Quantifying Neutron-Proton Equilibration using Molecular Dynamics Codes

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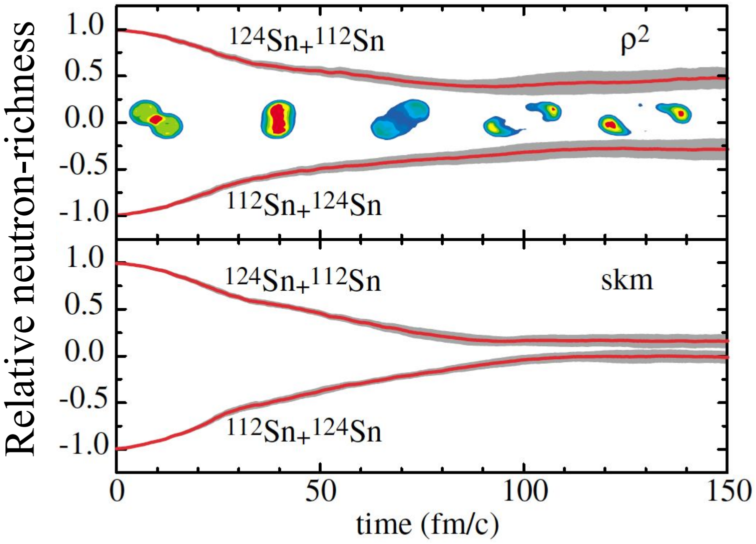
Overview

- Motivation
- Experimental Results
- Simulation Results
- Improvements

Neutron-proton (NZ) Equilibration

- Neutron-proton equilibration can be used to probe the nEoS
- Degree of equilibration determined by:
  - Contact time
  - Strength of driving potential (Equation of State)
- Asymptotic values give insight into EoS
- Can we measure the equilibration as a function of time?

BUU simulations

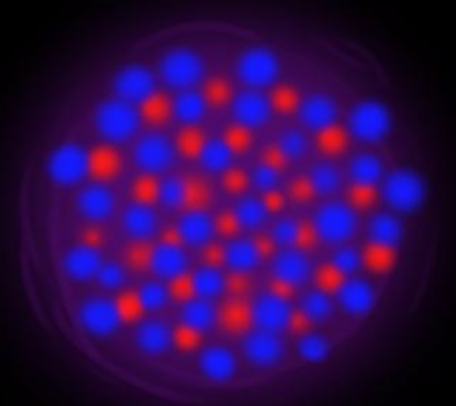


“stiff”

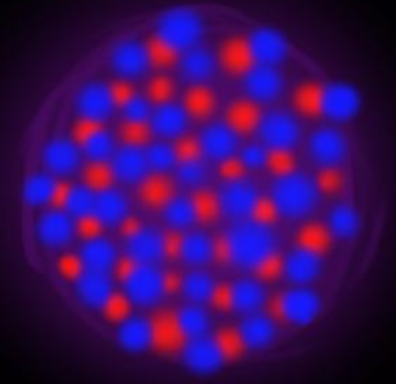
“soft”

Tsang et al, PRL 92, 06270 (2004)

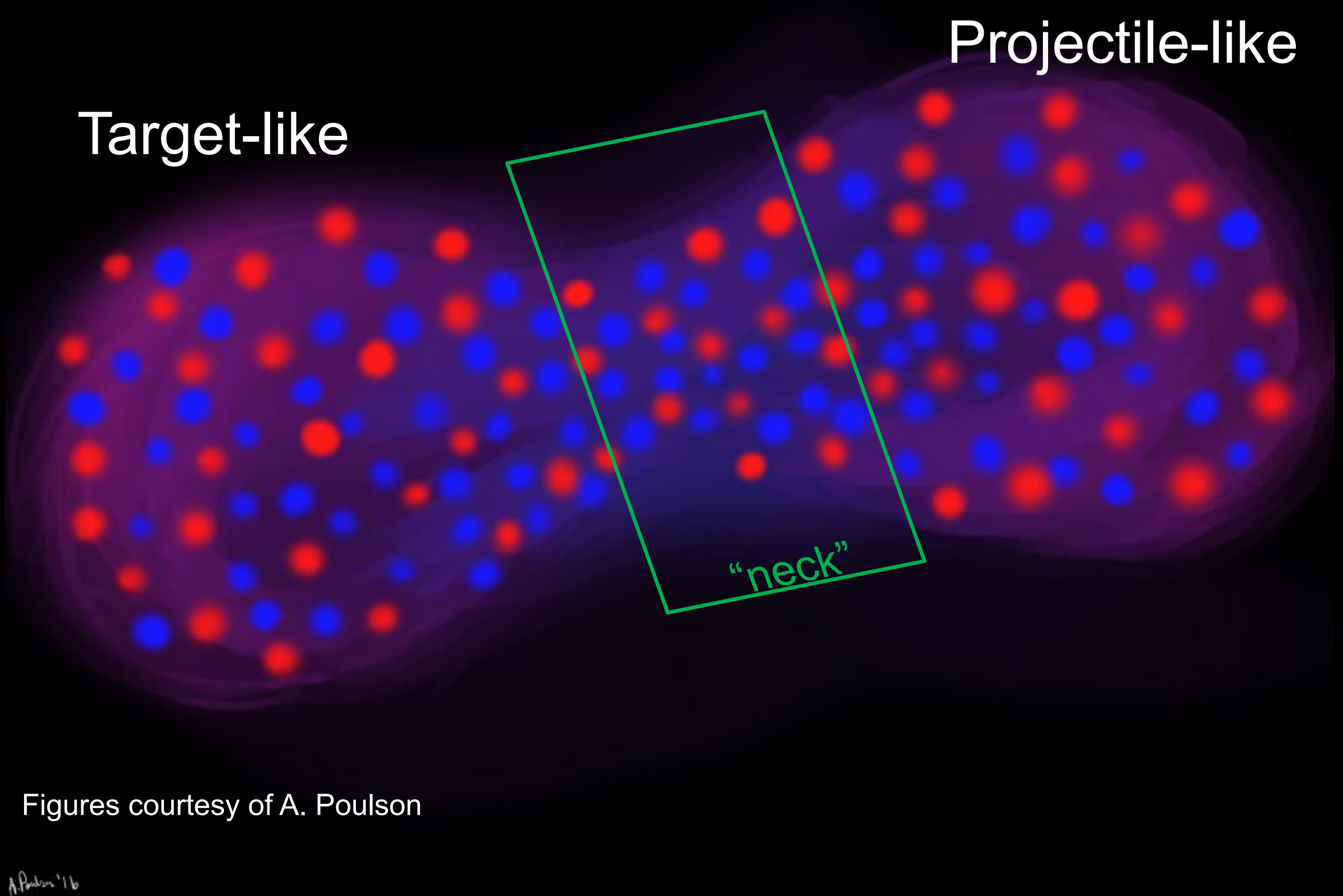
Target



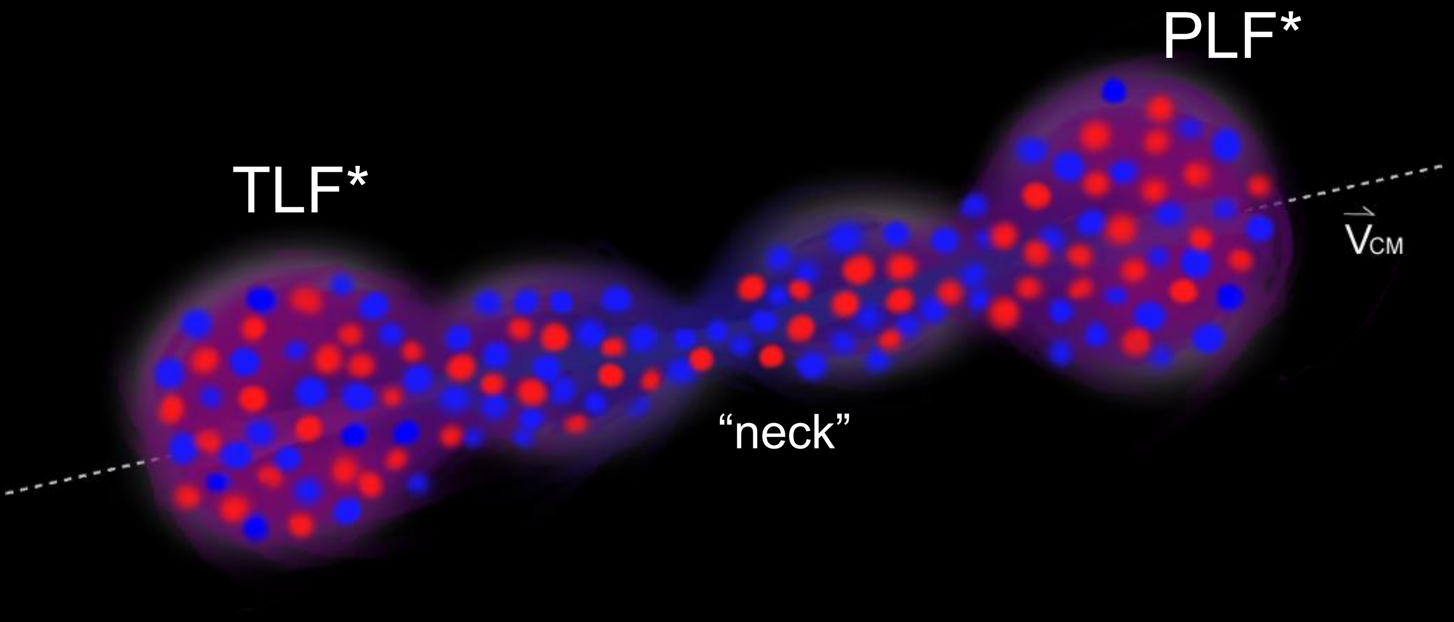
Projectile



Figures courtesy of A. Poulson

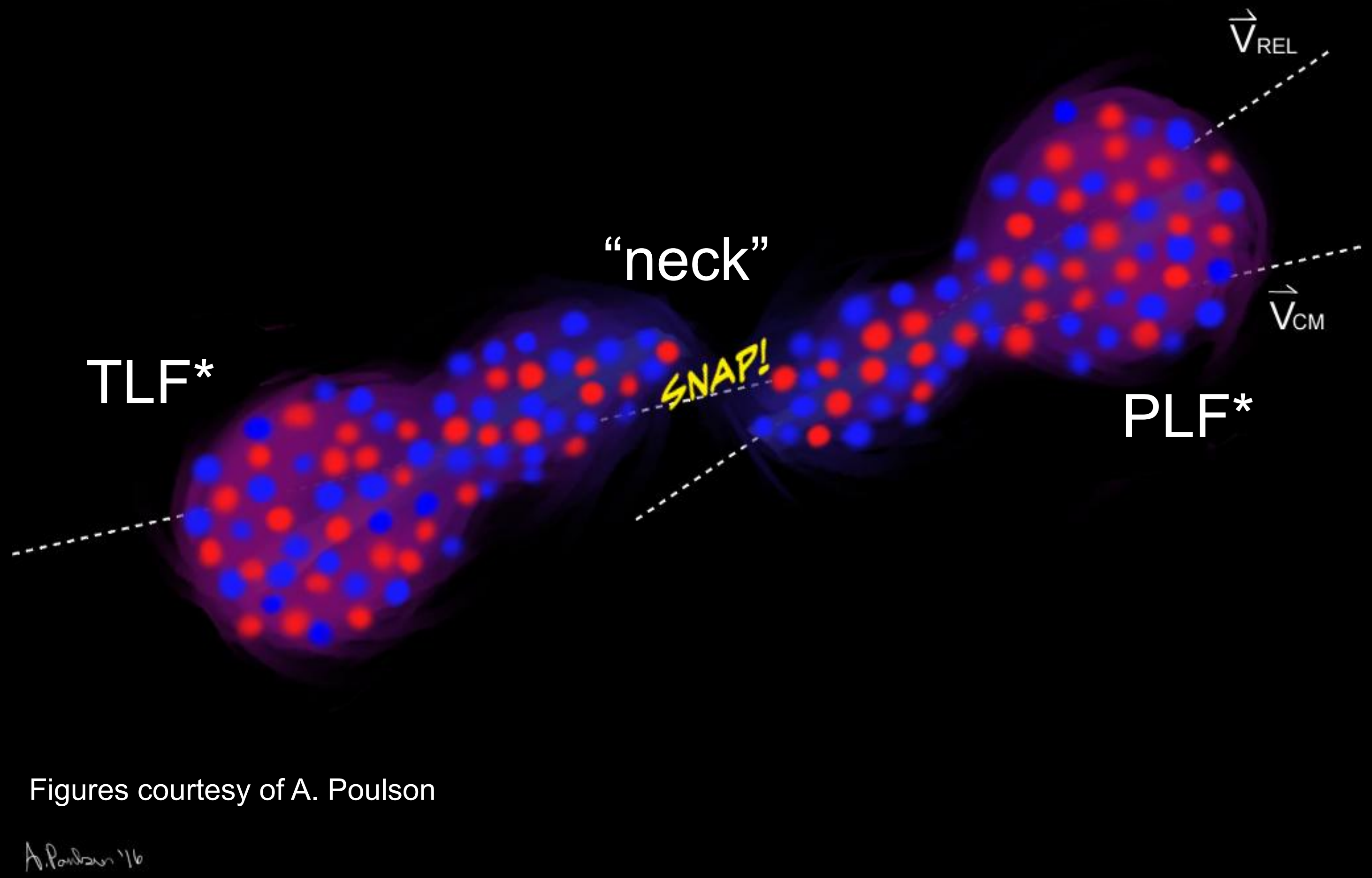


Figures courtesy of A. Poulson

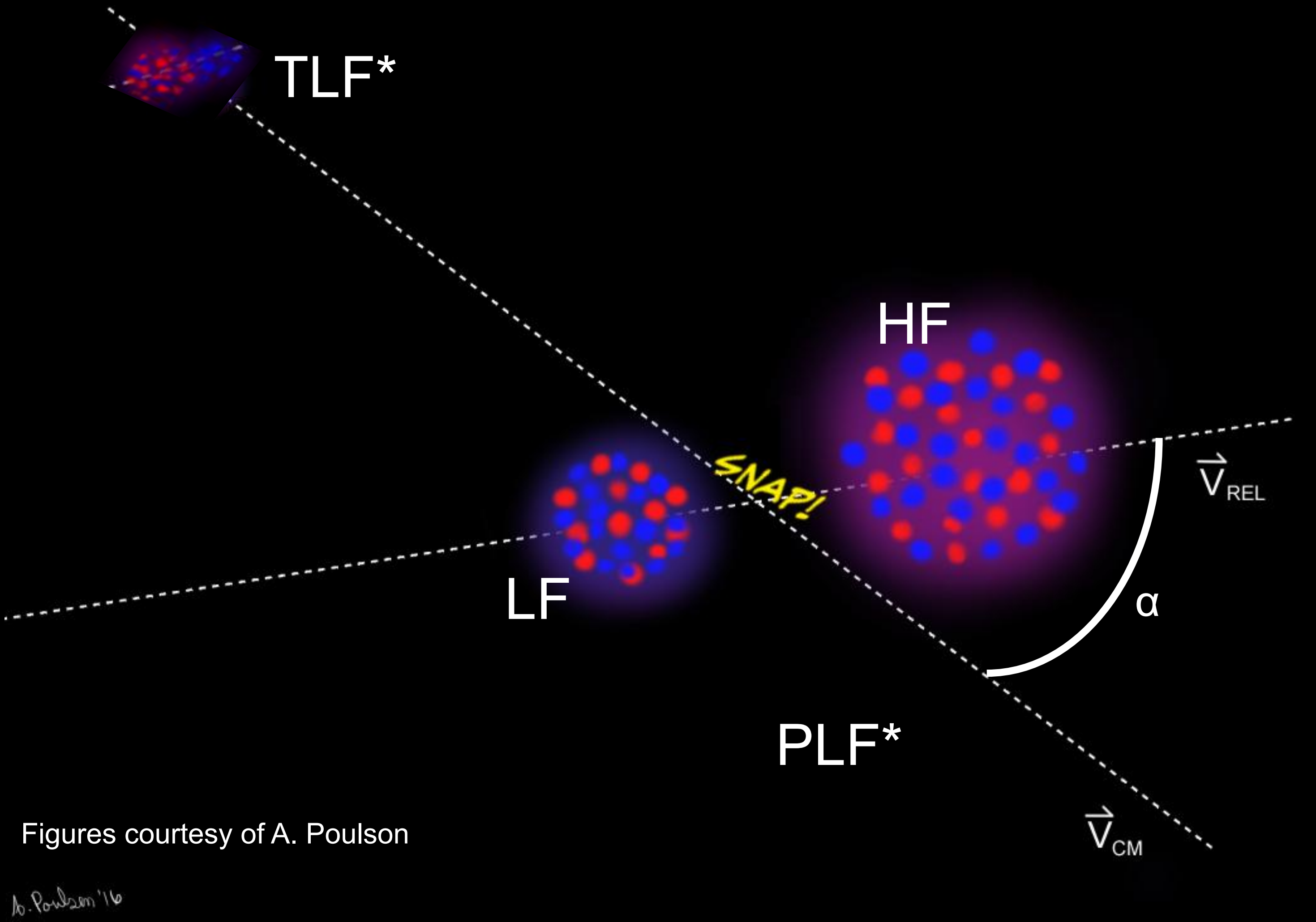


Figures courtesy of A. Poulson

A. Poulson '16



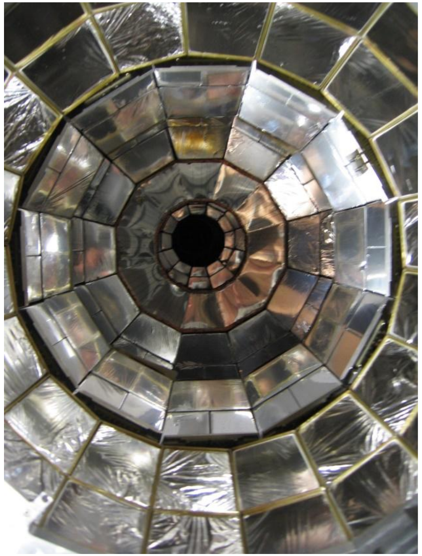
Figures courtesy of A. Poulson



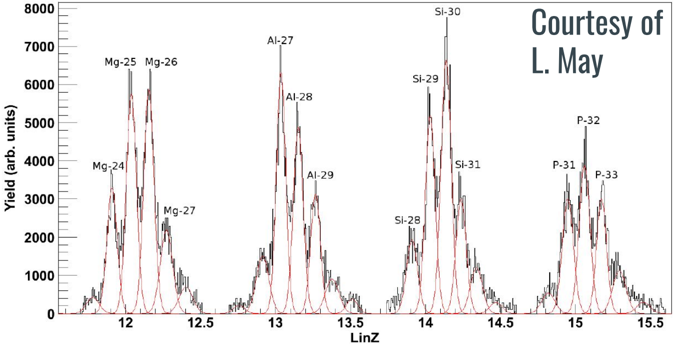
Figures courtesy of A. Poulson

Experimental Results

NIMROD 4π Array



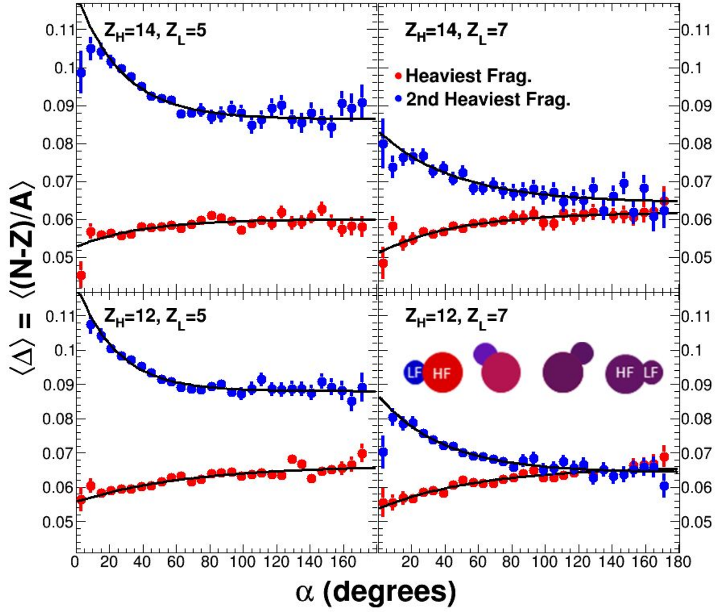
- $^{70}Zn + ^{70}Zn$, $^{64}Zn + ^{64}Zn$, $^{64}Ni + ^{64}Ni$ @ 35 MeV/nuc
- Why NIMROD?
  - Large angular coverage
  - Great isotopic resolution
    - Z = 17 many detectors
    - Z ≥ 20 in some Si-Si stacks



- Analysis cuts:
  - $Z_H \geq 12$
  - $Z_L \geq 3$
  - $21 \leq Z_{total} \leq 32$

Wuenschel et al. NIMA 604 (2009) 578-583 Picture courtesy of S. Wuenschel L. May, PhD Thesis (2015)

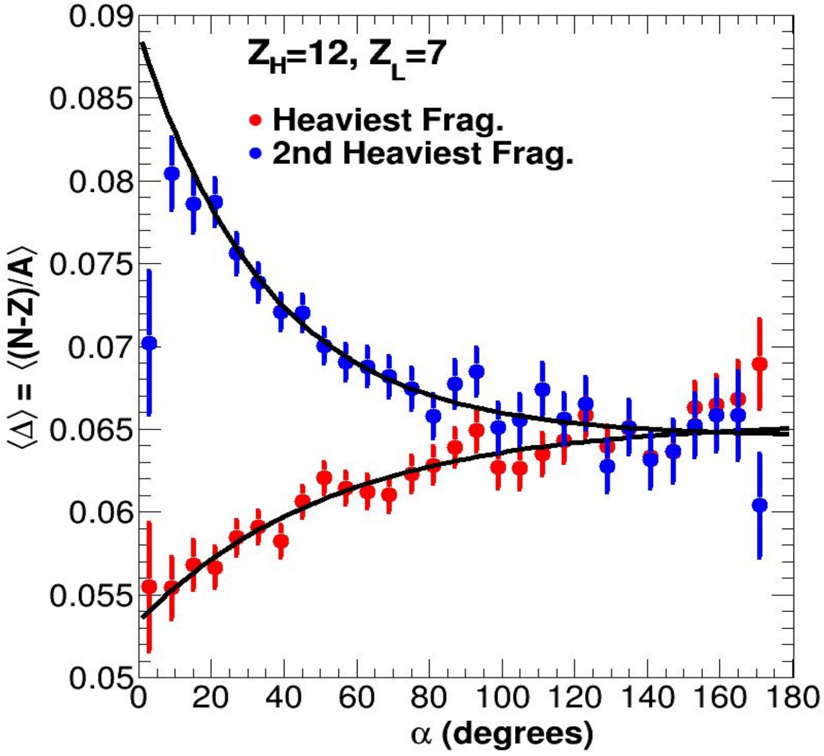
Composition of two heaviest fragments



- 1^{st} data set to measure HF
- As PLF* rotates:
  - Lighter fragment (**LF**) less neutron rich
  - Heavier fragment (**HF**) more neutron rich
- Evolution is exponential
  - Consistent with first-order kinetics
- The timescale for **HF** and **LF** are approximately equal
  - Most equilibration occurring within 60°

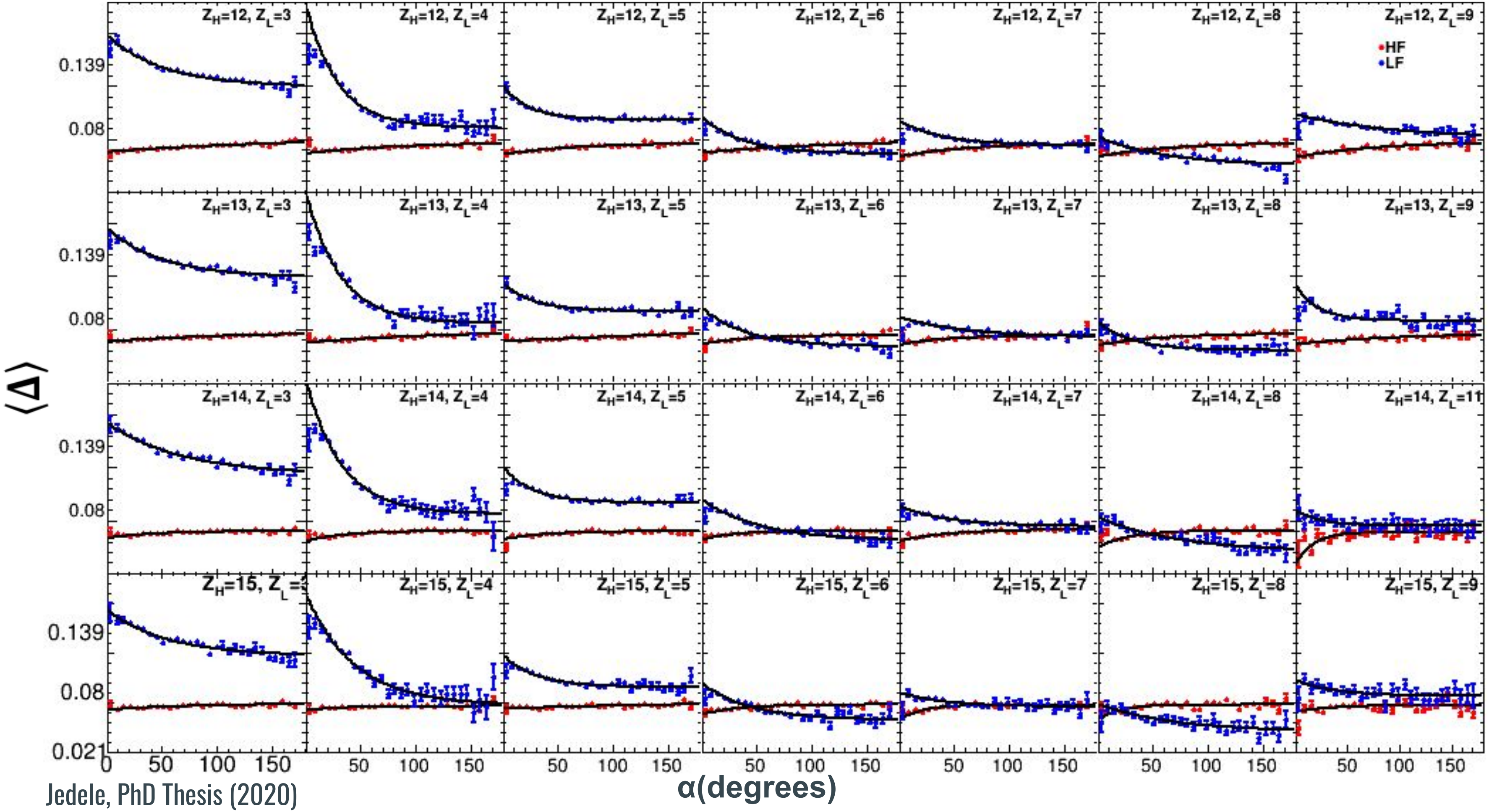
Jedele et al, PRL 118, 062501 (2017)

Rate of Equilibration and Conversion of Angle to Time



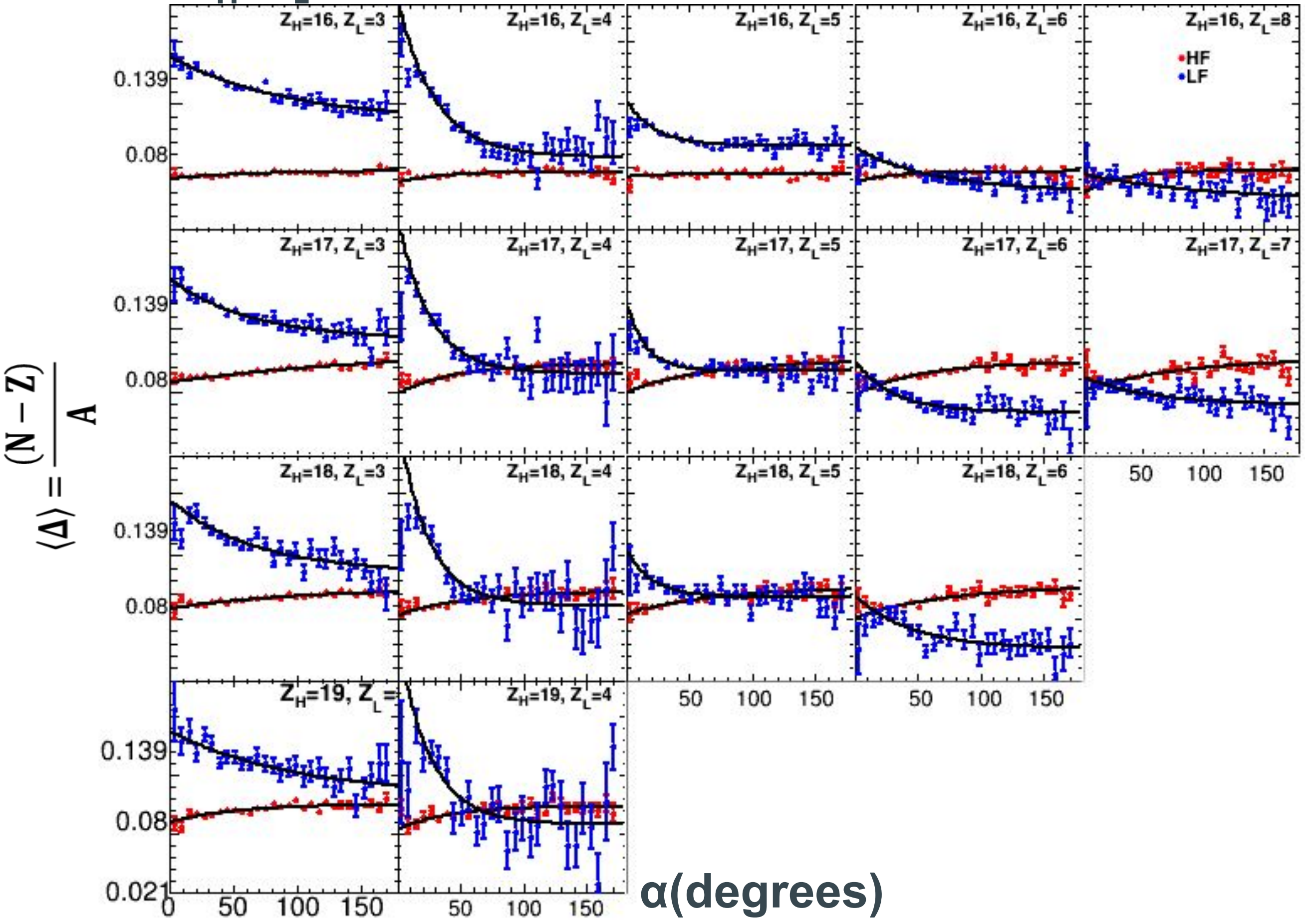
- Fit: $\Delta = a + b \cdot e^{-c\alpha}$
  - a: equilibrium value
  - b: distance from equilibrium
  - NZ equilibration rate
- $t = \alpha / \omega$
- $\omega = J \hbar / I_{eff}$
  - ω: angular frequency
  - J: angular momentum
  - I_{eff}: moment of inertia
    - 2 touching spheres

⟨Δ⟩ vs. α for all Z_H, Z_L pairings with converged fits



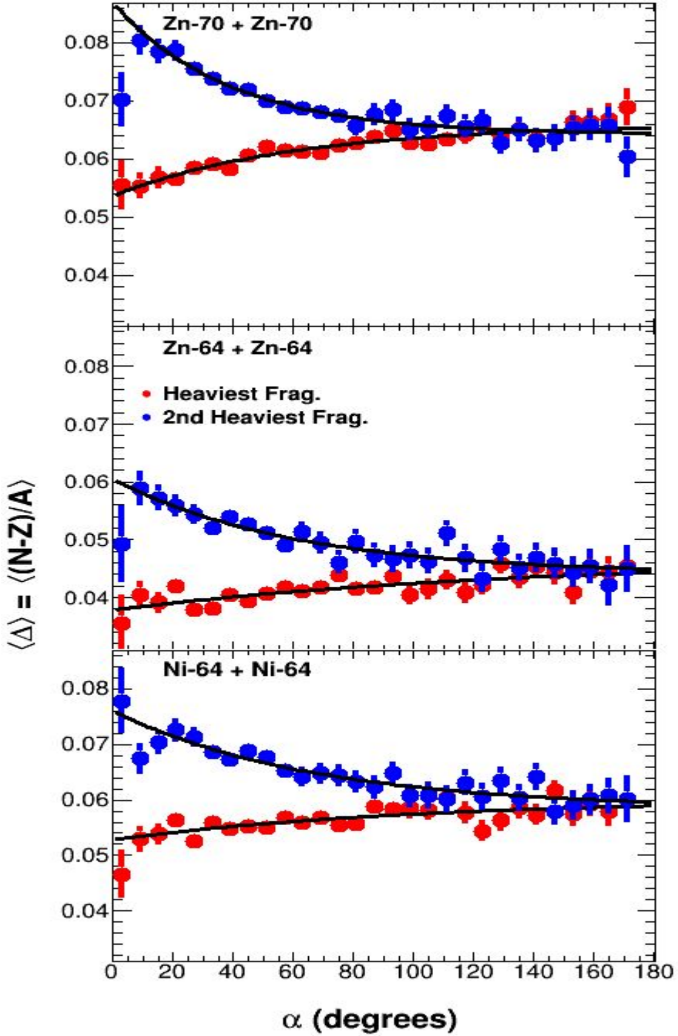
Jedele, PhD Thesis (2020)

⟨Δ⟩ vs. α for all Z_H, Z_L pairings with converged fits



Comparing ^{70}Zn + ^{70}Zn, ^{64}Zn + ^{64}Zn, ^{64}Ni + ^{64}Ni reaction systems

Reaction System	Z_H,Z_L Pairing	k_H (zs^{-1})	k_L (zs^{-1})	τ_H (zs)	τ_L (zs)
^{70}Zn+^{70}Zn	12,7	$2\pm^{3}_{1}$	$4\pm^{4}_{2}$	$0.5\pm^{0.6}_{0.3}$	$0.3\pm^{0.6}_{0.1}$
^{64}Zn+^{64}Zn	12,7	$1\pm^{2}_{1}$	$2\pm^{3}_{2}$	$1\pm^{2}_{1}$	$0.4\pm^{0.5}_{0.3}$
^{64}Ni+^{64}Ni	12,7	$1\pm^{2}_{2}$	$2\pm^{3}_{1}$	$0.7\pm^{1}_{0.8}$	$0.5\pm^{0.3}_{0.6}$
^{70}Zn+^{70}Zn	Average	$3\pm^{4}_{2}$	$4\pm^{4}_{2}$	$0.3\pm^{0.5}_{0.3}$	$0.3\pm^{0.3}_{0.2}$
^{64}Zn+^{64}Zn	Average	$4\pm^{5}_{3}$	$4\pm^{5}_{3}$	$0.3\pm^{0.4}_{0.2}$	$0.3\pm^{0.3}_{0.2}$
^{64}Ni+^{64}Ni	Average	$4\pm^{5}_{3}$	$4\pm^{5}_{3}$	$0.3\pm^{0.4}_{0.2}$	$0.3\pm^{0.3}_{0.2}$



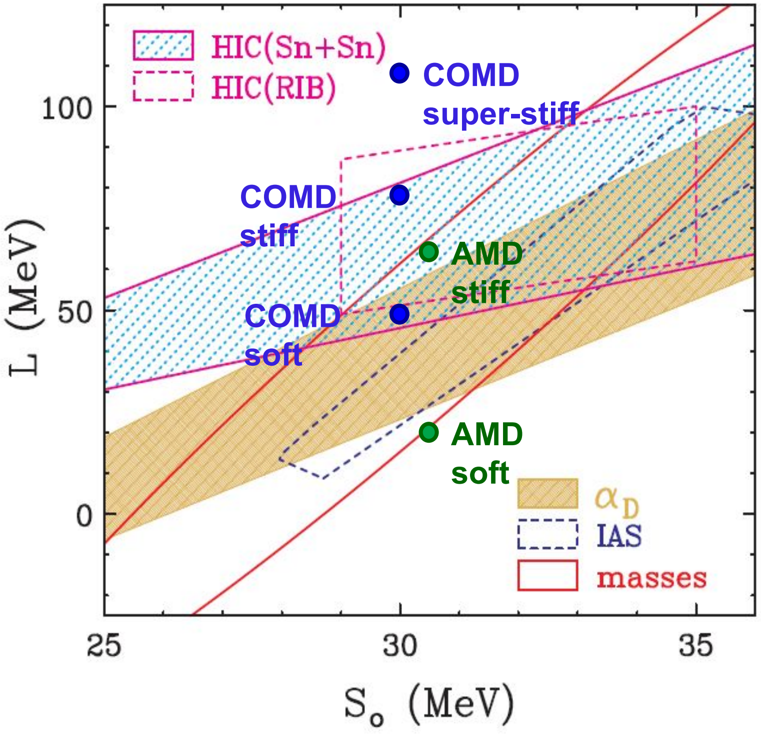
Rodriguez Manso et al., PRC 95, 044604 (2017)

Simulations

Zn-70 + Zn-70 @ 35 MeV/nuc

Simulations

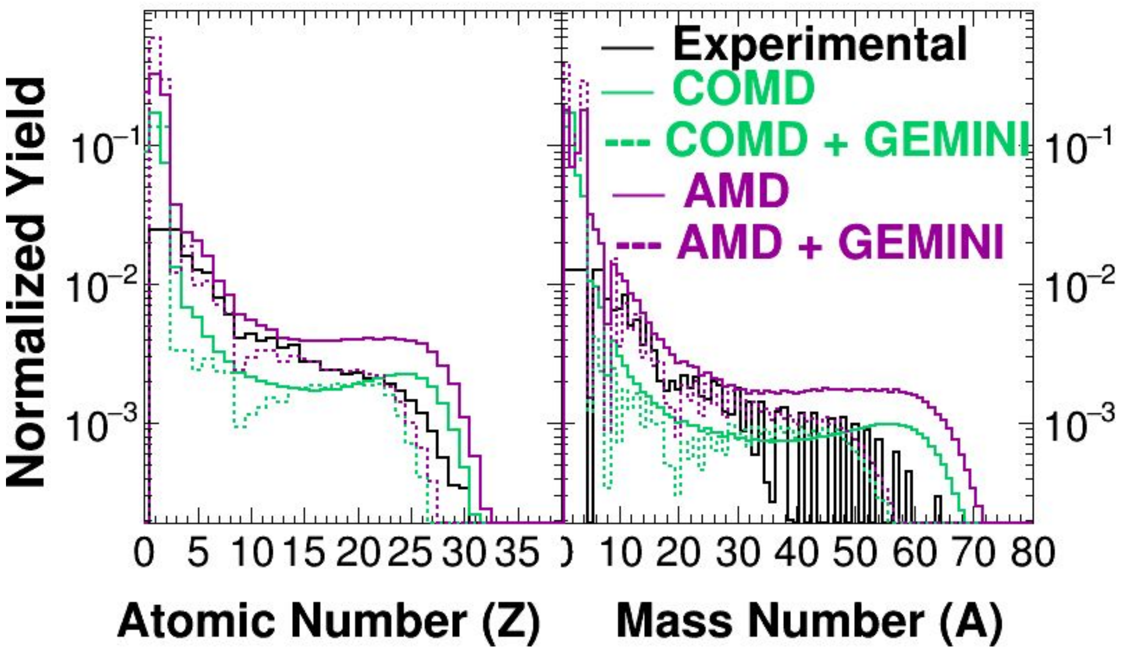
- COMD
  - 10^7 events
  - Simulation stopped at 1000 fm/c
  - 3 different COMD interactions used
    - soft, stiff and super-stiff
- AMD
  - 10^5 events
  - Simulation stopped at 300 fm/c
  - 2 interactions used
    - soft and stiff
- GEMINI++
  - Used to de-excite fragments after simulation stopped



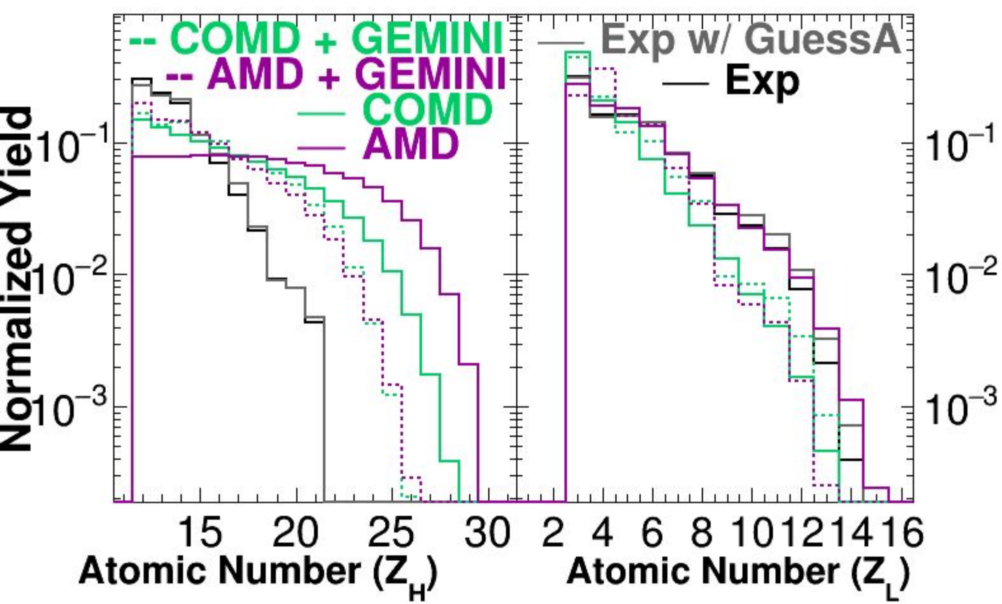
Horowitz J. Phys. G, 41 (2014)

Charge and Mass Distributions for Total System

- Fairly good agreement between experimental and COMD/AMD distributions pre- and post-GEMINI
- Zig-zag distribution in experimental results due to isotopic resolution



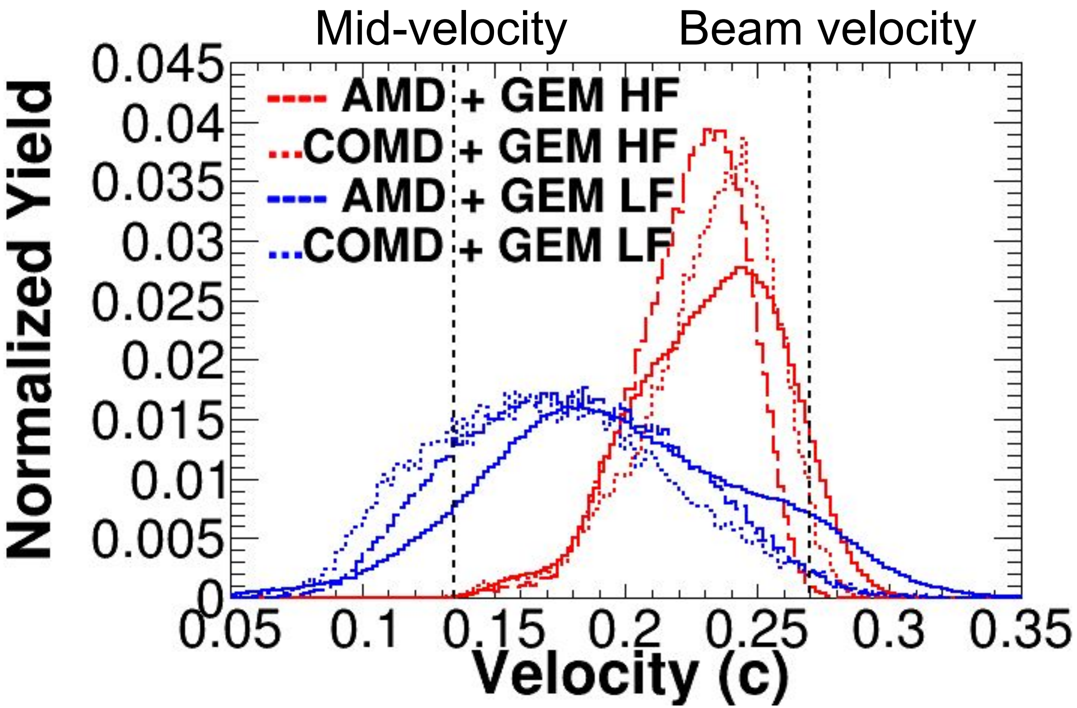
Charge Distributions for Z_H and Z_L



- Simulations passed through a NIMROD software filter
- Simulation distributions for the **LF** close experimental distributions
- Simulation over-predicts **HF** distribution at high Z
  - Results with GEMINI are closer
  - Expt results have cut off at Z=21 due to NIMROD isotopic limitations

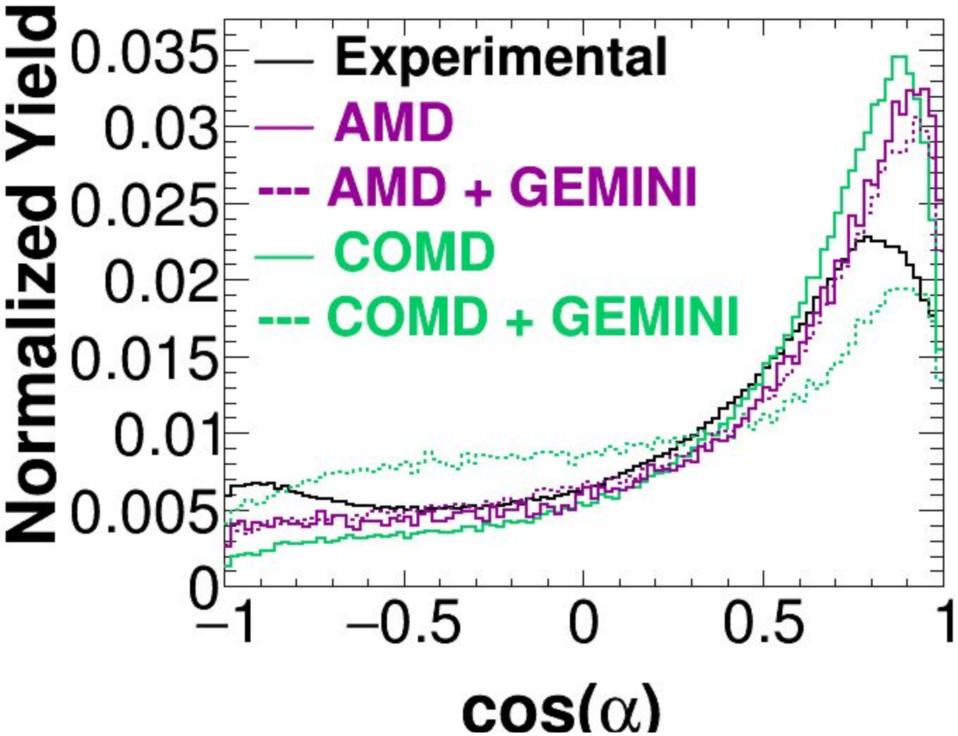
Velocity Distribution

- Solid line is experimental results
- In all cases, the **HF** and **LF** are forward of mid-velocity
  - Fragments originate from the PLF*

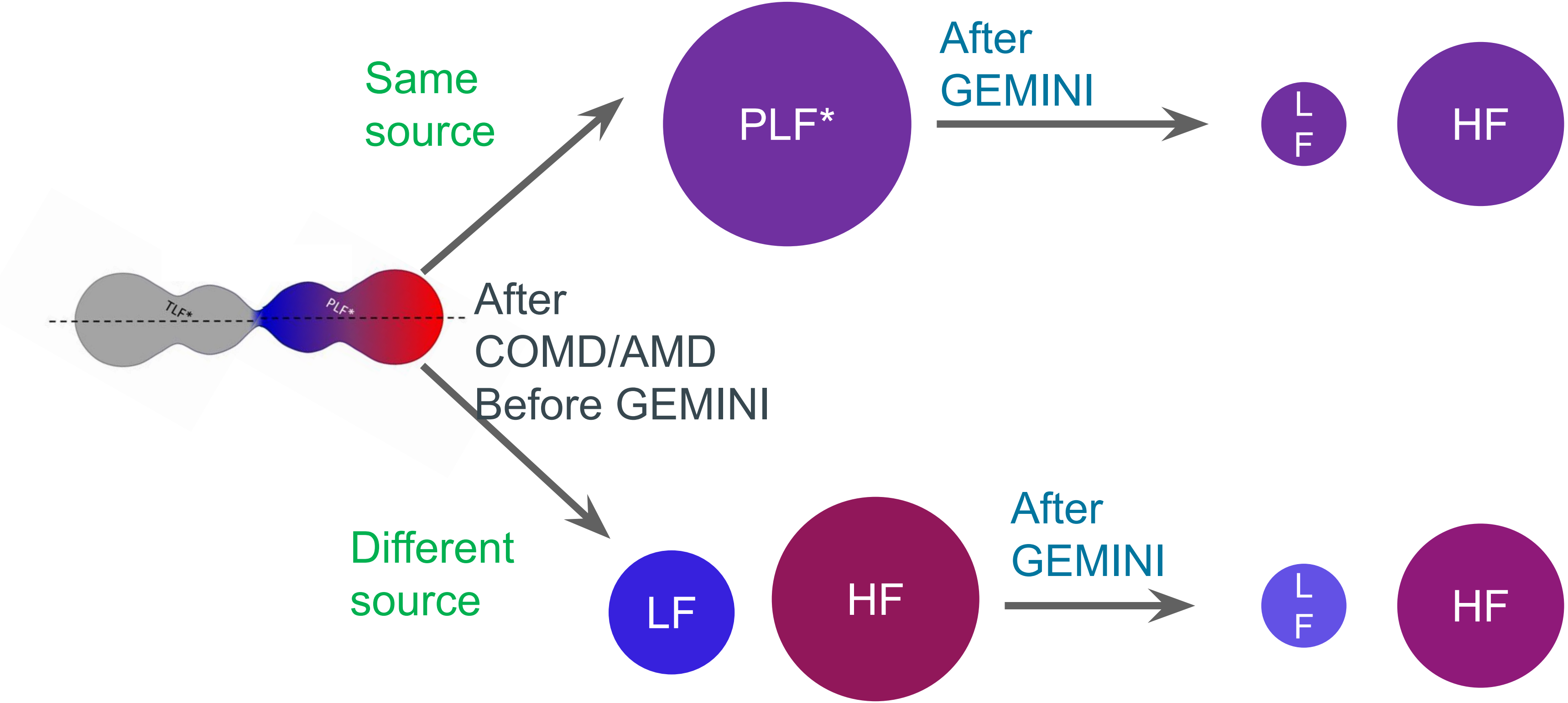


Angular Distribution

- Yield enhancement at cos(α) =1 is replicated
    - Consistent with dynamical decay
- Enhancement pronounced for before GEMINI de-excitation
    - Gated on events from “different” source

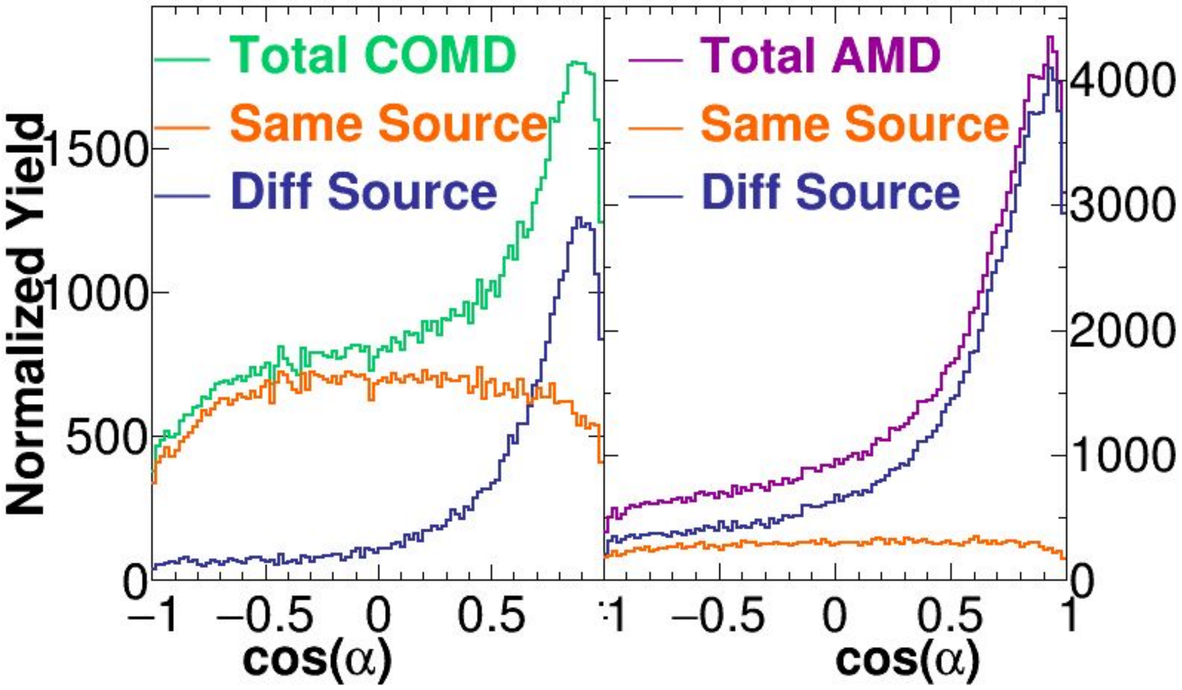


“Same” vs “different” source



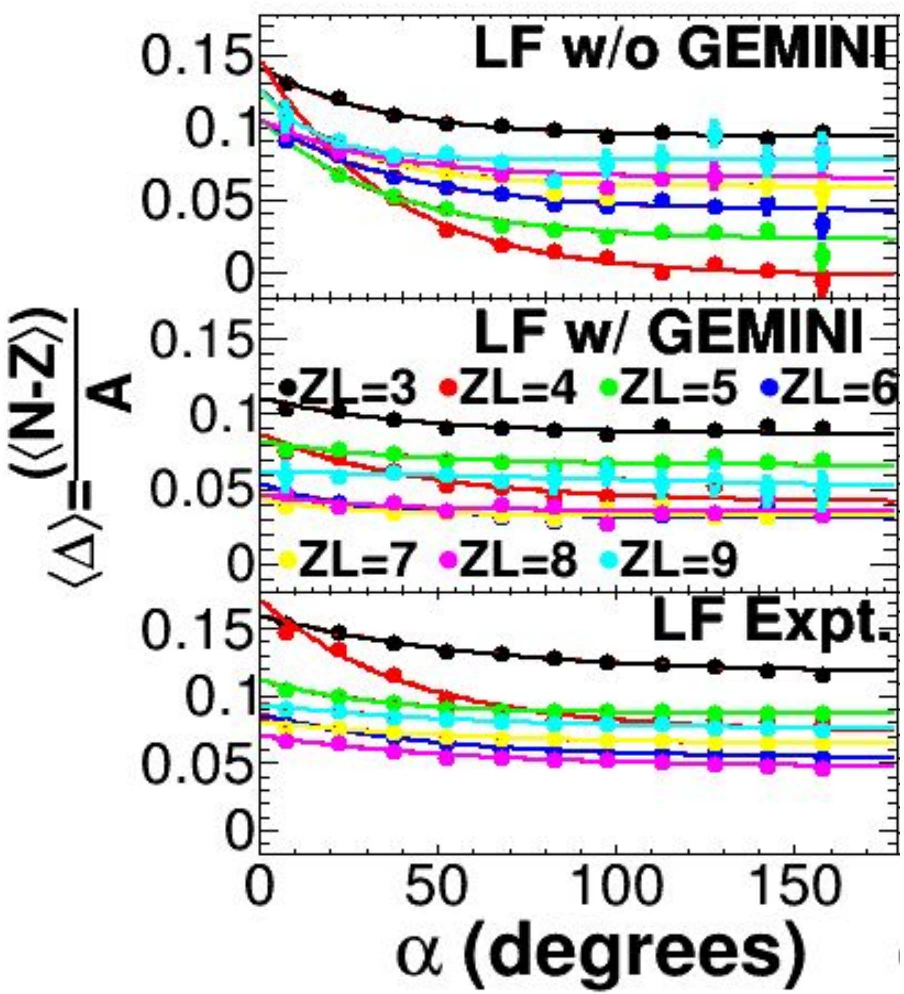
Angular Distributions

- Dynamical effects still present for different source
- Isotropic distribution seen for same source
- Focus on different source event for remainder of presentation



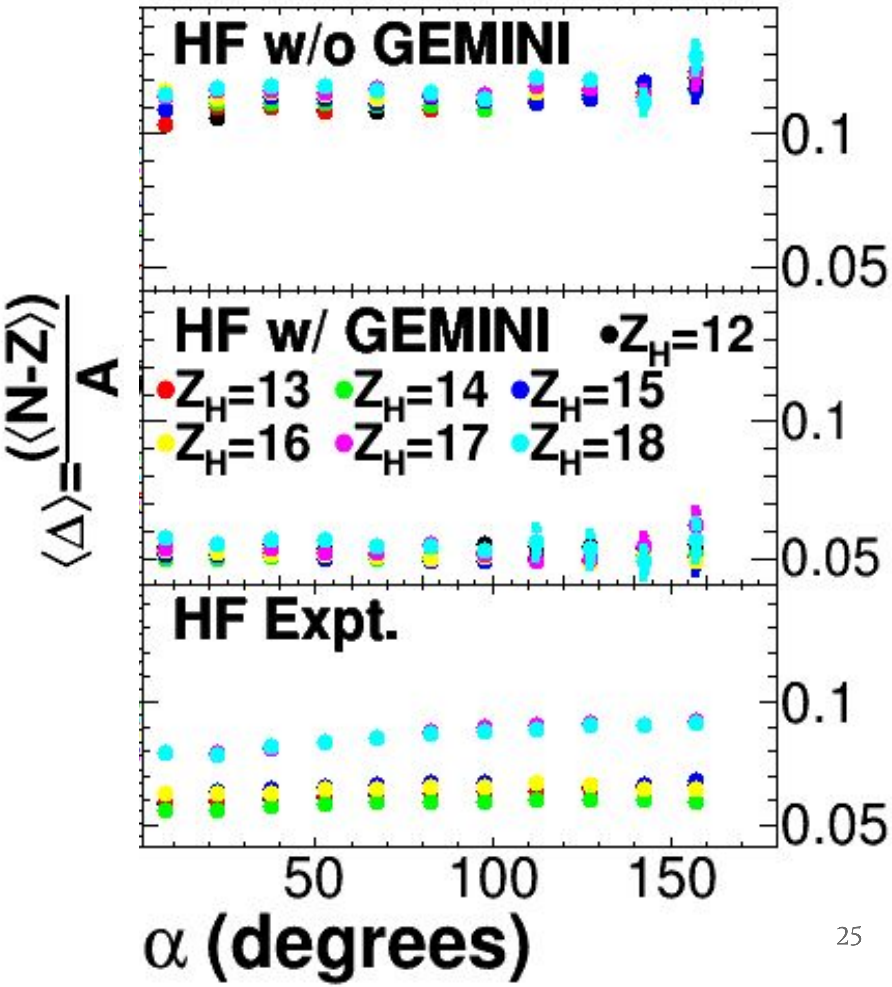
COMD soft interaction - **LF**

- Trend well reproduced for **LF**
- Without COMD:
  - Over-prediction of Δ
  - Initial clustering
  - Ordering issue
- With GEMINI
  - Better agreement for LF
  - Ordering consistent with odd-even effects



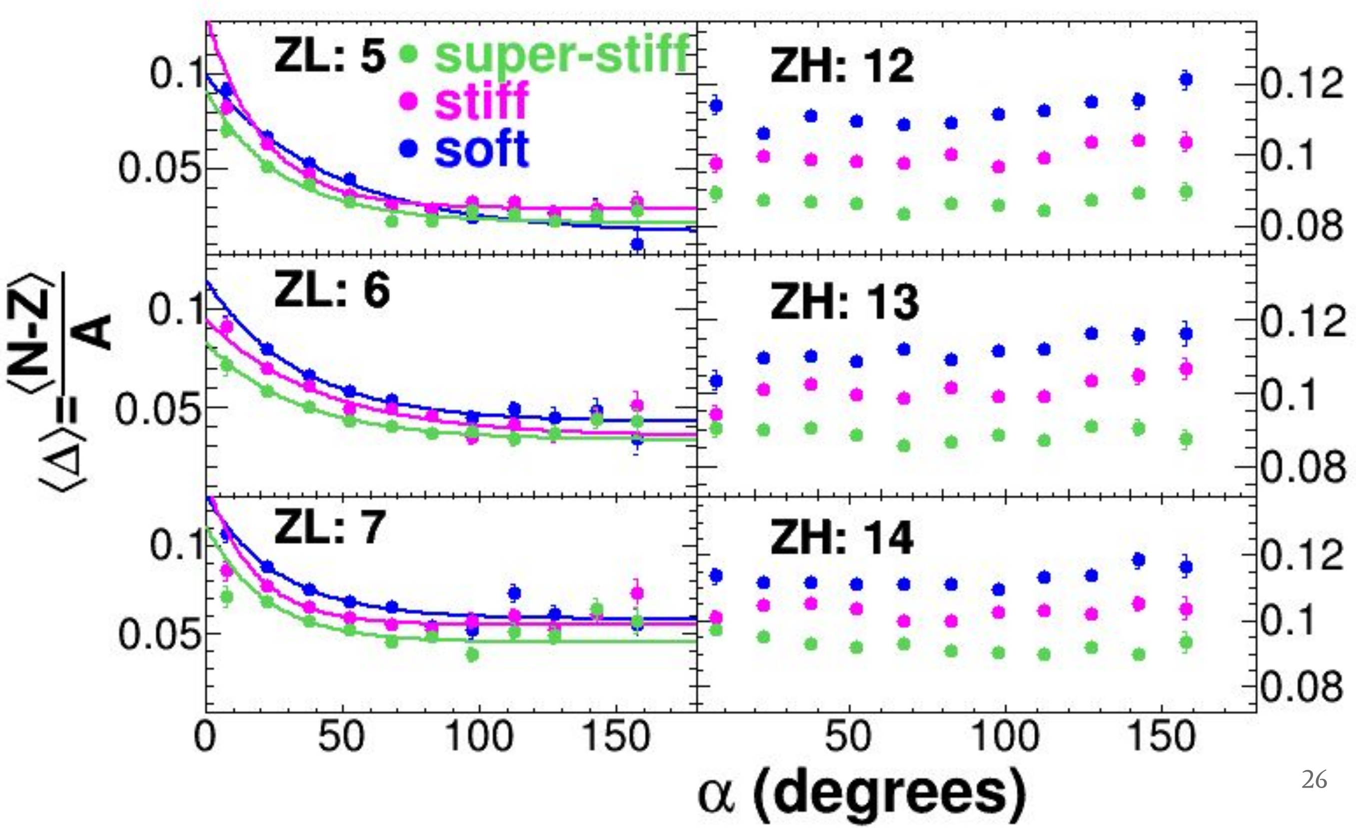
COMD soft interaction - HF

- Trend is not reproduced for **HF**
- Without GEMINI:
  - Significant over-prediction of Δ
  - Minor increase in Δ
- With GEMINI:
  - Flat distribution
  - Δ in good agreement with expt results



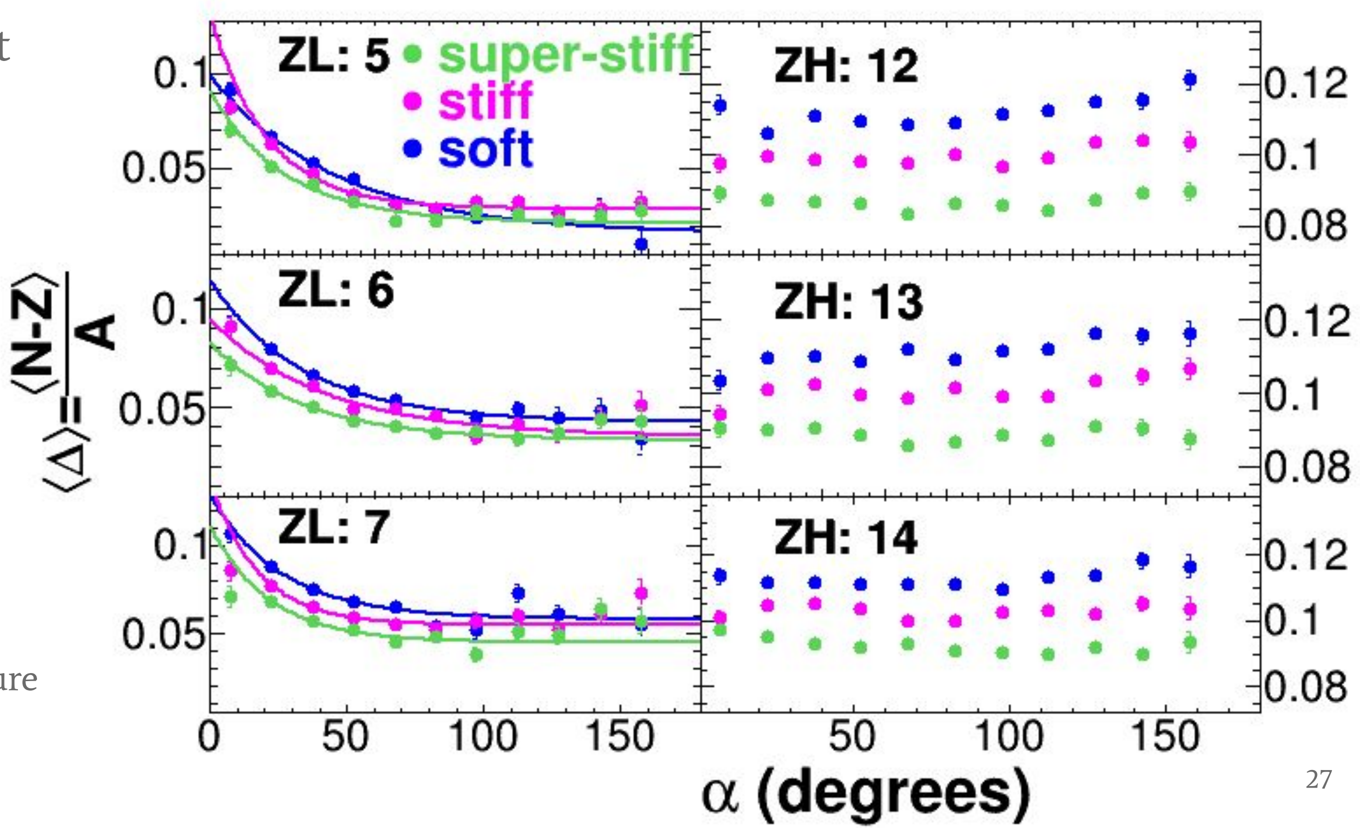
Comparing stiffnesses - LF

- Exponential trend reproduced well
- Extent of equilibration is consistent
  - ~ 0.5 neutrons
- Ordering where stiffest is least neutron-rich
  - Consistent with largest potential barrier for super-stiff interaction



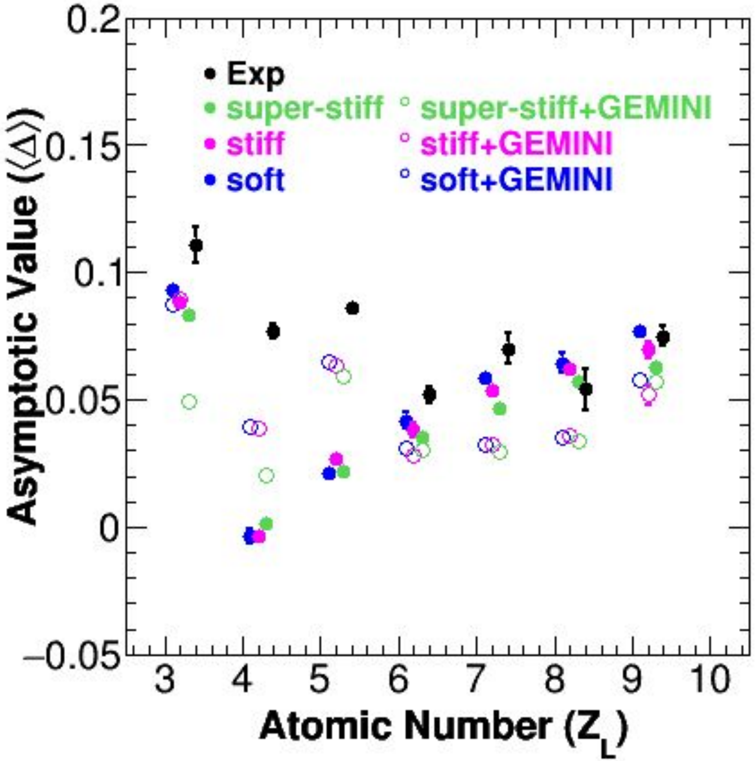
Comparing stiffnesses - HF

- Exponential trend not reproduced
- Flat distribution for stiffest interaction
  - Increase in Δ as interaction becomes softer
- Ordering issues
  - Most neutron-rich is also soft interaction
  - Inconsistent with potential barrier picture



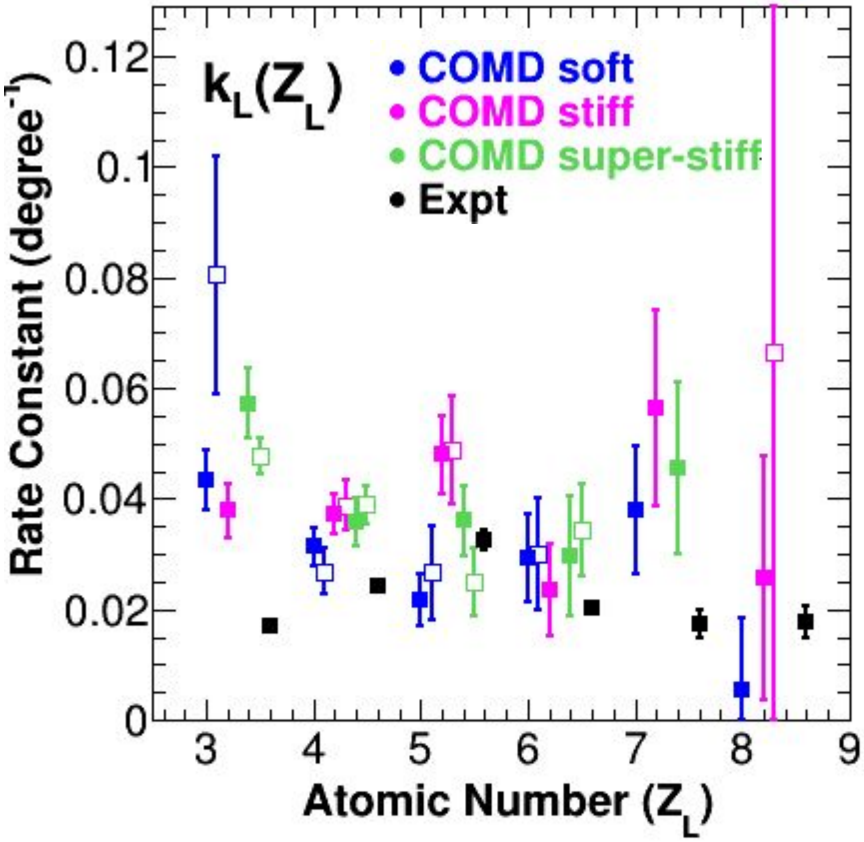
Asymptotic Values

- Fit: $\Delta = a + b \cdot e^{-c\alpha}$
- Even-odd trend reproduced with GEMINI de-excitation
- Under prediction of asymptotic values
  - Most prevalent for results with GEMINI



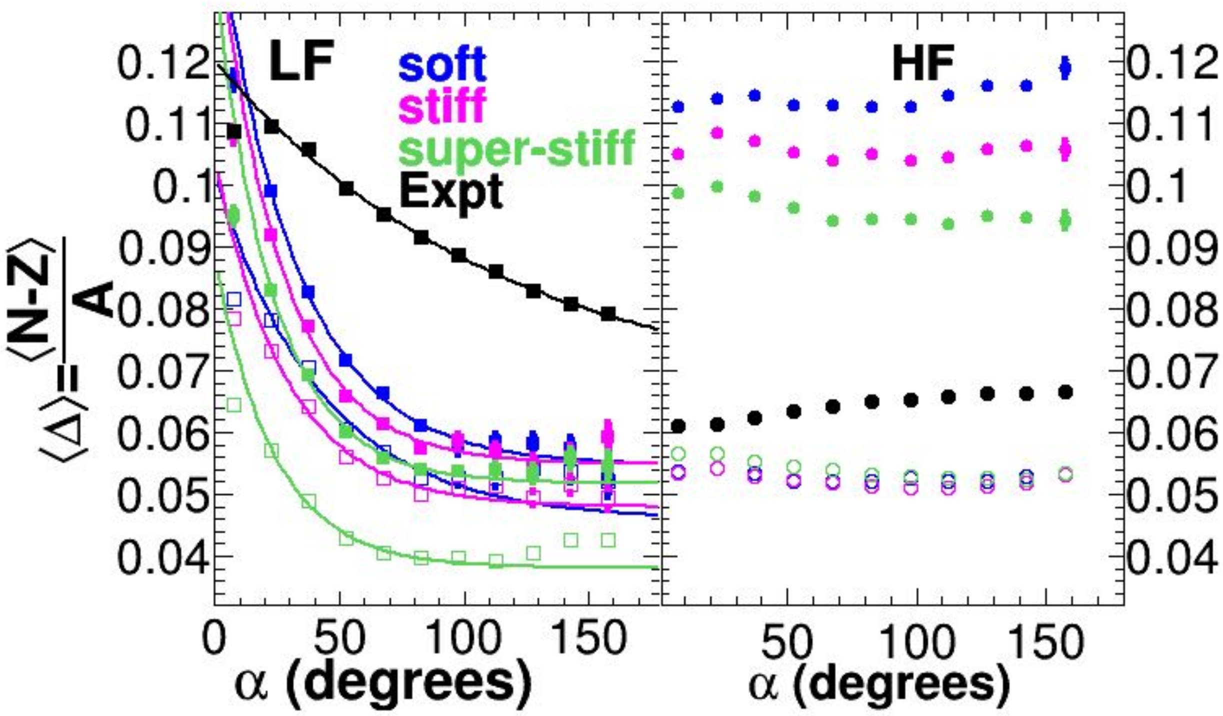
Rate Constants

- Good consistency for all **LF** equilibrium values with each other
- No notable difference seen for the various interactions



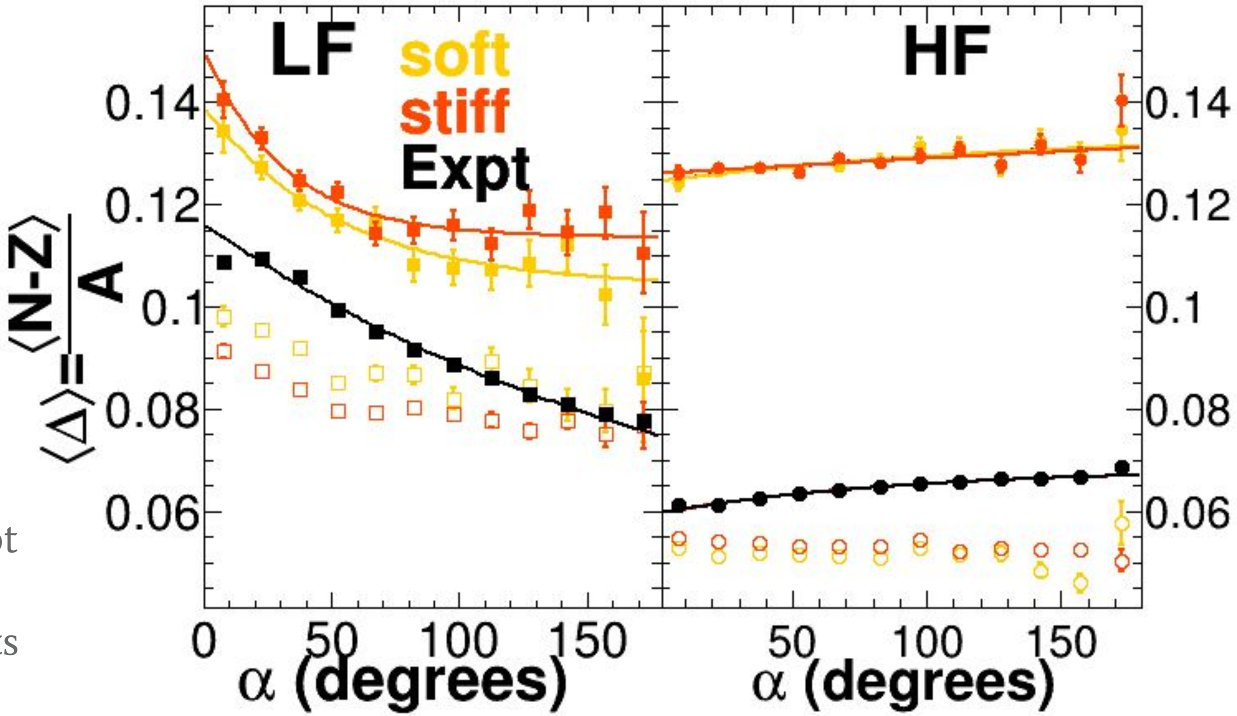
Total COMD Results with and without GEMINI

- Experimental results are for **all** Z_H and Z_L combined
- In all cases, extent of **LF** equibration is over-predicted
- **HF** is inconsistent
  - S-shaped behavior
  - Decrease in GEMINI
    - Excitation energy input?



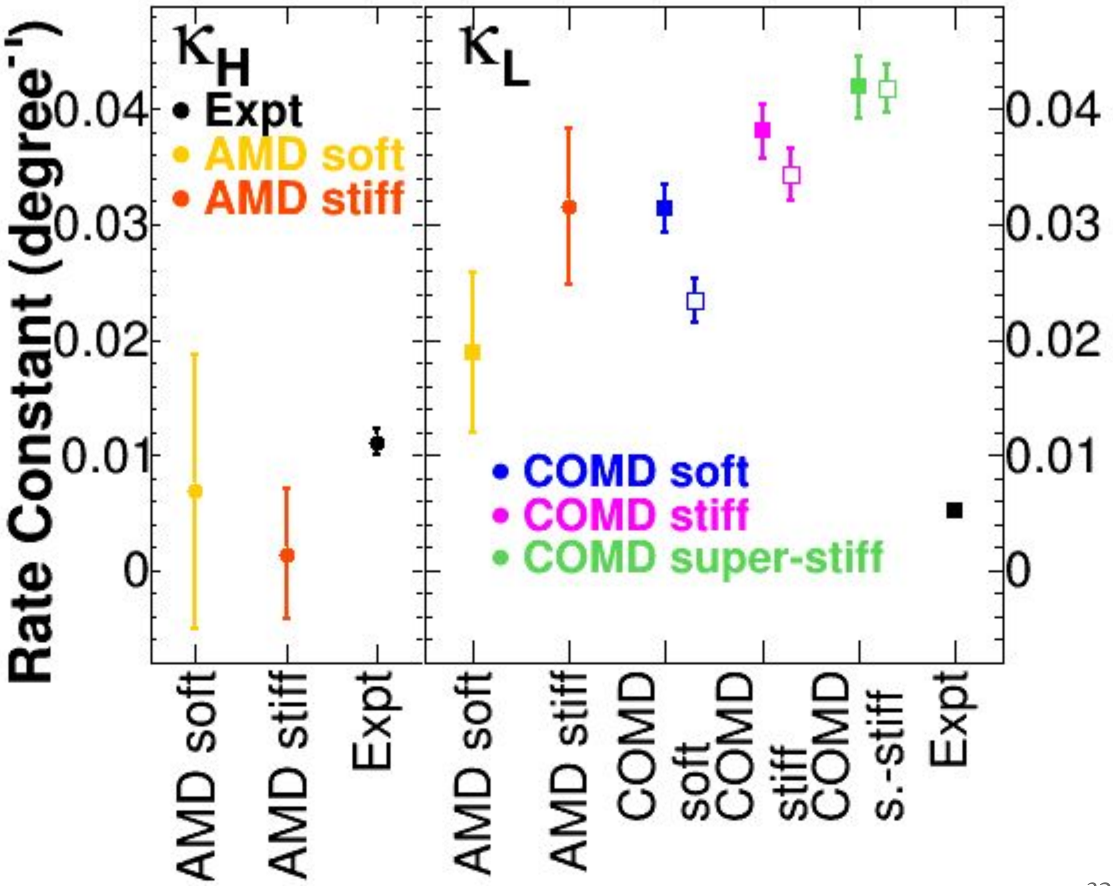
AMD results

- Exponential trend reproduced for **LF**
  - Faster rate for stiff interaction
  - S-shaped distribution for results with GEMINI
    - Excitation energy input?
- Exponential trend is reproduce for **HF** without GEMINI
  - Extent of equilibration not as large as expt results
  - Flat distribution for results with GEMINI



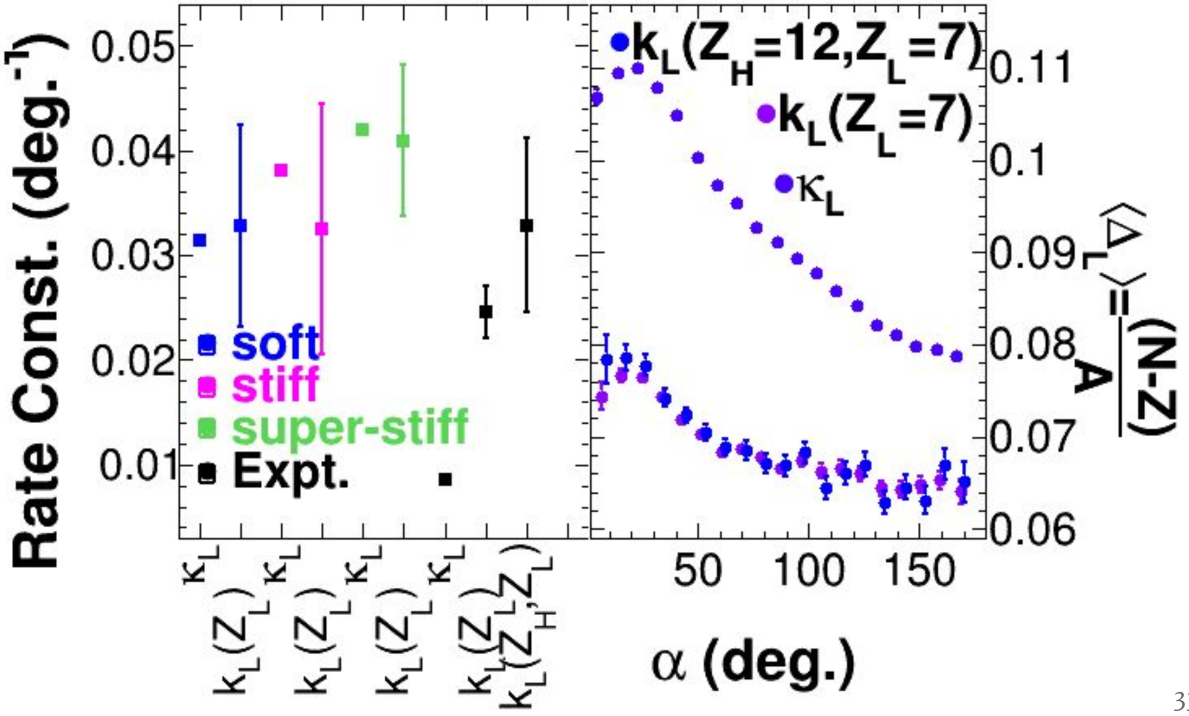
Rate Constants

- κ is rate constant for all Z_H and Z_L combined
- Consistency in κ_H between AMD soft and expt values
- Increase in κ_L as a function of interaction stiffness
  - Largest for COMD without GEMINI
- Inconsistency between κ_L for simulation and expt



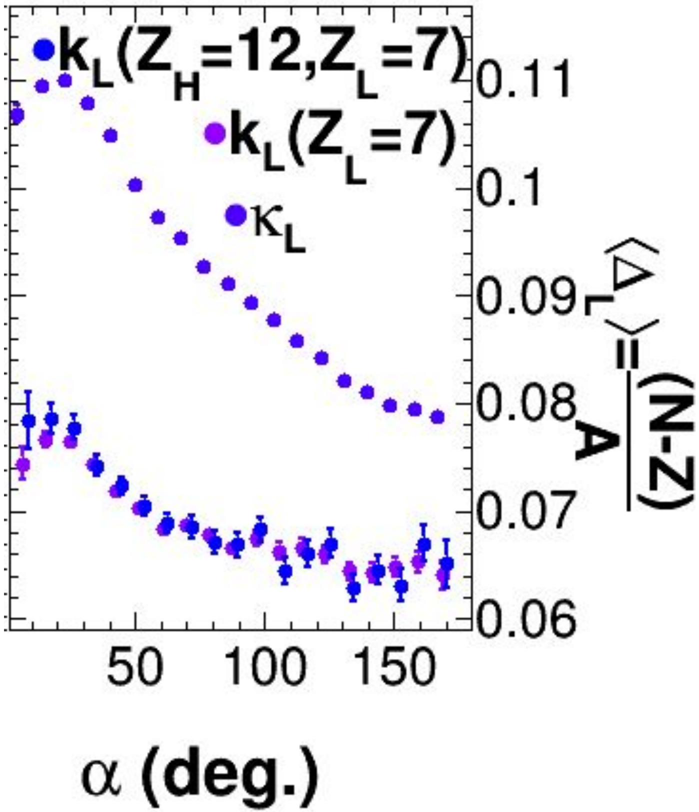
Looking further at Experimental Data

- Simulation data not highly affected by Z selection
- Expt data is **highly** dependent on the Z selection!
  - Increase of approx. 0.1 deg^{-1} b/n $k_L(Z_H, Z_L)$ and $k_L(Z_L)$
  - Most significant difference between κ_L and $k_L(Z_L)$



Velocity Distributions

- Distribution dominated by Z_L=3, 4
- Enhanced relative contribution at α>50° from larger Z_L values
  - Larger Z_L has lower Δ



Open-ended Questions or Improvements

FAZIA? ;)

Improvements

1. Reaction plane versus detector resolution?
2. Ternary decay versus ‘string of pearls’?
3. Number of pearls?
4. Missing large portion of charge

Summary

- Used COMD and AMD with and without GEMINI to simulate NZ Equilibration
- Good agreement between AMD and Expt results for **LF** and **HF**
- Exponential trend for **LF** reproduced by COMD, but the **HF** is not
- Issues with GEMINI washing out signature of **HF**
- Experimental results very sensitive to charge selection!

Collaborators

- Yennello Research Group
  - K. Hagel, A.B. McIntosh, A. Abbott, A. Hannaman, B. Harvey, A. Hood,J. Gauthier, Y. Lui, L. McIntosh, M. Sorensen, Z. Tobin, R. Wada, M. Youngs, S.J. Yennello
- Collaborators (Indiana U.)
  - S. Hudan, R. De Souza

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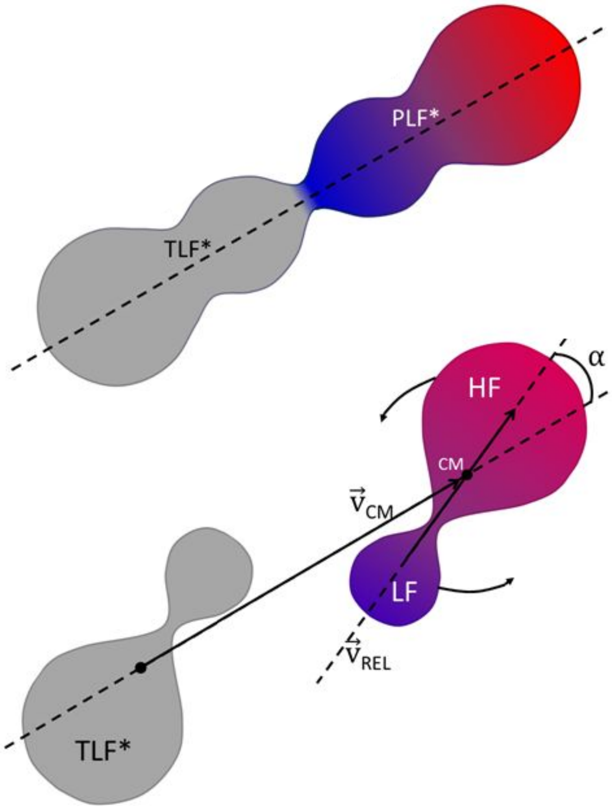
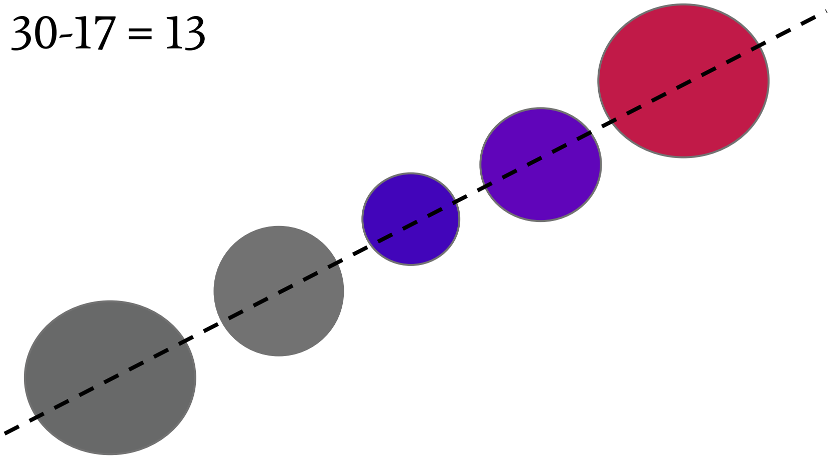
Merci!
Questions?

Back-up Files

Correct Pearls?

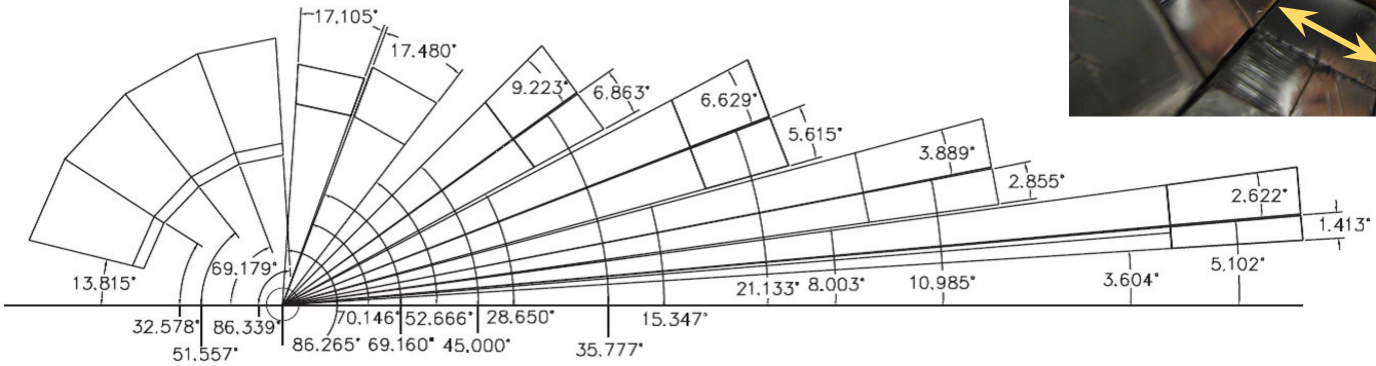


$Z_H + Z_L = 12 + 5 = 17$
$Z_{total} = 30$
$Z_{remain} = 30\text{-}17 = 13$



Angular resolution of NIMROD

- θ resolution is good
- ϕ resolution is 15 or 30° depending on the position
  - For telescopes with Si-Si-CsI, all quadrants of NIMROD read out
  - For Si-CsI telescopes, quadrants in same ring, same detector were tied together



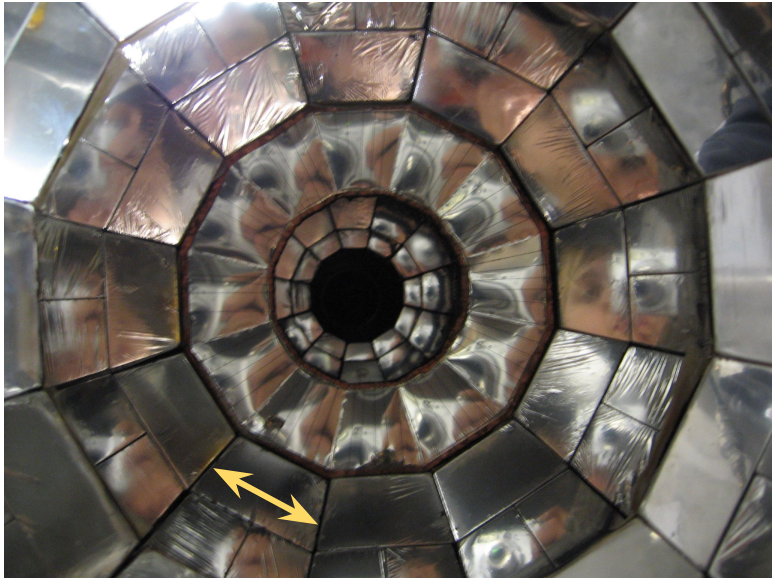
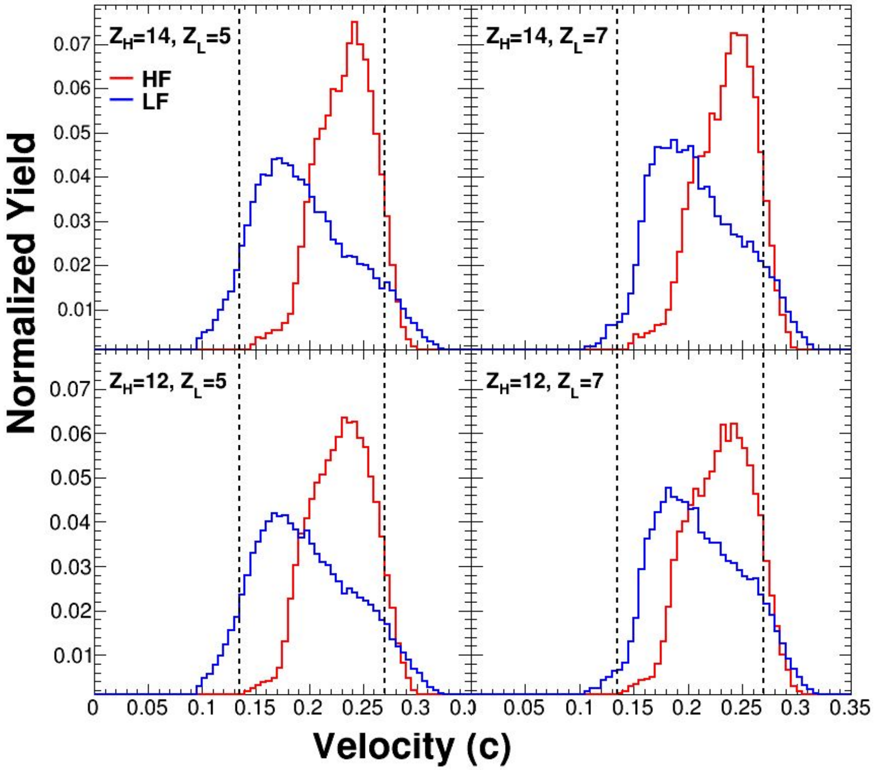


Photo courtesy of S. Wuenschel

Velocity distributions

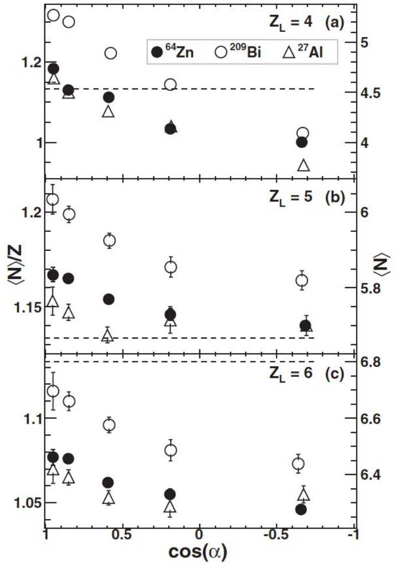


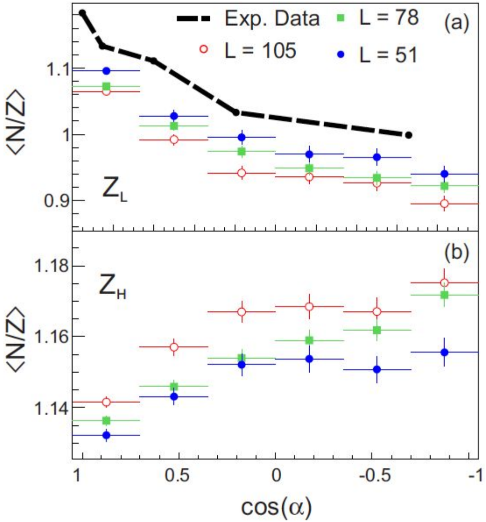
Jedele et al, PRL 118, 062501 (2017)

- Both fragments predominantly forward of mid-velocity
  - Fragments originated from PLF*

- Heavier fragment is on average faster
  - Consistent with dynamical decay

Target effects and simulations
Zn + Al, Zn, Bi @ 45 MeV/nuc.

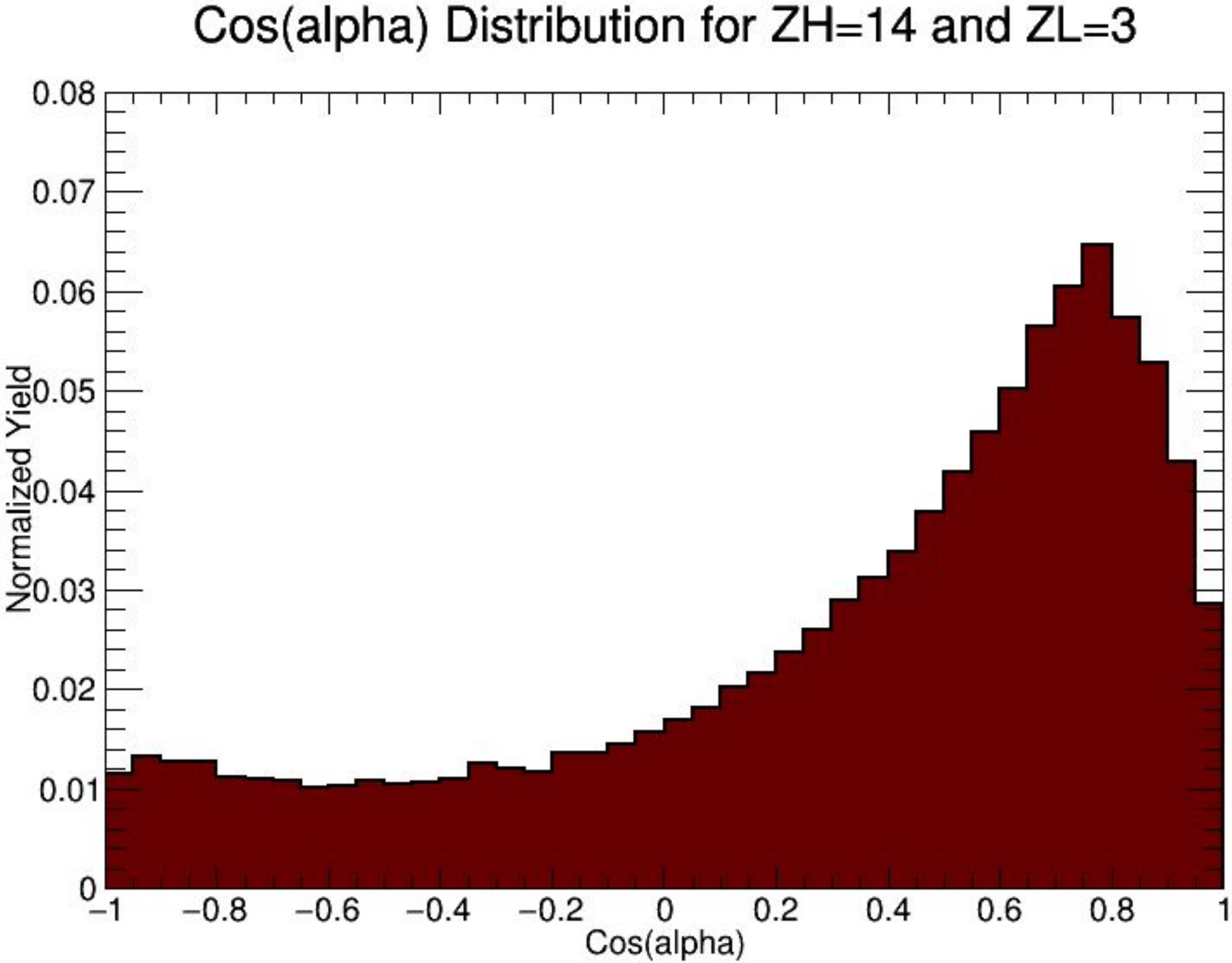


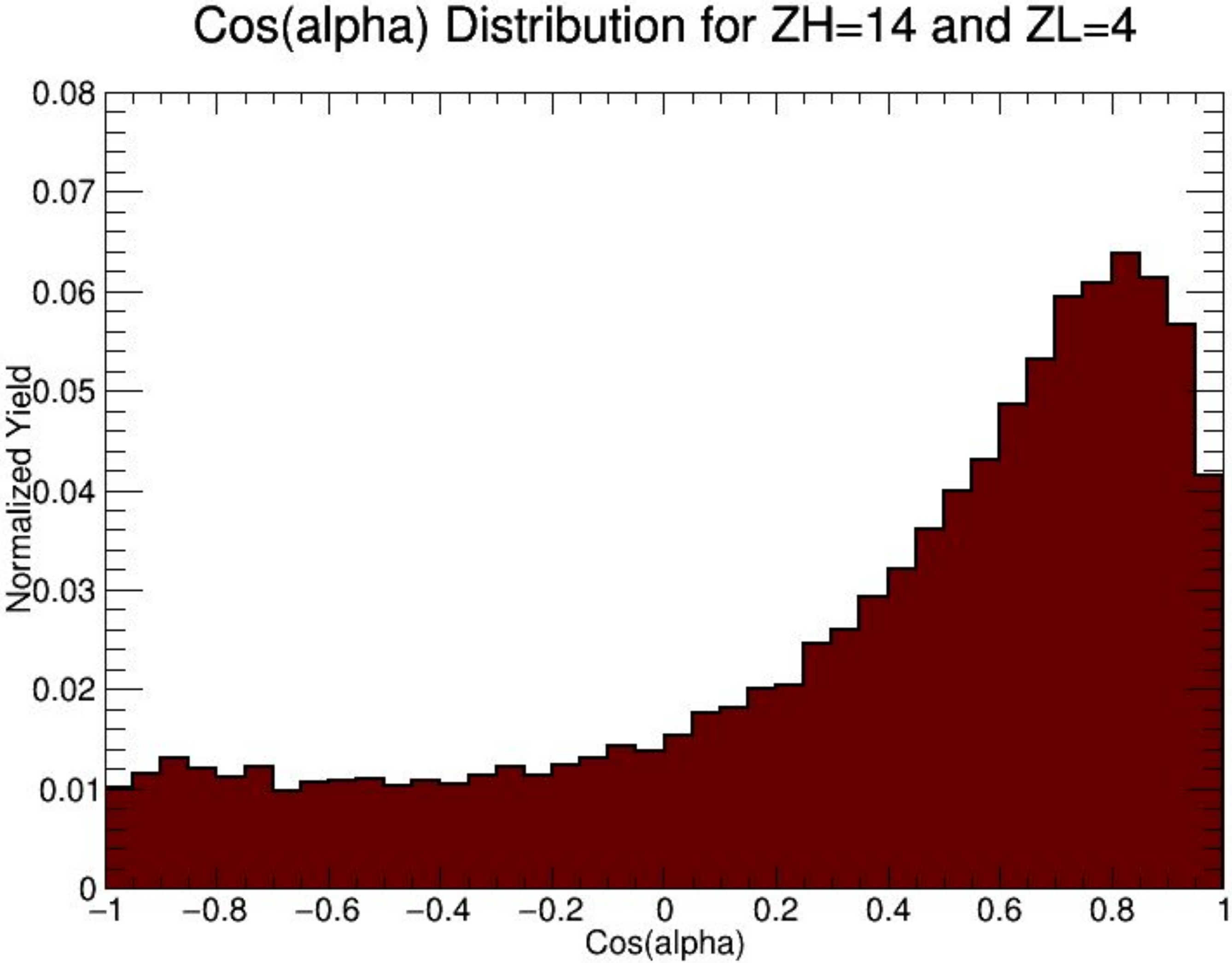


- Consistent with Hudan
- NZ composition depends on NZ target composition

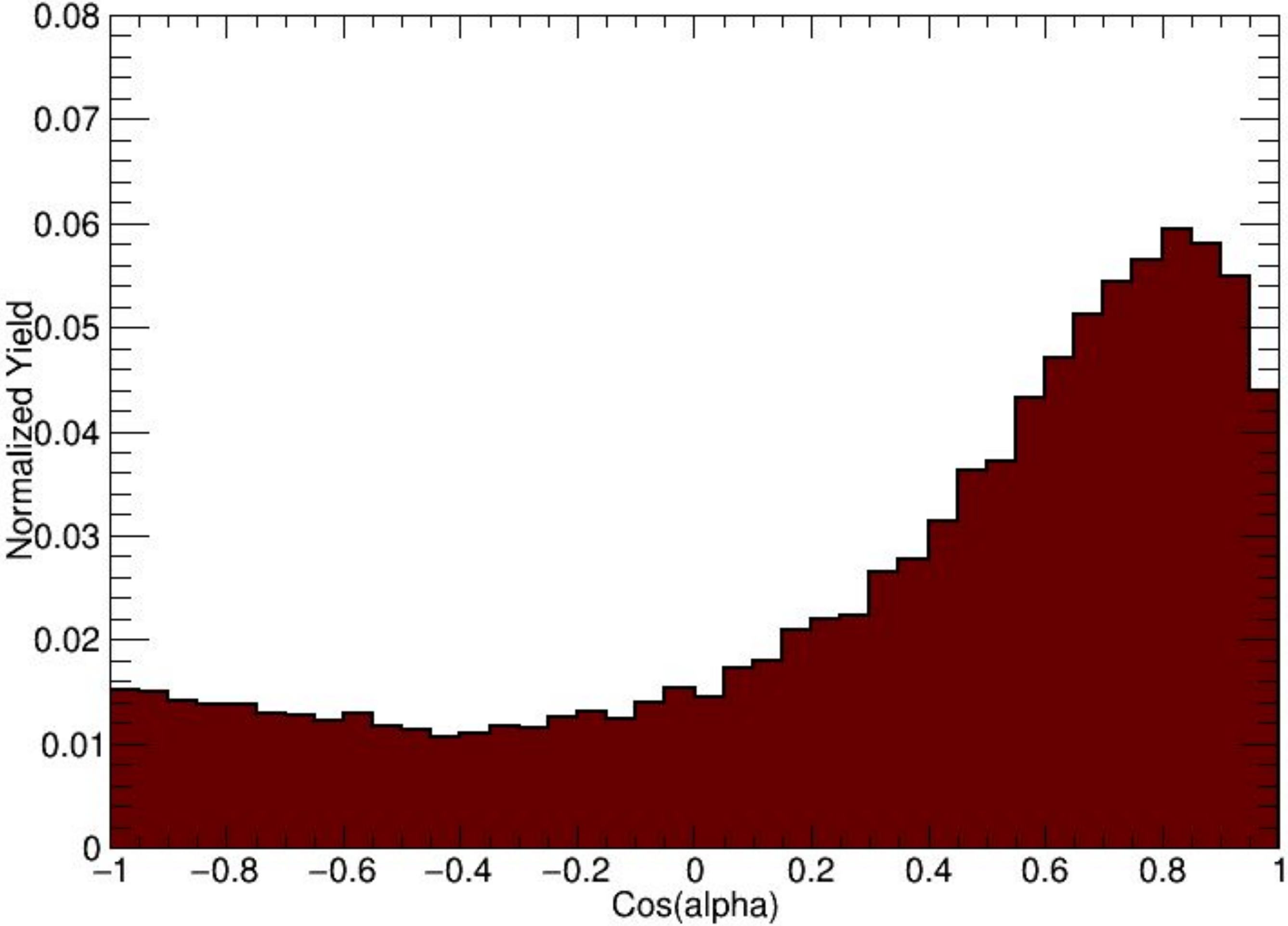
- Agrees with data
- Dependent on nEoS stiffness

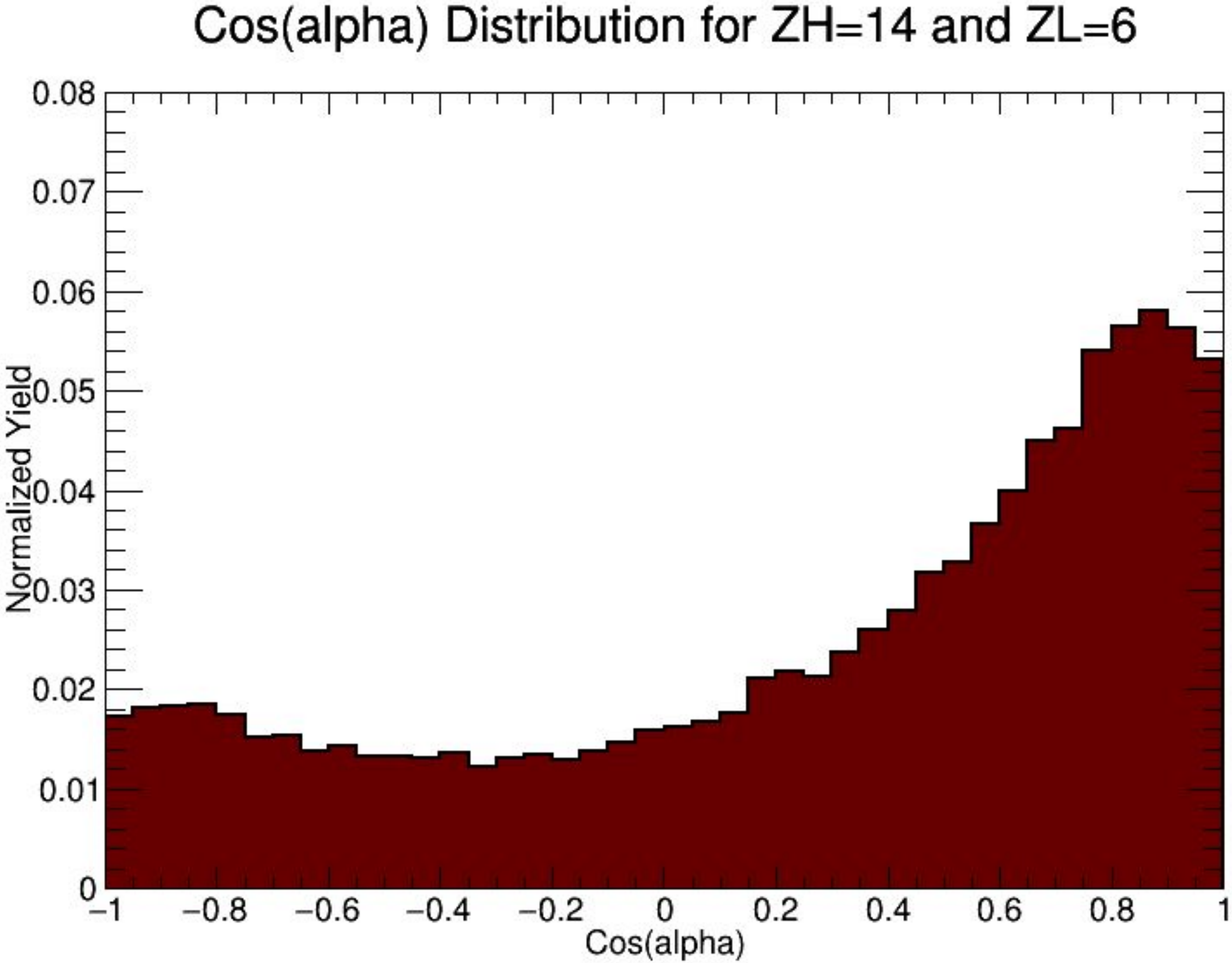
Brown et al. PRC 87, 061601(R) (2013)
Stiefel et al. PRC 90, 061605(R) (2014)

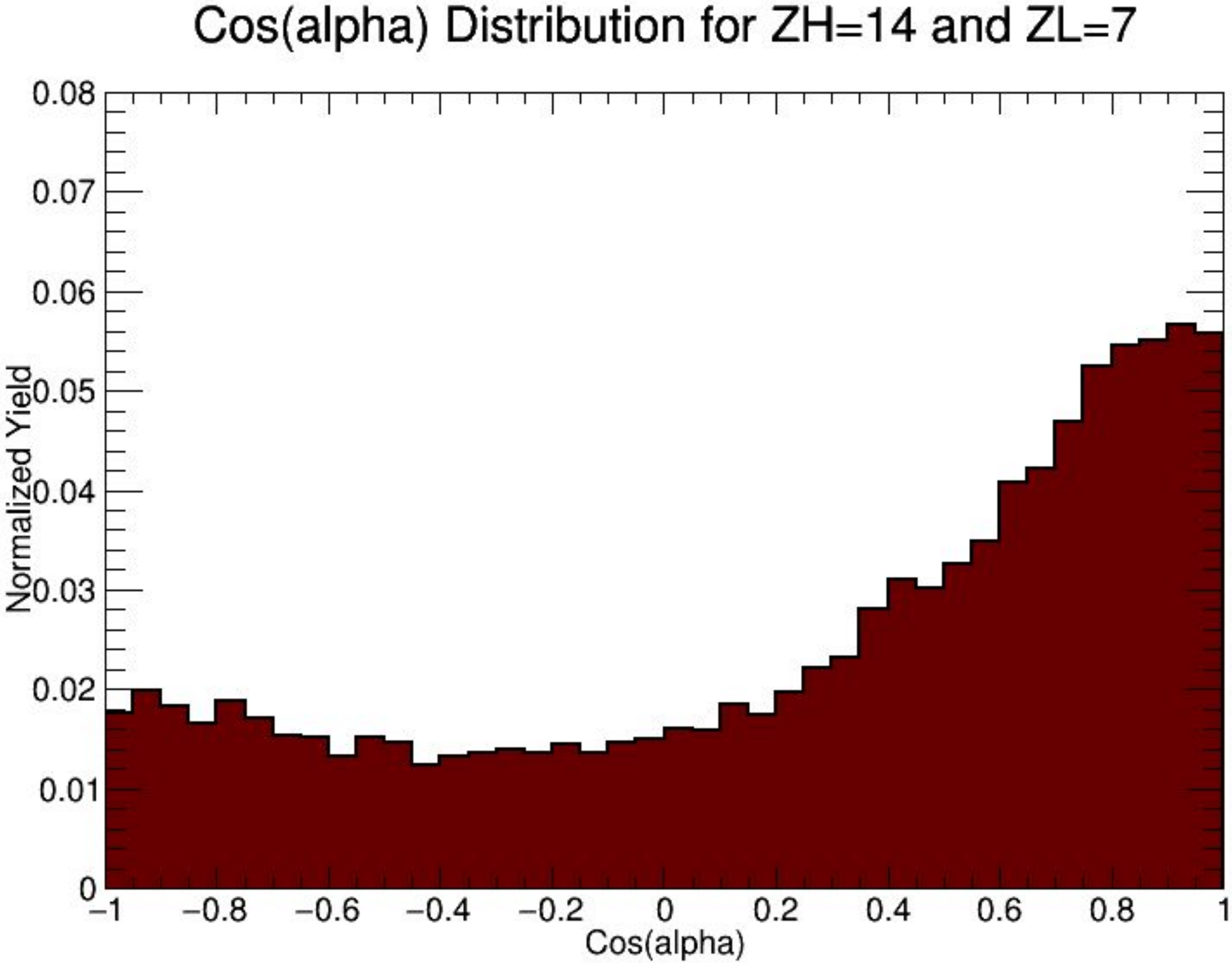

Cos(alpha) Distribution for ZH=14 and ZL=3
Normalized Yield
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
Cos(alpha)

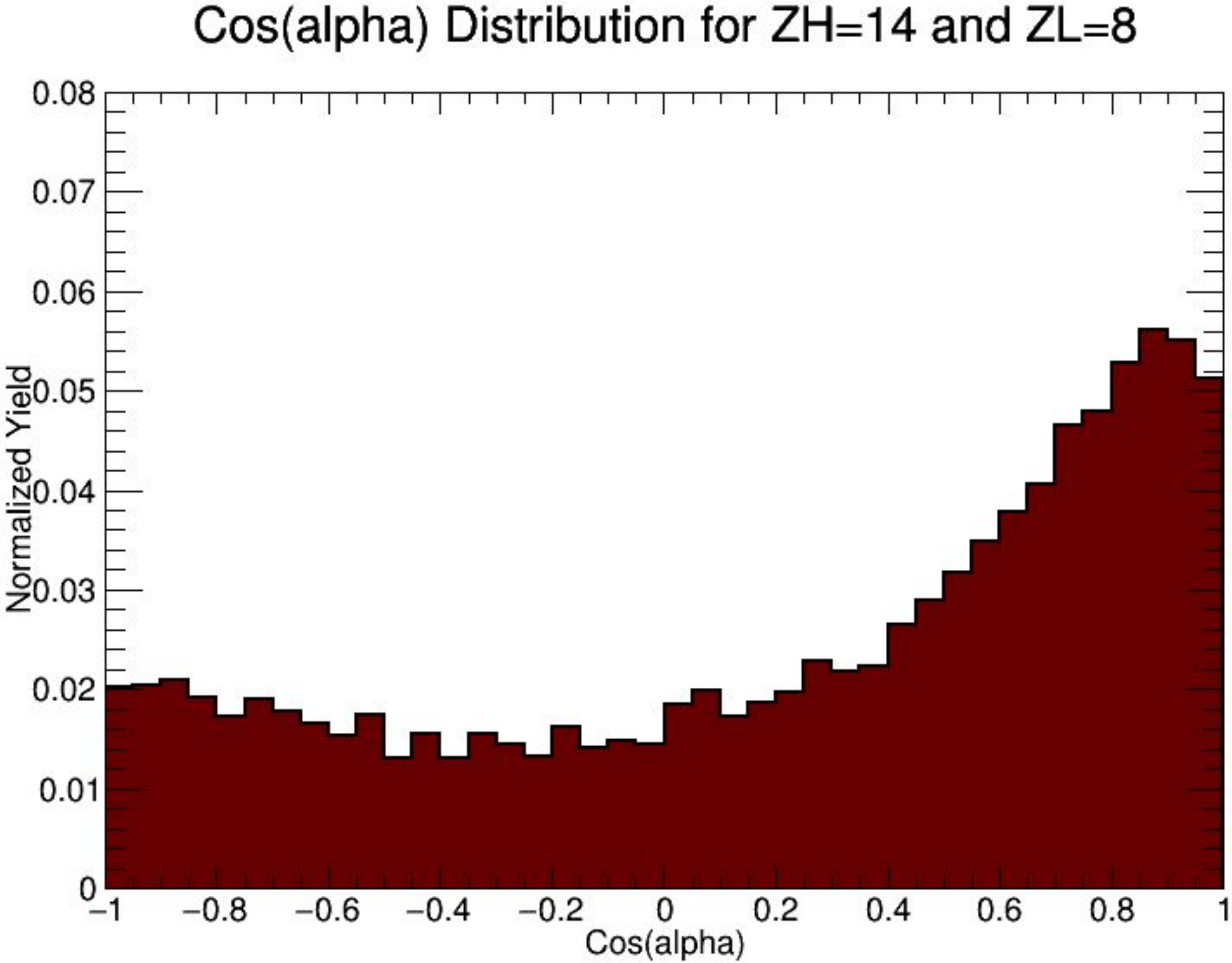

Cos(alpha) Distribution for ZH=14 and ZL=4
Normalized Yield
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
Cos(alpha)

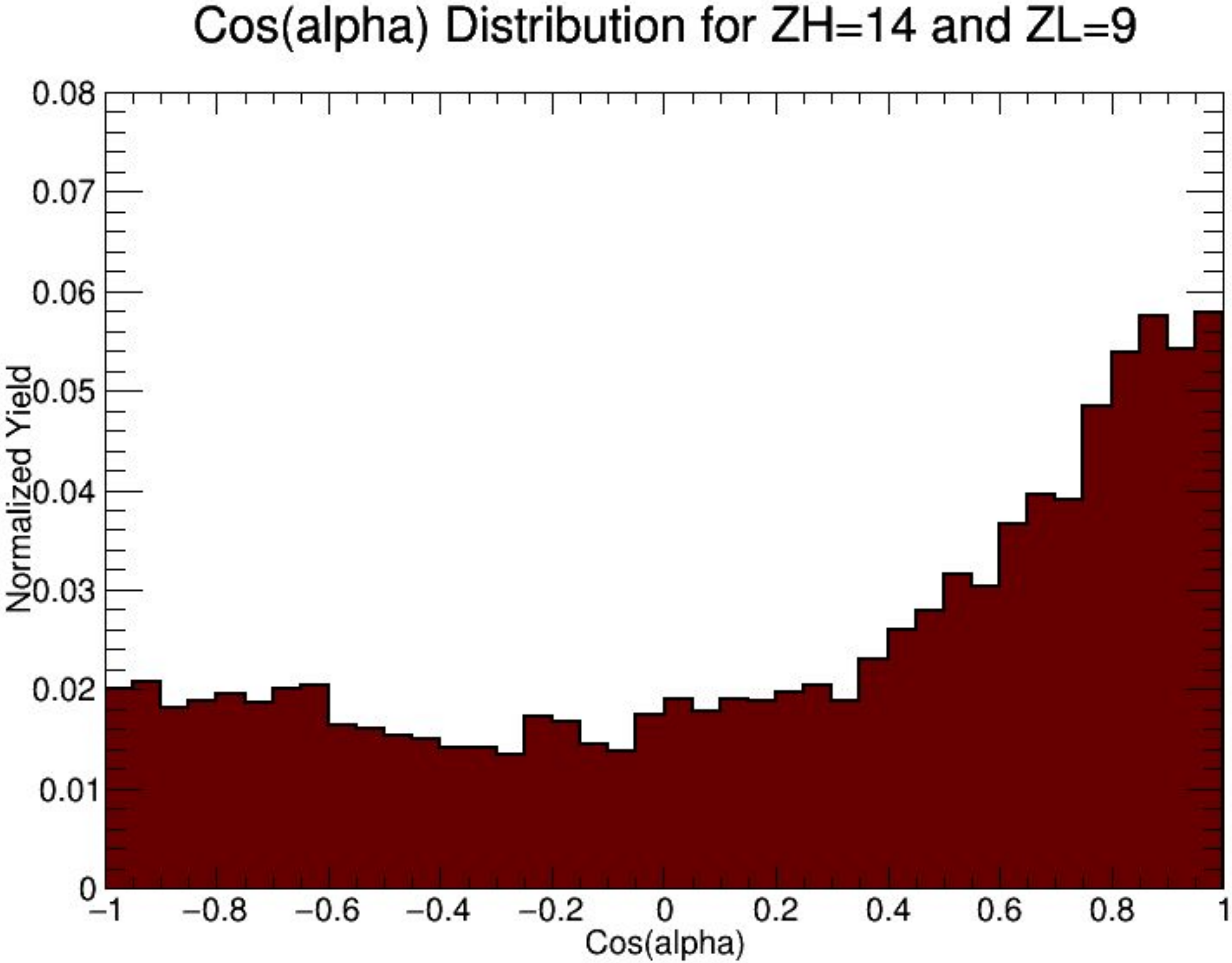
Cos(alpha) Distribution for ZH=14 and ZL=5

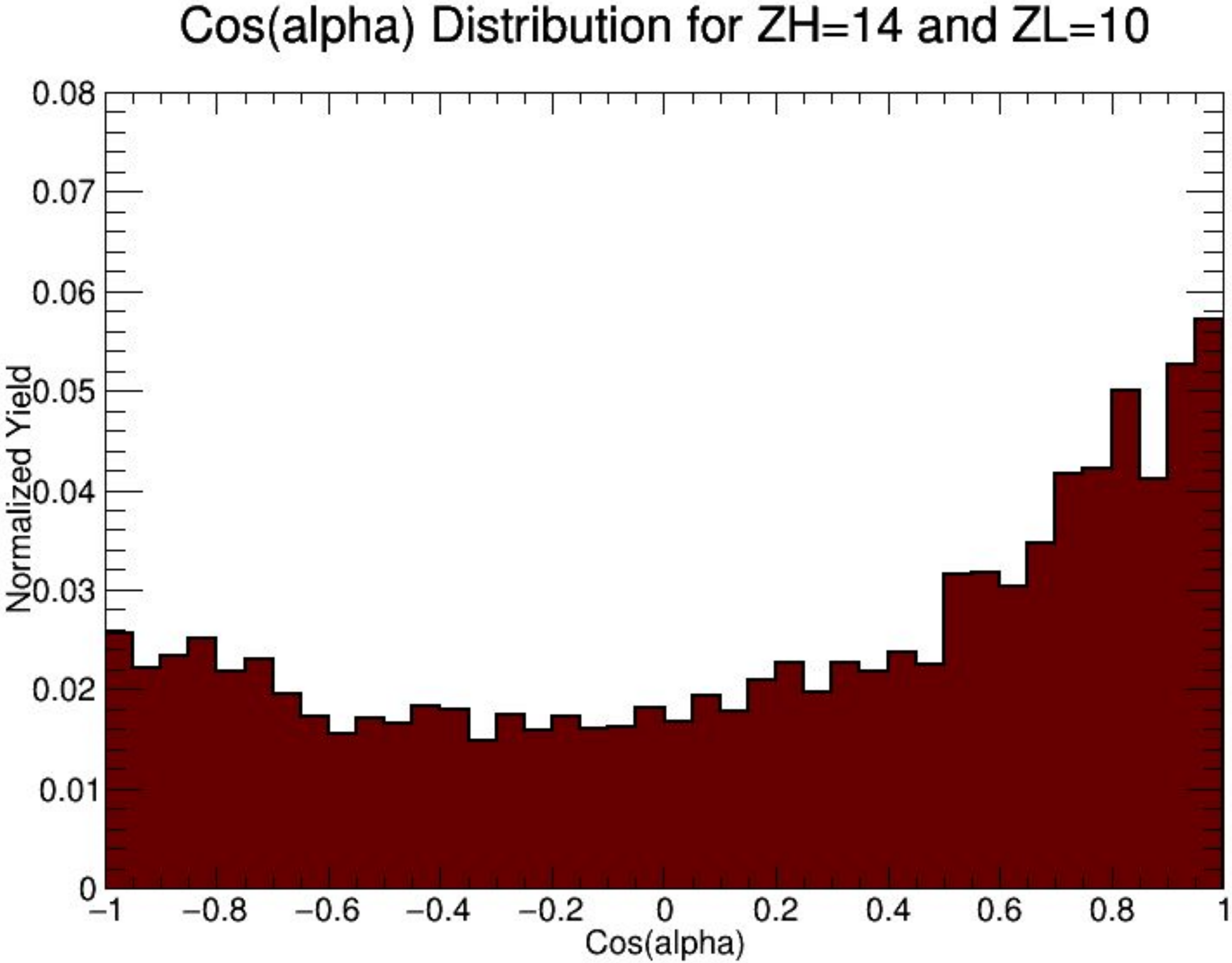



Cos(alpha) Distribution for ZH=14 and ZL=6
Normalized Yield
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
Cos(alpha)

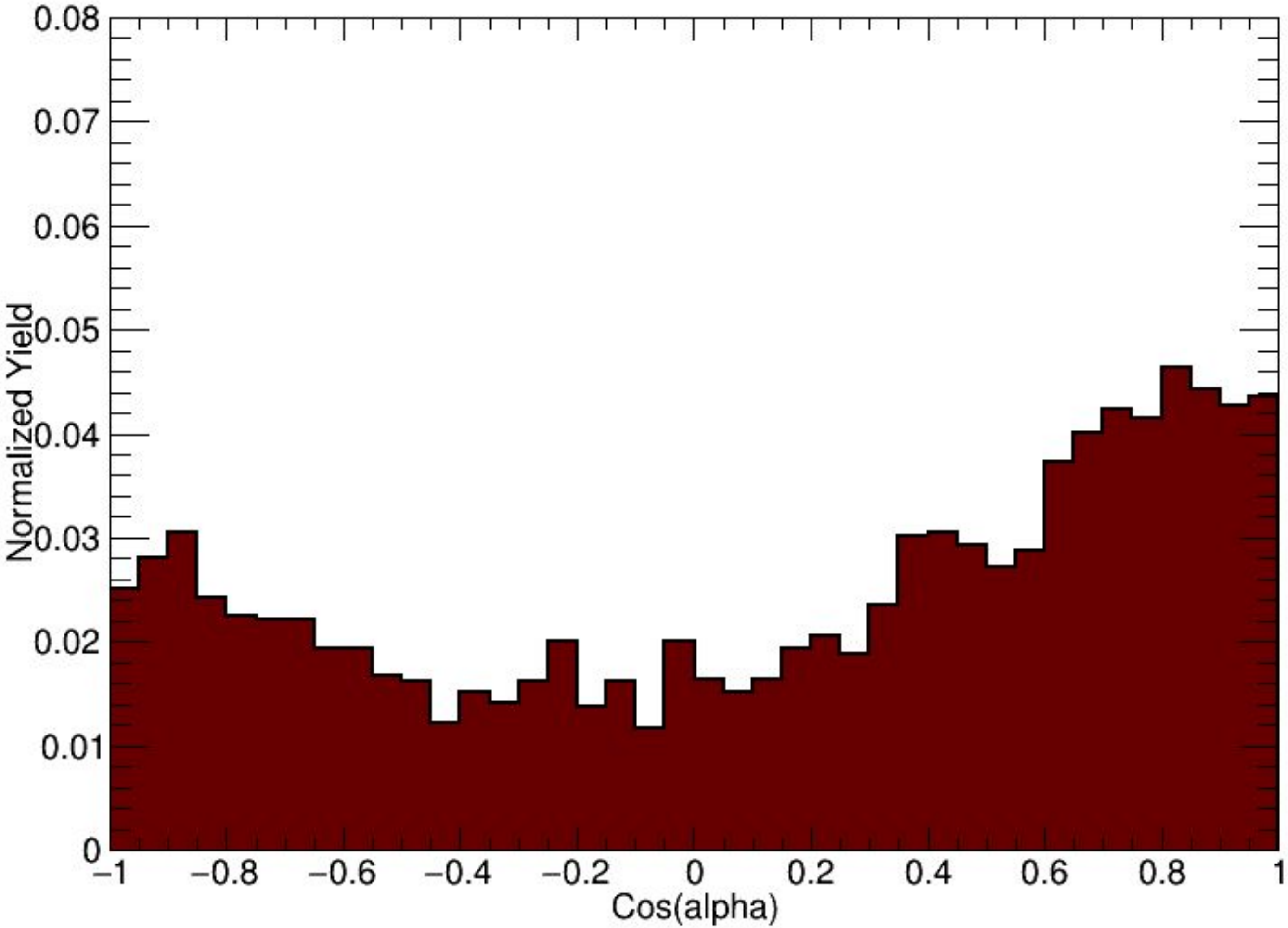

Cos(alpha) Distribution for ZH=14 and ZL=7
Normalized Yield
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
Cos(alpha)

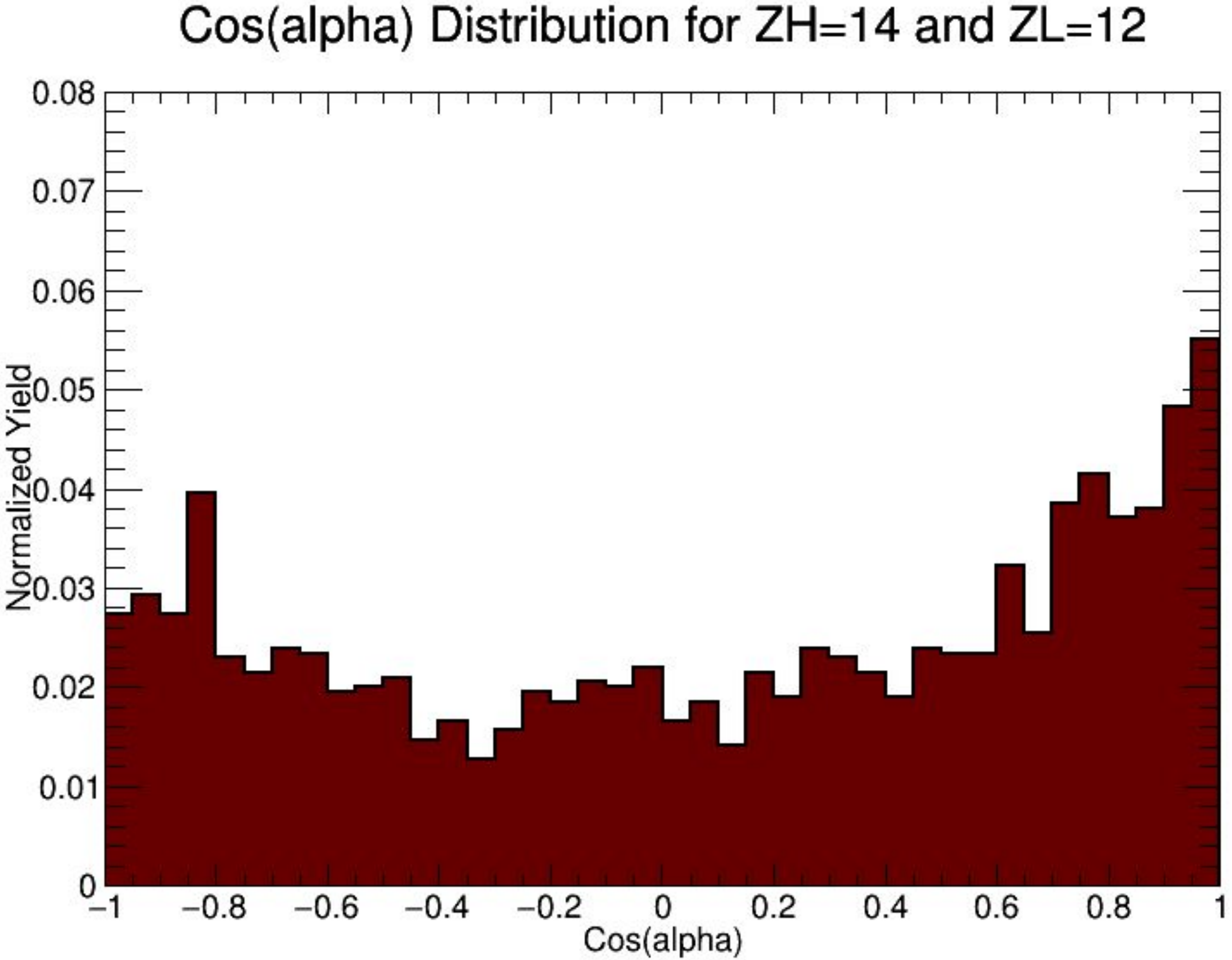

Cos(alpha) Distribution for ZH=14 and ZL=8
Normalized Yield
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
Cos(alpha)


Cos(alpha) Distribution for ZH=14 and ZL=9
Normalized Yield
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
Cos(alpha)

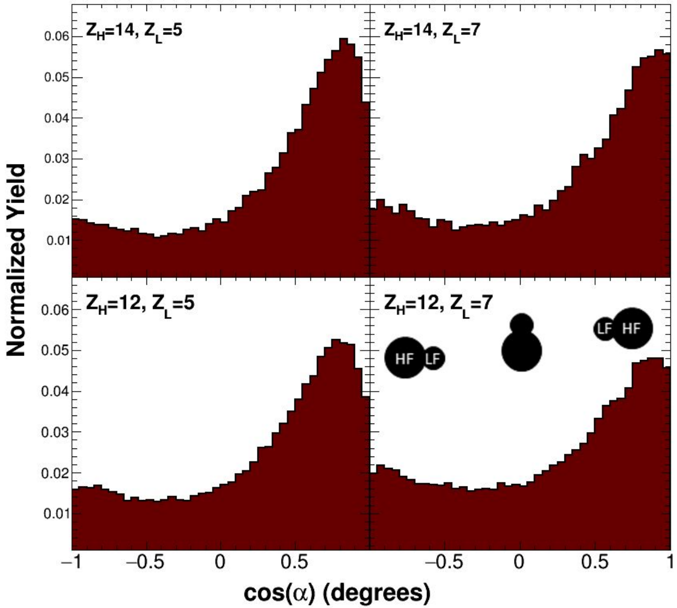

Cos(alpha) Distribution for ZH=14 and ZL=10
Normalized Yield
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
Cos(alpha)

Cos(alpha) Distribution for ZH=14 and ZL=11

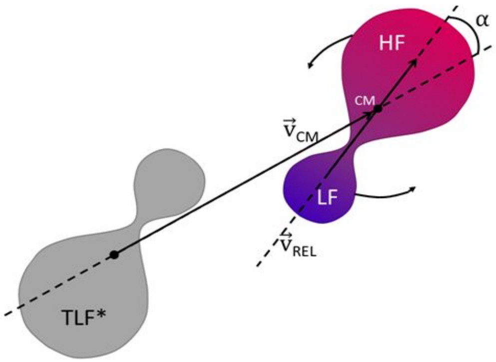



Cos(alpha) Distribution for ZH=14 and ZL=12
Normalized Yield
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
Cos(alpha)

Angular Distribution

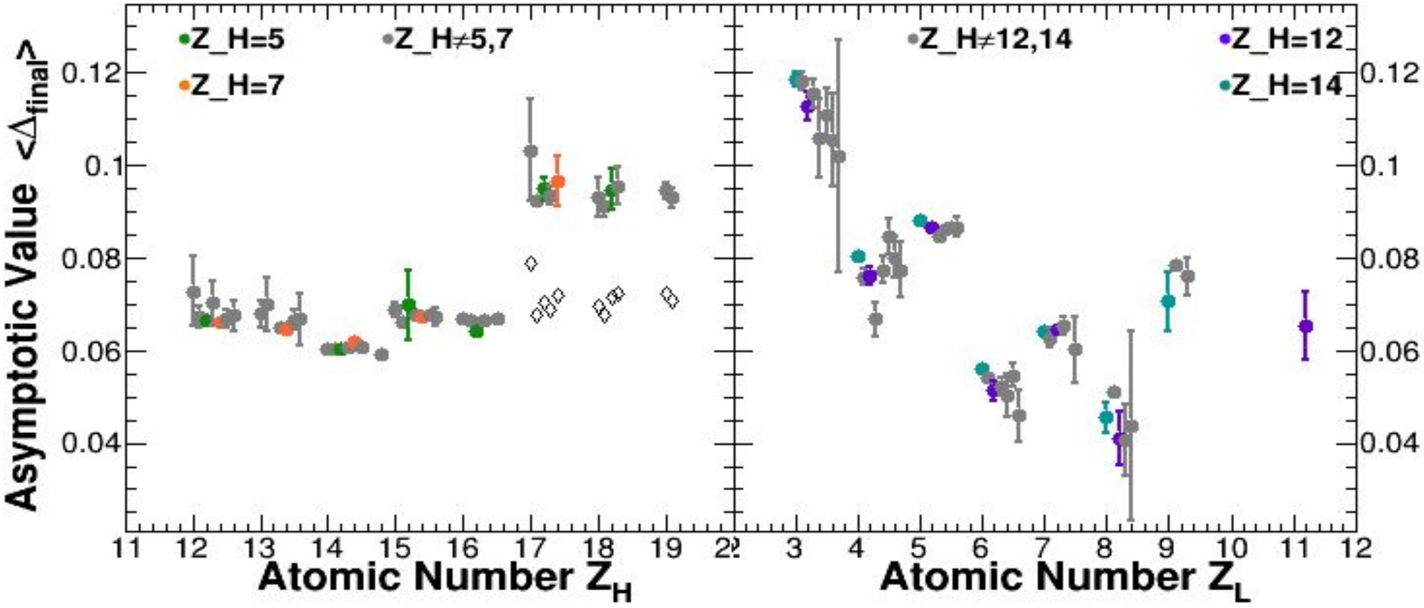


- Strong alignment
  - Consistent with dynamical decay
  - Decay timescale is faster than rotational period



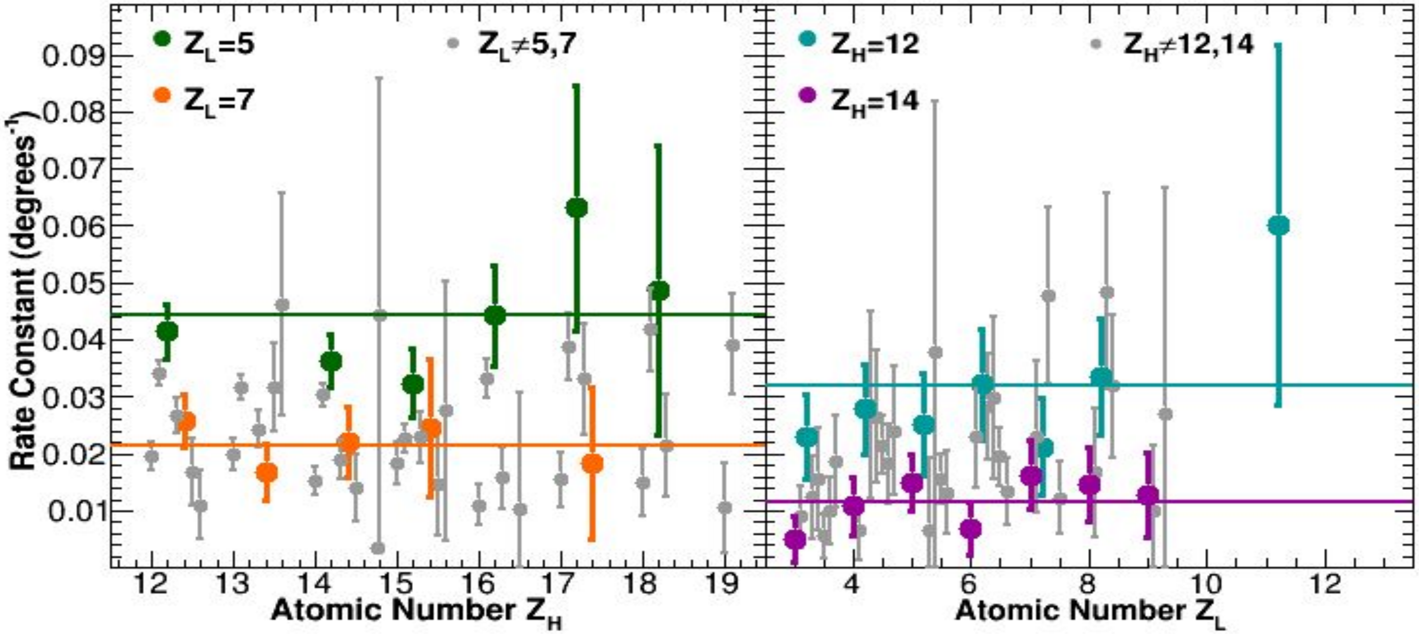
Jedele et al, PRL 118, 062501 (2017)

Asymptotic Values



- Asymptotic values for all Z_H,Z_L pairings
- Black diamonds are the corrected asymptotic values assuming 1 n offset

Rate Constants



- Rate constants for all Z_H,Z_L pairings

Angular Momentum from out-of-plane angular distributions

- Evaporative emission of alpha particles used
- Data fit with Gaussian distribution
- GEMINI simulations:
    - J = 10ħ at E*/A=0.8 MeV
    - J = 50ħ at E*/A=1.2 MeV
    - J=22ħ (geometric mean) used