NUCLEAR STRUCTURE AND QUASIFISSION DYNAMICS

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for ANU/GSI/HIM/JGU collaboration

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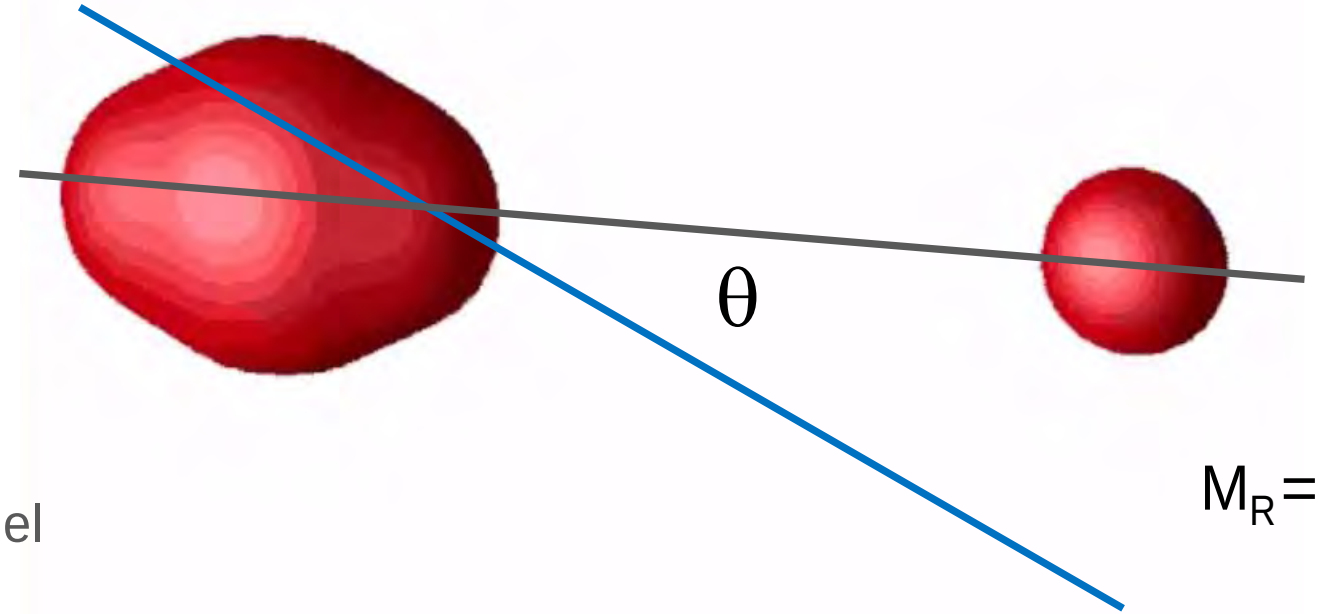
TASCA workshop GSI 1/9/2017

$$P_{CN} + P_{QF} = 1$$

$$P_{SHE} = P_{capture} \cdot P_{CN} \cdot P_{fission\ survival}\ (E, L)$$



$M_R = M_1/(M_1 + M_2)$

TDHF: C. Simenel

Quasifission: non-equilibrium process

Sticking time: a key characteristic

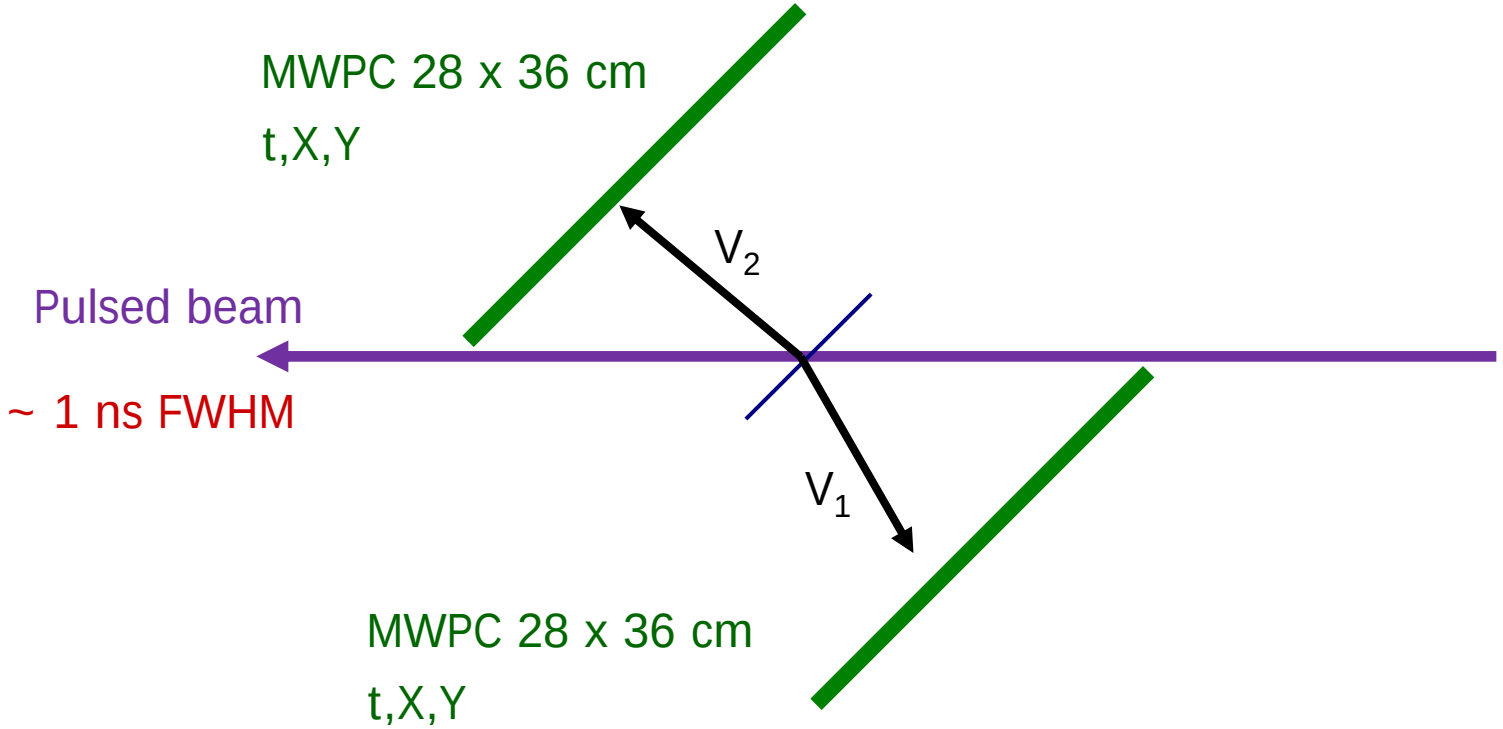
Dependence of quasifission probability and characteristics (time scale) on collision variables (related to P_{CN}):

- Compound nucleus fissility (~Z^2/A);
- Entrance channel fissility (~Z_1Z_2);
- Angular momentum;
- Nuclear structure of the colliding nuclei:
  - static deformation
  - closed shells (magic numbers)

} Many variables!

Structure effects important in Superheavy Element synthesis reactions!

ANU experiments



Hinde et al., PRC **53** (1996) 1290
Rafiei et al., PRC **77** (2008) 024606
Thomas et al., PRC **77** (2008) 034610
Hinde et al., PRL **100** (2008) 202701
Hinde et al., PRL **101** (2008) 092701

du Rietz et al., PRL **106** (2011) 052701
Lin et al., PRC **85** (2012) 014611
Simenel et al., PLB 710 (2012) 607
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Wakhle et al., PRL **113** (2014) 182502
Hammerton et al., PRC **91** (2015)041602
Prasad et al., PRC **91** (2015)064605
Khuyagbaatar et al., PRC **91** (2015) 054608
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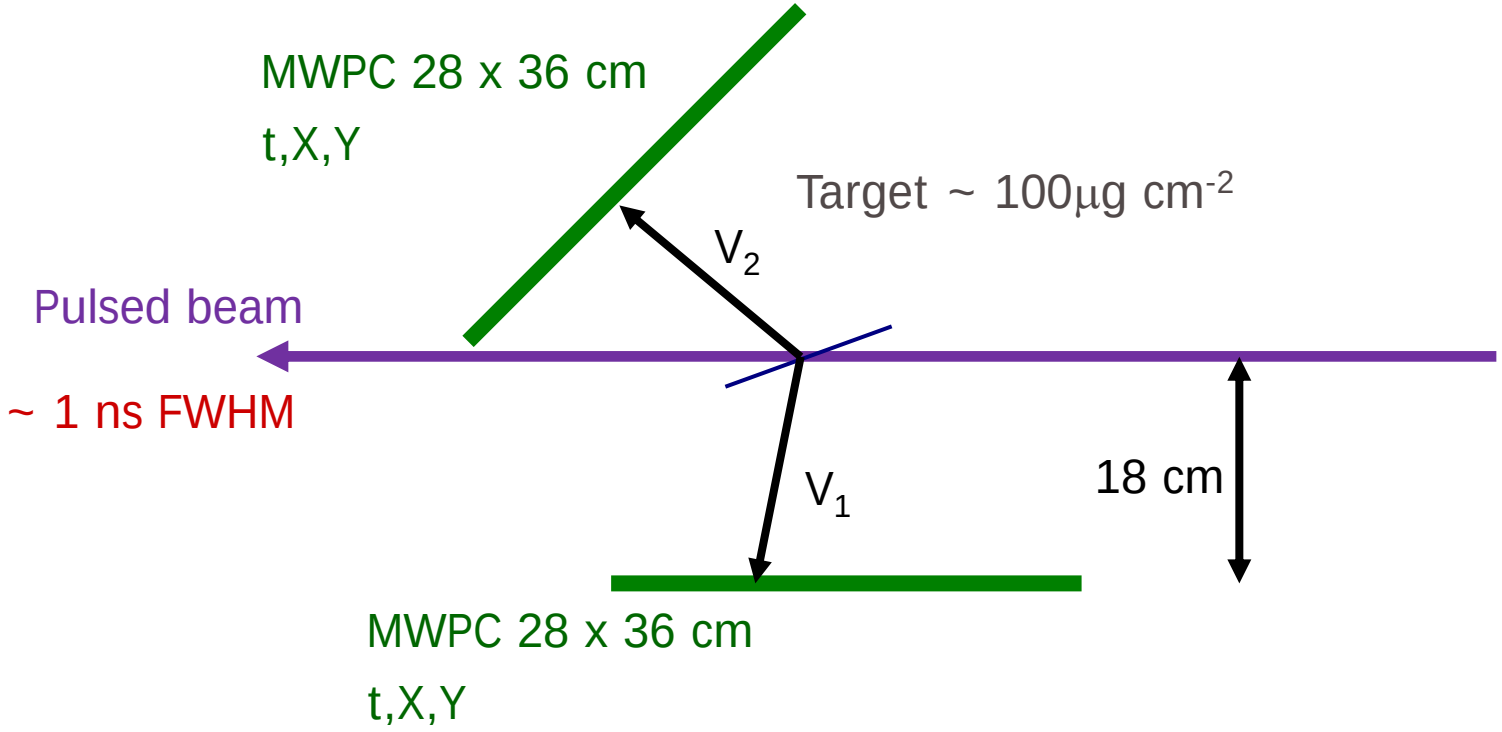
Prasad et al., Williams et al., Morjean et al.,
Mohanto et al., Palshetkar et al., Hinde et al.,
H.David, Khuyagbaatar et al., Jeung et al.

ANU experiments



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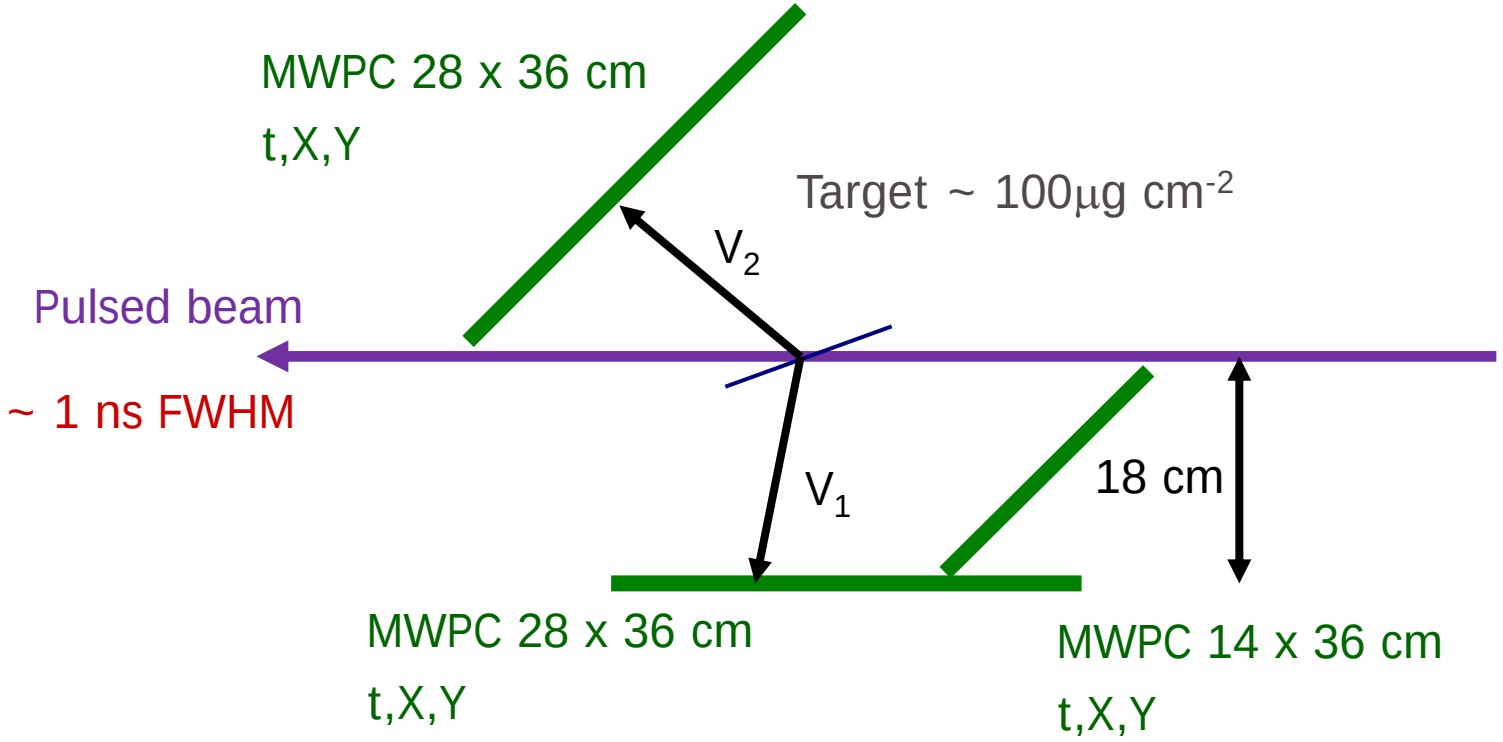
ANU experiments



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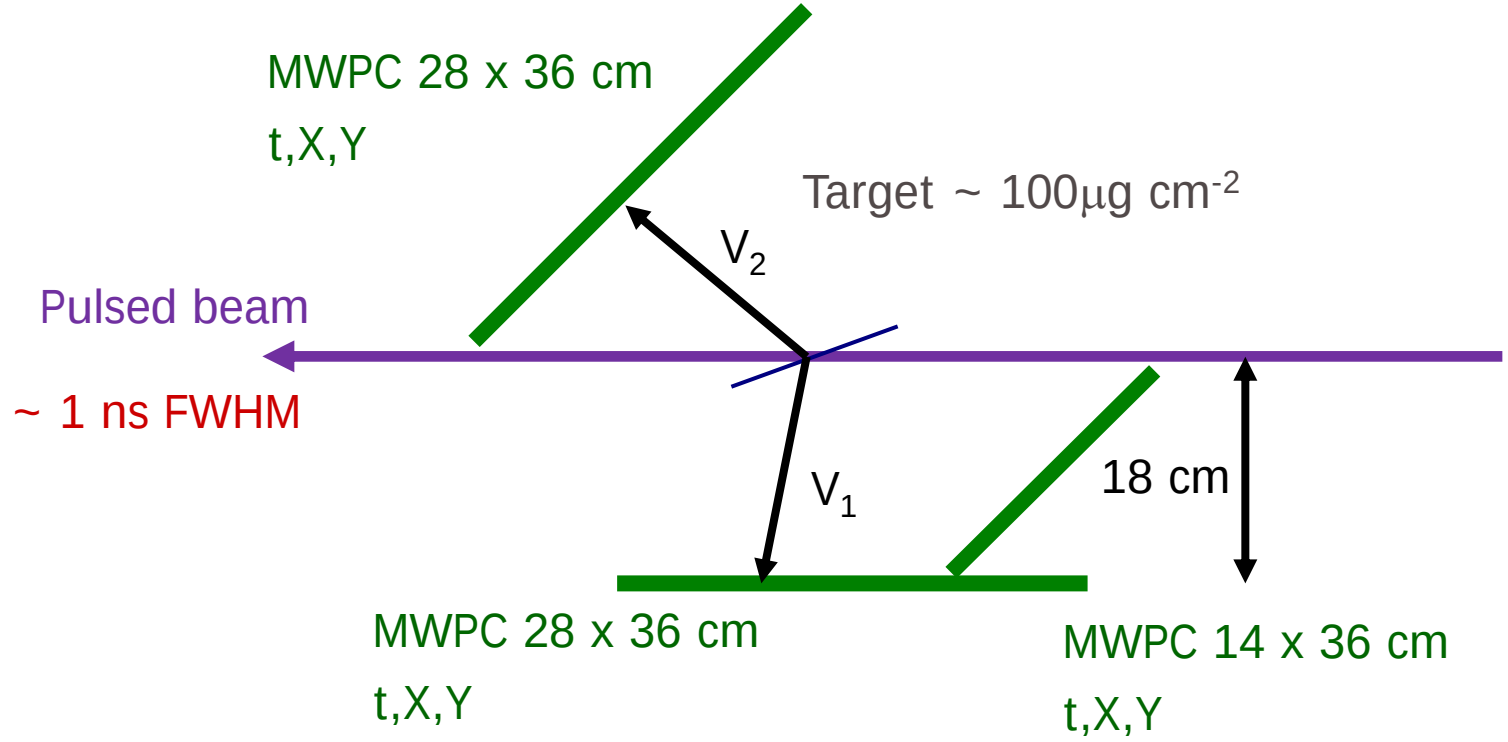

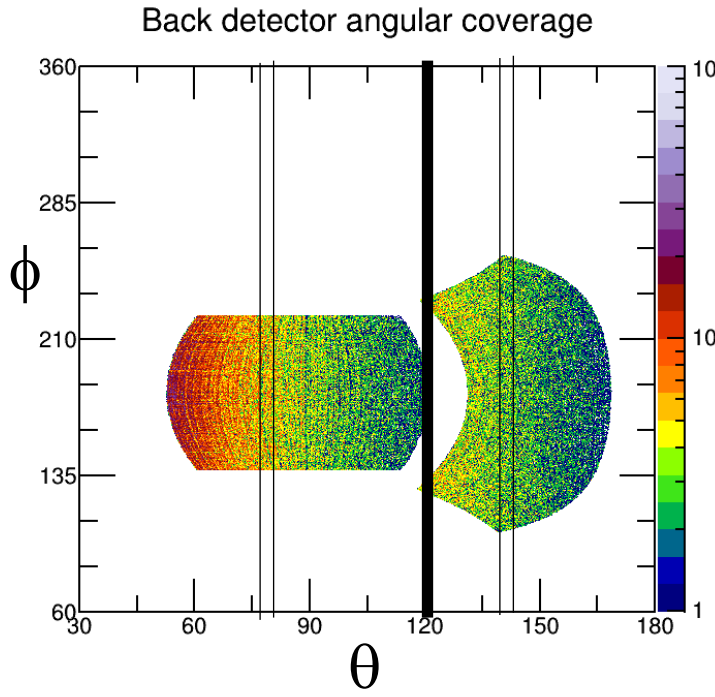

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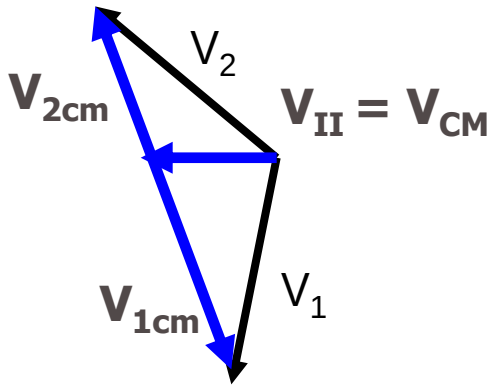

Kinematic coincidence:

Determine (binary) mass-ratio $M_{R1} = A_{F1}/(A_{F1}+A_{F2}) = V_{2cm}/(V_{1cm}+V_{2cm})$

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Effects of nuclear structure in the entrance channel: (i) Spherical magic nuclei and N/Z matching

^{248}No

$^{48}_{22}\mathrm{Ti}_{26} + {}^{200}_{80}\mathrm{Hg}_{120}$

0 0

$N_M = 0$

N/Z = 1.18 N/Z = 1.44

$\Delta N/Z = 0.26$

^{248}No

$^{44}_{20}\mathrm{Ca}_{24} + {}^{204}_{82}\mathrm{Pb}_{122}$

1 1

$N_M = 2$

N/Z = 1.20 N/Z = 1.49

$\Delta N/Z = 0.29$

^{256}No

$^{48}_{20}\mathrm{Ca}_{28} + {}^{208}_{82}\mathrm{Pb}_{126}$

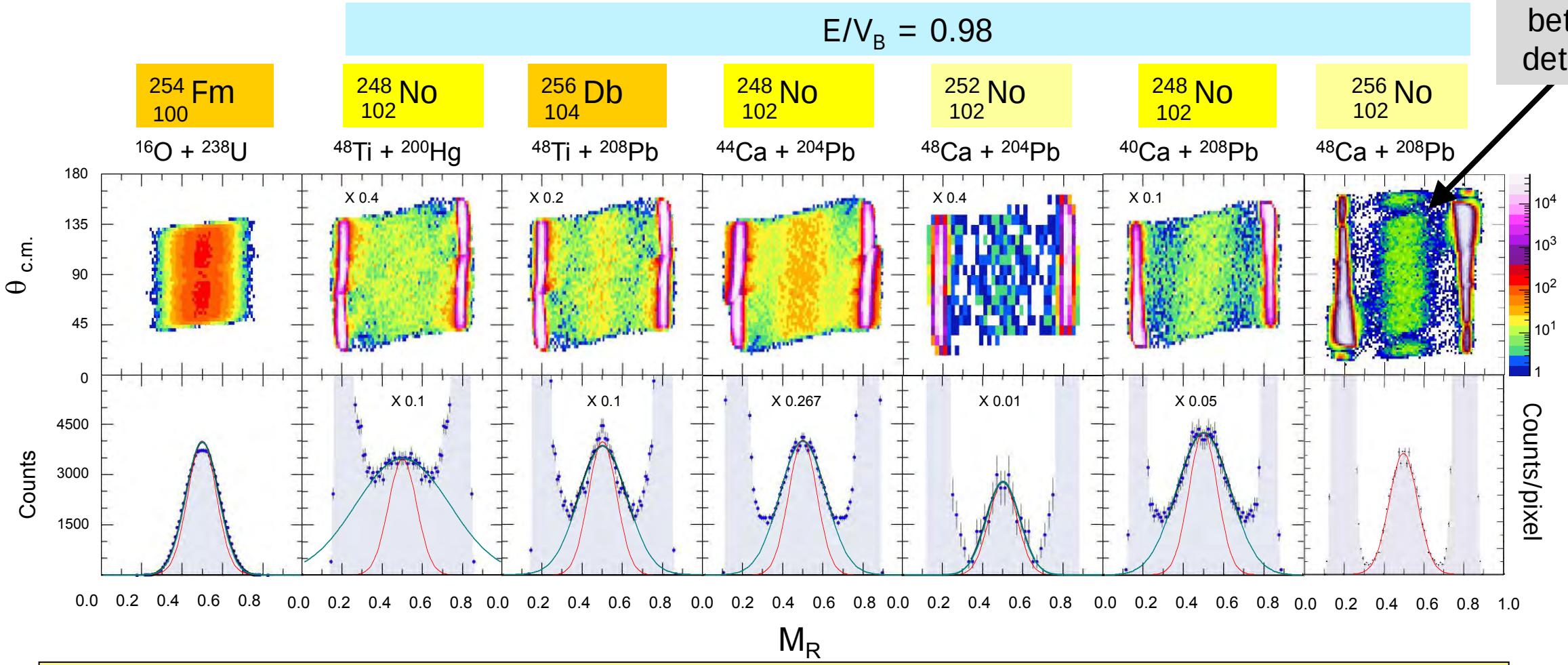
2 2

$N_M = 4$

N/Z = 1.40 N/Z = 1.54

$\Delta N/Z = 0.14$

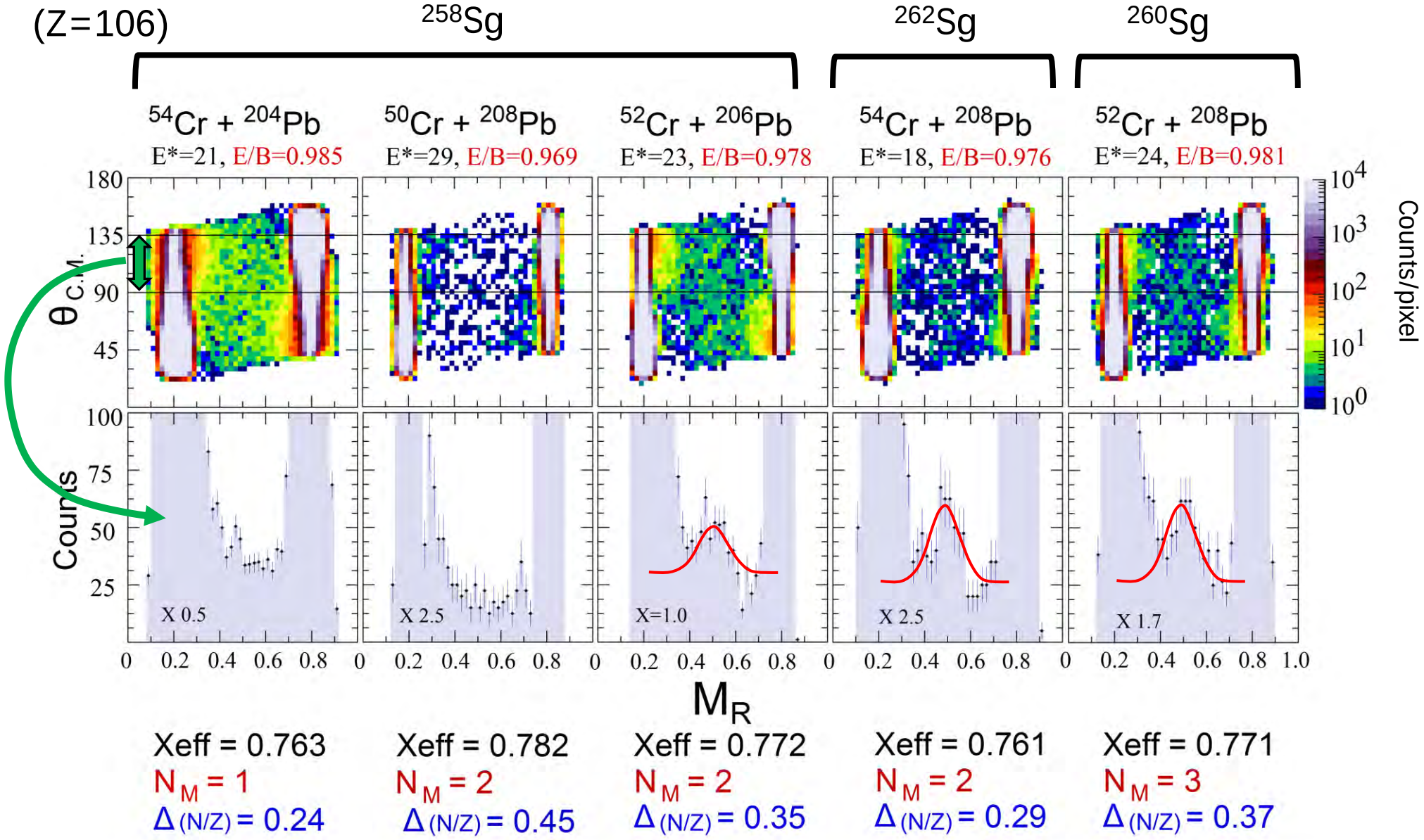
Spherical magic nuclei and N/Z matching



N_{magic}	2	0	2	2	3	4	4
$\Delta(N/Z)$	0.57	0.32	0.35	0.29	0.09	0.54	0.14

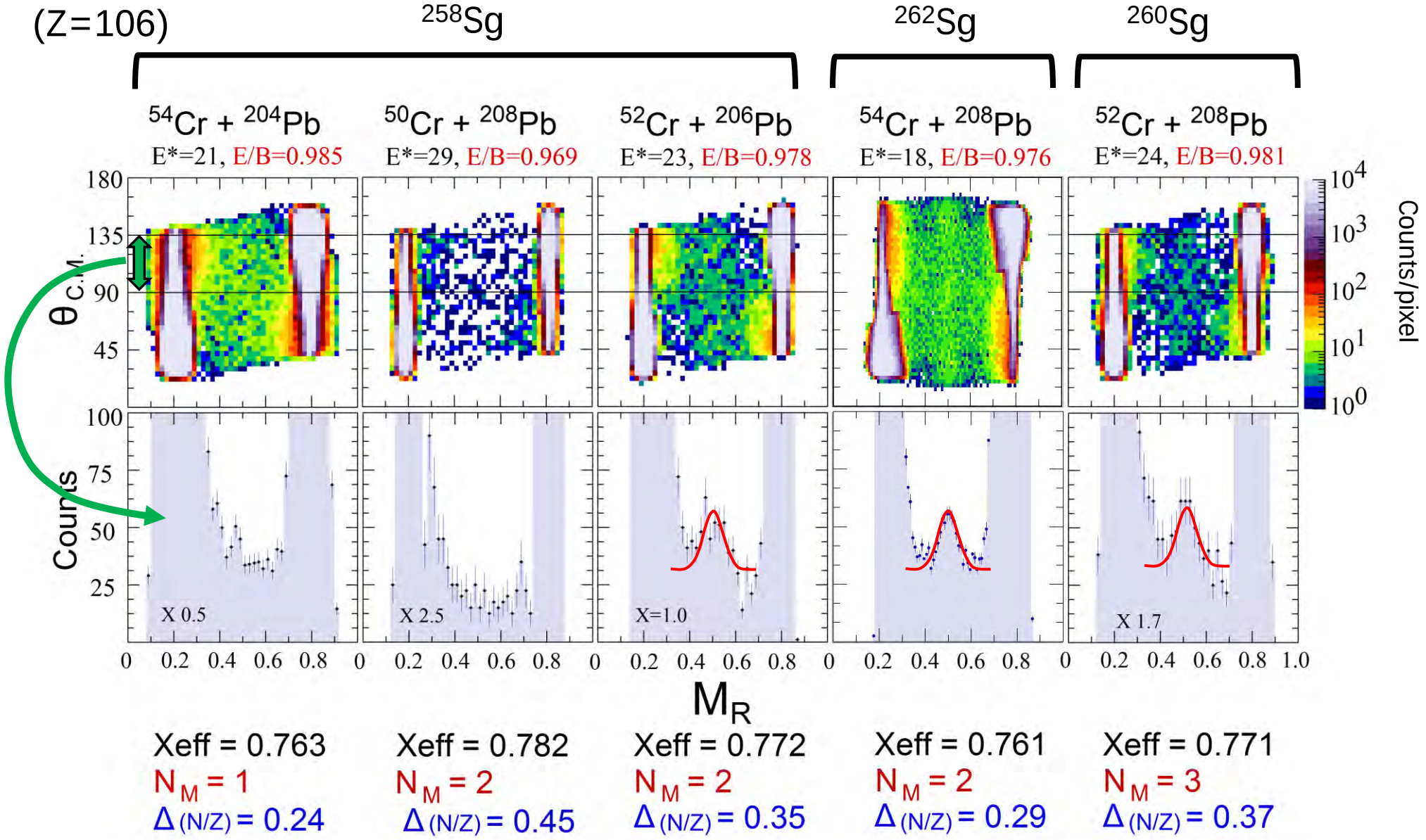
C. Simenel et al., PLB 710 (2012) 607 E. Prokhorova et al., NP A802(2008)45 D.Y. Jeong, T. Valentini et al., ANU, unpublished

Energy below barrier: magic numbers, N/Z matching – strong effect



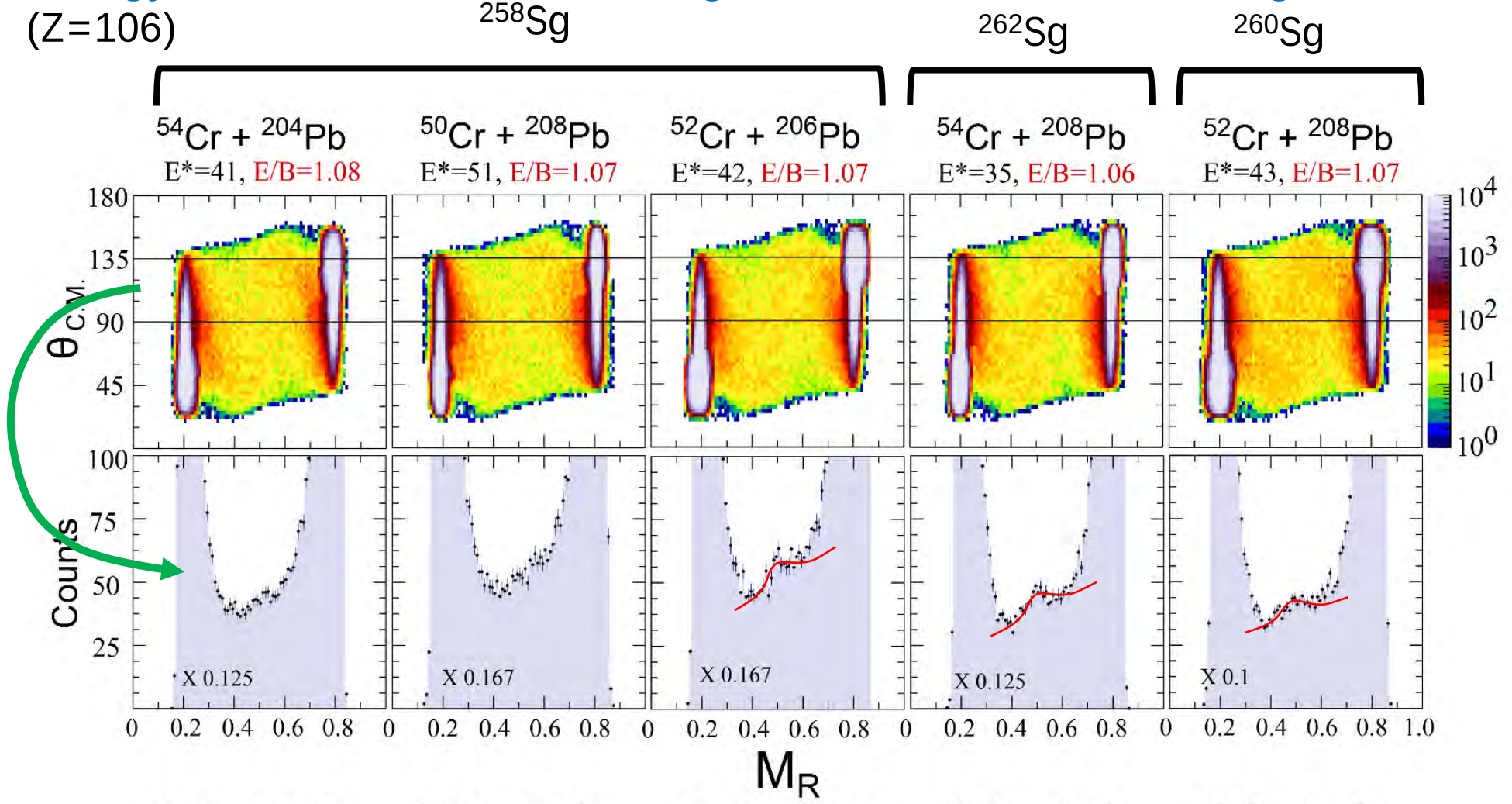
G. Mohanto et al., ANU, in preparation

Energy below barrier: magic numbers, N/Z matching – strong effect

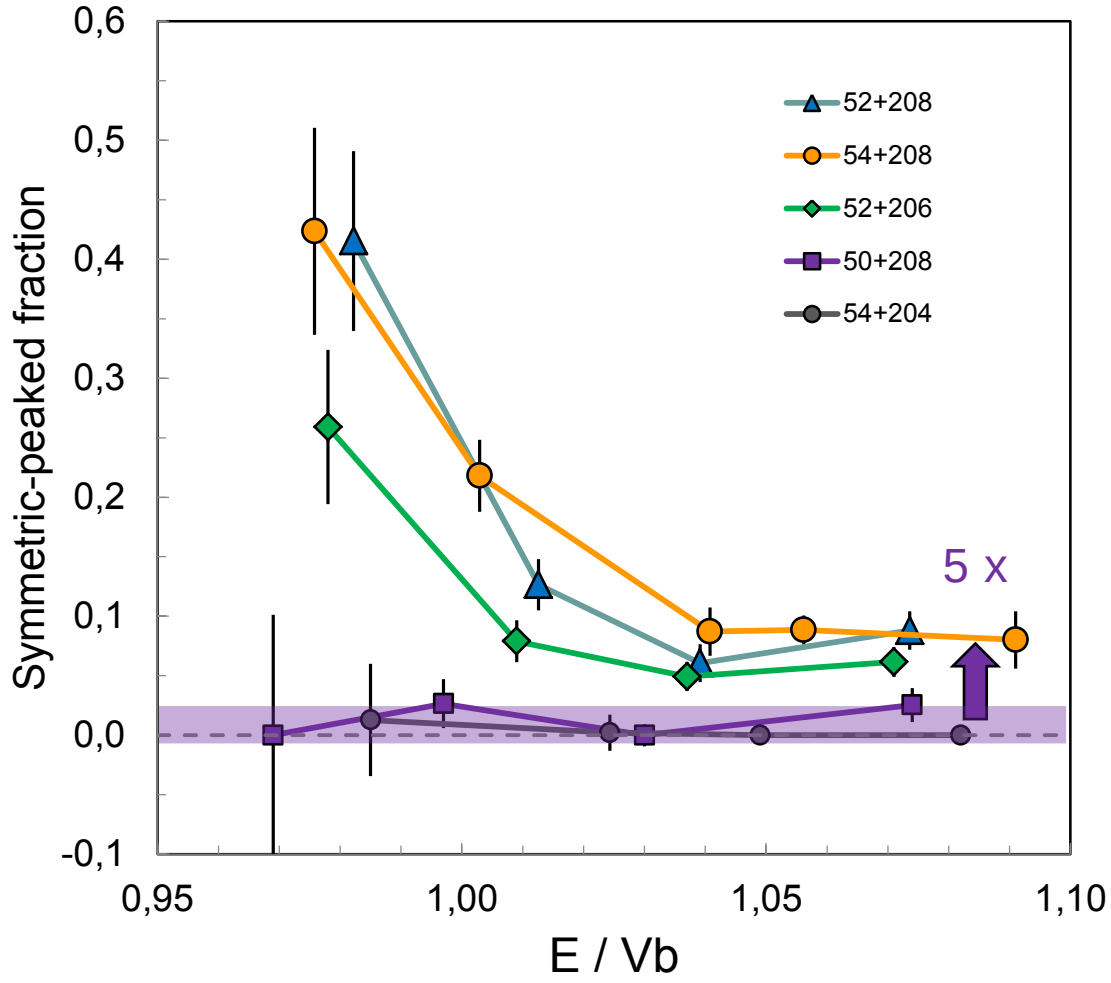


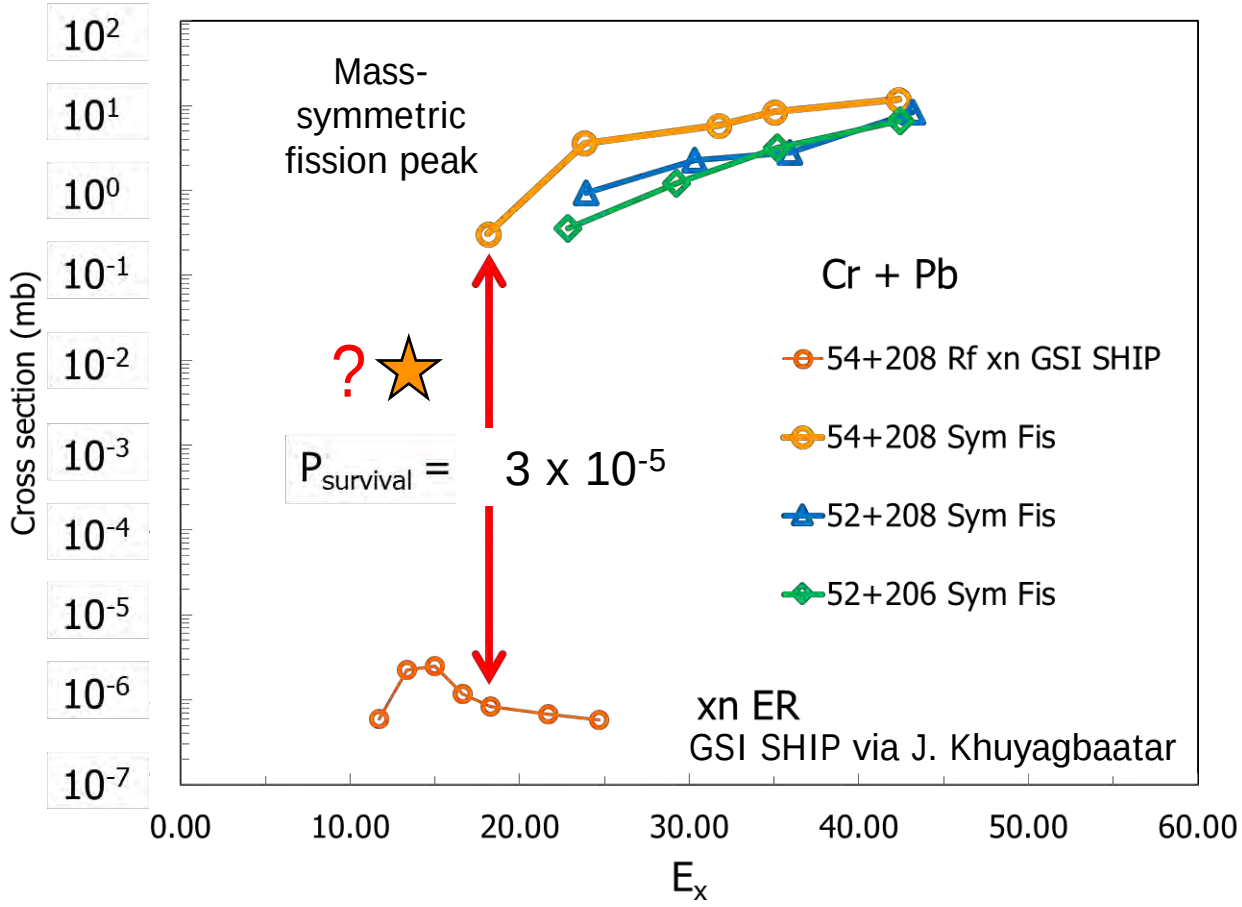
G. Mohanto et al., ANU, in preparation

Energy well above-barrier: magic numbers, N/Z matching – little effect



G. Mohanto et al., ANU, in preparation



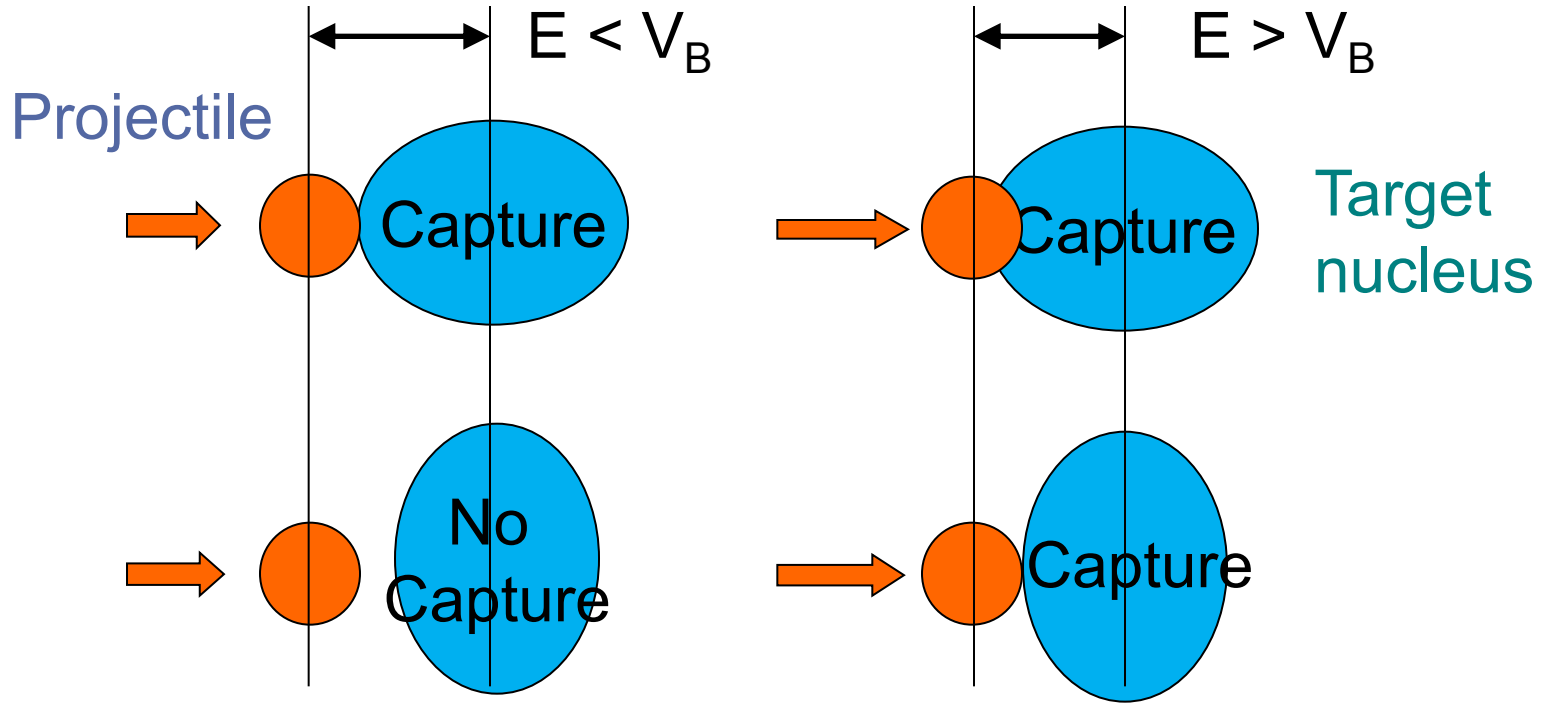


Mass-symmetric and mass-asymmetric – trajectory bifurcation

Mass-symmetric component is narrow – fusion fission?

Effects of nuclear structure in the entrance channel:

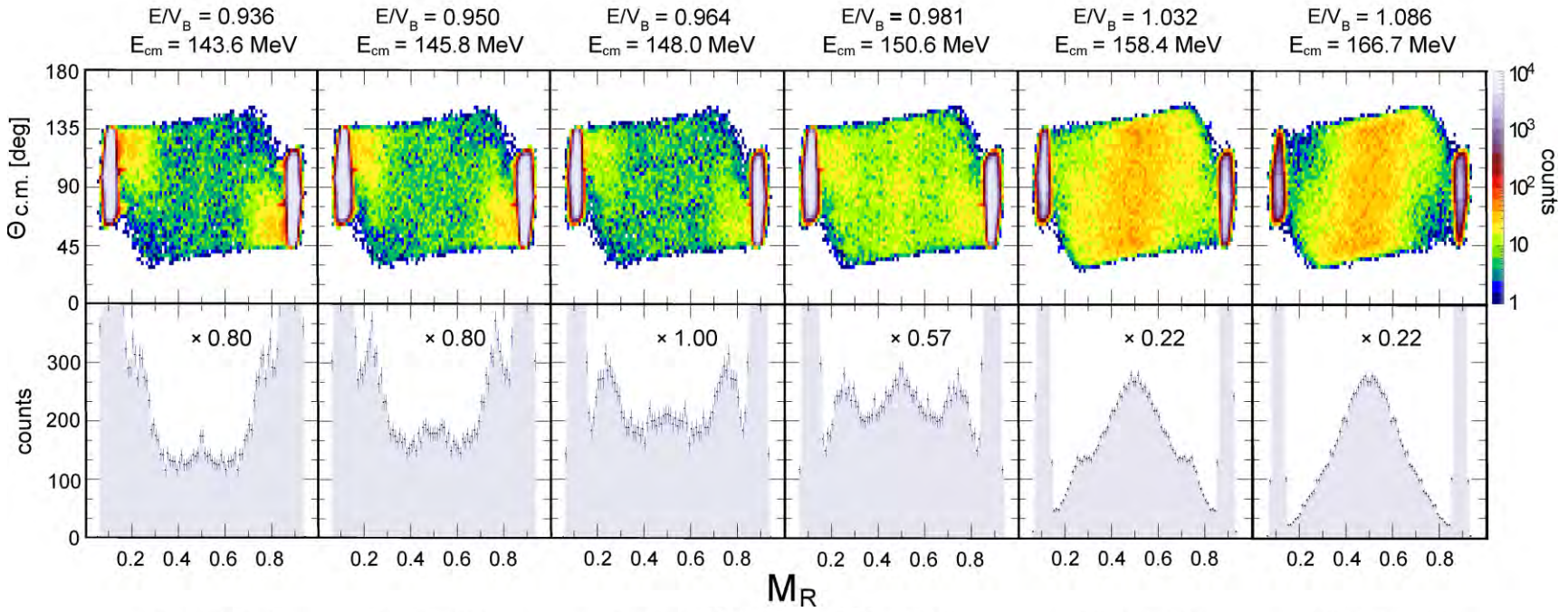
(ii) Static deformation alignment



Beam energies below average capture barrier:

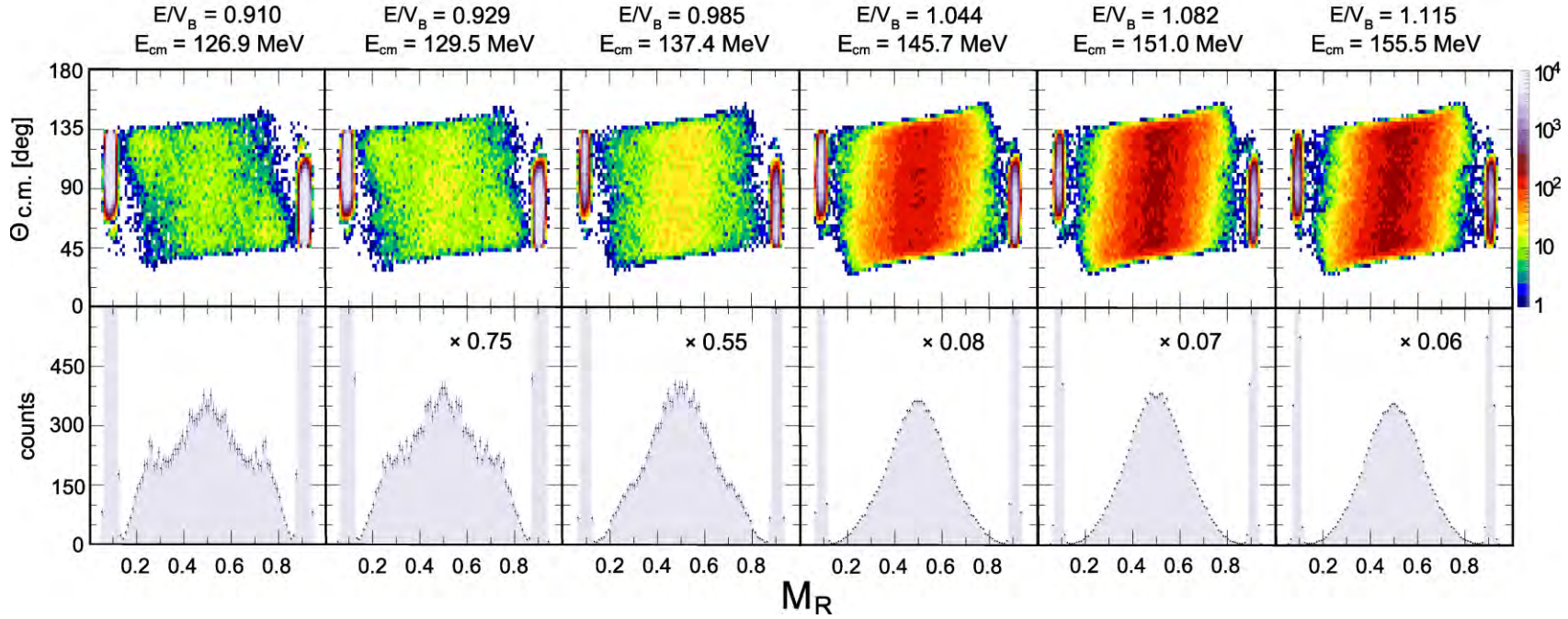
➡ Aligned deformed target nuclei

Hinde et al., PRL **74** (1995) 1295; Hinde et al., PRC **53** (1996) 1290



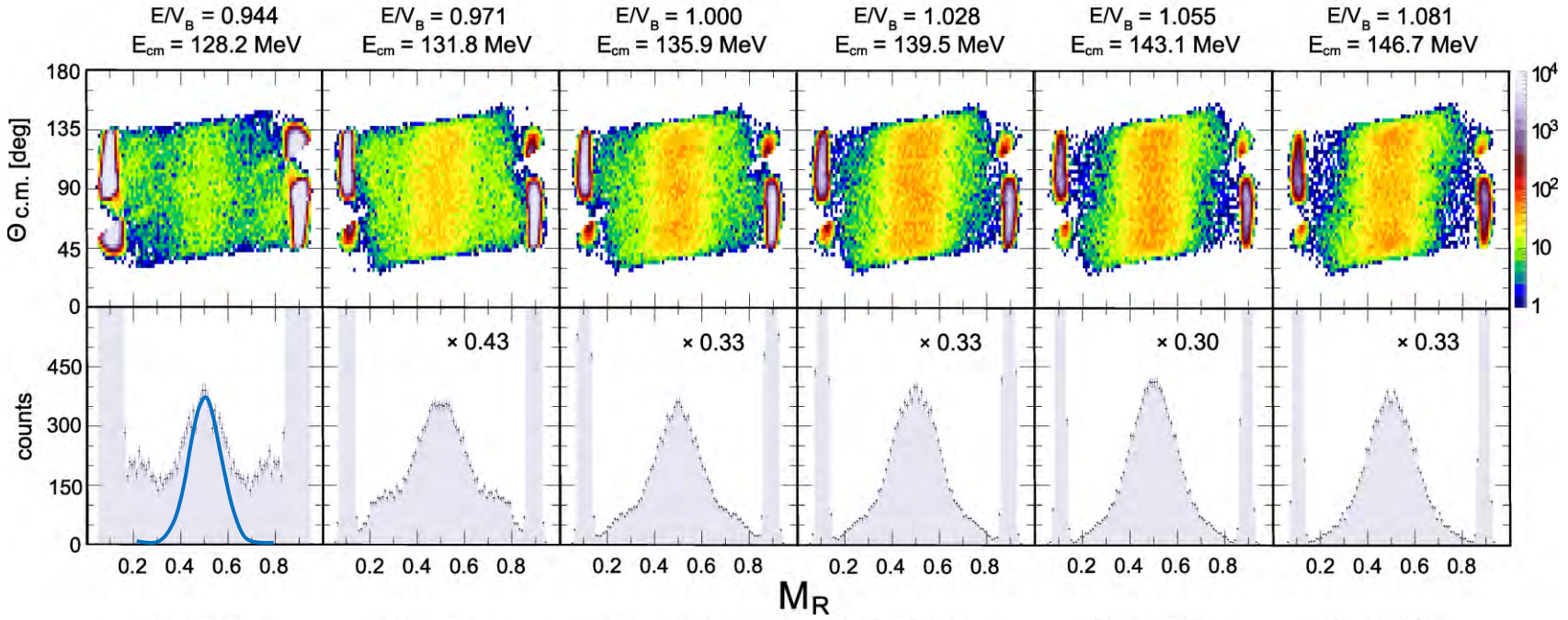
$^{34}S + {}^{232}Th \rightarrow {}^{266}Sg$

(Z=106)



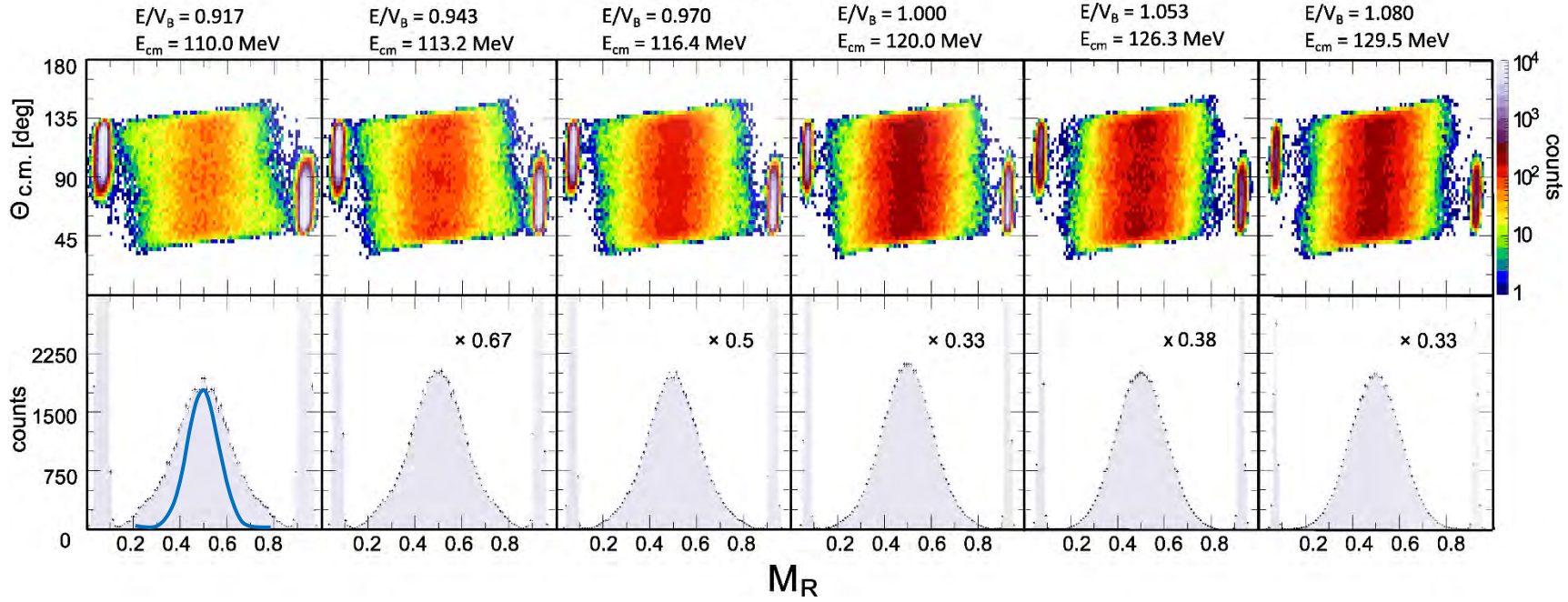
$^{28}Si + {}^{238}U \rightarrow {}^{266}Sg$

(Z=106)



$^{30}Si + {}^{232}Th \rightarrow {}^{262}Rf$

(Z=104)

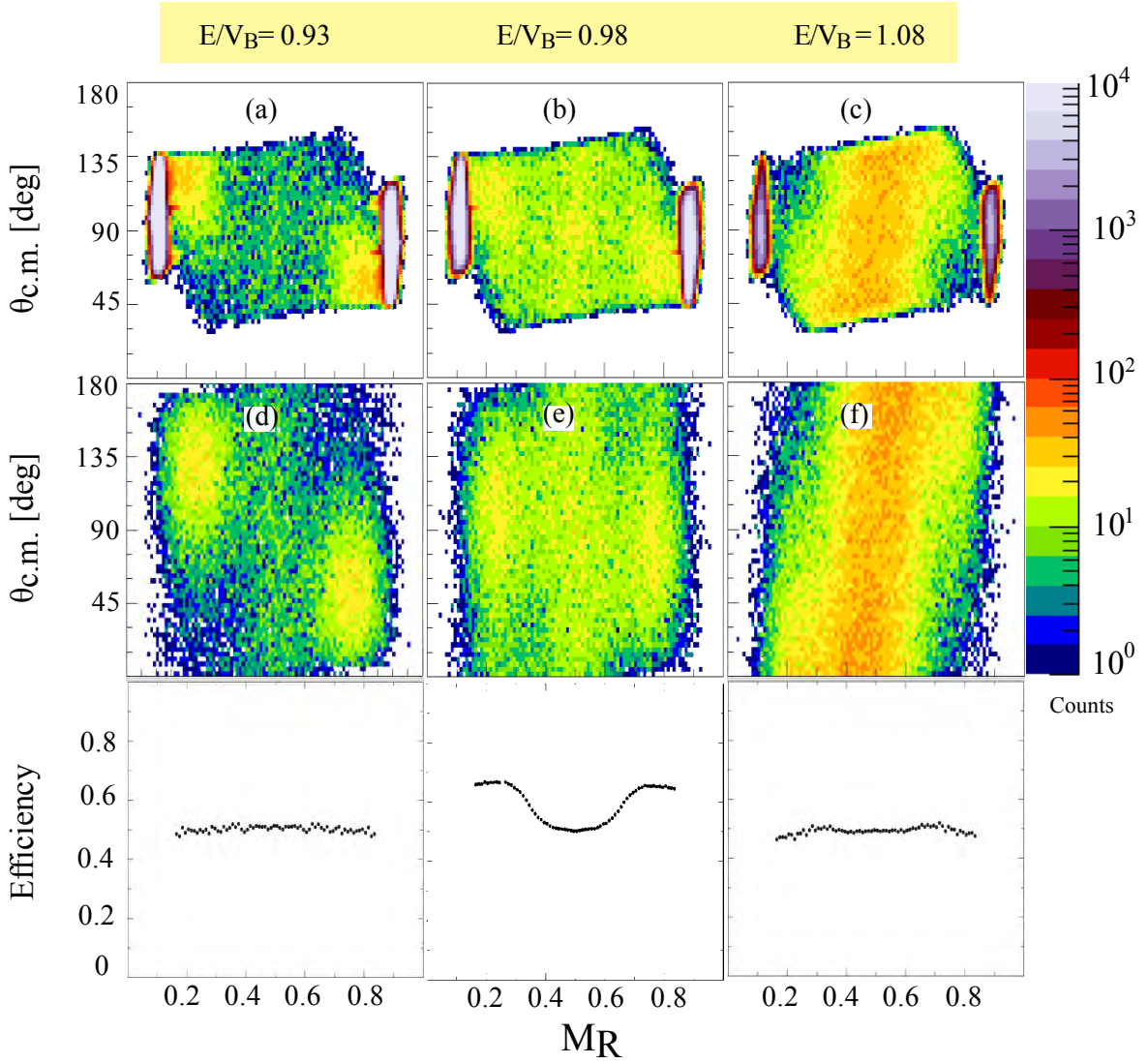


$^{24}Mg + {}^{238}U \rightarrow {}^{262}Rf$

(Z=104)

Correcting for limited angular coverage: QF simulation

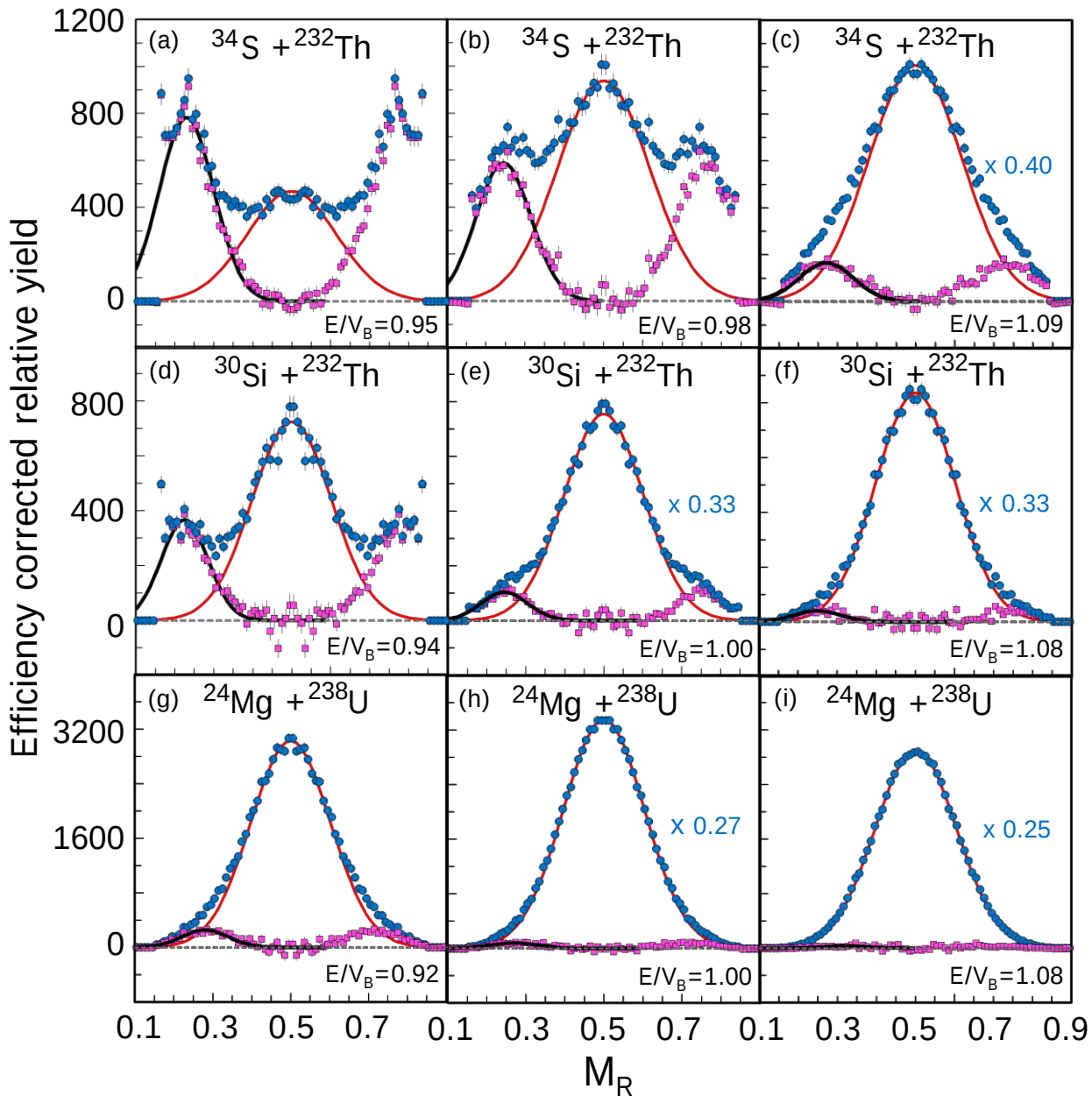
$^{34}S + {}^{232}Th \rightarrow {}^{266}Sg\ (Z=106)$



Experiment

Simulation

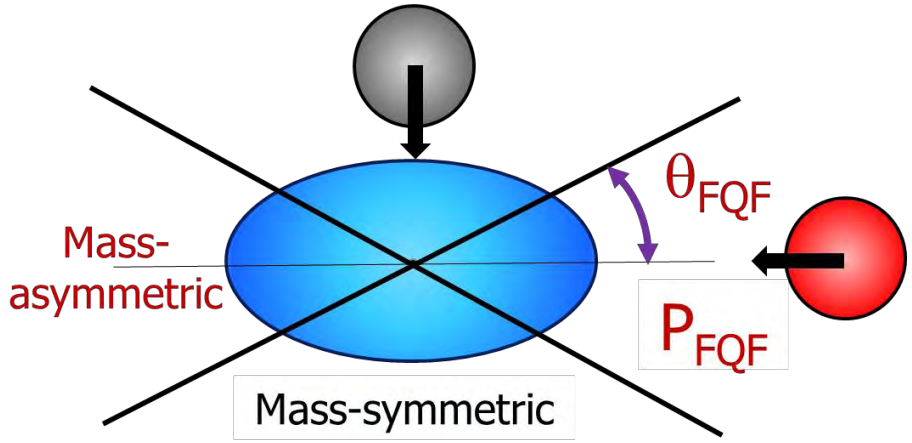
Detector Coverage vs. M_R

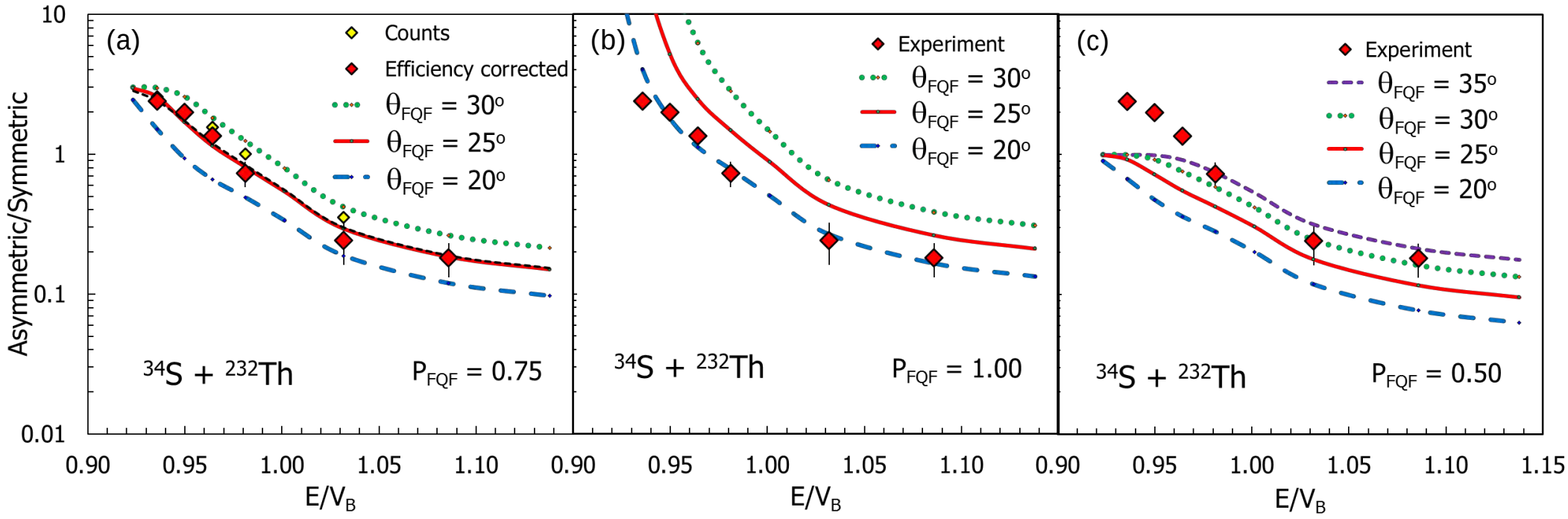

(a) ^{34}S + ^{232}Th
(b) ^{34}S + ^{232}Th
(c) ^{34}S + ^{232}Th
x 0.40
E/V$_B$=0.95
E/V$_B$=0.98
E/V$_B$=1.09
(d) ^{30}Si + ^{232}Th
(e) ^{30}Si + ^{232}Th
(f) ^{30}Si + ^{232}Th
x 0.33
x 0.33
E/V$_B$=0.94
E/V$_B$=1.00
E/V$_B$=1.08
(g) ^{24}Mg + ^{238}U
(h) ^{24}Mg + ^{238}U
(i) ^{24}Mg + ^{238}U
x 0.27
x 0.25
E/V$_B$=0.92
E/V$_B$=1.00
E/V$_B$=1.08
Efficiency corrected relative yield
M$_R$

S

Si

Mg

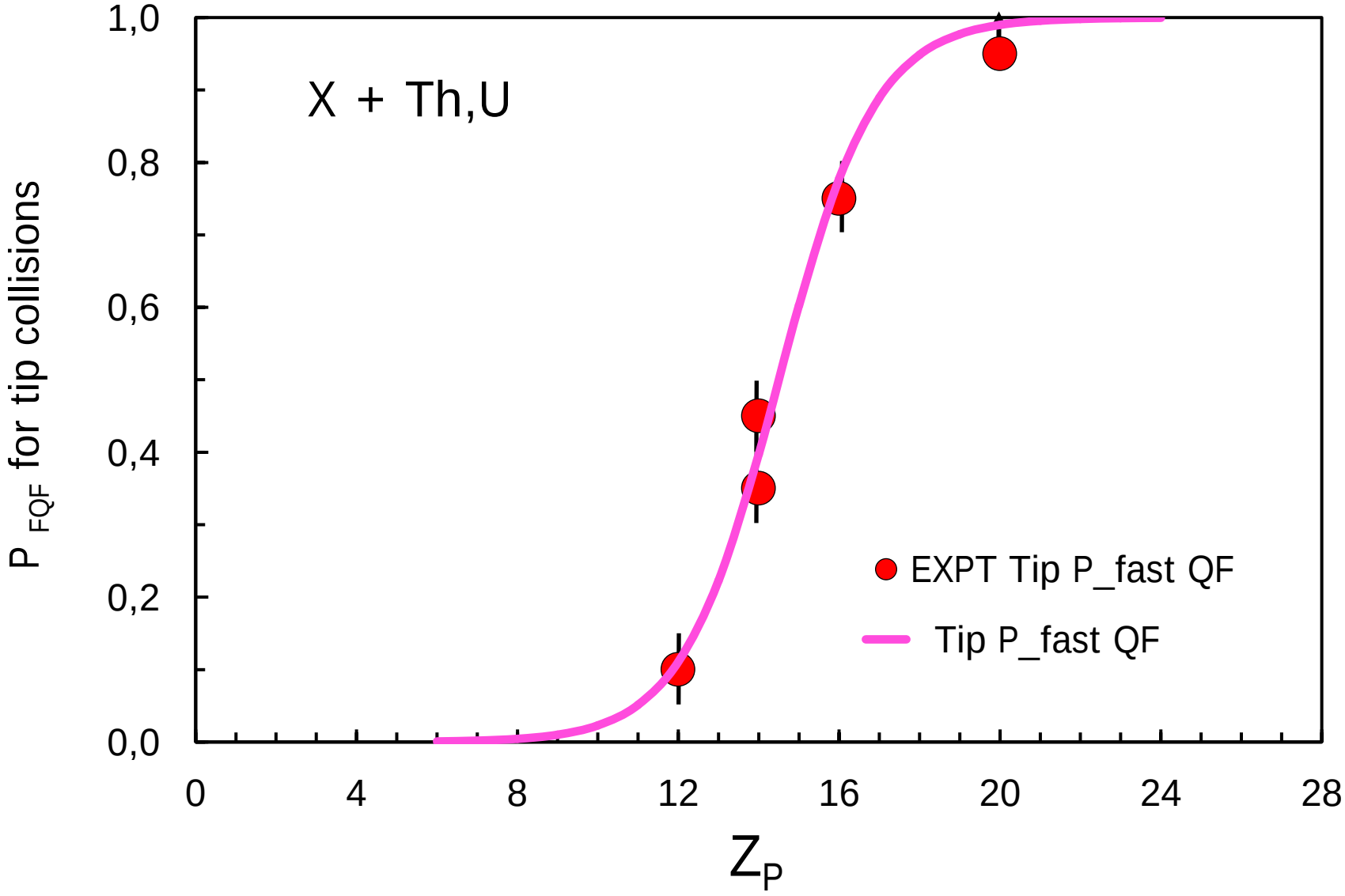

Mass-asymmetric
θ$_{FQF}$
P$_{FQF}$
Mass-symmetric

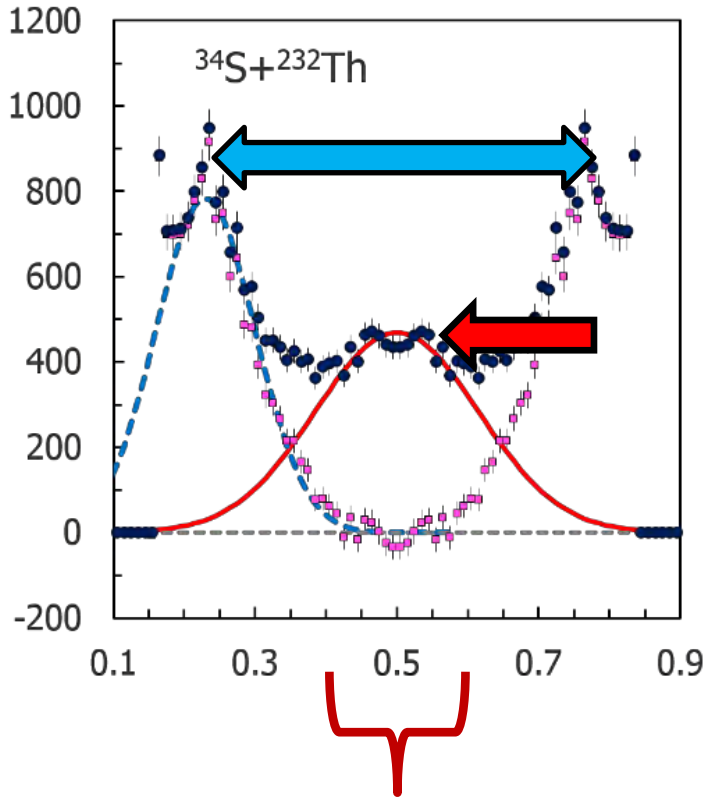


Far below V_B, all capture reactions are in the axial (deformation aligned) configuration

Dependence of tip/side collision yields calculated with CC capture model (CCFULL,CCMOD)

Vary θ_{FQF} and P_{FQF} for tip collisions to reproduce experiment





Mass Width

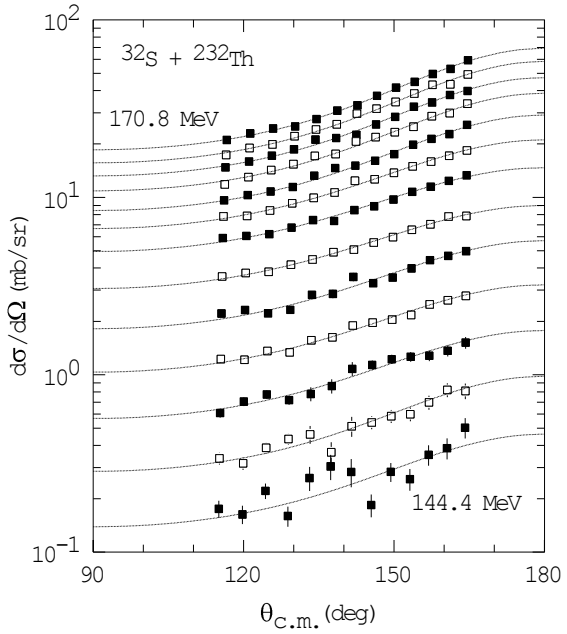
Angular distribution

TKE

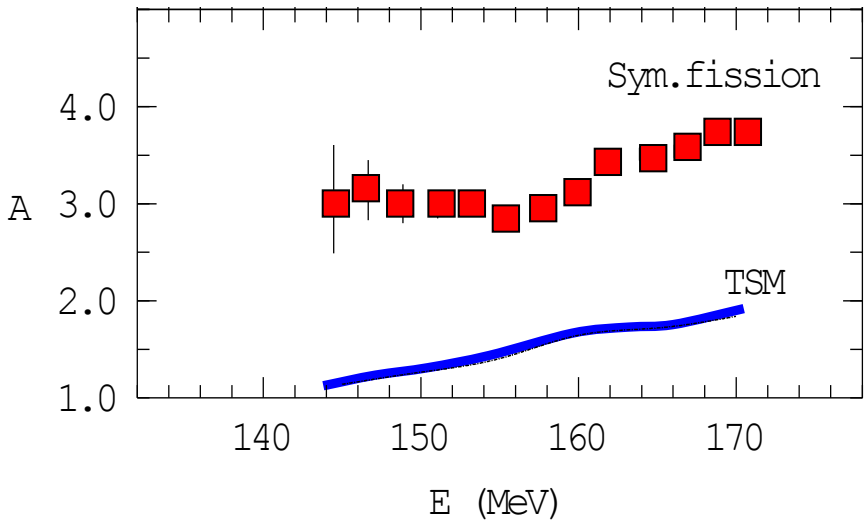
Mass-symmetric fission fragment angular distributions

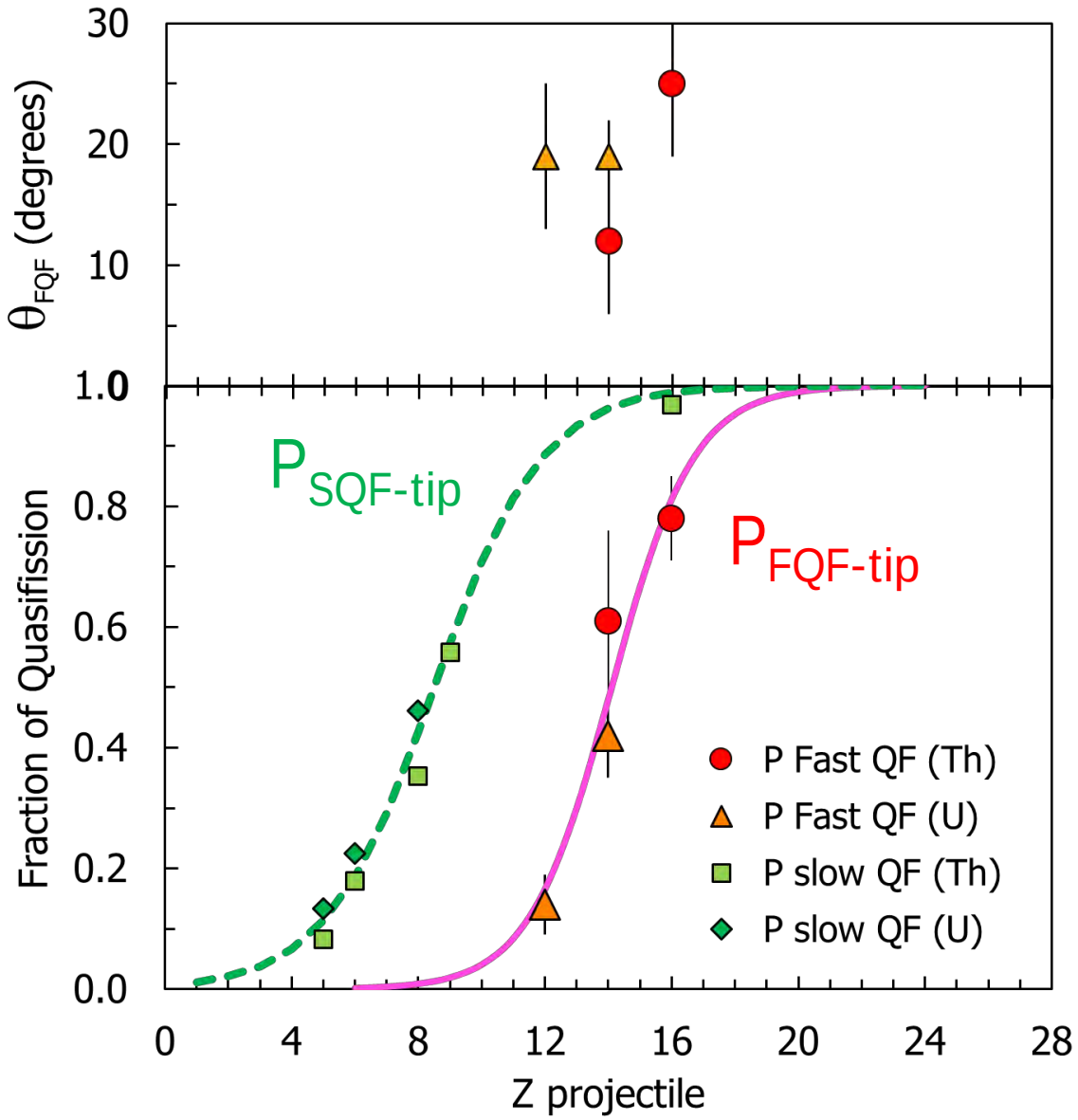
- Mass-symmetric component shows large angular anisotropies – QF (B.B. Back 1983)

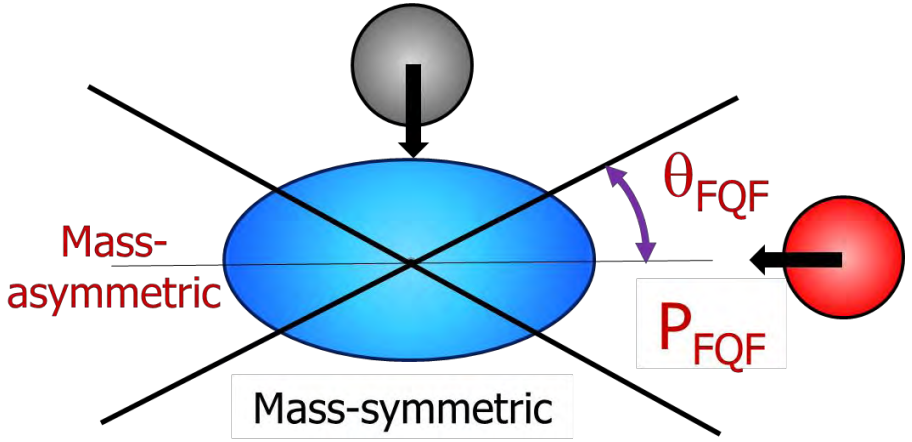
$^{32}S + ^{232}Th$



Hinde et al., J. Nucl. Radiochem. Sci. **3** (2002) 31
Hinde et al., PRL **101** (2008) 092702







Sub-barrier (axial or tip collisions):

$$P_{CN} = (1-P_{FQF})(1-F_{SQF})$$

M. Dasgupta

C. Simenel

E. Williams

D.Y. Jeung

E. Prasad

R. Rafiei (ANU, ANSTO,.....)

A. Wakhle (ANU, MSU,..)

R.G. Thomas (ANU, BARC)

R. du Rietz (ANU, Malmo)

C.J. Lin (ANU, CIAE)

G. Mohanto (ANU, BARC)

J. Khuyagbaatar (GSI/Mainz)

Ch.E. Düllmann (GSI/Mainz)

H. David (GSI) .....

Z. Kohley (MSU)

K. Hammerton (MSU) .....

M. Morjean (GANIL)

D. Jacquet (Orsay) .....

+ many ANU students and postdocs running the ANU accelerator

Conclusions

- Magic numbers, N/Z matching important in cold fusion reactions
  - more magic numbers are better – $^{48}Ca+^{208}Pb$ – sub-barrier F-F(?)
  - trajectory bifurcation $^{52,54}Cr + ^{206,208}Pb$ – fast QF + F-F(?)
- Deformation alignment – "tip collisions" – lower P_{CN}
  - fast QF below-barrier – measured P_{FQF}
  - slow QF also below-barrier – P_{SQF} additional reduction of P_{CN}
- Challenge for models of SHE synthesis: reproduce QF observables!
  - Average collision outcomes
  - Fluctuations, trajectory bifurcations, probabilities