Investigating the Fragmentation of Excited Nuclear Systems

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2010 Cyclotron REU

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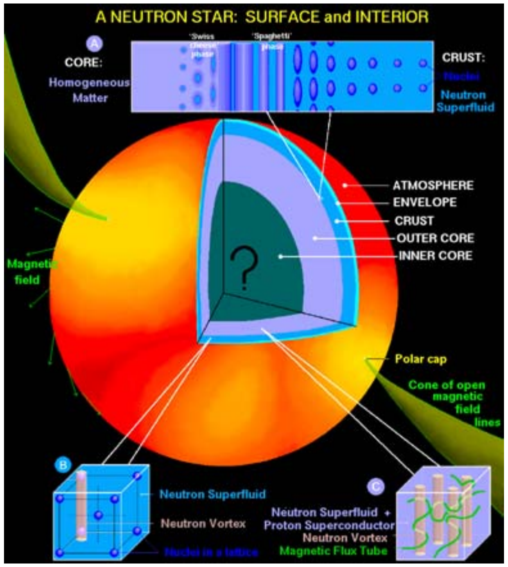
Nuclear Equation of State

- Equation of State (EoS)
- EoS for isospin asymmetric nuclear matter:

$$E(\rho, \delta) = E(\rho, \delta = 0) + E_{sym}(\rho)\delta^2 + O(\delta^4)$$

- *baryon density* $\rho = \rho_n + \rho_p$
- *isospin asymmetry* $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$
  - $\delta = (N-Z)/(N+Z)$
- *energy per nucleon in symmetric nuclear matter* $E(\rho, \delta = 0)$
- *nuclear symmetry energy* $E_{sym}(\rho)$



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Li, Nuc.Phy. A. **834**. 509. (2010)

Symmetry Energy

- Symmetry Energy related to Isospin

Heavy Ion Collisions

- Nuclear collision reactions…

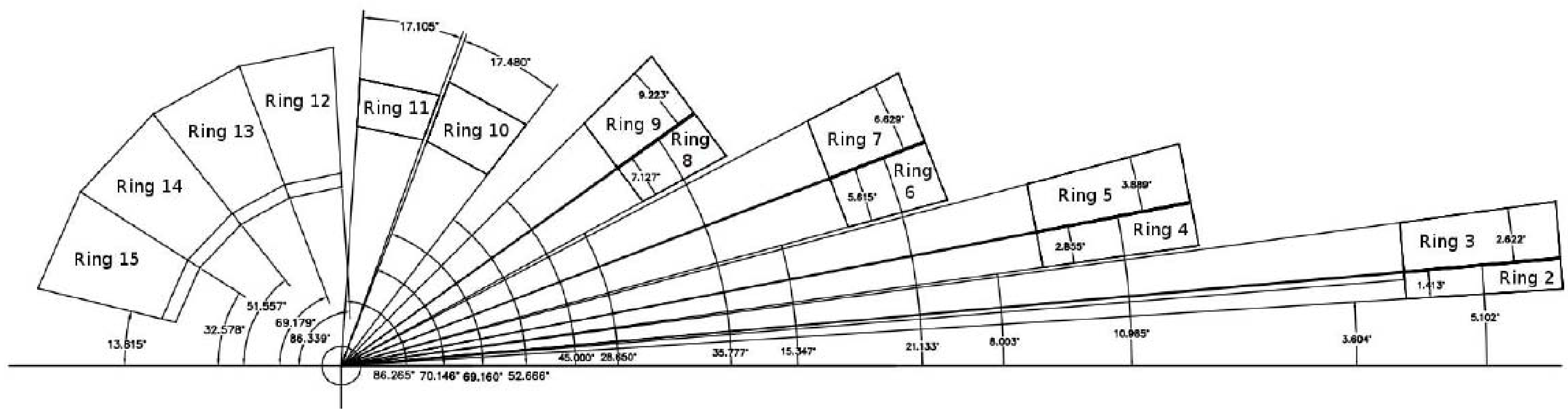
Time (fm/c) = 1

Heavy Ion Collisions

11	10	9	8
7	6	5	4
3	2	1	0

Heavy Ion Collisions

- Detect the Z and A of most fragments with NIMROD, and free neutrons with the Neutron Ball



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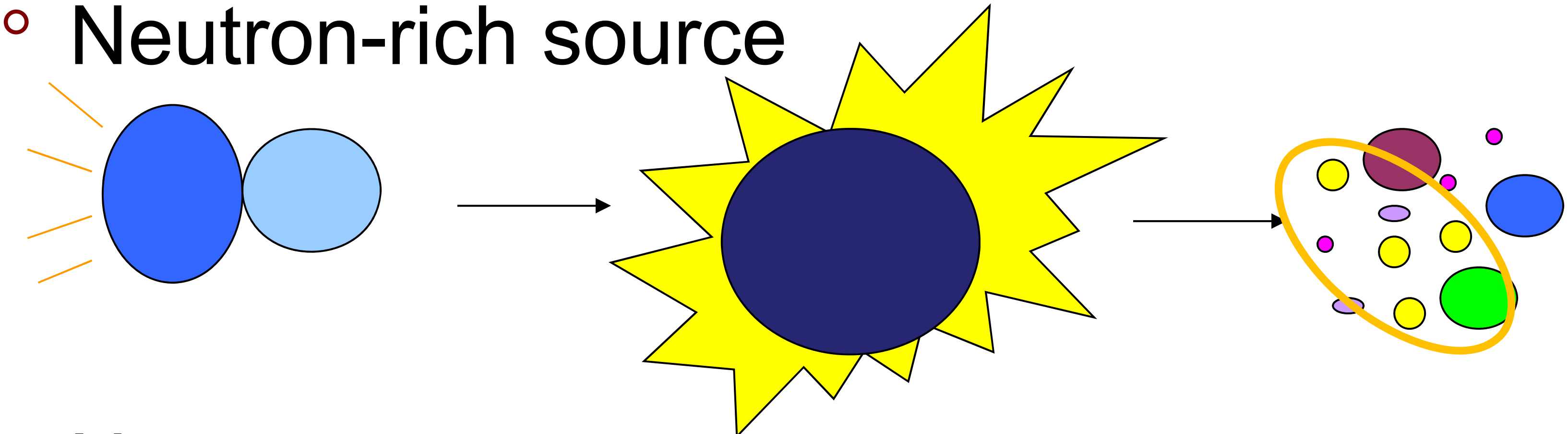
Comparing Identified Fragments

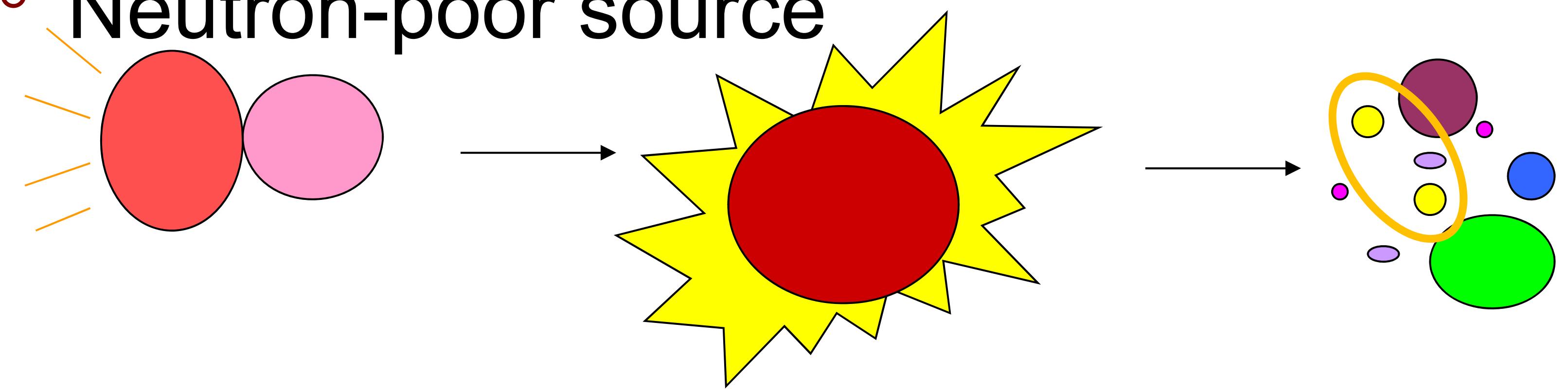
Tsang PRC Vol. 64 041603

$$R_{21}(N,Z) = \underbrace{\boxed{Y_2(N,Z)}}_{\text{Neutron-rich}} / \underbrace{\boxed{Y_1(N,Z)}}_{\text{Neutron-poor}} = C\exp(N\alpha + Z\beta)$$

- Neutron-rich source



- Neutron-poor source



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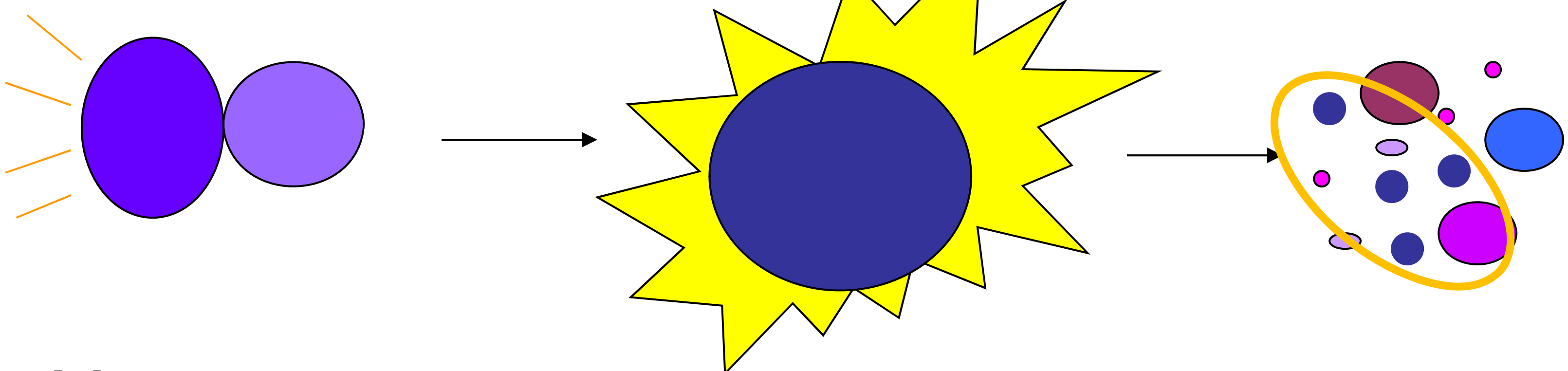
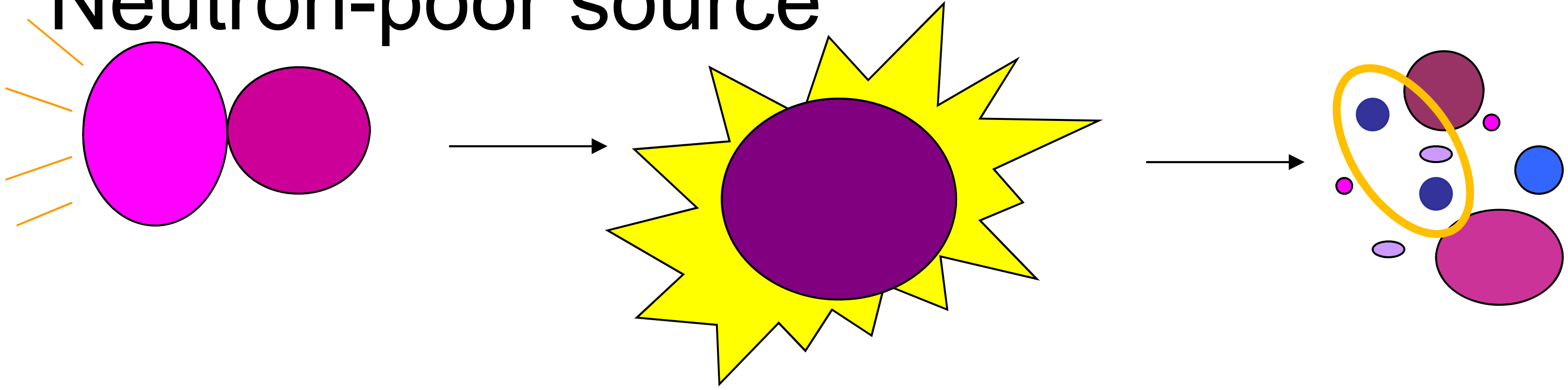


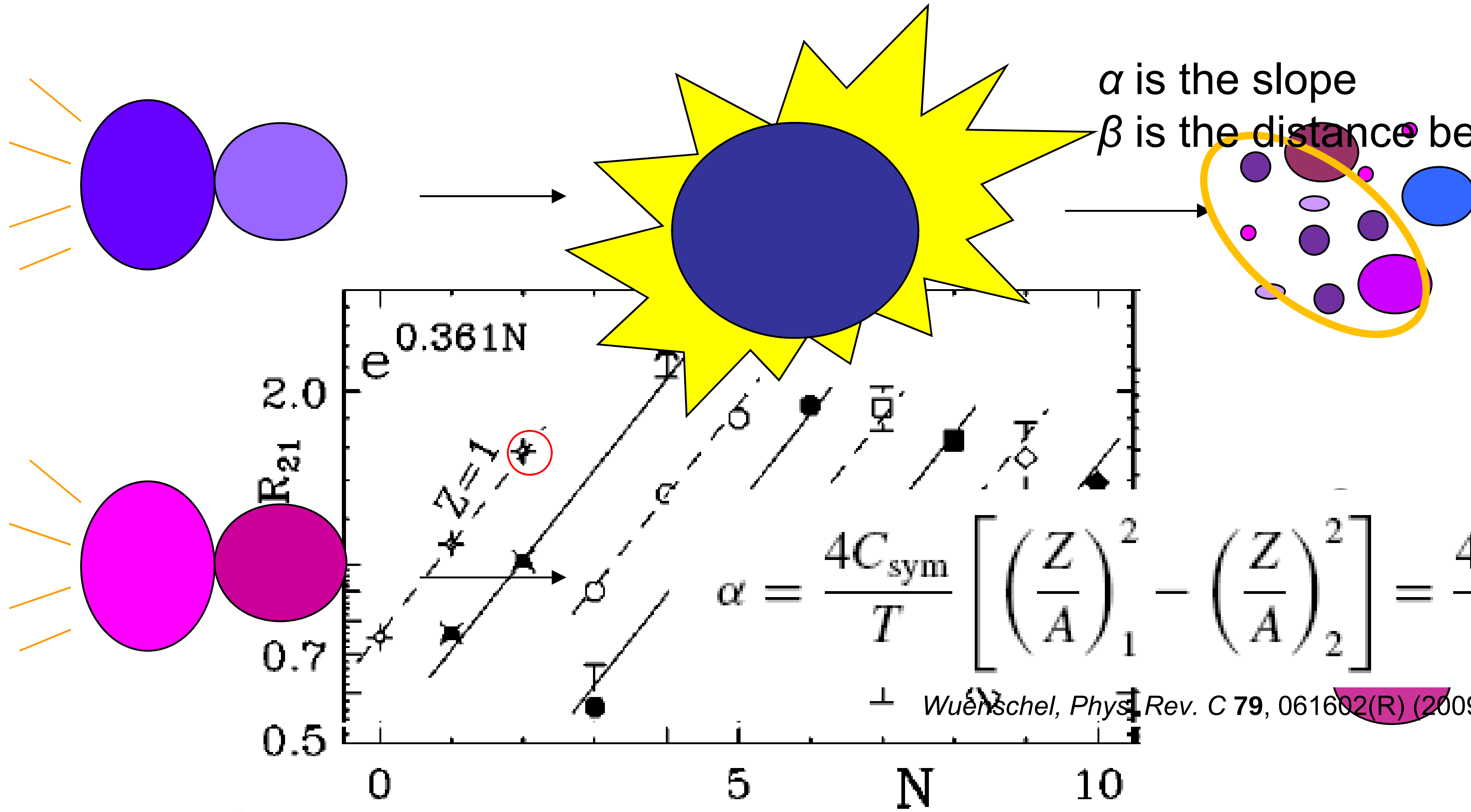
- Neutron-poor source



Comparing Identified Fragments

$$R_{21}(N,Z) = \boxed{Y_2(N,Z)} / \boxed{Y_1(N,Z)} = C\exp(N\alpha + Z\beta)$$

Neutron-rich Neutron-poor



α is the slope
β is the distance between

$$\alpha = \frac{4C_{sym}}{T}\left[\left(\frac{Z}{A}\right)_1^2 - \left(\frac{Z}{A}\right)_2^2\right] = \frac{4C_{sym}}{T}\Delta$$

Wuenschel, Phys. Rev. C **79**, 061602(R) (2009)

Tsang. Phys. Rev. C **64**, 041603(R) (2001)

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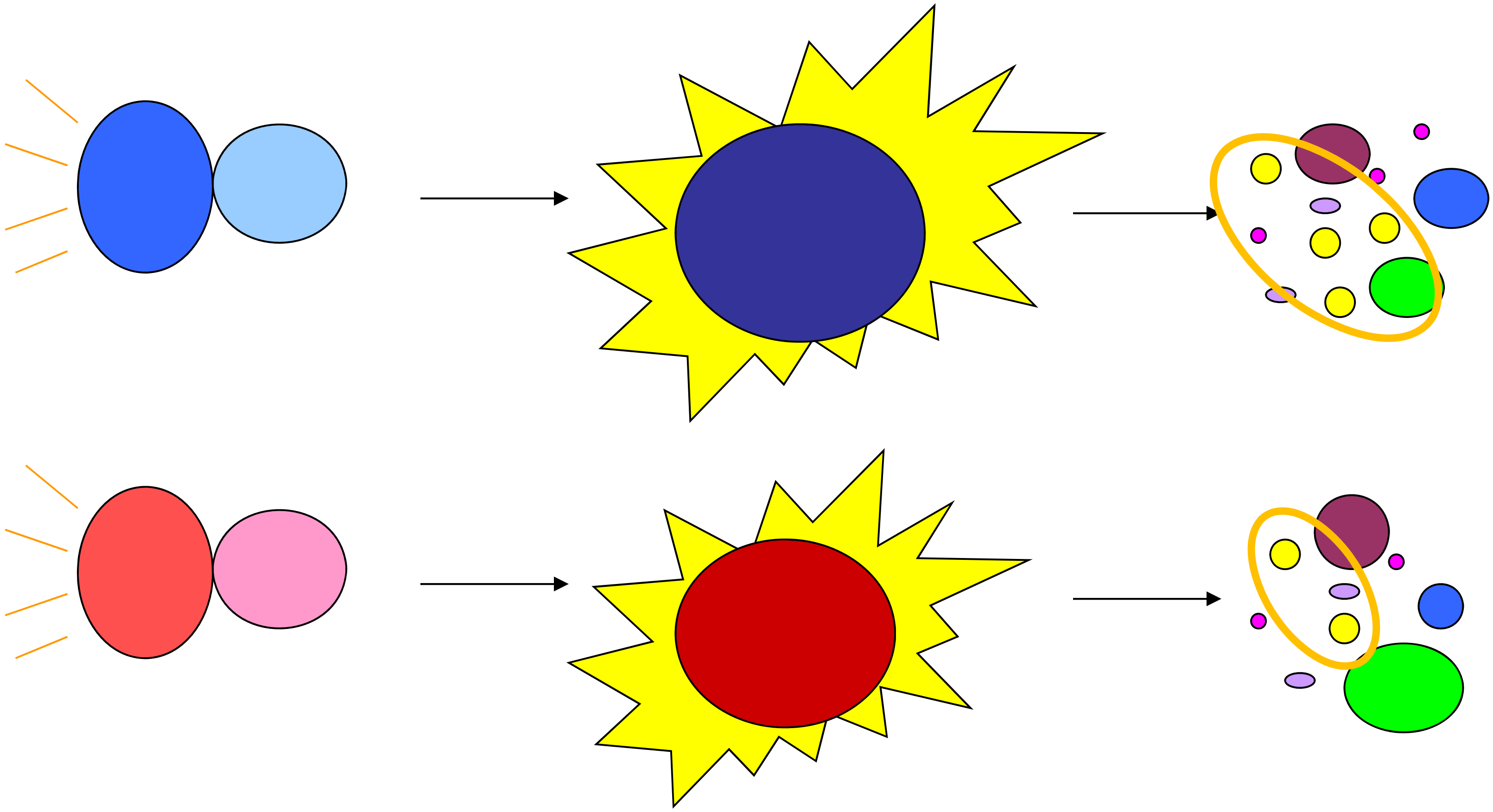

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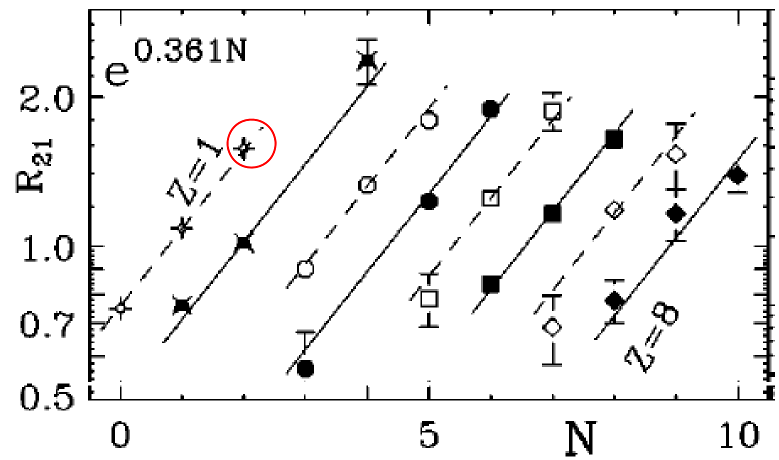
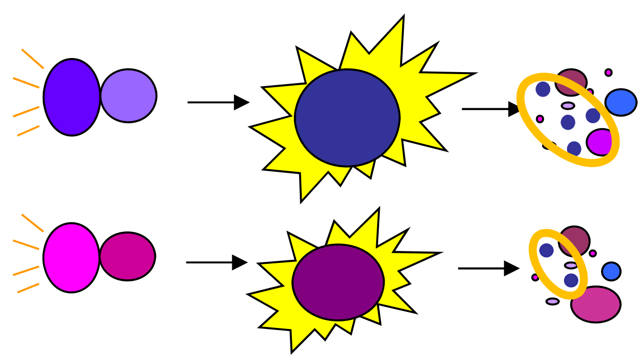
Tsang. Phys. Rev. C **64**, 041603(R) (2001)

Evolution of Isoscaling

- System-to-System Isoscaling
  - Tsang at MSU, etc.
  - Sources are compound nuclei
  - Isoscaling with global alpha and global beta
  - Lines are parallel and evenly spaced, but do not align perfectly with points



Tsang. Phys. Rev. C **64**, 041603(R) (2001)



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Isostopic Scaling…It can get us to the symmetry energy

- Ratio of isotopic yields

$$R_{21}(N,Z) = Y_2(N,Z)/Y_1(N,Z) = C\exp(N\alpha + Z\beta)$$

Neutron-rich Neutron-poor

Normalization constant

Difference in neutron chemical potentials

Difference in proton chemical potentials

$\alpha=\Delta\mu_n/T$ $\beta=\Delta\mu_p/T$

Tsang PRC Vol. 64 041603

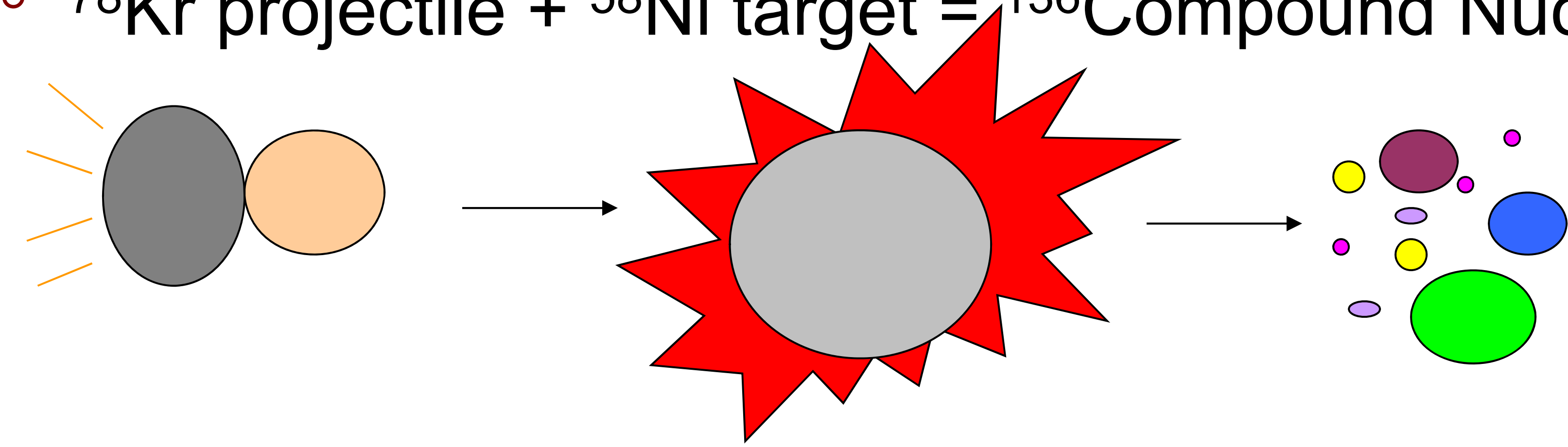
- Relation of α to E_{sym} (C_{sym})

$$\alpha = \frac{4C_{\text{sym}}}{T}\left[\left(\frac{Z}{A}\right)_1^2 - \left(\frac{Z}{A}\right)_2^2\right] = \frac{4C_{\text{sym}}}{T}\Delta$$

Wuenschel, Phys. Rev. C **79**, 061602(R) (2009)

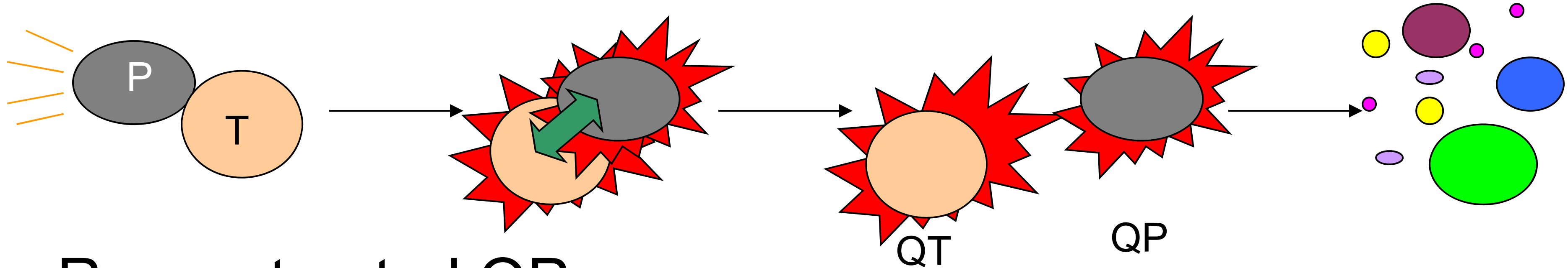
Source Definition

- ^{86}Kr projectile + ^{64}Ni target = ^{150}Compound Nucleus
- ^{78}Kr projectile + ^{58}Ni target = ^{136}Compound Nucleus

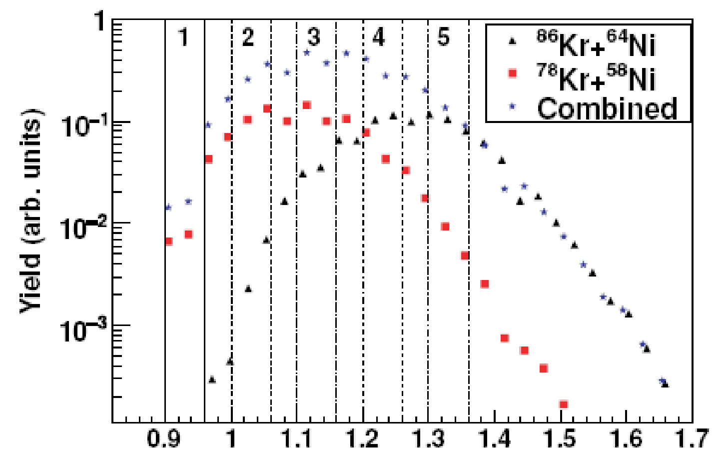


Source Reconstruction

- Peripheral collisions ⟶ Quasiprojectile (QP) & Quasitarget (QT)



- Reconstructed QP as source
- Distribution of QP sources (in N/Z of source)
- Better defines source



Wuenschel, Phys. Rev. C **79**, 061602(R) (2009)

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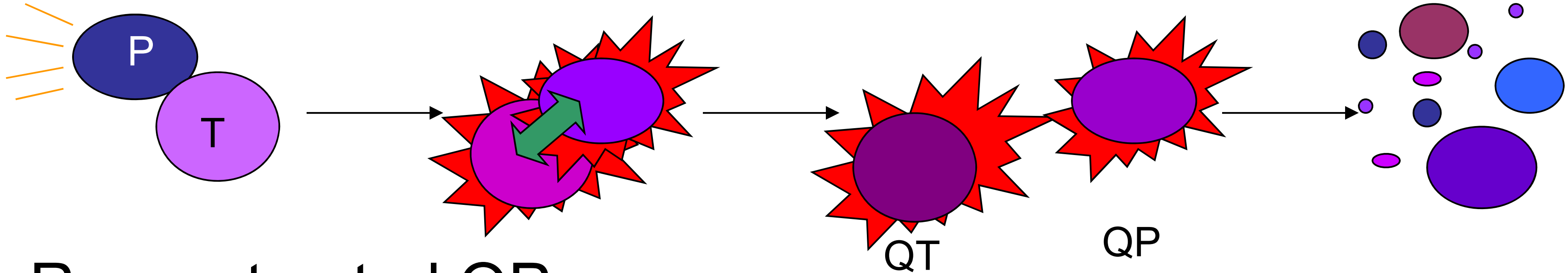

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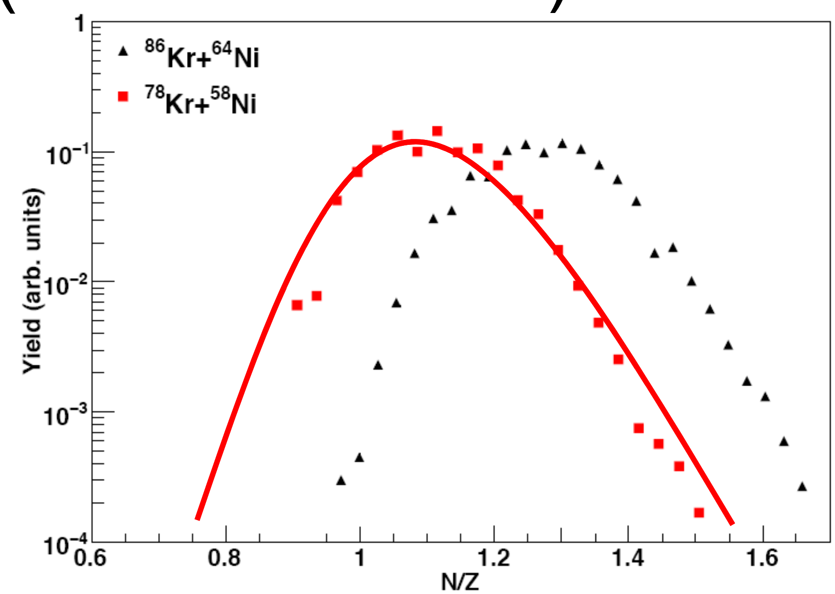

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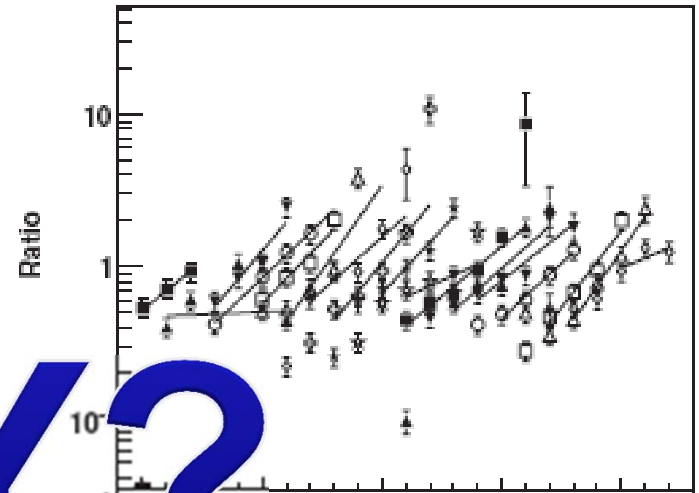
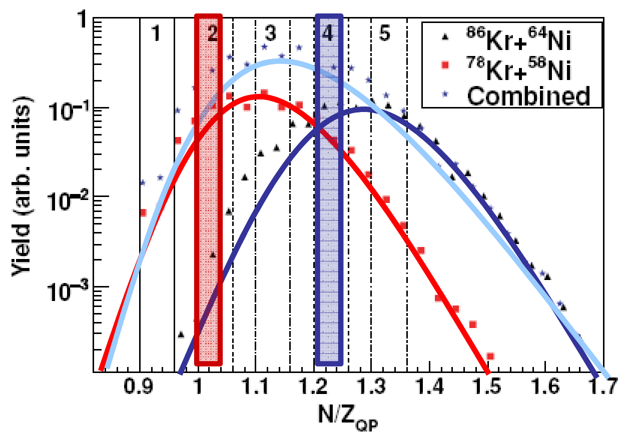
Transition in Isoscaling

System-to-System Isoscaling



WHY?

Bin-to-Bin Isoscaling



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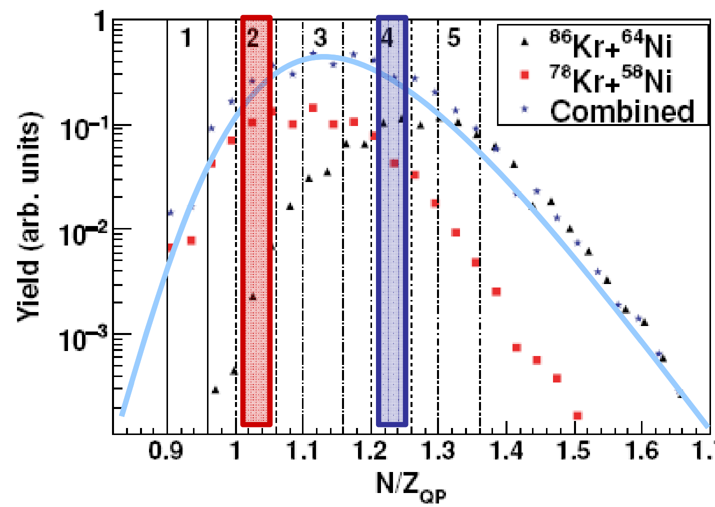
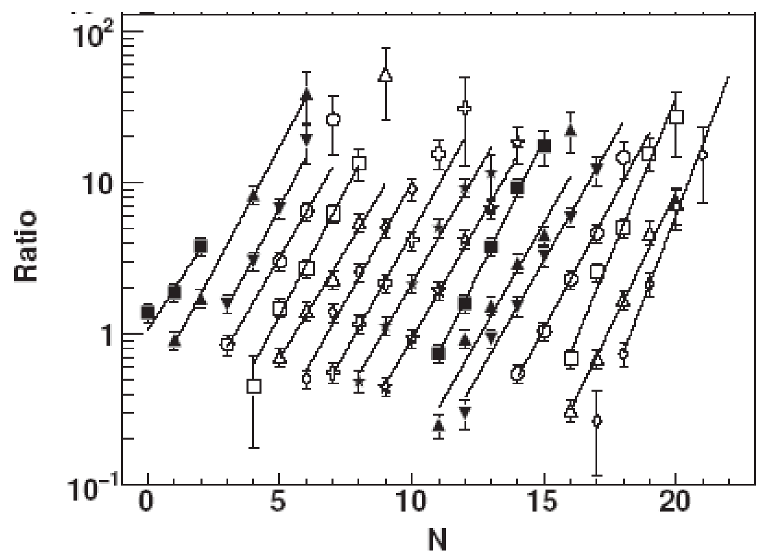
Wuenschel, Phys. Rev. C **79**, 061602(R) (2009)

Evolution of Isoscaling

- Bin-to-Bin Isoscaling
  - Combine systems and divide into bins
  - Isoscaling with individual alphas and betas for each Z
  - Better resolution from better definition of the delta
- Better defined α and Δ should mean better defined C_{sym}

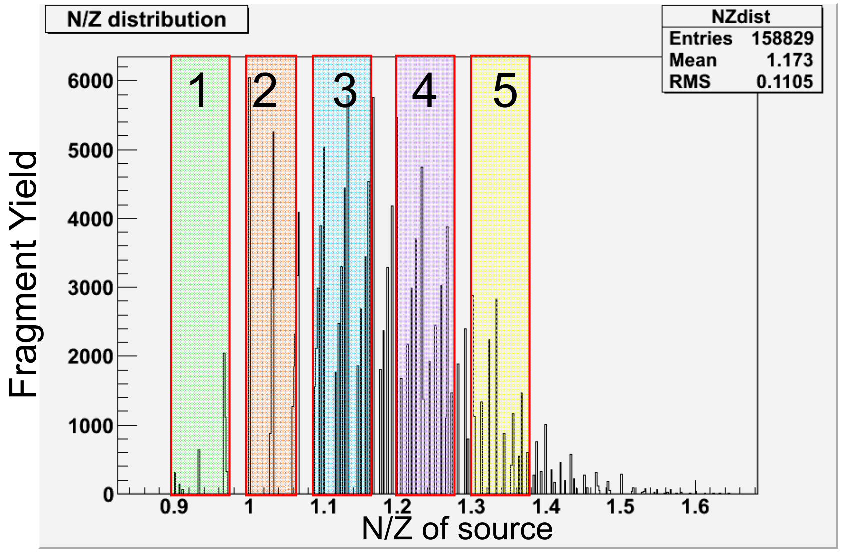




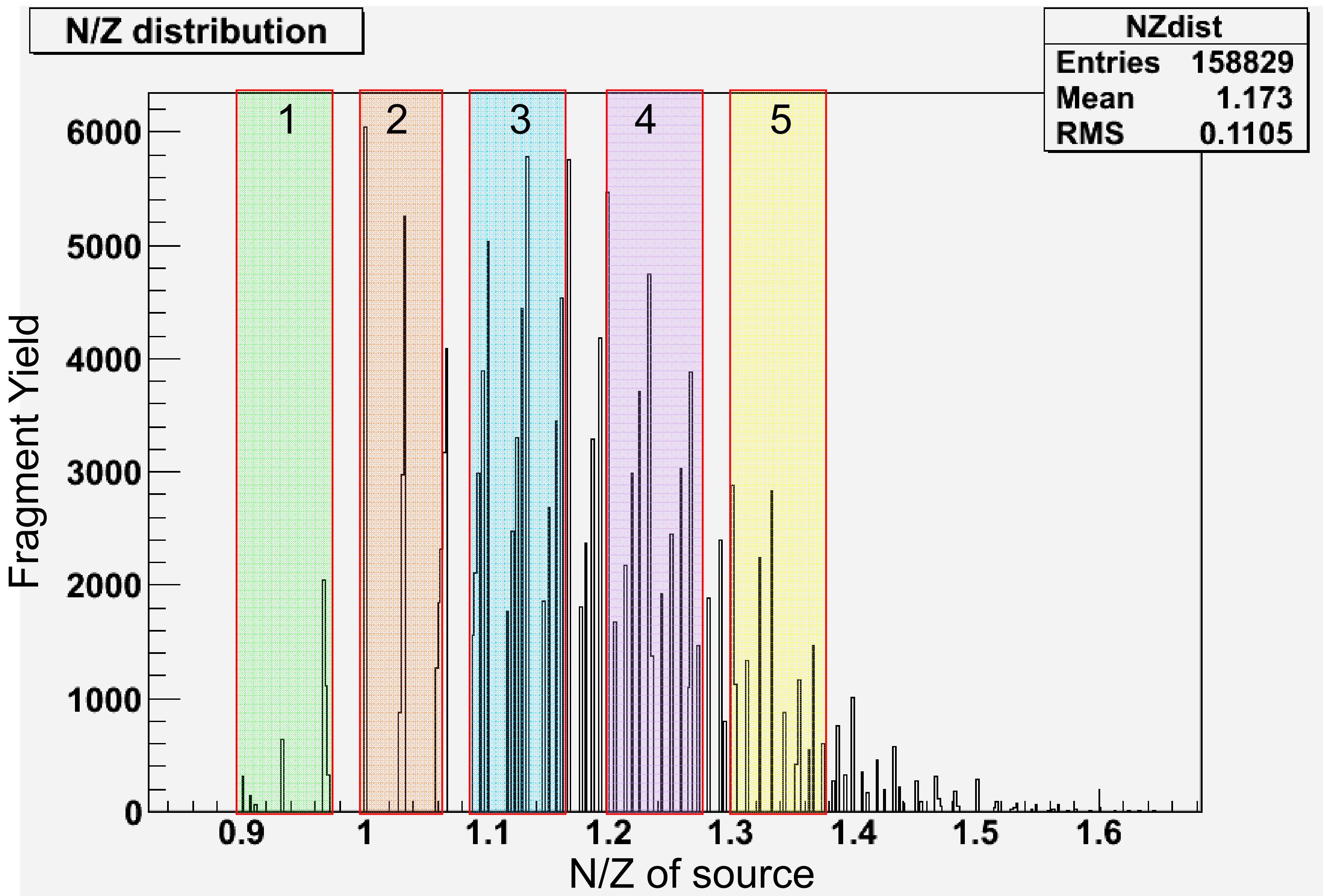
Wuenschel, Phys. Rev. C **79**, 061602(R) (2009)

Improving Isoscaling

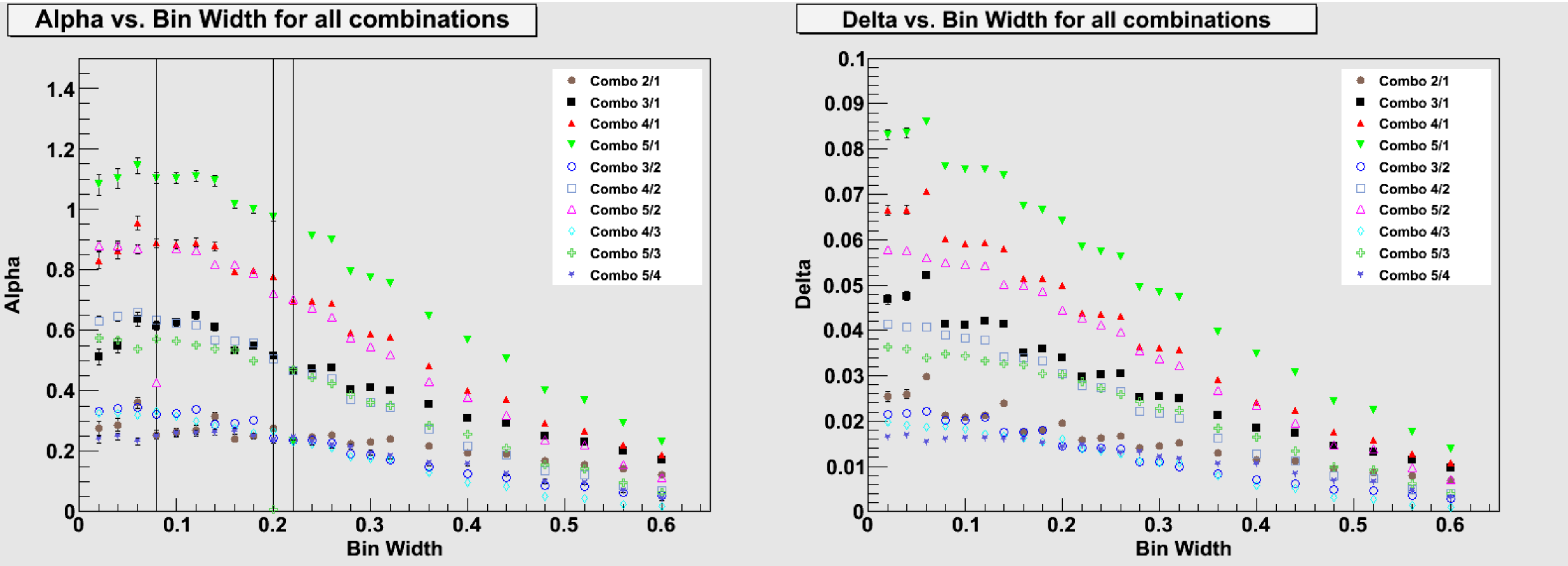
- Wuenschel used bins in N/Z, of width 0.06, and always compared bins 2 and 4



- But what if you changed the width, or range, in N/Z, or changed the bins that were being compared?
  - Bin widths: 0.02 – 0.28 in increments of 0.02,and 0.28-0.60 in increments of 0.04
  - All comparisons of Bins 1-5

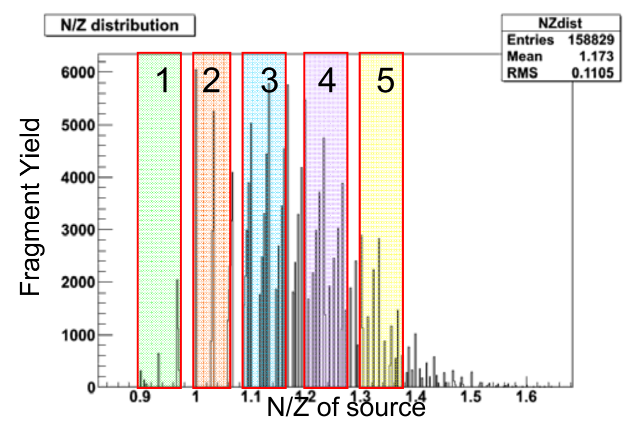

N/Z distribution
NZdist
Entries 158829
Mean 1.173
RMS 0.1105
1
2
3
4
5
Fragment Yield
0
1000
2000
3000
4000
5000
6000
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
N/Z of source

$$\alpha = \frac{4C_{\mathrm{sym}}}{T}\left[\left(\frac{Z}{A}\right)_1^2 - \left(\frac{Z}{A}\right)_2^2\right] = \frac{4C_{\mathrm{sym}}}{T}\Delta$$



Bin comparisons trend by bin separation

Convergence of α and Δ for large bin widths



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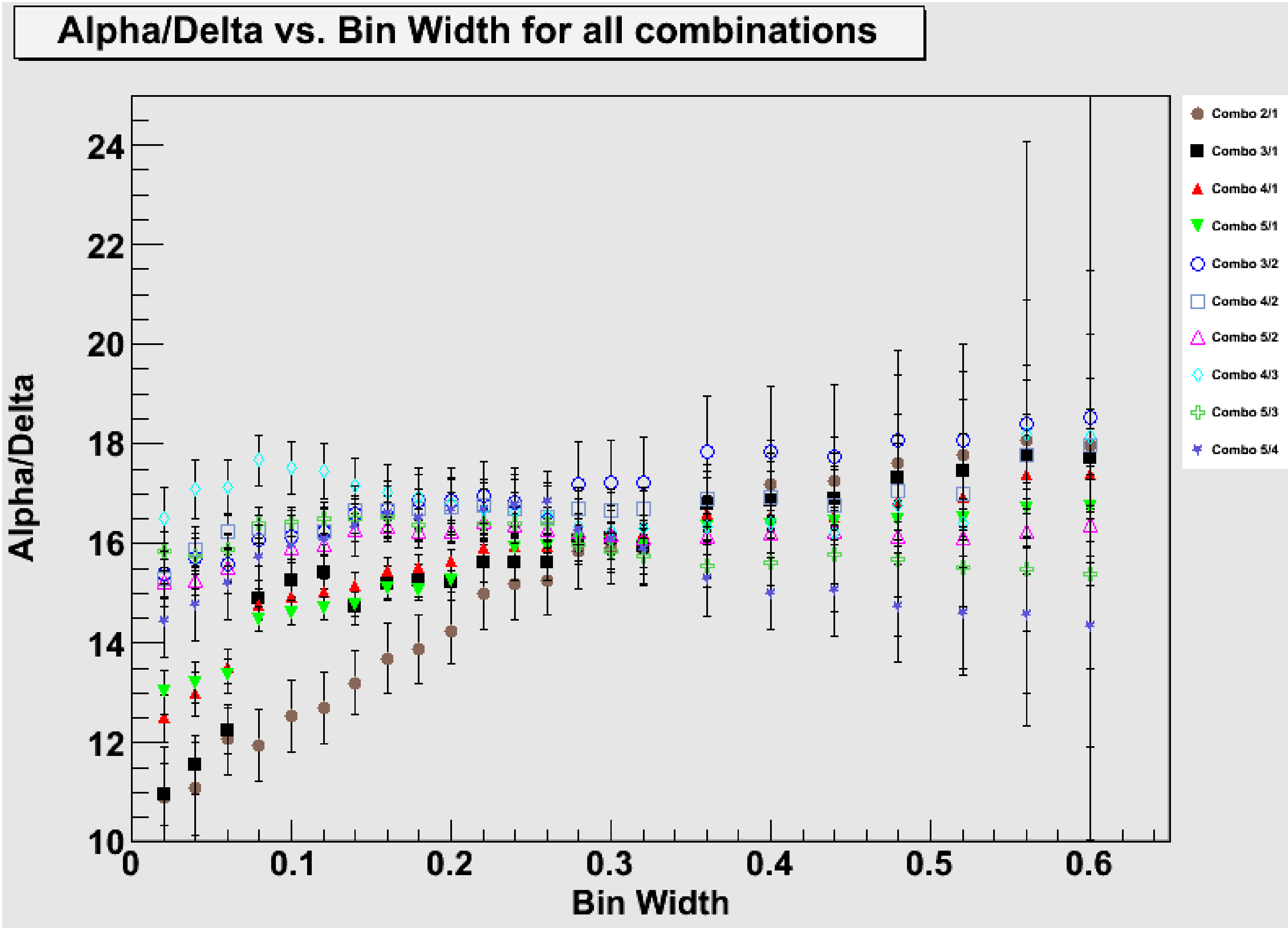
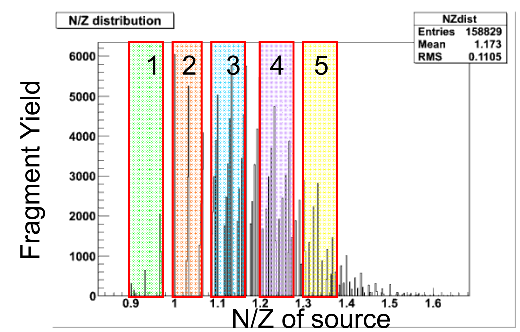


$$\frac{\alpha}{\Delta} = \frac{4}{T} C_{sym}$$

Roughly around the C_{sym}

Convergence around 0.3



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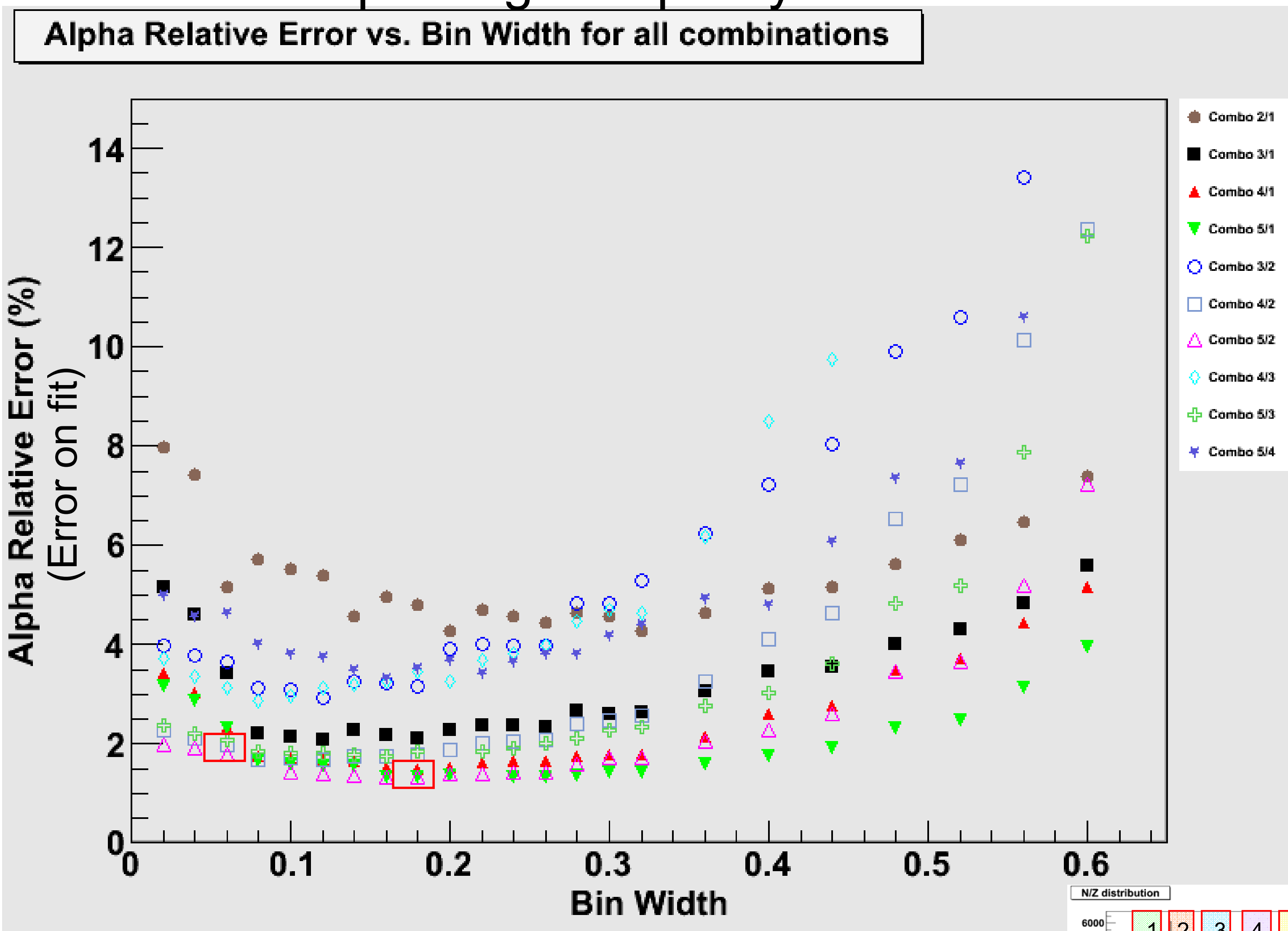
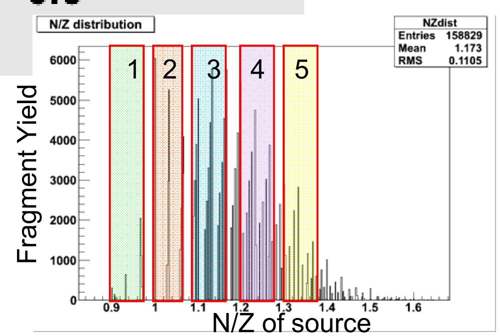
Improving the quality of the fit





Minimum of the relative error in alpha is with a bin width of 0.18 (in N/Z) using the 5/2 comparison

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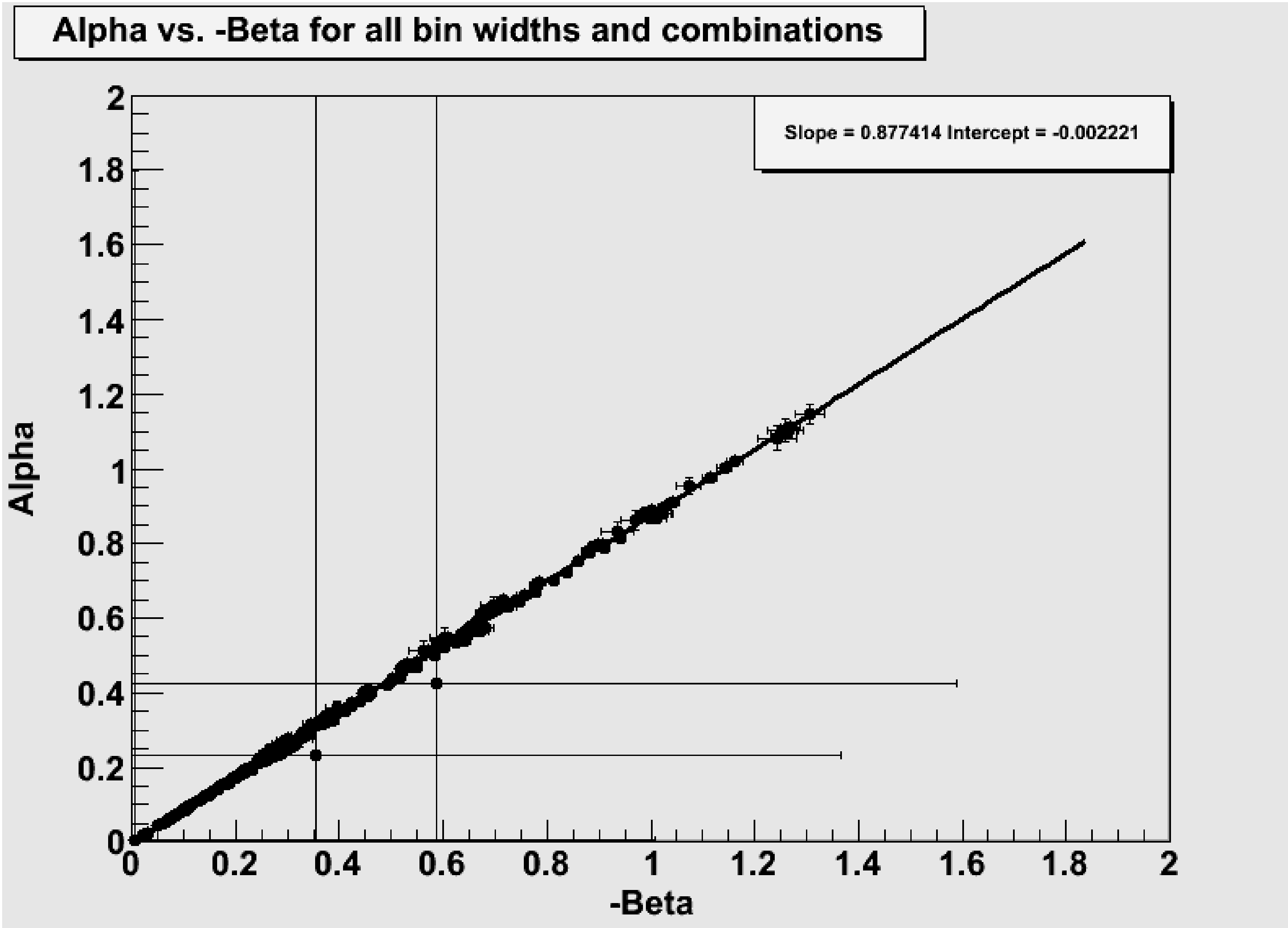
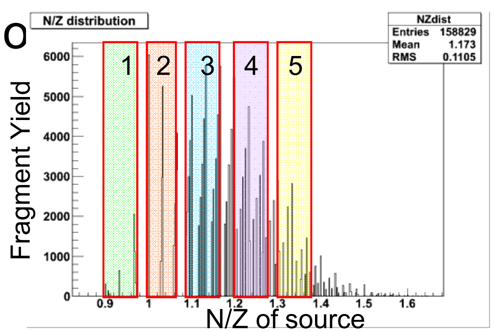
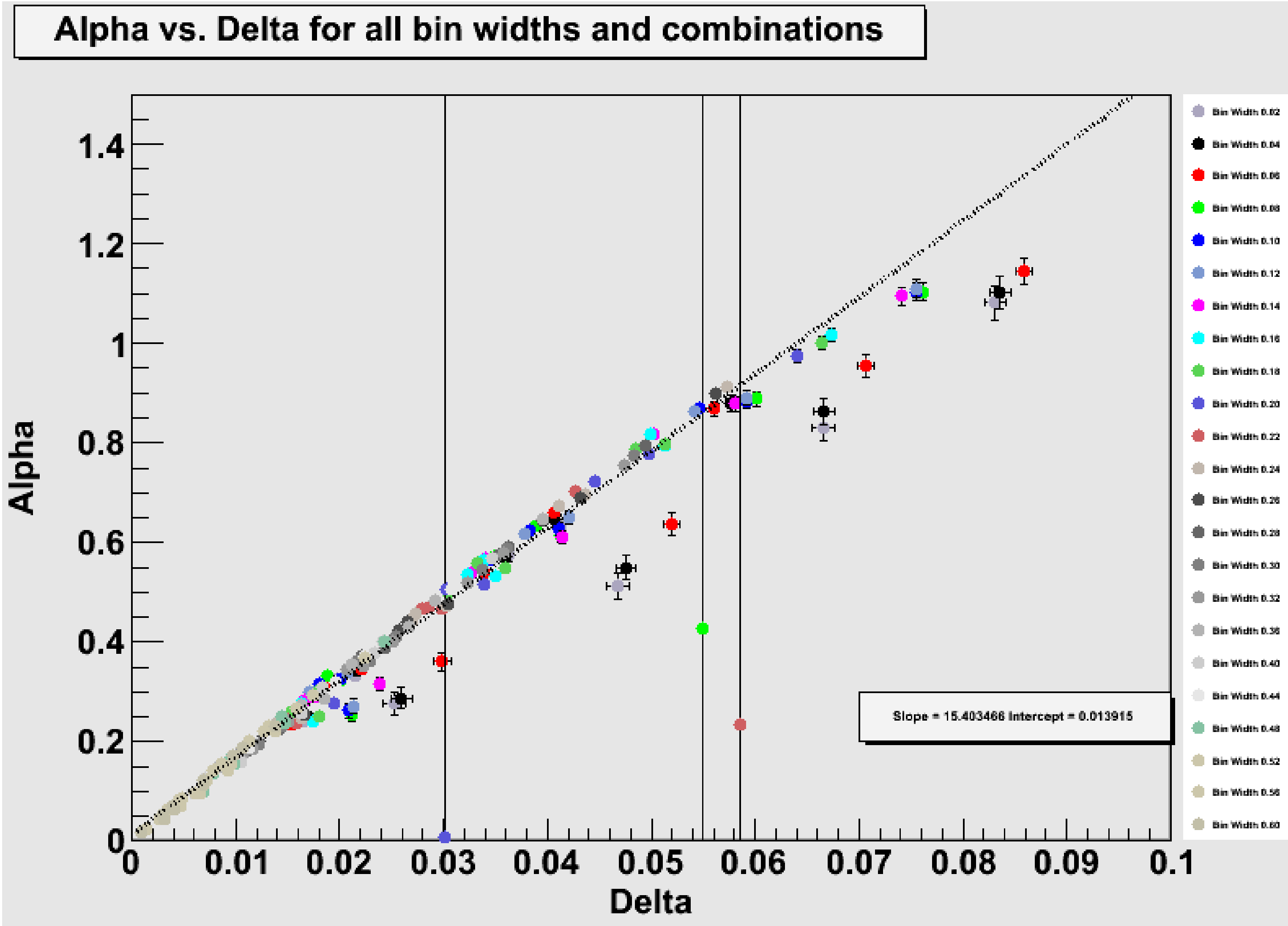
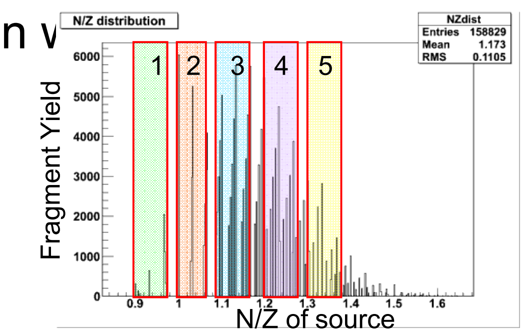


Theoretically, α should equal –β. Ours is pretty clo





Some outliers, but groups are the smallest three bin w



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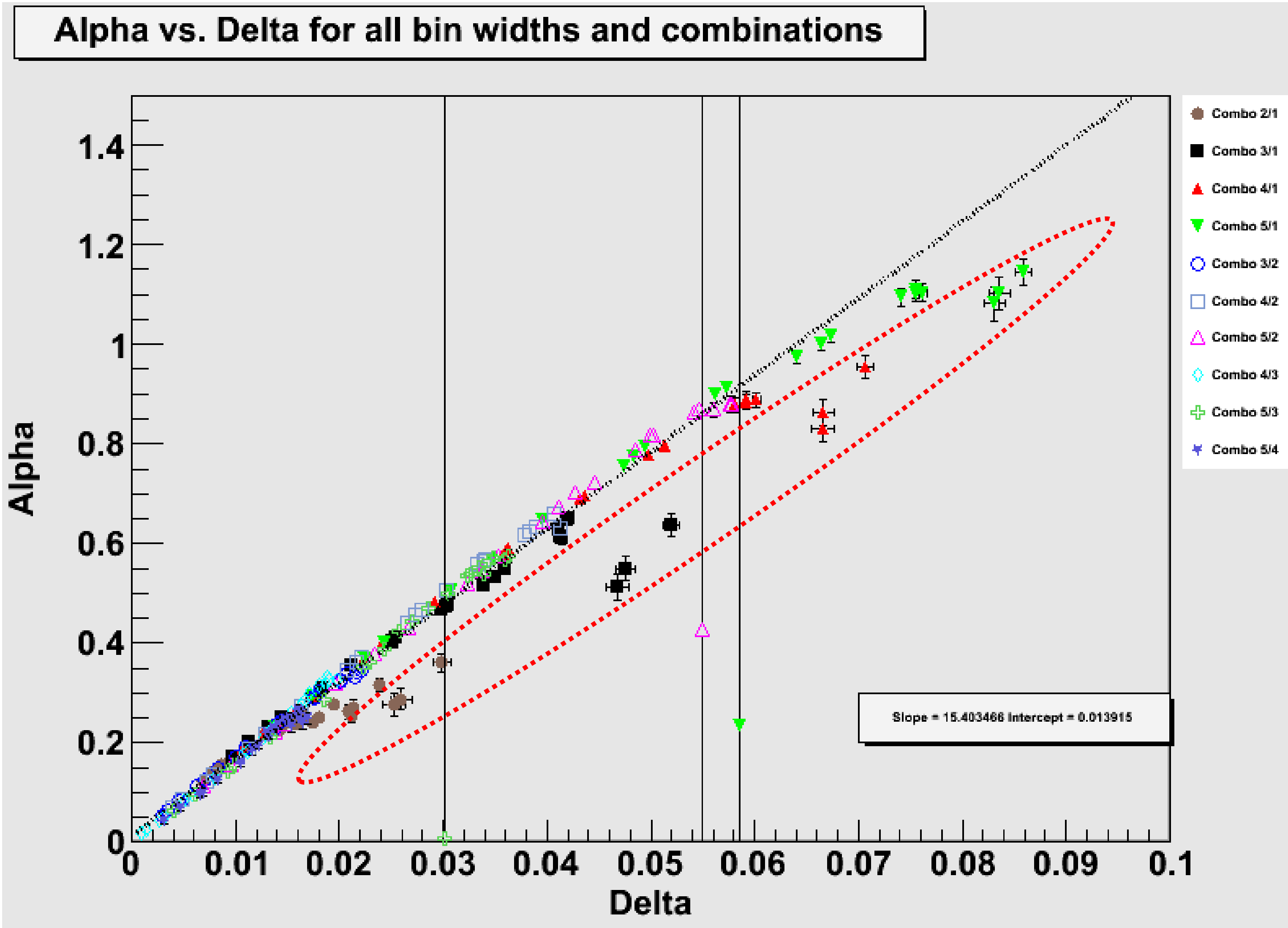
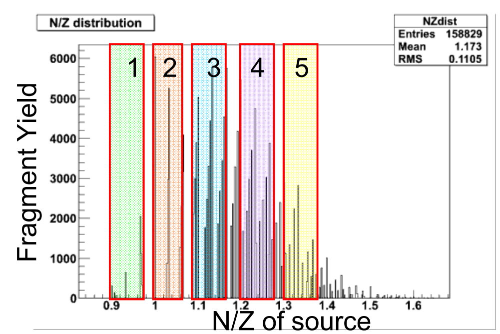


$$\alpha = \frac{4C_{\mathrm{sym}}}{T}\Delta$$

Consistent α/Δ means consistent C_{sym}.
All the offset groups involve Bin 1
and the 3 smallest bin widths!



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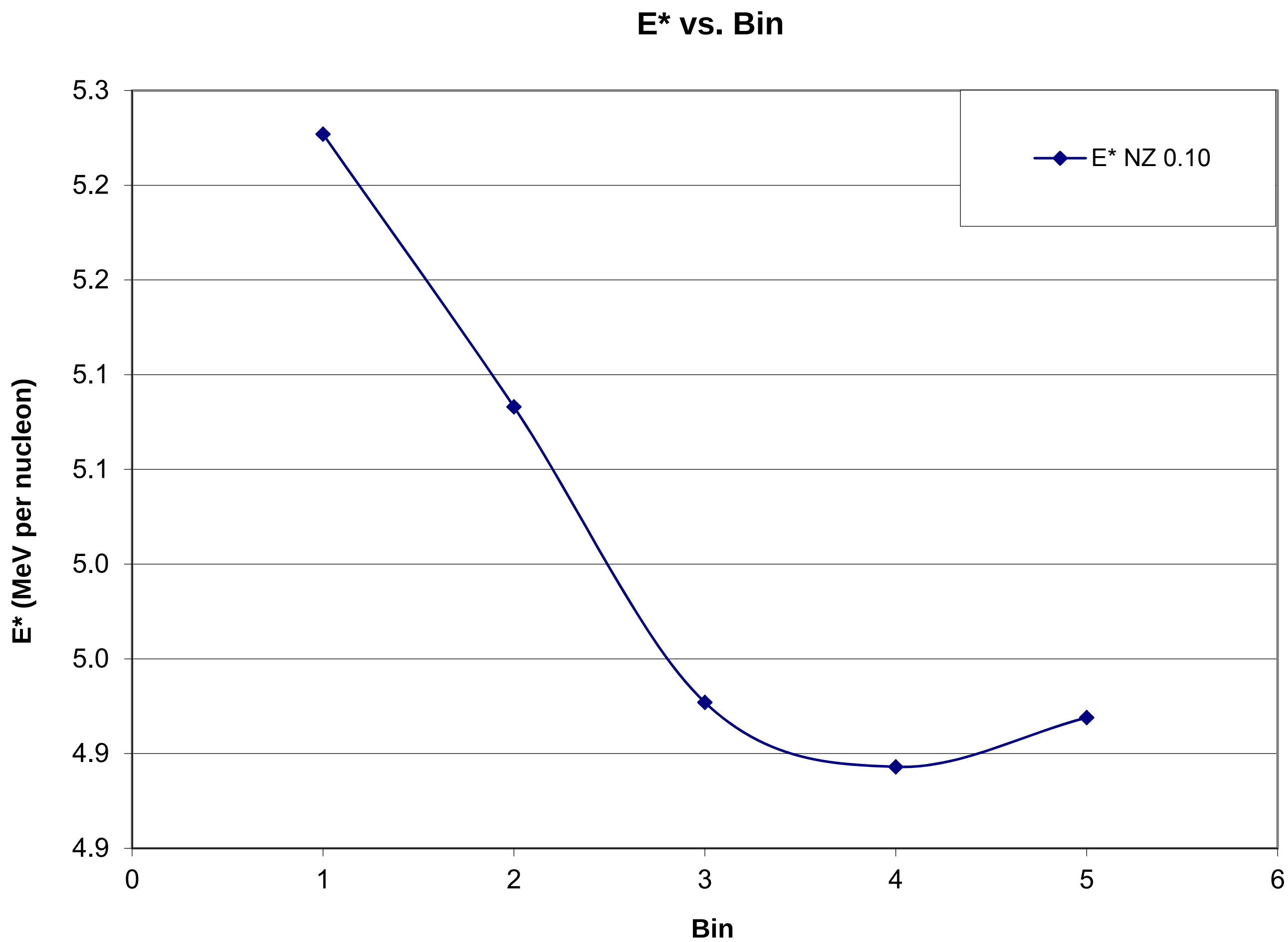
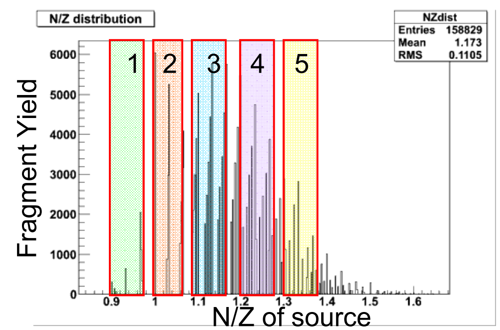


The excitation energies of bin 1 are quite a bit higher than the other bins!

$$\alpha = \frac{4C_{\text{sym}}}{T}\Delta$$

E* is proportional to T^2 and a higher temperature would mean lower α



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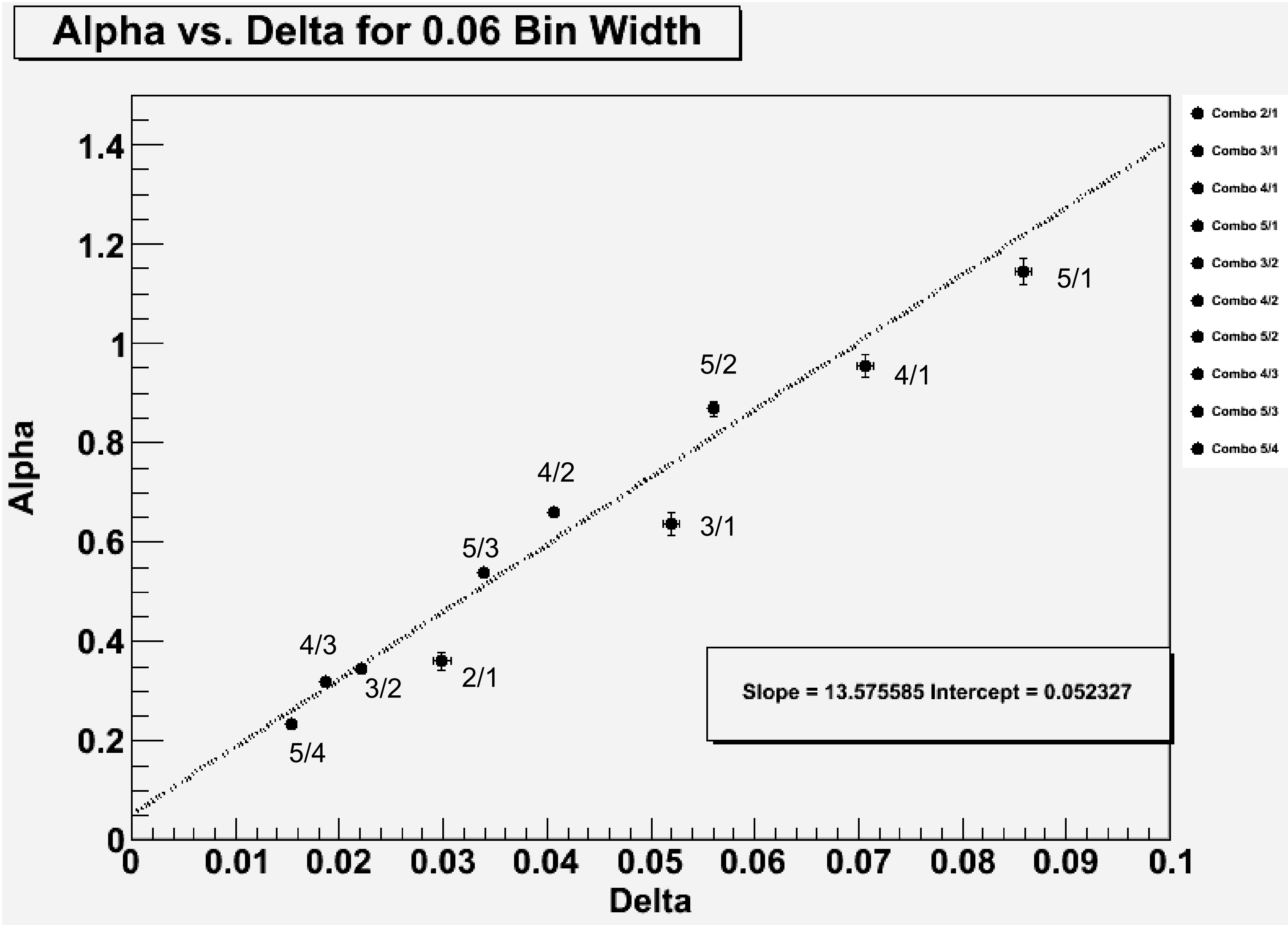
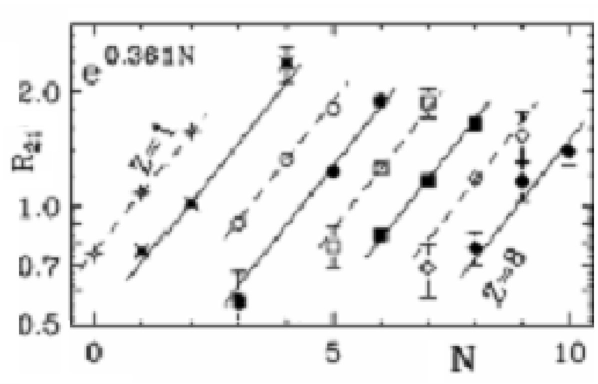


Bin 1 combinations are obviously off the line.

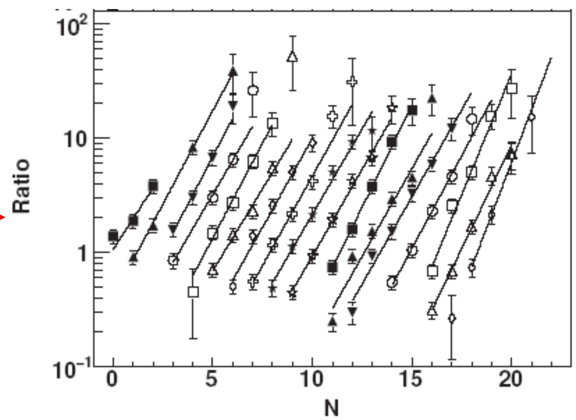
What We've Learned So Far

- Varying the source selection (bin width) changes the isoscaling
- Using a bin width of 0.18 (in N/Z) when comparing bins 5 and 2 will give the optimum results
- Some characteristic of bin 1 is causing a systematic difference in the α, shown on the α vs. Δ plot

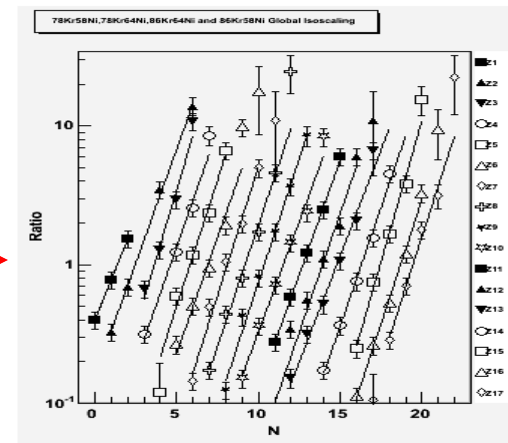
Evolution of Isoscaling



Tsang. Phys. Rev. C **64**, 041603(R) (2001)

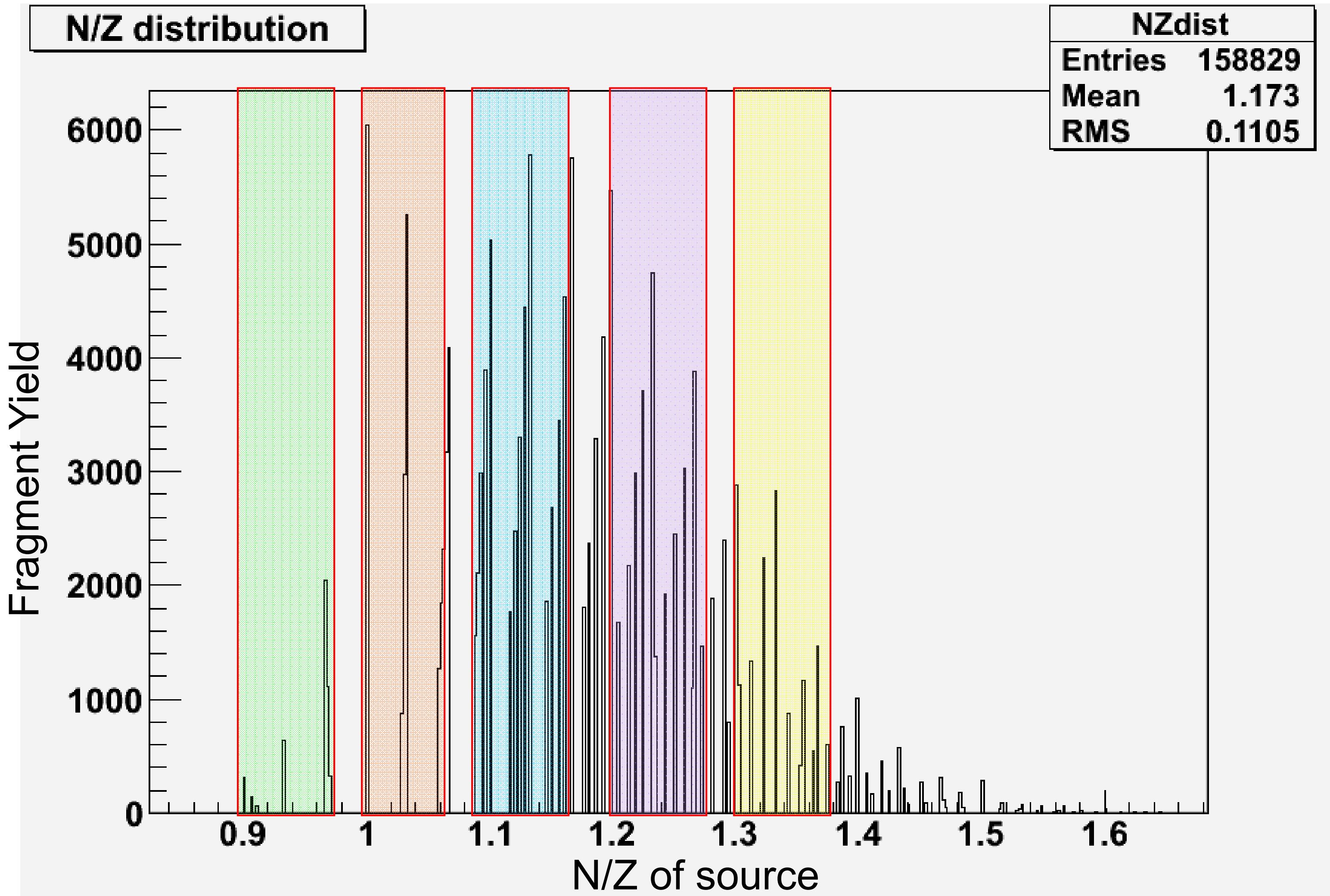


Wuenschel, Phys. Rev. C **79**, 061602(R) (2009)

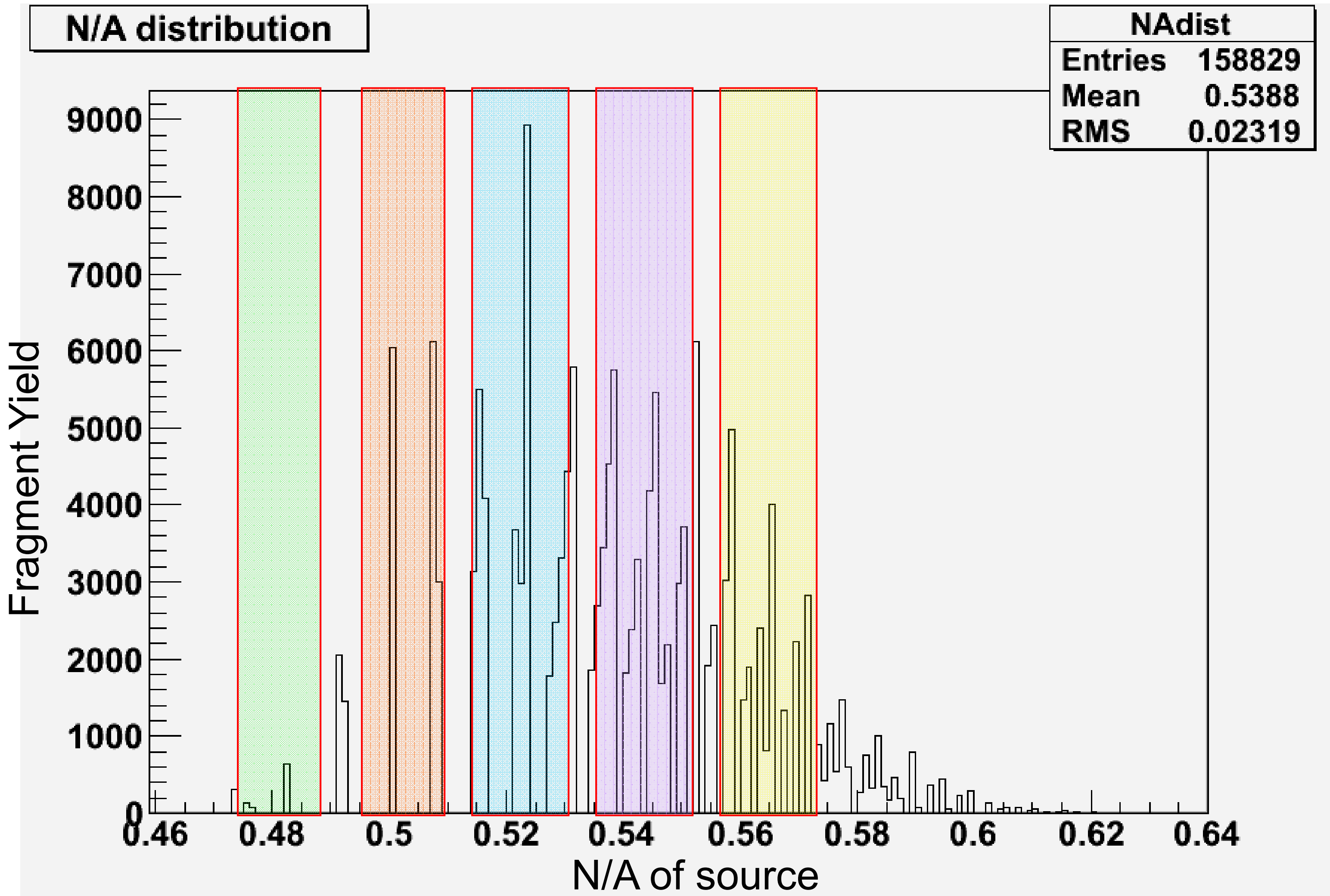


Where we went next…

- Examine Bin 1
  - Is the excitation energy of bin 1 different from the other bins?
- N/Z to N/A
  - N/Z has been used by convention
  - Technically, isoscaling should be in terms of concentration (N/A)

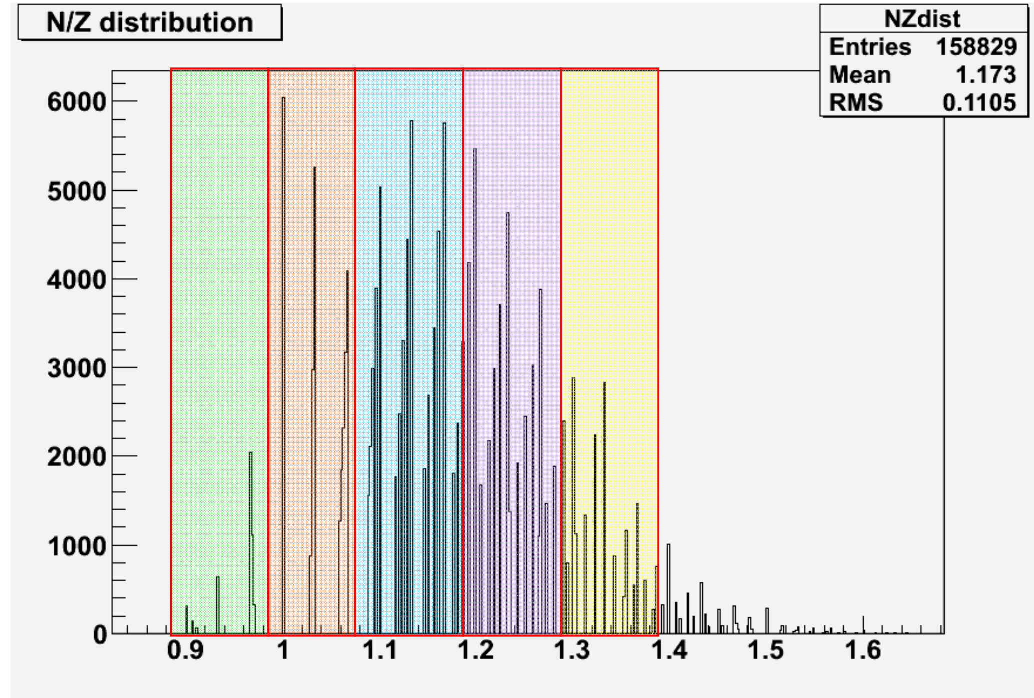


These are the N/Z bins used by Wuenschel in her isoscaling.

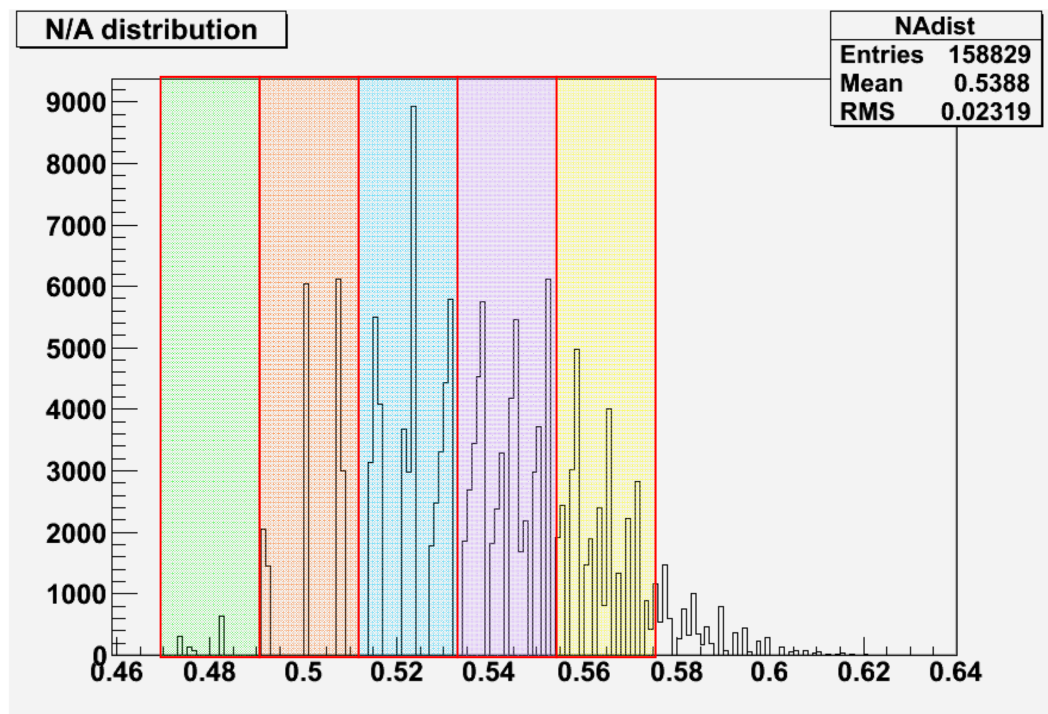


These are the corresponding N/A bins.
Variations in the N/A bins can also be studied.

N/Z bins of 0.10 width



N/A bins of 0.020 width



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Conclusions

- Source definition affects quality of isoscaling, alpha, C_{sym}
- Bin width of 0.18, comparison of bins 5/2 are optimal
- Bin 1 has significantly higher excitation energy than the other bins, which affects α

Where do we go from here?

- Further exploration into excitation energy effects
- Possibly looking into the effect of free neutrons in the reconstruction

Acknowledgements

- SJY Group
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- US Department of Energy
- YOU!

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Questions?

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- *Tsang, Eur. Phys. J. A* **30**, 129-139 (2006)