Tracking with OFT

AGATA data analysis workshop

11-15/09/2023

Legnaro

Aim of tracking

Read for each event the list of deposited energies and positions of all the interactions points in AGATA

e_1, x_1, y_1, z_1
e_2, x_2, y_2, z_2
…………….
e_n, x_n, y_n, z_n

Disentangle the interaction points i.e reconstruct individual photon trajectories and extract photon energies and 1st & 2nd interaction positions (for Doppler correction & polarization measurements)

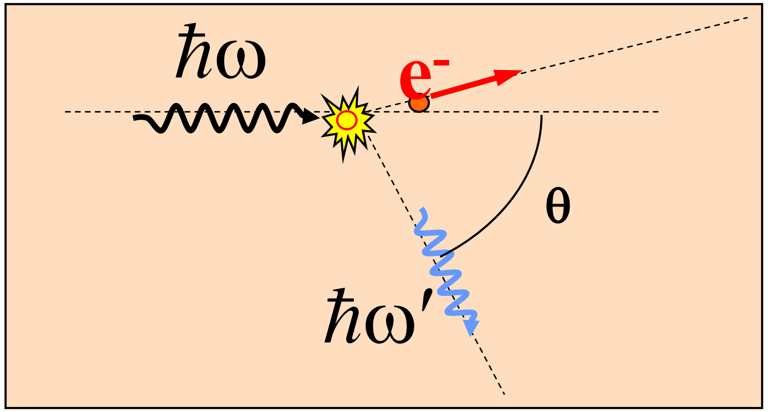
$E_{\gamma 1}, (x,y,z)_{1st}, (x,y,z)_{2nd}$
$E_{\gamma 2}, (x,y,z)_{1st}, (x,y,z)_{2nd}$
$E_{\gamma 3}, (x,y,z)_{1st}, (x,y,z)_{2nd}$
……………………..

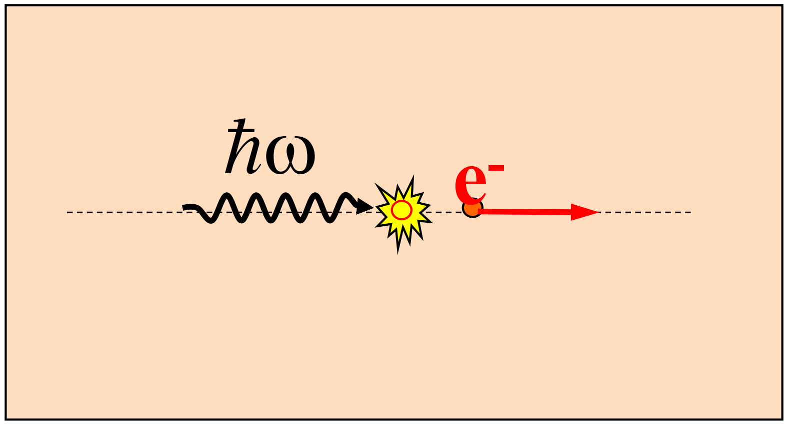
Processes in Germanium

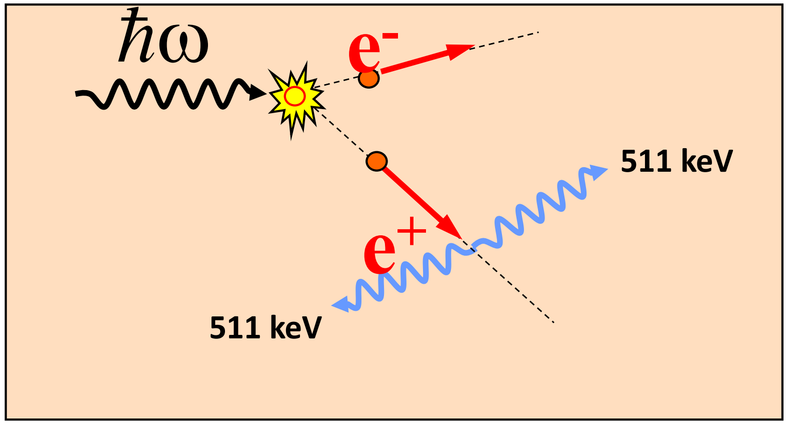
~ 100 keV → ~ 10 MeV

γ-ray energy

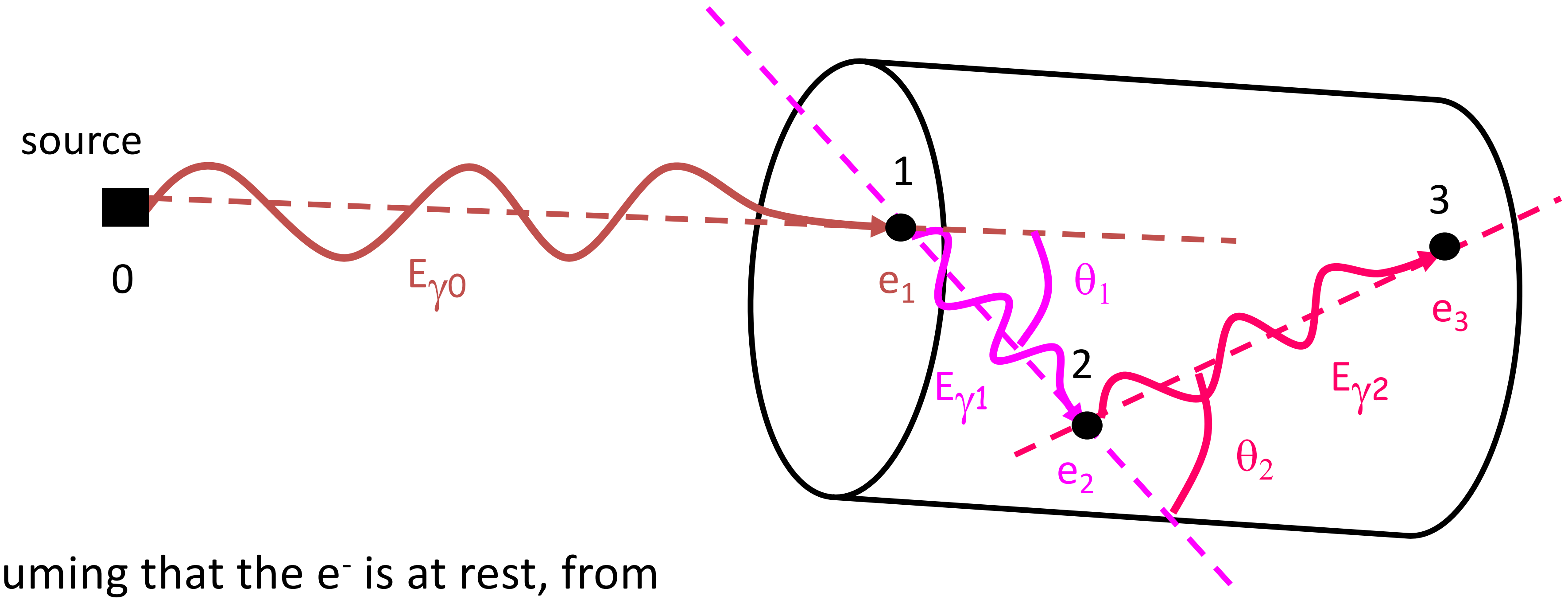
Photoelectric	Compton Scattering	Pair Production







Compton scattering



assuming that the e^- is at rest, from conservation of energy & momentum:

incident energy at i

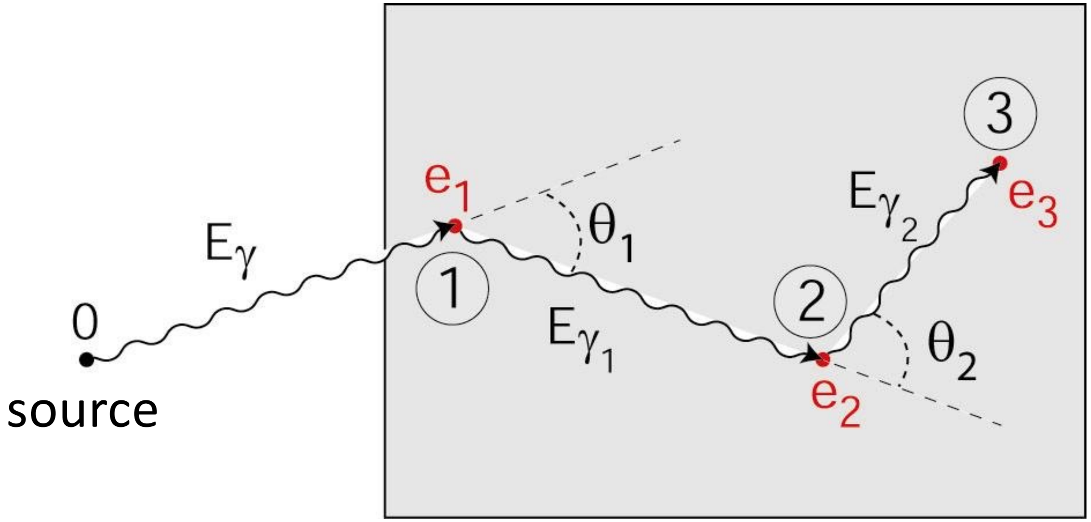
$$\cos(\theta_i) = 1 - m_e c^2 \left(1/E_{\gamma i} - 1/E_{\gamma(i-1)}\right)$$

scattered energy at i = $E_{\gamma(i-1)} - e_i$

What tracking does

Questions :

1) Is the event complete : $\sum e_i = E_\gamma$
2) What is the right sequence



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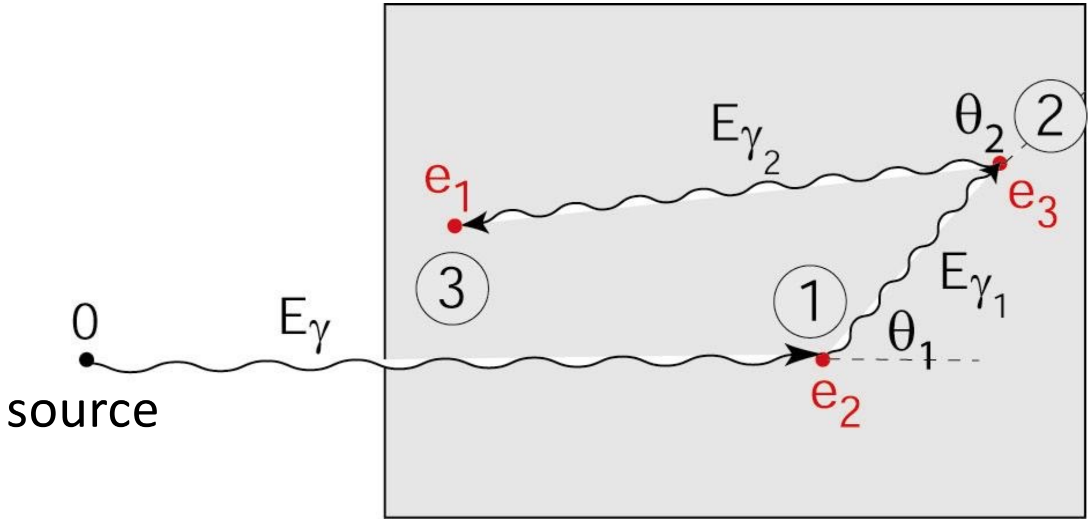

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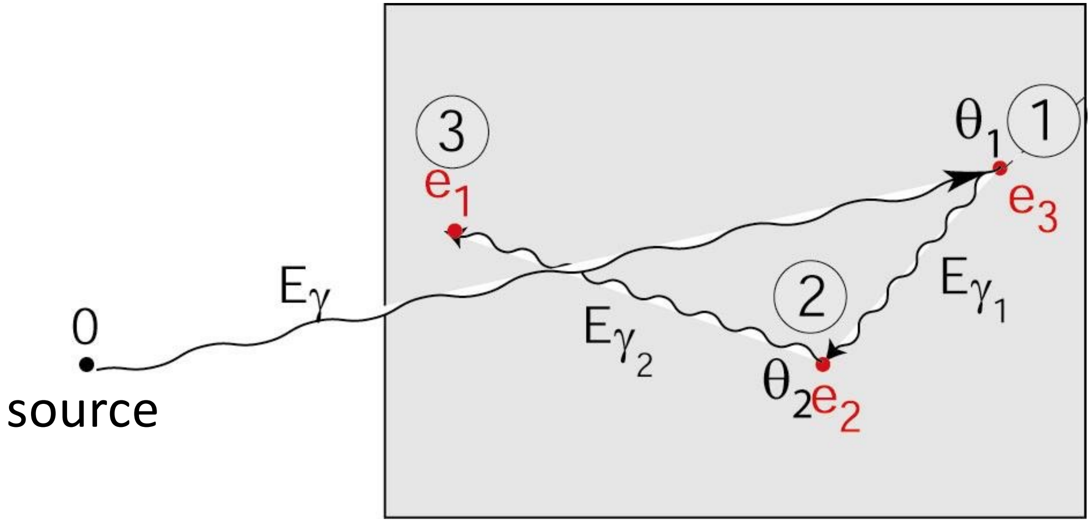


1) from source + interaction positions :

$$\cos(\theta_1) = \frac{\vec{01}\cdot\vec{12}}{|\vec{01}|\cdot|\vec{12}|}$$

$$E_{\gamma 1,pos} = \frac{E_\gamma}{1+\frac{E_\gamma}{m_e c^2}(1-\cos(\theta_1))}$$

from energy deposition + incident energy:

(incident energy = sum of energy depositions assuming that the event is complete)

$$E_{\gamma 1} = E_\gamma - e_1$$

2)

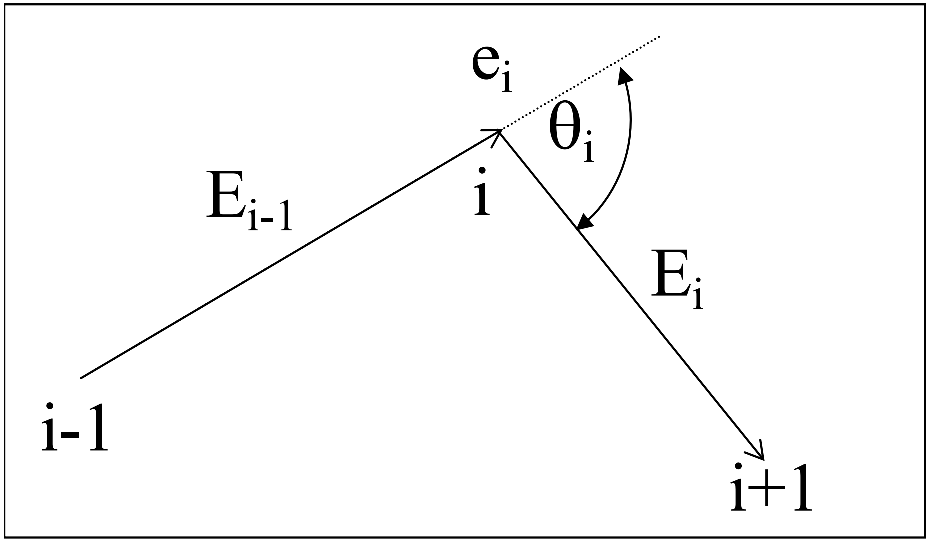
$$E_{\gamma 2,pos} = \frac{E_{\gamma 1}}{1+\frac{E_{\gamma 1}}{m_e c^2}(1-\cos(\theta_2))}$$

$$E_{\gamma 2} = E_{\gamma 1} - e_2$$

Track order = sequence which minimizes the difference between position- and energy-determined quantities at each Compton vertex

Track deemed « complete » & accepted if the FoM of the best sequence > threshold

Compton vertex test



$$E_i = \frac{E_{i-1}}{1 + \frac{E_{i-1}}{mc^2}\left(1 - \cos\theta_i\right)}, E_i = E_{i-1} - e_i$$

1) $V_i^E = E_i - E_i^P$

2) $V_i^e = e_i - e_i^P$

3) $V_i^{\cos\theta} = \cos\theta_i^E - \cos\theta_i$

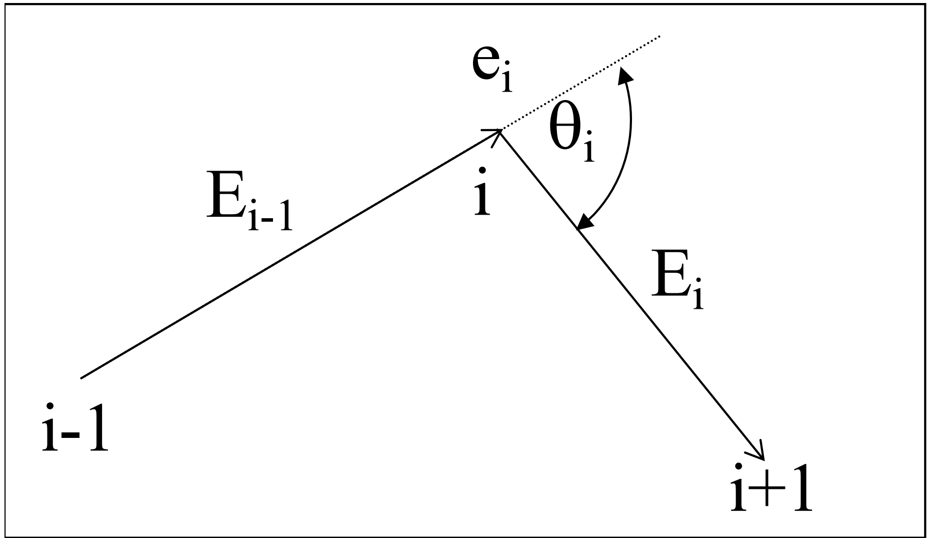
4) $V_i^{\theta} = \theta_i^E - \theta_i$

$$\chi^2 = \sum_{i=1}^{N_V} \left(\frac{V_i^x}{\sigma\left(V_i^x\right)} \right)^2$$

$$\sigma^2(V_i^x) = \sum \left(\frac{\partial V_i^x}{\partial w} \Delta w \right)^2$$

(assuming normality and independence)

Compton vertex test



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3) $V_i^{\cos\theta} = \cos\theta_i^E - \cos\theta_i$

4) $V_i^{\theta} = \theta_i^E - \theta_i$

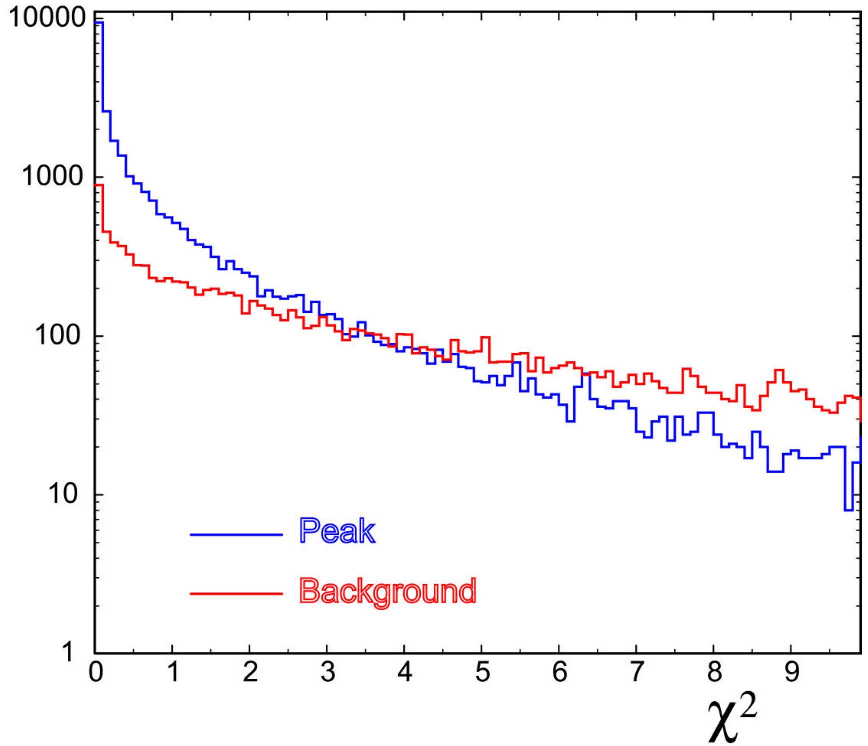
mgt: $$\chi^2 = \sum_{i=1}^{N_V} w_i \left(\frac{V_i^E}{E_{i-1}}\right)^2$$

Gretina: $$FOM = \frac{1}{N_V}\sqrt{\sum_{i=1}^{N_V}\left(V_i^{\theta}\right)^2}$$

OFT: $$L = \prod_{i=1}^{N_V} P_i \exp^{-a\left(\frac{V_i^E}{\sigma_E}\right)^2}$$

Full energy deposition or not ?

The identification is not 100% sure



⇨ spectra will always contain background

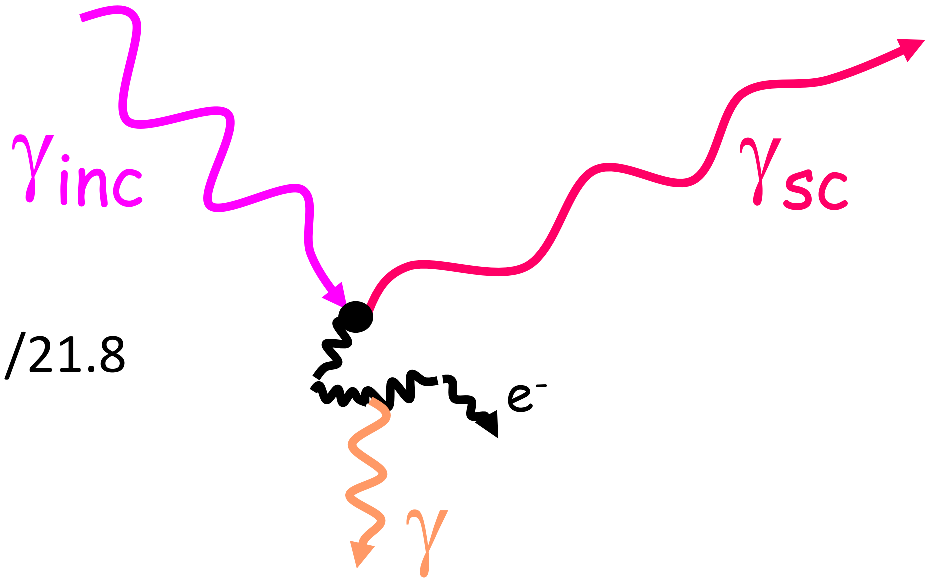
⇨ Acceptance value determines the quality of the spectrum

⇨ Use R = Efficiency x P/T to qualify the reconstructed spectrum

What limits tracking performance ?

- Interaction position $\neq$ position of energy deposition

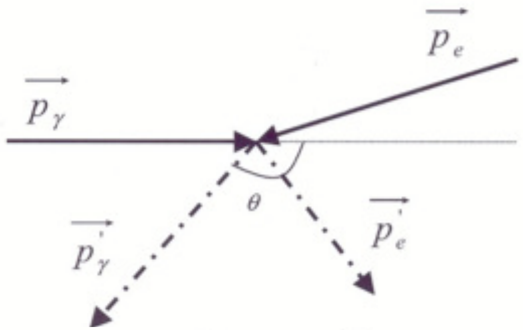
$\sigma_{ion}/\sigma_{Brem} \sim E_{e-}$ (MeV) /21.8



- Rayleigh scattering (relevant at low gamma energies and end of track)

⇨ change in incident direction

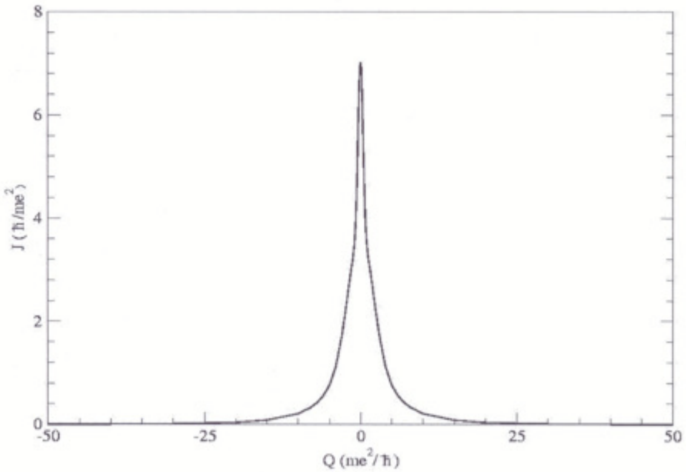
Electron Momentum Profile



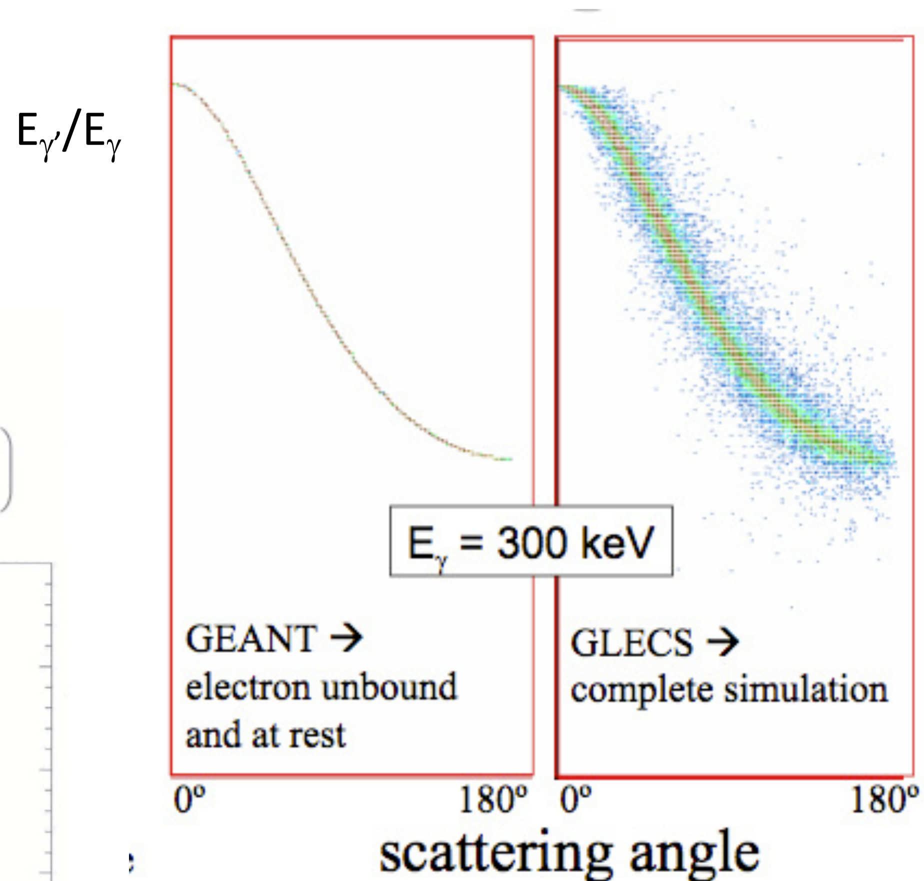
$$\cos\theta = 1 - m_e c^2\left(\frac{1}{E'_\gamma} - \frac{1}{E_\gamma}\right) - \frac{1}{E_\gamma E'_\gamma}\left(Q^2c^2 - Qc\left\{Q^2c^2 + 2m_e c^2\left(E_\gamma - E'_\gamma\right) + \left(E_\gamma - E'_\gamma\right)^2\right\}^{\frac{1}{2}}\right)$$

$$Q = -\vec{p}_e \frac{\overrightarrow{\Delta p_\gamma}}{\left|\overrightarrow{\Delta p_\gamma}\right|}$$

$$\overrightarrow{\Delta p_\gamma} = \vec{p}'_\gamma - \vec{p}_\gamma$$



Biggs *et al.,* At. Data and Nucl. Data Tab. 3 (1975) 16

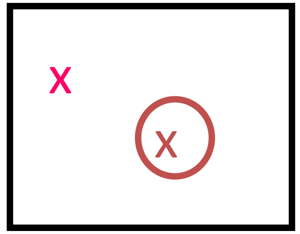


Low-Energy Compton Scattering for Geant4
by R. Marc Kippen www.batse.msfc.nasa.gov

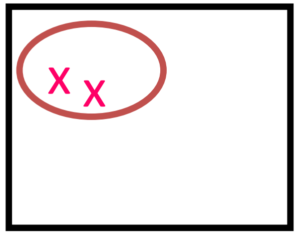
Some more complications

From Pulse Shape Analysis:

uncertainty in position of interaction $\delta p(e_i, x_i, y_i, z_i)$:

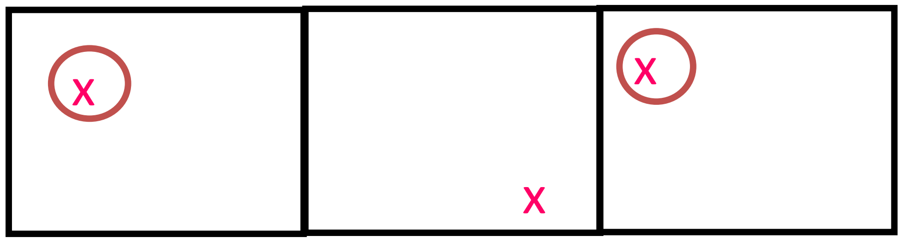


position resolution



From preamplifier:

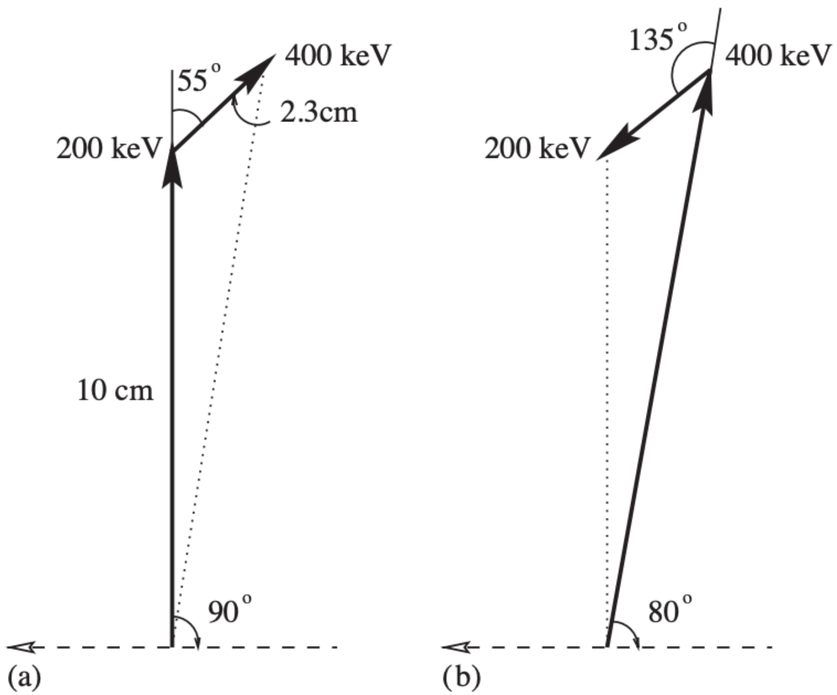
energy threshold



From preprocessing:

energy resolution

Some ambiguities….



Track order may be ambiguous

➔ Bad Doppler correction
➔ Reduced polarization sensitivity

N.J. Hammond et al., Nucl. Instr. Meth. A 547 (2005) 535–540

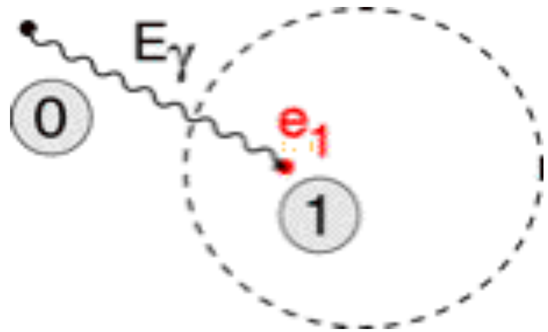
Not exactly tracking …

1. Single interaction points:

There is not much we can do....:

- Does the interaction point satisfy photoelectric conditions (interaction depth, energy) ?

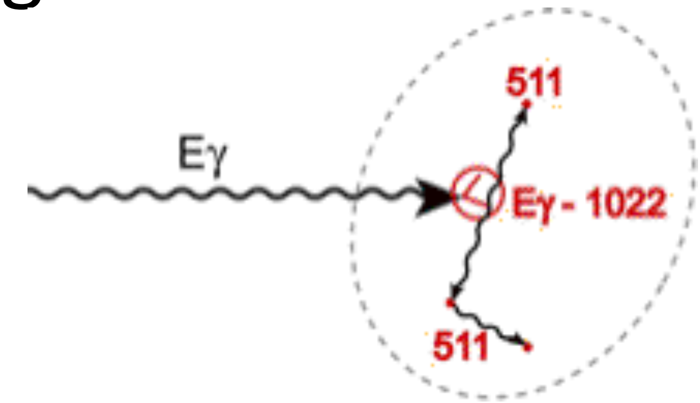
- Is the interaction point sufficiently isolated from other points ?



!! With the AGATA PSA algorithm: ~20% of full absorption 1 MeV events end up in single interaction points (GEANT4 says this number should be ~10%)
GRETINA PSA on the other hand yields ~1% 1 MeV single interaction points

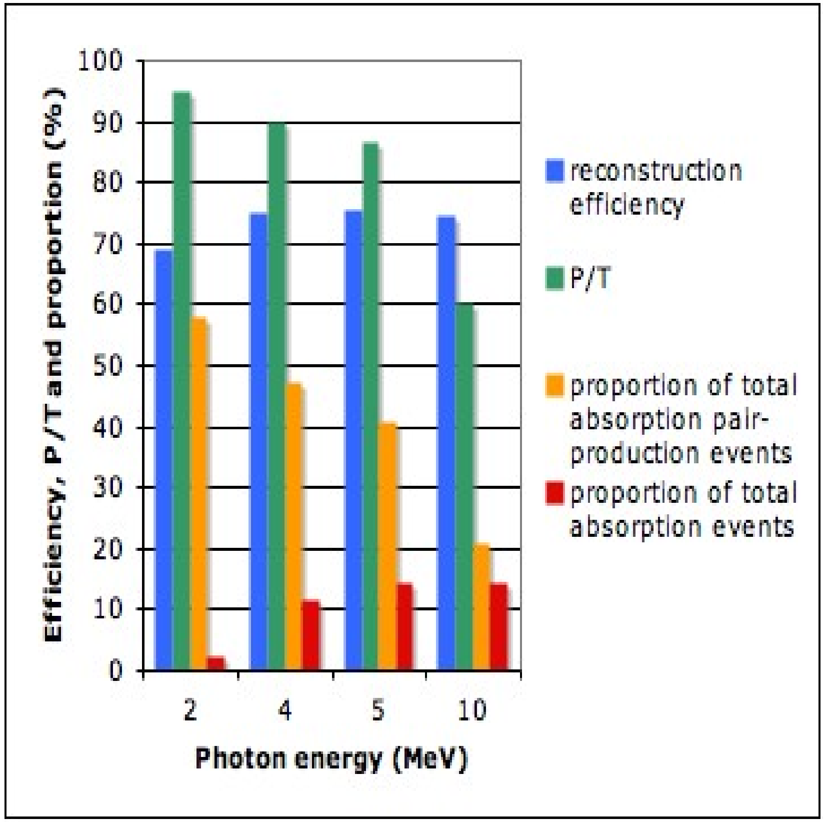
Not exactly tracking …

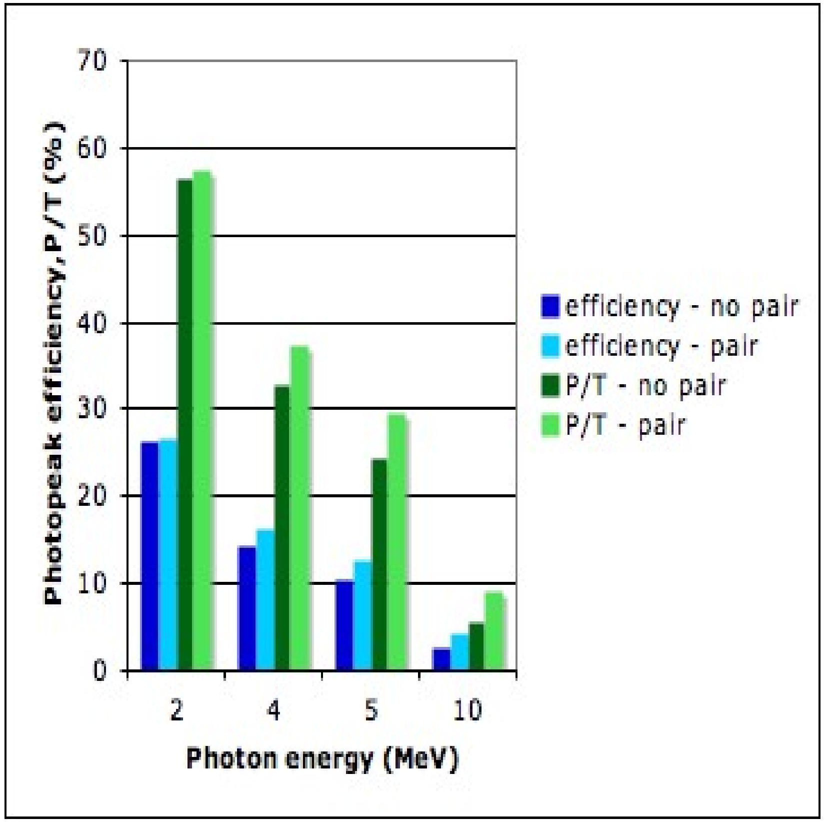
2. Pair production interaction points:



Do the interaction points correspond to a pair production event ?

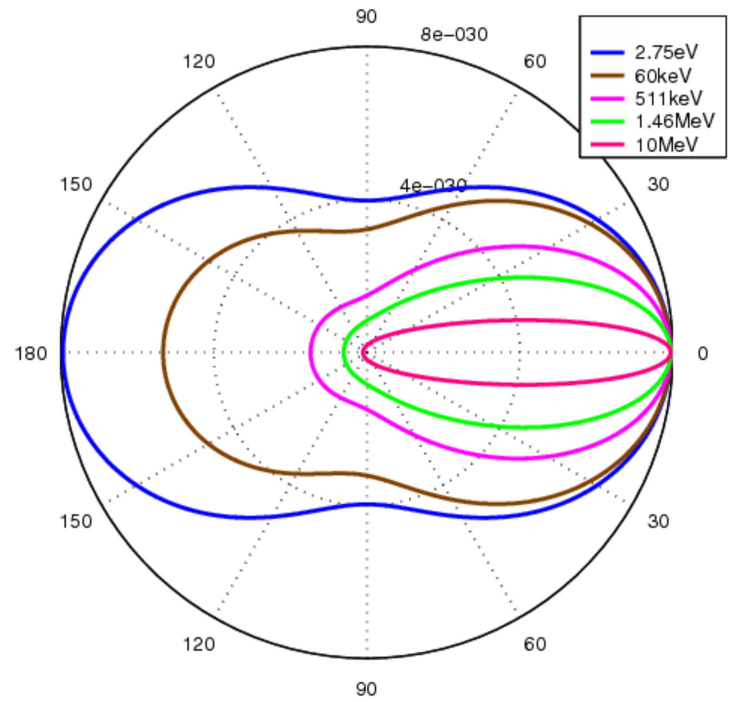
$$e_1 = E_\gamma - 2\ m_e c^2$$





Clusterisation & Forward tracking

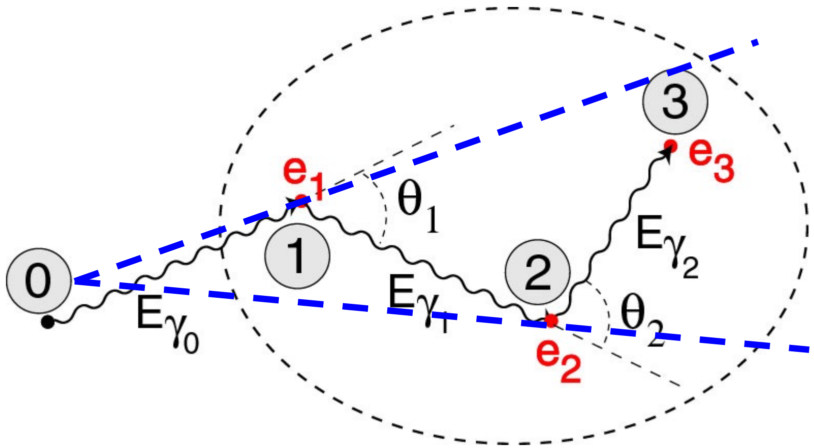
G. Schmidt *et al.,* Nucl. Instr. Methods 430 (1999) 69



* Forward peaking of Compton scattering (Klein-Nishina)

* Decreasing range as the photon loses energy

⇨ Clusterisation of interaction points in (θ,ϕ) space

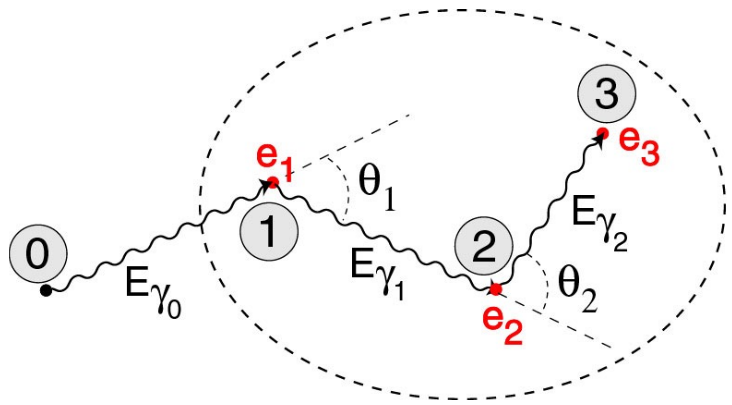


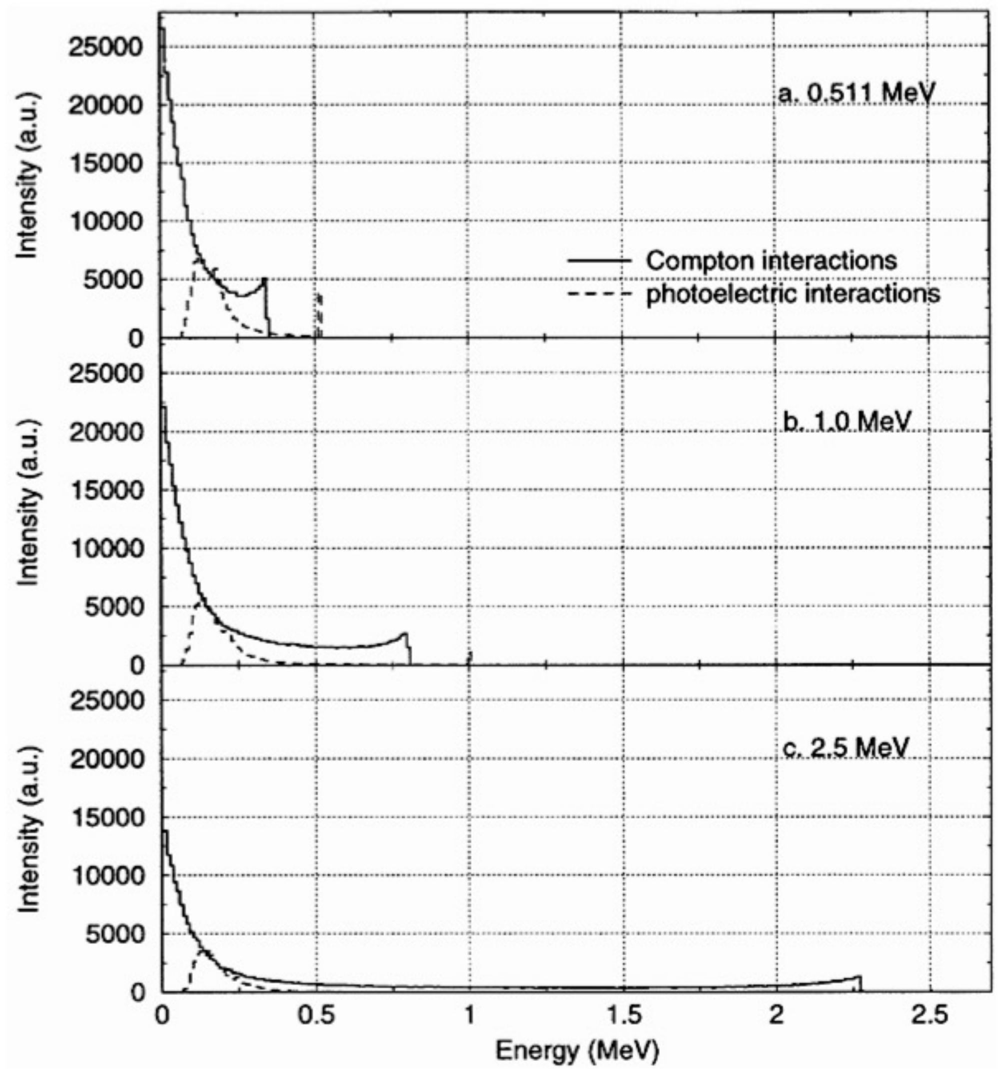
Interaction points with an angular distance ≤ α between each other (link alg.) or with respect to a given point (leader alg.) constitute a CLUSTER

Backtracking

J. Van der Marel and B. Cederwall,Nucl. Instr. Meth. 437 (1999) 538

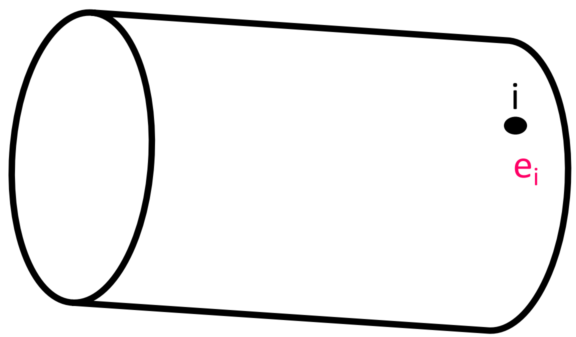
- Photoelectric energy deposition is ~ independent of incident energy
- Peaks around 100-250 keV





Bactracking

1. Create photoelectric interaction pool: $e_{min} < e_i < e_{max}$



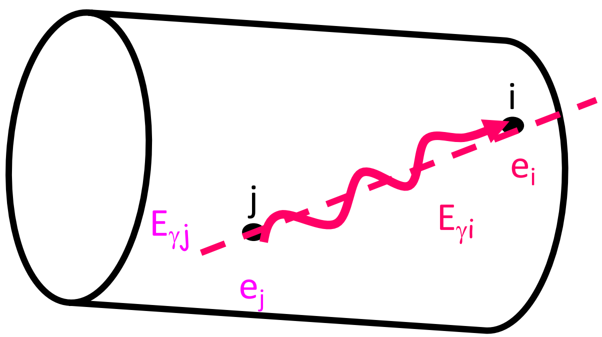
Bactracking

1. Create photoelectric interaction pool: $e_{min} < e_i < e_{max}$

2. Find closest interaction j to photoelectric interaction i:

distance between interaction points < $\lambda 1$

$E_{inc} = e_i + e_j$, $E_{sc} = e_i$



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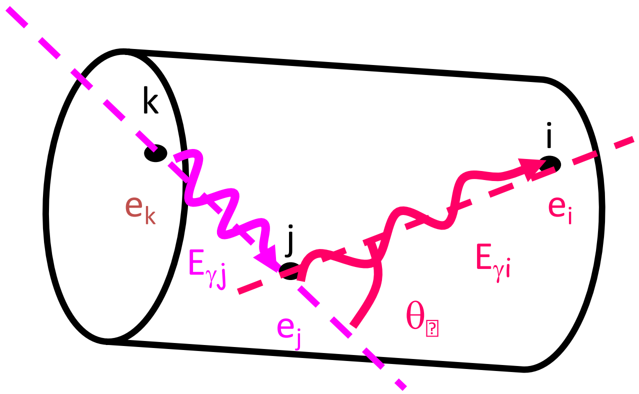

3. Find incident direction :

$\cos(\theta) = 1 - m_e c^2 (1/E_{sc} - 1/E_{inc})$

4. Find previous interaction k or source along direction

$|\cos(\theta_{energy}) - \cos(\theta_{geometry})| <$ limit
Prob(Compton interaction) > $P_{Comp,min}$
distance between interaction points < $\lambda 2$
$E_{inc} = e_i + e_j + e_k$, $E_{sc} = e_i + e_j$

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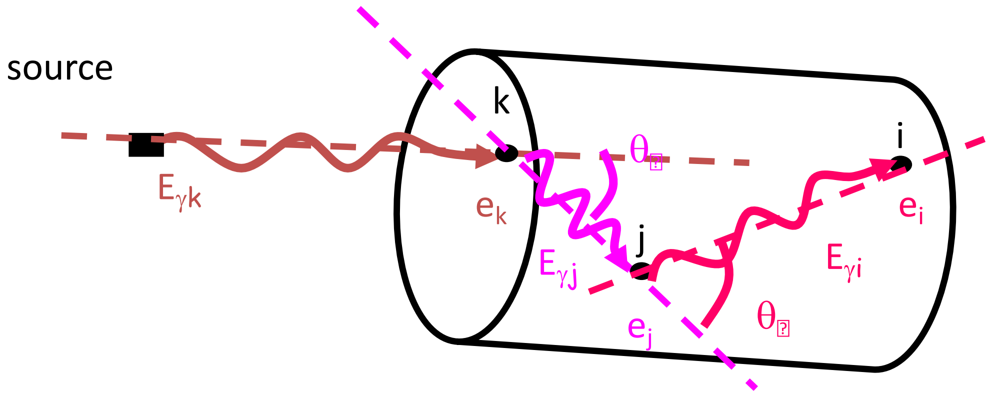

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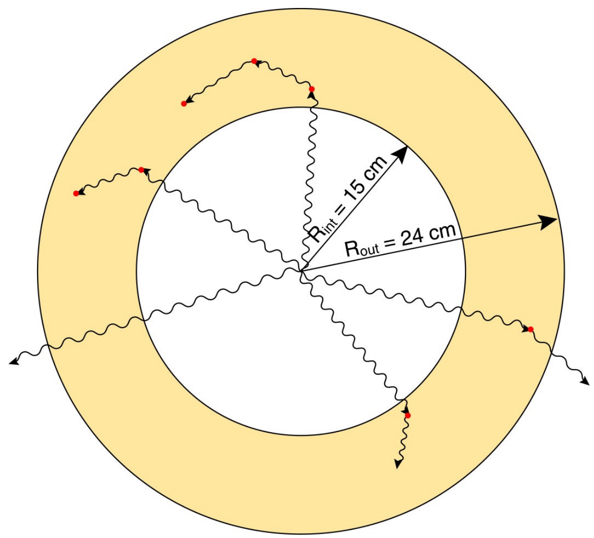
$E_{inc} = e_i + e_j + e_k$, $E_{sc} = e_i + e_j$

Why does one use forward tracking ?

A. Lopez-Martens *et al.,* Nucl. Instr. Meth. A 533 (2004) 454

- Geant4 => Ph. Eff. = 76%

  P/T = 81%

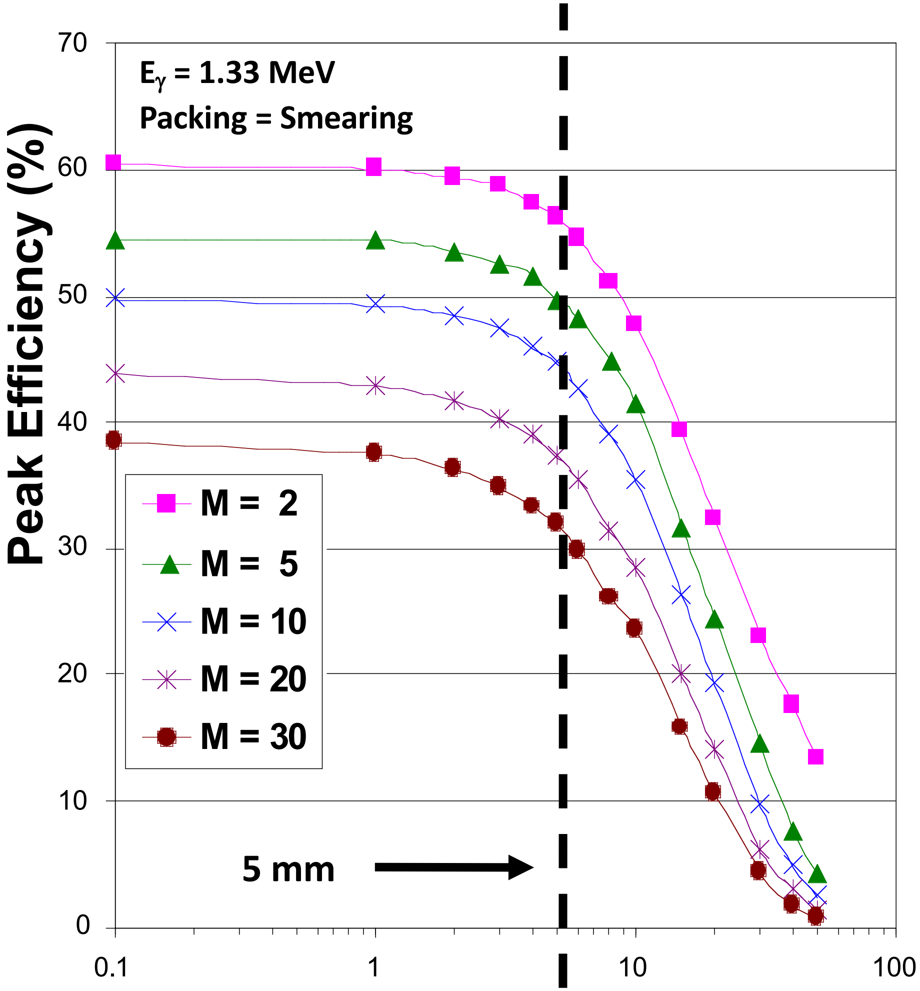


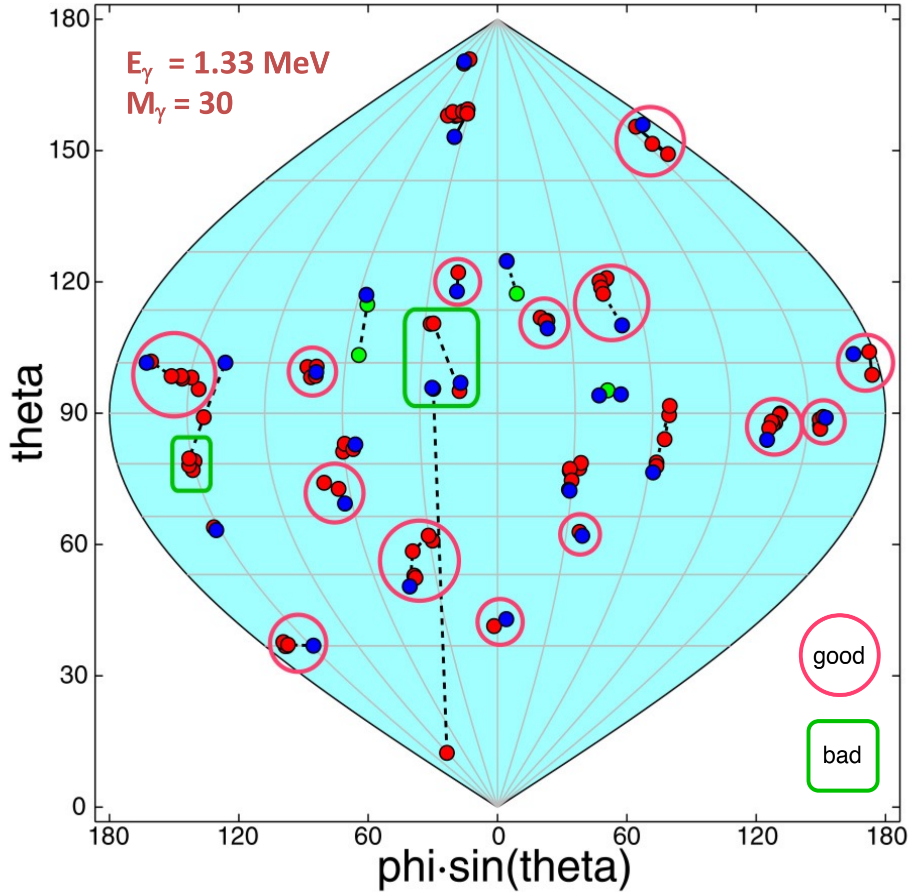
Photon Energy = 1 MeV
Multiplicity 1 and 30
Smearing - packing - energy threshold

	Ph. Eff.	P/T
Forward-tracking	61.6 (33.9)	84.2 (57.7)
backtracking	40.3 (25.3)	67.0 (46.7)

Backtracking: the last points of the sequence are of low energy and close to each other → **easily packed together -> energy deposition of the "photoelectric" interaction can be much larger than 250 keV**

Performances vs position resolution & gamma multiplicity

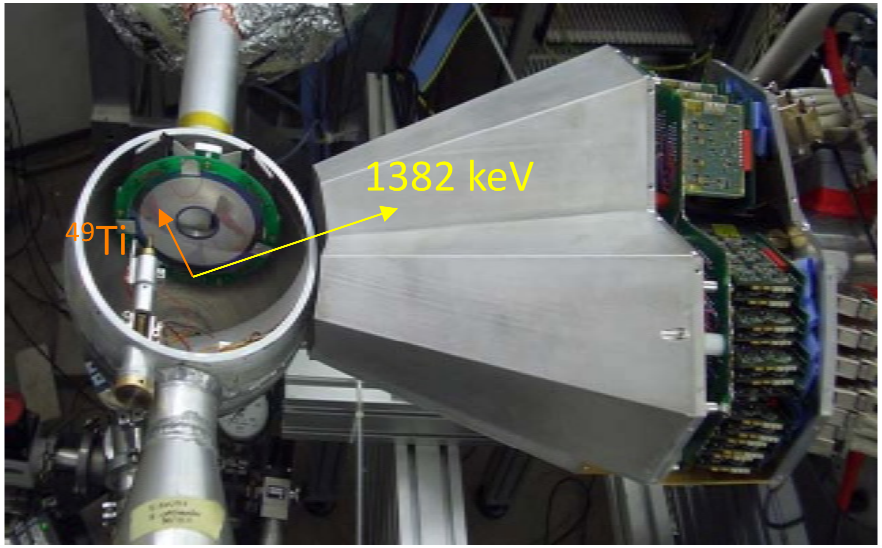




27 photons interacted - 24 with total absorption
16 tracks reconstructed
14 good

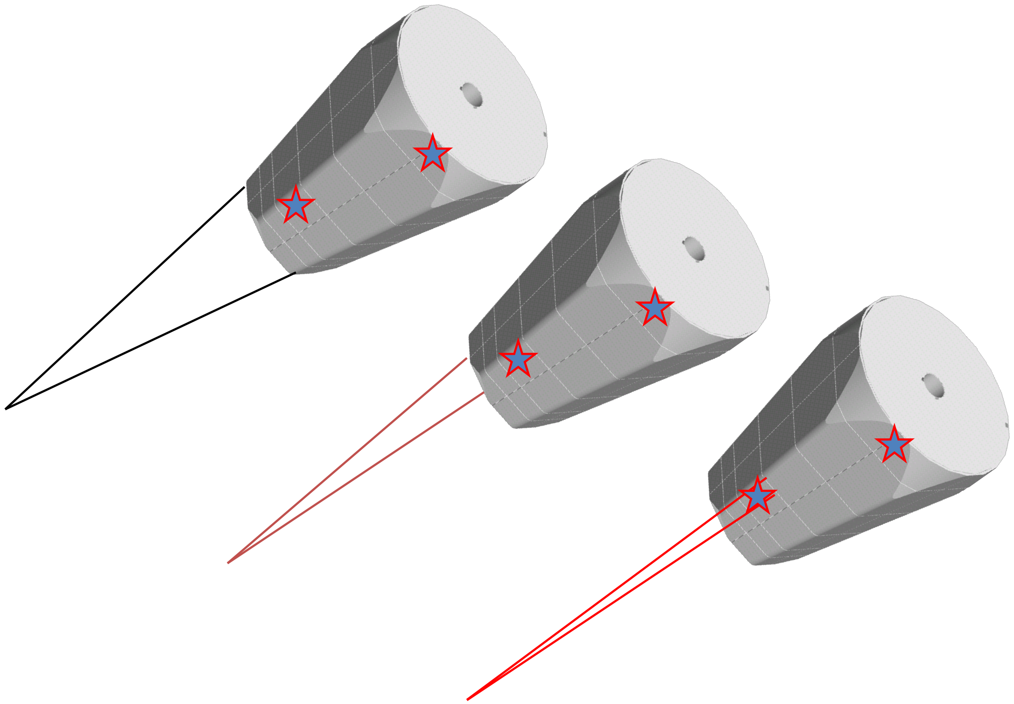
The biggest losses are due to multiplicity (mixing points)

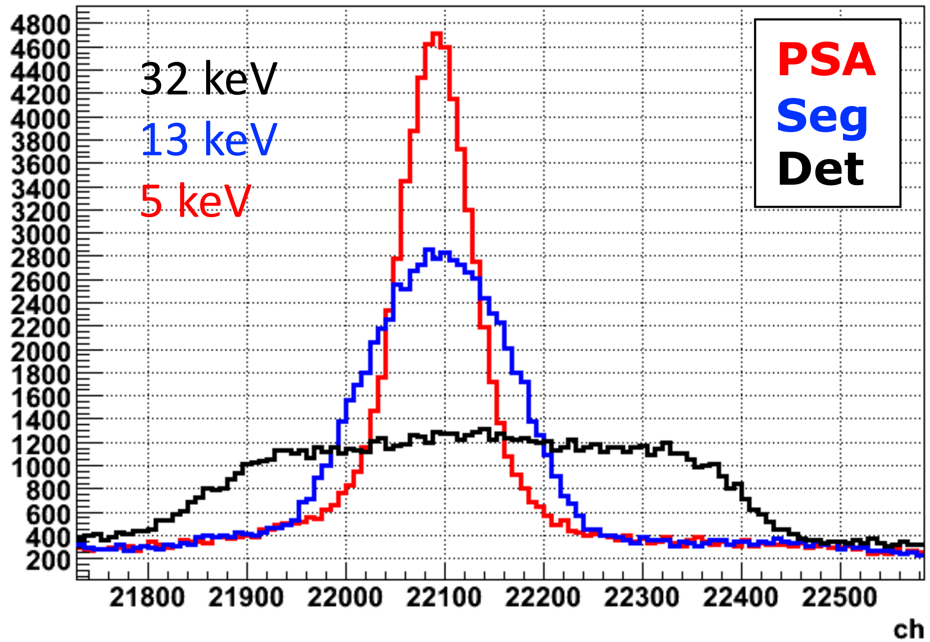
Deduced position resolution @ AGATA



REACTION CHANNEL: ^{48}Ti(d,p)^{49}Ti

beam	^{48}Ti	100 MeV
target	^{48}Ti + ^{2}H	220 μg/cm^2
Si detector	thickness	300 μm
	segmentation	32 rings, 64 sectors
AGATA triple symmetric cluster		



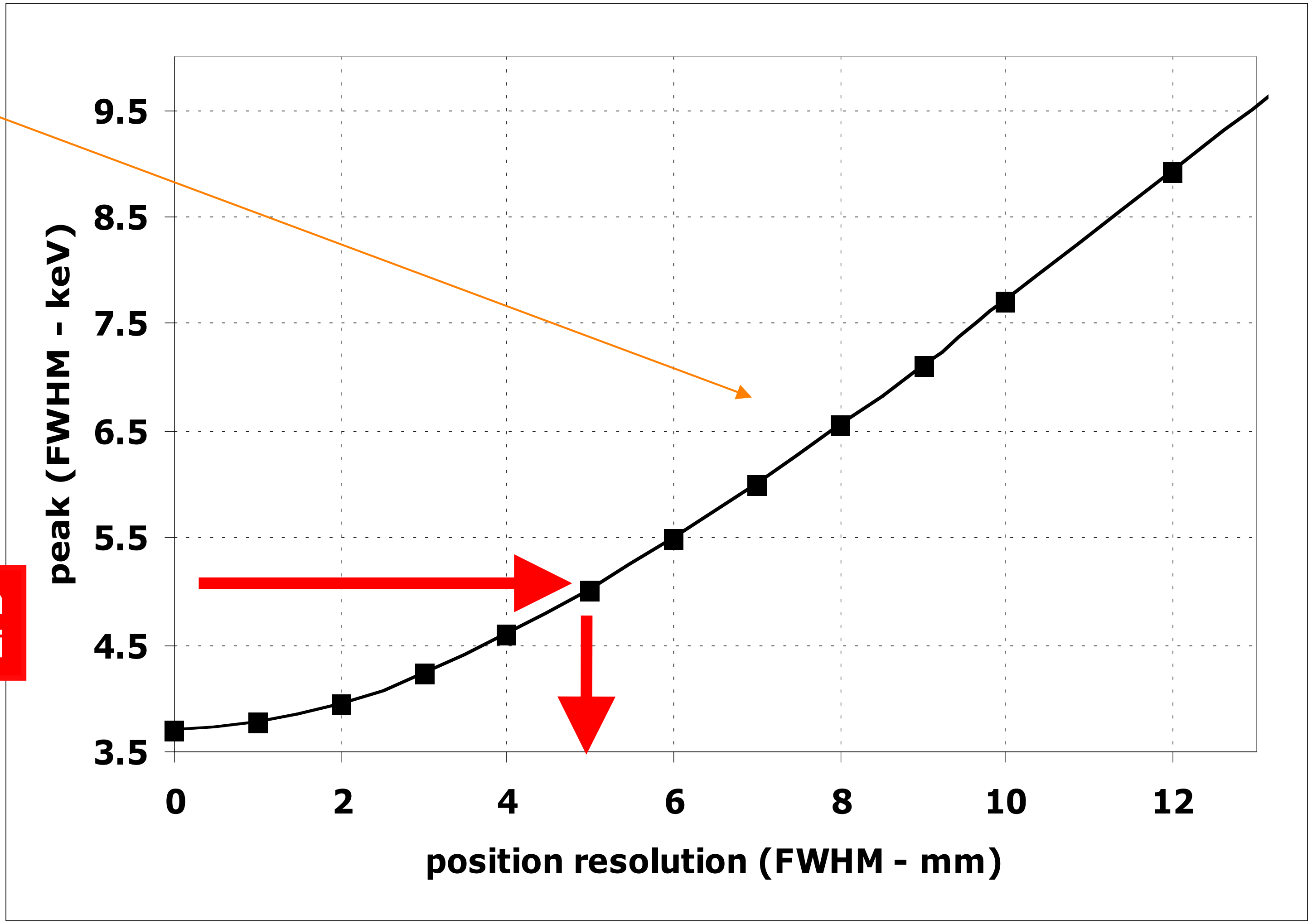


Deduced Position resolution

F. Recchia et al., Nucl. Instr. Meth. A 604 (2009) 5555

simulations
of the reaction
+
detector
responses

Grid Search
R. Venturelli



Deduced Position resolution

F. Recchia et al., Nucl. Instr. Meth. A 604 (2009) 5555

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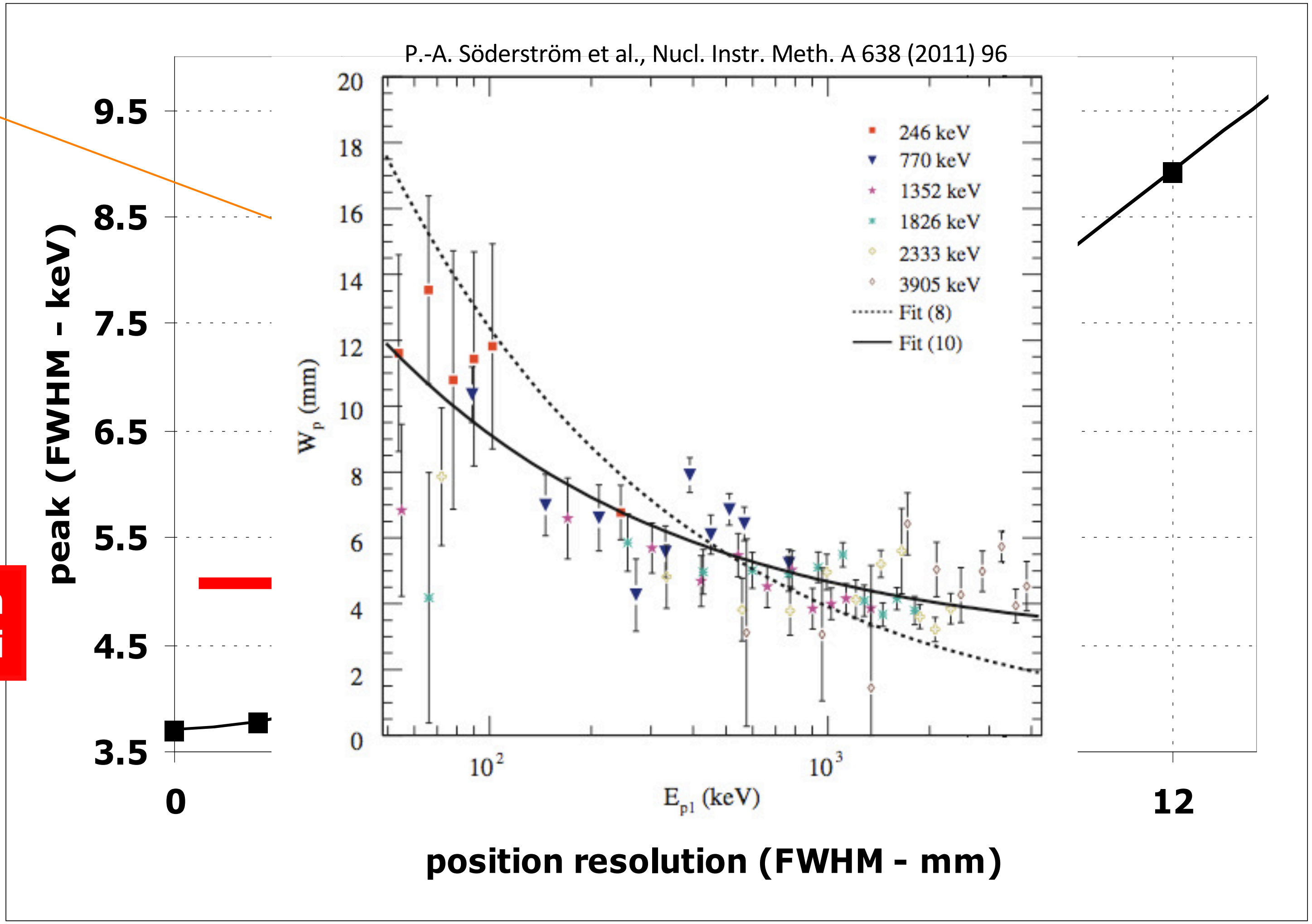


Grid Search
R. Venturelli

Is the position resolution the same in all directions?

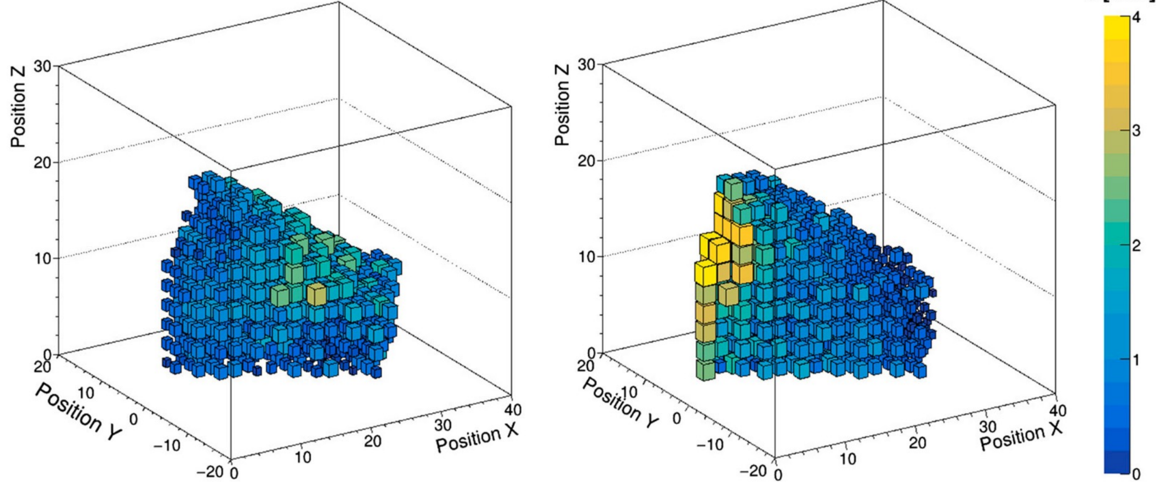
(The Doppler correction is sensitive to mostly only x & y .....)

More recently…

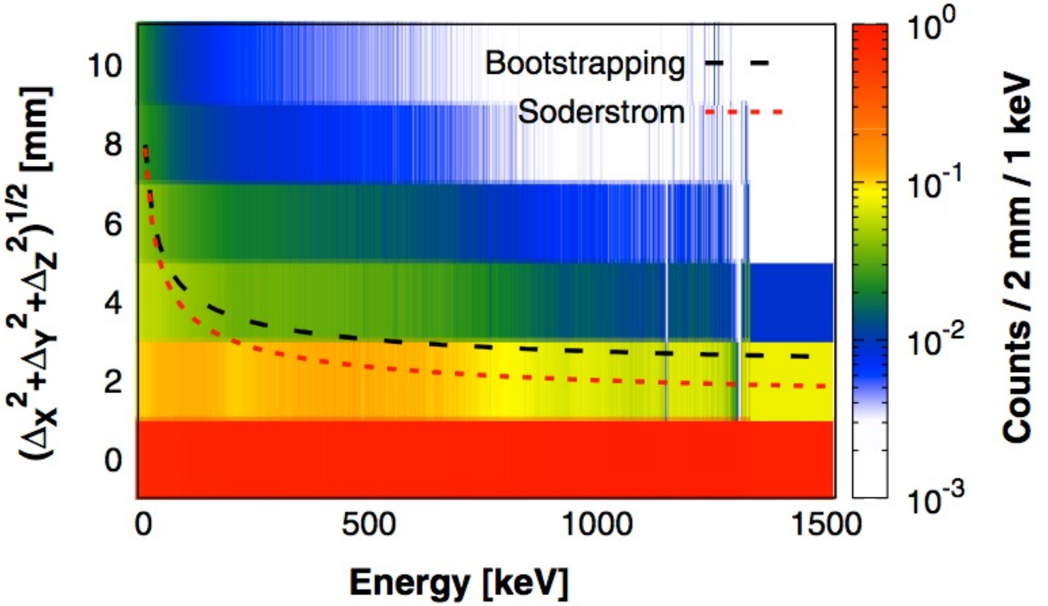
Realistic uncertainties $\sigma_{x,y,z}(e,x,y,z)$ extracted from PSA using the bootstrapping technique

M. Siciliano et al., Eur. Phys. J. A (2021) 57:64

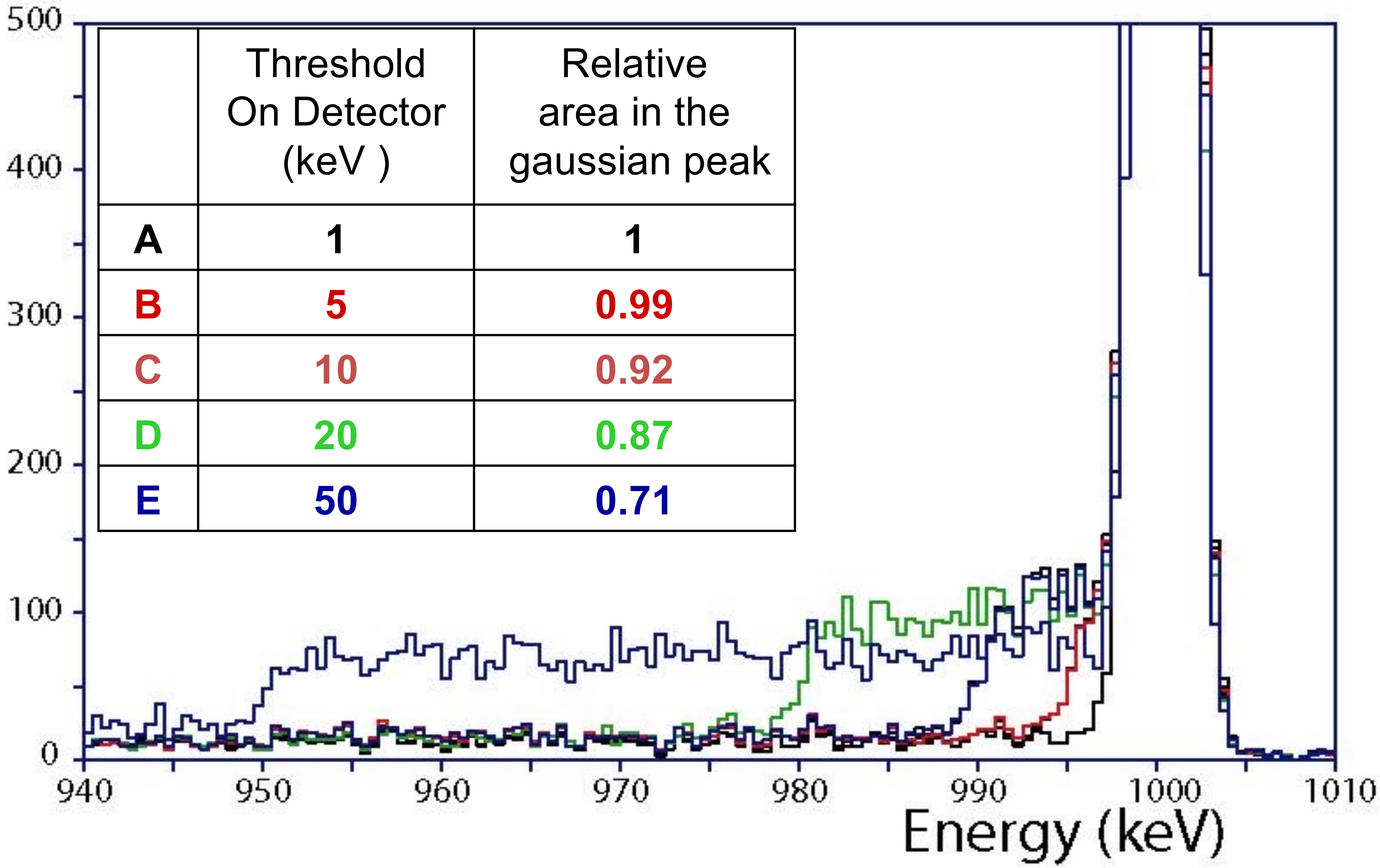
$-\sigma_x$(64 keV – 128 keV) $+\sigma_x$(64 keV – 128 keV)



Segment A1 of detector C013



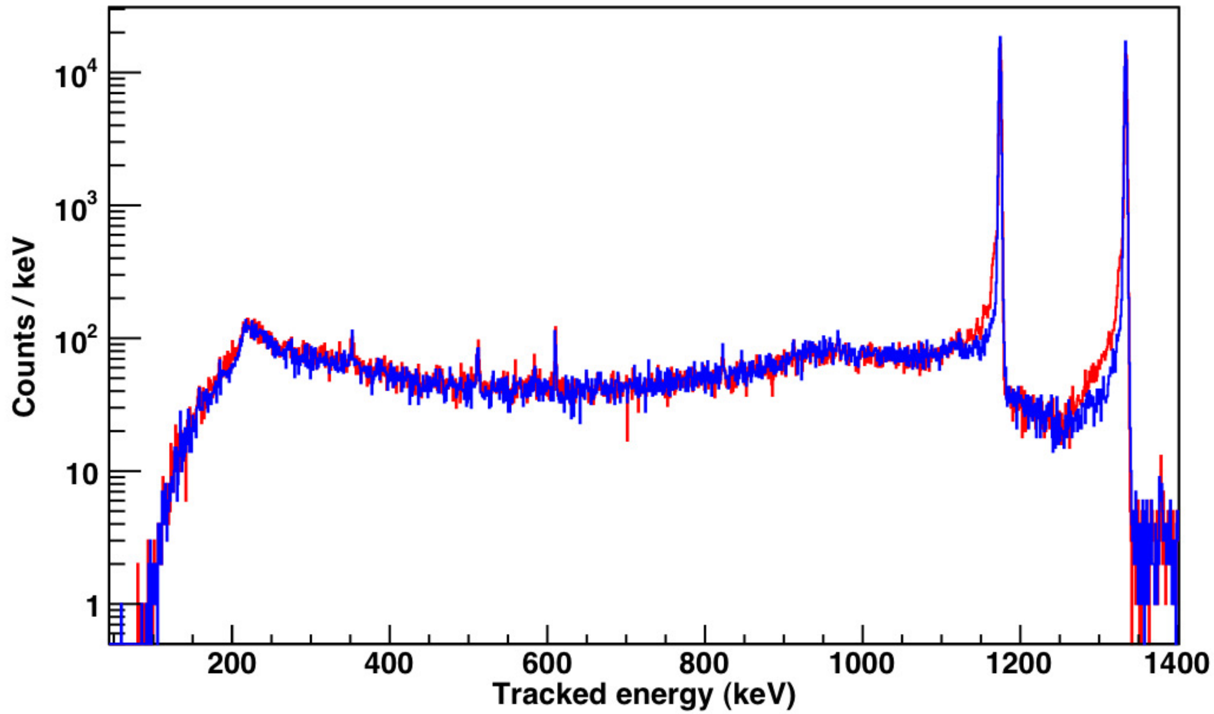
Effect of segment energy threshold



	Threshold On Detector (keV)	Relative area in the gaussian peak
A	**1**	**1**
B	**5**	**0.99**
C	**10**	**0.92**
D	**20**	**0.87**
E	**50**	**0.71**

Force segments to core correction

Tracked spectra (no single interactions)



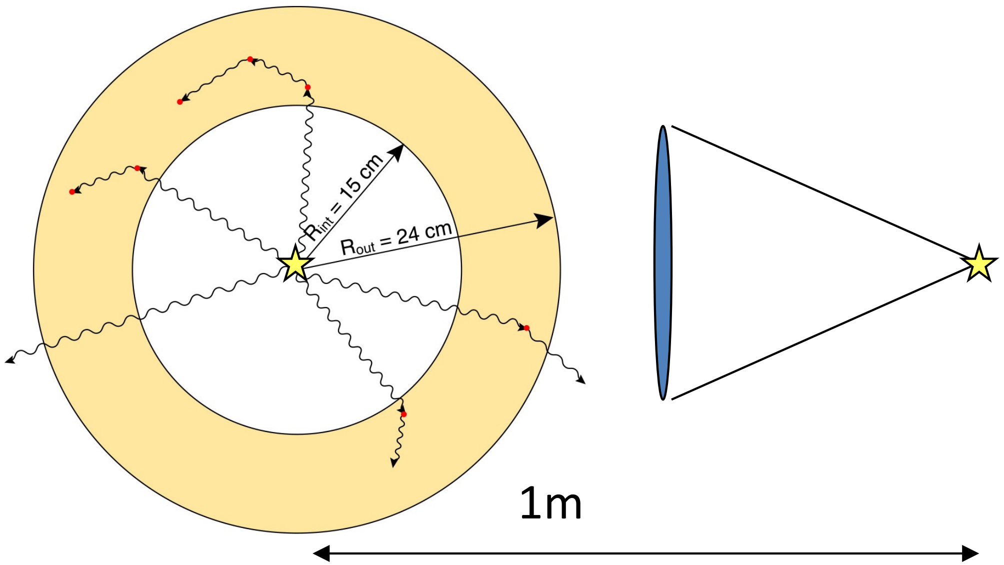
E_{core}-Σsegments redistributed among segments

+10% peak

+12% P/T

⚠ Might not ”improve” the quality of tracked spectra for cores with bad resolution

Background rejection



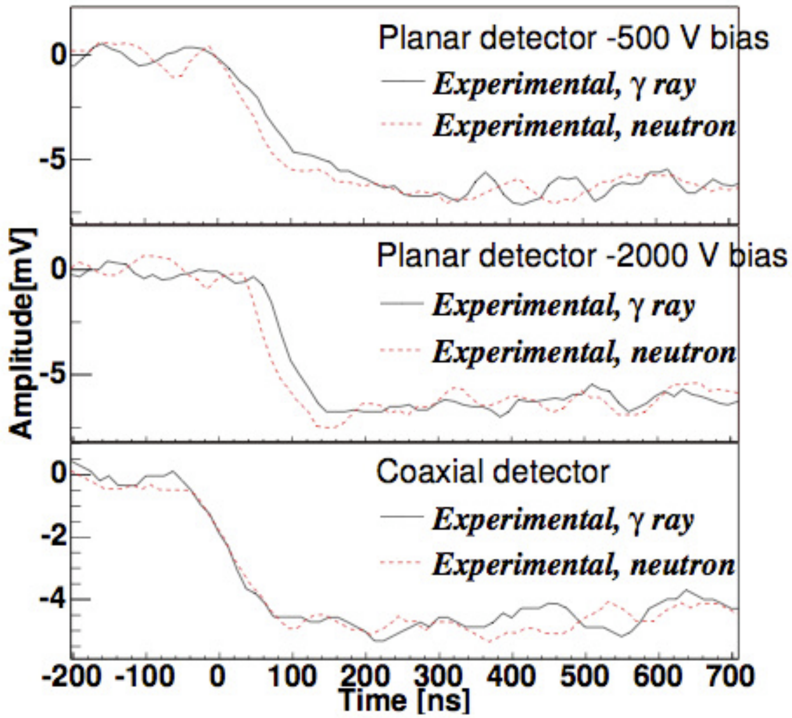
(same data used)	200 keV	500 keV	1 MeV
Centered source	P/T = 97.4% Tr. Eff = 90.5% Mgt: P/T=96.6% Tr. Eff = 95.3%	P/T=89.2% Tr. Eff. = 81.5 % Mgt: P/T=91.0% Tr. Eff = 94.5%	P/T=83.7% Tr. Eff = 80.1% Mgt: P/T=80.0% Tr. Eff = 92.7%
Off-centered source (1m from center)	P/T = 93.0% Tr. Eff = 1.6% Mgt: P/T=99.4% Tr. Eff = 57.4%	P/T=79.2% Tr. Eff. = 31.8% Mgt: P/T=77.3% Tr. Eff = 74.4%	P/T = 60.1% Tr. Eff = 40.1 % Mgt: P/T=66.6% Tr. Eff = 78.7%

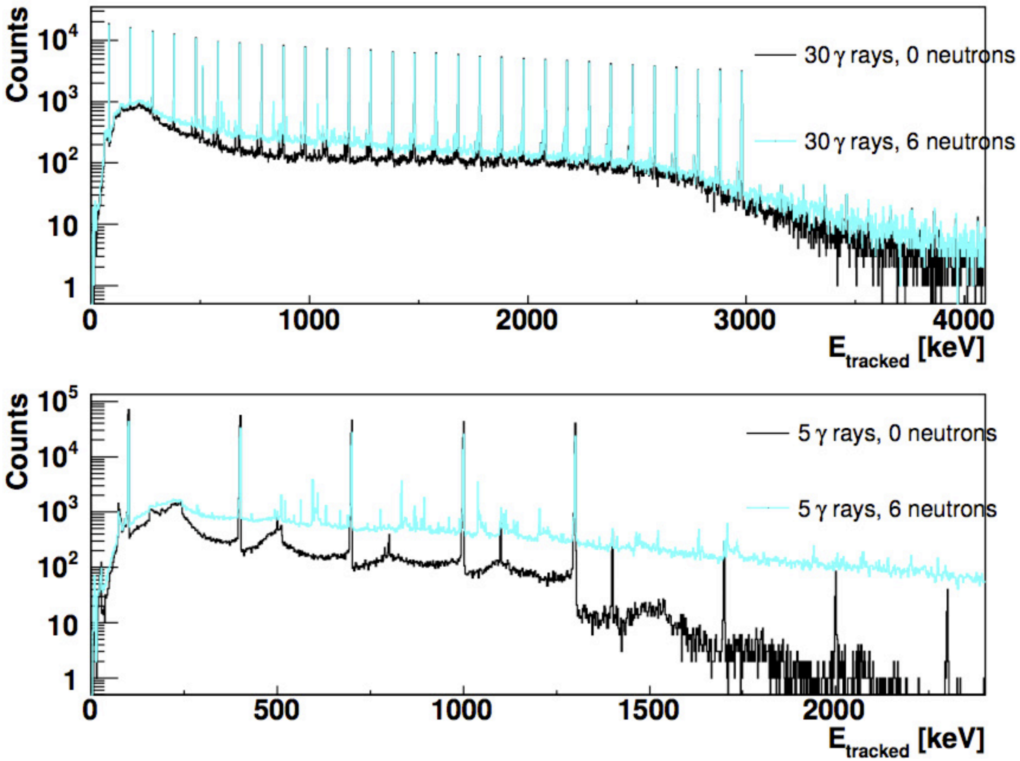
Effect of neutrons

J. Ljungvall and J. Nyberg, Nucl. Instr. Meth. A 550 (2005) 379

Neutrons & Gammas

- similar signals
- similar distribution of interaction points





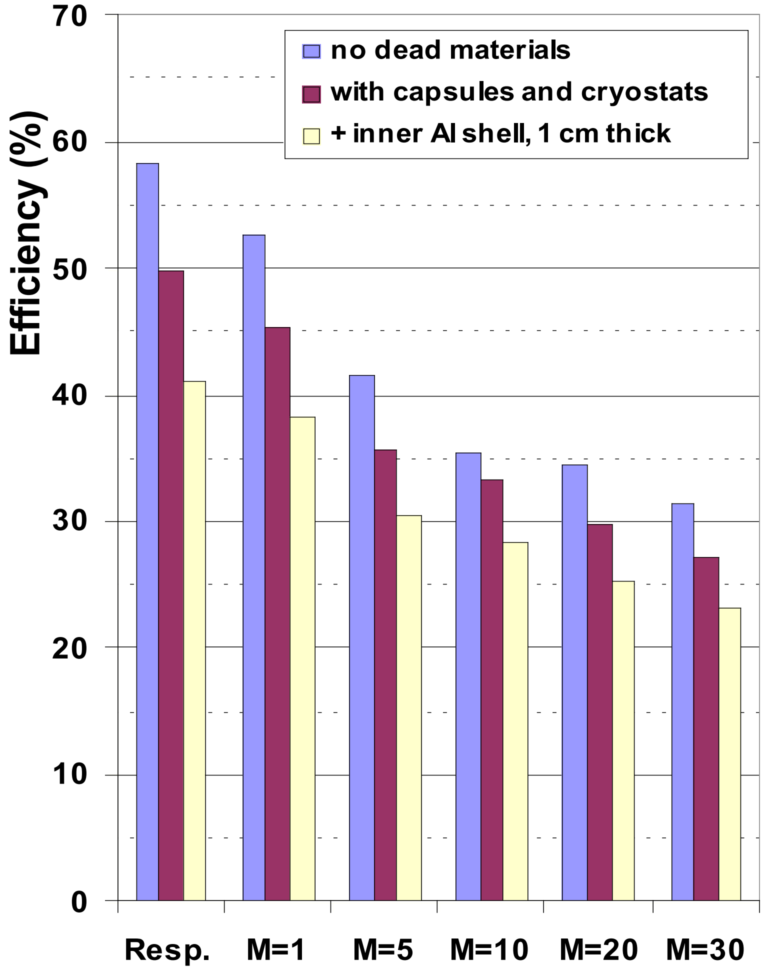
⇨ Large effect on P/T for low gamma multiplicities

⇨Ph. Eff = -1% /n

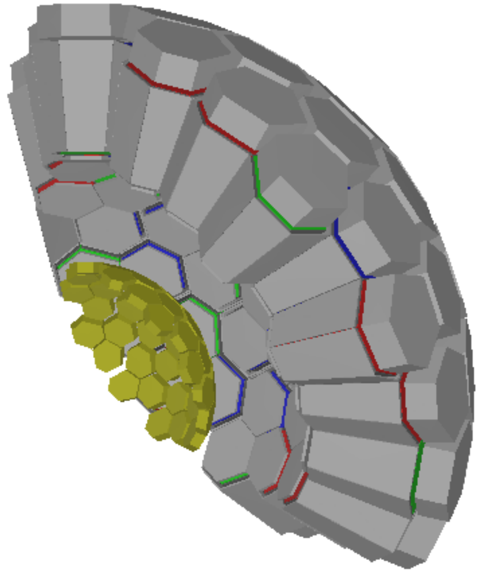
⇨ Can only discriminate n's and γs with good timing (can also reduce some background due to inelastic reactions (n,n'γ) with extra conditions on angles and deposited energies)

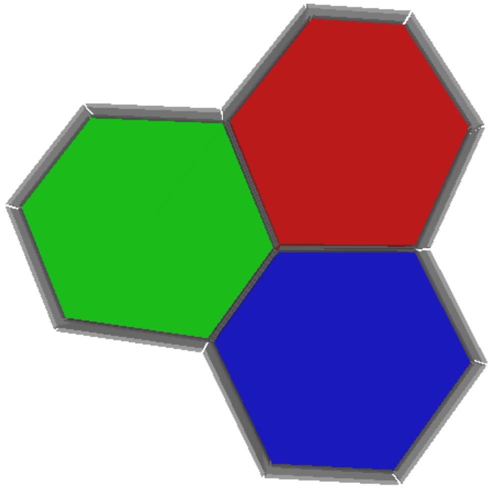
M. Senyigit et al., Nucl. Instr. Meth. A 735 (2014) 267

Effect of encapsulation and other dead materials



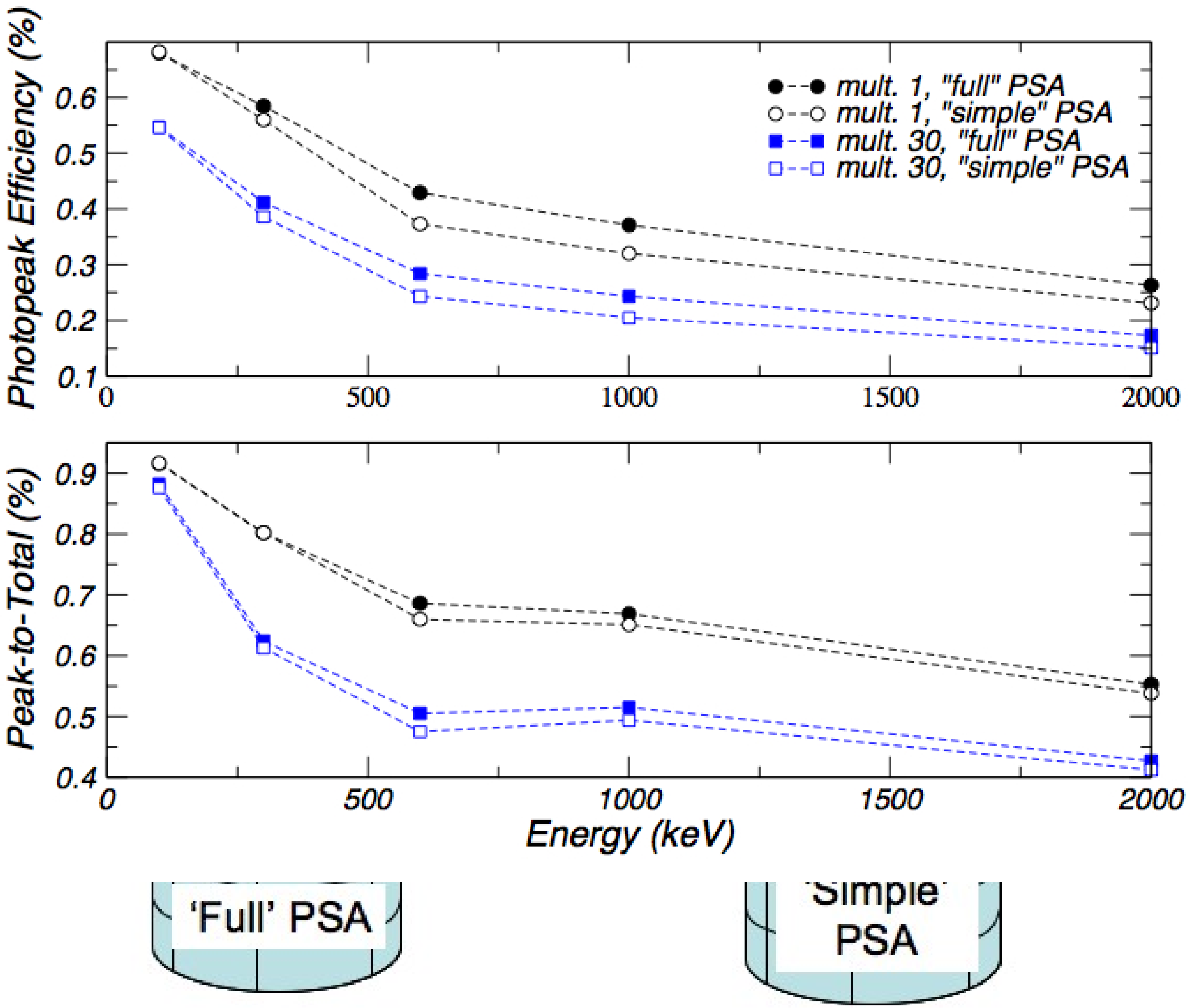
Thickness of	mm
Capsule side	0.8
Cryostat side front back	1.5 3.0 30
Inner “ball”	10





⇨ Careful design of ancillary devices !

Effect of simplified PSA



Inputs to OFT

- Latest version requires 4 tracking parameters:

OftMinProbTrack	0.05	minprobtrack (default: 0.05) ⇦ FoM threshold
OftSigmaThetha	0.8	sigma_thet (default: 0.8) ⇦ Position uncertainty (cm)
OftClustRedFact	1	cluster_max_angle_reduction_factor (default: 1-> no reduction)
OftFixedAngle	0	fixed openning angle (default: 0 -> variable opening angle) ⇦ in rad

- Requires PSA hits e[i],x[i],y[i],z[i] within a given prompt coincidence time window

- Requires energies in MeV

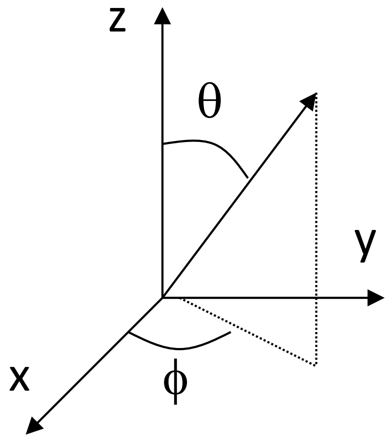
- Requires positions in the laboratory frame in cm

- Requires knowledge of the position of the source (SourcePosition from TrackingFilter.conf)

!! The source position is defined wrt to the center of the AGATA shell

- Does NOT require the recoil velocity or direction

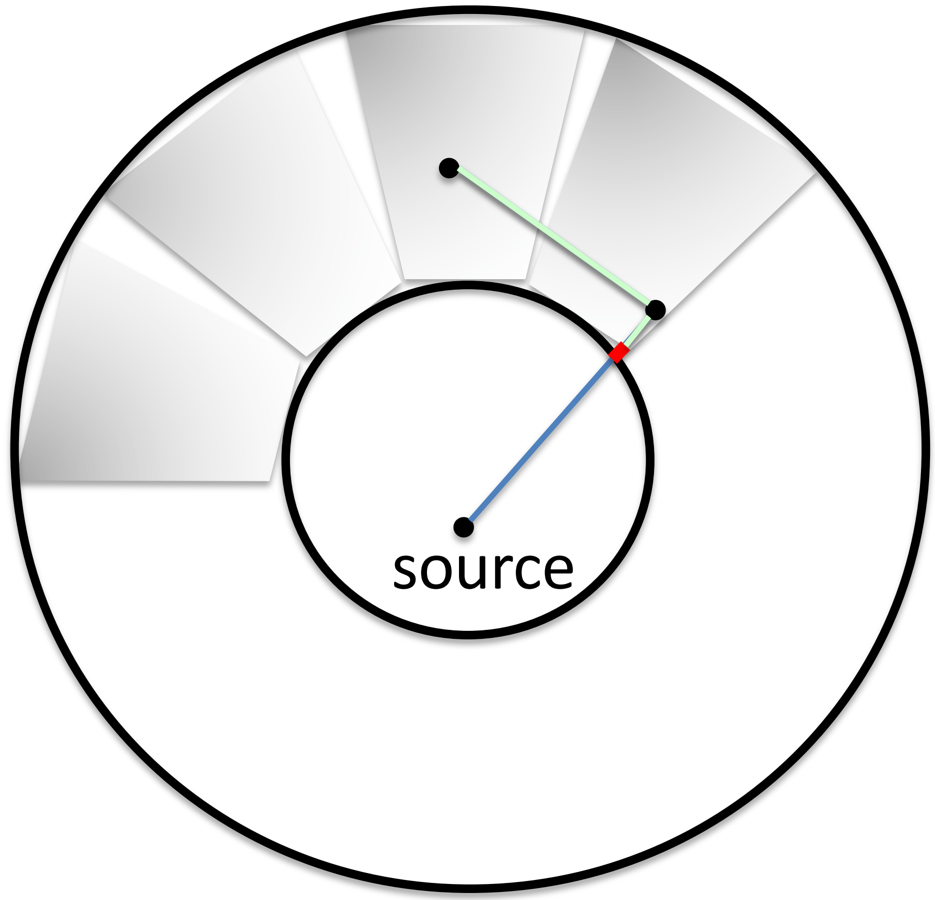
OFT – 1st steps



Calculate angles and sorts points according to increasing θ

Calculate effective distances in Ge
between points and between points and source

To compute proper distances, need to
know positions in each detector reference
frame ⇨ CrystalPositionLookUpTable

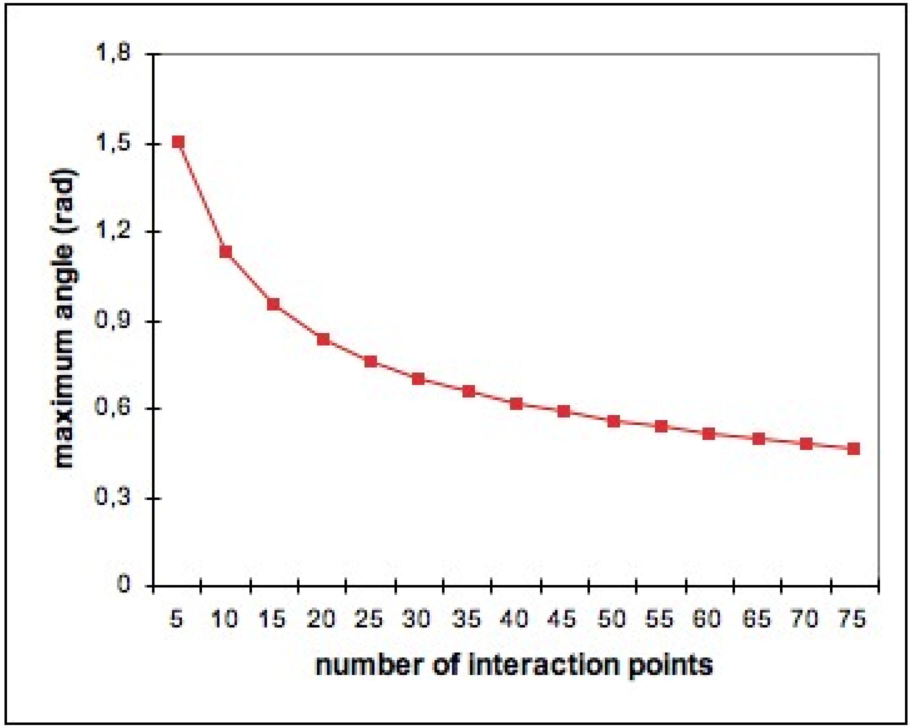


OFT - clusterisation

If FixedAngle =0, compute the maximum angular separation α_{max} between points in a cluster = f(n_{int})

$$\alpha_{\max} = \cos^{-1}\left(1 - \frac{2}{\left((n_{\text{int}}+2)/3\right)^{0.9}}\right)$$

Can reduce α_{max}=α_{max}/ClusterRedFact

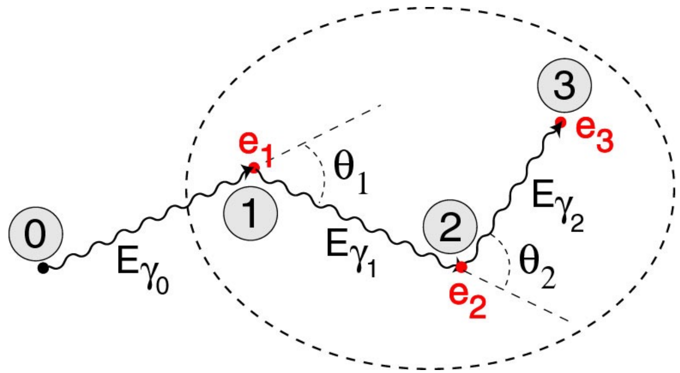


Assign interaction points i and j to the same cluster if:

$$\left|\cos^{-1}\left(\sin\theta_j \sin\theta_i \cos(\varphi_j - \varphi_i) + \cos\theta_i \cos\vartheta_j\right)\right| \leq \alpha$$

If FixedAngle =0, loop on α_{min}(=0.15) < α < α_{max} and find n different clusters ($\delta\alpha$=0.1 rad) with total energy e_{clust}

OFT - tracking



If n_{int}= 1 (mechanism 1), give the cluster the minimal probability = MinProbTrack

If n_{int}> 1 :
If e_{clust}> 1022 keV and at least one interaction point gathers e_{clus}-1022 keV, compute the pair production probability for the cluster

Evaluate each Compton vertex of the cluster

$$E_{\gamma 1} = E_{\gamma 0} - e_1$$

$$E^P_{\gamma 1} = \frac{E_{\gamma 0}}{1 + \frac{E_{\gamma 0}}{mc^2}(1 - \cos\theta_i)}$$

$$e^{\left[\frac{-(E_{\gamma 1} - E^P_{\gamma 1})^2}{\Delta E^2 + \Delta P^2}\right]}$$

source -	1 - 2 - 3
`	1 - 3 - 2
	2 - 1 - 3
	2 - 3 - 1
	3 - 1 - 2
	3 - 2 - 1

$$\Delta E = \sqrt{(n_{int} + 1)} \times \sigma_E$$ average energy resolution

$$\Delta P \propto \sigma_\theta \sqrt{\left(\frac{\partial \cos 1}{\partial x_0}\right)^2 + \left(\frac{\partial \cos\theta_1}{\partial y_0}\right)^2 + \left(\frac{\partial \cos\theta_1}{\partial z_0}\right)^2 + \left(\frac{\partial \cos\theta_1}{\partial x_1}\right)^2 + \left(\frac{\partial \cos\theta_1}{\partial y_1}\right)^2 + \left(\frac{\partial \cos\theta_1}{\partial z_1}\right)^2 + \left(\frac{\partial \cos\theta_1}{\partial x_2}\right)^2 + \left(\frac{\partial \cos\theta_1}{\partial y_2}\right)^2 + \left(\frac{\partial \cos\theta_1}{\partial z_2}\right)^2}$$

SigmaTheta = average position resolution

OFT - tracking

1) multiply by the probability to undergo a Compton interaction at i and the probability to Compton scatter at i+1 (if i+1 is the end of the track test for photoelectric interaction):

2) multiply by the probability for ranges in Ge between i-1, i and i+1

3) skip the rest of a sequence after a bad scattering point and go to next sequence

2 3 1 4 5
2 3 1 5 4
2 3 4 1 5
2 3 4 5 1
2 3 5 1 4
2 3 5 4 1
2 4 1 3 5

4) Repeat for all the steps in the sequence: the total trackFOM for each sequence is the Nth square root of product of probabilities – where $N=(n_{int}x2)-1$

5) Award to the cluster the trackFOM of the best sequence or the pair production trackFOM if it is larger (and assign trackType 2 or 3 respectively)

OFT – cluster validation

Clusters are sorted according to their figure of merit (clusters with smaller figure of merit than others and with at least one matching interaction point are flagged)

Clusters with n_{int}>1 are accepted if trackFOM > threshold = MinProbTrack

Evaluate the FOM of the remaining unflagged single interaction clusters:

OLD METHOD

```
distance to closest interaction point > 4 cm
cross1=σphoto(eclus)
cross2=σphoto(eclus)+σcompt(eclus)+σpair(eclus);
λ=range_process(cross2);
probability = sqrt(proba(λ,rge) x cross1/cross2);
```

Accept cluster if trackFOM > MinProbSing (used to be an OFT parameter)

NEW METHOD

```
distance to closest interaction point > 4 cm
if (proba(λ,rge) > f(eclus), accept single-interaction point and set trackFOM to 1.15
and trackType to 1
```

function f fitted from data (hence PSA dependent)

OFT at work

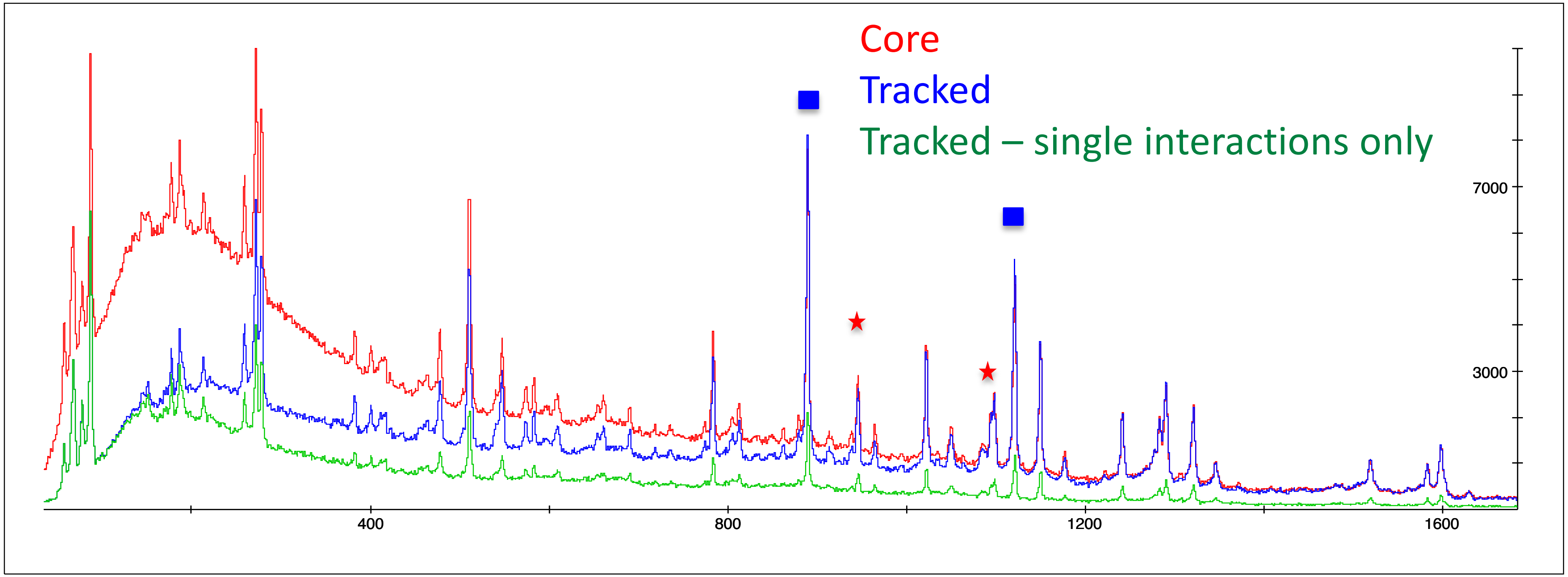
AGATA + NEDA + DIAMANT @ GANIL, 2018, GANIL

$^{36}Ar(^{40}Ca,2p\alpha)^{70}Se$

Contaminant reaction: $^{36}Ar(^{16}O,2p\alpha)^{46}Ti$

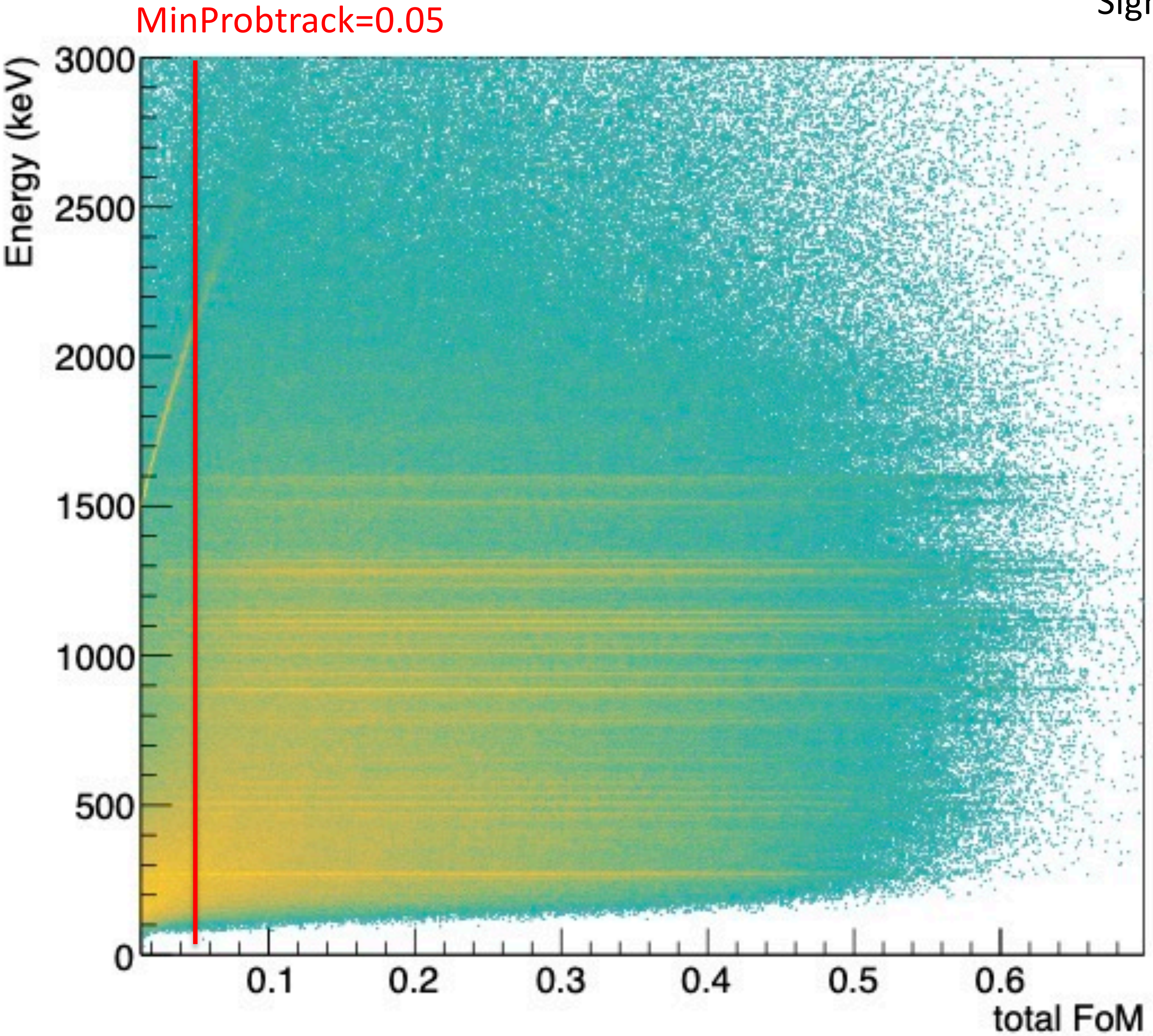
MinProbTrack = 0.05

SigmaTheta= 0.8



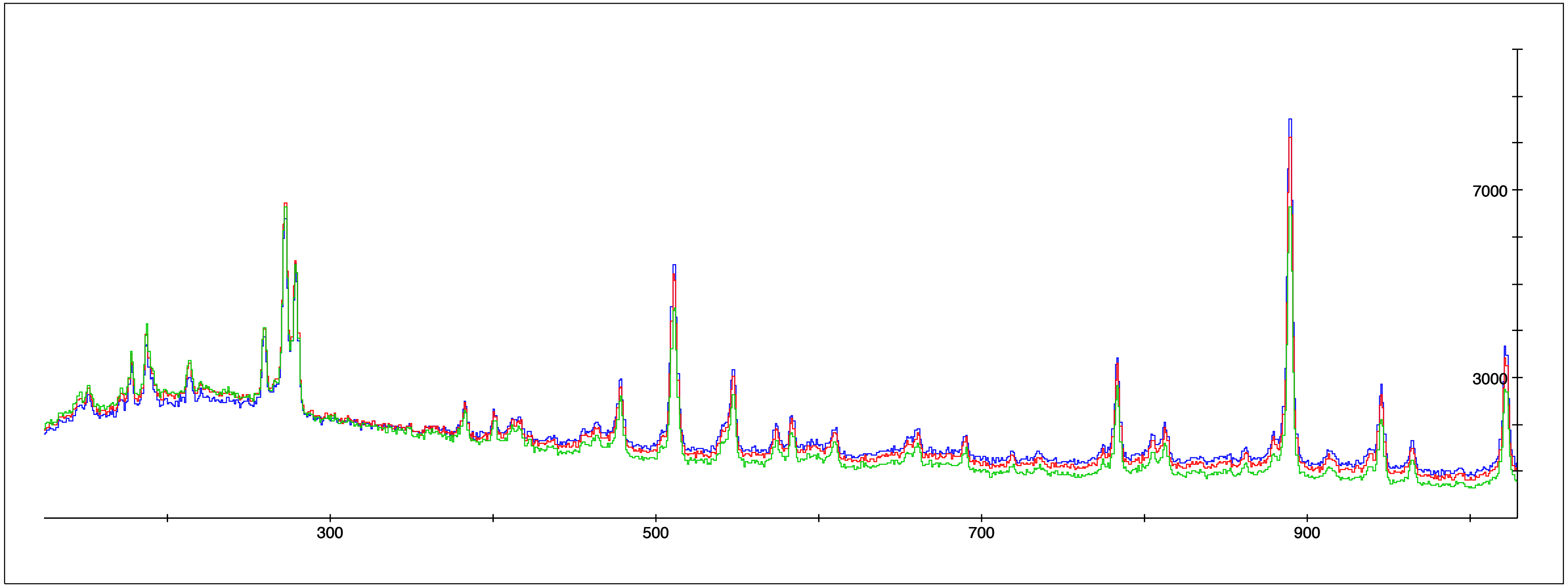
Compton & Pair production clusters

SigmaTheta=0.8



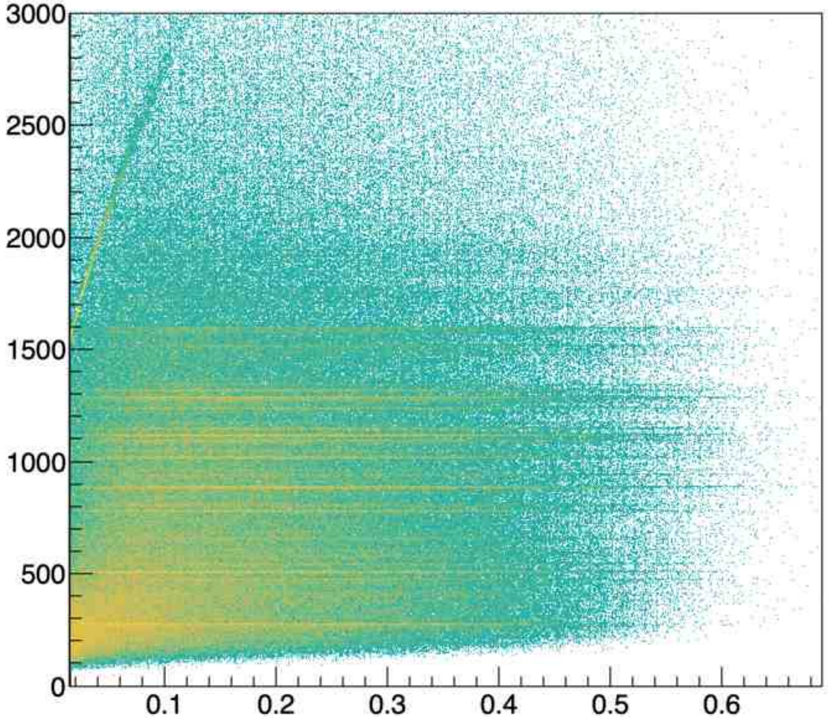
Changing parameters

SigmaTheta = 1.6
SigmaTheta = 0.8
SigmaTheta = 0.4

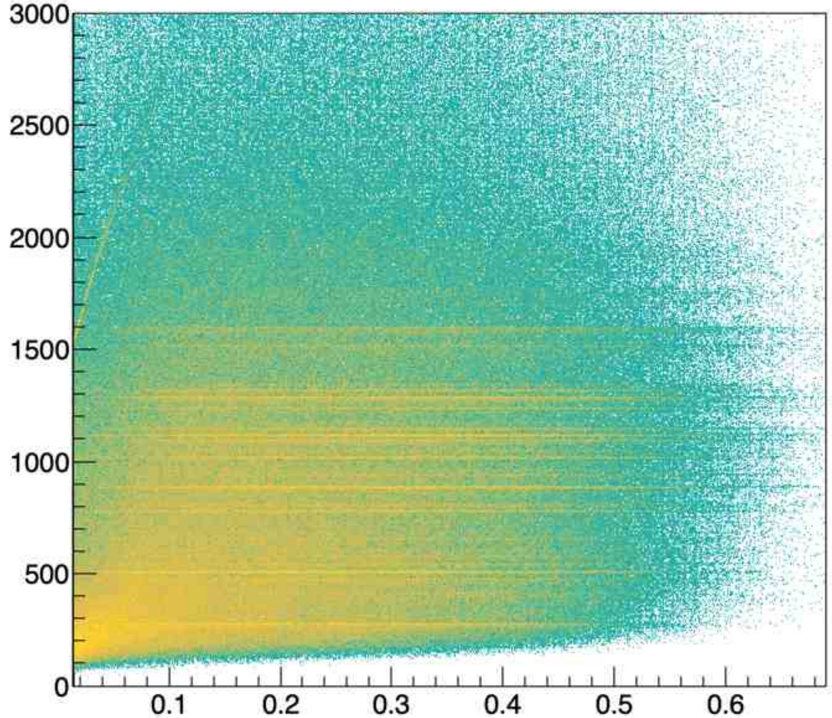


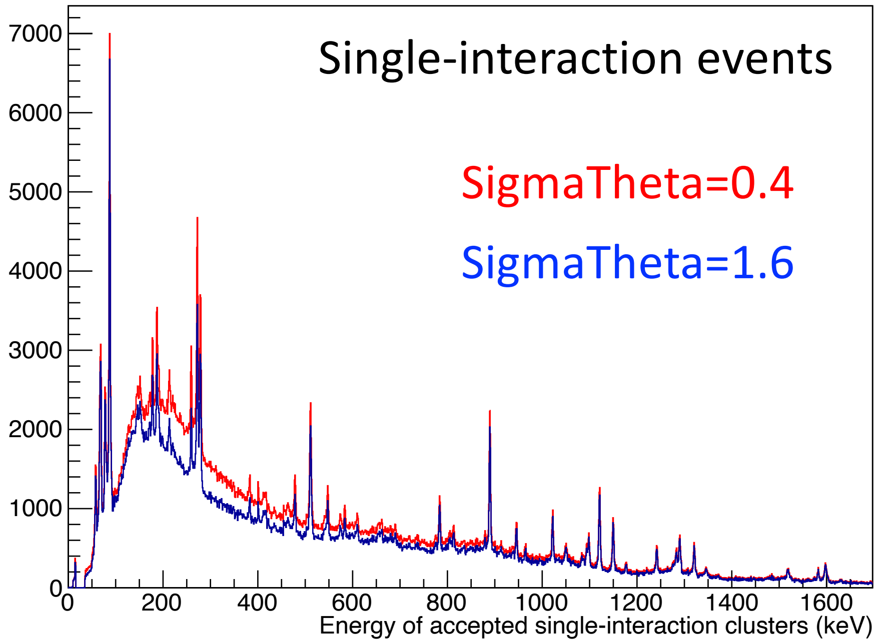
Optimum between gain at high energy and loss at low energy

SigmaTheta=0.4



SigmaTheta=1.6





As sigma_theta increases, more "bad events" are accepted as Compton or pair-production clusters, reducing the number of single-interaction point clusters to be treated at the end…..and therefore reducing the efficiency at low energy and increasing the intensity of sum peaks & background at high energy

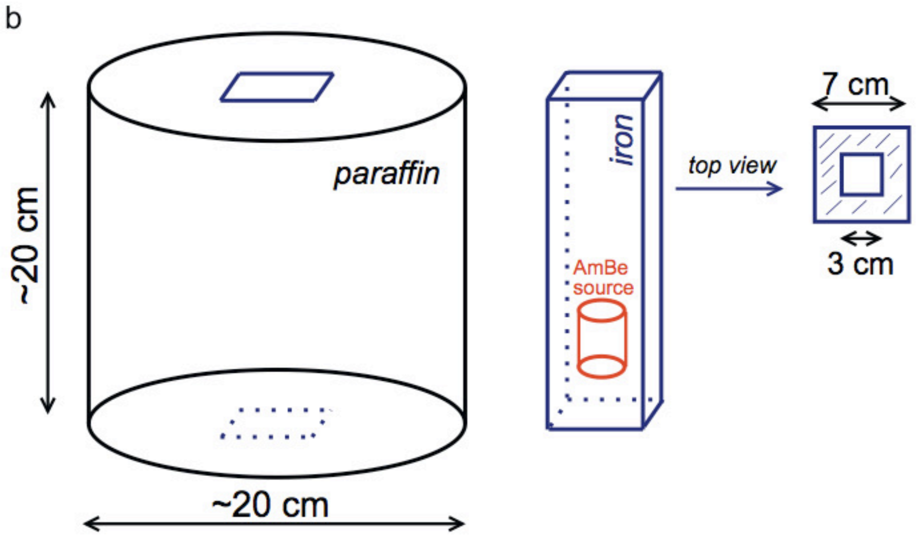
Tracking at high-energy

Legnaro source data

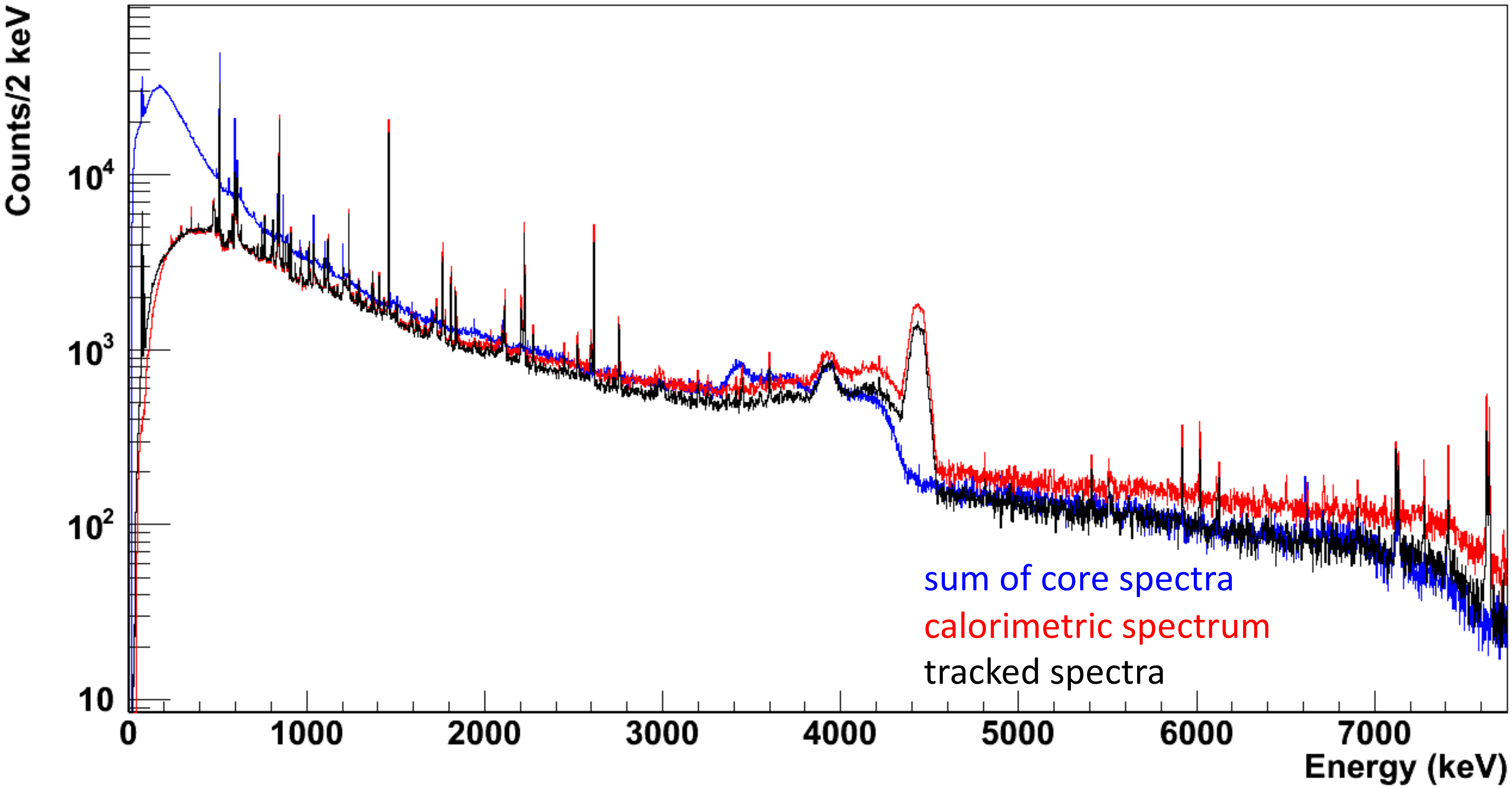
Agata demonstrator (4 triple clusters)
AmBe(Fe) high energy gamma-ray source
source=(0,0,+5 cm)
(!! the x pos. of the
source is actually lower)

↓

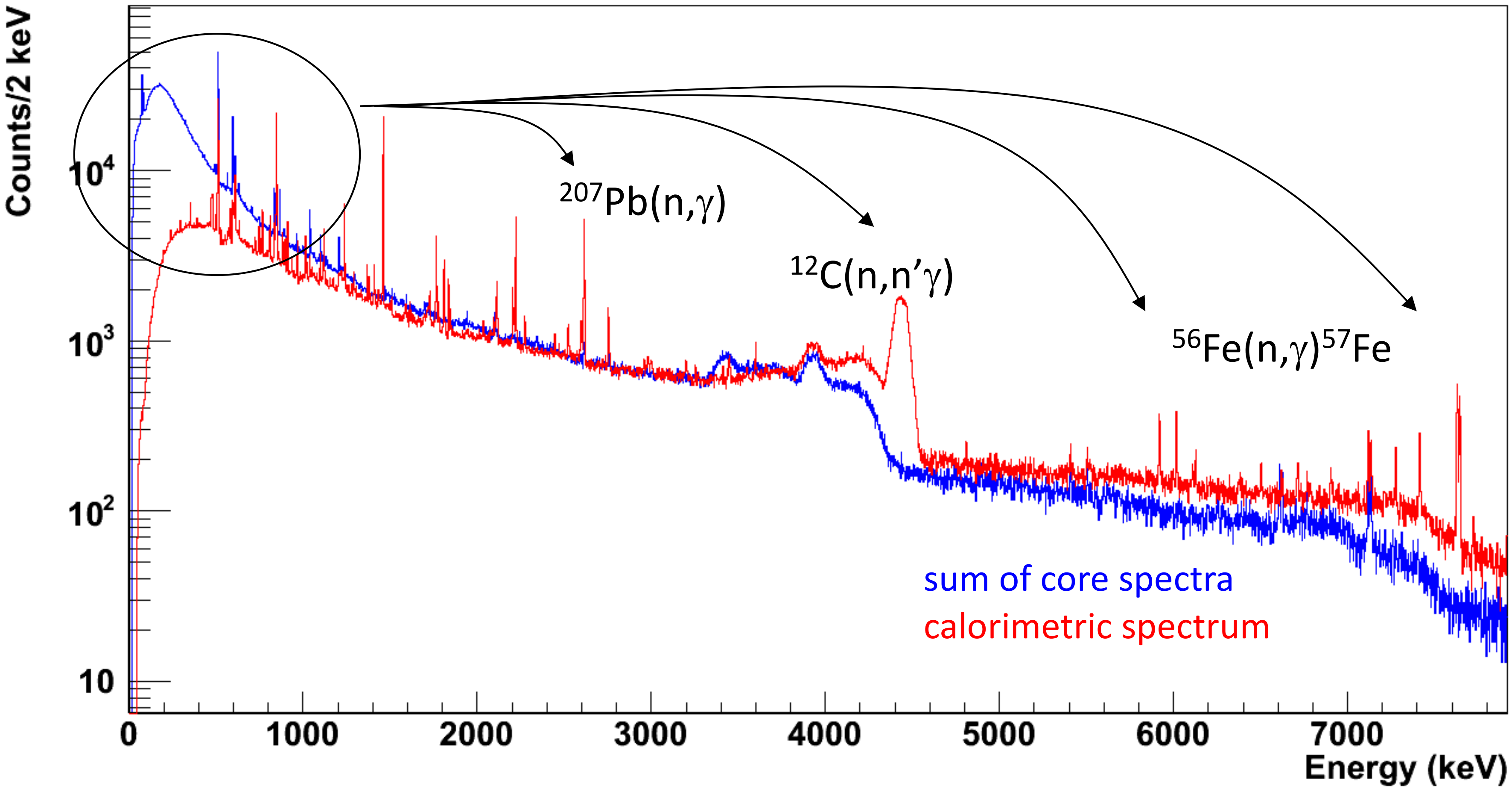
might have some
effect on the performance
of OFT



Tracking at high energy

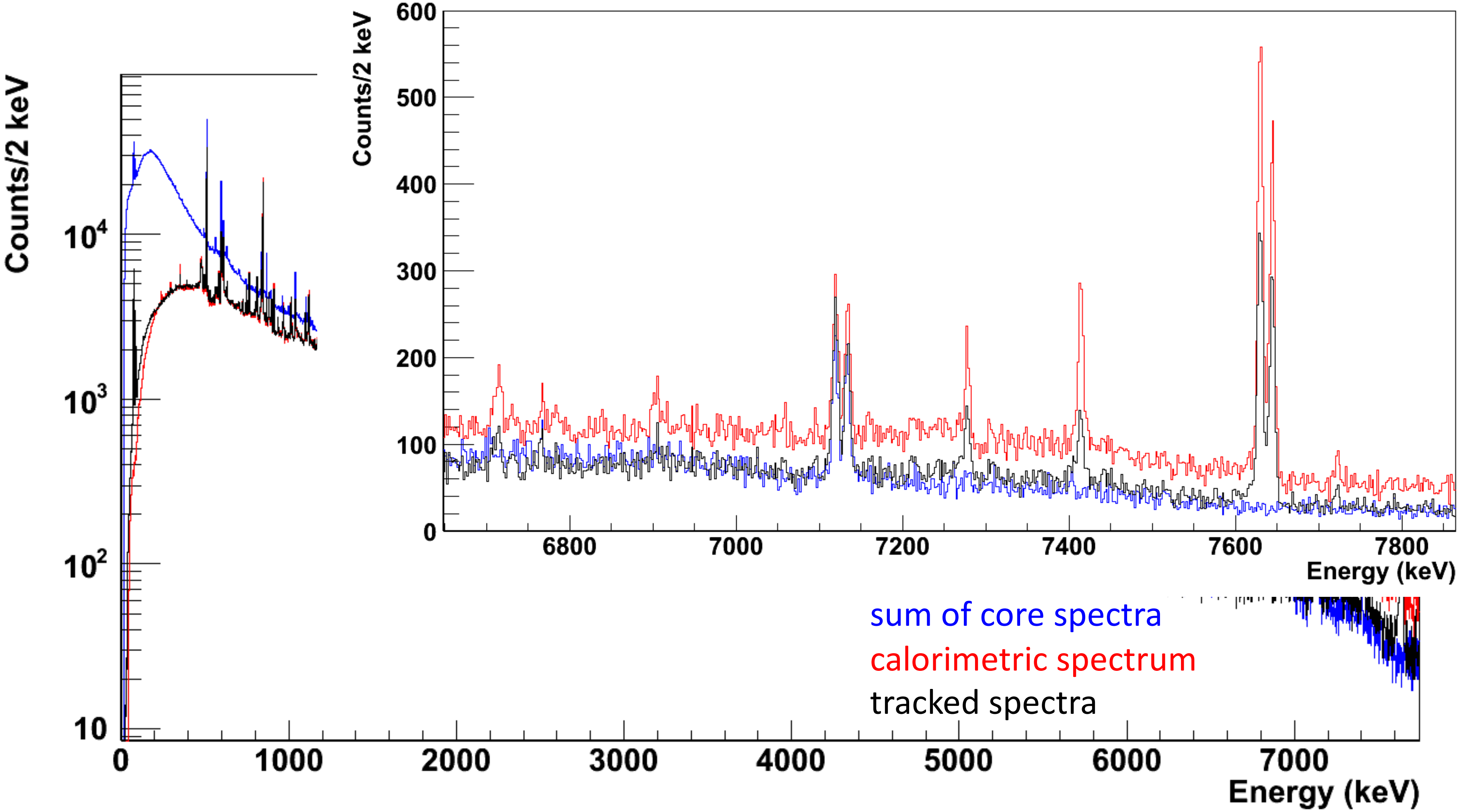


Spectra



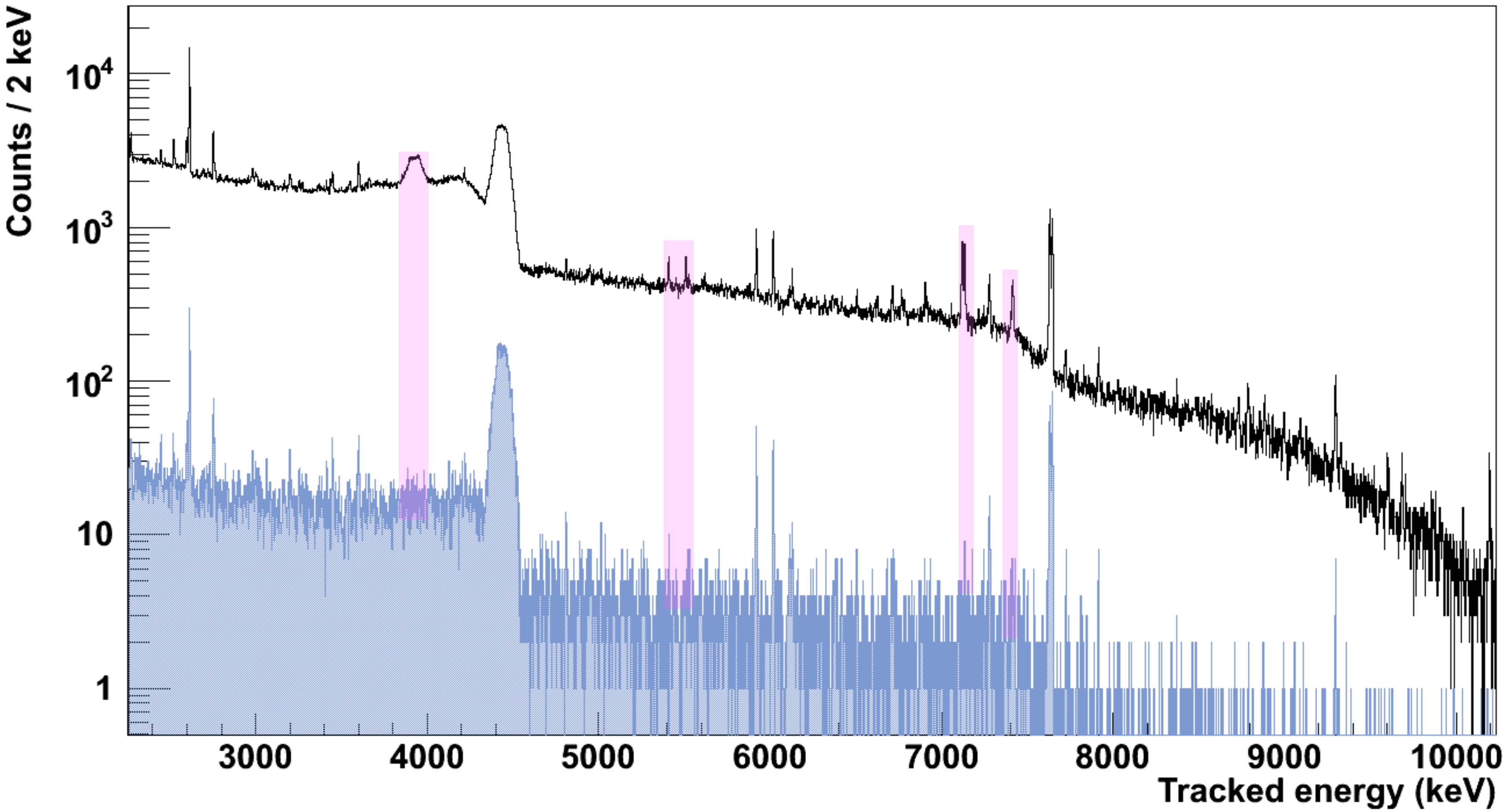
Counts/2 keV
10^4
10^3
10^2
10
0
1000
2000
3000
4000
5000
6000
7000
Energy (keV)
$^{207}Pb(n,\gamma)$
$^{12}C(n,n'\gamma)$
$^{56}Fe(n,\gamma)^{57}Fe$
sum of core spectra
calorimetric spectrum

Tracking at high energy



Compton vs Pair production

(trackType 2 vs trackType 3)

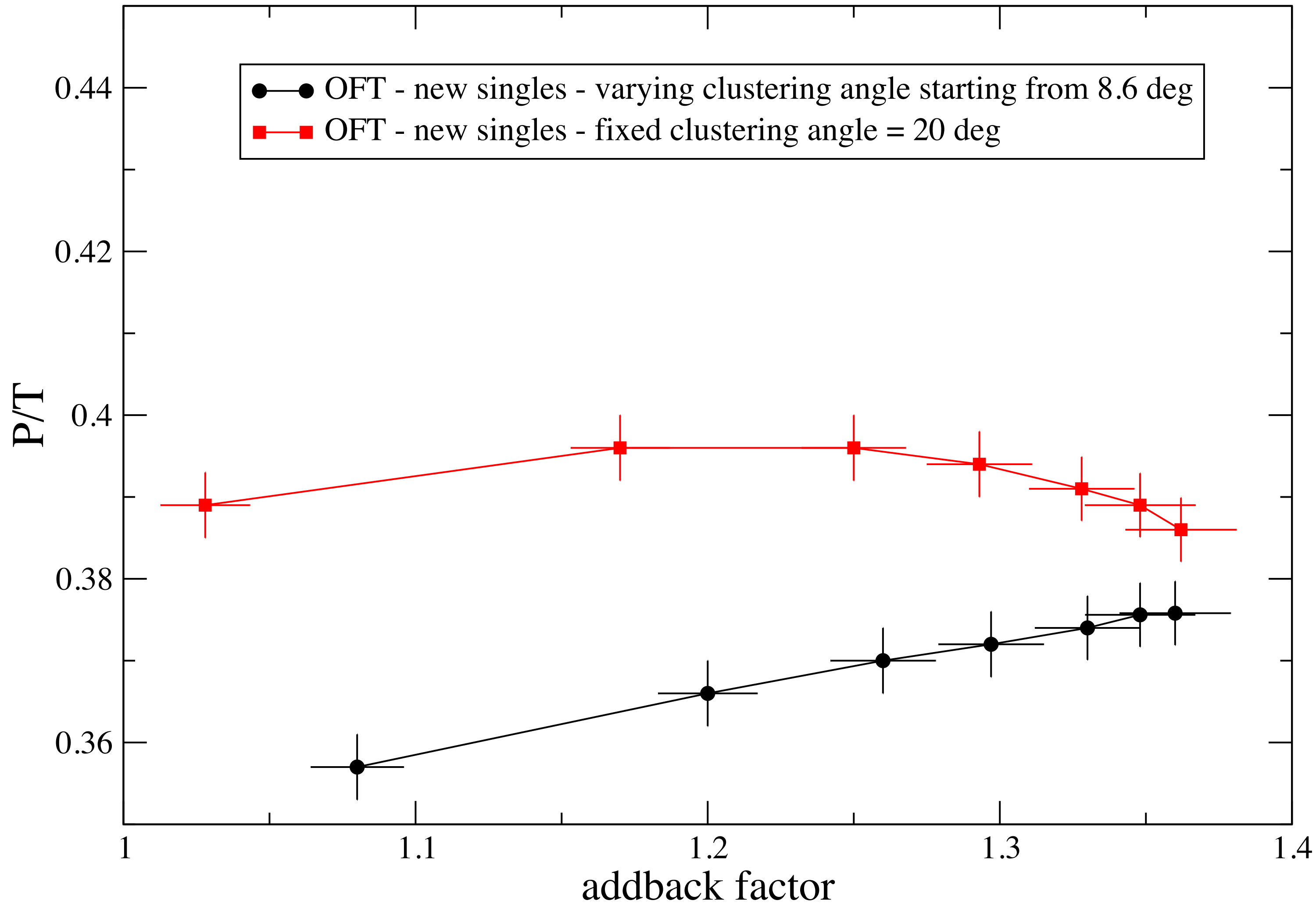


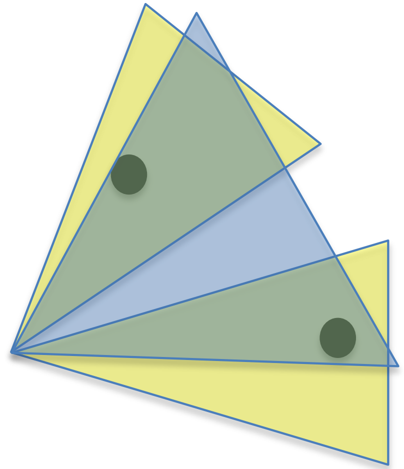
★at 7.6 MeV, reconstruction of pair-production events contributes to ~6% of the total photopeak eff. => Compton dominates !

★Algorithm can recognize escape and pileup peaks – very clean pair-production spectrum

Fixed clustering angle

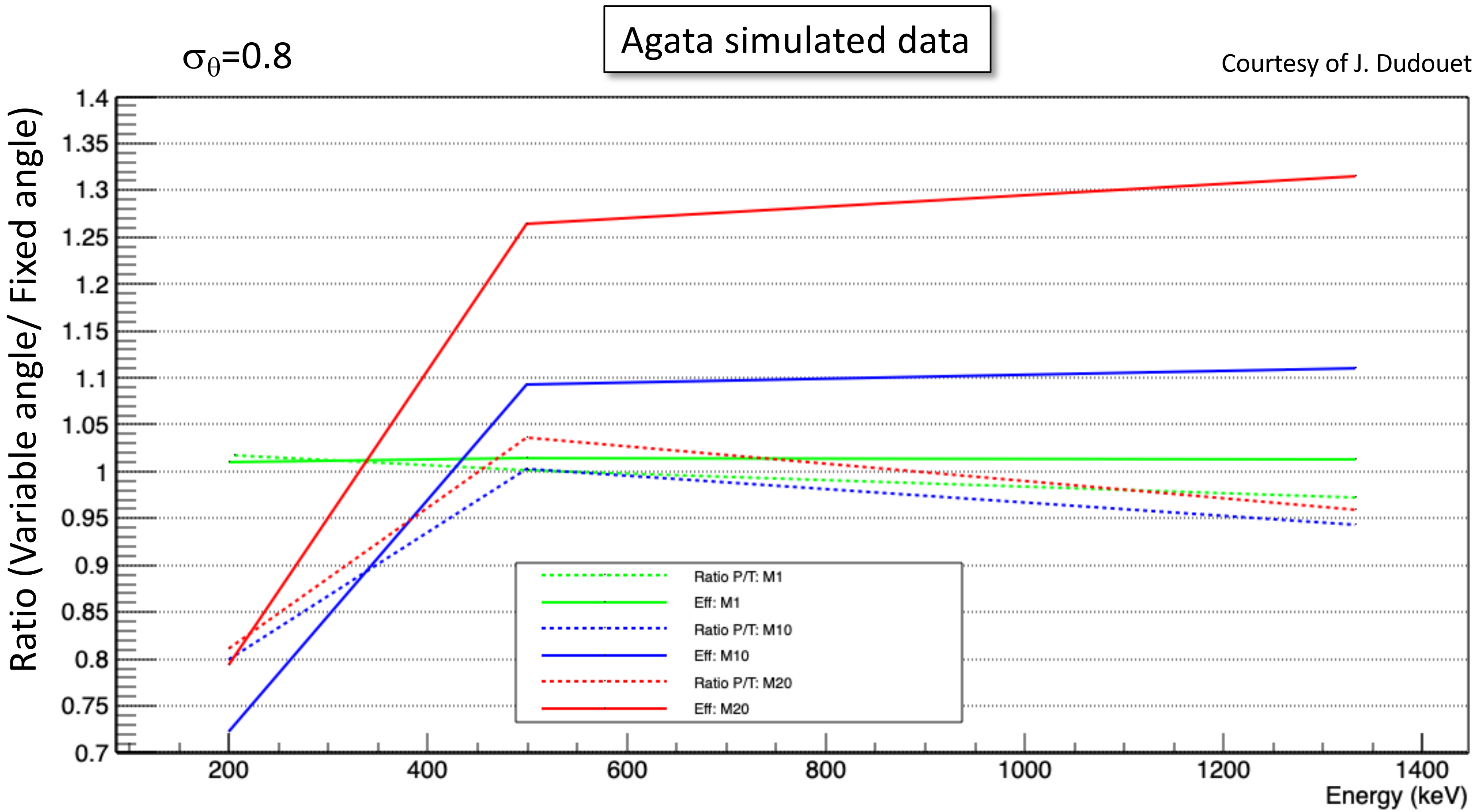
σ_θ=0.4, 0.6, 0.8, 1, 1.3, 1.6, 2





1172 keV (^{60}Co source data, 2016)

Different behaviours…..



Fixed angle yields better performance at low energy

Variable angle is better at high energy & medium-to-high multiplicities

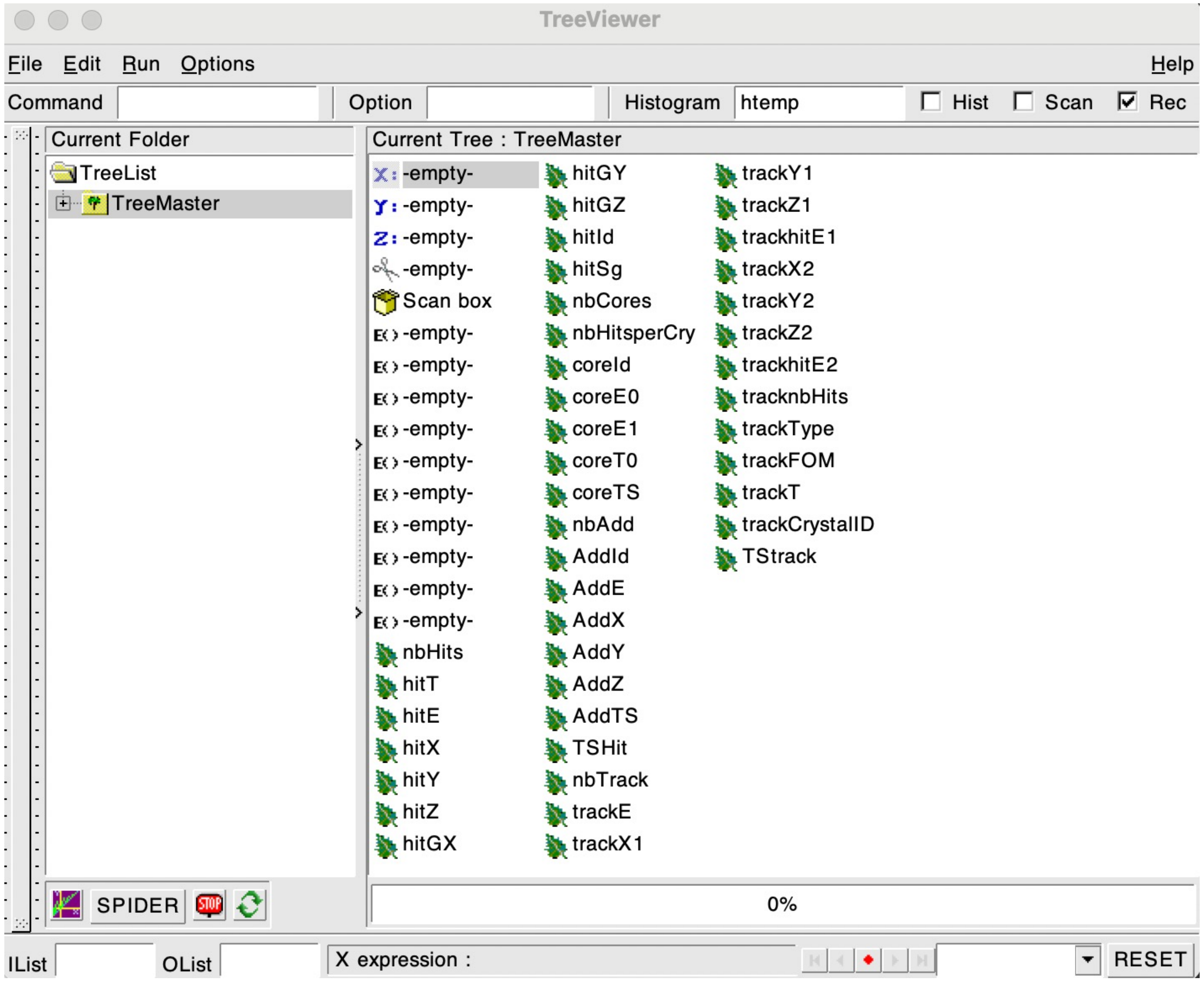
⇨ **fine tuning of OFT parameters is needed for every experiment !**

Tracking ^{152}Eu PSA hits

In gen_conf.py, modify the tracking parameters to see how the tracked quantities vary
Run gen_conf script and then femul (as on tuesday), sending the data to different OUT directories each time (mkdir NameofOut and then ln –s NameofOut OUT)

```
TrackingFilter=(
"ActualClass            TrackingFilterOFT",          # name of the used
daugther class (TrackingFilterOFT or TrackingFilterMGT)
"SaveDataDir            $SAVEDIR/$MERGER",           # Out/Global
"EnergyGain             4",                          # channels/keV of
the calibrated energy spectra
#"ExcludeTracking",                                  # skip the
tracking part of the actor; remains only the data processing
#"OftParams            0.05 0.02 0.8 100",              #  minprobtrack
minprobsing sigma_thet (0==default)
"OftMinProbTrack     0.05",
"OftSigmaThetha         0.8",
"OftClustRedFact        1",
"OftFixedAngle          0",
#"MgtParams            0                             #  max value of
Chi2 to accept a tracked gamma (0==default)
"SourcePosition         0 0 0",                      # position of
source with respect to the center of AGATA Position of source
"DiscardEmpty           0",      # to discard events that does not pass
the tracking (don't discard allows to keep the events in the PSA hits)
```

Tracked data



Can Doppler correct with trackX1,trackY1 and trackzZ1 position of 1st interaction (using average beta and average beta direction or information from ancillary)

To mock “high multiplicity” data

Change time window of hits sent to tracking filter to a much much larger value (> x1000) and play with the parameters (especially angles) to try and optimize peak intensities

```
EventBuilder=(
"ActualClass            EventBuilder",           # name of the used
daugther class
"SaveDataDir            $SAVEDIR/$BUILDER",      # Out/Builder
"Window                 45",                     # EventNumber also
possible but not working well
#"TstampWindow   ui64 ui64",                     # coincidence window
'width' or 'from to' (timestamp units)
"keyIn                  data:psa",               # key of 1st
queue.
"keyIn                  data:psa",               # key of 2nd queue.
'None' to not have the surrounding frame
"keyOut                 event:data:psa",         # key of the output
frame default is event:data. 'None' to not have the surrounding frame
"MinFold                1",                      # 2 if you want to
force the coincidence between 2 AGATA
```