Background Reduction by Gamma-Ray Tracking

Mario Cromaz
Lawrence Berkeley National Laboratory

Overview

Gamma-ray tracking:

A set of technologies enabling one to track the path of a gamma-ray through a Ge crystal.

- will have a dramatic impact on gamma-ray spectroscopy
- grew from work started in 1995 on a next-generation Ge spectrometer
- enabled by several new technologies:
  - contact segmentation of Ge detectors
  - advent of fast, high-resolution, inexpensive digitizers
  - improved computing capability

Community Effort

- gamma-ray tracking is a community effort involving both U.S. universities and national laboratories
- initiative in the NSAC long-range plan
- overseen by:
  - Gamma-Ray Tracking Coordination Committee (GRTCC)
  - GRETA steering committee
- similar efforts are being carried out internationally
- gamma-ray tracking, Ge detector segmentation are also pursued in other fields:
  - medical applications
  - observational astrophysics
  - double β–decay (Majoranna project)

Outline

- motivation for pursuing tracking technology
  tracking arrays (Gretina)
- technology
  - detector segmentation
  - signal decomposition
  - electronics
  - tracking
- applications to background suppression
- status
- summary

Limitations

- required to meet a number of conflicting requirements:
  - maximize efficiency
  - increase P/T
  - maintain energy resolution (Doppler broadening)
  - reduce summing from high-multiplicity events
- suppressors limit efficiency:
  - veto Compton scattered events from crystal
  - cover a large fraction of the solid angle

Ideal Solution

- homogeneous sphere of HPGe detectors to maximize active detector volume
- no suppression shields

The Tracking Approach

- focus on characterizing the scattering points of the incident γ-ray
  - scattering locations
  - charge deposition
- reconstruct the energy and path of the incident gamma-rays
- benefits of gamma-ray tracking
  - efficiency
  - peak/total
  - position resolution
  - counting rate
  - directional information
  - gamma-ray polarization

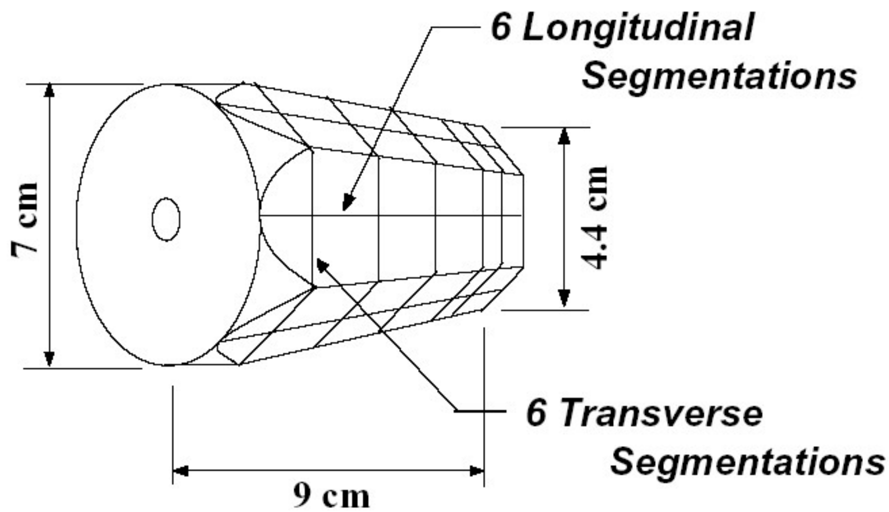
4π Tracking Array - Capabilities

Reaction	$\langle E_\gamma \rangle$ (MeV)	v/c	M_γ	RP	$\frac{RP(GRETA)}{RP(GS)}$
Stopped	5.0	0.0	4	2.1×10^7	200
	1.5	0.0	4	4.4×10^7	77
High Spin Normal Kinematics	1.0	0.04	20	2.4×10^6	55
High Spin Inverse Kinematics	1.0	0.07	20	2.2×10^6	120
Coulex/Transfer	1.5	0.1	15	3.7×10^6	510
Fragmentation	1.5	0.5	6	5.9×10^6	12490
In-beam Coulex	5.0	0.5	2	2.7×10^3	110
	1.5	0.5	2	4.1×10^3	50

RP: resolving power

Detector Segmentation

- electrically segment outer contact of an N-type HPGe detector



- detectors are 36-way segmented:
  - 6 radial $\times$ 6 longitudinal segments
  - observation of induced signal in neighbouring segment sets maximum size of segments

- performance (prototype 2):
  - energy resolution:
    1.94 keV (avg) @ $E_\gamma = 1.33$ MeV
  - 4 keV (bandwidth 40MHz)

Signal Decomposition

- preamp signal from each segment digitized with flash-ADC's
- each charge deposition produces:
  - a net induced current signal in the segment which contains the scattering site
  - induced current signals in neighbouring segments
- each segment signal is a superposition of net and induced currents from multiple interaction points
- decomposition:
  - calculate "basis signal" for a set of grid points in the crystal
  - fit measured signals against a linear combination of basis signals
  - interpolate to improve resolution
- position resolution:
  - 1mm @ 374 keV (single interaction, meas.)
  - 2mm (multiple interactions, sim.)

Electronics

preamplifiers:

- high-bandwidth, low noise to preserve information from the transient signal on segment

- low power, highly miniaturized as >100 such preamps are required for each 3-detector cryostat

digital pulse processing:

- require 100 MHz sampling with 12-bit resolution to preserve position, time resolution

- digitally emulates functions of standard analog systems (and adds new ones):
  - leading edge, constant fraction discriminator
  - algorithm to compute energy
  - pileup rejection
  - pulse window
  - flexible trigger system

- 8 channel digitizer boards have been developed and tested
  - excellent noise performance (≤ 0.5 bits)
  - energy resolution competitive with analog systems

Tracking

- recover gamma-ray tracks and energies from interaction points

- 2 step process:
  1. assign a group of n interaction points to a given gamma-ray (clusterization)
  2. fit energies and scattering angles to n! sequences with the Compton scattering formula:

$$E_{\gamma}\prime = \frac{E_{\gamma}}{1+\frac{E_{\gamma}}{m_0 c^2}(1-\cos\theta)}$$

- select minimum $\left(\text{fom} = \sum \frac{|\theta_{\text{meas}}-\theta_{\text{calc}}|}{\Delta\theta}\right) < \text{fom}_{\text{cut}}$
  - yields correct scattering sequence
  - rejects Compton scattering events with incomplete energy deposition
  - rejects improperly clustered interaction points

Background Reduction by Gamma-Ray Tracking

- directed to measurement of low cross-section capture reactions for nuclear astrophysics

$$^{26}\text{Mg} + p \rightarrow {}^{27}\text{Al} + \gamma$$

- apply to cases where γ is the only trigger

- experimental sensitivity limited by cosmic-ray induced background

Solutions:

1. active suppression

2. shielding (i.e. underground experiments)

3. gamma-ray tracking

Approaches to Background Reduction

1. reject γ-rays that do not originate from the target position

2. place cuts of the detector volume to preferentially reject background gamma-rays

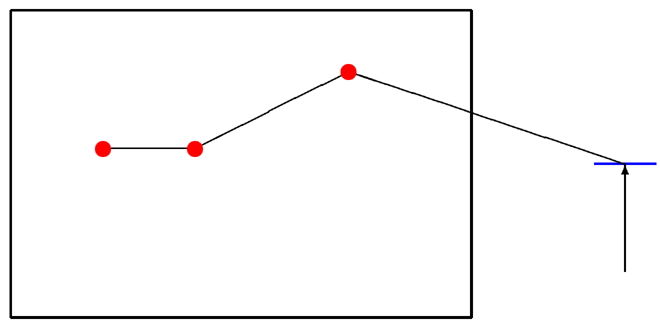
3. reject single interaction points

4. increase P/T by tracking

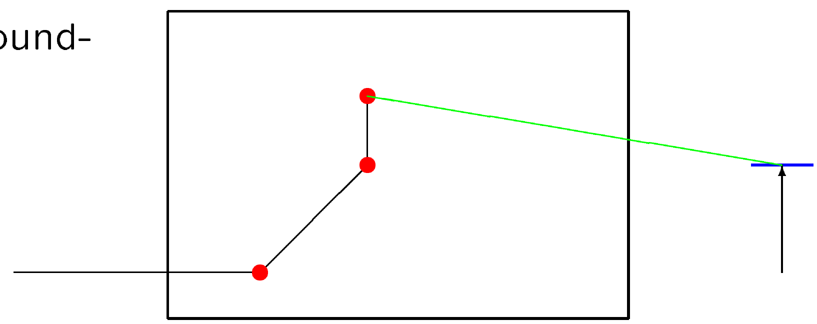
5. Doppler corrections for inverse reactions

Background Rejection by Tracking

target-
like



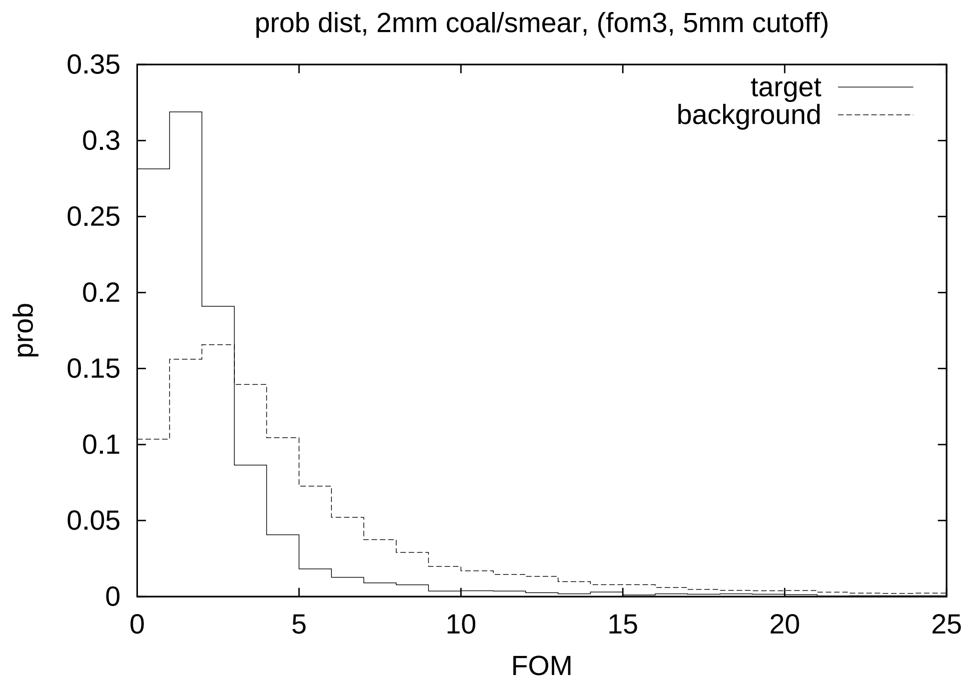
background-
like

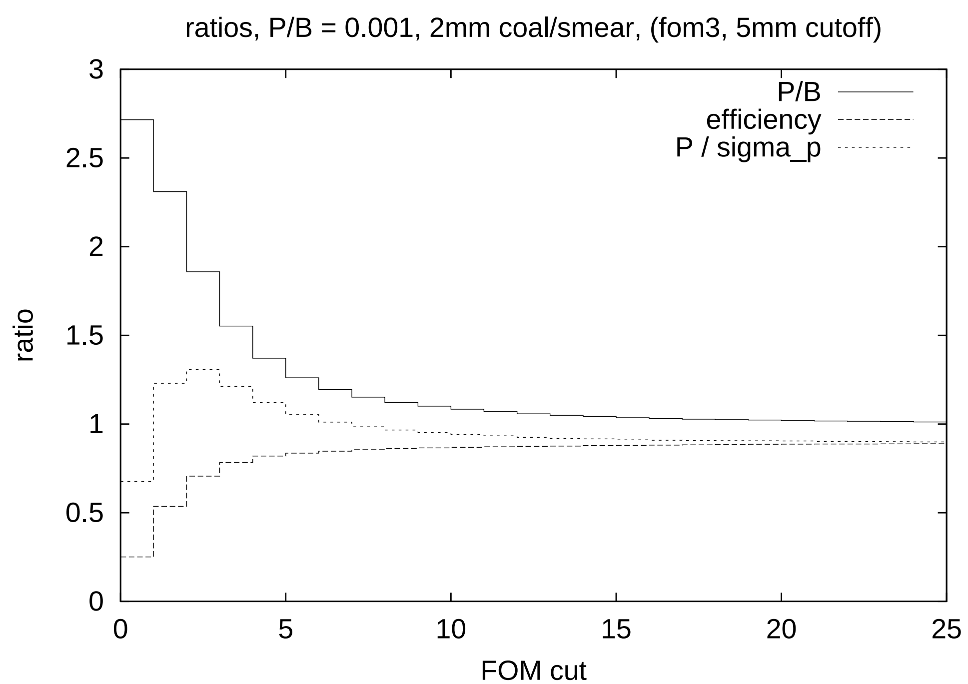


- assume all γ's originate from target

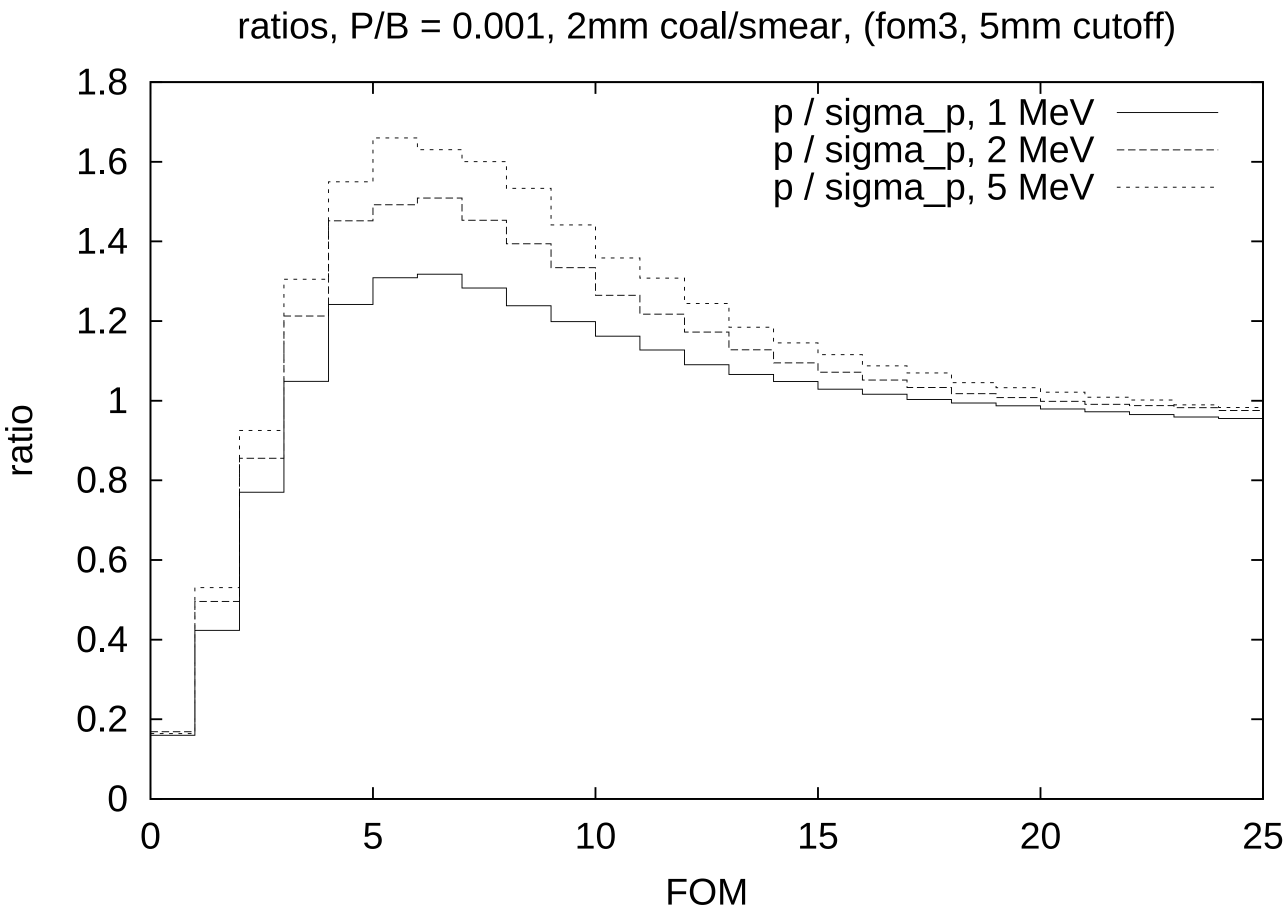
- pick the scattering sequence which best fits the Compton scattering relation – assign a figure of merit – apply cut

Tracking


prob dist, 2mm coal/smear, (fom3, 5mm cutoff)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
prob
0
5
10
15
20
25
FOM
target
background

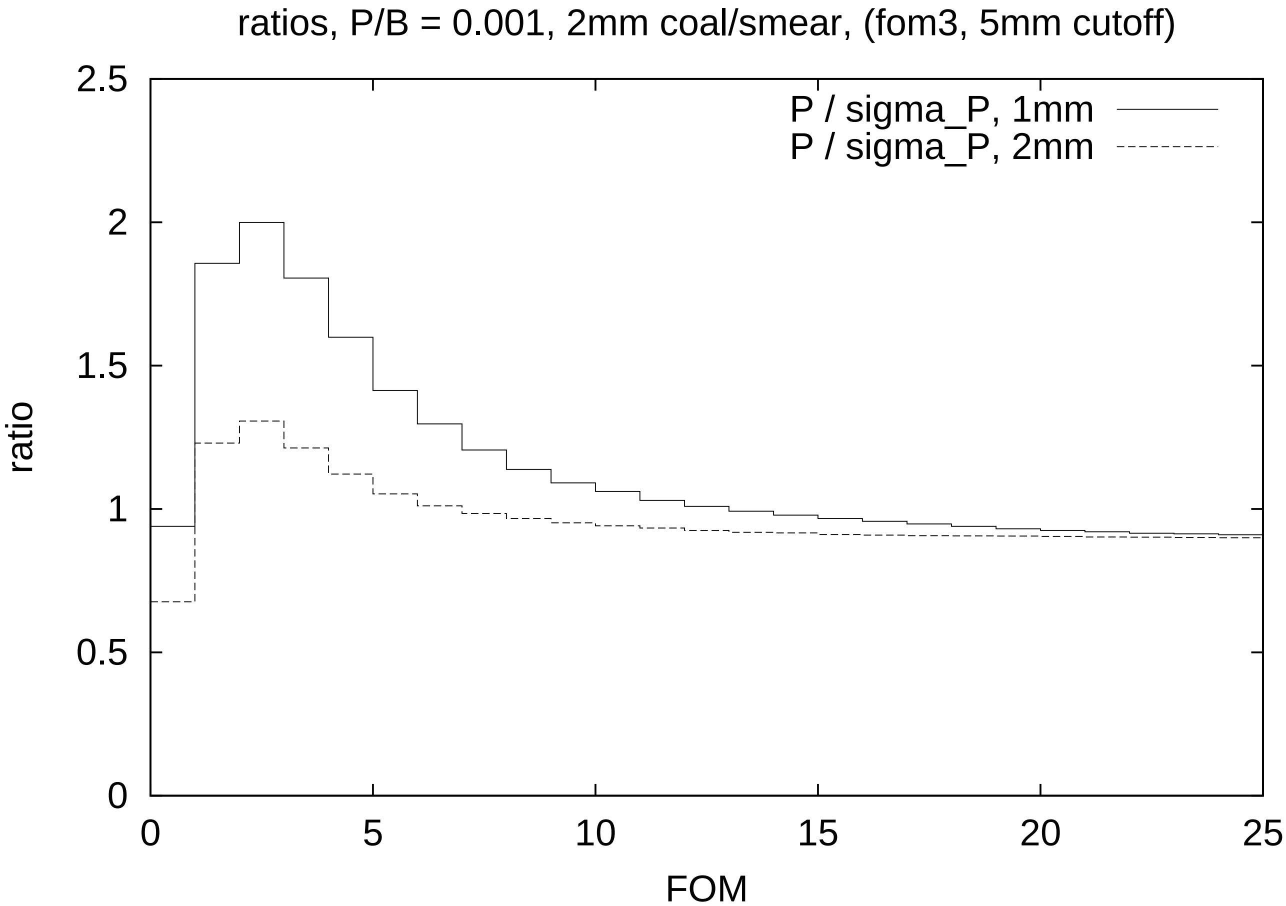

ratios, P/B = 0.001, 2mm coal/smear, (fom3, 5mm cutoff)
3
2.5
2
1.5
1
0.5
0
ratio
0
5
10
15
20
25
FOM cut
P/B
efficiency
P / sigma_p

Energy Dependence



r_{max} = 1.32 @ 1 MeV
1.51 @ 2 MeV
1.66 @ 5 MeV

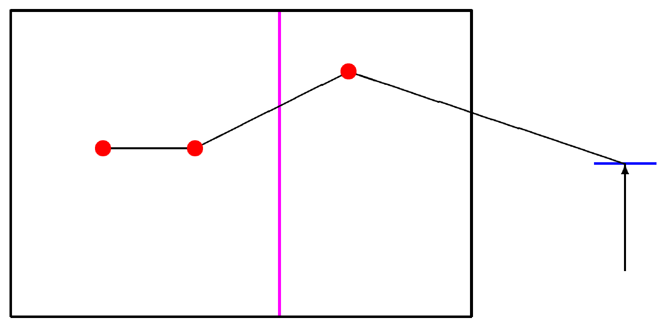
Effect of Position Resolution



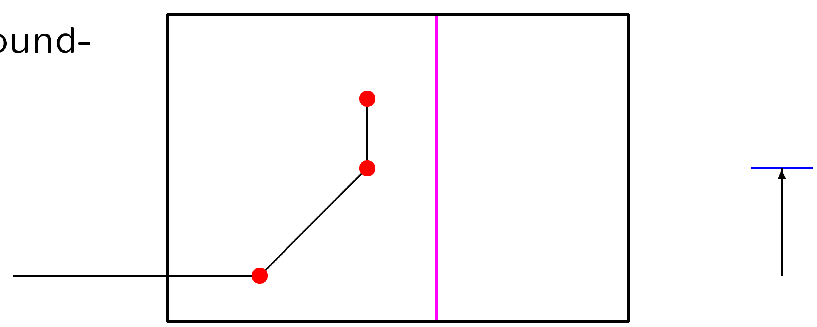
$r_{max} = 2.00$ @ 1 mm
1.31 @ 2 mm

Background Rejection by Volume Cuts

target-like

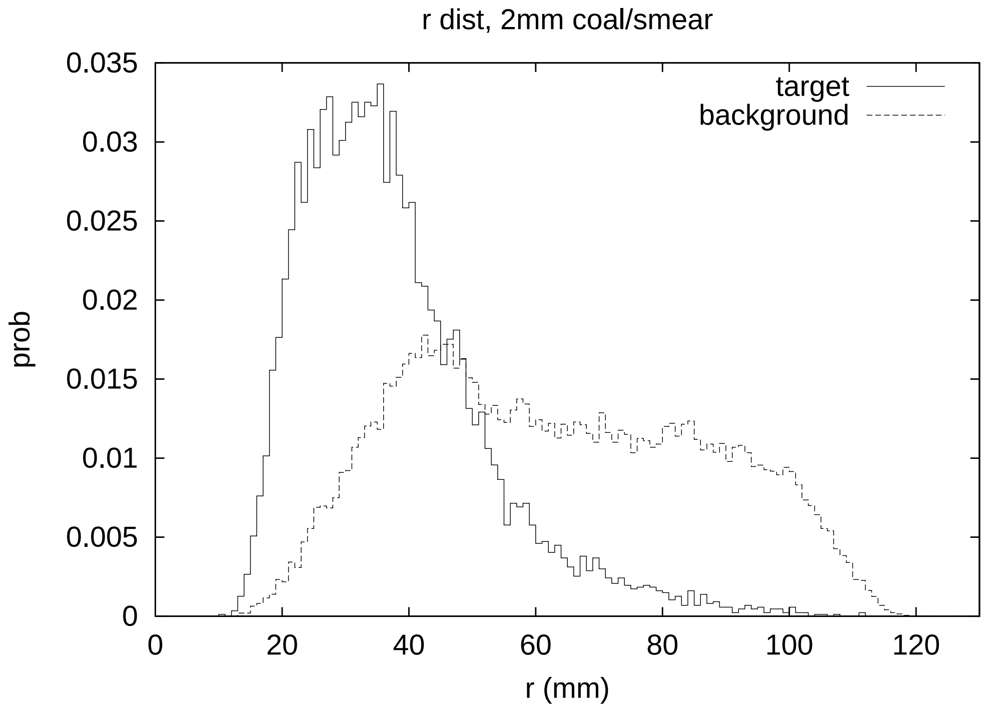


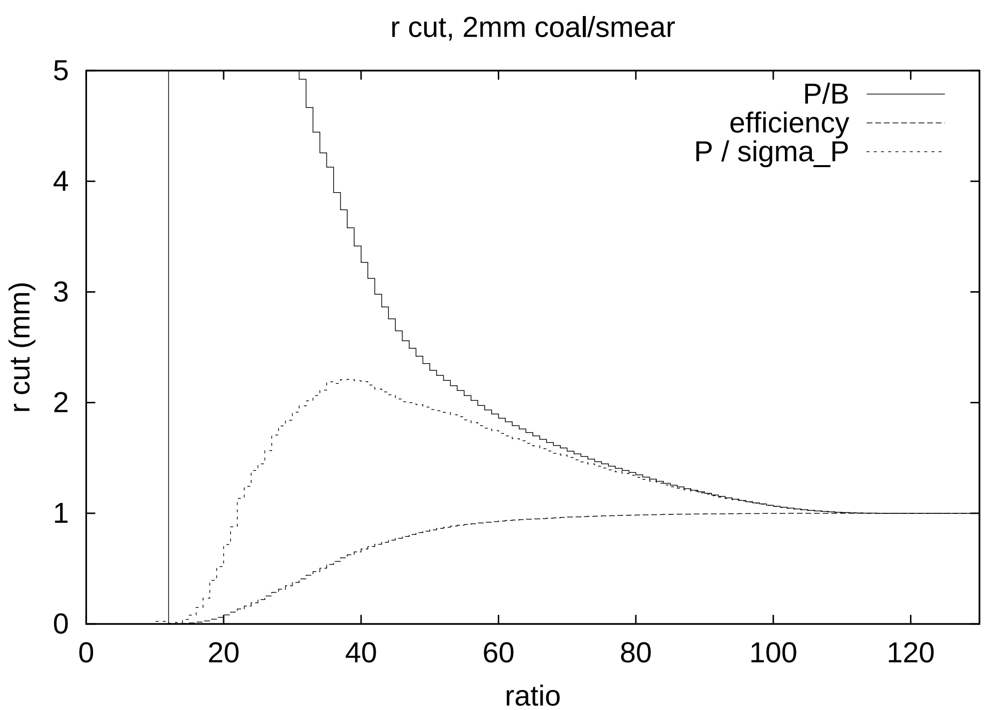
background-like



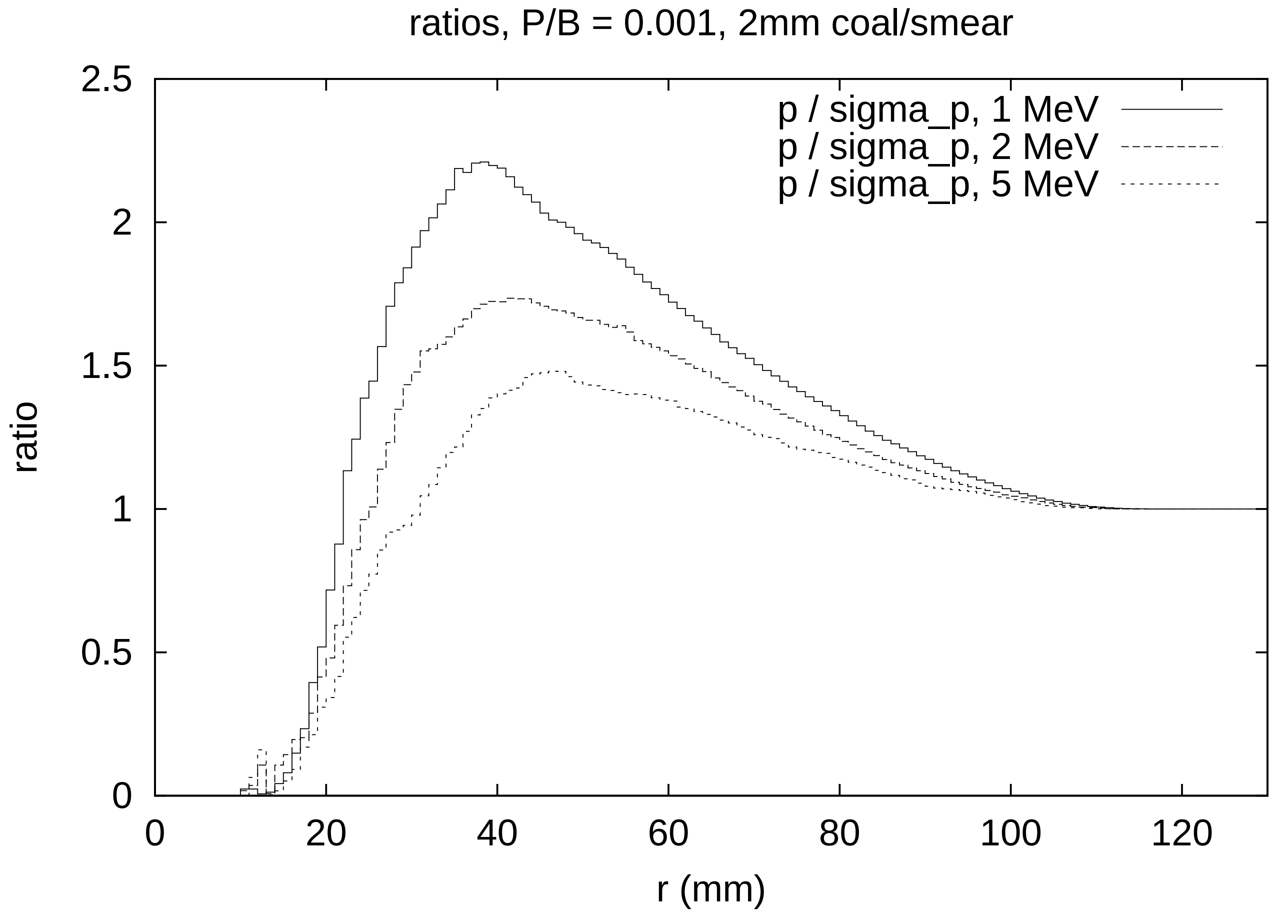
- require interaction points in certain regions of the detector

Volume Cut


r dist, 2mm coal/smear
target
background
prob
r (mm)
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
20
40
60
80
100
120


r cut, 2mm coal/smear
P/B
efficiency
P / sigma_P
r cut (mm)
ratio
5
4
3
2
1
0
0
20
40
60
80
100
120

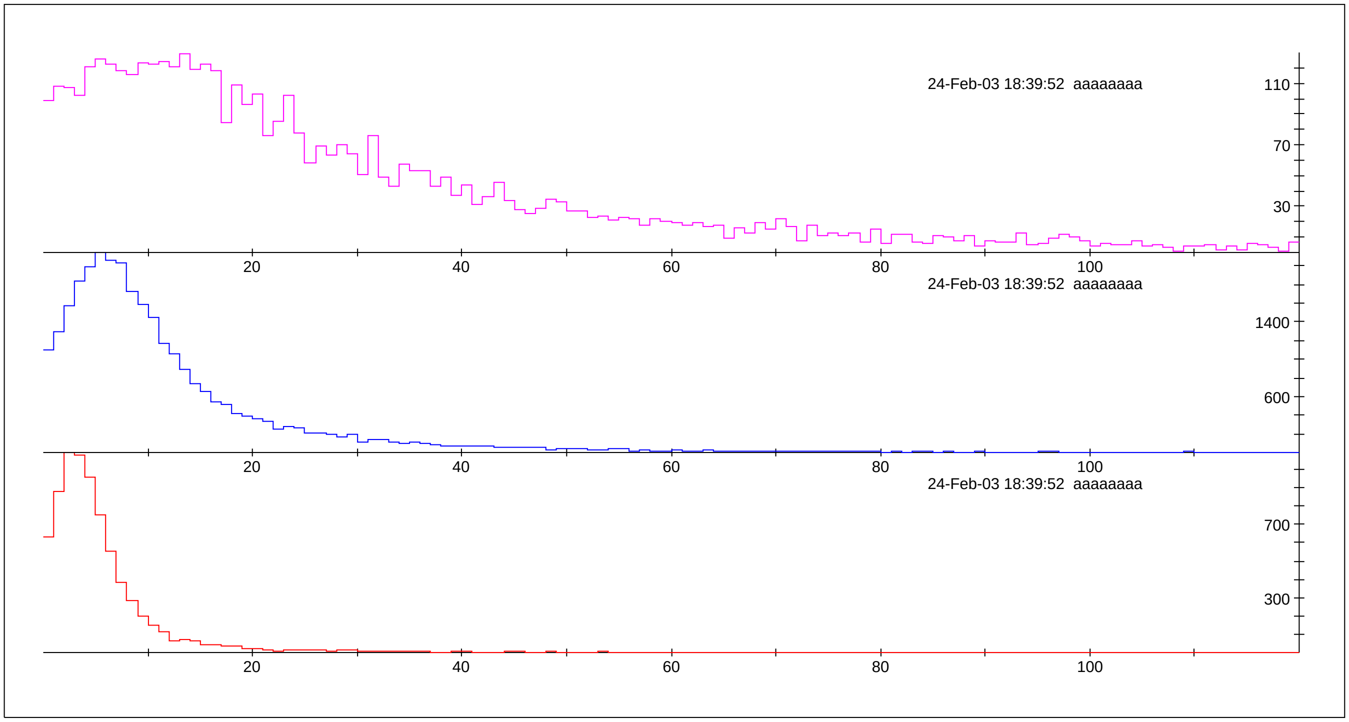
Energy Dependence



r_{max} = 2.21 @ 1 MeV
1.73 @ 2 MeV
1.48 @ 5 MeV

Additional Advantages

- peak/total improvements:
  - rejection of single interaction points
  - tracking cuts



- γ-rays can be fully characterized in low statistics runs

Doppler Broadening Reduction

- gamma-ray energies must be Doppler corrected to account for the velocity of the source:

$$E' = E \left(\frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta} \right) \tag{1}$$

- Doppler broadening arises from:
  - $\vec{v}$ distribution of emitter ($\delta\vec{v}$)
  - detector opening angle ($\delta\theta$)

- tracking detectors reduce Doppler broadening by fixing the position of the first interaction point accurately.
  - 10–50 mm $\rightarrow$ 2 mm

- important for reactions employing inverse kinematics

- crucial when detectors close in

Project Status

- CD0 for Gretina taken by DOE (π coverage array, 10 detector modules)
- conceptual design review (CDR) in Dec. 03
- have demonstrated the critical technologies required by tracking arrays:
  1. detector fabrication
  2. signal decomposition
  3. electronics
  4. tracking
- have ordered the final 3-detector module prototype (arrives late 03)
- completed design of second revision of digitizer modules
- performance improvements made to the decomposition algorithm

Summary

- gamma-ray tracking is a compelling technology
- enables Ge arrays to have:
  - significantly higher efficiency, P/T
  - excellent Doppler correction capability
  - background rejection capability
- several methods exist to employ tracking for background reduction
- factor of 2 improvements in running time for single crystal (greater for arrays or when methods combined)
- To Do:
  - detailed, experiment specific simulations
  - examine design options for small (6 crystal) arrays coupled to efficient suppressor systems
  - heuristics to avoid full tracking
  - segmentation + low background detector materials
- costs will drop as manufacturers gain expertise