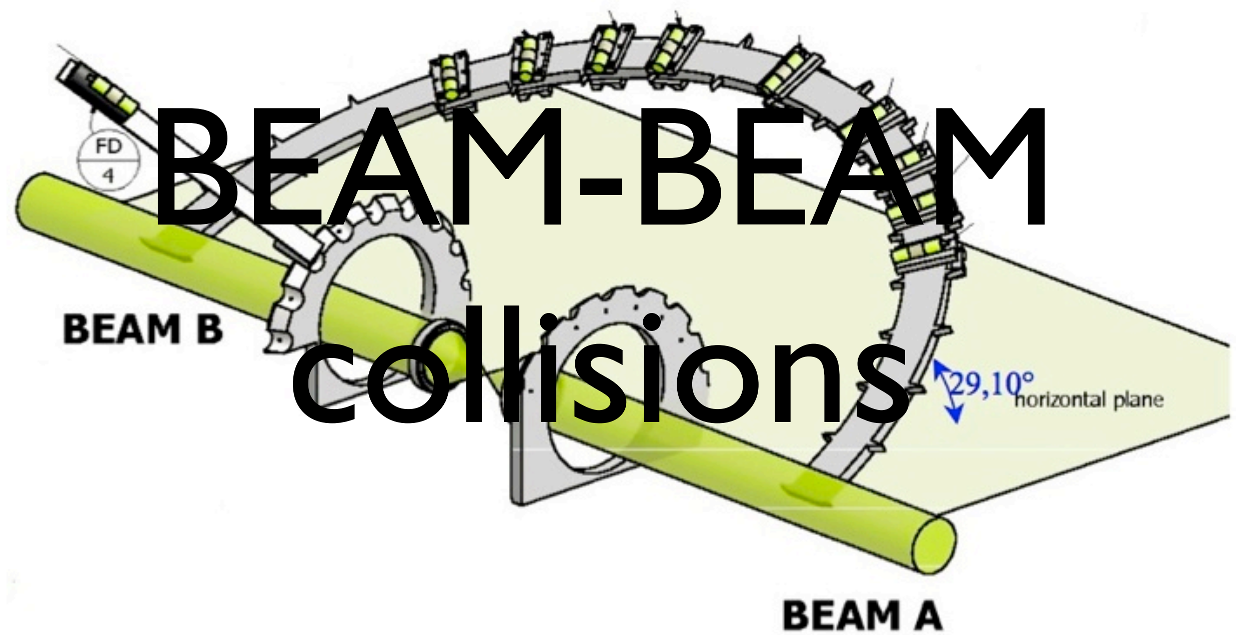

Plasma volume can be determined from the targets geometry. Number of ions is measured.

DATA ANALYSIS

The two lasers have

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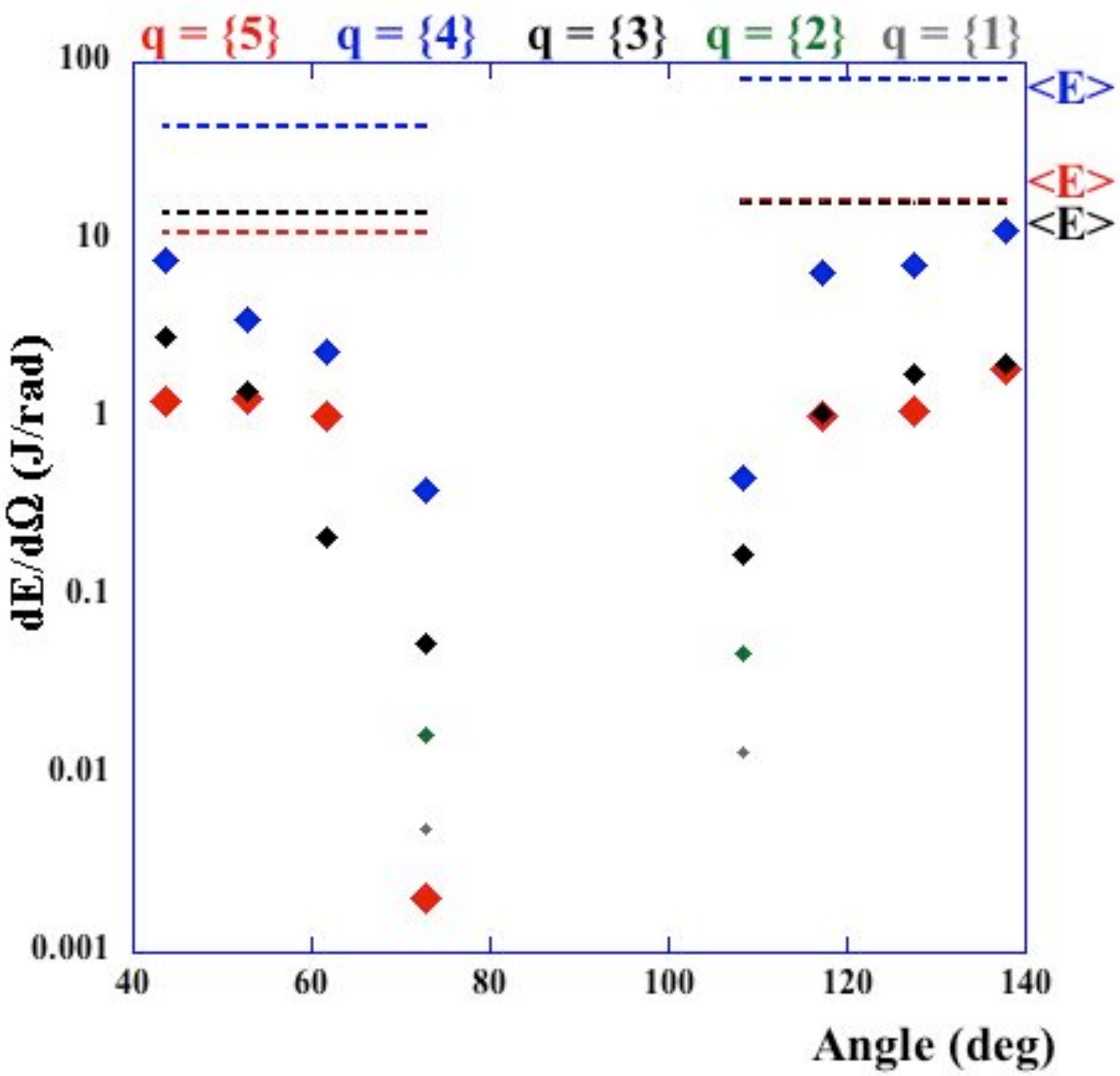

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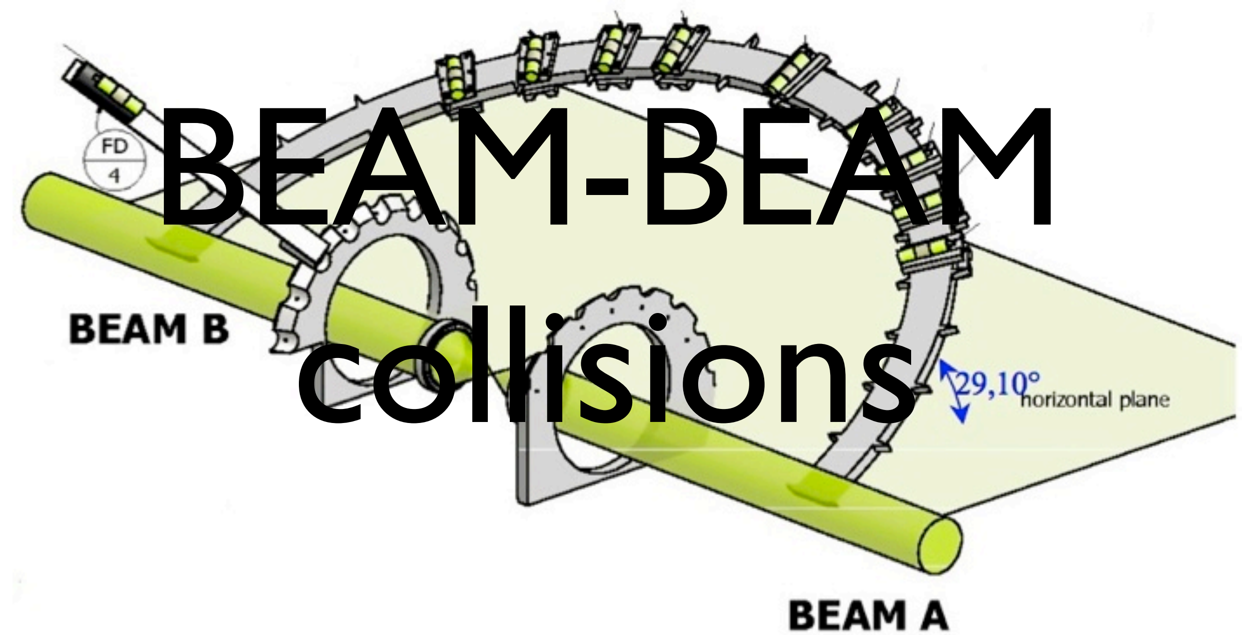

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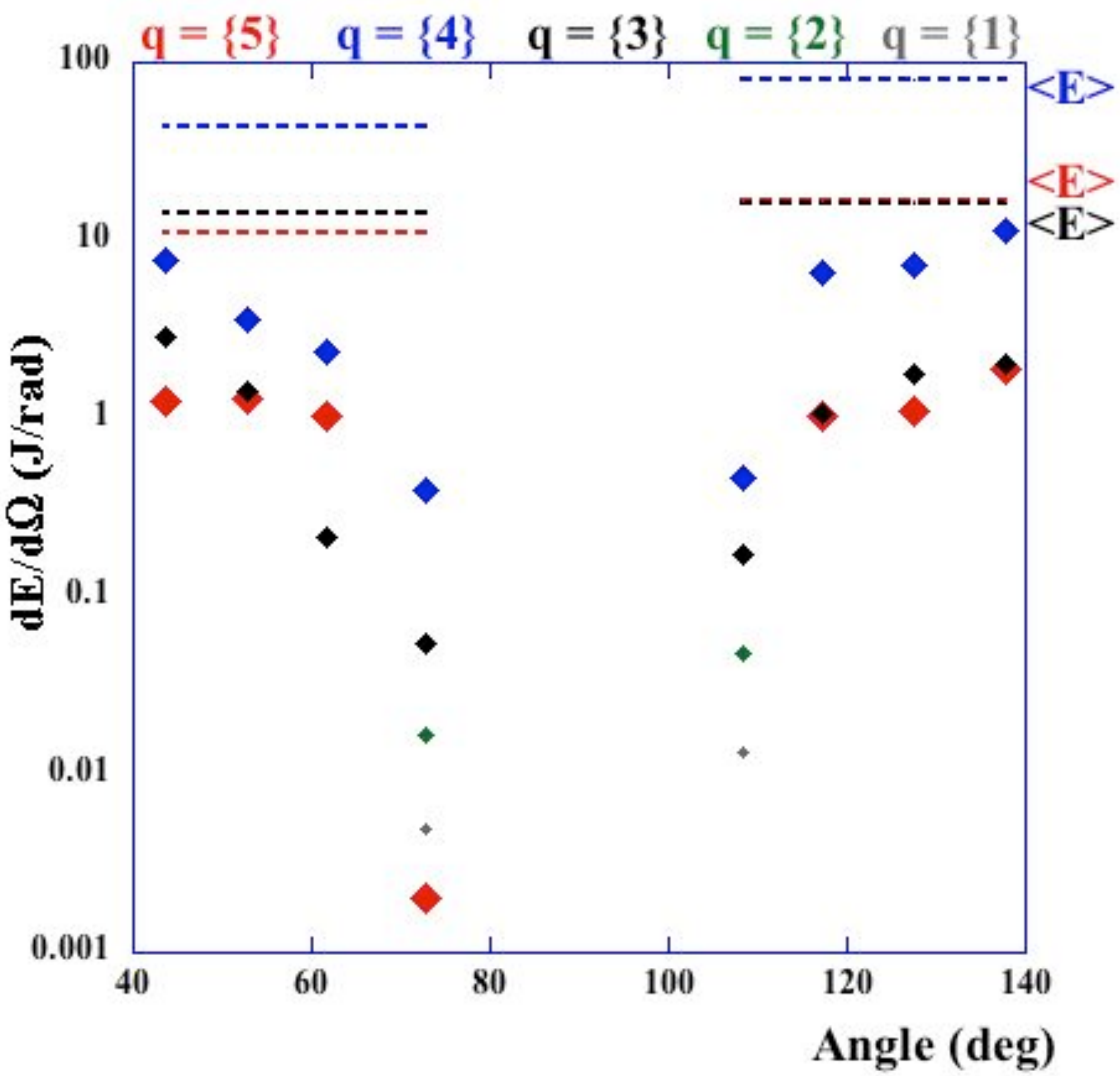

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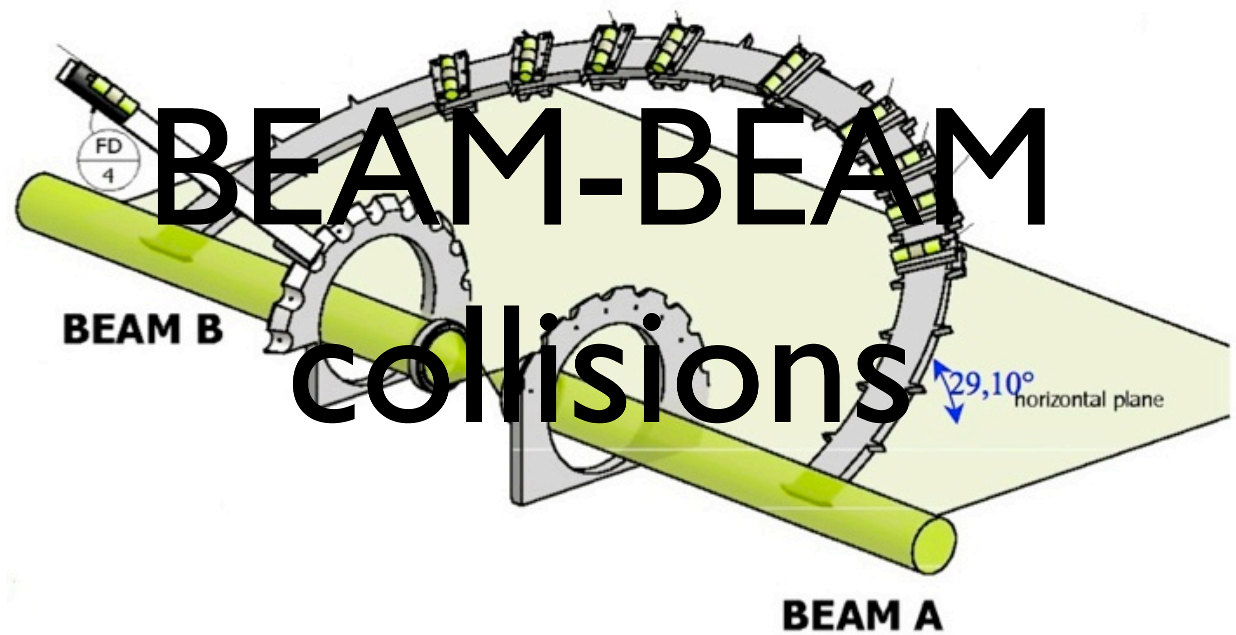

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DENSITY

CONCLUSIONS

- Next stop: $p+^{11}B$ fusion reactions!

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Work in collaboration with:

CONCLUSIONS

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[b] *INFN - LNS, via S. Sofia 62, I-95123 Catania, Italy*
[c] *Cyclotron Institute, Texas A&M University, College Station, TX, 77843, USA*
[d] *Dipartimento di Fisica G. Galilei, Università degli Studi di Padova, via F. Marzolo 8, I-35131 Padova, Italy*
[e] *Texas Center for High Intensity Laser Science, University of Texas at Austin, Austin 78712, TX, USA*
[f] *Heavy Ions Laboratory, University of Warsaw, ul. Pasteura 5a, 02-093 Warszawa, Poland*

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Thank you !

DATA ANALYSIS

Laser Efficiency: almost 90%

summing up all charges in some cases