Monte Carlo Study of the Noble Liquid GEM EM Calorimeters

(M. Seman, Columbia University)

* INTRODUCTORY REMARKS

* DESIGN CONSIDERATIONS

* ENERGY RESOLUTION

* POSITION AND ANGULAR RESOLUTION

* PI zero and JET rejection

* LKr vs. LAr

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V.Radeka, S.Rescia, B.Willis, ...

Acknowledgment :

Close colaboration with RD3 group at CERN

- Non projective version of accordion GEANT code (M. Lefevbre)
- Projective versions - developed independently (exchange of experience)
- Usefull discussions on general approach Preshover, ENDCAP geometry

SELECTION OF ACCORDION STRUCTURE FOR WELL ESTABLISHED LIQUID IONIZATION CALORIMETRY BASED ON FEATURES LIKE :

- extraction of signal without degrading high frequency component

- convenient to implement longitudinal and transversal segmentation

- integrated PRESHOVER

- rigid structure even when using thin absorber

- good hermeticity

- succesfull tests at CERN and BNL, generaly in good agreement with MC simulations

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Design Optimization EM Calorimeter:

Energy Resolution.

Jet Rejection.

π^0 Rejection.
Isolation criteria.

Position Resolution, Pointing.

Mass Resolution.

Acceptance.

EM Optimization:

→ 1) Krypton .vs. Argon in the Barrel and endcap.

→ 2) Transverse Segmentation.

→ 3) Longitudinal Segmentation

→ 4) Strips in the 1st longitudinal section

→ 5) Massless Gap.

→ 6) Total Depth of the Em calorimeter.

7) Barrel to endcap transition.

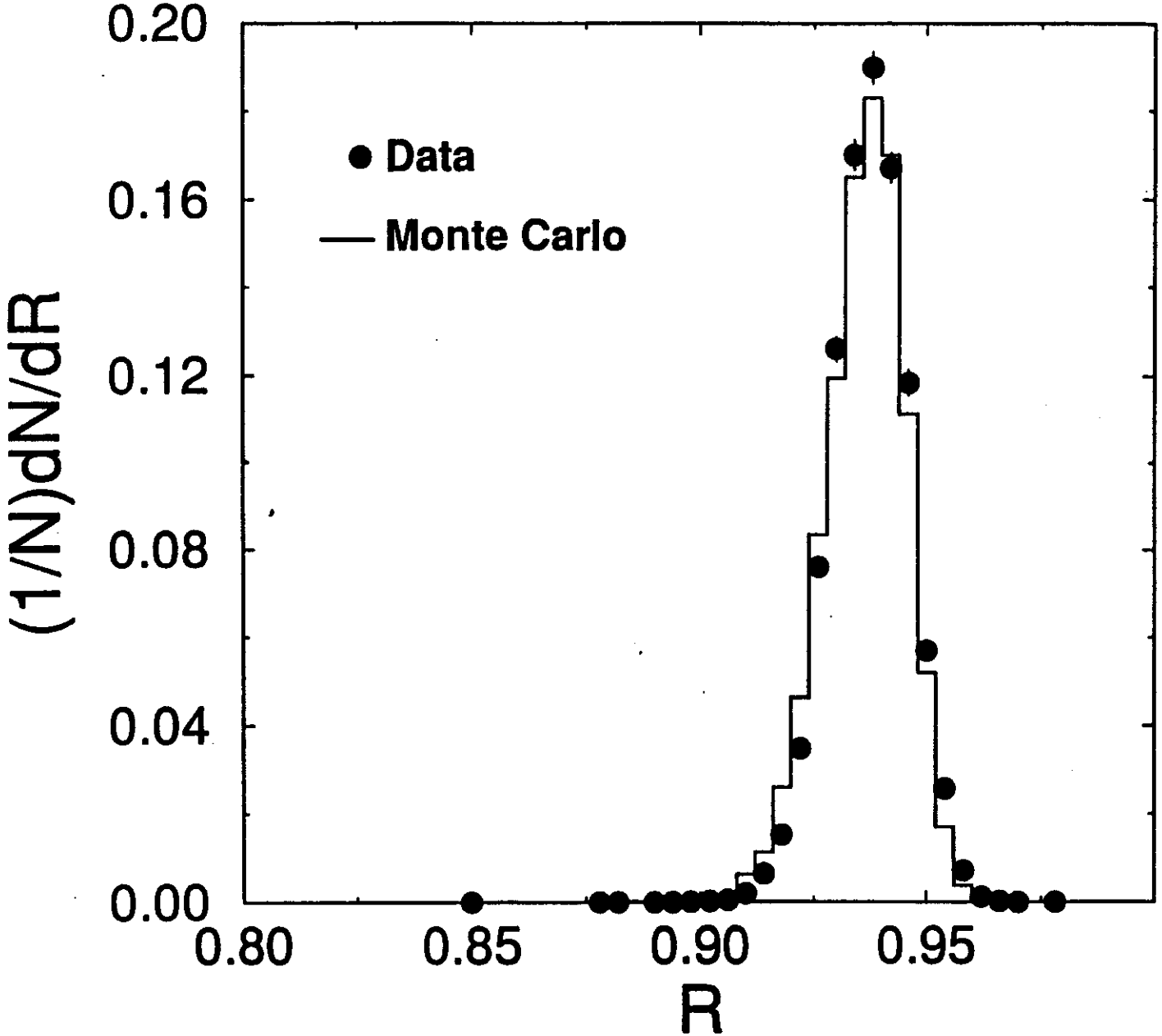
8) Calibration

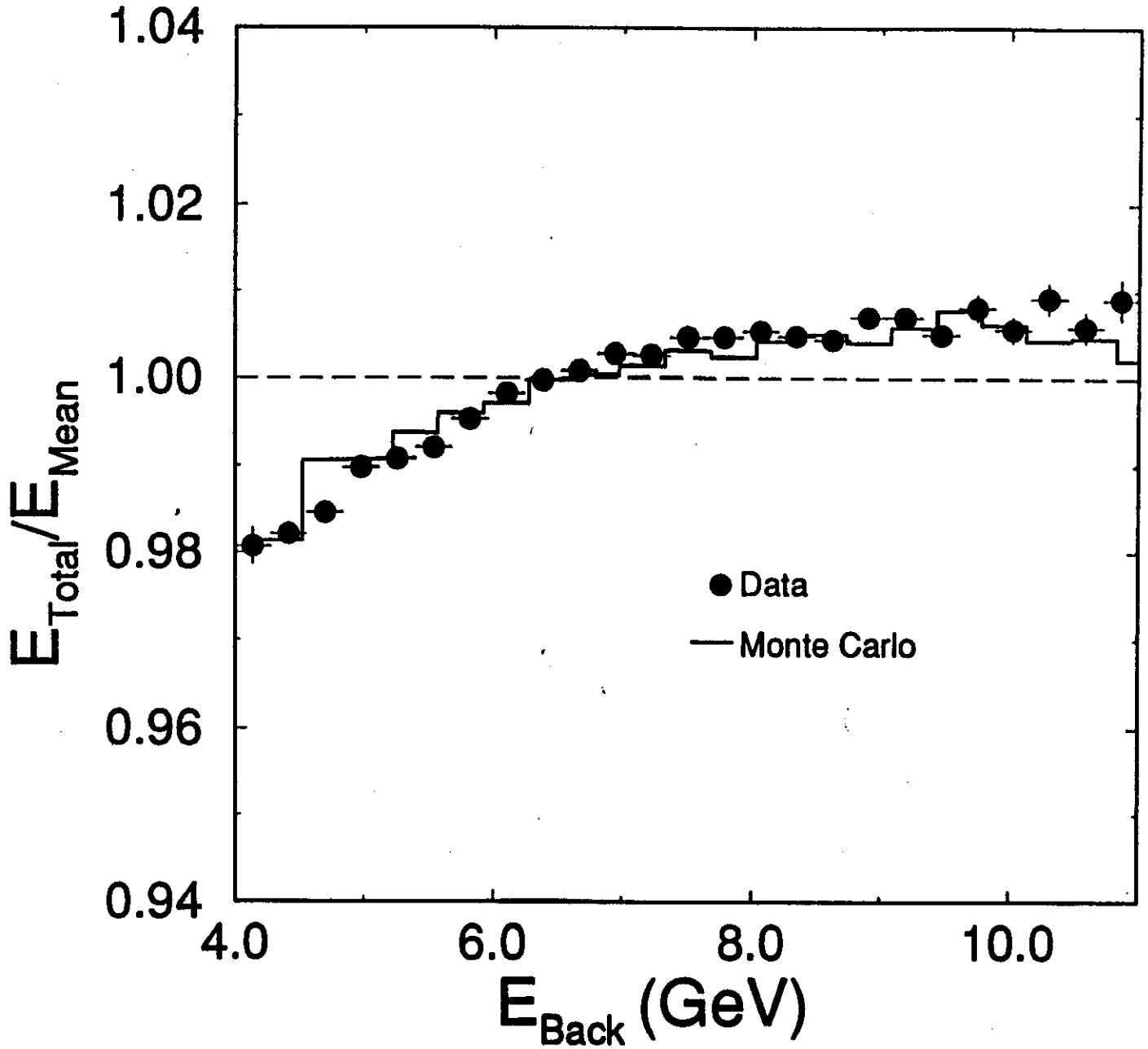
12) Dynamic Range requirements. Dynamic Range. 2^{18}

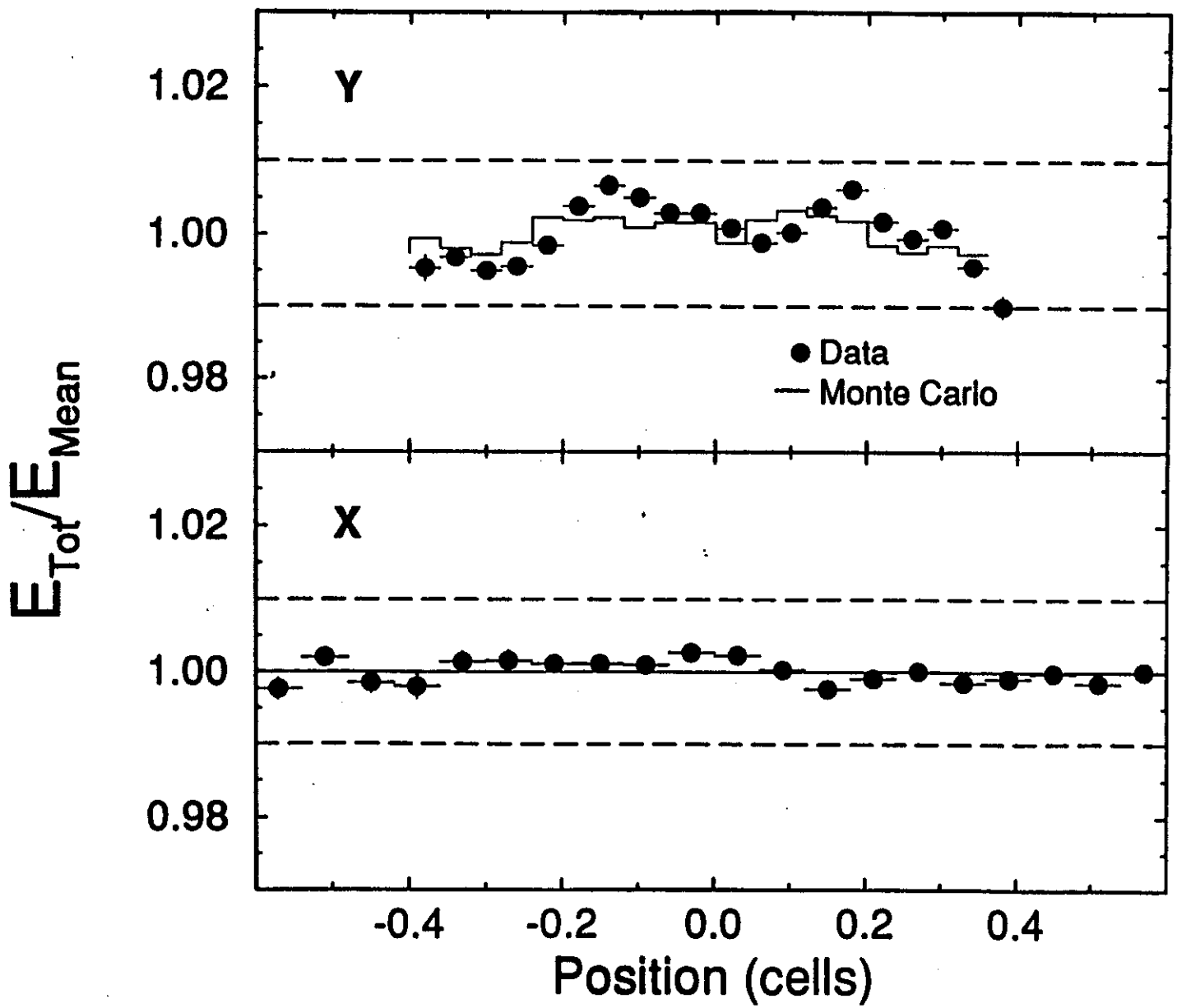
13) *Failure analysis.* *How well do we do as we drop a channel.*

14) mechanical tolerance on the uniformity.

BNL TEST RESULTS

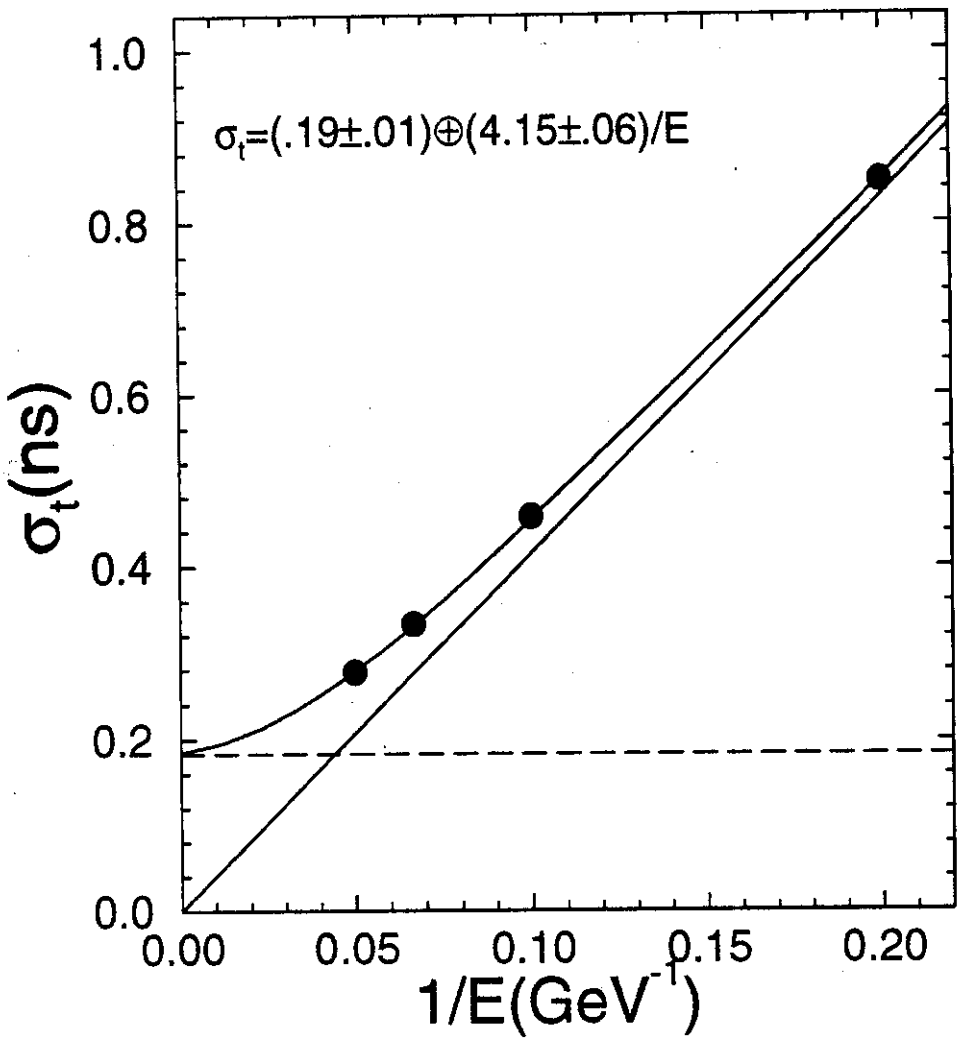

0.20
0.16
0.12
0.08
0.04
0.00
(1/N)dN/dR
Data
Monte Carlo
0.80
0.85
0.90
0.95
R


1.04
1.02
1.00
0.98
0.96
0.94
4.0
6.0
8.0
10.0
E_{Total}/E_{Mean}
E_{Back} (GeV)
Data
Monte Carlo


Y
X
1.02
1.00
0.98
1.02
1.00
0.98
Data
Monte Carlo
E_{Tot}/E_{Mean}
-0.4
-0.2
0.0
0.2
0.4
Position (cells)

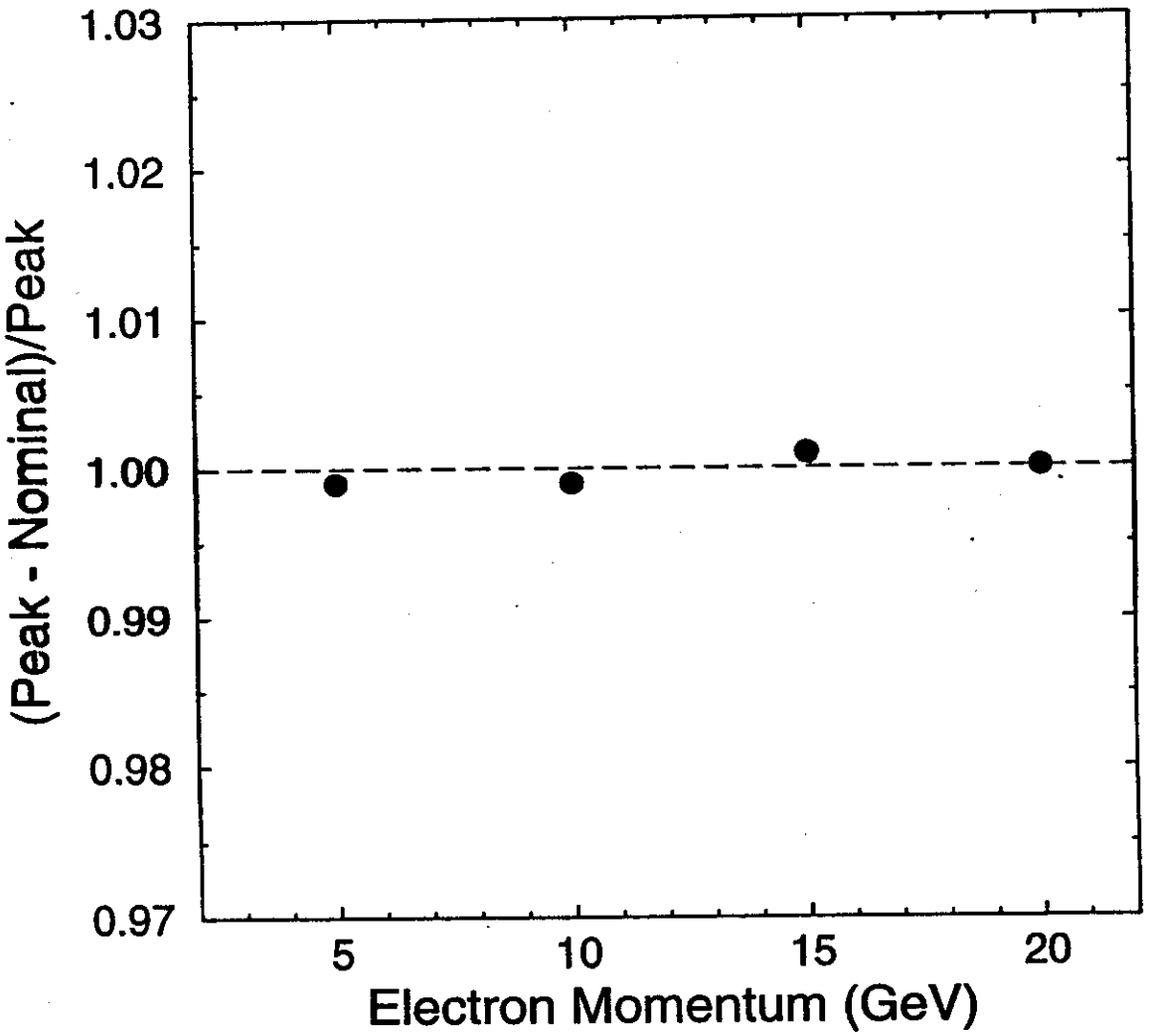
Test Run Results

Energy Dependence of Timing Resolution



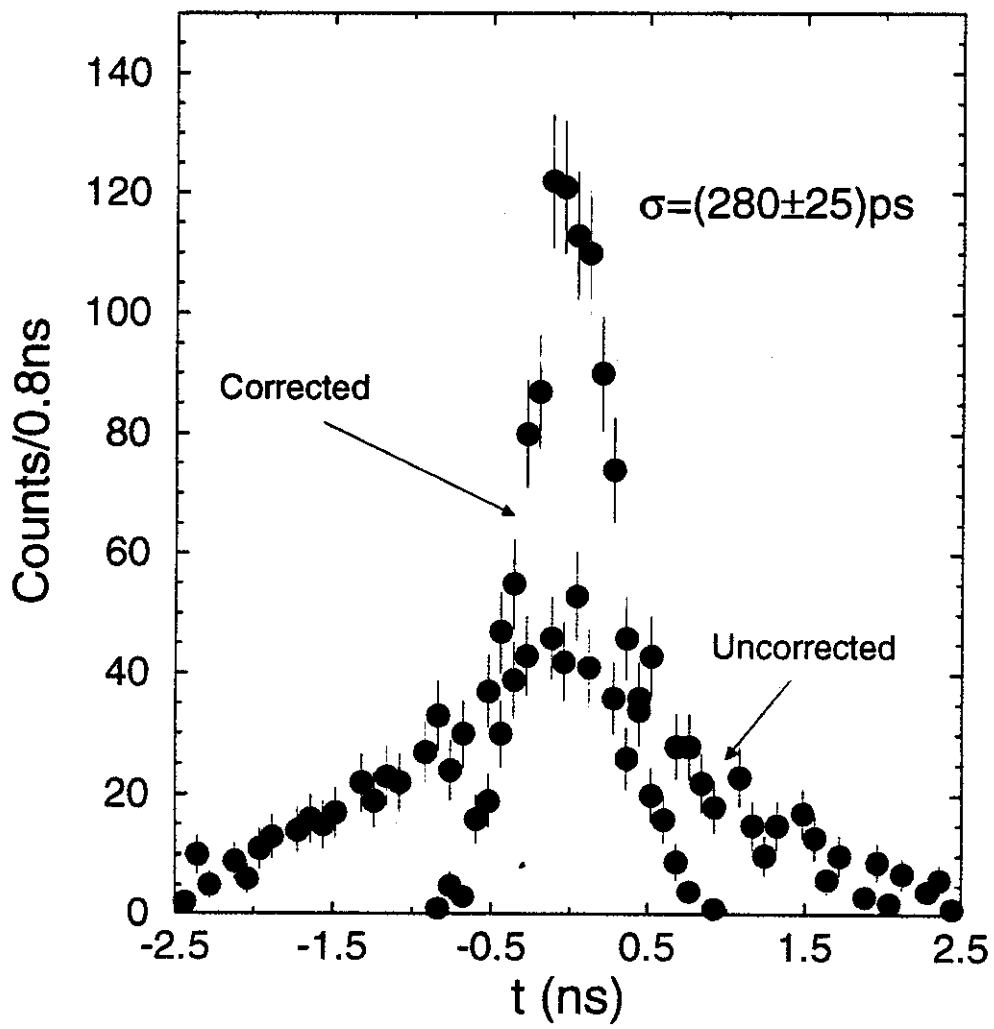
Test Run Results

Linearity



Test Run Results

Timing Distribution - 20 GeV e^-



FRAMEWORK

GEANT 3.15 ENVIROMENT

CALORIMETER SET_UP

FOR 7 x 7 TOWERS > 3000 POSITIONED VOLUMES IN BARREL
> 4500 IN ENDCAP

GEANT CAN'T STANDARD WAY OPTIMIZE SEARCH OF THE VOLUMES

- IT WILL SPEND MOST OF THE TIME IDENTIFIING IN WHICH VOLUME IS IT CURRENTLY AND WHERE TO STEP NEXT

- OVER 20 min/GeV with 100 keV CUTS ON SGI

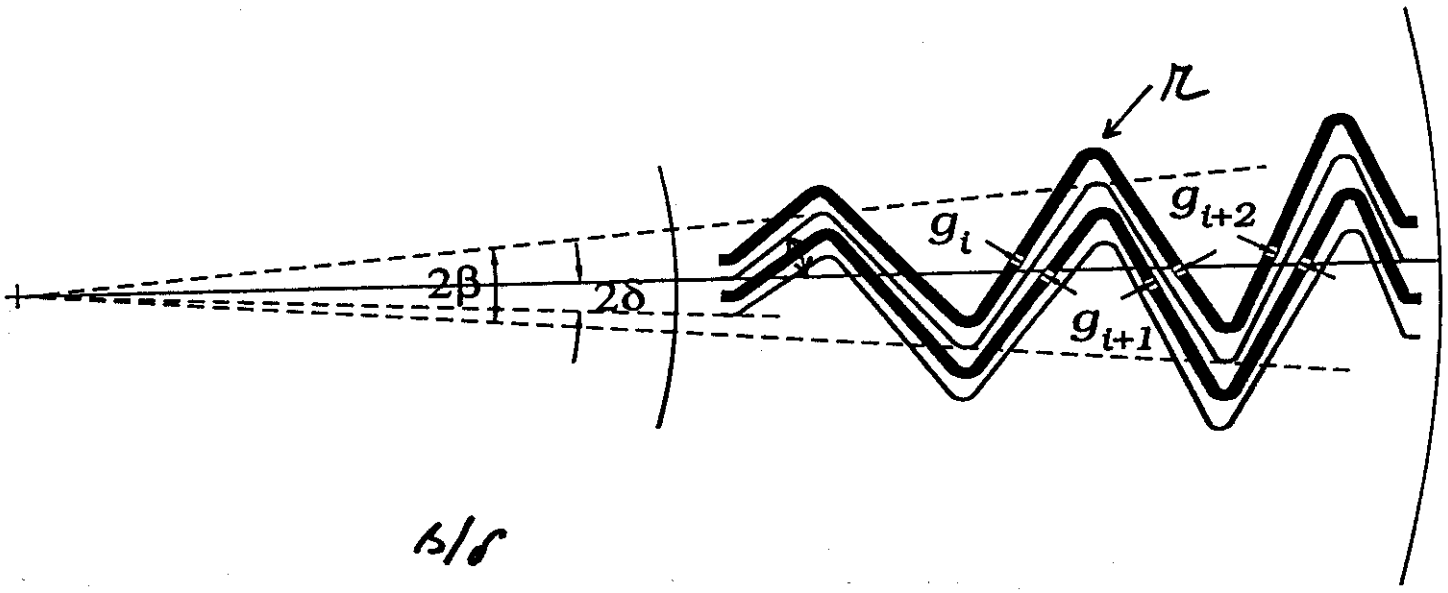
- TABLE OF NEIGHBORN VOLUMES PREPARED off-line HELPS (code runs ~100 times faster - on HP ~ 5 sec/GeV)

- CAUTION
  - SEARCH IS CONTROLED BY USER
  - ALL POSSIBLE NEIGBORN VOLUMES MUST BE SPECIFIED IN TABLE
  - NO GEANT WARNING IF VOLUME IS MISSING IN THE LIST !!!!

- VERIFICATION - RANDOM GENERATOR SEED NUMBER AFTER GENERATED EVENTS HAVE TO BE THE SAME FOR BOTH SLOW AND FAST VERSIONS

- CUTS
  gama's - 10 KeV
  electron's - 100 KeV

Accordion Electrode
β and δ definitions



	β/δ
BARREL :	3.89
ENDCAP :	2.87

STARTING CONSTRAINS :

BARREL :

~ 52 cm available for active calorimeter depth
~ 25 Xo required at ETA = 0

ENDCAP :

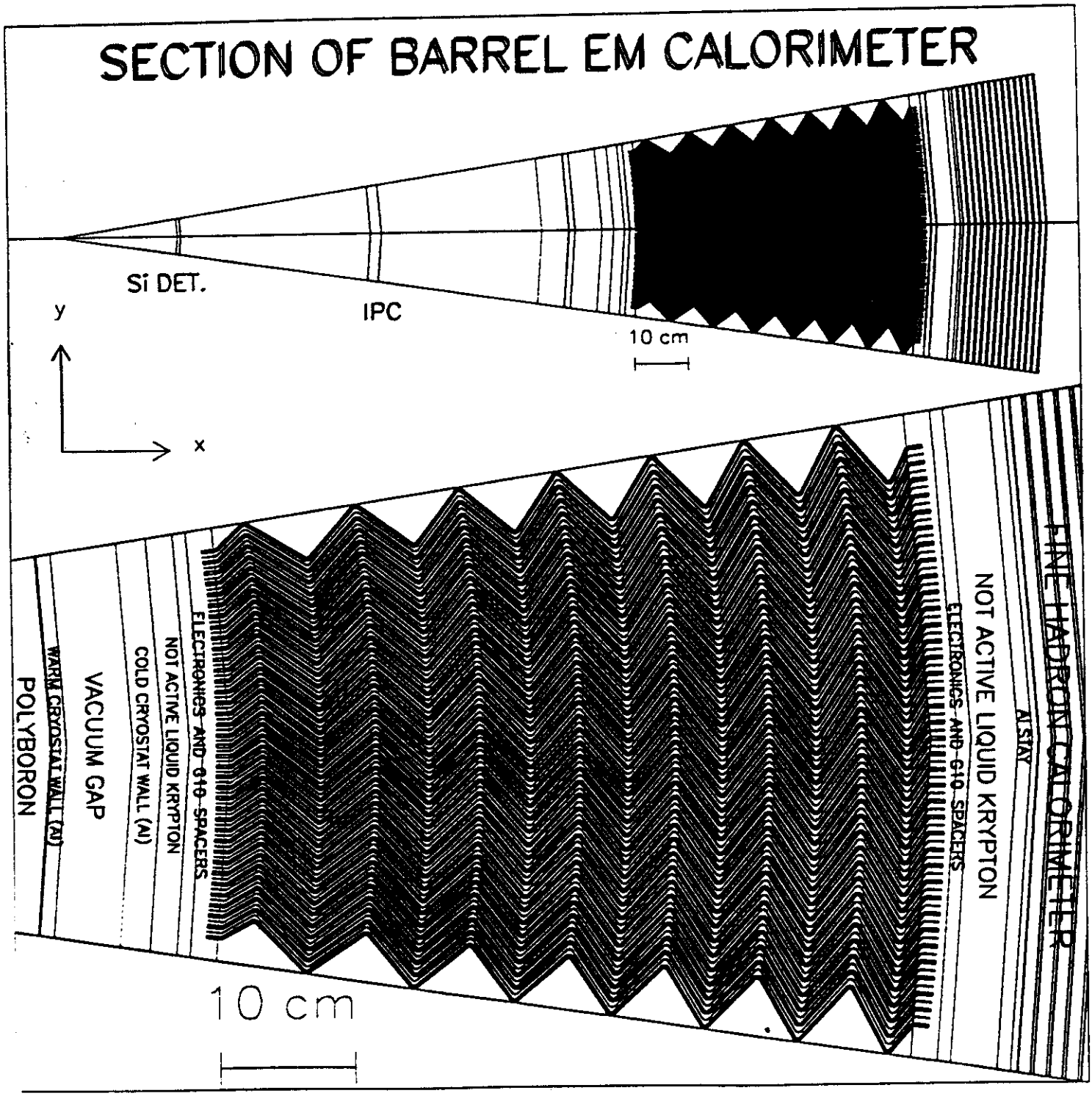
~ 80 cm available for active calorimeter depth
~ 27 Xo required at ETA = 3

ACCORDION STRUCTURES :

CONSTANT MEAN SAMPLING RATIO AND FREQUENCY

RESULT OF OPTIMIZATION KEEPING IN MIND PRACTICABILITY

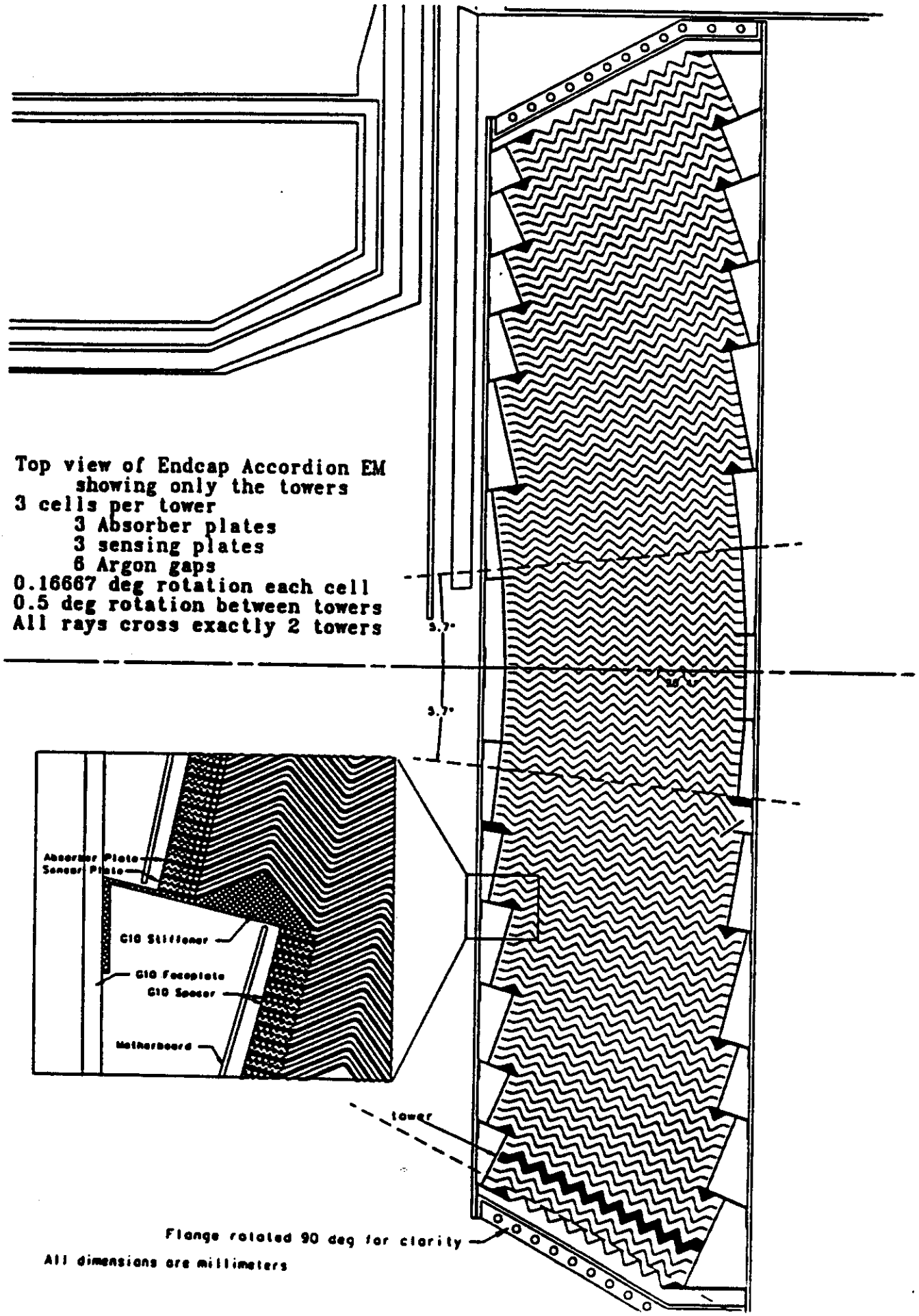
* cell dimensions	=>	tower size structure of trigger towers
* beta/delta	=>	tower size energy resolution position and angular resolution isolation weak dependence for 3-5
* starting angle	=>	local inhomogenities (number and magnitude)
* mean corner radius	=>	PHI density modulation energy resolution


SECTION OF BARREL EM CALORIMETER
Si DET.
IPC
10 cm
y
x
FINE HADRONIC CALORIMETER
AL STAY
NOT ACTIVE LIQUID KRYPTON
ELECTRONICS AND G10 SPACERS
ELECTRONICS AND G10 SPACERS
NOT ACTIVE LIQUID KRYPTON
COLD CRYOSTAT WALL (Al)
VACUUM GAP
WARM CRYOSTAT WALL (Al)
POLYBORON
10 cm

BARREL STRUCTURE

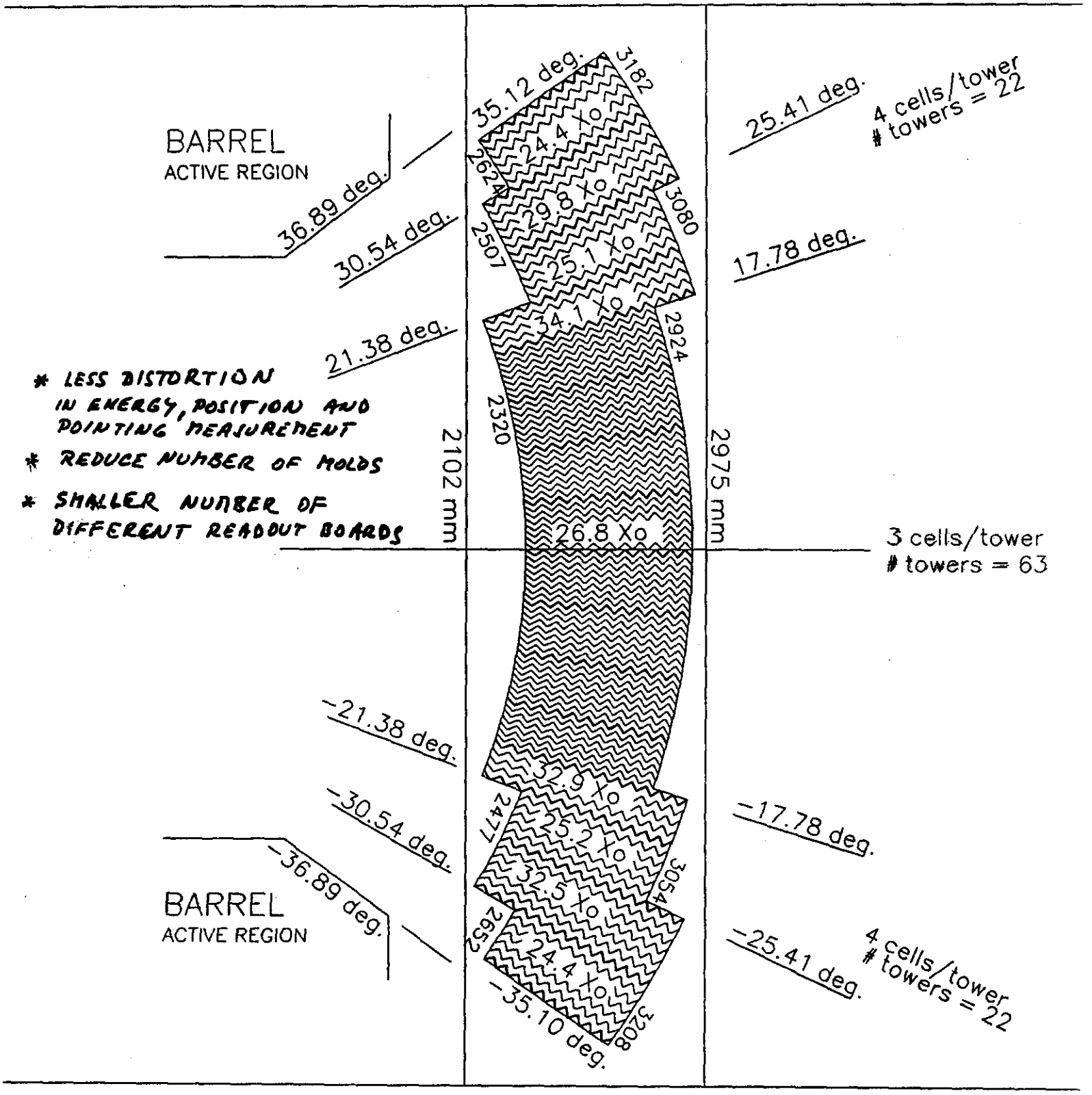
```
*** UTMED *** geantino used
*** UTMED *** LKr; all active
STARTING ALPHA =   35.00000
1

Users DIRECTIVES OPTIMIZED for this run :

     95.00 cm  - Rin  of WARM CRYO wall
     96.10 cm  - Rout of WARM CRYO wall
    101.10 cm  - Rin  of COLD CRYO wall
    103.30 cm  - Rout of COLD CRYO wall
               - FRONT STRUCTURE :
                   2.00 cm  - LKr GAP
                   1.00 cm  - G10 for Electronics+Cables+Spacers
                   2.00 cm  - G10 FRAME with SS sheet holders
    108.31 cm  - INNER RADIUS of ACCORDION STRUCTURE
               - ACCORDION STRUCTURE :
                 0.101064 cm  - LEAD thickness
                 0.157064 cm  - ABSORBER thickness
                 0.198967 cm  - LKr thickness
                 0.594998 cm  - CELL thickness
                      960     - Total number of CELLS
                        4     - Number of CELLS in TOWER
                      240     - Number of TOWERS
                 0.026180 rad - TOWER dimension in PHI
                 0.026180 rad - TOWER dimension in ETA
                 0.003272 rad - DELTA
                    3.890     - Ratio BETA/DELTA
                 0.012730 rad - BETA
                 32.99467 deg - ALFA of first stack
                 55.47296 deg - ALFA of last stack
                       16     - Number of STACKS
    160.54 cm  - OUTER RADIUS of ACCORDION STRUCTURE
               - BACKWARD STRUCTURE :
                   2.00 cm  - G10 FRAME with SS sheet holders
                   1.00 cm  - G10 for Electronics+Cables+Spacers
                   3.50 cm  - LKr GAP
    167.04 cm  - Rout of EM CAL


   0.27800 cm  - Mean corner radius
   0.02000 cm  - Thickness of stainless steel
   0.00800 cm  - Thickness of glue
   1.00000 cm  - Sheet holder length
```

BASELINE 1


Top view of Endcap Accordion EM
showing only the towers
3 cells per tower
3 Absorber plates
3 sensing plates
6 Argon gaps
0.16667 deg rotation each cell
0.5 deg rotation between towers
All rays cross exactly 2 towers
3.7°
3.7°
Absorber Plate
Sensor Plate
G10 Stiffener
G10 Faceplate
G10 Spacer
Motherboard
tower
Flange rotated 90 deg for clarity
All dimensions are millimeters

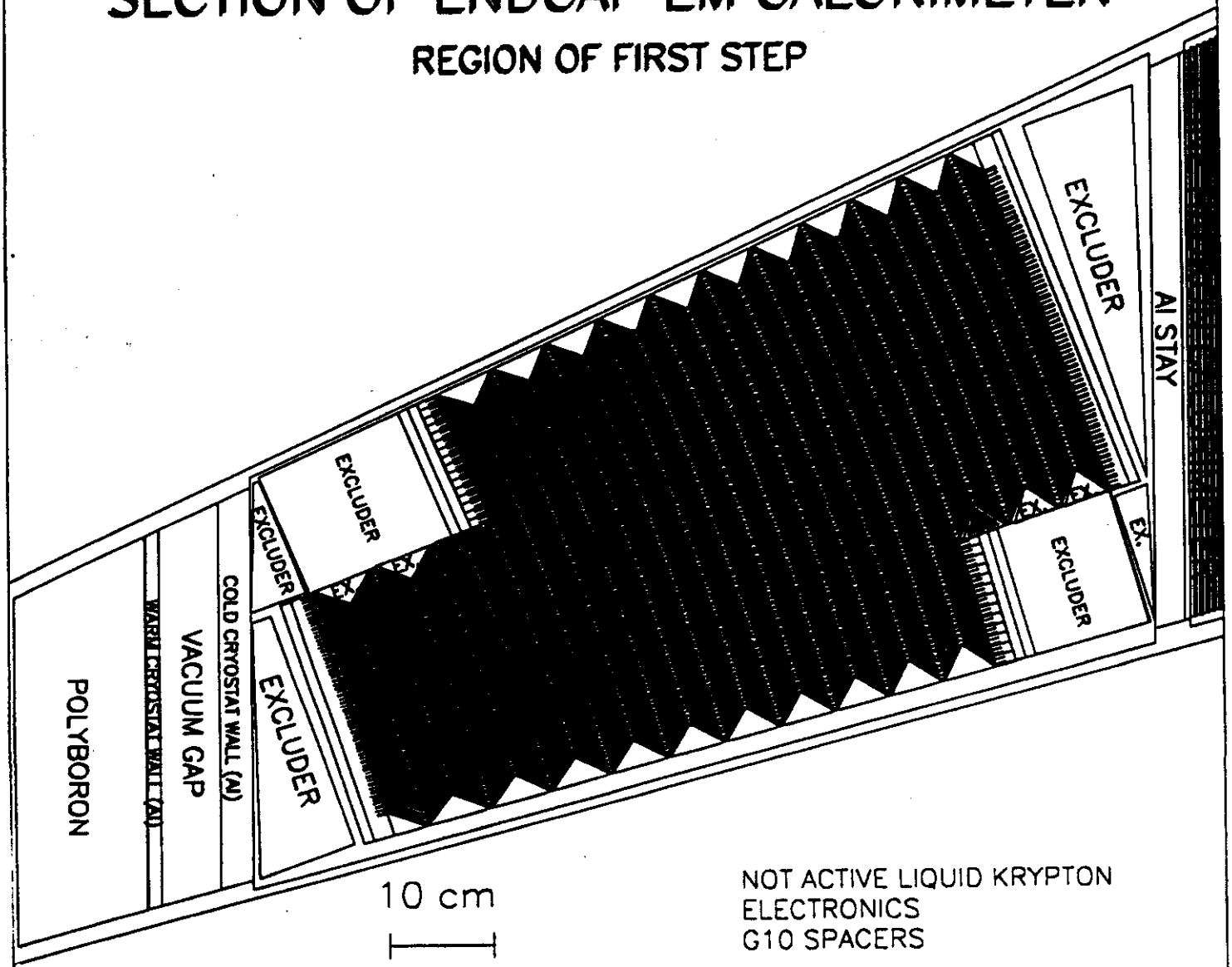
TDR VERSION

Top view of Endcap EM Calorimeter



SECTION OF ENDCAP EM CALORIMETER

REGION OF FIRST STEP



NOT ACTIVE LIQUID KRYPTON
ELECTRONICS
G10 SPACERS

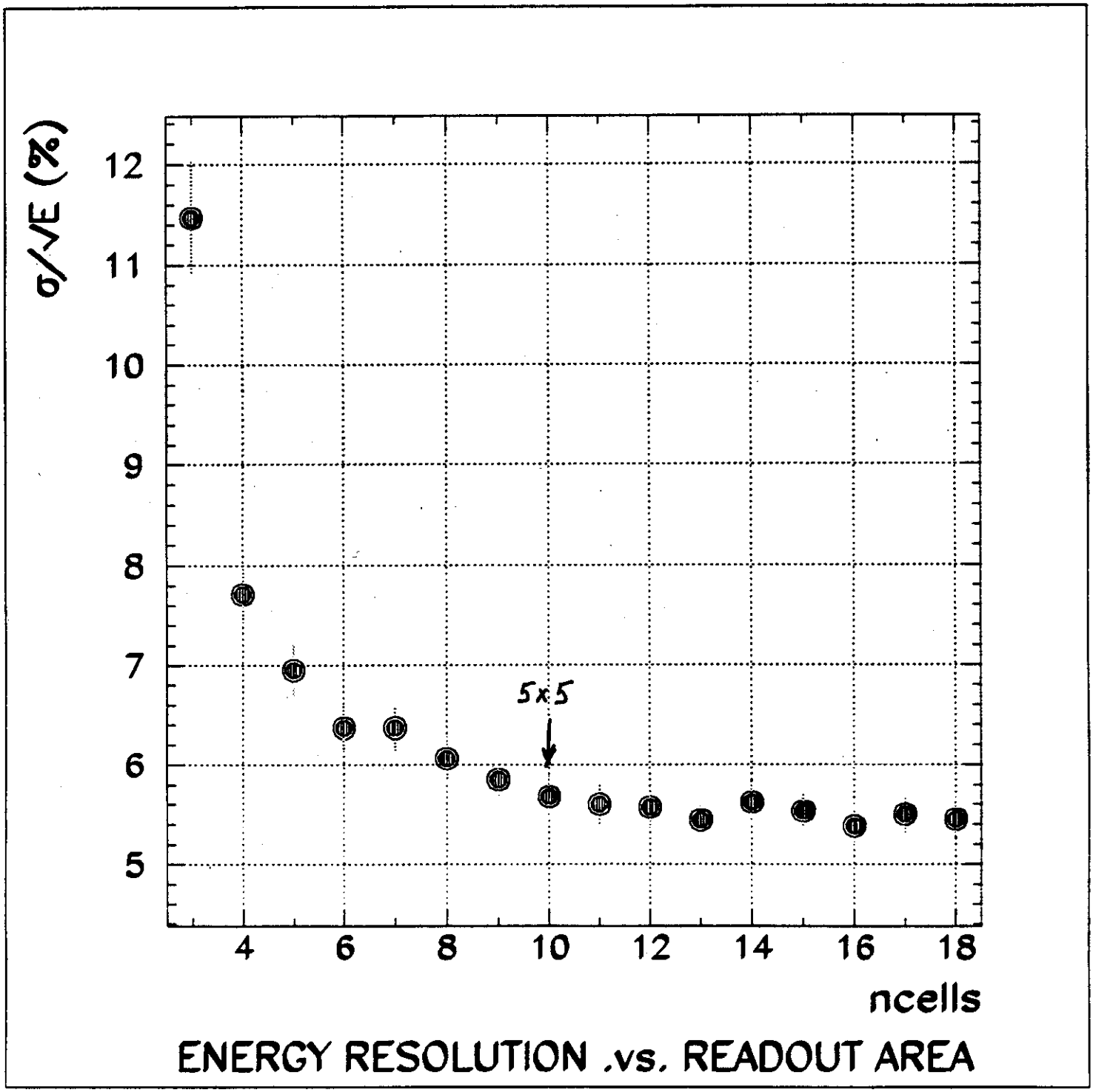
```
*** UTMED *** geantino used
*** UTMED *** LAr; all active
STARTING ALPHA =    38.00000
1

Users DIRECTIVES OPTIMIZED for this run :

    200.00 cm  - Z-in  of WARM CRYO wall
    201.30 cm  - Z-out of WARM CRYO wall
    207.00 cm  - Z-in  of COLD CRYO wall
    210.20 cm  - Z-out of COLD CRYO wall
               - FRONT STRUCTURE :
                 1.00 cm  - LAr GAP
                 1.00 cm  - G10 for Electronics+Cables+Spacers
                 2.00 cm  - G10 FRAME with SS sheet holders
                 1.00 cm  - Sheet holder length
    232.01 cm  - INNER RADIUS of ACCORDION STRUCTURE
               - ACCORDION STRUCTURE :
                 0.0150 cm       - STAINLESS STEEL thickness
                 0.0080 cm       - PREPREG thickness
                 0.1400 cm       - LEAD thickness
                 0.1860 cm       - ABSORBER thickness
                 0.2930 cm       - Mean arc radius
                 0.2001 cm       - LAr thickness
                 0.6262 cm       - CELL thickness
                 1886            - Total number of CELLS - in TWOPI
                 0.00166574 rad  - DELTA
                 2.870           - Ratio BETA/DELTA
                 0.00478068 rad  - BETA
                 35.91440 deg    - ALFA of first stack
                 54.03089 deg    - ALFA of last stack
                       34        - Number of STACKS
    292.45 cm  - OUTER RADIUS of ACCORDION STRUCTURE
               - BACKWARD STRUCTURE :
                 2.00 cm  - G10 FRAME with SS sheet holders
                 1.00 cm  - Sheet holder length
                 1.00 cm  - G10 for Electronics+Cables+Spacers
                 1.00 cm  - LAr GAP
    296.45 cm  - Z-in of STAY after EM CAL
```

SEGMENTATION

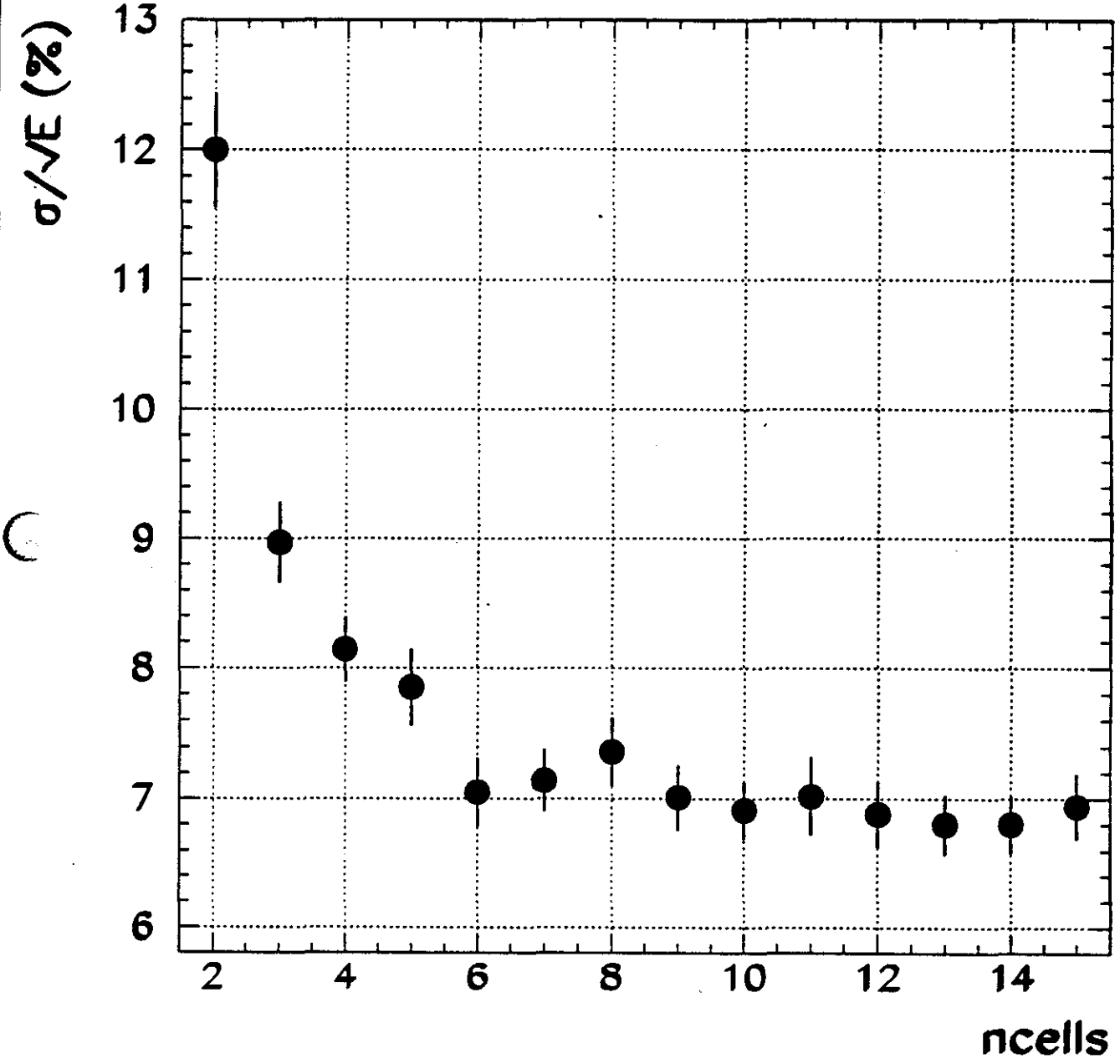
* TRANSVERSE	LONGITUDINAL
↑ - ENERGY RESOLUTION	
↓ - THERMAL & PILEUP NOISE	
↓ - POSITION RESOLUTION	
↓ - ANGULAR RESOLUTION	!
↓ - SHOWER SEPARATION	
$H \to ZZ \to e^+e^-e^+e^-$	
M_H (600 GeV) => $R = 0.3$	
- π^0 REJECTION	!
- e/h WEIGHTING	!

40 GeV

BARREL

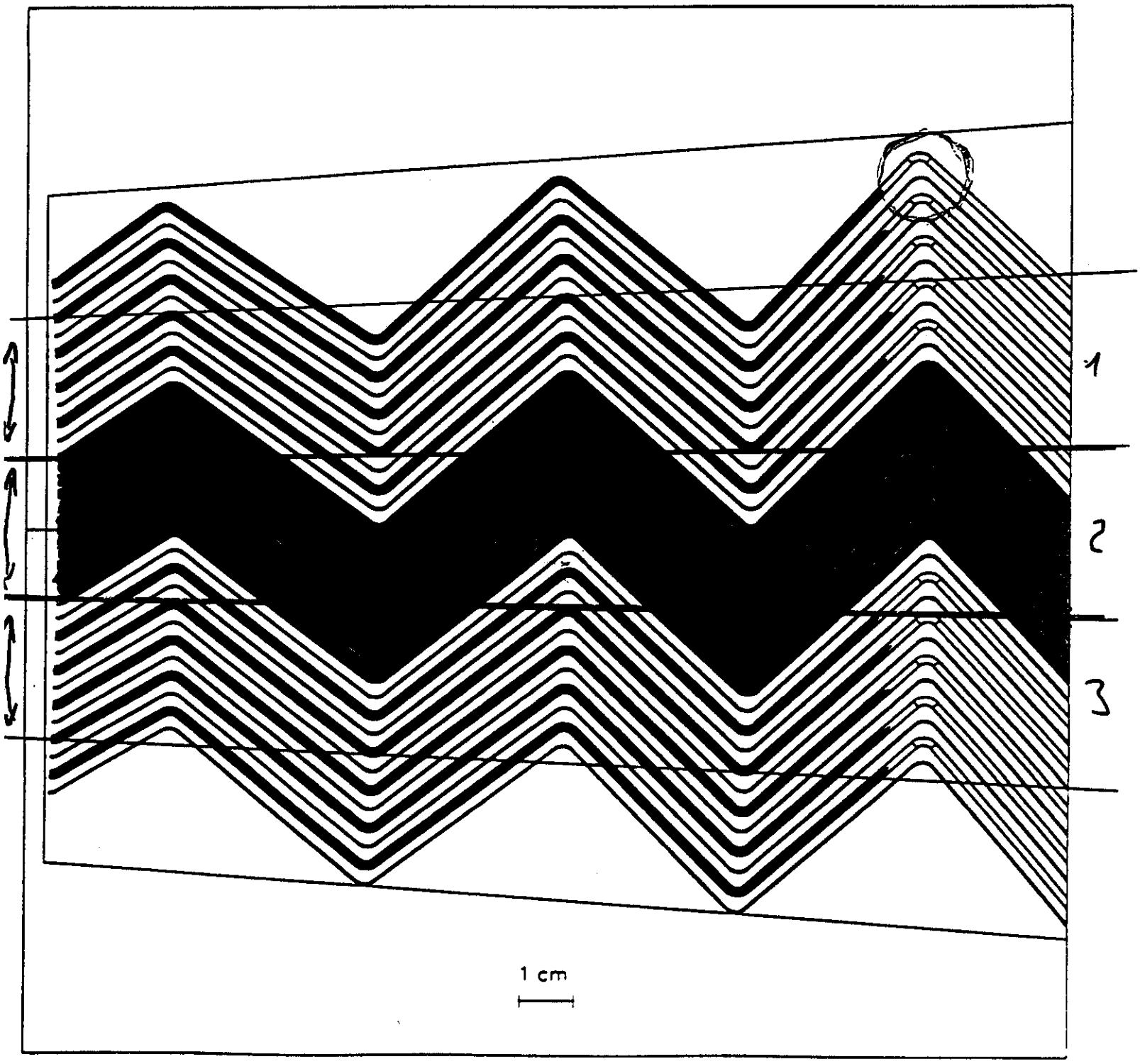


ENDCAP



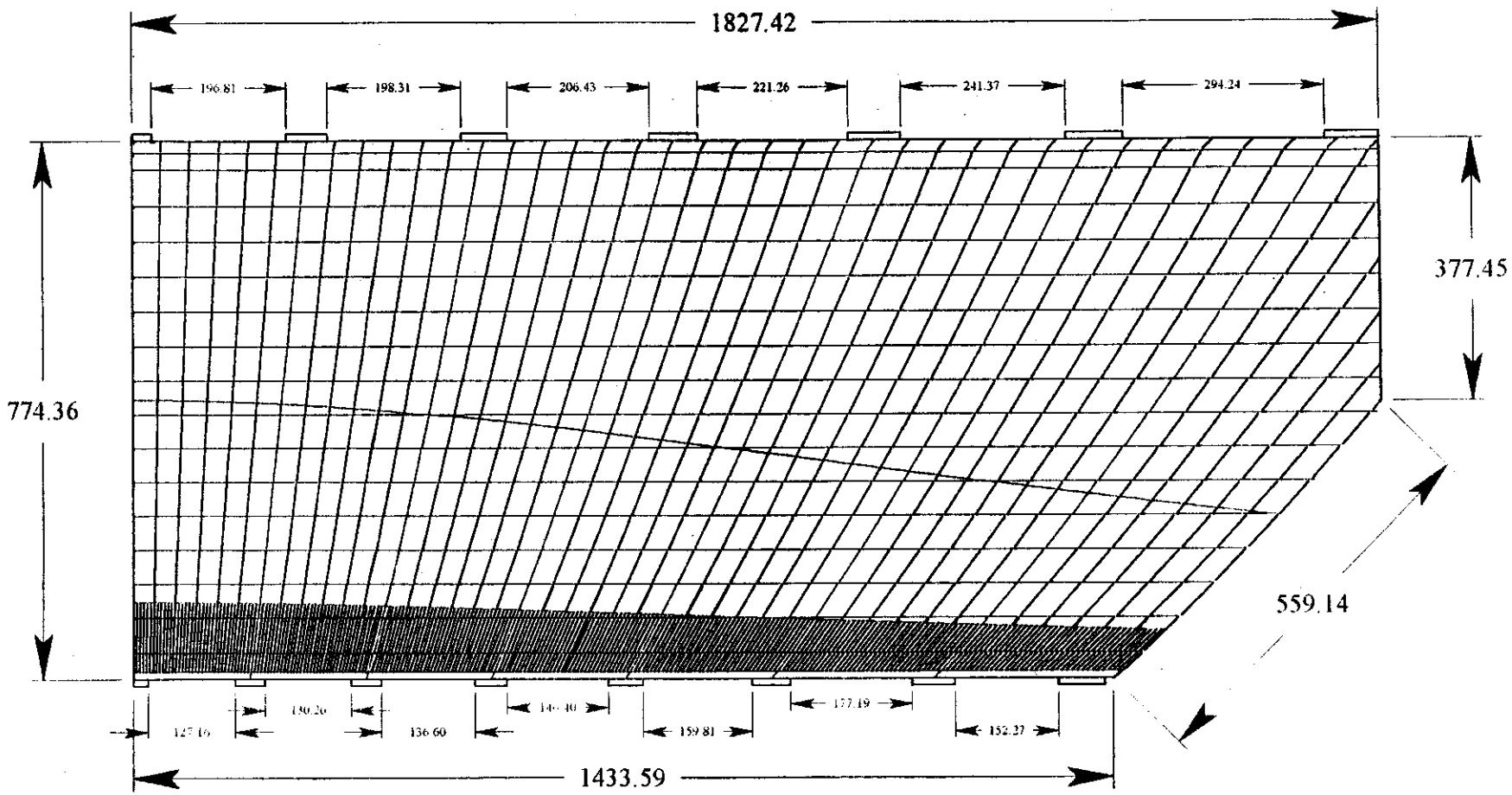
ENERGY RESOLUTION .vs. READOUT AREA

ENERGY IN TOWERS
0
500
1000
1500
2000
2500
3000
3500
HORIZONTAL – PHI – x-coor TOWERS
0
1
2
3
4
5
6
7
VERTICAL – THETA – y-coor TOWERS
0
1
2
3
4
5
6
7

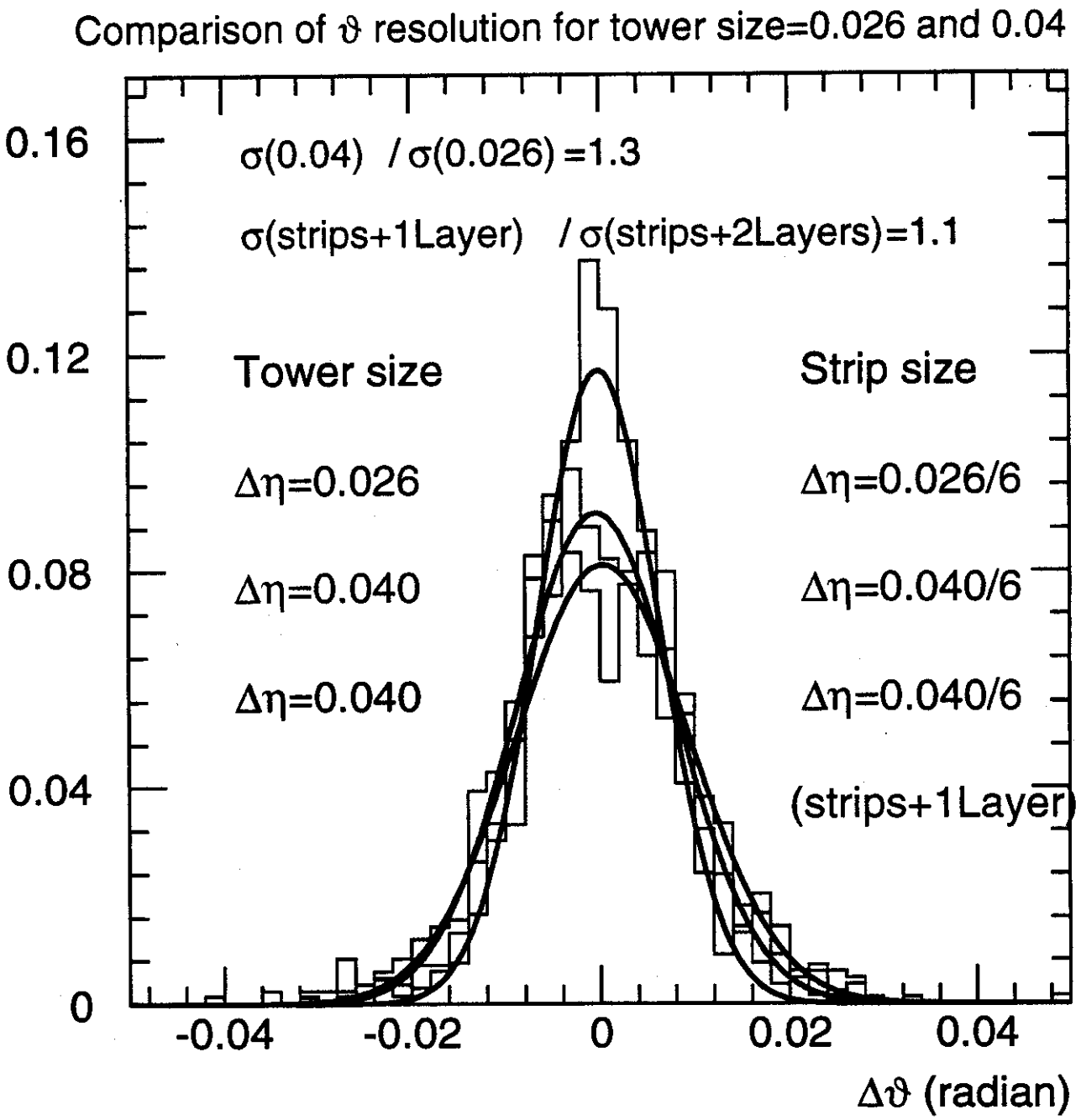

1
2
3
1 cm

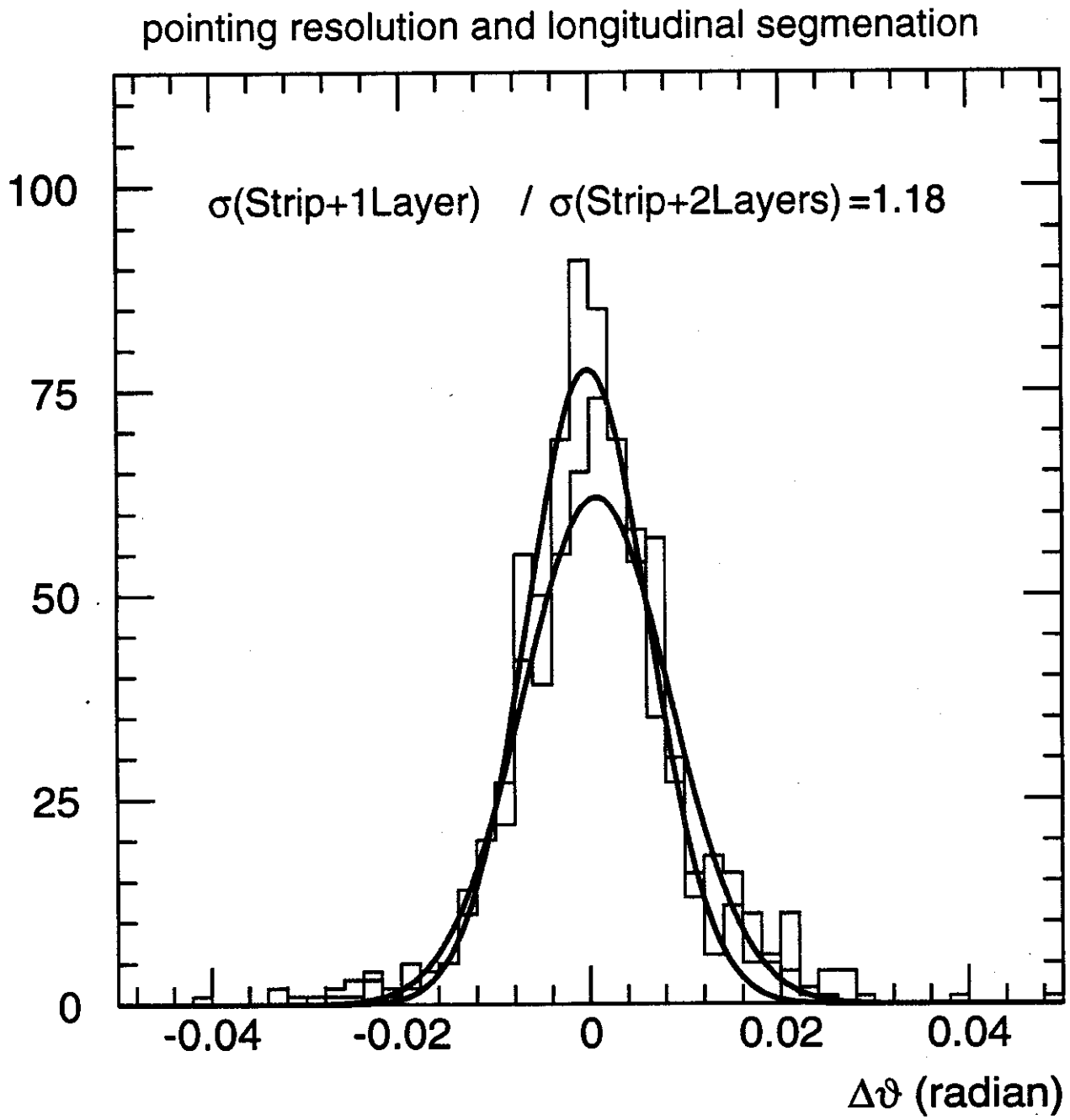
Signal Electrode

(Flat and Ambient Temperatures)



DSM
4/1`2/93


Comparison of ϑ resolution for tower size=0.026 and 0.04
σ(0.04) / σ(0.026) =1.3
σ(strips+1Layer) / σ(strips+2Layers)=1.1
Tower size
Δη=0.026
Δη=0.040
Δη=0.040
Strip size
Δη=0.026/6
Δη=0.040/6
Δη=0.040/6
(strips+1Layer)
0.16
0.12
0.08
0.04
0
-0.04
-0.02
0
0.02
0.04
Δϑ (radian)


pointing resolution and longitudinal segmenation
σ(Strip+1Layer) / σ(Strip+2Layers) =1.18
100
75
50
25
0
-0.04
-0.02
0
0.02
0.04
Δϑ (radian)

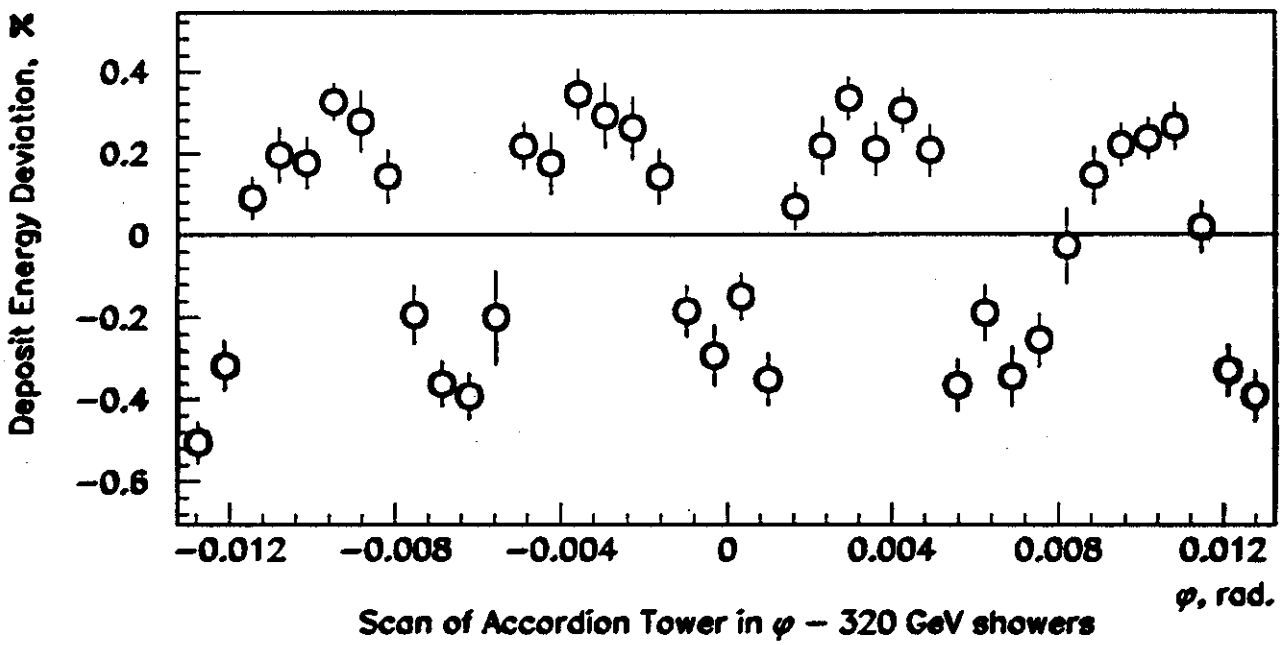
PERFORMANCE REQUIREMENTS :

QUANTITY	OPTIMIZATION TOOL
* energy resolution we believe to control constant term down to 0.4 % σ_s as small as possible for low mass higgs	active liquid sampling ratio sampling frequency massless gap depth calorimeter depth
* position resolution to not contribute to width of higs mass e, γ separation	transverse segmentation
* pointing resolution to not dominate over contribution of energy resolution to HIGGS width	strip width transverse segmentation longitudinal segmentation
* e,gama separation from jets & π^0 rejection to suppress under irreducible QCD background	strip width transverse segmentation longitudinal segmentation
* isolation	transverse segmentation noise, speed

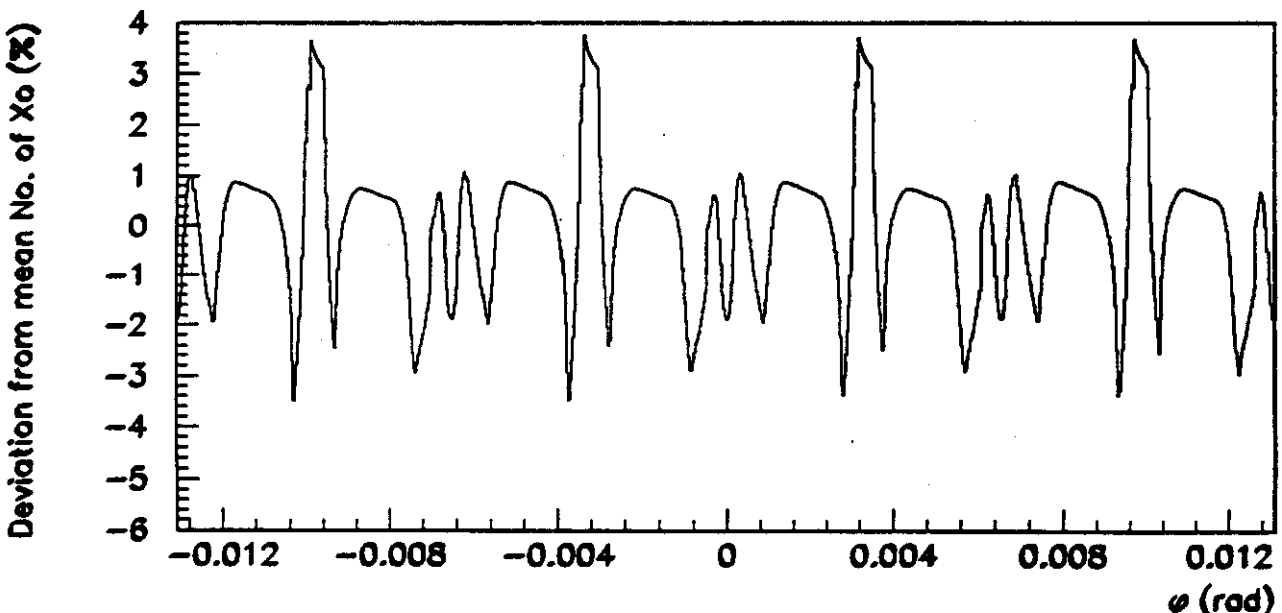
ENERGY RESOLUTION

- PHI MODULATION OF DENSITY
- CALORIMETER DEPTH
- MASSLES GAP
- ELECTRIC FIELD EFFECT

93/05/16 17.24



Scan of Accordion Tower in φ – 320 GeV showers

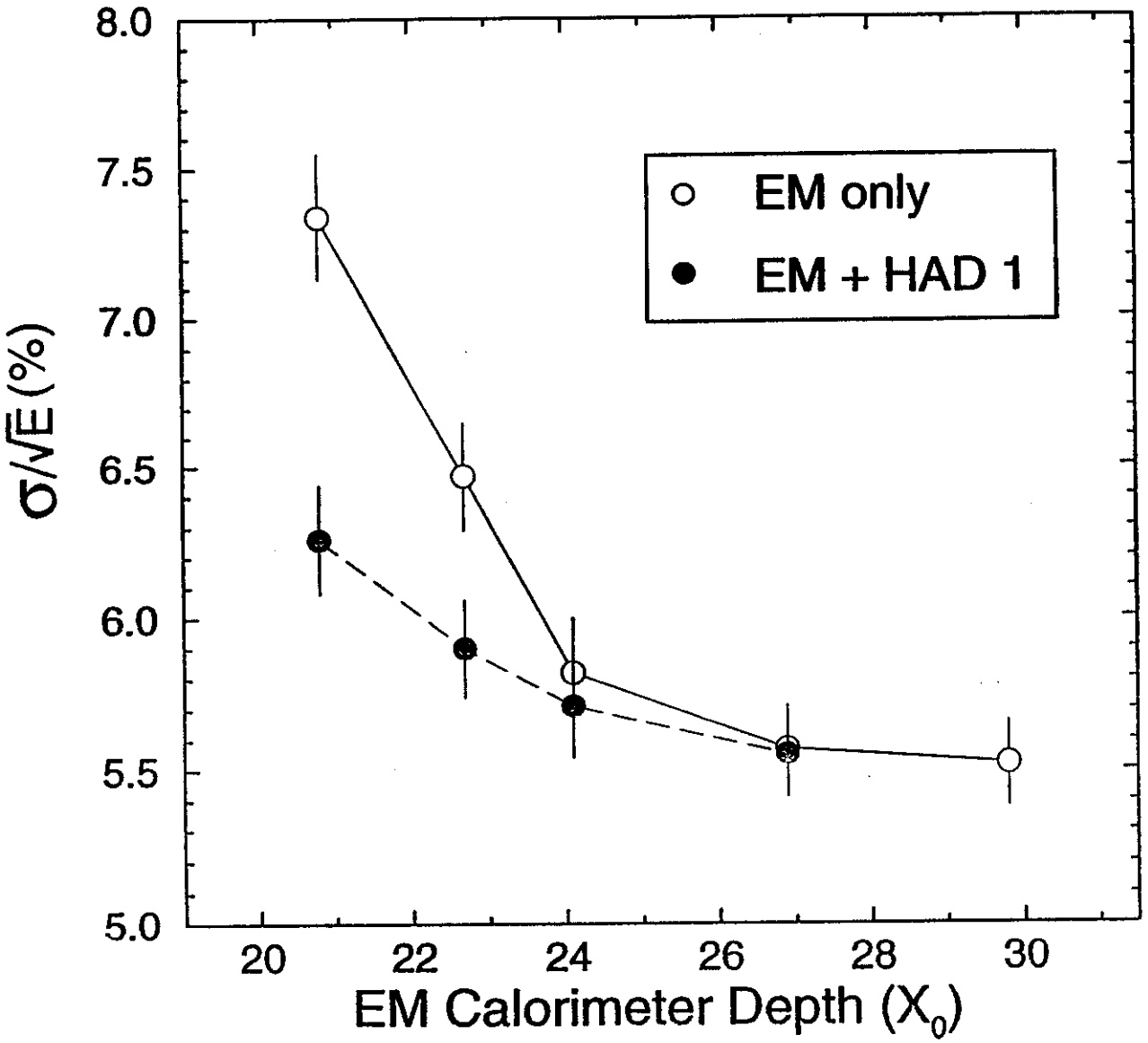


Scan of Accordion tower in φ – geantino

EM Calorimeter - Barrel

Energy Resolution vs calorimeter depth

E_γ= 80 GeV



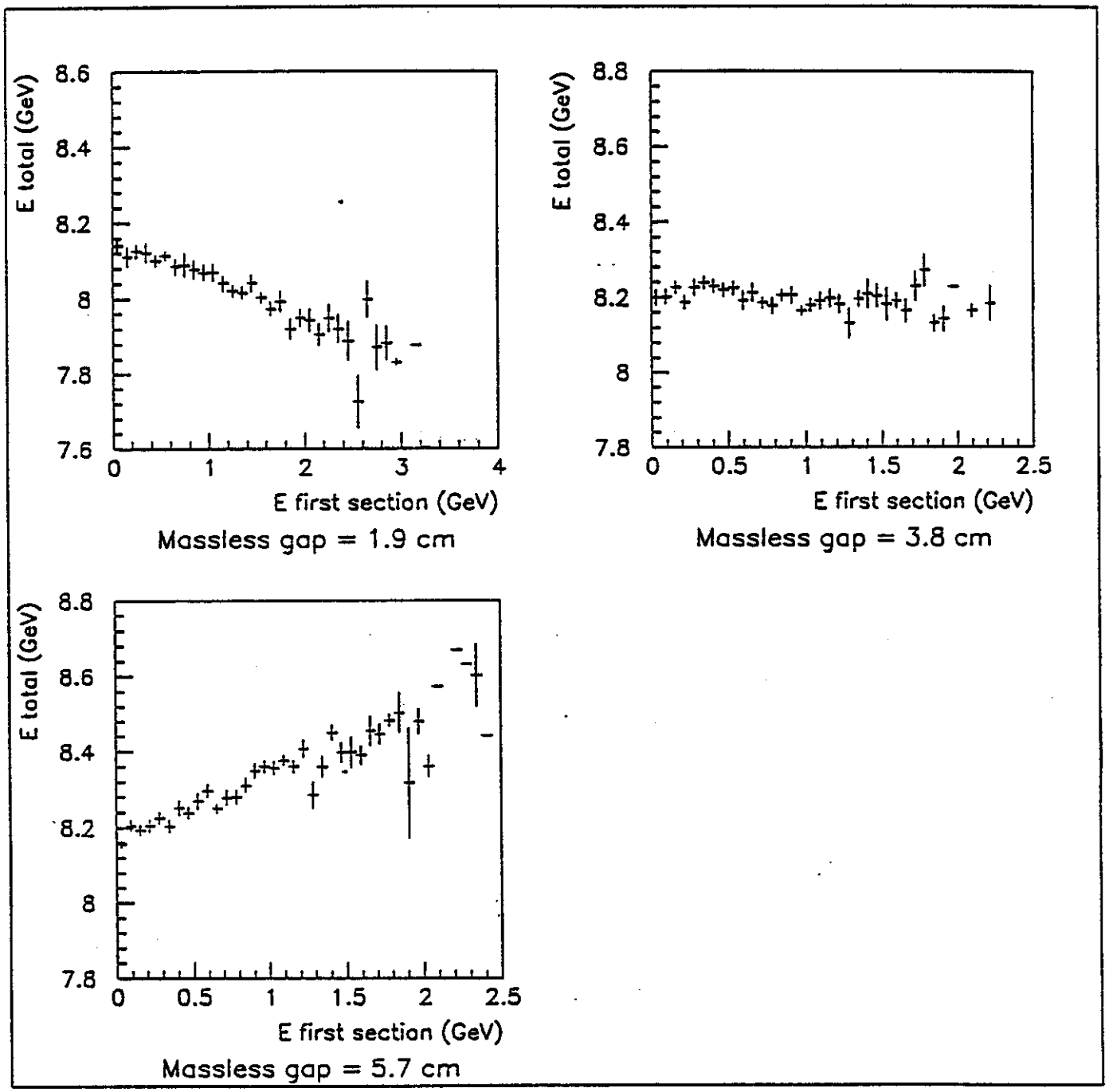


Figure 4: Search of optimal massless gap at 25 GeV. Total energy in liquid as a function of the energy measured in the first layer, for 3 different massless gap depth.

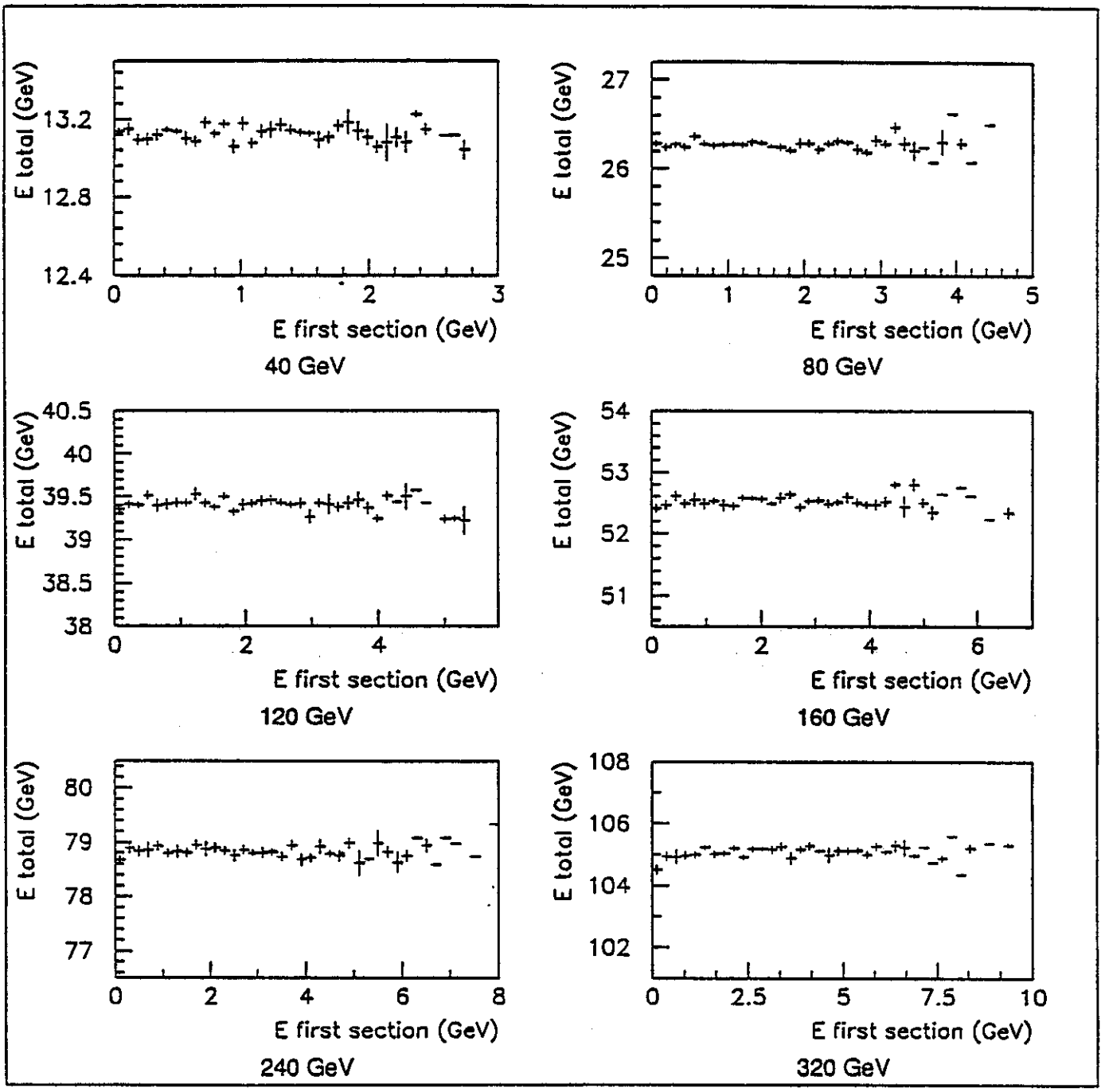
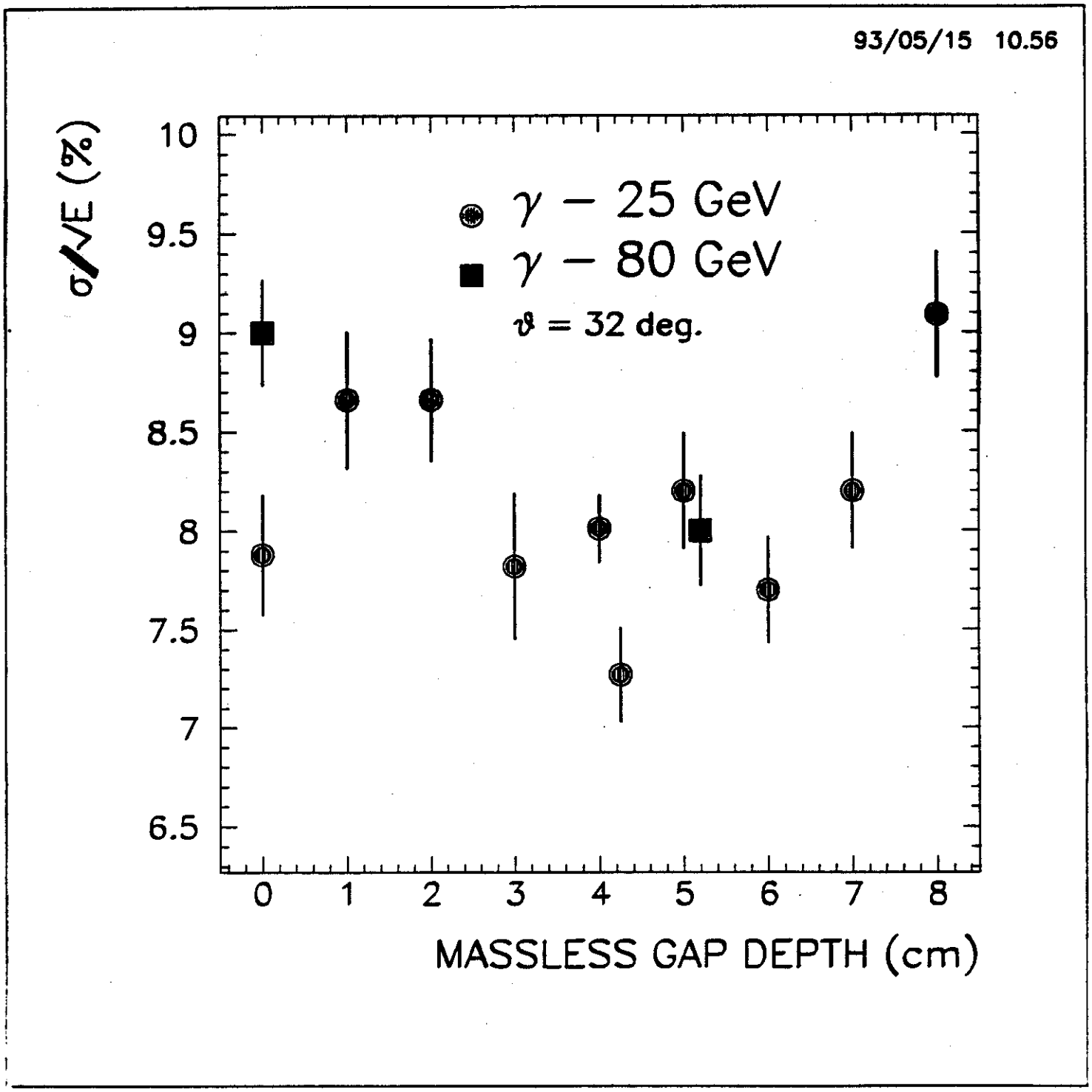


Figure 6: Massless gap of 3.8 cm for different energies, similar to Fig 4

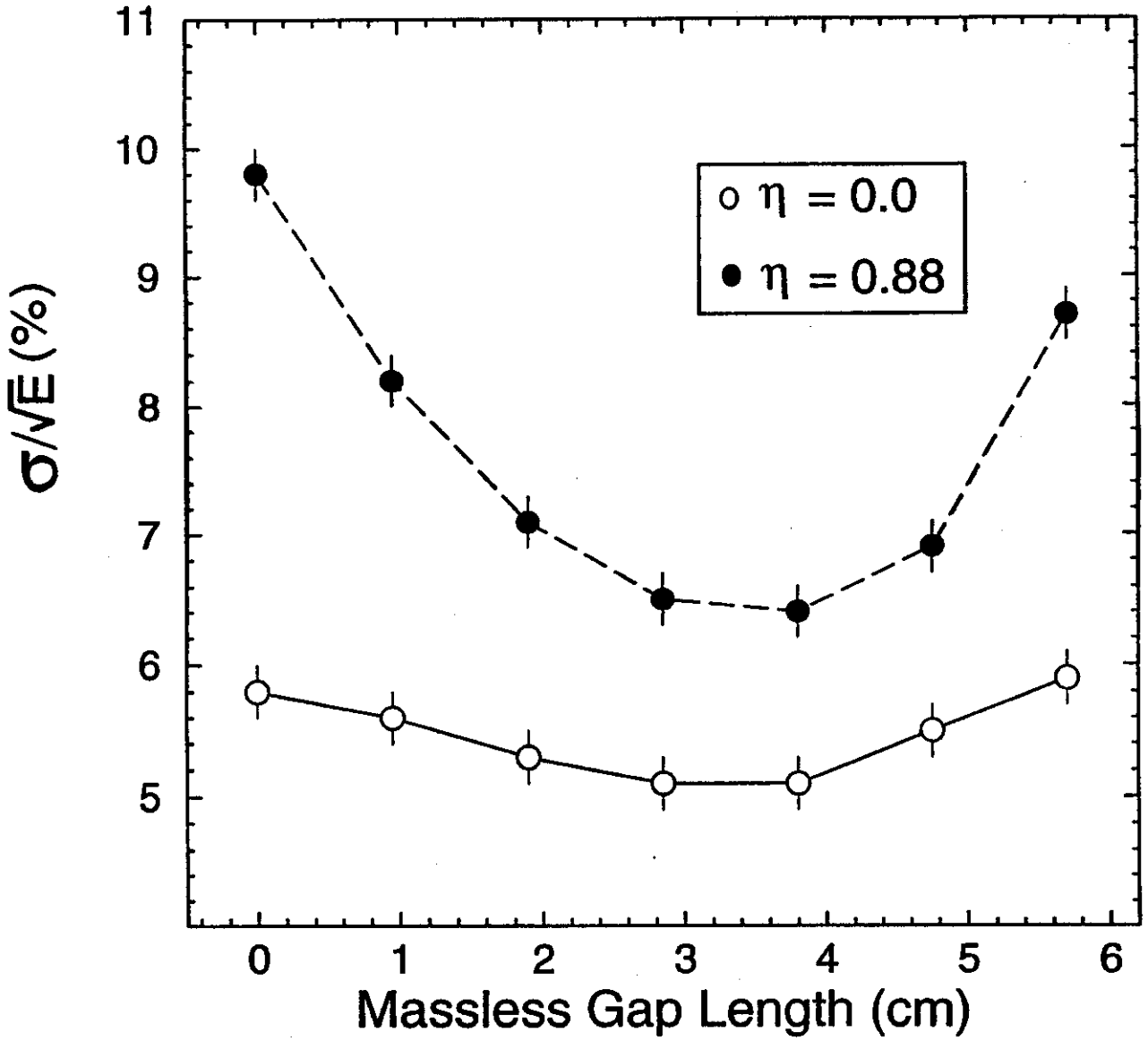
ENDCAP

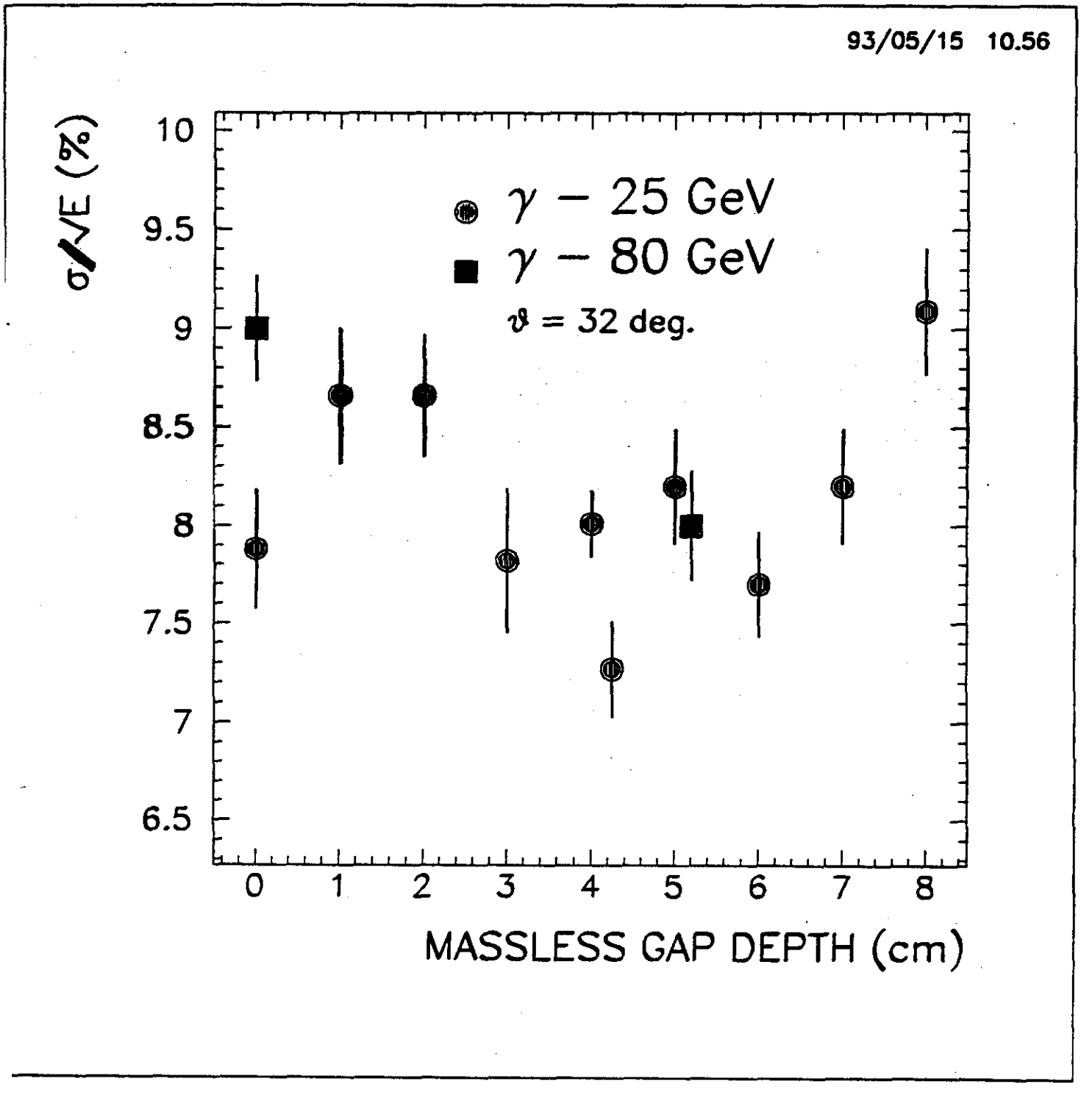

93/05/15 10.56
σ/√E (%)
10
9.5
9
8.5
8
7.5
7
6.5
γ − 25 GeV
γ − 80 GeV
ϑ = 32 deg.
0
1
2
3
4
5
6
7
8
MASSLESS GAP DEPTH (cm)

EM Calorimeter - Barrel

Energy Resolution vs Massless Gap Length

E_γ= 25 GeV




93/05/15 10.56
σ/√E (%)
10
9.5
9
8.5
8
7.5
7
6.5
γ − 25 GeV
γ − 80 GeV
ϑ = 32 deg.
0
1
2
3
4
5
6
7
8
MASSLESS GAP DEPTH (cm)

CHARGE COLLECTION AND PULSE SHAPING

* ELECTRIC FIELD INHOMOGENITIES IN THE CORNERS

* VARIATION OF GAP WIDTH IN THE STRAIGHT SECTIONS

* CHARGE RECOMBINATION

* DRIFT VELOCITY

* RD3
  - FOR NOT OPTIMIZED NONPROJECTIVE VERSION :

    - M.C. DID'NT SHOW ANY CHANGE IN RESOLUTION

    - EXPERIMENT

      VOLTAGE IN THE RANGE FROM 6 - 12 kV/cm APPLIED
      NO CHANGE IN THE ENERGY RESOLUTION AT 122 GeV
      WAS OBSERVED

* PROJECTIVE GEOMETRY

  - ANGLES AND DIMENSIONS OF CORNERS VARY

  - DETAILED STUDY, FIELD MAPS, RECOMBINATION
    DONE BY IULIU STUMER

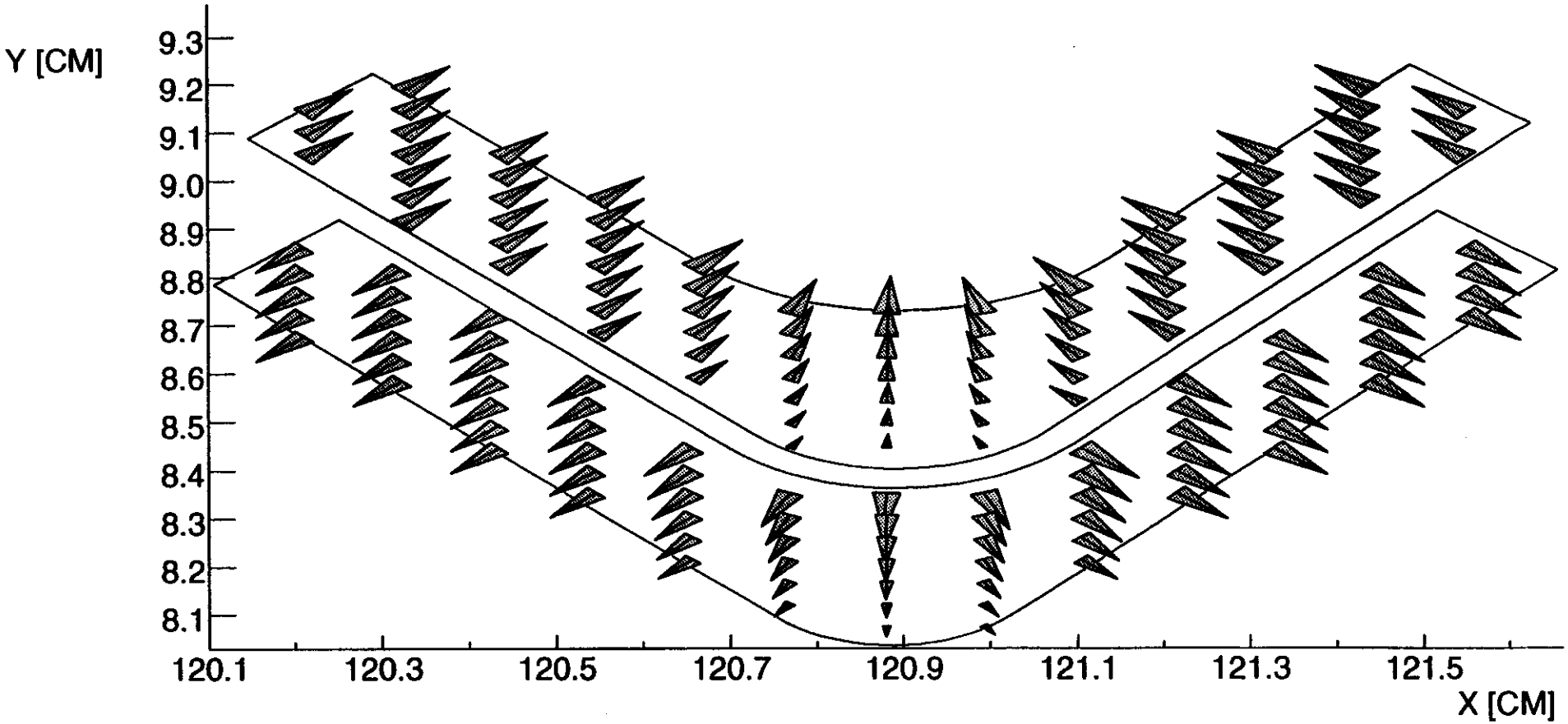
  - RESULT - EFFECTS, IF MEASURABLE, MAY START TO BE VISIBLE
    AT ENERGIES OVER 300 GeV

  - INFLUENCE OF SPACERS IN THE CORNERS HAS BEEN STUDIED
    - ADDITIONAL RIGIDITY TO THE STRUCTURE
      WITHOUT ENERGY RESOLUTION DETORIATION

20 GeV ; 100 keV CUTS ; SUBSTEPS = 100 microns

SPACERS [mm]	MEAN ENERGY IN ACTIVE MEDIUM [GeV]	RESOLUTION (+/- 0.2)%
NO	6.832 +/- 0.0036	5.29
1.25	6.699 +/- 0.0035	5.24
1.875	6.636 +/- 0.0035	5.27
2.5	6.576 +/- 0.0035	5.31

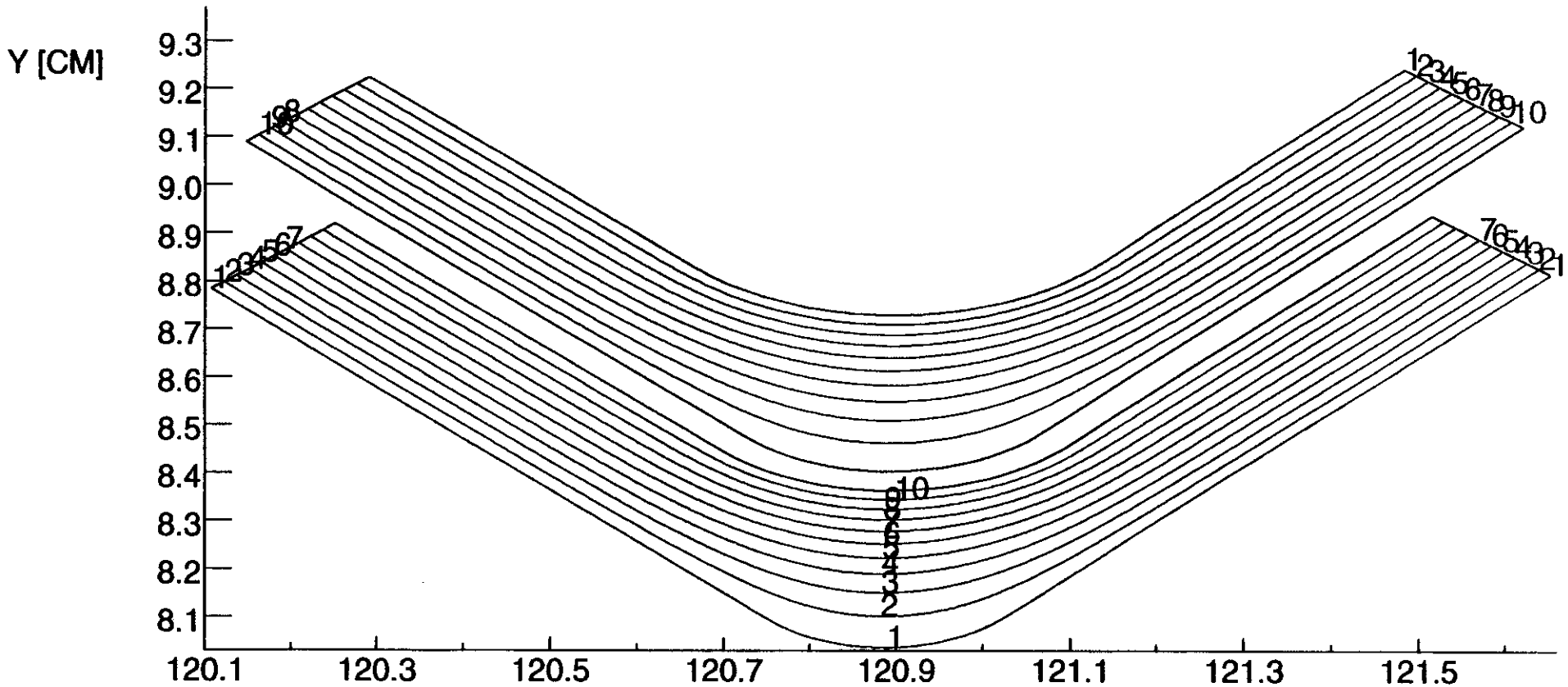
AC07.STRES
23/Oct/92 17:39:50 Page 8 : RECO MESH=NO MATE=BOUND +ERASE



ELEM=QUAD SYMM=XY SOLN=V SCALE=1.0 FIEL=ELEC
Static Solution Mesh 2400 Elements 6 Regions

VF/PE

AC07.STRES
23/Oct/92 17:03:18 Page 4 : CONT COMP=POT LINES=10 +ERASE

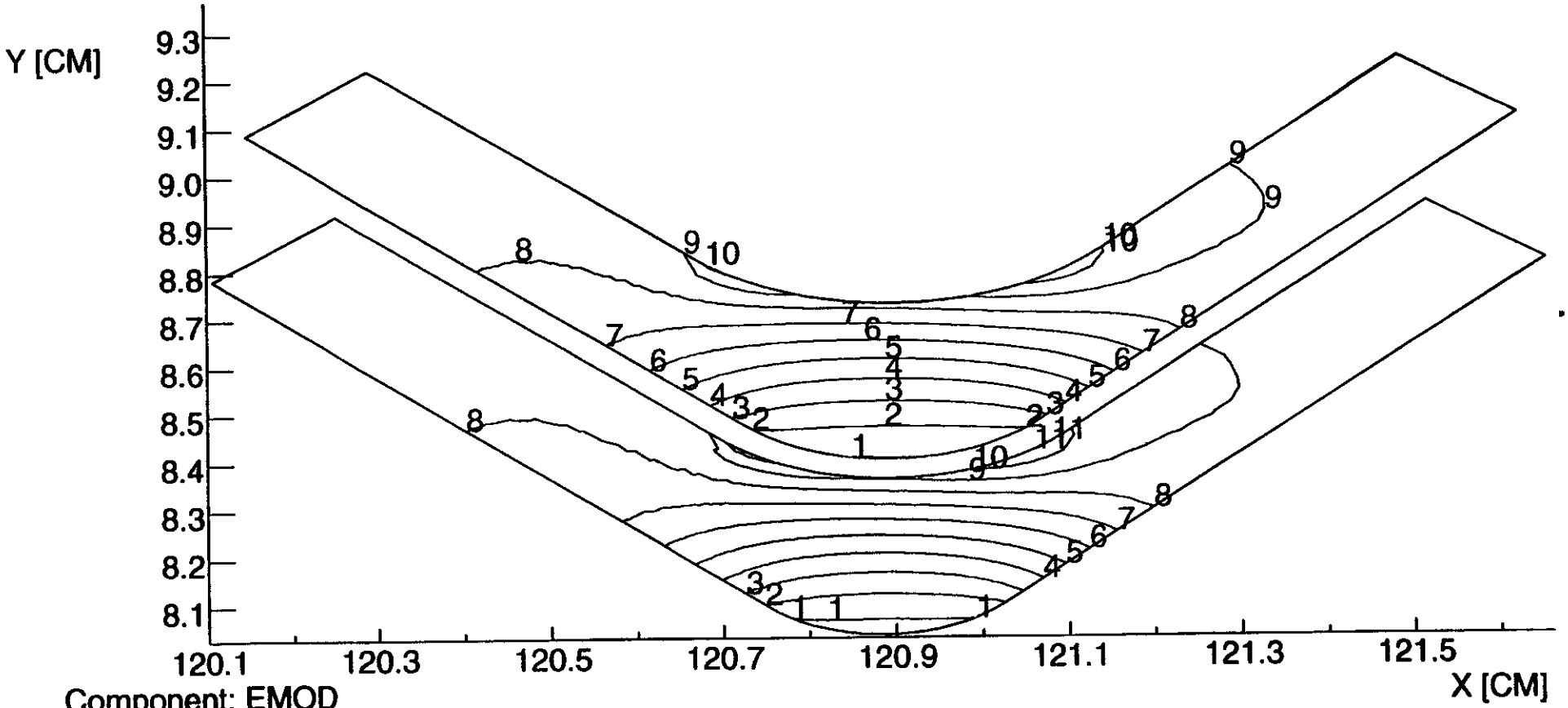


Component: POT
Minimum: 0.0, Maximum: 2000.0, Interval: 200.0

ELEM=QUAD SYMM=XY SOLN=V SCALE=1.0 FIEL=ELEC
Static Solution Mesh 2400 Elements 6 Regions

VF/PE

AC07.STRES
23/Oct/92 17:04:07 Page 5 : CONT COMP=EMOD LINES=10 +ERASE



Component: EMOD
Minimum: 3000.0, Maximum: 13000.0, Interval: 1000.0

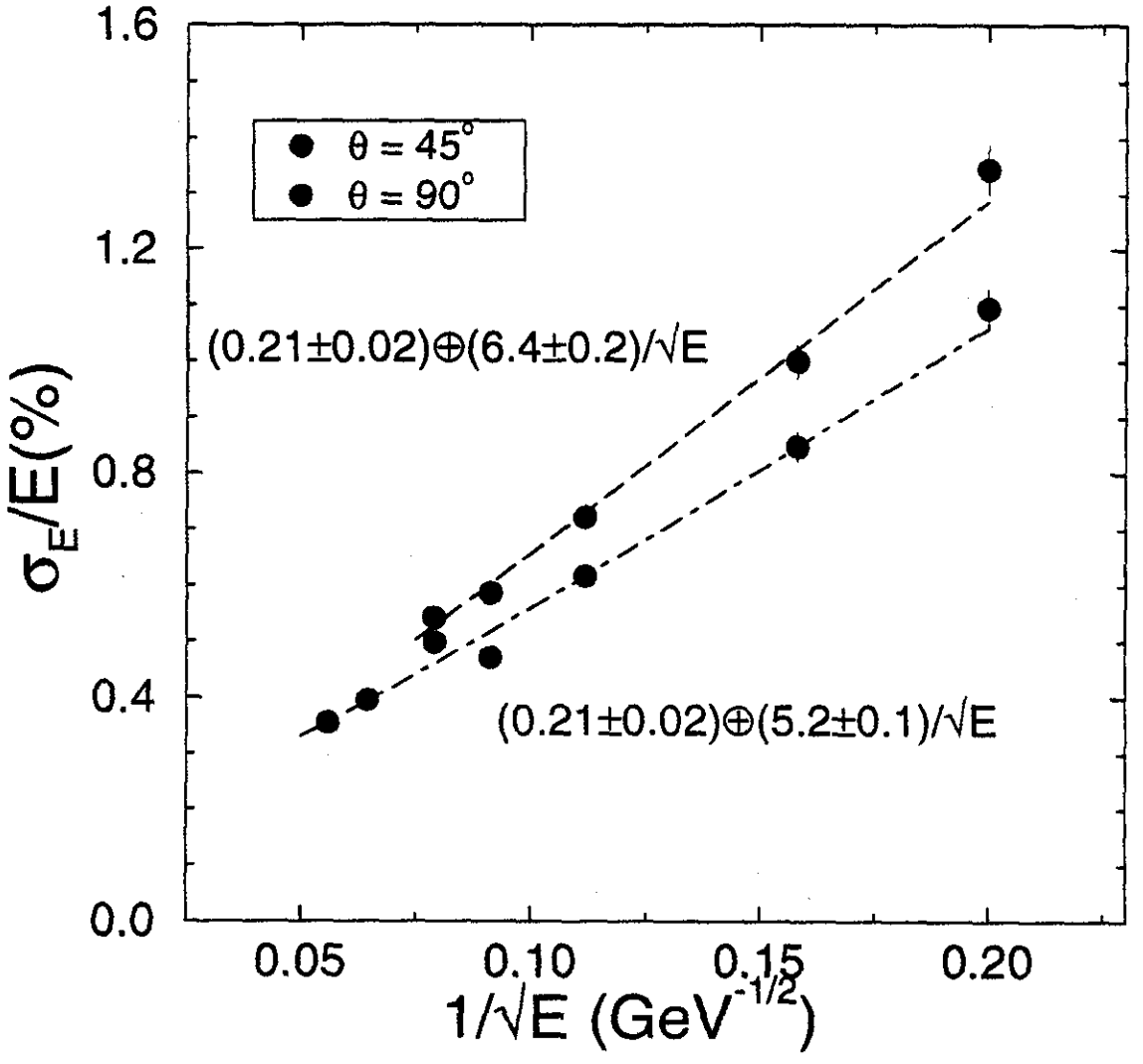
ELEM=QUAD SYMM=XY SOLN=V SCALE=1.0 FIEL=ELEC
Static Solution Mesh 2400 Elements 6 Regions

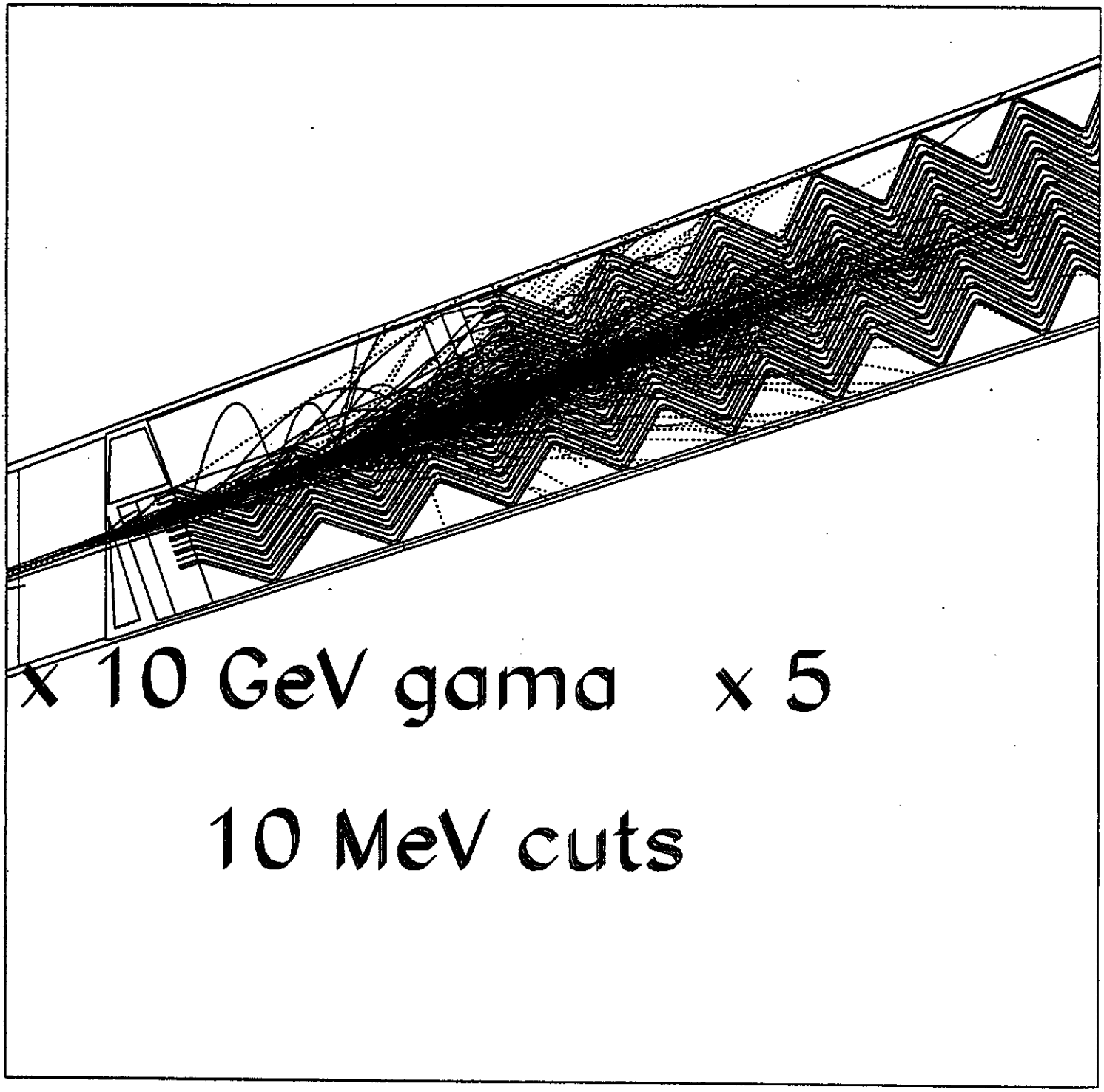
VF/PE

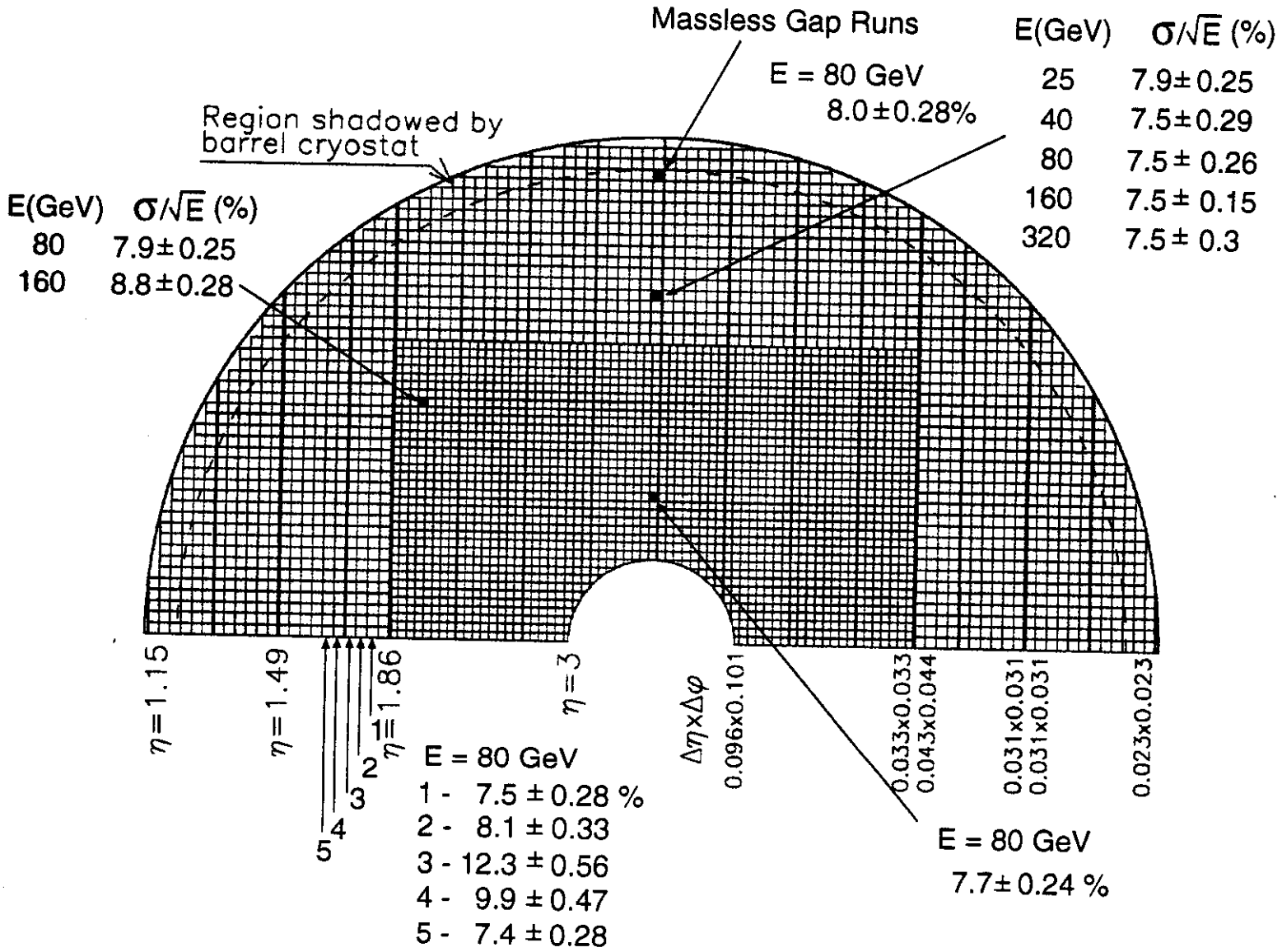
EM Calorimeter - Barrel

Energy Resolution

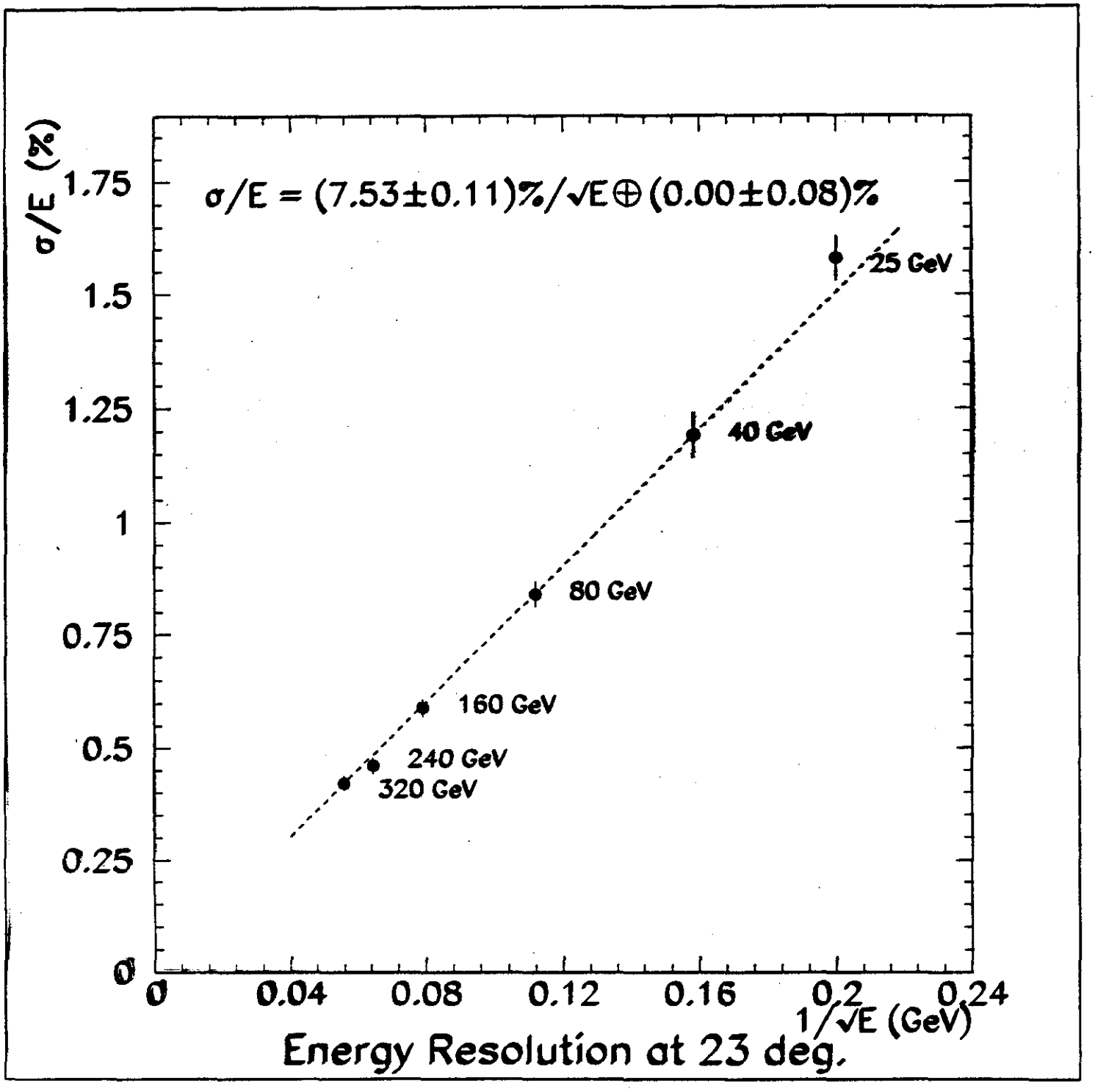
(Monte Carlo Simulation)



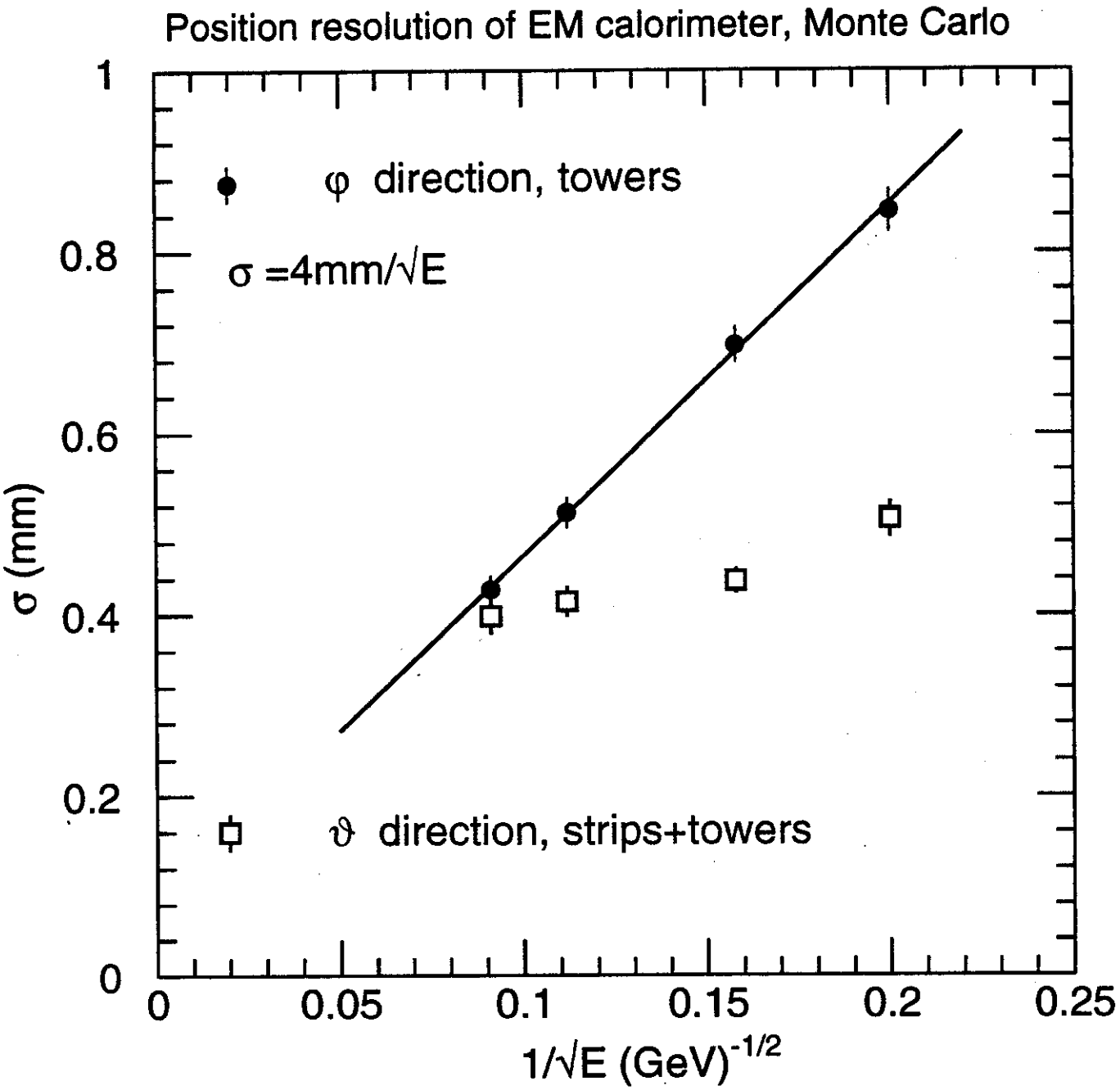

x 10 GeV gama x 5
10 MeV cuts

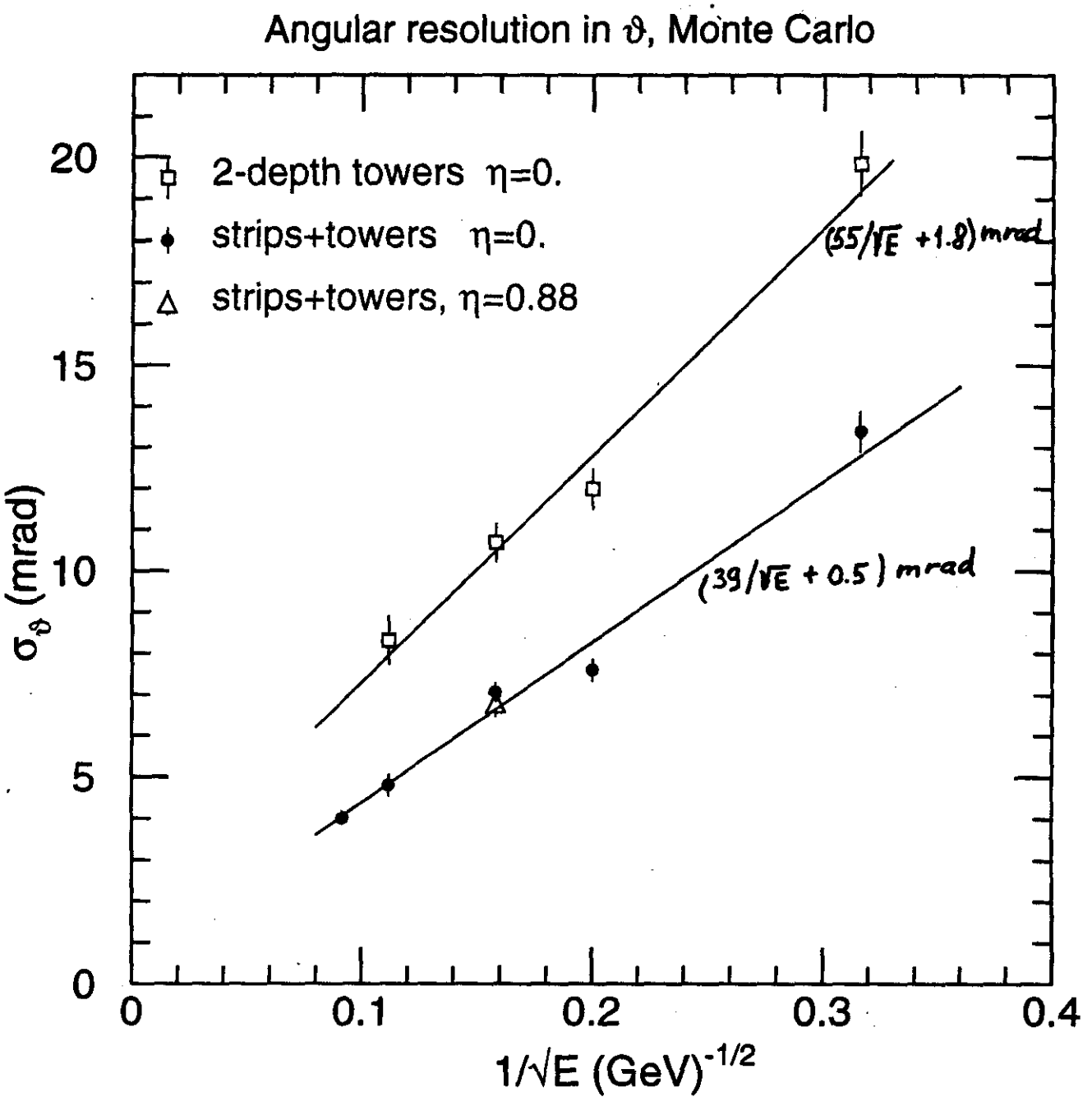

Massless Gap Runs
E = 80 GeV
8.0 ± 0.28%
E(GeV) σ/√E (%)
25 7.9 ± 0.25
40 7.5 ± 0.29
80 7.5 ± 0.26
160 7.5 ± 0.15
320 7.5 ± 0.3
Region shadowed by barrel cryostat
E(GeV) σ/√E (%)
80 7.9 ± 0.25
160 8.8 ± 0.28
η = 1.15
η = 1.49
η = 1.86
η = 3
Δη x Δφ
0.096x0.101
0.033x0.033
0.043x0.044
0.031x0.031
0.031x0.031
0.023x0.023
1
2
3
4
5
E = 80 GeV
1 - 7.5 ± 0.28 %
2 - 8.1 ± 0.33
3 - 12.3 ± 0.56
4 - 9.9 ± 0.47
5 - 7.4 ± 0.28
E = 80 GeV
7.7 ± 0.24 %

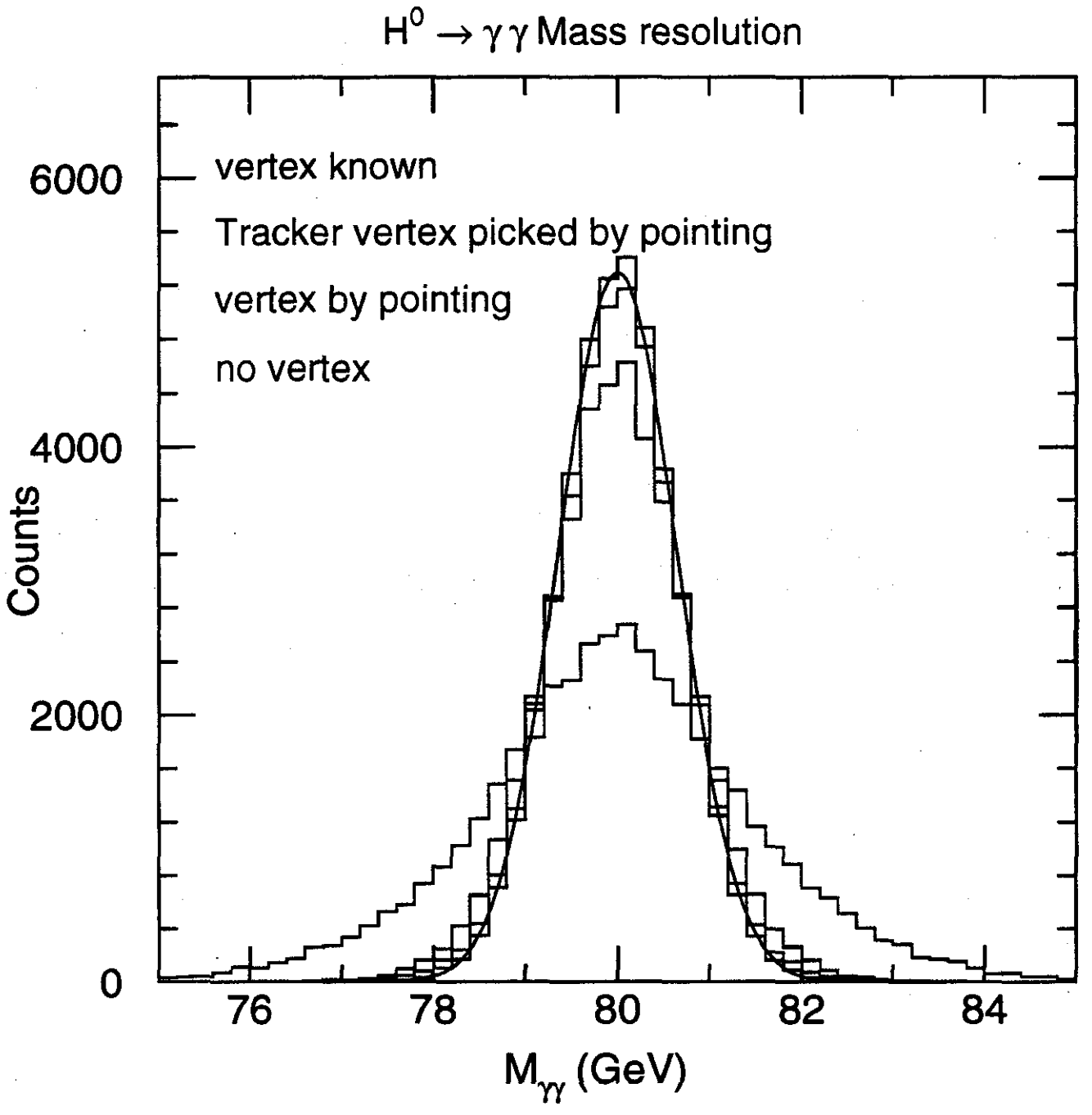
ENDCAP

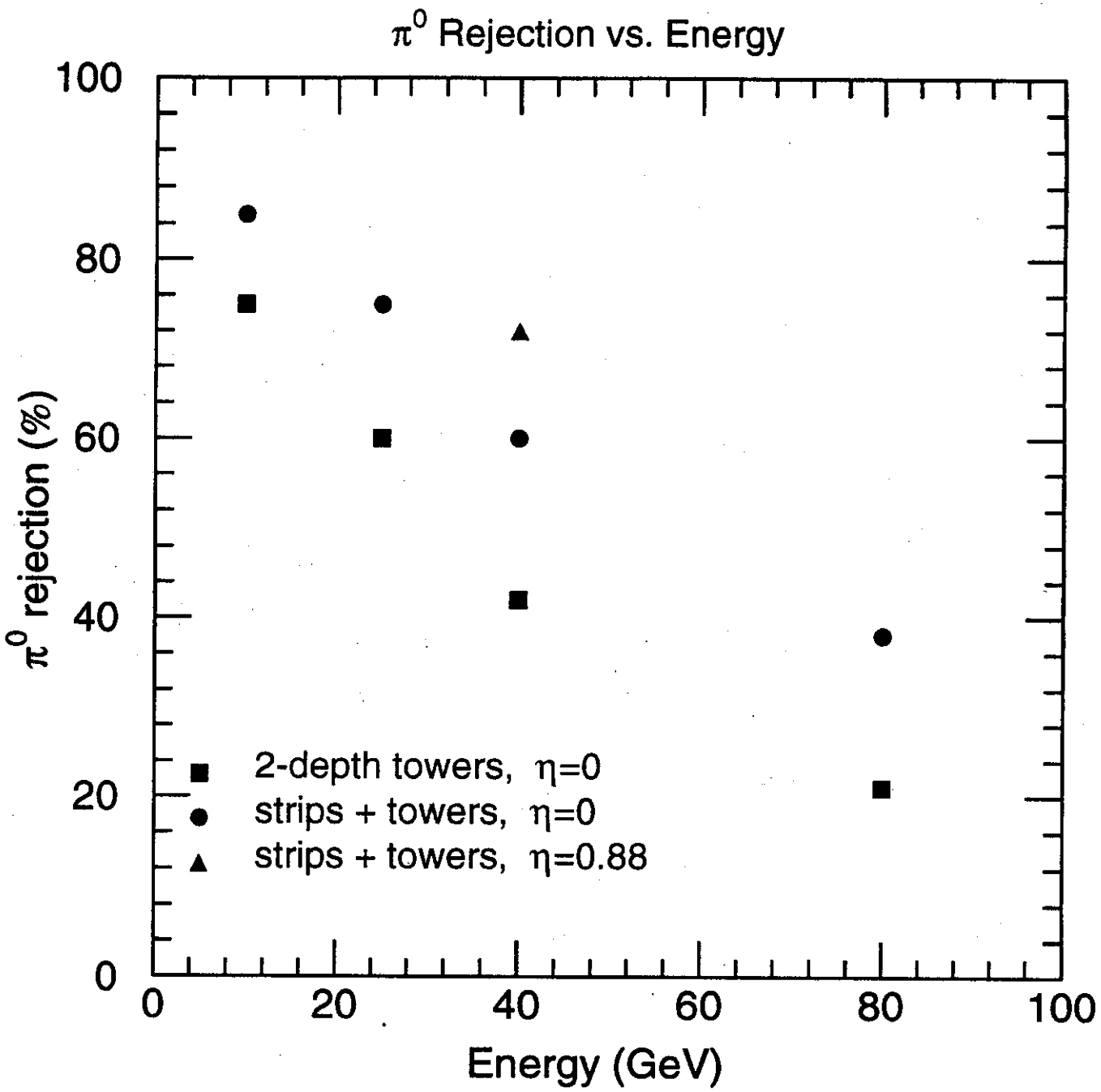


Energy Resolution at 23 deg.


Position resolution of EM calorimeter, Monte Carlo
φ direction, towers
σ =4mm/√E
ϑ direction, strips+towers
σ (mm)
1/√E (GeV)^-1/2
0
0.2
0.4
0.6
0.8
1
0
0.05
0.1
0.15
0.2
0.25


Angular resolution in ϑ, Monte Carlo
2-depth towers η=0.
strips+towers η=0.
strips+towers, η=0.88
(55/√E +1.8) mrad
(39/√E + 0.5) mrad
σϑ (mrad)
1/√E (GeV)^-1/2
0
5
10
15
20
0
0.1
0.2
0.3
0.4


$H^0 \rightarrow \gamma\gamma$ Mass resolution
vertex known
Tracker vertex picked by pointing
vertex by pointing
no vertex
Counts
6000
4000
2000
0
76
78
80
82
84
$M_{\gamma\gamma}$ (GeV)


π^0 Rejection vs. Energy
100
80
60
40
20
0
π^0 rejection (%)
0
20
40
60
80
100
Energy (GeV)
2-depth towers, η=0
strips + towers, η=0
strips + towers, η=0.88

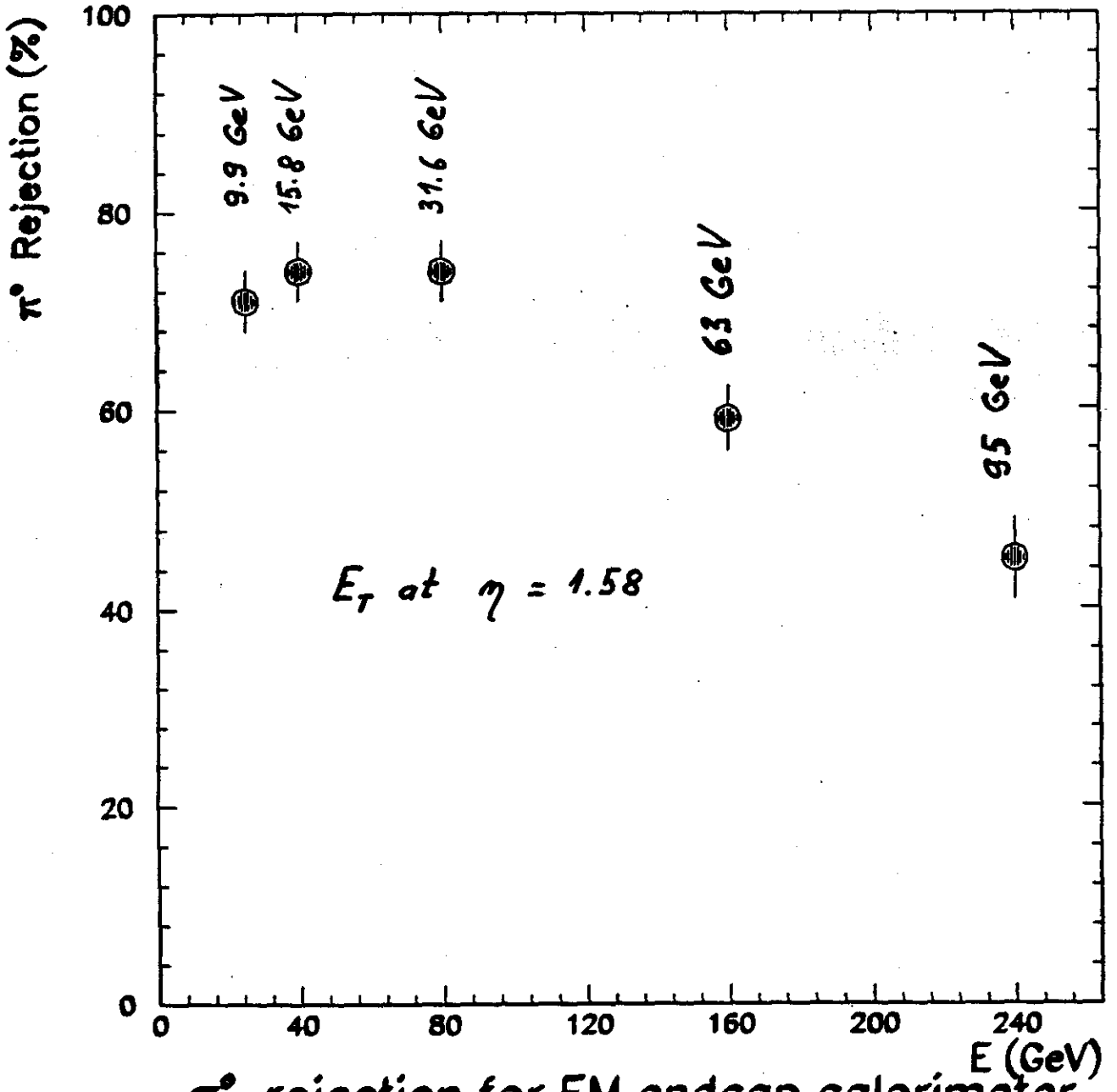
REJECTION OF MULTIPHOTONS EM CLUSTERS
&
JET REJECTION

VARIABLES :

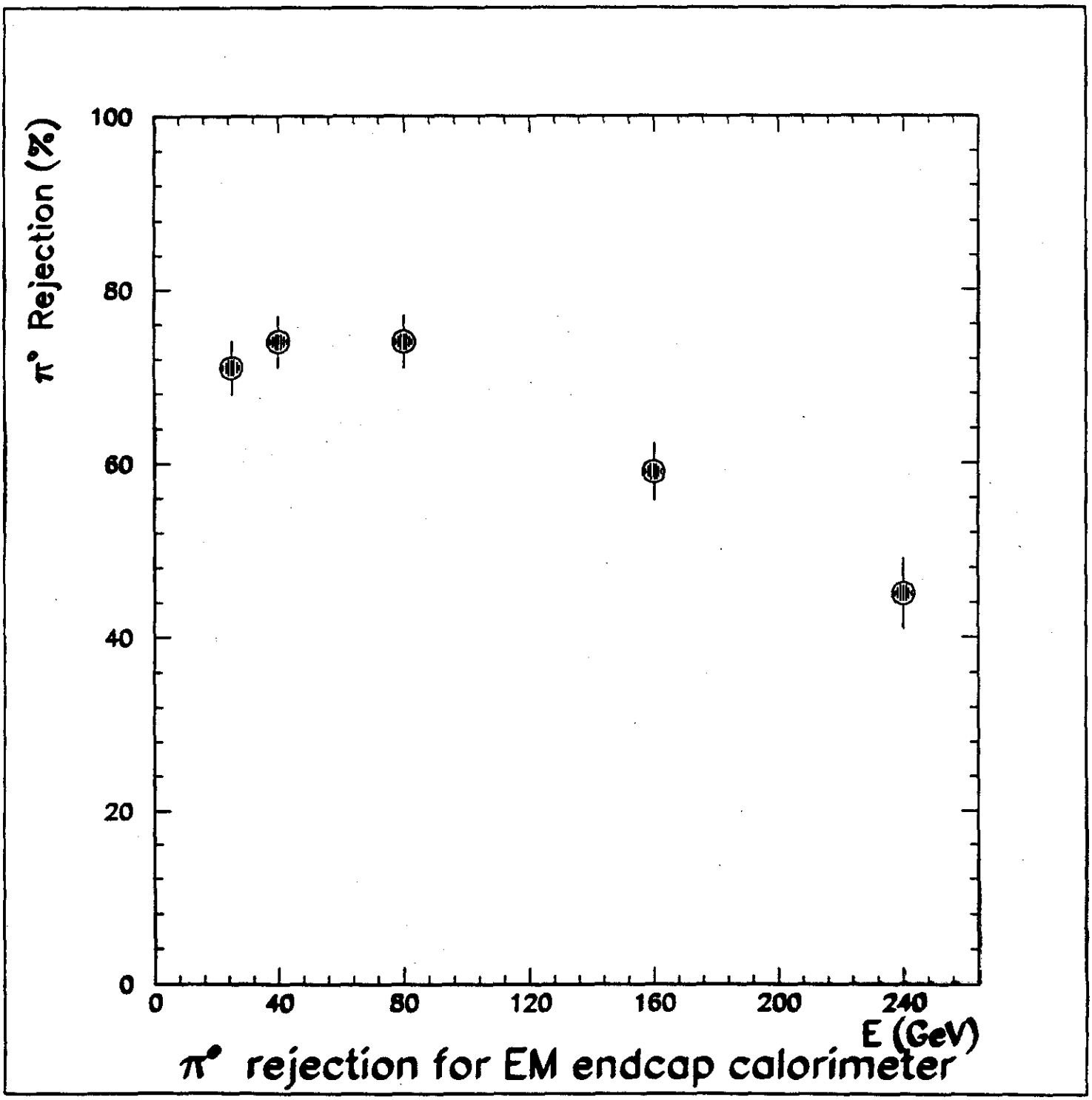
- WSEM = $(E_{RIGHT} + E_{LEFT})/E3$
  ASEM = $|E_{RIGHT} - E_{LEFT}|/E1$
  W2 (W3) = DISTANCE BETWEEN CENTER AND SECOND (THIRD) HIGHEST STRIP
  WR = WIDTH at 10% of E1+E2
  H3(H4,H5) = E in 3 (4,5) HIGHEST STRIP NORMALIZED TO E1+E2

  E1 (E2) = ENERGY IN THE HIGHEST (SECOND) STRIP
  E3 = ENERGY SUM IN 3 STRIPS AROUND CENTER
  E_{RIGHT} = ENERGY SUM IN 3 STRIPS RIGHT TO THE CENTER
  E_{LEFT} = ENERGY SUM IN 3 STRIPS LEFT TO THE CENTER

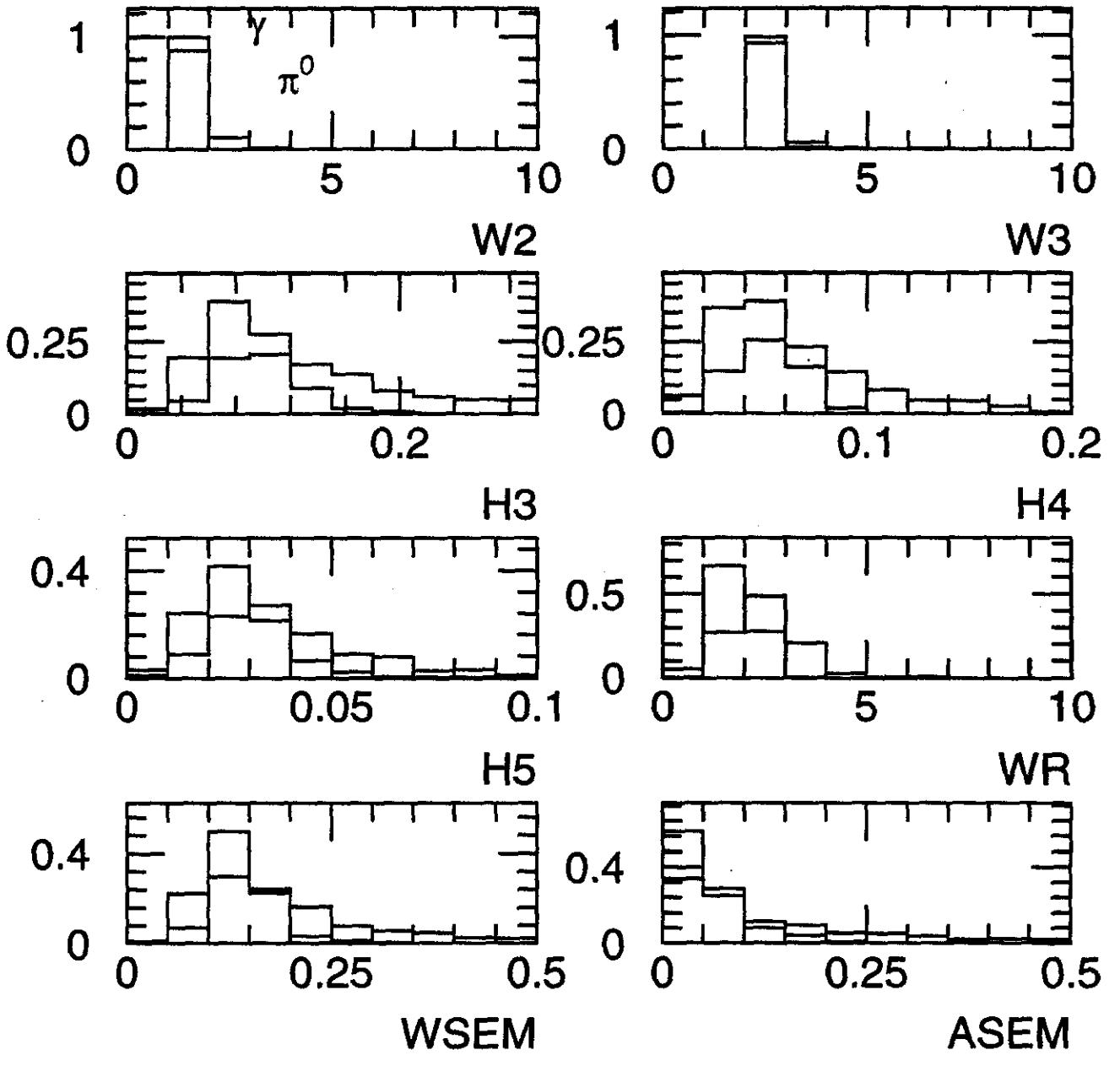
- SHOWER SIZE BY TOWERS
- IF E_{TOT}(STRIPS) < 100 MeV => γ

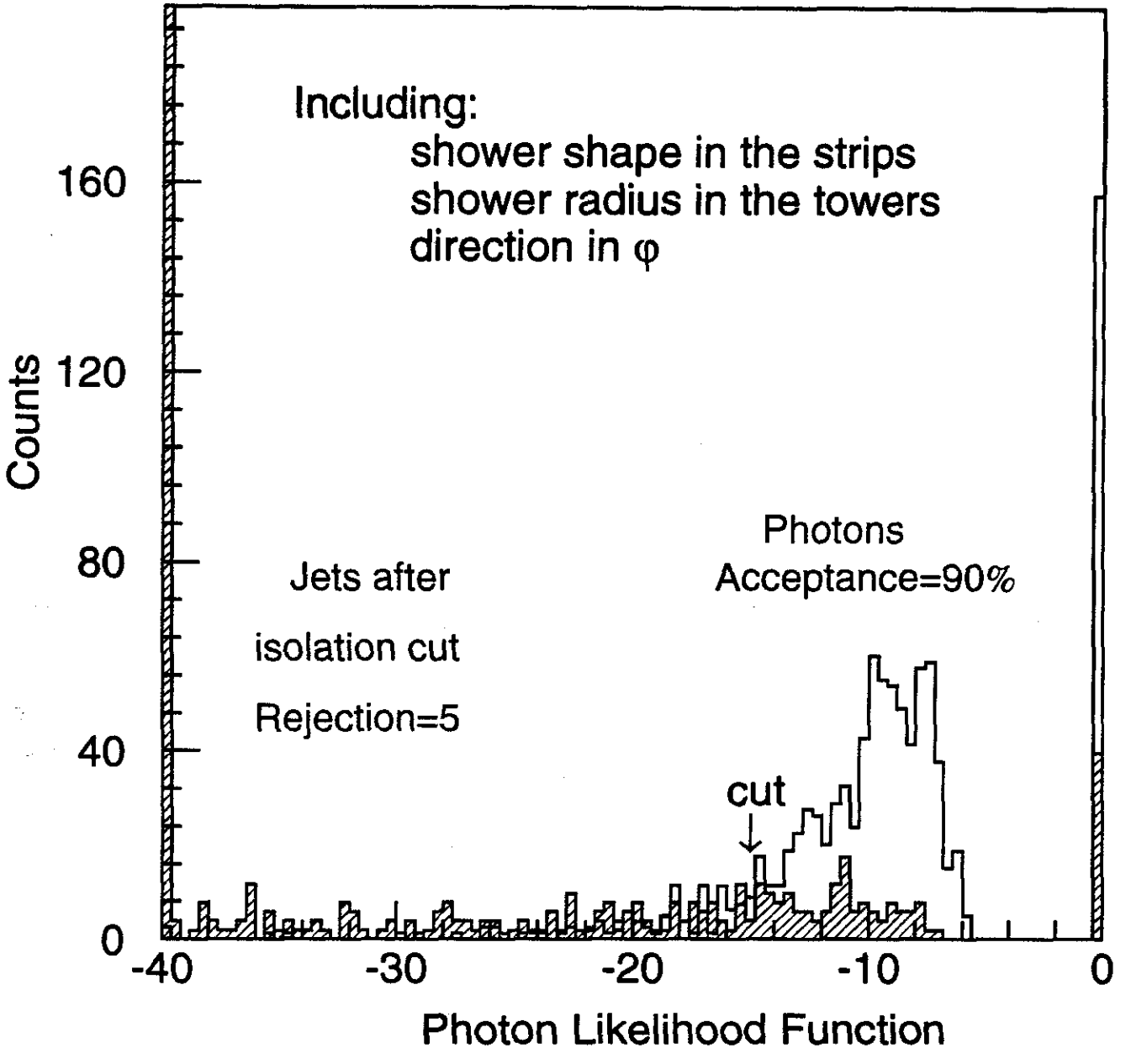


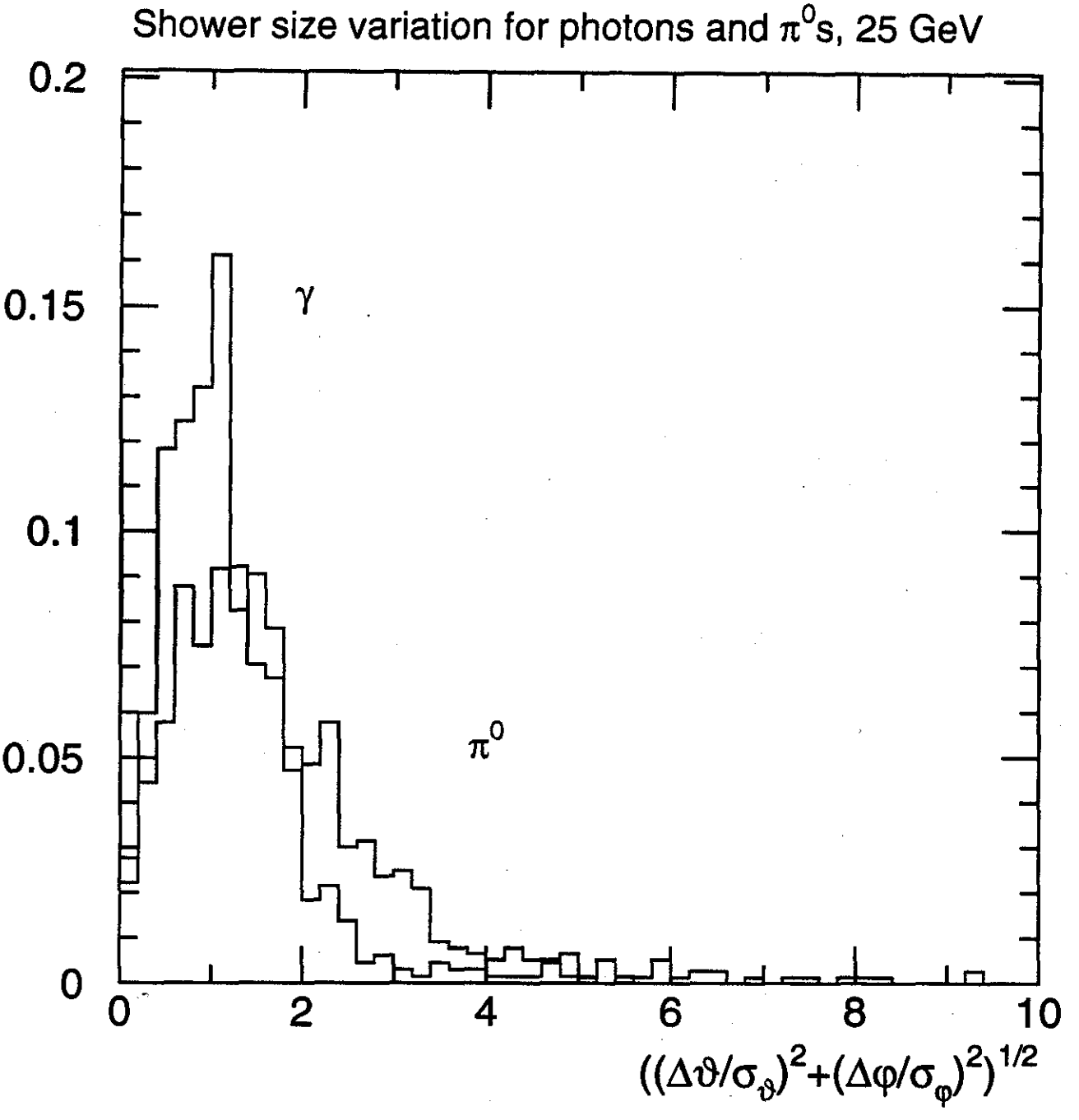
π° rejection for EM endcap calorimeter


π° Rejection (%)
100
80
60
40
20
0
0
40
80
120
160
200
240
E (GeV)
π° rejection for EM endcap calorimeter

distribution of variables derived from strip energy, 25 GeV




Including:
shower shape in the strips
shower radius in the towers
direction in φ
Counts
160
120
80
40
0
Jets after
isolation cut
Rejection=5
Photons
Acceptance=90%
cut
-40
-30
-20
-10
0
Photon Likelihood Function


Shower size variation for photons and π^0s, 25 GeV
0.2
0.15
0.1
0.05
0
0
2
4
6
8
10
γ
π^0
$((\Delta\vartheta/\sigma_\vartheta)^2+(\Delta\varphi/\sigma_\varphi)^2)^{1/2}$

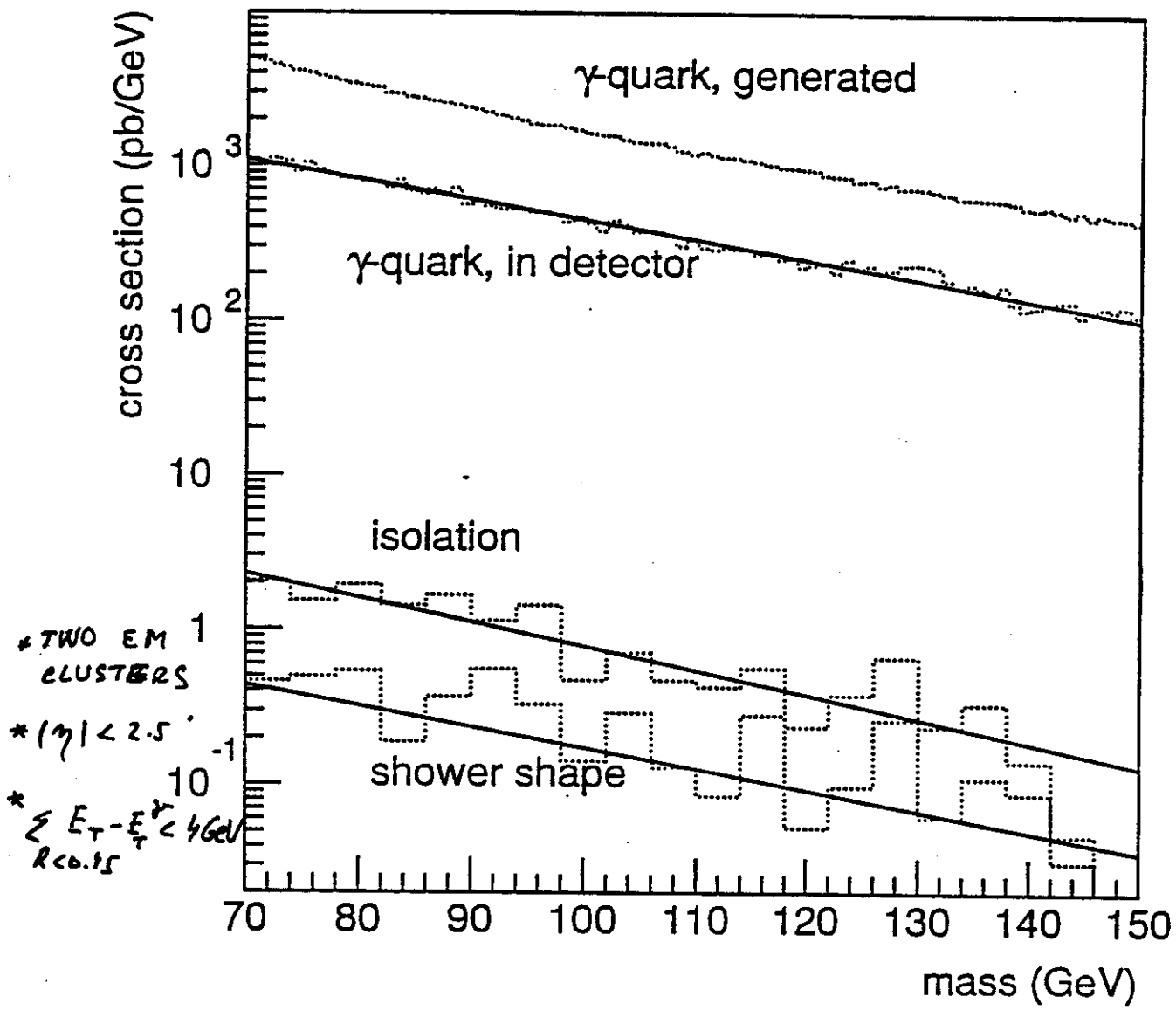


Figure 22: Cross section of γ-quark final state as a function of the invariant mass.

40 GeV jets

* 1 charged particle $p > 1$ GeV
* $\sum_{R<0.45} E_T - E_T^{\gamma} < 5$ GeV

*

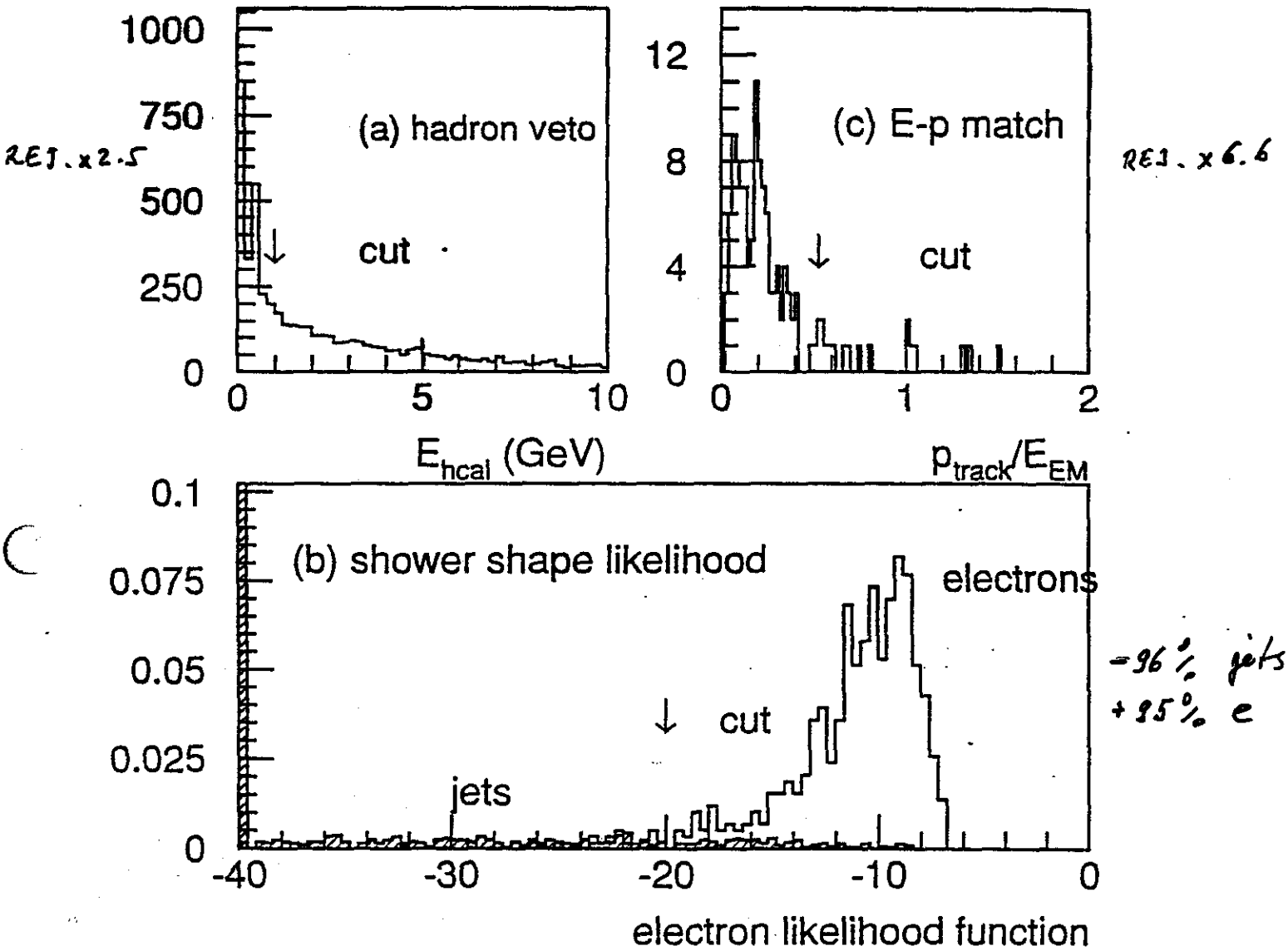


Figure 25: Subsequent cuts to obtain electron/jet separation. (a) distribution of energy in hadron calorimeter for jets; (b) distribution of electron likelihood function for electrons (solid) and jets (shaded); (c) Charged track momentum match with energy measured in the EM calorimeter.

WIT ISOLATION ~300

$< 10^{-5}$

LIQUID KRYPTON .vs. ARGON :

* LIQUID ARGON AS ACTIVE MEDIUM

TO ~ 25 Xo IN 52 cm 1.25 mm LEAD ABSORBER IS NEEDED
=>

SIGMA/SQRT(E) = (7.03 +/- 0.2) % AT 50 GeV
(6.91 +/- 0.2) % AT 10 GeV

FOR 0.95 mm ABSORBER, WHICH GIVES WITH LKr 25 Xo IN 52 cm, DEPTH of 65 cm IS NEEDED WITH LAr FOR THE SAME RAD. LENGTH, WHILE

SIGMA/SQRT(E) = (6.25 +/- 0.2) % AT 50 GeV

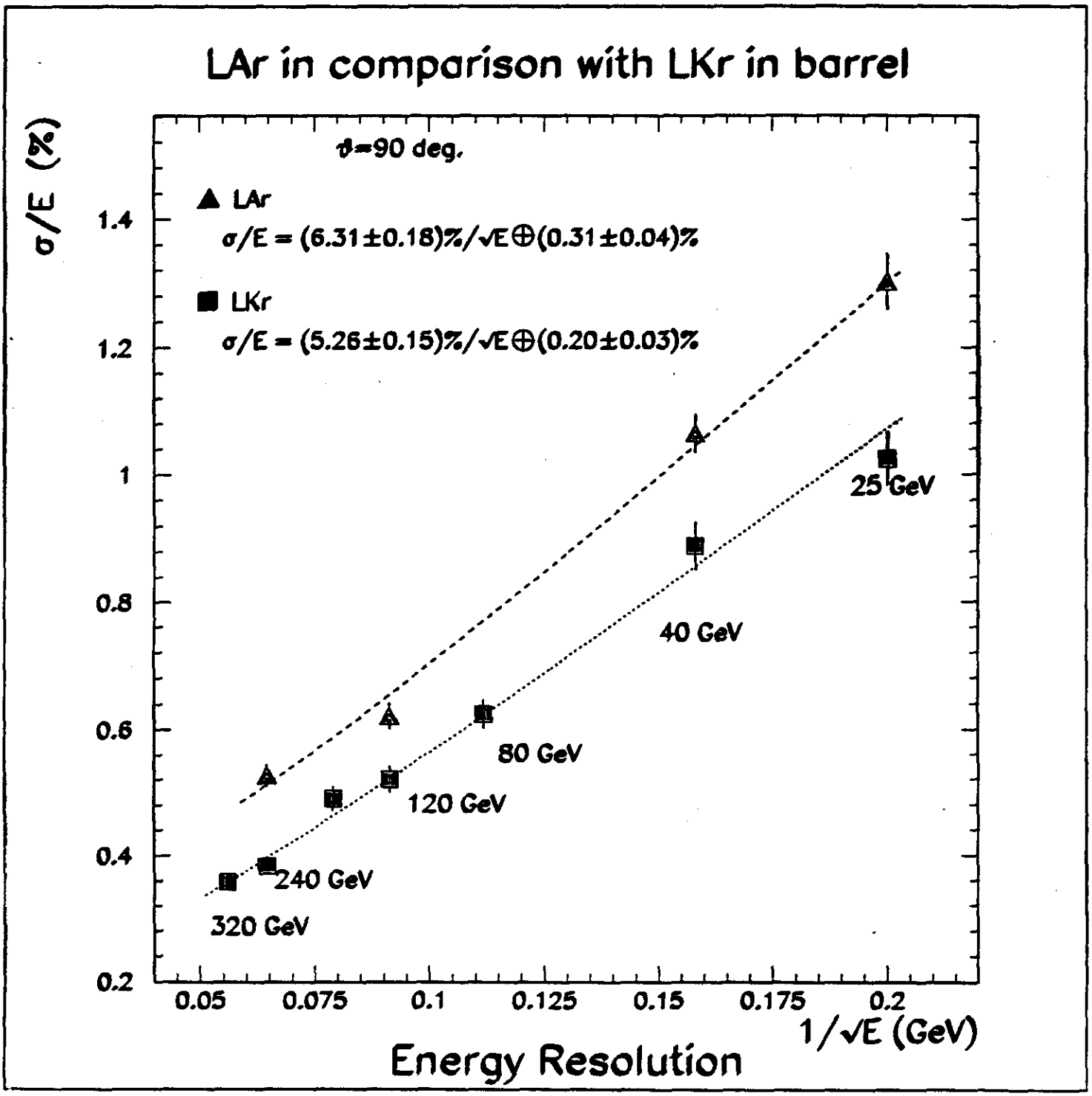
* LIQUID KRYPTON AS ACTIVE MEDIUM

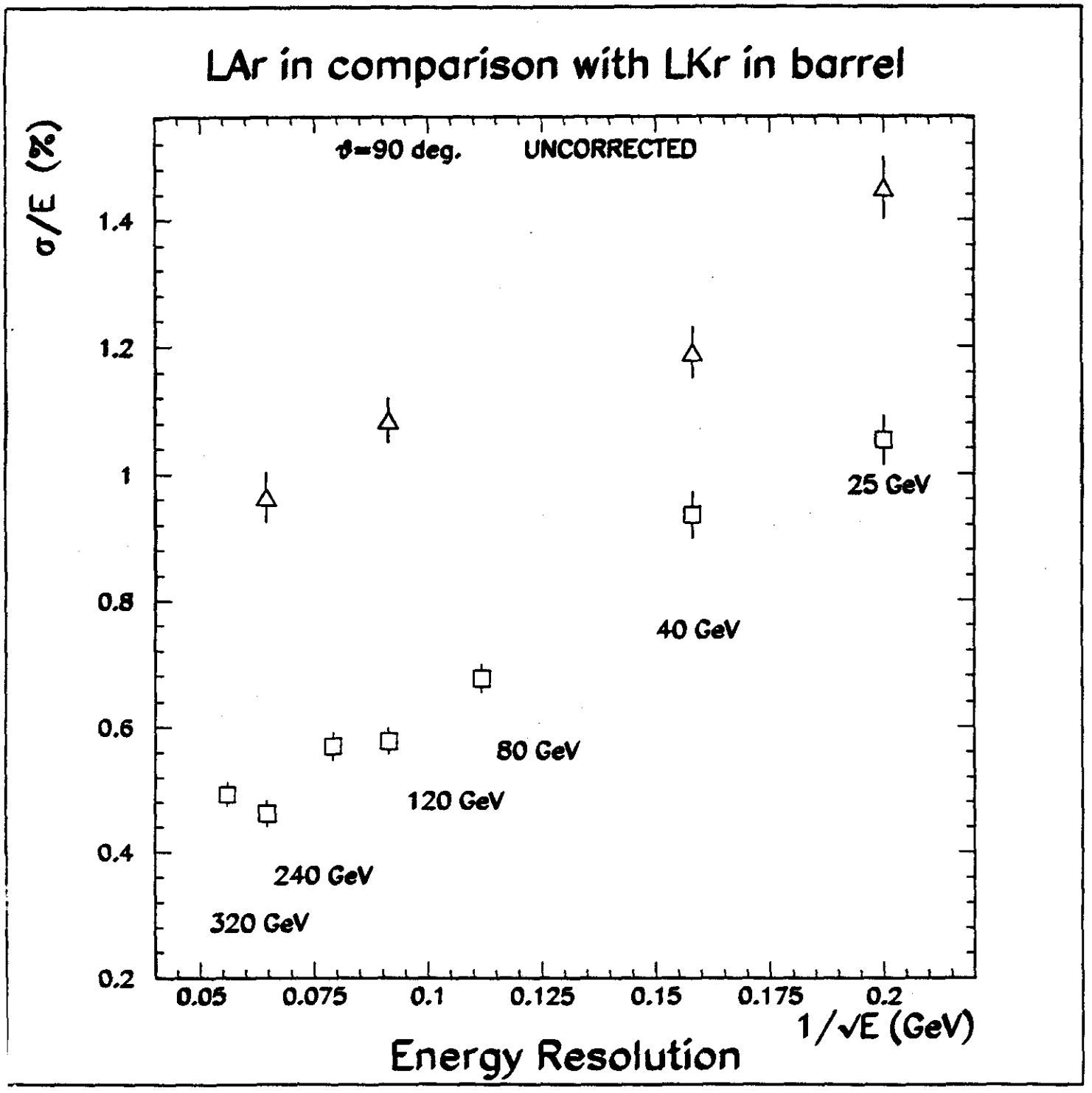
SIGMA/SQRT(E) = (5.4 +/- 0.2) % AT 50 GeV

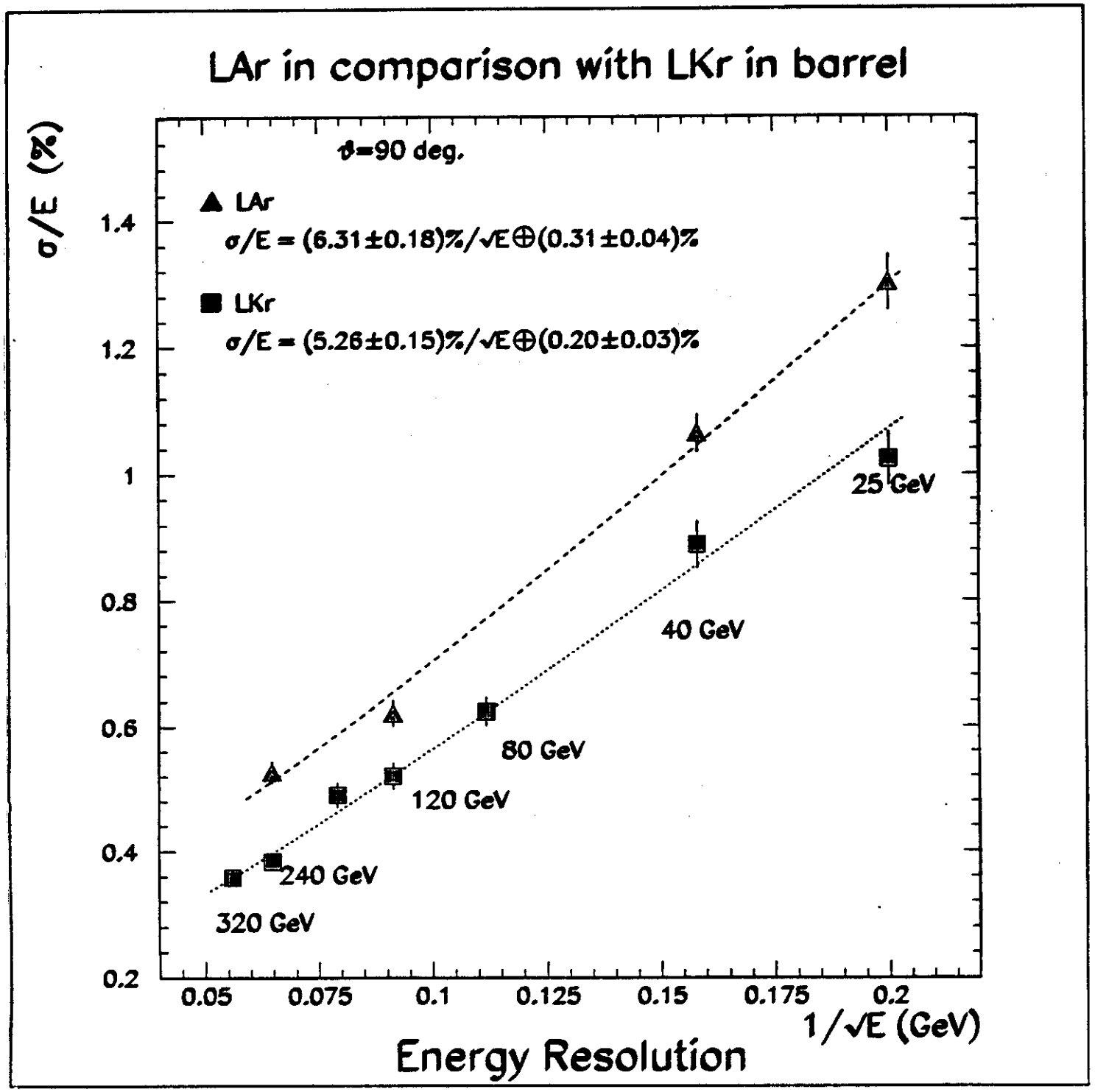
* PARALLEL PLATE GEOMETRY WITH THE SAME STRUCTURE

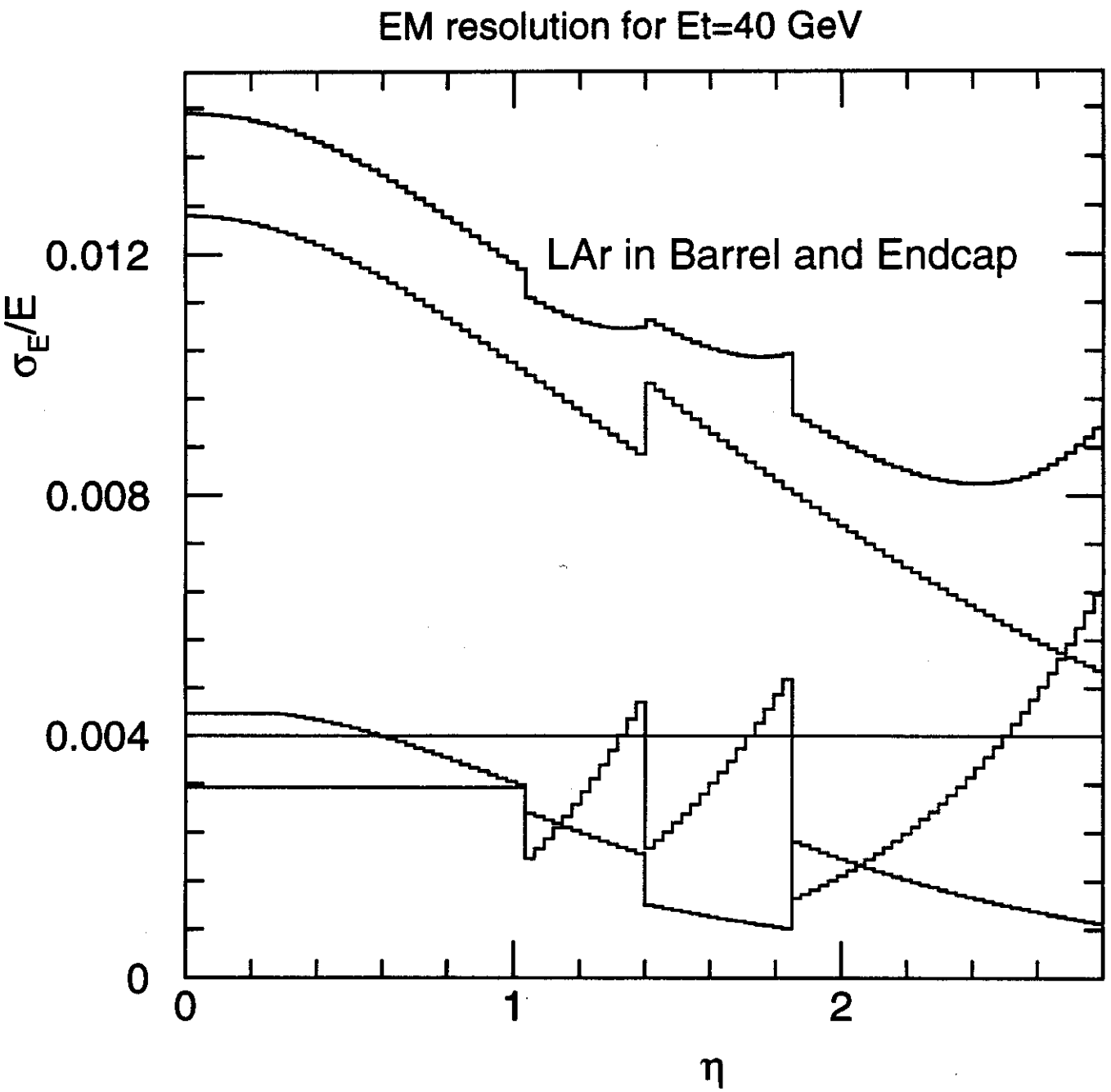
SIGMA/SQRT(E) = (4.7 +/- 0.2) % AT 90
(4.9 +/- 0.2) % AT 45

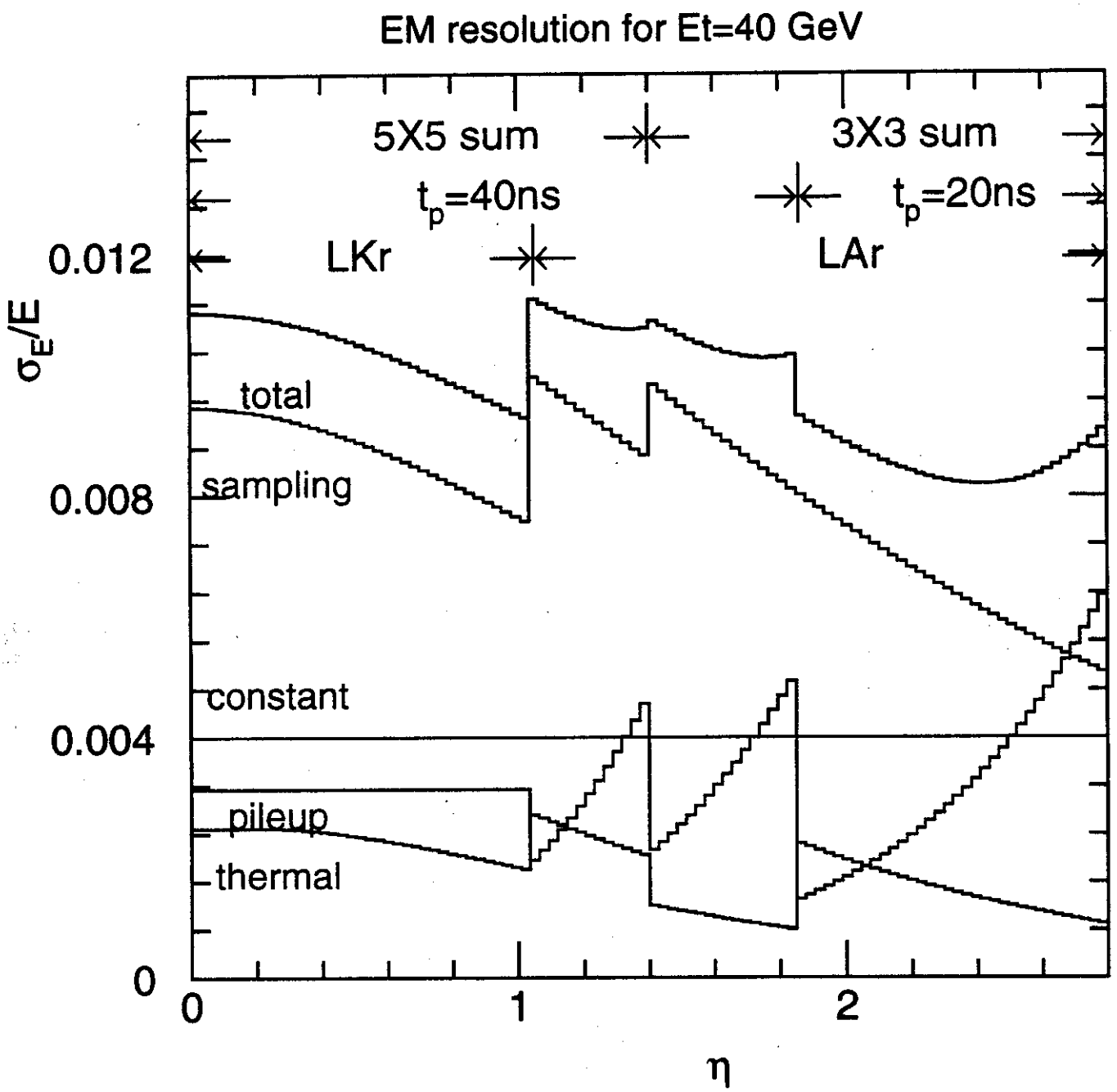
BACK LEAKAGE CORRECTED



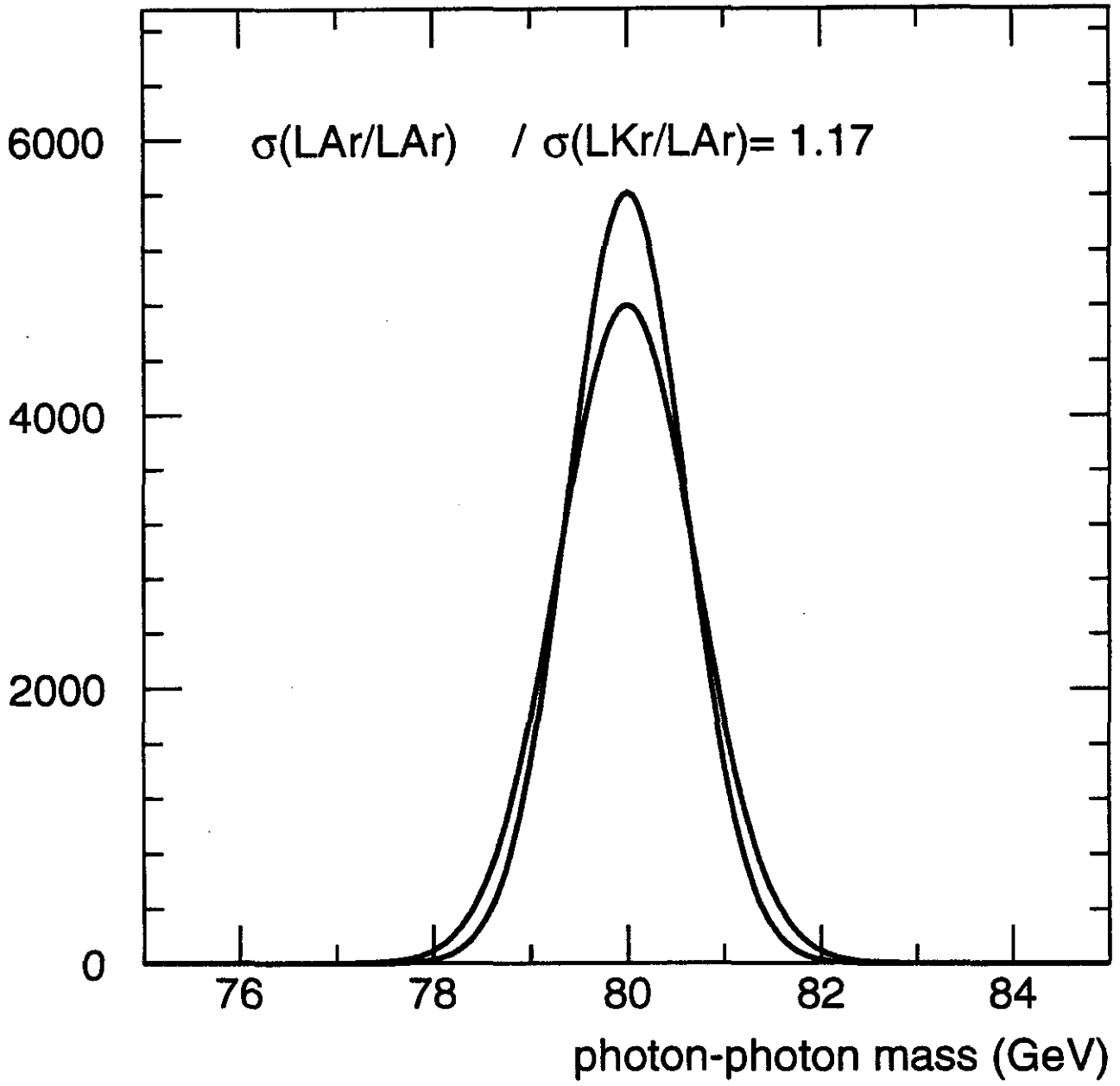

LAr in comparison with LKr in barrel
ϑ=90 deg.
UNCORRECTED
σ/E (%)
1.4
1.2
1
0.8
0.6
0.4
0.2
0.05
0.075
0.1
0.125
0.15
0.175
0.2
1/√E (GeV)
25 GeV
40 GeV
80 GeV
120 GeV
240 GeV
320 GeV
Energy Resolution


LAr in comparison with LKr in barrel
ϑ=90 deg.
LAr
σ/E = (6.31±0.18)%/√E⊕(0.31±0.04)%
LKr
σ/E = (5.26±0.15)%/√E⊕(0.20±0.03)%
25 GeV
40 GeV
80 GeV
120 GeV
240 GeV
320 GeV
σ/E (%)
1.4
1.2
1
0.8
0.6
0.4
0.2
0.05
0.075
0.1
0.125
0.15
0.175
0.2
1/√E (GeV)
Energy Resolution


EM resolution for Et=40 GeV
LAr in Barrel and Endcap
0.012
0.008
0.004
0
σ_E/E
0
1
2
η


EM resolution for Et=40 GeV
5X5 sum
3X3 sum
t_p=40ns
t_p=20ns
LKr
LAr
total
sampling
constant
pileup
thermal
σ_E/E
0.012
0.008
0.004
0
0
1
2
η

Energy resolution contribution to Higgs mass resolution



CONCLUSION

* ENERGY RESOLUTION

  $< (6\%/\sqrt{E} \oplus 0.4\%$ BARREL

  $< (8\%/\sqrt{E} \oplus 0.4)\%$ ENDCAP

* POSITION $4.4\ mm/\sqrt{E}$

* POINTING $40\ mrad/\sqrt{E}$ BARREL

  $40\ mrad/\sqrt{E}$ ENDCAP VERTICAL

  ? $55\ mrad/\sqrt{E}$ ENDCAP HORIZONTAL

* TIMING (5x5 towers) $5\ GeV * ns/E$

* π^0-rejection at 90% γ-acceptance

  up to 80% in BARREL

  up to 75% in ENDCAP

* JET REJECTION ($H \to \gamma\gamma$)

γ-quark	$2 * 10^{-3}$	$4 * 10^{-4}$
γ-gluon	$3.8 * 10^{-4}$	$1.3 * 10^{-4}$

* JET REJECTION ($H \to$ leptons)

  $< 10^{-5}$