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NZ equilibration in two and three bodies dynamically deformed nuclear systems

(^{70}Zn+ ^{70}Zn @ 35 MeV/nucleon)

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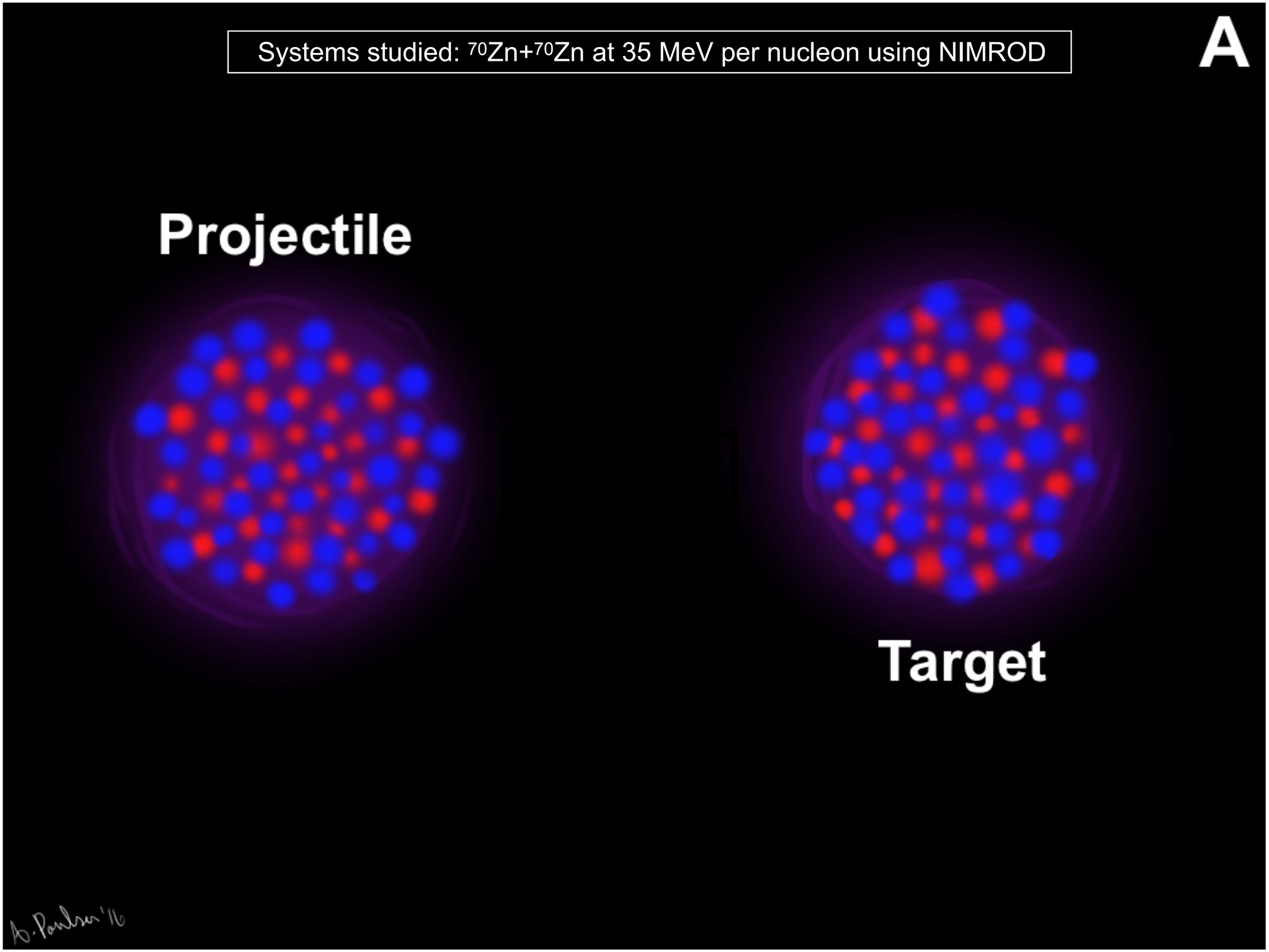
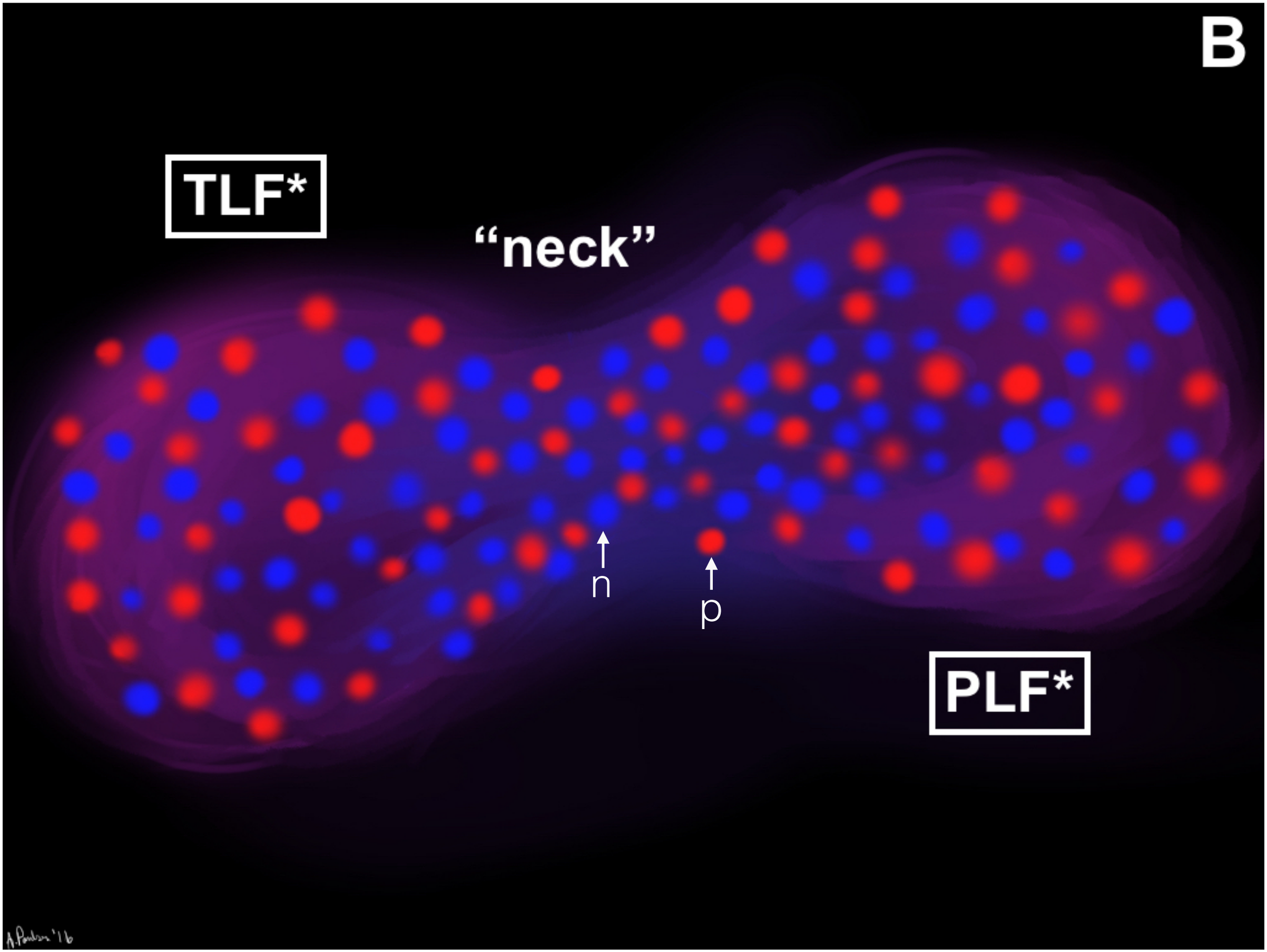
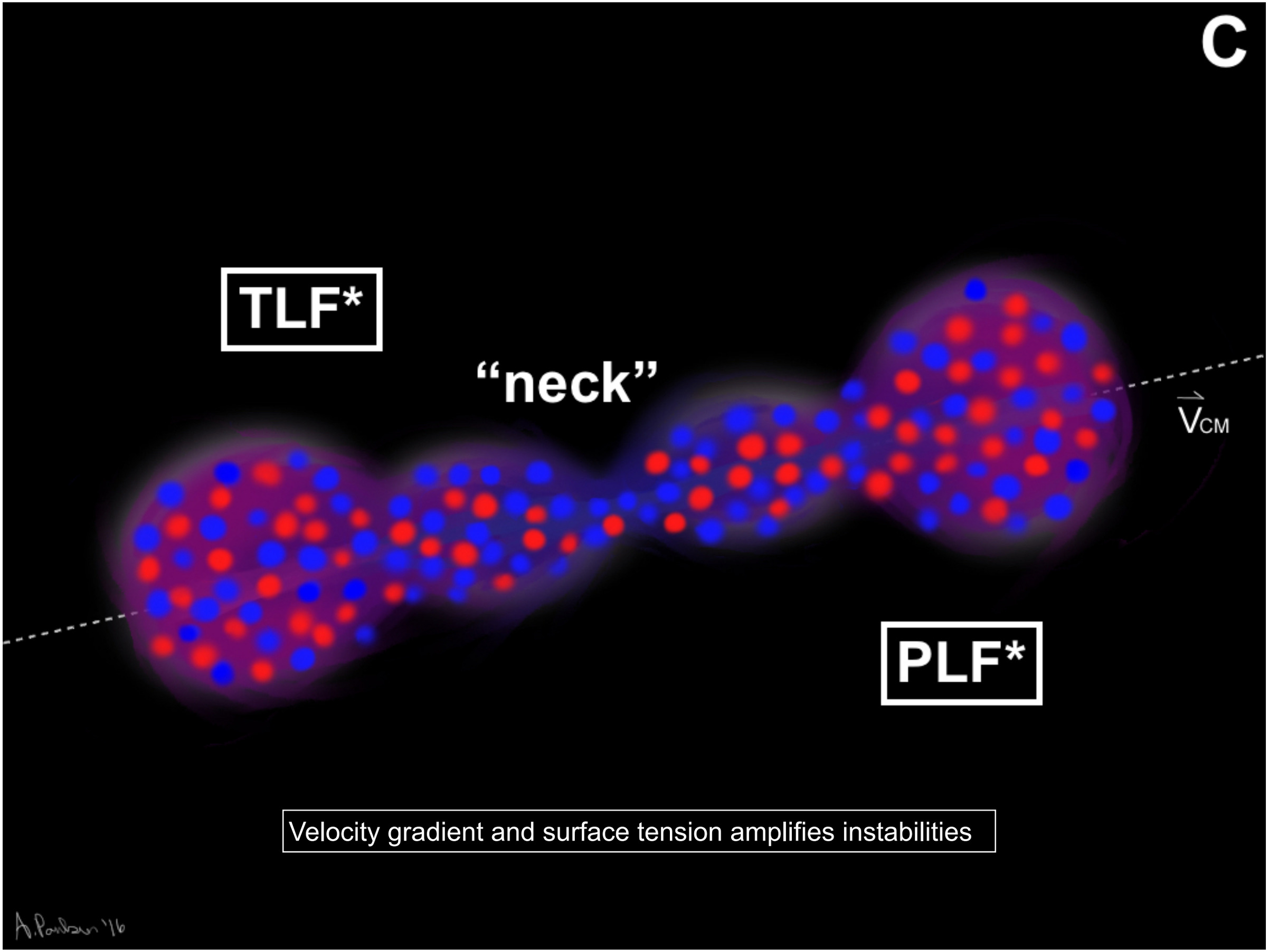
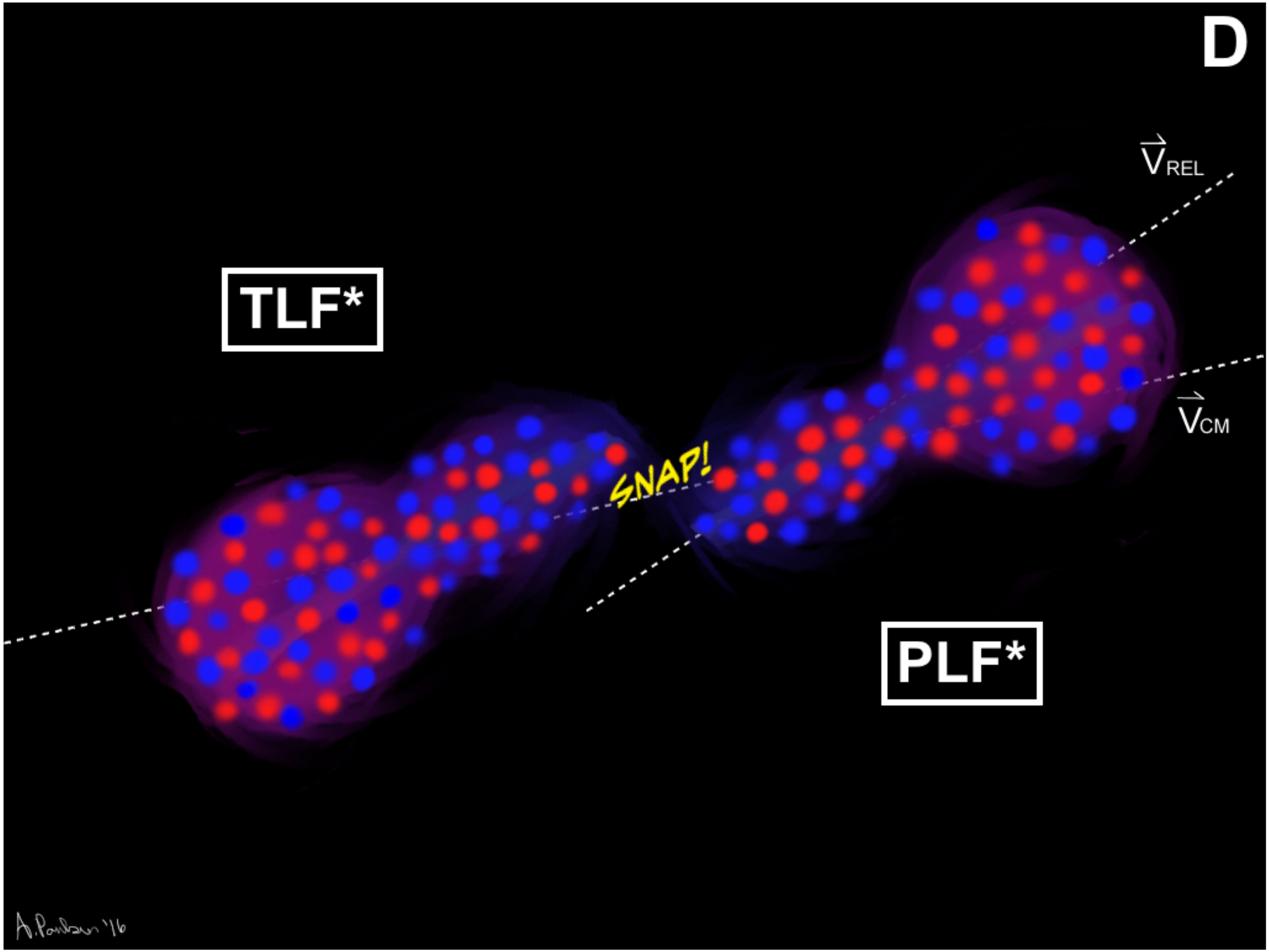
Systems studied: $^{70}Zn+^{70}Zn$ at 35 MeV per nucleon using NIMROD

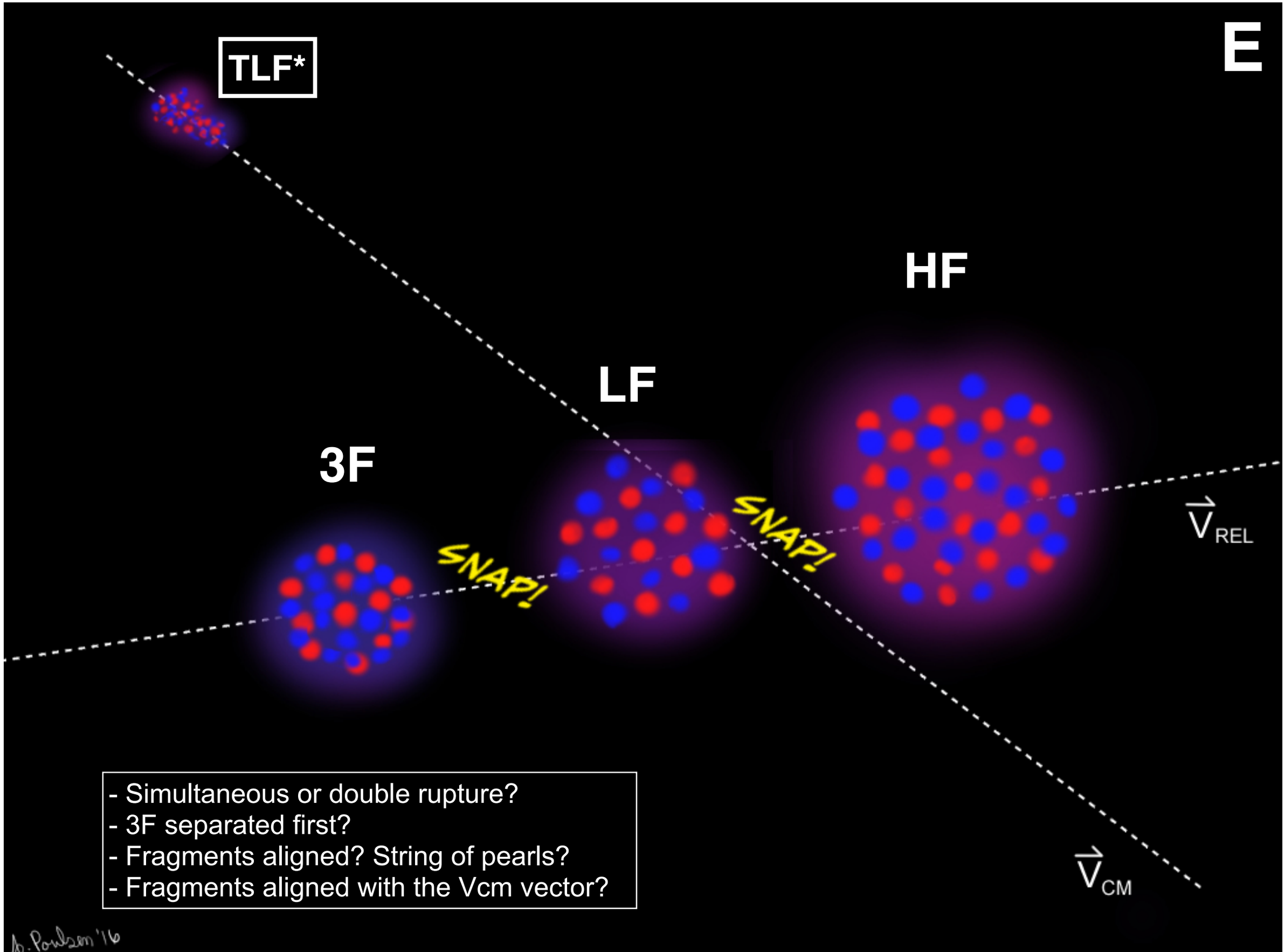
A




B
TLF*
“neck”
n
p
PLF*


C
TLF*
"neck"
$\vec{V}_{CM}$
PLF*
Velocity gradient and surface tension amplifies instabilities


D
$\vec{V}_{REL}$
TLF*
$\vec{V}_{CM}$
SNAP!
PLF*
A. Poulsen '16


E
TLF*
HF
LF
3F
SNAP!
SNAP!
$\vec{V}_{REL}$
$\vec{V}_{CM}$
- Simultaneous or double rupture?
- 3F separated first?
- Fragments aligned? String of pearls?
- Fragments aligned with the Vcm vector?

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Previously on NZ equilibration…

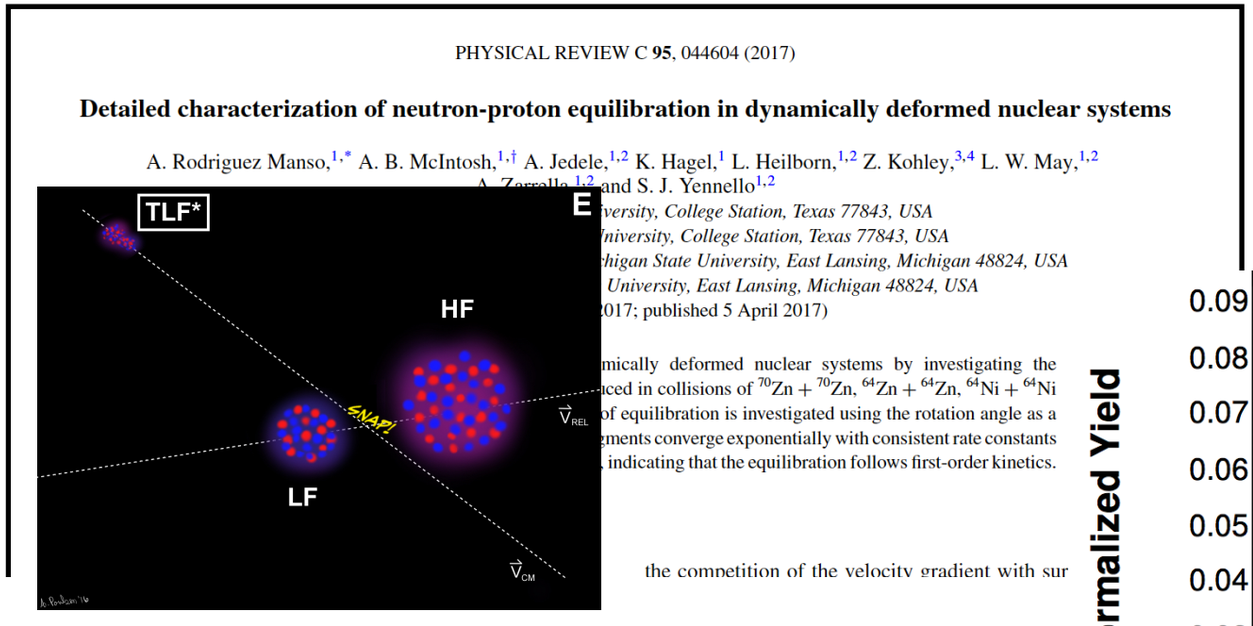
Time-dependence of NZ equilibration examining composition of HF-LF emitted from PLF* vs the breakup alignment angle (serves as clock for equilibration)

Variation of composition vs alignment angle shows exponential behavior for LF & HF, suggesting 1st-order kinetics, for all systems studied

Yield and measured composition, used to extract an estimate for purely dynamical component

Small systematic effects in composition for reactions of relatively n-poor projectile with n-rich target

No significant differences in rate cts between systems of different initial composition


PHYSICAL REVIEW C **95**, 044604 (2017)

Detailed characterization of neutron-proton equilibration in dynamically deformed nuclear systems

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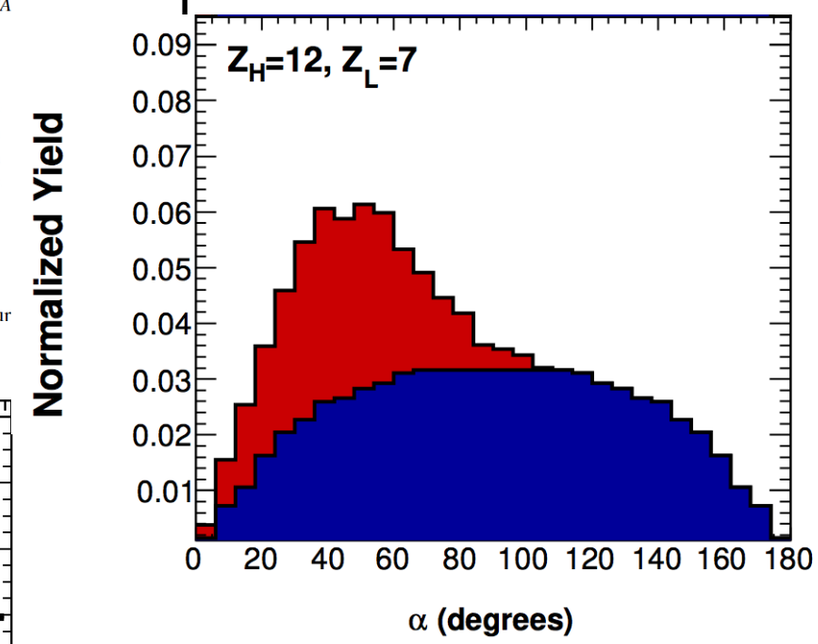
…higan State University, East Lansing, Michigan 48824, USA
… University, East Lansing, Michigan 48824, USA
…2017; published 5 April 2017)

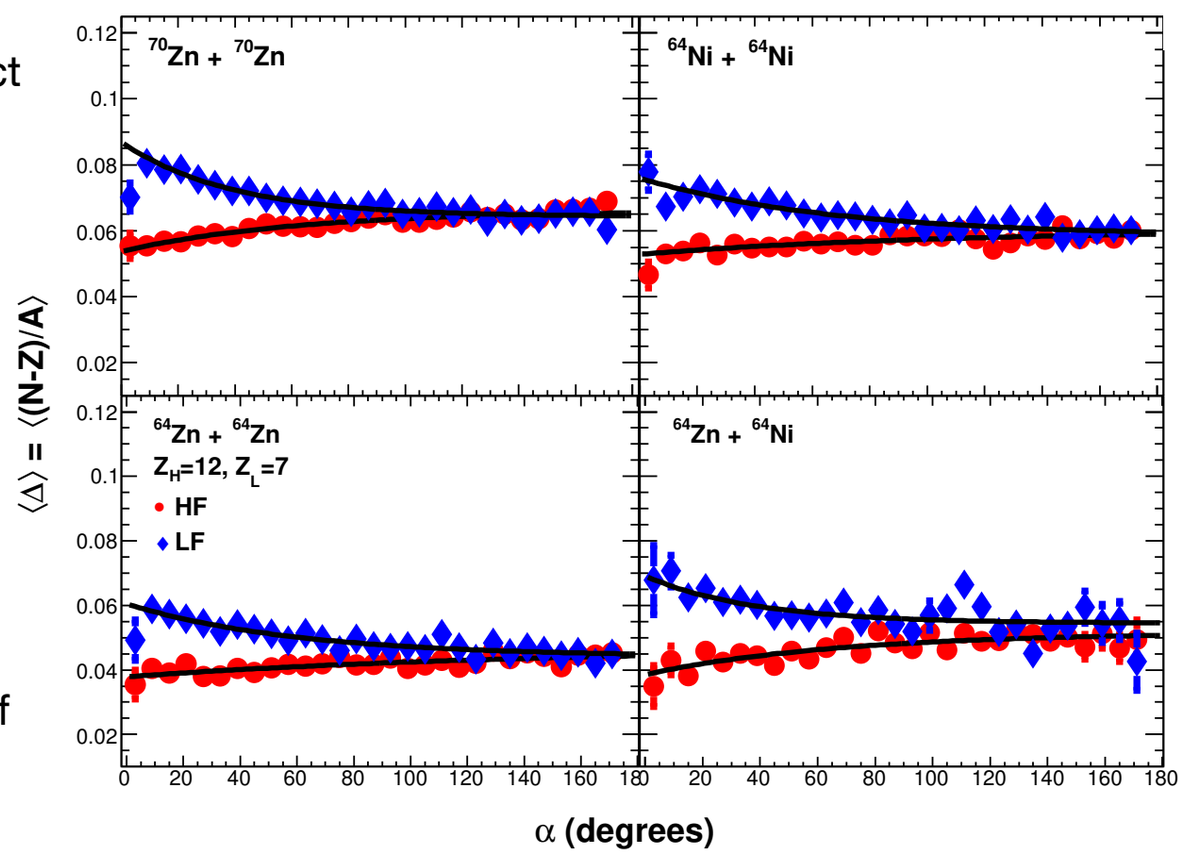
…mically deformed nuclear systems by investigating the …ced in collisions of ^{70}Zn + ^{70}Zn, ^{64}Zn + ^{64}Zn, ^{64}Ni + ^{64}Ni …of equilibration is investigated using the rotation angle as a …gments converge exponentially with consistent rate constants … indicating that the equilibration follows first-order kinetics.

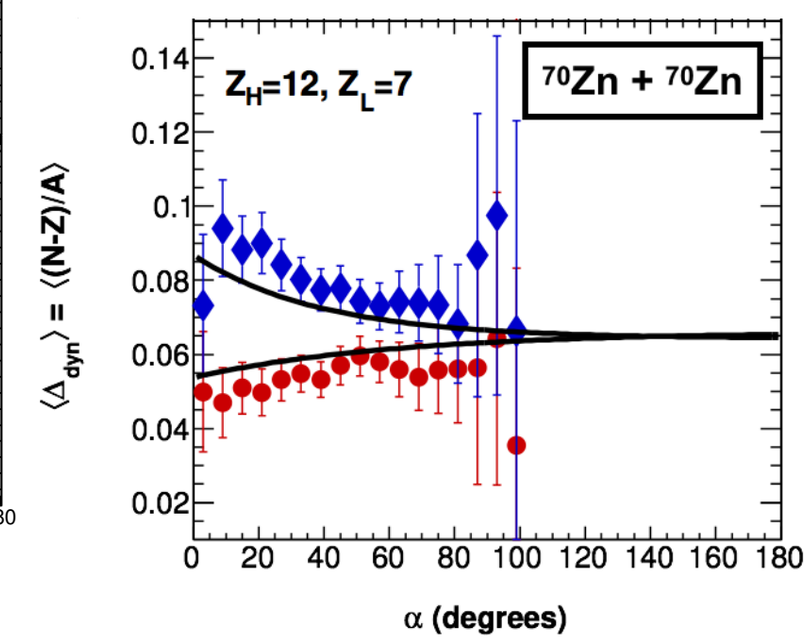
…the competition of the velocity gradient with sur

PRL 118, 062501 (2016)

PRC 95, 044604 (2017)

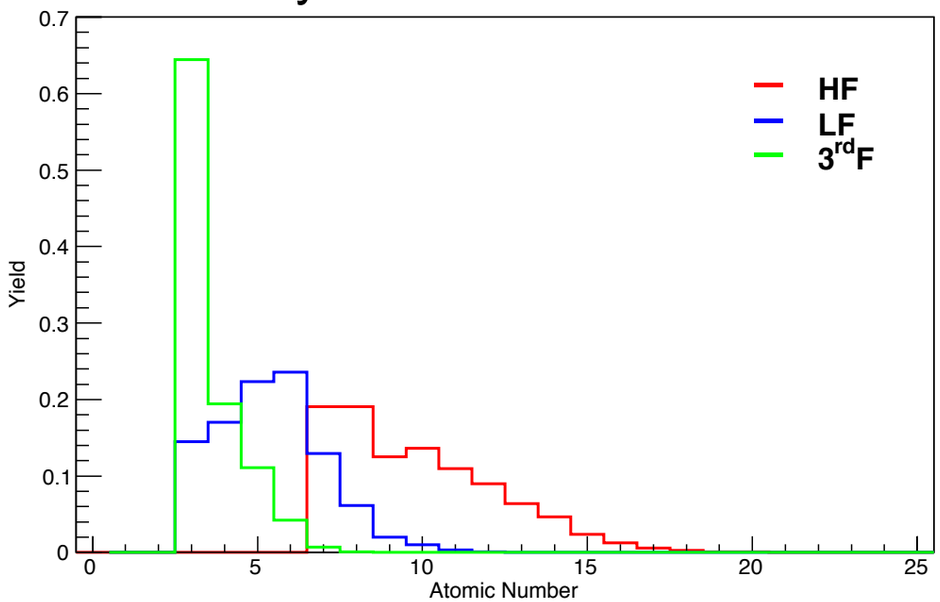


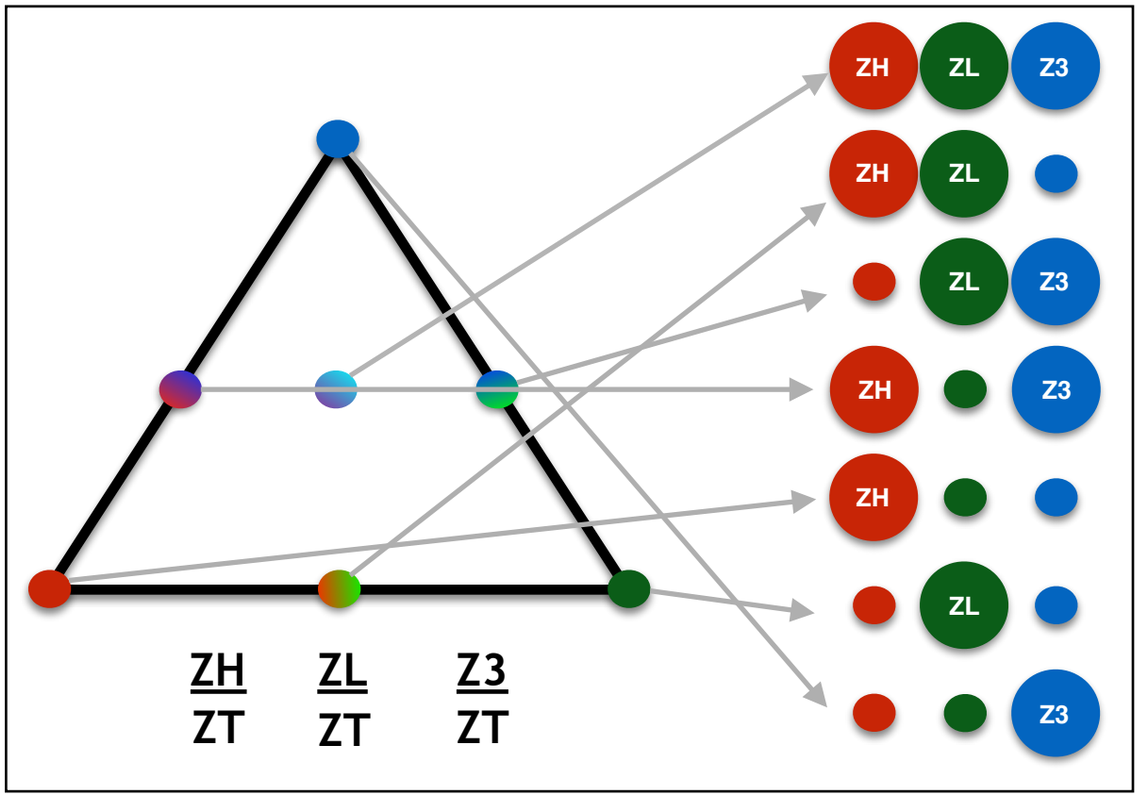




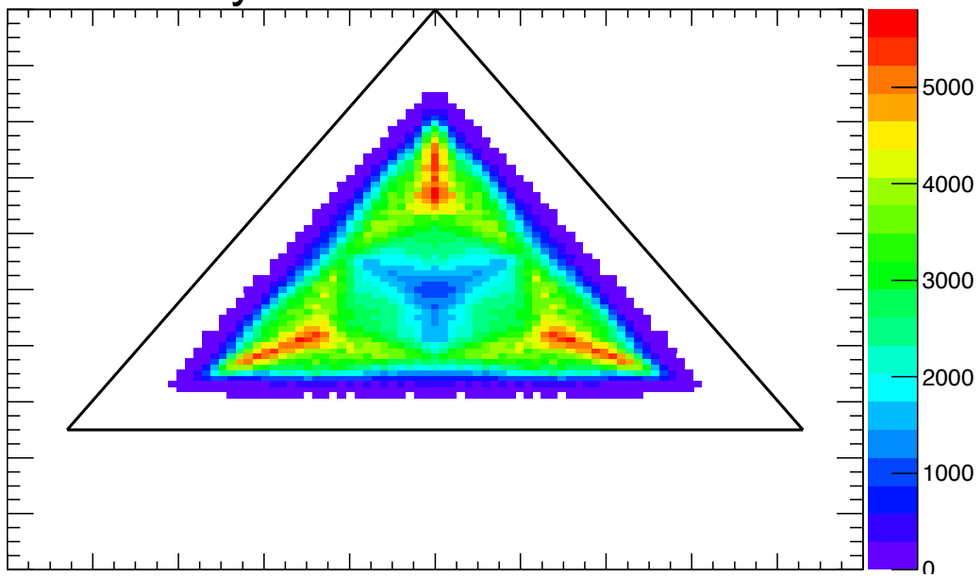
Symmetrize Dalitz plot

Preliminary





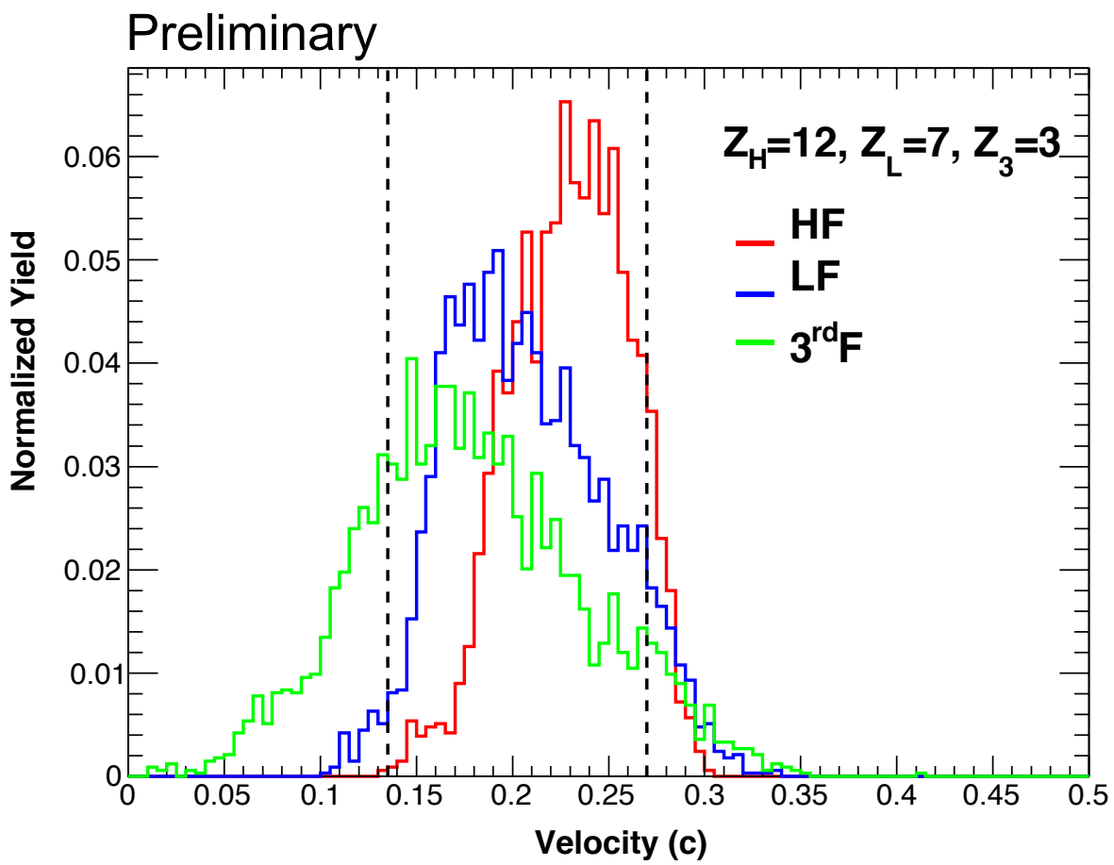
Preliminary



2Z's are approximately equal
1Z is different (and bigger)

Velocity distributions of HF, LF and 3F

- Dashed lines = beam velocity (i.e. 0.27c) and mid-velocity (i.e. 0.13c).
- The three of them peaked above mid-velocity (indicating that HF, LF and 3F originate from the PLF*).
- LF (3F) produced at velocities > than mid-velocity and < than the HF (LF). HF produced closer to beam velocity.



Hierarchy in the velocity distributions (correlated to the charge sorting):

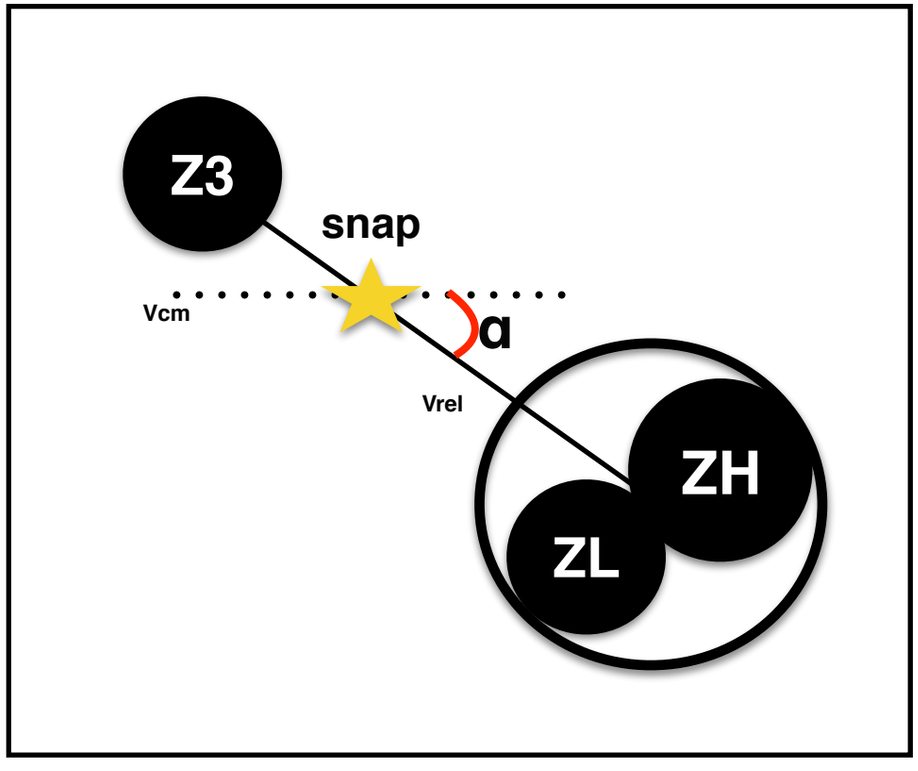
HF forward from LF, and both are forward respect to 3F.

Rupture scenarios:

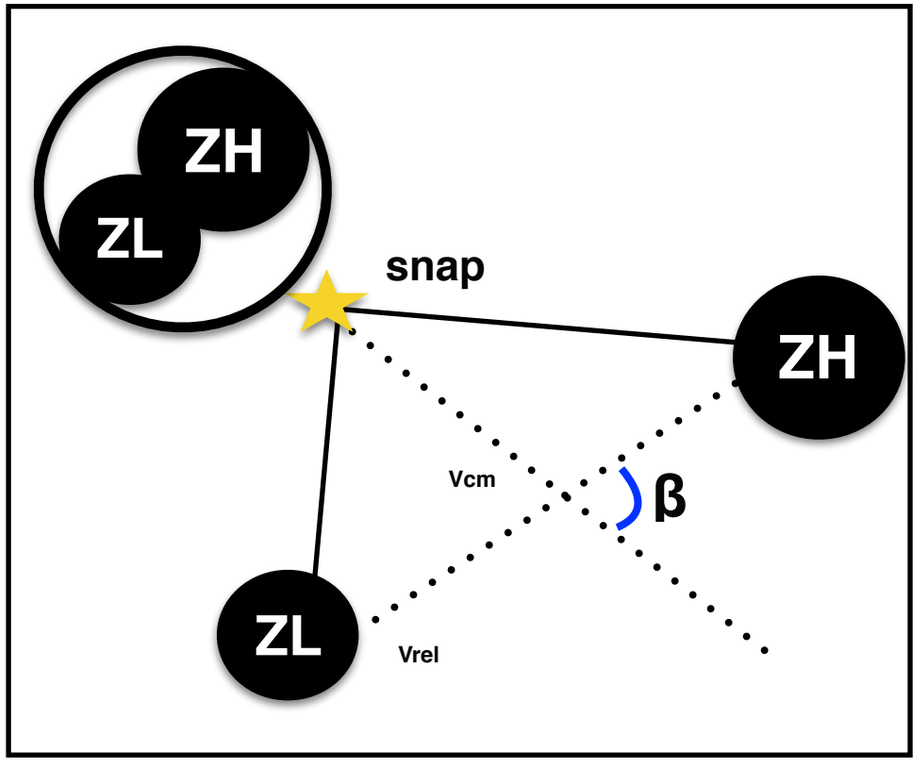
Who is separating first ?

Example of the rupture scenario where Z3 separates first

First rupture

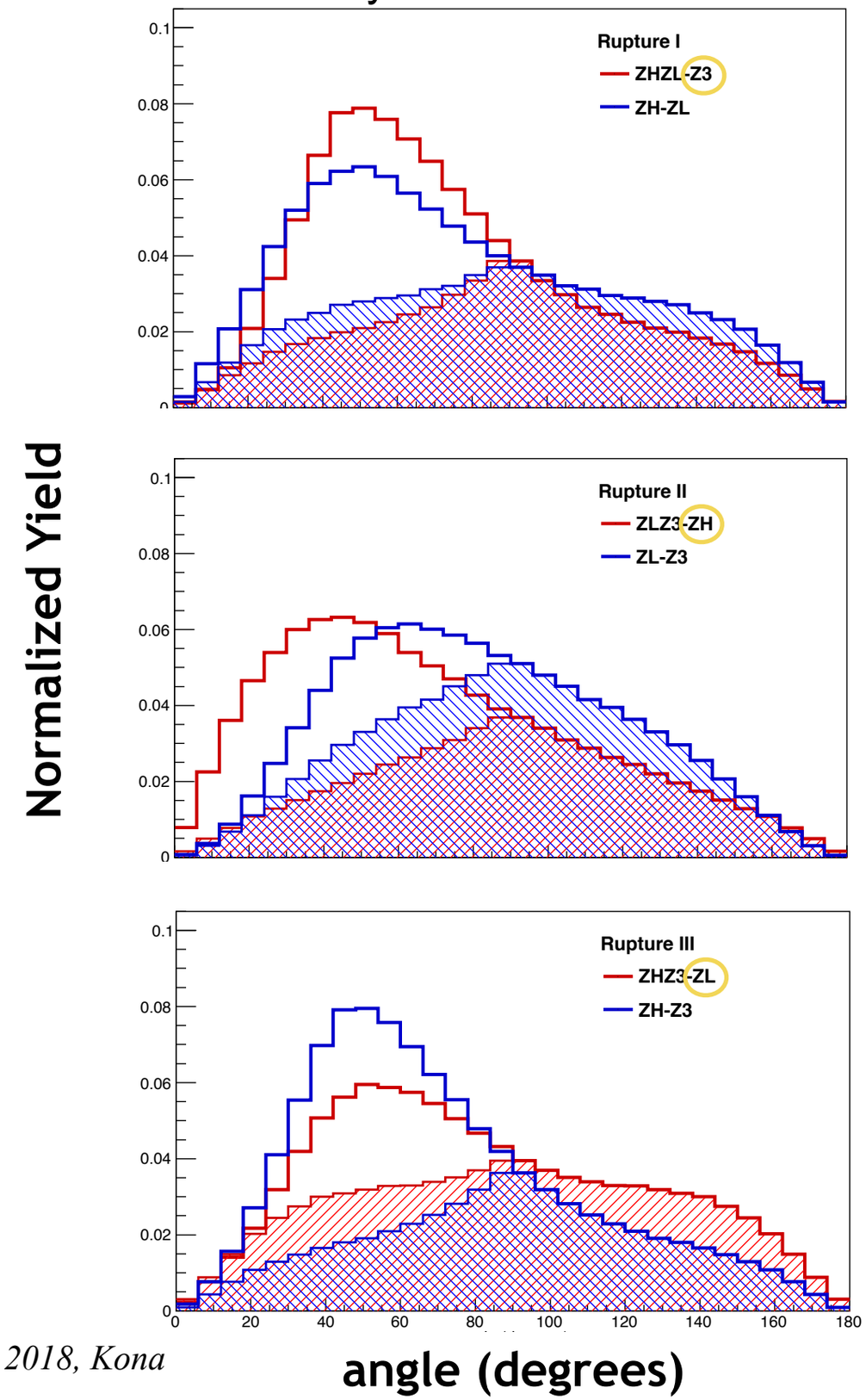


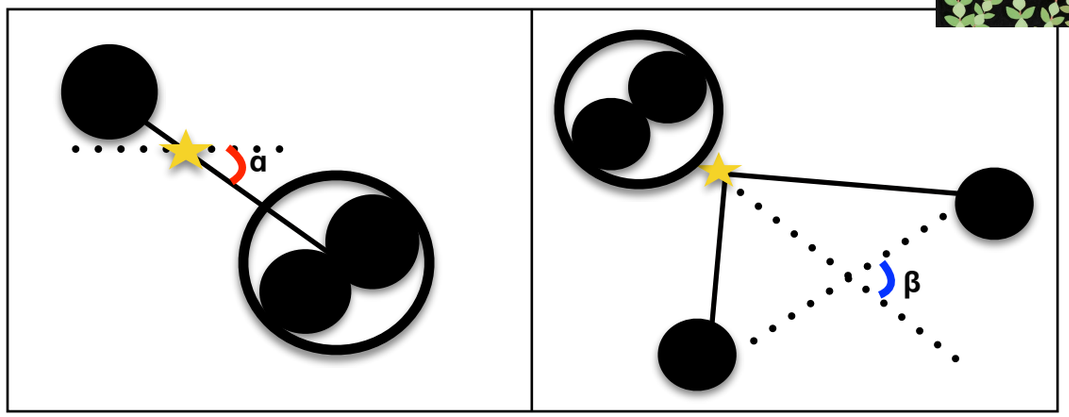
Second rupture



Rupture scenarios: Angular distributions

Preliminary



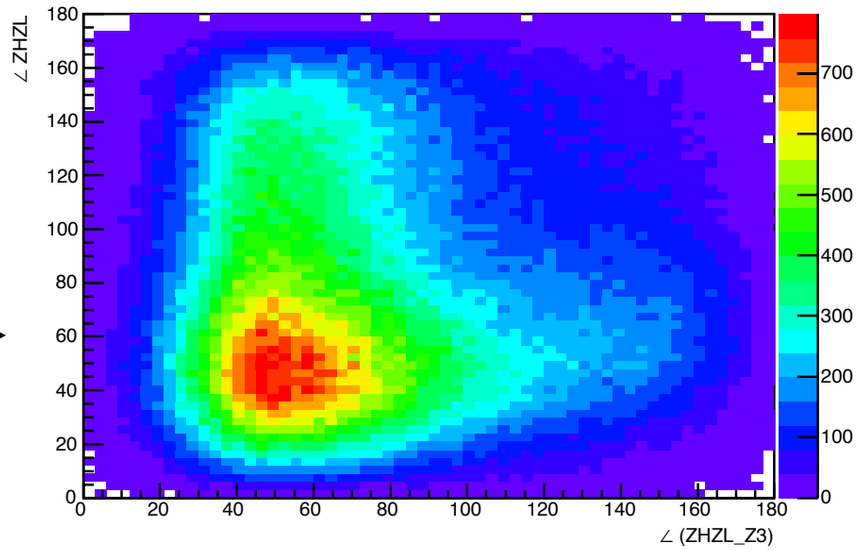


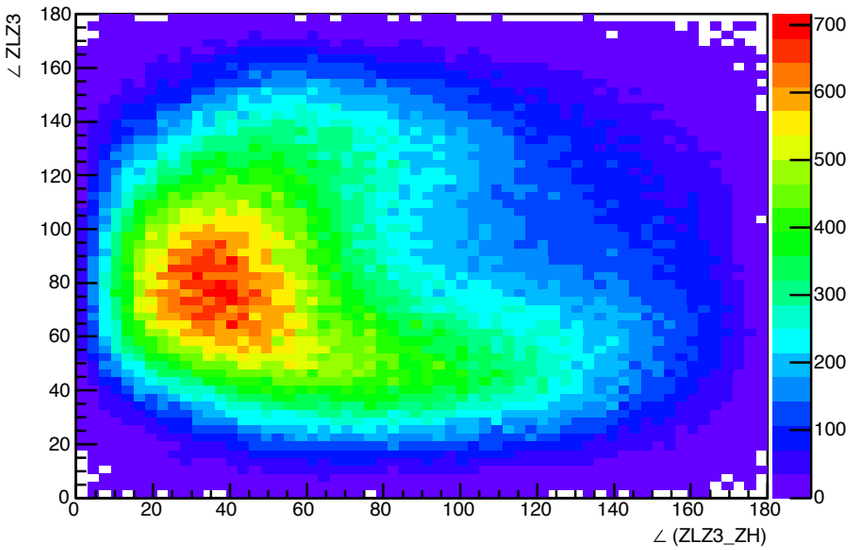
- Statistical contribution (color hatches)
- ZH forward from ZL, and both forward from Z3
- Peak in the angular yield when Z3 and ZL separate first
- When ZH separates first, the dynamical contribution seems to be smaller that when Z3 or ZL separate first

Rupture scenarios: correlations between the angles of both breakings

Another way to show the angular correlation

More dyn-dyn and dyn-stad combinations

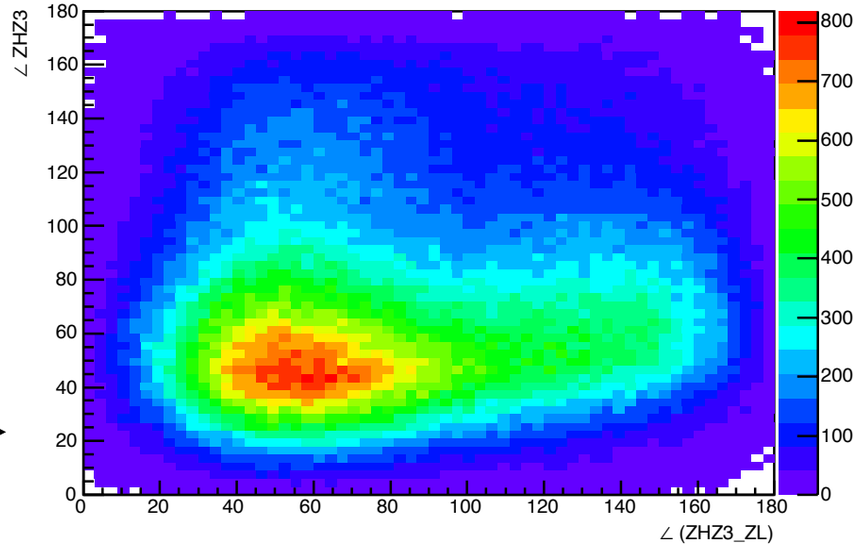


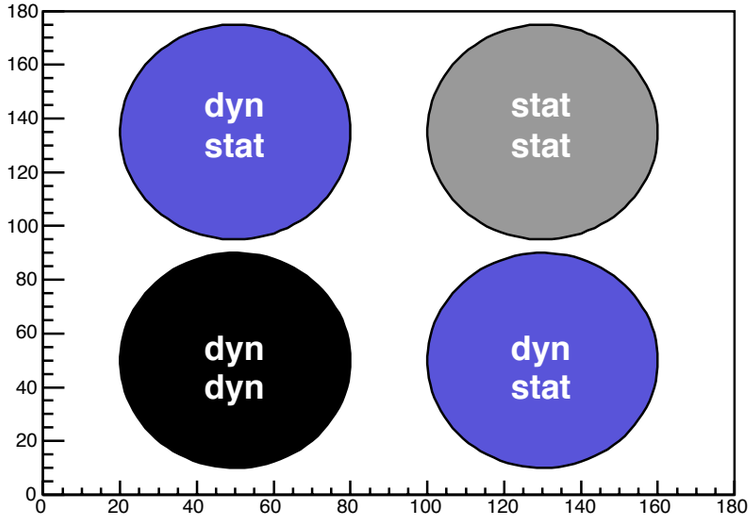


More stad-dyn combinations

Preliminary

More dyn-dyn and stad-dyn combinations



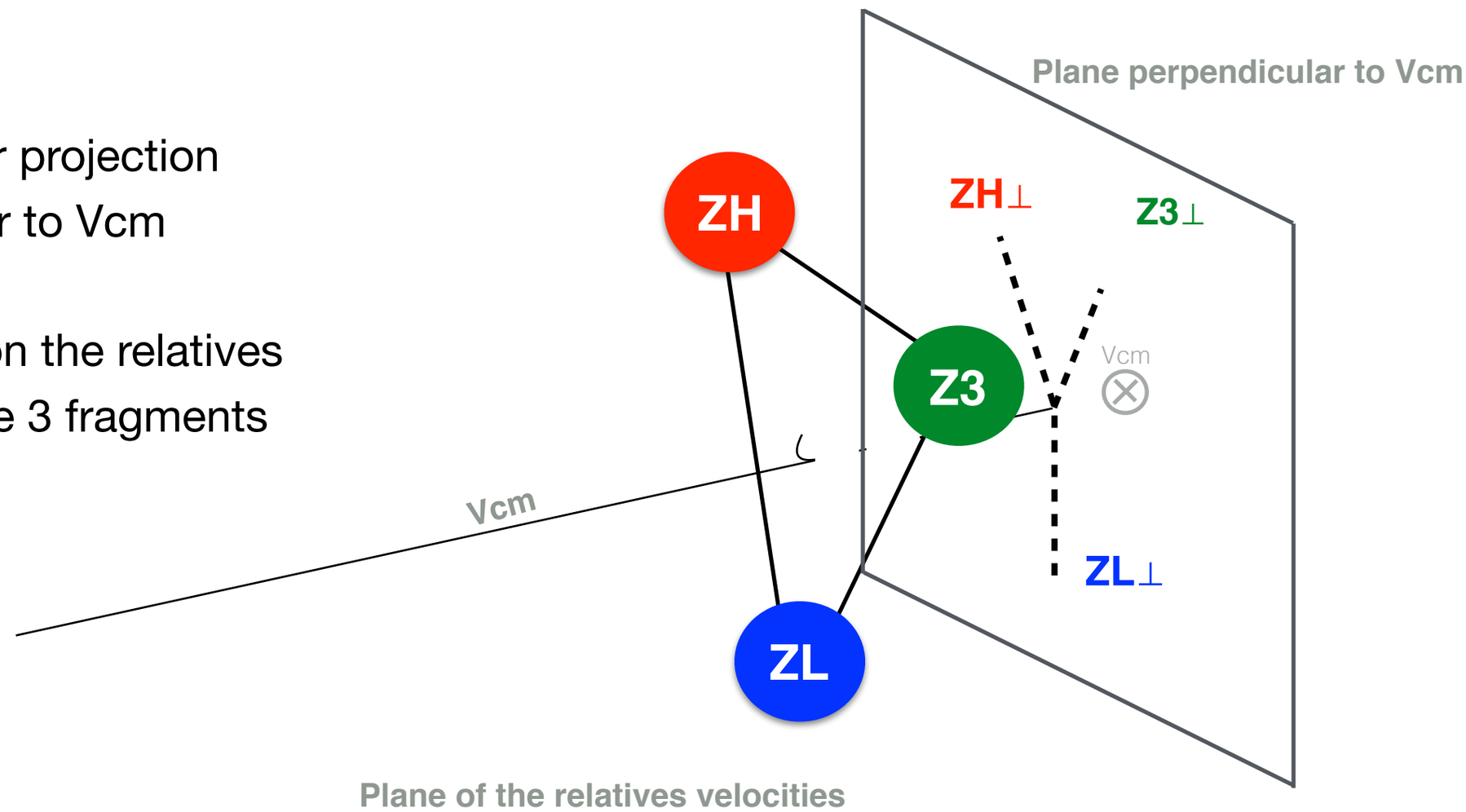


Looks like HF is not separating first

Angles between the relatives velocities & Angle between the projections of HF, LF and 3F velocities, in a plane perpendicular to Vcm

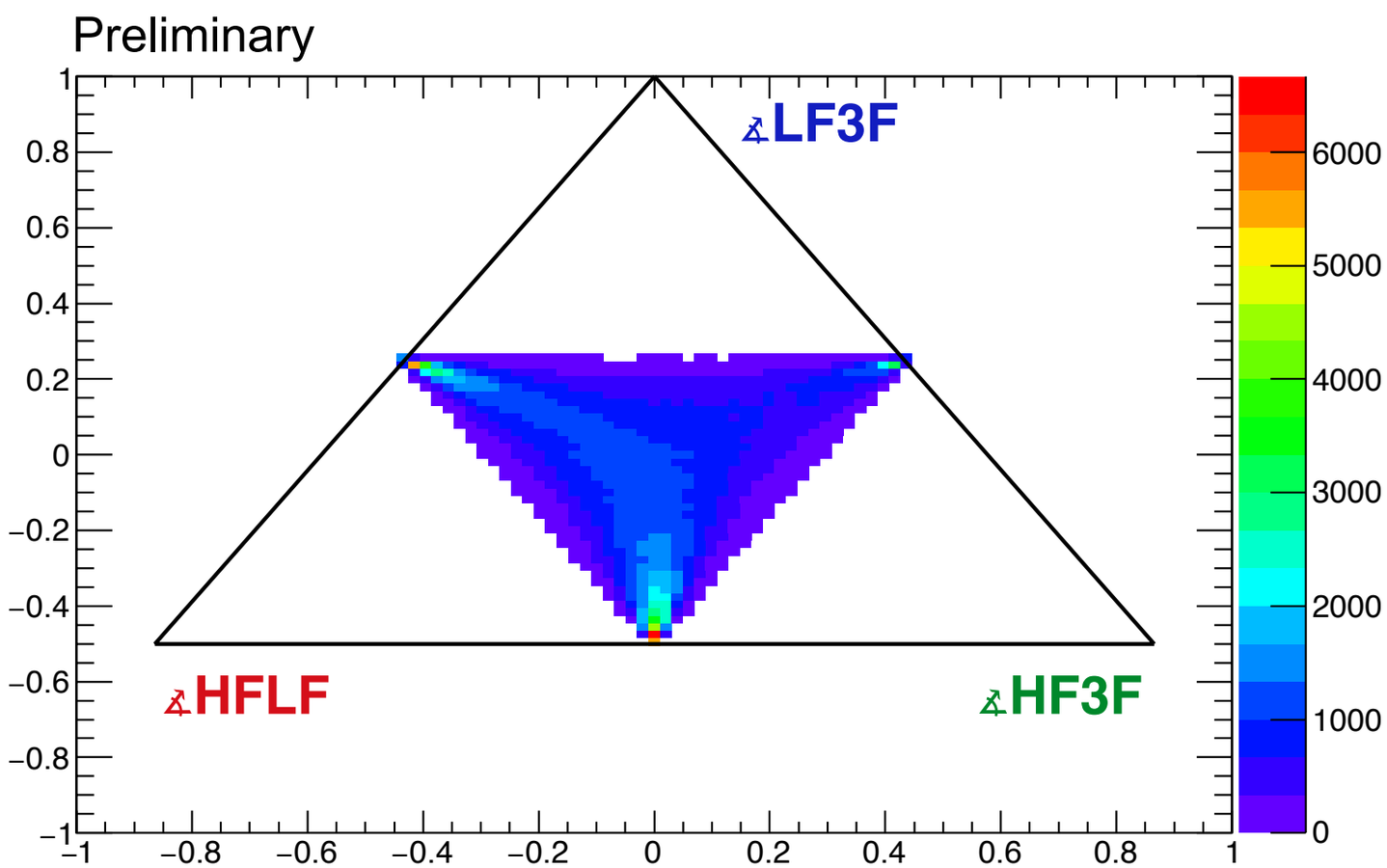
Cartoon of a plane perpendicular to Vcm and a plane formed by the three fragments

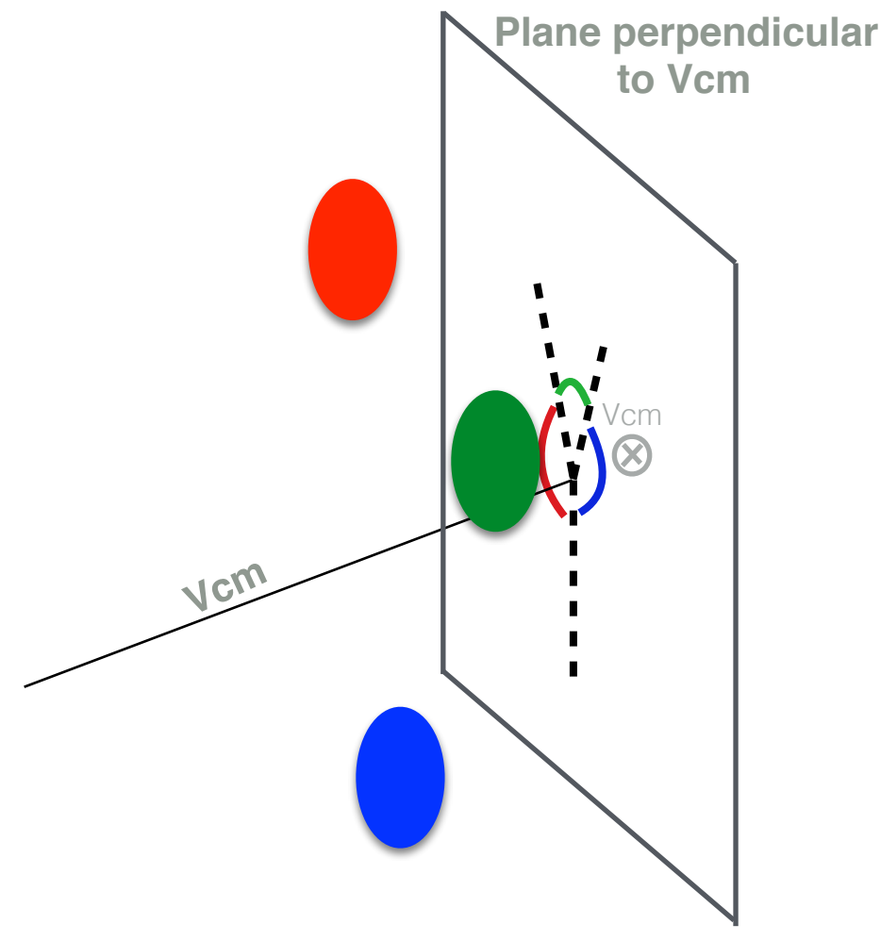
asymmetric angular projection
plane perpendicular to Vcm
+
symmetric angles on the relatives
velocity plane of the 3 fragments
↓
?



Angles between the projections of HF, LF and 3F velocities, in a plane perpendicular to Vcm

The majority of events populate combinations of (180°,0°,180°)

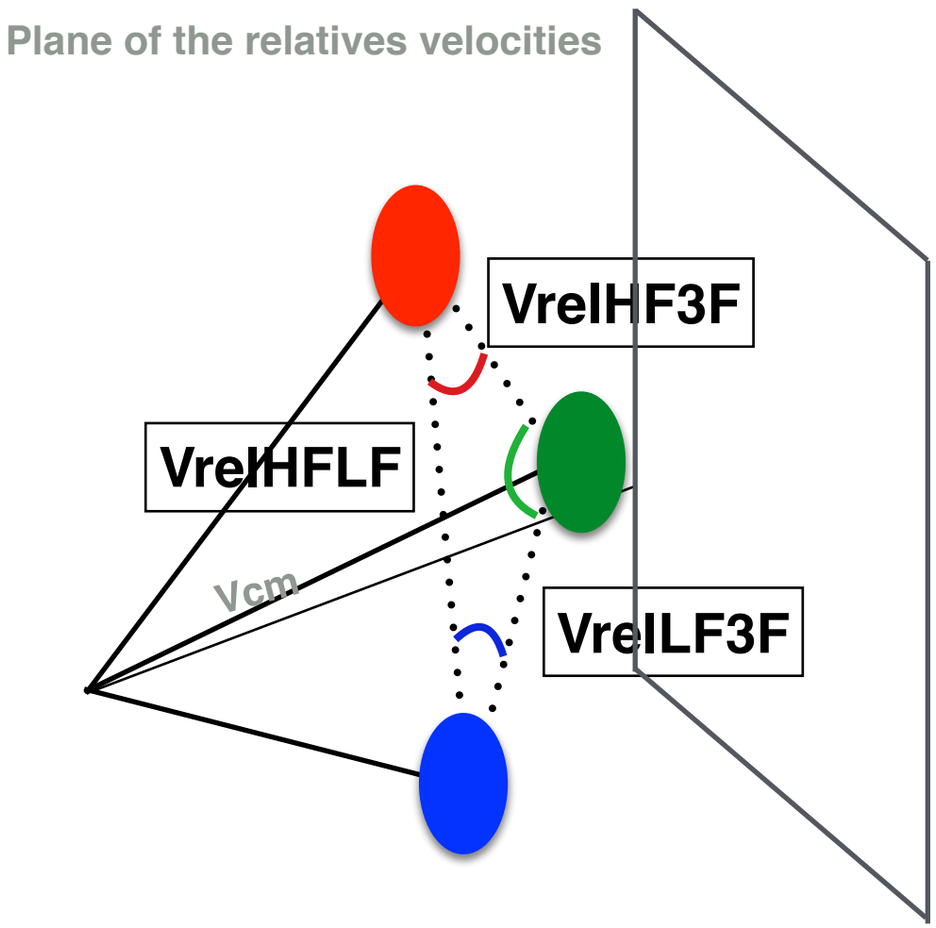


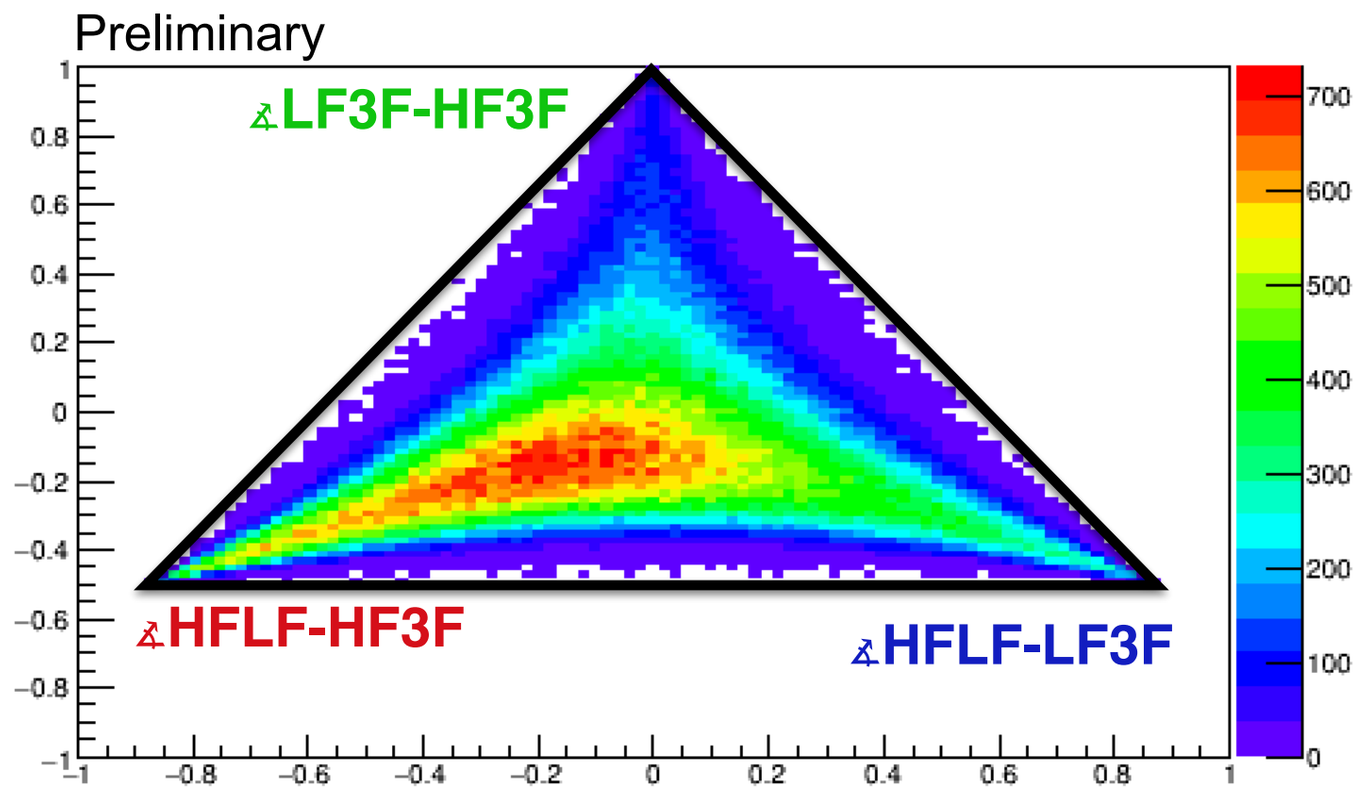


➜ Two fragments are closer to each other, and apart from the other one.

Angles between the relatives velocities

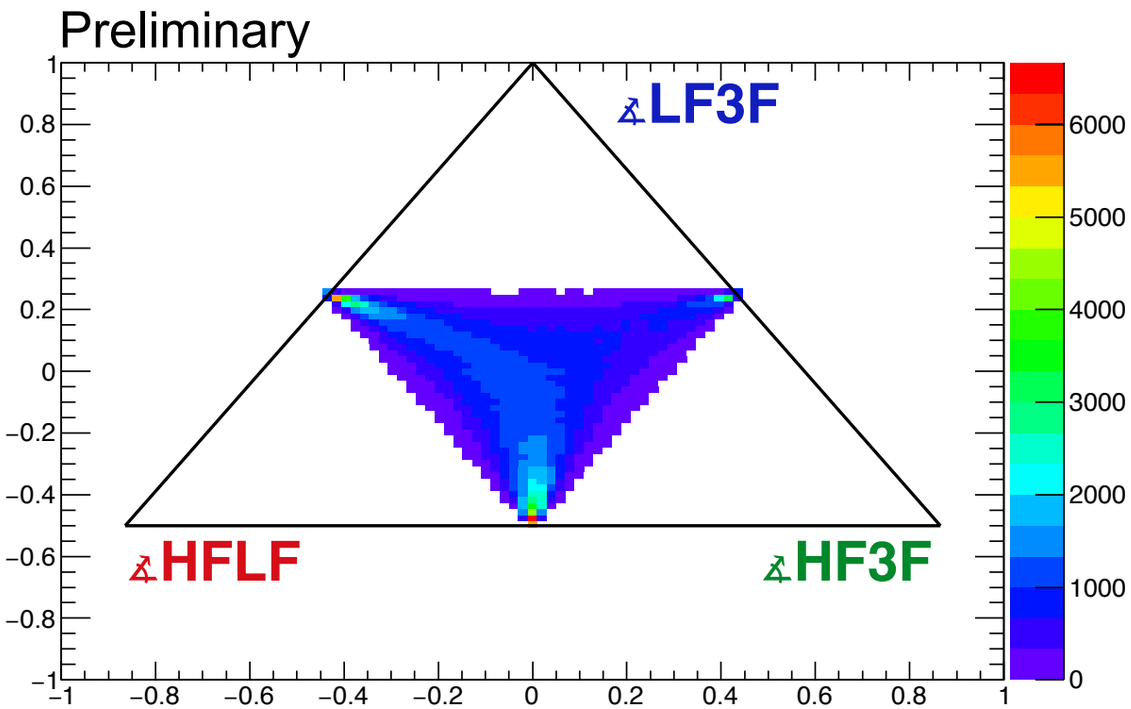
Plane formed by the 3 fragments

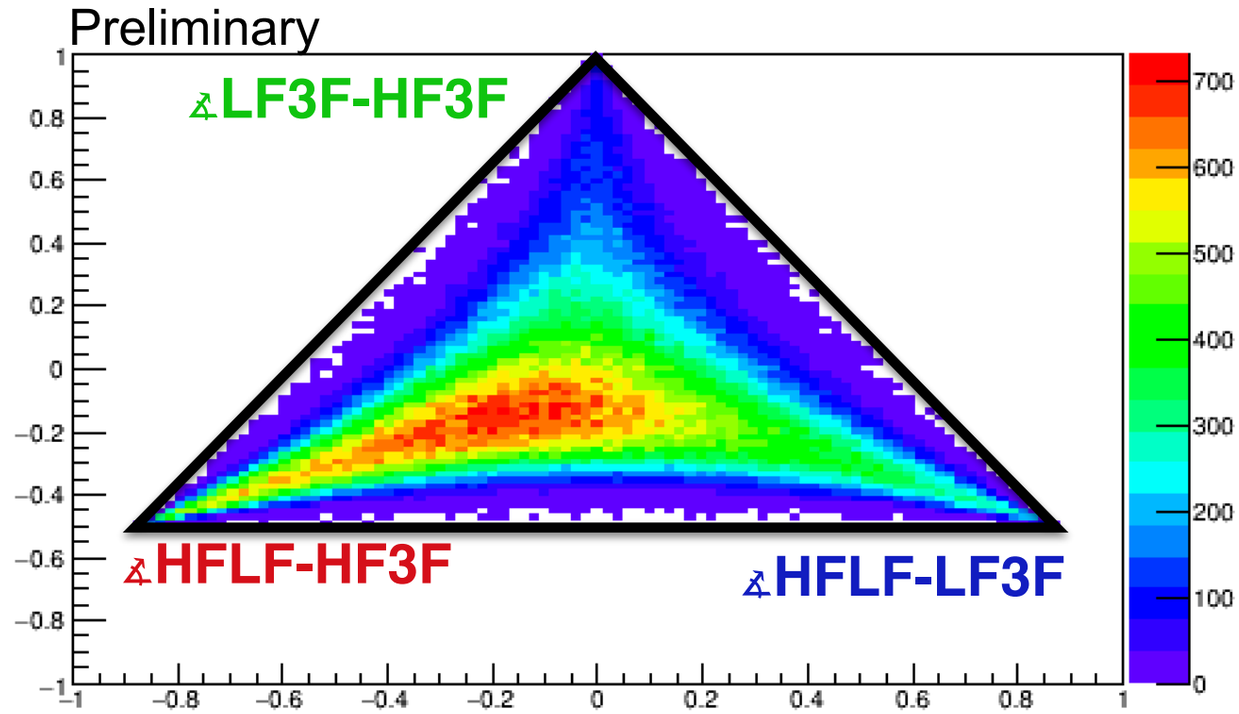




➜ It looks like red, blue and green angles are similar (slightly following r > b > g)

...the show down

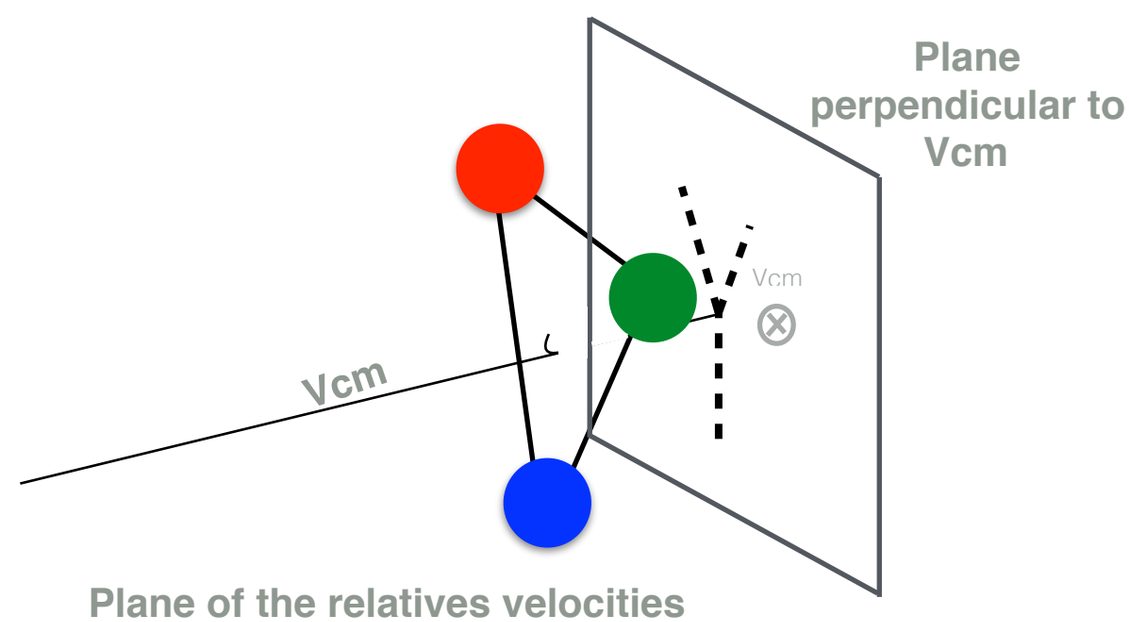




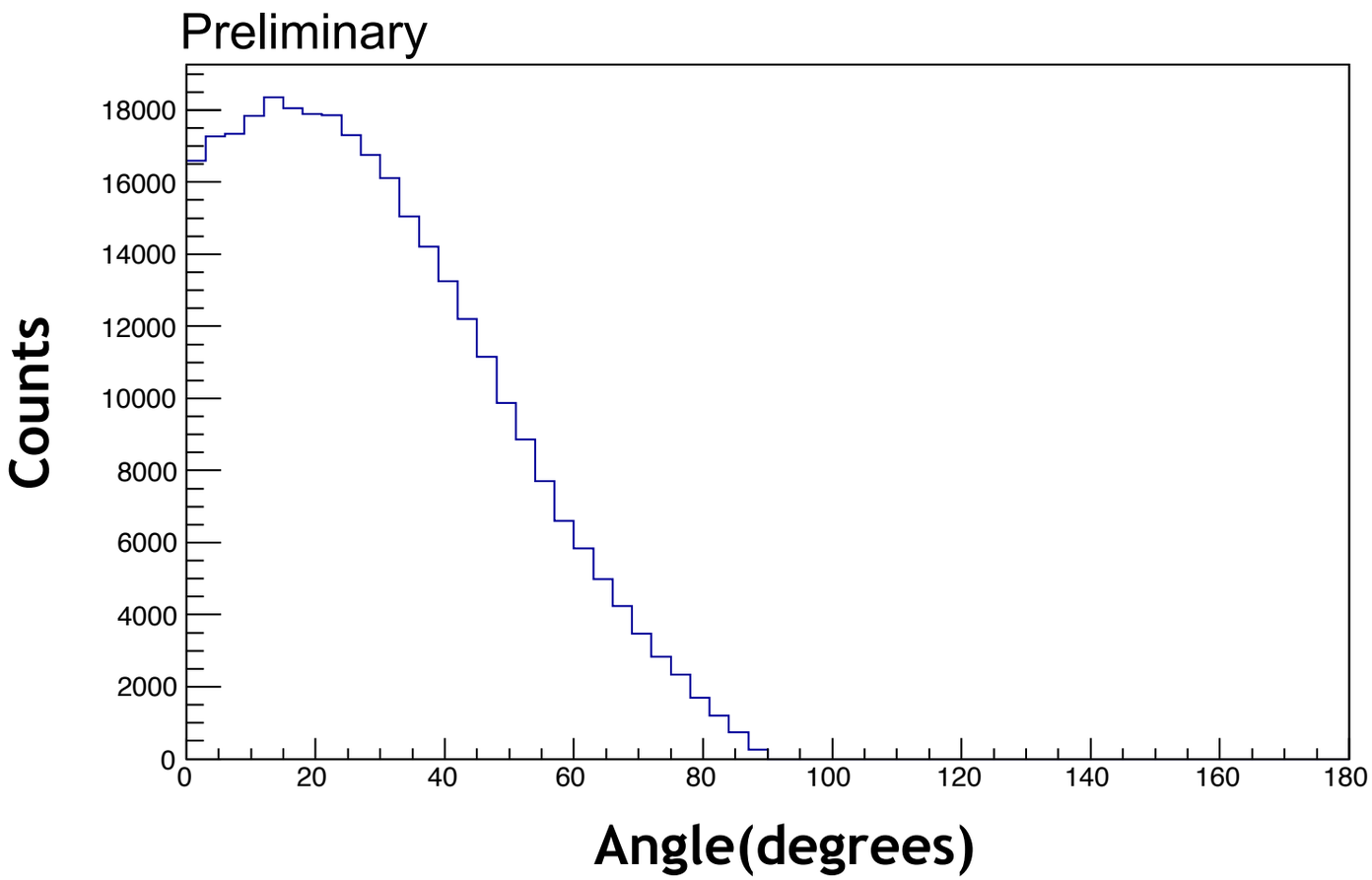
Two fragments seemingly closer to each other and apart from the third one

The three angles are approximately similar

Combining both:
. Relative velocities' plane is oblique to Vcm
. The three fragments don't seem to be aligned



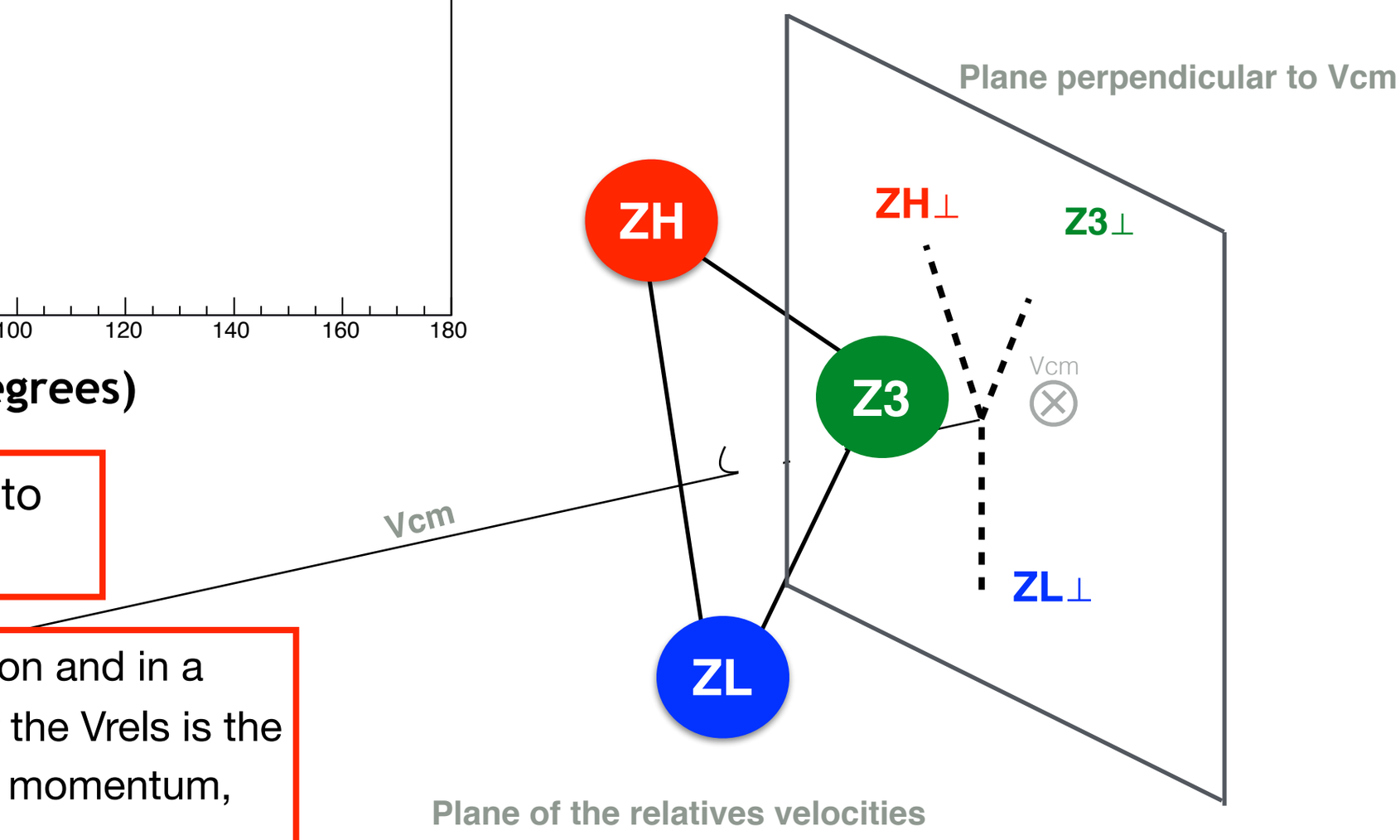
Angle between Vrels and Vcm: oblique angle



➜ The angular momentum is controlling the rupture, because it is occurring in preferential planes.

➜The rotation is perpendicular to the direction of the movement.

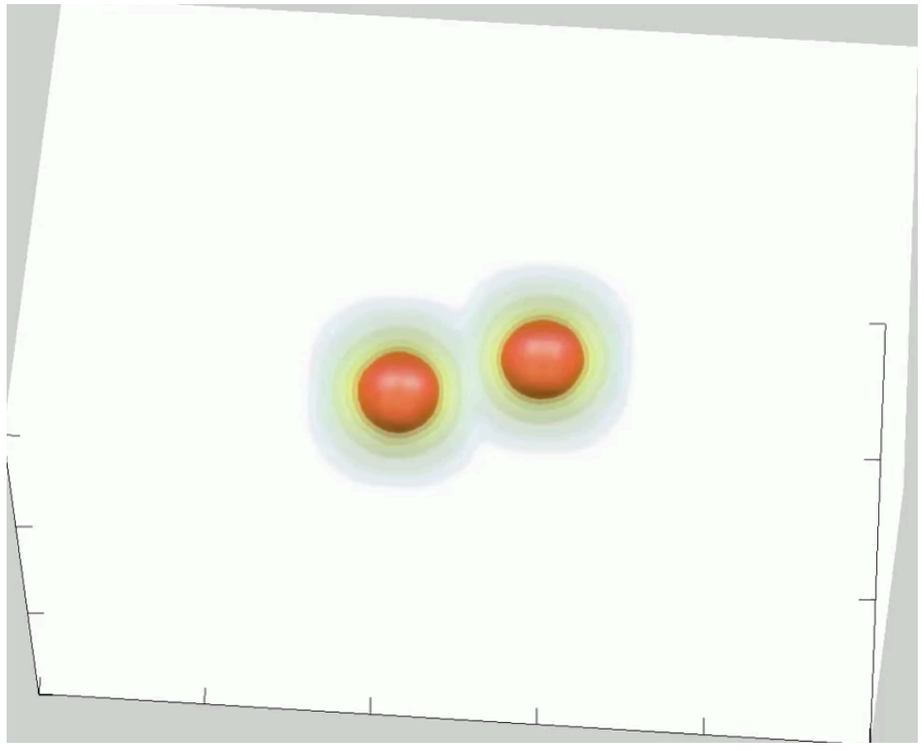
➜ The system breaks due to rotation and in a double rupture, where the plane of the Vrels is the plane perpendicular to the angular momentum, (very oblique to Vcm)



Comparison to Boltzmann-Langevin One Body (BLOB):

Something else we want to explore…

BLOB calculation:
Violent nuclear reaction dynamics, neck fragmentation



^{70}Zn+^{70}Zn 35AMeV (b=5.7) producing ^{45}Ca,^{40}Cl,^{6}Li,d (at 400fm/c)

https://www.youtube.com/watch?v=l5ul-iux1ik
Paolo Napolitani

Dynamical transport model

Unifies in a common approach the **description of fluctuations** in nuclear matter, **and** a predictive description of the **disintegration of nuclei into nuclear fragments**

Characterize the very fast early stages of the collision process which are out of equilibrium

Sizable neck fragments

work in progress

Summary

Studied **time dependence of the NZ equilibration**, examining composition of fragments from the PLF* vs angle (serves as clock for the equilibration). Composition follows exponential behavior suggesting **first-order kinetics**. We extracted a purely **dynamical composition component**, found **target effects** and no significant differences in rate constants among HF-LF or different systems.

- Hierarchy in the velocity distributions (strongly correlated to the charge sorting)
- Sizes: one big, two smaller and similar.
- The relative velocities' plane is oblique to Vcm and the three fragments don't seem to be aligned.

The physics is dominated by the angular momentum, so the system breaks due to rotation and in a double rupture scenario.

Comparing with dynamical transport models (BLOB), with sizable neck fragments

Thank you!

SJY group and collaborators:

A. Rodriguez Manso, A.B. McIntosh, J. Gauthier, K. Hagel, L. Heilborn, A. Jedele, Z.W. Kohley, Y.W. Lui, L.W. May, A. Zarrella, R. Wada, A. Wakhle and S.J. Yennello

Department of Energy
DE-FG02-93ER40773

Welch Foundation
A-1266

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Backup Slides

Neutron **I**on **M**ultidetector **for** **R**eaction **O**riented **D**ynamics **(NIMROD)**

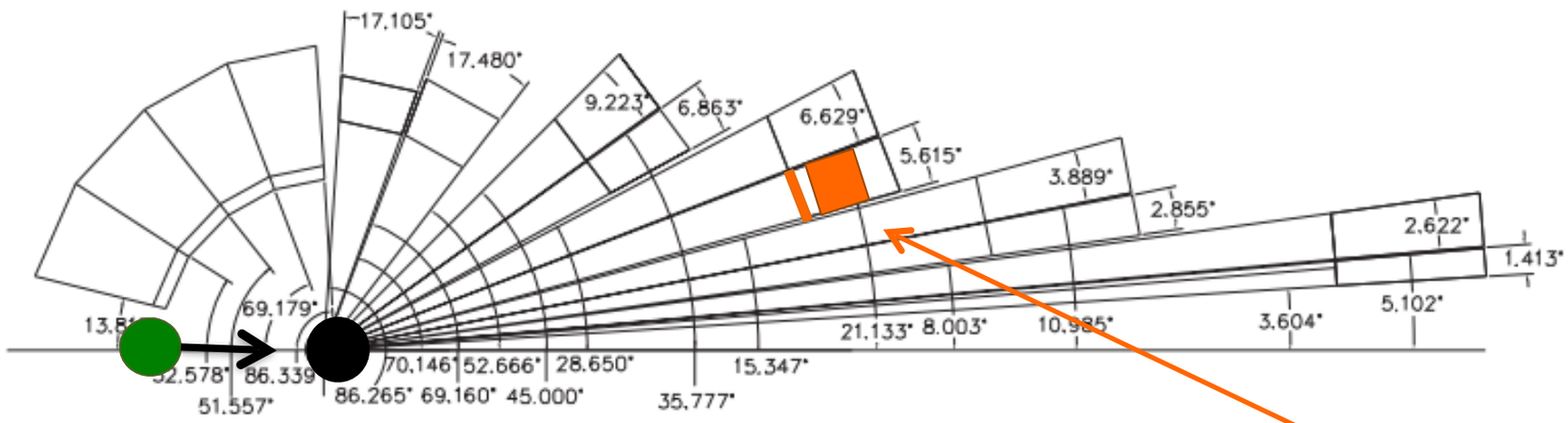
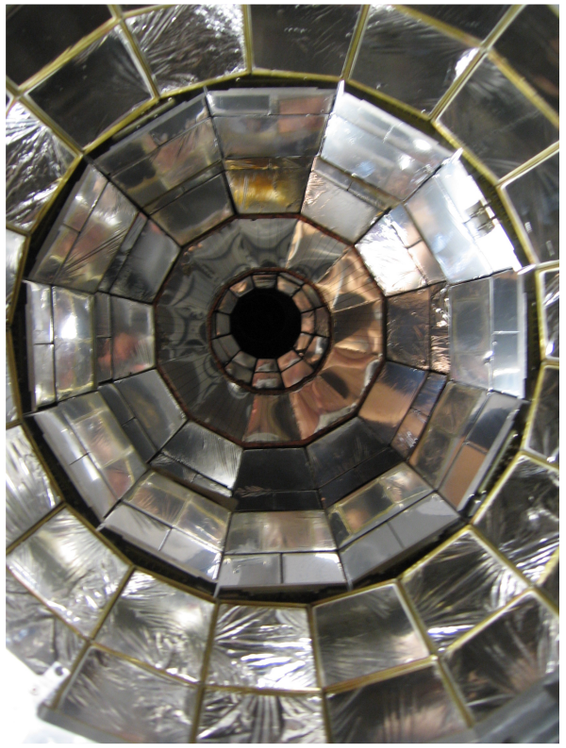
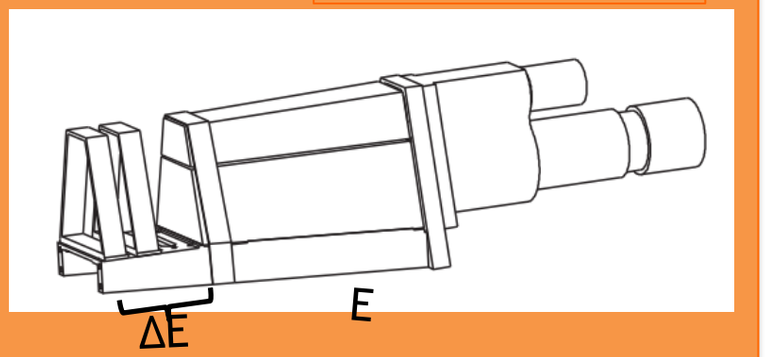


Fig. 1. Angular configuration of the NIMROD–ISiS detector.



Detector Module

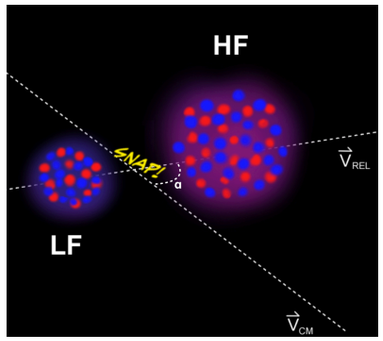


Multidetector array for reactions between massive target and projectiles:

- Total of 228 detector modules arranged in 14 annular rings (2-3 detectors/module)
- Projectile energies go from 20MeV to 4GeV
- 4π coverage (3.6° to 167.0°) = nearly complete geometrical coverage
- excellent isotopic ID

Angular (α) distributions:

- Lifetime of PLF* correlated with rotation angle:



$$\alpha = \mathrm{acos}\left(\frac{\vec{v}_{cm} \cdot \vec{v}_{rel}}{|\vec{v}_{cm}||\vec{v}_{rel}|}\right)$$

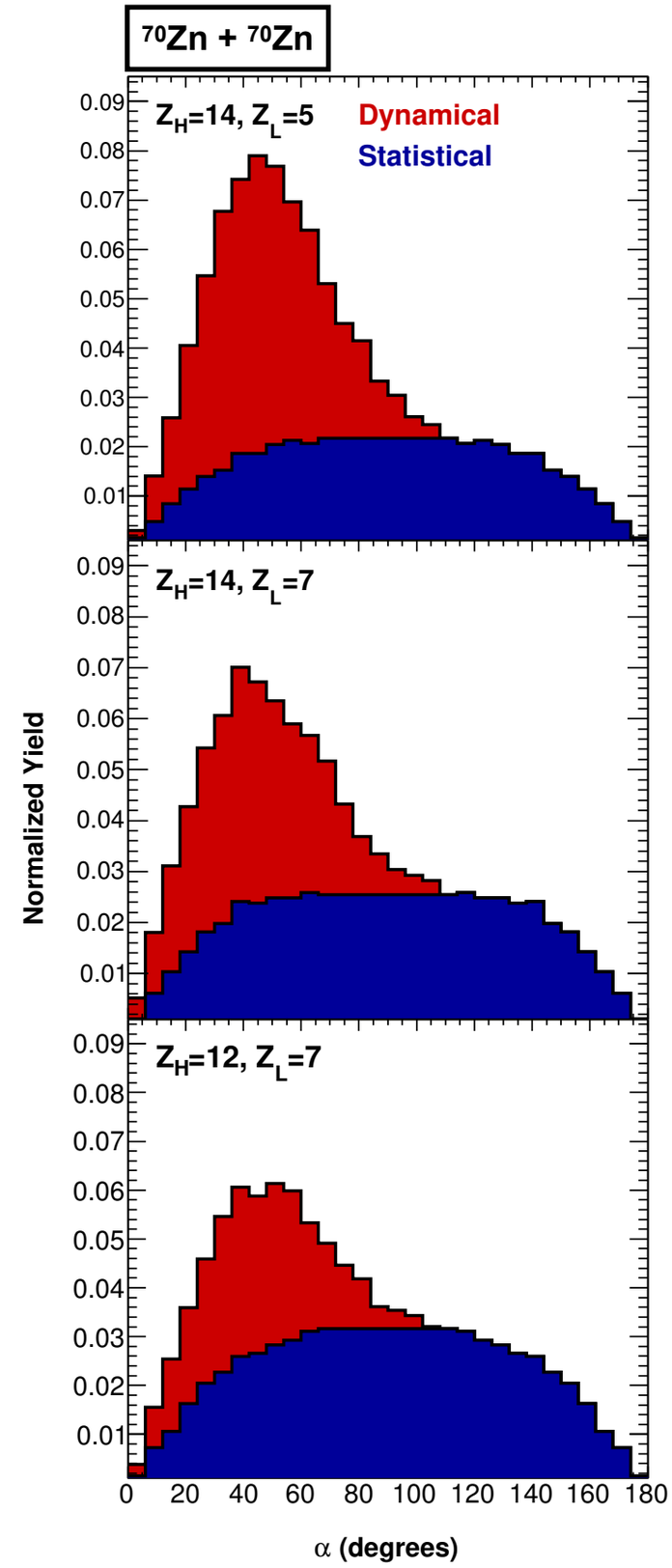
- Angular distribution peaked for most aligned configuration. Decreases in yield with decreasing alignment.

- Excess yield largest and most strongly aligned for most asymmetric splits.

- Less aligned decays represent longer decay times.

$$Y_T = Y_d + Y_s$$

- Dynamical yield dominates at small angles and decreases as α increases.



Composition vs decay alignment:

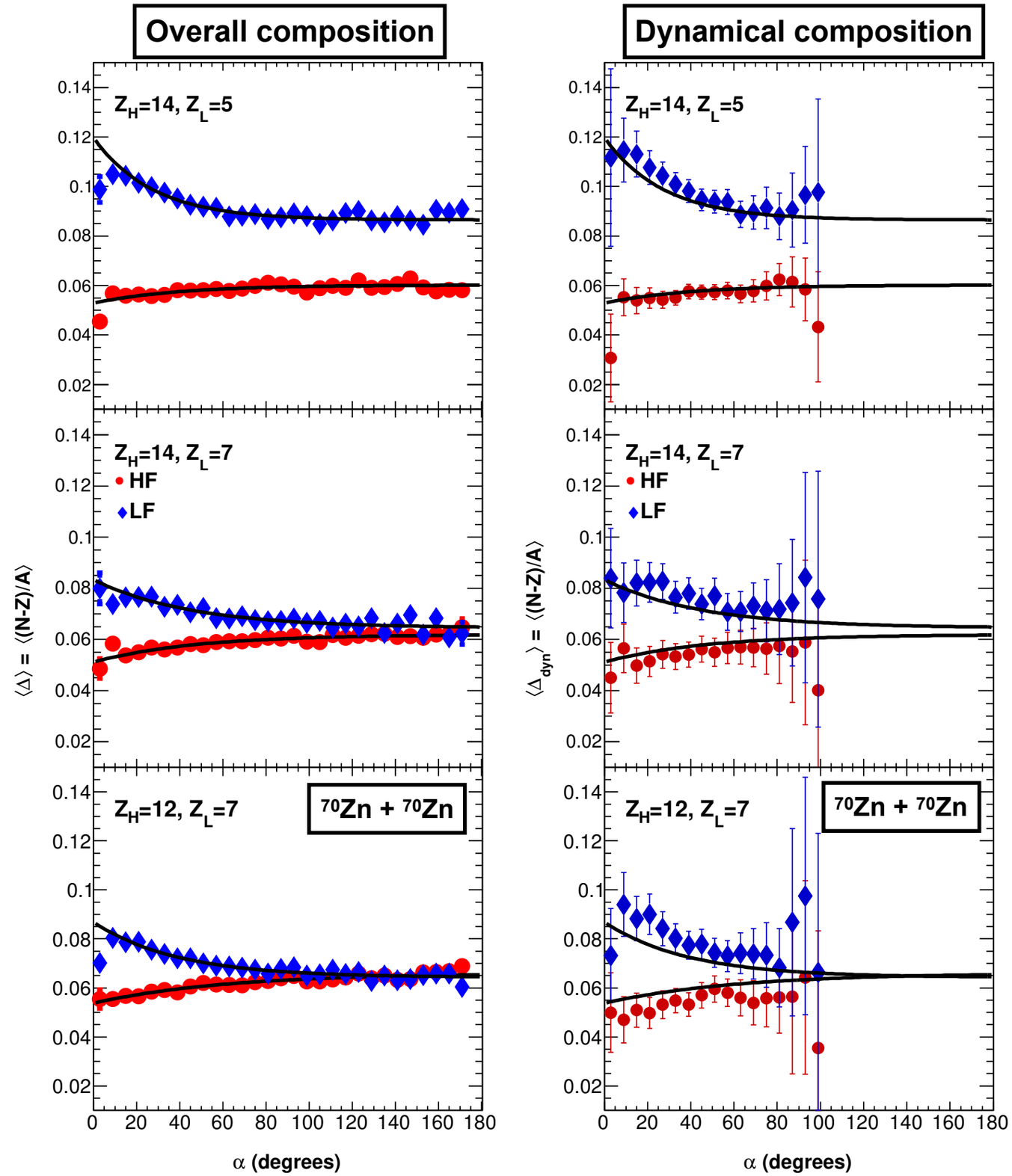
$$\Delta_{Observable} = f_s\Delta_S + f_d\Delta_d$$

- As angle of rotation increases, Δ_{HF} (Δ_{LF}) start off very n-poor (n-rich), then evolve towards each other.

- Exponential fit: $a + b\, e^{-c(\alpha)}$
  - a = equilibrium value
  - c = rate constant for equilibration
- First-order kinetics.

- Dynamical composition generally follows the same trend as the overall composition (more extreme).

- Rate of change of the composition unaffected by correction

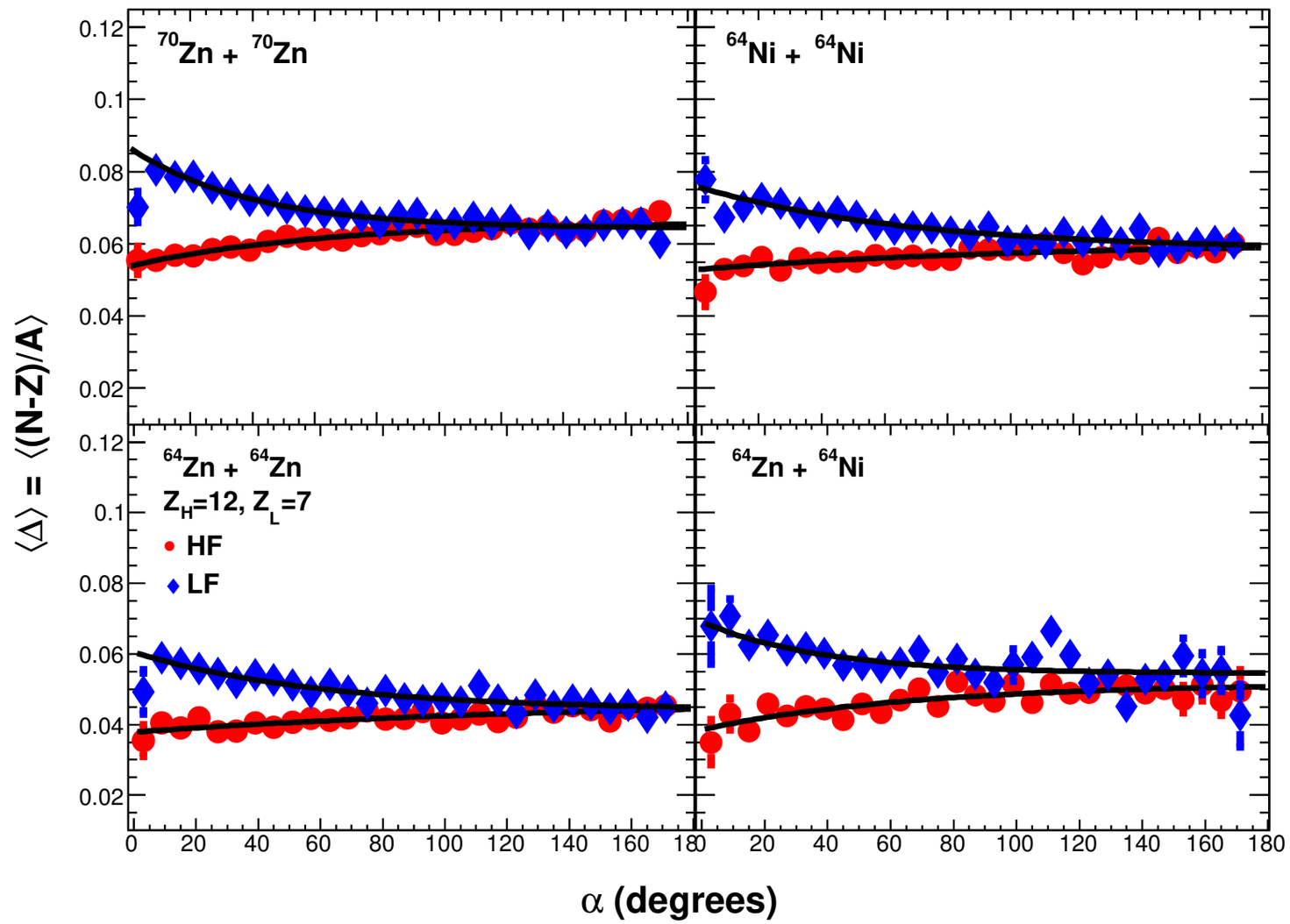


Composition vs decay alignment: for different systems

- Δ/α (^{70}Zn, ^{64}Ni) correlations essentially the same.
- Δ/α (^{64}Zn) correlation shifted to lower values (i.e. lower equilibrium composition). Same rate constants and change from initial to final value.

Comparing the symmetric and the asymmetric systems:

- Δ/α correlations for the symmetric system are systematically lower
  → **target effects.**

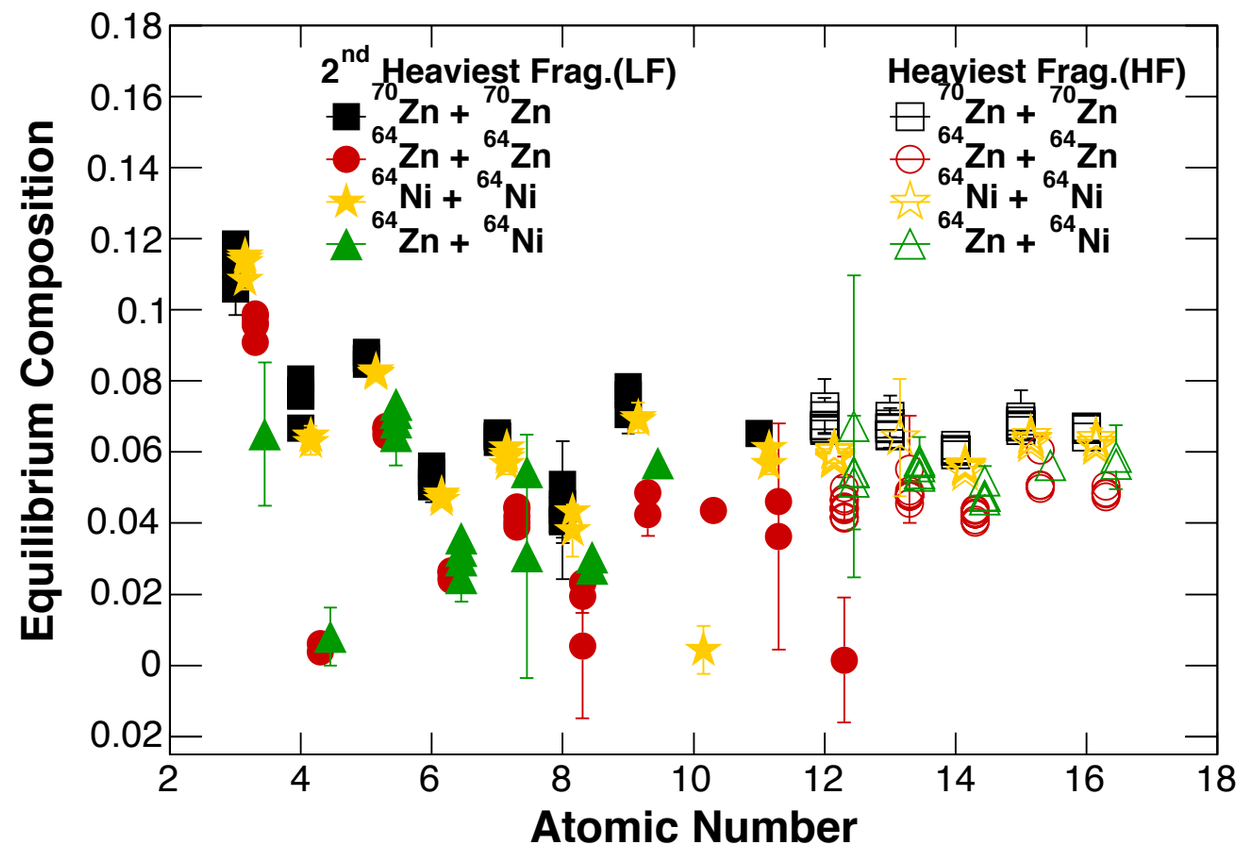


Equilibrium composition

$$\langle\Delta\rangle = a + b\, e^{-c(\alpha)}$$

- Z_L, Z_H values fairly clustered → equilibrium value for LF (HF) depends on Z_L (Z_H) but not on Z_H (Z_L).
- Comparing ^{70}Zn (■) and ^{64}Ni (★) systems (similar n-rich system composition): ~ same equilibrium composition.
- ^{64}Zn (●): consistently less n-rich equilibrium compositions
- The asymmetric ^{64}Zn + ^{64}Ni system (▲): slightly + n-rich daughters than the n-poor syst. slightly - n-rich daughters than the n-rich syst.

→ **target effect**



Rate constant for equilibration:

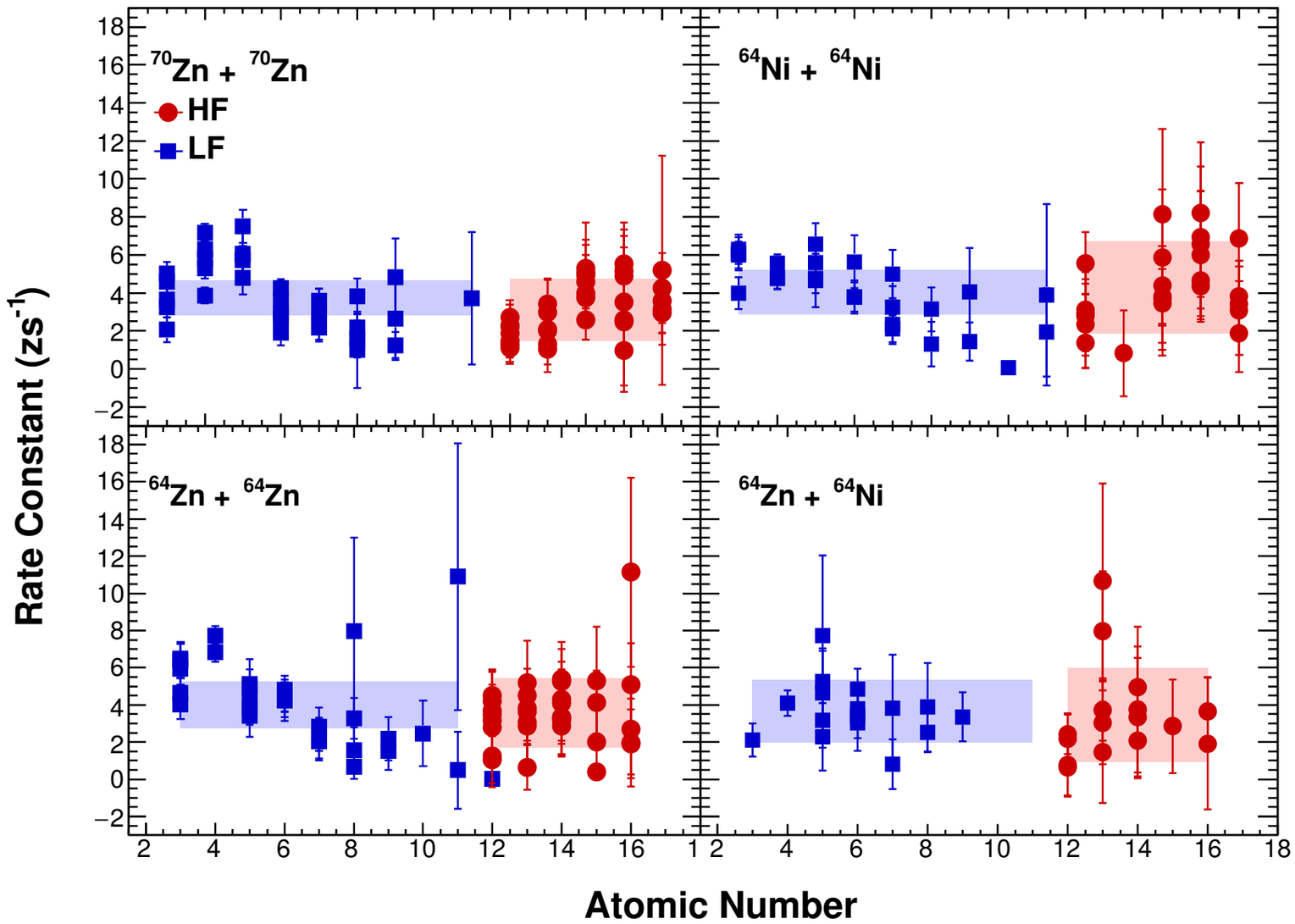
$$\langle\Delta\rangle = a + b\, e^{-c(\alpha)}$$

- Exponential slope

- Average rate constant zs^{-1}:
  LF 4 ± 1
  HF 4 ± 2

- Relevant parameter to calculate the equilibration times.

- Describes how fast the equilibration occurs within the PLF*.



- Agreement of rates → force driving the equilibration is independent of the size of both partners only depends on the difference in asymmetry

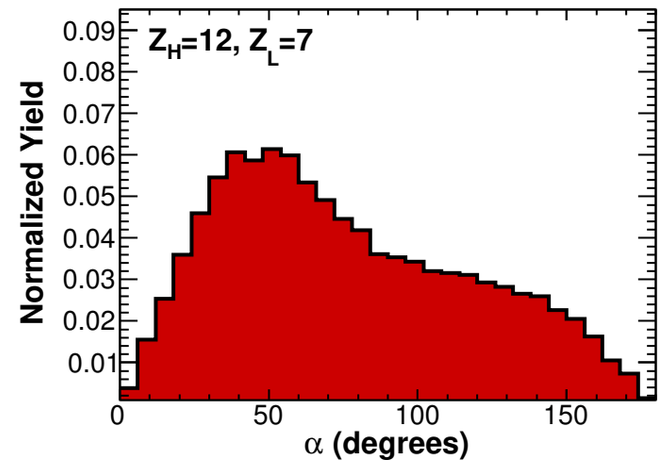
Angular (α, φ_{in} and Θ_{out}) distributions: why α?

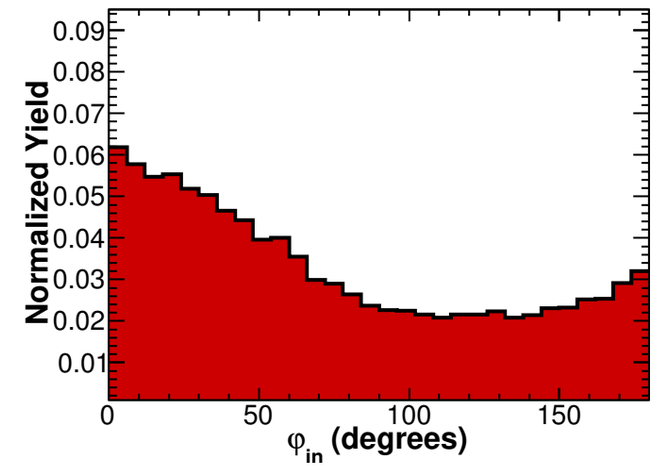
- Consistent with a significant amount of dynamical decay.

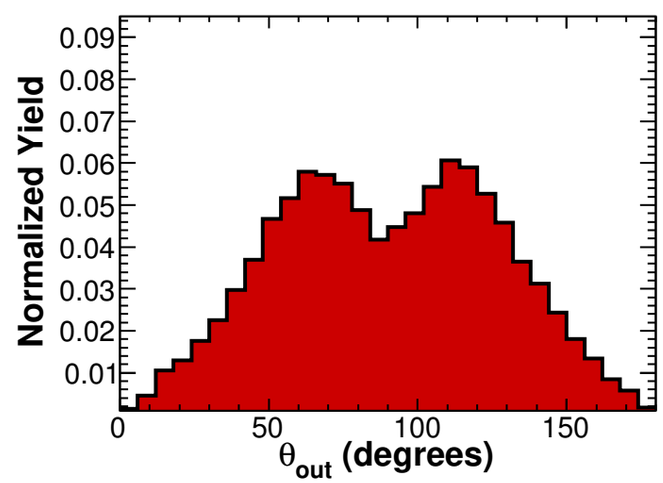
- Statistical decay α and φ_{in}:
  Symmetric distribution about 90^0
  ~ sinusoidal for low spin
  Squashed out symmetrically toward edges as spin increases.

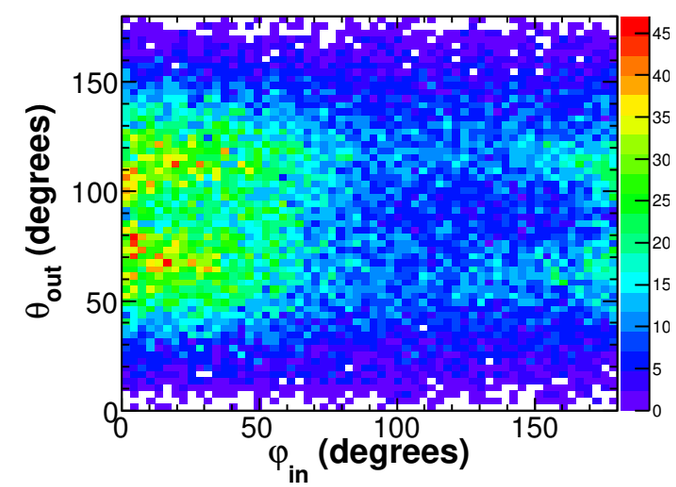
- Distributions strongly peaked toward 0^0 and asymmetric
  → large yield of non-statistical decay.

- The distributions:
  φ_{in} (Θ_{out} near 70^0 or 110^0) looks like the total φ_{in}
  φ_{in} (Θ_{out} near 30^0 or 150^0) looks much flatter.
  ↓
  dynamical yield is preferentially closer to the plane.







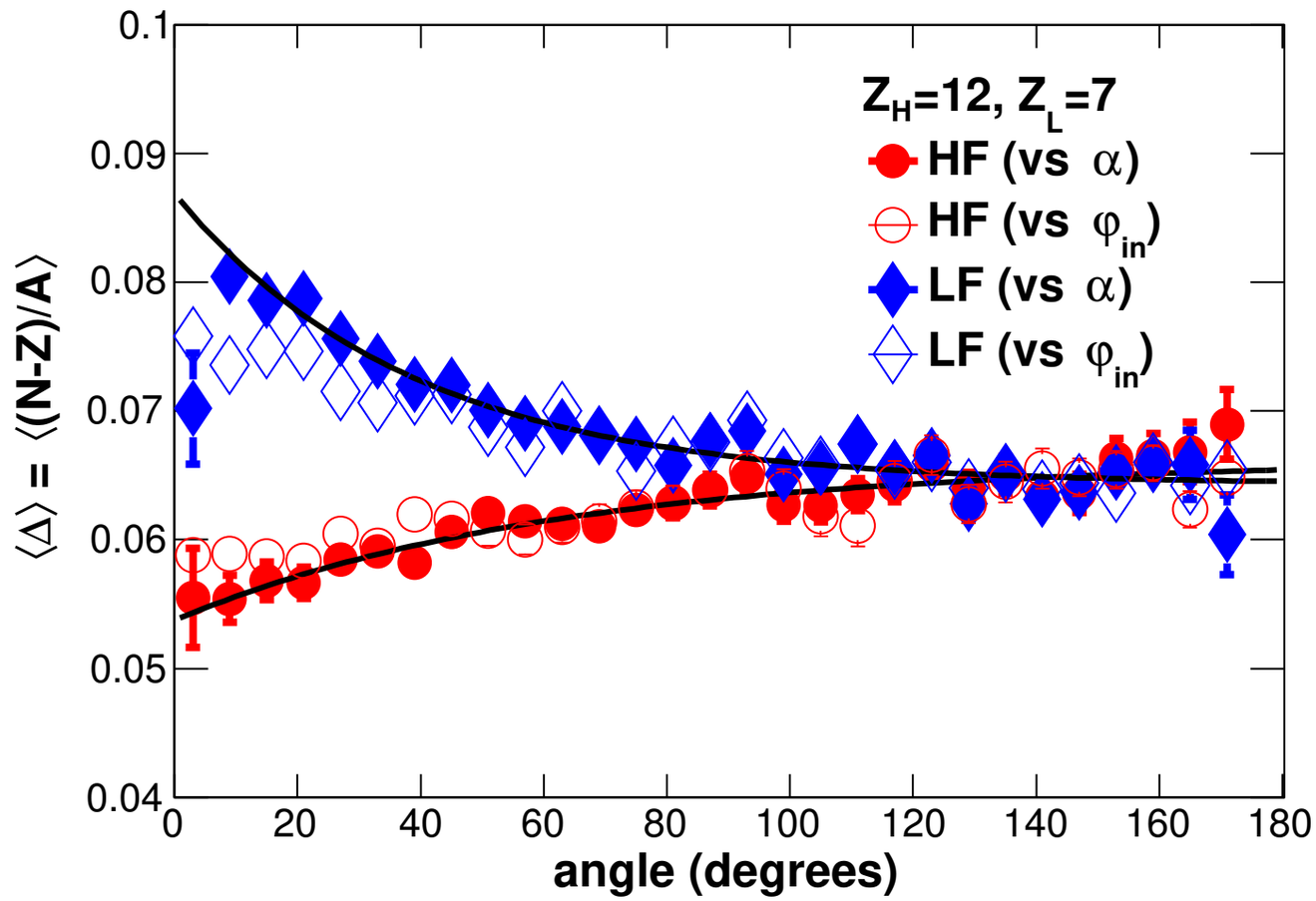


φ_{in} angle should describe the deformation alignment in a similar manner as it does the α angle.

Composition vs decay alignment, for α, φ_{in} :

- Rotation of the PLF* as it decays into HF and LF is predominantly around an axis perpendicular to the RP.

- Composition as a function of these two angles expected to be similar.



- Rotation axis can be canted from perpendicular, we expect that α would provide a truer measure of the time.

Secondary decay (SD):

using GEMINI++
open markers: <Δ> of the final state fragments

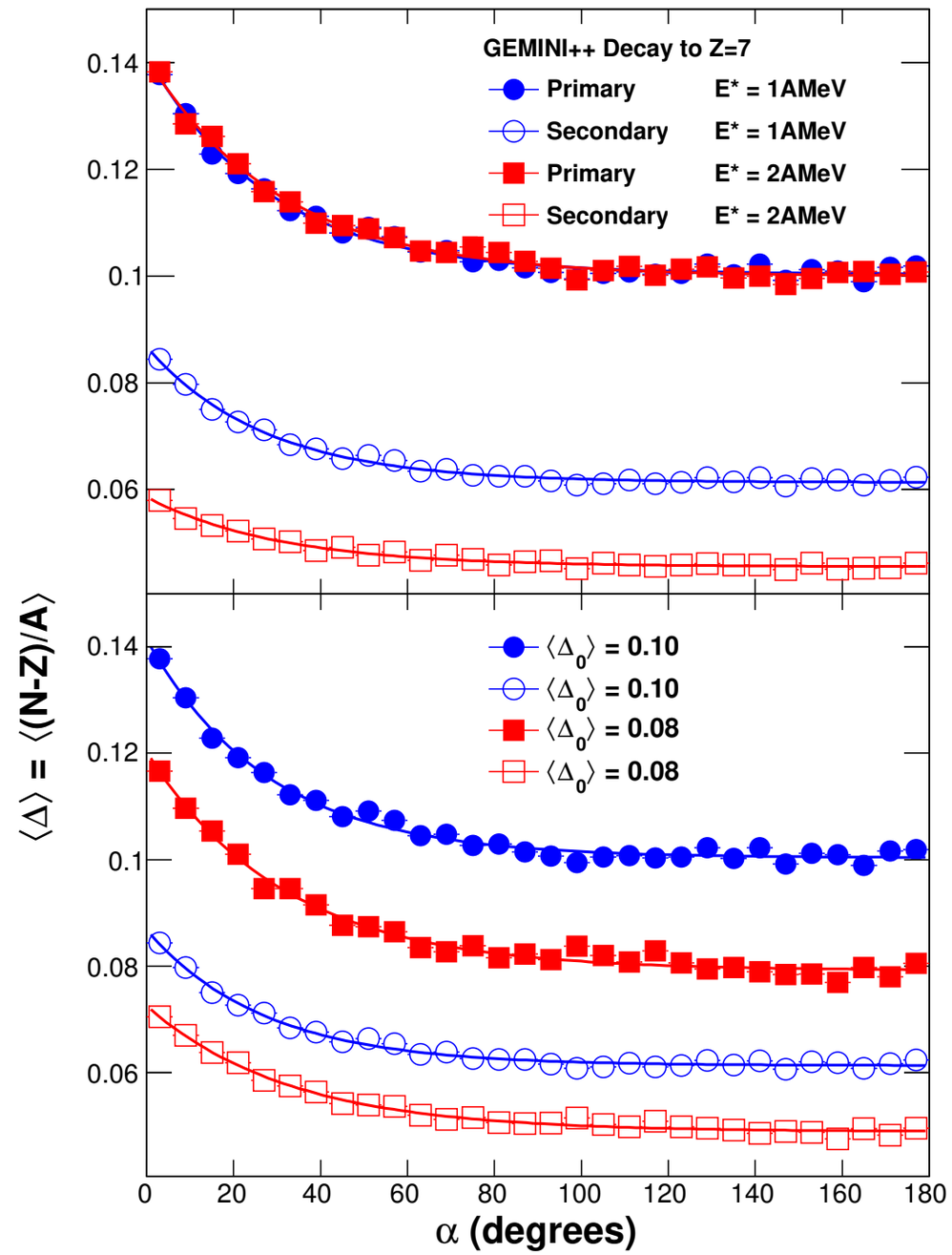
Varying the initial excitation energy:

- In both cases (● ■), exponential dependence maintained.
- Shift to lower composition and muting of the amplitude (stronger for higher excitation energy)

Varying the starting <Δ>:

- System with initially larger asymmetry shifted down strongly by SD. (System farther from valley of stability feels a stronger force driving it back toward the valley)
- After SD, the more n-rich system remains more n-rich.

The trend is not destroyed or created, and the characteristic rate of the exponential is retained.



Rate of equilibration:

Average rate constant degree^{-1}:

Symmetric systems:

LF 0.03 ± 0.01

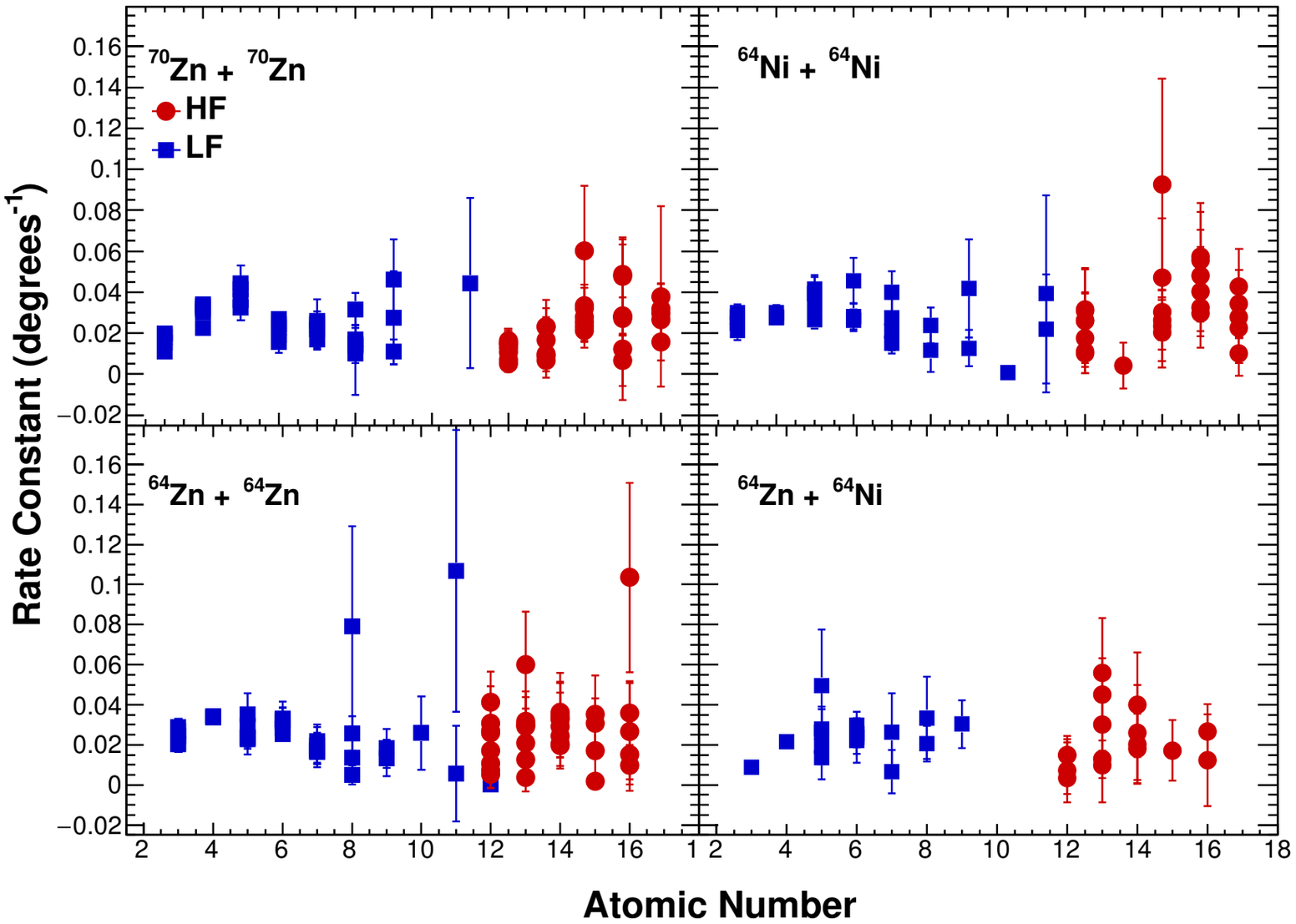
HF 0.02 ± 0.01

Asymmetric system:

LF 0.02 ± 0.01

HF 0.01 ± 0.02

- Relevant parameter to calculate the equilibration times.
- Describes how fast the equilibration occurs within the PLF*.



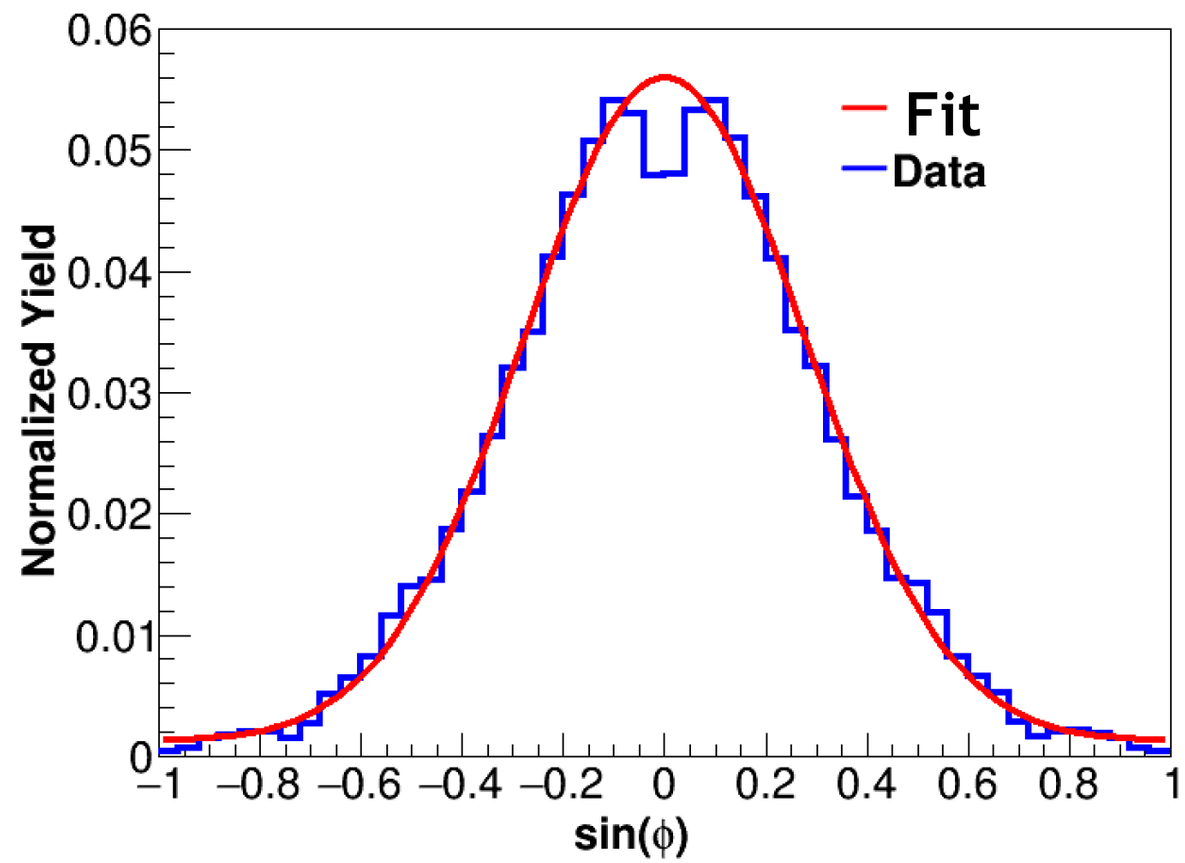
- Agreement of rates → force driving the equilibration is independent of the size of both partners only depends on the difference in asymmetry

Time-Scale

$t = \alpha/\omega$ where $\omega = J\hbar/I_{eff}$

ω(angular frequency),
J (angular momentum)

- The J is determined using the width of the out-of-plane α particle distribution



- GEMINI++ simulations: reproducing this width can be done with spin from 10ħ (E*/A=0.8MeV) to 50ħ (E*/A=1.2MeV). We can take J=22ħ with a factor of 2.2 uncertainty.

- Moment of inertia is calculated using a 2 touching spheres model:

$$I_{eff} = m_{ZH} r_{CM,ZH}^2 + \tfrac{2}{5} m_{ZH} r_{ZH}^2 + m_{ZL} r_{CM,ZL}^2 + \tfrac{2}{5} m_{ZL} r_{ZL}^2$$

- Using a complete rotational period:

$$t = (1\text{-}4)\ zs$$