INDRA at high energy: the GSI data legacy

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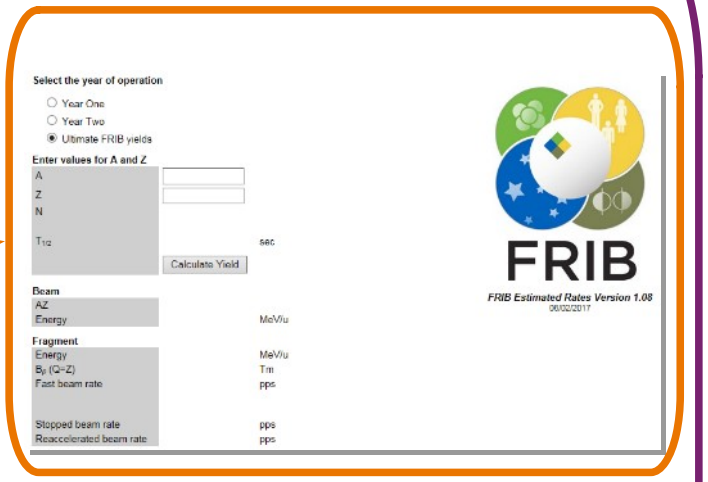
Context

FRIB : Facility for Rare Isotope Beams at MSU

- FRIB facility (see also G. Verde talk) :
  - FRIB200 (now) → FRIB400(> 2027 ???) ;
  - Radioactive beams at E/A>100 MeV/u (but also below) ;
  - Info concerning beams available at FRIB :
    - https://groups.nscl.msu.edu/frib/rates/fribrates.html
    - https://groups.nscl.msu.edu/frib/rates/FRIB_rates_readme_2_10.pdf



- Physics cases at FRIB :
  - Supra-saturation density ;
  - K. Brown experiment (approved at FRIB-PAC3 in Feb. 2023) :
    - ^{56,70}Ni + ^{58,64} Ni @ 200 MeV/nuc ;
    - Energy spectra of neutrons and LCP, single/double n-p ratio, flow study.

  - Future proposal :
    - Use a bigger system ? Sn+Sn@180AMeV/nucleon ;
    - Coupling of FAZIA/INDRA and existing detectors (HIRA, LANA,etc...)
    - What can we expect from a multi-array like INDRA ?

Context : INDRA@GSI

Summary of INDRA 4th campaign (Available at CCLyon)

Proj	Targ	E*/A MeV/u	#Runs
^{197}Au	^{197}Au	150	54
^{197}Au	^{197}Au	100	100
^{197}Au	^{197}Au	80	30
^{197}Au	^{197}Au	60	43
^{197}Au	^{197}Au	50	8
^{197}Au	^{197}Au	40	31

Au+Au

Proj	Targ	E*/A MeV/u	#Runs
^{124}Xe	^{124}Xe	250	14
^{124}Xe	^{124}Sn	150	20
^{129}Xe	^{124}Sn	150	21
^{124}Xe	^{112}Sn	100	36
^{124}Xe	^{124}Sn	100	42
^{129}Xe	^{112}Sn	100	43
^{129}Xe	^{124}Sn	100	58
^{129}Xe	^{124}Sn	80	29
^{129}Xe	^{124}Sn	65	27
^{129}Xe	^{nat}Sn	50	12

≠ initial N/Z

Xe+Sn

Proj	Targ	E*/A MeV/u	#Runs
^{12}C	^{197}Au	1800	23
^{12}C	^{197}Au	1000	63
^{12}C	^{197}Au	600	76
^{12}C	^{197}Au	300	60
^{12}C	^{197}Au	95	25
^{12}C	^{197}Au	30	6
^{12}C	^{238}U	1000	16
^{12}C	^{112}Sn	1000	7
^{12}C	^{112}Sn	600	15
^{12}C	^{124}Sn	600	13
^{12}C	^{112}Sn	300	35
^{12}C	^{124}Sn	300	31
^{12}C	^{112}Sn	95	6

^{12}C proj

Overview of Xe+Sn data

- **For this work, we will focus on ^{129,124}Xe+^{112,124}Sn INDRA@GSI data at 100 MeV/u**

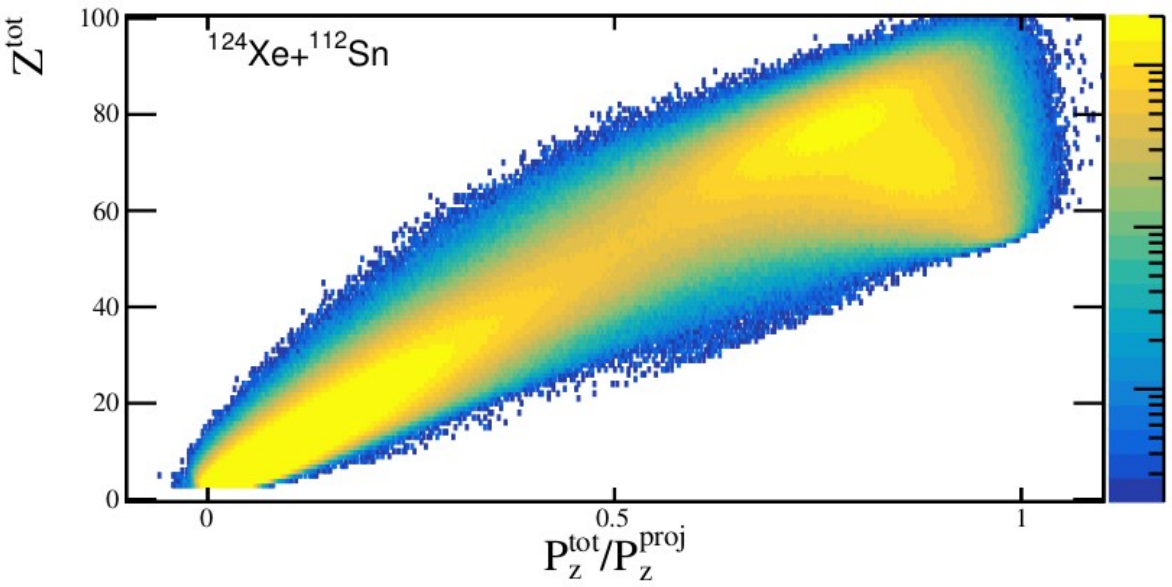
- **In the context of a future experiment at FRIB, we will present :**
  - **An overview of global observables ;**
  - **A (preliminary) study of the directed and elliptic flow.**

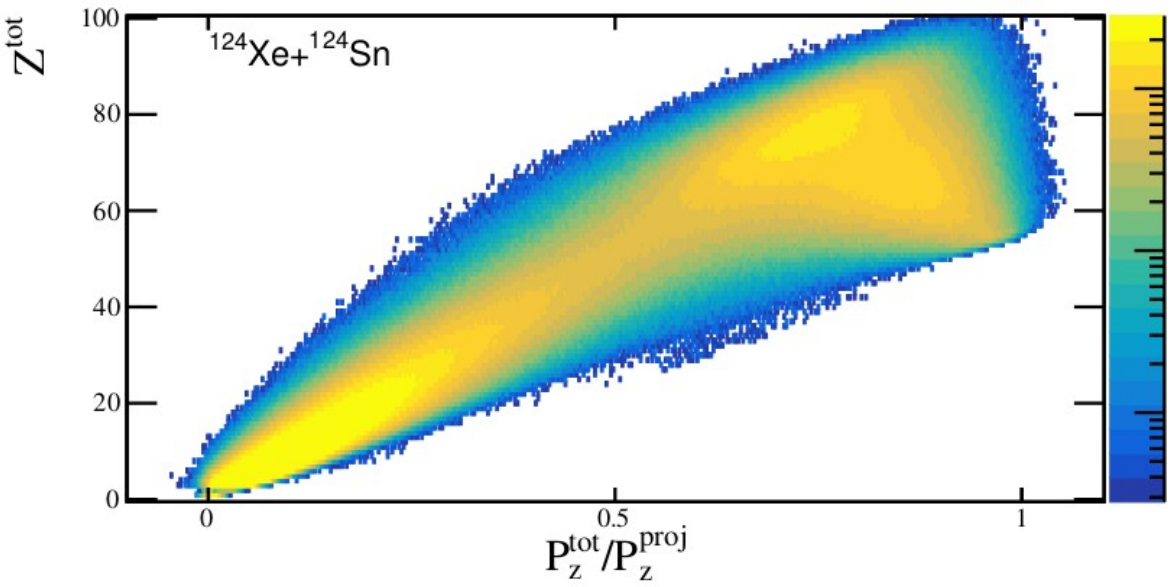
Proj	Targ	E*/A MeV/u	N/Z	#Runs	#Evts
^{124}Xe	^{112}Sn	100	1.269	36	8962246
^{124}Xe	^{124}Sn	100	1.385	42	11787816
^{129}Xe	^{112}Sn	100	1.317	43	11153195
^{129}Xe	^{124}Sn	100	1.433	58	7847850

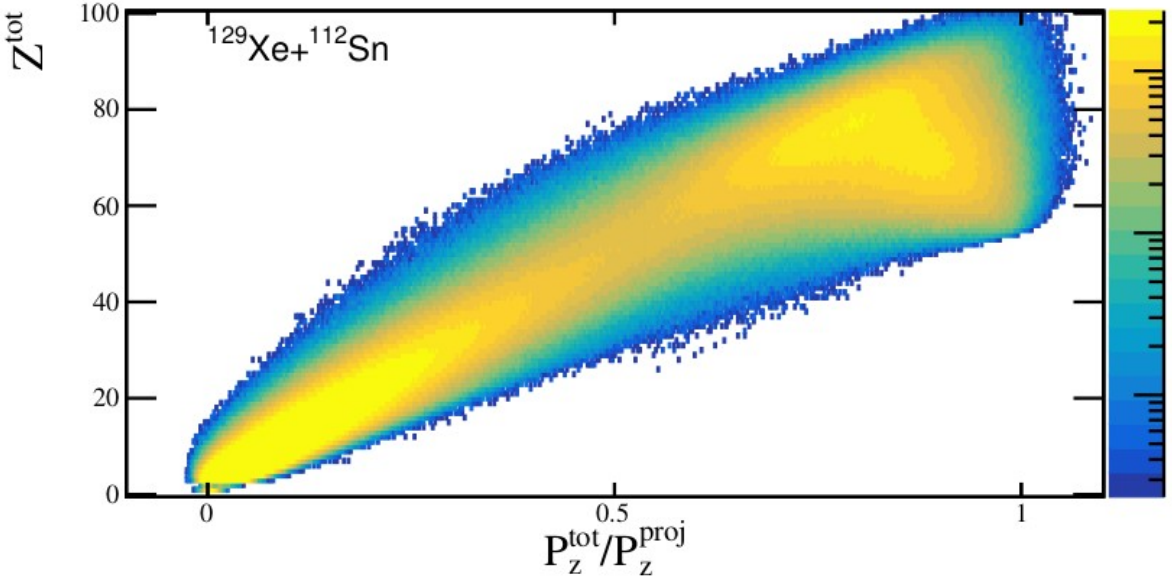
NOTE : Global trigger of M>3

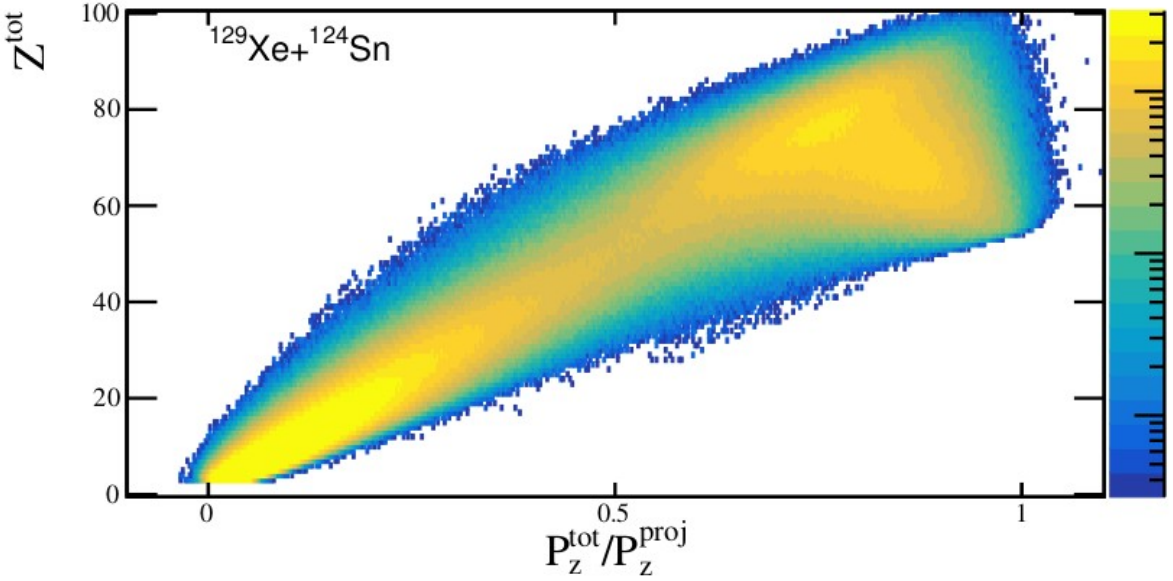
Completeness

$$Z^{tot} = \sum_i Z_i \qquad P_z^{tot} = \sum_i Z_i V_z^i$$



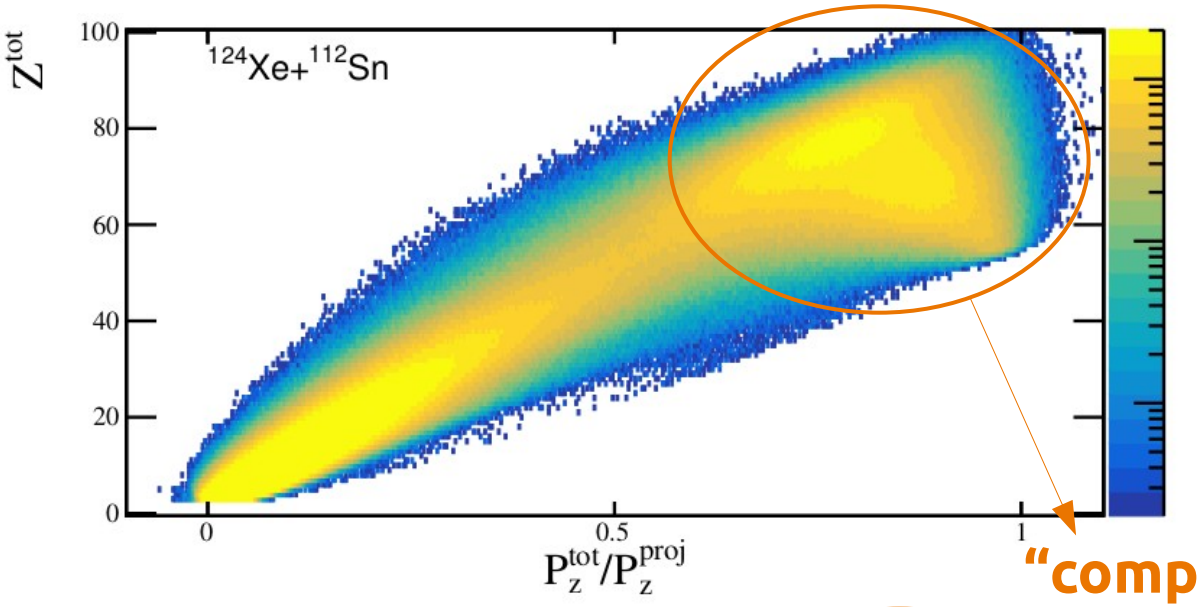


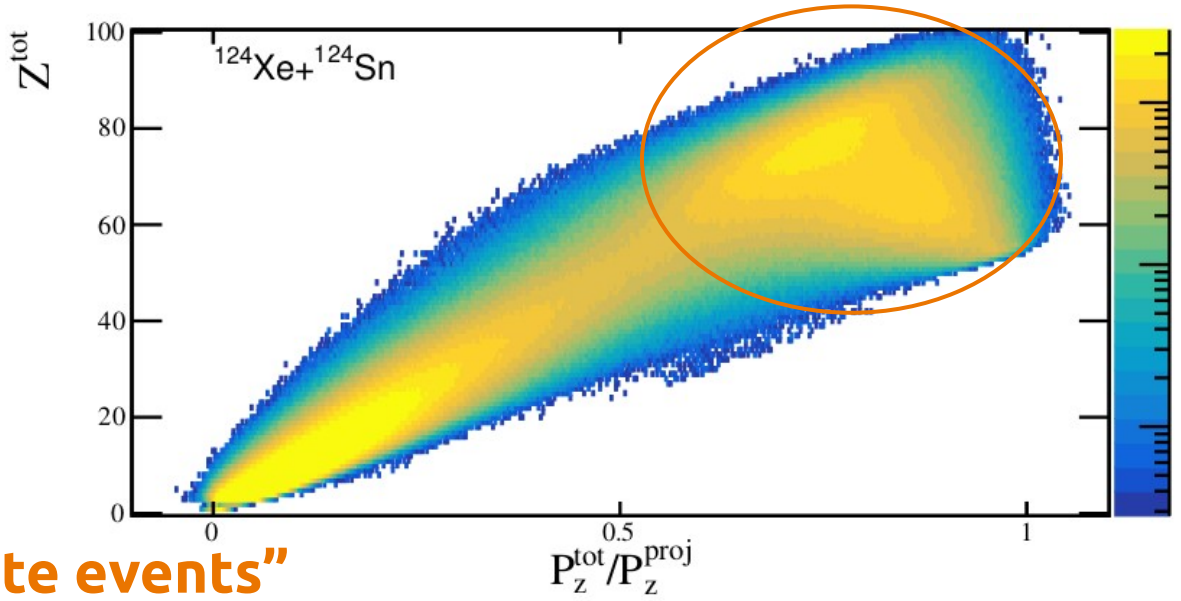




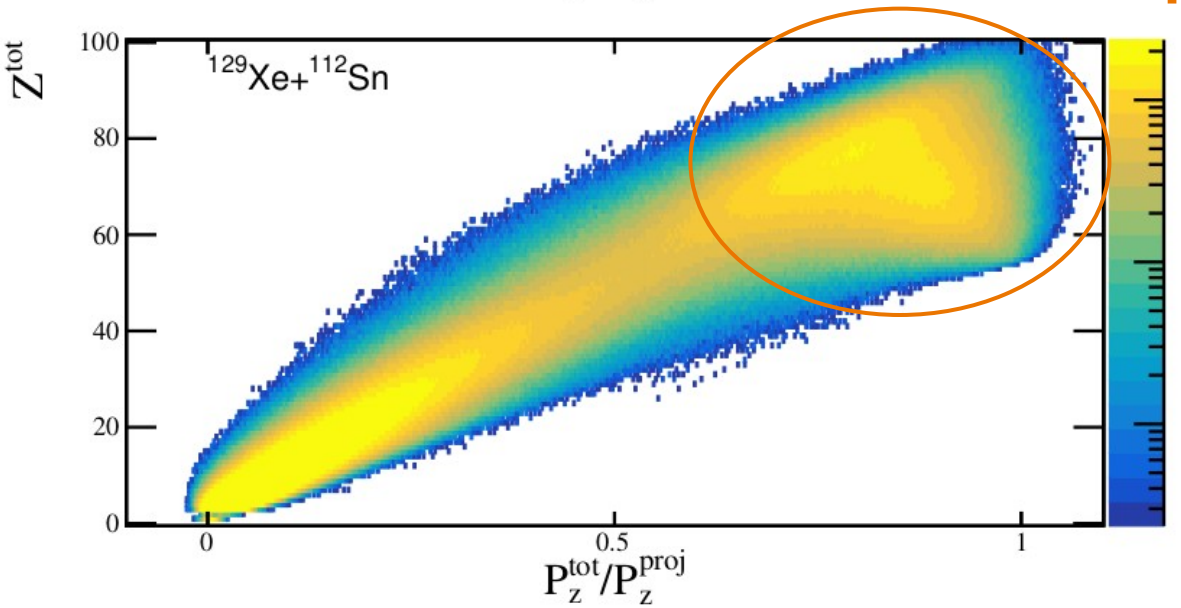
Completeness

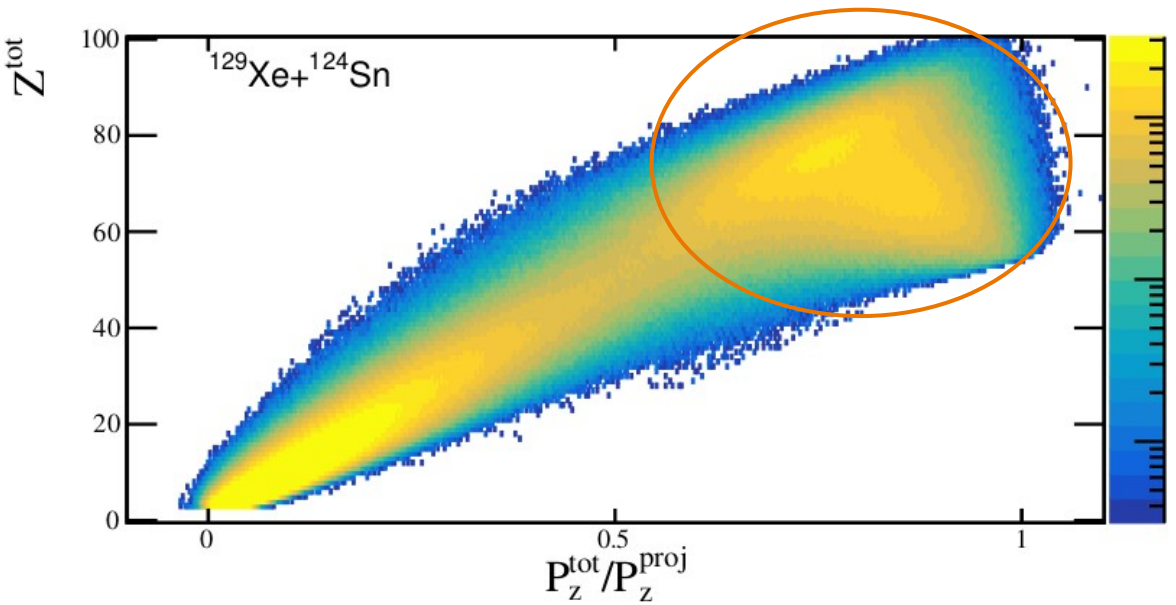
$$Z^{tot} = \sum_i Z_i \qquad P_z^{tot} = \sum_i Z_i V_z^i$$





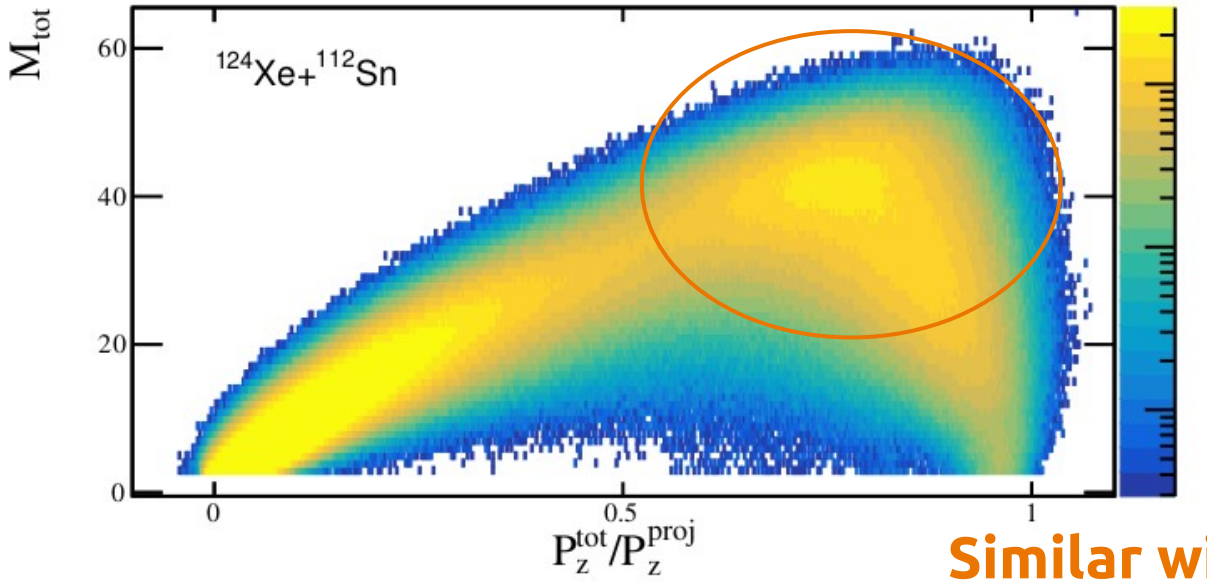
"complete events"

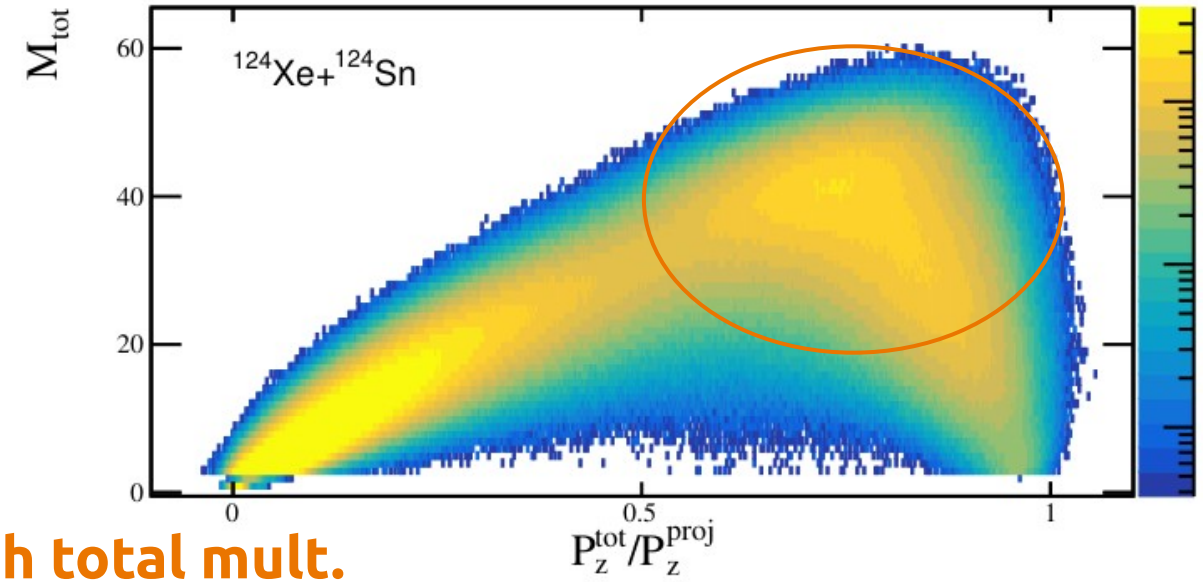




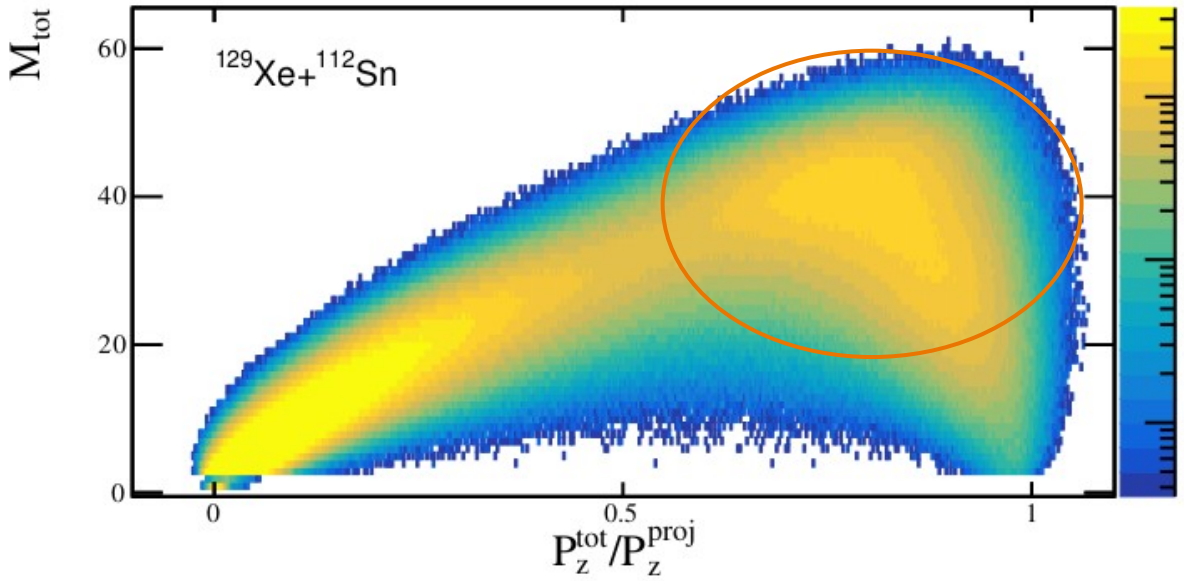
Completeness

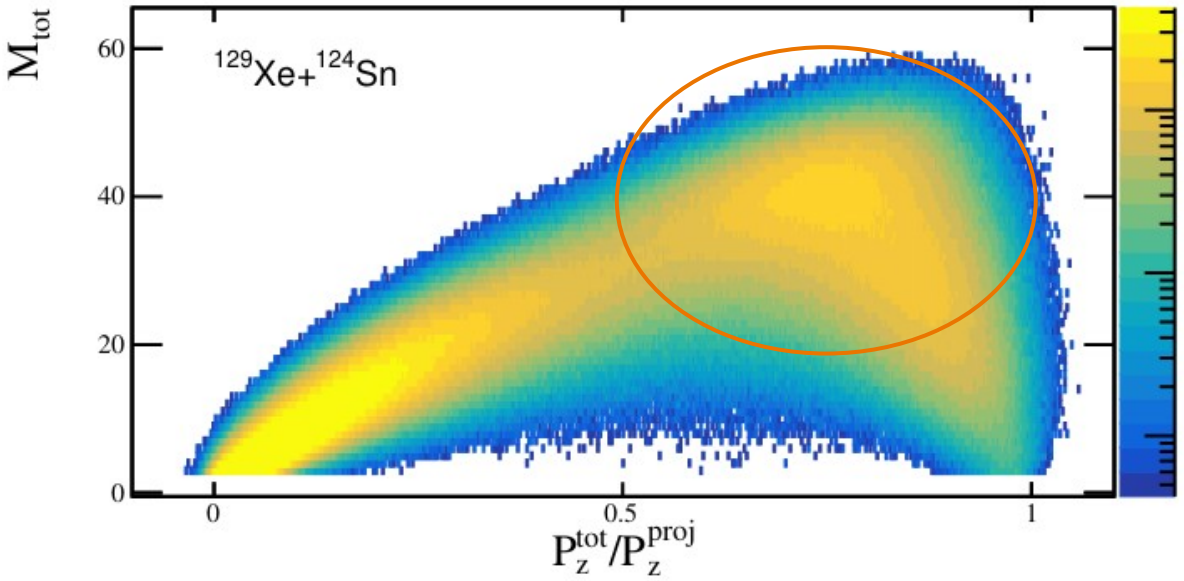
$$P_z^{tot} = \sum_i Z_i V_z^i$$



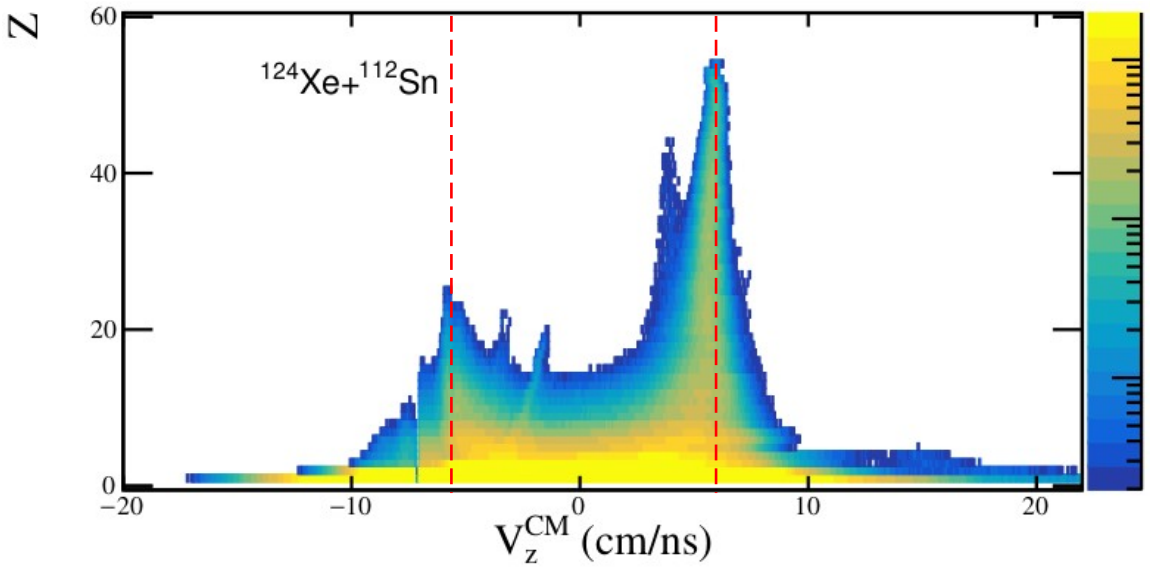


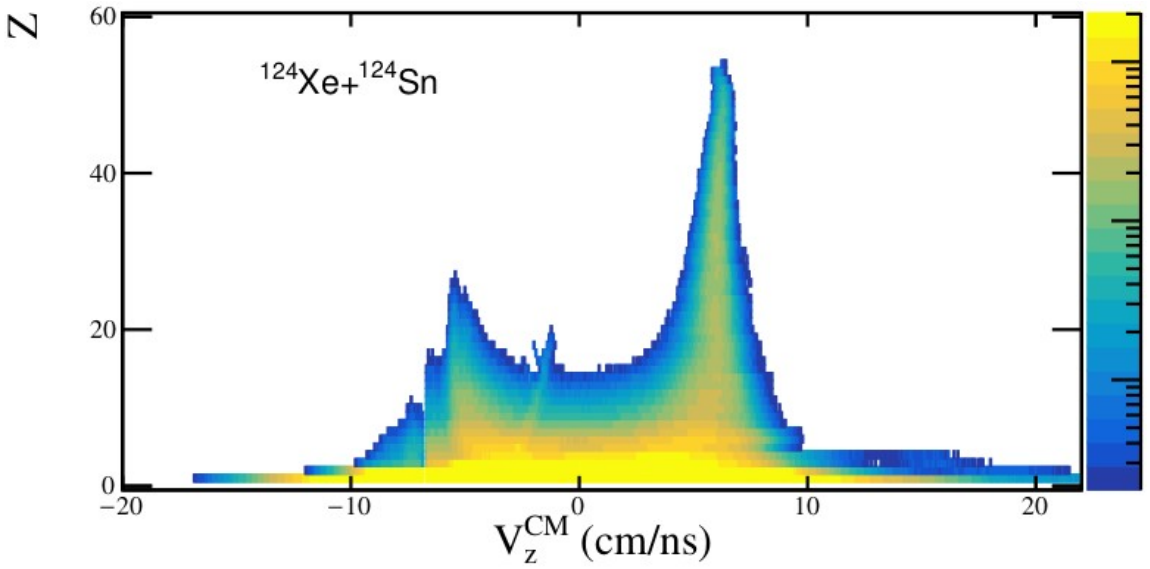
Similar with total mult.

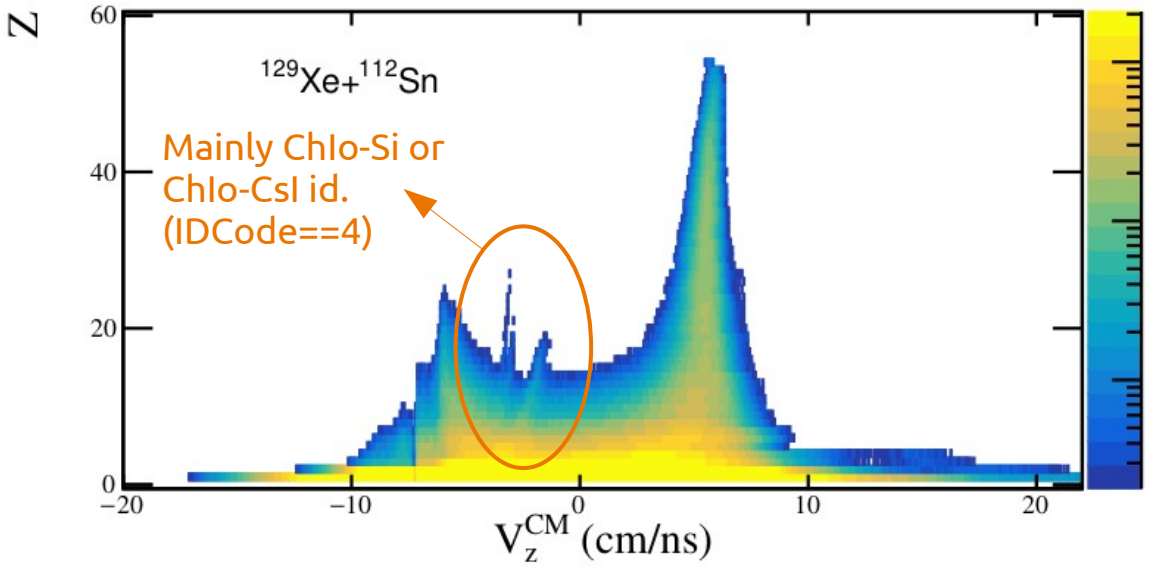


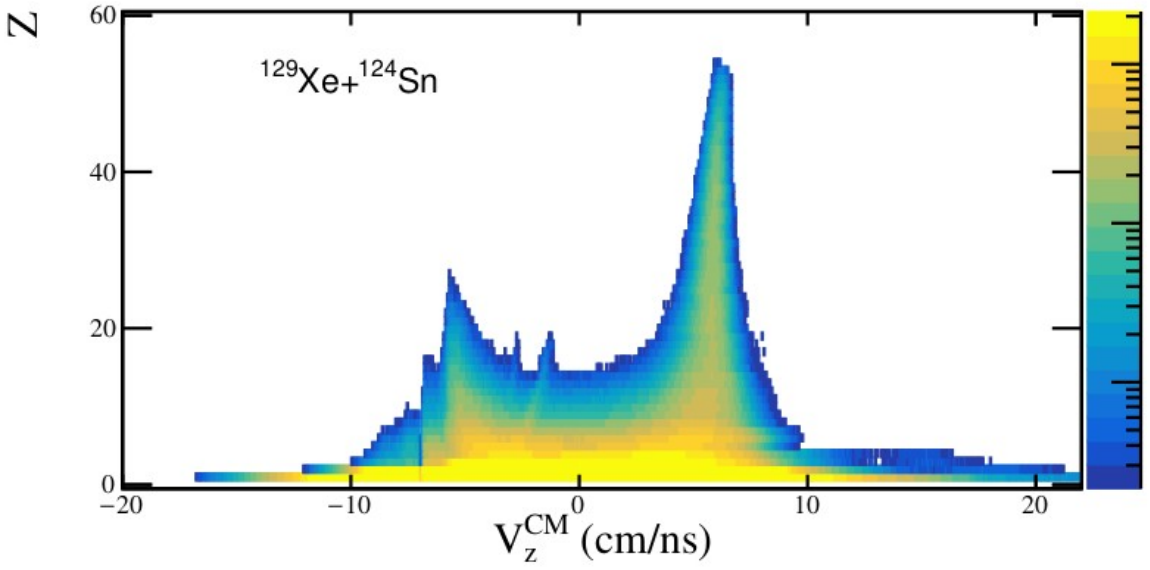


Topology

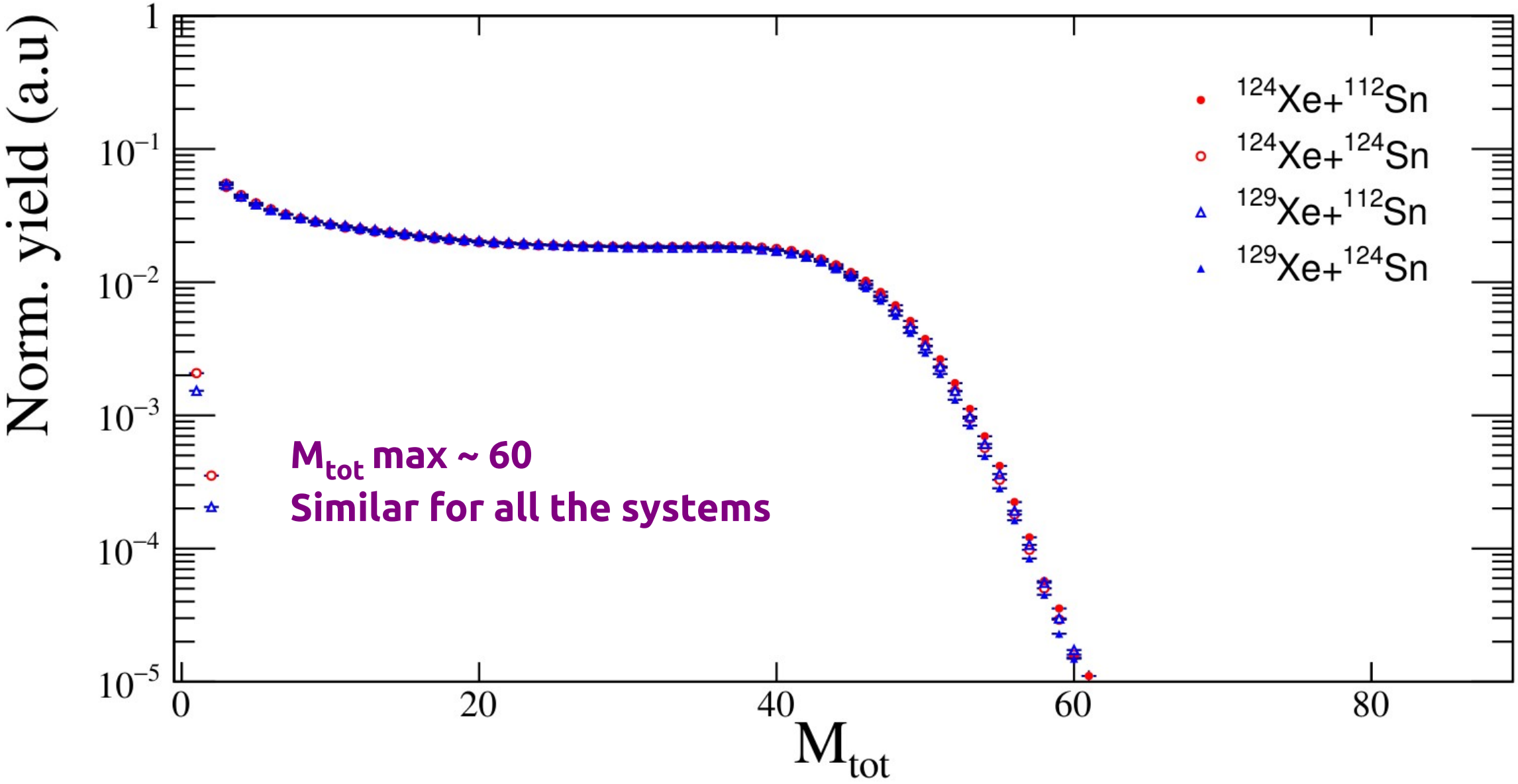

Z
^{124}Xe+^{112}Sn
V_z^{CM} (cm/ns)


Z
^{124}Xe+^{124}Sn
V_z^{CM} (cm/ns)

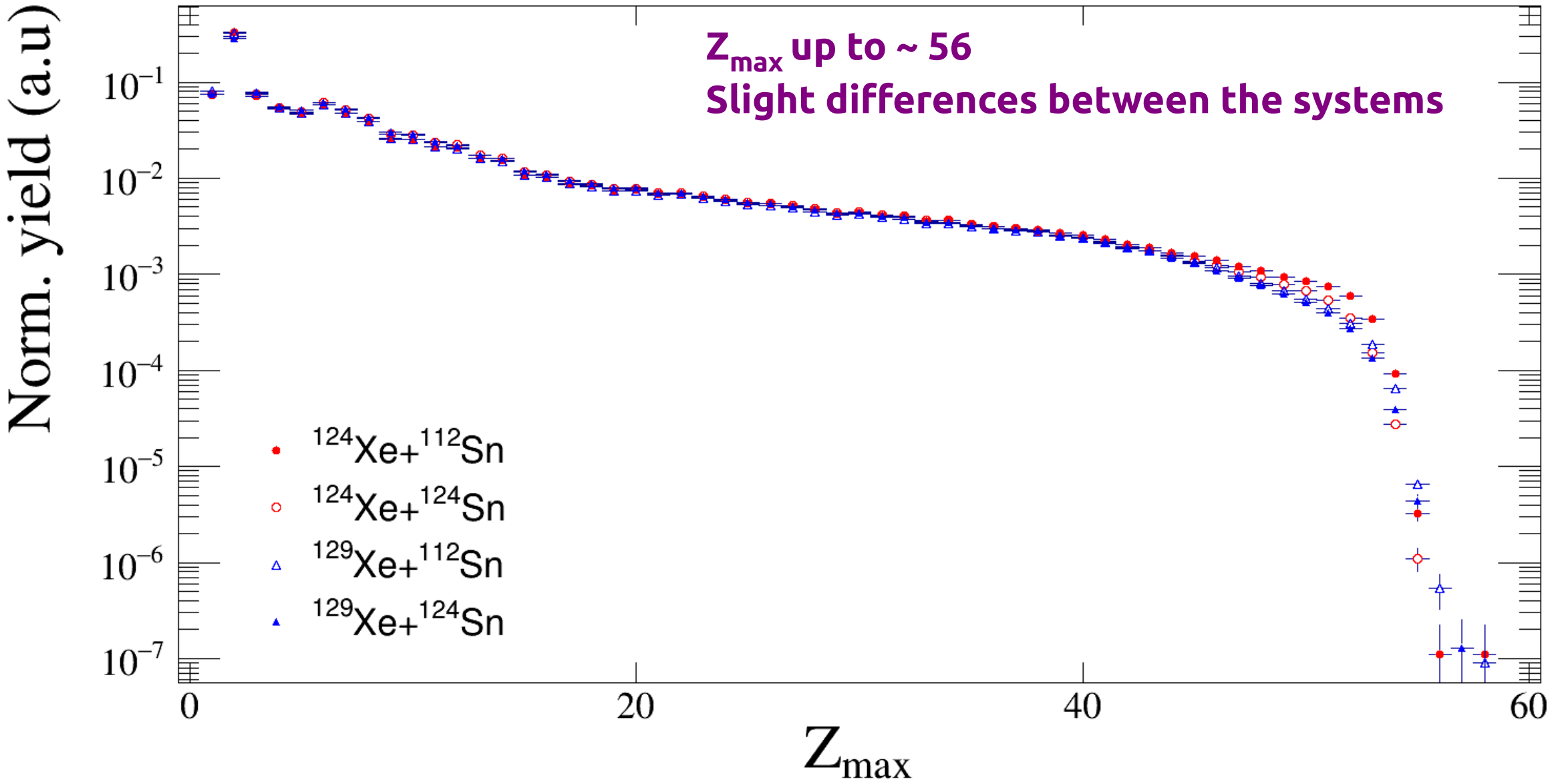

Z
^{129}Xe+^{112}Sn
Mainly ChIo-Si or
ChIo-CsI id.
(IDCode==4)
V_z^{CM} (cm/ns)


Z
^{129}Xe+^{124}Sn
V_z^{CM} (cm/ns)

Global observable : M_{tot}

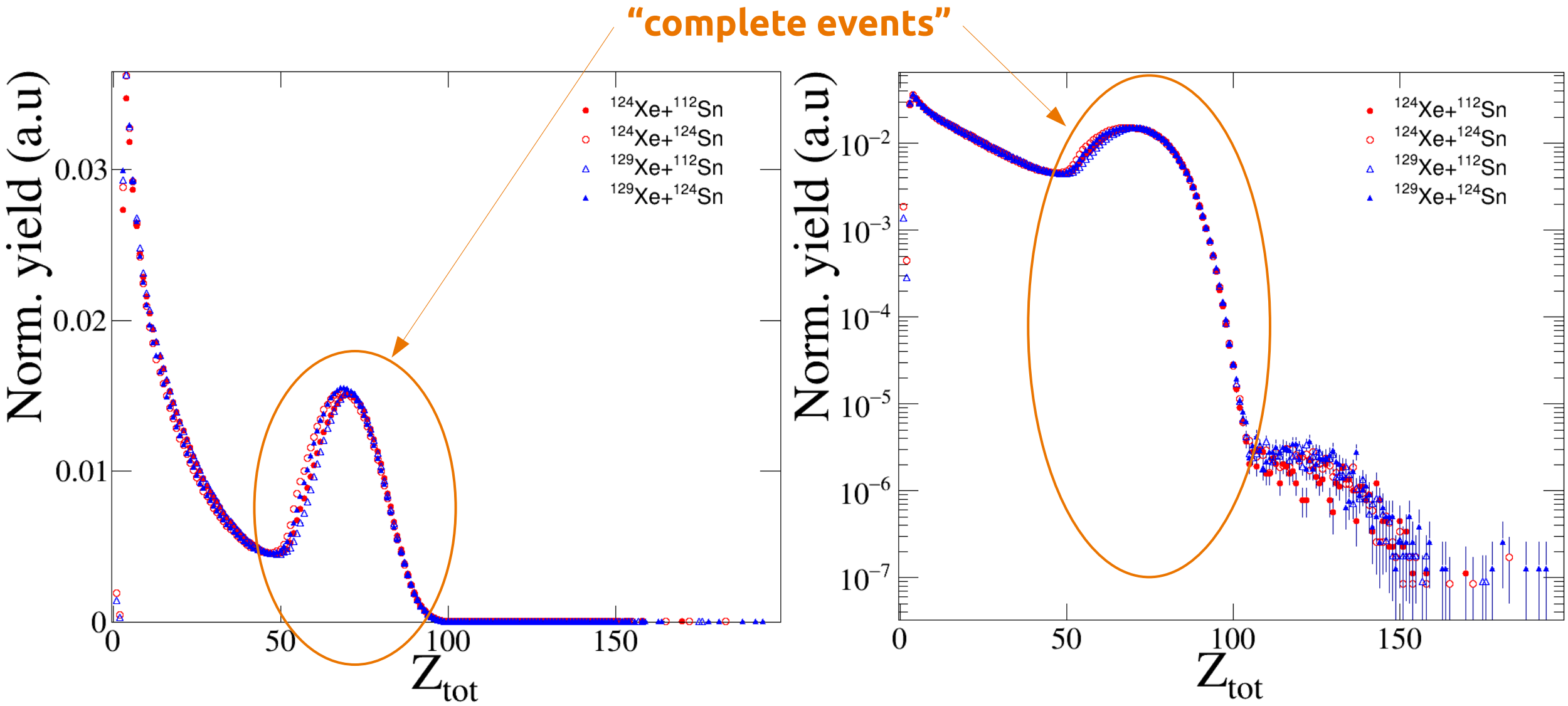


Global observable : Z_{max}

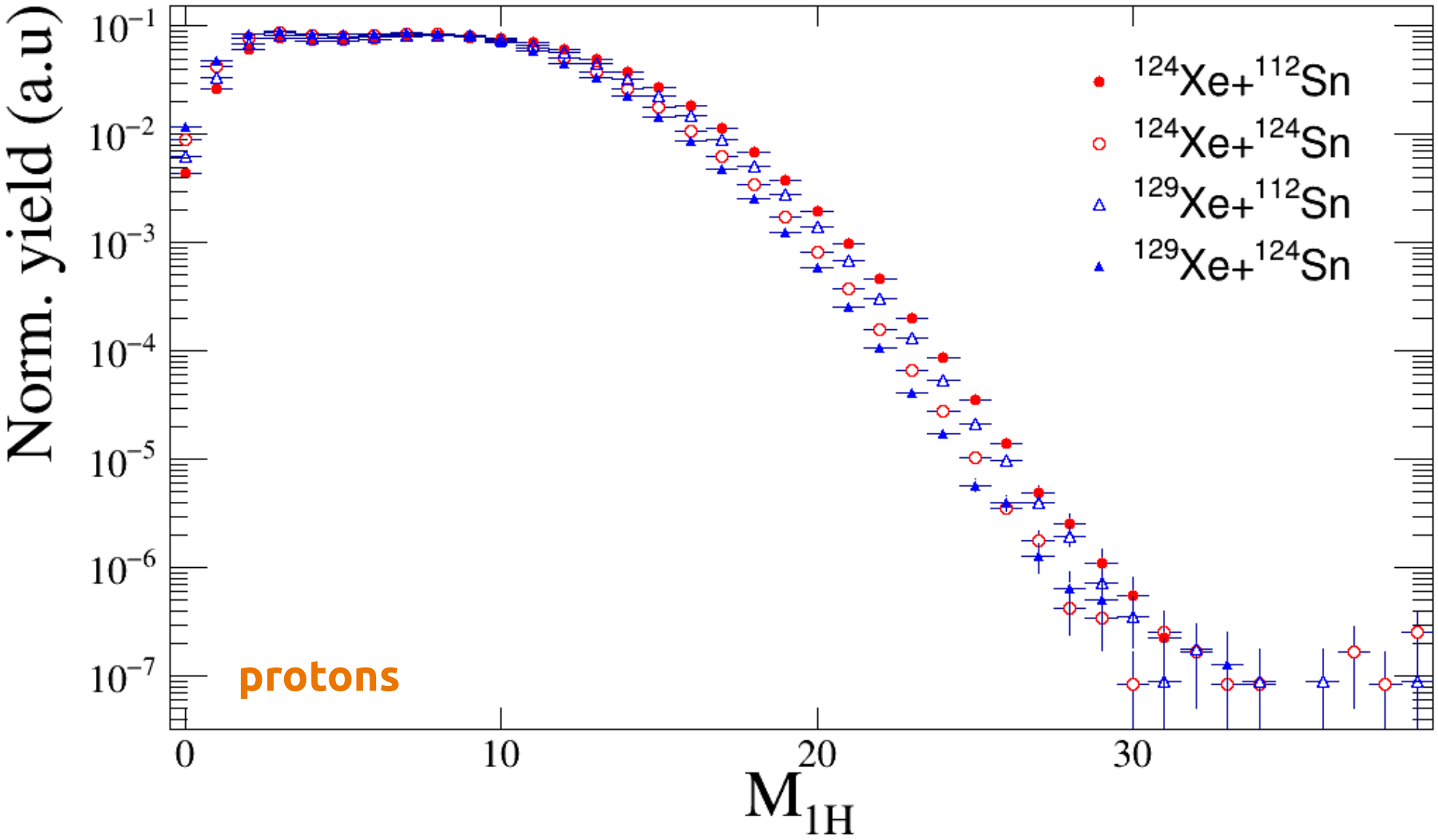


Z_{max} up to ~ 56
Slight differences between the systems

Global observable : Z_{tot}



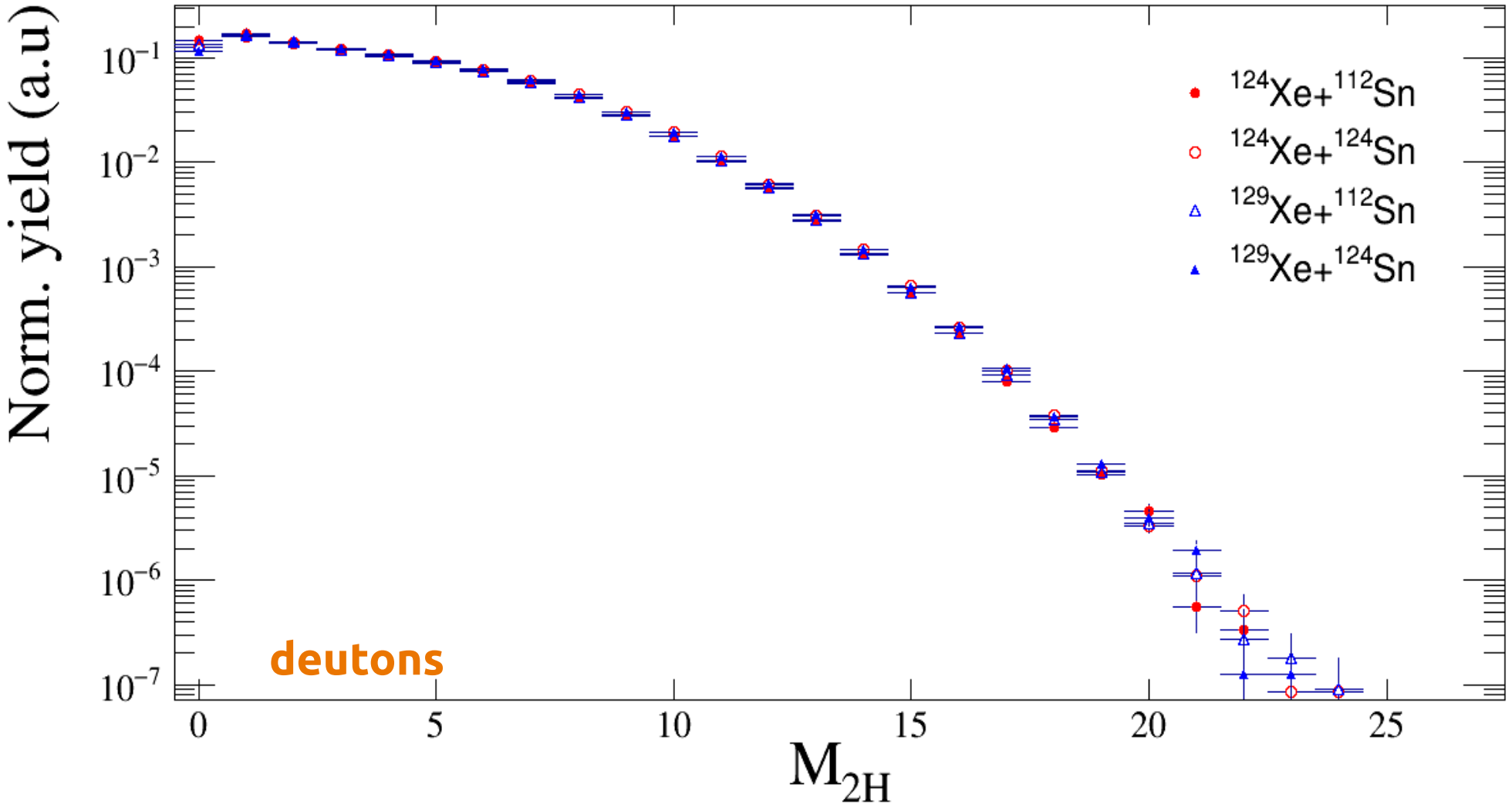
Global observable : LCP mult.



M_{1H} max ~ 30

Hierarchy according to the n-deficiency of the system

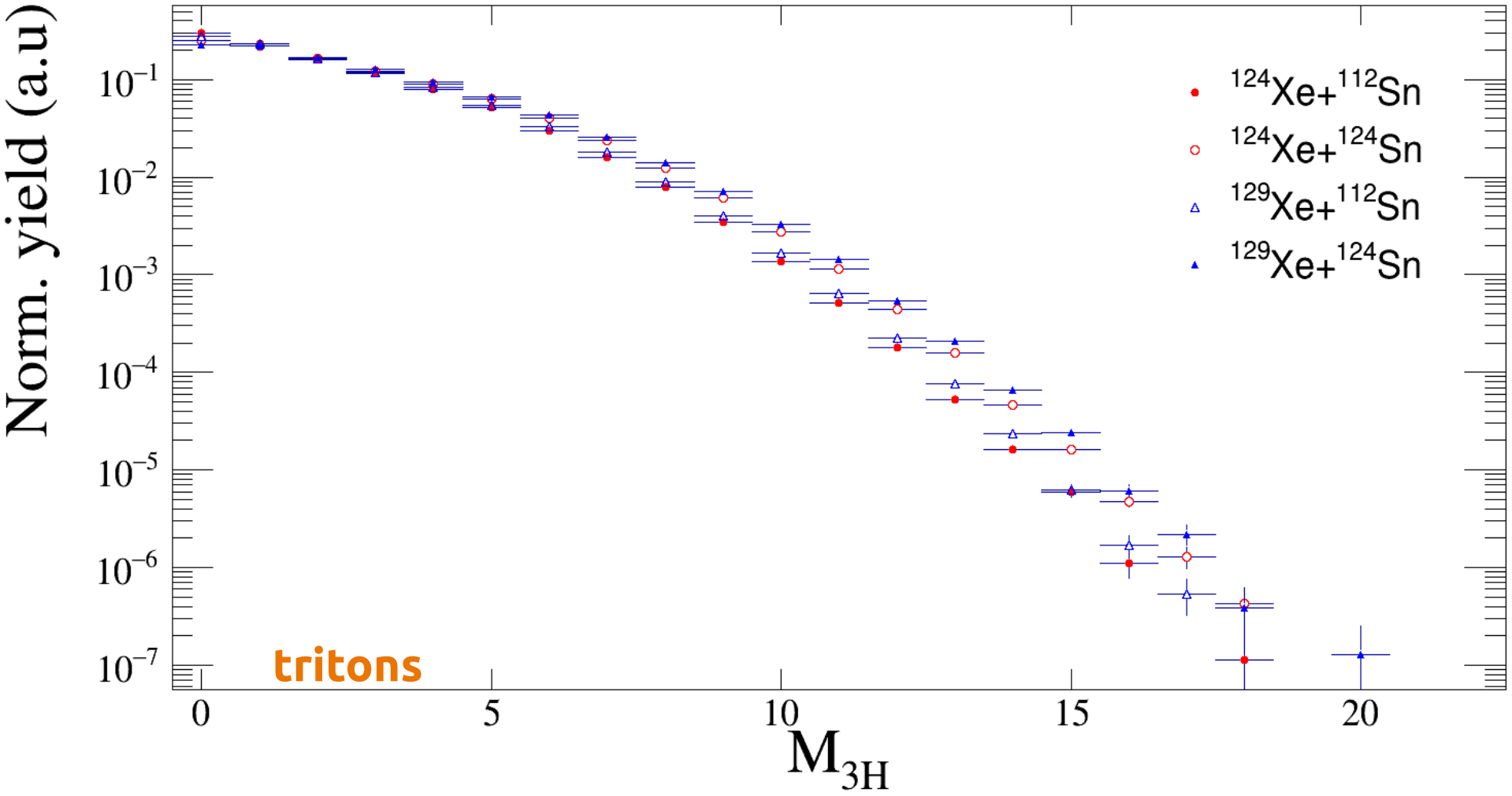
Global observable : LCP mult.



M_{2H} max ~ 25

No clear hierarchy

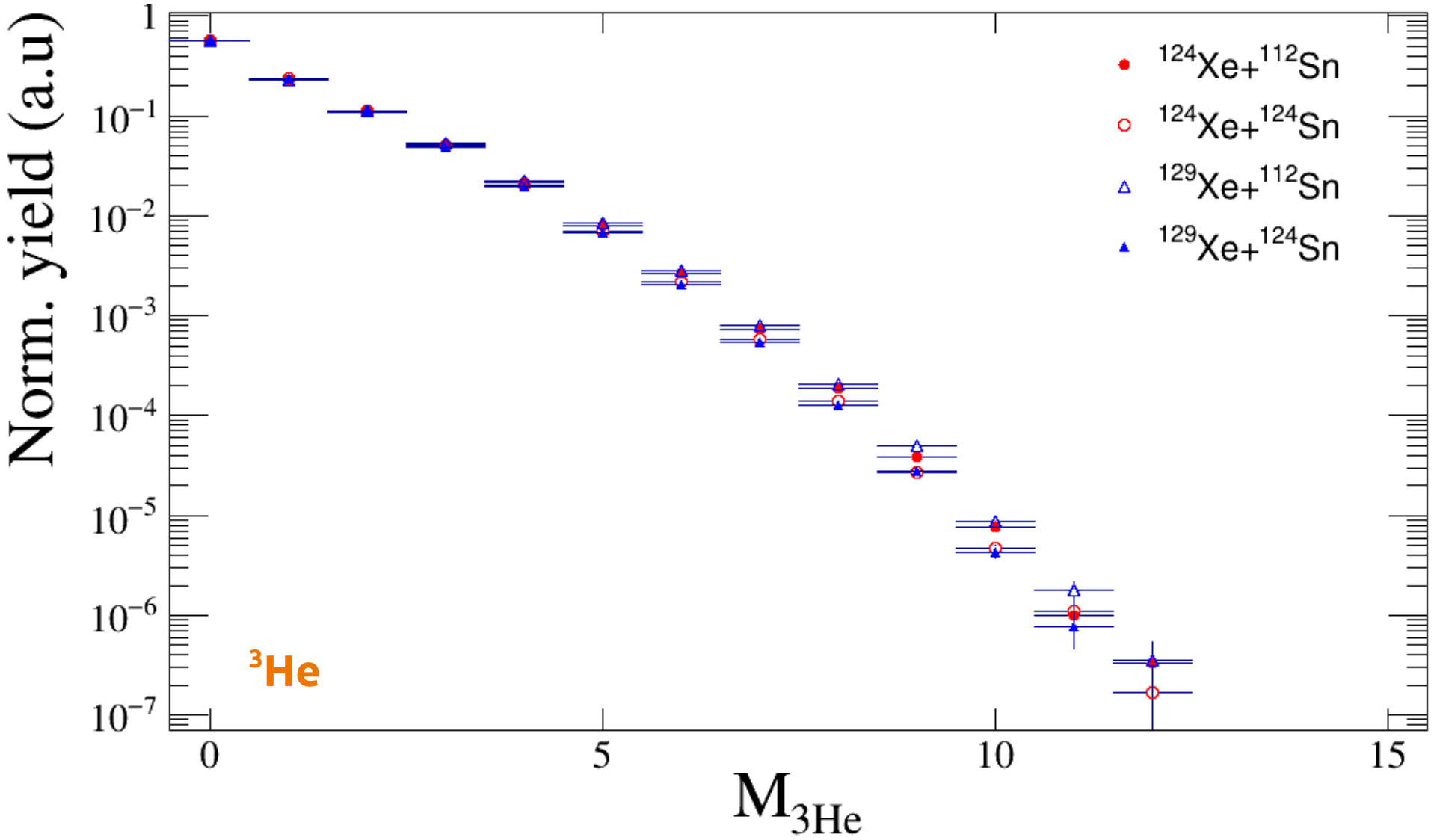
Global observable : LCP mult.



M_{3H} max ~ 17

Hierarchy according to the n-richness of the system

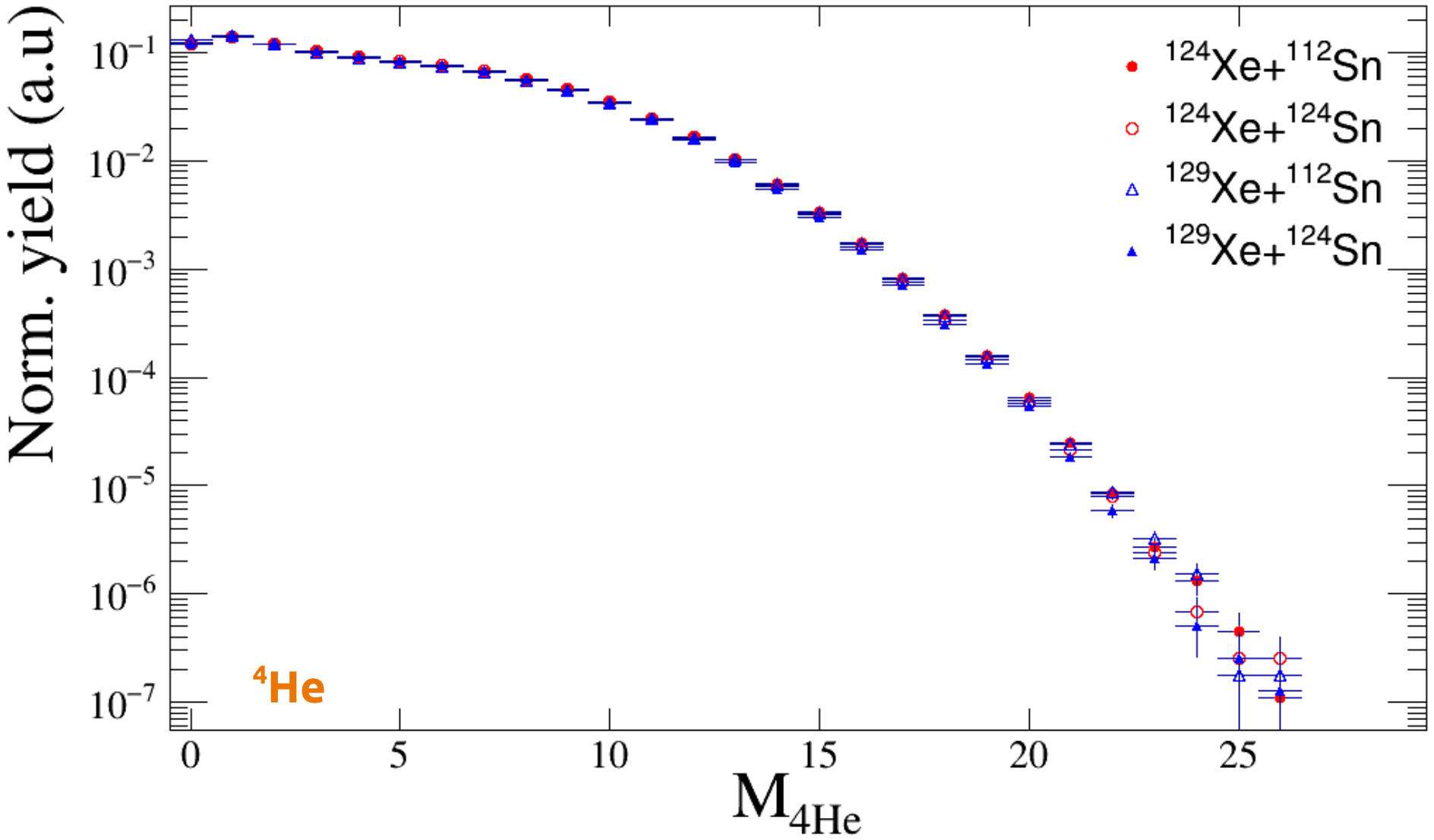
Global observable : LCP mult.



M_{3He} max ~ 12

No clear hierarchy

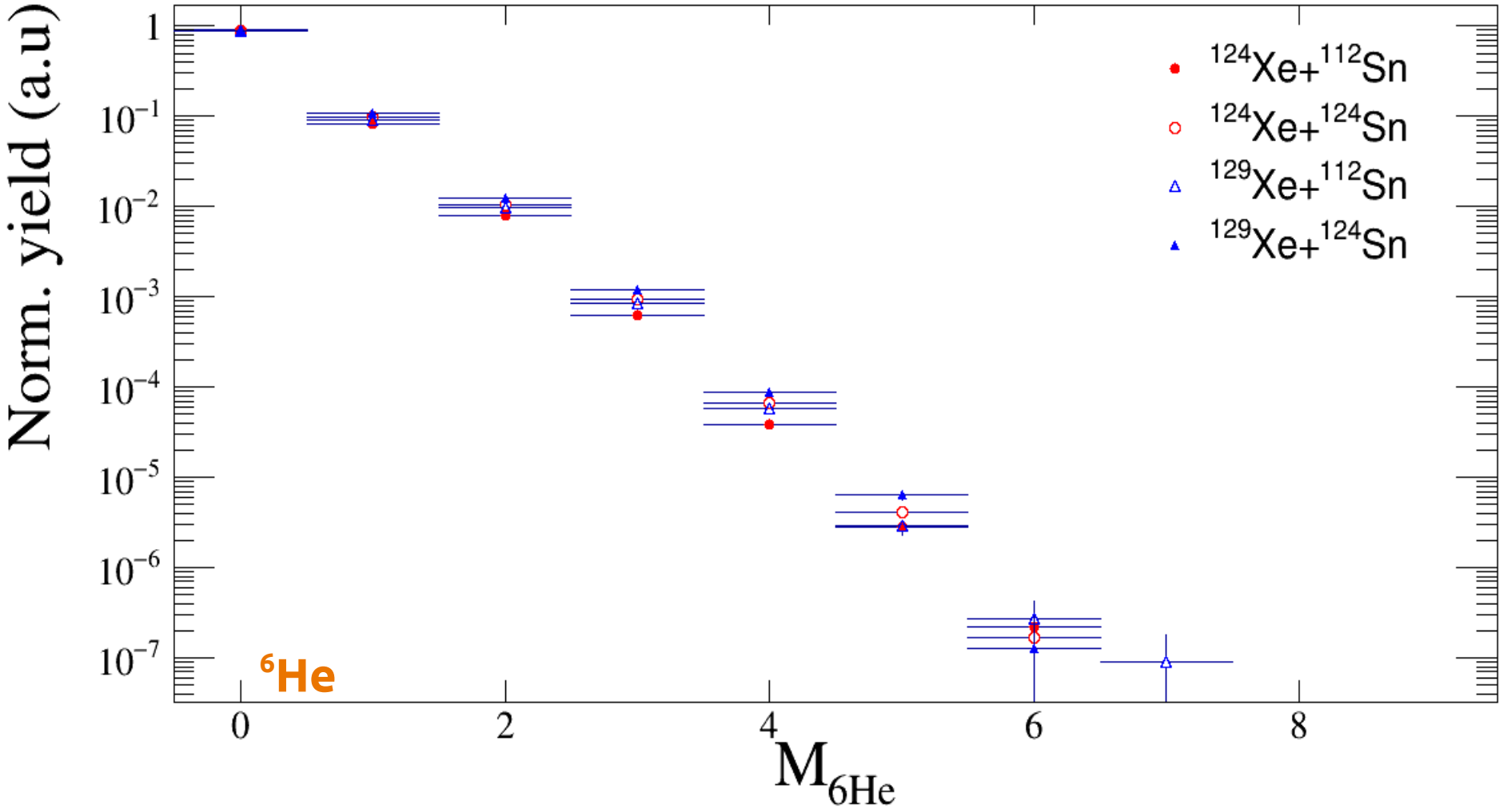
Global observable : LCP mult.



M_{4He} max ~ 25

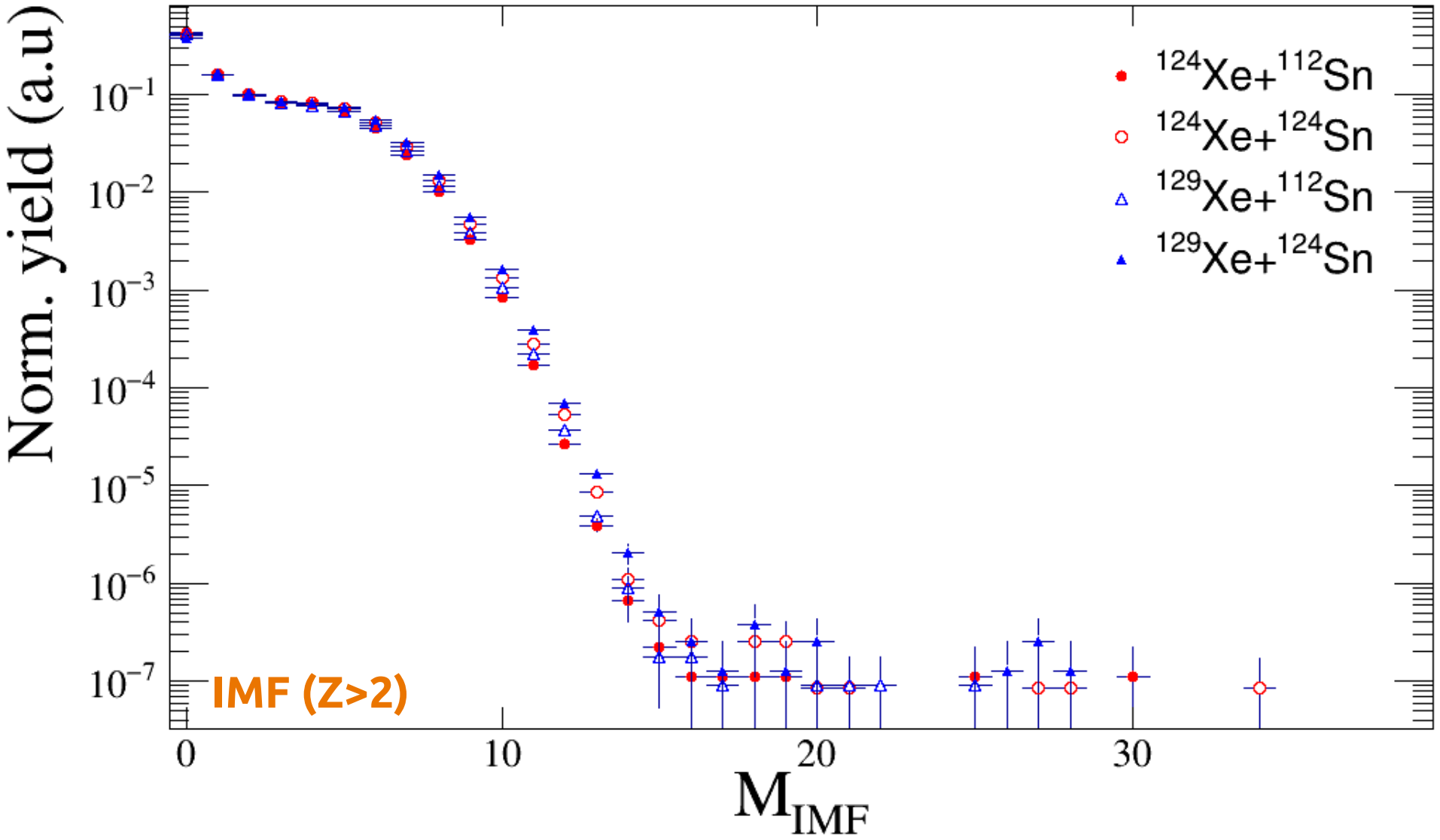
No clear hierarchy

Global observable : LCP mult.



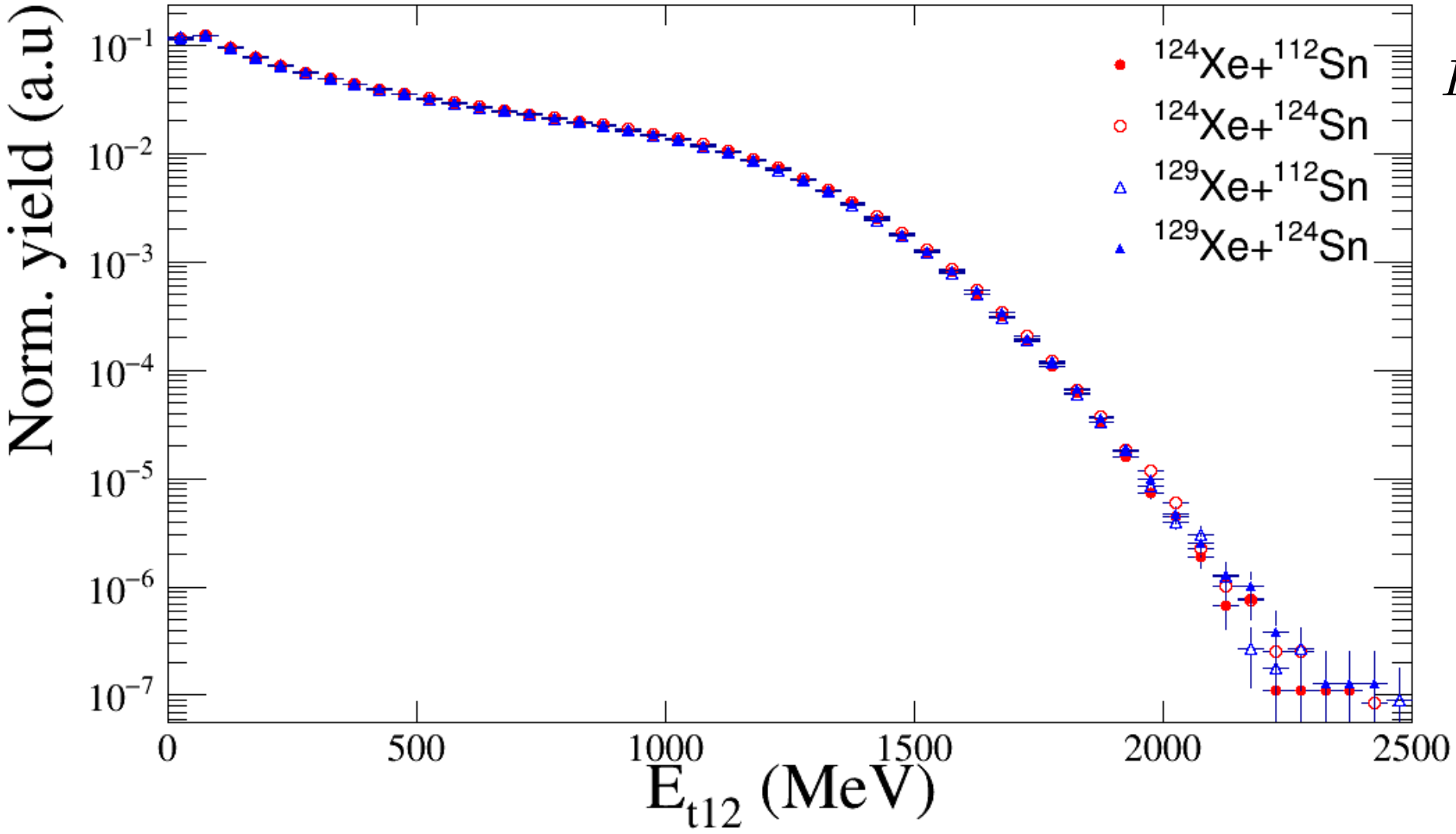
M_{6He} max ~ 6

Global observable : IMF mult.



M_{IMF} max ~ 16

Global observable : Transverse KE



$$E_{t12} = \sum_{i:Z_i \leq 2} E_i \sin^2 \theta_i$$

Sum over all Z-ident nuclei

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Flow parameters

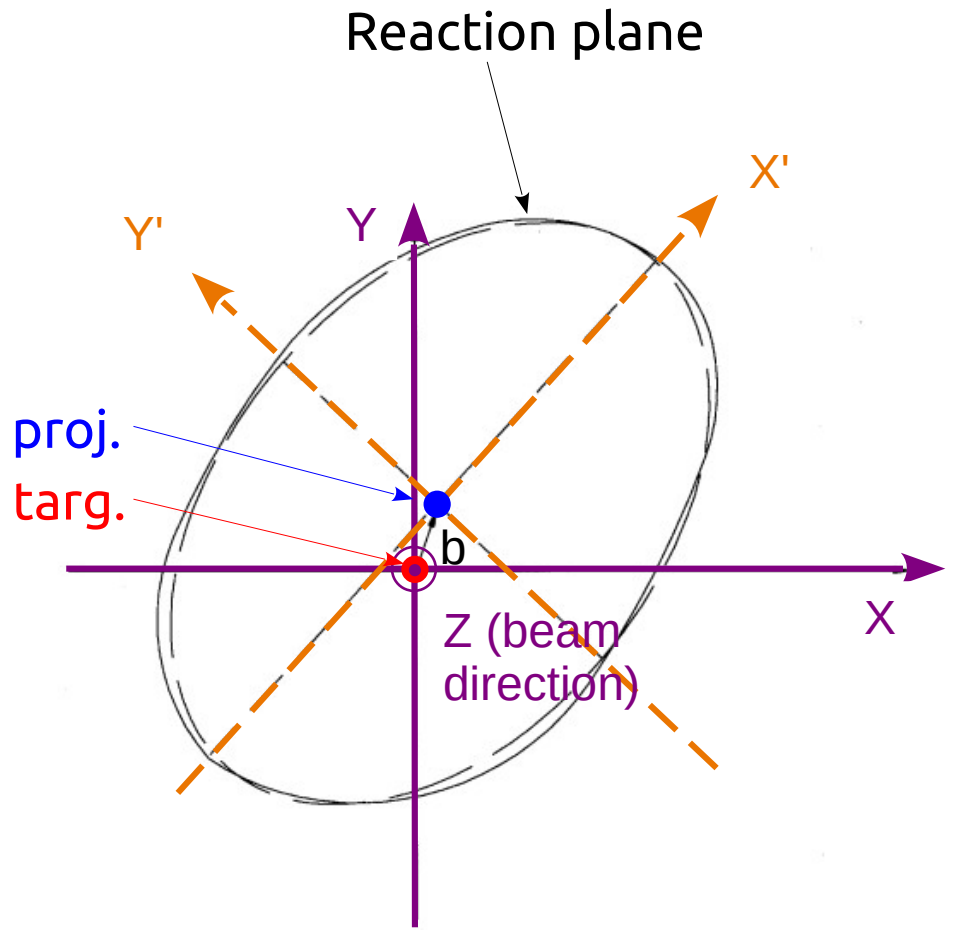
Study of anisotropy in particle azimuthal distributions with respect to the reaction plane :

- Observable = transverse momentum p_t
- Z-axis = beam direction
- Reaction plane defined by :
  - Impact param. vector (from the center of the targ. to the center of the proj.)
  - transverse plane X-Y

- Fourier expansion of the azimuthal distribution of p_t

$$\frac{dN}{d\phi} = v_0[1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi)]$$

- 1st harmonic (v1) : overall shift of p_t in the reaction plane → "directed flow" ;
- 2nd harmonic (v2) : difference between major and minor axes in an ellipse approximation → elliptic flow.



Voloshin and Zhang, Z. Phys. C 70 (1996)

Flow : directed and elliptic flow

$$\frac{dN}{d\phi} = v_0[1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi)]$$

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

(average over all considered particles and events)

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

- Both directed and elliptic flows may depend on :
  - The colliding system, beam energy, impact parameter, type of particle ;
  - Transverse momentum and rapidity.

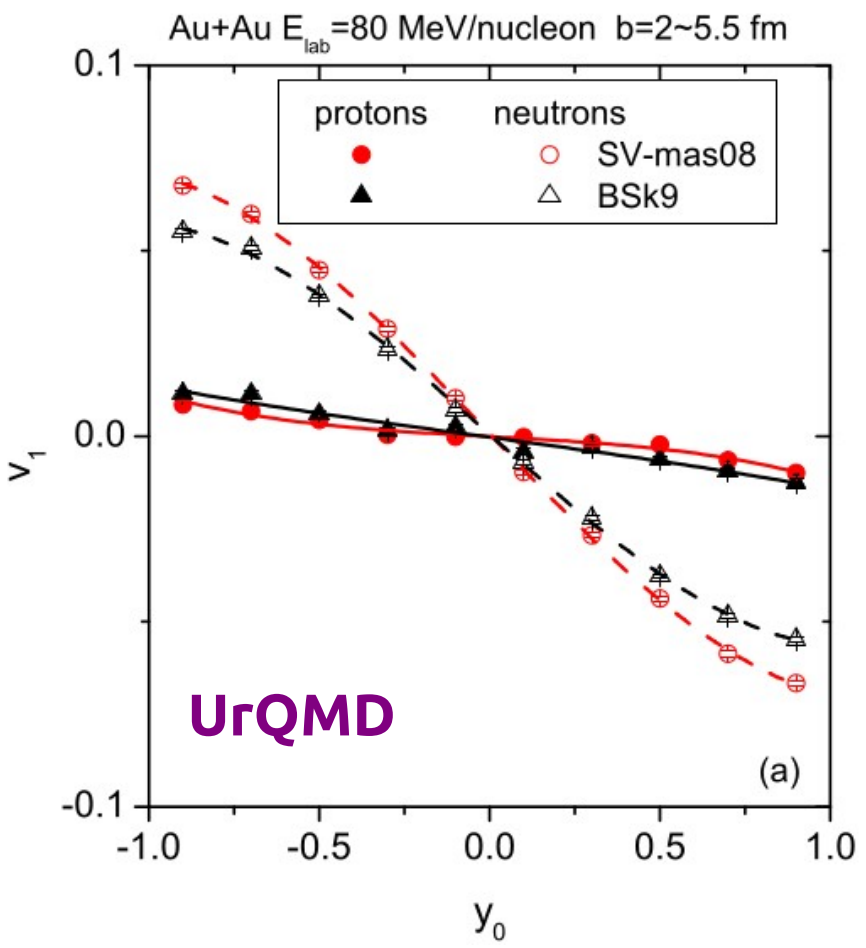
- According to various model calculations they can also be used as sensitive probes to study the high-density behaviour of the nuclear symmetry energy :

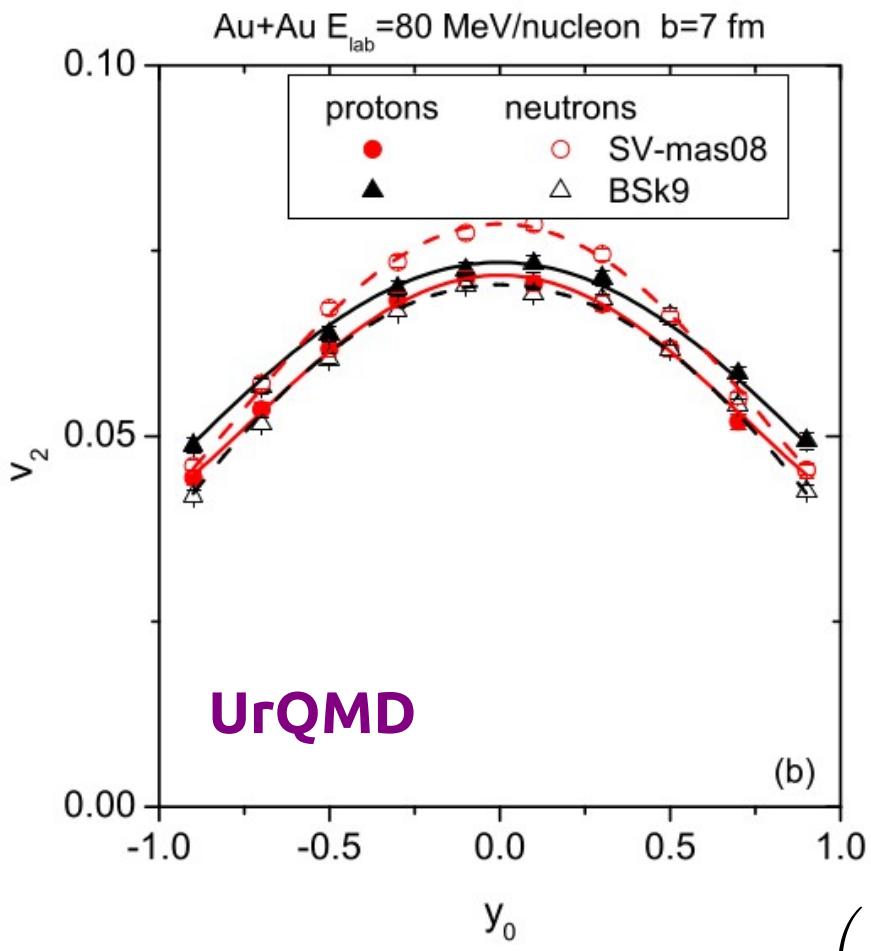
  - UrQMD : P.Russotto et al., PRC 94, 034608 (2016)
    C. Guo et al., PRC 91, 054615 (2015)
    C. Guo et al., PRC 90, 034606 (2014)
    Q. Li et al., PRC 83, 044617 (2011)
  - IQMD : see review from W. Reisdorf et al. (FOPI collaboration), Nuc. Phys. A 876 (2012)

Flow : directed and elliptic flow

$$v_1 \equiv \frac{dN}{}$$

- Bo
  - T
  - T
- Ac
  hig
  - I
  - I





→ ≠ in the slopes at mid-rapidity are observed with ≠ EOS parameterizations

$$y_0 = \left(\frac{y}{y_{proj}}\right)^{cm}$$

C. Guo et al., PRC 91, 054615 (2015)

Reaction plane reconstruction

- For this study, we will analyse the flow patterns by constructing a kinetic flow tensor on an event-by-event basis.

- Allow to associate an event shape/orientation from a set of N measured nuclei momenta ;
- Weighted flow tensor :

$$F_{ij} = \sum_{\nu=1}^{N} w_\nu p_i^\nu p_j^\nu \qquad i, j = x, y \text{ or } z \qquad w_\nu = \text{ weight given to a given nuclei } \nu$$

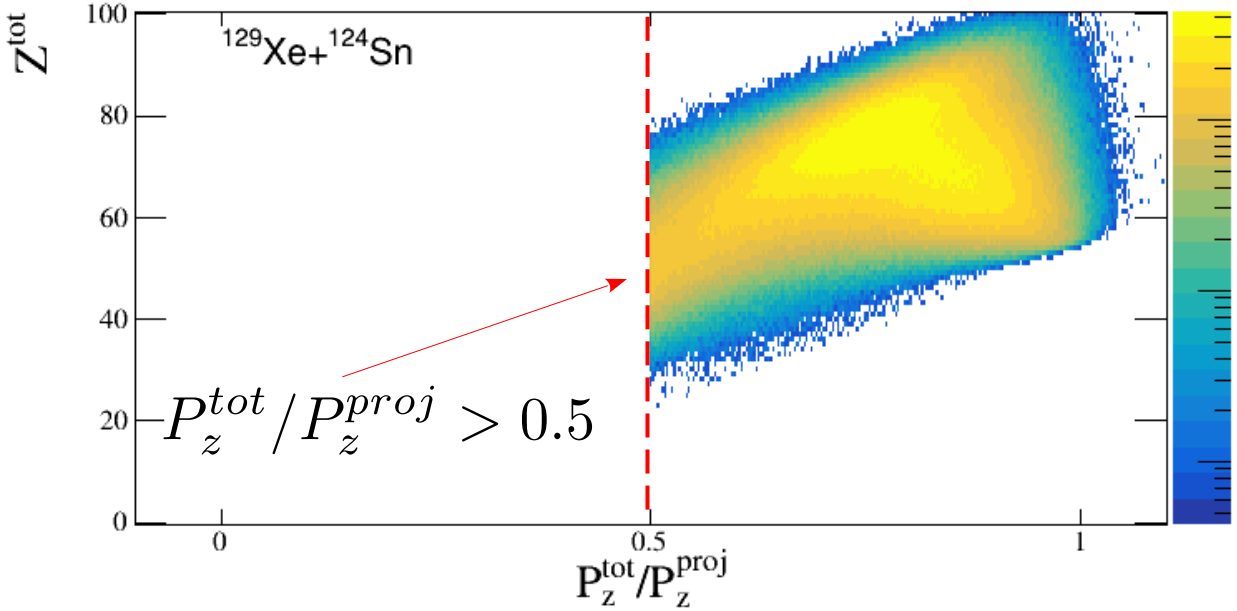
(see KVFlowTensor)

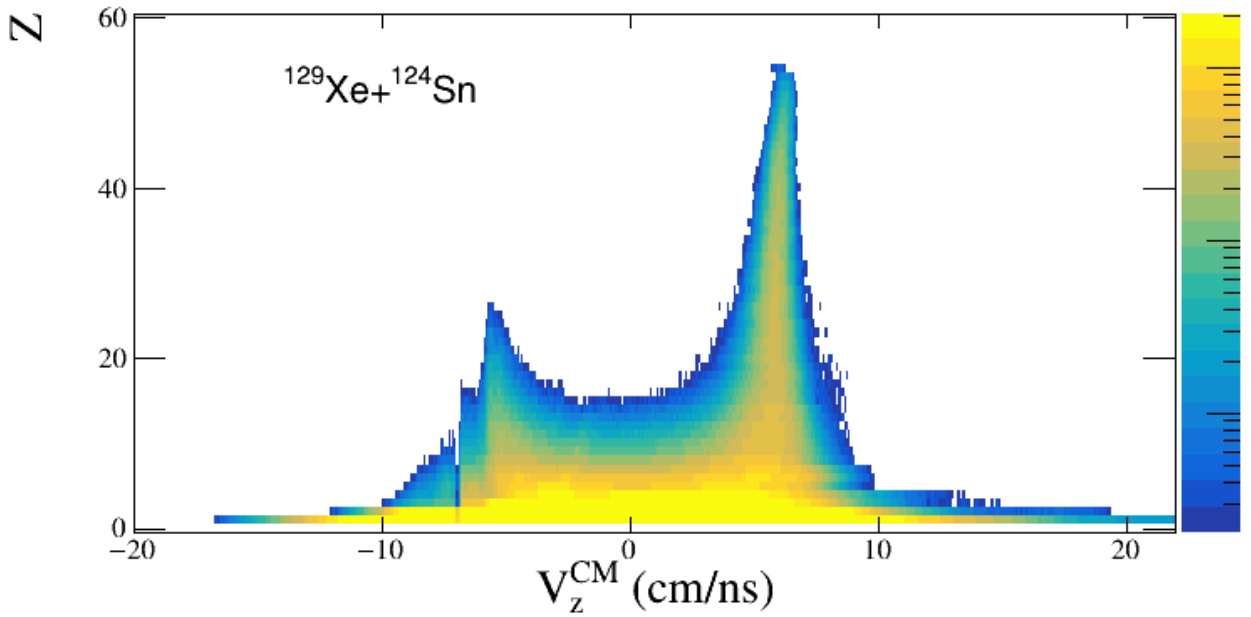
  - Diagonalisation of the tensor gives :
    - 3 orthogonal eigenvectors $(\vec{e}_1, \vec{e}_2, \vec{e}_3)$
    - 3 eigenvalues $\lambda_1 \geq \lambda_2 \geq \lambda_3$

- These values specifies the form of an ellipsoide in momentum space
  - In reaction CM ref. Frame
  - Need a completeness criterion to select events where a large portion of the products is detected

Gyulassy *et. al*, Phys. Lett. B 110 (1982)

Application INDRA@GSI : Event selection





→ Remove around 50% of the full statistics

Centrality selection

"exp-centrality"

$$c_x \equiv \int_x^{+\infty} P(X)\, dX$$

increasing X with decreasing b

$$X = M_{tot} \text{ or } Et_{12}$$

Sampling of 10% steps in centrality

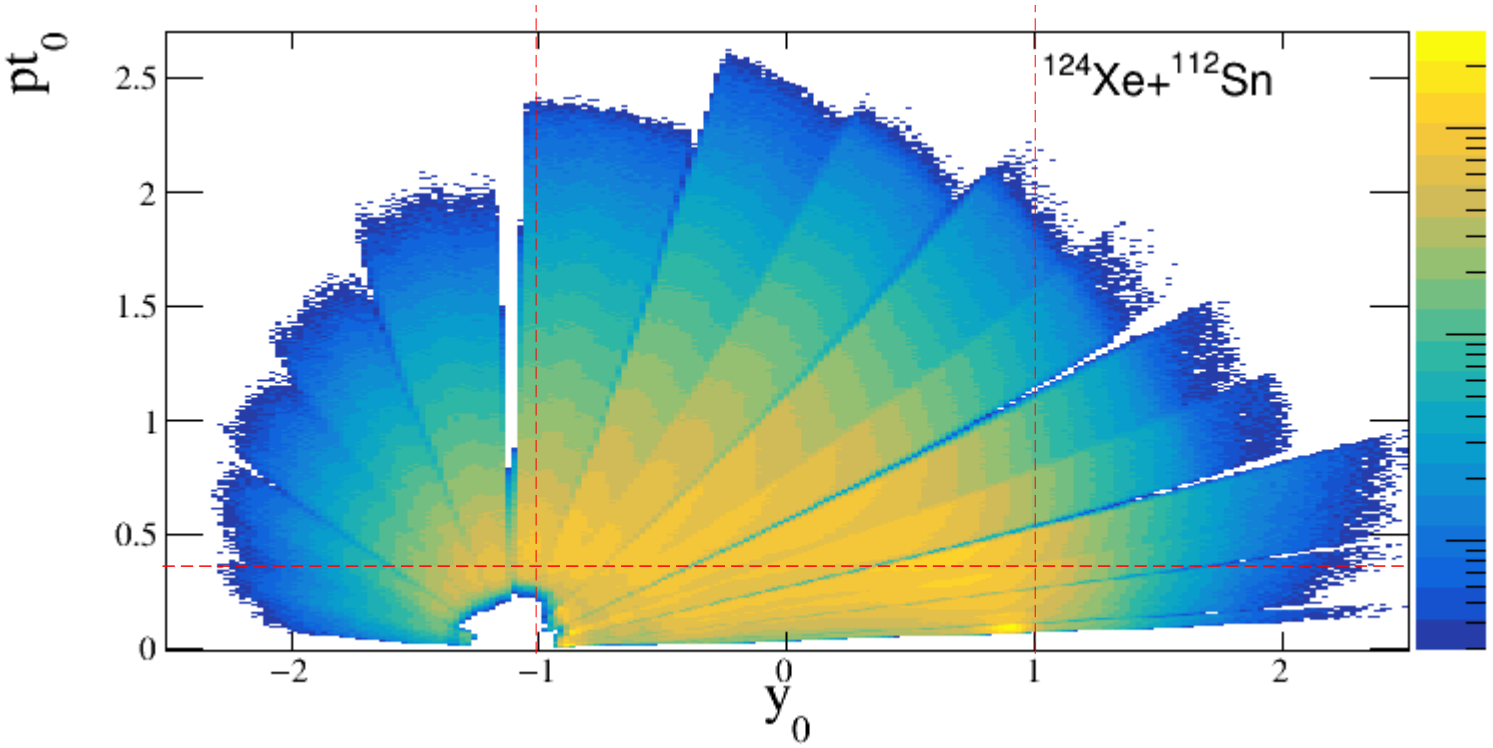
To be used for impact parameter distribution estimation
(see Frankland et al., PRC 104, 034609

Application INDRA@GSI : Event selection

$$pt_0 = \frac{pt/A}{pt^{cm}_{proj}/A_{proj}} \qquad y_0 = \left(\frac{y}{y_{proj}}\right)^{cm}$$

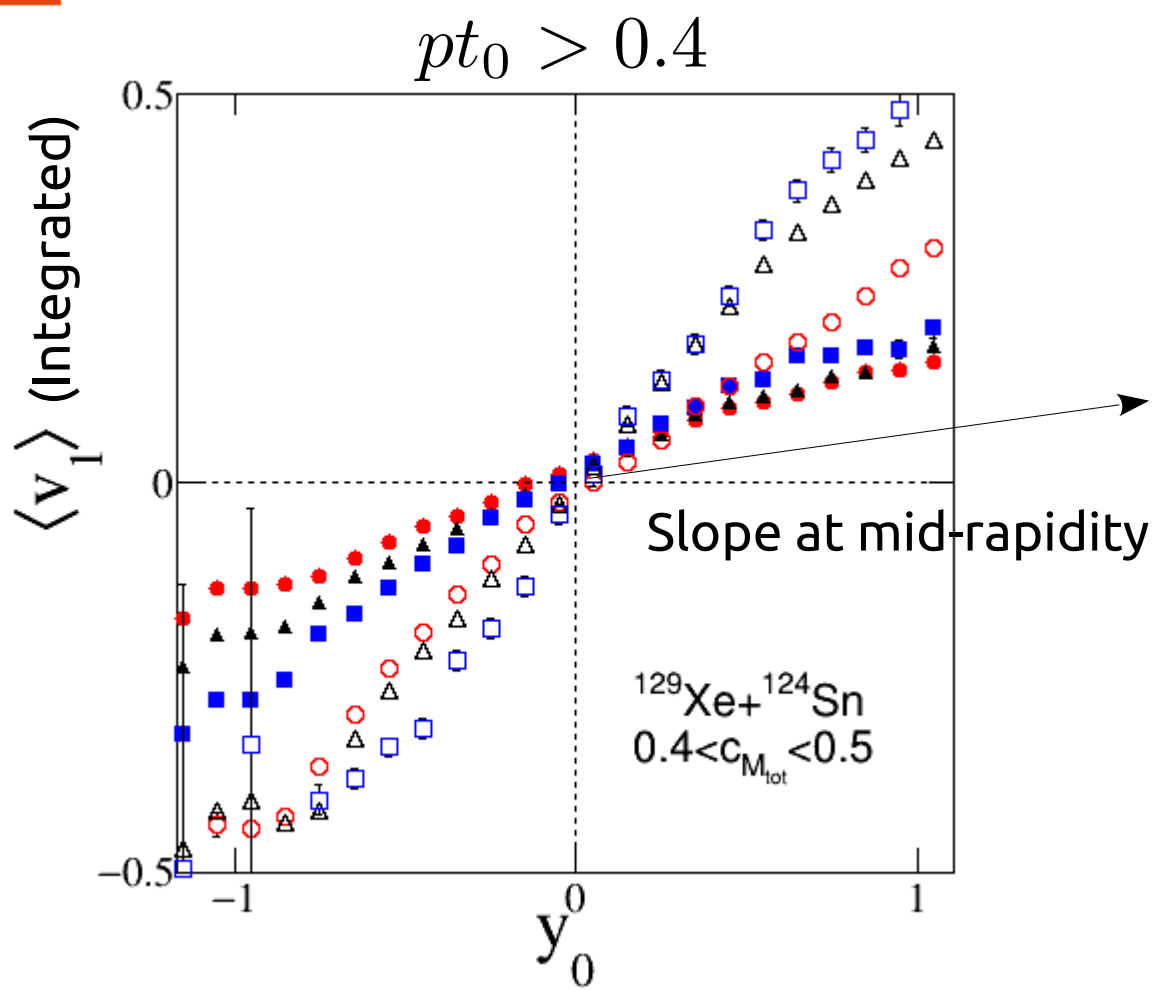
Directed and elliptic flow are usually studied as a function of the reduced rapidity or reduced transverse momentum

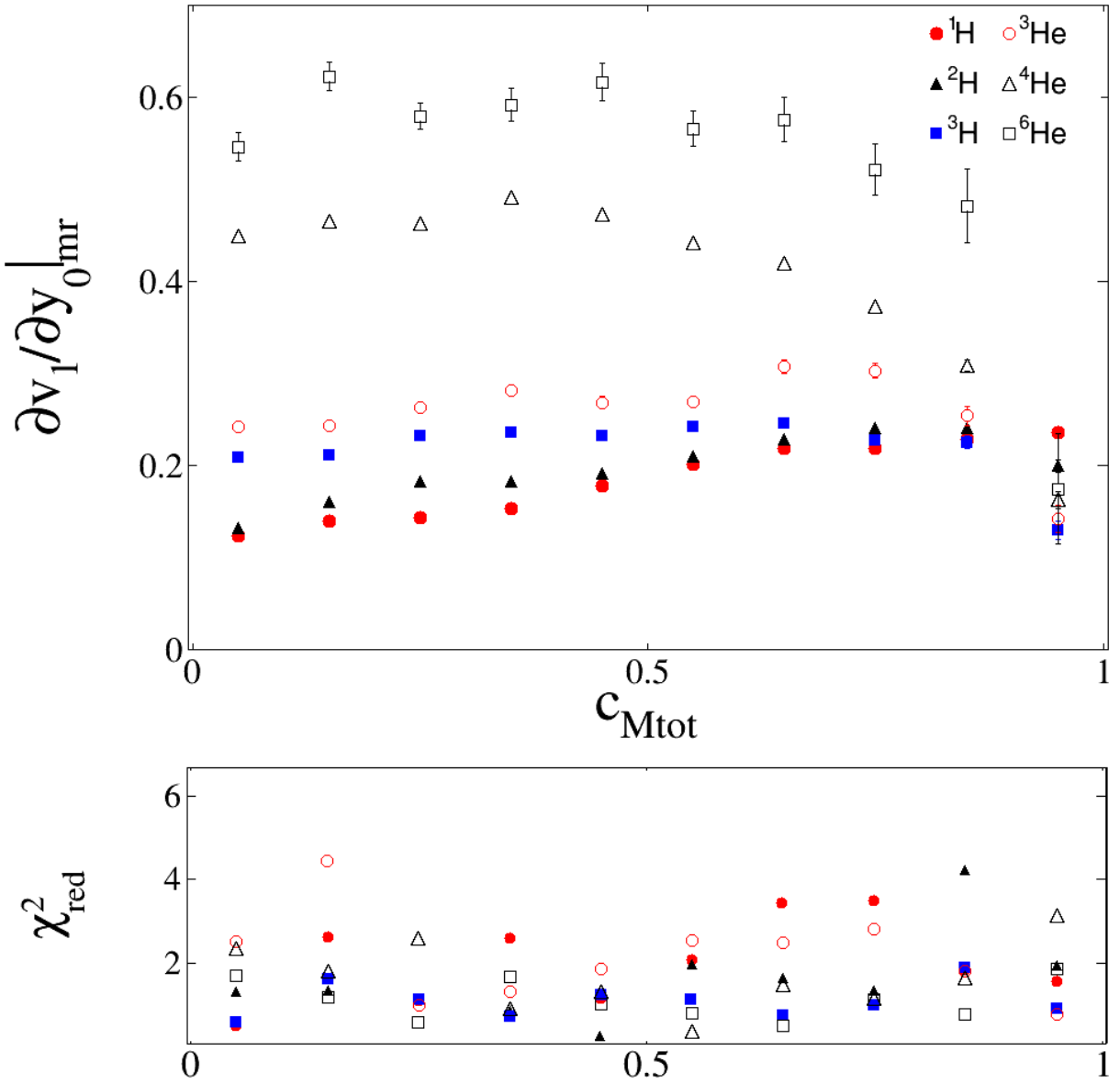
Most of the analysis apply cuts on those observables :
- to pin down region of maximum flow values
- to correct from acceptance effect that would break the (a)symmetry of v1 and v2



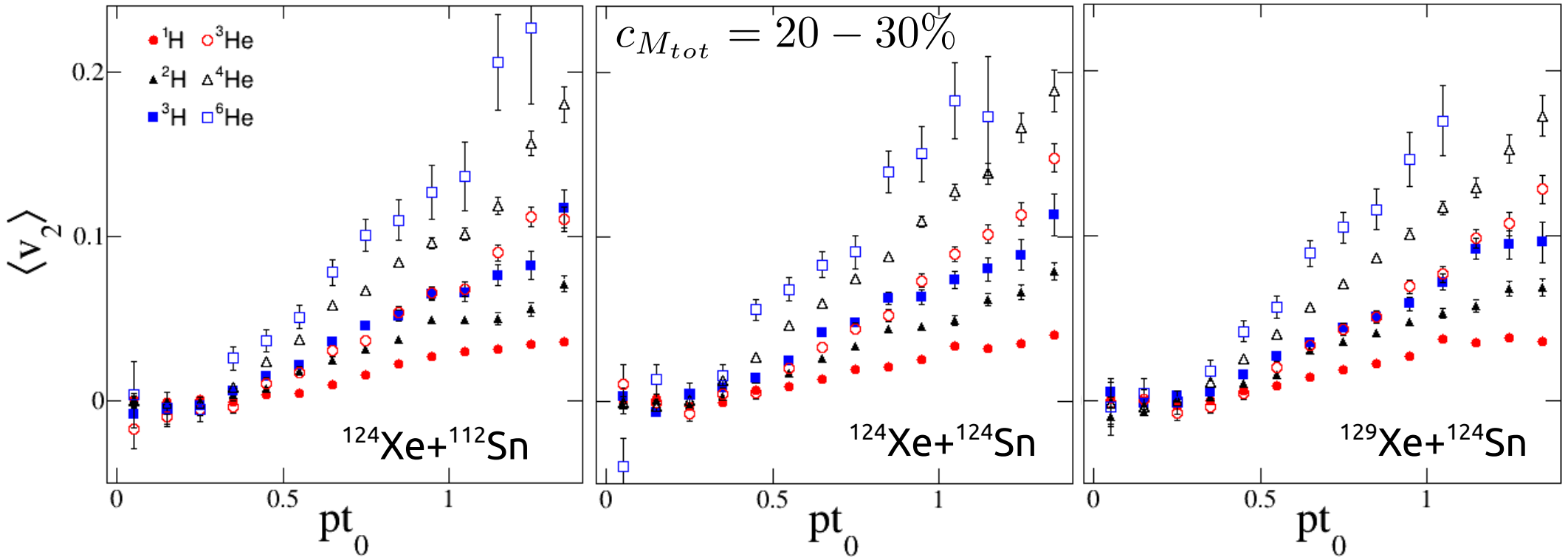
W. Reisdorf et al. (FOPI collaboration), Nuc. Phys. A 876 (2012)
Andronic et al.,

Application INDRA@GSI : directed flow





Application INDRA@GSI : elliptic flow



→ To be investigated...