# Characterization of γ–ray tracking arrays : performance of the first phase of AGATA and GRETA using $^{60}$Co source

Introduction

Performance of Tracking arrays

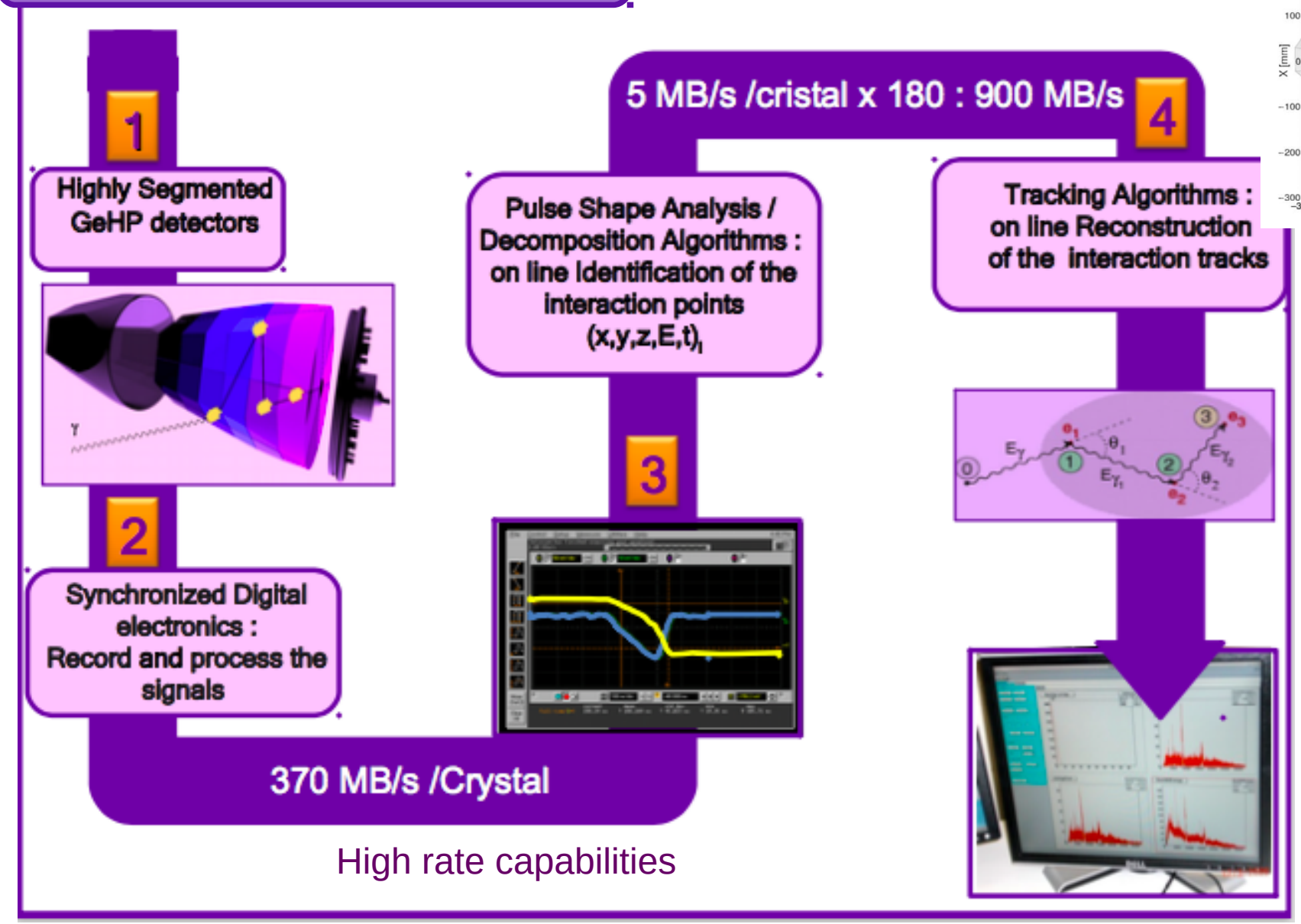
AGATA and GRETINA comparison

Conclusion

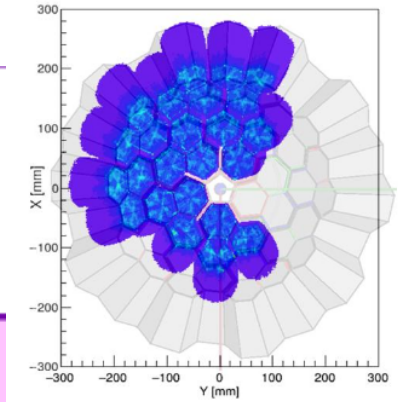
Amel Korichi Torben Lauritsen

For the AGATA & GRETINA collaboration

# Idea of GAmma Tracking Array




High rate capabilities



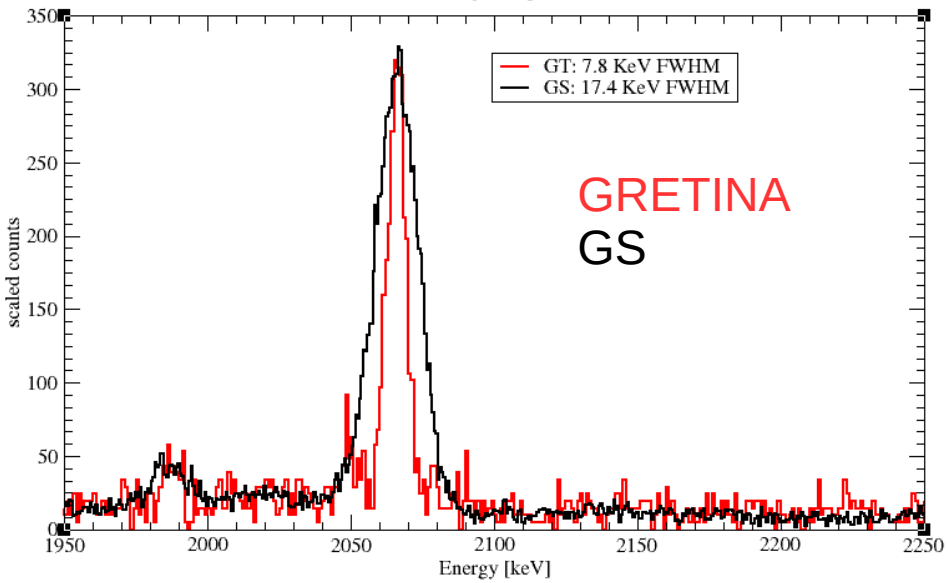

Event by event
Number of $\gamma$ rays,

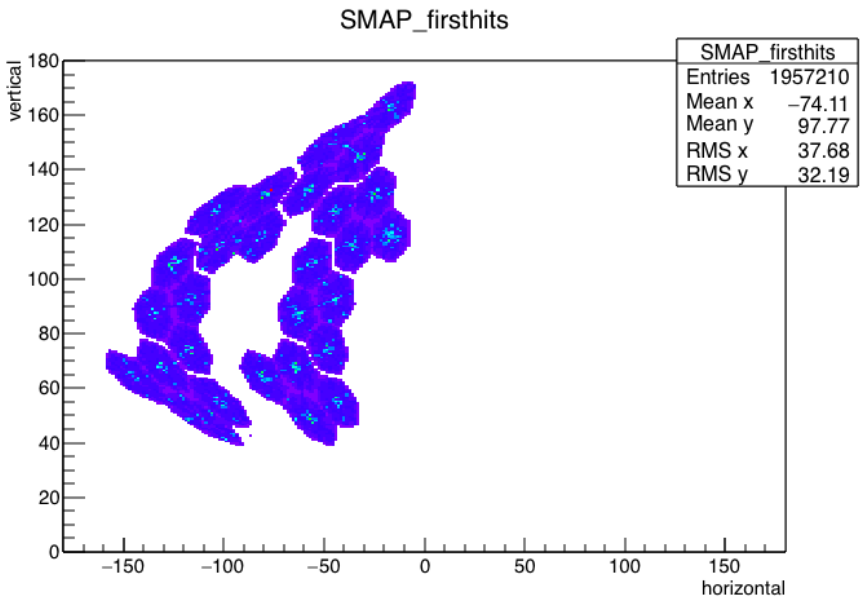
For each $\gamma$ ray:
1st and 2nd interaction points, path

For the best performances :
Energy resolution, absolute photo-peak efficiency, peak-to-total ratio

# Energy Resolution of AGATA & GRETINA

$$^{12}C(^{84}Kr[394MeV],4n)^{92}Mo$$

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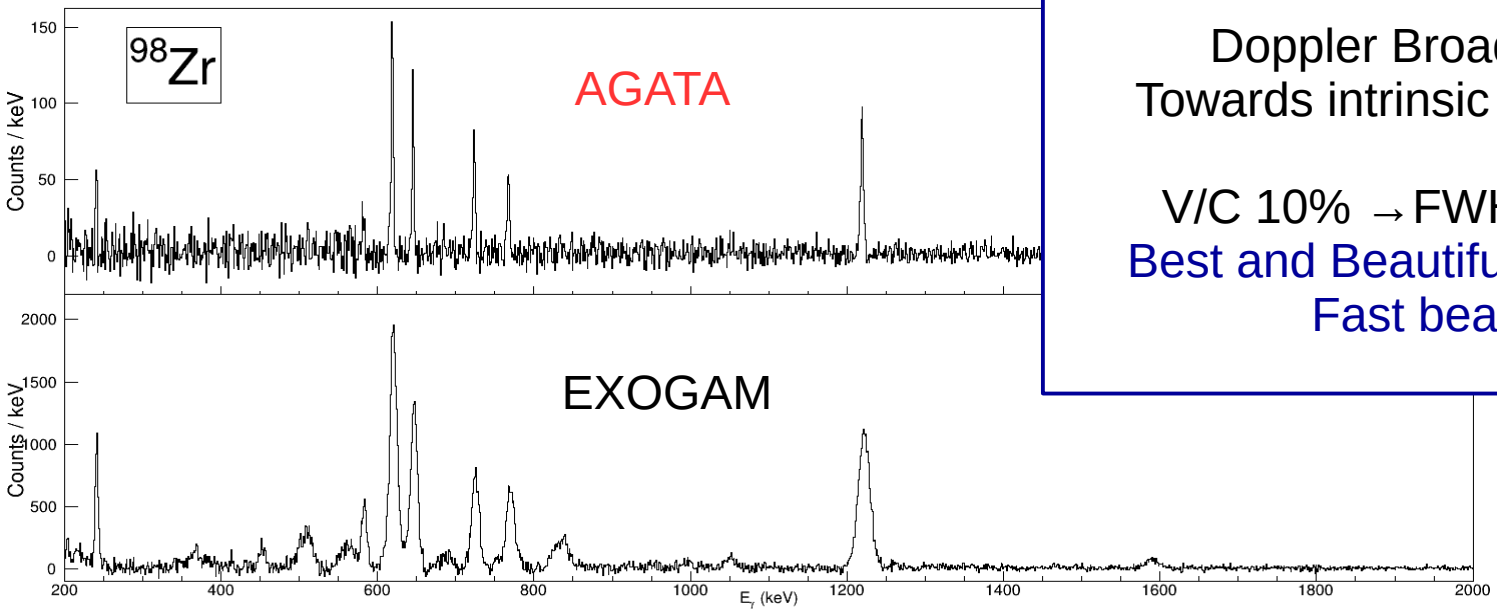
Be($^{238}$U,fission)




Doppler Broadening :
Towards intrinsic resolution !

V/C 10% → FWHM 0.4%

Best and Beautiful arrays for Fast beams

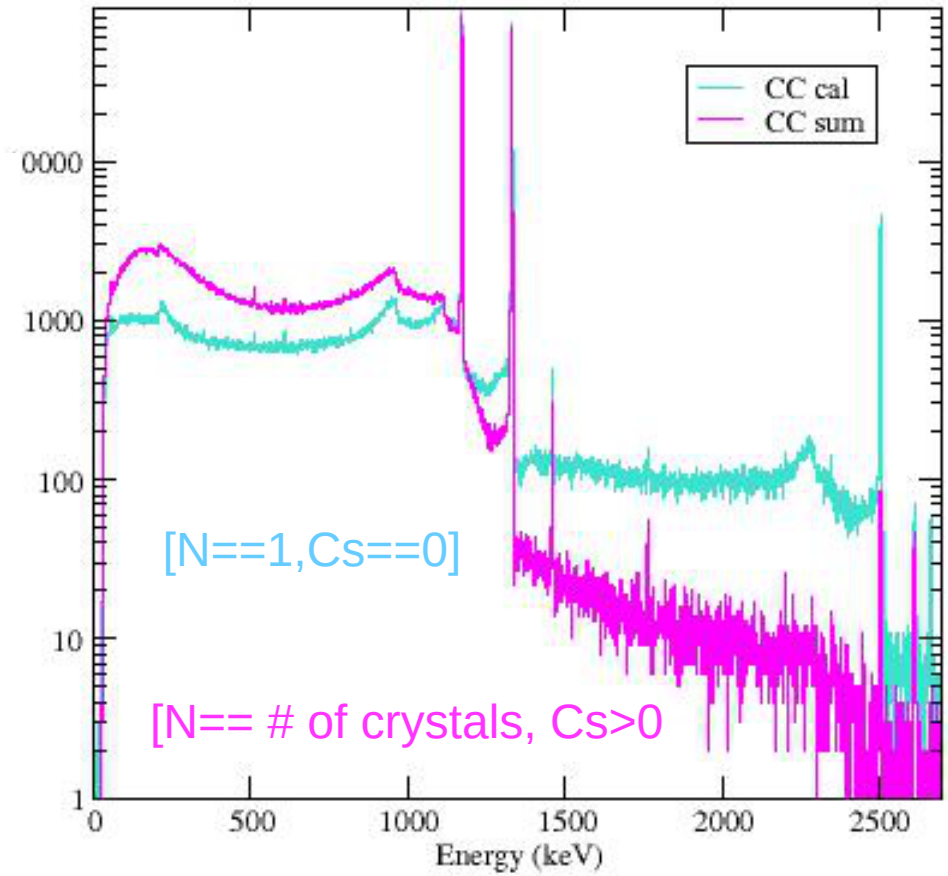
# Efficiency and P/T of tracking arrays

Observed areas for $^{60}$Co source

$$A^{obs}(1173) = S\,\epsilon_p(1173)(1 - C_k(1333)) \times (1 - C_R)(1 - C_s(1173)),$$

$$A^{obs}(1333) = S\,\epsilon_p(1333)(1 - C_k(1173)) \times (1 - C_R)(1 - C_s(1333)),$$

$$A^{obs}(2506) = \frac{1}{N} S\,\epsilon_p(1173)\epsilon_p(1333) C_f (1 - C_R) \times (1 - C_s(1173))(1 - C_s(1333)),$$




$C_f$ is the angular correlation factor

Correct for the fact that the 1173 can knock out counts in the 1333 line and vice versa.

$$C_k(e) = \frac{C_f \epsilon_T(e)(1 + C_s(e))}{N},$$

$$C_s = \frac{F - 1}{F}$$

$$(P/T) \equiv \epsilon_p / \epsilon_T,$$

$$C_R = \frac{\epsilon_R \Delta t}{N} \frac{dR}{dt},$$

$$S = A_S t L_F.$$

CR is the correction for random γ rays hitting the detector

The probability for a γ ray to scatter out of a crystal, to be detected by other crystals in the array and successfully sum up to the photo-peak

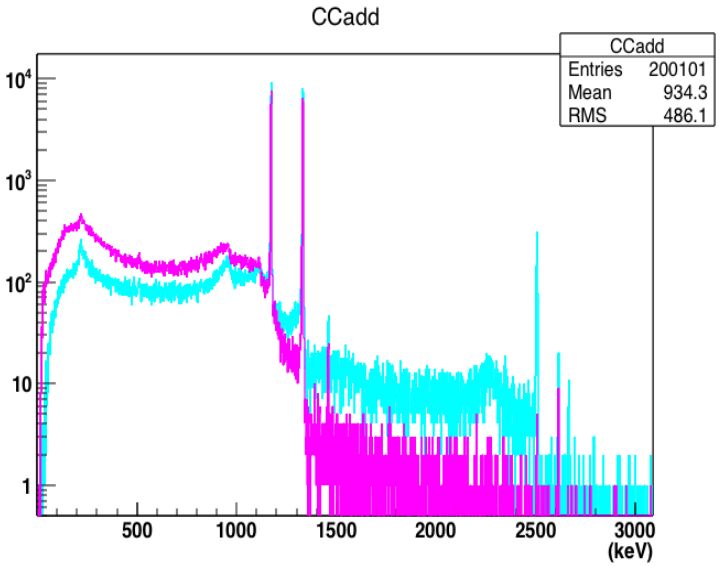
S is the Number of γ rays emitted
LF is the Life Fraction (dead time or other loss)

F: addback factor

## Summed Peak Method: SPM

[A(2506)/A(1173)]

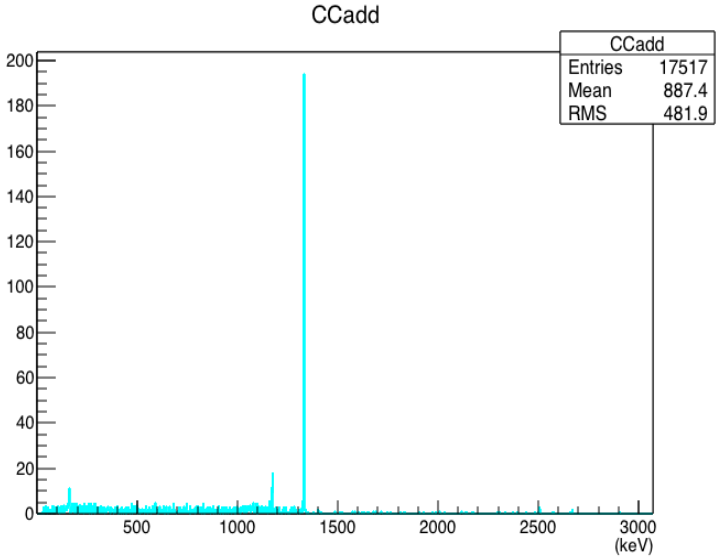
$$\epsilon_p(1333) = N\left\{\frac{A^{obs}(2506)}{A^{obs}(1173)C_f}\right\} / \left\{1 - C_s(1333) + \frac{A^{obs}(2506)}{A^{obs}(1173)}\frac{(1 + C_S(1173))}{N(P/T)(1333)}\right\}$$




## Calibrated Source Method: CSM

[S and $L_f$ must be known]

$$\epsilon_p(1333) = \frac{A^{obs}(1333)}{S(1 - C_R)(1 - C_s(1333))} + \frac{(1 + C_S(1173))A^{obs}(2506)}{NS((P/T)(1173))(1 - C_R)(1 - C_s(1173))(1 - C_s(1333}$$




## External Trigger Method

$$A^{obs}(1333) = A^{obs}_{ext}(1173) \times \epsilon_p(1333)C_f(1 - C_R)$$

With CCcal and CCsum:
six measurements of the <u>array efficiency</u>

# True P/T- True peak Areas (new concepts)- Tracking efficiency

We saw how the observed peak areas relate to the actual array efficiencies.

Once the peak areas have been correctly determined, efficiencies, true peak areas and peak–to–total ratios can be extracted.

$$A^{true}(1173) \equiv S\,\epsilon_p(1173) = \frac{A^{obs}(1173)}{(1-C_k(1333))(1-C_R)(1-C_s(1173))},$$

$$A^{true}(1333) \equiv S\,\epsilon_p(1333) = \frac{A^{obs}(1333)}{(1-C_k(1173))(1-C_R)(1-C_s(1333))},$$

$$A^{true}(2506) \equiv S\,\epsilon_p(1173)\epsilon_p(1333)C_f = \frac{A^{obs}(2506)}{(1-C_R)(1-C_s(1173))(1-C_s(1333))}.$$

$$(P/T)^{true} = \frac{A^{true}(1173) + A^{true}(1333) + A^{true}(2506)}{A^{true}_{tot}},$$

$$A^{obs}_{tot} = (1 + C_s)A^{true}_{tot}$$

Include for CCcal and CCsum but not for tracked spectra

$$(P/T)^{tracked} = \frac{A_T(1173) + A_T(1333)}{A_{tot}},$$

$$\epsilon_{track} = \frac{A_T(1333)}{S\,\epsilon_p(1333)}$$

$$\epsilon_{track} = \frac{A_T(1333)}{\frac{A^{obs}(1333)}{(1-C_k(1173))(1-C_R)(1-C_s)}} \equiv \frac{A_T(1333)}{A^{true}(1333)}$$

More details can be found in :

Characterization of gamma–ray tracking arrays: a comparison of GRETINA and Gammasphere using a $^{60}$Co source

T. Lauritsen[a], A. Korichi[b], S. Zhu[a], A.N. Wilson[c], D. Weisshaar[d], J. Dudouet[e], A.D. Ayangeakaa[a], M.P. Carpenter[a], C.M. Campbell[f], E. Clement[h], H.L. Crawford[f], M. Cromaz[f], P. Fallon[f], J.P. Greene[a], R.V.F. Janssens[a], T.L. Khoo[a], N. Lalović[k,i], I.Y. Lee[f], A.O Macchiavelli[f], R.M. Perez-Vidal[g], S. Pietri[i], D.C. Radford[j], D. Ralet[b], L. Riley[l], D. Seweryniak[a], O. Stezowski[e]

Nucl. Instrum. Meth A in press (2016)

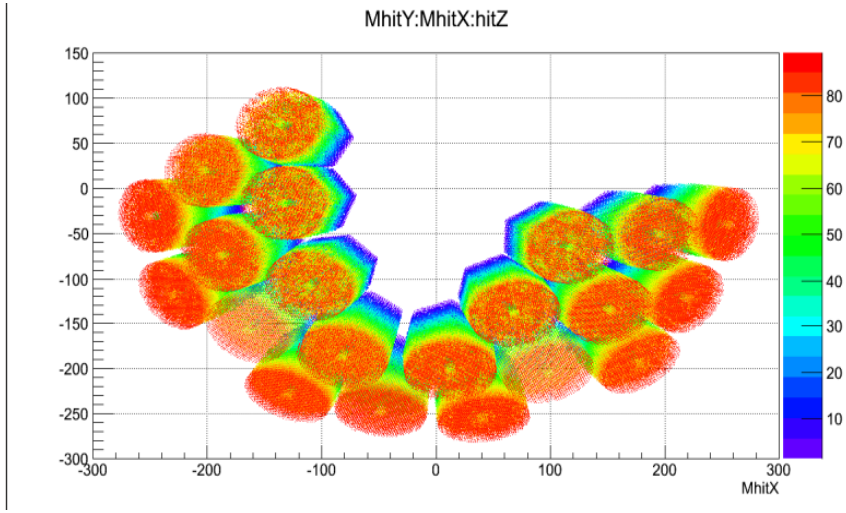
This method has been applied to AGATA

AGATA data translated into GRETINA format

All Data could be sorted with the same software and same tracking code

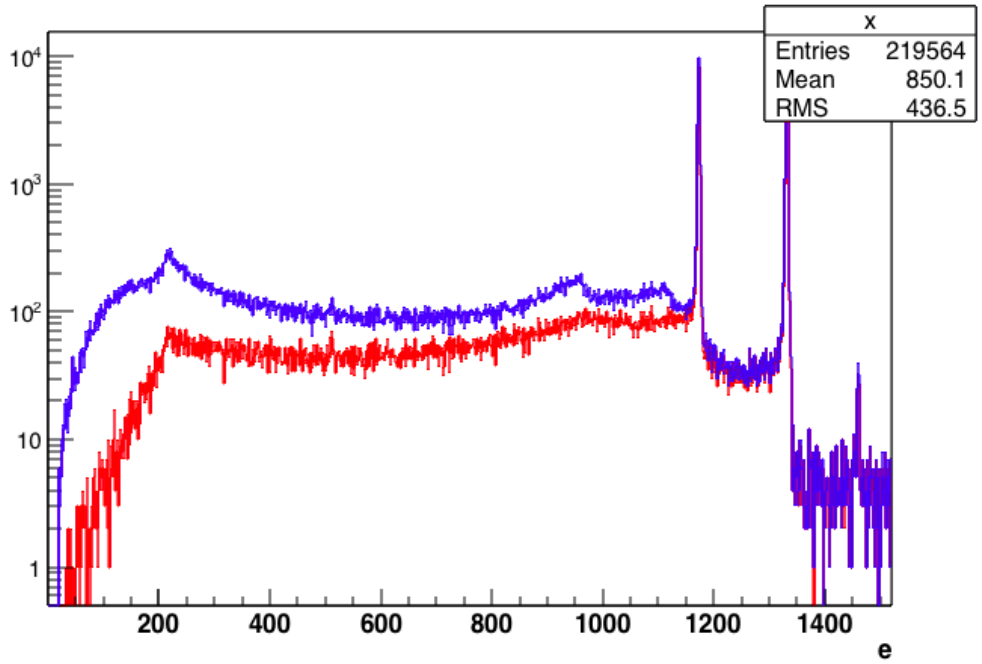
for the comparison of AGATA and GRETINA

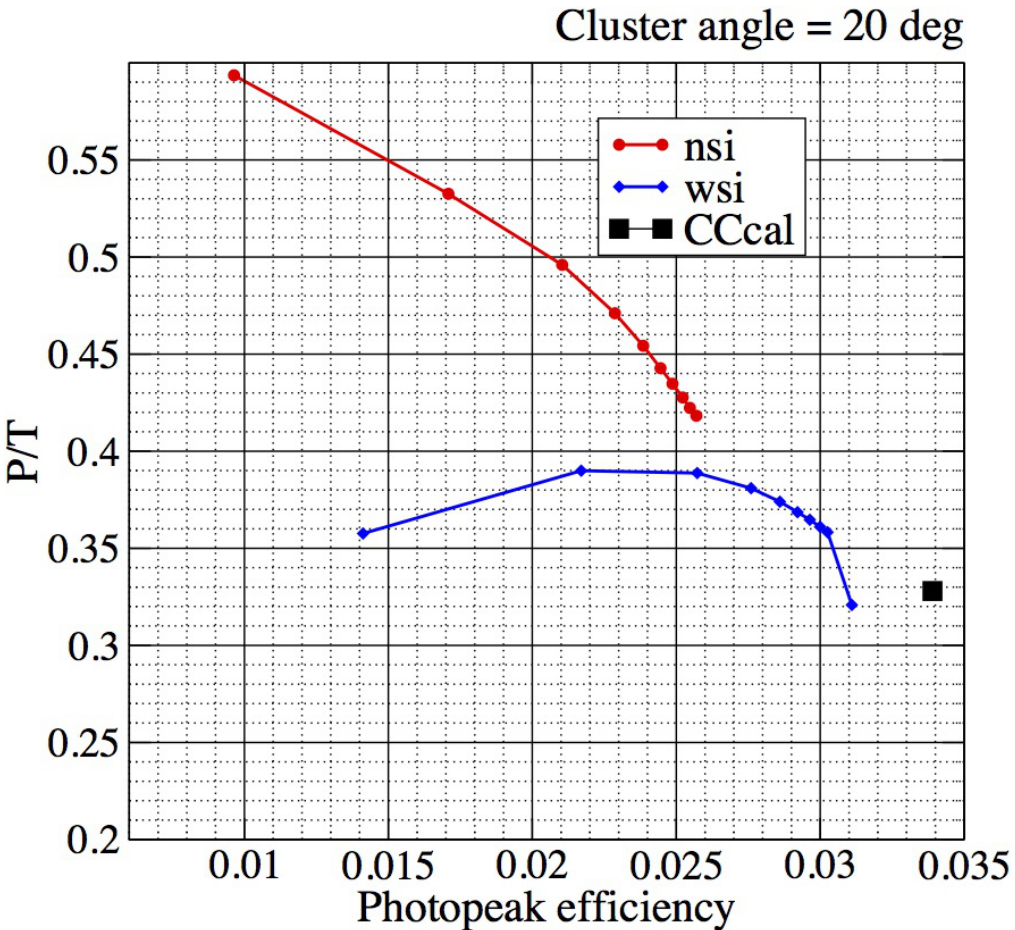
# Performance of AGATA@GSI with $^{60}$Co source




| | SPM cal | CSM cal | SPM sum |
|---|---|---|---|
| $\epsilon_P$(pure) | 3.39(3)% | 3.10(20)% | 3.50(12)% |
| $(P/T)^{obs}$ | 0.291(5) | 0.294(5) | 0.174(5) |
| $(P/T)^{true}$ | 0.331(5) | 0.327(5) | 0.333(5) |
| $\epsilon_{track,nsi}$ | 78(1)% | 78(1)% | 77(1)% |
| $\epsilon_{track,wsi}$ | 91(1)% | 94(1)% | 94(1)% |
| $C_f$ | 1.0342 | 1.0342 | 1.109 |
| $C_s$ | 0 | 0 | 0.299(5) |

A. Korichi to be published

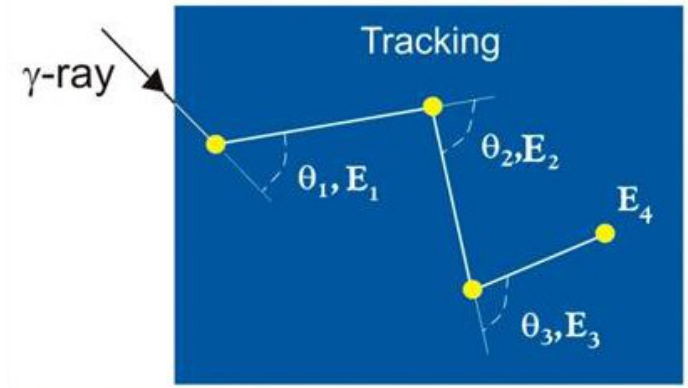


## *FOM spectrum, a measure of how well the interaction angles and interaction energies follow the Compton scattering formula inside a gamma ray. Typical spectrum of FOM values (in log):*

$$E'_\gamma = \frac{0.511}{1 + \frac{0.511}{E_\gamma} - cos(\theta)}$$

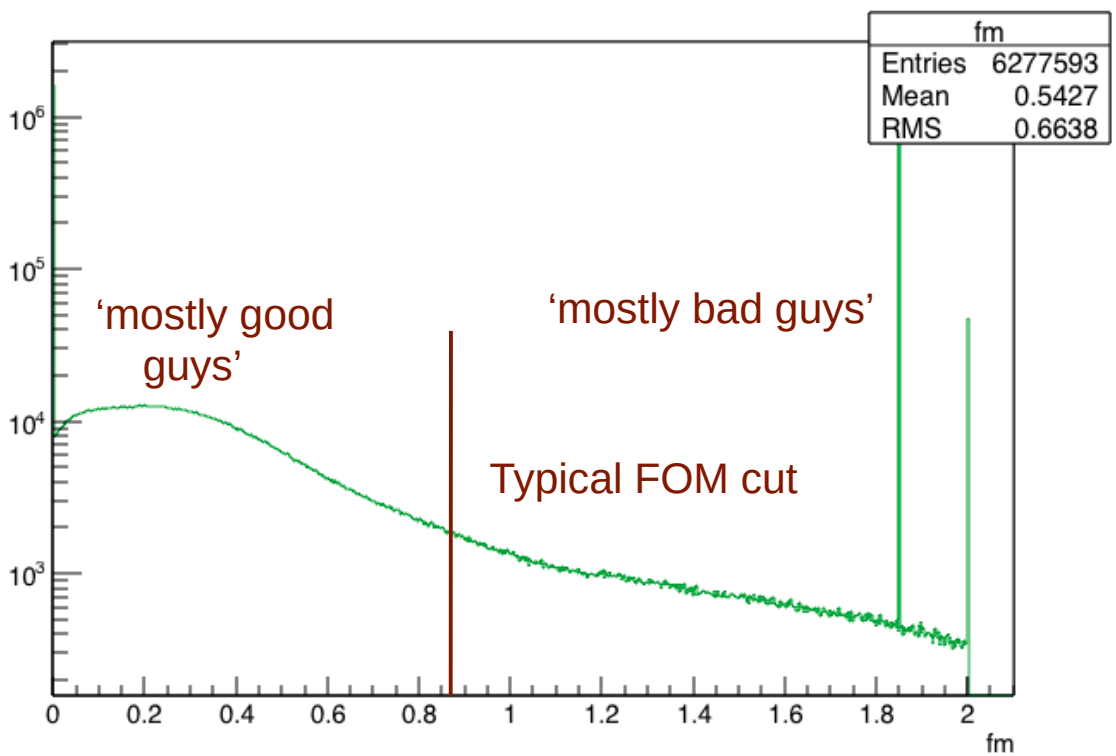
$$FOM = \sum_i \frac{\sqrt{(\sum_i(\theta_i^{theo} - \theta_i^{obs})^2)}}{n_i - 1}; n_i > 1$$

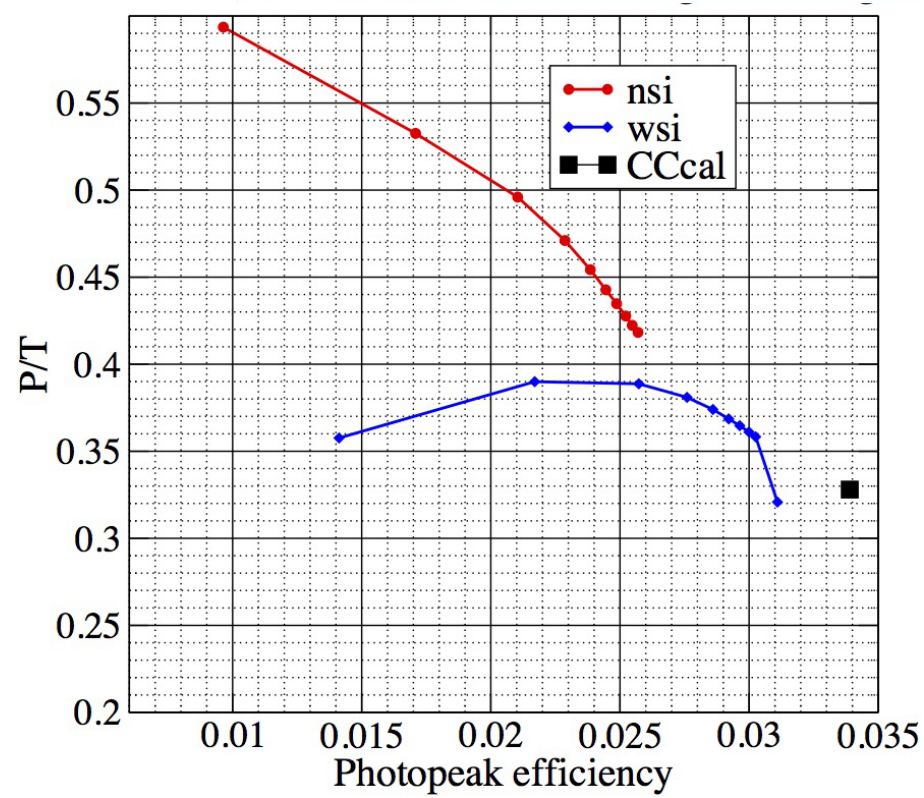



Single hits, FOM==0

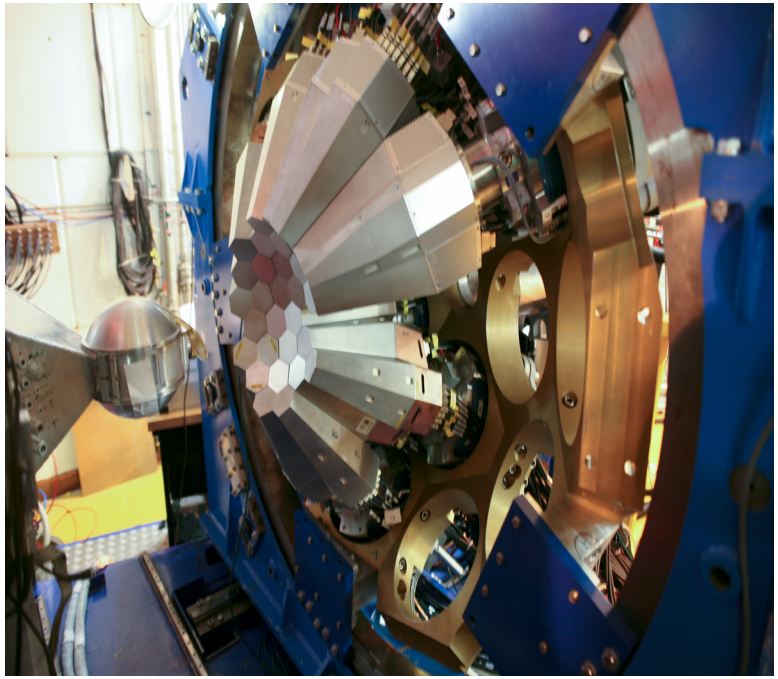
Single interaction located beyond their range

Overflow



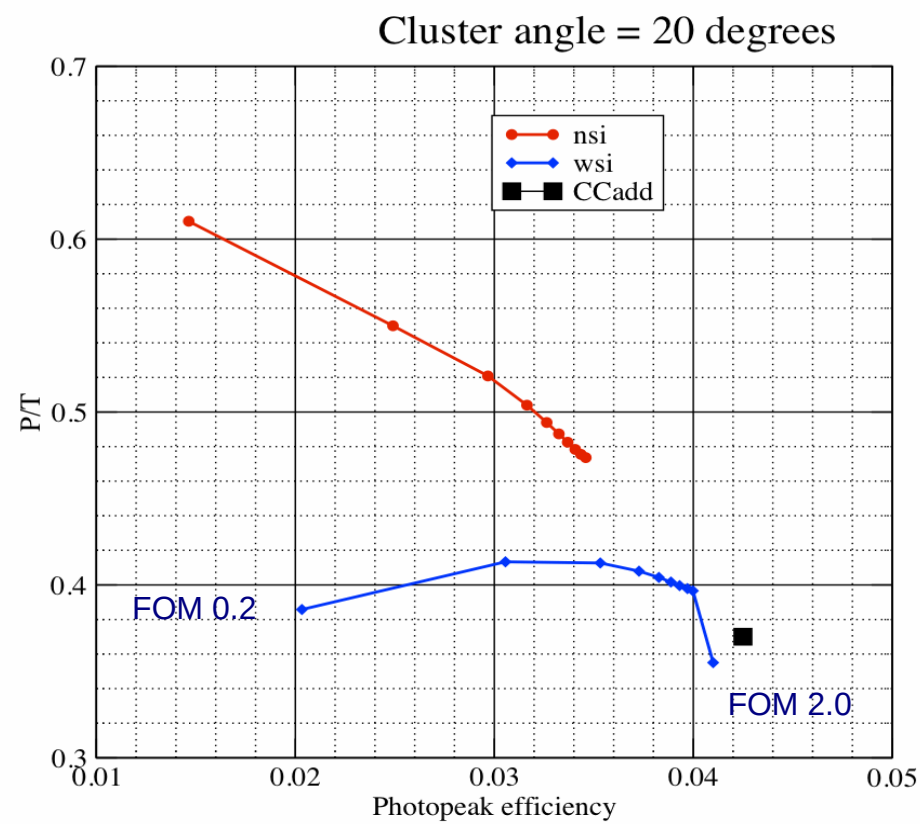



# Performance of AGATA@GANIL with $^{60}$Co source



| | SPM cal | CSM cal | SPM sum |
|---|---|---|---|
| | source1 | source2 | source1 |
| $\epsilon_P$(pure) | 4.26(12)% | 4.48(13)% | 4.00(16) % |
| $(P/T)^{obs}$ | 0.328(5) | 0.224(5) | 0.184(5) |
| $(P/T)^{true}$ | 0.371(5) | 0.270(5) | 0.363(5) |
| $\epsilon_{track,nsi}$ | 82(1)% | 81(1)% | 82(1)% |
| $\epsilon_{track,wsi}$ | 95(1)% | 94(1)% | 95(1)% |
| $C_f$ | 1.0275 | 1.0275 | 1.109 |
| $C_s$ | 0 | 0 | 0.307(5) |

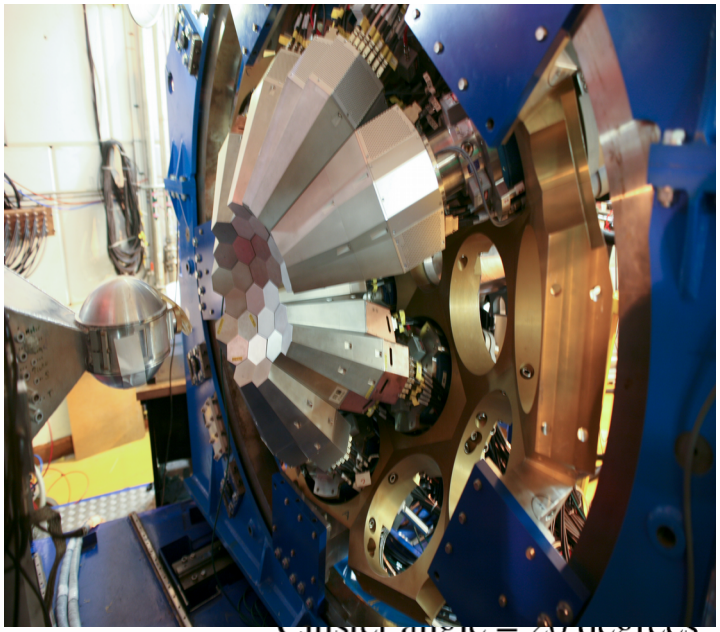
Abs_Eff_tracked=3.80% P/T=41% FOM cut=1.0
Abs_eff_tracked=3.25% P/T= 49 no_singles
(29 crystals )

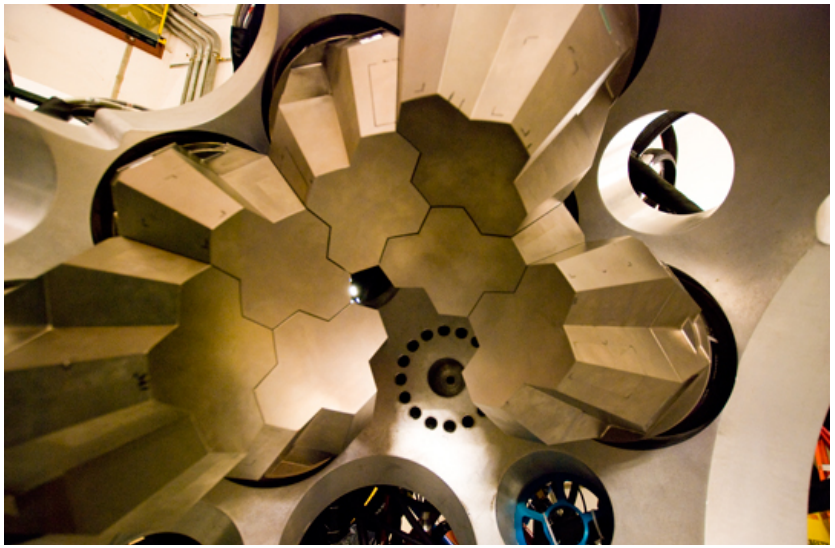


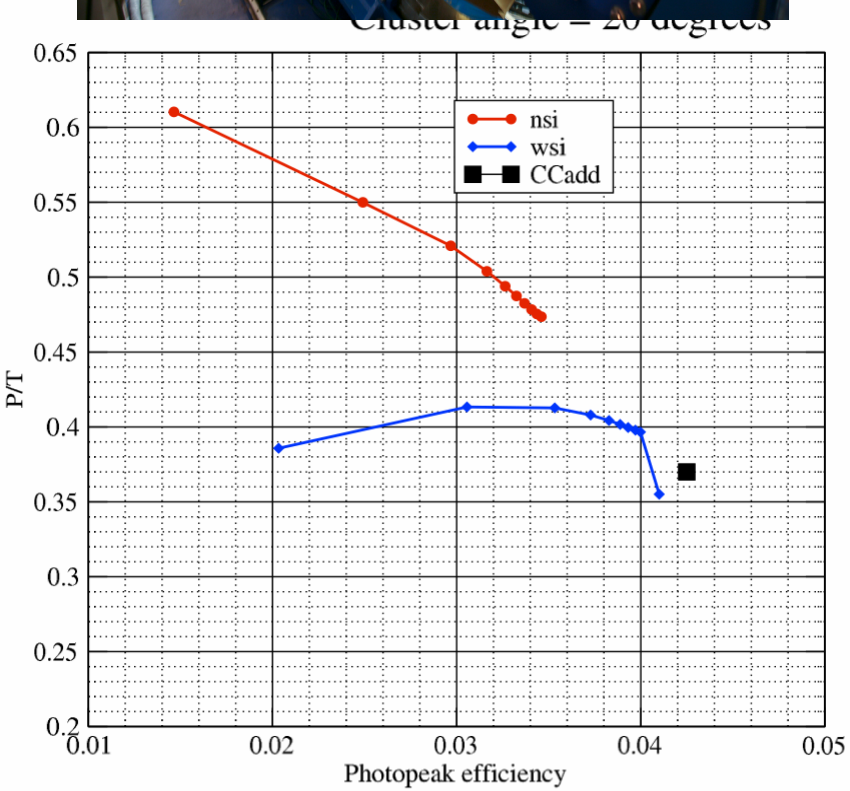

A Better P/T compared to GSI
But the array Is more compact :
72% versus 68%

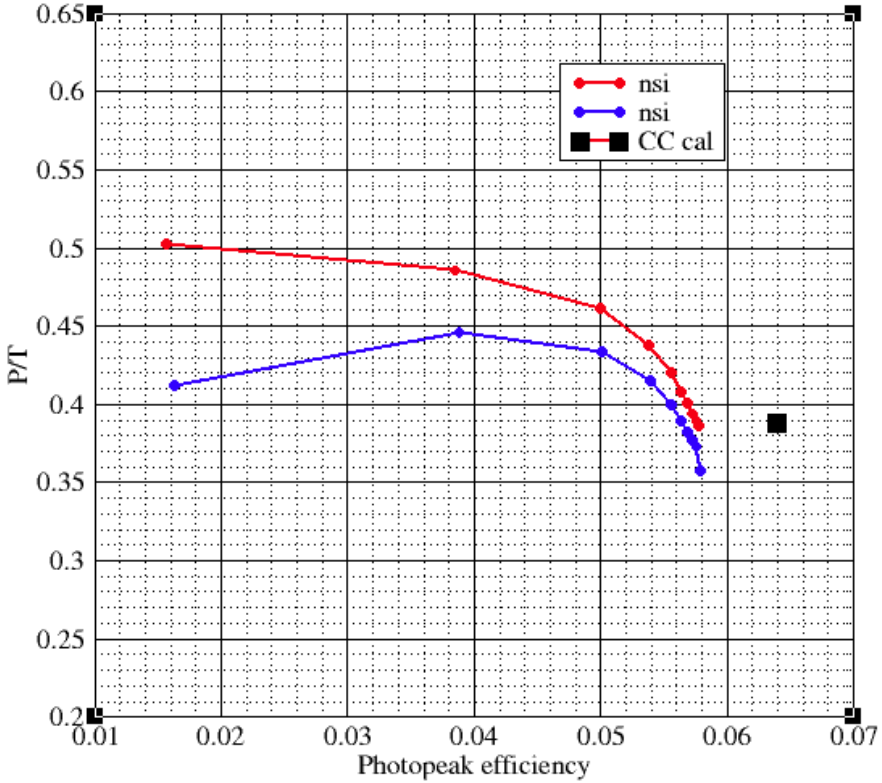
But also more passive material :
3 crystals not active at GSI

# Comparison AGATA@GANIL and GRETINA@ANL





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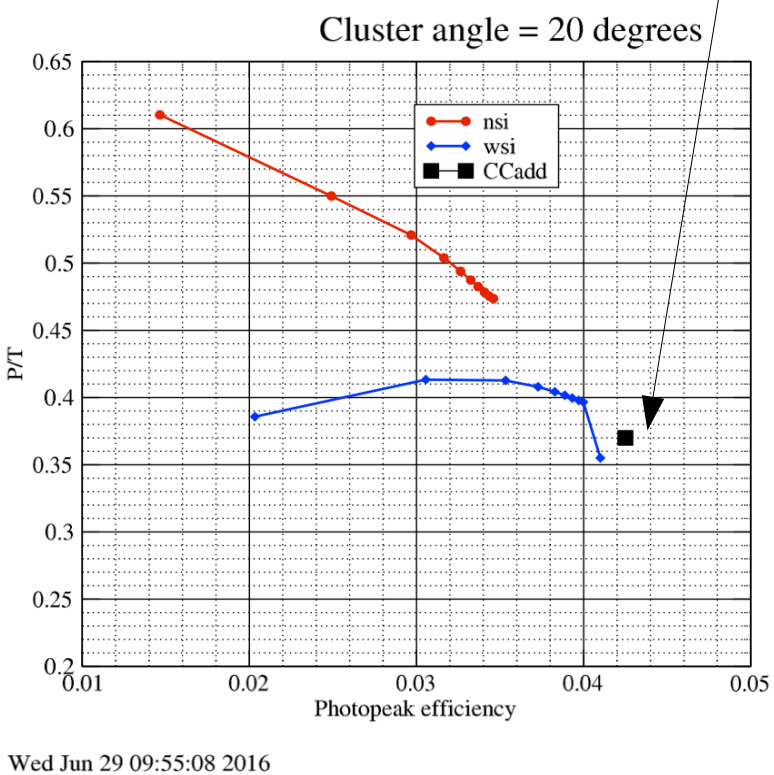
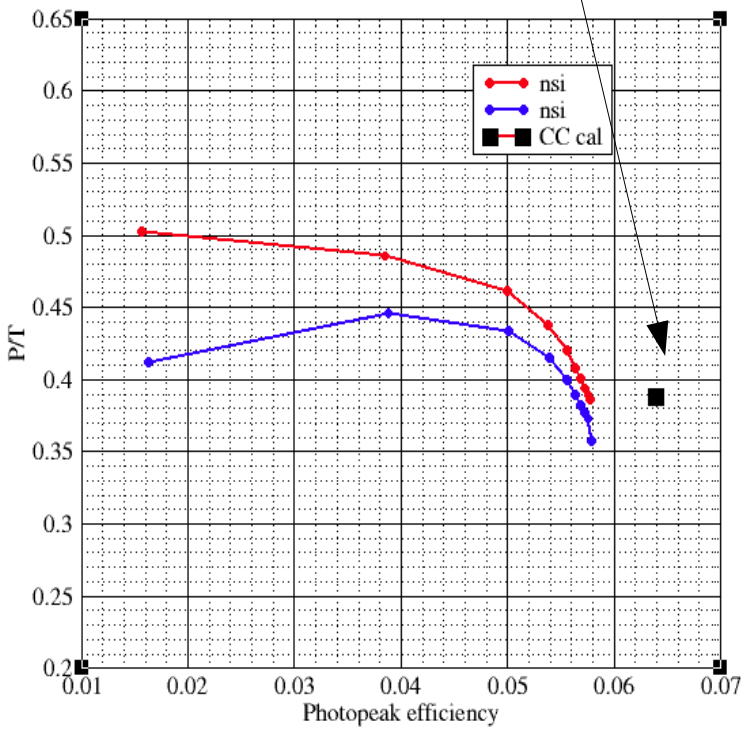
# AGATA and GRETINA

28 crystals positioned at 23.5 cm

28 crystals positioned at 18.5 cm

4.25% = [(18.5+3.5)/(23.5+3.5)]^2 * 6.4%




4π array scaling using GEANT4 simulations with 10% uncertainty

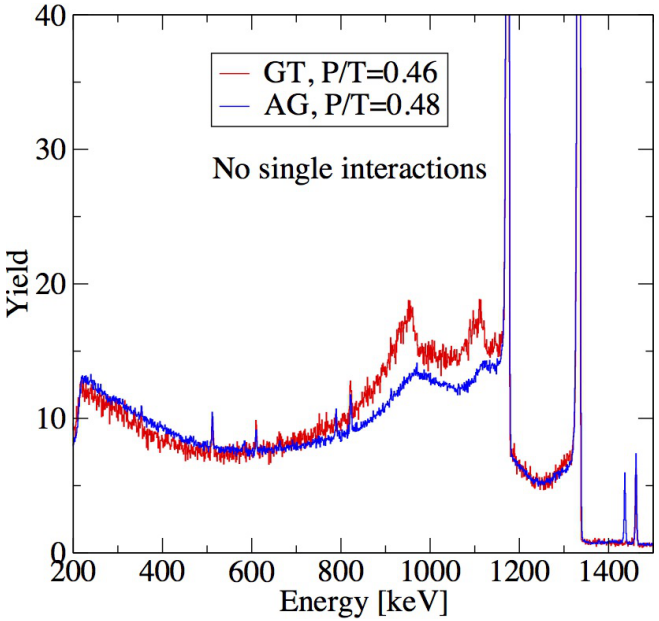
AGATA 180 crystals yields : 37(4)%

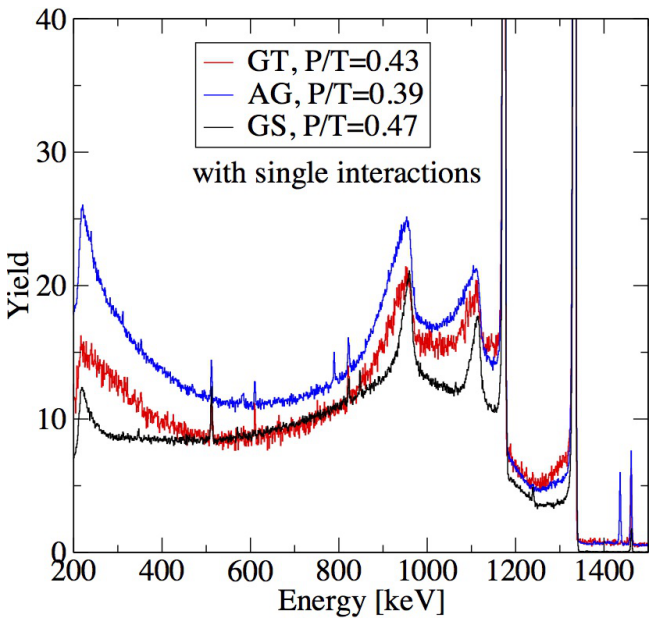
GRETA 120 crystals : 34(4)%

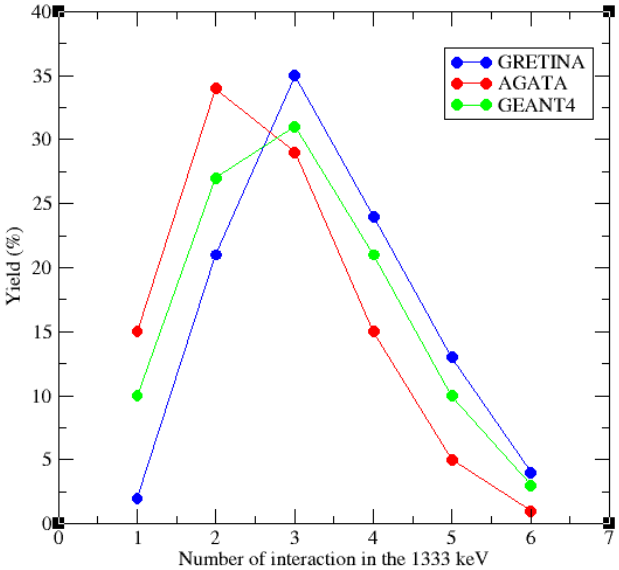
As expected!

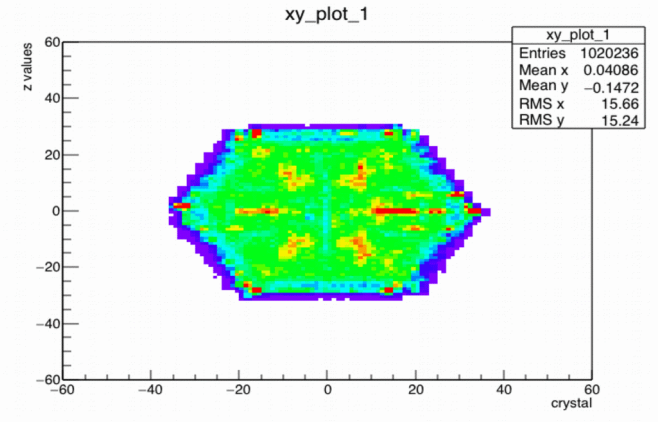
# Comparing the spectra : P/T

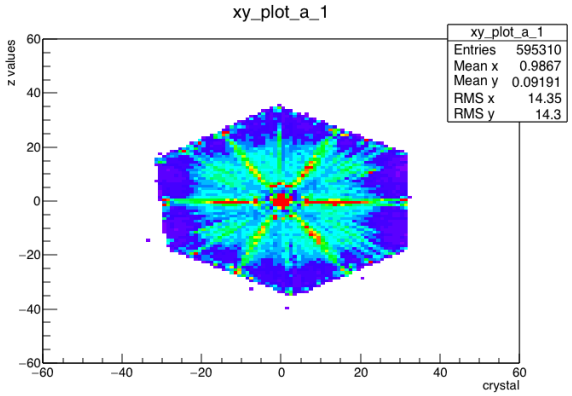
FOM cut : 0.8 for AG and 0.64 for GT
70% of gamma-rays in both arrays




PSA/Decomposition :

GRETINA:
more than one interaction/segment

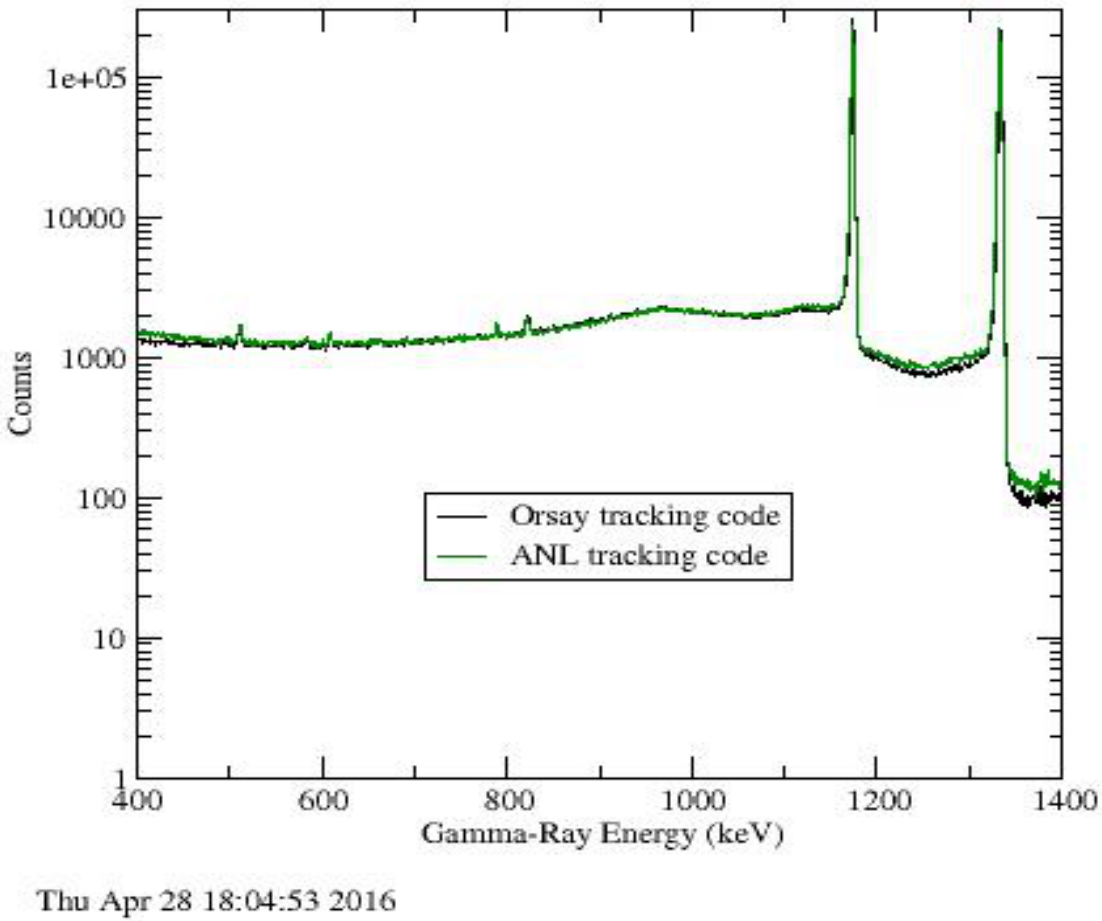
AGATA
only one interaction/segment

TBD : process the AGATA (or GRETINA) data through the same Decomposition PSA) to conclude

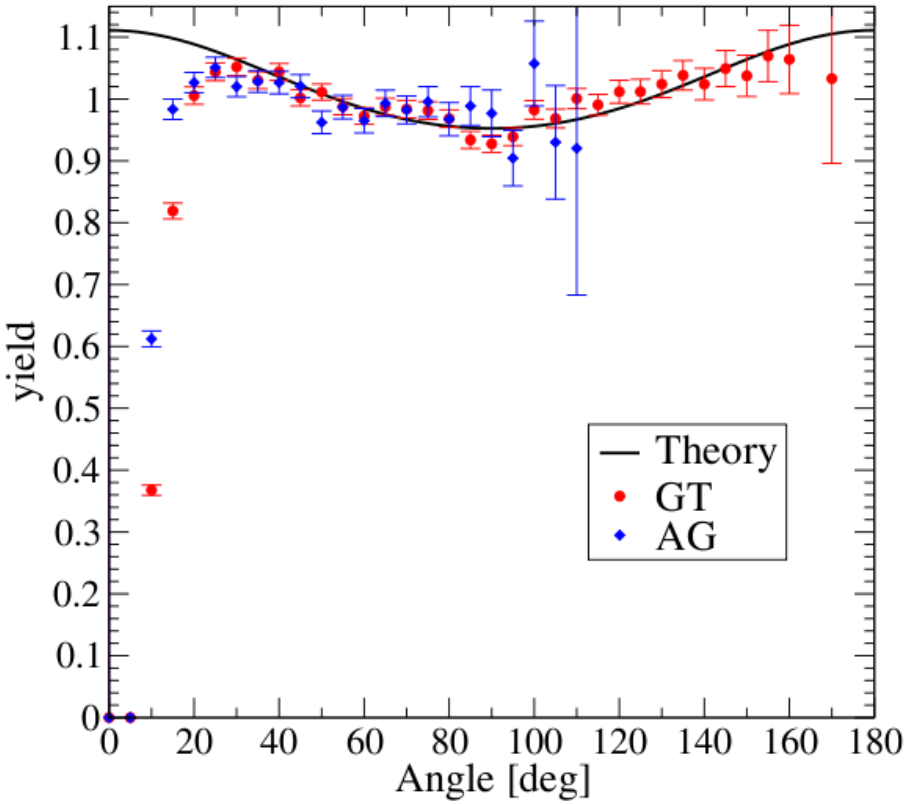
# Tracking codes comparison

OFT- AGATA tracking code

ANL- GRETINA tracking code




***They are doing a very good job!!!***




Linerar Polarization :fantastic

P.G Bizzettiet al, Eur. Phys. J.A (2015)51

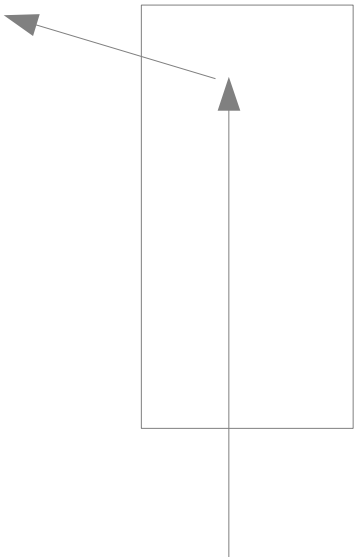
Partha Chowdhury contribution

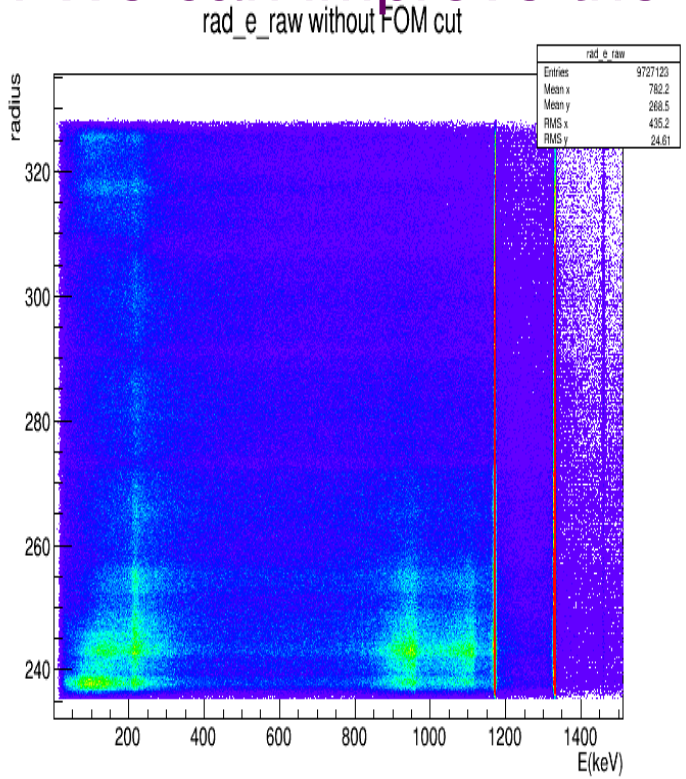
Tracking performance can even be improved by other means

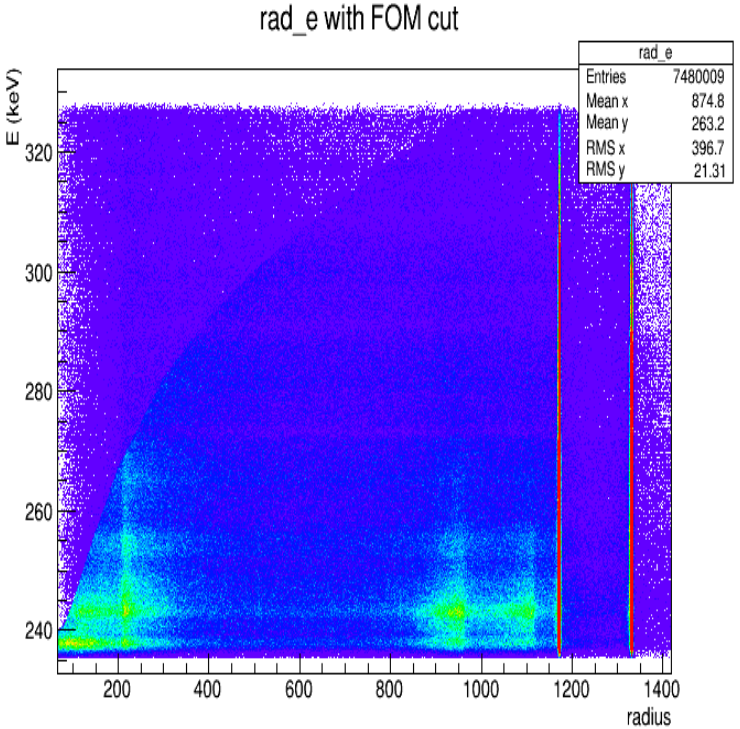
# For single hits: We can improve the tracking by other means:

Escape lost

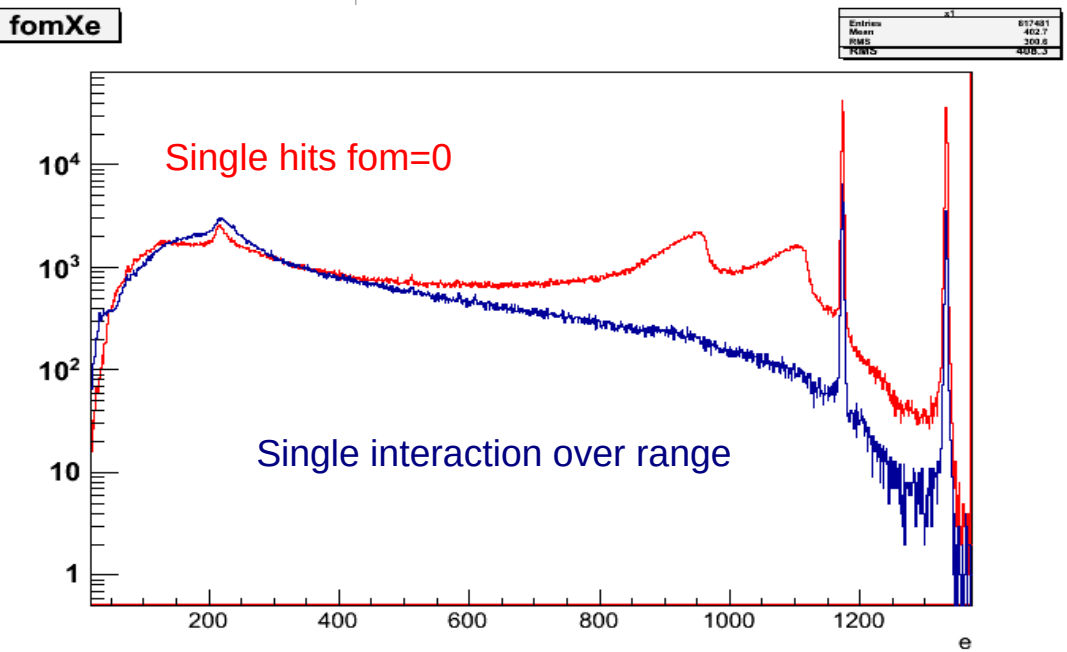
Looks like a low energy 'single interaction'

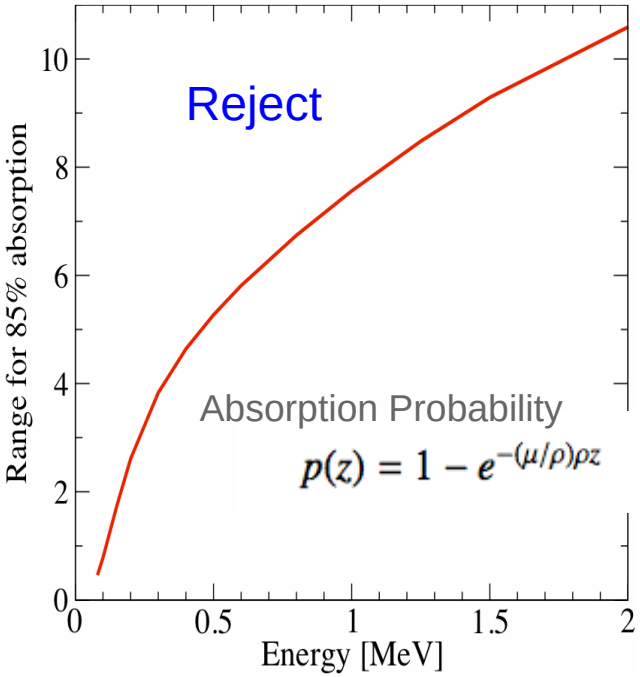





Helps! P/T → 27% to 34%

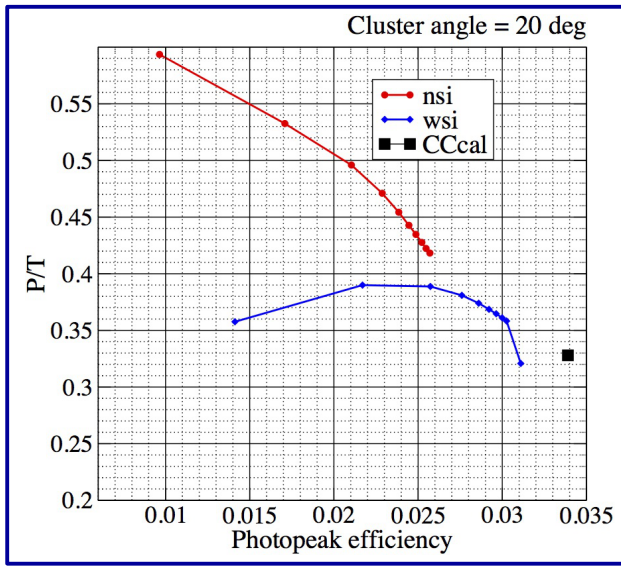


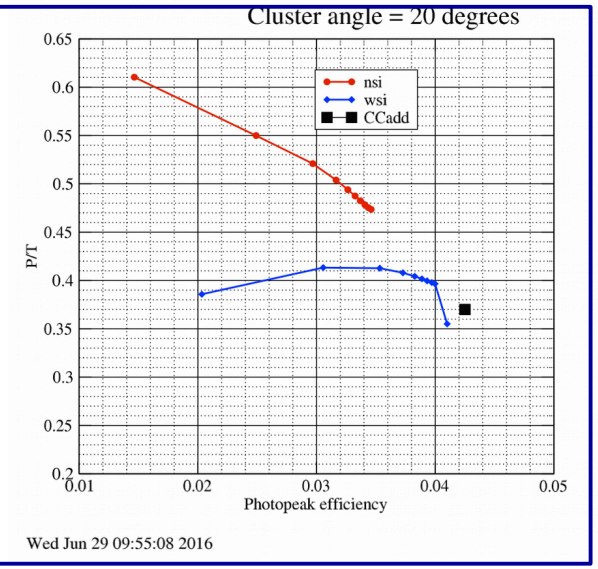
# Comparing the P/T :

Compactness: number of crystal sides that have close neighbors to total number of crystal sides.

AGATA@GSI



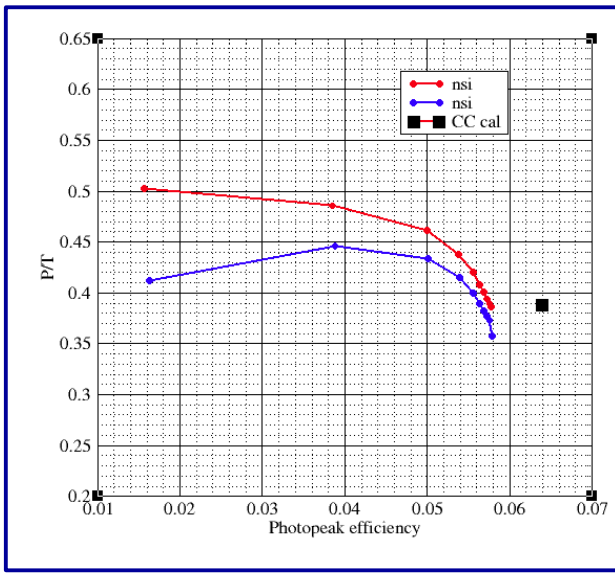

GANIL



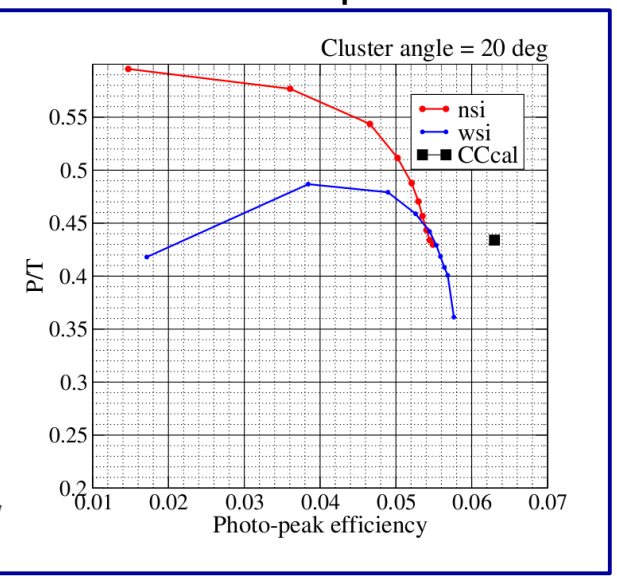

The packing of the array matters!

More compact
More crystals
Yields a better PT

GRETINA@ANL




MSU compact




Best setup compactness of 71% and yields a better P/T

# Conclusion

Doppler correction capabilities : beautiful for fast beams
Specification met
AG & GT similar

Tracking efficiency :
Specification met
AG & GT similar

Some issues still remain

But ...

**Combine our efforts**
**To make it!**

**First AGATA-GRETINA tracking arrays collaboration meeting**
***December 5-7, 2016***

***First Circular***

We are pleased to announce the first AGATA-GRETINA collaboration meeting to be held at ANL on 5-7 of December 2016.

The workshop will be devoted to discussions about common challenges related to tracking arrays, including the physics, technical details and analysis of data from these arrays. We intend to organize these workshops on a yearly or bi-yearly basis, alternating between meeting places in the US and EU.

We are hoping these workshops will foster collaborations between the AGATA and GRETINA communities and help define and accomplish our common challenges.

***Organizing and Advisory committee :***

***B. Birkenback, IKP-Koeln, Germany.***
***A. Boston, Liverpool University, UK.***
***M.P. Carpenter, ANL, USA.***
***A. Gadea, IFIC-Valencia, Spain.***
***A. Korichi (co-chair) CSNSM-CNRS, France.***
***T. Lauritsen (co-chair) ANL, USA.***
***A.O. Macchiavelli, LBNL, USA.***
***D. Radford, ORNL, USA.***
***O. Stezowski, IPNL-CNRS, France.***
***D. Weisshaar, NSCL, USA.***

This work has been performed  ANL – CSNSM collaboration

And the AGATA-GRETINA collaboration

# Thank you!

# First AGATA-GRETINA tracking arrays collaboration meeting

***December 5-7, 2016***

## *First Circular*

We are pleased to announce the first AGATA-GRETINA collaboration meeting to be held at ANL on 5-7 of December 2016.

The workshop will be devoted to discussions about common challenges related to tracking arrays, including the physics, technical details and analysis of data from these arrays. We intend to organize these workshops on a yearly or bi-yearly basis, alternating between meeting places in the US and EU.

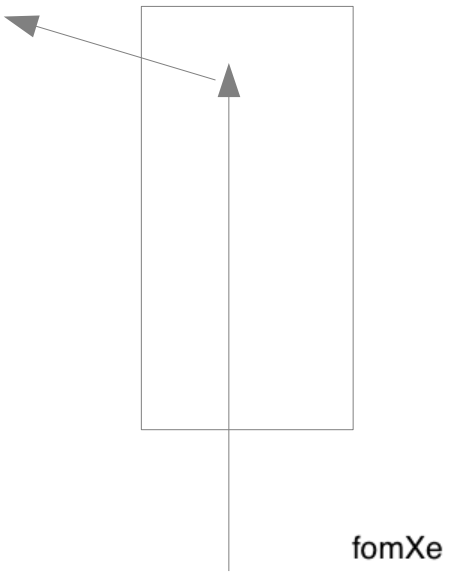
We are hoping these workshops will foster collaborations between the AGATA and GRETINA communities and help define and accomplish our common challenges.

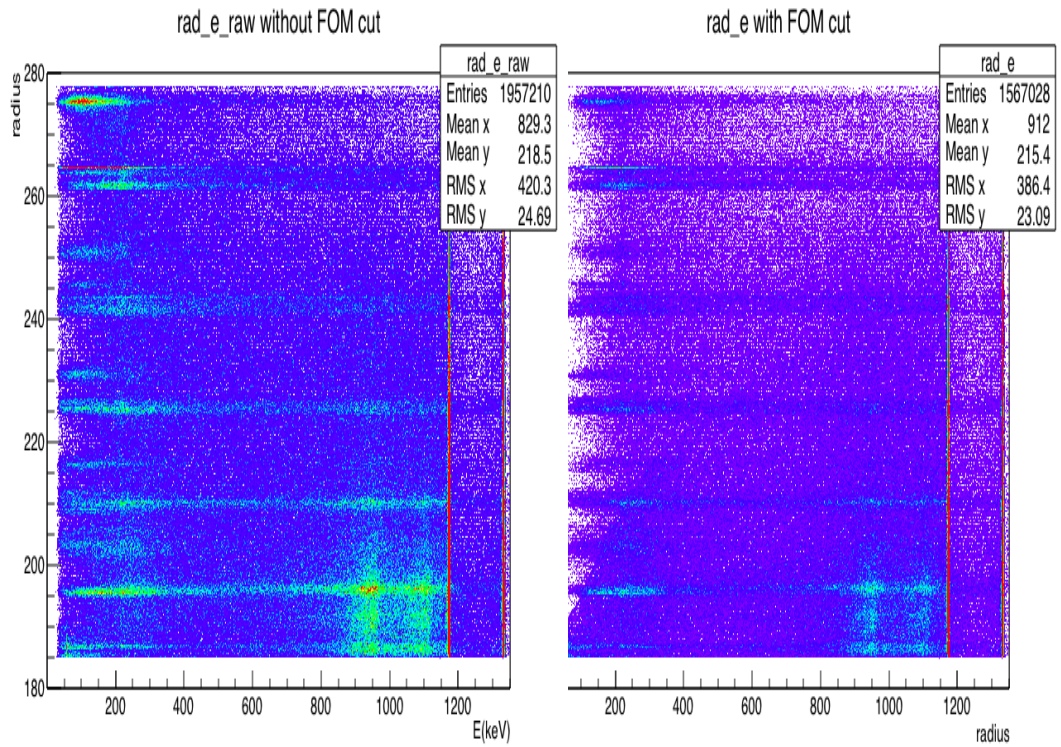
### *Organizing and Advisory committee :*

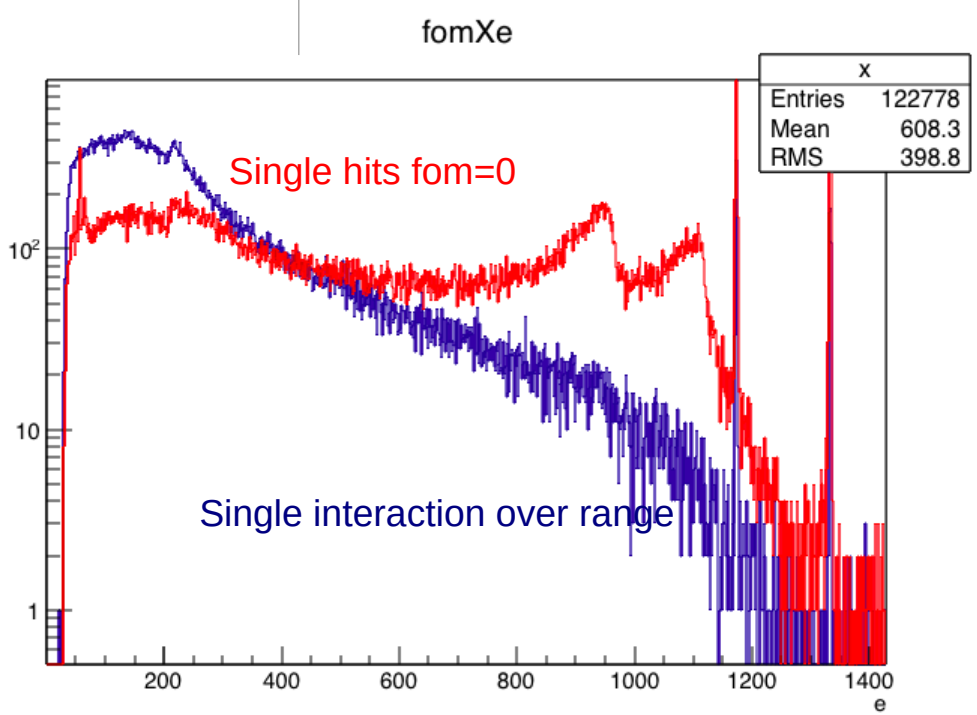
***B. Birkenback, IKP-Koeln, Germany.***
***A. Boston, Liverpool University, UK.***
***M.P. Carpenter, ANL, USA.***
***A. Gadea, IFIC-Valencia, Spain.***
***A. Korichi (co-chair) CSNSM-CNRS, France.***
***T. Lauritsen (co-chair) ANL, USA.***
***A.O. Macchiavelli, LBNL, USA.***
***D. Radford, ORNL, USA.***
***O. Stezowski, IPNL-CNRS, France.***
***D. Weisshaar, NSCL, USA.***

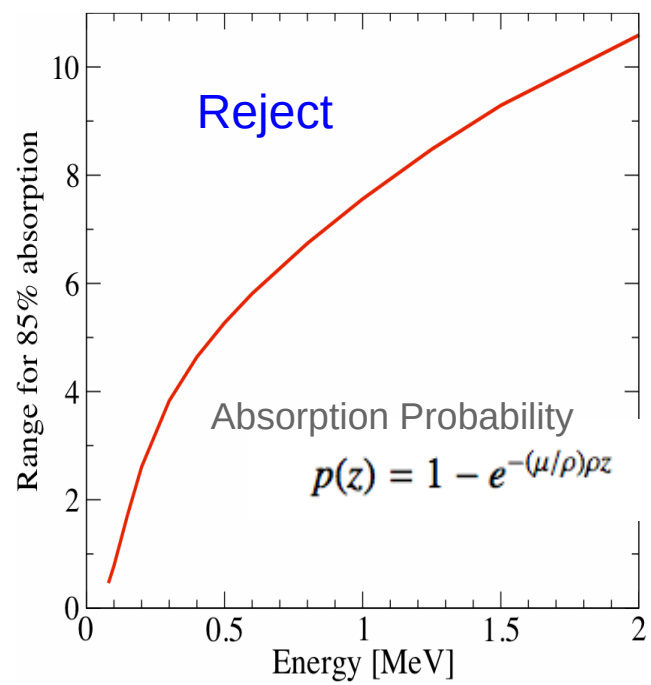
# Extra slides

# For single hits: We can improve the tracking by other means:



# Tracking efficiency and P/T for GRETINA

$$\epsilon_{track} = \frac{A_T(1333)}{\frac{A^{obs}(1333)}{(1-C_k(1173))(1-C_R)(1-C_s)}} \equiv \frac{A_T(1333)}{A^{true}(1333)}$$

$$(P/T)^{tracked} = \frac{A_T(1173) + A_T(1333)}{A_{tot}},$$

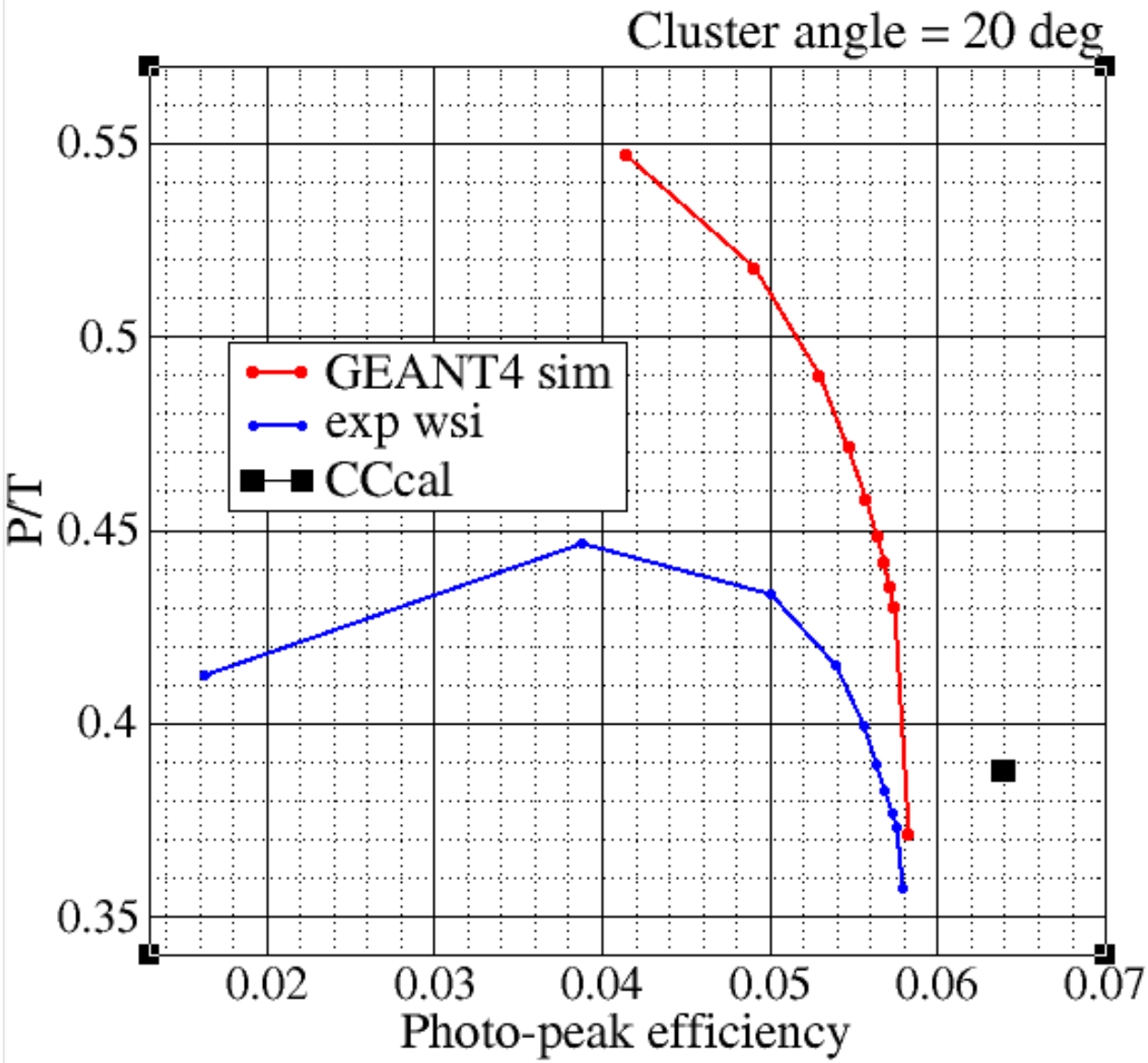
Analysis of data from GRETINA at ANL:

Compactness was 63%. Best setup had compactness of 71% and yielded a better P/T

| | SPM cal | CSM cal | SPM sum |
|---|---|---|---|
| $\epsilon_P$(mixed) | 6.11(9)% | 6.05(9)% | - |
| $\epsilon_P$(pure) | 6.42(6)% | 6.0(6)% | 6.5(6)% |
| $(P/T)^{obs}$ | 0.321(5) | 0.321(5) | 0.192(5) |
| $(P/T)^{true}$ | 0.385(5) | 0.381(5) | 0.363(11) |
| $\epsilon_{track,nsi}$ | 92(1)% | 93(1)% | 92(1)% |
| $\epsilon_{track,wsi}$ | 93(1)% | 94(1)% | 93(1)% |
| $C_s$ | 0 | 0 | 0.293(5) |

Weighted mean: 6.27(4)% for 28 crystals (included external/internal measurements too)

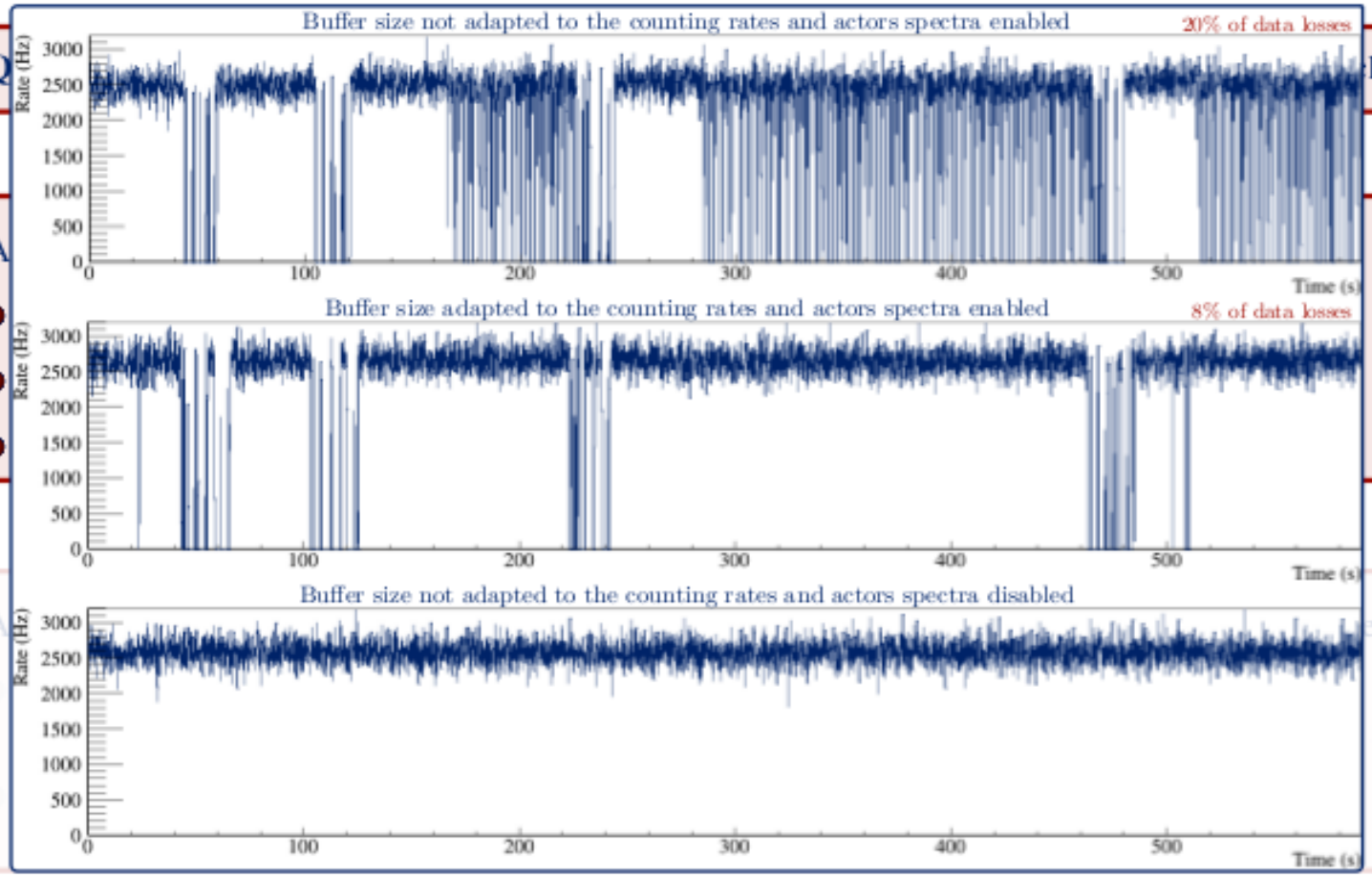
# P/T curves: GEANT4 and measured




Regarding the P/T: GEANT4 says we should be doing better than we are..

Simulation needs to be improved too

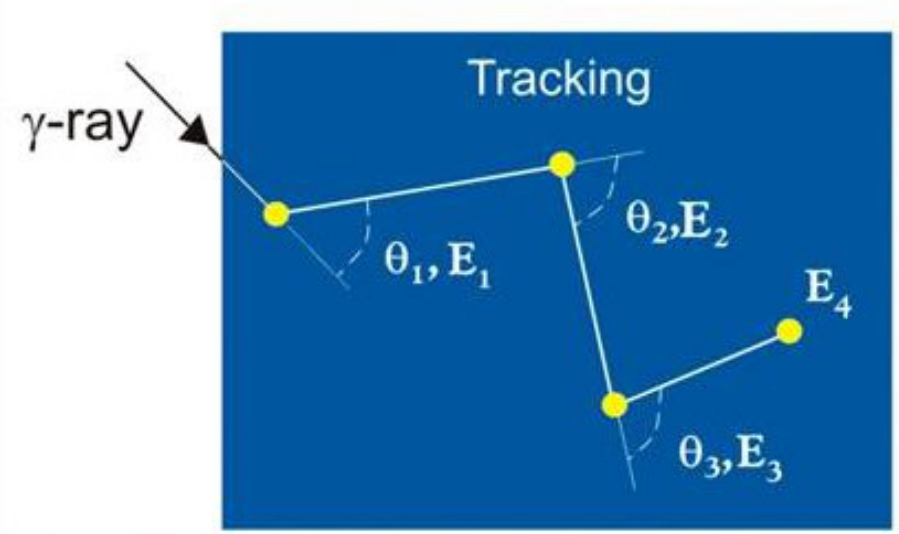
# Quasi-online data analysis






Courtesy of J. Dudouet- IPNL

# Tracking 101: determining the interaction sequence and how 'good' a gamma ray is




Cluster, find interaction sequence
Evaluate scattering angle
<–> energy consistency with
the Compton scattering formula:

$$E'_\gamma = \frac{0.511}{1 + \frac{0.511}{E_\gamma} - cos(\theta)}$$

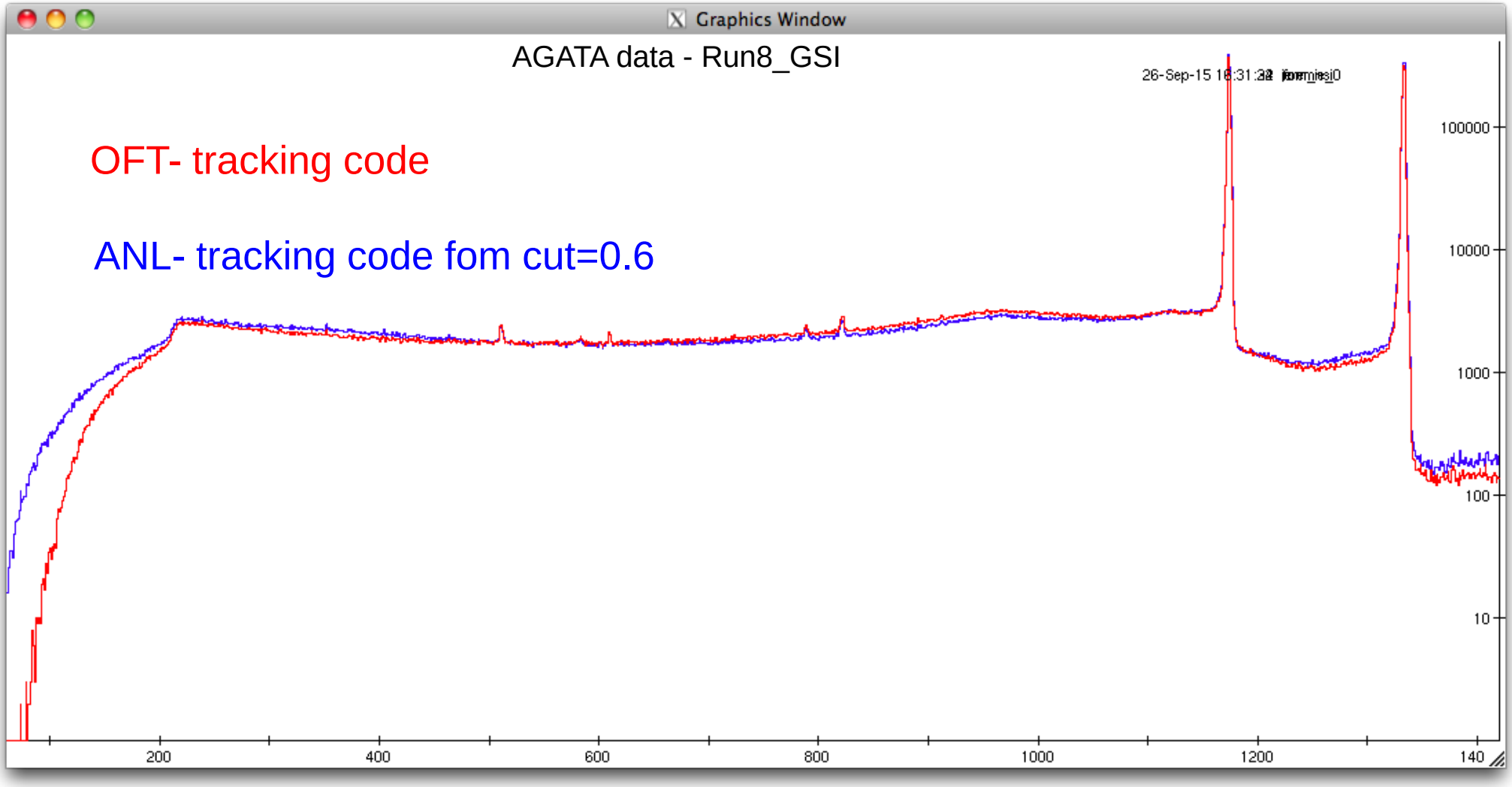
$$FOM = \sum_i \frac{\sqrt{(\sum_i (\theta_i^{theo} - \theta_i^{obs})^2)}}{n_i - 1}; n_i > 1$$

(in rad)

FOM < ~0.6-0.8
considered GOOD

FOM > ~0.8
considered BAD
(Compton events)

Note: Single interactions cannot be tracked



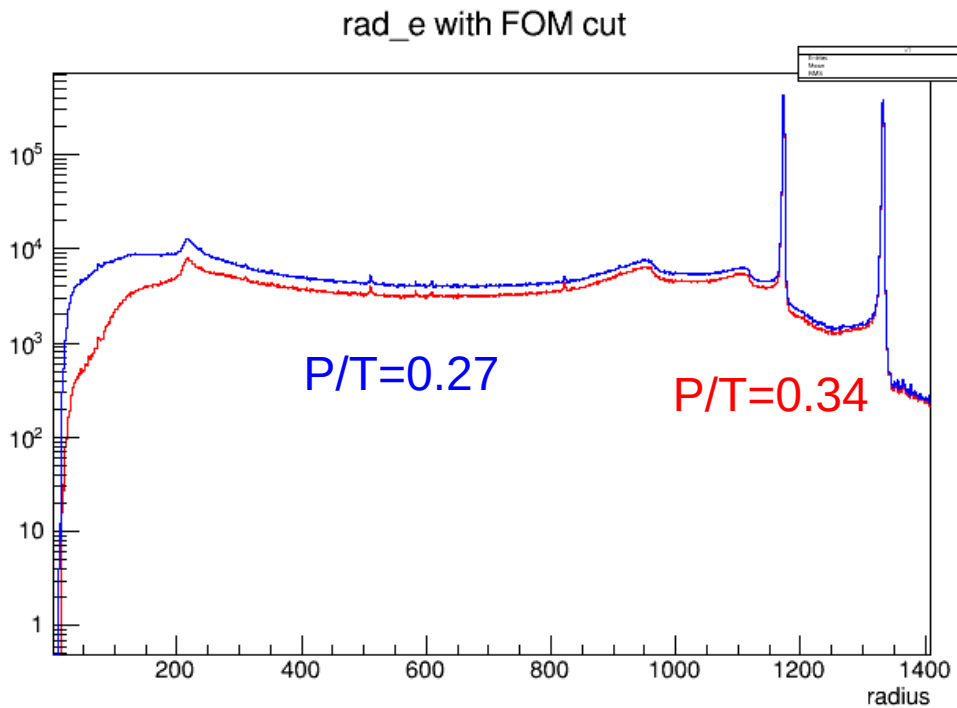

Tracking codes are doing the job

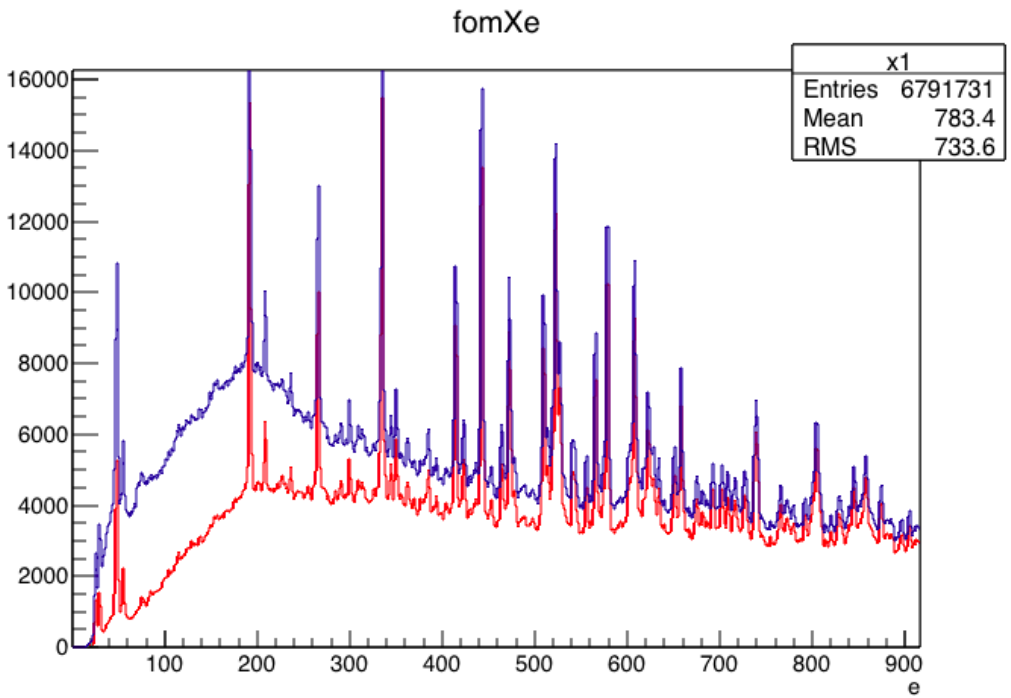
jeremie_nsi.spe ;P/T= 0.468 ;p1/p2/sum= 1146917/ 1084651/ 4764551 :: photoeff = 0.045 ;
totaleff = 0.095 ; p2eff = 0.043 ; *= 0.9791

fom_nsi06.spe ;P/T= 0.488 ;p1/p2/sum= 1247299/ 1184123/ 4984402 :: photoeff = 0.049 ;
totaleff = 0.100 ; p2eff = 0.047 ; *= 1.1571

fom_nsi08.spe ;P/T= 0.462 ;p1/p2/sum= 1353925/ 1289846/ 5722022 :: photoeff = 0.053 ;
totaleff = 0.114 ; p2eff = 0.052 ; *= 1.1288

# It Helps!




- $^{122}Sn(^{40}Ar[170MeV],4n)^{158}Er$
- June 5-6, 2015-