Direct and elliptic flow parameters in 129,124Xe + 124,112Sn @100 MeV/u and 58,64Ni + 58,64Ni @ 52 MeV/u

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Nuclear symmetry energy

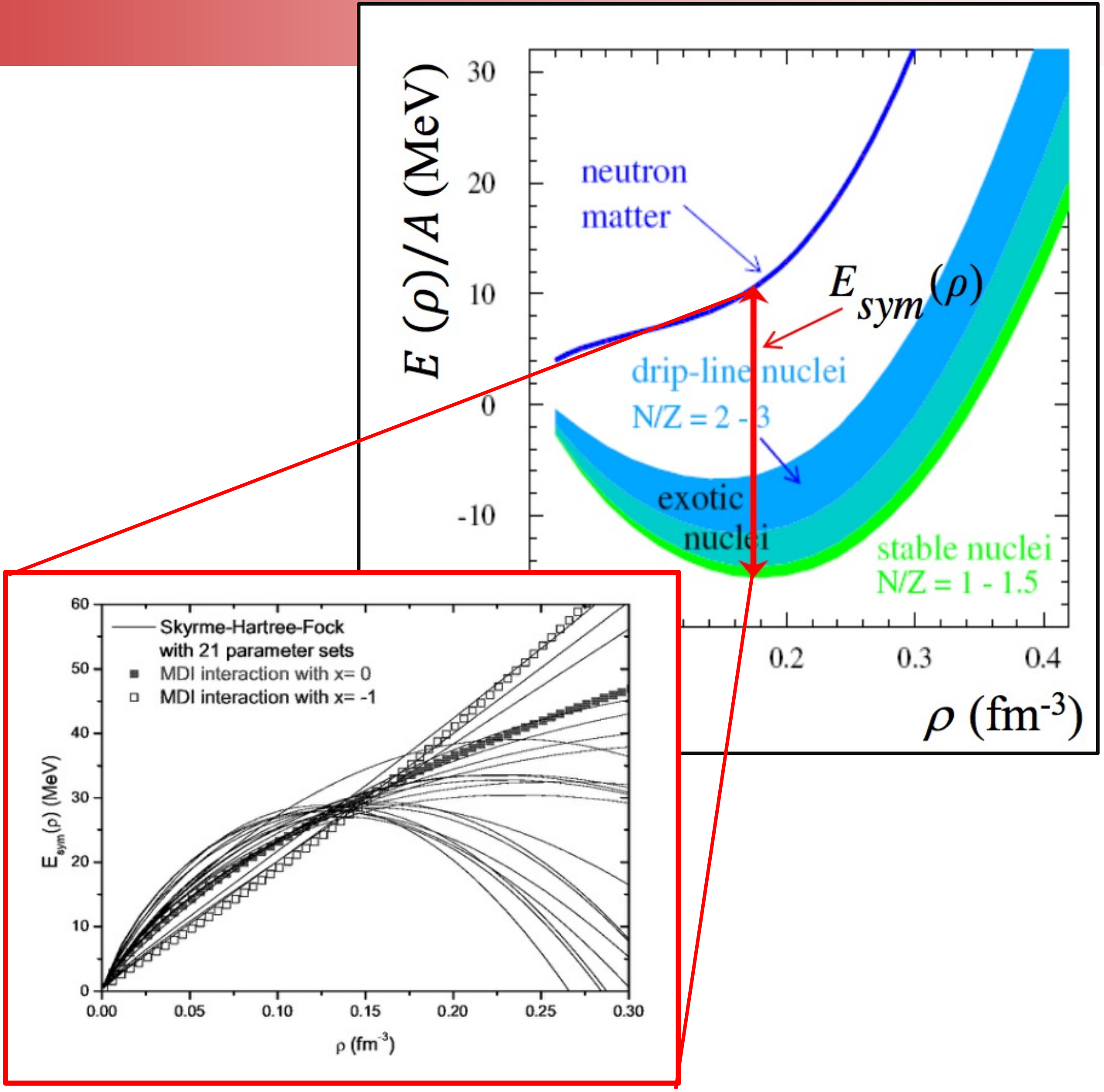
Nuclear Equation of State(NEoS)

$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\delta^2 + O(\delta^4)$$

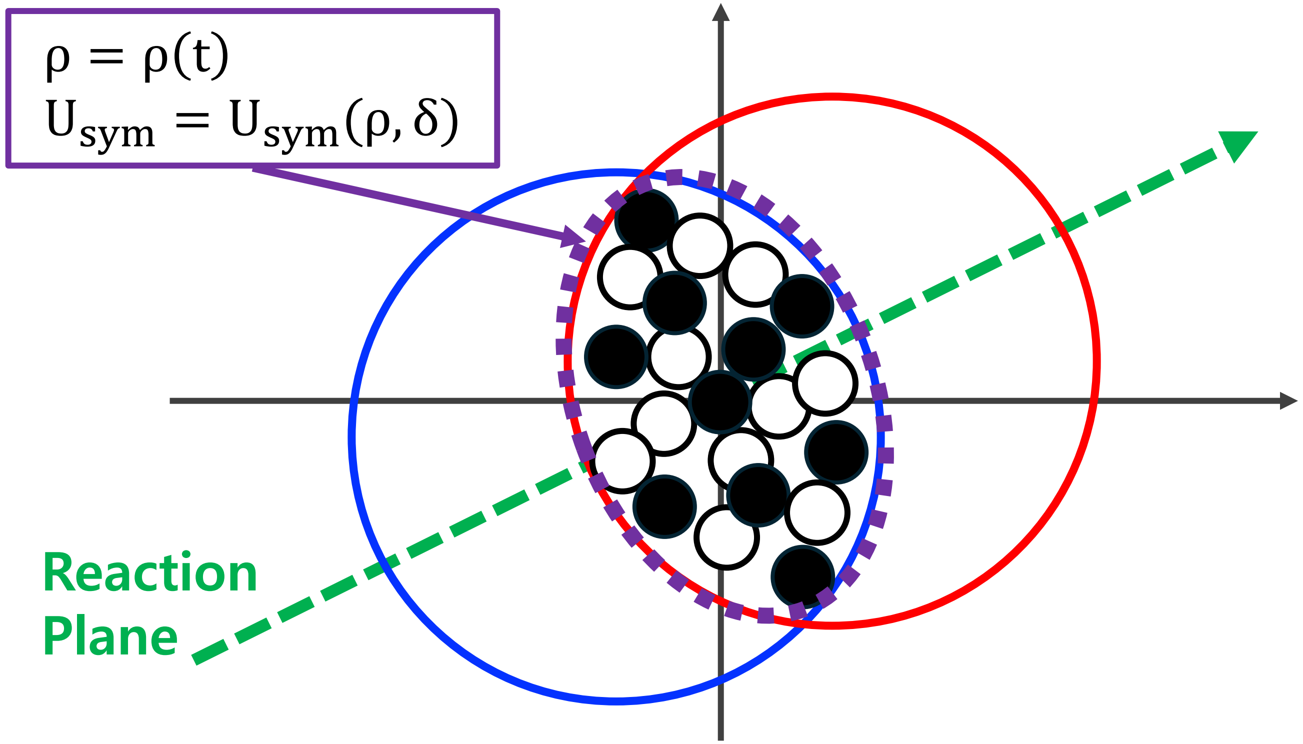
$$\text{where}, \delta = \frac{\rho_n - \rho_p}{\rho}$$

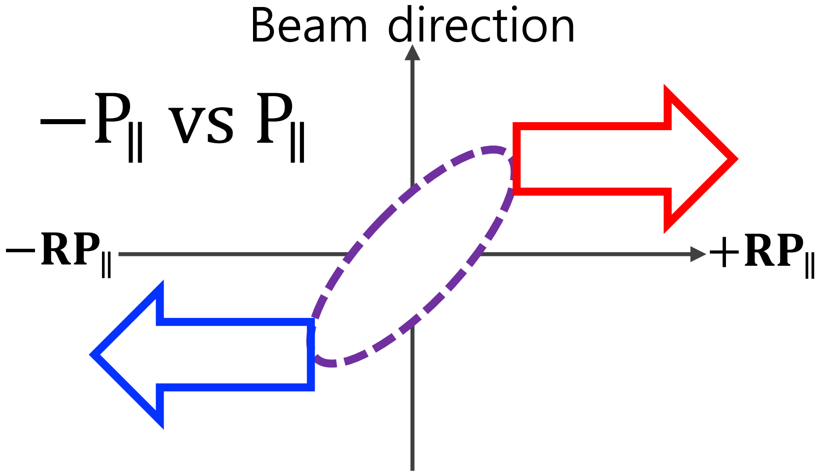
$$E_{sym}(\rho) = E_{sym}(\rho_0)\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

$$= S + \frac{L_{sym}}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 \ldots$$

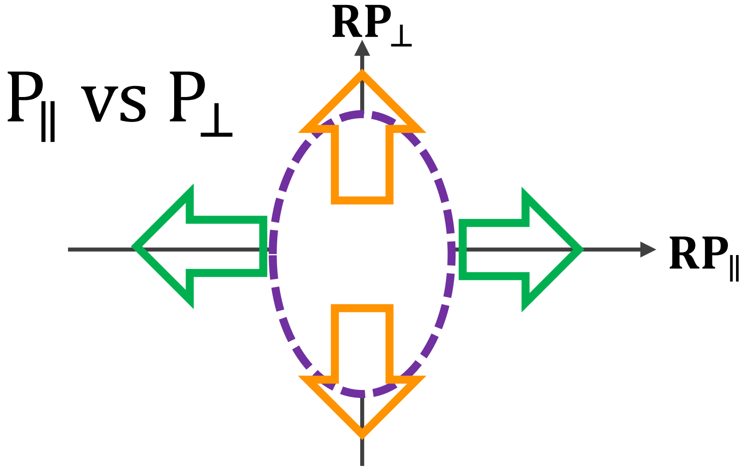


Collective flow





Direct flow : $v_1 \equiv \langle \cos(\phi - \psi_r) \rangle = \left\langle \frac{p_\parallel}{p_t} \right\rangle$



Elliptic flow : $v_2 \equiv \langle \cos 2(\phi - \psi_r) \rangle = \left\langle \frac{p_\parallel^2 - p_\perp^2}{p_t^2} \right\rangle$

Fourier expansion of azimuthal distributions :

$$\frac{dN}{d(\phi - \psi_r)} = \frac{N_0}{2\pi}\left(1 + 2\sum_{n\geq 1} v_n \cos n(\phi - \psi_r)\right)$$

where, ψ_r : azimuthal angle of reaction plane

Experiment and ImQMD

INDRA 4th campaign at GSI (1998-1999)
(INDRA-ALADIN collaboration)

$^{129,124}_{54}\mathrm{Xe} + {}^{124,112}_{50}\mathrm{Sn}$
@ 100AMeV

E789 at GANIL (2019.4->5)
(INDRA-FAZIA collaboration)

$^{64,58}_{28}\mathrm{Ni} + {}^{64,58}_{28}\mathrm{Ni}$
@ 52 AMeV

ImQMD with Skyrme parameter sets + GEMINI++

Para	ρ_0	E_0	K_0	S_0	L
SLy4	0.160	-15.97	230	32	46
SkM*	0.160	-15.77	217	30	46
	K_{sym}	m^*/m	m_n^*/m	m_p^*/m	
SLy4	-120	0.69	0.68	0.71	
SkM*	-156	0.79	0.82	0.76	

- Currently, ImQMD calculations have been performed only for Xe+Sn @ 100MeV/u.
- 5 discrete b_0 are chosen for time efficiency. (0.1, 0.2, 0.3, 0.4 and 0.5)≈ IW1
- About 10^6 events for each b_0

...

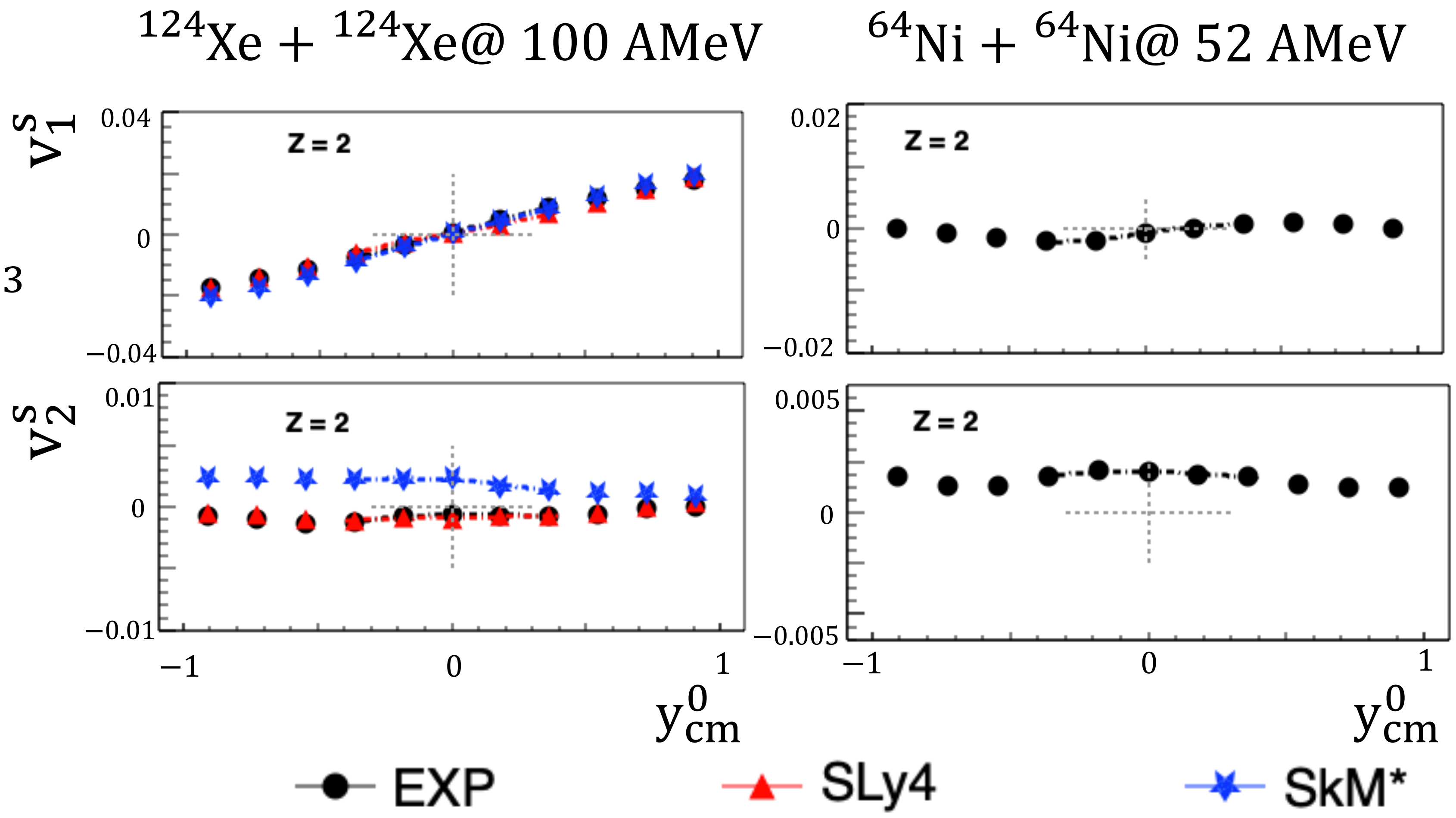
v_n^s vs y_{cm}^0

v_n^s(system size scaled v_n)

$$= v_n \left\langle p_t^{(0)} \right\rangle / \left(A_P^{1/3} + A_T^{1/3}\right)$$

fit v_1^s: $a + \text{Slope} * y + by^3$

fit v_2^s: $\text{Offset} + ay + by^2$



$$p_t^0 = (p_t/A)/\left(\left(2p_t^P/A_{P+T}\right)\right)$$

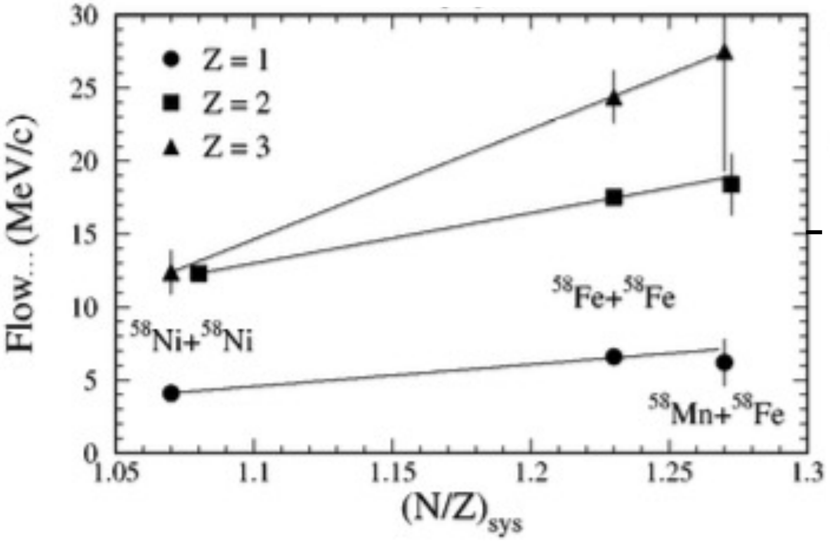
$$y_{cm}^0 = \begin{cases} y_{cm}/y_{cm}^P & (y_{cm} > 0) \\ y_{cm}/y_{cm}^T & (y_{cm} < 0) \end{cases}$$

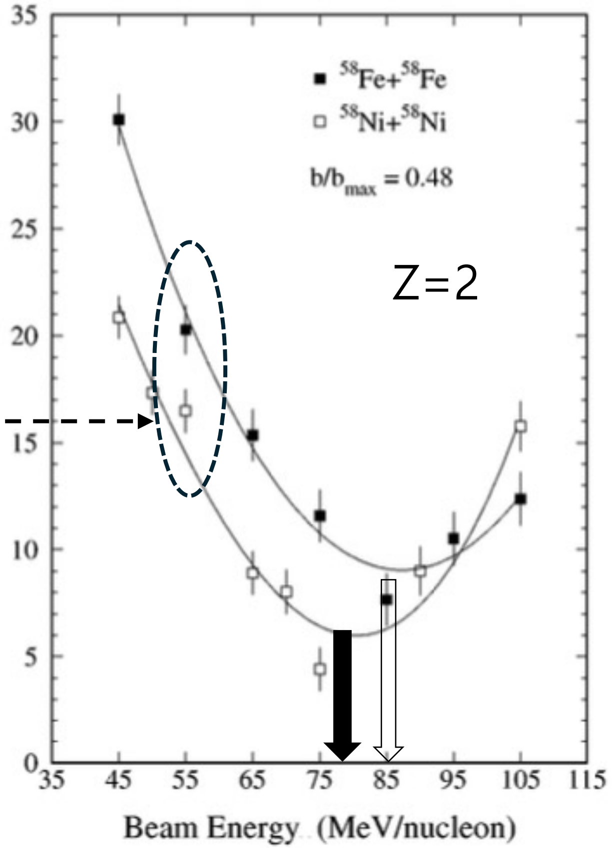
Compare with Isobaric system study

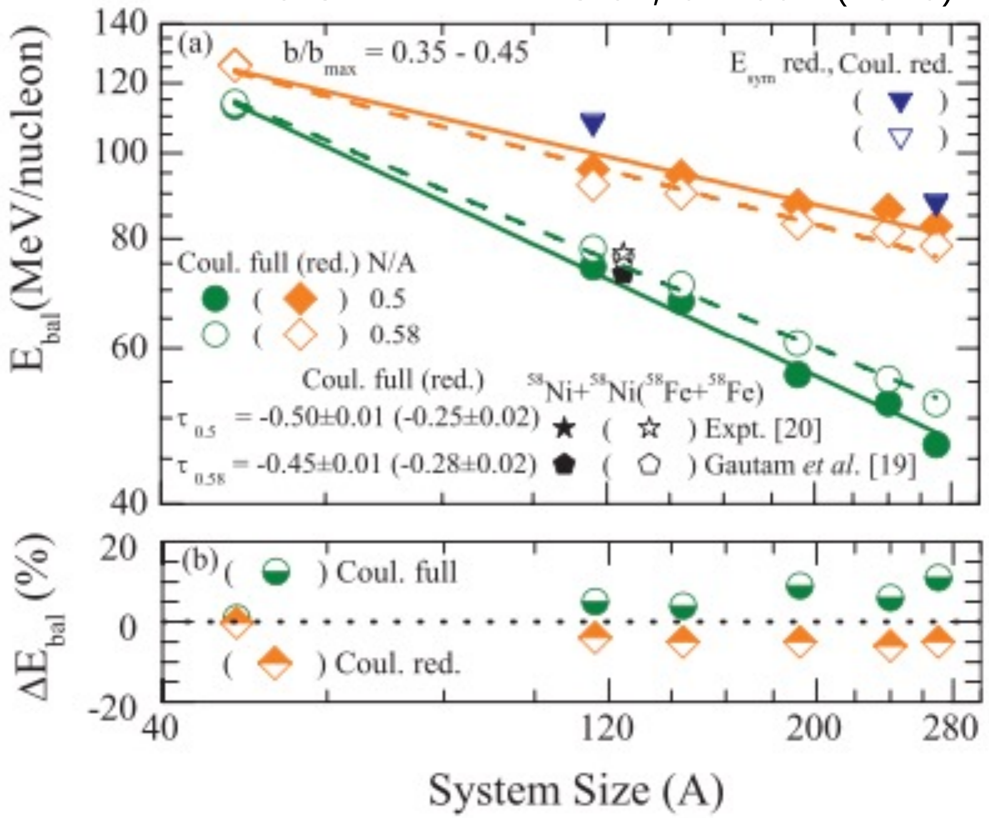
PHYSICAL REVIEW C 82, 014604 (2010)

Flow : Slope of $\langle P_x \rangle$ linear fit

$$-0.5 < (y/y_{proj})^{cm} < 0.5$$







$$\mathrm{Slope}_{n-rich} > \mathrm{Slope}_{n-poor}$$

$$E^{bal}_{Fe+Fe} > E^{bal}_{Ni+Ni}$$

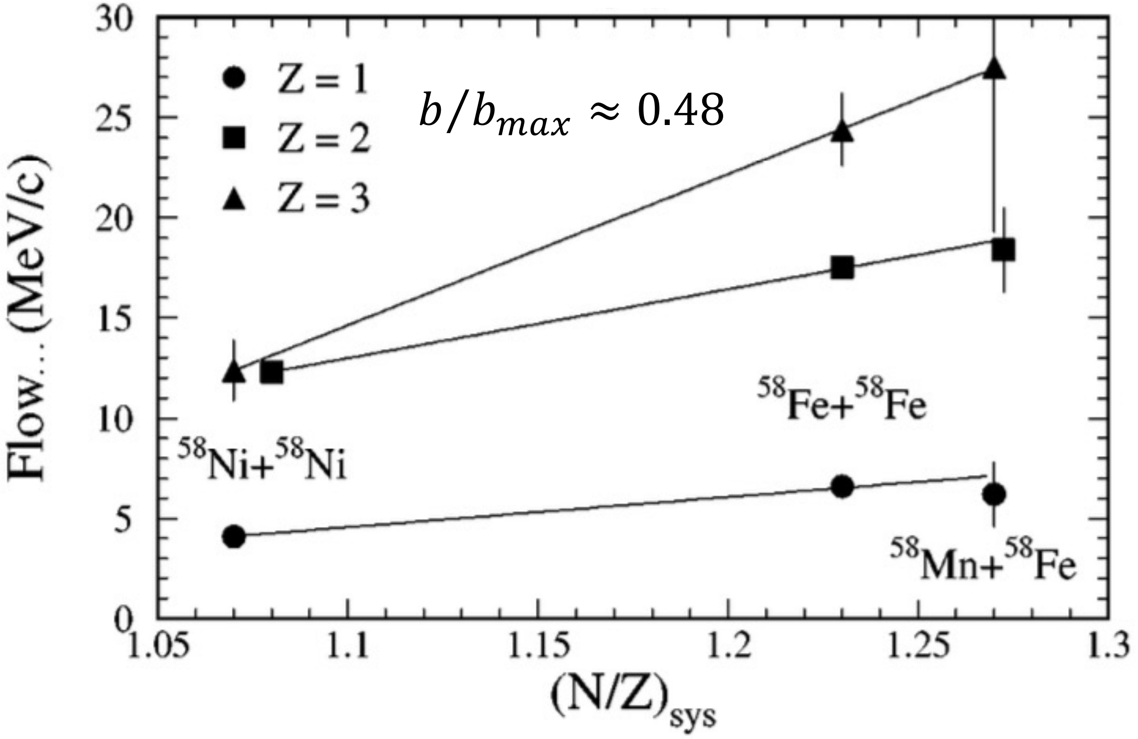
IQMD

Open Yellow : n-rich w/ reduced coulomb
Solid Yellow : n-poor w/ reduced coulomb

Open Green : n-rich w/ full coulomb
Solid Green : n-poor w/ full coulomb

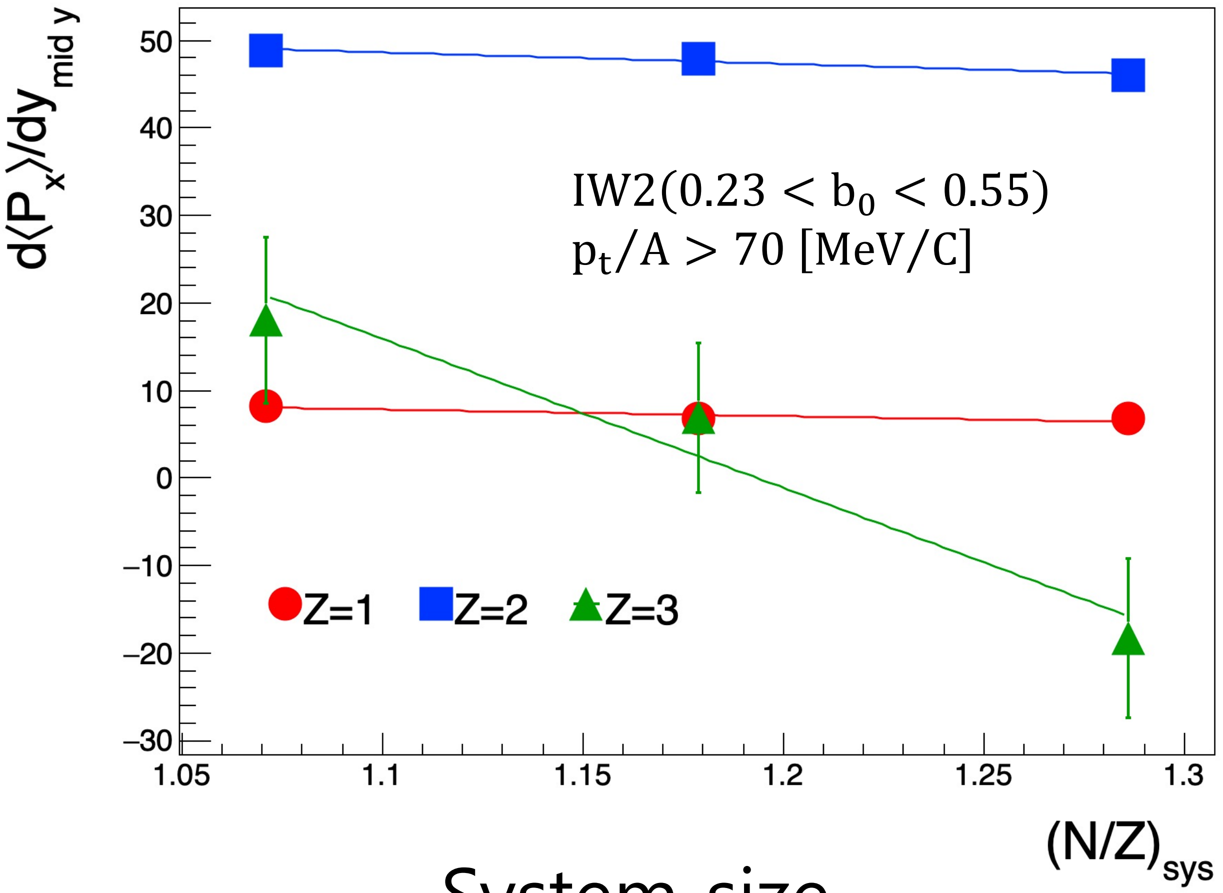
PhysRevLett.78.1022(1997)

Isobaric



Coulomb is not constrained

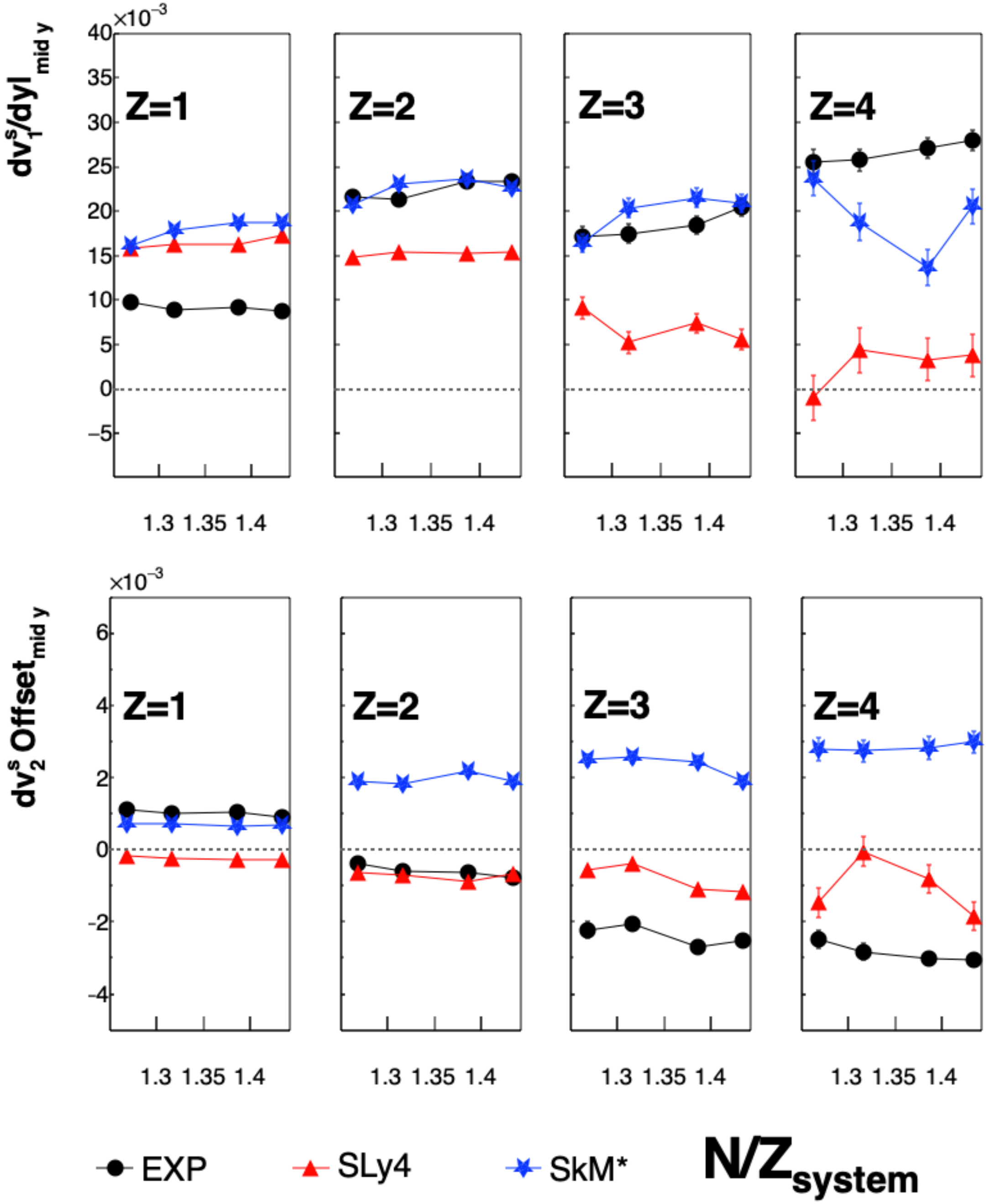
Isotopic

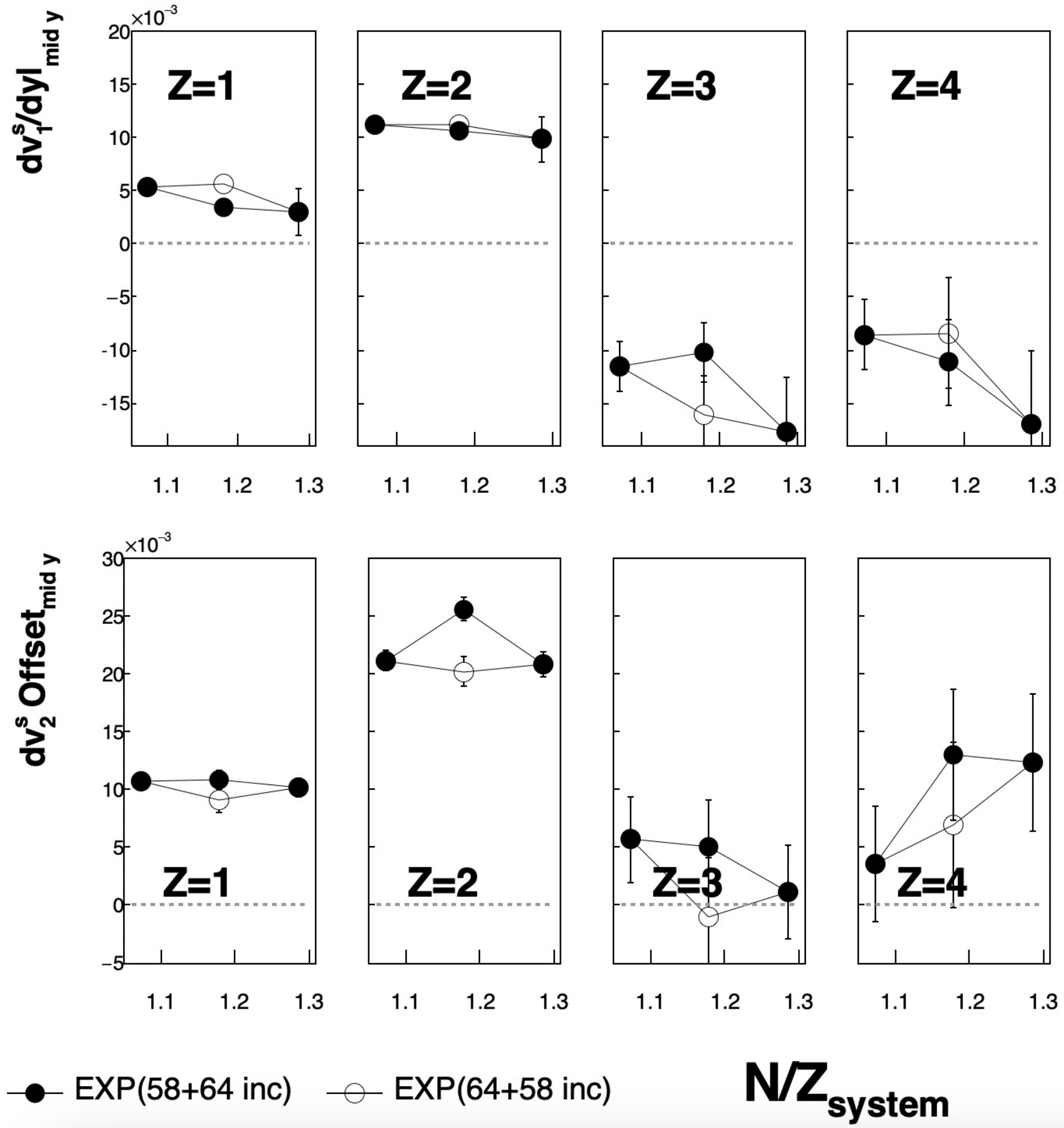


System size
(# of nucleons)
is not constrained

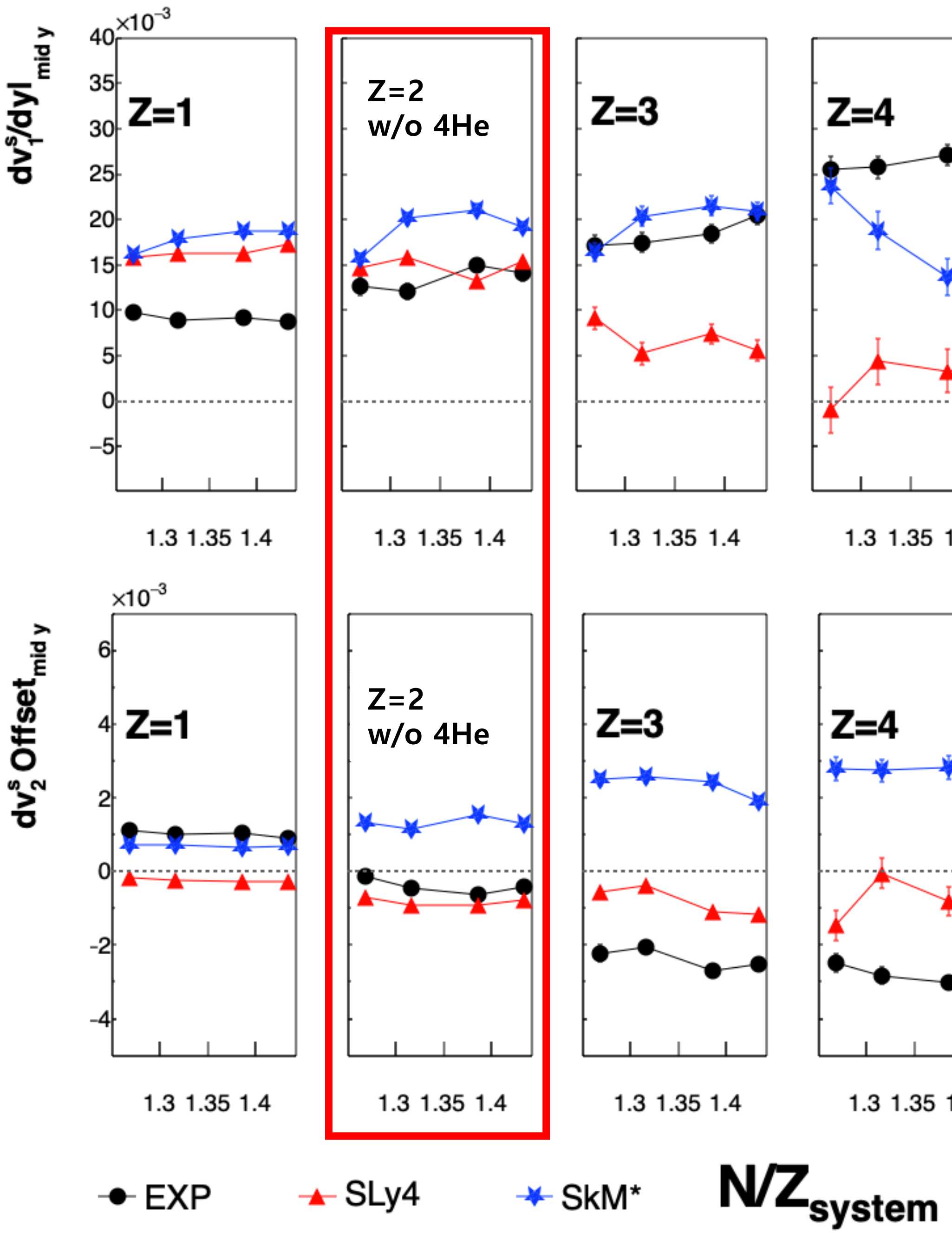
IW1 Xe + Sn @ 100 AMeV

EW1 Ni + Ni @ 52 AMeV

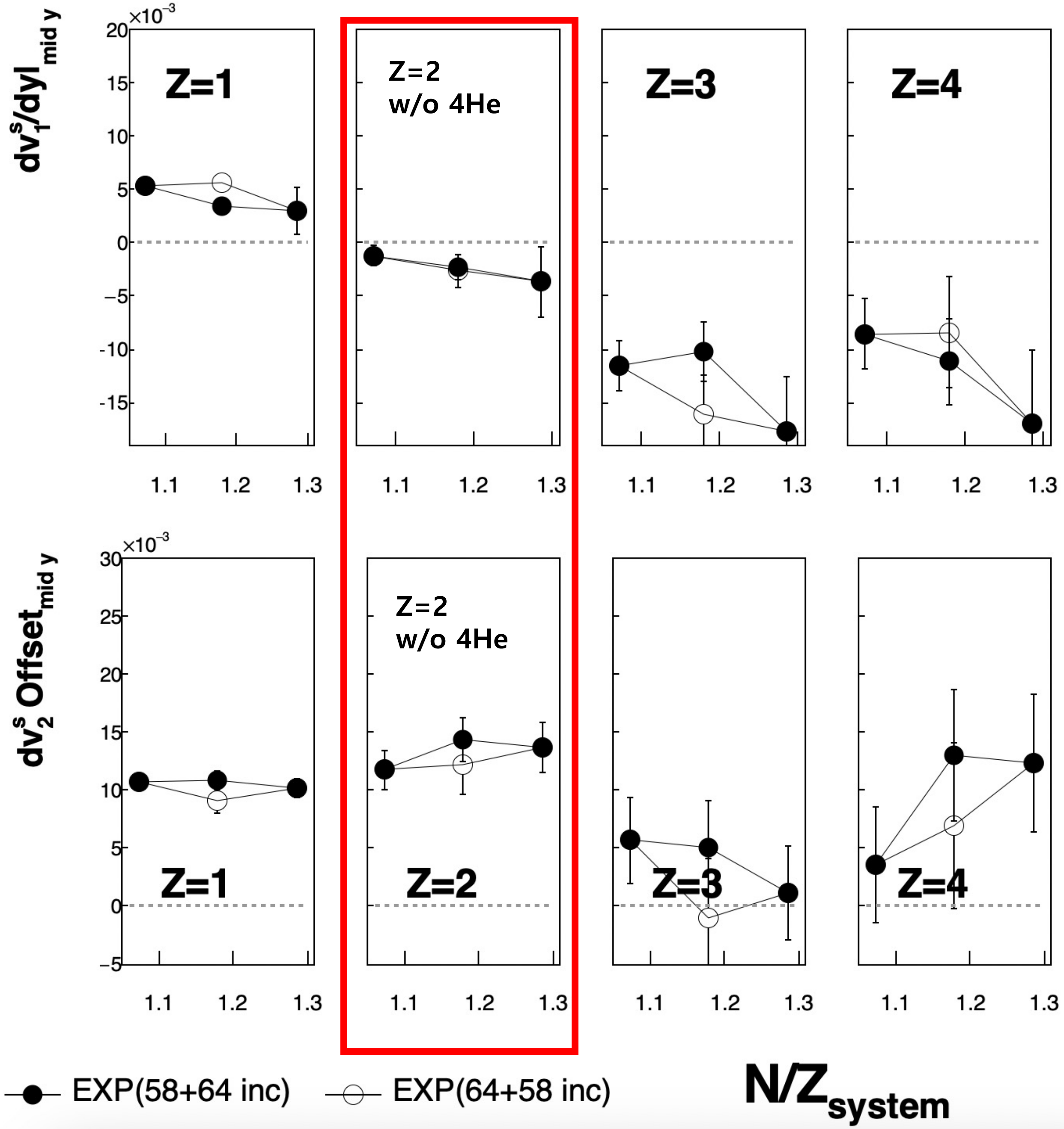




IW1 Xe + Sn @ 100 AMeV



EW1 Ni + Ni @ 52 AMeV



Correlation between N/Z of fragments and systems

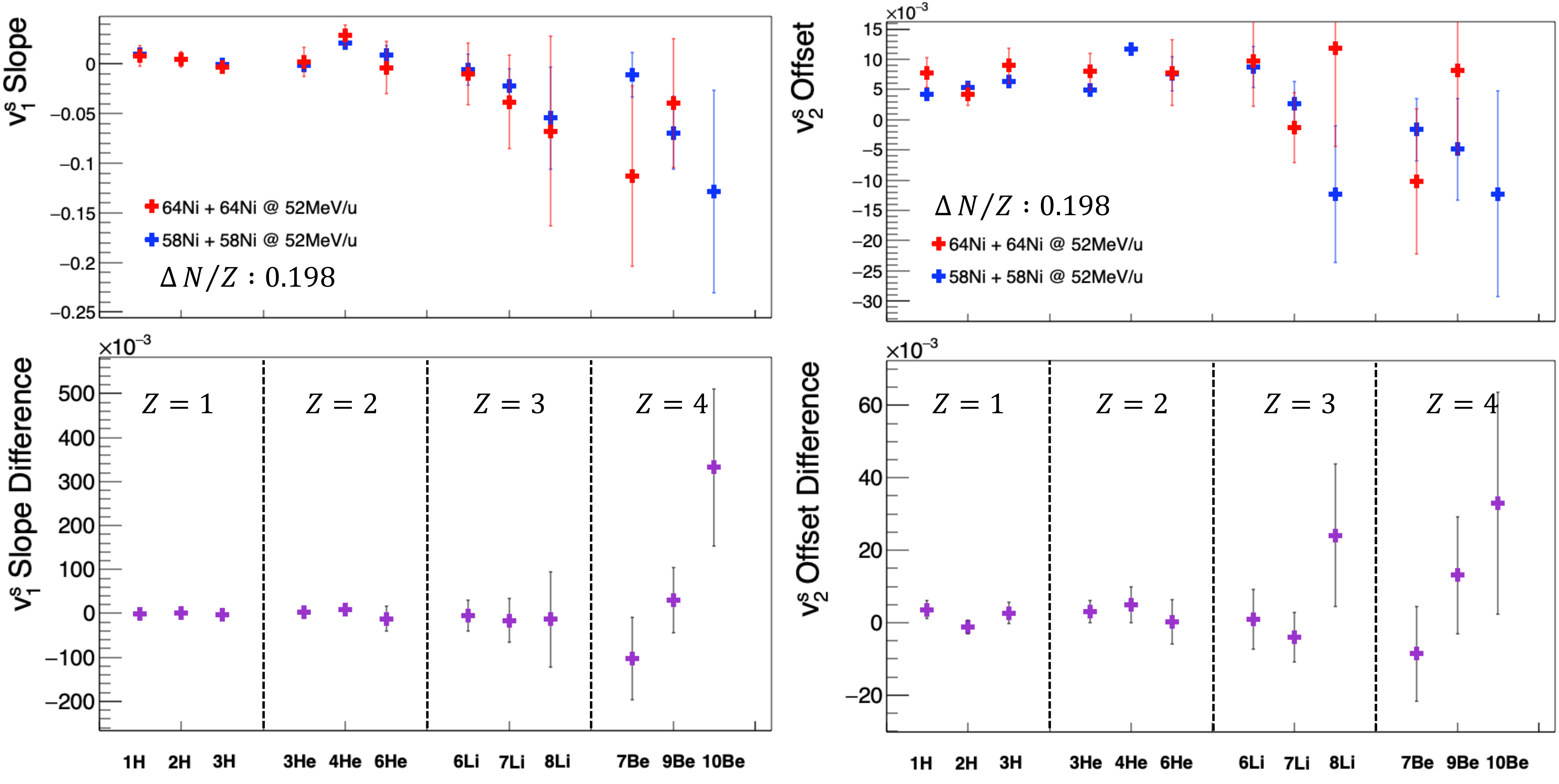
Flow parameters are affected by many un-constrained effects
(l.e. origin of fragments, emission time, collision systems size…)

Difference of flow parameter → **Can it constrain un-wanted effects?**

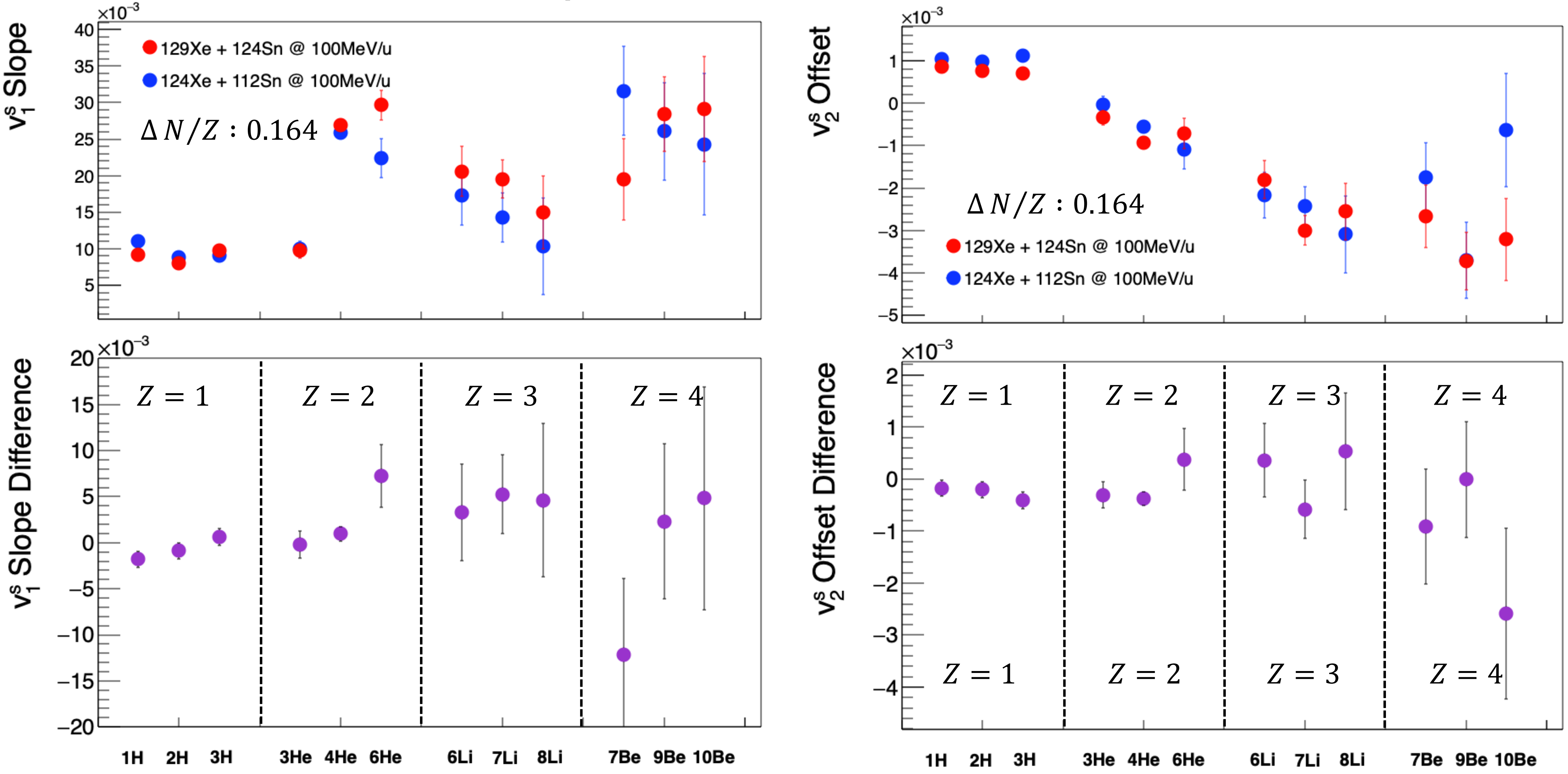
$$\mathbf{v_1^s\ \ Slope\ Difference}$$
$$= \mathrm{v_1^s\ Slope_{high\ (N/Z)\ system}} - \mathrm{v_1^s\ Slope_{low\ (N/Z)\ system}}$$

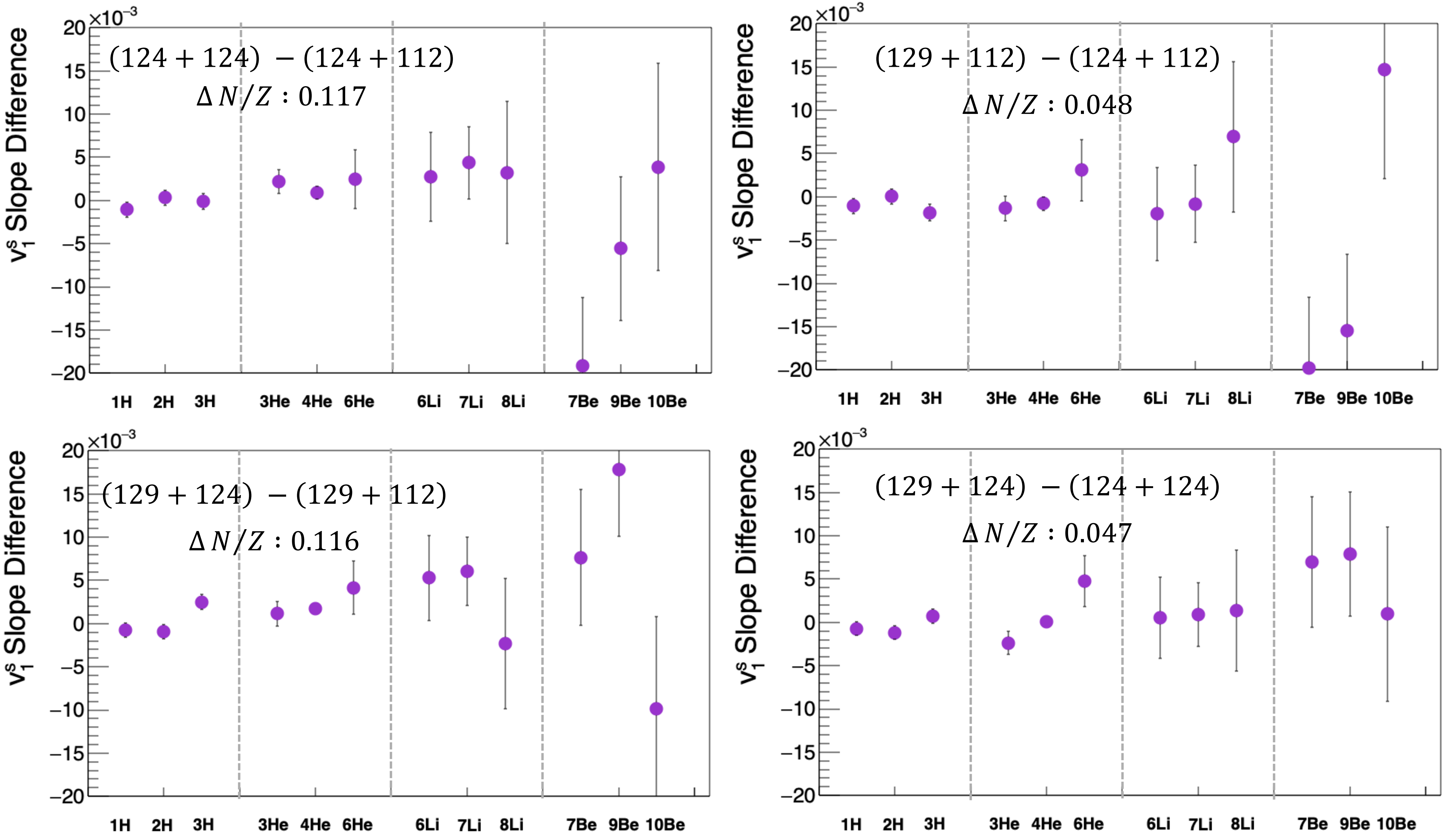
$$\mathbf{v_2^s\ \ Offset\ Difference}$$
$$= \mathrm{v_2^s\ Offset_{high\ (N/Z)\ system}} - \mathrm{v_2^s\ Offset_{low\ (N/Z)\ system}}$$

E789 Ni + Ni @ 52AMeV



INDRA Camp 4th Xe + Sn @ 100AMeV





$(124 + 124) - (124 + 112)$
$\Delta N/Z : 0.117$
$(129 + 112) - (124 + 112)$
$\Delta N/Z : 0.048$
$(129 + 124) - (129 + 112)$
$\Delta N/Z : 0.116$
$(129 + 124) - (124 + 124)$
$\Delta N/Z : 0.047$
v_1^s Slope Difference
$\times10^{-3}$
20
15
10
5
0
−5
−10
−15
−20
1H 2H 3H 3He 4He 6He 6Li 7Li 8Li 7Be 9Be 10Be

Summary

1. Flow parameters from isotopes collision systems at 100 and 52 MeV/u are studied.

2. Flow parameters are easily affected by non-constrained effects.

3. Compare between ImQMD and experiment data will continue after modification of the model calculation.

4. Correlation between N/Z of collision system and fragments is founded but they are somewhat ambiguous.

감사합니다!
Thank you very much!

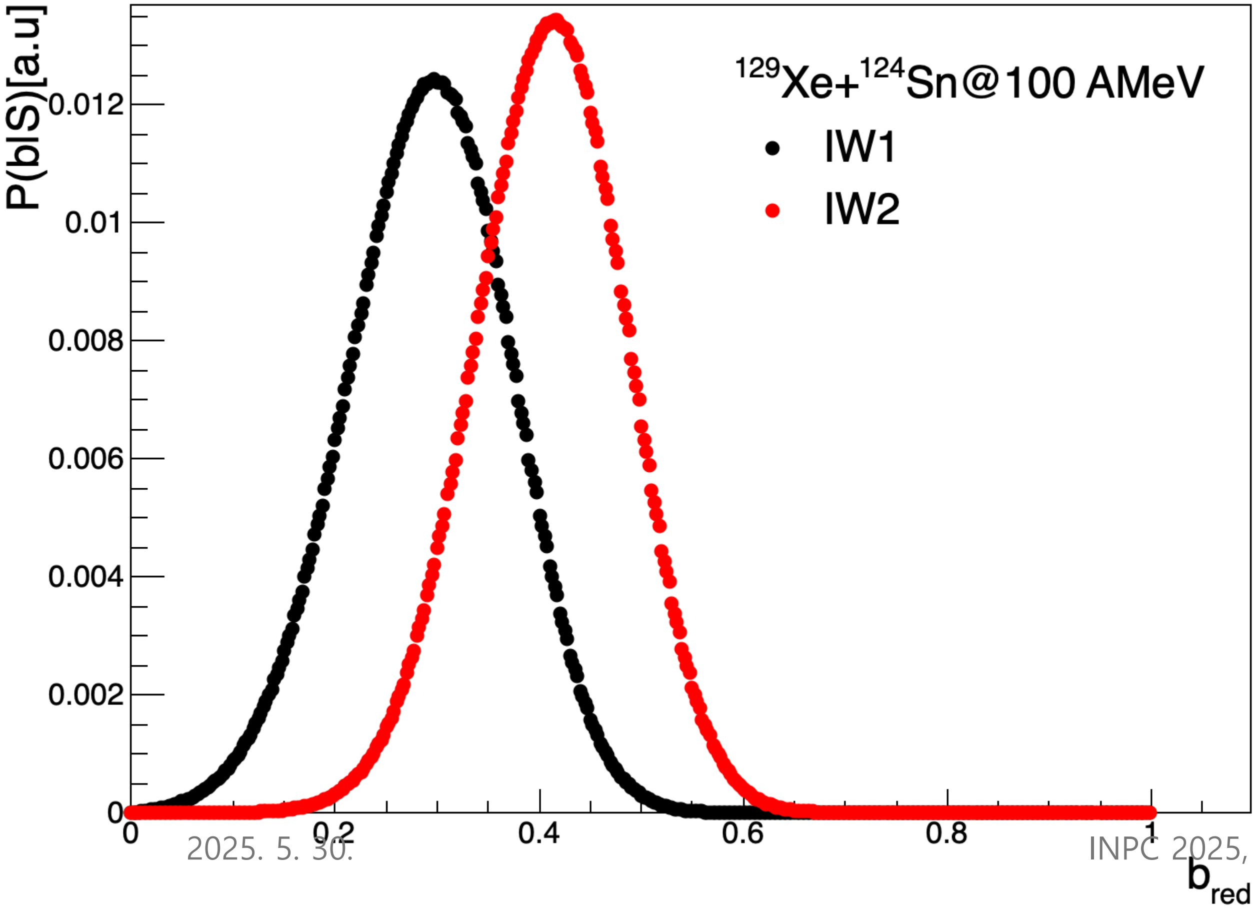
INPC 2025

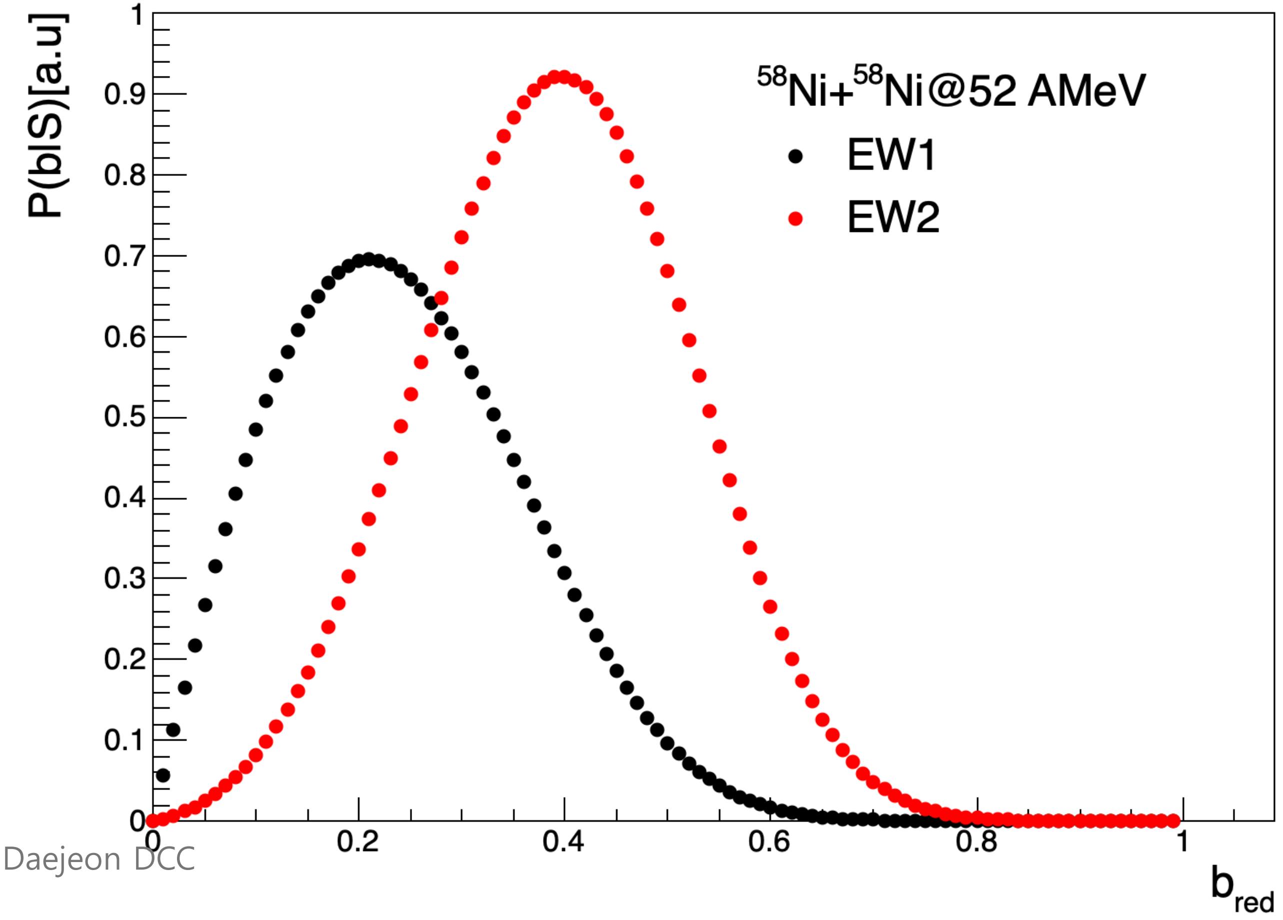
中国原子能科学研究院
中核集团 CNNC
CHINA INSTITUTE OF ATOMIC ENERGY

Back Up

Bayesian estimated reduced impact parameter

	IW1	IW2	EW1	EW2
et_{12} [MeV]	750~1050	510~770	245~720	180~230
b_0(FWHM)	0.21~0.42	0.35~0.55	0.05~0.4	0.23~0.55

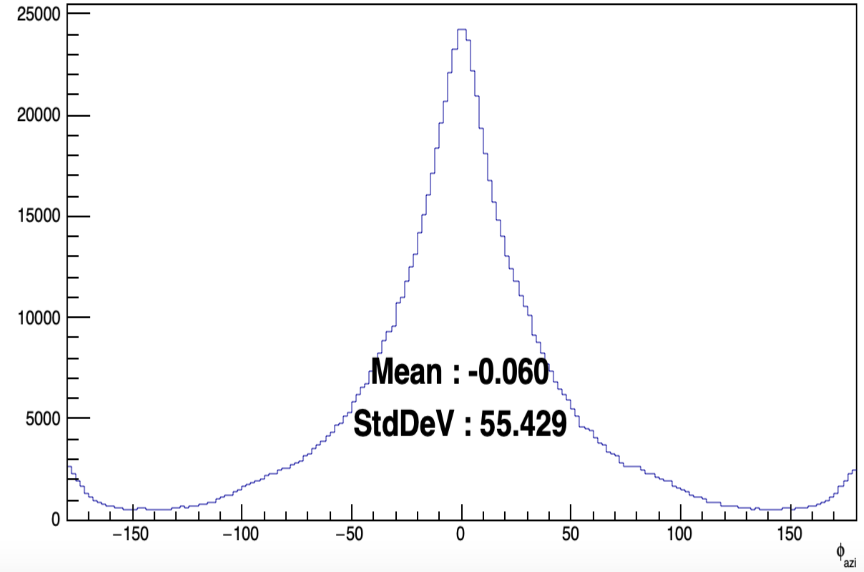




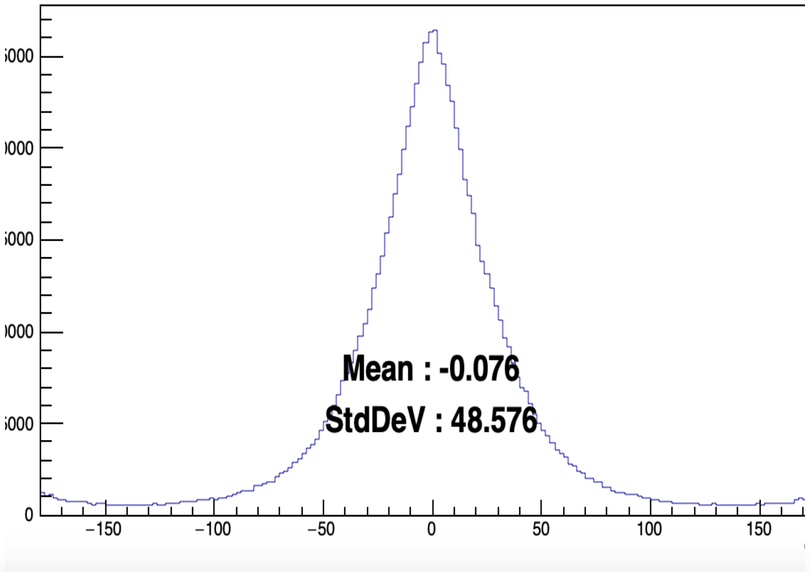
Estimated reaction plane dispersion(using ImQMD)

$\mathrm{Xe} + \mathrm{Sn}\ @\ 100\mathrm{AMeV}\ \ \mathrm{b_0} : 0.1, 0.2, 0.3, 0.4\ \&\ 0.5$

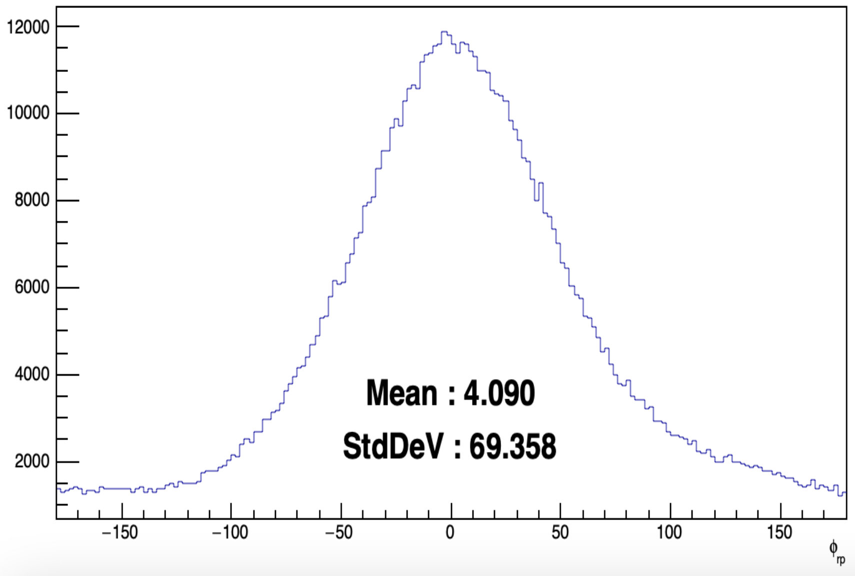
Azimuthal Correlation



Transverse Momentum



Tensor



$$\phi_{Esti} - \phi_{Actual}$$

Kinetic Tensor method

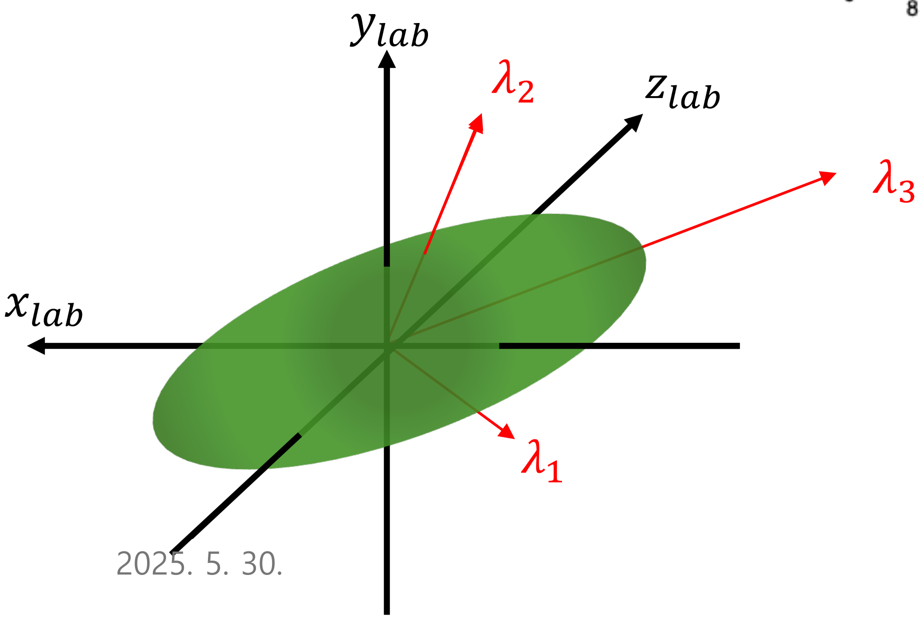
$$\boldsymbol{F}_{ij} = \sum_{\nu \neq poi} p_i(\nu) p_j(\nu)/m_\nu \qquad i, j = x, y, z$$

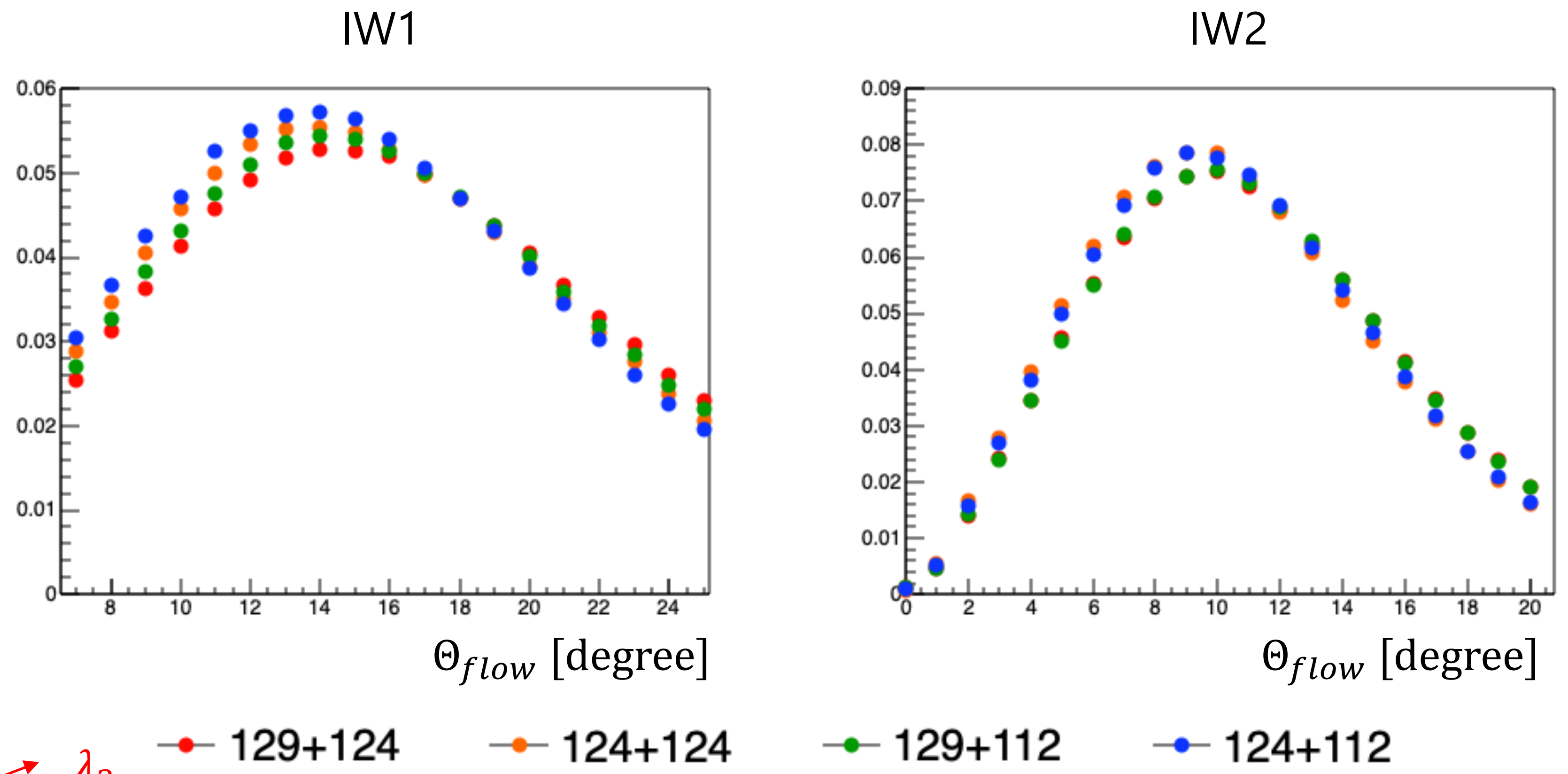
$$\begin{bmatrix} F_{xx} & F_{xy} & F_{xz} \\ F_{yx} & F_{yy} & F_{yz} \\ F_{zx} & F_{zy} & F_{zz} \end{bmatrix} \rightarrow \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}$$

λ_3 : *largest eigen value*

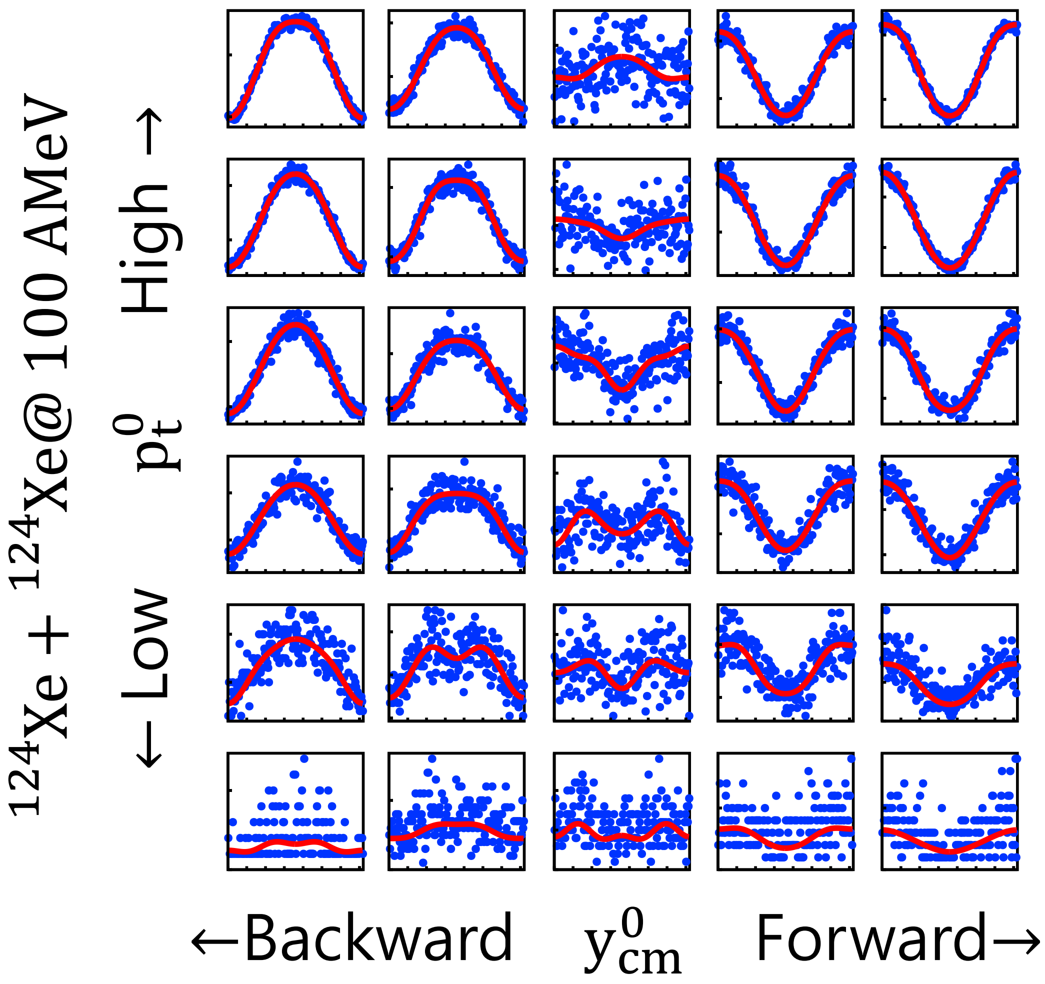
$(\lambda_3^x, \lambda_3^y, \lambda_3^z)$ *eigen vector of largest* λ_3

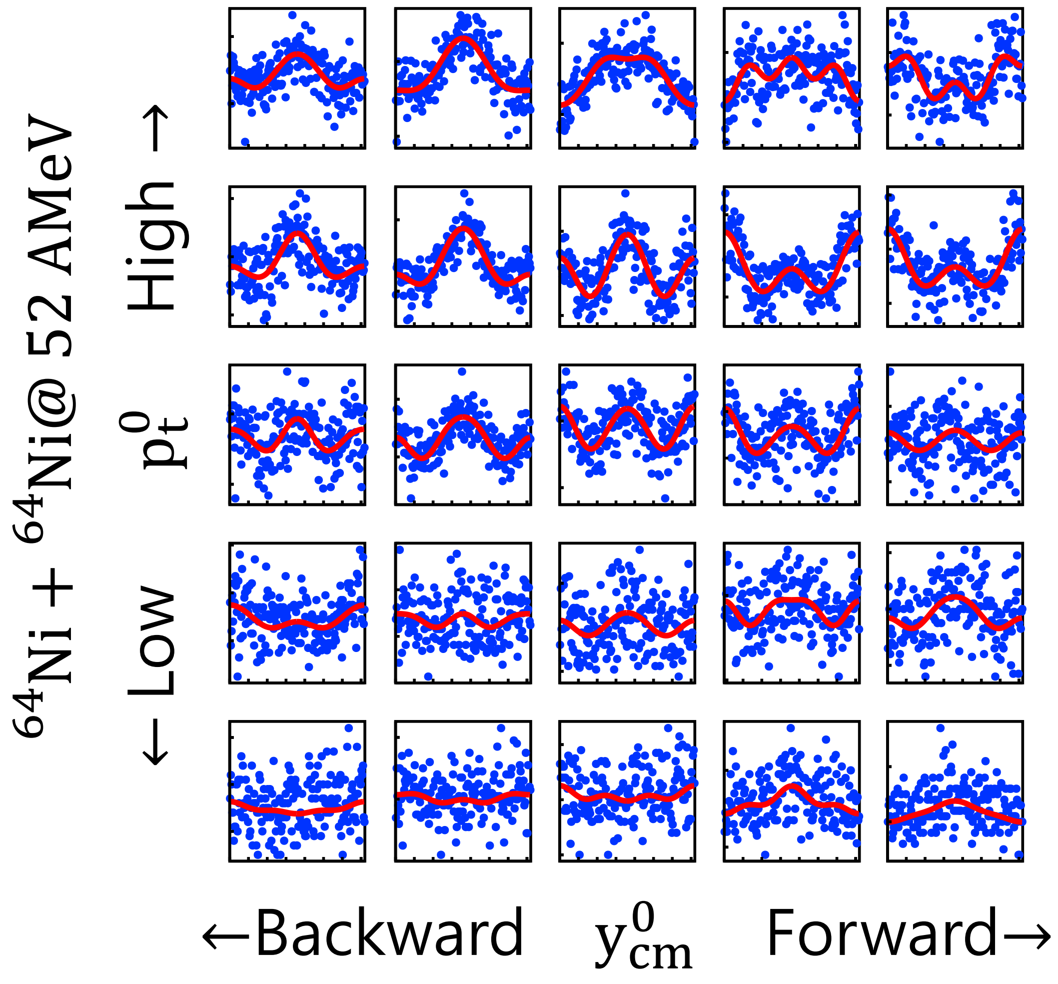
θ_{flow} : Polar angle $\widehat{\lambda_3}$
i.e. angle between $\widehat{\lambda_3}$ and $\hat{k}$(beam direction)





$\phi - \psi_r$ Distribution $(Z = 2\,, 0 \rightarrow 2\pi)$

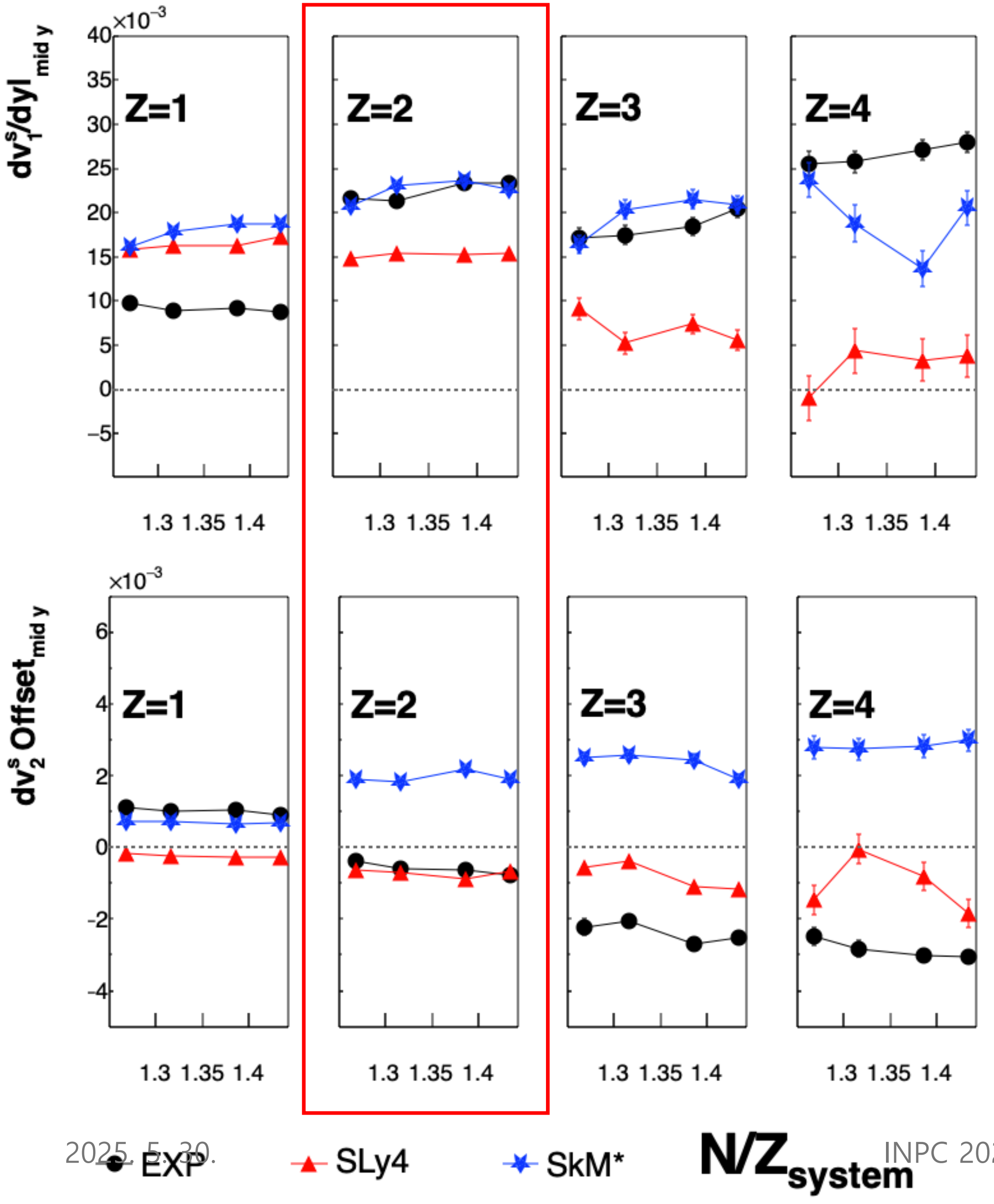


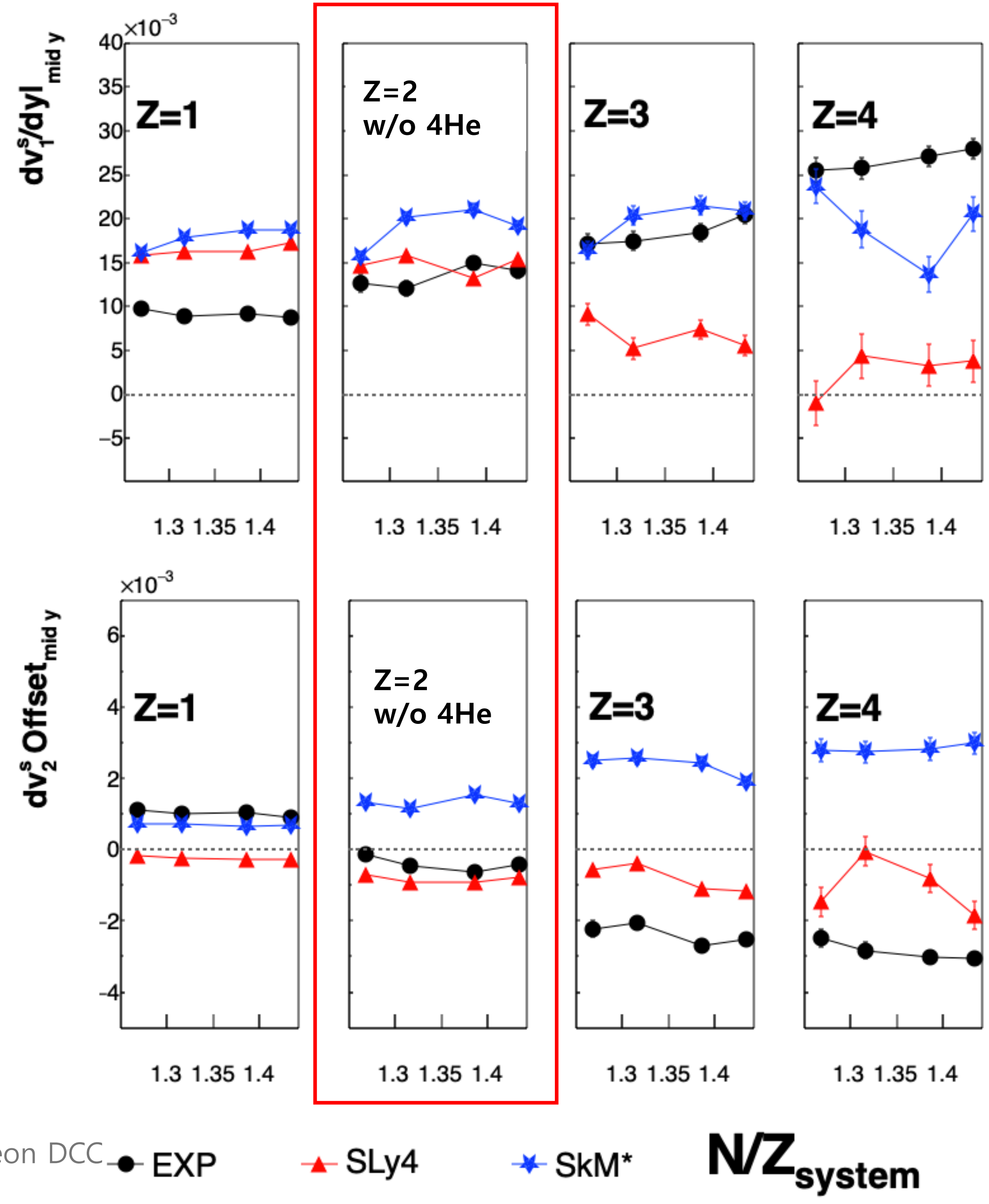


$$p_t^0 = (p_t/A)\Big/\Big(\big(2p_t^P/A_{P+T}\big)\Big)$$

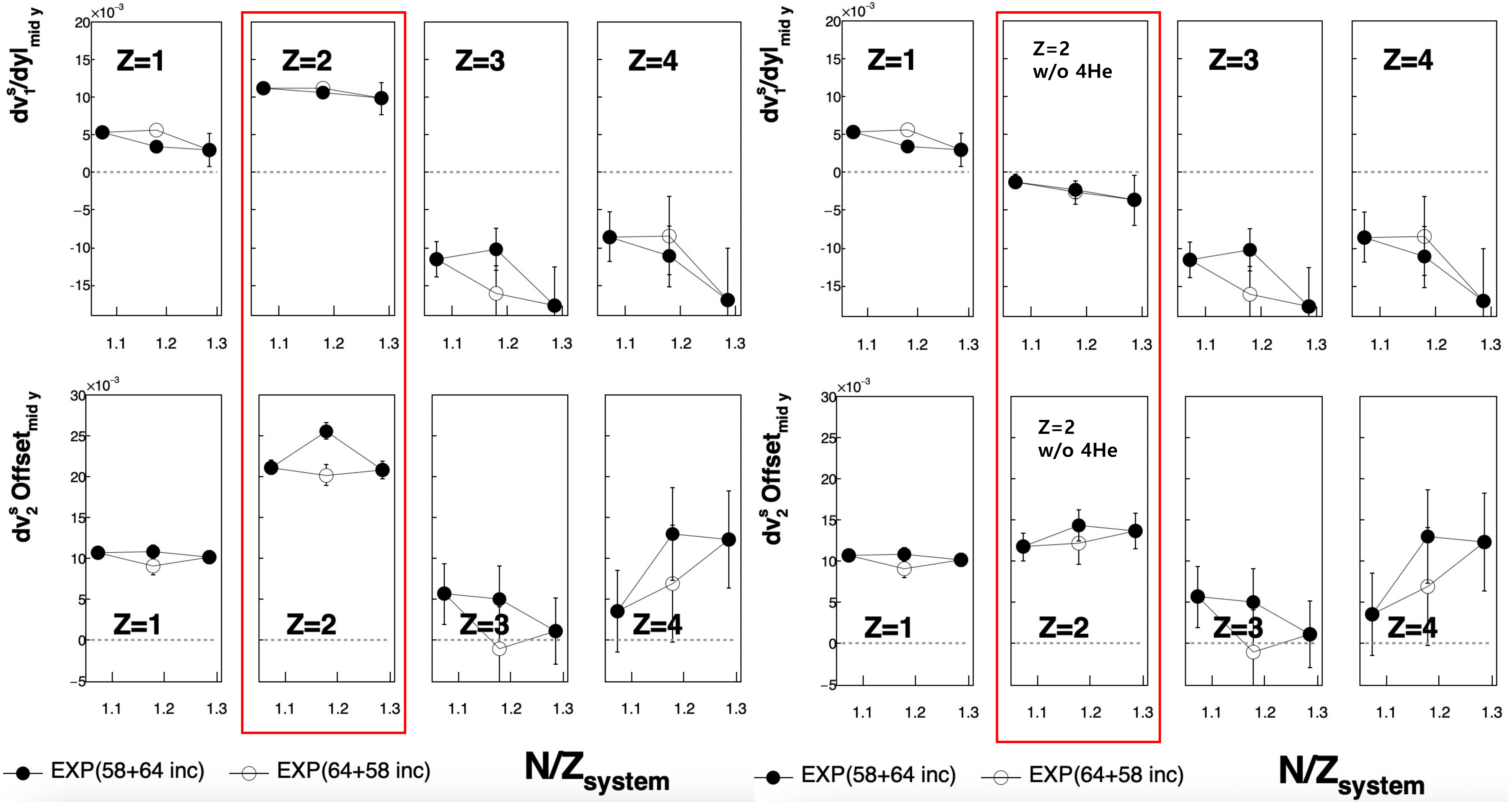
$$y_{cm}^0 = \begin{cases} y_{cm}/y_{cm}^P & (y_{cm} > 0) \\ y_{cm}/y_{cm}^T & (y_{cm} < 0) \end{cases}$$

IW1 Xe + Sn @ 100 AMeV





EW1 Ni + Ni @ 52 AMeV



IW1

P_x vs P_z

$Z = 2$

IW2