Isoscaling behavior from Sn+Sn collisions at 270 MeV/u

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SπRIT Collaboration

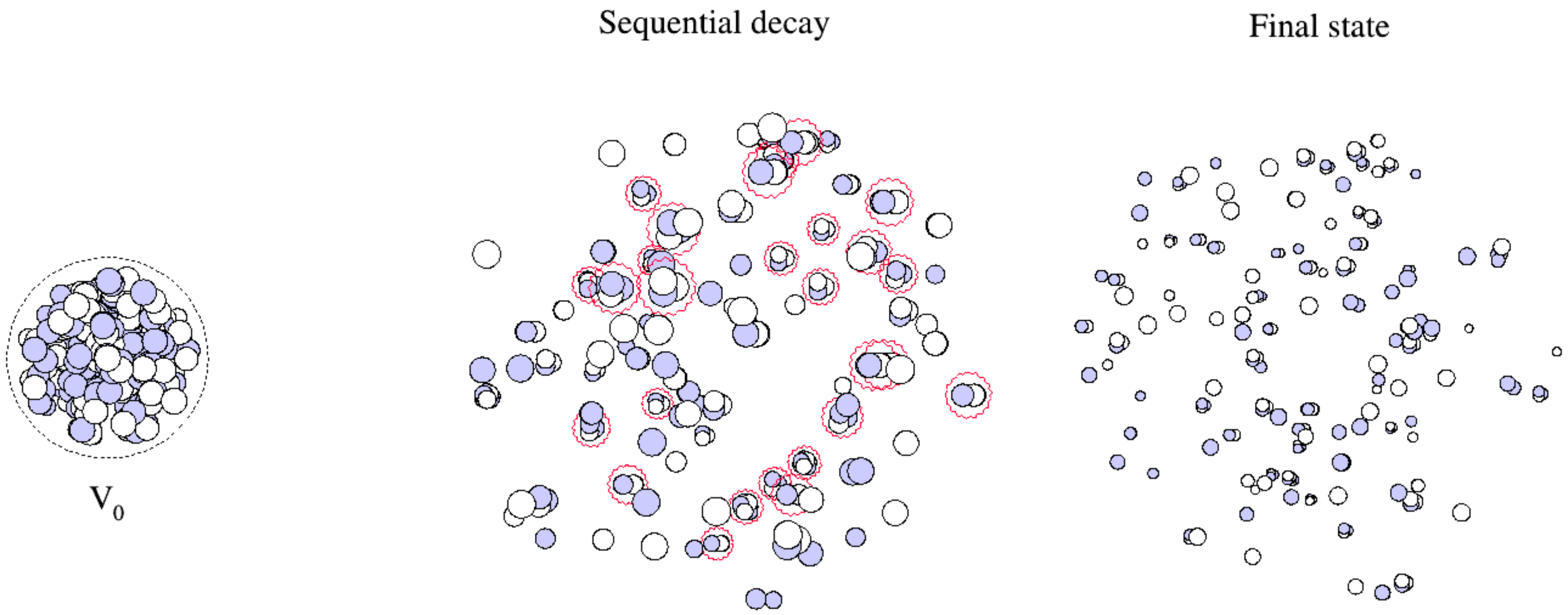
Motivation

- Fragment yield from heavy-ion collision in grand canonical ensemble, thermal equilibrium assumption:

$$Y(N,Z,T) \simeq f(N,Z,T)\,\frac{VA^{\frac{3}{2}}}{\lambda_T^3}\,\omega(N,Z,T)\,\exp\left[\frac{E_B(N,Z)+N\mu_n+Z\mu_p}{T}\right].$$

* S. Albergo et al. Nuovo Cimento Soc. Ital. Fis., A 89 (1985) 1

(f : sequential decay factor, N, Z, A : neutron, proton, mass number, V : volume, T : temperature, ω : partition function, E_B : binding energy, μ_n, μ_p : chemical potential of n and p)



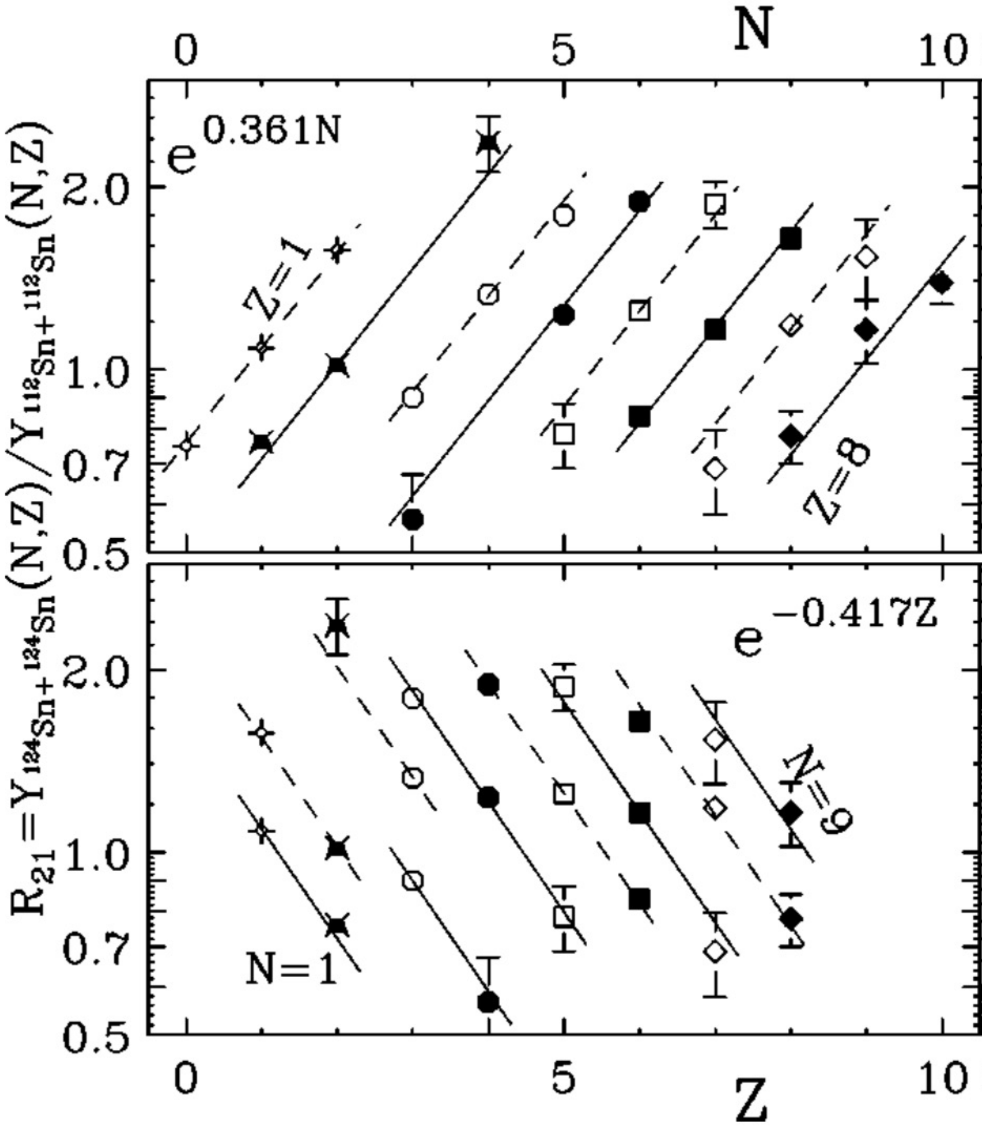
Isoscaling

* M. B. Tsang et al. (MSU) Phys. Rev. C 64 (2001) 041603

- $Y(N,Z,T) \simeq f(N,Z,T)\frac{VA^{\frac{3}{2}}}{\lambda_T^3}\omega(N,Z,T)\exp\left[\frac{E_B(N,Z)+N\mu_n+Z\mu_p}{T}\right].$
- Isoscaling is phenomenon that arise under assumption of thermal and chemical equilibrium.
- We compare two collision system 2 and 1 with similar size and temperature. Conventionally system 2 has larger isospin asymmetry; $N_2/Z_2 > N_1/Z_1$.
- The fragment yield ratio $R_{21}=Y_2/Y_1$ between two systems exhibit exponential behavior:

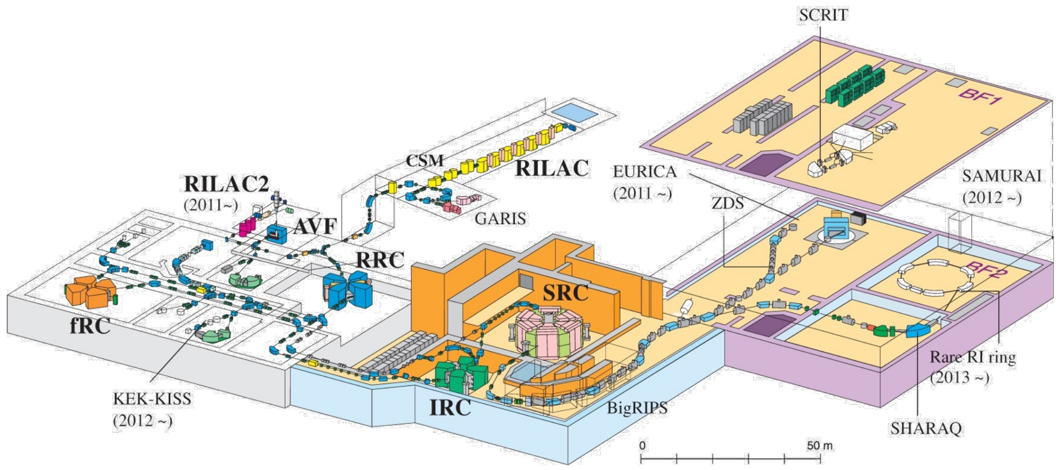
$$R_{21} = C\exp(\alpha N + \beta Z)$$

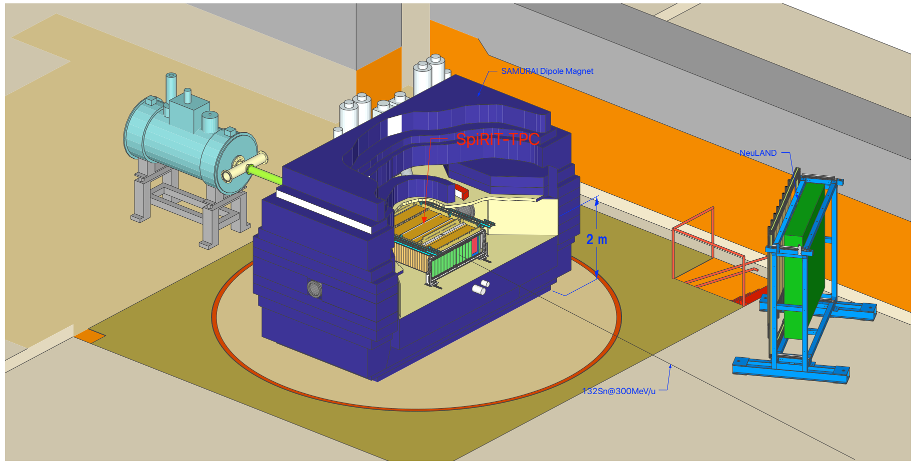
$$\alpha = \frac{\Delta\mu_n}{T}, \beta = \frac{\Delta\mu_p}{T}$$



SπRIT Experiment

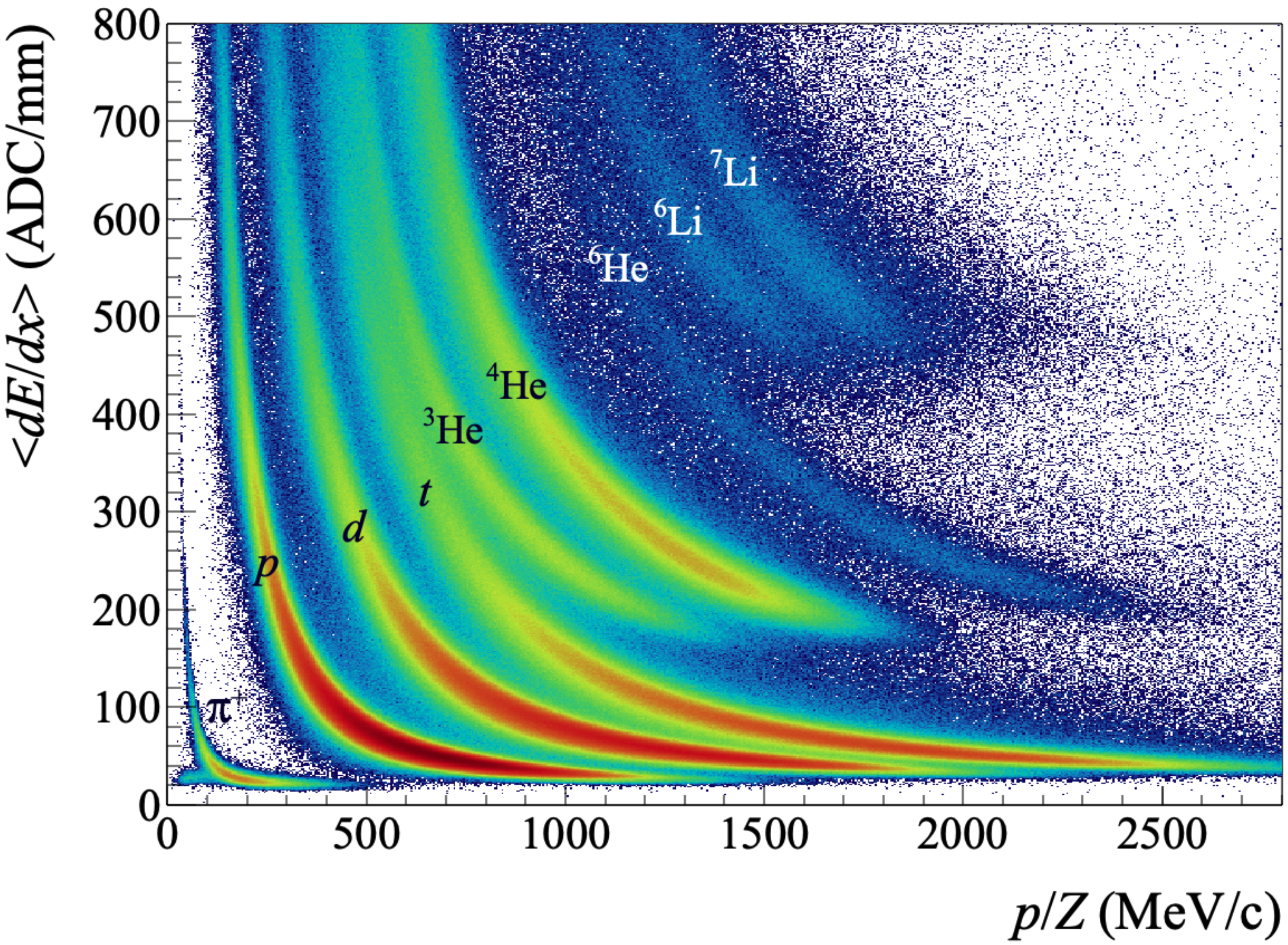
- The SπRIT experiment of Sn + Sn collisions at the energy of 270 MeV/u were performed in 2016.
- SπRIT Time Projection Chamber (TPC) was used to detect the charged particles produced from the collision.





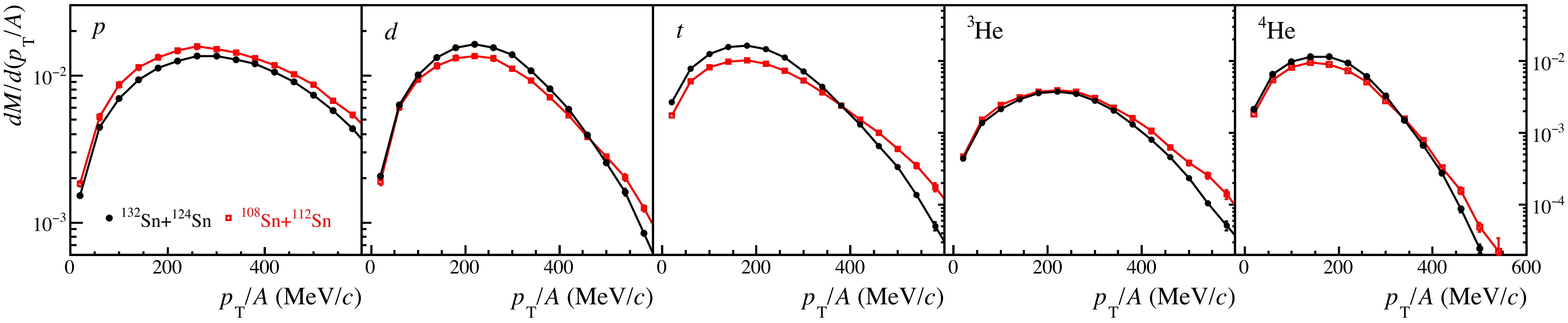
- The Z=1 and Z=2 particles are analyzed through the phenomenon called Isoscaling.
- The models, Statistical Multi-fragmentation Model (SMM) and Antisymmetrized Molecular Dynamics (AMD) are compared with the experiment data to see how isoscaling is shown from the calculations.

SπRIT Experiment



p_T Distribution

- In the yield distribution as a function of p_T/A, particles like *d*, *t* and ^{4}He which have same or more neutrons to protons, are expected to be produced more in the neutron rich system
- In a simple point of view, triton (consist of 1 proton and 2 neutron) for example should be produced more from the neutron rich system compared to the nearly symmetric system.
- However, the yield cross over at p_T/A ~ 400 MeV/c for *d*, *t*, ^{4}He which is not explained.



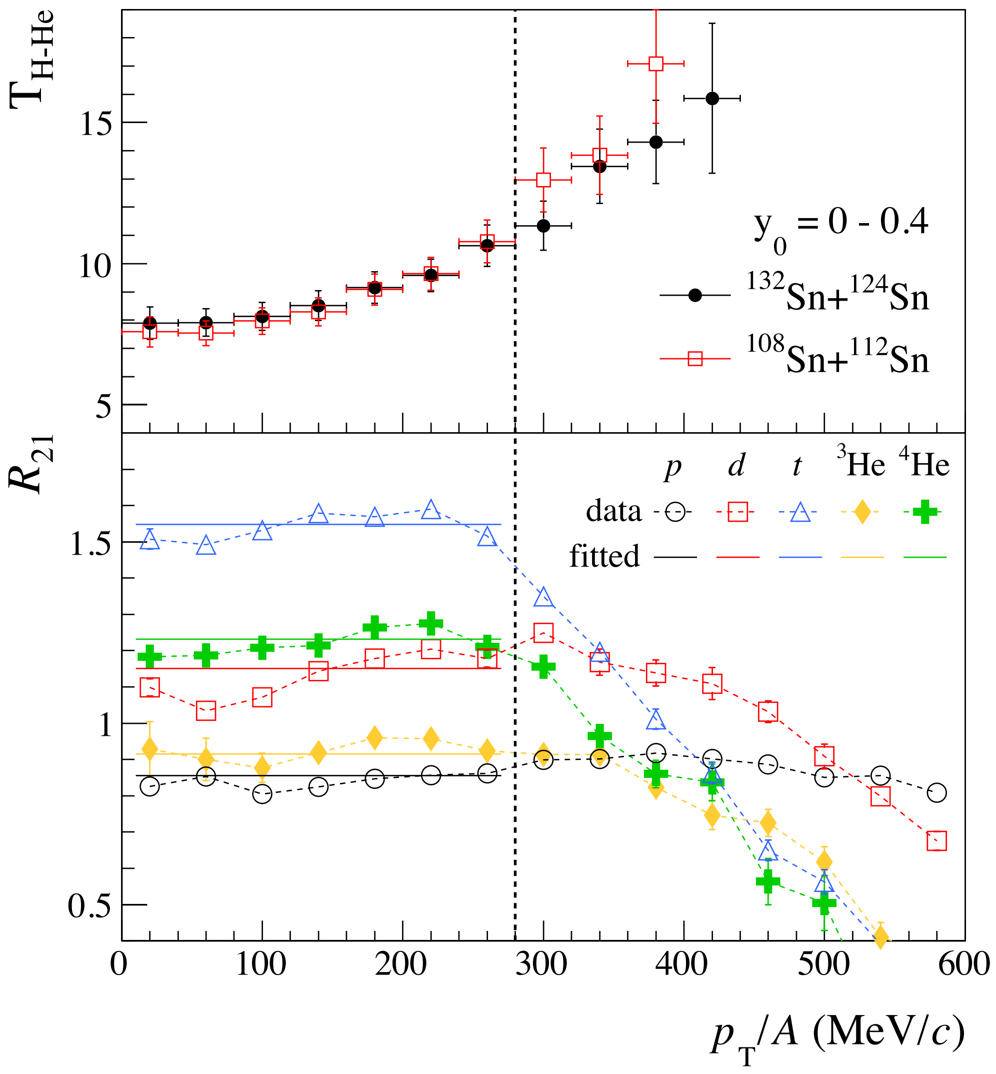
Temperature and Yield Ratio R_{21}

- Apparent Temperature of the system can be evaluated from the H-He double ratio with the same assumption of isoscaling:

$$T_{H-He} = 1.43\ln^{-1}\left[1.6\frac{Y(d)/Y(t)}{Y(^3He)\,/Y(^4He)}\right].$$

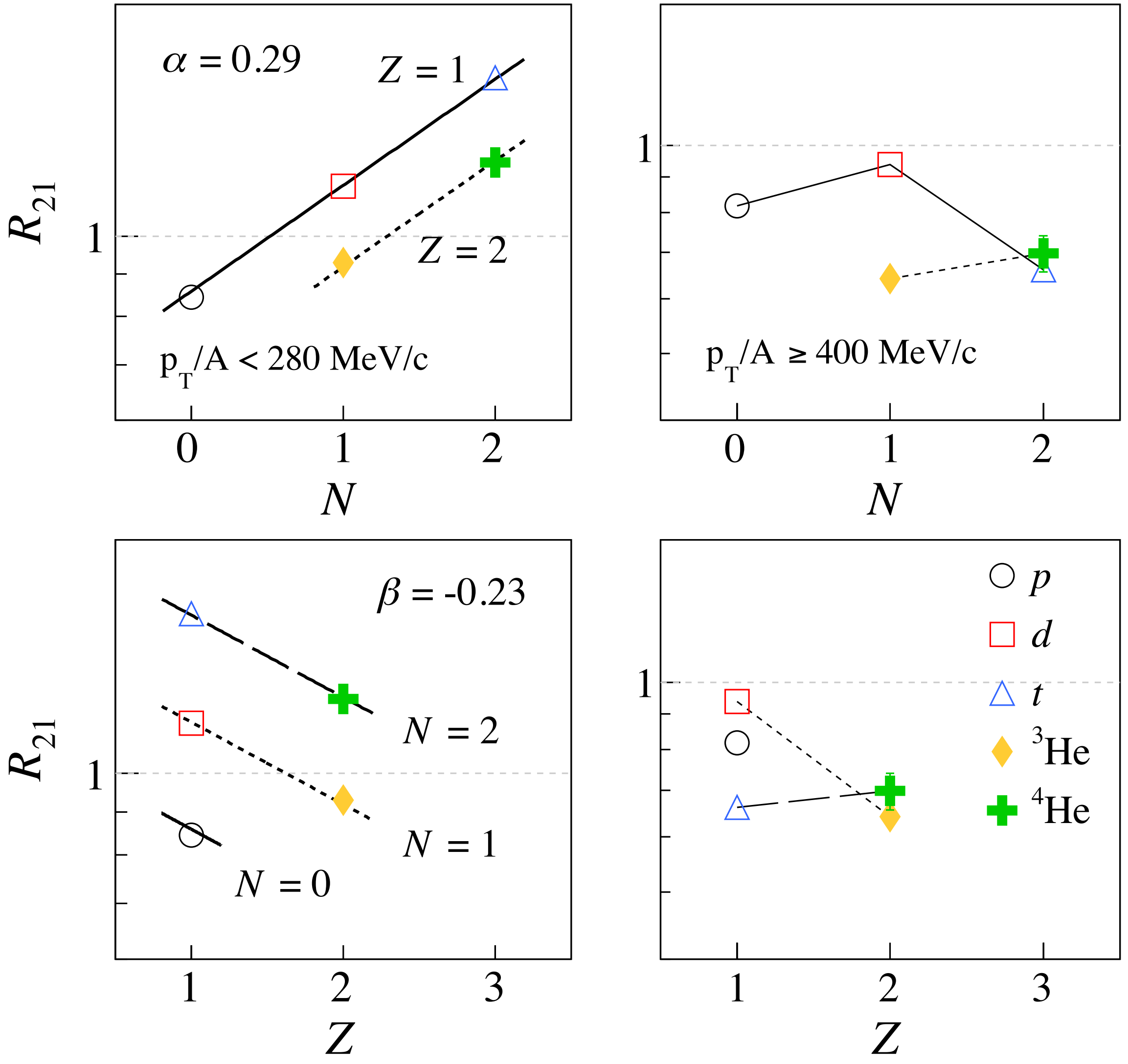
- Emperically, the α and β values are similar with opposite sign. From the equation $R_{21} = C\exp(\alpha N + \beta Z)$, particles in the same (N-Z) group, will show similar values.

- p_T/A < 280 MeV/c
  - p and ^{3}He show are grouped with R_{21} values just below 1.
  - d and ^{4}He are grouped with R_{21} values just above 1.
  - t stay around 1.5 alone.
- p_T/A > 280 MeV/c
  - The R_{21} values break down except for proton.
  - t, ^{3}He, ^{4}He show similar R_{21} values p_T/A > 400.



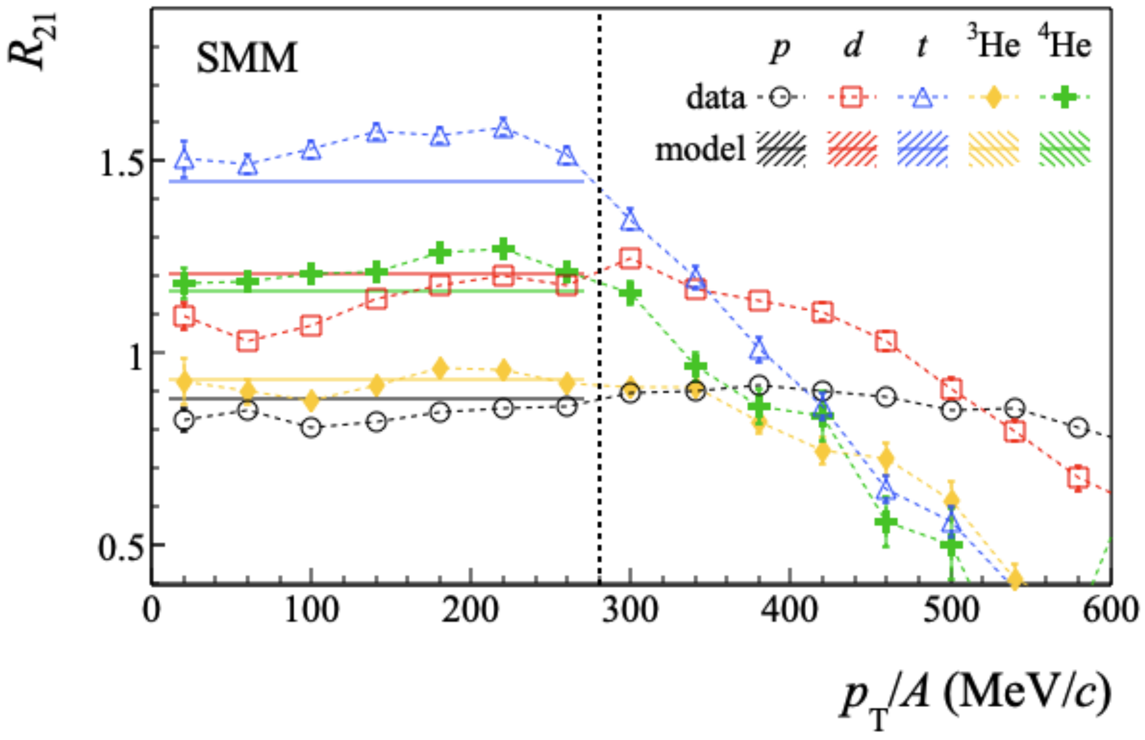
Isoscaling Result

- The R_{21} of p, d, t , ^{3}He, ^{4}He are simultaneously fitted using equation $R_{21} = C\exp(\alpha N + \beta Z)$.
- p_T/A < 280 MeV/c
  - Isoscaling fit is observed with good agreement.
  - α = 0.29 and β = -0.23.
- p_T/A > 400 MeV/c
  - Isoscaling completely break down with R_{21} values of all particles are below 1.
  - Triton have the largest drop of R_{21} value.



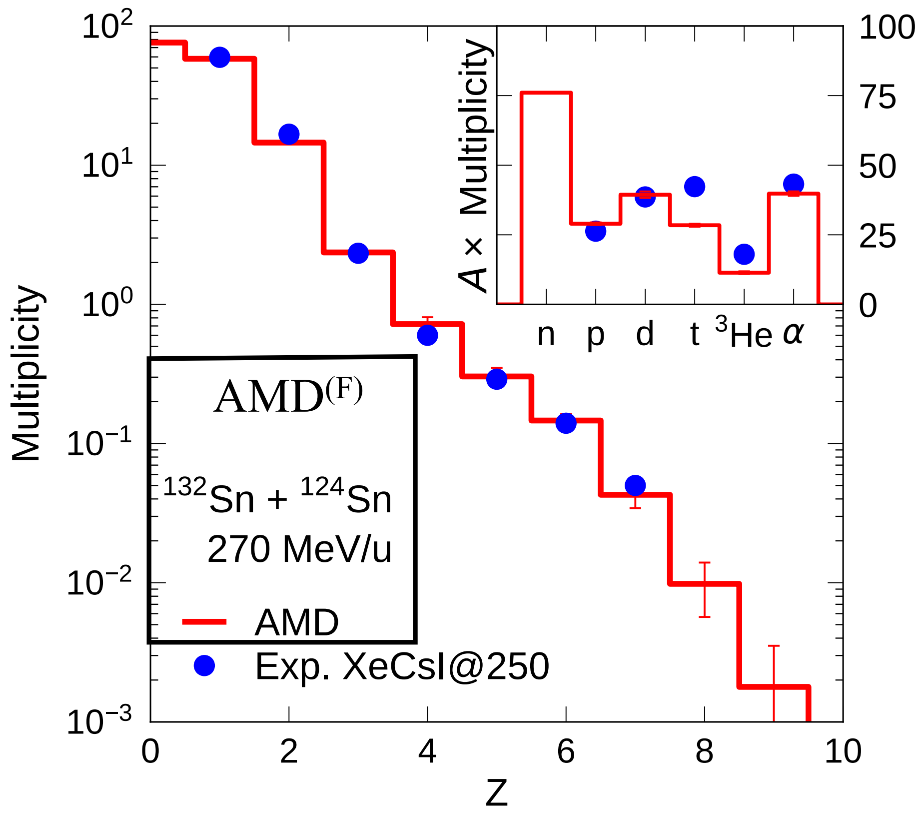
Statistical Multi-fragmentation Model (SMM)

- Statistical Multi-fragmentation model
- Condition at breakup :
  - Volume V = 3 × V_0.
  - Temperature T = 8 MeV
  - Source of ^{132}Sn + ^{124}Sn : N = 93 and Z = 79.
  - Source of ^{108}Sn + ^{112}Sn : N = 71 and Z = 71.
- The condition of SMM was fitted to the data, however, we could not find the case that really explain the data.
- This is because the temperature is fixed in SMM while the apparent temperature shown in the data increase as a function of p_T/A from 8 MeV to 11 MeV (p_T/A < 280 MeV/c).



Antisymmetrized Molecular Dynamics (AMD)

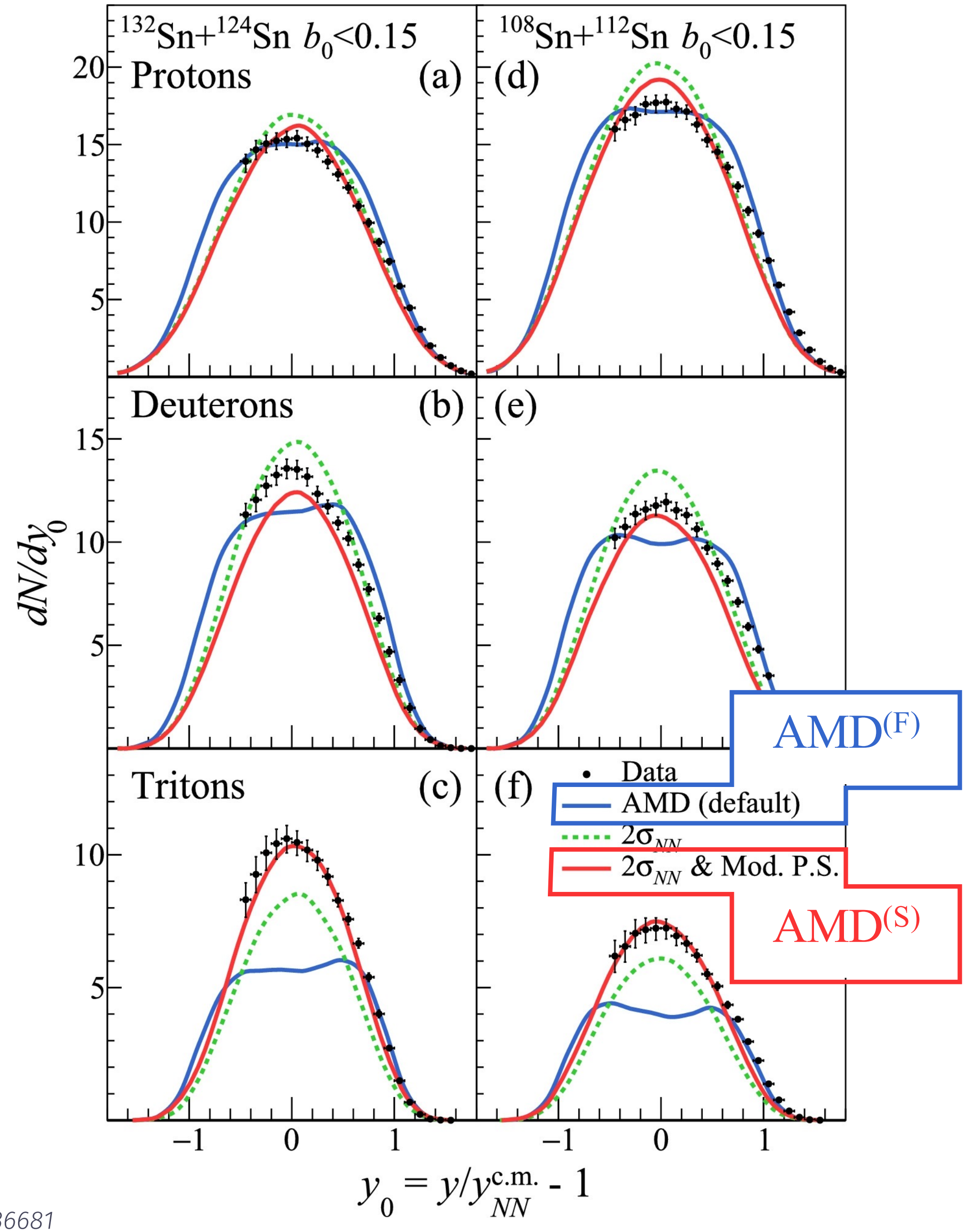
- Antisymmetrized Molecular Dynamics (AMD) model was compared with the result.
- **AMD$^{(F)}$** parameter set was chosen to reproduce the cluster multiplicity of FOPI data (Xe + ScI at 250 MeV/u) using the same reaction used in SπRIT experiment Sn + Sn at 270 MeV/u.



* *Akira Ono JPS Conf. Proc. 32 (2020) 010076*

AMD

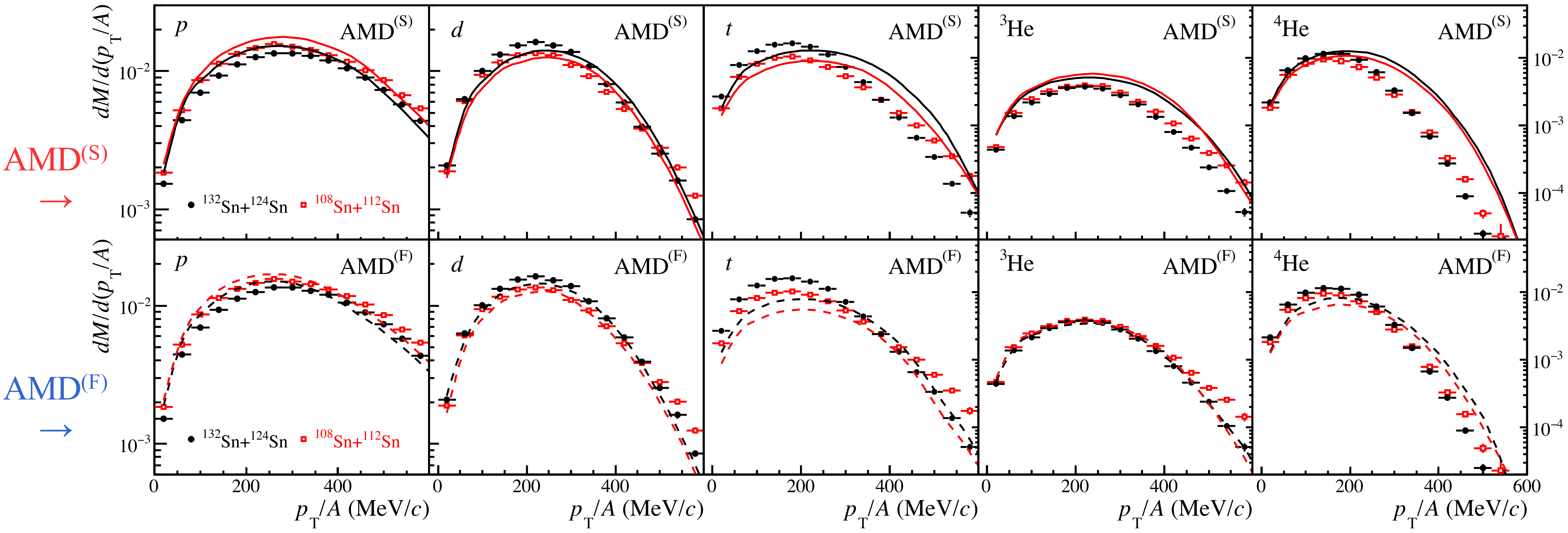
- **AMD$^{(S)}$** parameter set was chosen to reproduce the SπRIT experiment data of Sn + Sn at 270 MeV/u for rapidity distribution of hydrogen isotopes.
  Compared to AMD$^{(F)}$,
- In medium cross section was increased by the factor of 2 (dotted green from the figure).
- Phase space for the clusters was modified so that, for example, the decrease in the number of tritons for $t \gtrsim 50$ fm/c due to the low energy collisions is reduced.



* M. Kaneko et al. Phys. Lett. B 822 (2021) 136681

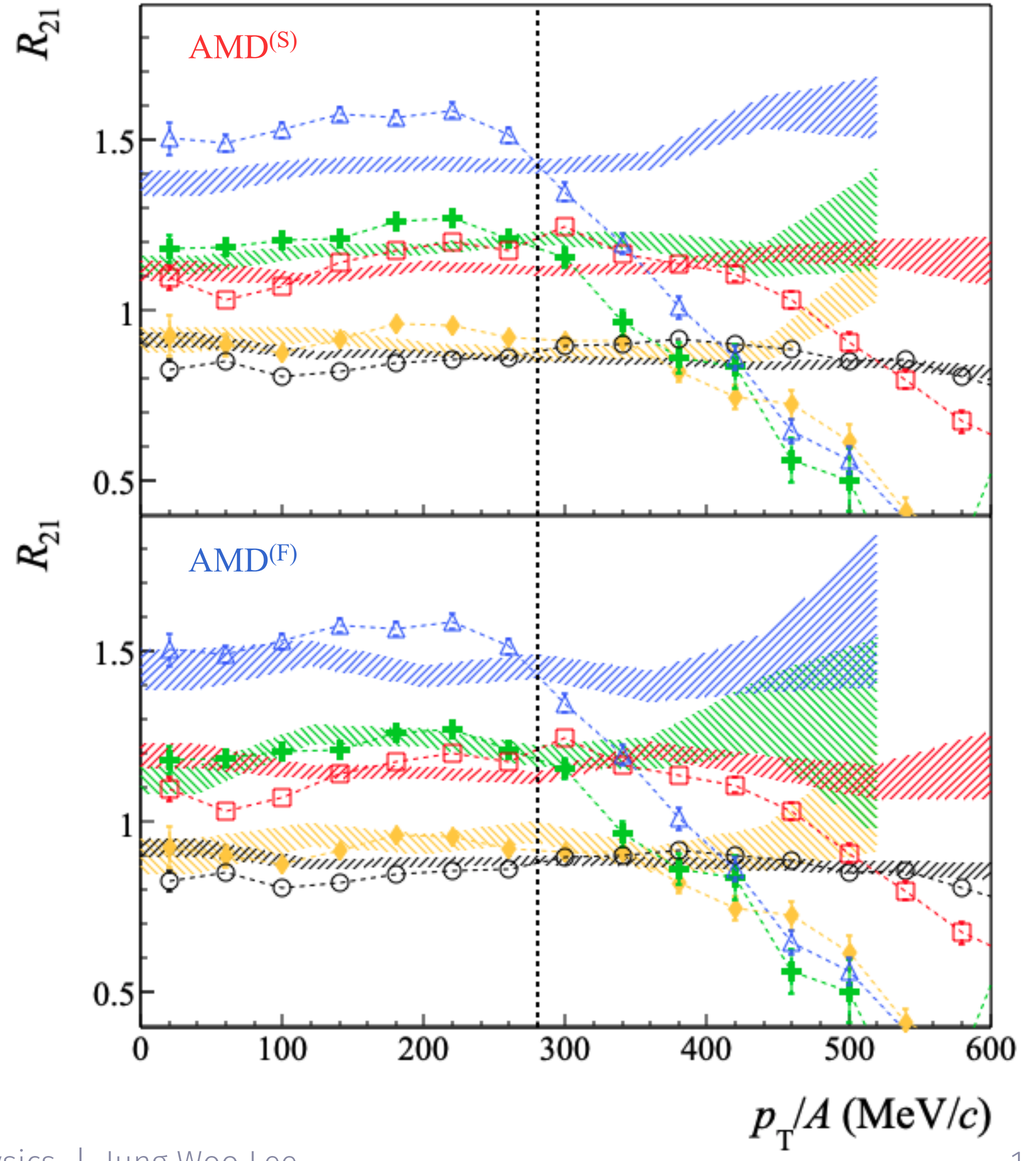
Yield compared to AMD

- No crossing is seen in AMD models.
- There is no preferences between AMD parameter sets (AMD$^{(F)}$ and AMD$^{(S)}$) unlike rapidity distributions.



Yield Ratio compared to AMD

- R_{21} of models (SMM, AMD) qualitatively explain the data points. Protons are explained well but slightly lower values are shown for other particles. Tritons show the largest differences.
- The models show isoscaling at high momentum regions unlike the experimental data.



Summary

- Isoscaling properties are studied in $^{132}Sn + ^{124}Sn$ and $^{108}Sn + ^{112}Sn$ systems at 270 MeV/u. Compared to the previous studies on isoscaling, we explored collision systems with comparably large energy (270 MeV/u) and larger isospin difference ($N/Z_2 = 1.56$ and $N/Z_1 = 1.20$).
- The yield ratio R_{21} show constant trend up to p_T/A = 280 MeV/c but R_{21} of triton and ^{4}He decrease above this region. Consequently, isoscaling breaks above this boundary.
- Isoscaling is expected in SMM since it assumes equilibrium of the collision system. AMD is dynamical model where particles are transported in time evolution but also show Isoscaling.
- AMD show isoscaling up to p_T/A = 280 MeV/c but do not show break down of isoscaling at high p_T/A.
- Thermal equilibrium approximation might not be appropriate (or partly applicable) for high energy particles in heavy-ion collisions at energy range around 270 MeV/u. More studies with other similar systems are needed.

Back up

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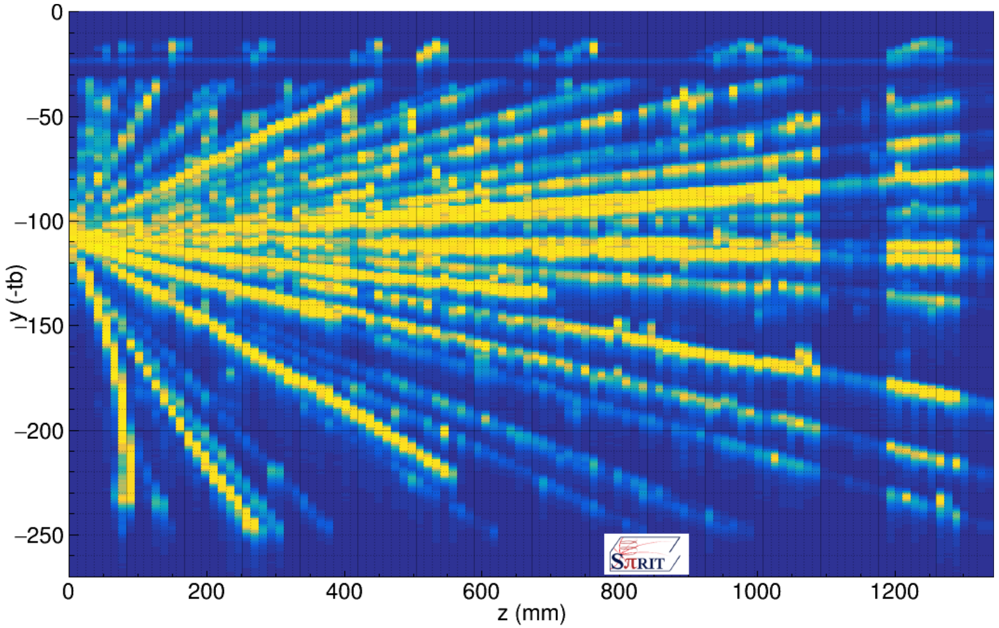
- Isoscaling is studied in the mid-rapidity region (y_0 = 0 – 0.4) because we look for the chemical and thermal equilibrated system which is more likely to happen in the mid-rapidity region. ($y_0 = y/y_{CM,NN} - 1$)
- The data is shown as a function of p_T/A since systems are found to be partly equilibrated. The upper limit of p_T/A is 600 MeV/*c* because yield of ^{4}He above this region is 0.
- This analysis is extended work of *M. Kaneko et al. Phys. Lett. B 822 (2021) 136681* as it discuss the rapidity distribution of hydrogen isotopes from the SπRIT experiment and AMD model was compared.
- The yield error estimated for the region of interest (y_0 = 0 – 0.4) between Kaneko's work and this work is about 3 %.

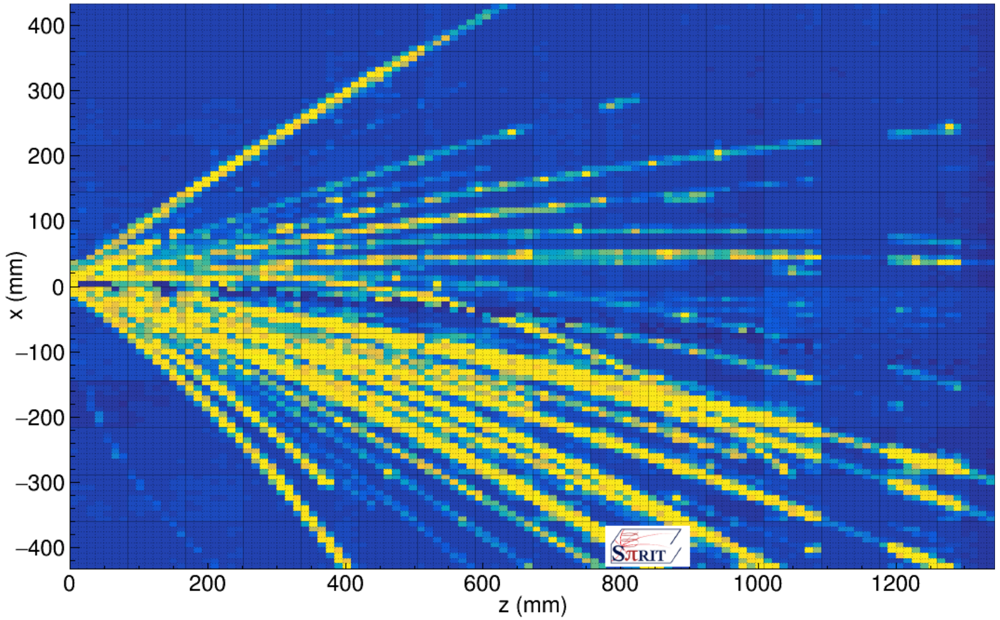
Applied Cuts	Values
Charged Particle Multiplicity (Mult)	Mult ≥ 57, 56 (b < 1.5 fm)
PID-probability (Prob)	Prob > 70 %
PID sigma (SD)	$\lvert SD \rvert < 2.2\ \sigma_{PID}$
Number of clusters (NCl)	NCl ≥ 20
Distance to vertex (DistV)	DistV ≤ 15 mm
Polar angle (φ)	-30° < φ < 20°, 160° < φ < 210°
Azimuthal angle (θ)	θ < 80°

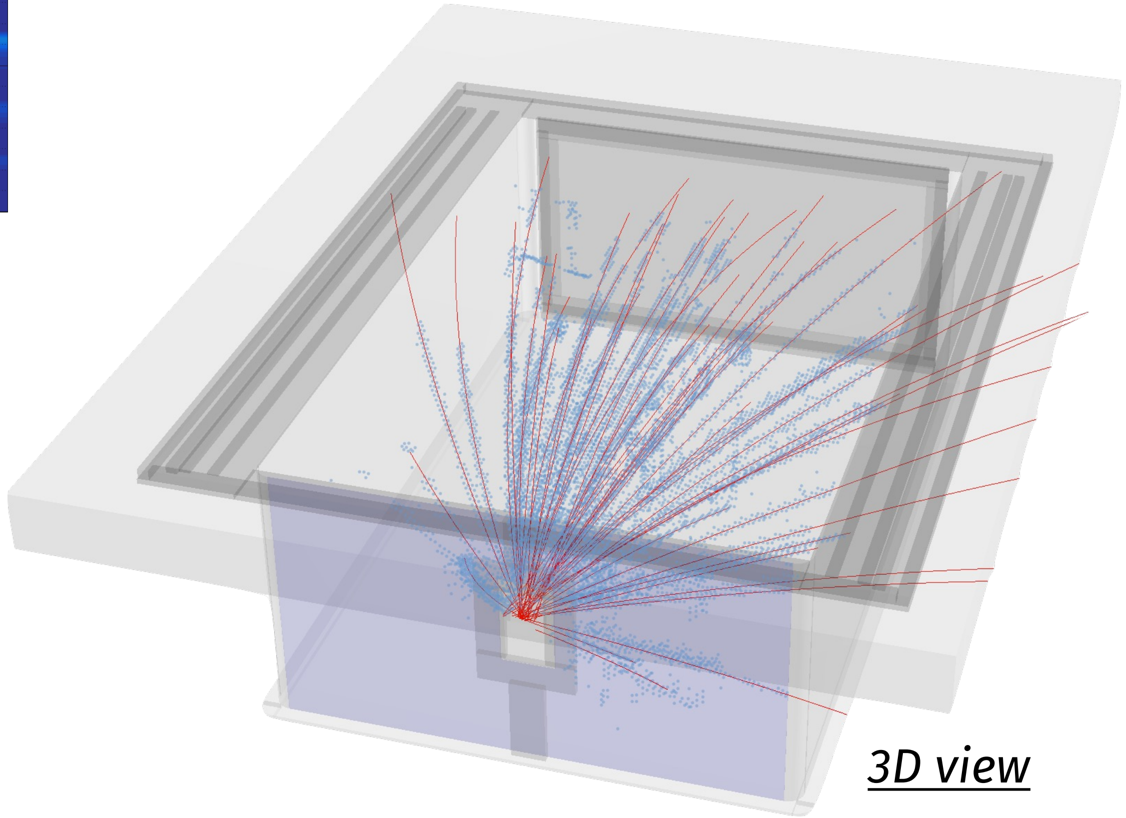
Sys. Error (%)	Y(^{132}Sn + ^{124}Sn)	Y(^{108}Sn + ^{112}Sn)	Yield Ratio
Average	**4.0**	**3.8**	**1.8**
p	3.8	3.7	1.0
d	3.6	3.5	1.4
t	3.3	3.7	2.0
^{3}He	5.4	4.8	2.1
^{4}He	4.0	3.4	2.3

Side view



Top view



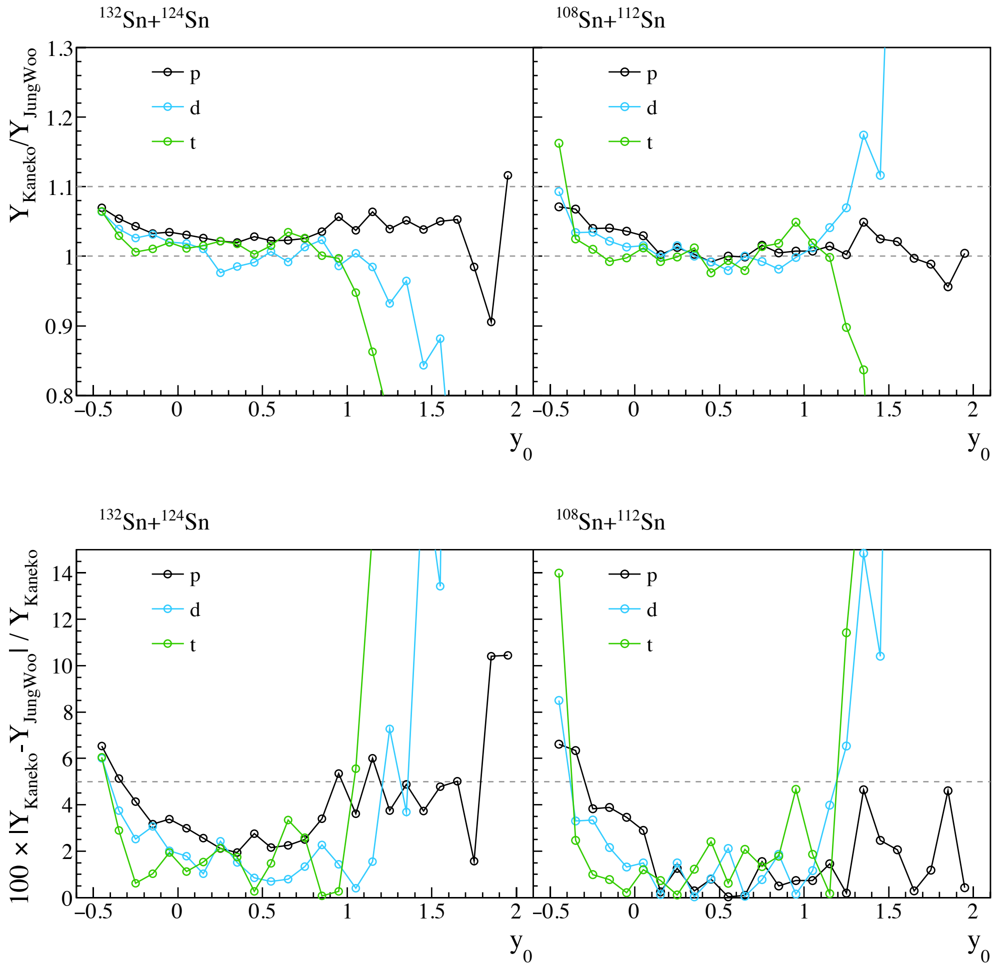


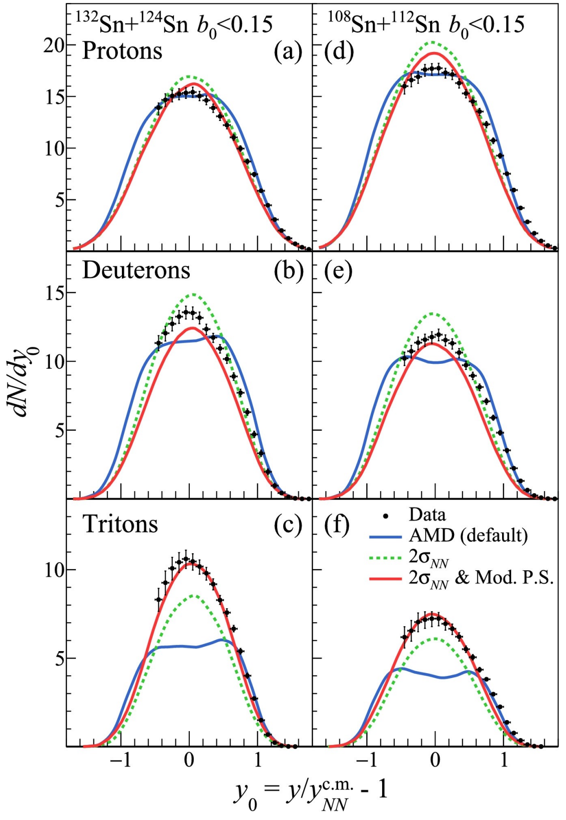
3D view

Consistency check

- In Kaneko's work (Y_{kaneko})
  - The b_{max} was chosen from the hard surface approximation (11 - 12 fm) and select reduced impact parameter b_0< 0.15 (b ≲ 1.65).
  - Mass was estimated from the modified Bethe-Bloch formula and mass cut p(500, 1400), d(1400, 2300), and t(2300, 3400) MeV/c^2 was given for the PID cut.

- In this work ($Y_{JungWoo}$)
  - Experimental b_{max} (~7 fm) is used and select impact parameter b < 1.5 fm.
  - PID center is fitted from the Bethe-Bloch formula and gaussian fit as a function of <dE/dx> is performed for each particle. PID is selected by 2.2 sigma distance and 70 % (50 %) PID-probability cut.

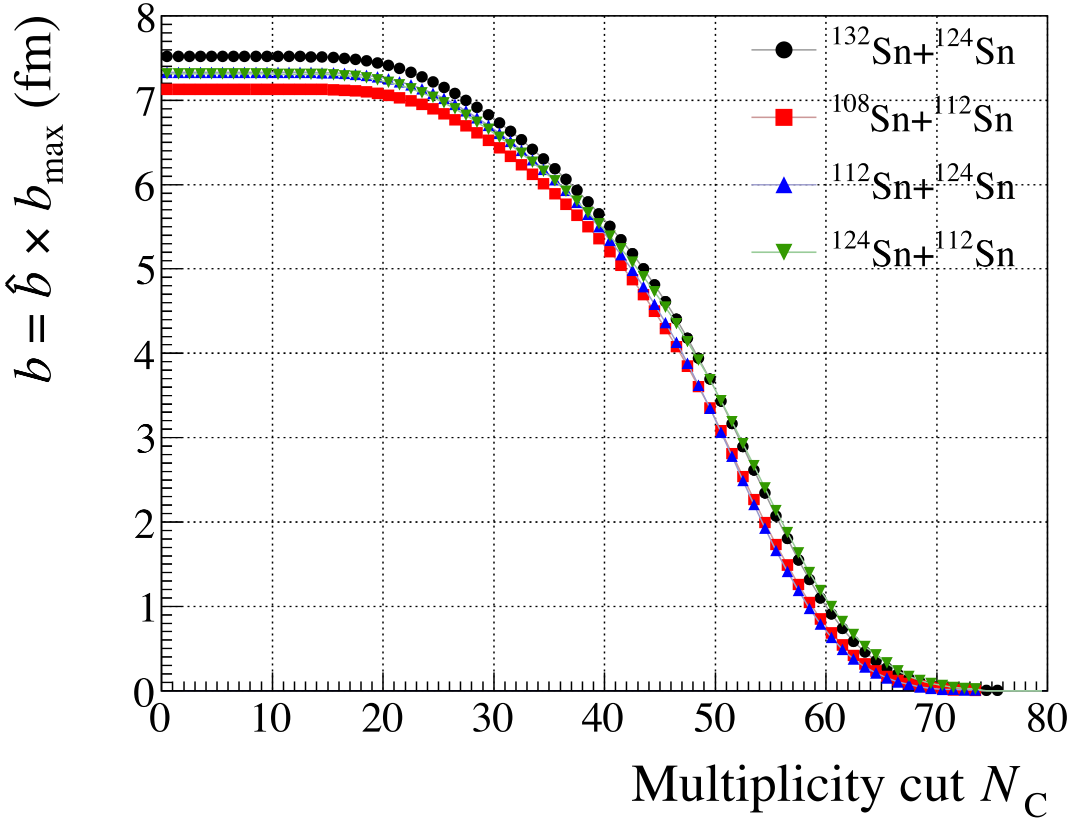




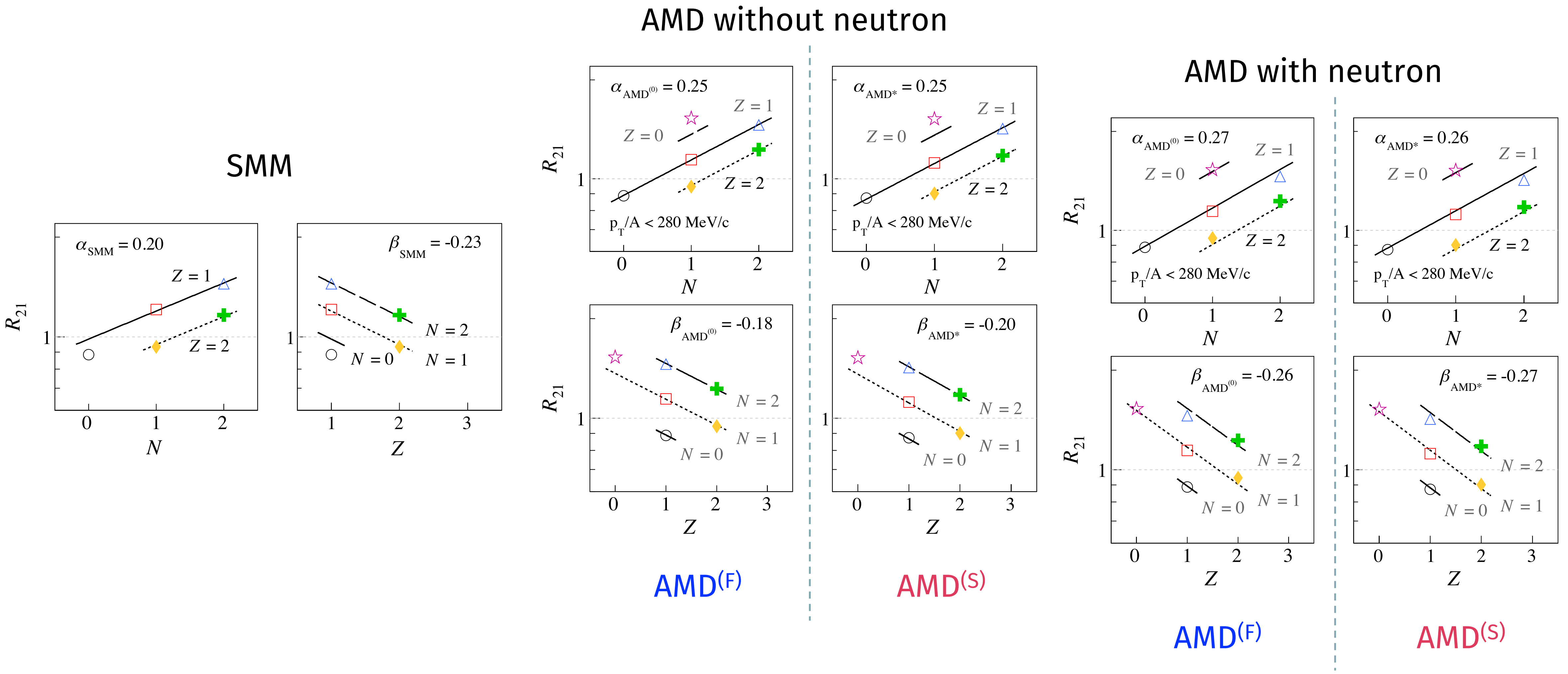
Impact parameter analysis

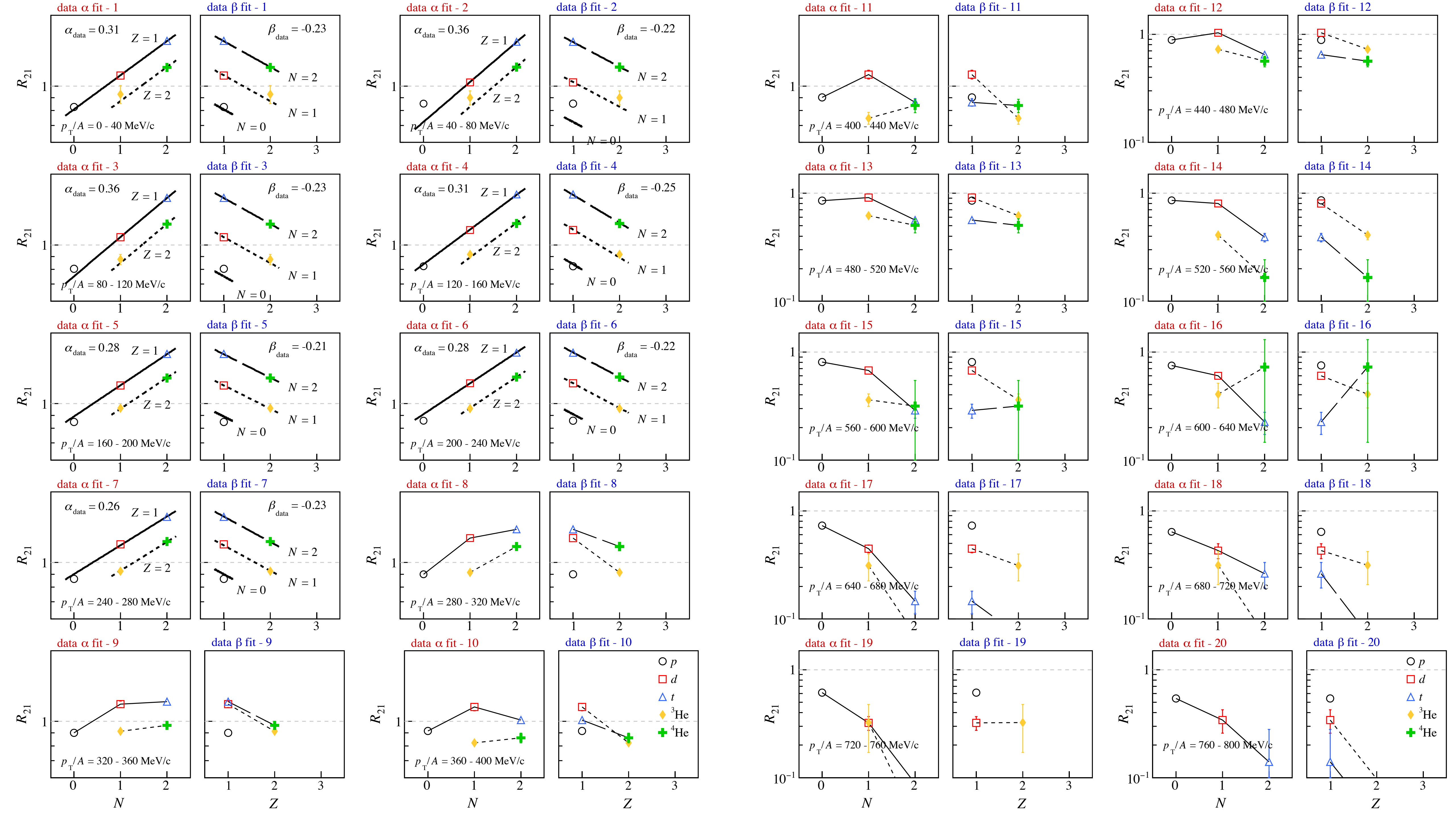
- Impact parameter b is estimated assuming that it decreases multiplicity.
- By choosing the impact parameter cut $b < 1.5$ fm, following multiplicity cuts are chosen for the syste

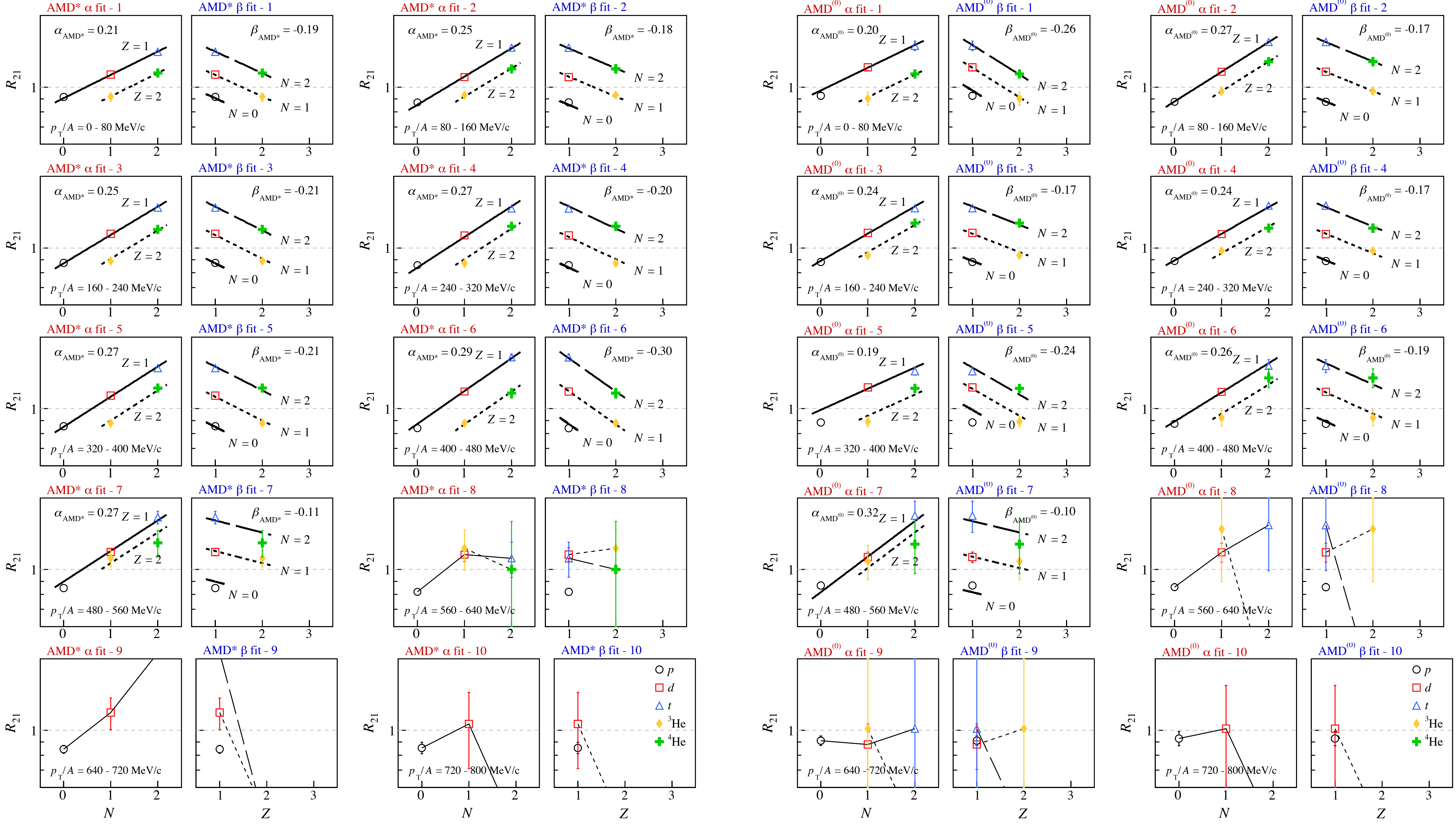
System	N_C (Mult. ≥ N_C)
$^{132}Sn + ^{124}Sn$	57
$^{108}Sn + ^{112}Sn$	56



Isoscaling Fit : SMM and AMD




data α fit - 1
α_{data} = 0.31
Z = 1
Z = 2
p_T/A = 0 - 40 MeV/c
data β fit - 1
β_{data} = -0.23
N = 2
N = 1
N = 0
data α fit - 2
α_{data} = 0.36
p_T/A = 40 - 80 MeV/c
data β fit - 2
β_{data} = -0.22
data α fit - 3
α_{data} = 0.36
p_T/A = 80 - 120 MeV/c
data β fit - 3
β_{data} = -0.23
data α fit - 4
α_{data} = 0.31
p_T/A = 120 - 160 MeV/c
data β fit - 4
β_{data} = -0.25
data α fit - 5
α_{data} = 0.28
p_T/A = 160 - 200 MeV/c
data β fit - 5
β_{data} = -0.21
data α fit - 6
α_{data} = 0.28
p_T/A = 200 - 240 MeV/c
data β fit - 6
β_{data} = -0.22
data α fit - 7
α_{data} = 0.26
p_T/A = 240 - 280 MeV/c
data β fit - 7
β_{data} = -0.23
data α fit - 8
p_T/A = 280 - 320 MeV/c
data β fit - 8
data α fit - 9
p_T/A = 320 - 360 MeV/c
data β fit - 9
data α fit - 10
p_T/A = 360 - 400 MeV/c
data β fit - 10
data α fit - 11
p_T/A = 400 - 440 MeV/c
data β fit - 11
data α fit - 12
p_T/A = 440 - 480 MeV/c
data β fit - 12
data α fit - 13
p_T/A = 480 - 520 MeV/c
data β fit - 13
data α fit - 14
p_T/A = 520 - 560 MeV/c
data β fit - 14
data α fit - 15
p_T/A = 560 - 600 MeV/c
data β fit - 15
data α fit - 16
p_T/A = 600 - 640 MeV/c
data β fit - 16
data α fit - 17
p_T/A = 640 - 680 MeV/c
data β fit - 17
data α fit - 18
p_T/A = 680 - 720 MeV/c
data β fit - 18
data α fit - 19
p_T/A = 720 - 760 MeV/c
data β fit - 19
data α fit - 20
p_T/A = 760 - 800 MeV/c
data β fit - 20
R_{21}
N
Z
p
d
t
^{3}He
^{4}He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α_{AMD^*} = 0.21
Z = 1
Z = 2
p_T/A = 0 - 80 MeV/c
AMD* β fit - 1
β_{AMD^*} = -0.19
N = 2
N = 1
N = 0
AMD* α fit - 2
α_{AMD^*} = 0.25
p_T/A = 80 - 160 MeV/c
AMD* β fit - 2
β_{AMD^*} = -0.18
$AMD^{(0)}$ α fit - 1
$\alpha_{AMD^{(0)}}$ = 0.20
p_T/A = 0 - 80 MeV/c
$AMD^{(0)}$ β fit - 1
$\beta_{AMD^{(0)}}$ = -0.26
$AMD^{(0)}$ α fit - 2
$\alpha_{AMD^{(0)}}$ = 0.27
p_T/A = 80 - 160 MeV/c
$AMD^{(0)}$ β fit - 2
$\beta_{AMD^{(0)}}$ = -0.17
AMD* α fit - 3
α_{AMD^*} = 0.25
p_T/A = 160 - 240 MeV/c
AMD* β fit - 3
β_{AMD^*} = -0.21
AMD* α fit - 4
α_{AMD^*} = 0.27
p_T/A = 240 - 320 MeV/c
AMD* β fit - 4
β_{AMD^*} = -0.20
$AMD^{(0)}$ α fit - 3
$\alpha_{AMD^{(0)}}$ = 0.24
p_T/A = 160 - 240 MeV/c
$AMD^{(0)}$ β fit - 3
$\beta_{AMD^{(0)}}$ = -0.17
$AMD^{(0)}$ α fit - 4
$\alpha_{AMD^{(0)}}$ = 0.24
p_T/A = 240 - 320 MeV/c
$AMD^{(0)}$ β fit - 4
$\beta_{AMD^{(0)}}$ = -0.17
AMD* α fit - 5
α_{AMD^*} = 0.27
p_T/A = 320 - 400 MeV/c
AMD* β fit - 5
β_{AMD^*} = -0.21
AMD* α fit - 6
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p_T/A = 320 - 400 MeV/c
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$\alpha_{AMD^{(0)}}$ = 0.26
p_T/A = 400 - 480 MeV/c
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$\beta_{AMD^{(0)}}$ = -0.19
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α_{AMD^*} = 0.27
p_T/A = 480 - 560 MeV/c
AMD* β fit - 7
β_{AMD^*} = -0.11
AMD* α fit - 8
p_T/A = 560 - 640 MeV/c
AMD* β fit - 8
$AMD^{(0)}$ α fit - 7
$\alpha_{AMD^{(0)}}$ = 0.32
p_T/A = 480 - 560 MeV/c
$AMD^{(0)}$ β fit - 7
$\beta_{AMD^{(0)}}$ = -0.10
$AMD^{(0)}$ α fit - 8
p_T/A = 560 - 640 MeV/c
$AMD^{(0)}$ β fit - 8
AMD* α fit - 9
p_T/A = 640 - 720 MeV/c
AMD* β fit - 9
AMD* α fit - 10
p_T/A = 720 - 800 MeV/c
AMD* β fit - 10
$AMD^{(0)}$ α fit - 9
p_T/A = 640 - 720 MeV/c
$AMD^{(0)}$ β fit - 9
$AMD^{(0)}$ α fit - 10
p_T/A = 720 - 800 MeV/c
$AMD^{(0)}$ β fit - 10
p
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t
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^{4}He
R_{21}
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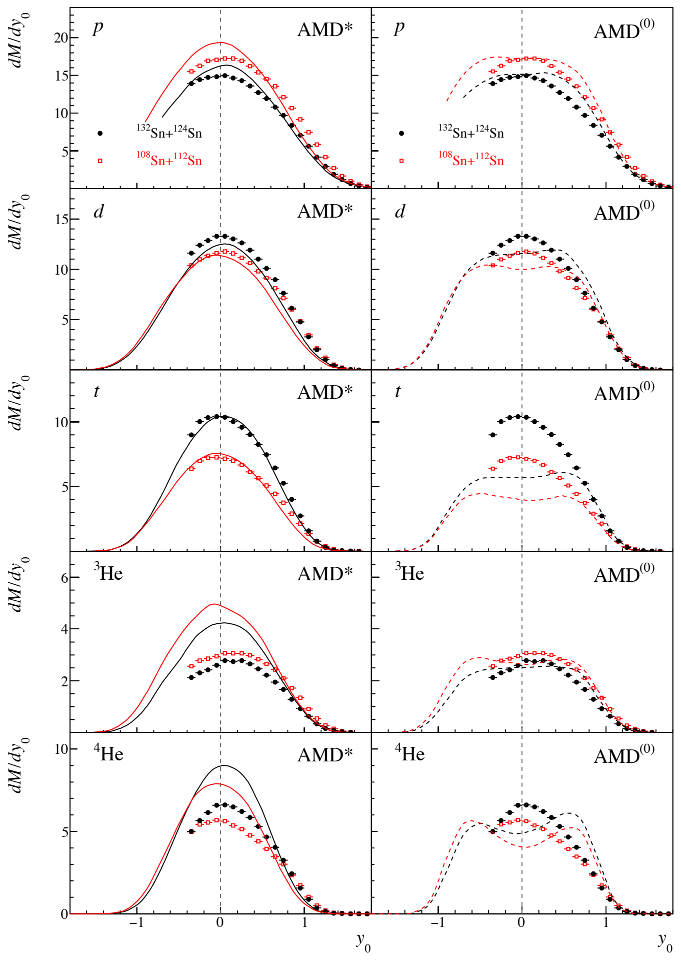
Rapidity distribution



Uncertainties