Experiment and ImQMD comparison using Flow parameters of Xe + Sn @ 100 AMeV and Ni + Ni @ 52 AMeV

2025 CENuM Workshop in Jeju

2025 .1 .16 .木
Seon ho Nam

Physics Motivation

Nuclear symmetry energy

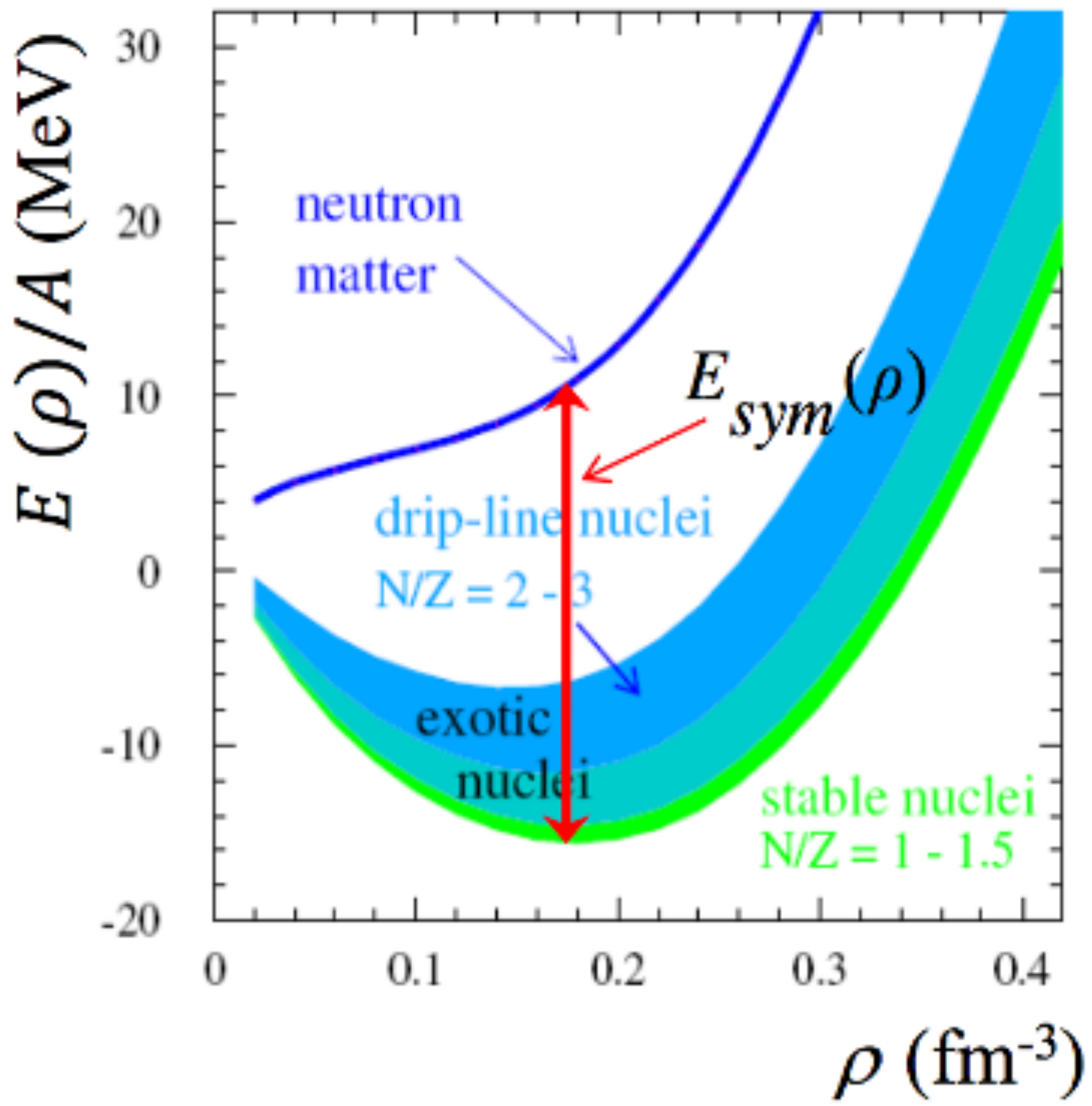
$$E(\rho,\delta)/A = E(\rho_n=\rho_p) + E_{sym}(\rho)\delta^2$$

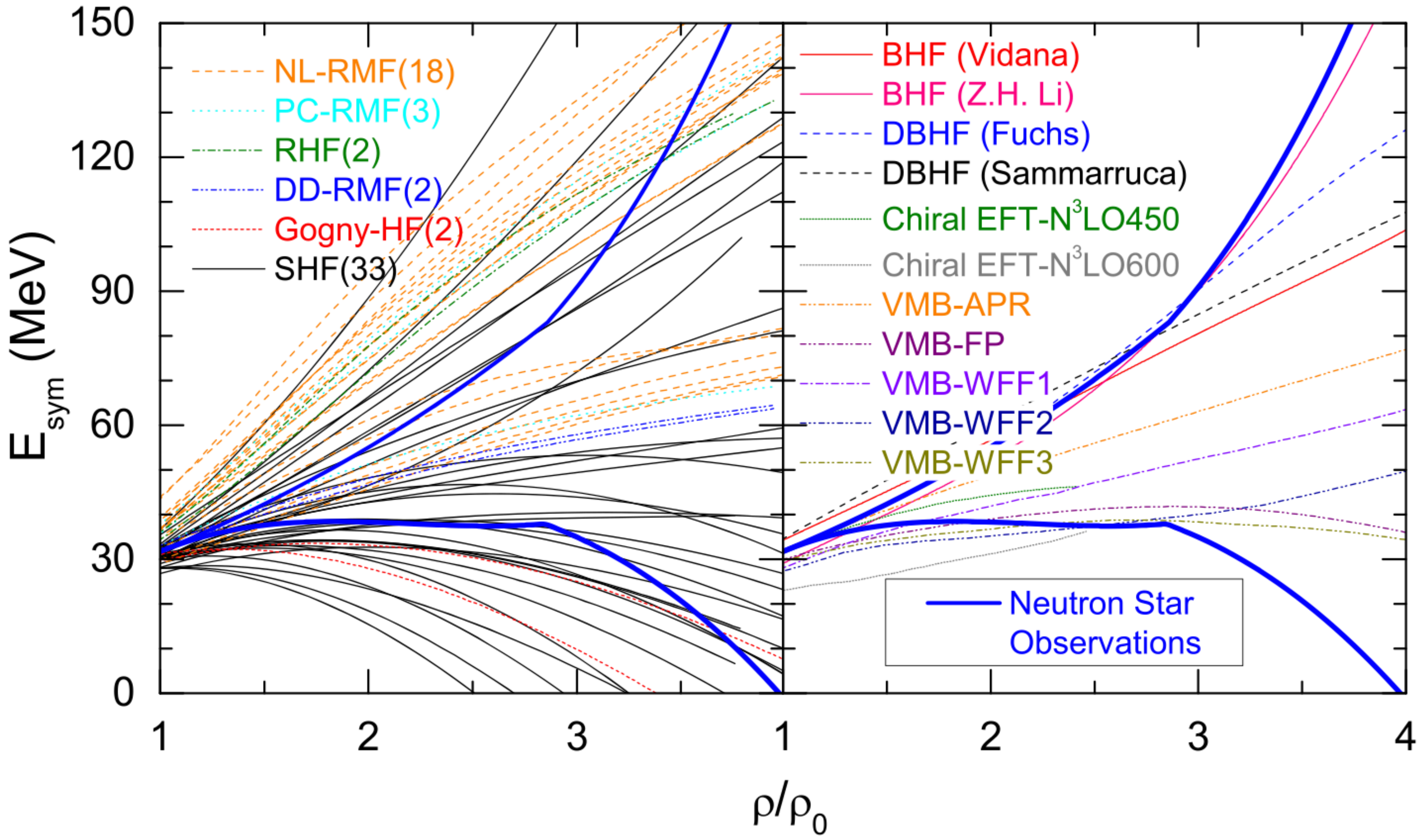
Iso scalar Iso vector

$$E_{sym}(\rho) = \frac{1}{2}\frac{\partial^2 E}{\partial \delta^2} \sim E(\rho_{\text{pure neutron}}) - E(\rho_{\text{symmtric}})$$

$$\rho = \rho_n + \rho_p\,, \qquad \delta = (\rho_n - \rho_p)/\rho$$

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





The Astrophysical Journal, 902:38 (12pp), 2020 October 10

Collective flow

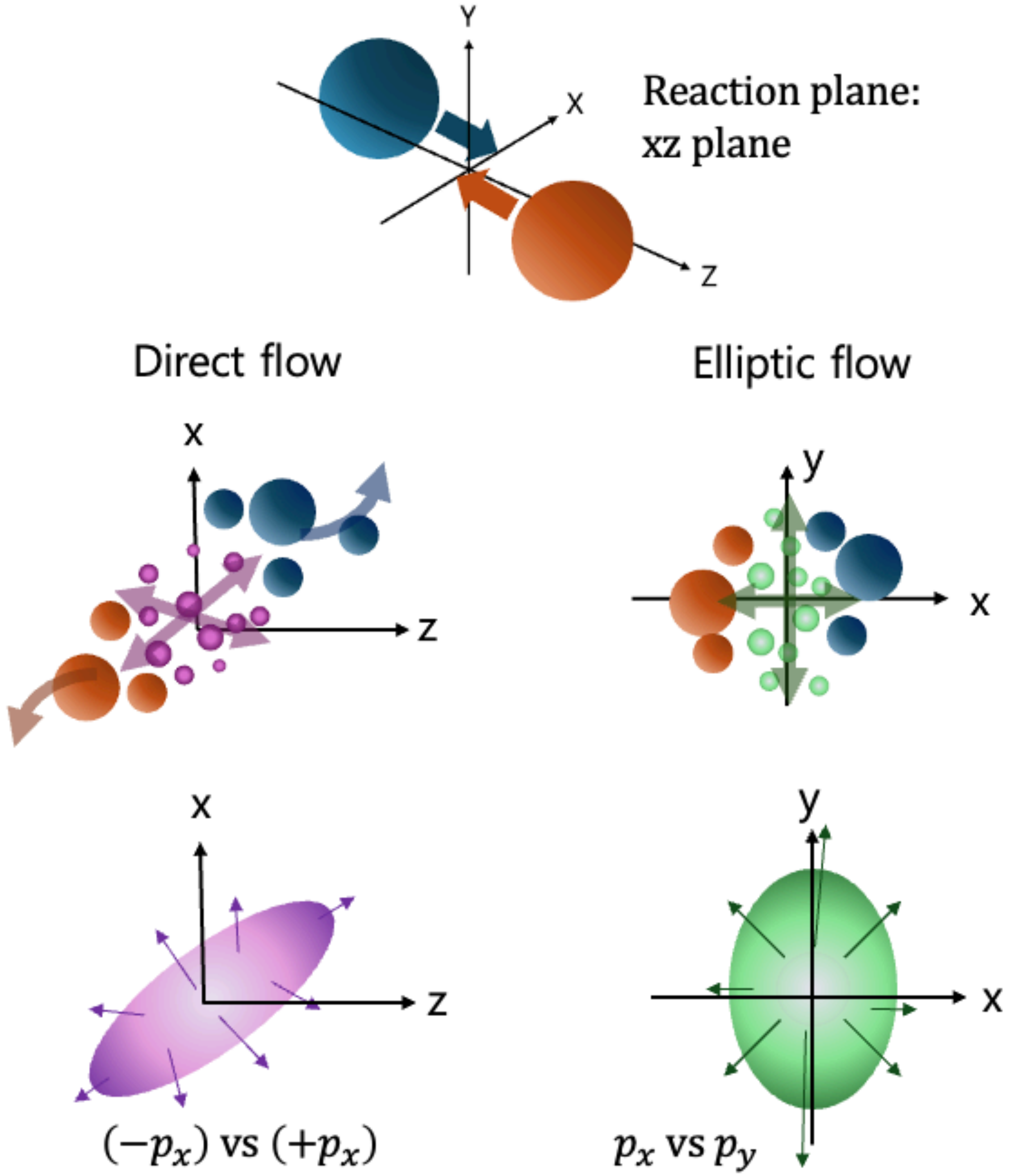
Fourier expansion of azimuthal distribution

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

v_1 : Direct flow , v_2 : Elliptic flow

$$v_1 = \langle \cos(\phi - \psi_r) \rangle = \left\langle \frac{p_x}{p_t} \right\rangle$$

$$v_2 = \langle \cos 2(\phi - \psi_r) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_t^2} \right\rangle$$



Data sets

Experiment and ImQMD with 2 parameter sets

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

$^{129,124}\mathrm{Xe} + ^{124,112}\mathrm{Sn}$ @100MeV/u

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

$^{64,58}\mathrm{Ni} + ^{64,58}\mathrm{Ni}$ @52MeV/u

ImQMD with 2 Skyrme parameters

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	

Impact parameter windows

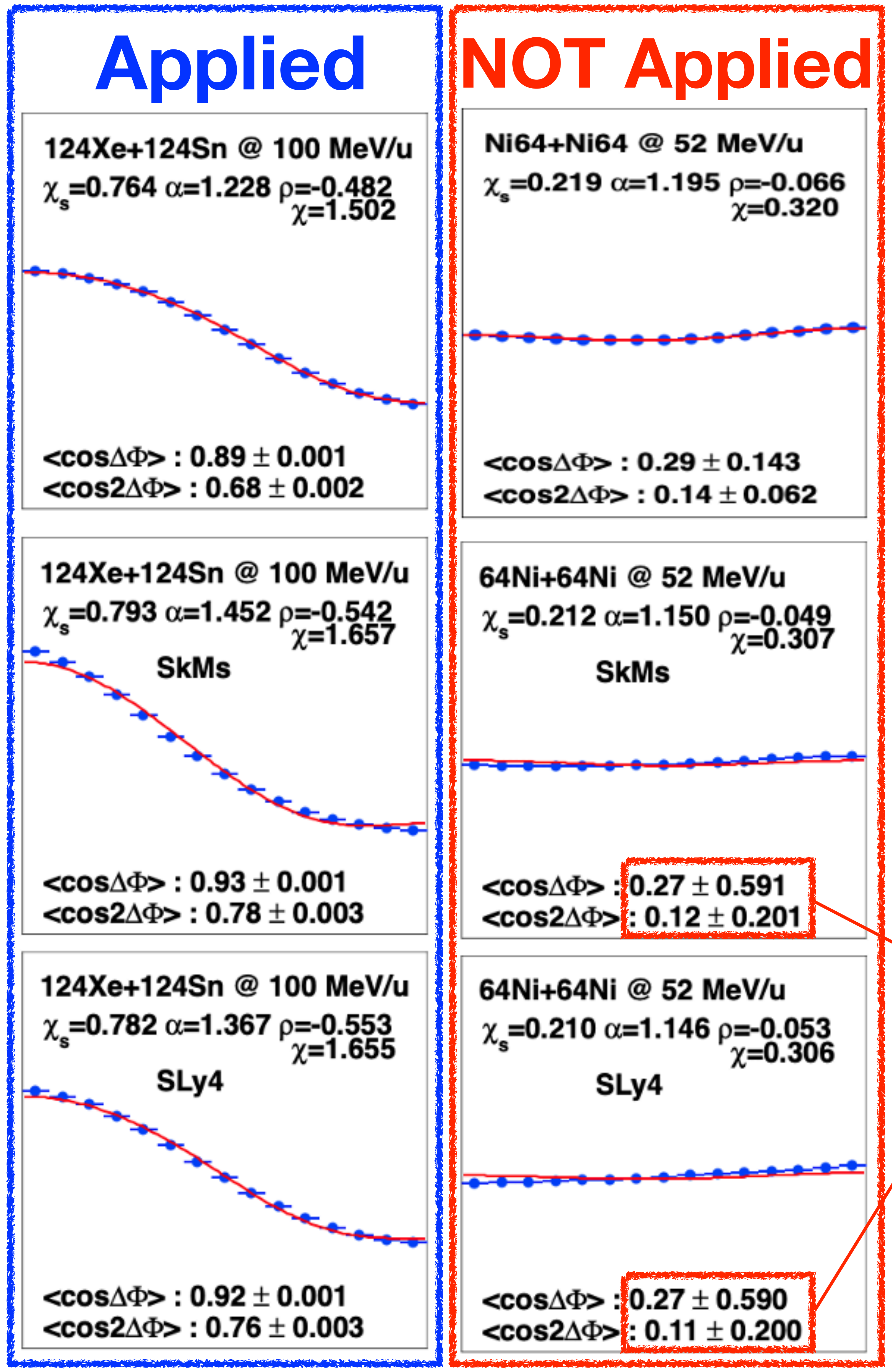
INDRA Camp 4th	IW1 (0.21 < b0 < 0.42)
E789	EW1 (0.03 < b0 < 0.4)

Reaction plane reconstruction and correction factor

Transverse momentum method

$$\mathbf{Q} = \sum_{i \neq poi}^{N} \omega_i (\mathbf{p}_t^i + m_i \mathbf{v}_b)$$

$$\mathbf{v}_b = \frac{\mathbf{p}_t}{m_{sys} - m_{poi}} \qquad \begin{aligned} \omega_i &= Z_i(y_{cm} > 0) \\ &= -Z_i(y_{cm} < 0) \end{aligned}$$

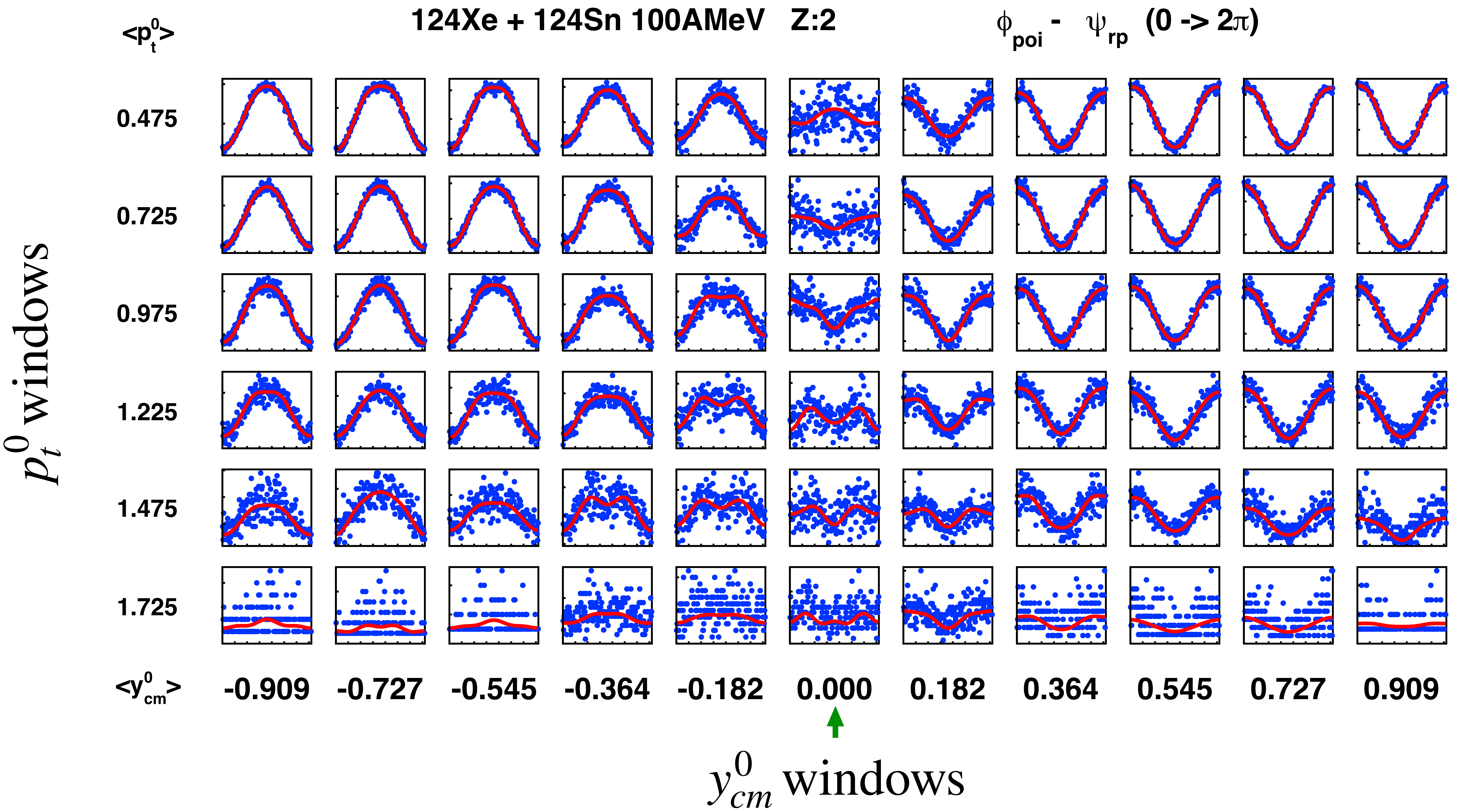


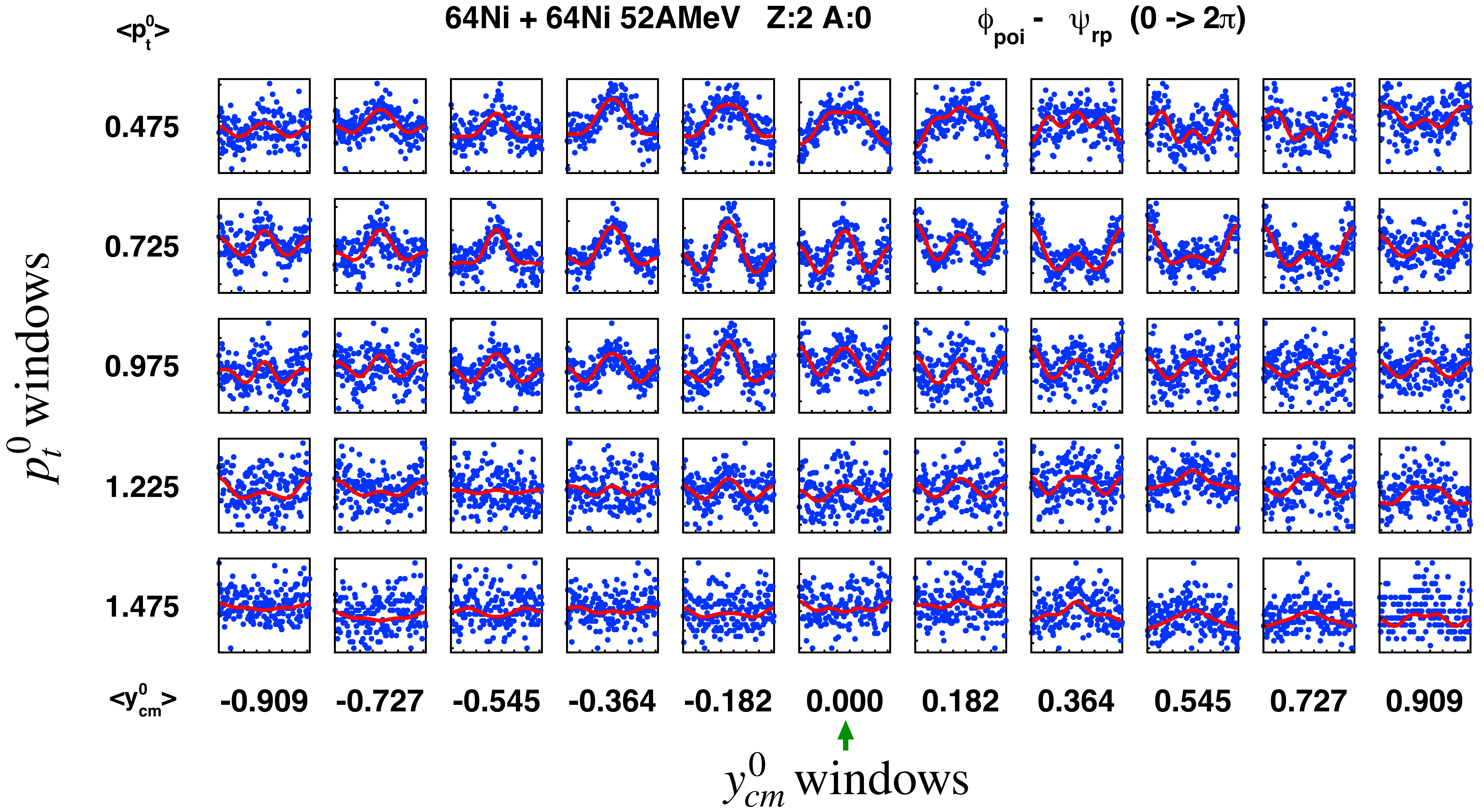
Too large Error!

$0 \rightarrow \pi$ [rad]

$$\text{Fit}: y = \frac{N_0}{2\pi}\left(1 + 2\sum_{n=1}^{4} v_n \cos(\phi_{poi} - \psi_{rp})\right)$$

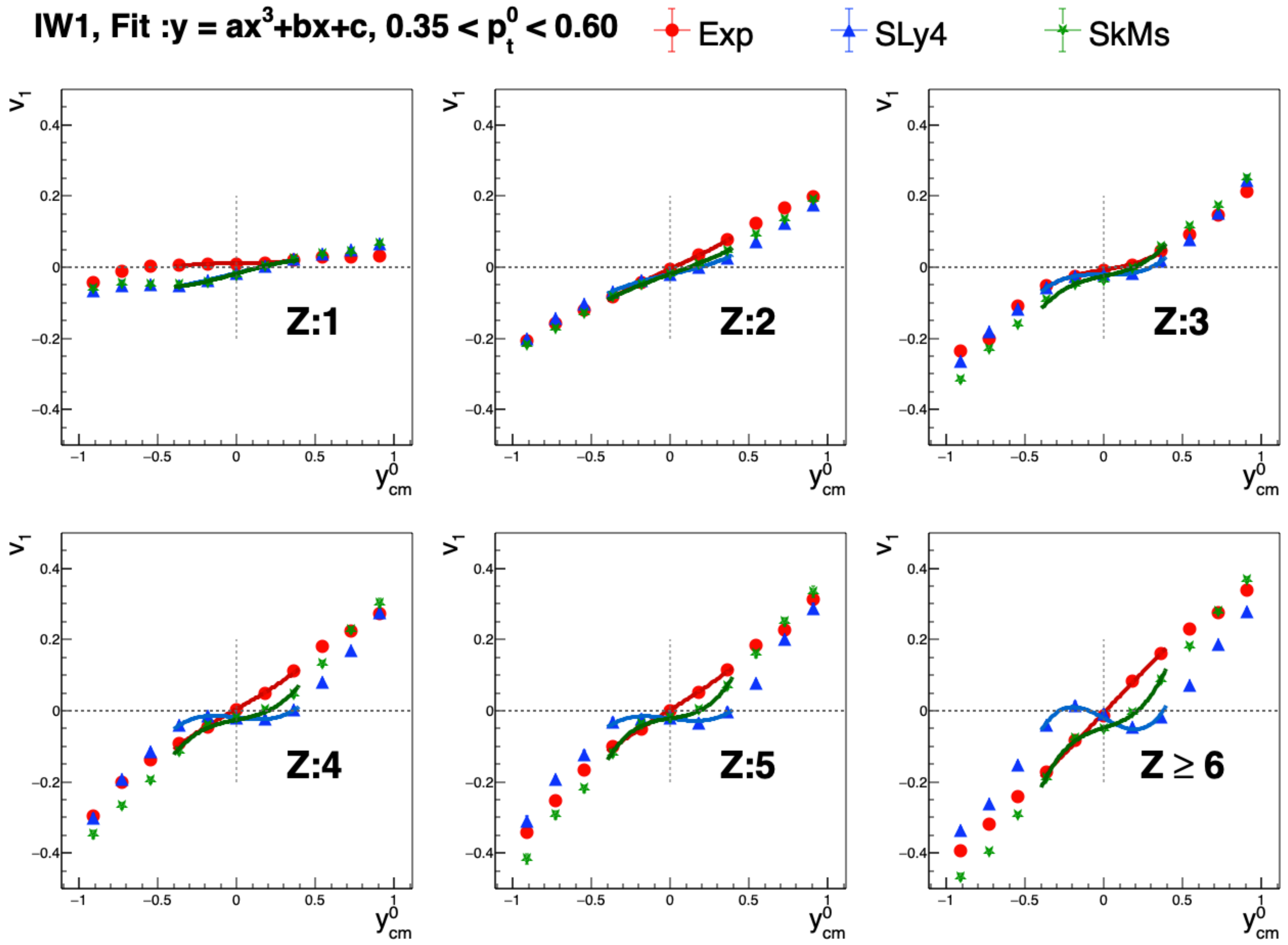
$$v_1 : Direct, v_2 : Elliptic, v_3 : triangular \ldots$$

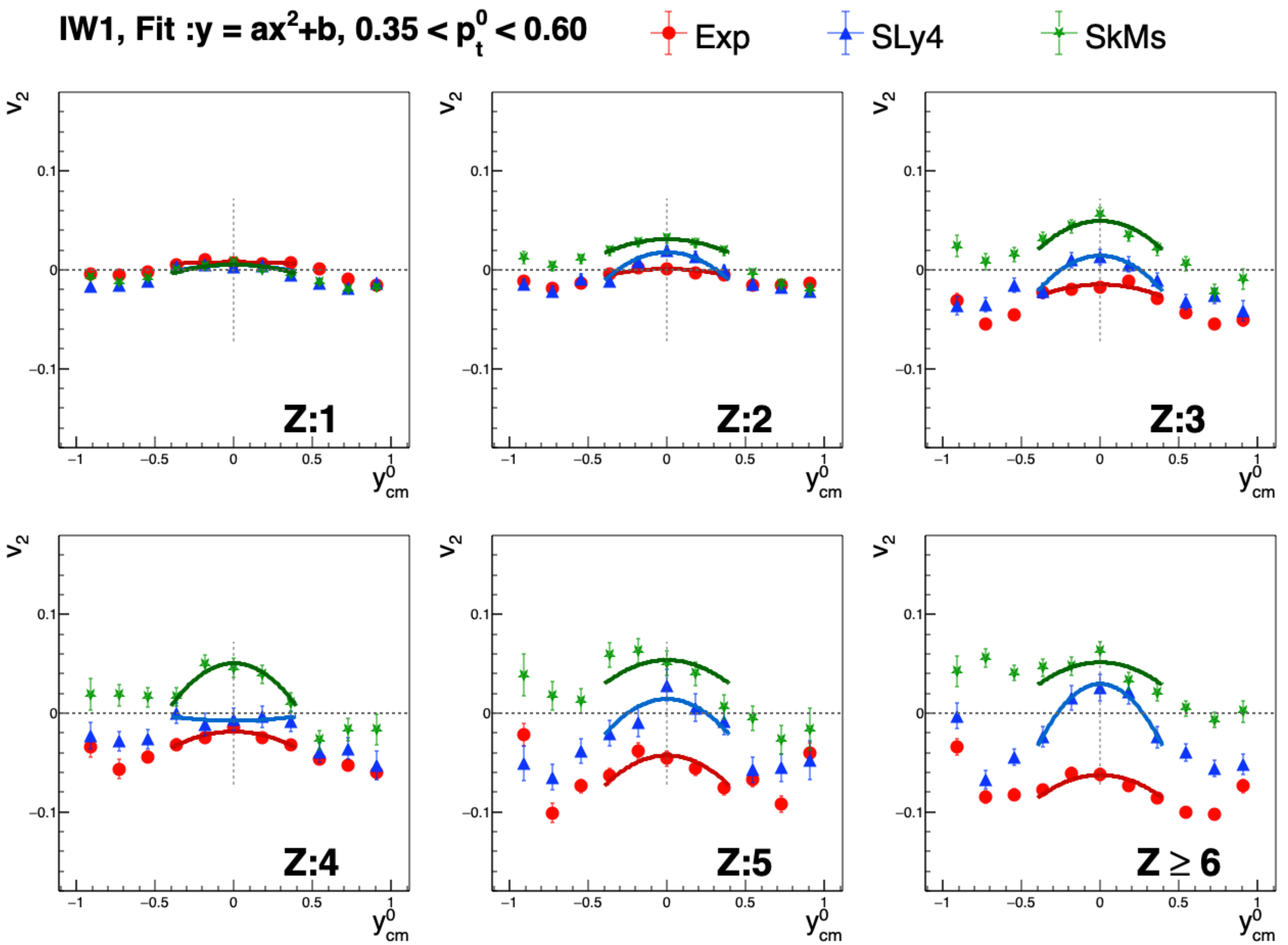



64Ni + 64Ni 52AMeV Z:2 A:0
ϕ_{poi} - ψ_{rp} (0 -> 2π)
$<p_t^0>$
0.475
0.725
0.975
1.225
1.475
p_t^0 windows
$<y_{cm}^0>$
-0.909
-0.727
-0.545
-0.364
-0.182
0.000
0.182
0.364
0.545
0.727
0.909
y_{cm}^0 windows

Direct flow vs y_{cm}^0

Elliptic flow vs y_{cm}^0





Parameter b : Slope of Direct flow

Parameter b : Offset of Elliptic flow

$$y_{cm}^0 = y_{cm}/y_{cm}^P\,(y_{cm} > 0)$$
$$y_{cm}/y_{cm}^T\,(y_{cm} < 0)$$

$$p_t^0 = \frac{p_t/A}{2p_t^P/(A_P + A_T)}$$

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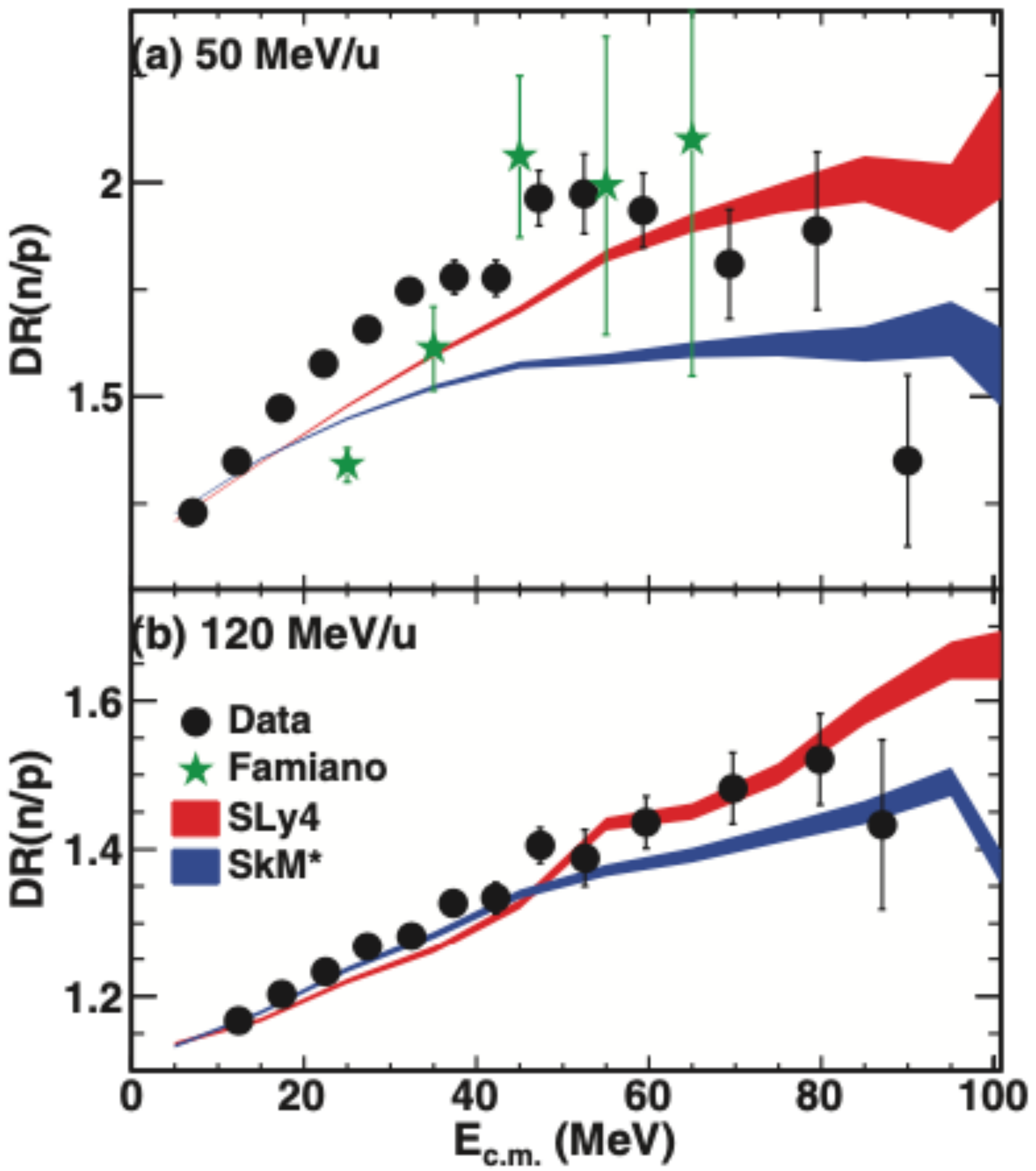

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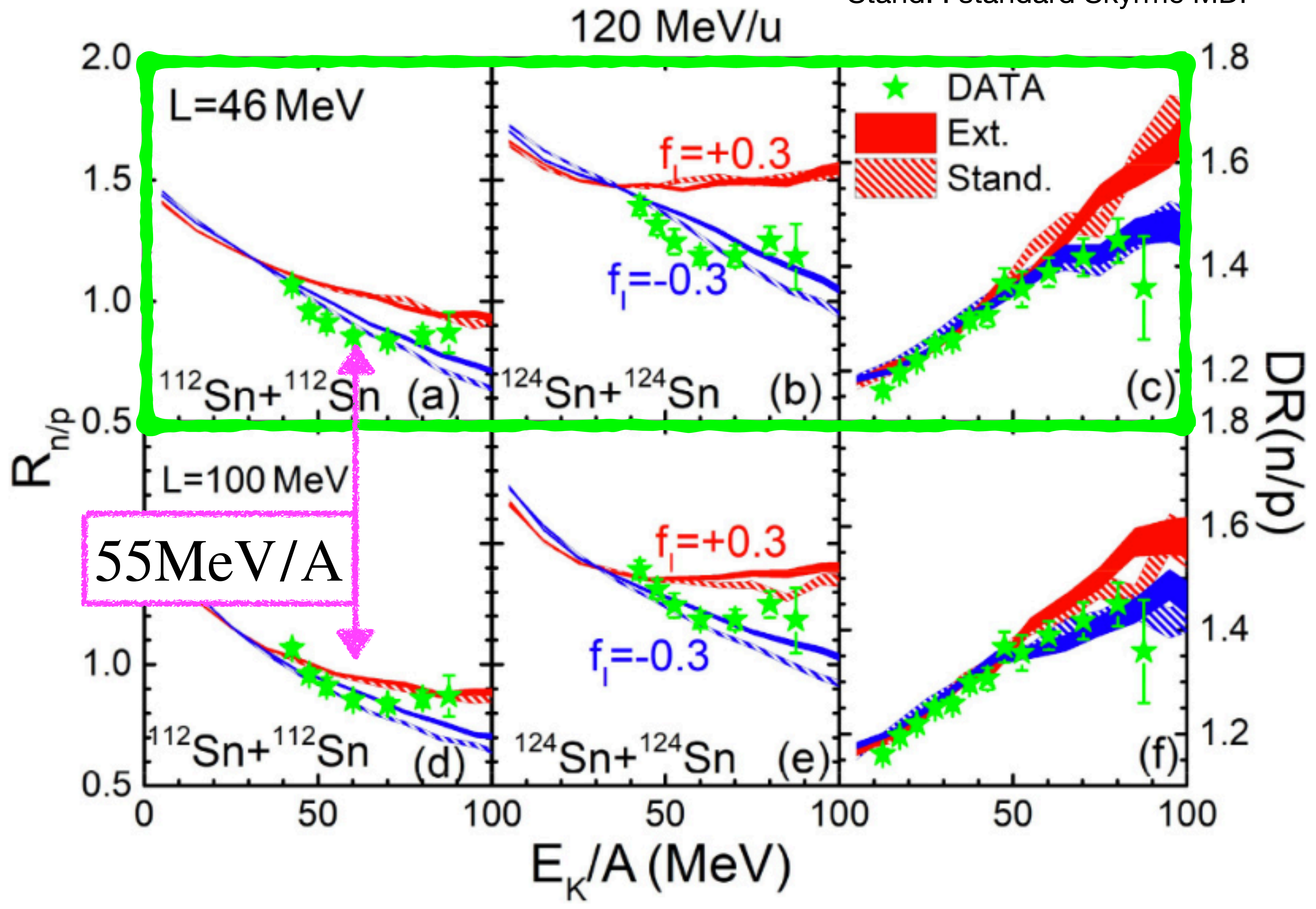
Ext. : extended Skyrme MDI

Stand. : standard Skyrme MDI



	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

$$R_{n/p} = Y_{\mathrm{CI}}(n)/Y_{\mathrm{CI}}(p) \quad \mathrm{DR}(n/p) = \frac{R(n/p,\mathrm{CI},124)}{R(n/p,\mathrm{CI},112)}$$

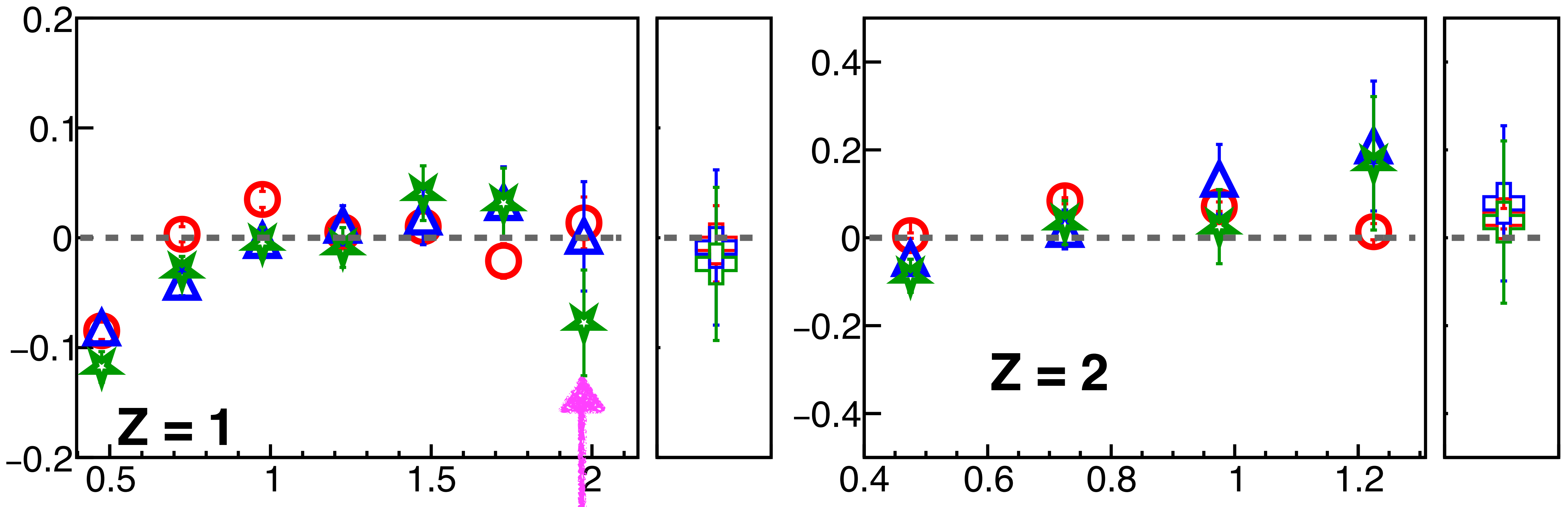
$$f_I = 0.3(m^*_n < m^*_p)$$

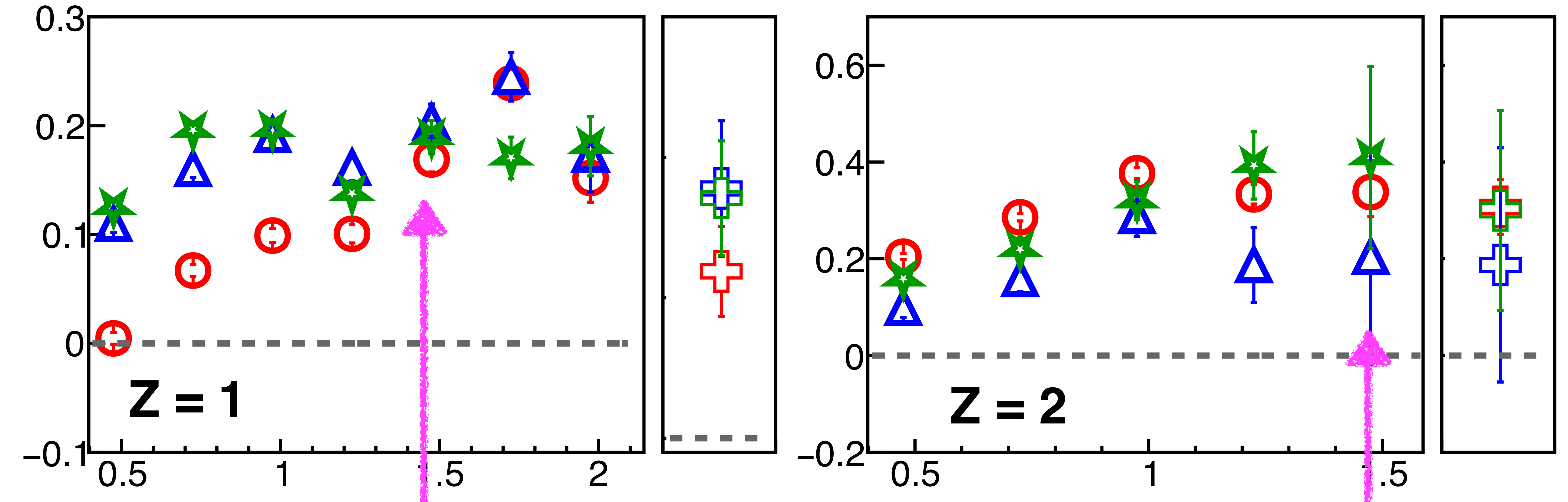
$$f_I = -0.3(m^*_n > m^*_p)$$

CI proton & neutron : $1 < A < 5$

v_1 slope

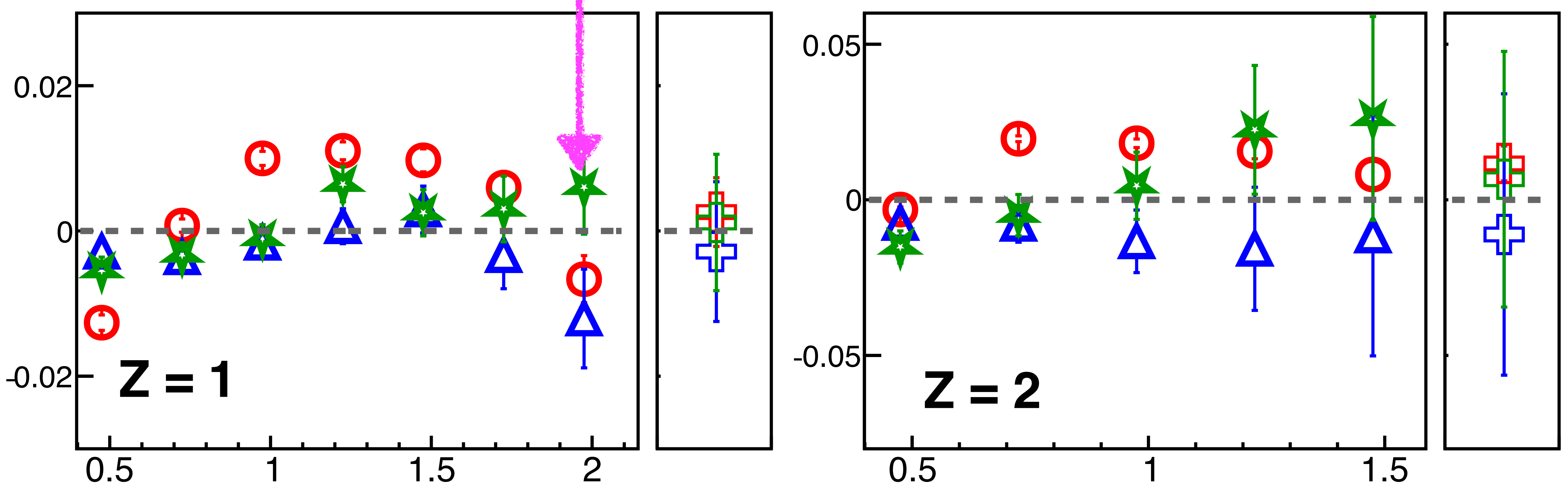
With correction factor

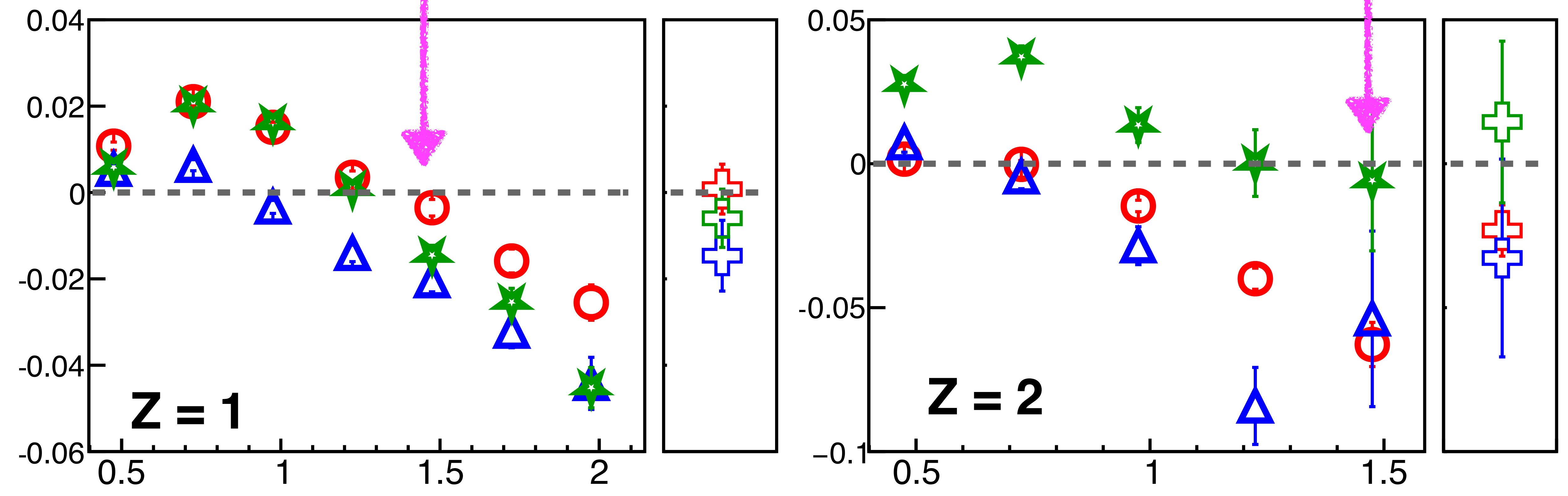




EW1 Ni + Ni @ 52AMeV

IW1 Xe + Sn @ 100AMeV





$55\,\mathrm{MeV/A} = p_t^0 \simeq 2.0$ for Ni + Ni @ 52AMeV

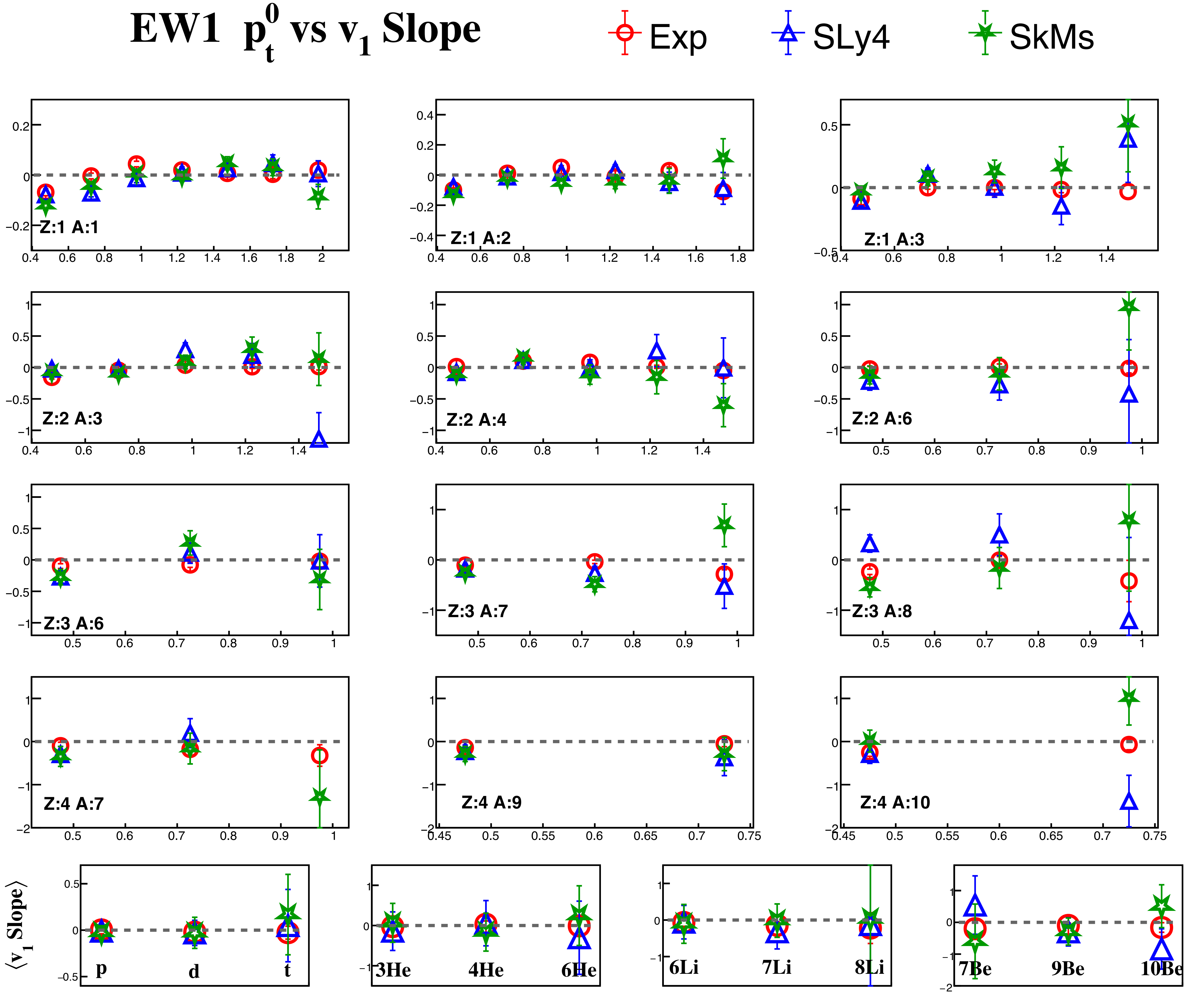
v_2 offset

$55\,\mathrm{MeV/A} = p_t^0 \simeq 1.5$ for Xe + Sn @ 100AMeV

	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

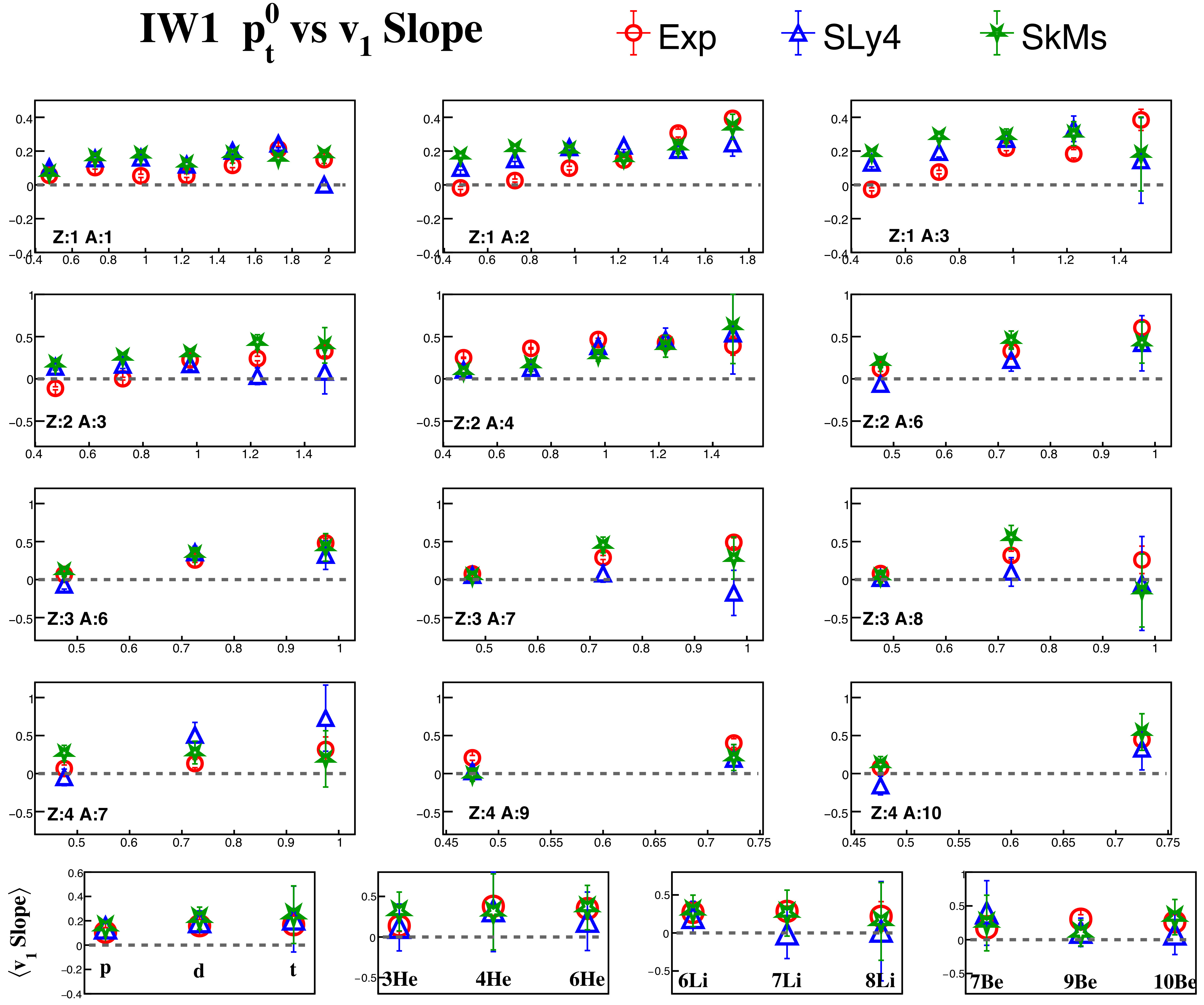
Slope of direct flow

$^{64}\mathrm{Ni} + ^{64}\mathrm{Ni}$ @ 52MeV/u



$^{124}\mathrm{Xe} + ^{124}\mathrm{Sn}$ @ 100MeV/u

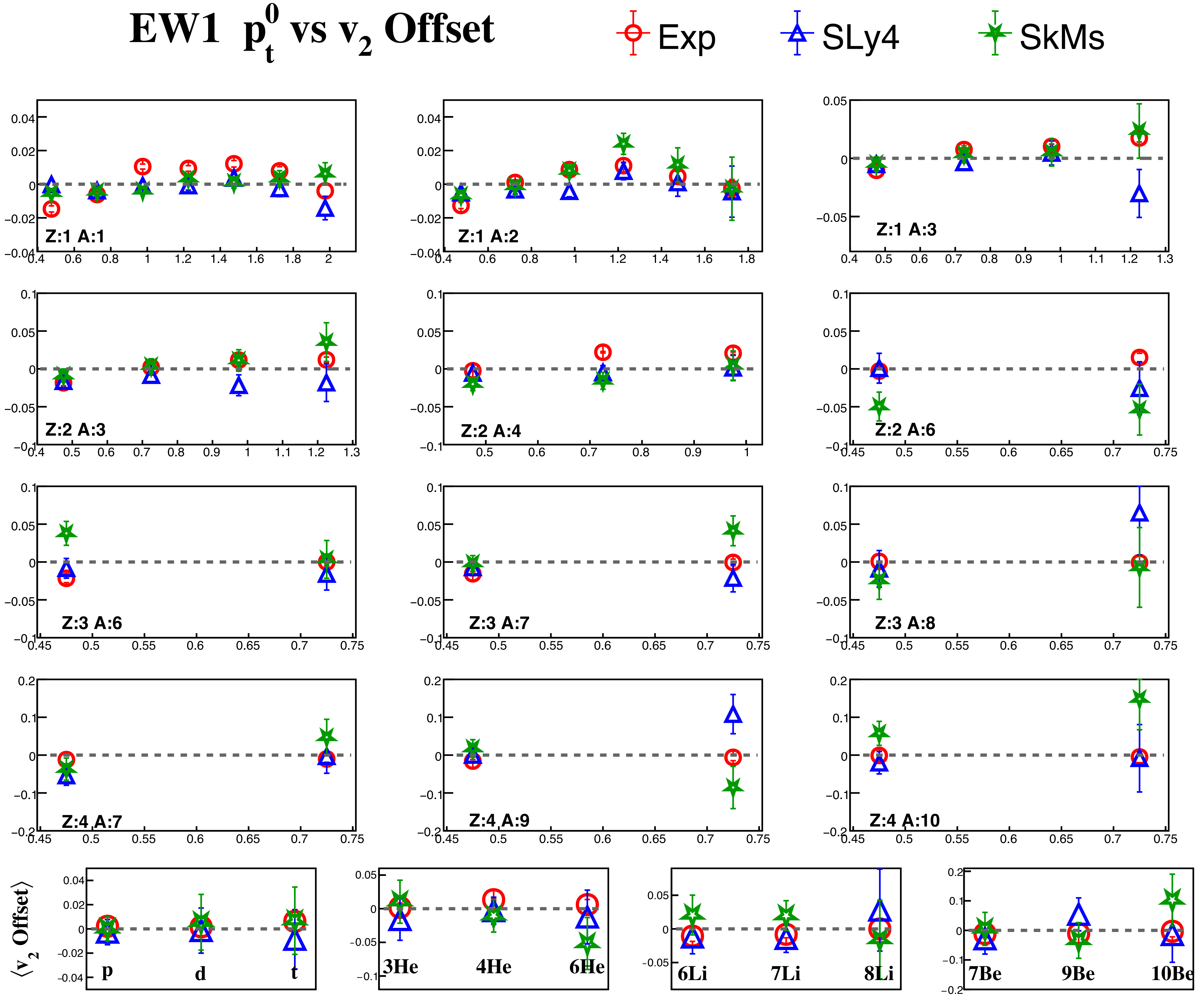
With correction factor



Offset of Elliptic flow

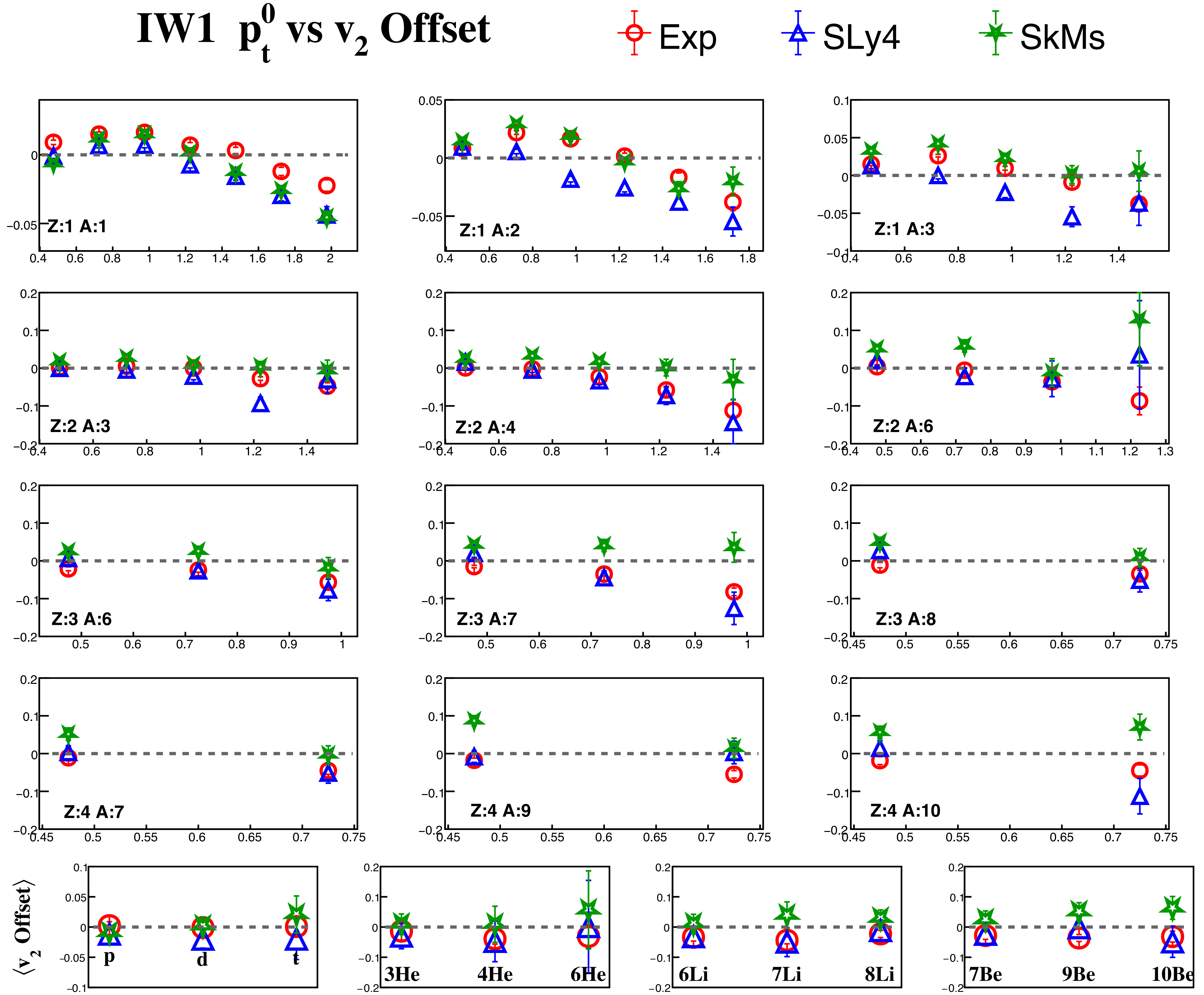
	K_{sym}	m^*/m	m_n^*/m	m_p^*/m
SLy4	-120	0.69	0.68	0.71
SkM*	-156	0.79	0.82	0.76

$^{64}\mathrm{Ni} + ^{64}\mathrm{Ni}$ @ 52MeV/u



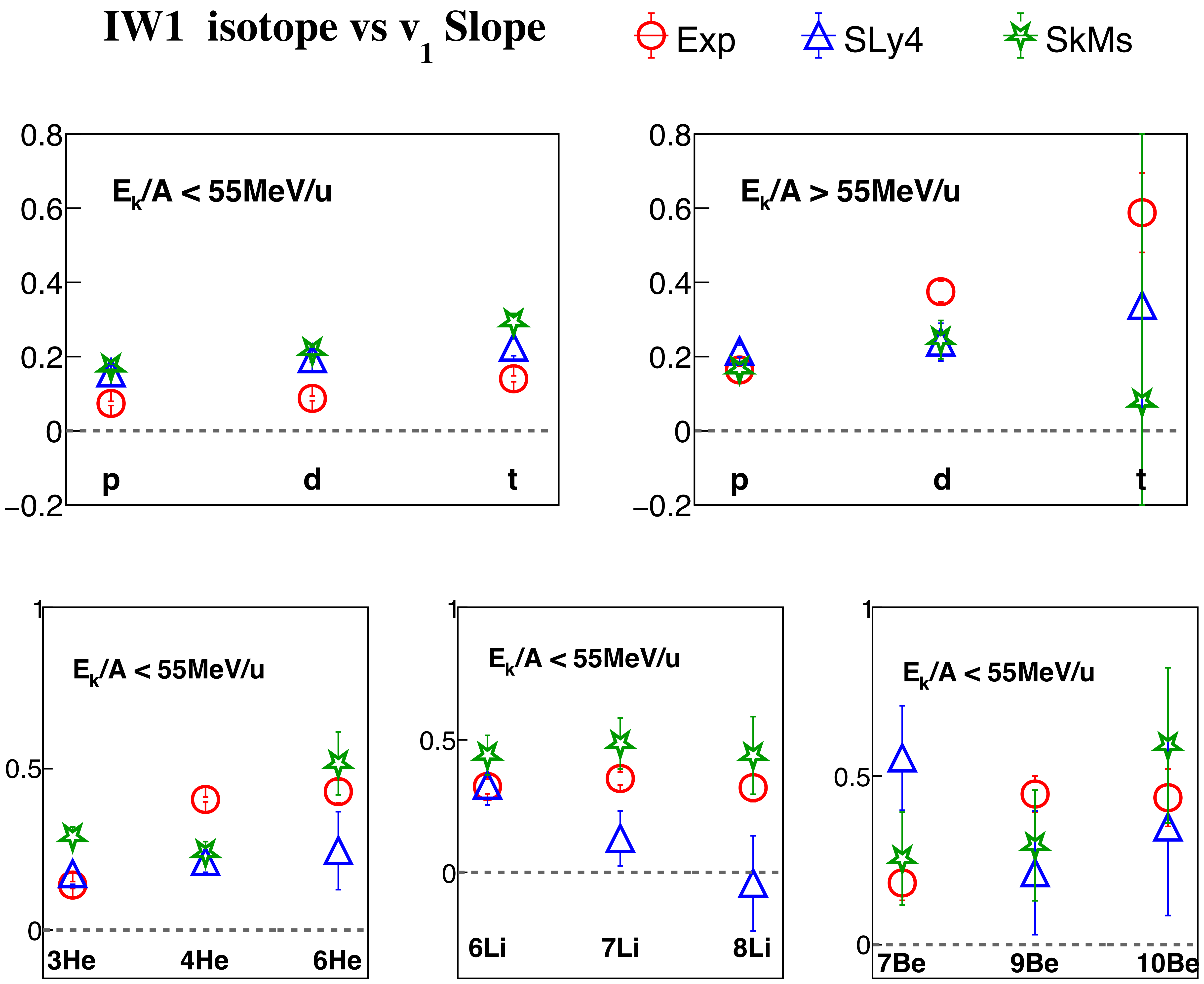
$^{124}\mathrm{Xe} + ^{124}\mathrm{Sn}$ @ 100MeV/u

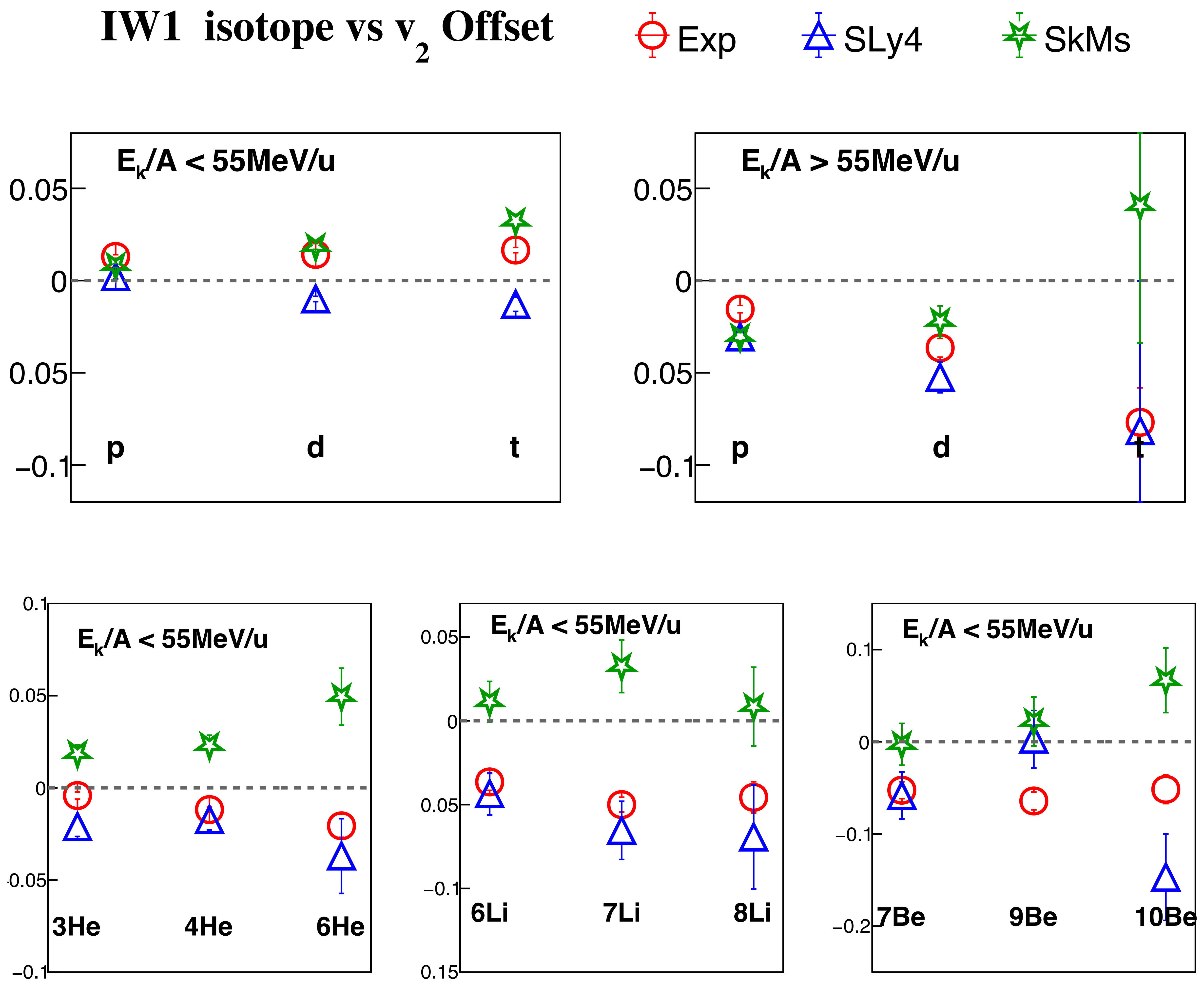
With correction factor



$^{124}Xe + ^{124}Sn @ 100 MeV/u$

With correction factor





Summary

1. Compare Experimental and ImQMD with 2 Skyrme parameters data using v_1 slope and v_2 offset.

2. v_1 and v_2 results of two model calculation using Ni+Ni @ 52 AMeV are not show clear difference and also models can not predict experimental results.

3. v_1 of Xe+Sn @ 100 AMeV from two parameter sets are not show specific difference relate to N/Z of fragment and also non of model predict experimental result especially at low p_t^0 regions.

4. v_2 from 2 parameters of Xe+Sn @ 100AMeV are represent clearly differences and this are affected by N/Z ratio of fragments.

Conclusion

1. Direct flow seems not sensitive to iso-vector effective mass difference.

2. Elliptic flow is more sensitive to iso-vector effective mass splitting of proton and neutron but direct flow is not in this energy region.

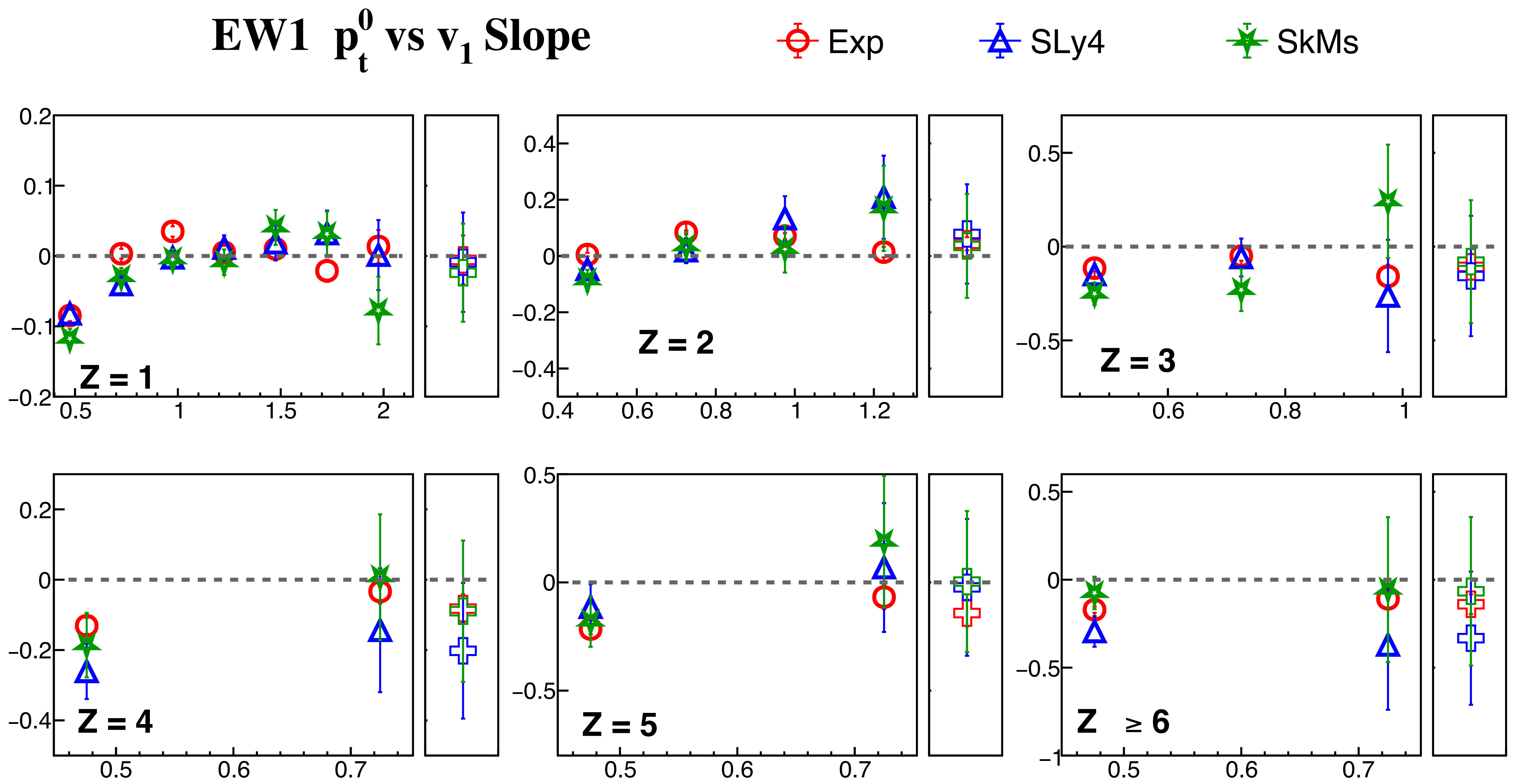
3. Effective mass of proton much heavier than value of SkM* at over $\mathrm{E_k} \sim 55\mathrm{MeV/u}$ but little heavier below $\mathrm{E_k} \sim 55\mathrm{MeV/u}$.

4. Effective mass of neutron is lighter than SkM* and heavier than SLy4 at below $\mathrm{E_k} \sim 55\mathrm{MeV/u}$.

Back up

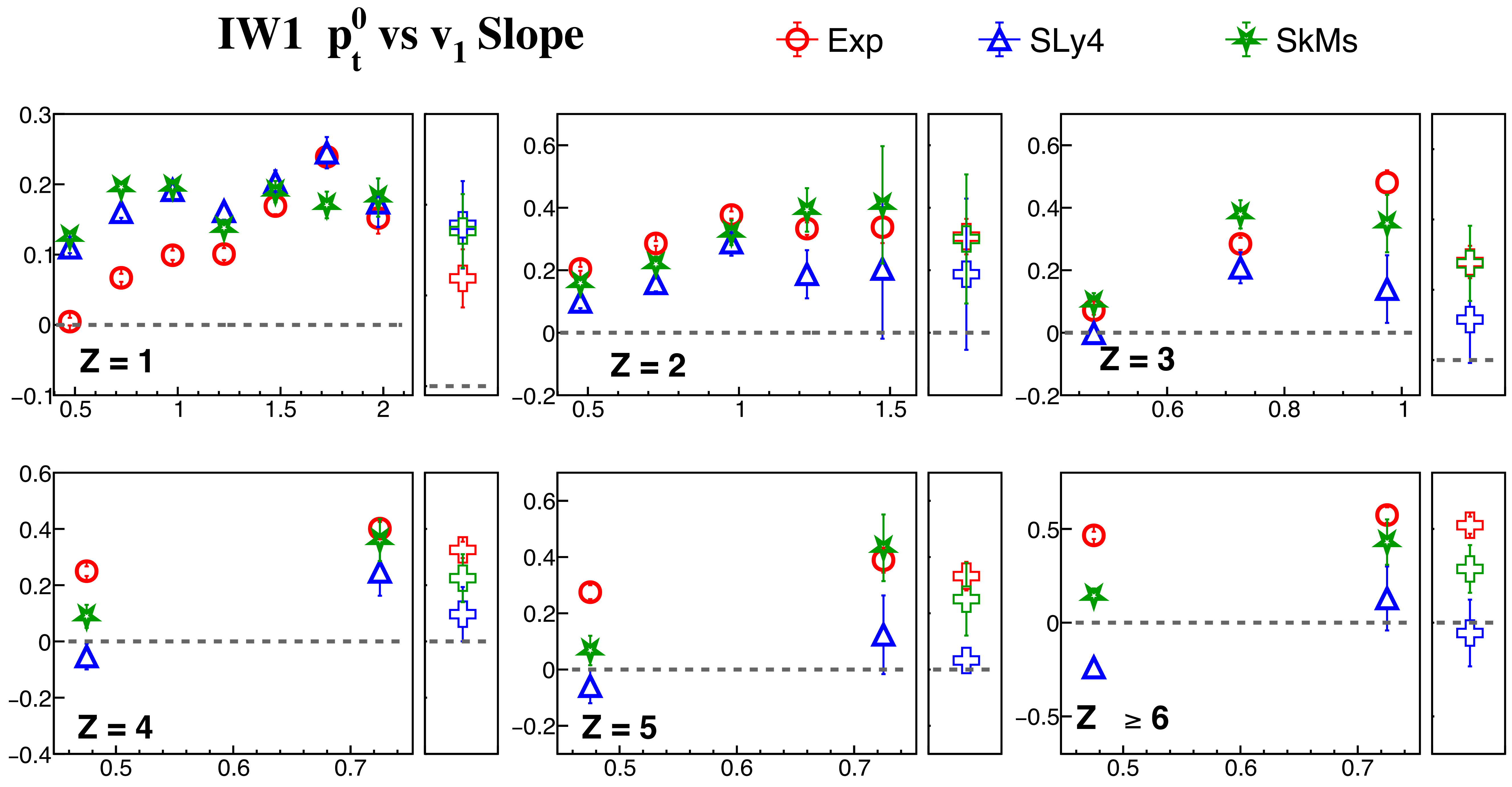
Slope of Direct flow

$^{64}\mathrm{Ni} + ^{64}\mathrm{Ni}\,@\,52\mathrm{MeV/u}$



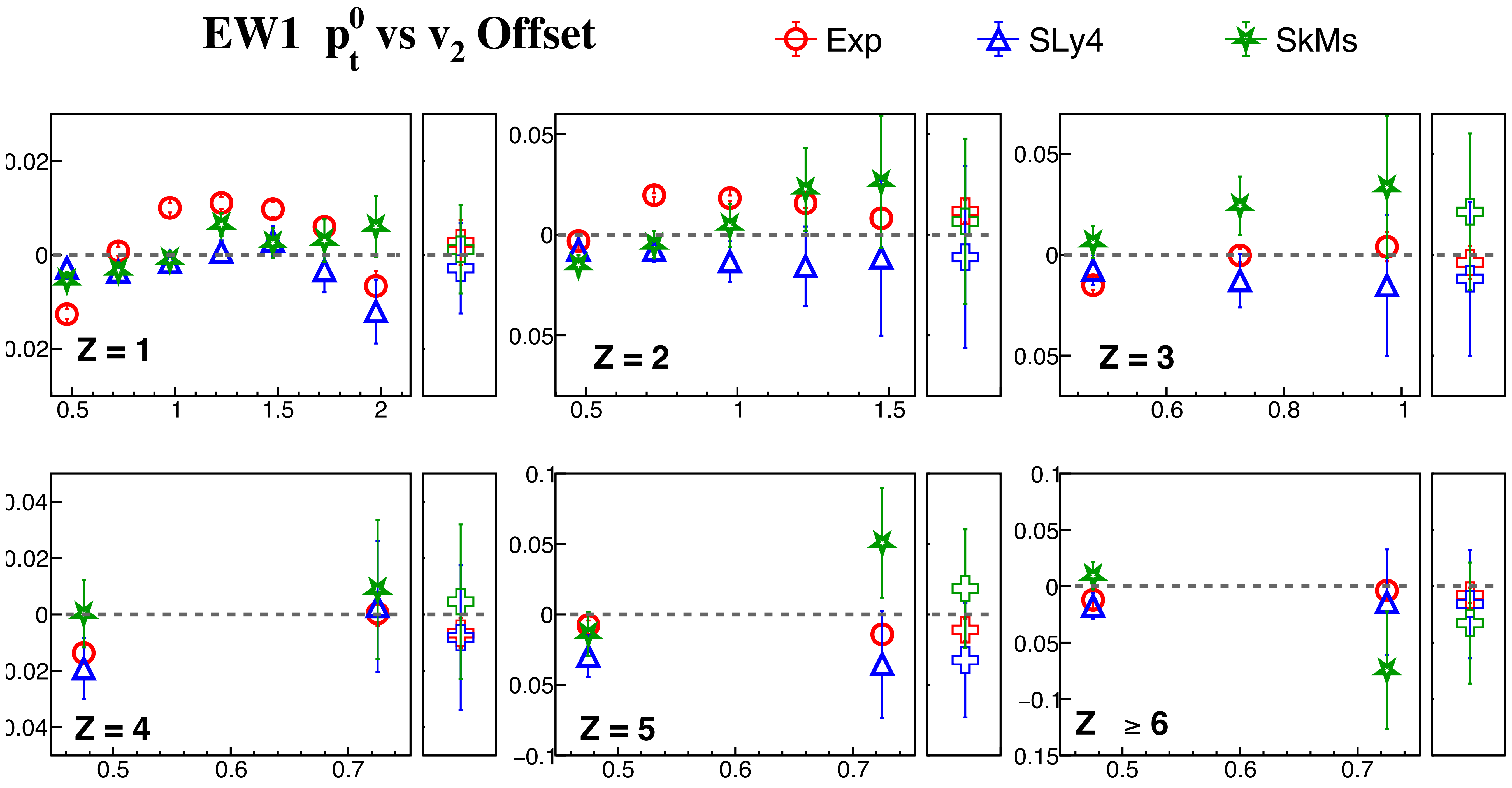
$^{124}\mathrm{Xe} + ^{124}\mathrm{Sn}\,@\,100\mathrm{MeV/u}$

With correction factor



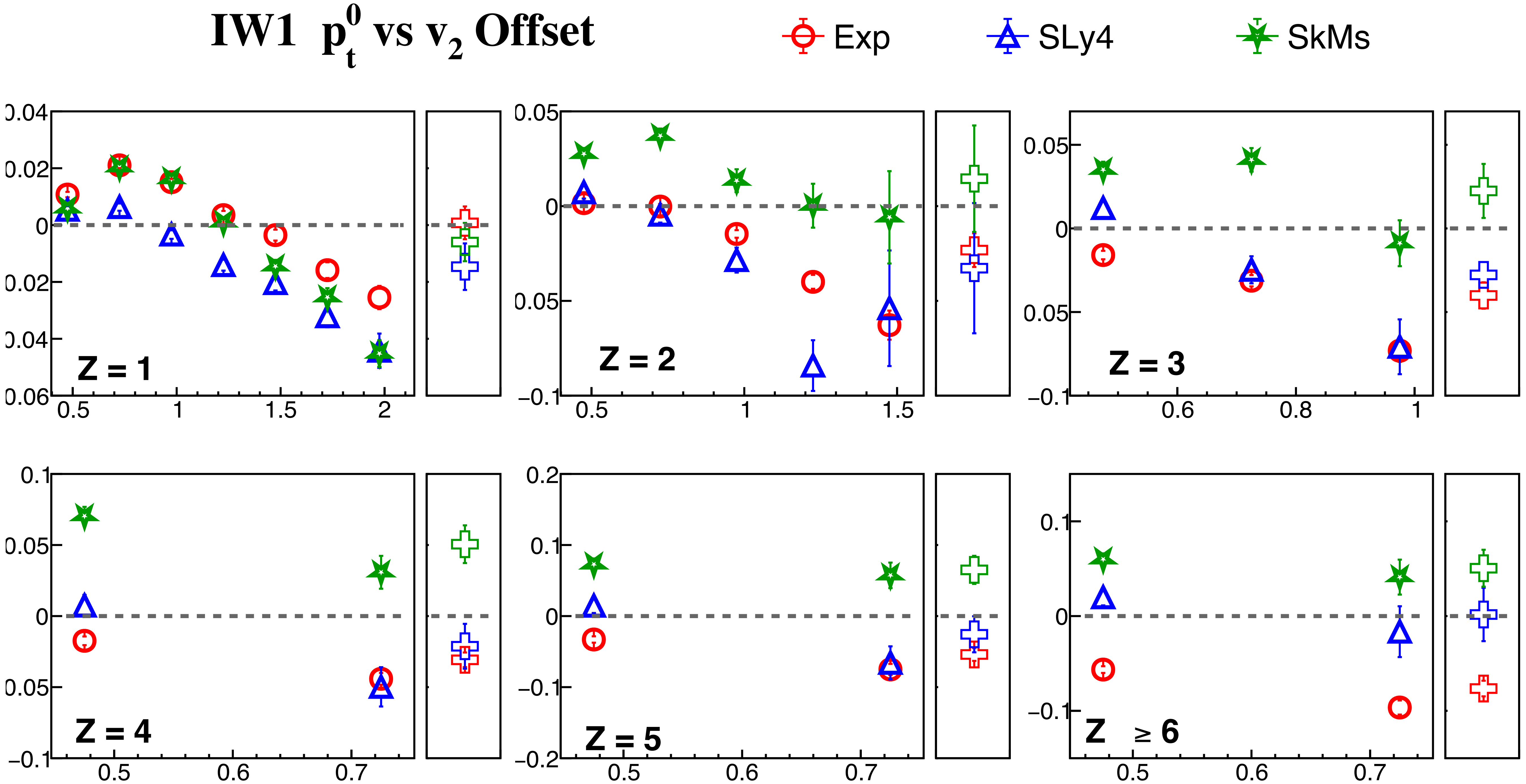
Offset of Elliptic flow

$^{64}Ni + ^{64}Ni @ 52 MeV/u$

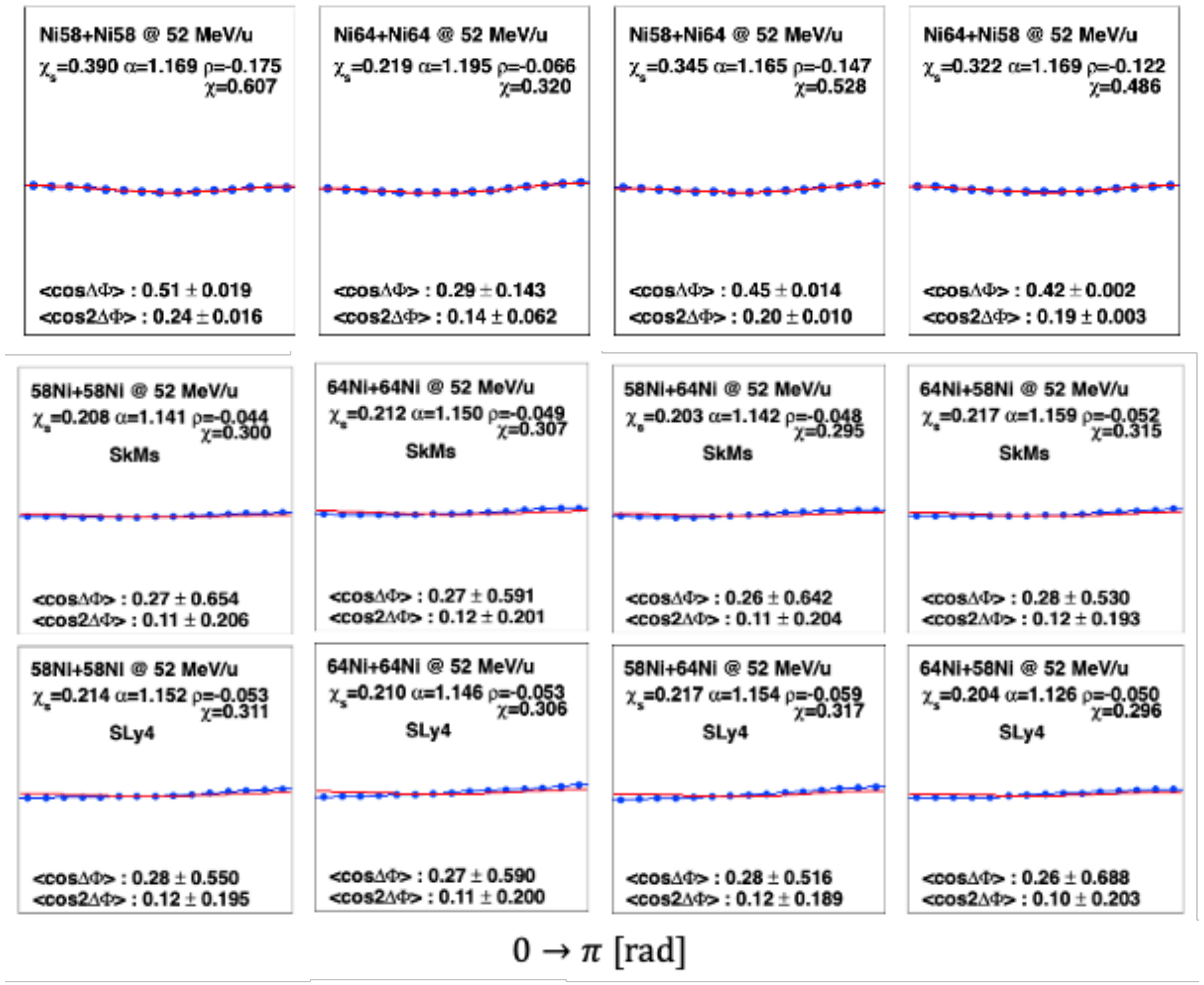


$^{124}Xe + ^{124}Sn @ 100 MeV/u$

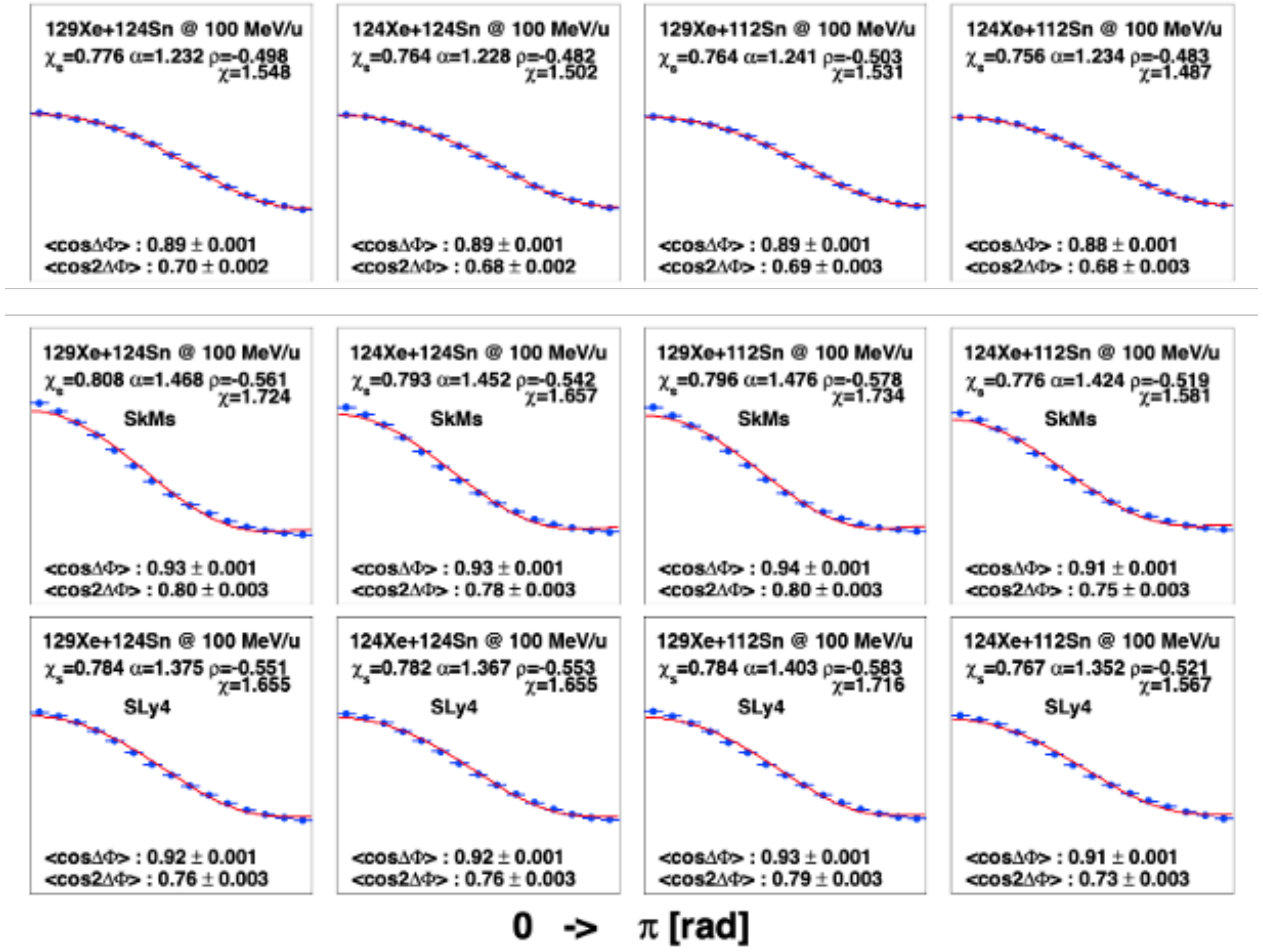
With correction factor



$^{64,58}\mathrm{Ni} + ^{64,58}\mathrm{Ni}$ @ 52MeV/u



$^{129,124}\mathrm{Xe} + ^{124,112}\mathrm{Sn}$ @ 100MeV/u

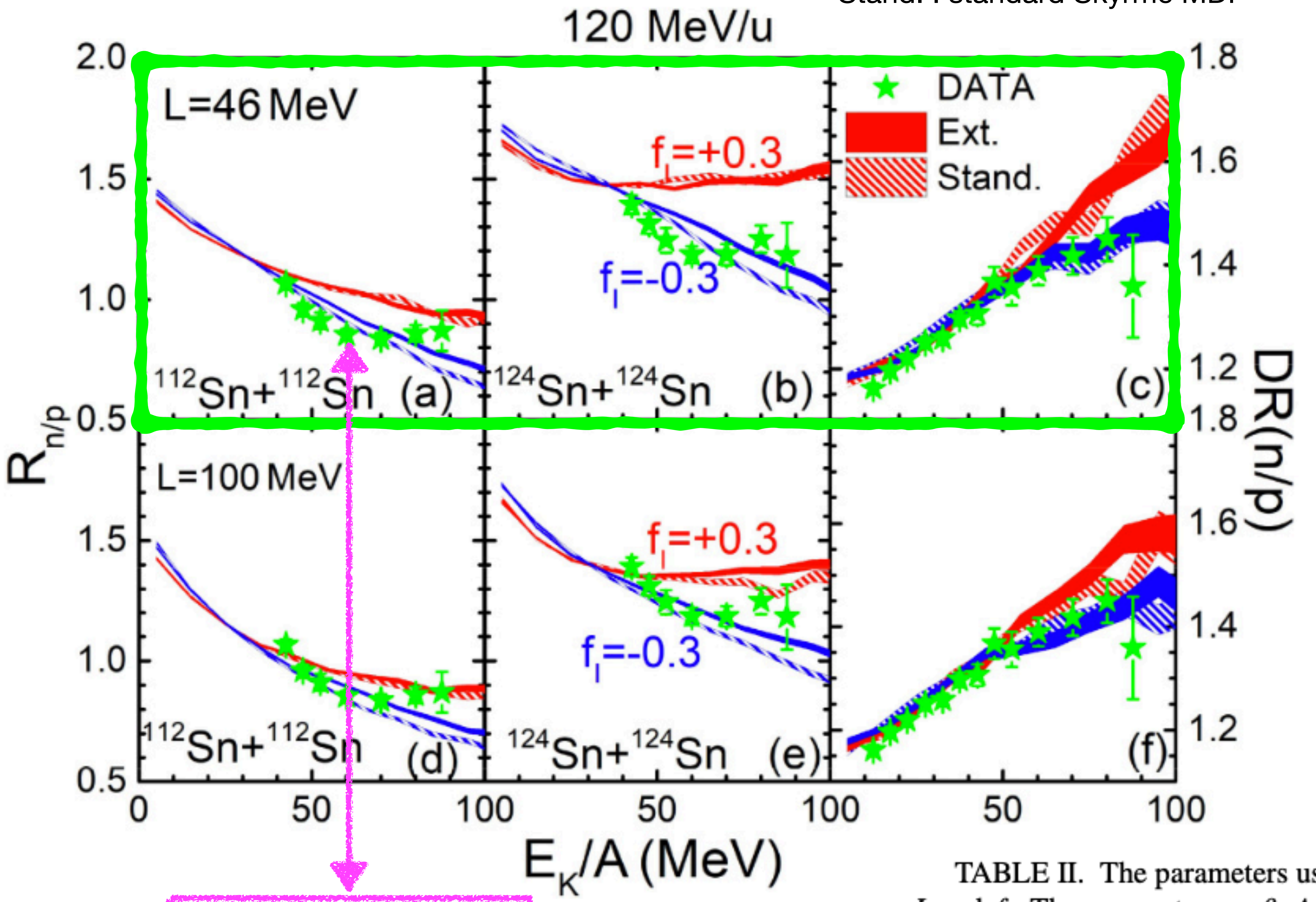


PHYSICAL REVIEW C **109**, 054624 (2024)

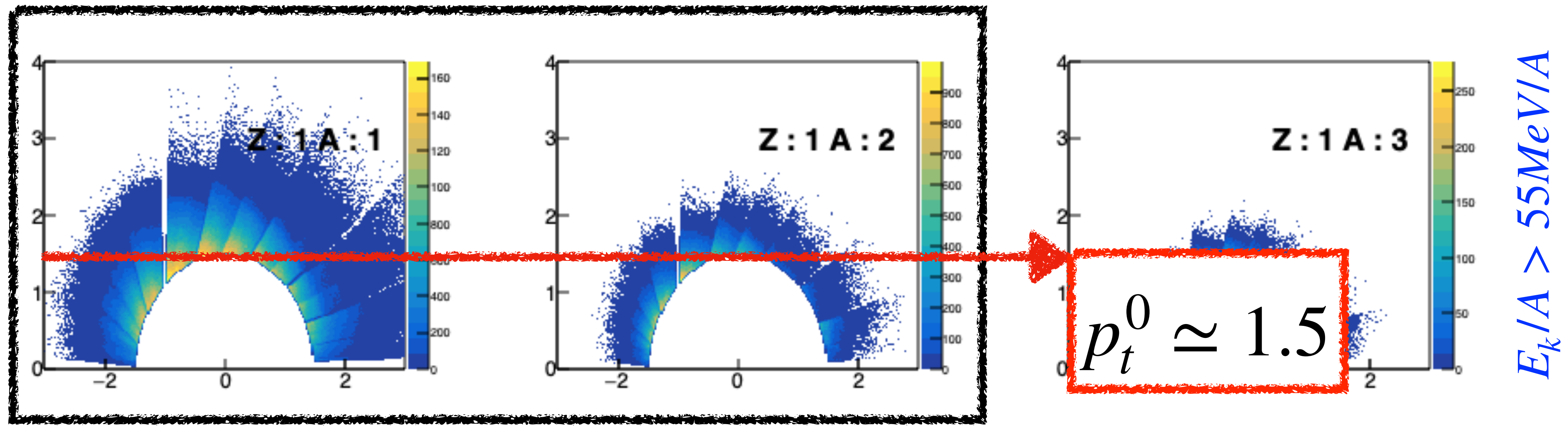
Ext. : extended Skyrme MDI

Stand. : standard Skyrme MDI

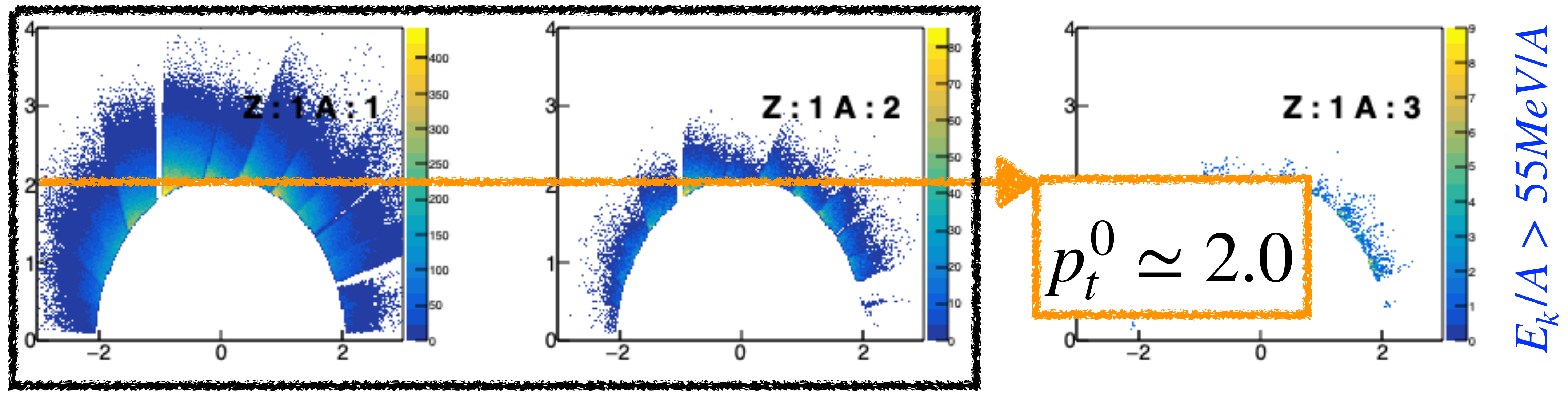
$55\,\mathrm{MeV/A} \;=\; p_t^0 \simeq 1.5 \quad \text{for Xe + Sn @ 100AMeV}$



p_T^0 vs y_{cm}^0



$55\,\mathrm{MeV/A} \;=\; p_t^0 \simeq 2.0 \quad \text{for Ni + Ni @ 52AMeV}$



55MeV/A

$$f_I = 0.3({m^*}_n < {m^*}_p)$$

$$f_I = -0.3({m^*}_n > {m^*}_p)$$

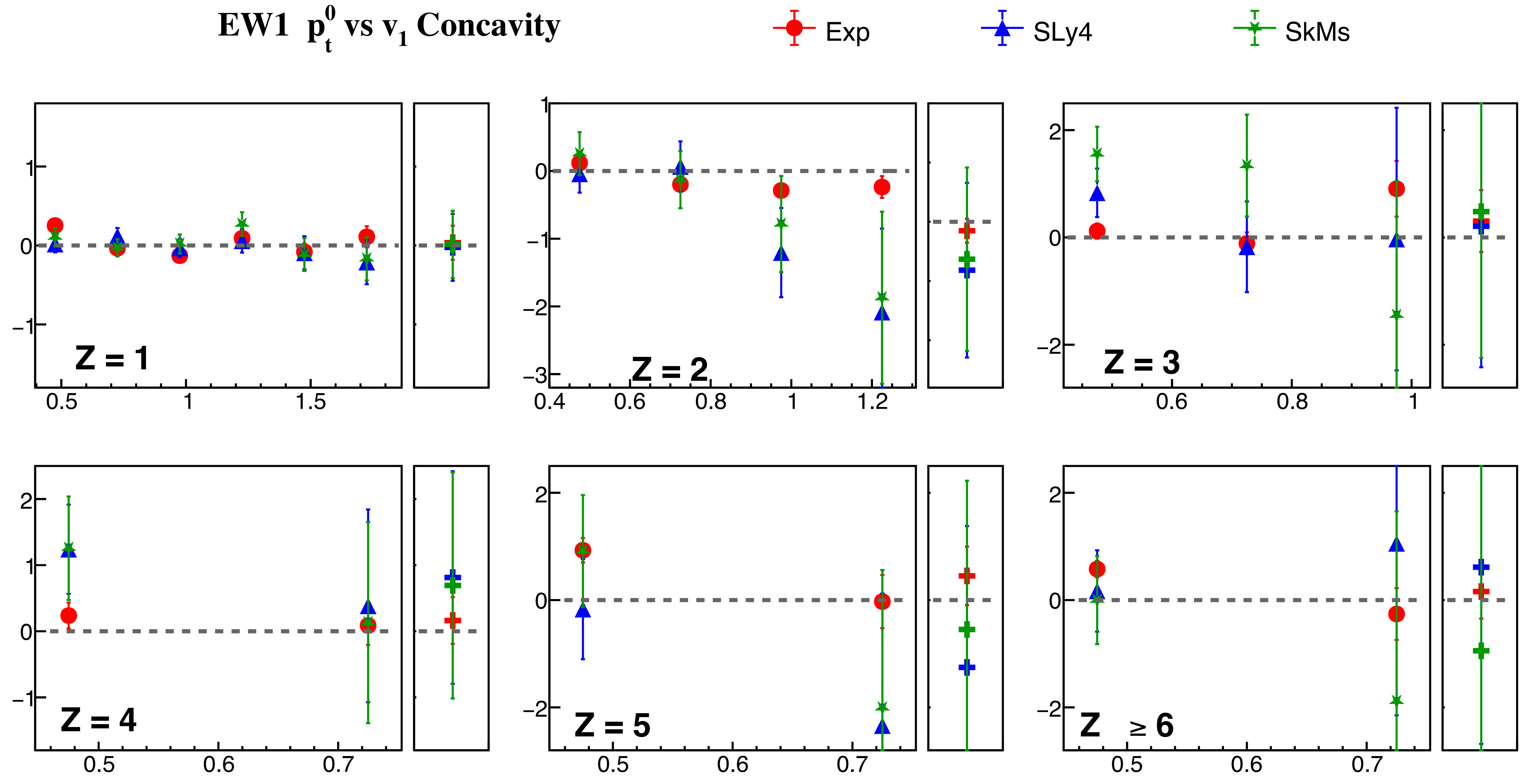
TABLE II. The parameters used in the calculations corresponding to $K_0 = 230$ MeV, $m_s^*/m = 0.77$, $S_0 = 32$ MeV, and different values of L and f_I. The parameters α, β, $A_{\rm sym}$, $B_{\rm sym}$ are in MeV. $\tilde{C}_0$ and $\tilde{D}_0$ are fm^3/GeV.

Para.	($L = 46$, $f_I = 0.3$)	($L = 46$, $f_I = -0.3$)	($L = 100$, $f_I = 0.3$)	($L = 100$, $f_I = -0.3$)
α		−236.58 (−265.78)		
β		163.95 (194.93)		
γ		1.26 (1.22)		
$A_{\rm sym}$	83.65 (108.44)	58.57 (62.73)	14.41 (25.32)	−10.67 (−20.40)
$B_{\rm sym}$	−79.48 (−103.69)	−30.52 (−35.38)	−10.25 (−20.34)	38.72 (47.96)
$\tilde{C}_0$	-7.92×10^{-4} (-2.08×10^{-3})	0.37 (1.00)	-7.92×10^{-4} (-2.08×10^{-3})	0.37 (1.00)
$\tilde{D}_0$	0.37 (1.00)	−0.37 (−1.00)	0.37 (1.00)	−0.37 (−1.00)

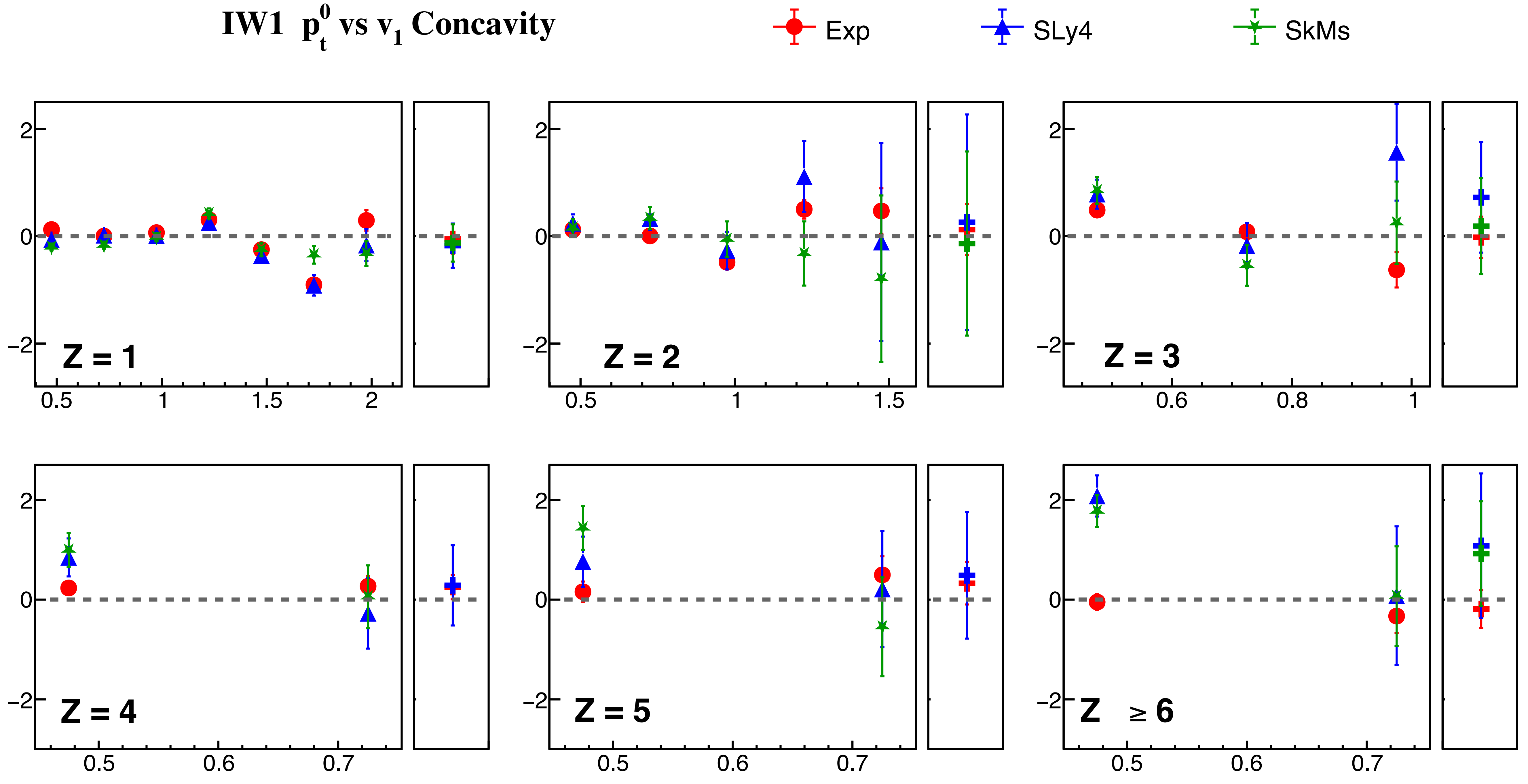
^{129}Xe + ^{124}Sn @ 100MeV/u
^{124}Xe + ^{112}Sn @ 100MeV/u
Slope of direct flow
IW1 p_t^0 vs v_1 Slope
Exp
SLy4
SkMs
Z = 1
Z = 2
Z = 3
Z = 4
Z = 5
Z ≥ 6
Offset of Elliptic flow
IW1 p_t^0 vs v_2 Offset

Concavity of Direct flow

$^{64}\mathrm{Ni} + ^{64}\mathrm{Ni} @ 52\mathrm{MeV/u}$

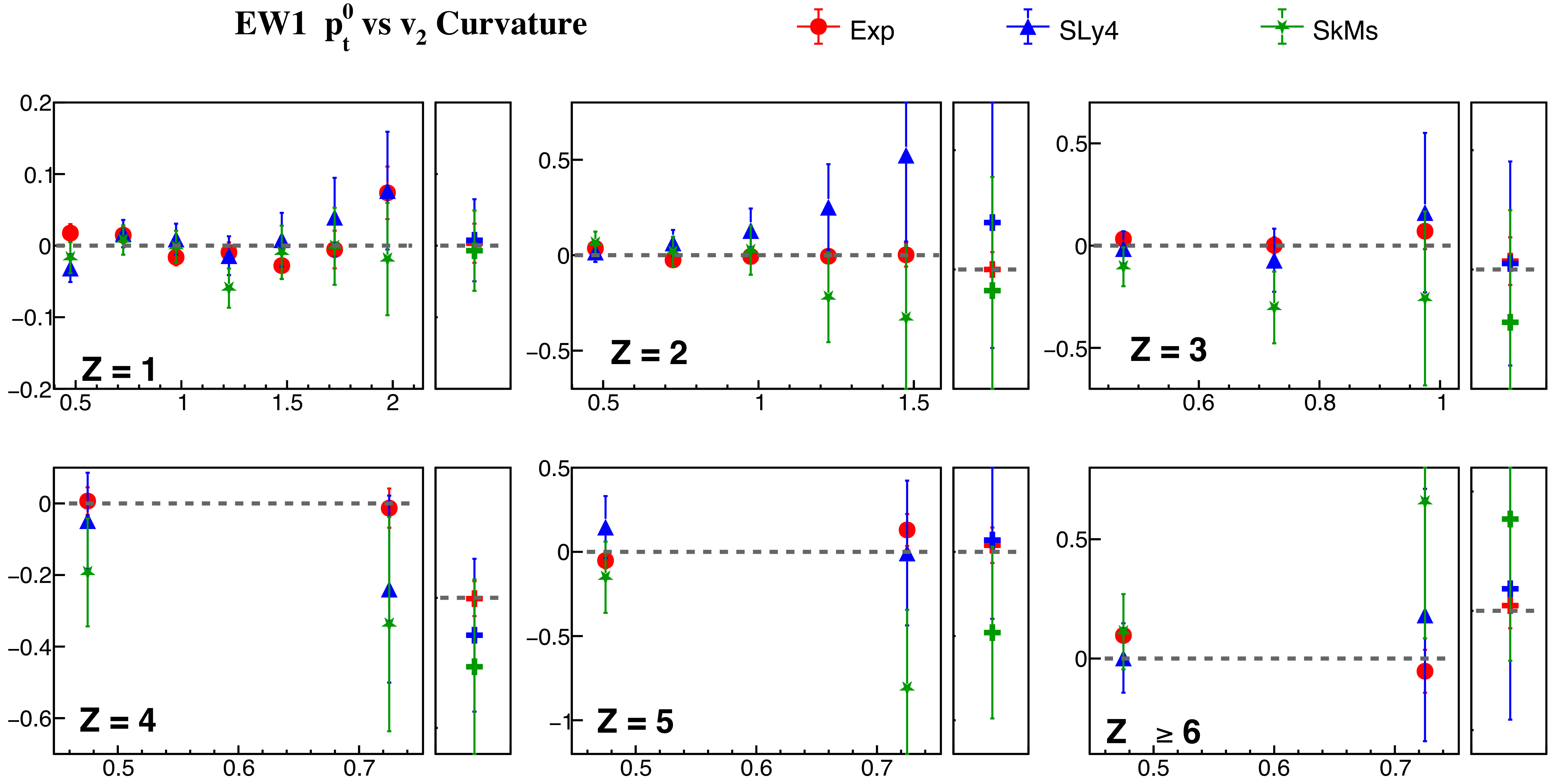


$^{124}\mathrm{Xe} + ^{124}\mathrm{Sn} @ 100\mathrm{MeV/u}$

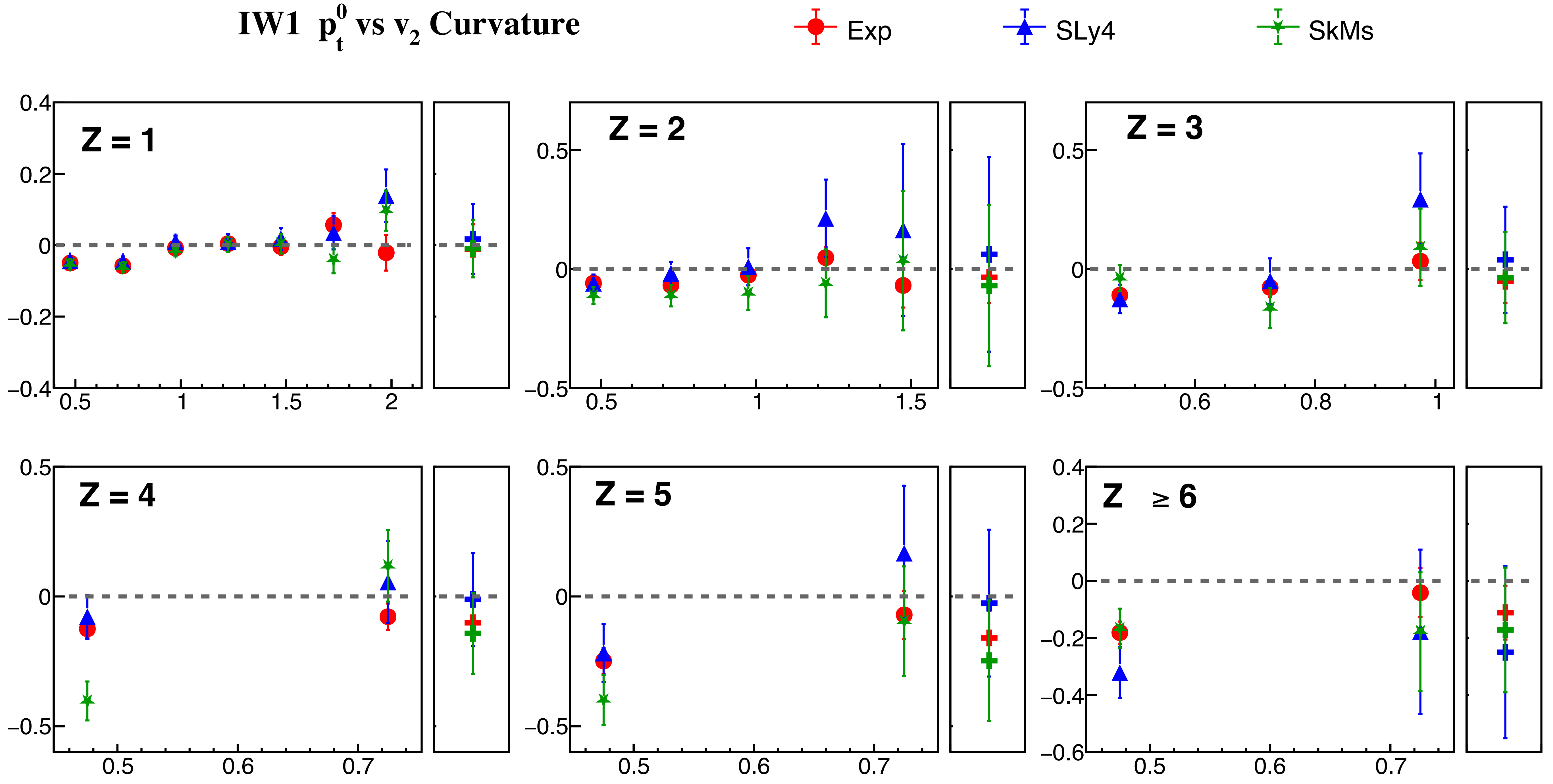


Curvature of Elliptic flow

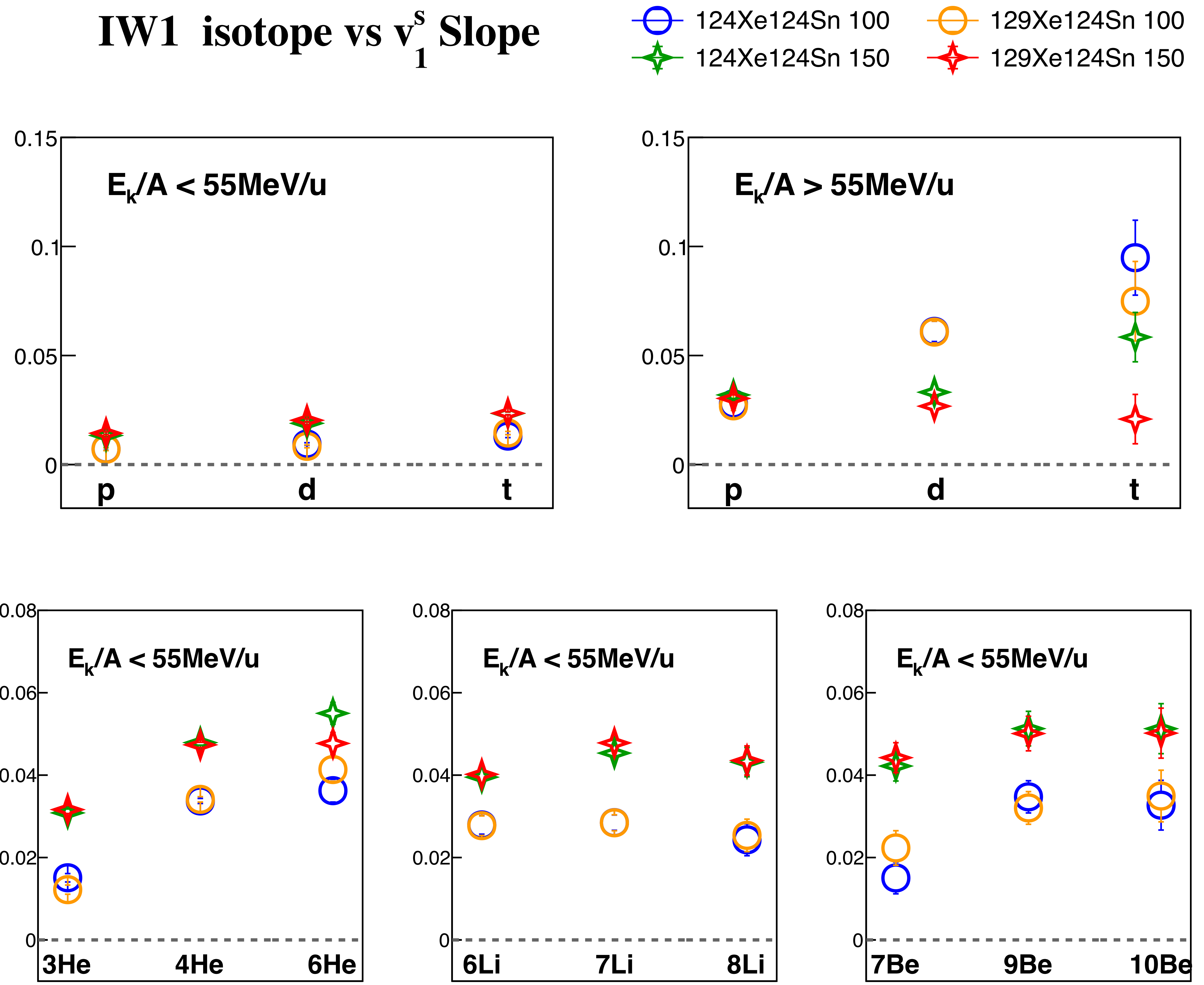
$^{64}Ni + ^{64}Ni @ 52 MeV/u$

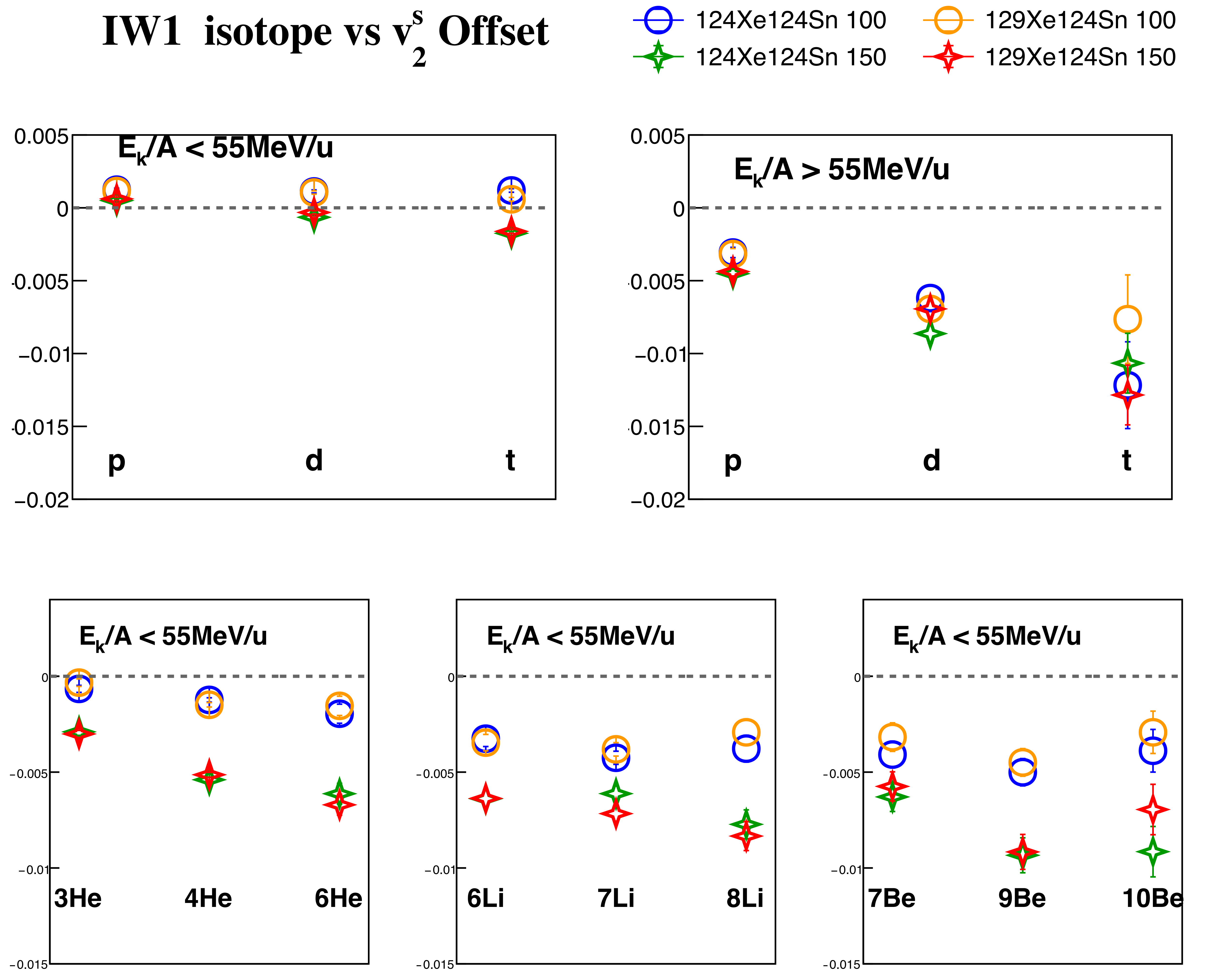


$^{124}Xe + ^{124}Sn @ 100 MeV/u$



$^{129,124}Xe + ^{124}Sn$ @ 100 & 150MeV/u
Exp, correction factor + system size scaling





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