On the Hunt for 3-Body Break-up Mechanisms in Intermediate, sub-Fermi Energy Heavy-ion Collisions

Paul Cammarata

Texas A&M University

IWM-EC 2014

CYCLOTRON INSTITUTE
TEXAS A&M UNIVERSITY

- Background /Theoretical Motivation for Experiment
- Experimental Design and Considerations
- Preliminary Experimental Results
- Future Direction of the Analysis
- Brief Summary

“Dynamical” IMF production in Semi-Peripheral Collisions at lower- Intermediate Energies

- Enhanced Z= 3-12 emission at mid-rapidity
- IMF relative velocity distributions not purely Coulombic
- Anisotropic Intermediate Mass Fragment (IMF) angular distributions
- Charge asymmetric system’s IMF emissions provides a “book-keeping” of neutron enrichment process occurring in the neck region.
  - Record of Interaction
    - Interaction time
    - Proximity of reaction
    - Violence of reaction

- Symmetry energy effects experimentally on:
  - Quadrupole/Octupole Moment Fluctuations of Quasi-projectile (QP)
  - Mass Partitioning of QP
  - Interaction time between Target and Projectile
  - Alignment of QP fragmentation
  - Velocity Correlations
  - Reaction dynamics in general

- Provides motivation behind:
  - Experimental Design and Data Analysis
  - Exploring New Analytical Techniques

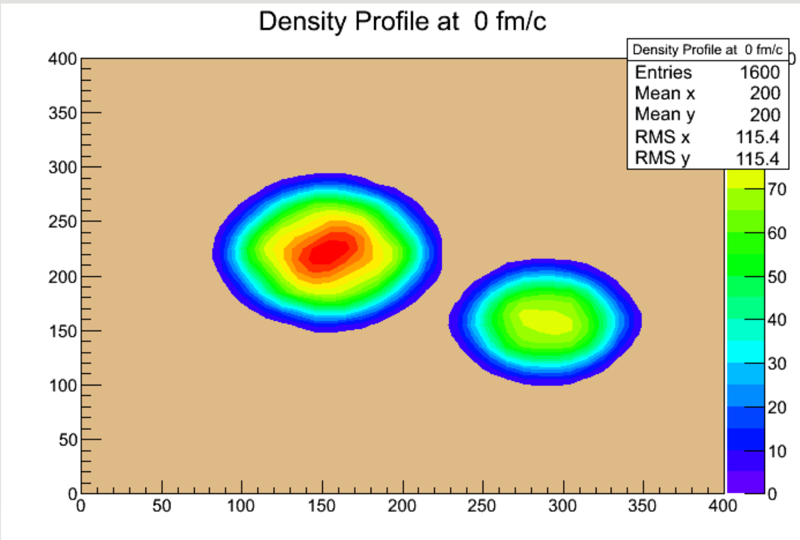
Baran et al., Nucl Phys A 730 (2004) 329
Baran et al., Physics Reports 410 (2005) 335
M. DiToro, V. Baran, M. Colonna, et al. Nucl.Phys.A 787 (2007) 585c.
Lukasik et al., Phys Rev C. 55 (1997) 1906
Sobotka et al., Phys Rev C. 55 (1997) 2109
M. Colonna, Workshop on Simulations of Low and Intermediate Energy Heavy Ion Collisions, 2009

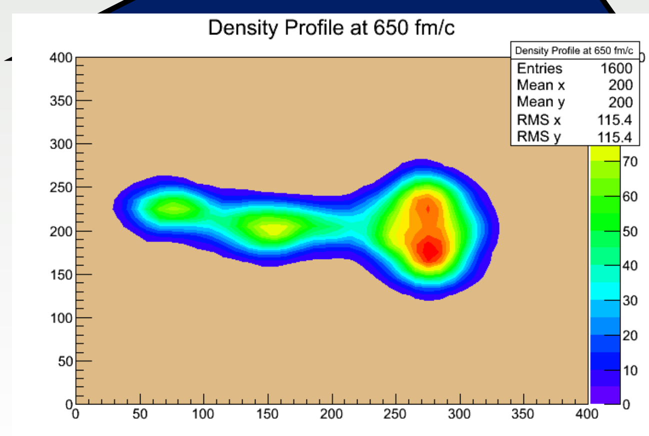
Colonna et al., Nucl. Phys A. 589 (1995) 160
Papa et al. Phys Rev C. 75 (2007) 054616
Colonna et al. Phys Rev C. 82, (2010) 054613
Shvedov et al., Phys Rev C. 81 (2010) 054605

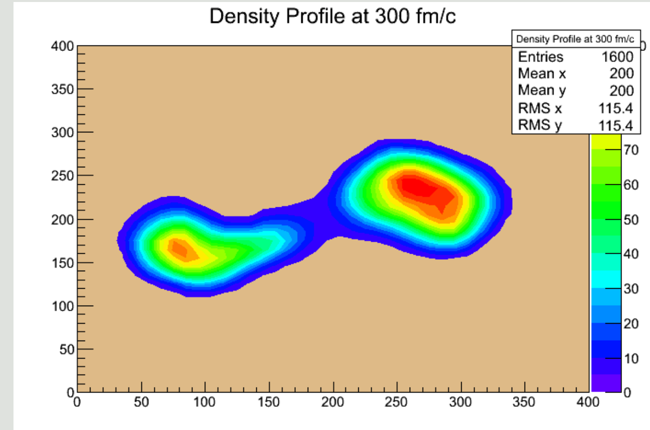
Some Effects Seen Through Stochastic Mean Field Transport Simulations

$^{124}Sn + ^{64}Ni$ @15A MeV

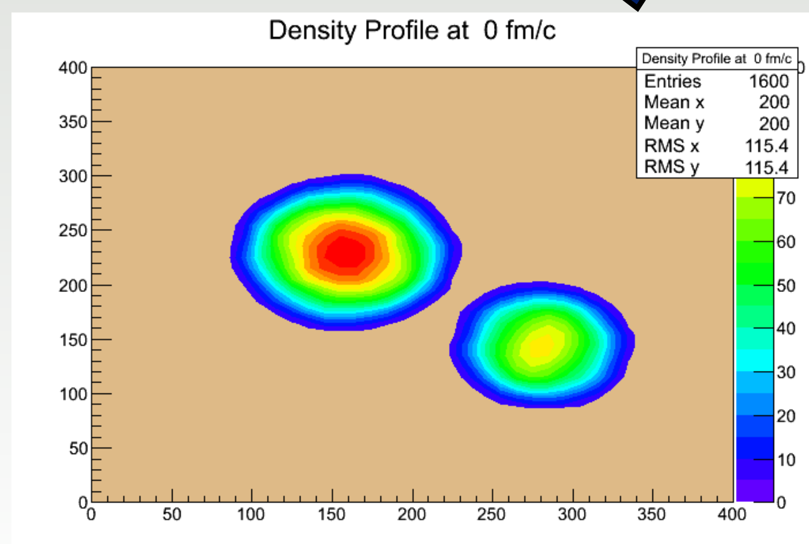
Impact Parameter = 6fm







Impact Parameter = 8fm



V. Greco, et al., Phys. Rev. C 59 (2) (1999) 810–816
L. Shvedov et al., Phys. Rev. C 81 (5) (2010) 054605

Reaction Dynamics and the Effects of the Symmetry Energy

- Using lower-intermediate energy heavy-ion collisions:
  - Theoretically clear difference between asy-stiff and asy-soft parameterizations
  - Some dynamic effects theorized to be sensitive seen experimentally:
    - $^{124}Sn + ^{64}Ni$ / $^{112}Sn + ^{58}Ni$ at 35A MeV (CHIMERA Collab.)
    - $^{100}Mo + ^{100}Mo$ / $^{120}Sn + ^{120}Sn$ ~20A MeV (GSI/GANIL)
    - $^{197}Au + ^{197}Au$ at 15A MeV (CHIMERA Collab.)
    - Xe+Sn at range of energies and isotopes (INDRA)
    - $^{86}Kr + ^{48}Ca$ / $^{78}Kr + ^{40}Ca$ at 10A MeV (CHIMERA Collab.)
    - and others (IUCF, MSU, …)

- Focusing in: Are the signatures more sensitive at lower energies for A_{sys}~200?
  - Lower energy theoretically more sensitive (10-15A MeV).
  - Specifically: focus on QP break up into heavy (Z≥3) PLF and IMF partners

Experimental Design and Considerations

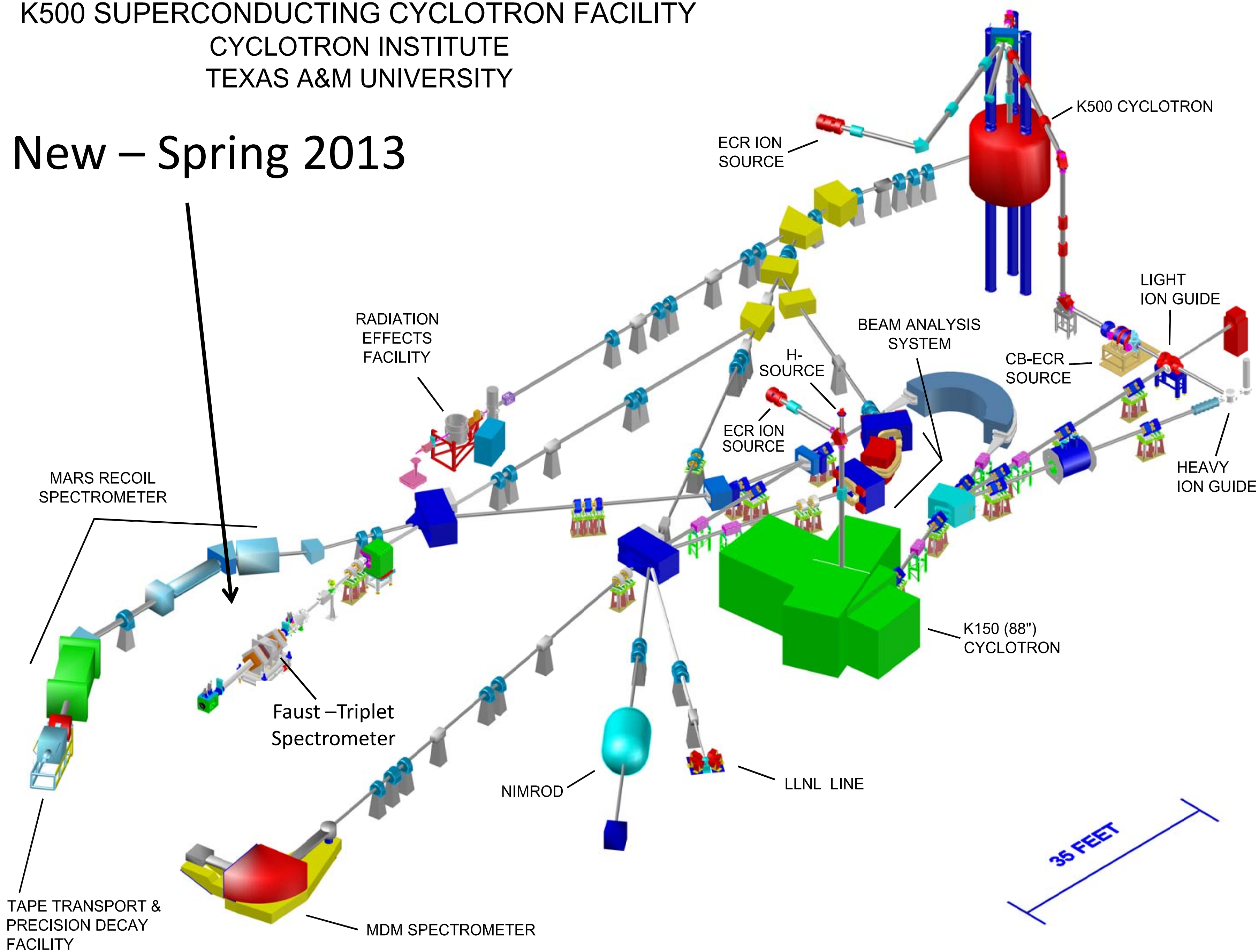
- Looking for 3- body breaking of the heavy systems at intermediate energy (less than the Fermi Energy)
  - QP breaking into PLF and Heavy (Z≥3) IMF

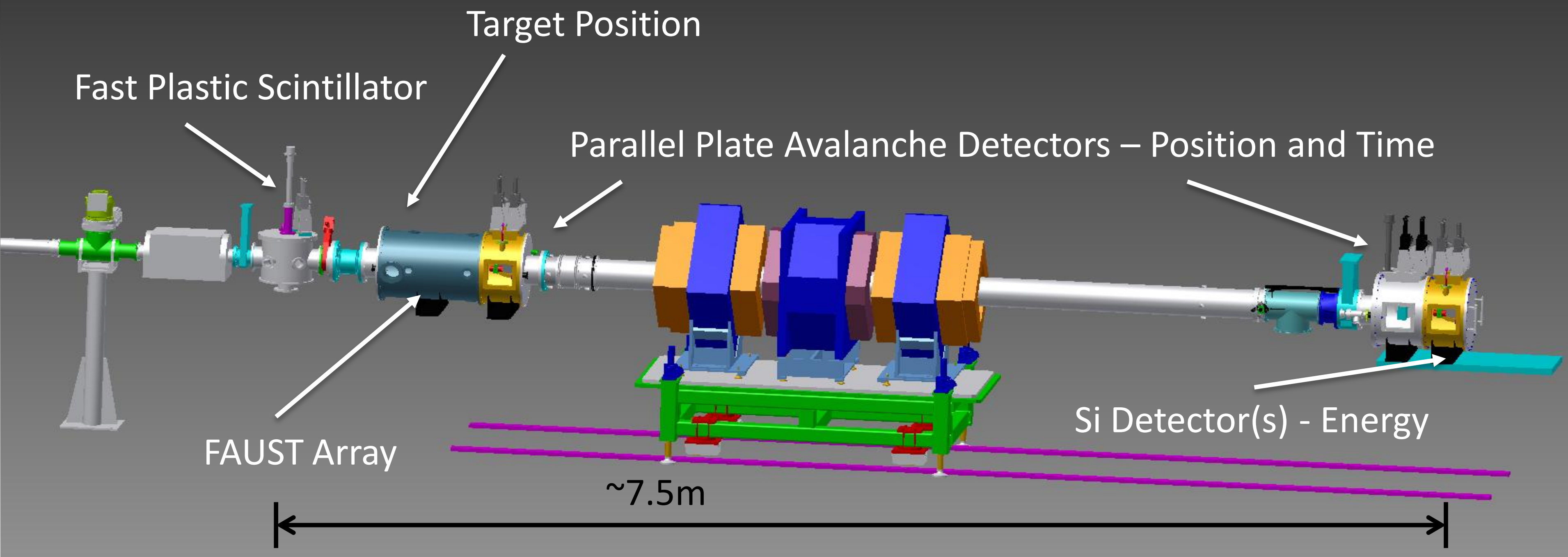
- 3 Systems – Account for different N/Z and well as Z systematic effects
  - $^{136}Xe+^{64}Ni$ at 15MeV/nucleon
  - $^{124}Xe+^{58}Ni$ at 15MeV/nucleon
  - $^{124}Sn+^{64}Ni$ at 15MeV/nucleon

- Designed an experiment sensitive to the observables of interest in an attempt to utilize the proper detection technique with the correct angular coverage while maximizing the rate of events of interest

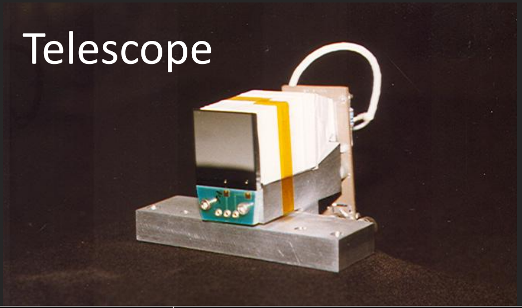
K500 SUPERCONDUCTING CYCLOTRON FACILITY
CYCLOTRON INSTITUTE
TEXAS A&M UNIVERSITY

New – Spring 2013



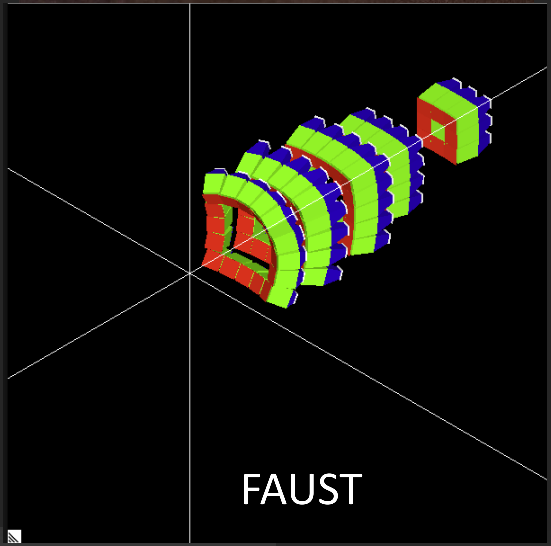

Target Position
Fast Plastic Scintillator
Parallel Plate Avalanche Detectors – Position and Time
Si Detector(s) - Energy
FAUST Array
~7.5m

[1] Gimeno-Nogues et al, NIM A,1997



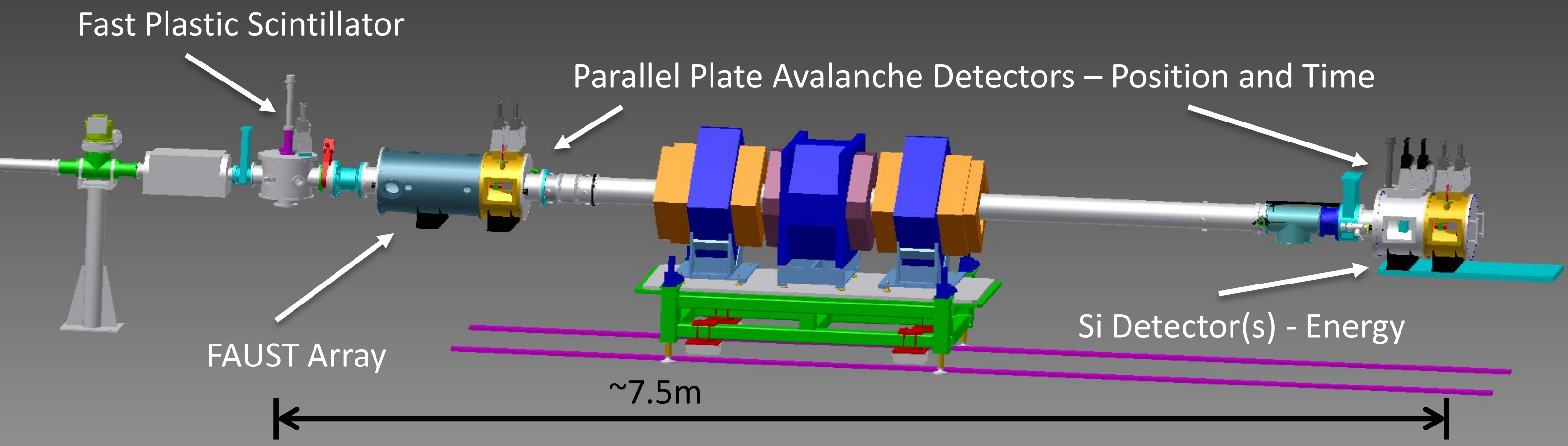
FAUST[1] – Forward Array Using Silicon Technology

- 68 ΔE-E Si-CsI(Tl) Telescopes – Isotopic ID of LCPs and IMFs arranged into 5 rings
- Coverage: approx θ=1.65-44.9°
- Upgraded for Time-of-Flight (ToF) mass ID of heavy fragments via custom CS-TPO pre- amplfiers
  - Mass ID of Heavy IMF and Energetic PLFs



Thin Film Fast Plastic Scintilator

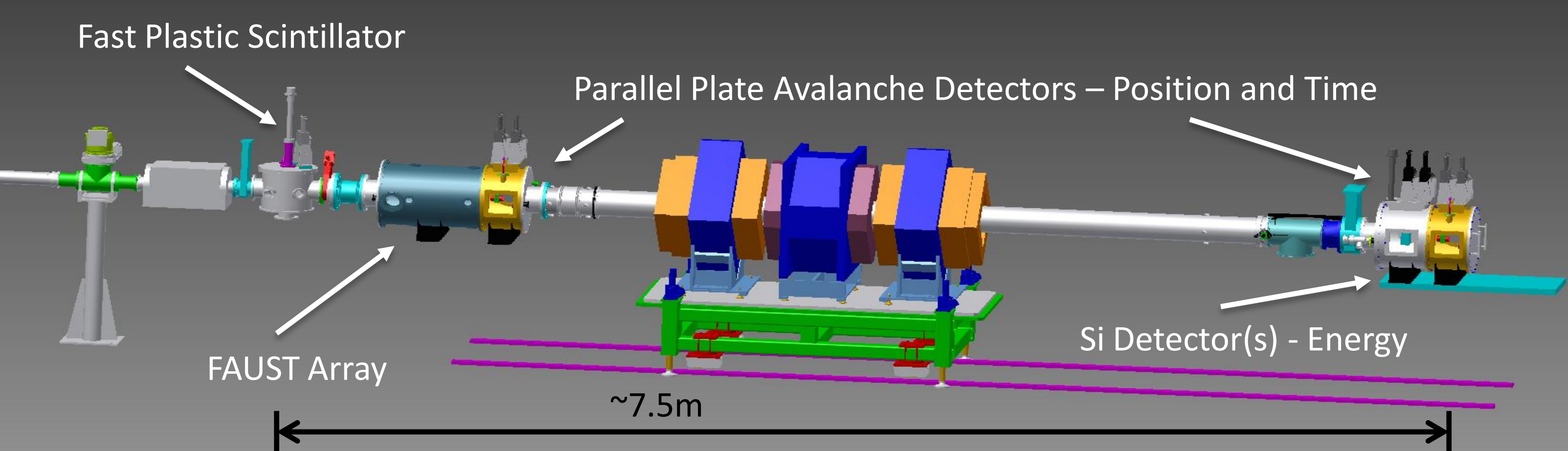
- Provides Start Signal for ToF Mass measurements in FAUST
- Accurate measurement of low beam intensity

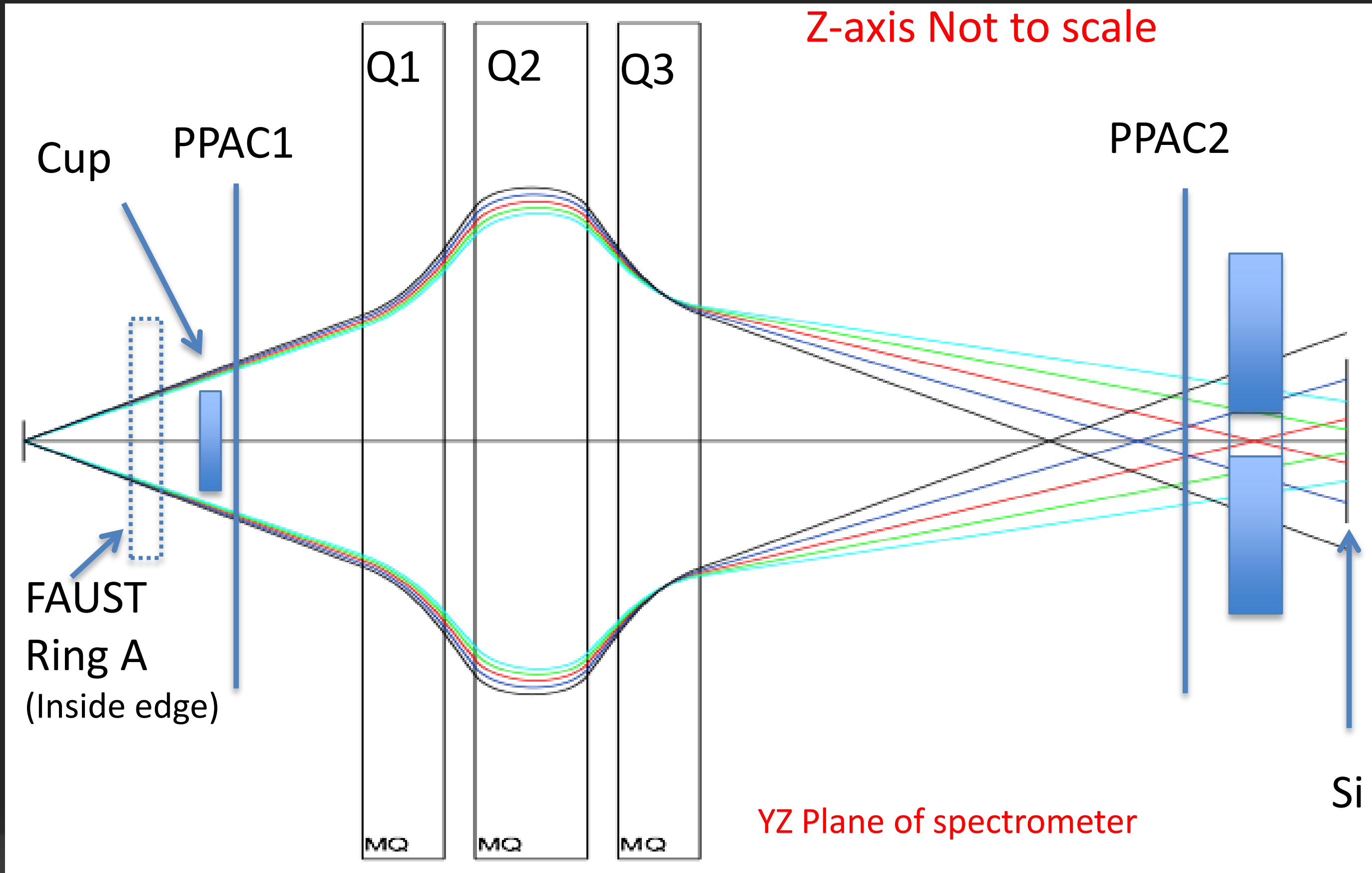


[1] Swan et al, NIM A, 1994

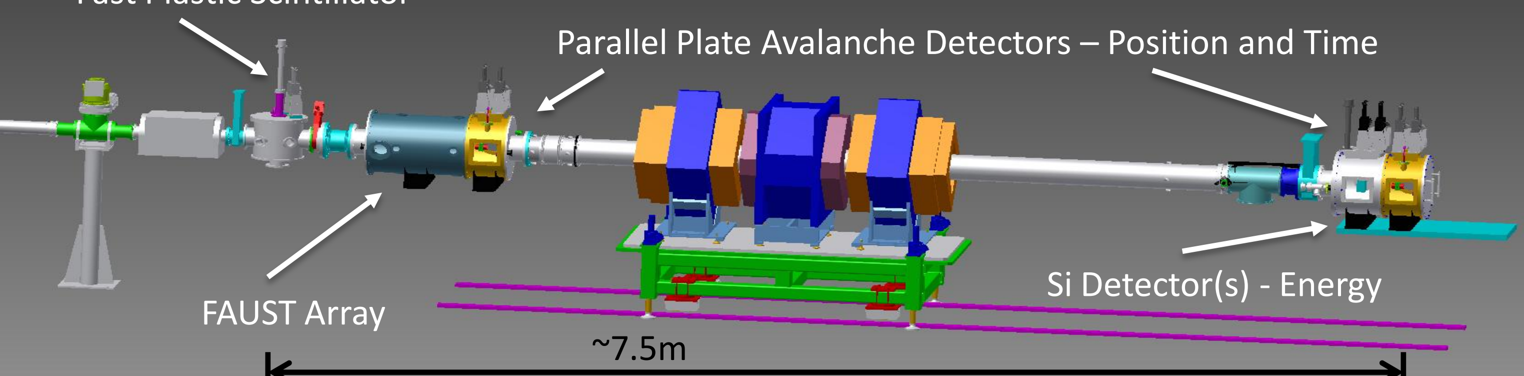
Parallel Plate Avalanche Counter[1] (PPAC)

- Heavy fragment flight time
- Position Sensitive
- Faraday cup on beam center between PPAC #1 and FAUST
  - Block elastics θ=0-0.9°
  - PLF acceptance θ=0.9-2.3°
  - Spectrometer tuned for PLFs
- Si Detector
  - Full E for PLFs
  - ToF mass ID of PLFs
  - Collimated to decrease elastic events





- Remove majority of elastics
- Bρ PLF close to Bρ Beam
  - Focus the PLFs
  - Attenuate elastics



Kyoko et al. NIM A 558 (2006) 346

Preliminary Results

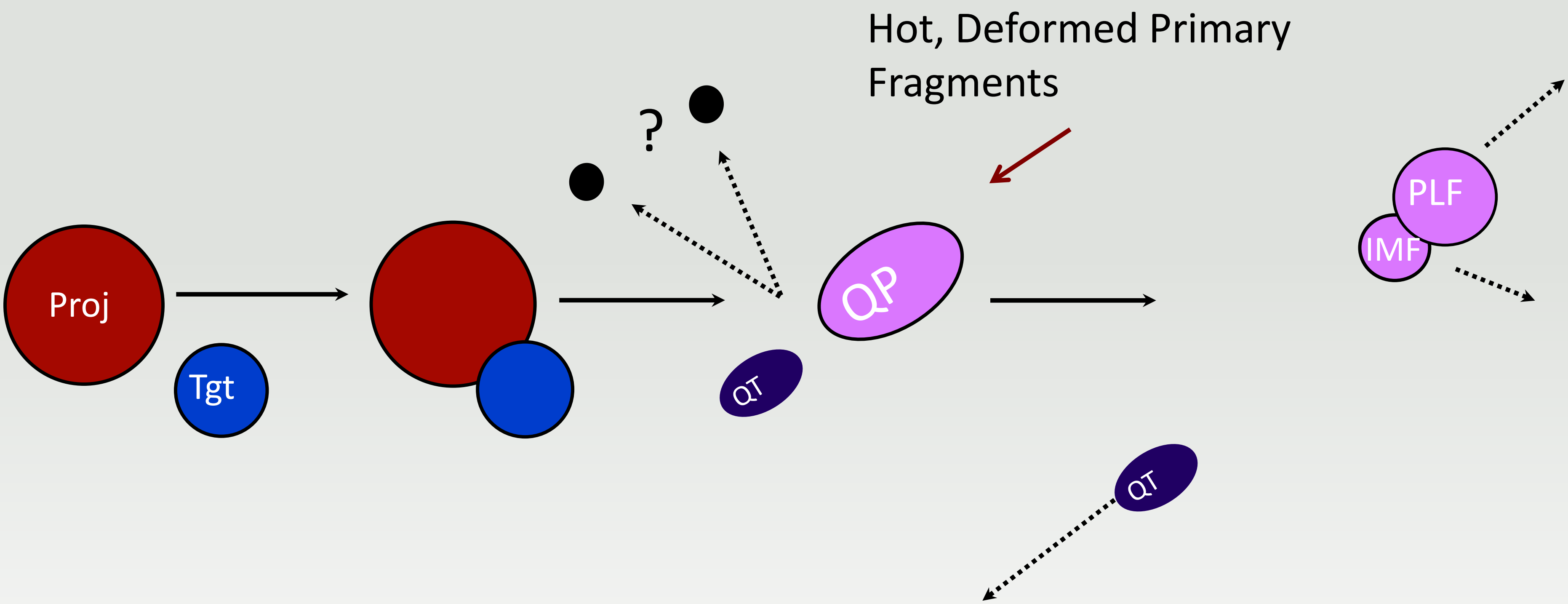
- Observations of the 3-Body Break-up of the system
  - PLF + IMF
  - QT by momentum conservation

- Alignment of the Breakup

- Mass Partitioning of QP➔PLF+IMF

- Possibly information about
  - Interaction time
  - Damping of collision
  - All as a function of mass and energy of the QP.

Events of Interest – Excited QP Dynamics Below the Fermi Energy

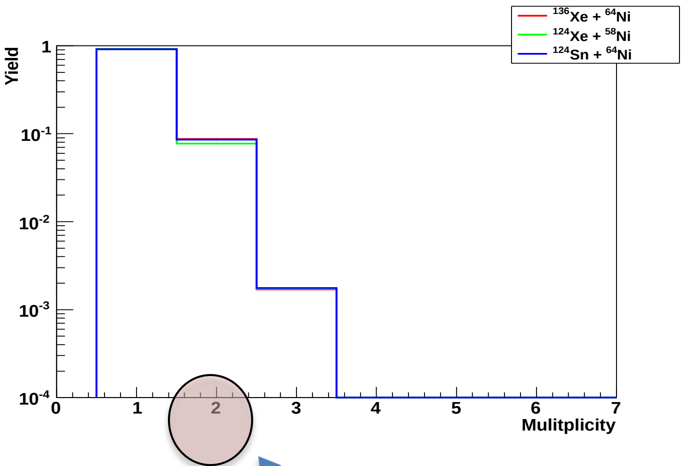


- Excited QP -> PLF + IMF
- Not going to see the QT in this experiment
  - Approximated via conservation of momentum

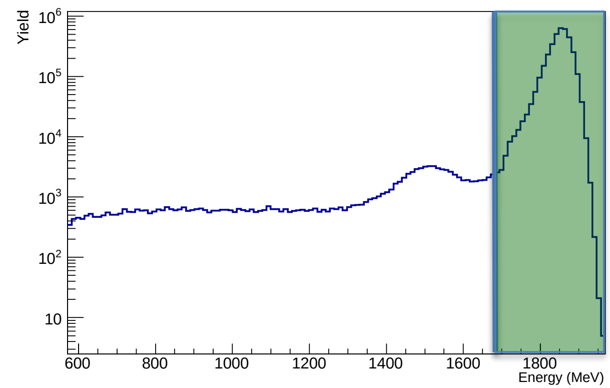
Events of Interest: Ternary (3-Body) Breaking of System

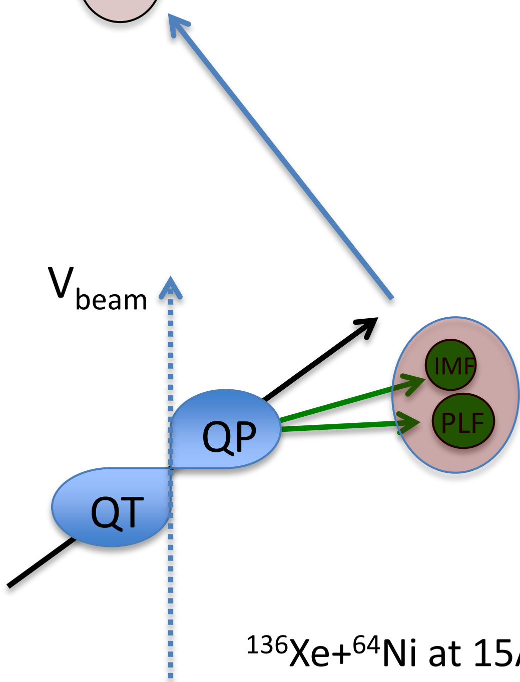
- Event Selection
  - PID in FAUST
- Multiplicity of Z≥3
  - Consider PID in Faust + Triplet
  - Triplet events must not be beam like
- Detect 2 Heavy Fragments
  - QP->PLF + IMF
  - QT by momentum conservation
  - E_{QP}>600MeV (>25% E_{beam})

Z≥3 Fragment Multiplicity



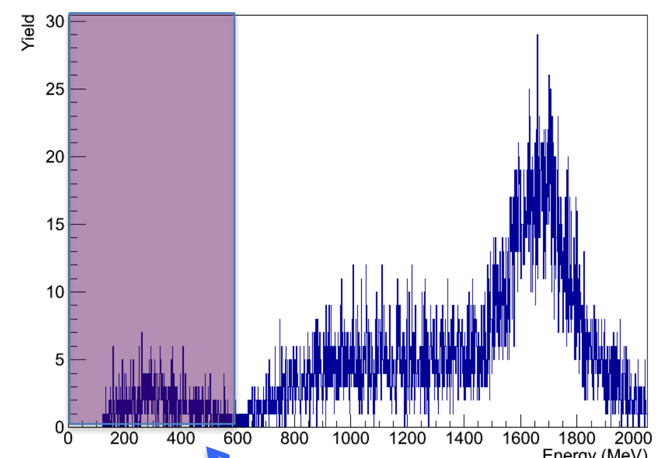
Triplet PLF Energy





^{136}Xe+^{64}Ni at 15A MeV shown. Similar Cuts apply to all systems.

QP Energy (PLF+IMF)

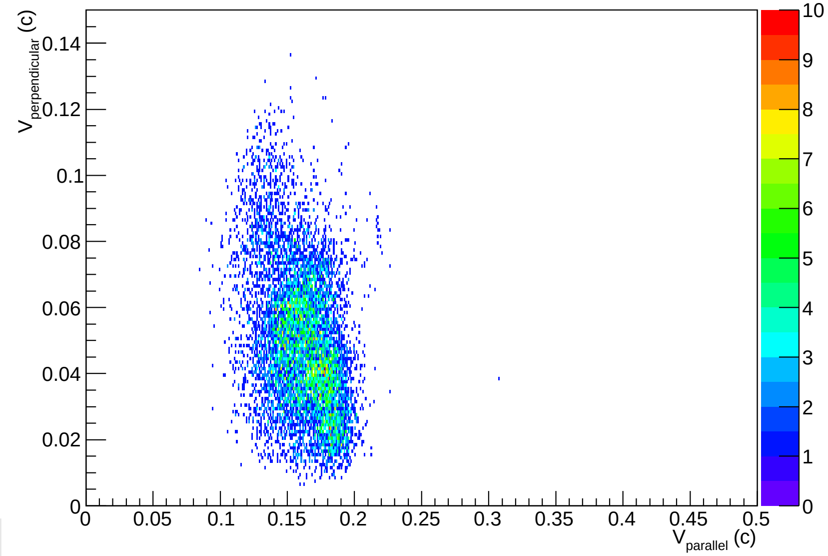


<25% beam energy

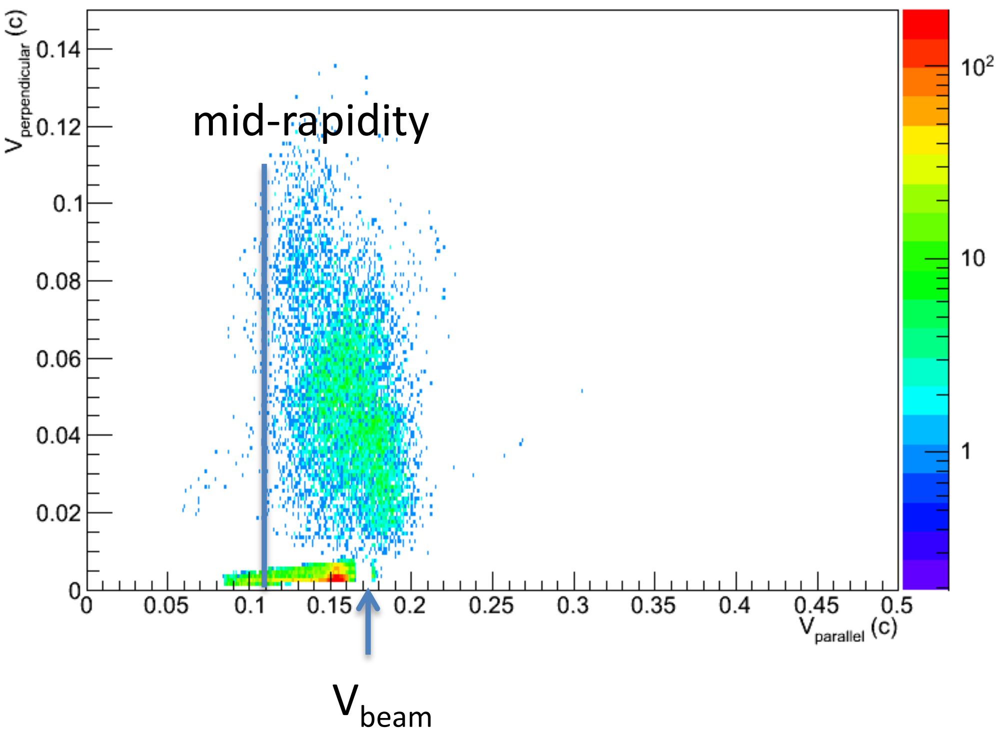
Heavy “Mult2” Velocities By Fragment ID (PLF or IMF)

- IMFs detected at $V_{IMF} > V_{Mid\text{-}rapidity}$
  - Detector Efficiency/Thresholds
  - Angular Coverage
- Preferential Sequential Decay vs. Prompt?
- Statistical vs. Dynamic Decay of PLF?
- Details or “book-keeping” of dynamics of interaction?

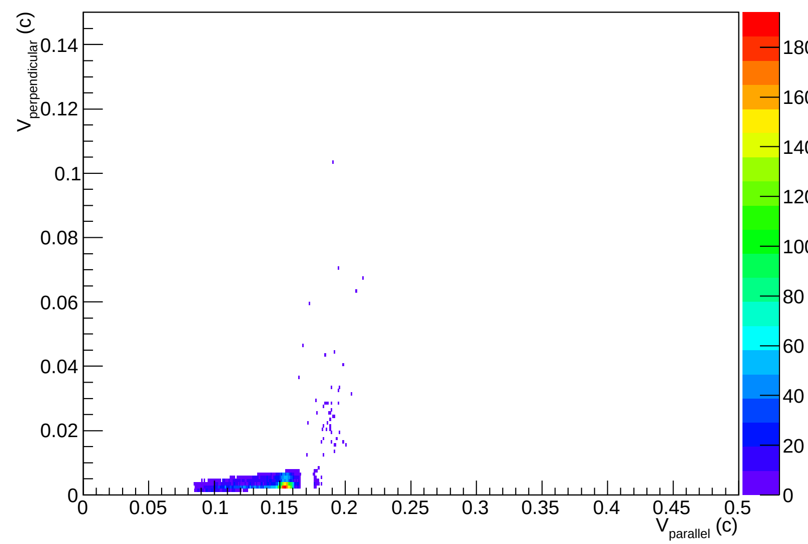
IMF V_{par} vs V_{perp} (All Detectors)



PLF + IMF V_{par} vs V_{perp} (all Detectors)

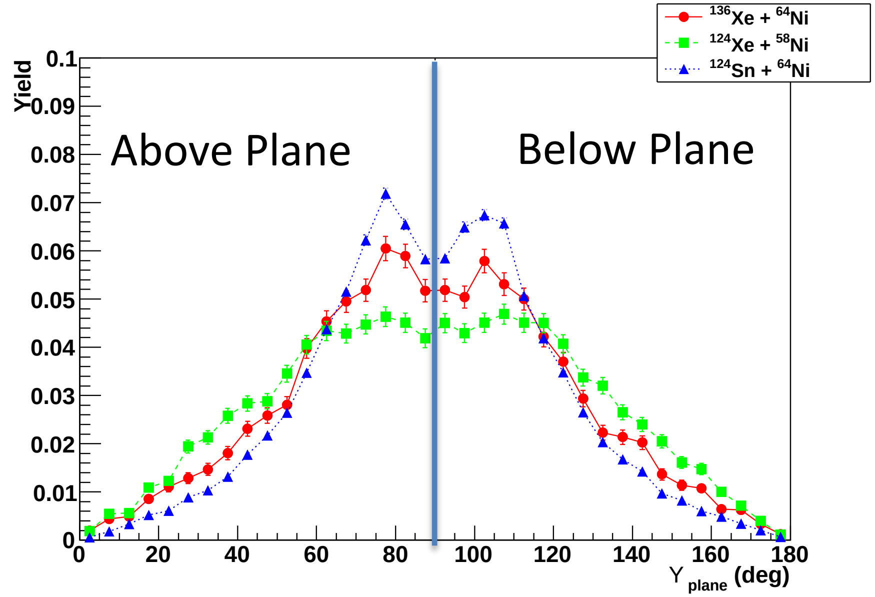


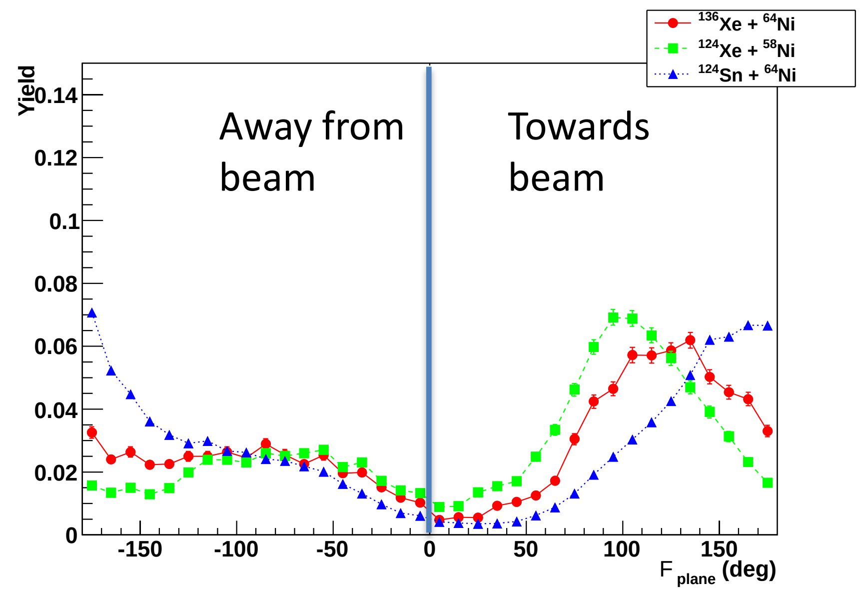
PLF V_{par} vs V_{perp} (All Detectors)

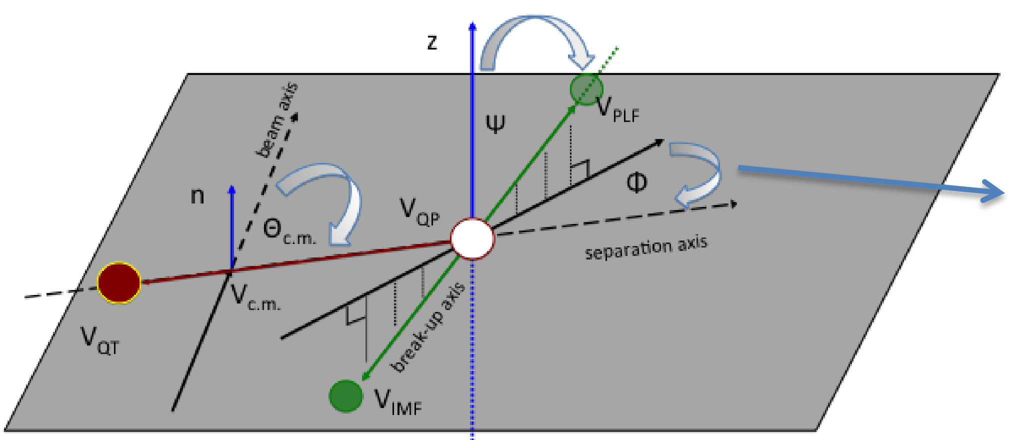


Angular Alignment of Fragmentation

- What does this say with respect to:
  - Stat vs Dyn?
  - Prompt vs Sequential?
  - Interaction
  - Composition of QP
- Not in great agreement with each other system-to-system
  - Convolution different interaction dynamics
  - Trend system-to-system







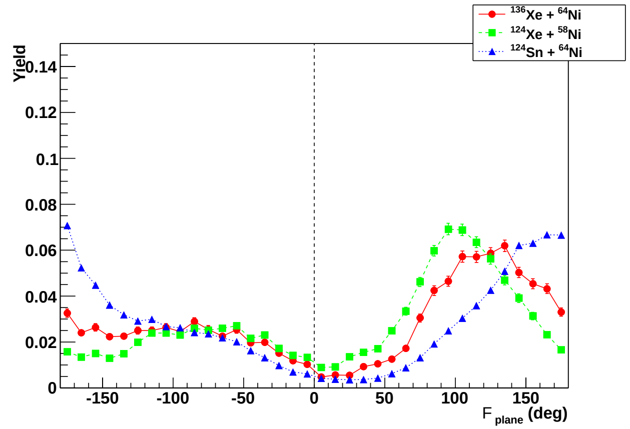
Reaction plane description in the style used by the CHIMERA collaborations

Angular Alignment of Fragmentation

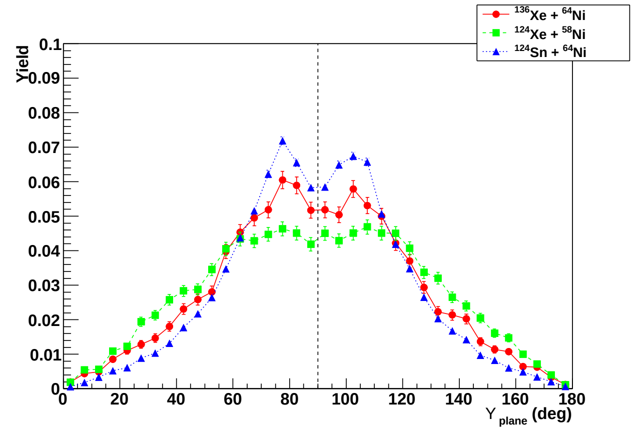
De-convolution via Cuts in E and A of the QP

- Energy Partitioning
  - $E_{QP} = E_{PLF} + E_{IMF}$
- Mass Partitioning
  - $A_{QP} = A_{PLF} + A_{IMF}$

Φ_{Plane}



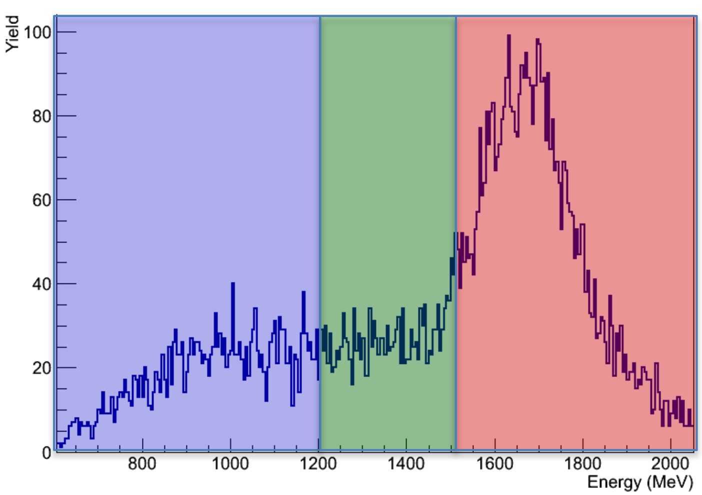
Ψ_{Plane}



E_{QP} Cuts

1. 600-1200 MeV
2. 1200-1500 MeV
3. 1500+ MeV

Energy QP

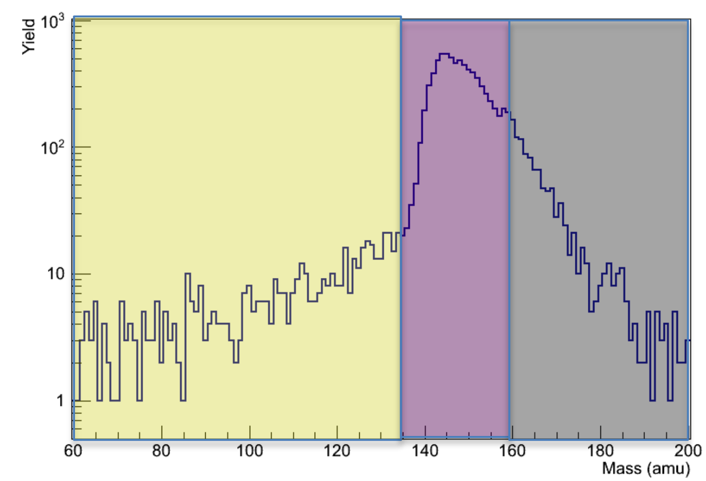


$^{136}Xe + ^{64}Ni$ at 15A MeV shown. Same cuts apply to all systems

A_{QP} Cuts

1. 60-135 A
2. 135-160 A
3. 160+ A

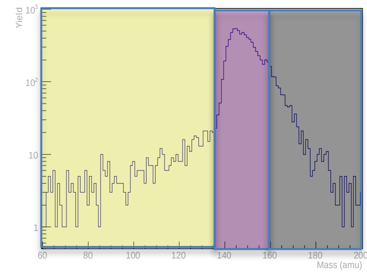
Mass QP



In-Plane Angular Alignment of Fragmentation (QP decay)

De-convolution via Cuts in E and A of the QP

- Energy Partitioning
  - $E_{QP} = E_{PLF} + E_{IMF}$
- Mass Partitioning
  - $A_{QP} = A_{PLF} + A_{IMF}$



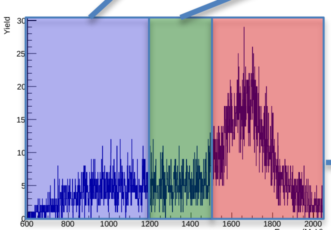
A_{QP}

Interesting Observations:

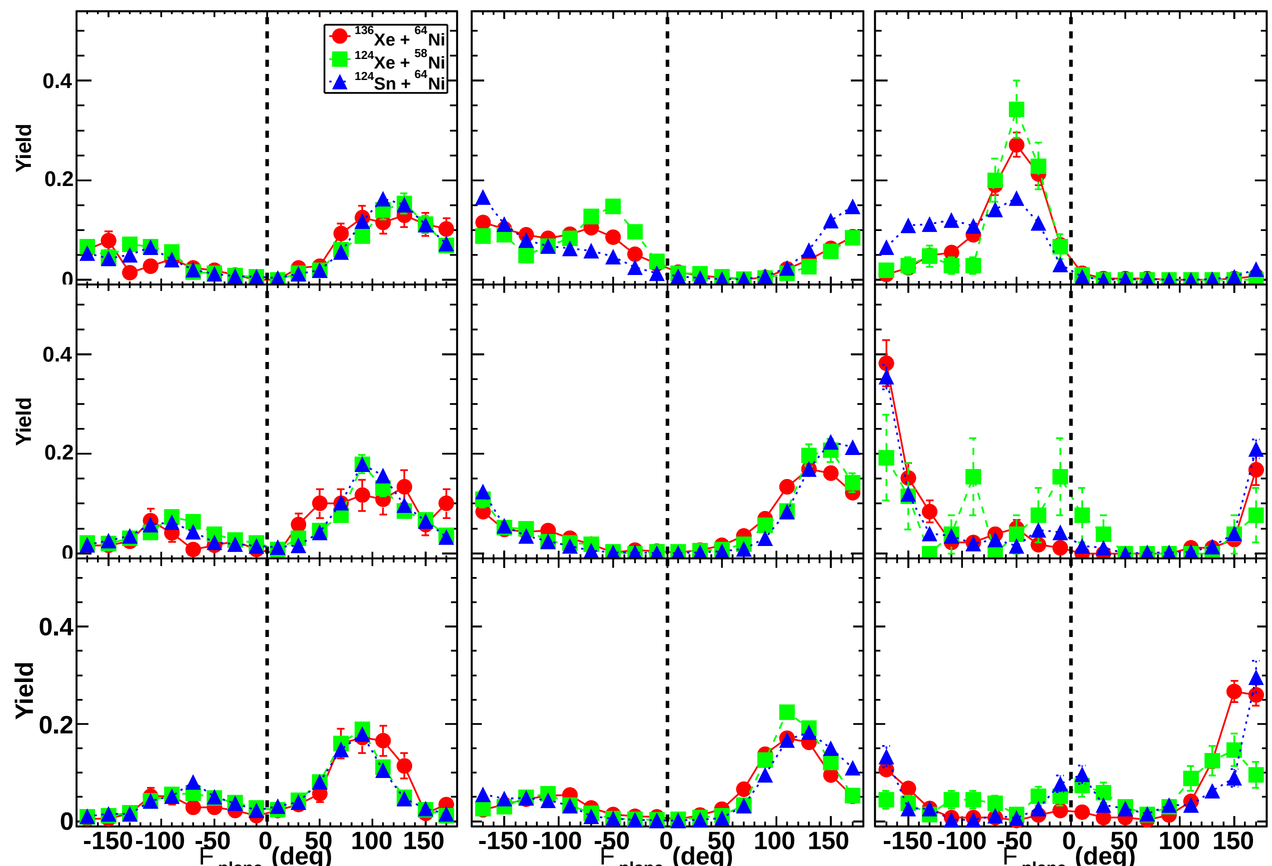
- Aligned decays for damped QPs
- Largest QPs are strongest aligned

Low A_{QP} ↔ High A_{QP}

Low E_{QP} ↔ High E_{QP}



E_{QP}

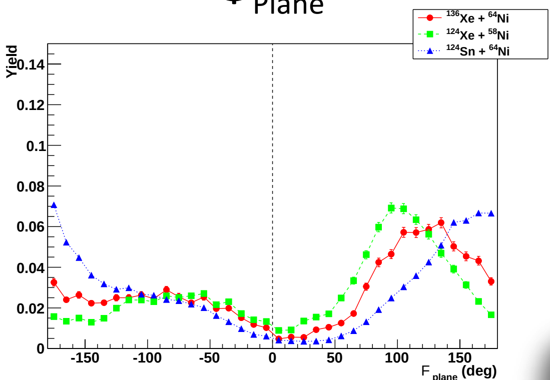


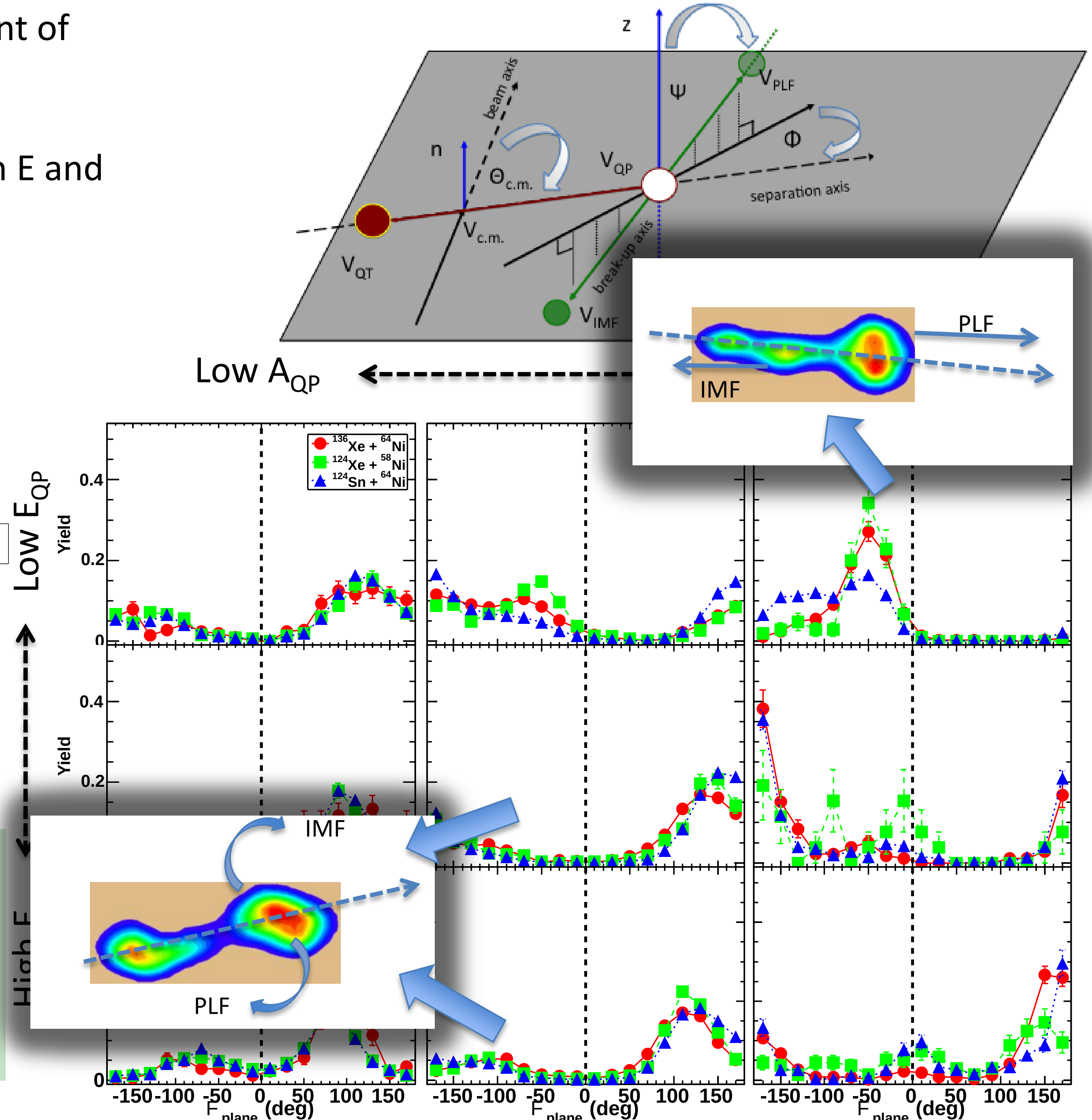
In-Plane Angular Alignment of Fragmentation

De-convolution via Cuts in E and A of QP

- Energy Partitioning
  - $E_{QP} = E_{PLF} + E_{IMF}$
- Mass Partitioning
  - $A_{QP} = A_{PLF} + A_{IMF}$

Φ_{Plane}





Interesting Observations:

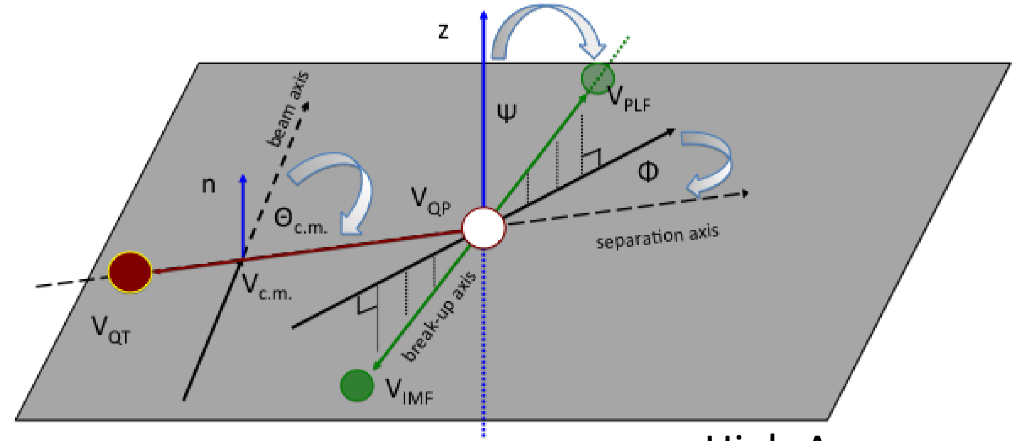
- Aligned decays for damped QPs
- Largest QPs are strongest aligned

Reaction plane description in the style used by the CHIMERA collabs

Out-of-Plane Angular Alignment of Fragmentation

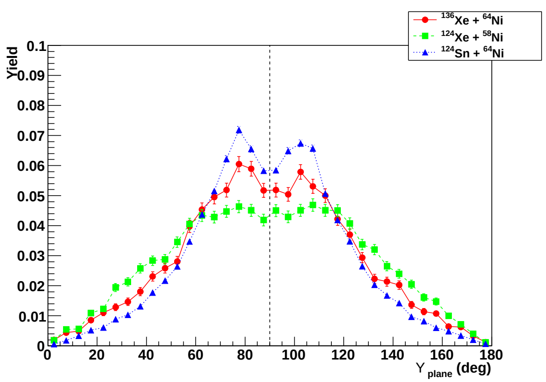
De-convolution via Cuts in E and A of QP

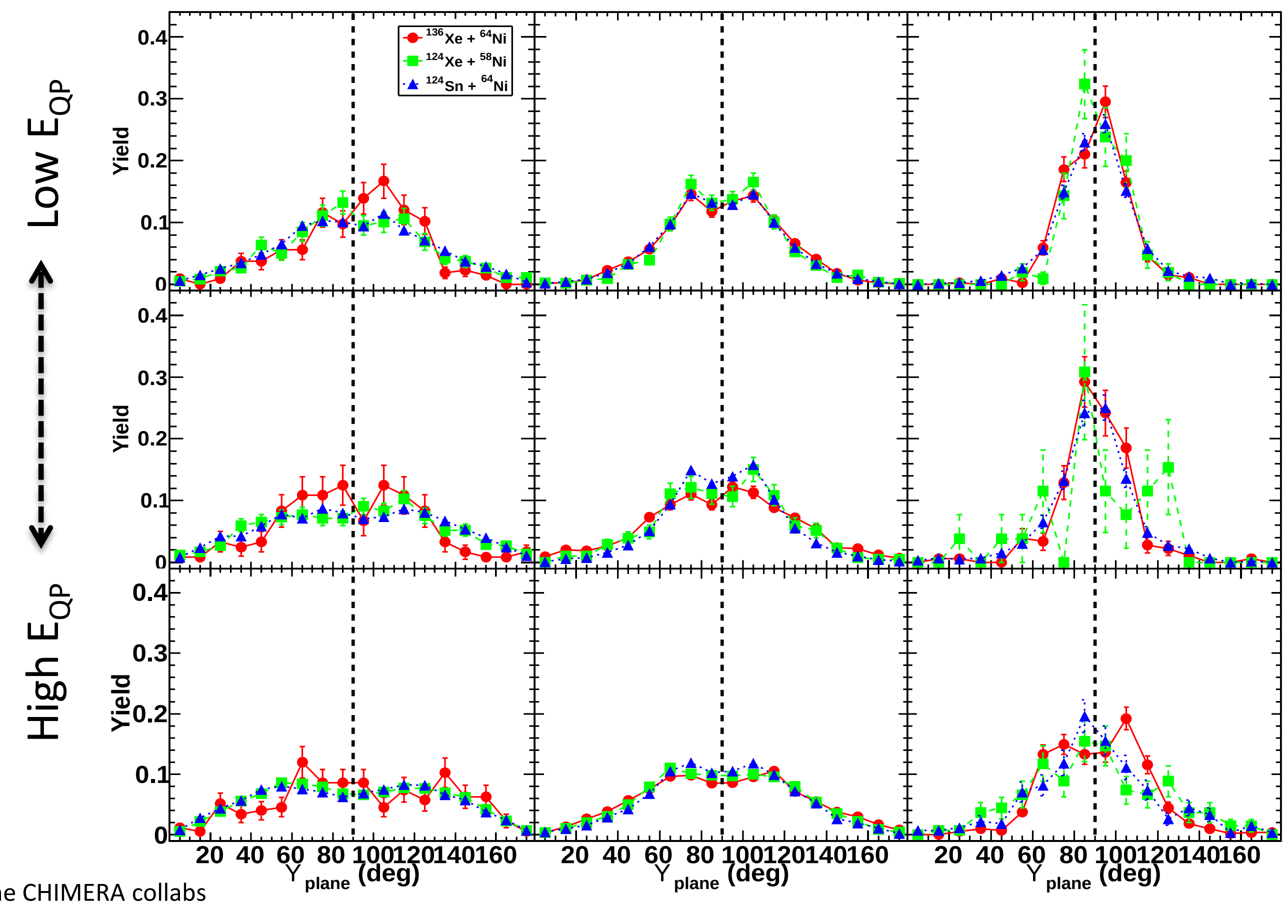
- Energy Partitioning
  - $E_{QP} = E_{PLF} + E_{IMF}$
- Mass Partitioning
  - $A_{QP} = A_{PLF} + A_{IMF}$



Low A_{QP} ⟵ - - - ⟶ High A_{QP}

Ψ_{Plane}





Interesting Observations:

- Aligned decays for damped QPs
- Largest QPs are strongest aligned

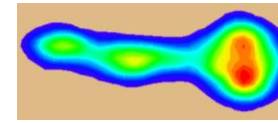
Reaction plane description in the style used by the CHIMERA collabs

Mass Partitioning of QP into PLF and IMF – A_{IMF} Distributions

Diagonal Lines Represent A_{QP} Cuts

A_{QP} Cuts

- A_{QP}=60-135
- A_{QP}=135-160
- A_{QP}=160+



De-convolution via Cuts in E and A of QP

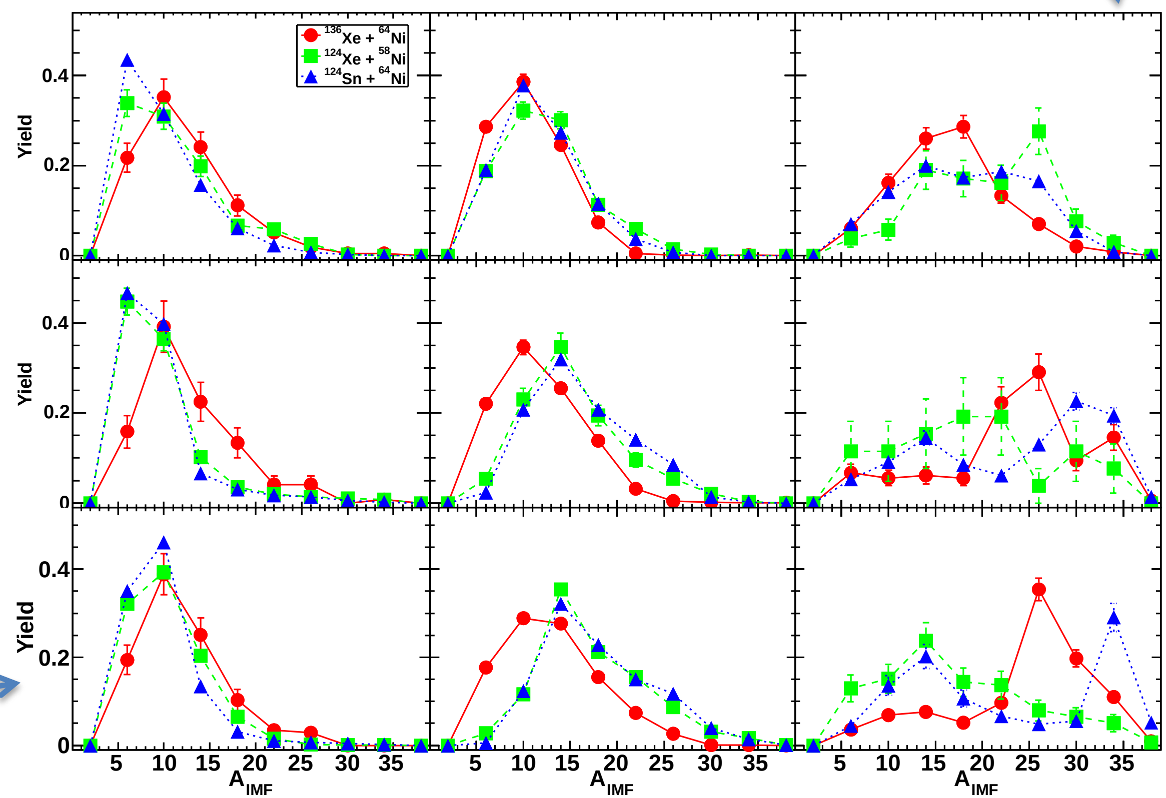
- Energy Partitioning
  - $E_{QP} = E_{PLF} + E_{IMF}$
- Mass Partitioning
  - $A_{QP} = A_{PLF} + A_{IMF}$

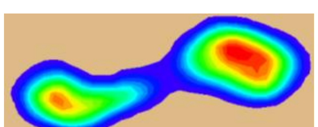
Low A_{QP} ⟵ - - - ⟶ High A_{QP}

Effects Observed

- With Increasing A_{QP}
  - A_{IMF} also increases
- With Increasing E_{QP}
  - A_{IMF} remains nearly the same

Low E_{QP} ⟷ High E_{QP}

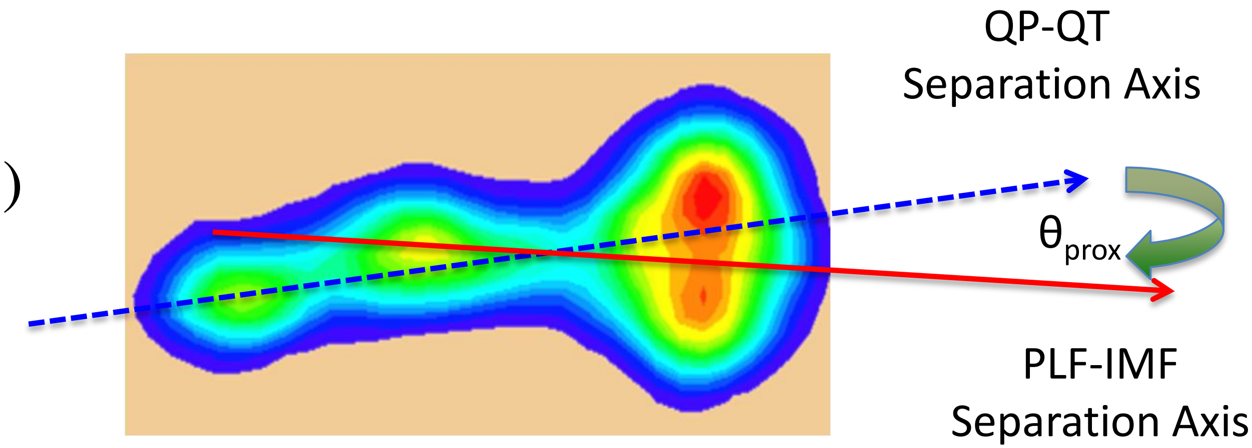




Correlations between Relative Velocity of PLF and IMF

$$\theta_{prox} = \vec{v}_{QP} \cdot \vec{v}_{rel} / (v_{QP} * v_{rel})$$

$$\vec{v}_{rel} = \vec{v}_{PLF} - \vec{v}_{IMF}$$

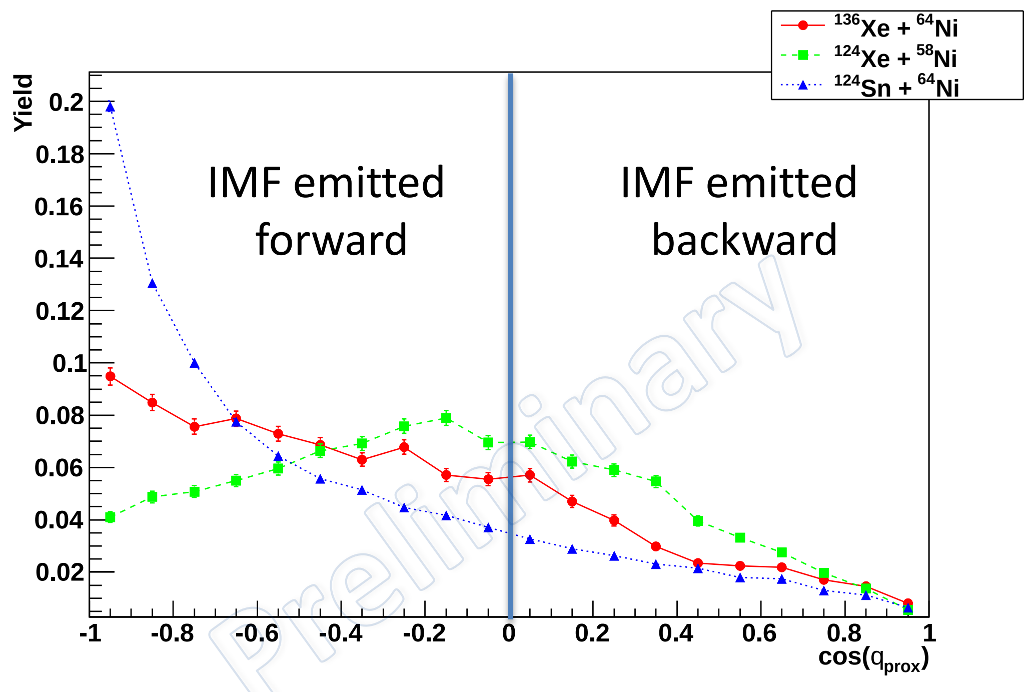


System $d = \frac{N - Z}{A}$:

$^{136}Xe + ^{64}Ni = 0.1800$

$^{124}Sn + ^{64}Ni = 0.1702$

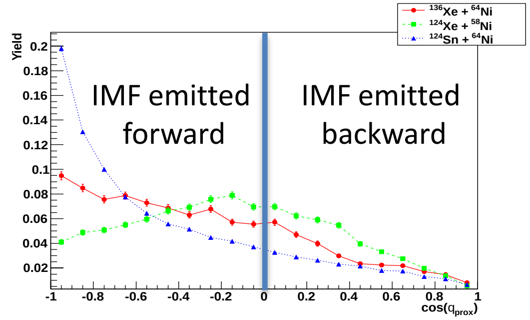
$^{124}Xe + ^{58}Ni = 0.0989$

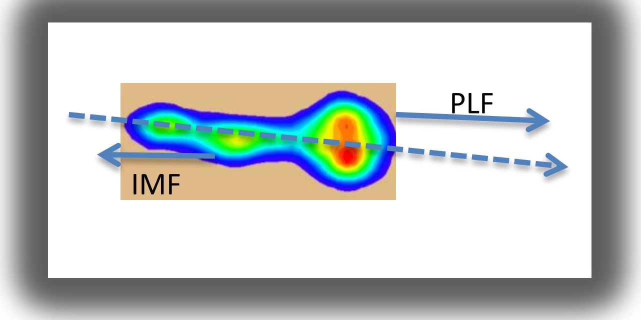


Relative Velocity Correlations between PLF and IMF

$$\cos(\theta_{prox}) = \vec{v}_{QP} \cdot \vec{v}_{rel} / (v_{QP} * v_{rel})$$

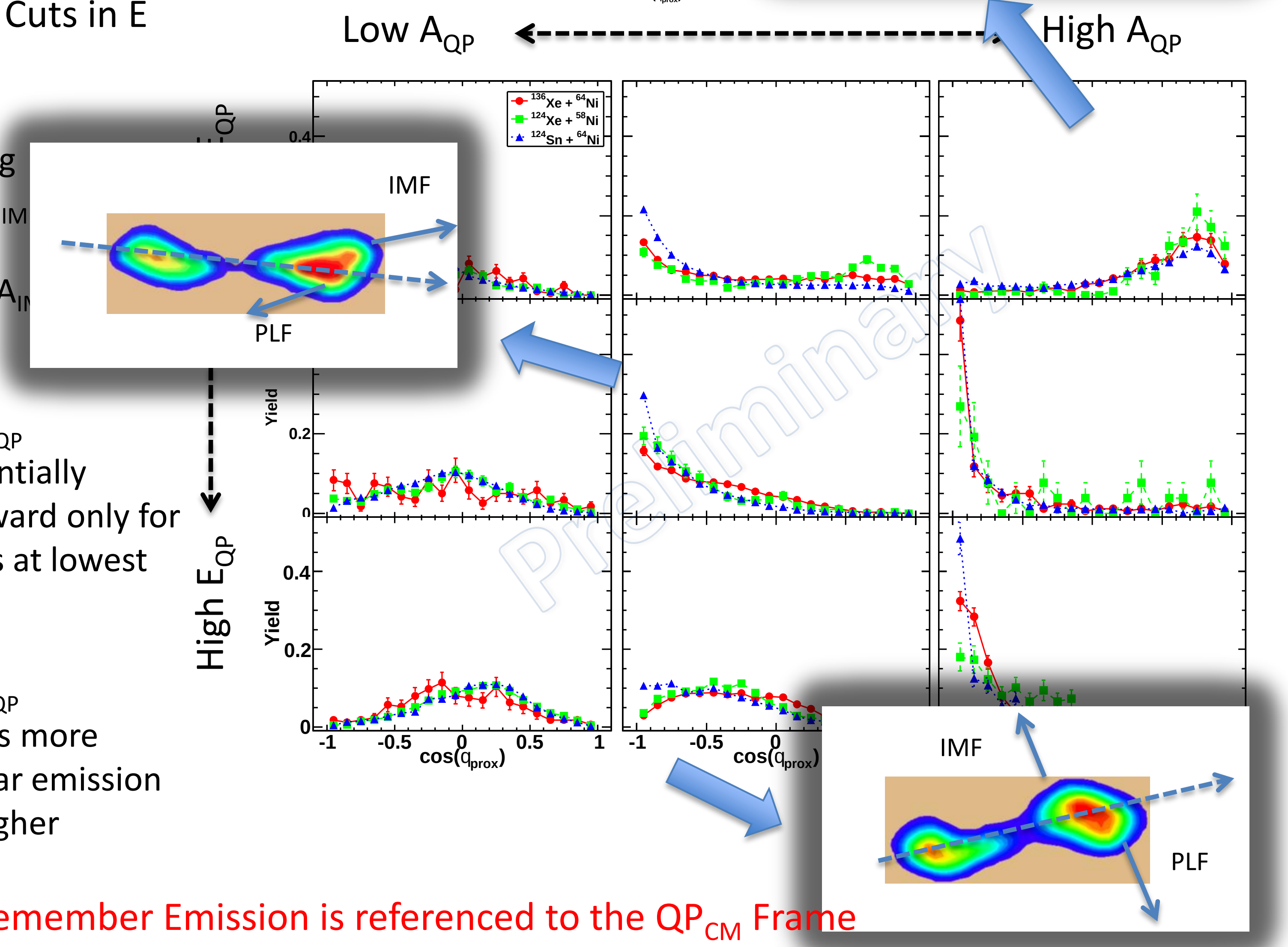
$$\vec{v}_{rel} = \vec{v}_{PLF} - \vec{v}_{IMF}$$





De-convolution via Cuts in E and A of QP

- Energy Partitioning
  - $E_{QP} = E_{PLF} + E_{IM}$
- Mass Partitioning
  - $A_{QP} = A_{PLF} + A_{I}$



Effects Observed

- With Increasing A_{QP}
  - PLFs Preferentially emitted forward only for heaviest QPs at lowest energy
- With Increasing E_{QP}
  - Shift towards more perpendicular emission of PLF for higher energies.

Remember Emission is referenced to the QP_{CM} Frame

Preliminary Effects Observed

- Combined Effects of
  - Angular Distribution
  - Mass Partitioning
  - Relative Velocity Correlations between PLF and IMF
- With Increasing A_{QP}
  - i.e. Heavier QP
  - PLF more Aligned with QT
- With Increasing E_{QP}
  - Decreased Damping
  - Higher Angular Momentum
  - PLF less aligned with QT
  - PLF aligned away from V_{beam} (in the reaction plane)
  - Possibly implying:
    - Lower Interaction time
    - Larger Impact Parameter
    - Time of emission/break-up

Future Perspectives

- More Detailed Analysis of Observables
  - Relative Velocity Correlations of Events of Interest
  - Neck Mechanics
- Attempt extraction of fundamental parameters
  - Time of Interaction
  - Impact parameter?
- Comparison to dynamics simulations
  - CoMD-II (t=3000fm/c)
  - SMF (Twingo+Fram_new)
- Determine Most Realistic Parameters for Machine Learning
  - Attempt to extract the most probable Esym
  - Model based analysis submitted to NIM-A

Papa et al., J. Comp Phys 208 (2005) 403
V. Greco, et al., Phys. Rev. C 59 (1999) 810–816
L. Shvedov et al., Phys. Rev. C 81 (2010) 054605
Brown et al., Phys Rev C. 87 (2013) 061601

Summary

- Angular alignment /Velocity correlations
  - Emission Angle Correlations Suggest Dynamic Processes
  - Preferential Emission of PLF Correlated with E_{QP} and A_{QP}

- Partitioning Trends
  - Some information about mass splitting
  - Heavier IMFs come from heavier QP's
  - Slight Increase in mass of emitted IMF as E_{QP} increases

- In the Future (going forward)
  - Comparisons to simulations
  - Possible information about
    - Interaction Times
    - Gross Impact Parameter
    - Emission /Break-up Time

Acknowledgements

SJY Group

Alan McIntosh, Mathew Chapman, George Souliotis, Layla Bakhtiari, Lauren Heilborn, Justin Mabiala, Larry May, Mike Youngs, Andrew Zarrella, and Sherry J. Yennello

Collaborators

Maria Colonna, Aldo Bonasera, and Zach Kohley

Texas A&M Supercomputing

Spiros Vellas and Michael Thomadakis

Chemistry Department

Will Seward and Lisa Perez

Cyclotron Institute

Kris Hagel, Fred Abegglin, Robert Burch, George Kim, and Brian Roeder

Funding:

Robert A. Welch Grant#A-1266, DOE#DE-FG03-93ER40773, NSF#CHE-0541587