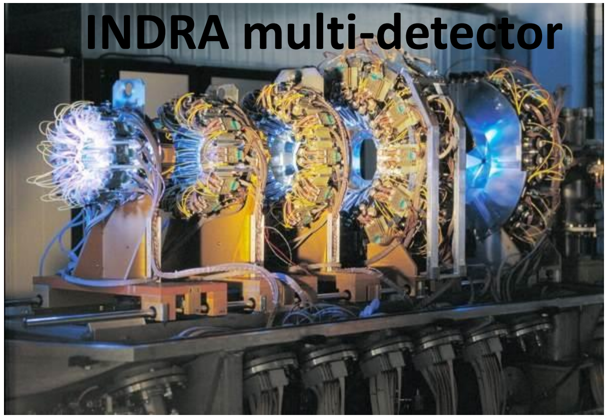
Nuclear Dynamics

IWM-ec2016
workshop
Caen, May 2016

Chemical equilibrium ^{3}He and ^{6}He production

32 A.MeV

- ^{124}Xe+^{112}Sn
- ^{124}Xe+^{124}Sn
- ^{136}Xe+^{112}Sn
- ^{136}Xe+^{124}Sn



IMPORTANCE OF CLUSTERS

R. Bougault INDRA/FAZIA collaboration

Equation of State

Importance of clusters

Clusters are important in the final states, at earlier times also!

SIMPLE EXAMPLE:

4 nucleons at T=10 MeV

- *Without correlation:*
  $\langle E \rangle = 3/2\ T \times 4 = 60$ MeV

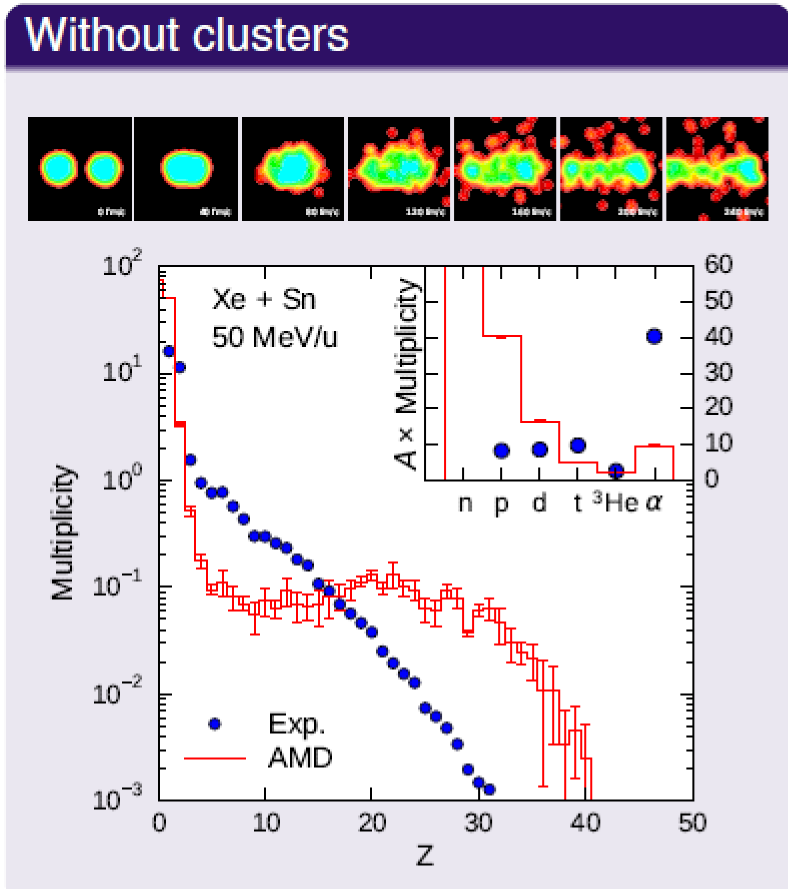
- *If they form an α:*
  $\langle E \rangle = 3/2\ T \times 1 - 28.3 = -13.3$ MeV

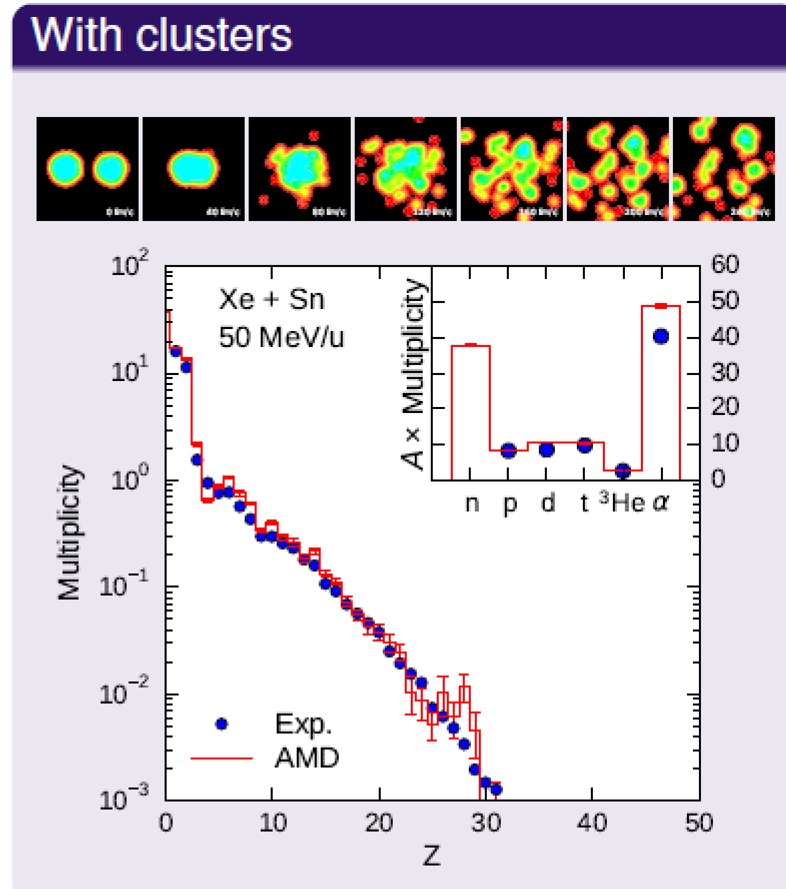
Clusters influence the reaction dynamics and the bulk nuclear matter properties

Importance of clusters

TRANSPORT MODEL with CLUSTERS: Extended AMD with cluster correlations

Xe + Sn central collisions at 50 MeV/nucleon (INDRA DATA & AMD calculations)





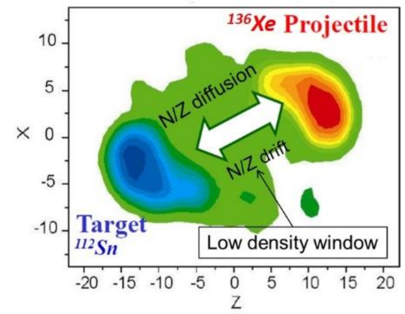
Cluster correlations in the final states of two nucleon collisions

Akira Ono (Tohoku University) NuSYM15-2015

LCP production

$$E(\rho,I)=E(\rho,I=0)+\underbrace{E_{sym}(\rho)}_{SYMMETRY\ ENERGY}I^2+\ldots$$

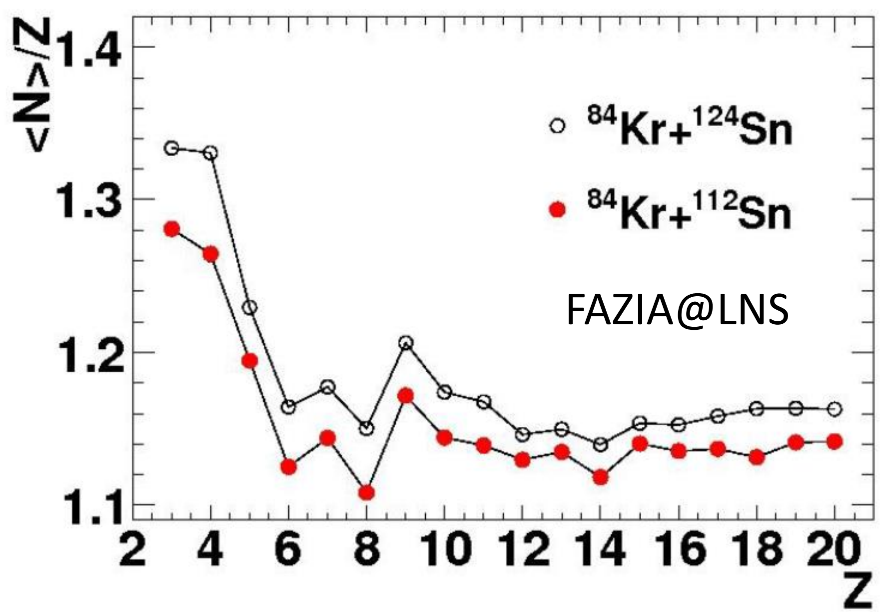
Projectile/Target nucleon exchange and mid-rapidity chemistry



are governed by drift and diffusion transport phenomena

Diffusion: isospin exhange projectile/target with different N/Z (tends to $N/Z_{composite}$)
Drift: neutron enrichment of low density zone created between projectile & target

S.Barlini et al. PRC 87, 054607 (2013)

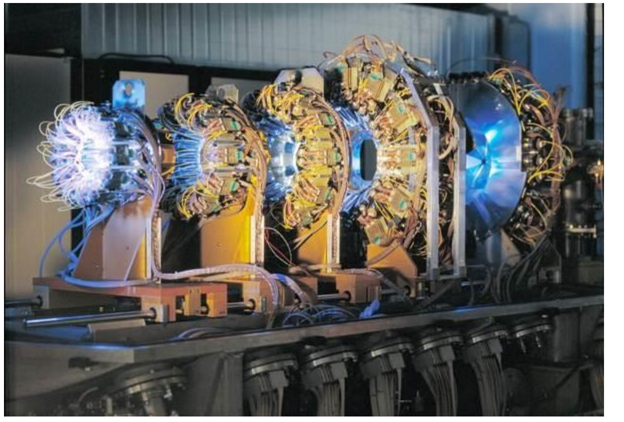


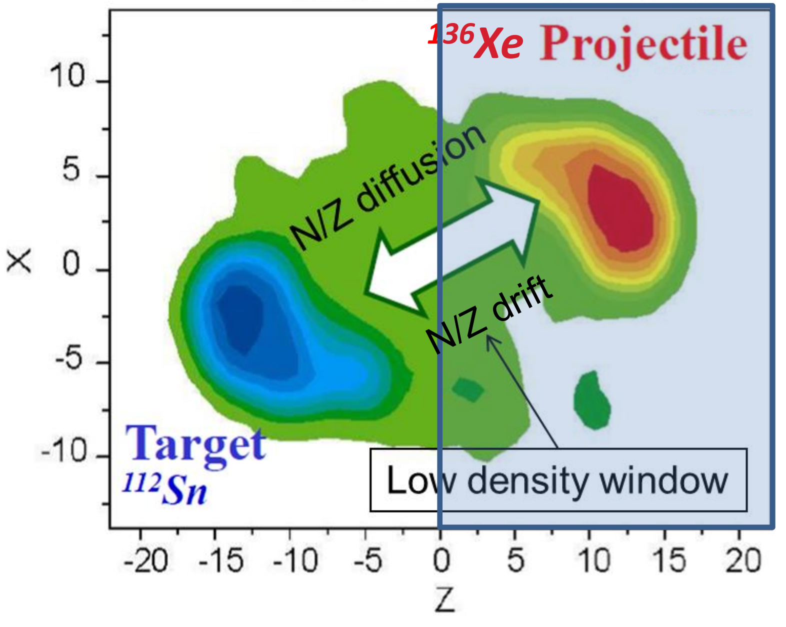
See also CHIMERA/MSU,… publications

Nuclear Dynamics

Study of chemical equilibration between PLF & TLF

Light Charged Particle emitted in the forward part of the c.m (neutrons are not detected) INDRA multi-detector





32 A.MeV

- **$^{124}Xe+^{112}Sn$**
- **$^{124}Xe+^{124}Sn$**
- **$^{136}Xe+^{112}Sn$**
- **$^{136}Xe+^{124}Sn$**

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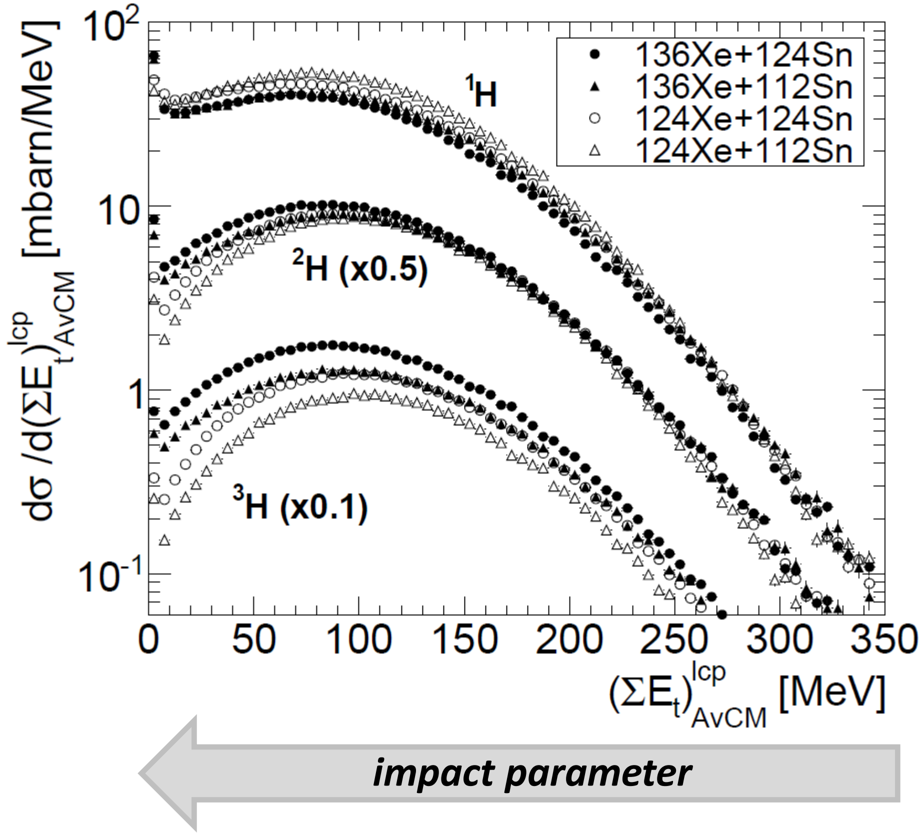
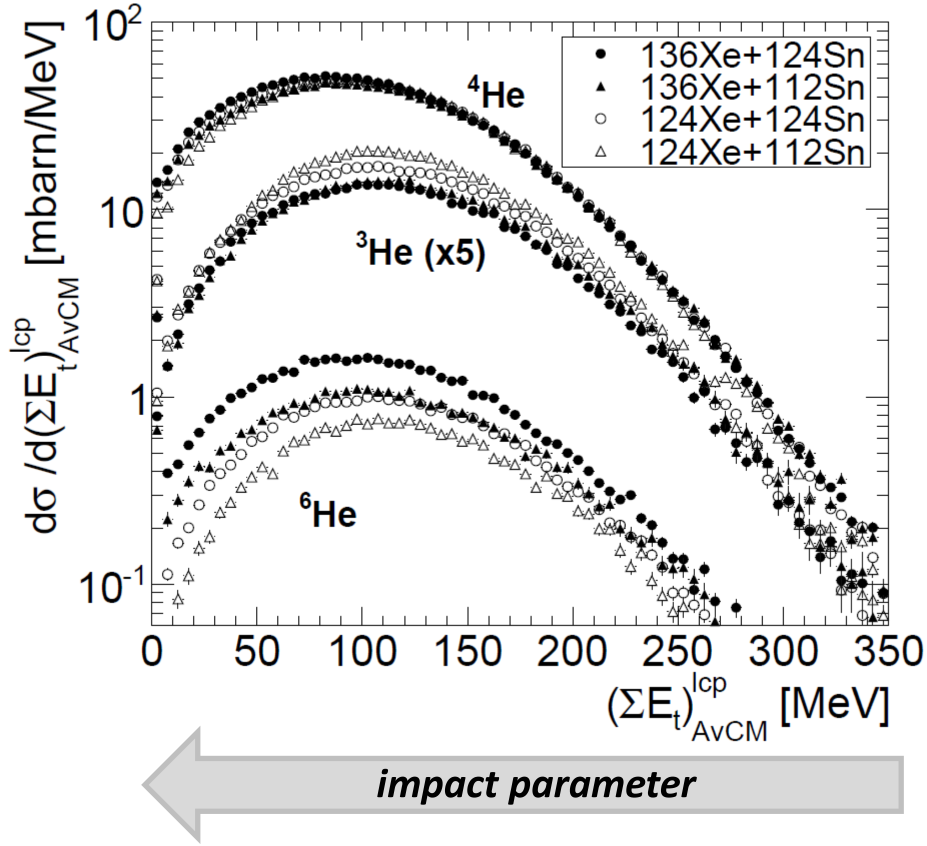
LCP production (forward c.m)





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LCP production *(forward c.m)*

mbarn	124+112	124+124	136+112	136+124
^{1}H	7960	7170	6620	6240
^{2}H	2490	2710	2770	3090
^{3}H	1340	1780	1970	2610
^{3}He	570	490	420	400
^{4}He	6990	7260	7010	7500
^{6}He	110	150	160	240
TOTAL	19460	19560	18950	20080

(Statistical error: few mbarns)

No data selection/Inclusive events except elastic events are excluded

LCP production *(forward c.m)*

mbarn	124+112	124+124	136+112	136+124
^{1}H	7960	7170	6620	6240
^{2}H	2490	2710	2770	3090
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Total lcp production is system independent (within 6%)

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^{1}H	7960	7170	6620	6240
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(Statistical error: few mbarns)

Total lcp production is system independent (within 6%) BUT THE CHEMISTRY IS!

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LCP production *(forward c.m)*

mbarn	124+112	124+124	136+112	136+124
^{1}H	7960	7170	6620	6240
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TOTAL	19460	19560	18950	20080

(Statistical error: few mbarns)

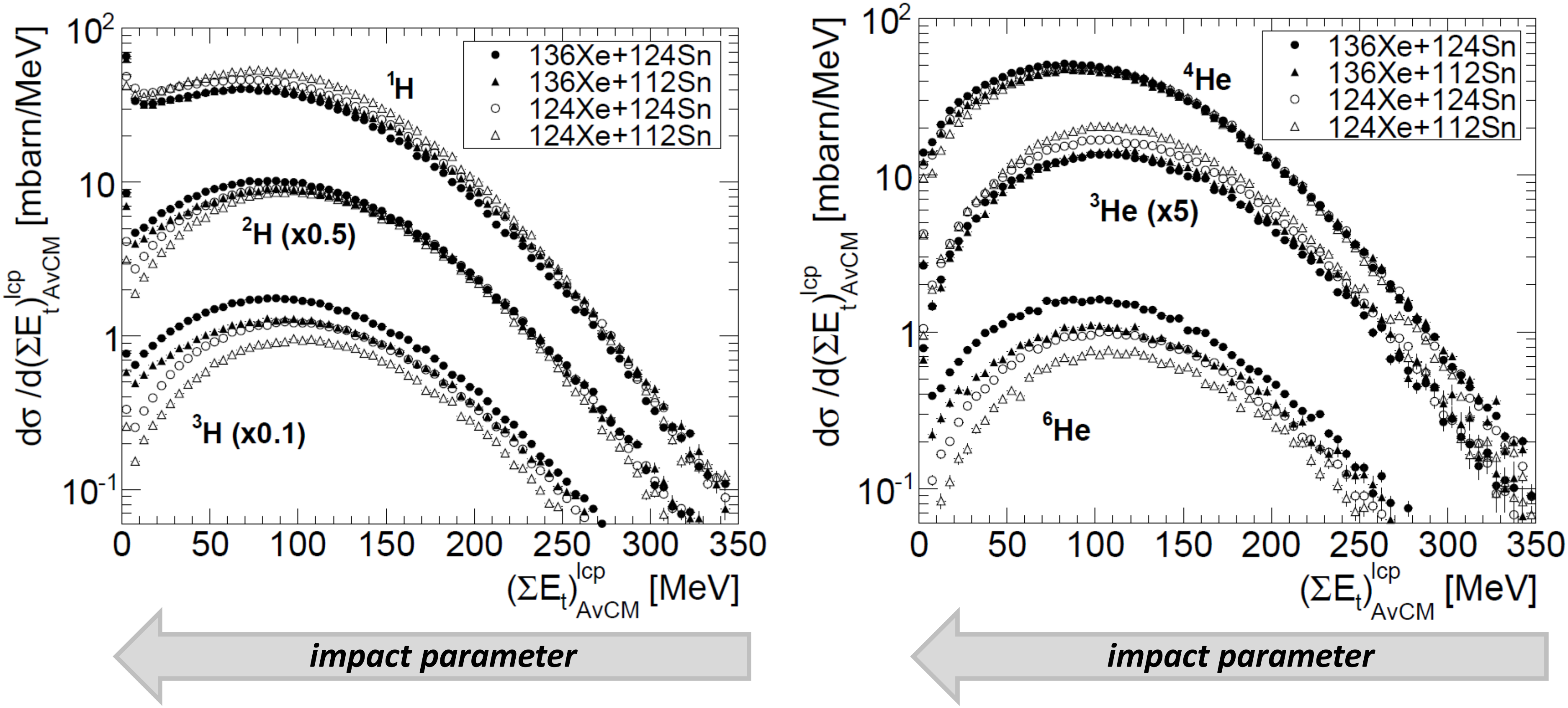
Increasing the system neutron richness: n-rich lcp production is doubled

LCP production *(forward c.m)*

mbarn	124+112	124+124	136+112	136+124
^{1}H				
^{2}H				
^{3}H				
^{3}He				
^{4}He				
^{6}He				
TOTAL				

Changing the projectile & target N/Z: isotope production cannot be summed up in solely neutron production difference

LCP production (forward c.m)



3He production is different

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LCP production: ^{3}He

PHYSICAL REVIEW C VOLUME 3, NUMBER 2 FEBRUARY 1971

Fragment Production in the Interaction of 5.5-GeV Protons with Uranium*

A. M. Poskanzer, Gilbert W. Butler,† and Earl K. Hyde
Lawrence Radiation Laboratory, University of California, Berkeley, California 94720

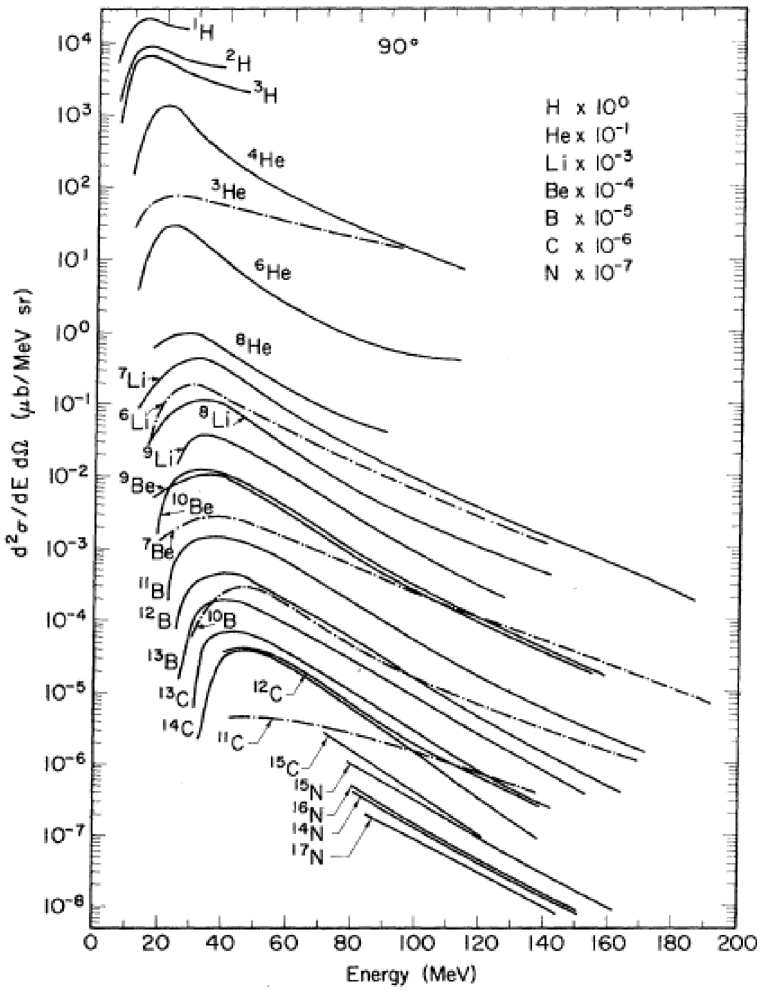


FIG. 13. Laboratory energy spectra at 90° to the beam. The curves for each element have been multiplied by a different factor which is indicated in the upper right part of the figure. The broken curves are for the most neutron-deficient isotope of each element. All the curves should be raised by the factor 1.10.

LCP production: ^3He

PHYSICAL REVIEW C VOLUME 16, NUMBER 2 AUGUST 1977

Central collisions of relativistic heavy ions*

J. Gosset,† H. H. Gutbrod, W. G. Meyer, A. M. Poskanzer, A. Sandoval, R. Stock, and G. D. Westfall
Lawrence Berkeley Laboratory, Berkeley, California 94720,
Gesellschaft für Schwerionenforschung, Darmstadt, Germany,
and Fachbereich Physik, Universität Marburg, Marburg, Germany

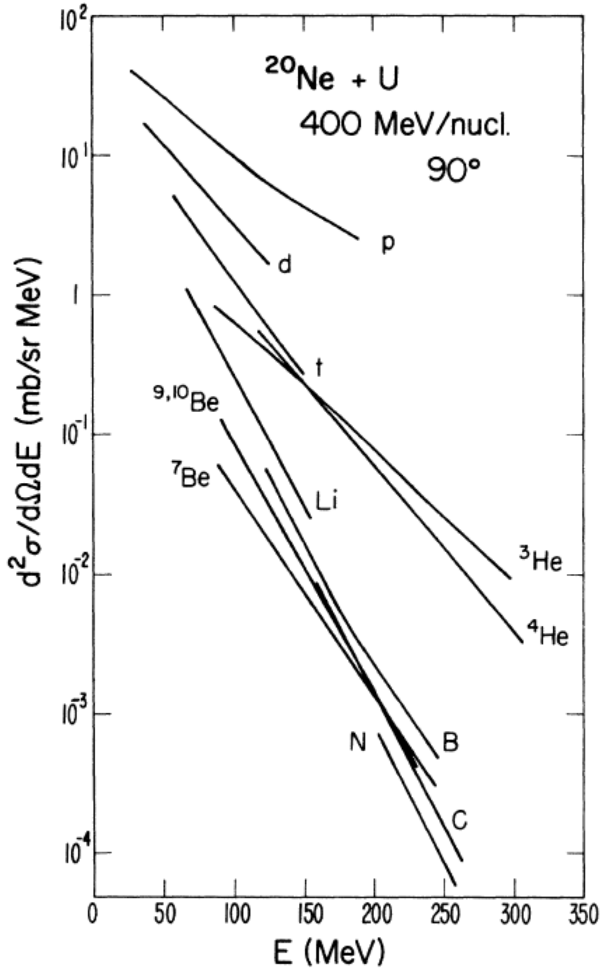


FIG. 19. Comparison of the energy spectra at 90° in the laboratory of proton through nitrogen fragments produced by the irradiation of uranium with ^{20}Ne ions at 400 MeV/nucleon.

LCP production: ^{3}He

VOLUME 47, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1981

Particle Emission at a ^{20}Ne Projectile Velocity Comparable to the Fermi Velocity

J. B. Natowitz, M. N. Namboodiri, L. Adler, R. P. Schmitt, R. L. Watson,
S. Simon, M. Berlanger, and R. Choudhury[a]
Cyclotron Institute, Texas A & M University, College Station, Texas 77843

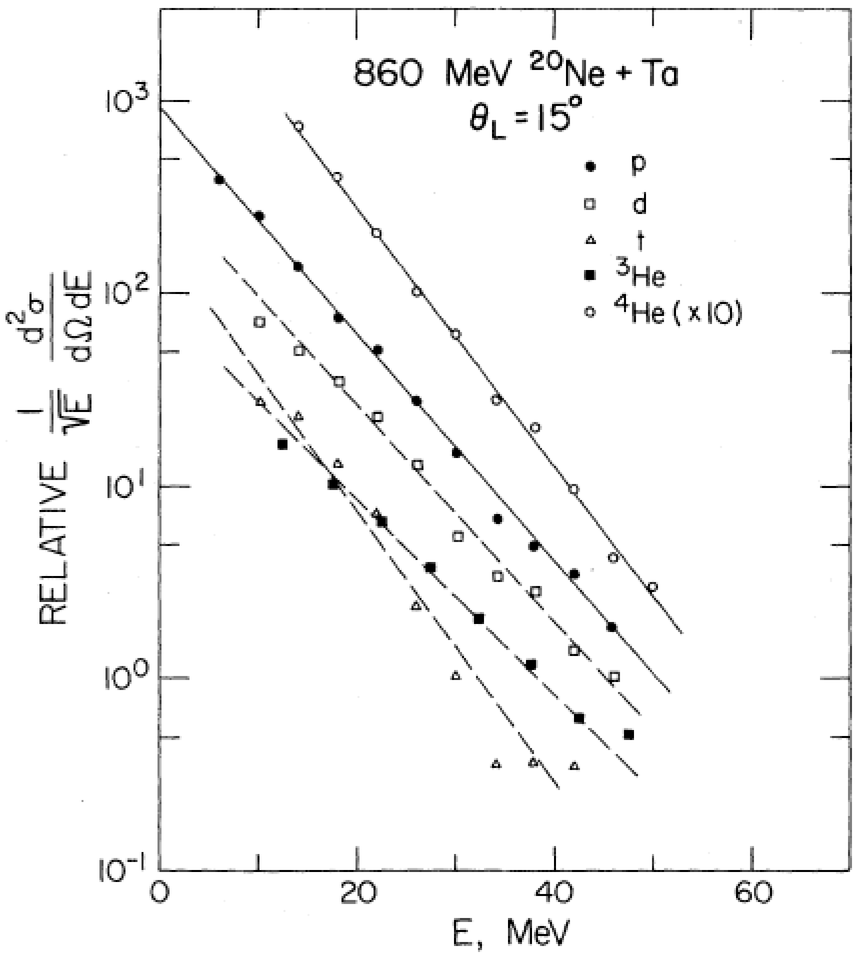


FIG. 2. Slope determinations for Ta data at $\theta_L = 15°$. The data have been transformed into the projectile frame.

LCP production

K.G.R. Doss et al. (PlasticBall)
Modern Phys Lett 9 (1988) 849

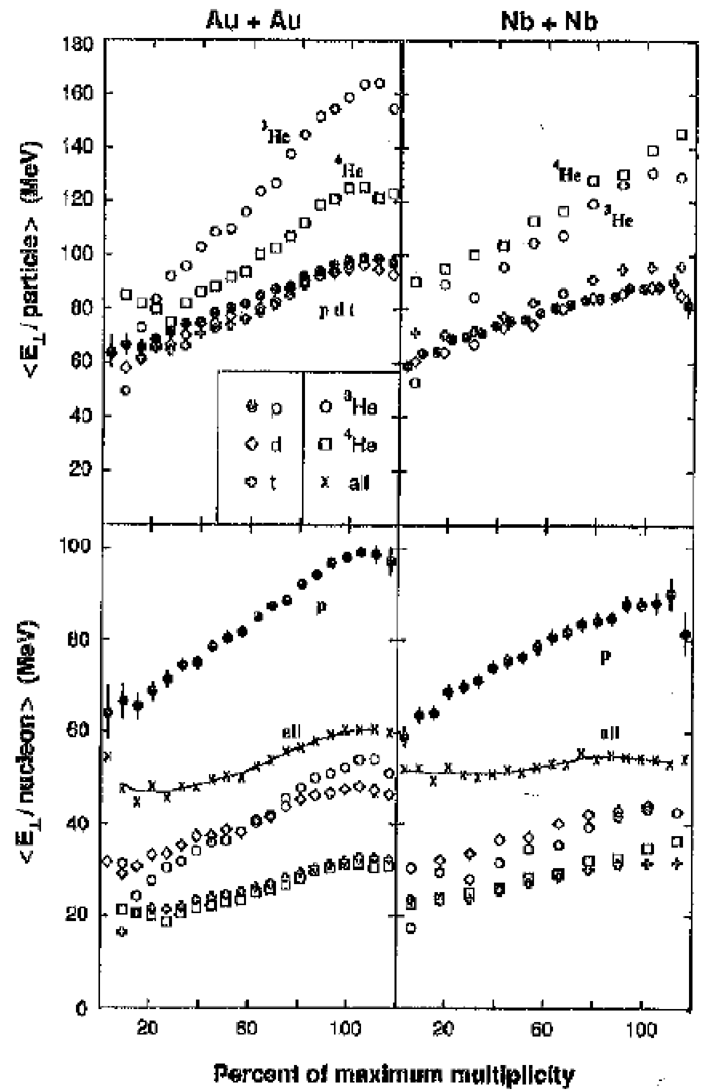


Fig. 3. Mean transverse energy per particle (upper half) and per nucleon (lower half) of p, d, t, ^{3}He and ^{4}He at $\theta_{cm} = 90°$ as a function of normalized multiplicity and the mean transverse energy per nucleon for the whole set of particles for collisions of Au + Au and Nb + Nb at 250 MeV per nucleon, respectively. (For errors see Fig. Caption 2).

LCP production: ^3He

50 A.MeV Xe+Sn « FUSION » events

Lcp: data versus Expanding Emitted Source-model (W.A. Friedman PRC42 (1990) 667.)

R. Bougault, J.P. Wieleczko et al. BORMIO 1997

$$C.Y.(time) = \frac{1}{Y}\int_0^{time} \frac{dY}{dt}\, dt$$

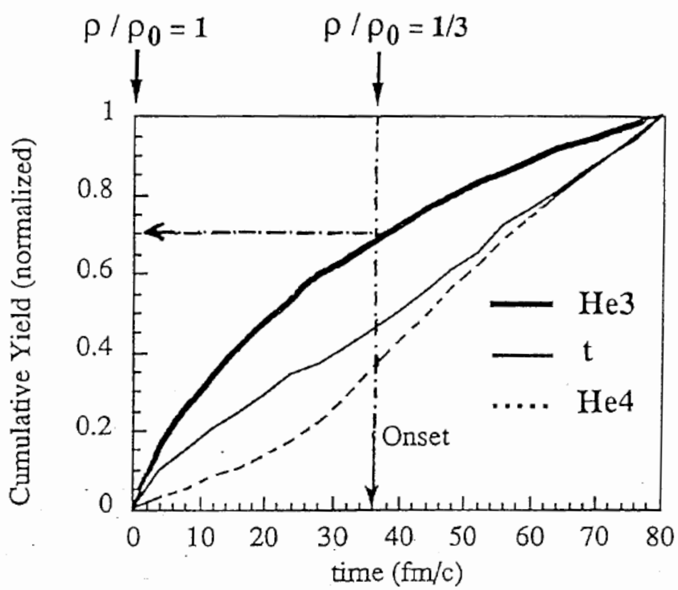


Figure 10: EES-calculation : cumulative yield for ^{4}He, ^{3}He and triton production. The first 35 fm/c corresponds to surface emission during the expansion phase.

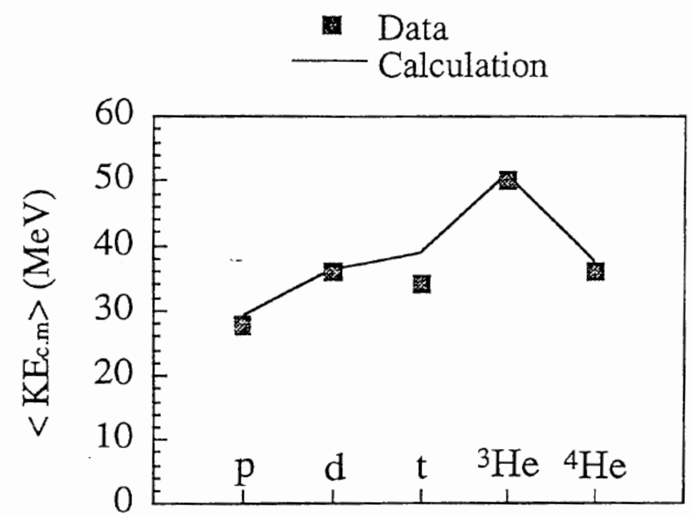


Figure 9: EES and light charged particles for 50 Xe+Sn : average c.m kinetic energy of the light charged particles (black squares are data) for a perpendicular emission ($70° \leq \Theta_{cm} \leq 110°$) in the center of mass. The result of the EES-calculation which reproduces the associated fragment characteristics is shown (line).

LCP production: ^{3}He

2.B: 2.L

Nuclear Physics **A285** (1977) 461 – 468; *North-Holland Publishing Co., Amsterdam*

Synchrotron SATURNE

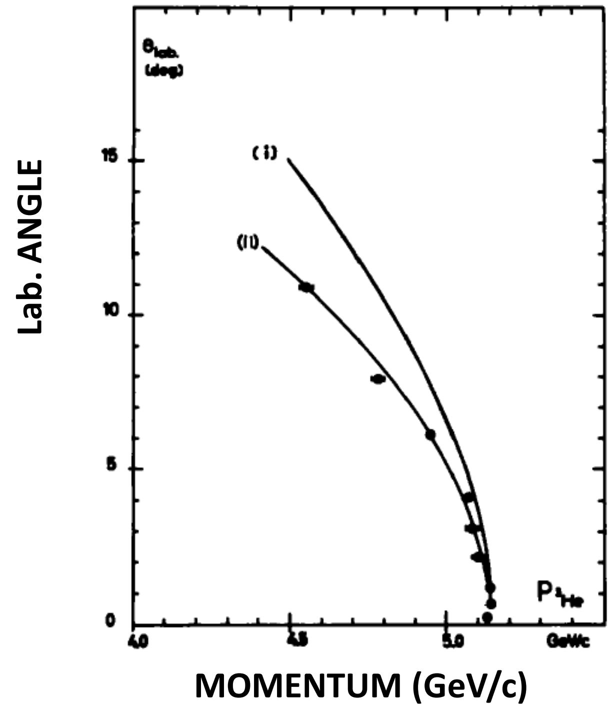


Fig. 3. Experimental ^{3}He peak position as a function of the lab angle, compared with the two hypotheses: (i) Knock-out of a neutron and (ii) elastic ^{3}He-p scattering.

^{3}He PRODUCTION IN ^{4}He FRAGMENTATION ON PROTONS AT 6.85 GeV/*c*

G. BIZARD and C. LE BRUN
CNRS, Université de Caen, France

J. BERGER, J. DUFLO, L. GOLDZAHL and F. PLOUIN
CNRS, Département Saturne, Saclay, France

J. OOSTENS †, M. VAN DEN BOSSCHE and L. VU HAI
Département Saturne, Saclay, France

and

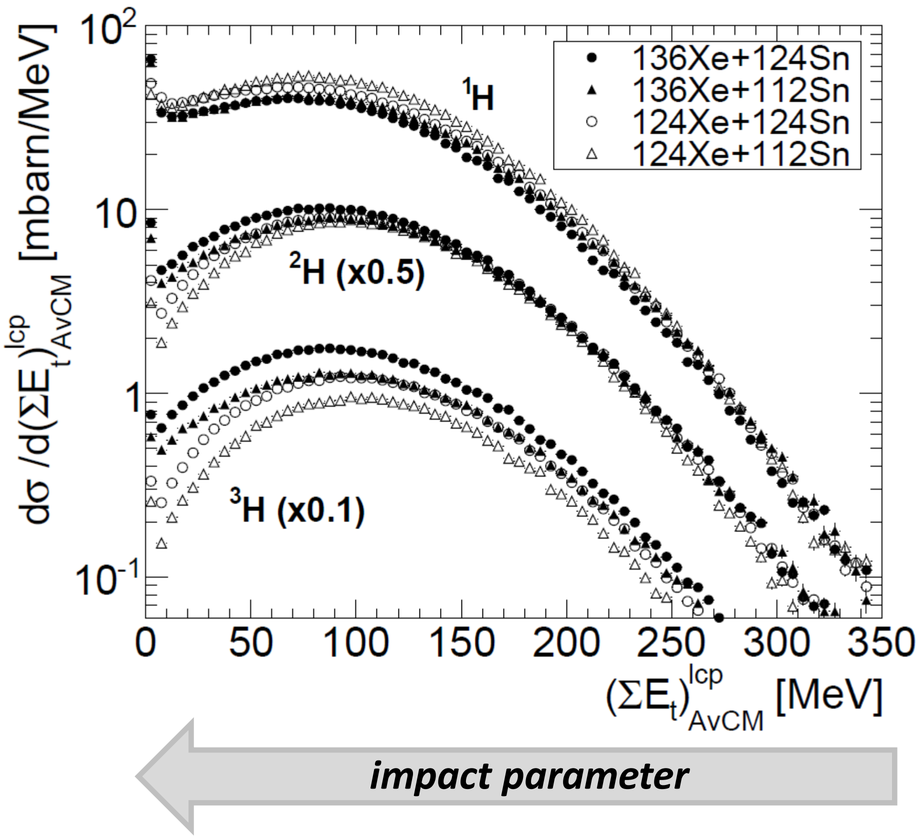
F. L. FABBRI, P. PICOZZA and L. SATTA
Laboratori Nazionali di Frascati, Italia

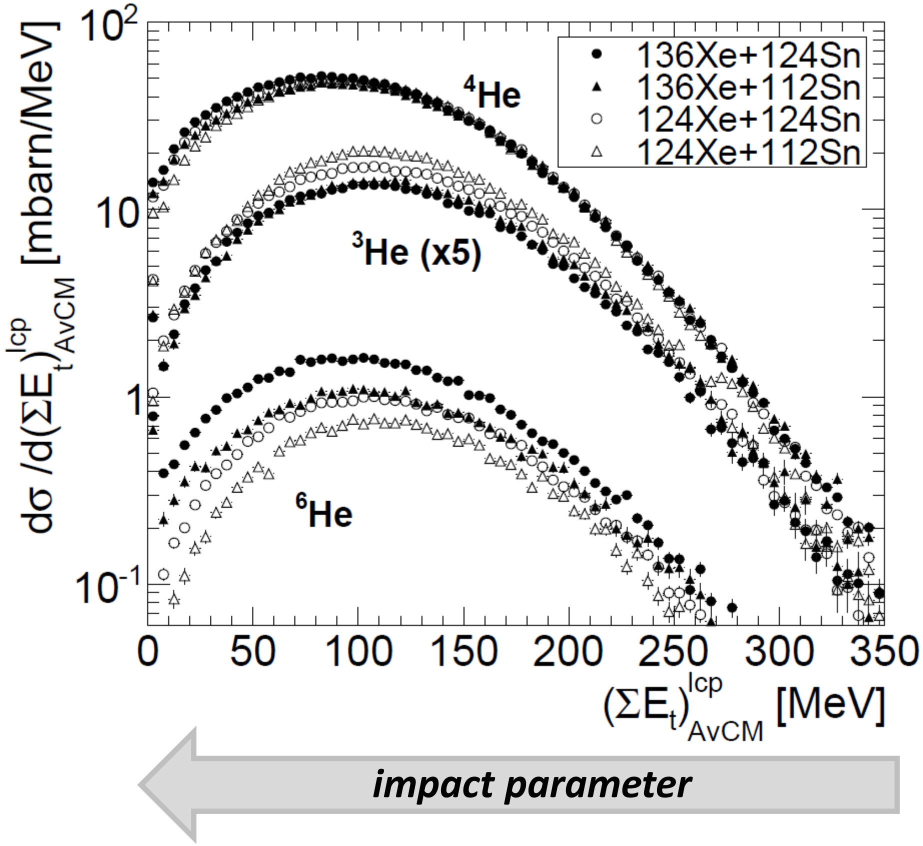
Received 15 November 1976

Abstract: The angular distribution of the inclusive reaction $^4He+p \rightarrow {}^3He+X$ was measured with 6.85 GeV/*c* incident alphas. At large angles, the observed kinematics corresponds to the elastic scattering on the target proton of an ^{3}He present in the incoming ^{4}He, the remaining neutron being a spectator. This shows the presence of an important component of ^{3}He in ^{4}He. The integrated cross section for ^{3}He production is $\sigma_{^3He} = 24.1 \pm 1.9$ mb.

(p+^{4}He reaction cross-section is 110 mb)

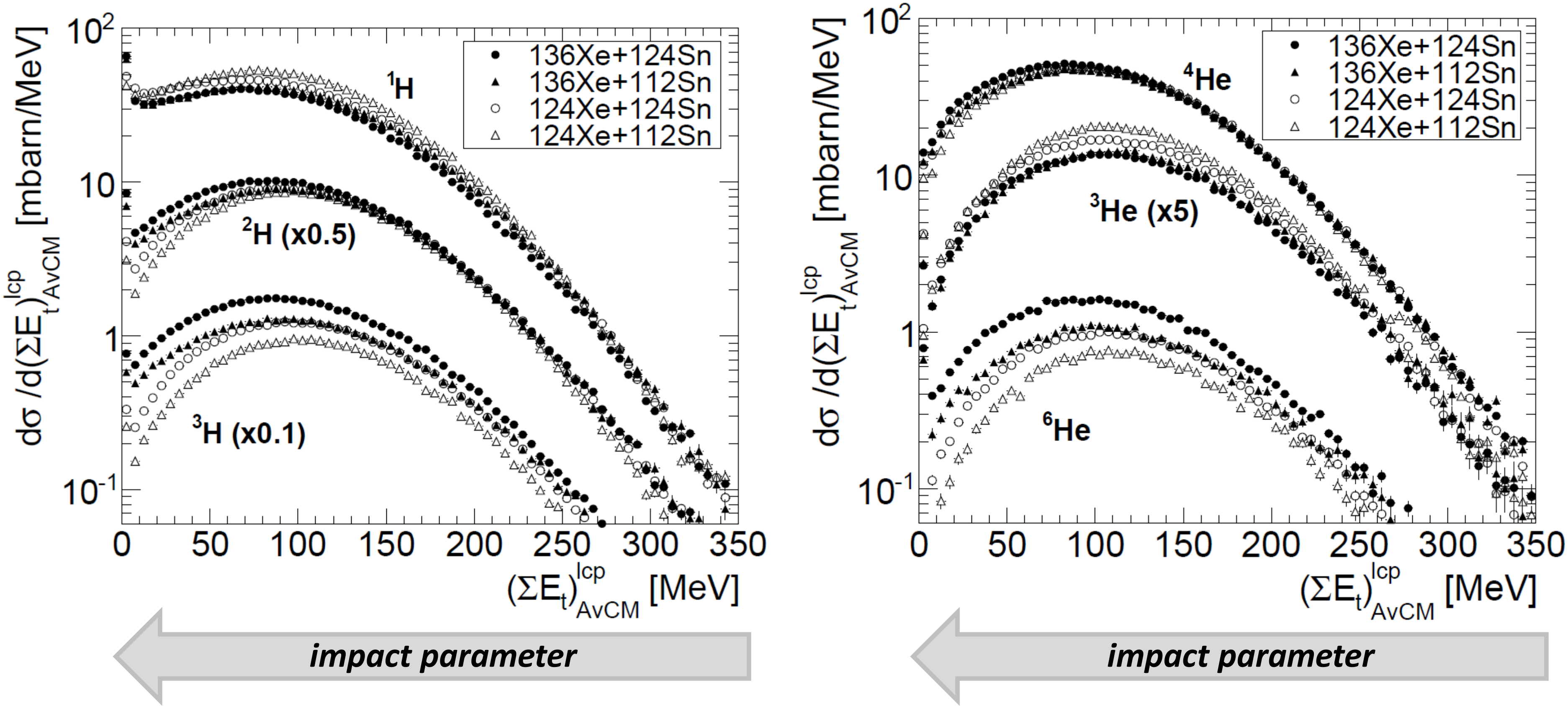
LCP production (forward c.m)





Lcp cross-sections: production probabilities folded by reaction cross-section

LCP production (forward c.m)



To study equilibrium:

Production probabilities (multiplicities) divided by 1H multiplicities to remove trivial size effects.

Chemistry related to concentrations thus Mx/Mproton (abundance ratio).

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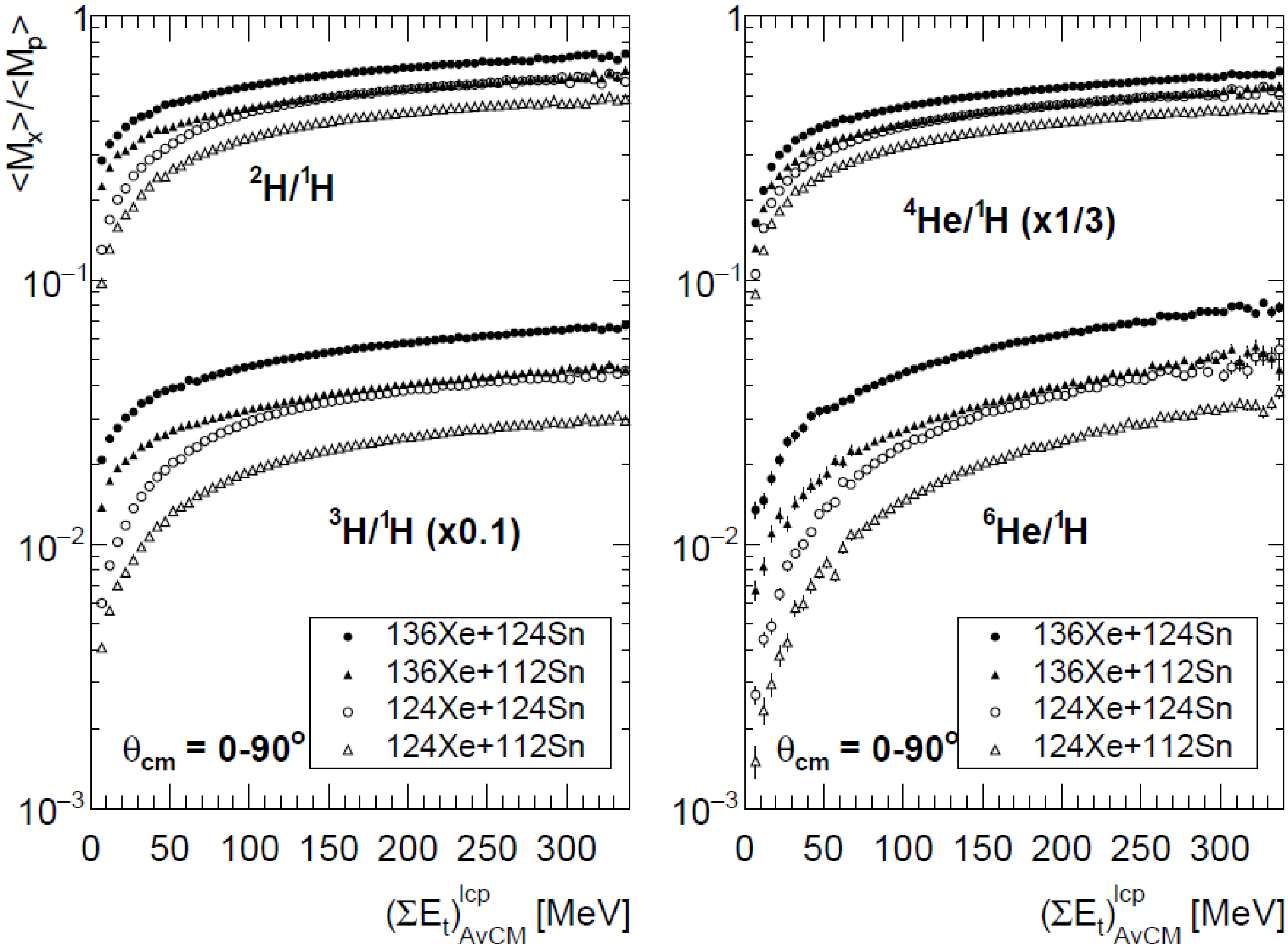
Cluster abundance ratios



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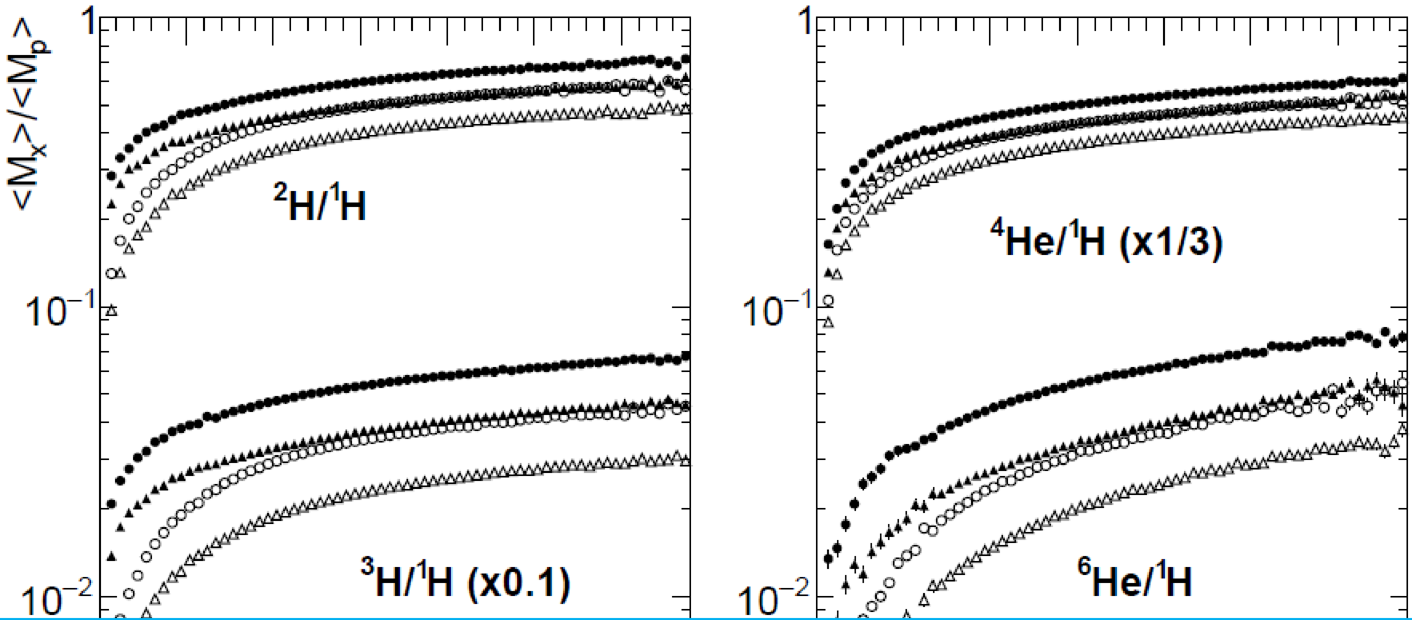
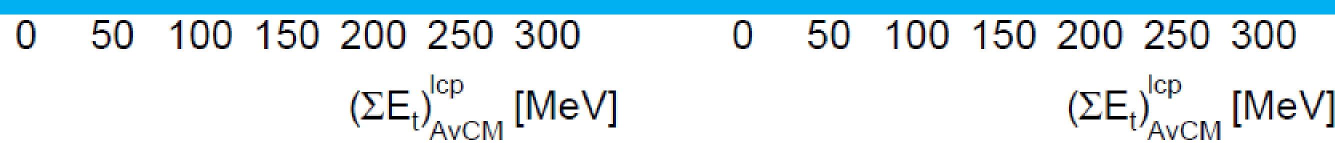
Cluster abundance ratios



Comparing ^{136}Xe+^{112}Sn and ^{124}Xe+^{124}Sn: abundance ratios are (projectile+target) N/Z dependent.

CHEMICAL EQUILIBRIUM IS ~ACHIEVED (central collisions)



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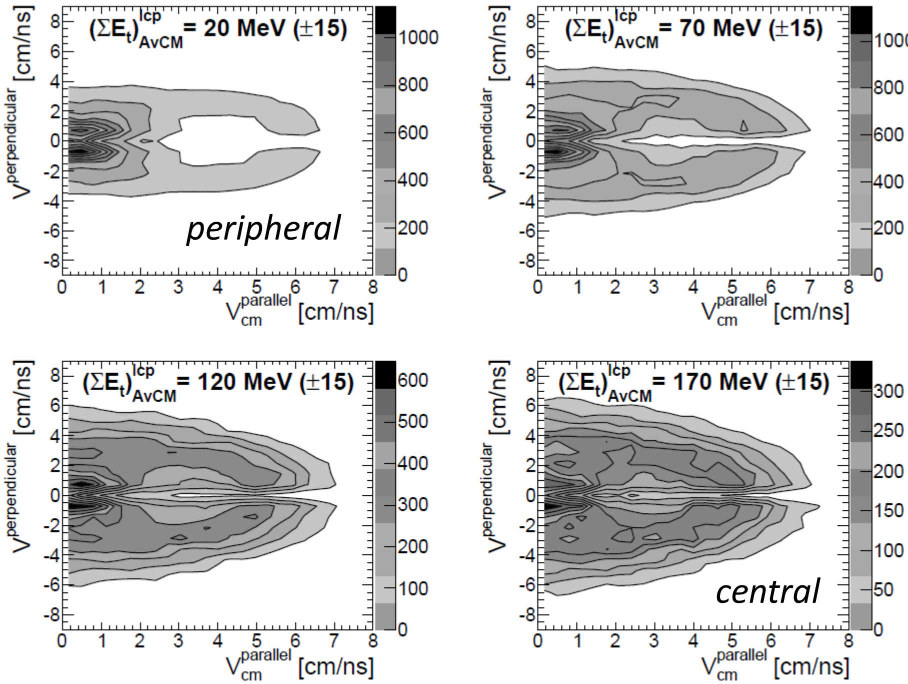
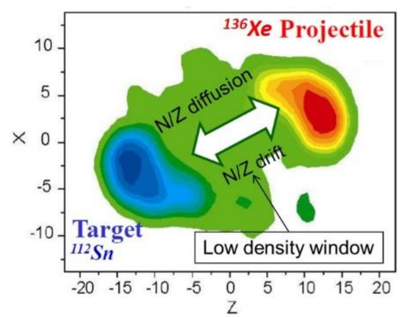
LCP production mode (forward c.m): ^{2}H



Emission from projectile-like fragment & at mid-rapidity

Projectile/Target nucleon exchange and mid-rapidity chemistry



are governed by drift and diffusion transport phenomena

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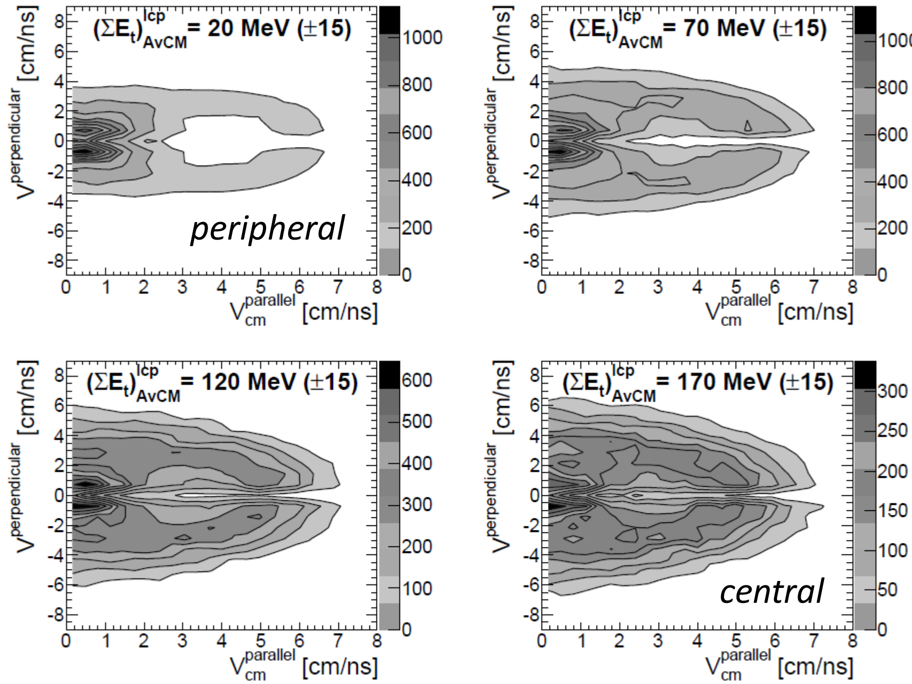
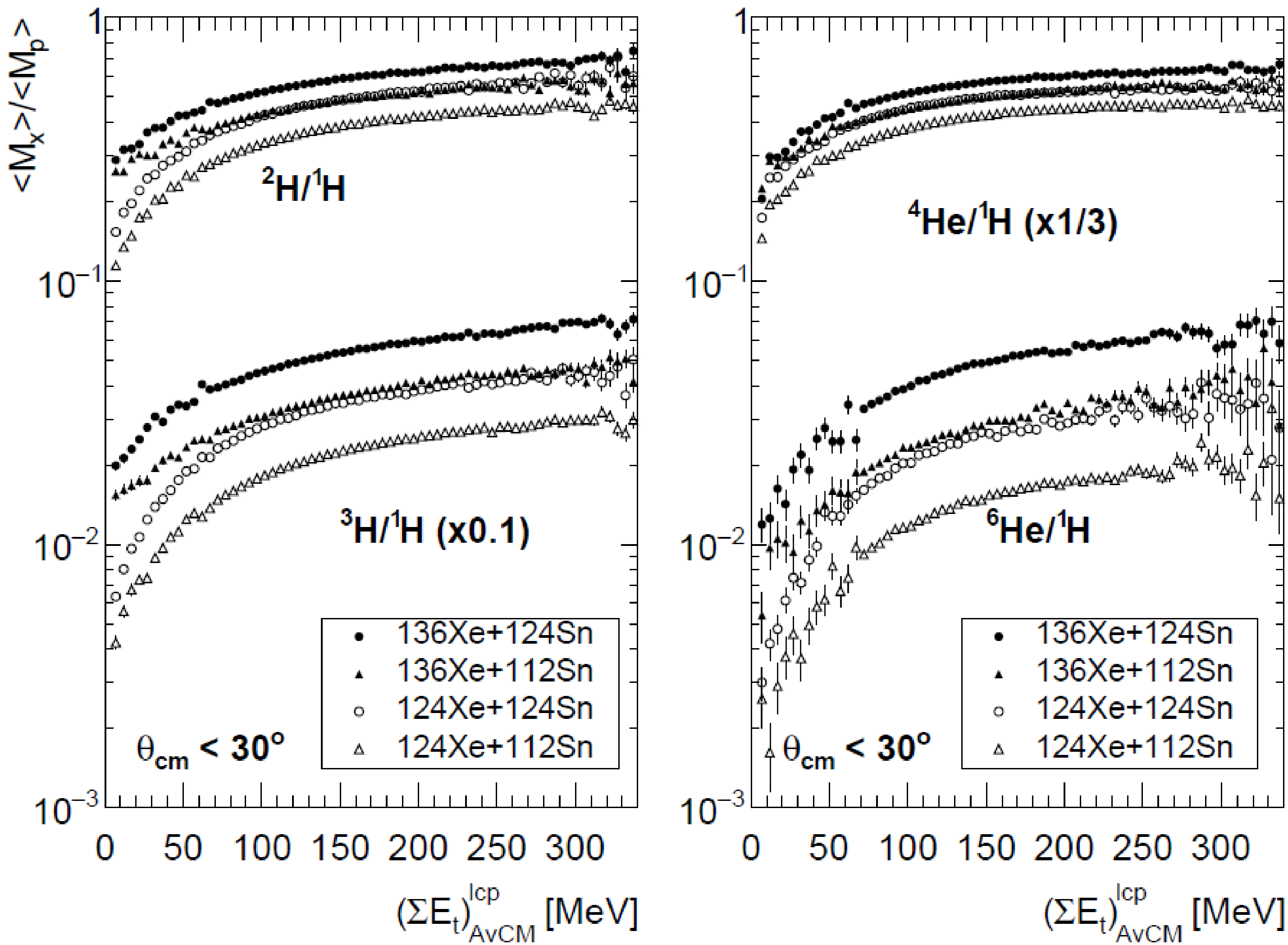
LCP production mode (forward c.m): ^2H



Emission from projectile-like fragment & at mid-rapidity

Projectile-like: 0°-30° angle selection
½ rapidity: 60°-90° angle selection

Cluster abundance ratios ("PLF")



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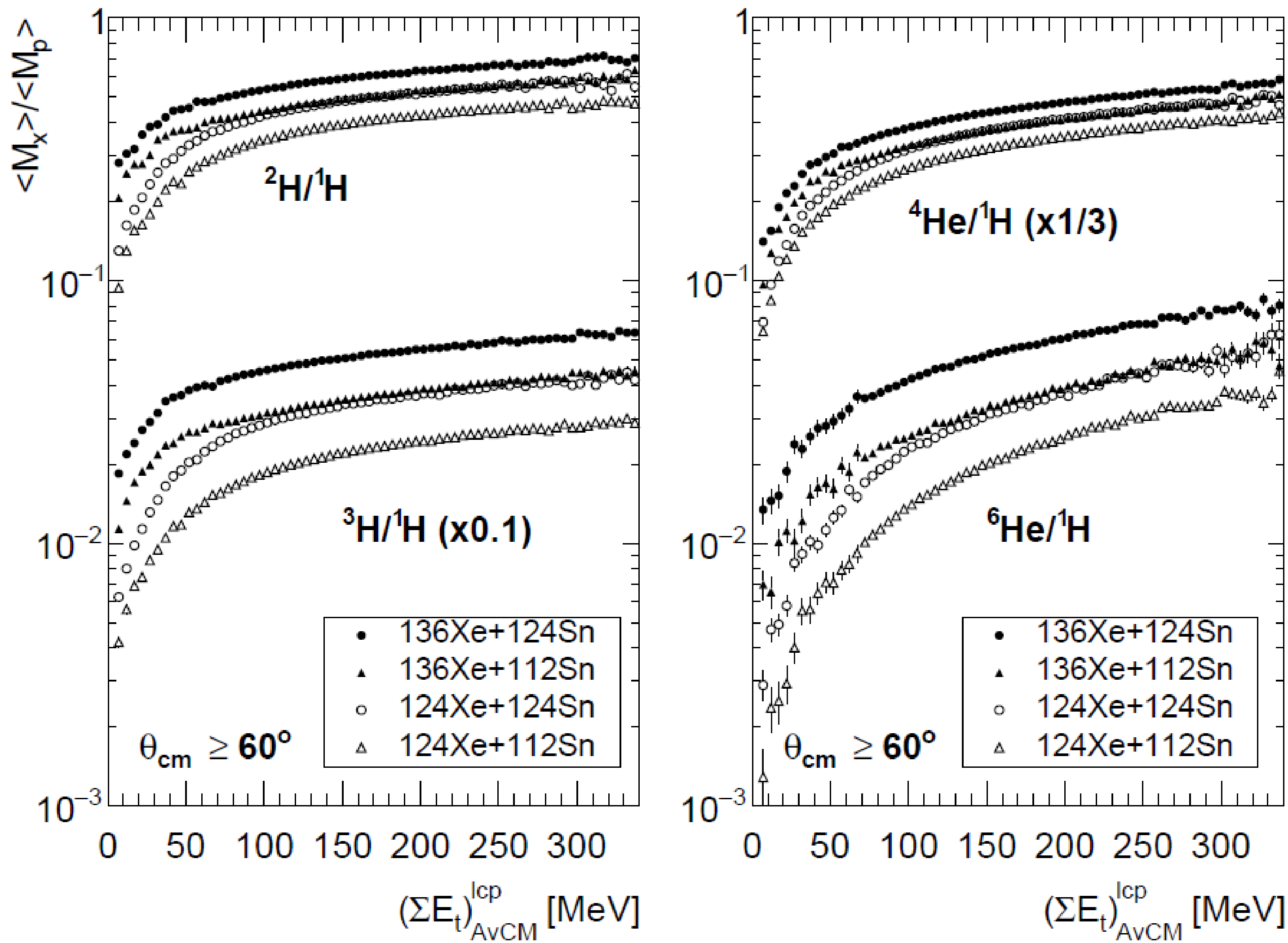
Cluster abundance ratios ("1/2 rapidity")



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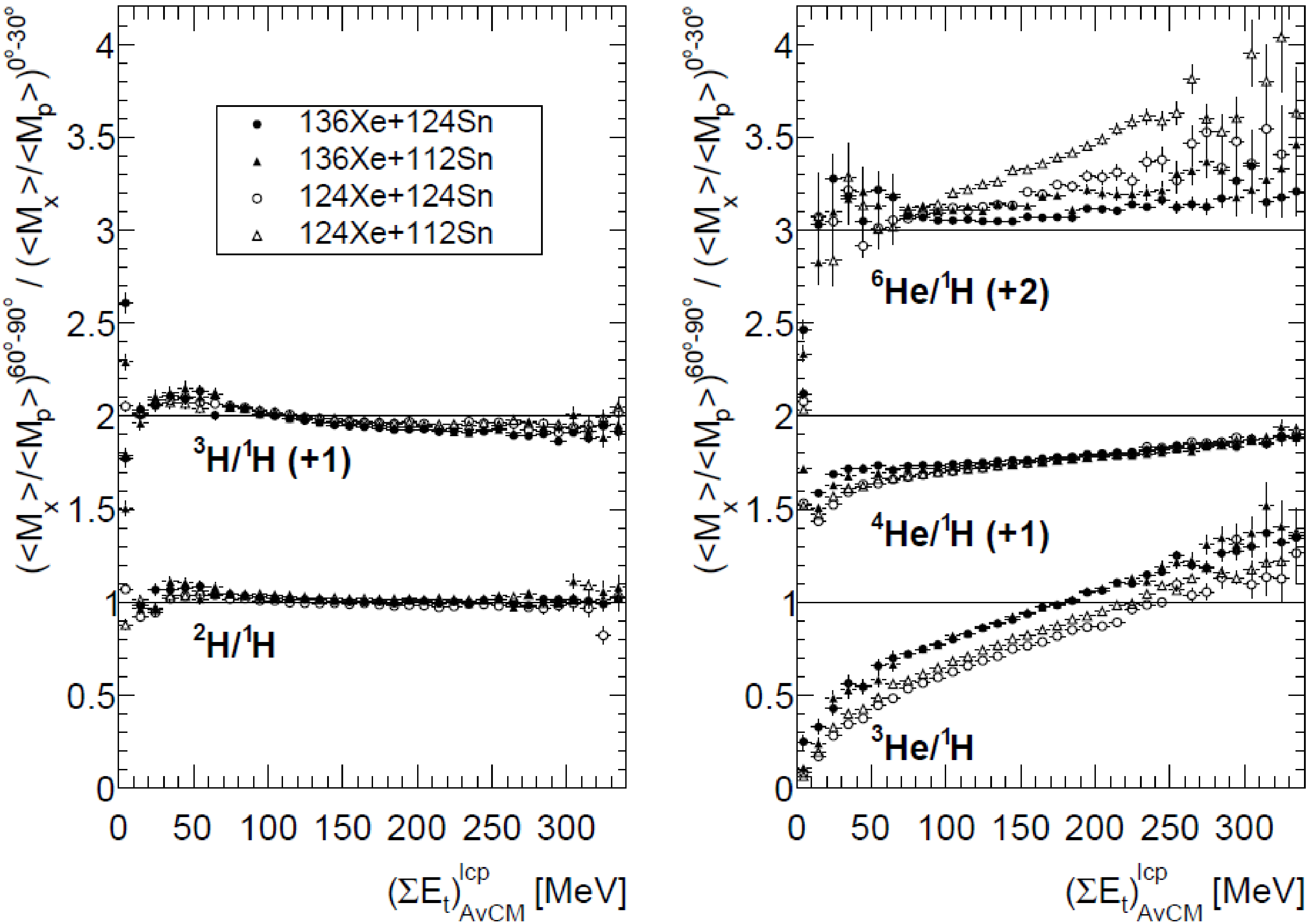
Cluster abundance ratios

1/2 rapidity divided by PLF



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Cluster abundance ratios

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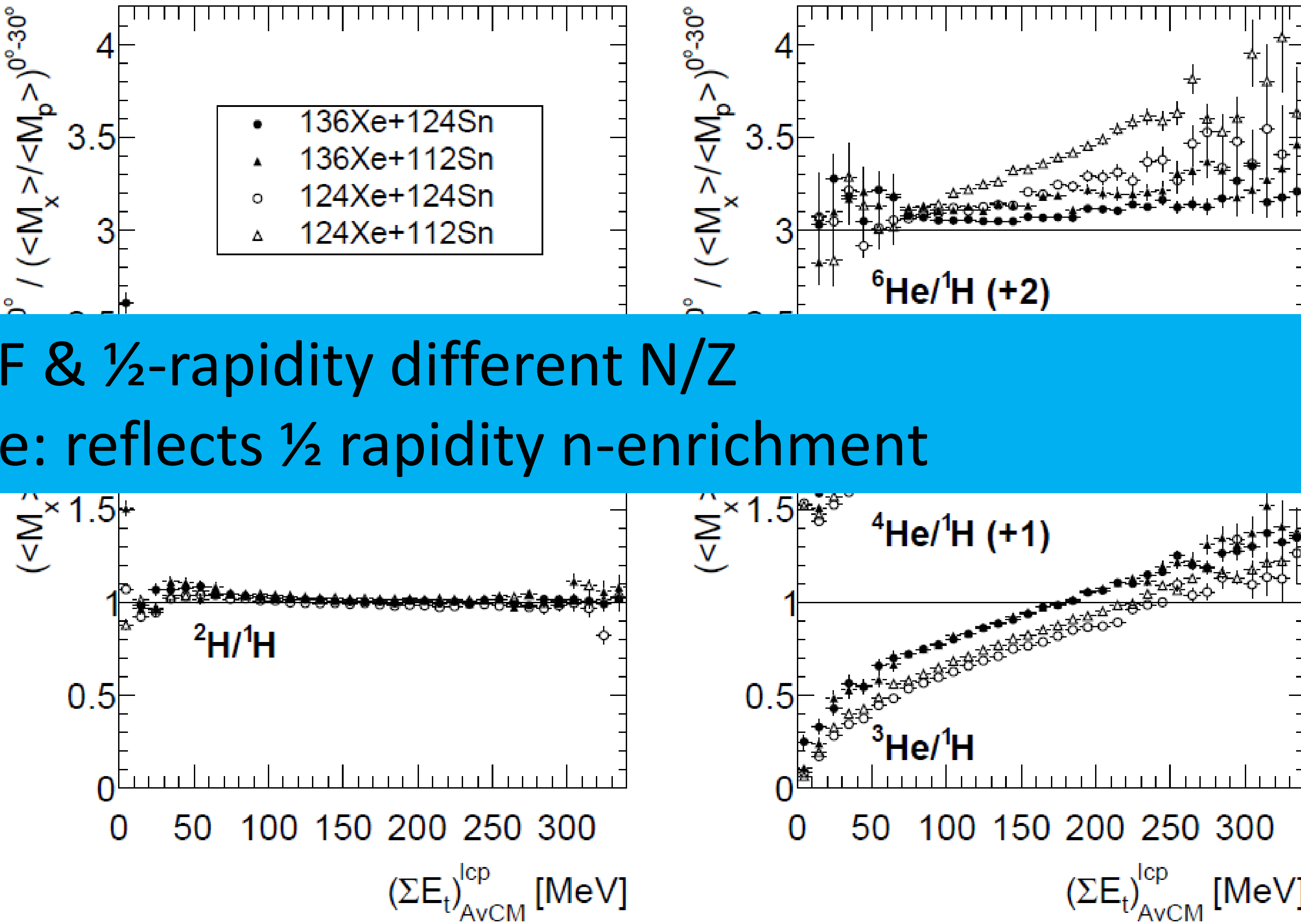

- PLF & ½-rapidity different N/Z
- ^{6}He: reflects ½ rapidity n-enrichment

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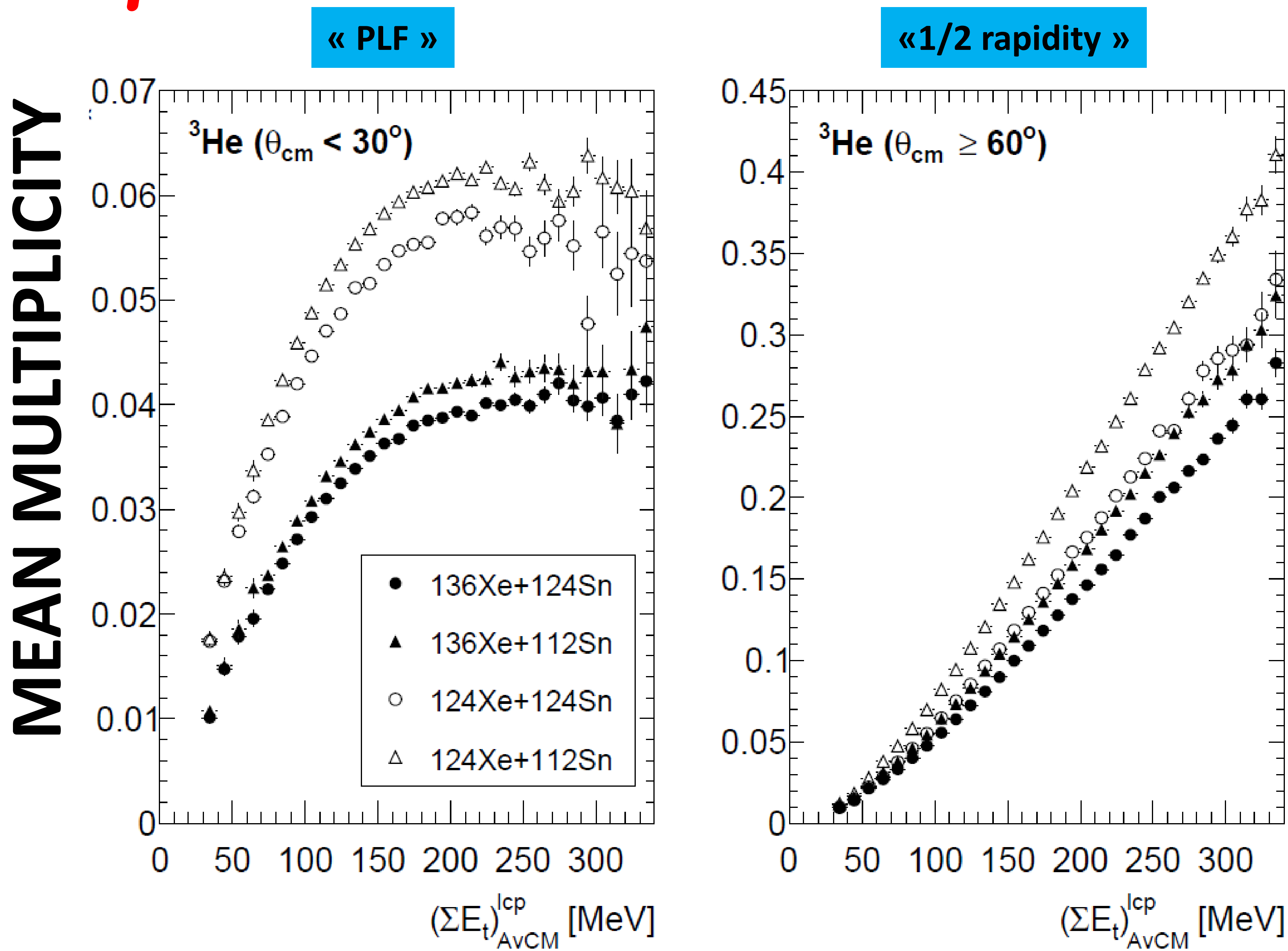
LCP production: ^3He



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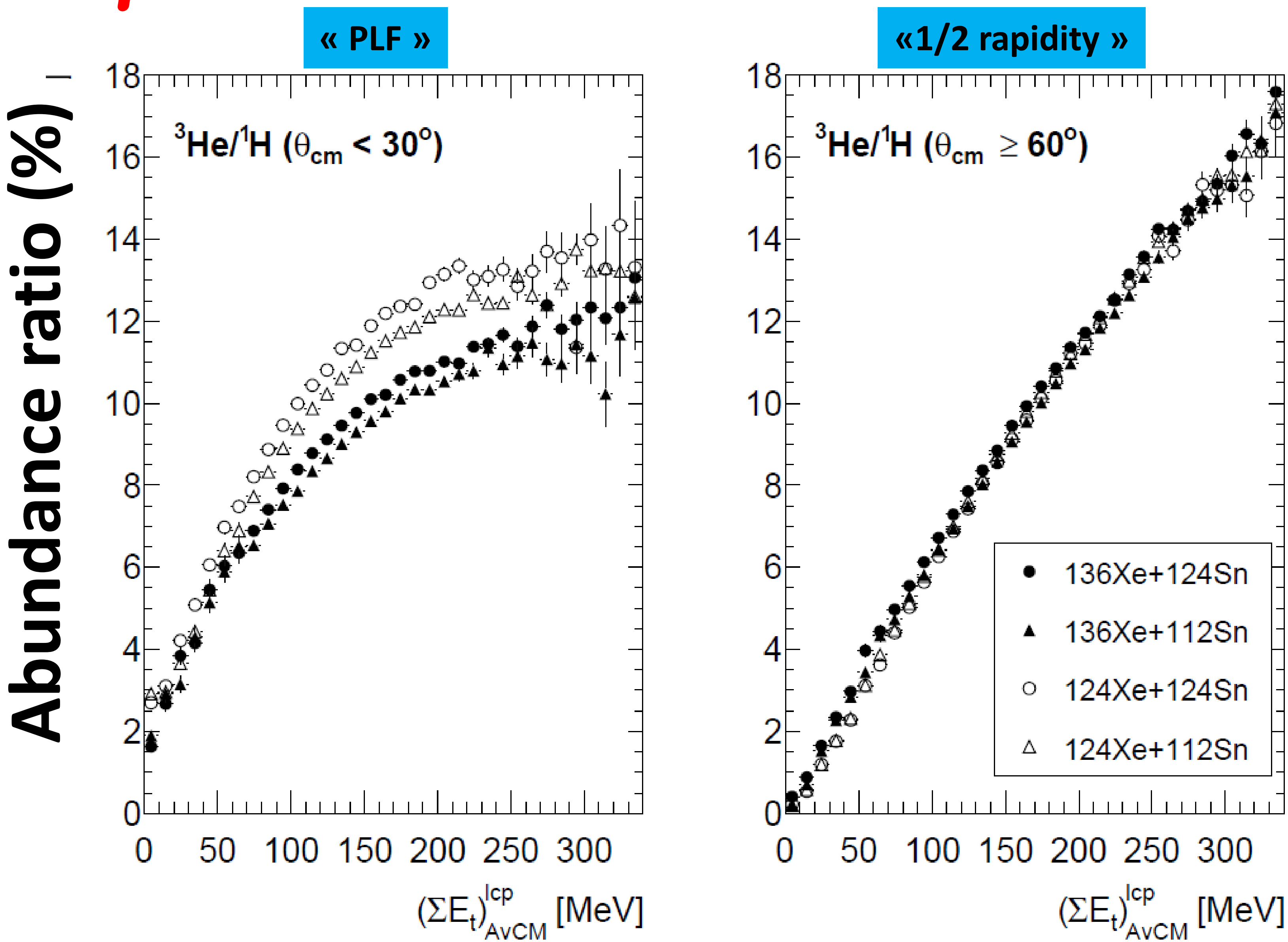
LCP production: ^3He



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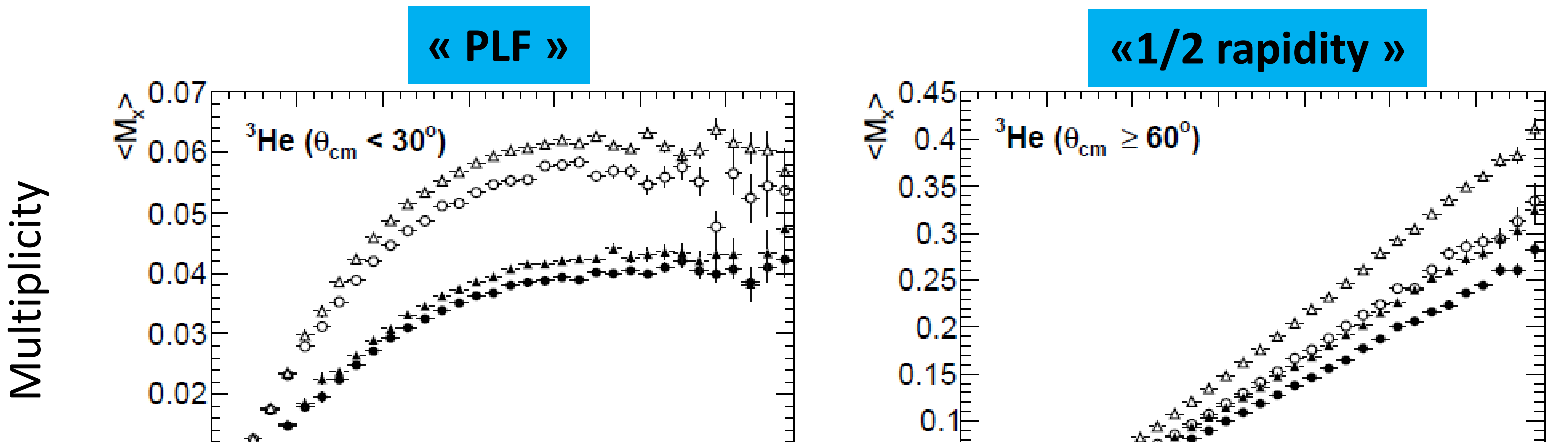
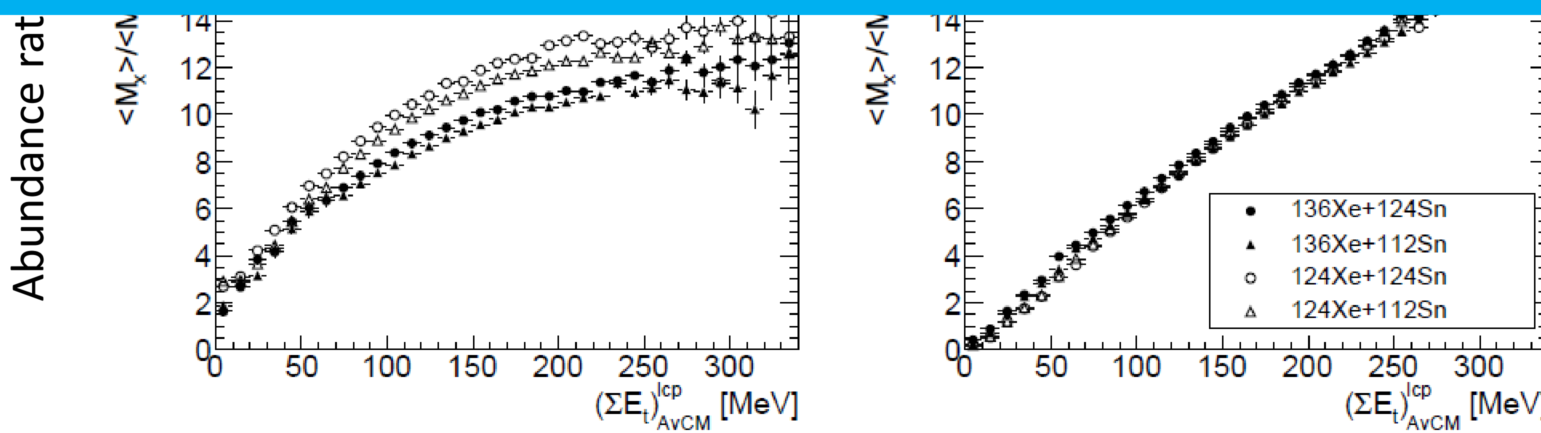
LCP production: ^3He



- PLF: N/Z dependence
- ½ rapidity: total size (not N/Z) dependence

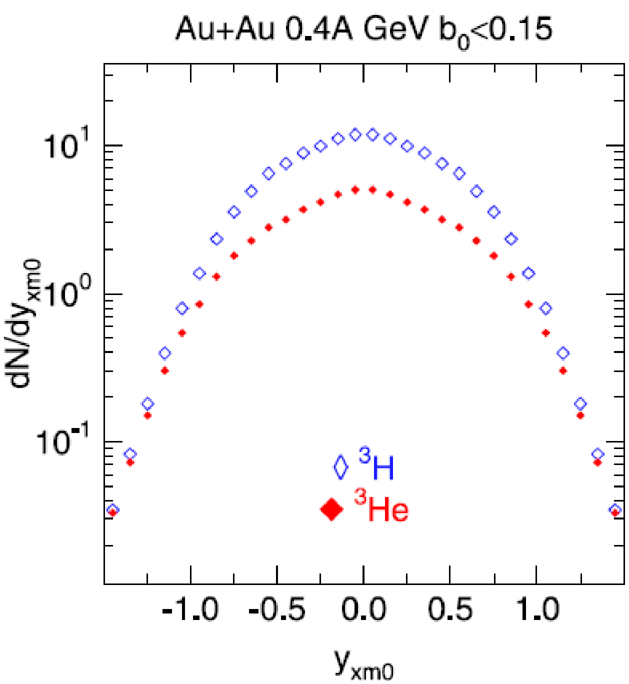
3He produced before chemical equilibrium achievement

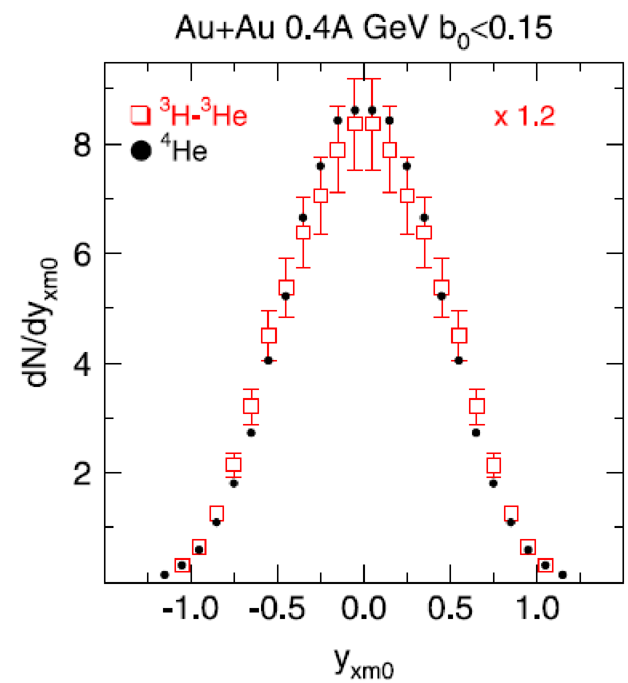


Coalescence prior thermalization: W. Neubert, A.S. Botvina Eur. Phys. J. A 7 (2000)

LCP production (forward c.m)

W. Reisdorf et al. (FOPI) NPA848 (2010) 366.

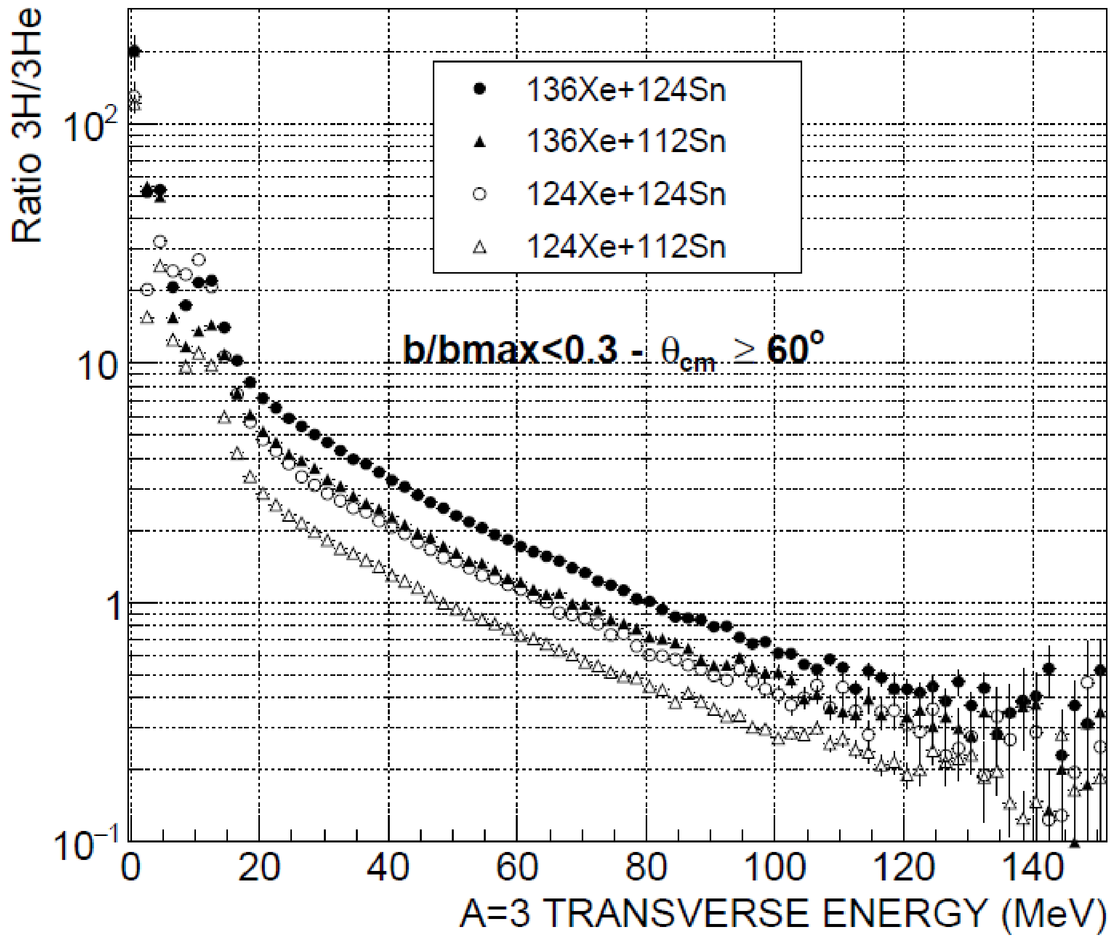




This conjecture is supported by Fig. 18 which shows the ^{3}H–^{3}He difference spectrum together with data for ^{4}He. The ^{3}H and the ^{3}He compete to be a condensation nucleus to a possible ^{4}He. If both mass 3 isotopes are in a neutron-rich environment, the ^{3}He will 'win' for two reasons:

a) it is easier to 'find' a single neutron to attach to ^{3}He than a single proton to attach to ^{3}H;
b) in contrast to ^{3}H, the ^{3}He nucleus does not Coulomb-repulse its needed partner.

LCP production



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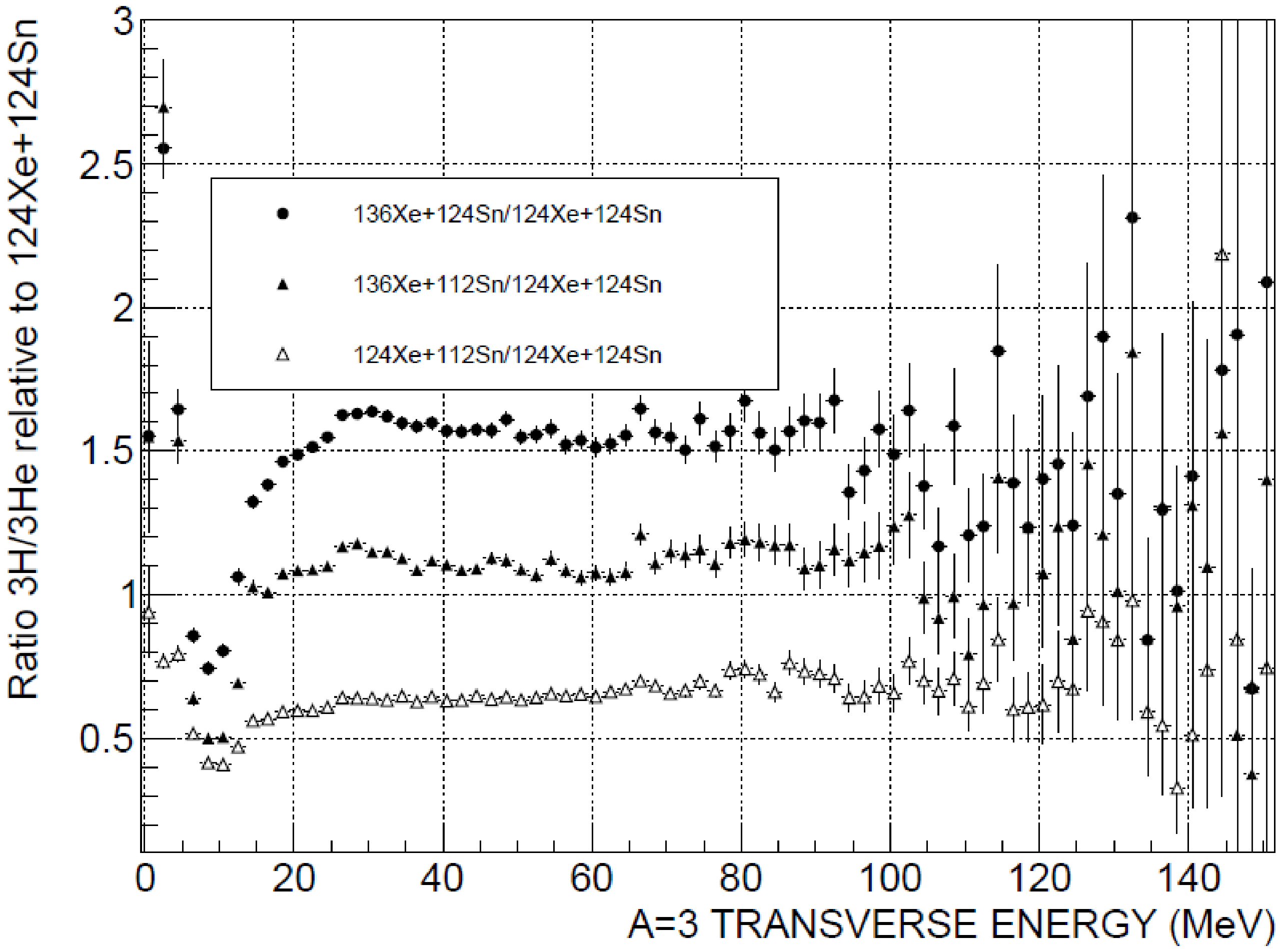
LCP production



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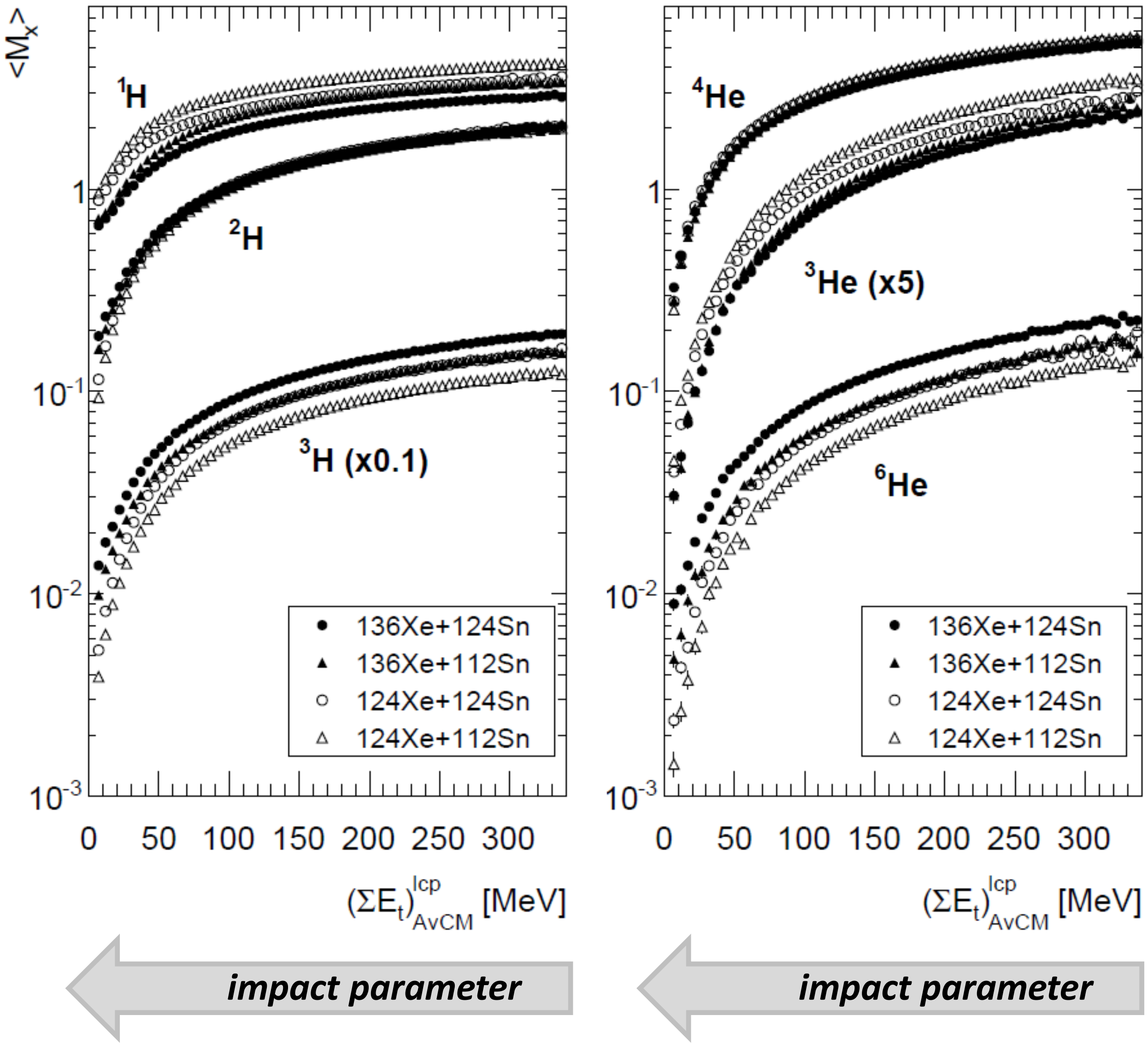
LCP production



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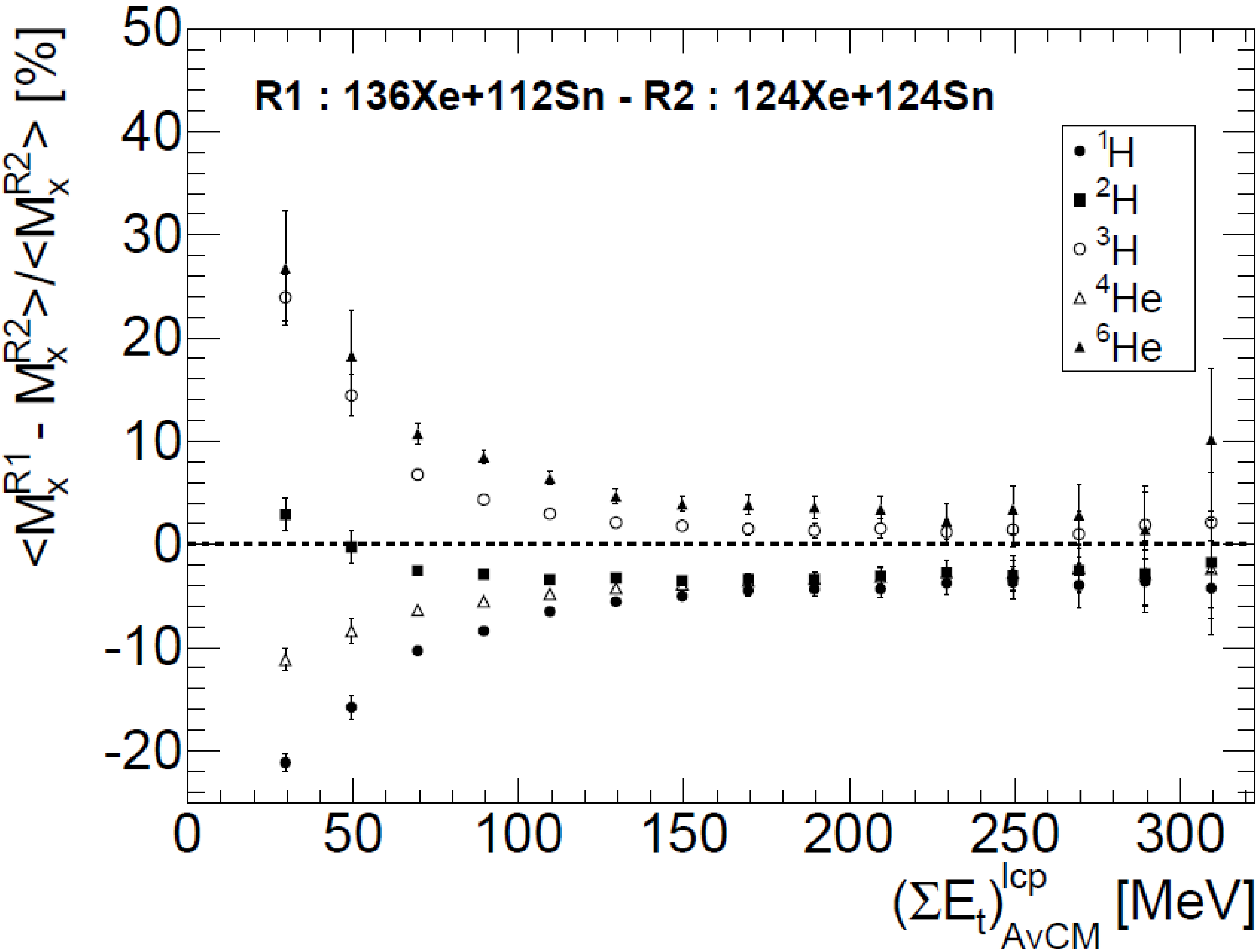
LCP production

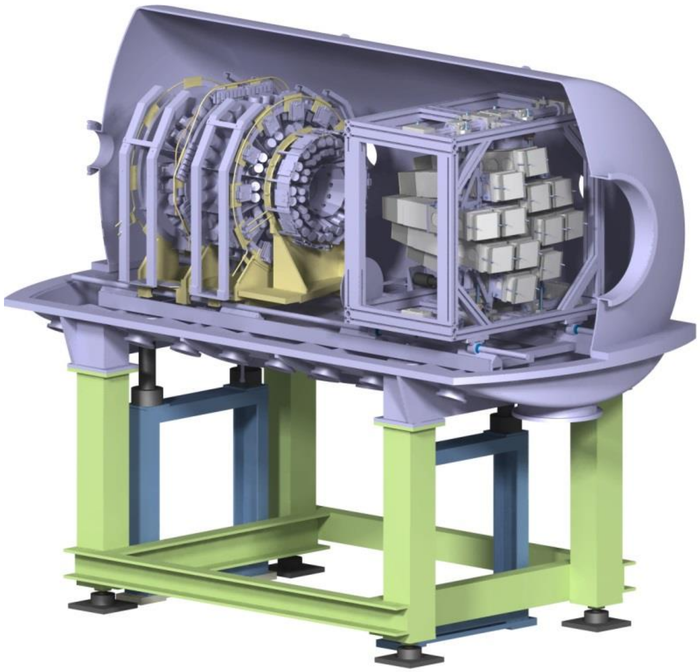


R. Bougault INDRA/FAZIA collaboration

Conclusions

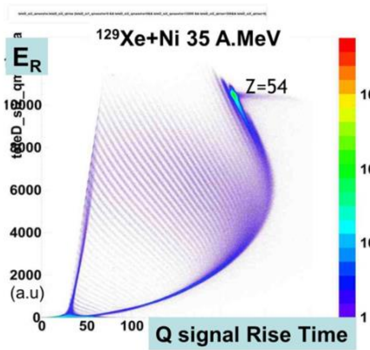
- Light Charged Particle abundance ratios dependence against impact parameter: high degree of chemical equilibrium is achieved in central collisions.
- ^{3}He mean characteristics strongly differ from other studied lcp's: helion production takes place before chemical equilibrium achievement.
- Achieved N/Z balance between PLF & TLF does not imply a pure 2-body mechanism: mid-rapidity source does exist with N/Z different as compared to PLF (n-enrichment).
- ^{6}He production is favored by the drift phenomena.
- Results obtained with INCLUSIVE DATA

- **Importance of clusters.**
- **^{3}He & ^{6}He should be used to compared data/transport models (stiff/soft Esym)**
- **Analysis will be extended (higher elements) using FAZIA@INDRA at GANIL**

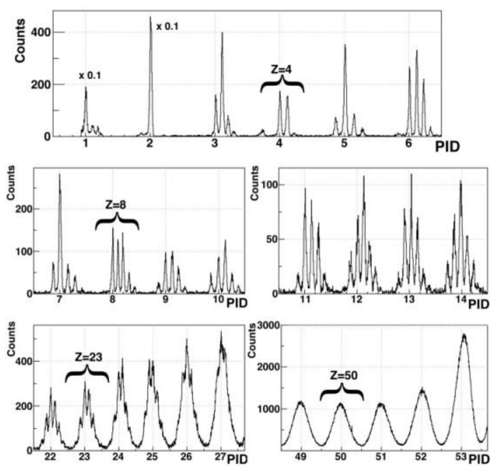


FAZIA DEMONSTRATOR at LNS

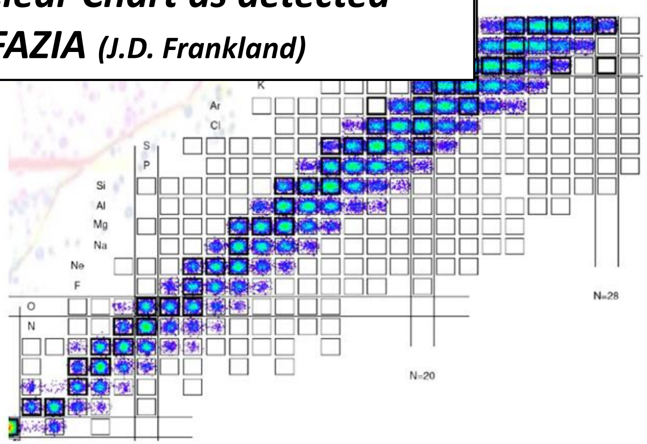
Pulse Shape identification



DE/E identification



***Nuclear Chart as detected by FAZIA** (J.D. Frankland)*

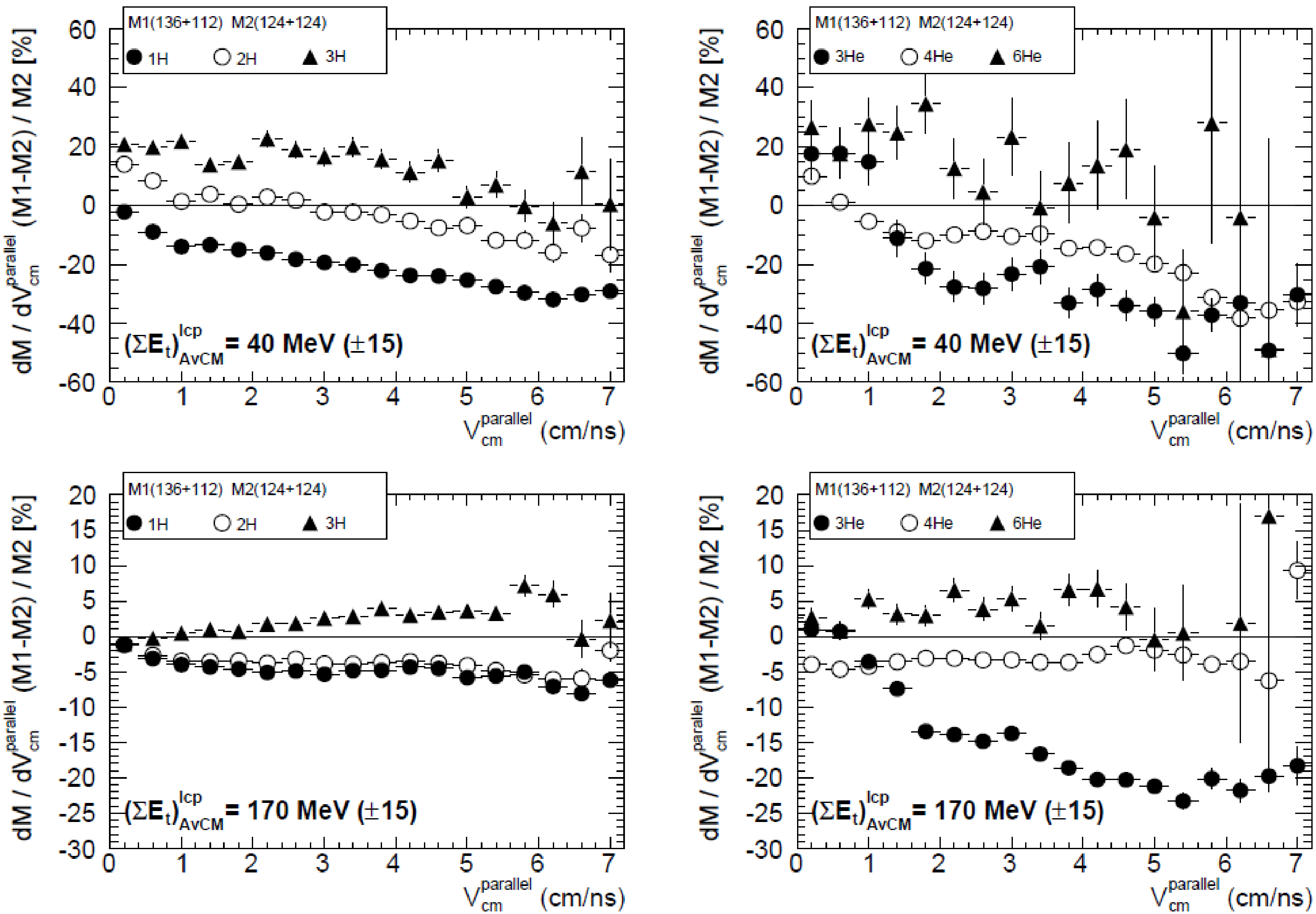


LCP production (forward c.m)

	$(N/Z)_{proj}$	$(N/Z)_{targ}$	drift	dif.
124+112	1.30	1.24	Yes	$\approx$ No
124+124	1.30	1.48	Yes	Yes
136+112	1.52	1.24	Yes	Yes
136+124	1.52	1.48	Yes	$\approx$ No

LCP production

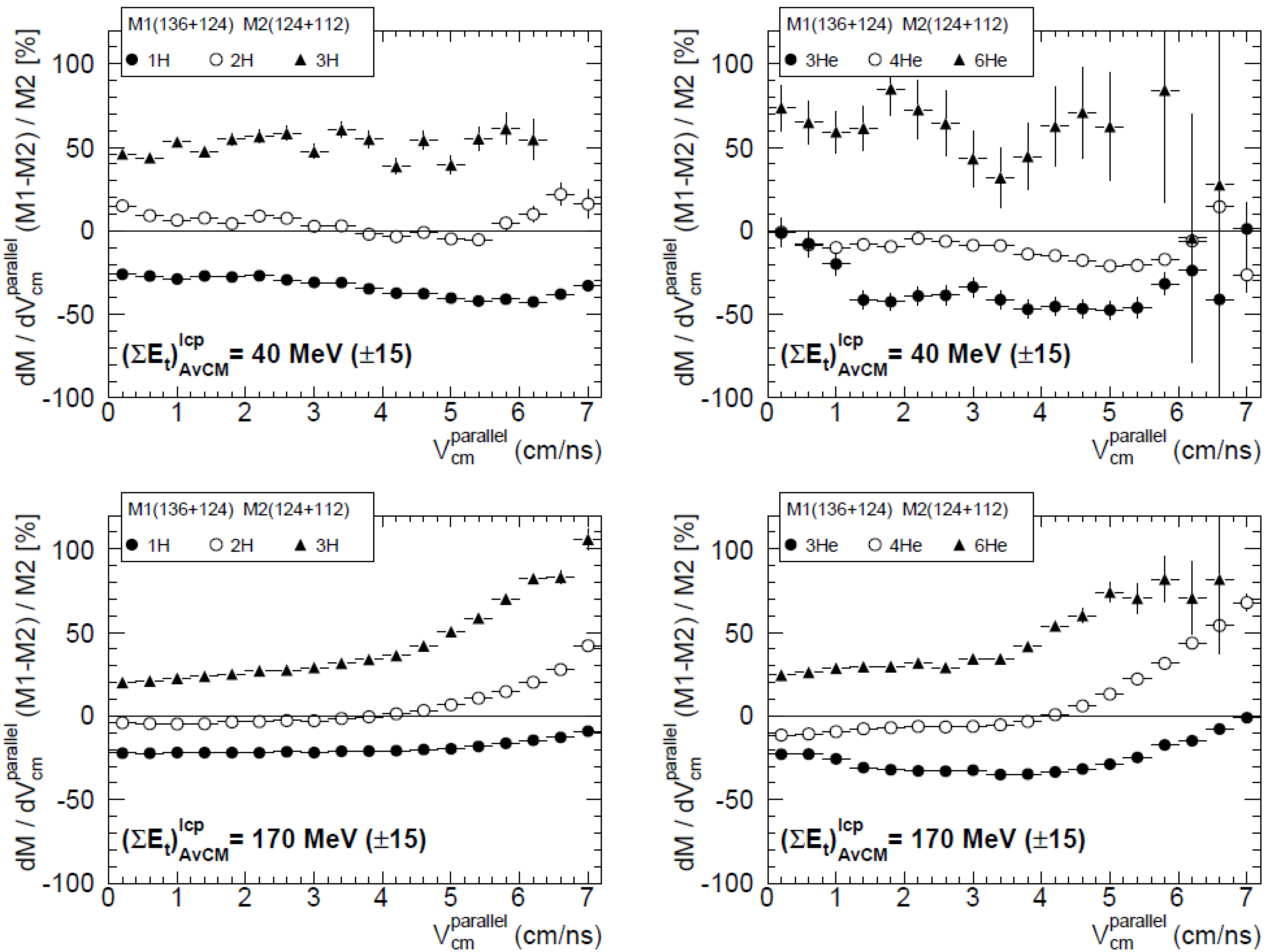
	(N/Z)$_{proj}$	(N/Z)$_{targ}$	drift	dif.
124+112	1.30	1.24	Yes	≈ No
124+124	1.30	1.48	Yes	Yes
136+112	1.52	1.24	Yes	Yes
136+124	1.52	1.48	Yes	≈ No



R. Bougault INDRA/FAZIA collaboration

LCP production

	$(N/Z)_{proj}$	$(N/Z)_{targ}$	drift	dif.
124+112	1.30	1.24	Yes	≈ No
124+124	1.30	1.48	Yes	Yes
136+112	1.52	1.24	Yes	Yes
136+124	1.52	1.48	Yes	≈ No



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LCP production

	$(N/Z)_{proj}$	$(N/Z)_{targ}$	drift	dif.
124+112	1.30	1.24	Yes	≈ No
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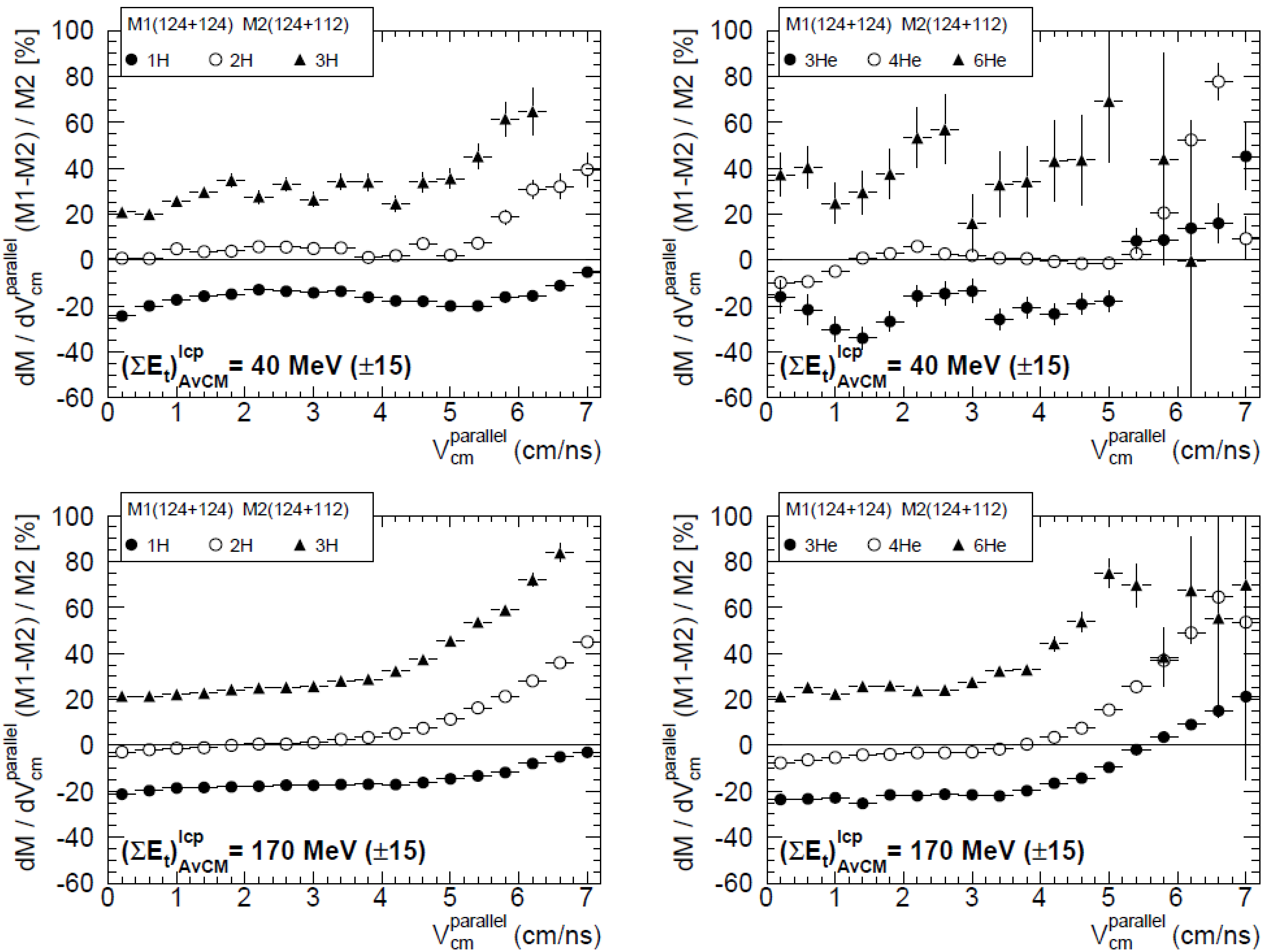

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LCP production

	$(N/Z)_{proj}$	$(N/Z)_{targ}$	drift	dif.
124+112	1.30	1.24	Yes	≈ No
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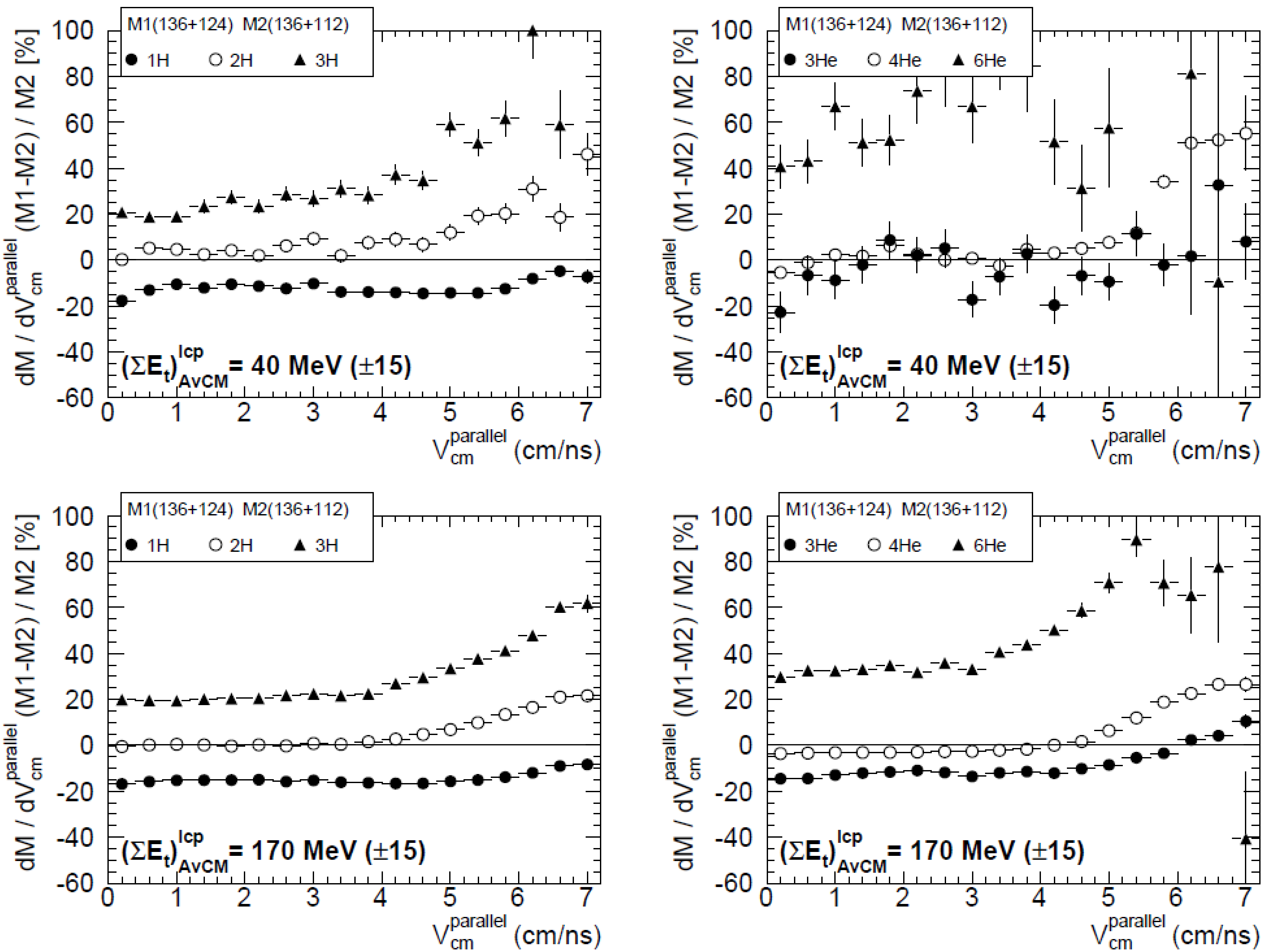

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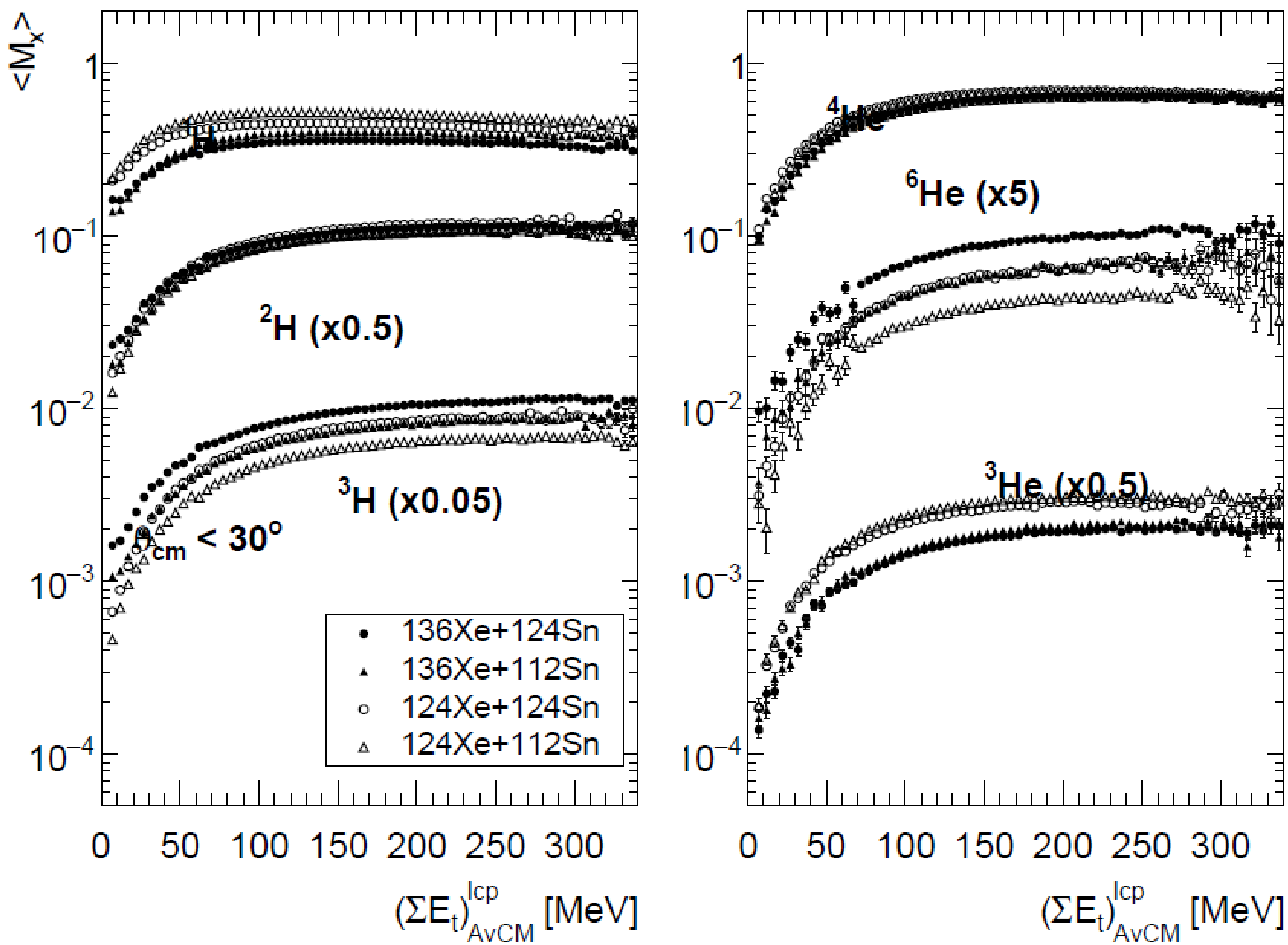
LCP production



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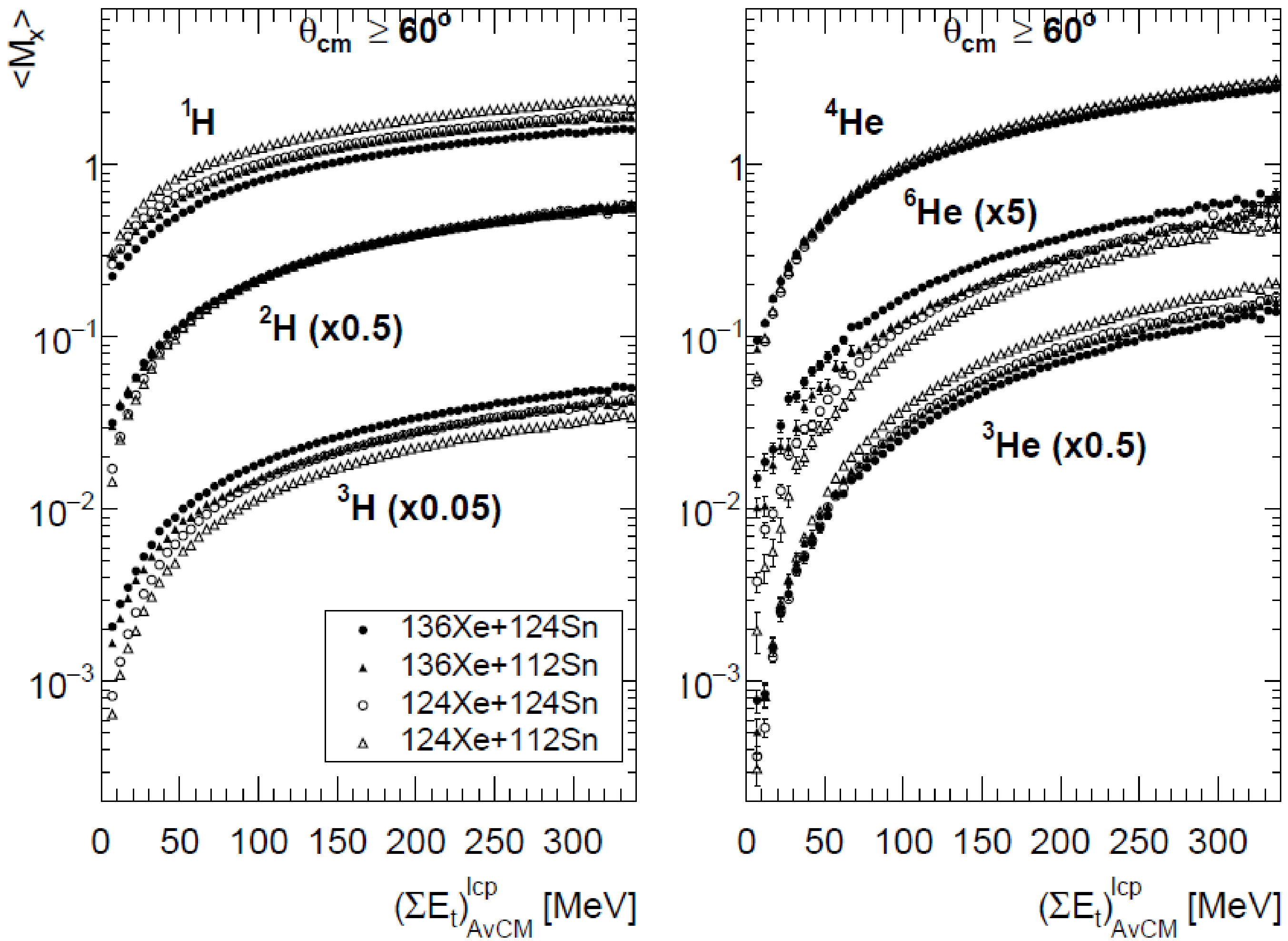
LCP production



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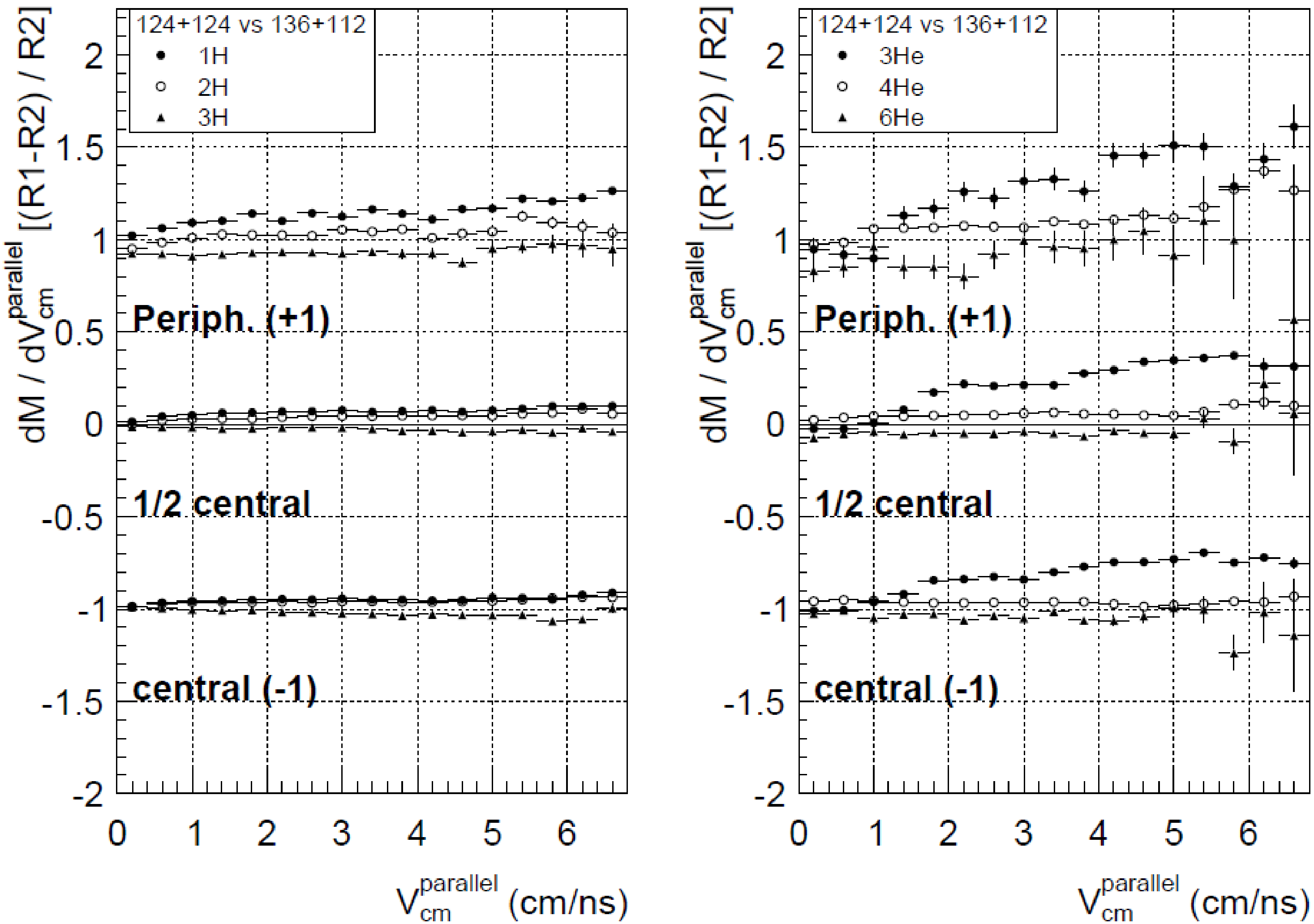
LCP production



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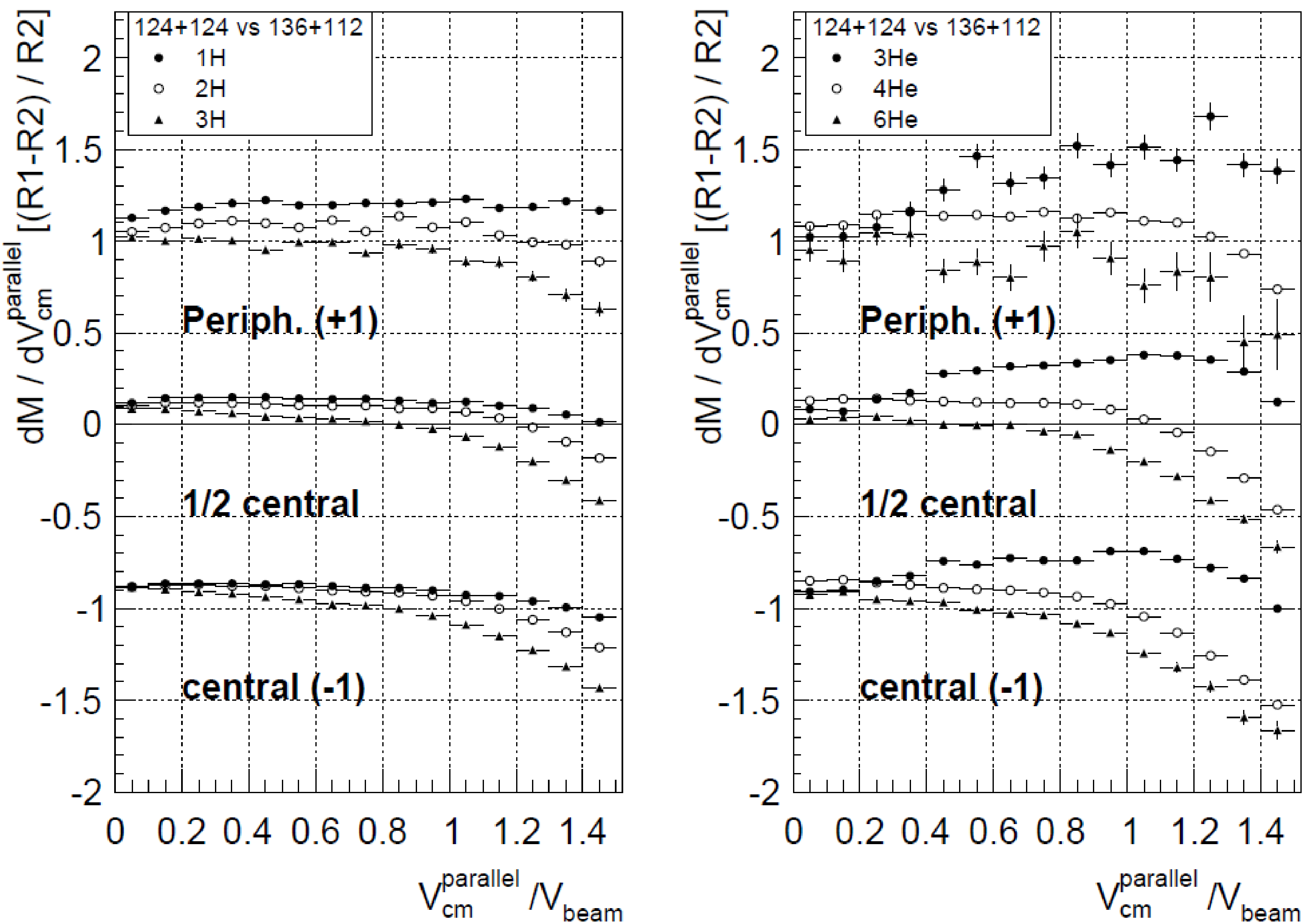
LCP production



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