Gamma-ray Tracking++

- The Compton suppressed arrays
- The tracking arrays
- Traces and decomposition
- Clustering and tracking
- Efficiency of tracking arrays
- Tracking efficiency and P/T
- Data quality issues
- Challenges and future

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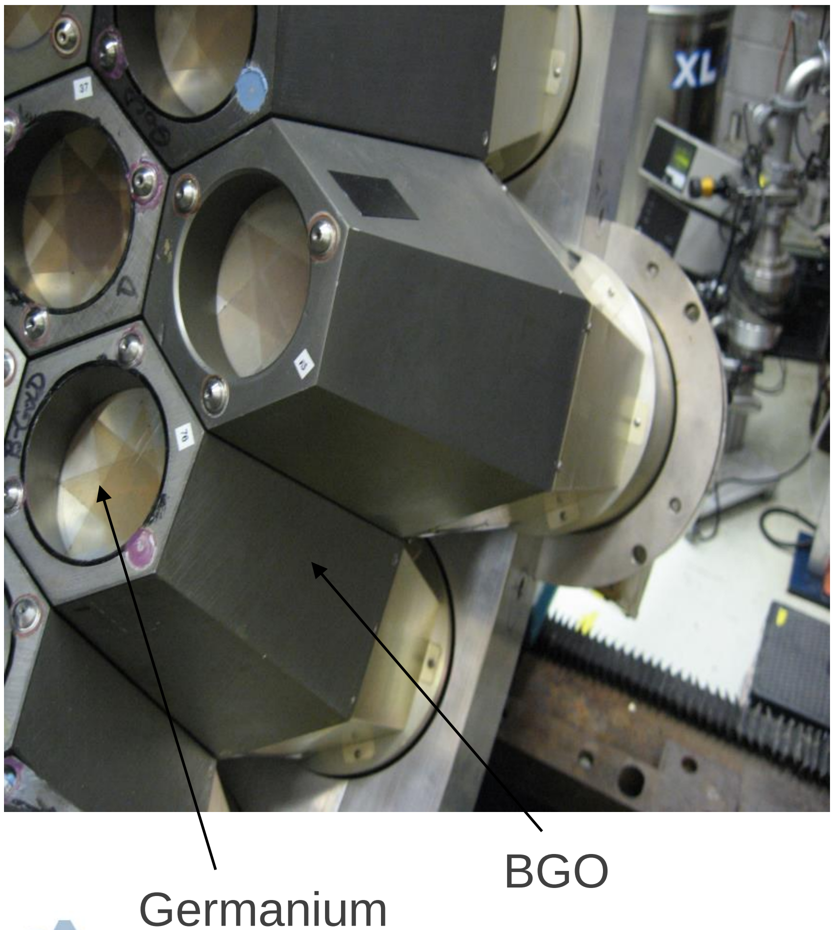
The Compton suppressed arrays

GAMMASPHERE 110/100 modules



Idea:

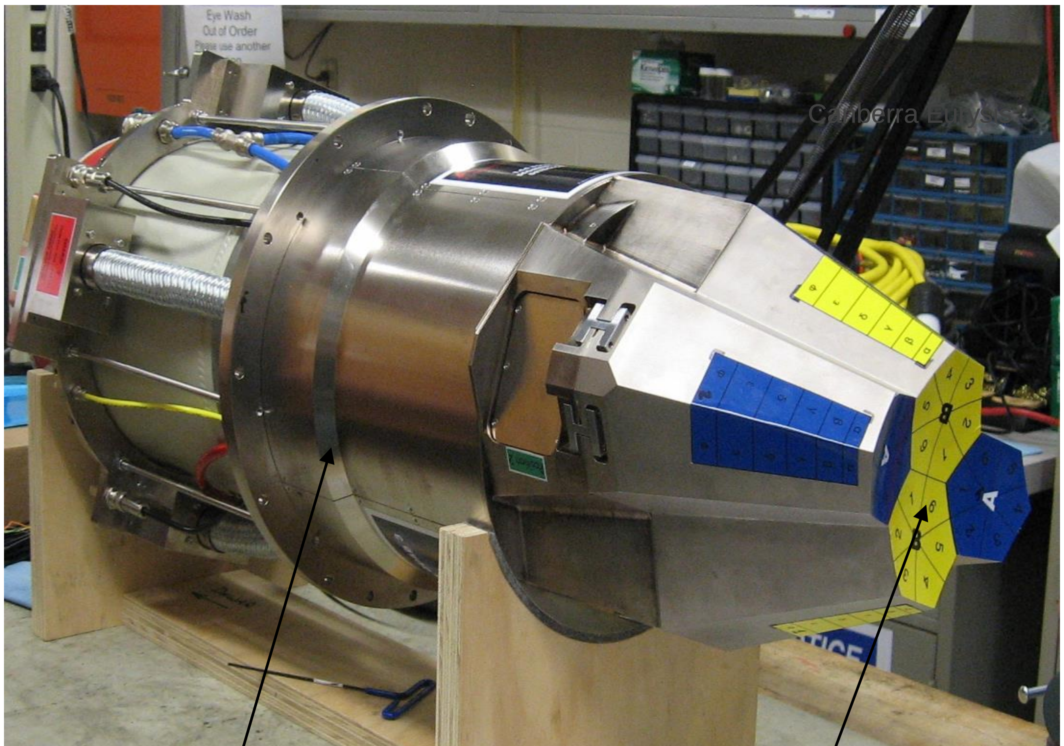
[Suppress gamma rays that scattered out] of the germanium crystal with highly efficient BGO detectors surrounding the crystal on all sides. Can 'honeycomb suppress' as well.

Works very well, but ~60% of the array is taken up by the BGO detectors. Fundamentally, we can't improve the Compton suppressed arrays!!

For Gammasphere, the Doppler correction cannot be done better than to ½ the opening angle of the ge crystals (for split crystals at 90 deg)

The new advent,
The tracking arrays (GRETINA and AGATA)

GRETINA module, 30/9 modules or 120/36 crystals from Canberra Eurisis (now Mirion)



module

Crystals x4, two types
36 segments

Idea:

<u>Replace the BGO with active segmented germanium crystals</u>

But the data analysis becomes quite a bit more complicated.

The efficiency can be about 4 times that of GAMMASPHERE and the gamma ray position resolution can be done with a precision of 2-3 mm (rms)

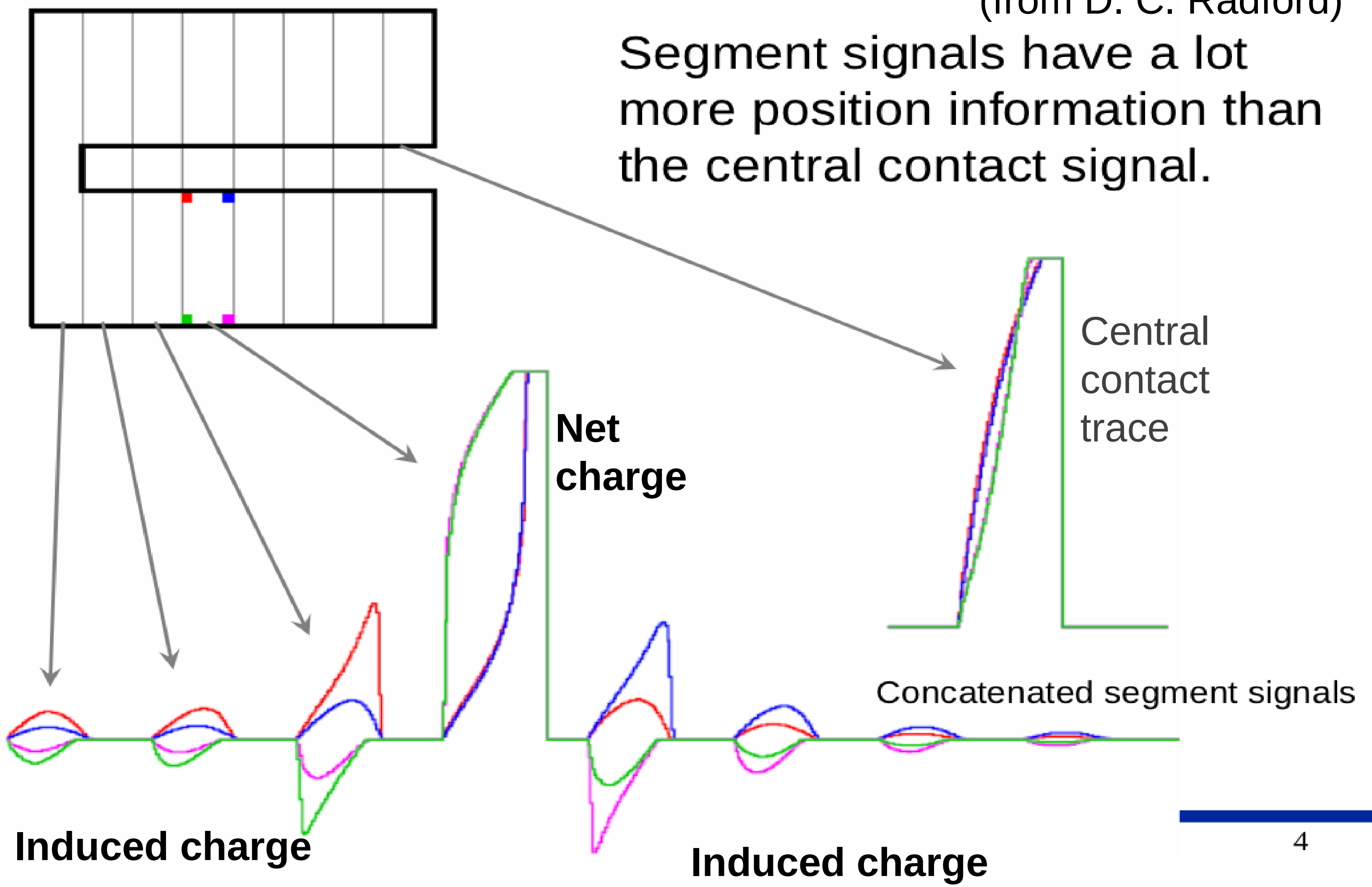
AGATA: 180 crystals,
3 per cryostat, 3 types

Key to understanding tracking arrays:

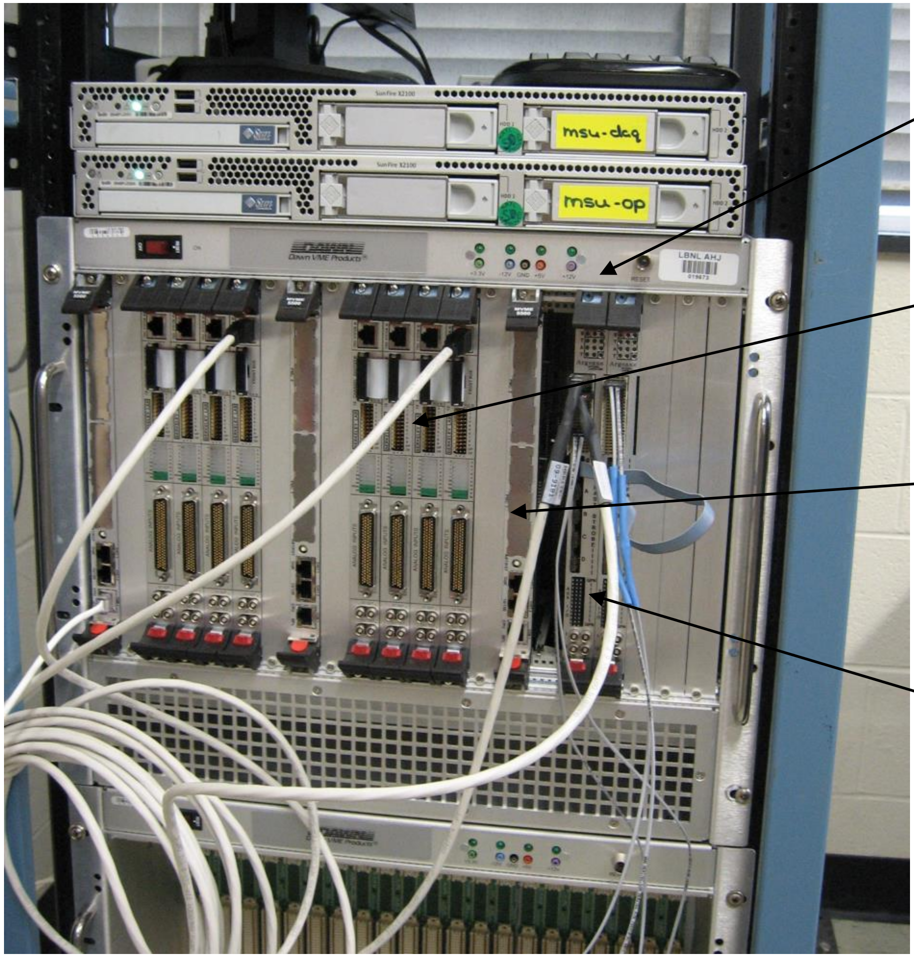
The signals from the traces:

(from D. C. Radford)

Segment signals have a lot more position information than the central contact signal.



Each segment signal feed to a 14 bit FLASH ADC (100 MHz)



3 VME crates

Digitizers
40 channels

VME IOC
MVME
5500

Trigger
Mods
(ANL)

(actually the MSU test stand)

We get complete **TRACES**

10x4 channels each
CC also digitized
[*same as DGS/DFMA !!*]

6X6=36 + few CC signals

Basic Idea:

The digital traces from the segments will determine the (x,y,z) and interaction energies at the Interaction points

Decomposition, the BASIC PRINCIPLES:

1) Unit charge placed a given point in crystal (in a fancy grid, see next slide)
2) Net and transient charges calculated for each 36 segments
3) Corrections are made for: pre-amp shaping, delay times, integral and differential cross talk, crystal impurities, etc.

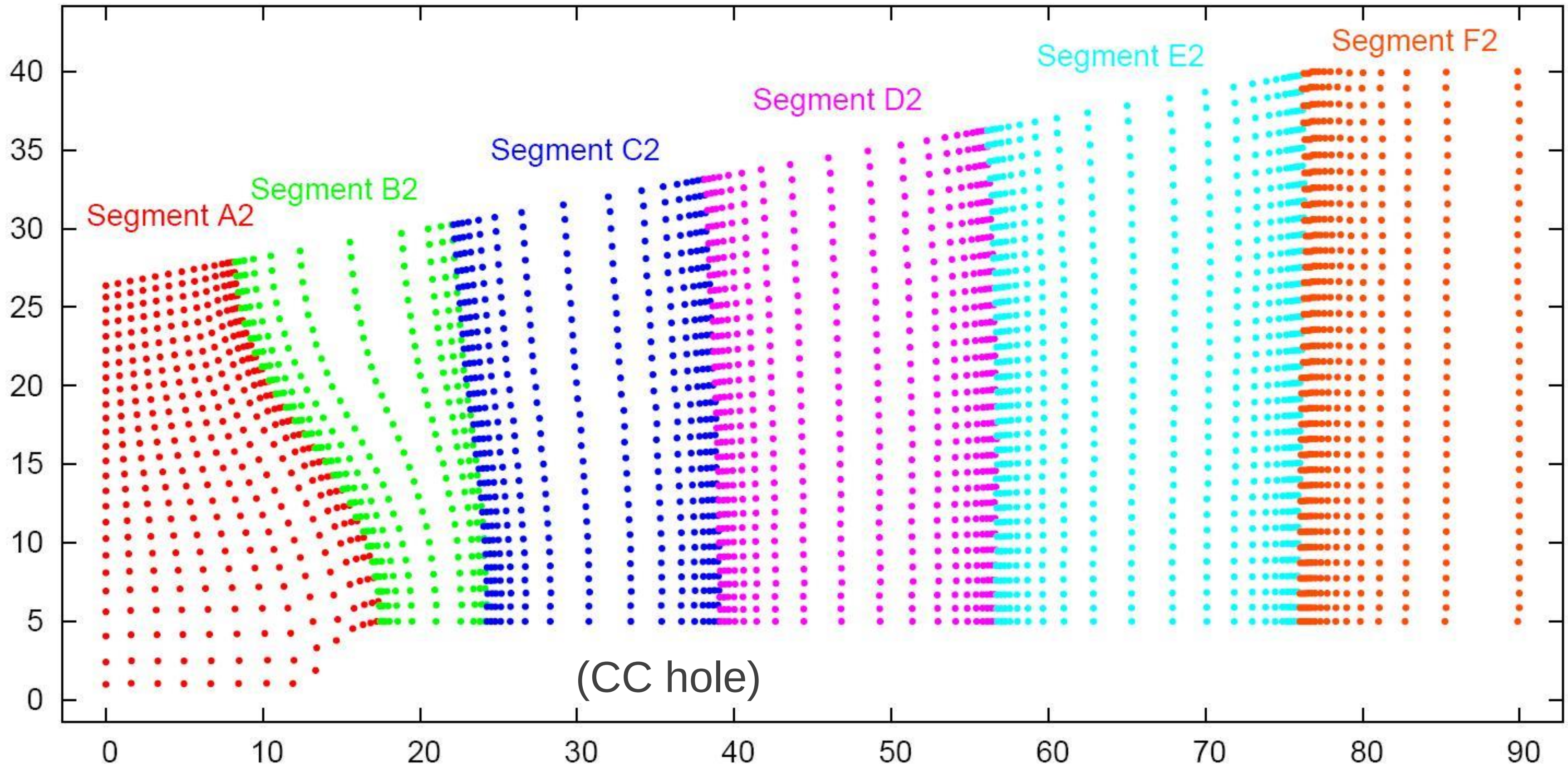
Result is termed a "basis" for the crystal

Compare/fit to Measured traces

Determine x,y,z,e
for the interaction points in the crystal

Decomposition grid (D.C. Radford et. al.) Cylindrical coordinates (AGATA use 3D grid)

1/2 detector side view



...Points according to how much traces 'change', segmentation and electri

Decomposition: A VERY BIG FITTING JOB!

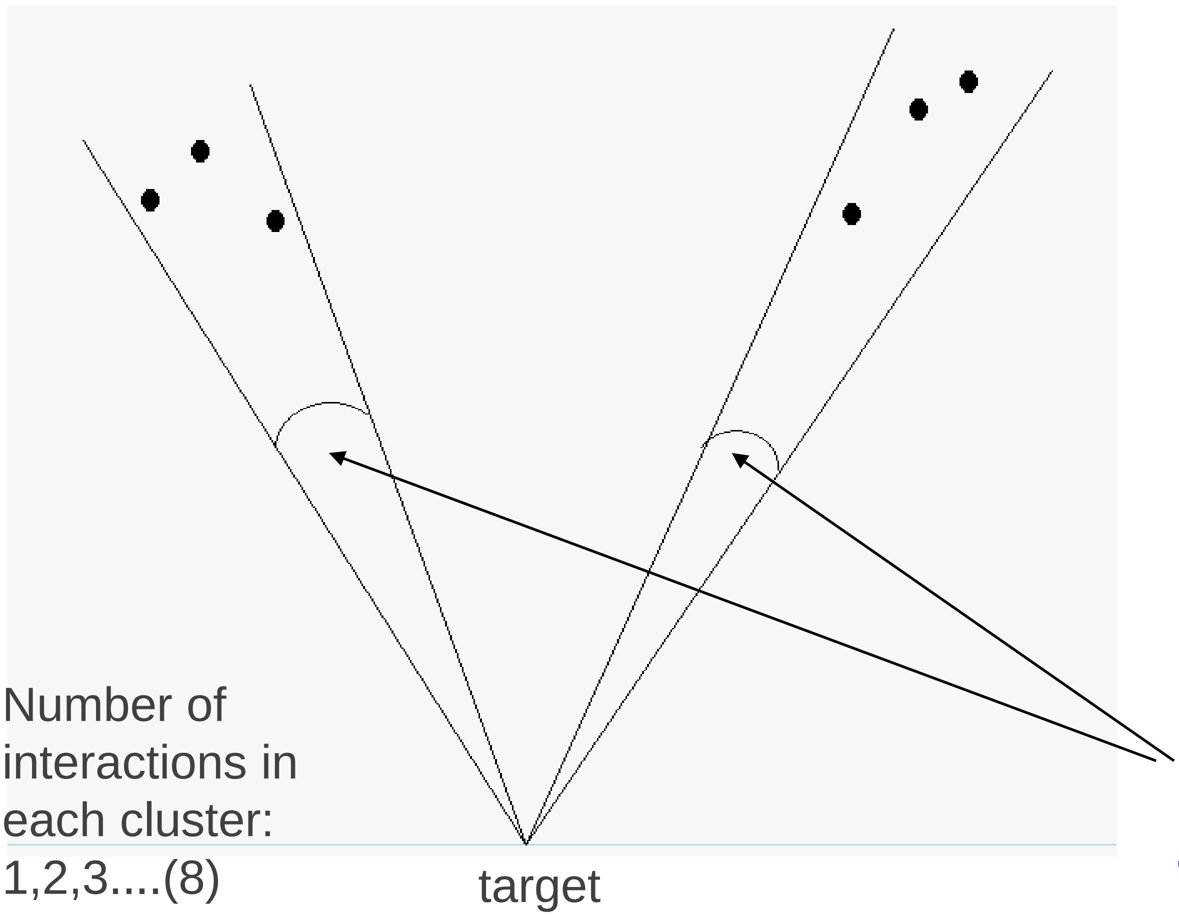
Use big cluster of ~70, 2x4-core fast Linux nodes for the decomposition

After this stage:

we only have x,y,z,e,t data!

The crystals, as such, are no longer relevant!

Clustering: the first step in finding the 'candidate' gamma rays that hit the array
(for interactions in time coincidence)



Effectively a 2D problem since we use the angles between the interaction points to define the problem

Clustering angle ~10-20 degrees

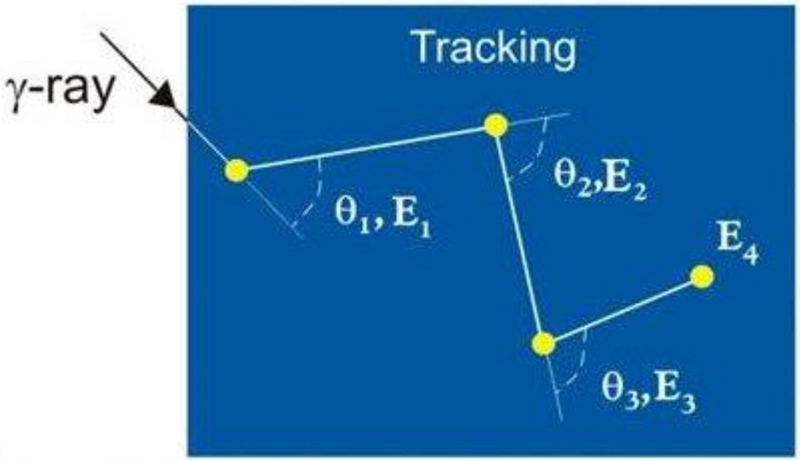
Number of interactions in each cluster: 1,2,3....(8)

Cluster angle and n, ***the virtual number of crystals we have***

alpha (deg)	n	
10	525	Typical tracking cluster angles
15	234	(Typical tracking cluster angles)
17	180	(Typical tracking cluster angles) **<- AGATA crystal, nominal dist**
20	132	(Typical tracking cluster angles)
21	120	**<- GRETINA crystals, nominal dist**
22	108	<- Gammasphere module

$$n = \frac{2}{(1 - cos(\alpha/2))}$$

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)

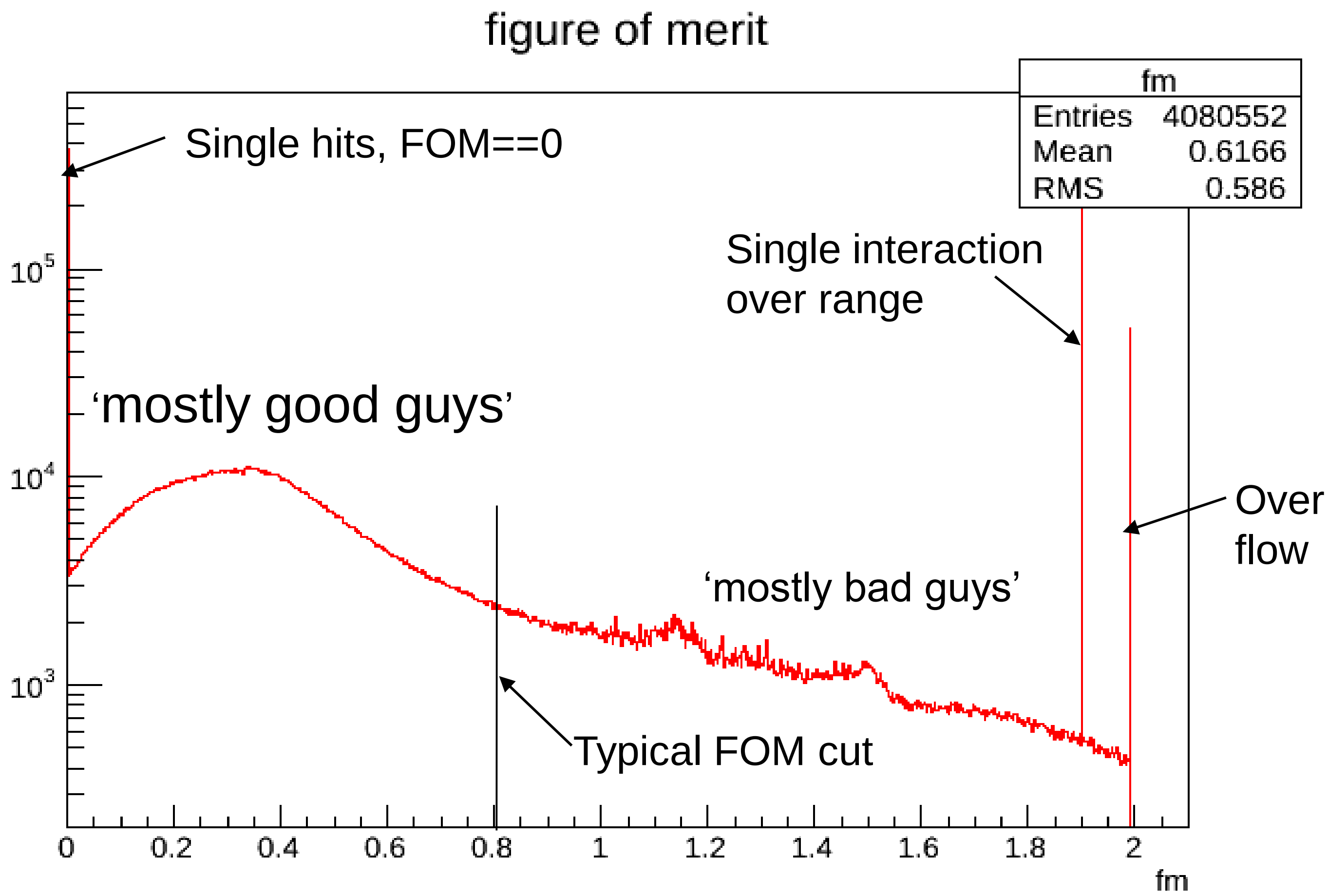
Note: Single interactions cannot be tracked

O We find the interaction sequence

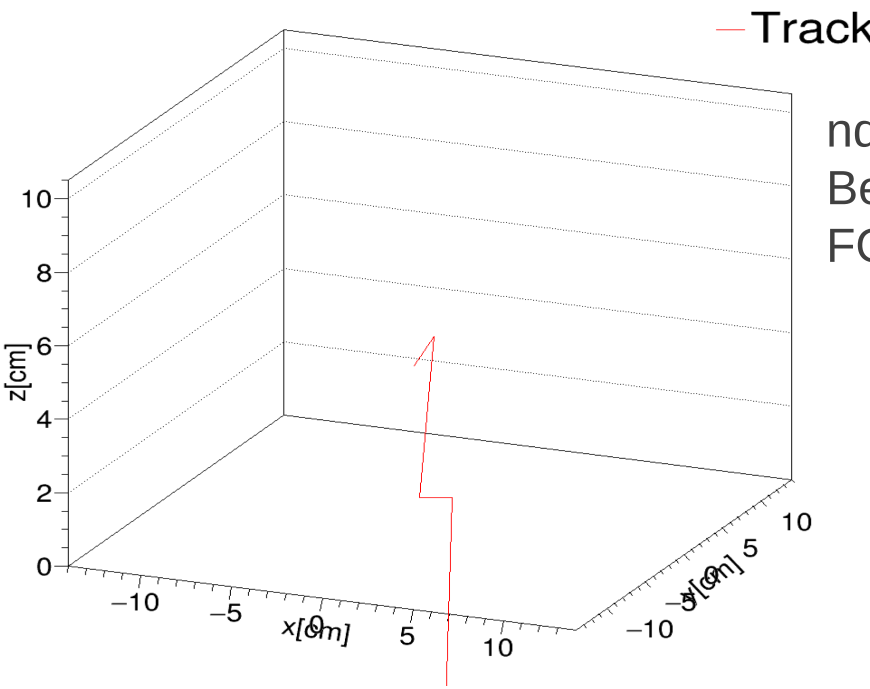
O We evaluate how 'good' the gamma rays is

(BTW: We re-scale to CC energy before tracking)

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



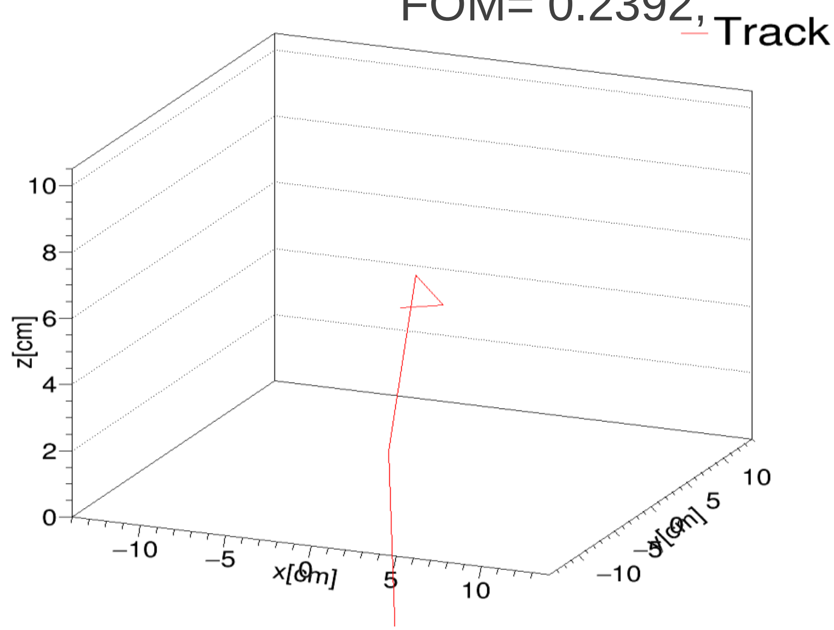
Examples of good photo peak events, 3D plots



^{166}Ho data

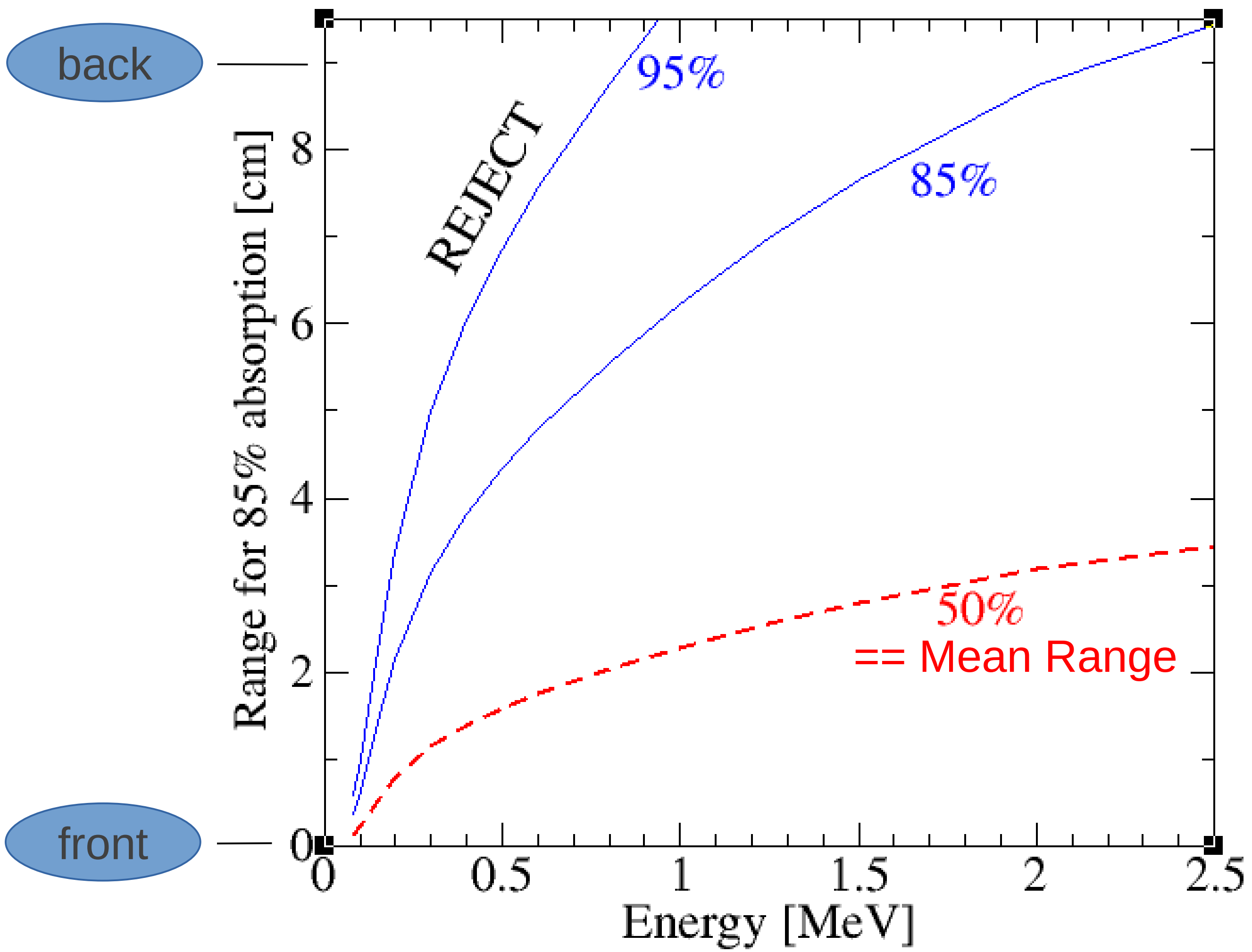
ndet= 4 esum= 0.8111/
Bestperm=00003/
FOM= 0.1333;

ndet= 4 esum= 0.7119/
Bestperm=00018/
FOM= 0.2392;



The interactions can be spread over more than one crystal, – <u>the tracking algorithm does not care</u>

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



== Mean Range

50 % absorption

Escape lost

Looks like a low energy 'single interaction'

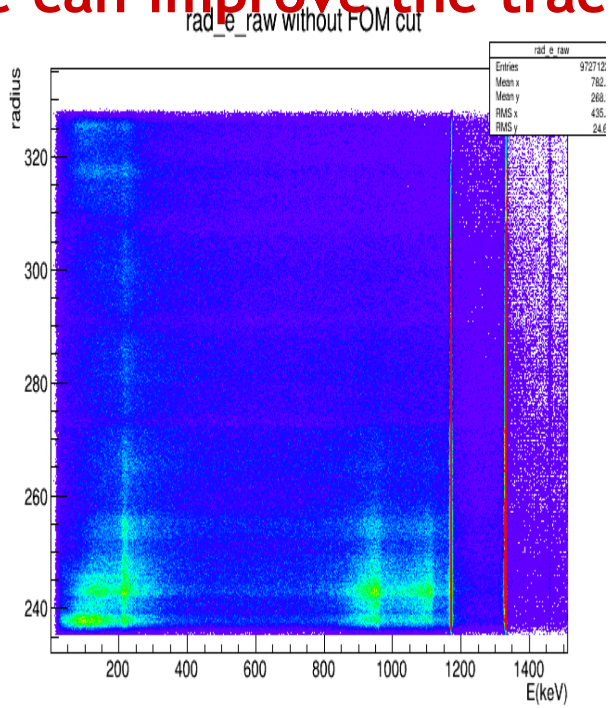
... it does help!

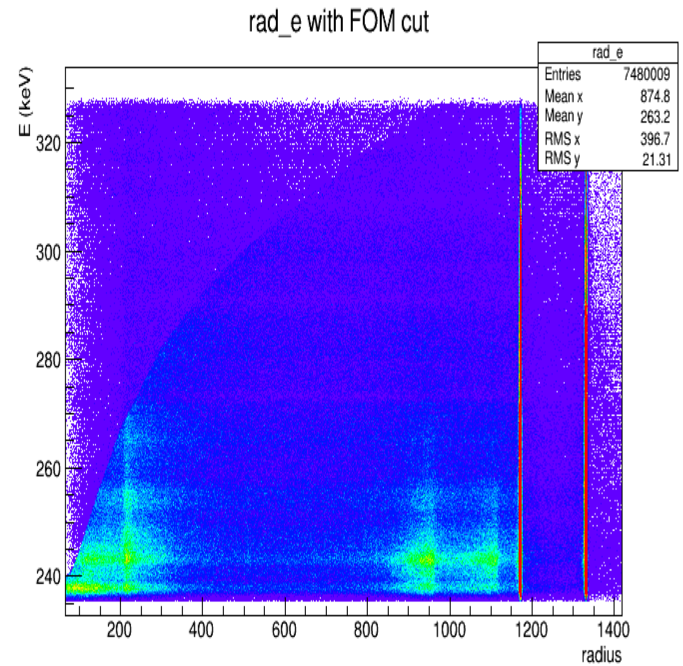
"Virtual Compton shield"

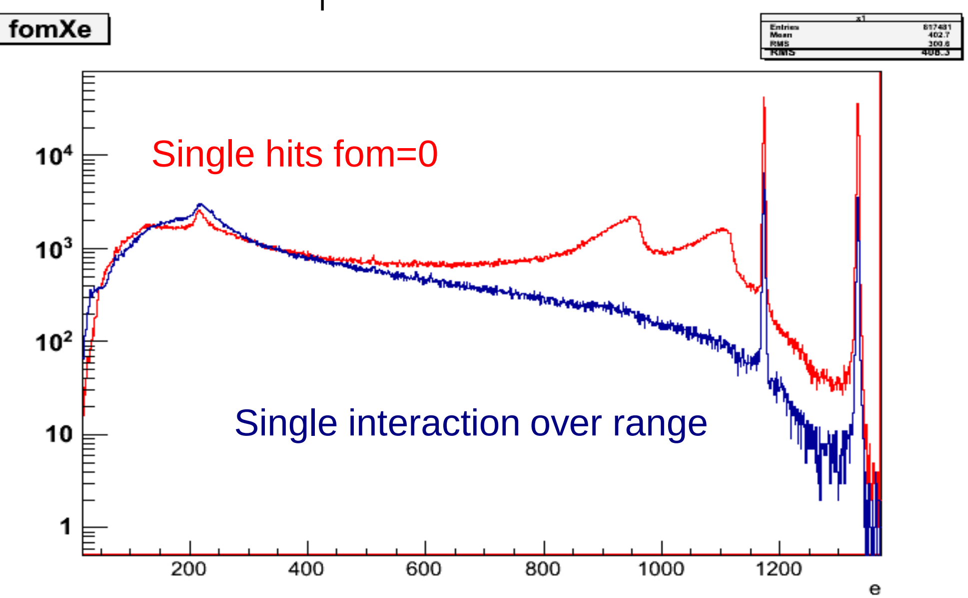
For single hits: We can improve the tracking by other means:

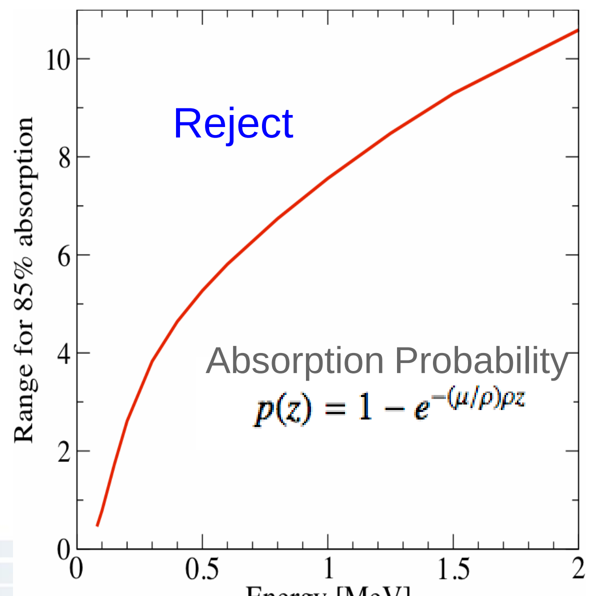
Escape lost

Looks like a low energy 'single interaction'

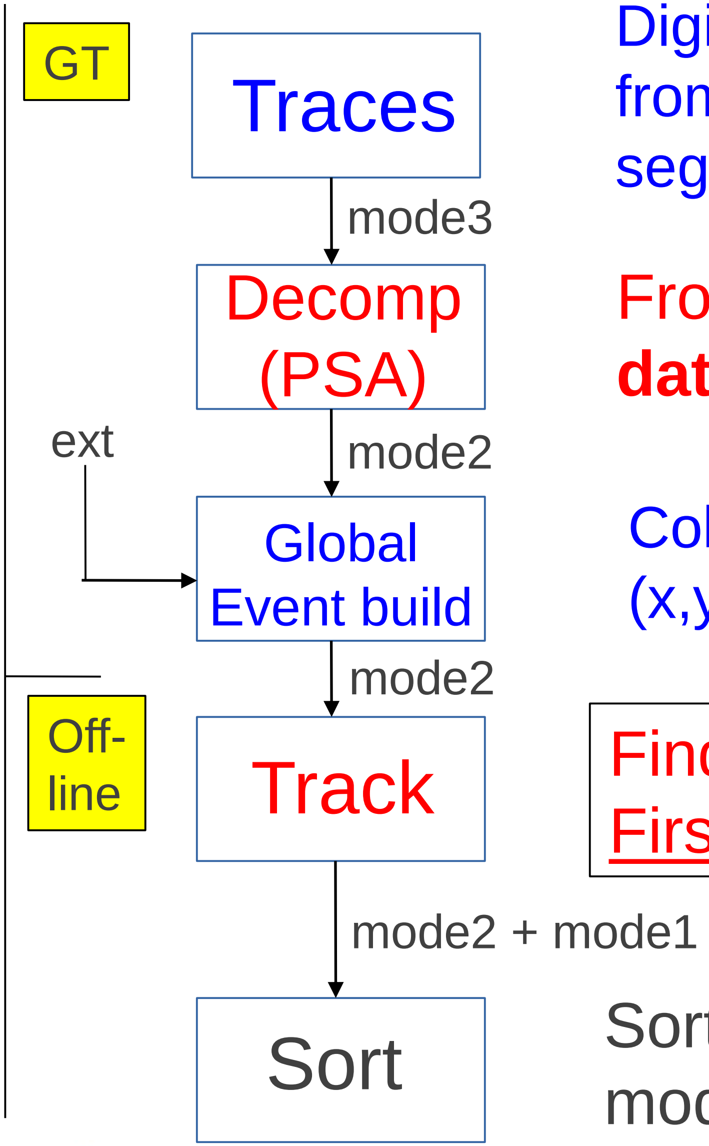








Summary: Tracking and sorting practicalities



Digitized traces of charge collections: from Central Contact (CC) and segments (net and induced)

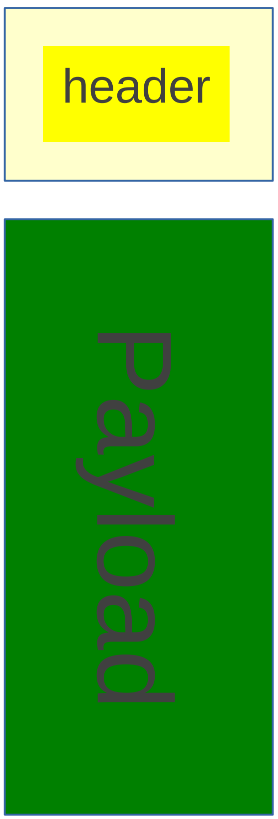
From the traces: **find the (x,y,z,e,t) data from fits to the traces**

Collect and time order the (x,y,z,e,t) data + add external data

Find coincidences, Cluster and Track.
<u>First time we can talk about 'gamma rays'</u>

Sort the [ext],(mode3), mode2 and mode 1 data (e.g., with GEBSort)

Universal: GT Header/Payload scheme also used for any AUX detector systems:




```
struct gebData {
  int type; /* type of data following
*/
  int length;
  long long timestamp;
};
```

```
#define GEB_TYPE_DECOMP        1
#define GEB_TYPE_RAW           2
#define GEB_TYPE_TRACK         3
#define GEB_TYPE_BGS           4
#define GEB_TYPE_S800_RAW      5
#define GEB_TYPE_NSCLnonevent  6
#define GEB_TYPE_GT_SCALER     7
#define GEB_TYPE_GT_MOD29      8
#define GEB_TYPE_S800PHYSDATA  9
#define GEB_TYPE_NSCLNONEVTS   10
#define GEB_TYPE_G4SIM         11
#define GEB_TYPE_CHICO         12
#define GEB_TYPE_DGS           14
#define GEB_TYPE_DGSTRIG       15
#define GEB_TYPE_DFMA          16
#define GEB_TYPE_PHOSWICH      17
#define GEB_TYPE_PHOSWICHAUX   18
.
.
```

Selected Chat file options:

```
./trackMain \
  track_GT.chat  \
  GTDATA/mode2.dat  \
  GTDATA/mode1.gtd >
GTDATA/trackMain.log
```

```
dtwin            30
target_x 0
target_y 0
target_z 0
CCcal CCenergy.cal
useCCEnergy
clusterangle   1  20
clusterangle  30  20
enabled "0-180"
trackingstrategy 1 0
trackingstrategy 2 0
trackingstrategy 3 0
trackingstrategy 4 0
trackingstrategy 5 0
trackingstrategy 6 5 ggtttt
trackingstrategy 7 5 gggtttt
trackingstrategy 8 5 gggttttt
```

← (10 nsec units)

```
recluster1   0.01  0.1  3 10  0.90
nprint 20
singlehitmaxdepth 23 1.9 18.5 1.0
0.000 0.59
.
.
.8.000 10.17
10.00 10.01
16.3  20.0
```

There are many more options!
Here we just show the basic ones.

We add mode1 data to the mode 2 data!!!!

Some functions in tracking

- Single interaction range (already covered)
- Splitclusters: try to split clusters that have a bad FOM into two gamma rays that have good FOMs. [**example later for summed lines**]
- Combine clusters: try to combine that have bad FOMs into one gamma rays that has a good FOM
- Recluster: split gamma rays with bad FOM decreasing the clustering angle. [*can go the other way too*]
- Matchmaker: combine two single interaction gamma rays into one gamma ray with a good FOM [tricky!]

We can execute these functions iteratively until we have made the best out of the data we were given

The problem: sometimes we make the wrong call because the experimental data is not perfect (i.e., we accidentally destroy good gamma rays)

Types of spectra we have:

- CCsum (core common): each energy in the central contact (CC) is binned in a spectrum. Natural spectrum in Gammasphere; but 'compromised' in tracking arrays because of the scattering between the crystals. A scattering correction factor Cs must be introduced.
- CCcal (or CCadd): the sum of all the energies in the CC is added up in a spectrum

This is the calorimetric spectrum. Used mostly to determine the efficiency of a tracking array. It treats the arrays as just one detector, corrections are substantial.

- After tracking, we have Tracked spectra: clustered and 'evaluated spectra'. They depends on the tracking parameters, in particular, the clustering angle and the FOM cut

We would like to determine the efficiency for these spectra. From CCsum and CCcal we get the array photopeak efficiency.

We have two methods
CSM: Calibrated Source Method
SPM: Summed Peak Method

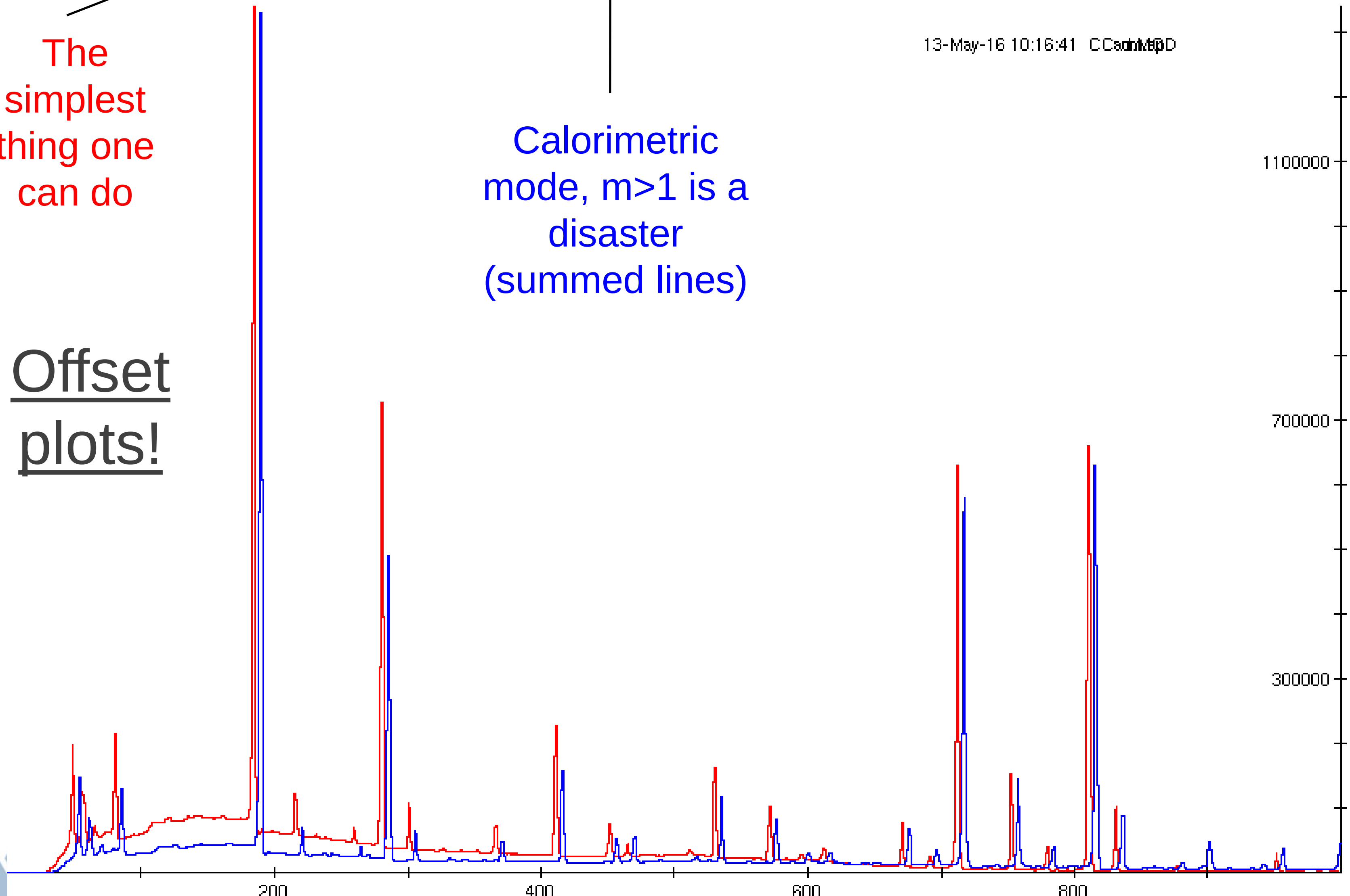
Both CCsum and CCcal are 'complicated' spectra in tracking arrays (compared to Gammasphere)

How tracking improves the spectra: ^{166}Ho compare: CCsum (ref), CCadd, clustered and tracked

The simplest thing one can do

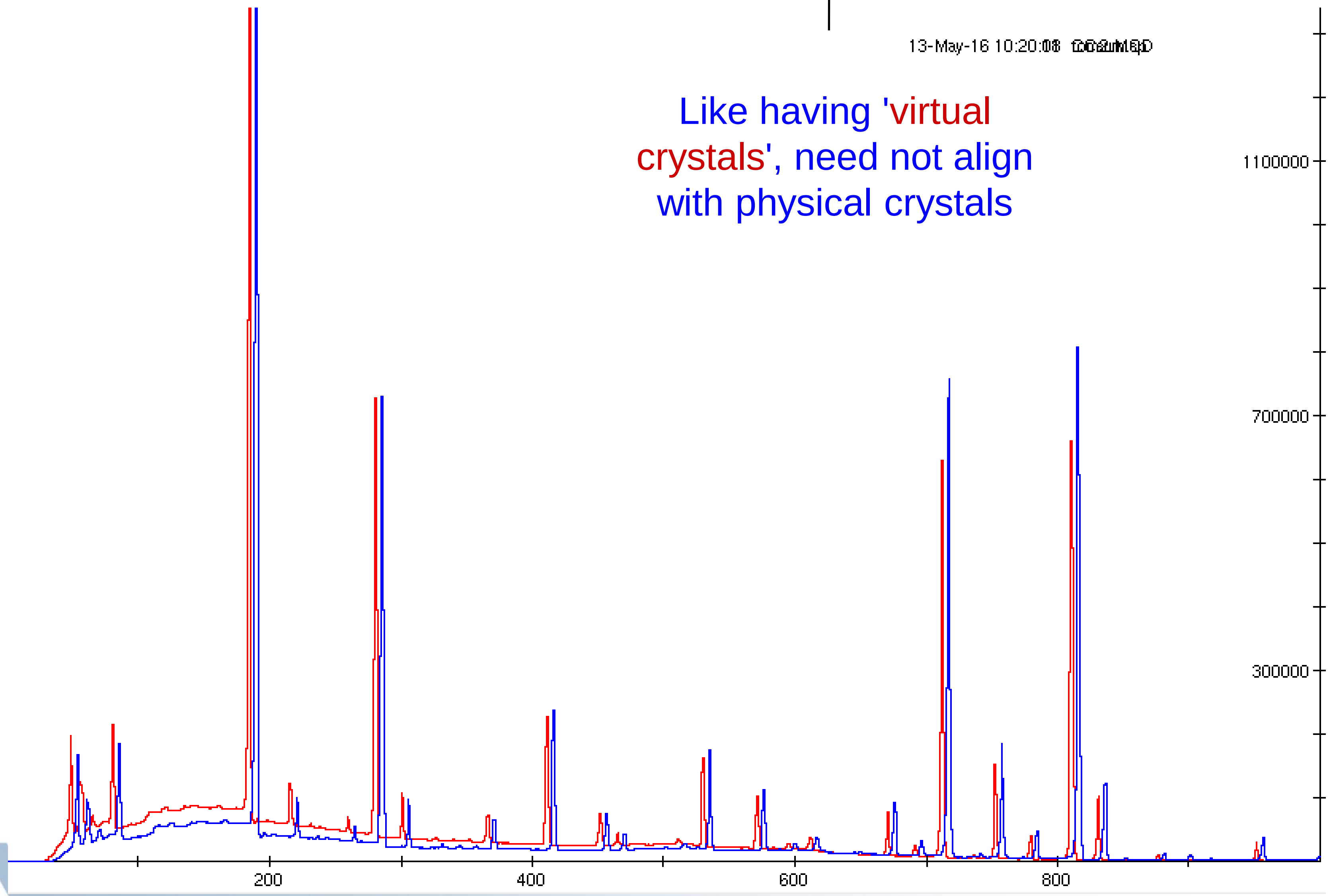
Calorimetric mode, m>1 is a disaster (summed lines)

Offset plots!

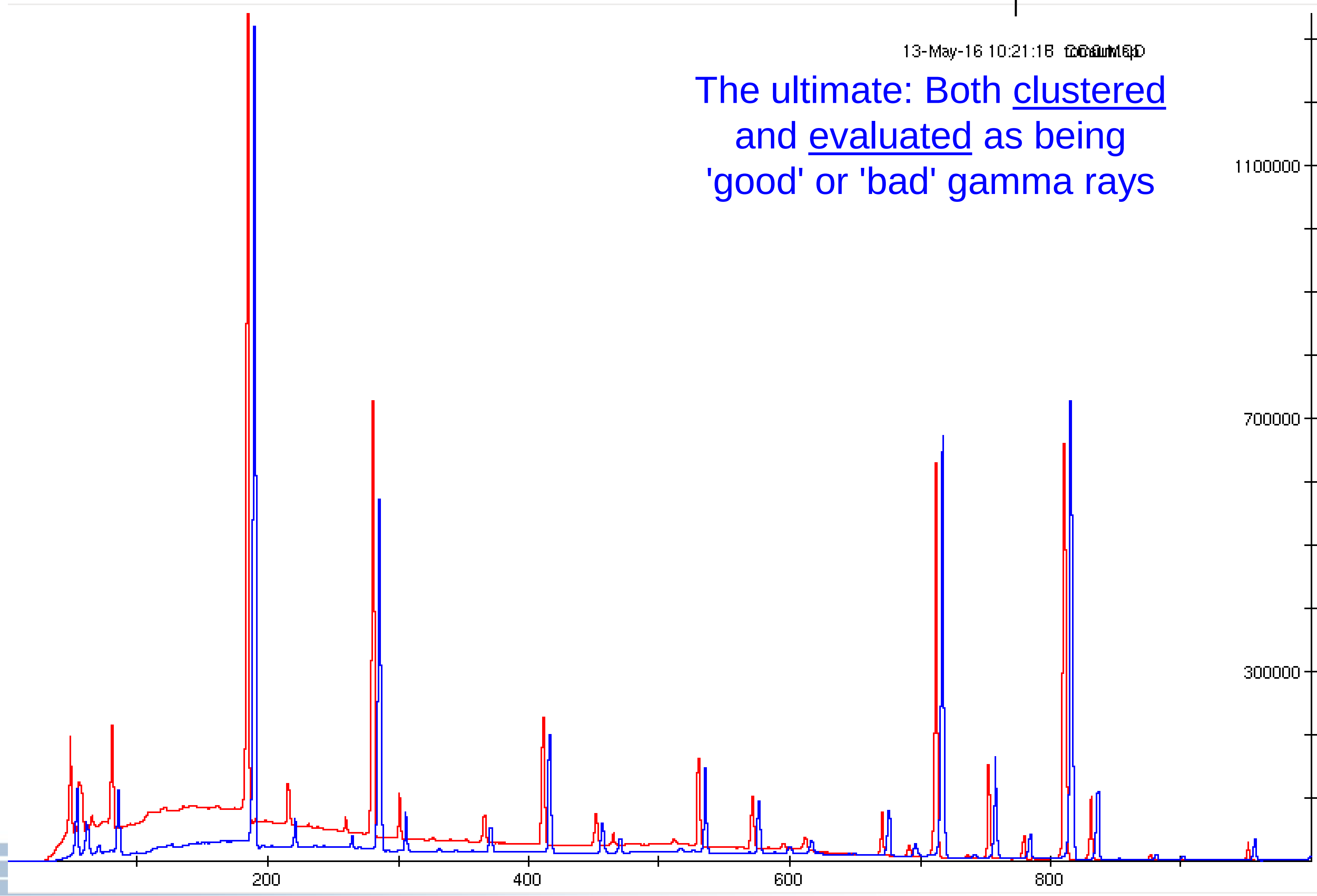


How tracking improves the spectra: ^{166}Ho compare: CCsum (ref), CCadd, clustered and tracked

Like having 'virtual crystals', need not align with physical crystals



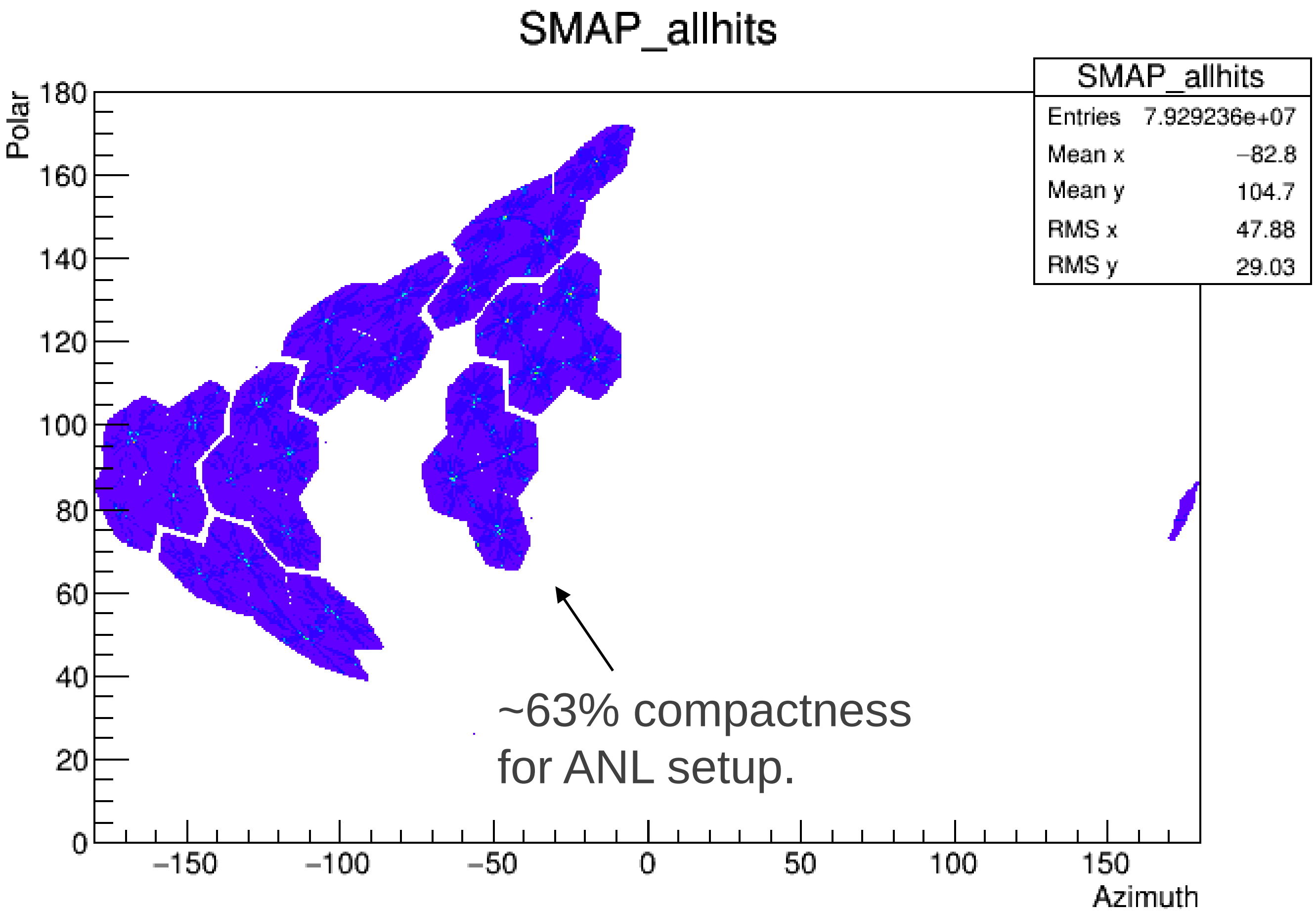
How tracking improves the spectra: ^{166}Ho compare: CCsum (ref), CCadd, clustered and tracked



The packing of the array matters!

Compactness: number of crystal sides that have close neighbors to total number of crystal sides. Best we had was 71% at MSU

BTW: at MSU, typically a more open packing is used in order to take advantage of the Lorenz boost. So tracking is not always used here...



~63% compactness for ANL setup.

Efficiency of tracking arrays, *it is complicated*

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

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

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

Observed areas for ^{60}Co source with [N==1,Cs==0] for ***CCadd*** and N number of crystals for ***CCsum*** where Cs>0

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

F: addback factor

Correct for the fact that the 1173 can knock out counts in the 1333 line and vice versa. CCcal: big effect, CCsum smaller effect →

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

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

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

$$S = A_S t L_F.$$

Live fraction

C_f is the angular correlation factor small correction for CCcal bigger for CCsum

See NIMA59201 (In print)

Summed Peak Method: SPM [A(2506)/A(1173 method]

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

Calibrated Source Method: CSM [S and L_f must be known]

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

Also have external/internal detections of 1173

With CCcal and CCsum: four measurements of the array efficiency

True areas and true P/T (new concepts)

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

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

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

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

Include for CCcal and CCsum but not for tracked spectra

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

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:

	SPM cal	CSM cal	SPM sum
ϵ_P(mixed)	6.11(9)%	6.05(9)%	-
ϵ_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)

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

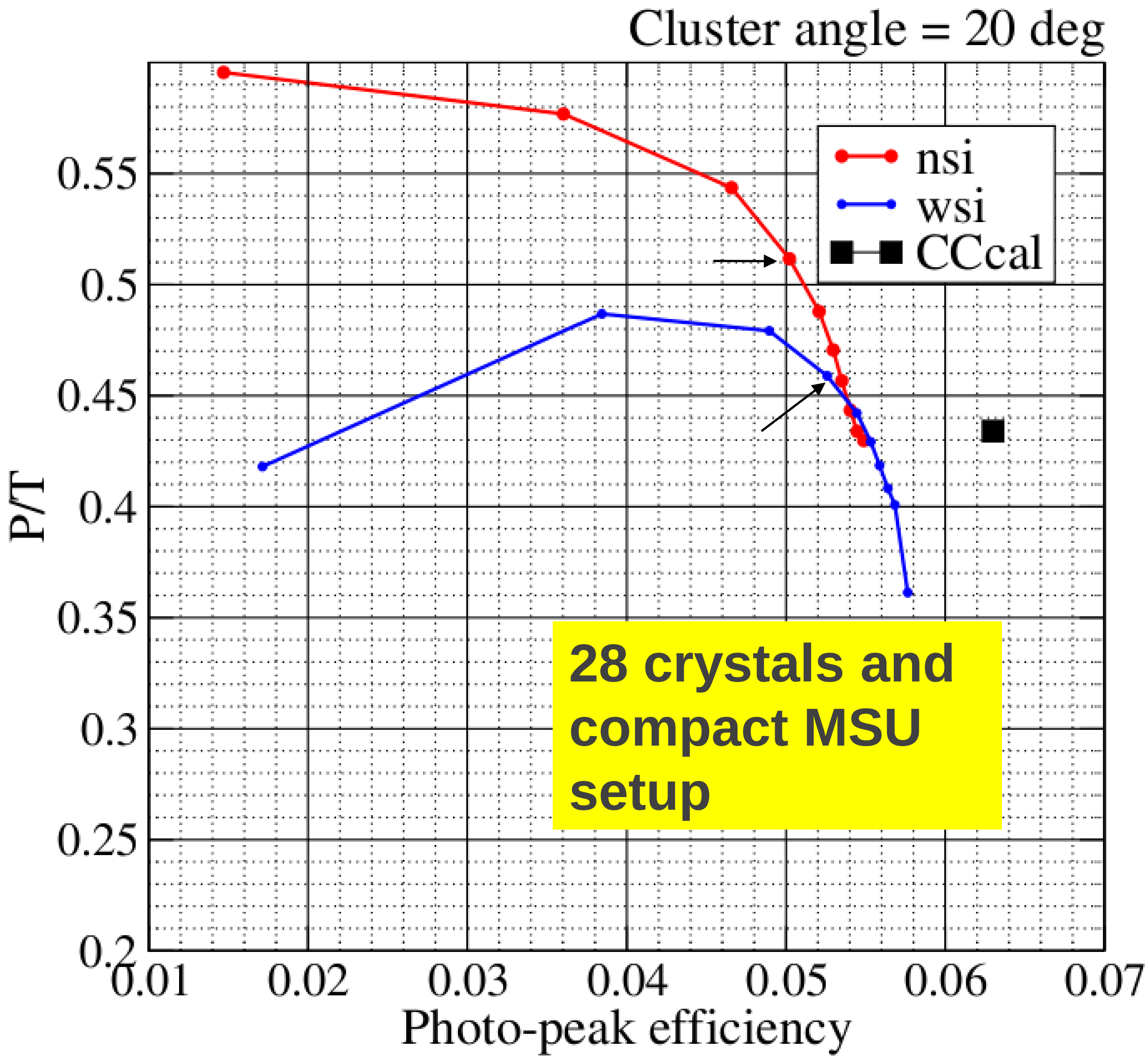
Weighted mean: 6.27(4)% for 28 crystals (included external/internal measurements too)

Tracking Basics:

The usual efficiency and P/T compromise!

nsi: no single interactions

wsi: with single interactions



Where GT shines:

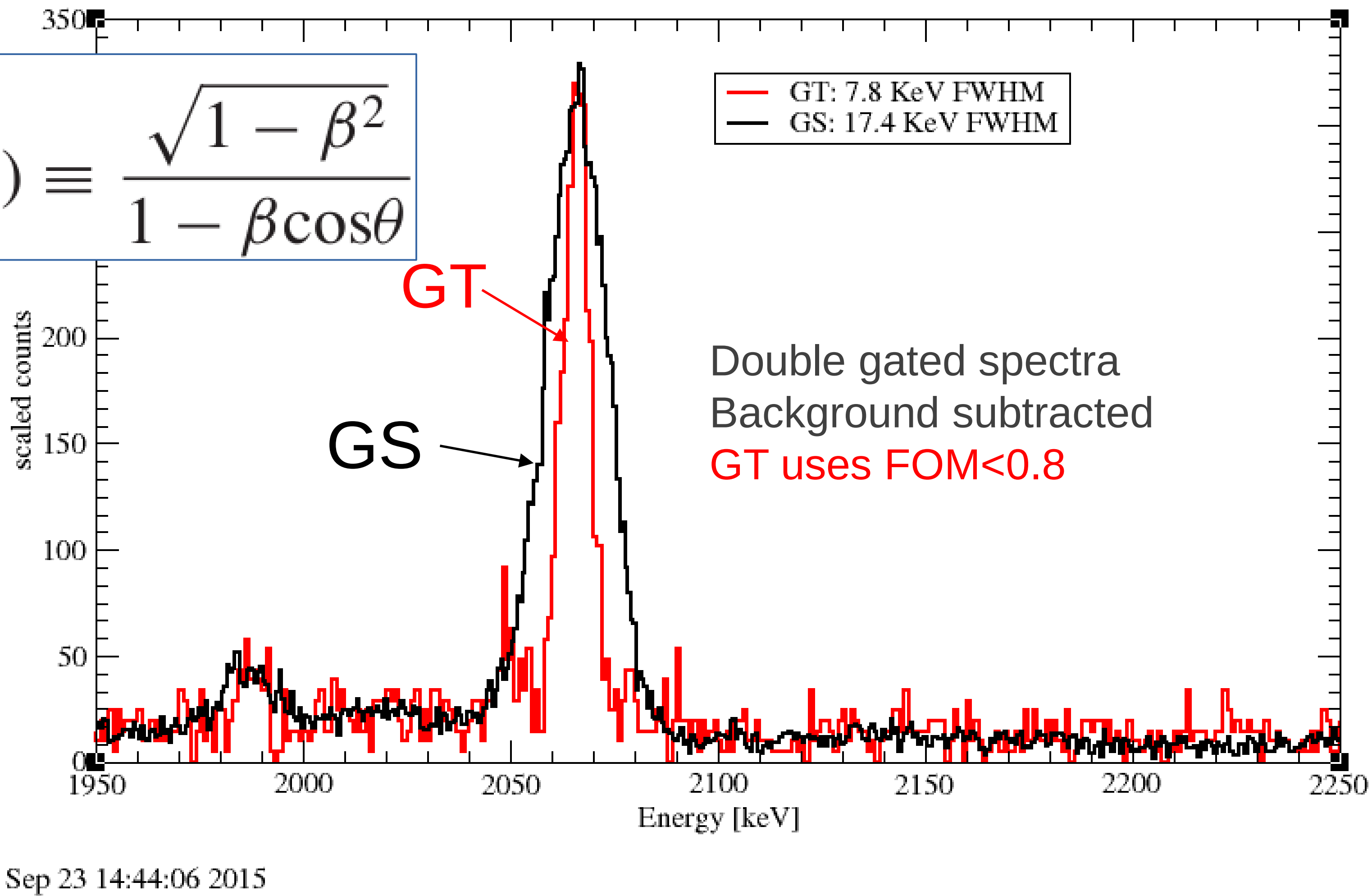
V/C=8.8%

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

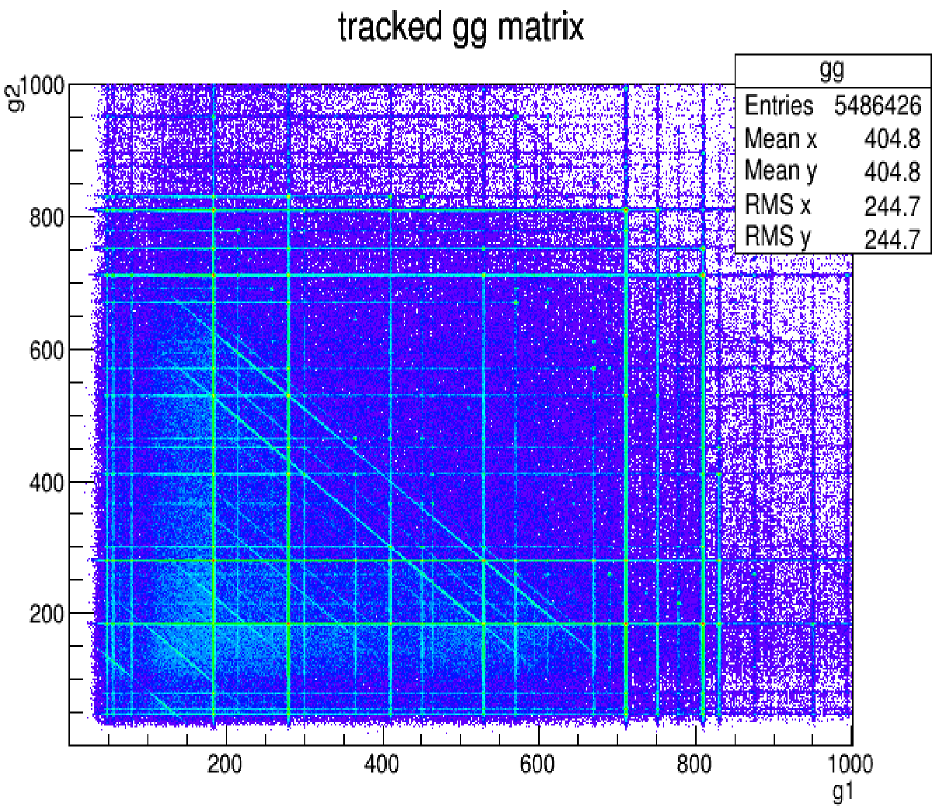
^{92}Mo case: energy resolution in GT is *much* better at 2 MeV for fast moving beams! Need tracking to find first interaction point

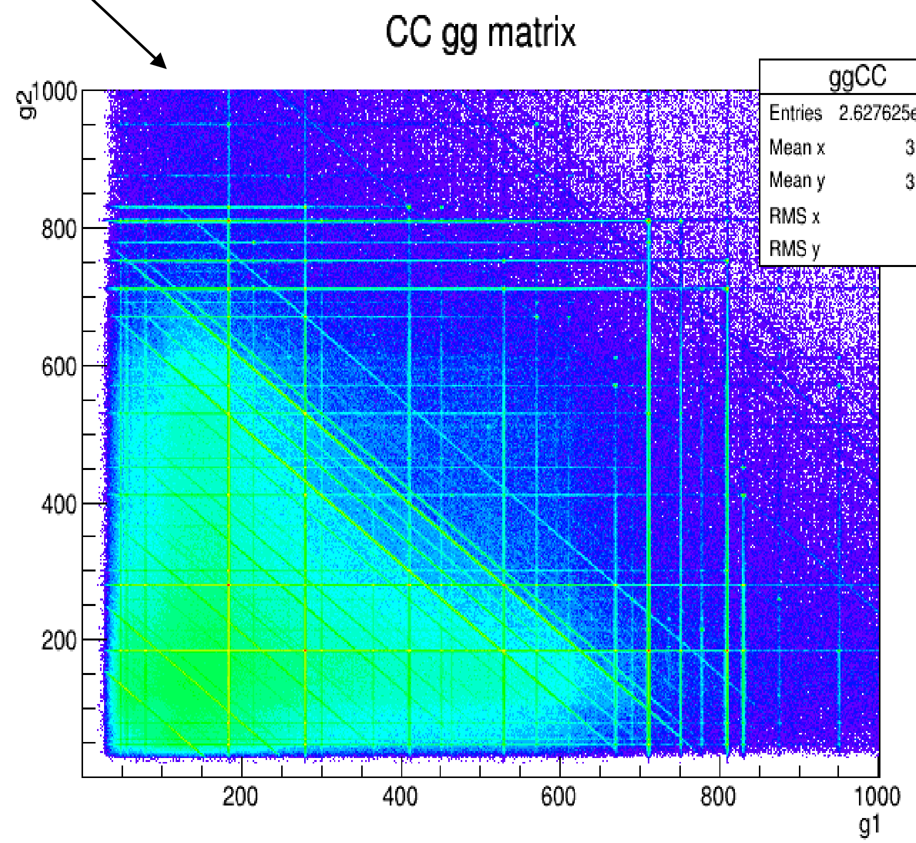
GS sort using side channels (rebel)

$$F(\beta,\theta) \equiv \frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta}$$



Matrices with and without tracking [^{166}Ho]





Much improved, but not perfect

Log scale

Lots of Compton-Compton coincidence that will obscure your photo peak coincidences

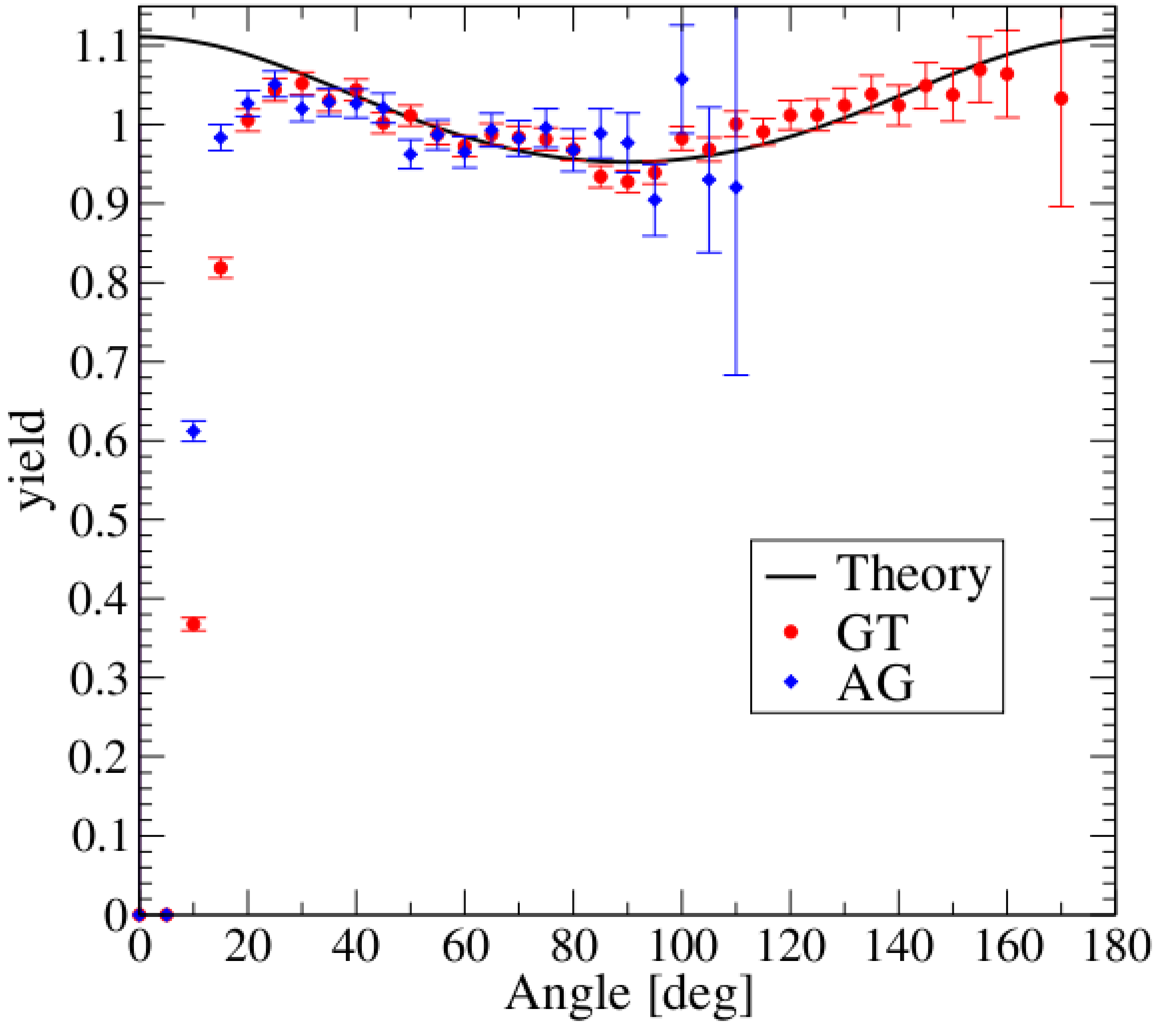
The clustering 'hole': observe it through the angular correlation

60Co source in GT and AG

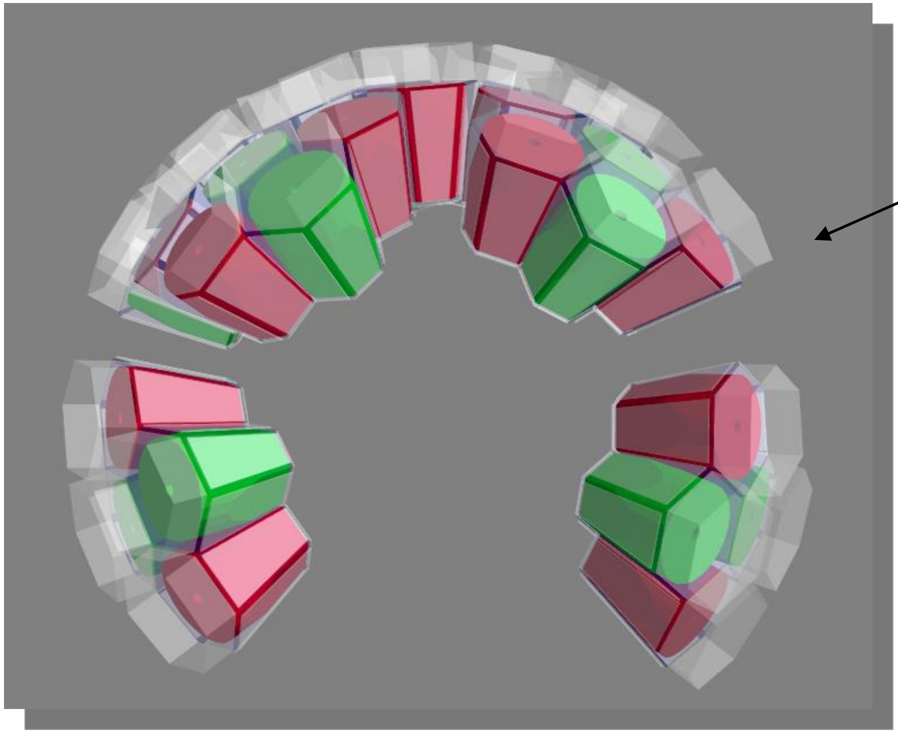
Clustering angle 10 deg

Gamma rays in the same clustering angle gets added up and not split as they should have been...

[there is a trick from the AG group: 'split before track']



GEANT4 Simulations



Typical MSU Configuration (not compact)

UCGRETINA

Lew Riley

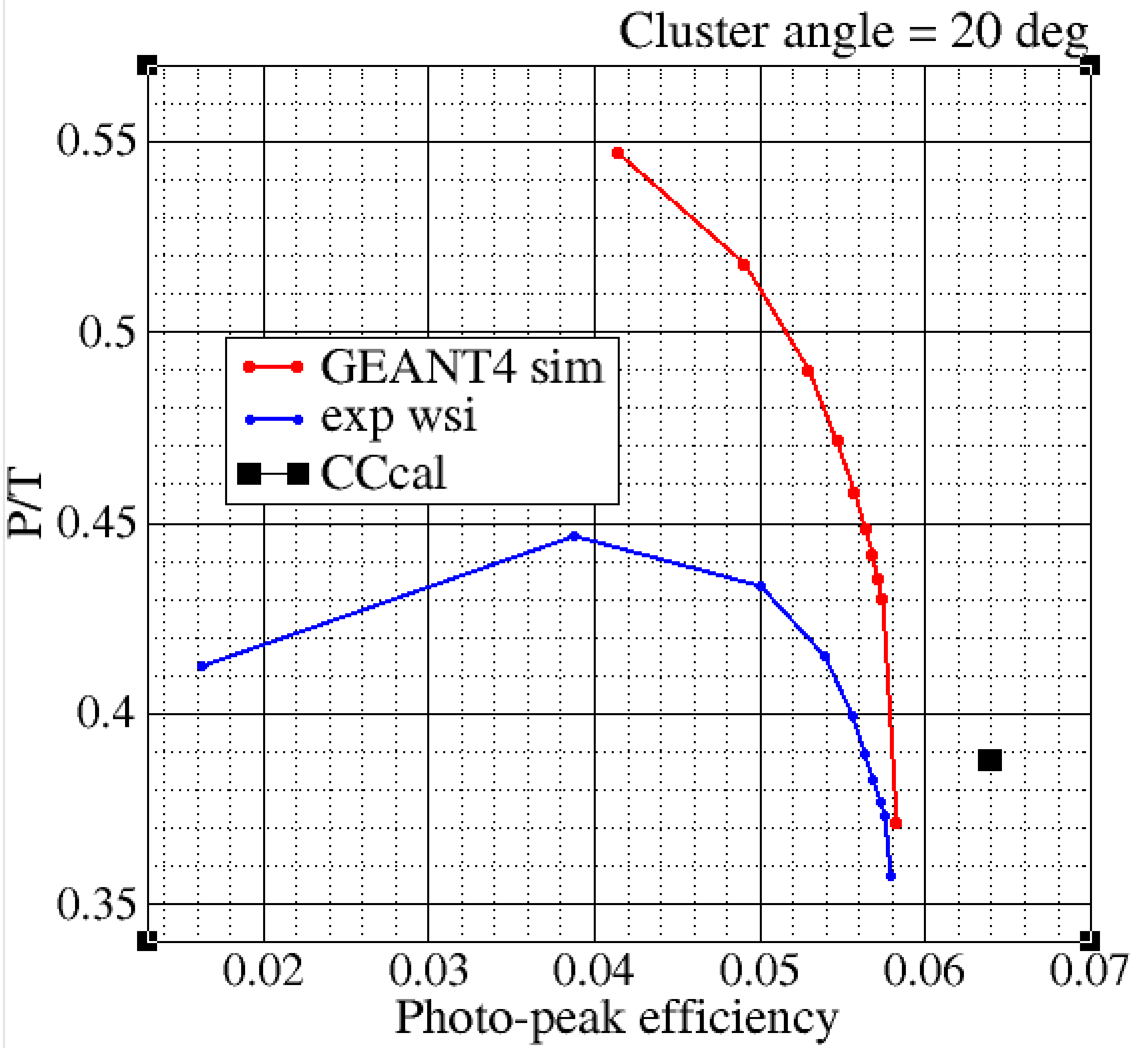
Ursinus College

GEANT4 - GRETINA Simulation

bitbucket.org/lriley/ucgretina

Adapted from the AGATA simulation code

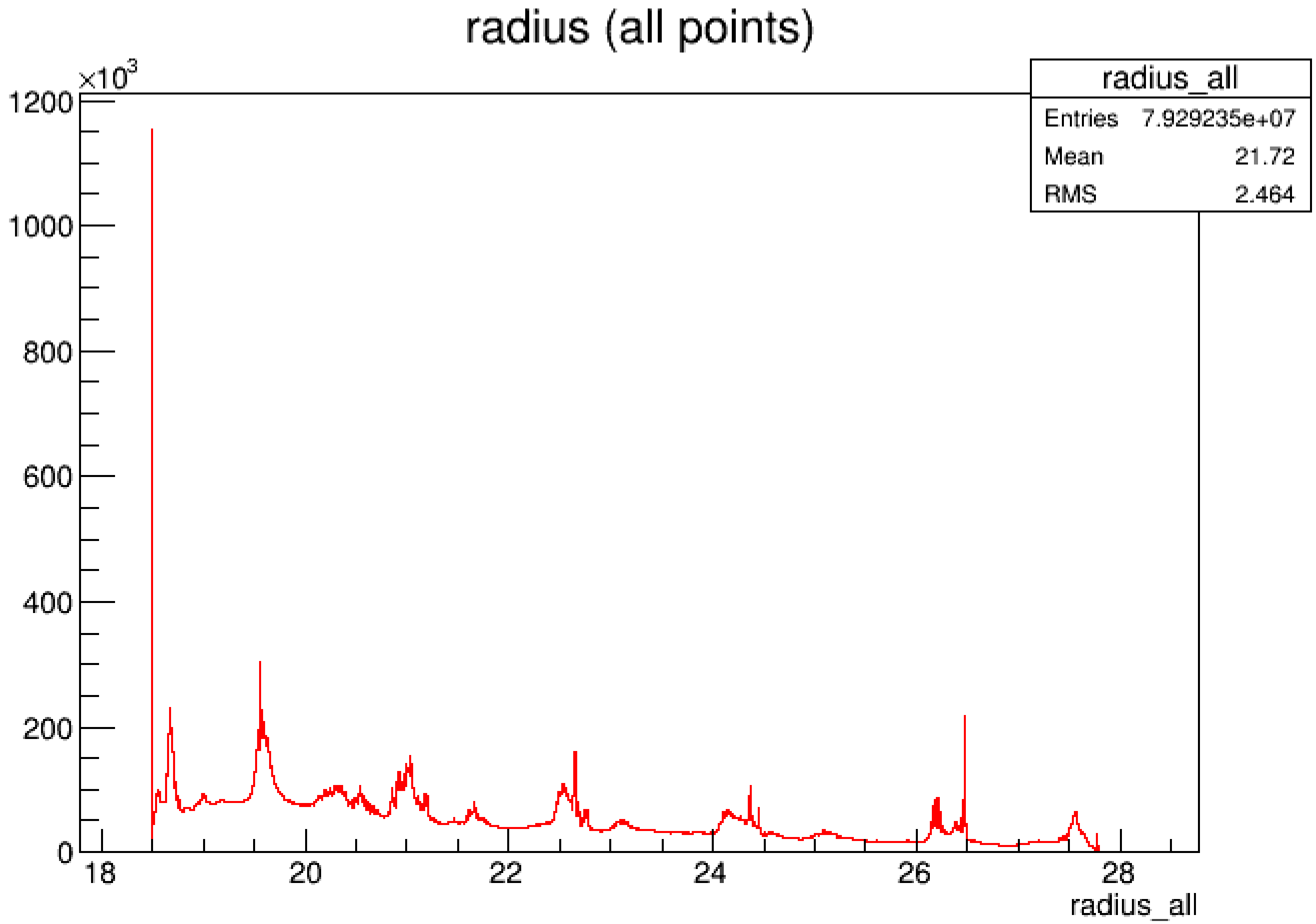
P/T curves: GEANT4 and measured for ^{60}Co



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

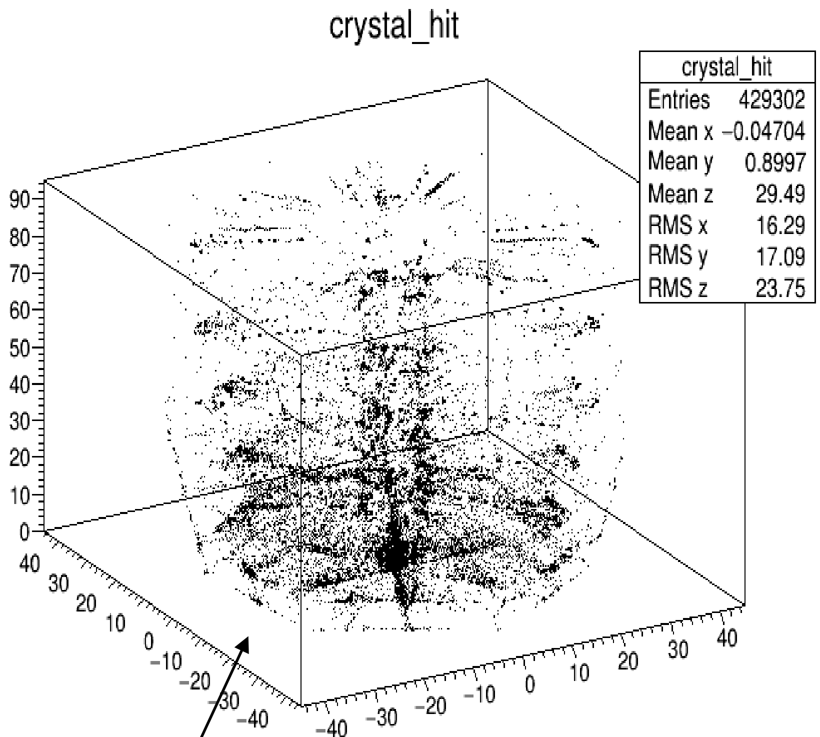
Simulation needs to be improved too

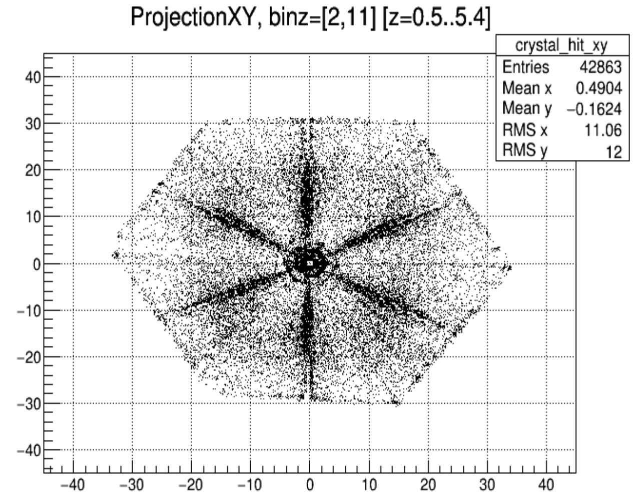
The radius spectrum. It should be smooth, but it has structure

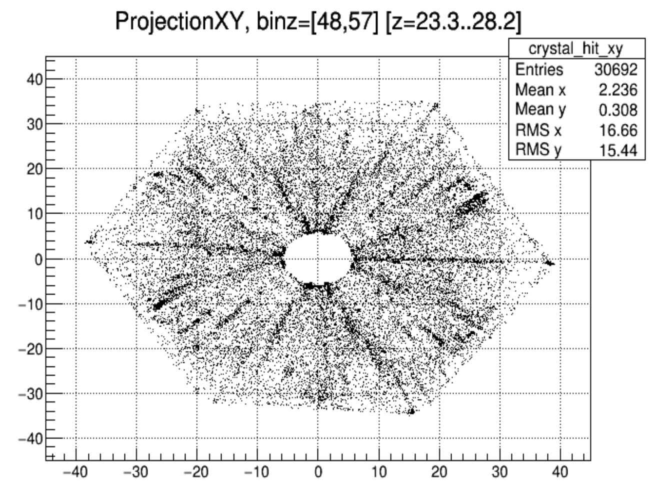


Decomposition (or electronics?) prefers to place Interactions near segment boundaries...

We have some GT and AG ‘data quality’ issues. Attempt to display interaction points in 3D using ROOT (preliminary analysis)







CAREFUL!!!! There are counts in between.
Just a ROOT display feature..

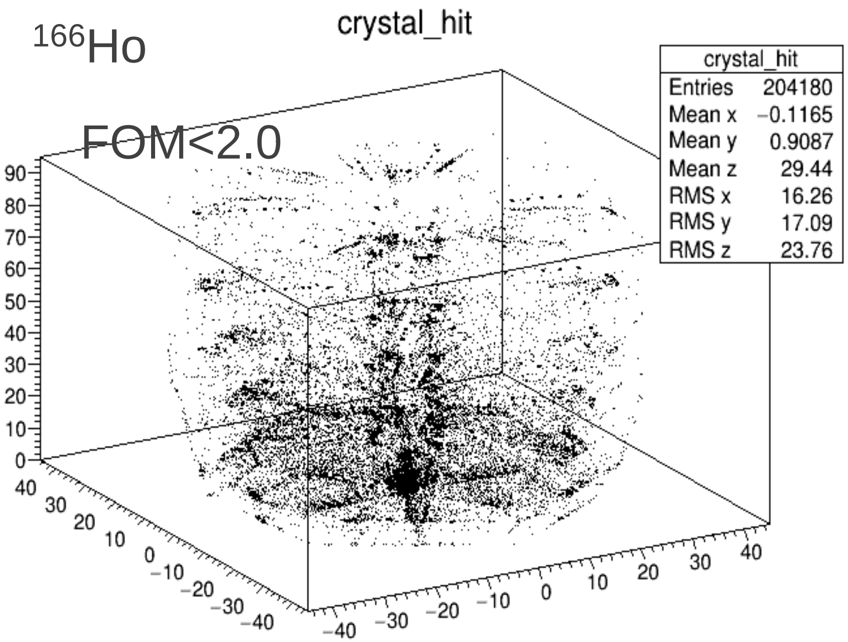
GT decomposition has ‘preferred’ interaction regions for most crystals.
We see that clearly when we slice through the crystals.
Not good for tracking

(AGATA has similar problems...)

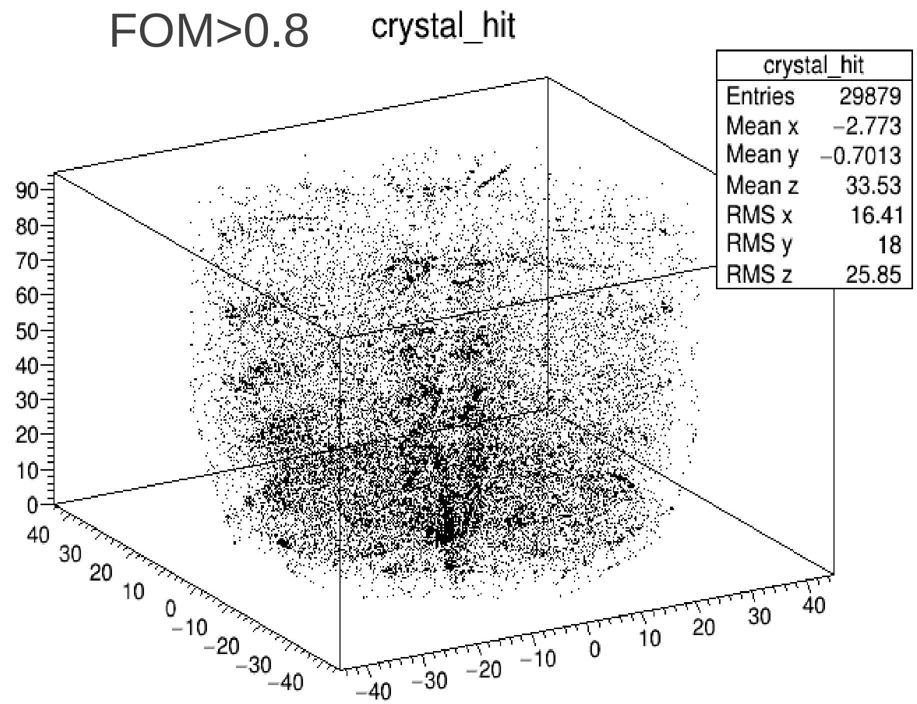
FOM cuts

^{166}Ho

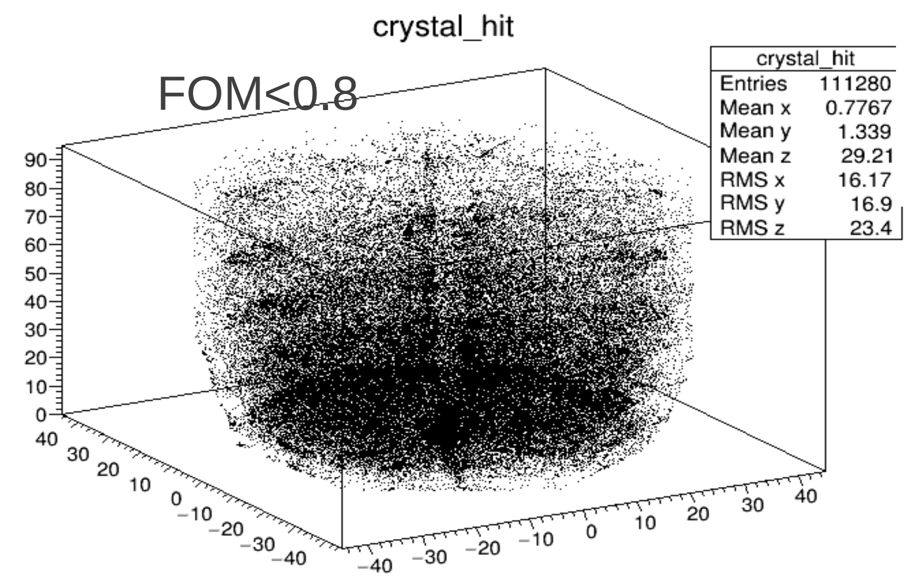
FOM<2.0



FOM>0.8



FOM<0.8



The bad interaction areas <u>are</u> associated with 'bad' FOM gamma rays

<u>But be careful with ROOT 3D plots....</u>

The 'pesky' summed lines, examples from ^{166}Ho source:

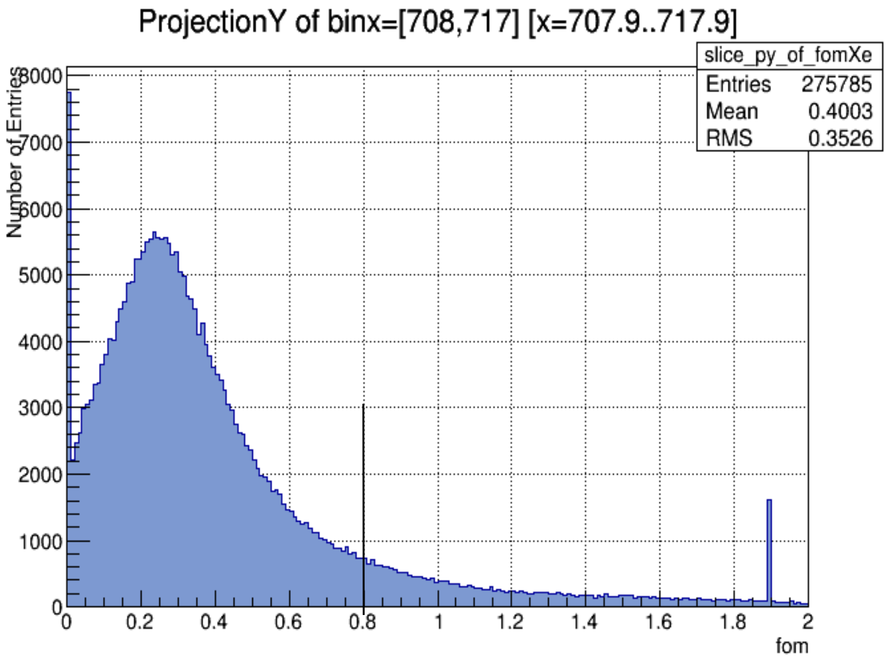
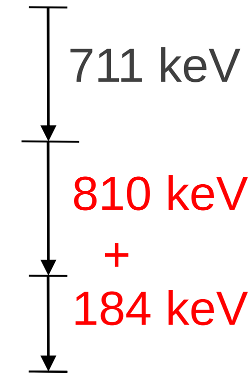
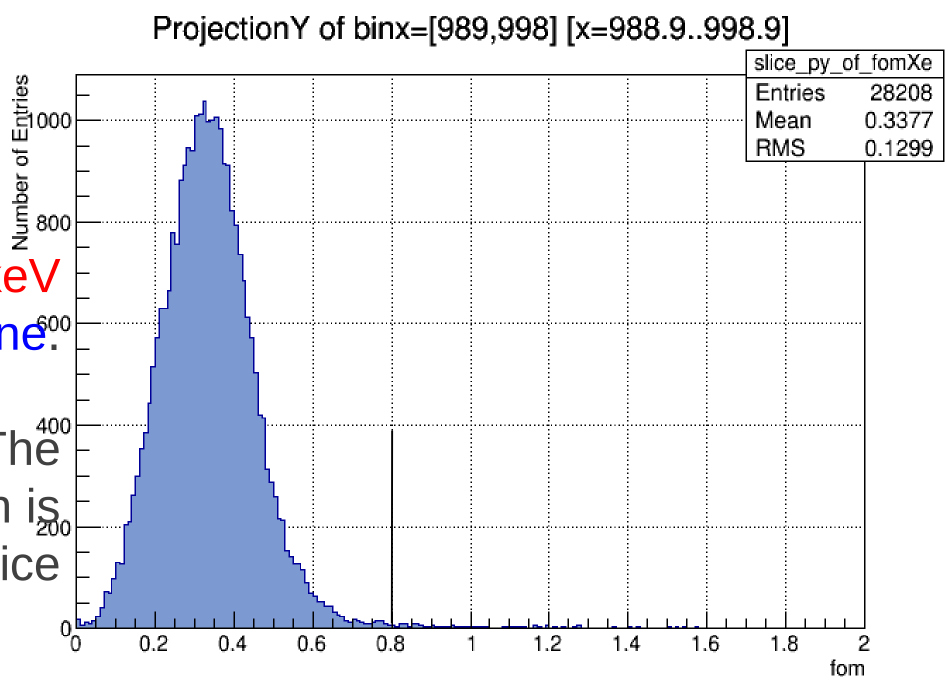


Photo peak
FOM distribution for 711 keV



184+810=994 keV
summed line:



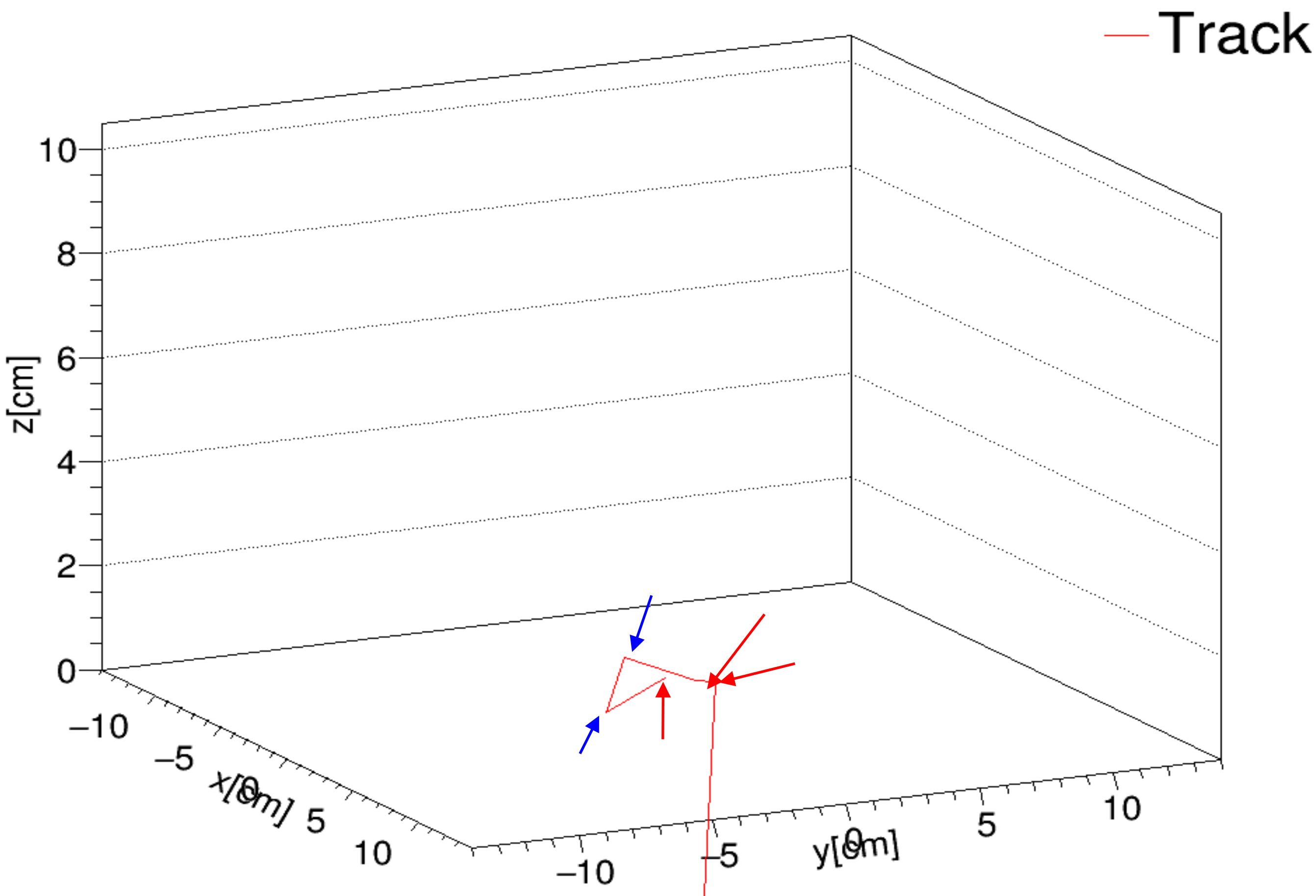
The FOM distribution is surprisingly nice

Example of tracks from summed line

182+810=992

0: (valid) ndet= 5 esum= 0.9922/bestperm=00005/FOM= 0.3248; (tracked)

IP-> (-17.69 7.36 1.76) order: 0 ; r= 19.25 cm e= 0.411/s= 0.411; 0, ts=25670256278;
.. (-17.91 6.79 1.56) order: 1 ; r= 19.22 cm e= 0.265/s= 0.676; 1, ts=25670256278;
.. (-18.03 6.35 0.15) order: 4 ; r= 19.11 cm e= 0.133/s= 0.809; 4, ts=25670256278;
.. (-18.30 3.92 0.44) order: 3 ; r= 18.72 cm e= 0.103/s= 0.912; 3, ts=25670256288;
.. (-19.02 4.95 0.38) order: 2 ; r= 19.66 cm e= 0.080/s= 0.992; 2, ts=25670256288;



FYI: We can handle AGATA data too.
It is instructive to compare!!

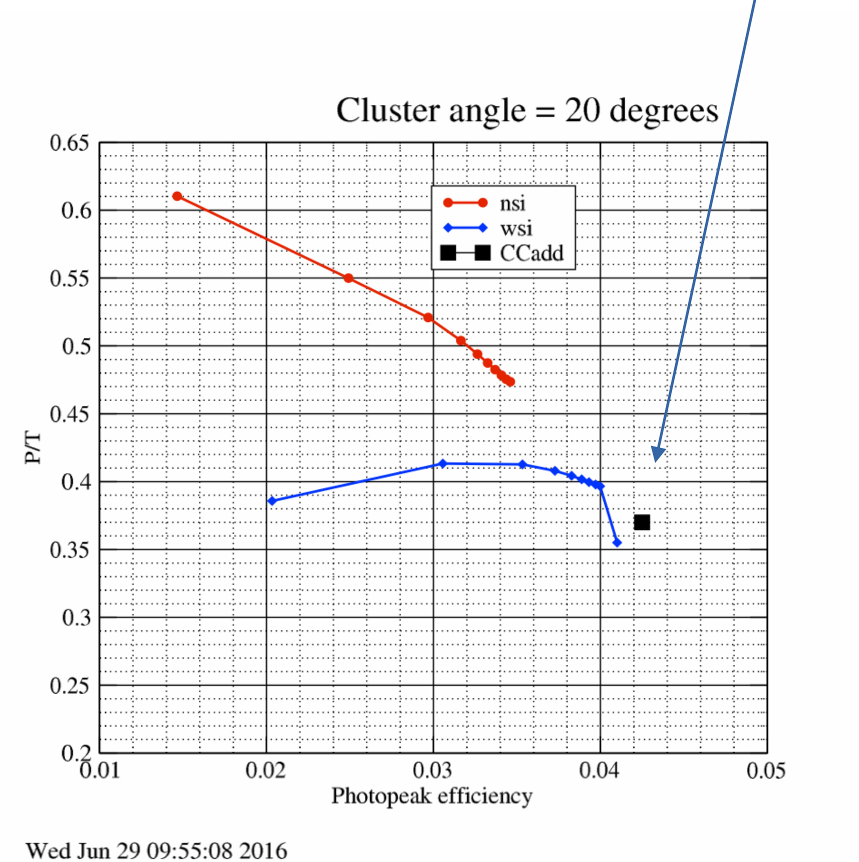
AGATA and GRETINA

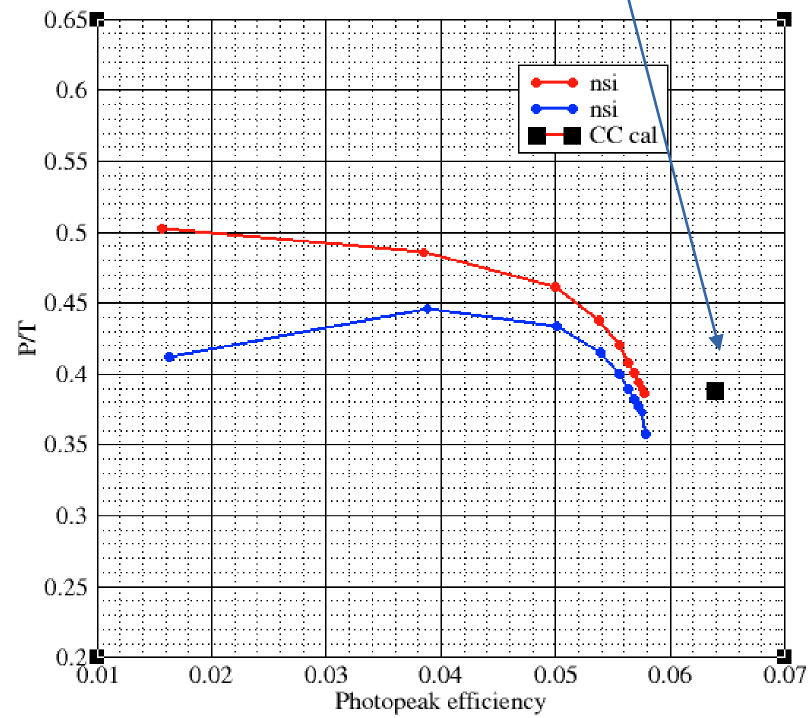
29 crystals positioned at 23.5 cm

28 crystals positioned at 18.5 cm

(GANIL data, from A. Korichi)

4.25% = 29/28 [(18.5/23.5)^2] * 6.4%





Interesting differences we can learn from...

Challenges and future:

- We are still working on optimizing the tracking parameters using a ^{166}Ho source
- **We need to improve the P/T.** We have to find out where the improvement might come from: electronics, decomposition or tracking
- The split-cluster tracking function has 'problems' (summed lines)
- We are working on improving the combinecluster function
- Move the GEANT4 simulations closer to the measured data
- More comparisons GRETINA ↔ AGATA to understand our problems (AGATA-GRETINA collaboration meeting at ANL Dec 5-7)

You can download the GRETINA tracking package from
http://www.phy.anl.gov/gretina/GEBSort
Or via the main GRETINA web page:
http://gretina.lbl.gov

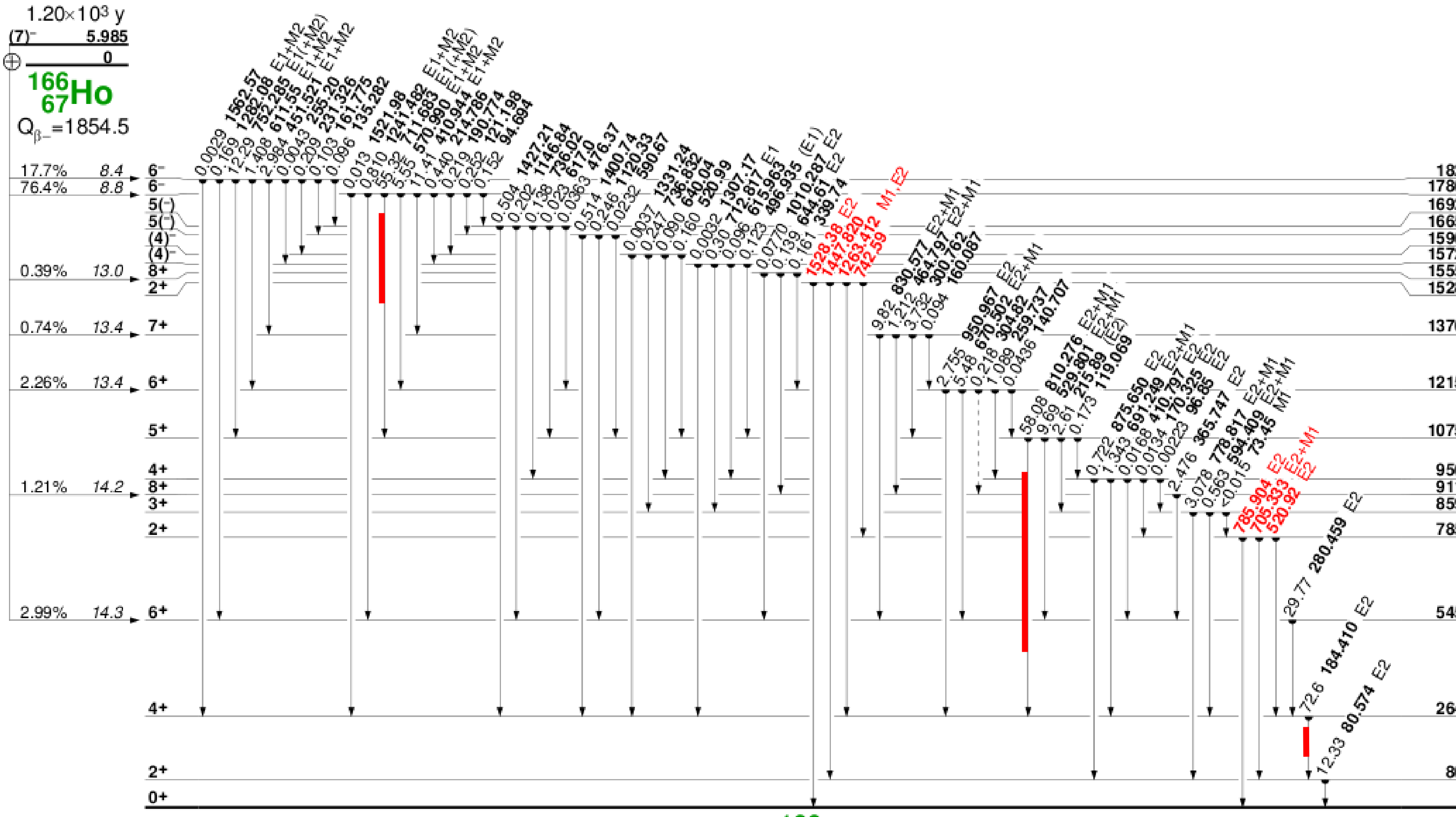
***Questions**: torben@anl.gov*

Extra slides

FYI: We can handle AGATA data too!

- We can translate Pulse Shape Analyzed (PSA) AGATA data to the GRETINA mode2 data
- We can then send the AGATA data trough the GRETINA tracking and sorting codes
- Thus, we can compare

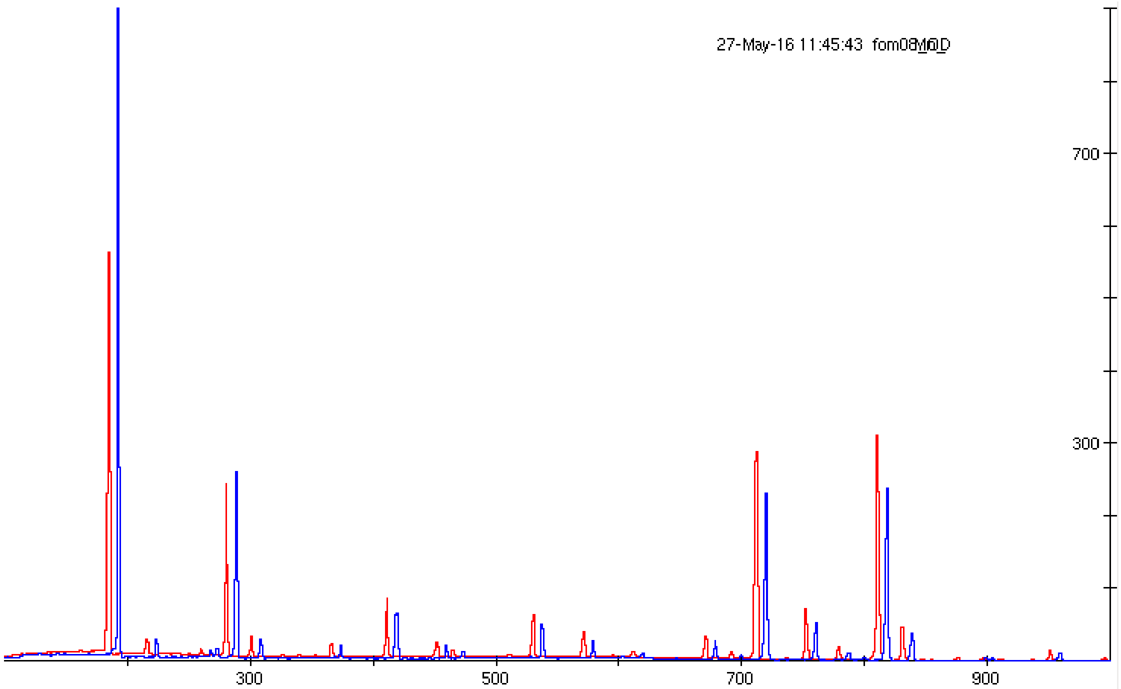
^{166}Ho source, T1/2=1200 years, not expensive

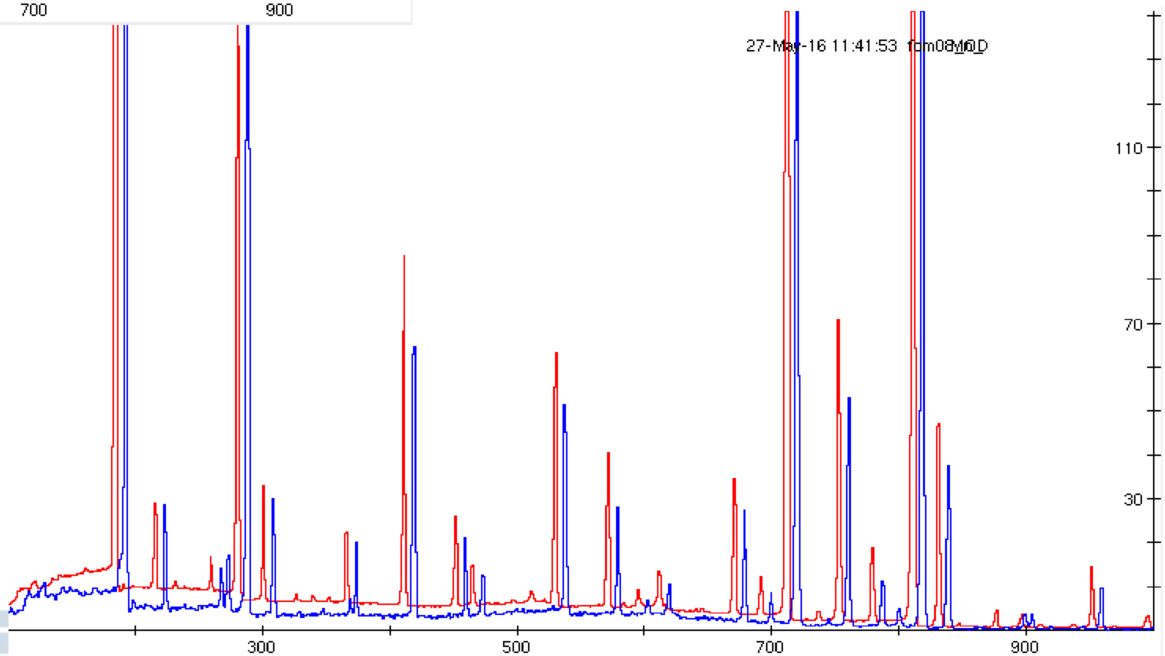


166Ho source lines

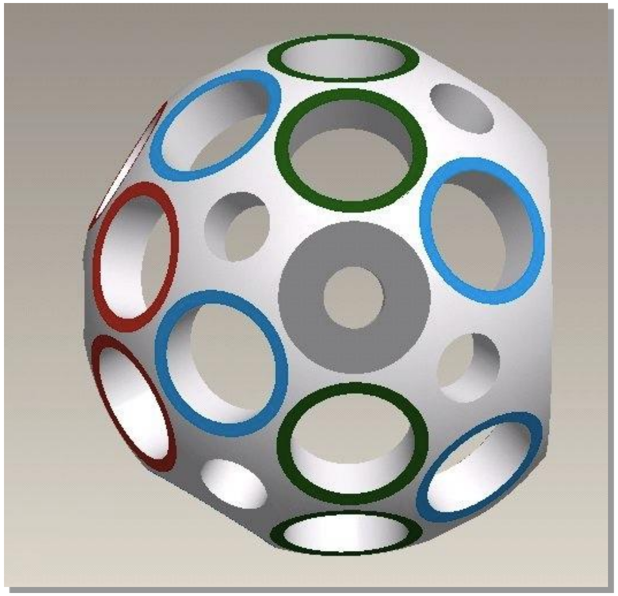
^{166m}Ho	1200 y	80.5725 *13*
		184.4107 *11*
		280.4630 *23*
		300.741 *3*
		410.956 *3*
		451.540 *4*
		529.825 *4*
		570.995 *5*
		670.526 *4*
		711.697 *3*
		752.280 *4*
		778.827 *6*
		810.286 *4*
		830.565 *4*
		875.663 *7*
		950.988 *4*
		1241.519 *4*
		1282.102 *5*

Compare **GEANT4 simulation** with **measured data** for the ^{166}Ho source





The Support Frame

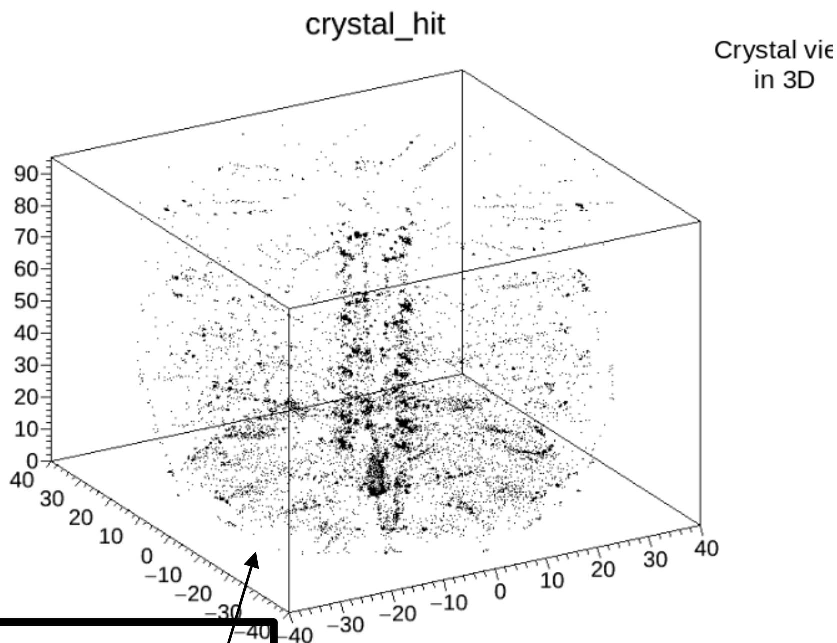


30 holes
120 crystals

RING	ANGLE	SLOTS
1	-	-
2	58	4
3	90	8
4	122	5
5	148	5

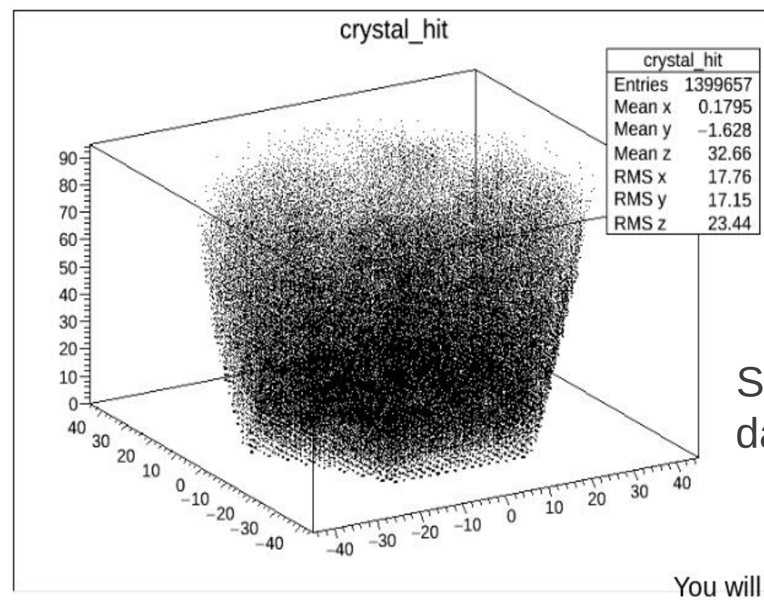
We have some GT and AG 'data quality' issues. Attempt to display interaction points in 3D using ROOT (preliminary analysis)

GT, 158Er, shootout, ID=32



AGATA data from GANIL

158Er second commissioning 2015



NOTE: Smoothed data looks different!

You will see a 3D grid of points...

CAREFUL!!!! There are counts in between. Just a ROOT display feature..

GT decomposition has 'preferred' interaction regions for most crystals. We see that clearly when we slice through the crystal

'Looks' more uniform: expect better tracking, but we don't see that **(we are working on this)**