GEM TN-92-208

Compensation, Resolution, Linearity, and the GEM Hadron Calorimeter Decision

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October 6, 1992

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We have performed Monte Carlo studies comparing the response to jets of a Liquid Krypton EM/Scintillating Fiber hadron calorimeter (hybrid) and a Liquid Krypton EM/Liquid Krypton hadron calorimeter (integrated). The starting point for these studies was the observation that unlike the lead/liquid Argon hadron calorimeter studied in the BNL test beam in 1991, the hadron calorimeter proposed for the integrated option has a copper absorber. This leads to a much less compensated response between electrons and hadrons, and consequently a larger constant term for jet energy resolution. Using optimistic assumptions about this untested device (e/h =1.6, 75%/ sqrt (E) stochastic term) and a simple fragmentation function, our model predicts a constant term of at least 2% - 3% in jet energy resolution due to this lack of compensation for the integrated device. The hybrid option shows less than 1% constant term due to this effect, and unlike the integrated option its response can be predicted without requiring knowledge of details of the fragmentation function at high energies; the latter point was discussed in detail in GEM Technical Note 92-67 by H. Paar and R. Wigmans. We have extended the work of Paar and Wigmans to include the current integrated design, and have found more than 1% variation in the nonlinearity of response for the integrated device with a relatively small change in the jet fragmentation function.

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1 Introduction

Lack of compensation (unequal response to electromagnetic and hadronic components of hadron showers) leads to a constant term in the energy resolution of EM/hadronic calorimeter systems in response to jets. Calorimeters response is typically parametrized in terms of $\frac{e}{h}$, with e the calorimeter response to electromagnetic deposition and h the response to low-energy hadronic activity. Noncompensation produces a nearly energy-independent contribution of $14\%|1-\frac{e}{h}|$ in the response to single charged hadrons in a uniform calorimeter (several experiments cluster about this average, see SDC EOI p. 39). The constant term for jets will be less (by an amount depending upon details of jet fragmentation) because of averaging over independent shower fluctuations and because of better resolution for neutral pion secondaries in the EM calorimeter. Compensation may be improved both by suppressing the electromagnetic response and by boosting the response to hadronic activity (e.g. recoil protons from evaporation neutrons in the hybrid). See Figure 1.

The lead/liquid Argon hadron calorimeter prototype which was tested at BNL had a measured e/π of 1.15 at 15 GeV, corresponding to $\frac{e}{h} \approx 1.3$. By comparison, the Zeus collaboration has measured $\frac{e}{h} = 1.34 \pm .05$ for a 5mm Pb, 5mm Scintillator sampling calorimeter. SDC has concluded that in order to not exceed contributions to the constant term in jet energy resolution caused by cone corrections and other uncertainties related to jet definition, $\frac{e}{h} = 1.2$ is adequate. In fact, because SDC estimates a 3% constant term for jets from intervening dead material (solenoid) and a 600 MeV charged particle cutoff (200 MeV for GEM), their specification is $\frac{e}{h} < 1.3$; this gives a less than 2% contribution to the constant term for jets.

In order to minimize multiple scattering and energy loss by muons, and to decrease system cost, the GEM hadron calorimeter will use a copper absorber. Compared to a lead device, a copper calorimeter does not get as much partial compensation through electromagnetic suppression. The cross section for ionization is proportional to Z, but pair production goes like Z^2 and the photoelectric effect goes like Z^5. Consequently, shower gammas produce low energy electrons preferentially in the high-Z absorber, where they range out. Figure 2 shows the result of an EGS calculation (Wigmans, NIM A259 389) contrasting $e/mip = 0.6$ for a Lead/Liquid Argon calorimeter with $e/mip = 0.8$ for an Iron/Liquid Argon device (compare $e/mip = 0.52$, 0.75 for

replacing the Liquid Argon with plastic scintillator in the two cases). Iron and Copper are very similar for these purposes, with Z=26 and Z=29. Assuming comparable hadronic response for LAr/Cu and LAr/Pb, we can expect $\frac{e}{h} = 1.3 \times (0.8/0.6) \approx 1.7$. This should be compared to recent measurements for an SDC Fe/Scintillator prototype (Corpus Christi Conference, J. Proudfoot talk) which with 10% scintillator by volume had a 7% constant term for single hadrons – corresponding to $\frac{e}{h} = 1.5$ WITH partial boosting of the hadronic response in the scintillator.

We have therefore conducted a study comparing a hadron calorimeter with $\frac{e}{h} = 1.6$ (an optimistic assessment of the integrated device) with a second device with $\frac{e}{h} = 1.0$ (our best estimate for the hybrid). For each device we set $\frac{e}{h} = 1.3$ in the EM calorimeter upstream. We use the same simple fragmentation function as Paar and Wigmans, given by $D(z) = (\alpha+1)(1-z)^{\alpha}/z$. We compared α=4 and α=6 cases (intermediate between LEP α=3 and CDF α=6). As did Paar and Wigmans, we use the Bock parametrization for the showers and D. Groom's expression for the average e.m.-fraction in hadron showers as a function of energy. Further details are given in Paar and Wigman's note. Following the baseline design specifications, we have assumed a stochastic term in the hadronic response of $75\%/\sqrt{E}$ for the integrated hadron calorimeter, and $90\%/\sqrt{E}$ for the hybrid device; note that the latter can be improved without changing $\frac{e}{h}$ by introducing more frequent sampling with slightly smaller fibers. For both devices, we assumed $8\%/\sqrt{E}$ resolution in the EM section, plus a 1/2% constant term.

For the hybrid device, we follow Paar and Wigmans in determining the optimal (energy-independent) relative weights for the two sections of the calorimeter: $E_{cor} = (E_{1det}/(\frac{e}{h})_1) + E_{2det}$. For the integrated device, this weighting did not in fact minimize the width of the response function; instead, we formed a weighted sum which minimized the width of 1 TeV jets. This optimal weight varied slowly with energy, so we used constant weighting of $E_{cor} = (E_{1det} * 0.95) + E_{2det}$. In each case, the overall response was normalized for the weighted sum of 100 GeV jets ("test beam calibration").

Energy (GeV)	Hybrid Resolution(%)	Integrated Resolution (%)
50	6.26	5.56
100	4.99	4.45
200	3.65	3.43
500	2.51	2.91
1000	1.90	2.96
2000	1.48	2.82
5000	0.99	2.63
10000	0.91	2.90

Table 1: $\alpha = 4$ Jet Energy Resolution

2 Results

Tables 1 and 2 indicates the resolution obtained for jets with the above procedure. Figure 3 conveys the same information as the tables. Note that the above resolution will add in quadrature with constant term contributions from other effects, such as the jet definition errors ("clustering algorithm") mentioned earlier.

Figure 4 and figure 5 give scatterplots of the EM calorimeter response *vs* the EM + hadronic response for the hybrid and intregrated calorimeters, respectively, to 100, 500, 1000 and 5000 GeV jets with α=4. The $\alpha = 6$ plots are similar. As discussed in the note by Paar and Wigmans, the compensated calorimeter in the hybrid causes its scatterplot to fall upon a single line which is independent of α.

Figures 6 - 9 ($\alpha = 4$) and 10 - 13 ($\alpha = 6$) illustrate the weighted response for the hybrid and integrated calorimeters to 50, 100, 200, 500, 1000, 2000, 5000, and 10000 GeV jets. These curves should be considered as a conservative upper limit of the system performance – we may be confident that neither device can do better than the curves illustrated. Once again, however, the hybrid is primarily limited by its stochastic resolution (which may be improved) while the integrated device is soon limited by its constant term (which is intrinsic to the choice of copper absorber and LAr or LKr).

Finally, we note the dependence of the linearity of response upon α in

Energy (GeV)	Hybrid Resolution(%)	Integrated Resolution (%)
50	6.30	5.17
100	5.15	4.34
200	3.62	3.31
500	2.55	2.79
1000	1.90	2.39
2000	1.35	2.21
5000	0.98	2.04
10000	0.72	2.05

Table 2: $\alpha = 6$ Jet Energy Resolution

Table 3. Both the magnitude of the nonlinearity and especially the extent of its dependence upon alpha are greater for the integrated device. Off-line correction for this nonlinearity is therefore much more reliable for the hybrid, and as noted earlier is independent of detailed knowledge of the jet fragmentation.

3 Conclusions

The integrated LAr or LKr calorimeter may be expected to have at least a 2-3% constant term in its jet energy resolution because of its grossly under-compensated Cu/LAr hadron calorimeter. With an initial advantage of a stochastic term of 75% for the integrated device (which has not been demonstrated) and 90% for the hybrid (demonstrated with our Baseline I prototype, and improvable in a straightforward manner) the cross-over point in resolution is approximately 300 GeV.

The GEM Letter of Intent reports the study of the decays $H \rightarrow l^+l^-jj$ for an 800 GeV Higgs and $Z' \rightarrow jj$ for a 1 TeV Z'. We note in passing that the isolation criterion used in the former study (< 5% of the total energy within between an R=0.7 and R=1.0 cone, for jets with $P_t > 50$ GeV in R=0.2) would be significantly compromised with a LAr hadron calorimeter operating at 10^{34} luminosity; this device would have of order 10 GeV pile-up noise within an R=0.7 cone, even with 100 ns shaping time. Considering only

Energy (GeV)	Hybrid Alpha=4	Hybrid Alpha=6	Integrated Alpha=4	Integrated Alpha=6
50	.9966	.9960	.9943	.9920
100	1.0000	1.0000	1.0000	1.0000
200	1.0095	1.0090	1.0074	1.0065
500	1.0168	1.0175	1.0201	1.0187
1000	1.0240	1.0240	1.0375	1.0282
2000	1.0285	1.0280	1.0489	1.0398
5000	1.0342	1.0350	1.0616	1.0530
10000	1.0375	1.0380	1.0740	1.0634

Table 3: Jet Linearity vs. α

the signal and no backgrounds for the Z', the worsening of the resolution from 2.9% to 3.5% with a 2% additional constant term was deemed acceptable.

Figure 1

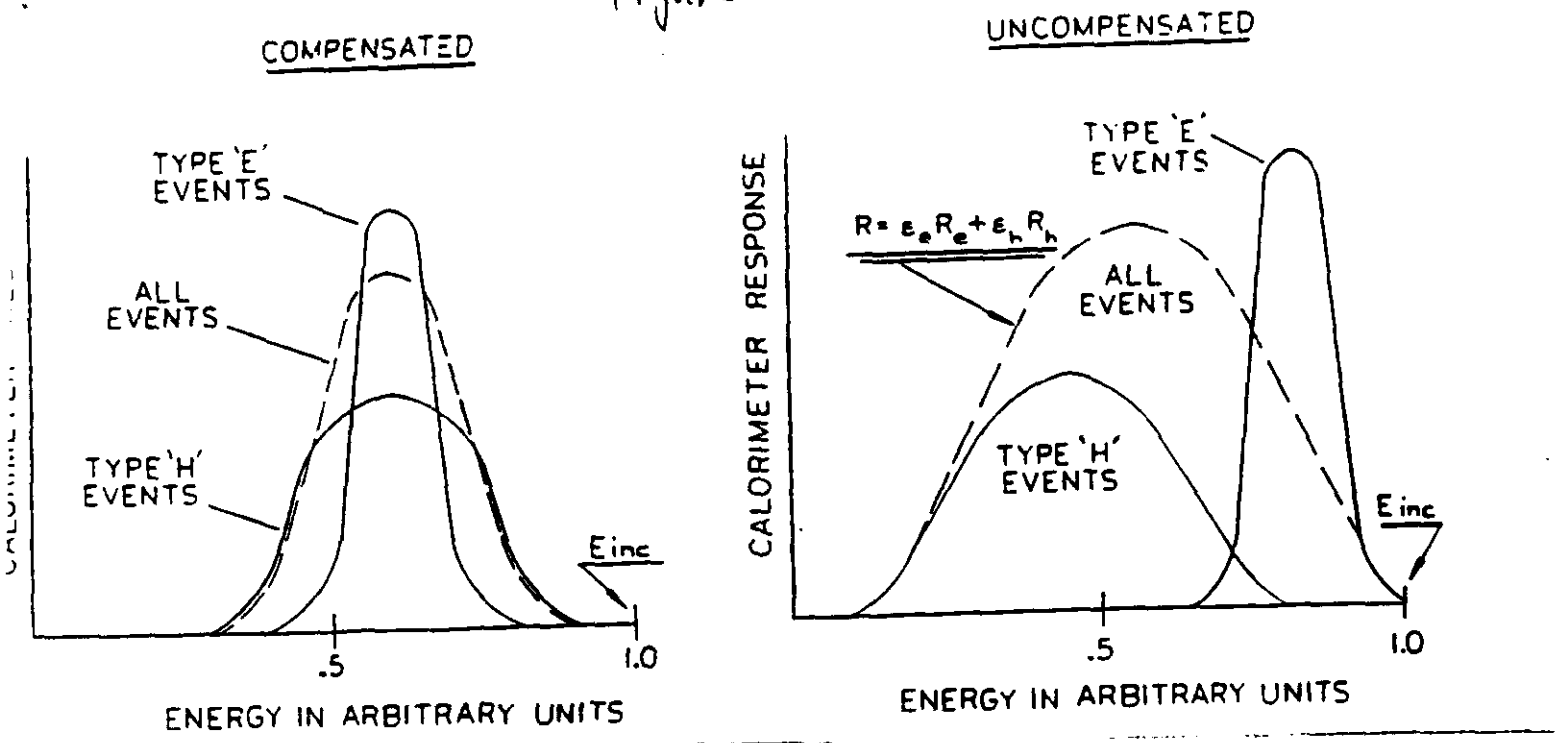
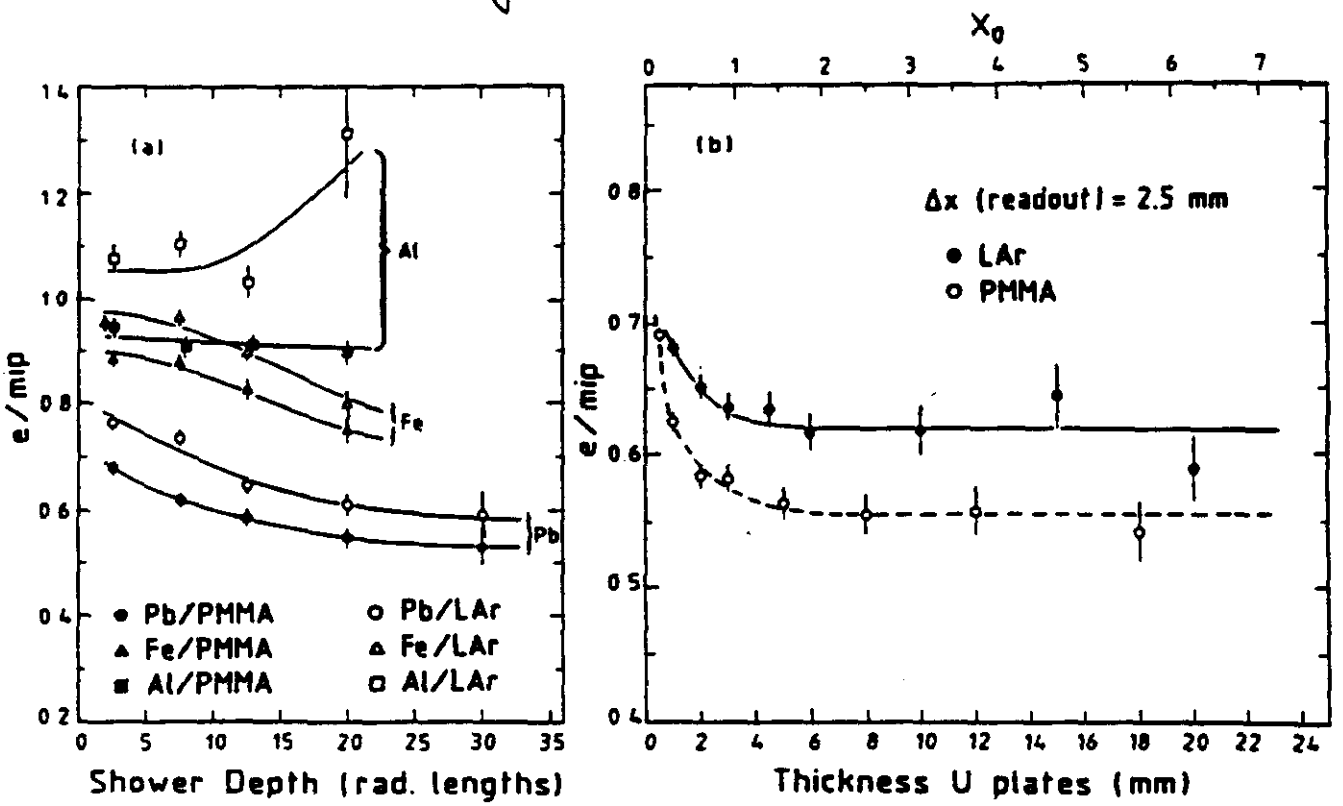


Figure 2



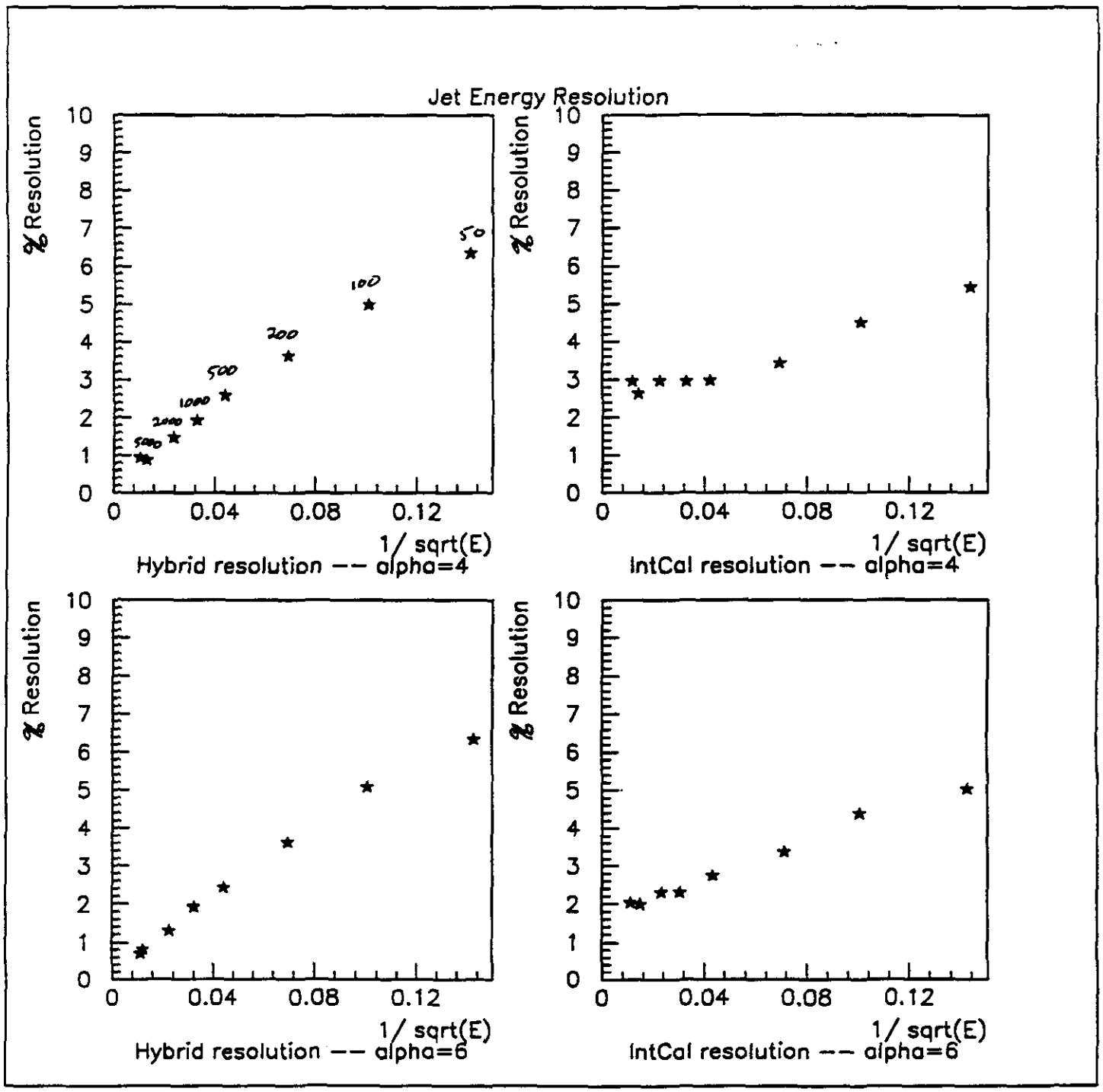

Jet Energy Resolution
% Resolution
1/ sqrt(E)
Hybrid resolution -- alpha=4
IntCal resolution -- alpha=4
Hybrid resolution -- alpha=6
IntCal resolution -- alpha=6
50
100
200
500
1000
2000
5000

Figure 3

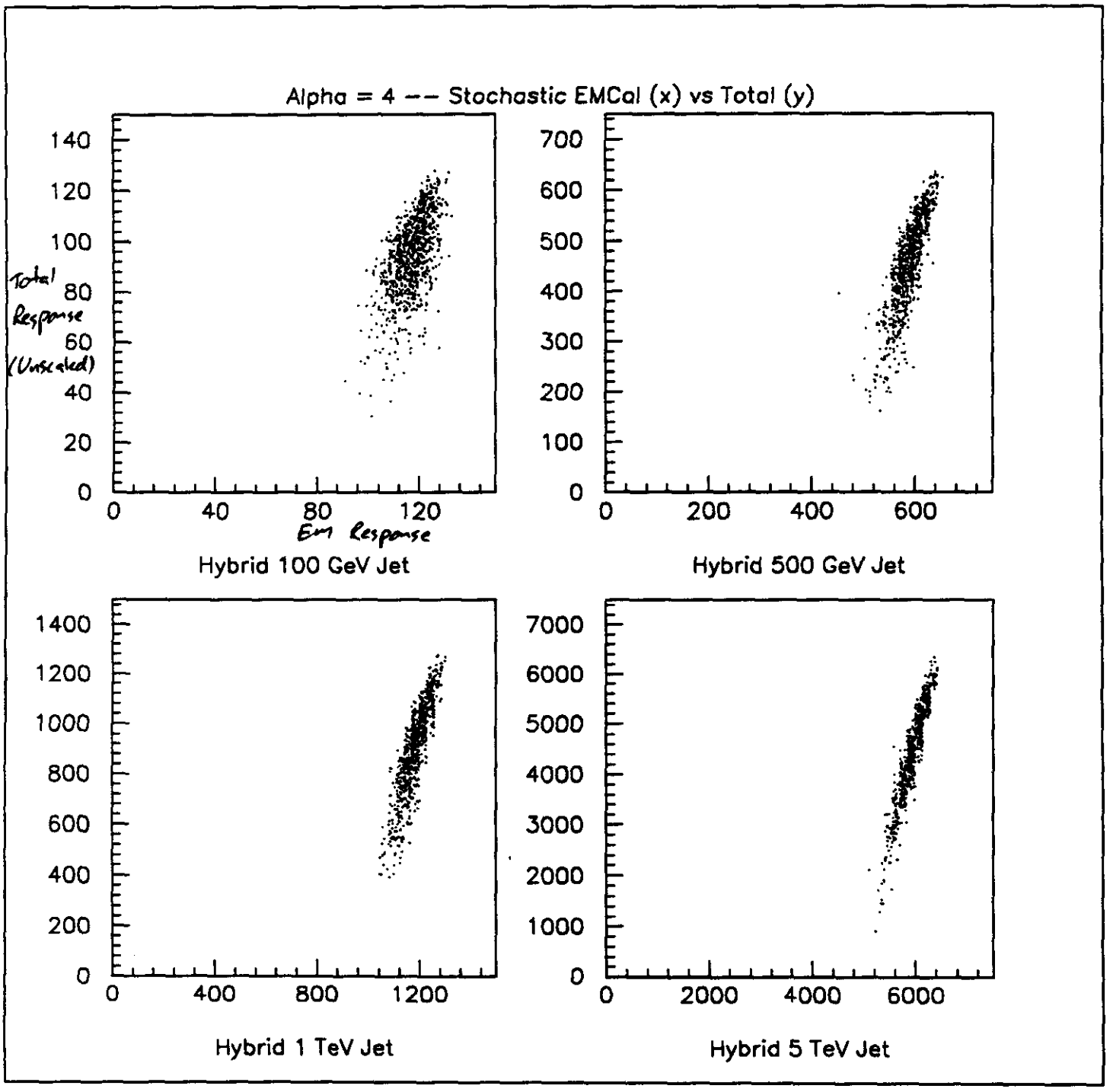

Alpha = 4 -- Stochastic EMCal (x) vs Total (y)
Total Response (Unscaled)
Em Response
Hybrid 100 GeV Jet
Hybrid 500 GeV Jet
Hybrid 1 TeV Jet
Hybrid 5 TeV Jet

Figure 4

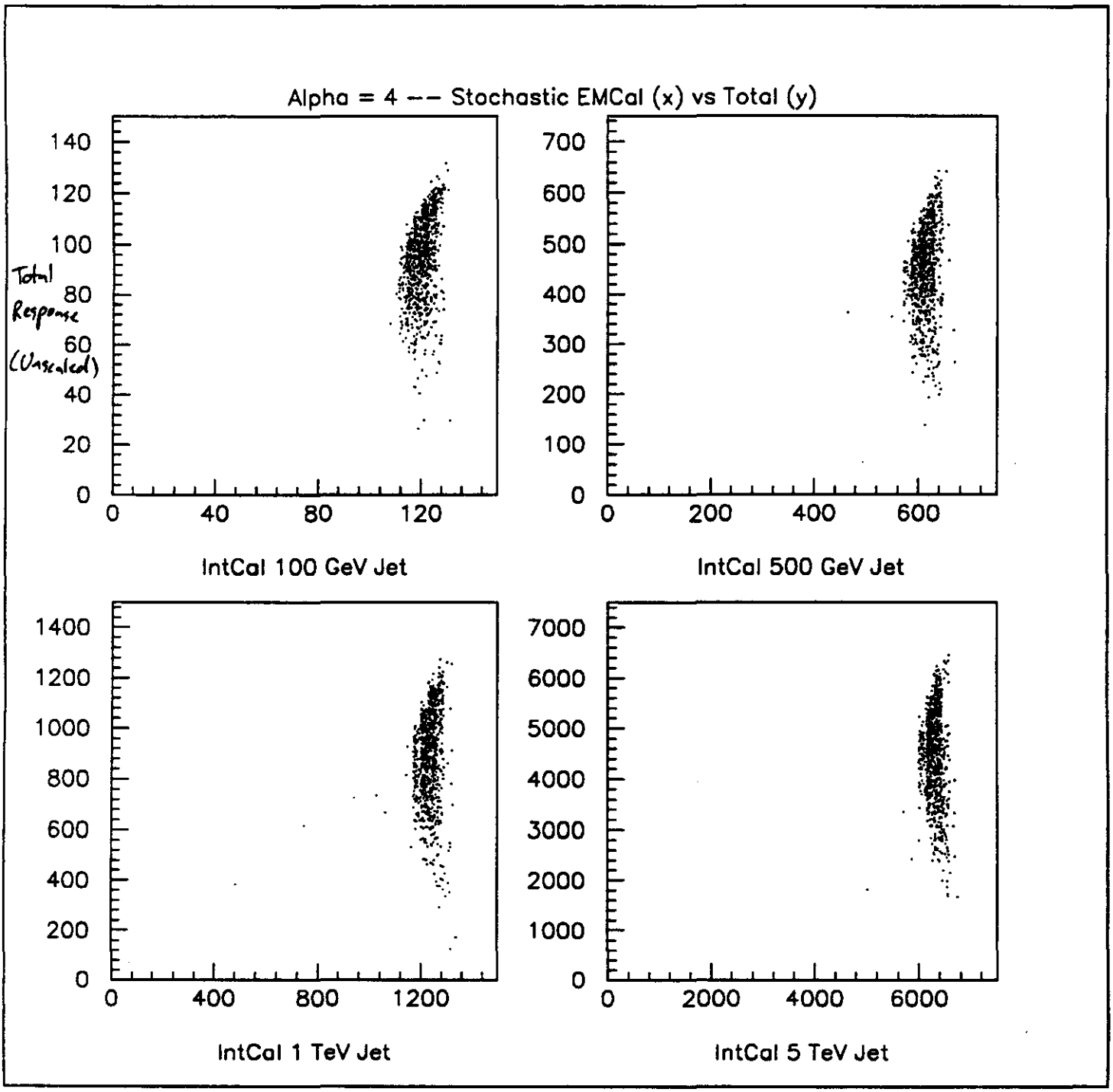

Alpha = 4 -- Stochastic EMCal (x) vs Total (y)
Total Response (Unscaled)
IntCal 100 GeV Jet
IntCal 500 GeV Jet
IntCal 1 TeV Jet
IntCal 5 TeV Jet

Figure 5

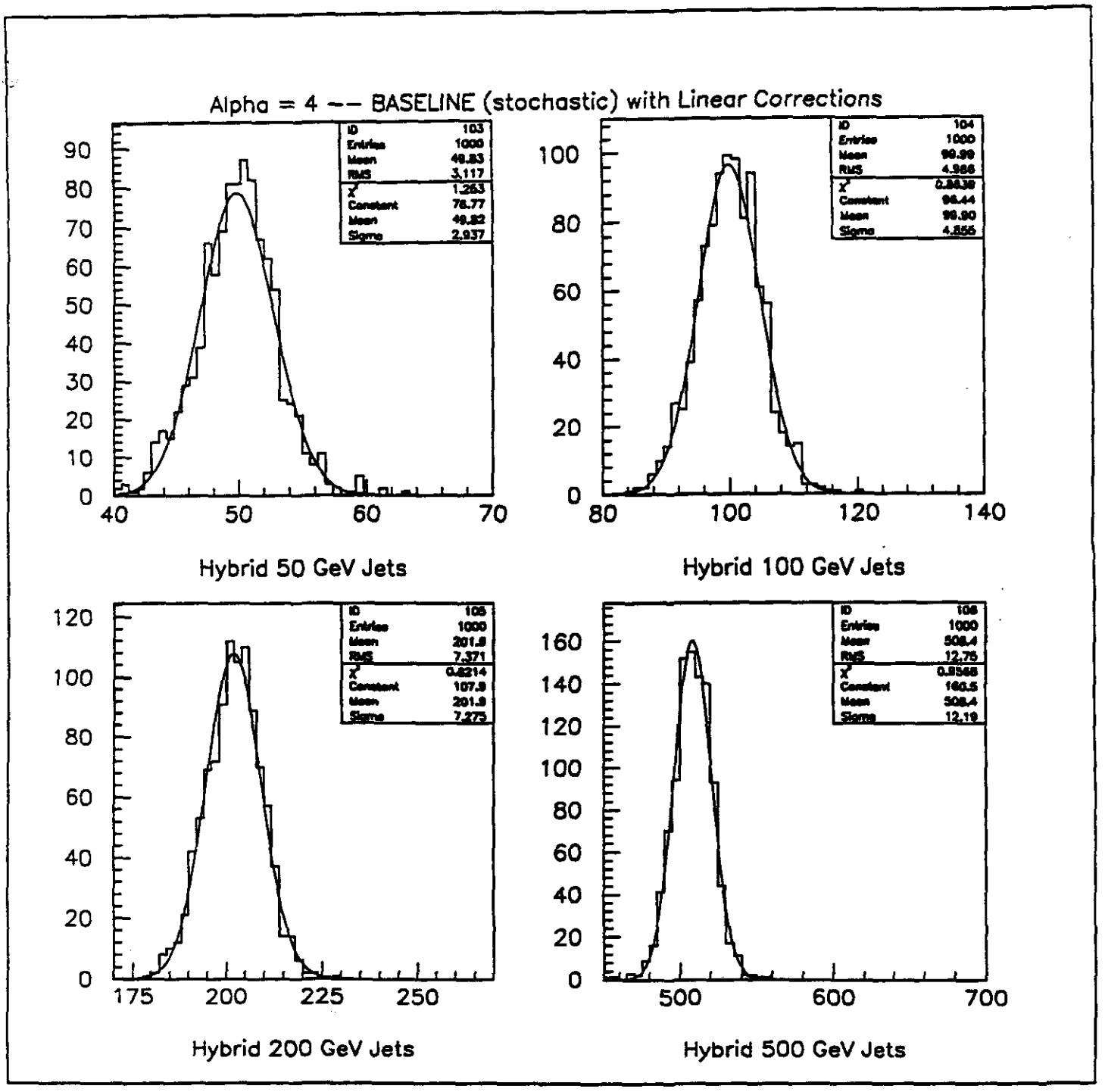

Alpha = 4 -- BASELINE (stochastic) with Linear Corrections
ID 103
Entries 1000
Mean 49.83
RMS 3.117
χ² 1.263
Constant 76.77
Mean 49.82
Sigma 2.937
Hybrid 50 GeV Jets
ID 104
Entries 1000
Mean 99.99
RMS 4.986
χ² 0.8839
Constant 96.44
Mean 99.90
Sigma 4.856
Hybrid 100 GeV Jets
ID 105
Entries 1000
Mean 201.9
RMS 7.371
χ² 0.8214
Constant 107.9
Mean 201.9
Sigma 7.275
Hybrid 200 GeV Jets
ID 106
Entries 1000
Mean 508.4
RMS 12.75
χ² 0.8566
Constant 160.5
Mean 508.4
Sigma 12.19
Hybrid 500 GeV Jets

Figure 6

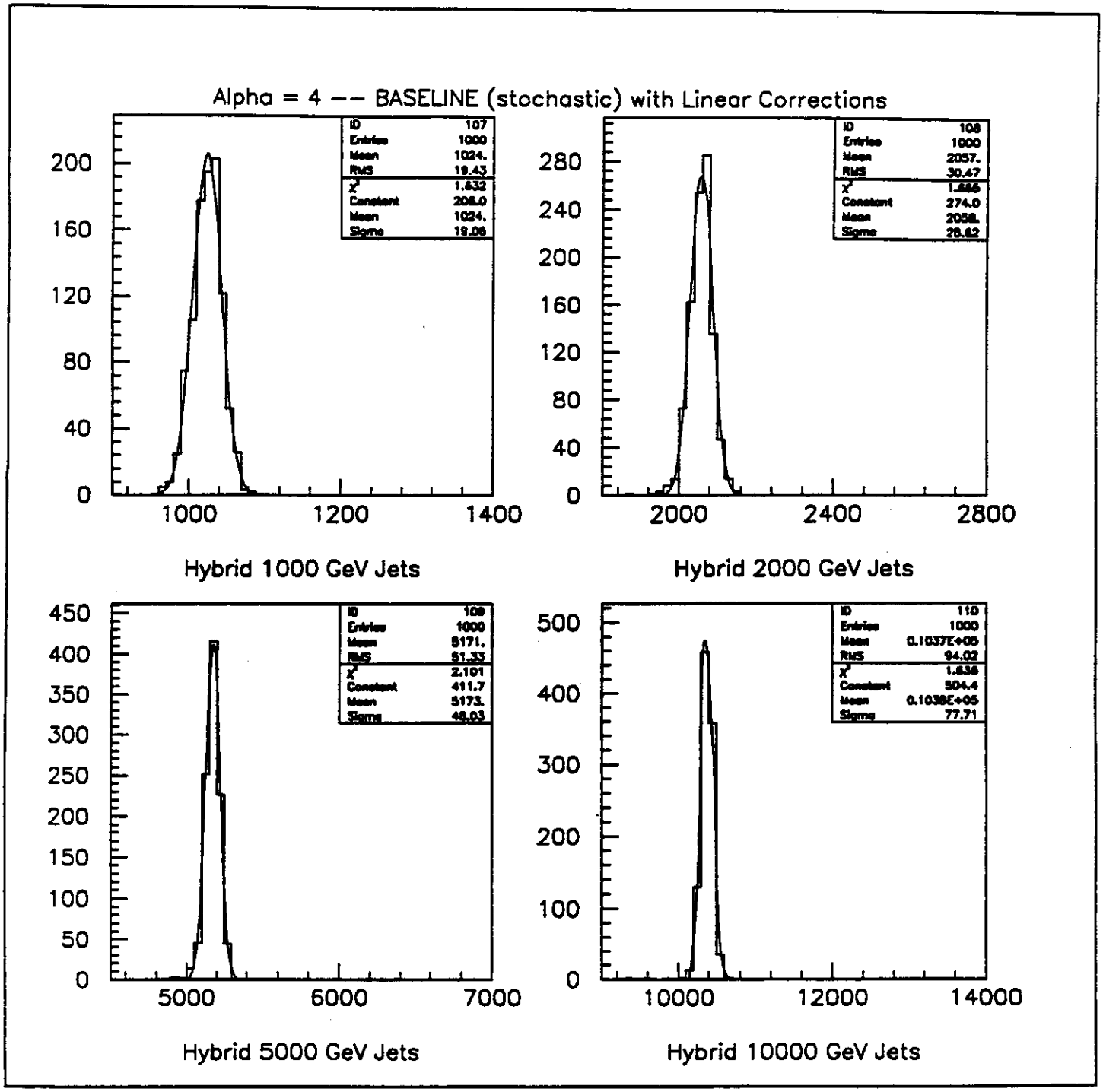

Alpha = 4 -- BASELINE (stochastic) with Linear Corrections
ID 107
Entries 1000
Mean 1024.
RMS 19.43
χ² 1.632
Constant 206.0
Mean 1024.
Sigma 19.06
Hybrid 1000 GeV Jets
ID 108
Entries 1000
Mean 2057.
RMS 30.47
χ² 1.686
Constant 274.0
Mean 2058.
Sigma 28.62
Hybrid 2000 GeV Jets
ID 109
Entries 1000
Mean 5171.
RMS 51.33
χ² 2.101
Constant 411.7
Mean 5173.
Sigma 48.03
Hybrid 5000 GeV Jets
ID 110
Entries 1000
Mean 0.1037E+05
RMS 94.02
χ² 1.636
Constant 504.4
Mean 0.1038E+05
Sigma 77.71
Hybrid 10000 GeV Jets

Figure 7

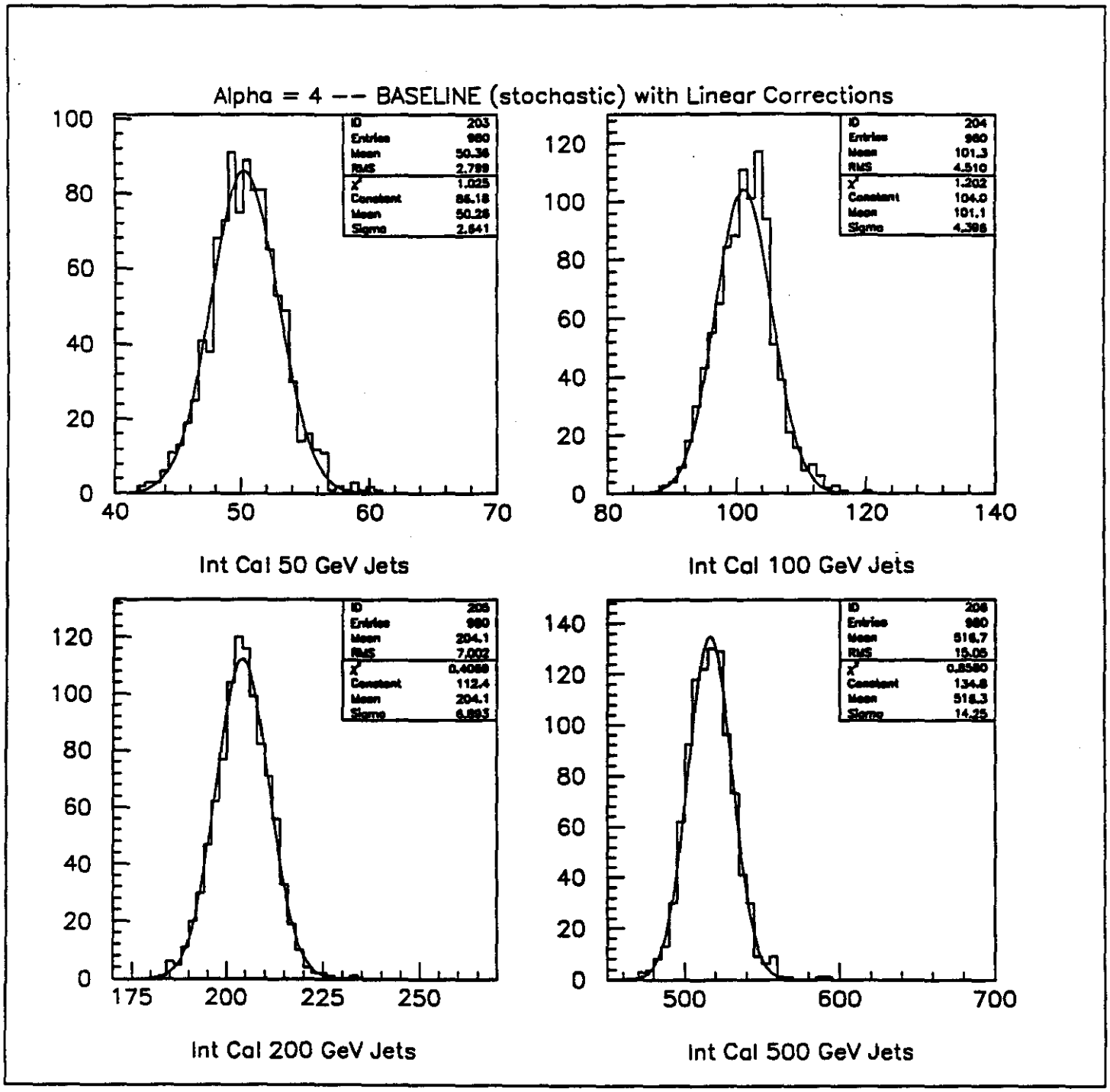

Alpha = 4 -- BASELINE (stochastic) with Linear Corrections
ID 203
Entries 980
Mean 50.36
RMS 2.799
χ² 1.025
Constant 86.18
Mean 50.26
Sigma 2.641
Int Cal 50 GeV Jets
ID 204
Entries 980
Mean 101.3
RMS 4.510
χ² 1.202
Constant 104.0
Mean 101.1
Sigma 4.398
Int Cal 100 GeV Jets
ID 205
Entries 980
Mean 204.1
RMS 7.002
χ² 0.4089
Constant 112.4
Mean 204.1
Sigma 6.893
Int Cal 200 GeV Jets
ID 206
Entries 980
Mean 516.7
RMS 15.05
χ² 0.8580
Constant 134.8
Mean 516.3
Sigma 14.25
Int Cal 500 GeV Jets

Figure 8

.05

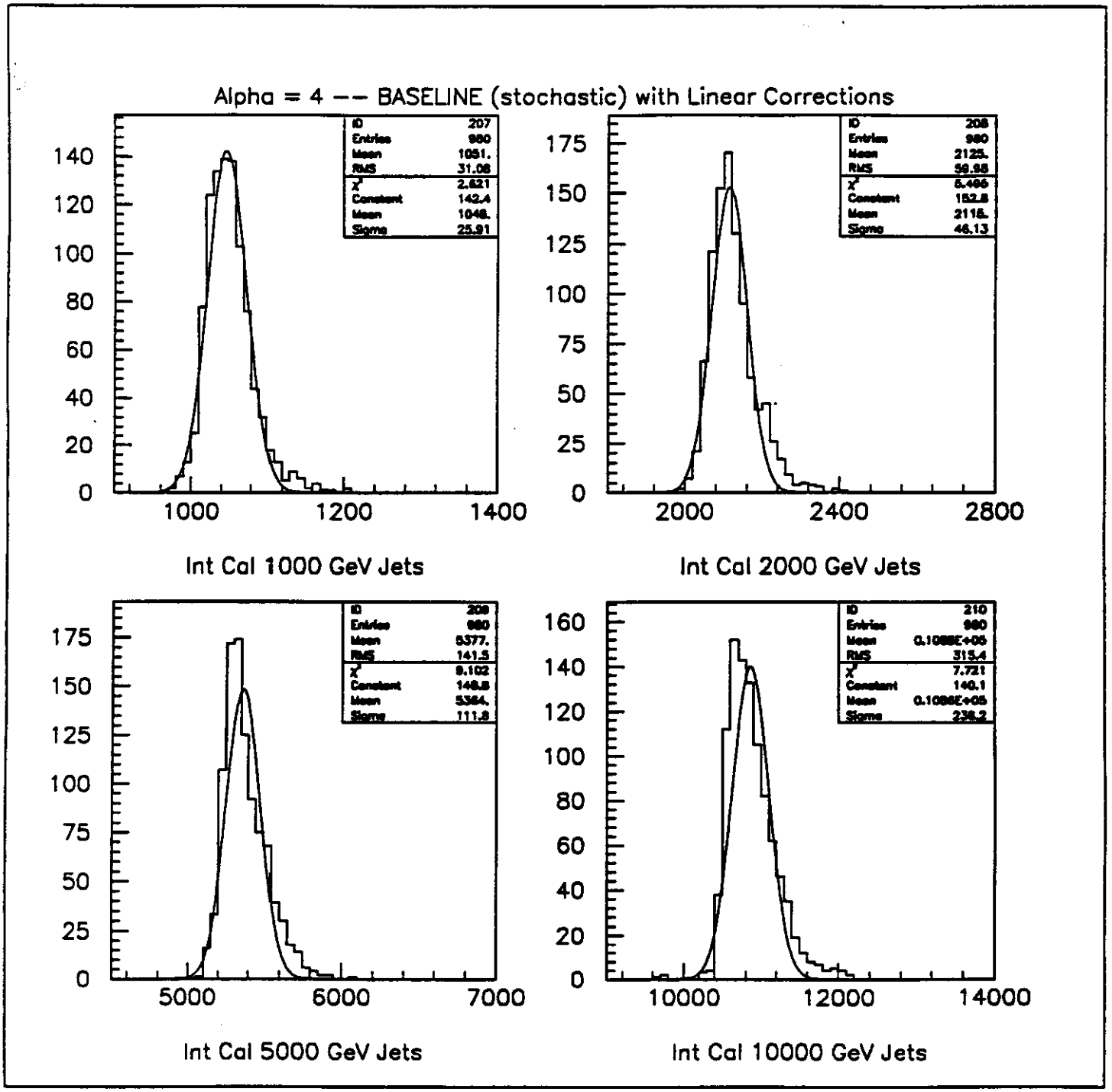

Alpha = 4 -- BASELINE (stochastic) with Linear Corrections
ID 207
Entries 980
Mean 1051.
RMS 31.08
χ² 2.621
Constant 142.4
Mean 1048.
Sigma 25.91
Int Cal 1000 GeV Jets
ID 208
Entries 980
Mean 2125.
RMS 59.98
χ² 5.496
Constant 152.8
Mean 2118.
Sigma 46.13
Int Cal 2000 GeV Jets
ID 209
Entries 980
Mean 5377.
RMS 141.5
χ² 9.102
Constant 148.8
Mean 5364.
Sigma 111.8
Int Cal 5000 GeV Jets
ID 210
Entries 980
Mean 0.1088E+05
RMS 315.4
χ² 7.721
Constant 140.1
Mean 0.1088E+05
Sigma 238.2
Int Cal 10000 GeV Jets

Figure 9

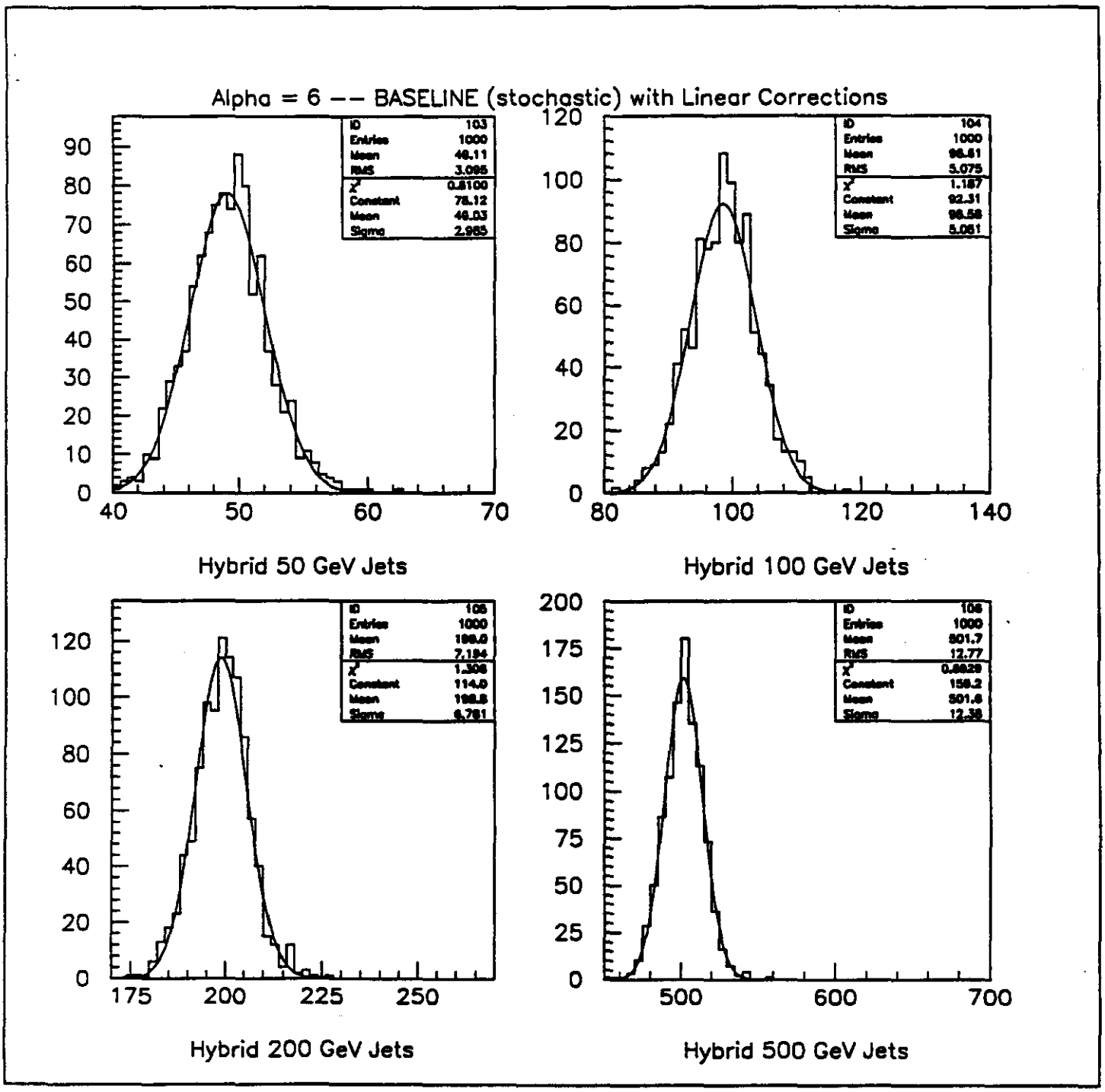

Alpha = 6 -- BASELINE (stochastic) with Linear Corrections
ID 103
Entries 1000
Mean 46.11
RMS 3.095
χ² 0.8100
Constant 78.12
Mean 46.03
Sigma 2.985
Hybrid 50 GeV Jets
ID 104
Entries 1000
Mean 98.61
RMS 5.075
χ² 1.187
Constant 92.31
Mean 98.56
Sigma 5.061
Hybrid 100 GeV Jets
ID 105
Entries 1000
Mean 199.0
RMS 7.194
χ² 1.306
Constant 114.0
Mean 198.8
Sigma 6.781
Hybrid 200 GeV Jets
ID 106
Entries 1000
Mean 501.7
RMS 12.77
χ² 0.8629
Constant 156.2
Mean 501.6
Sigma 12.38
Hybrid 500 GeV Jets

Figure 10

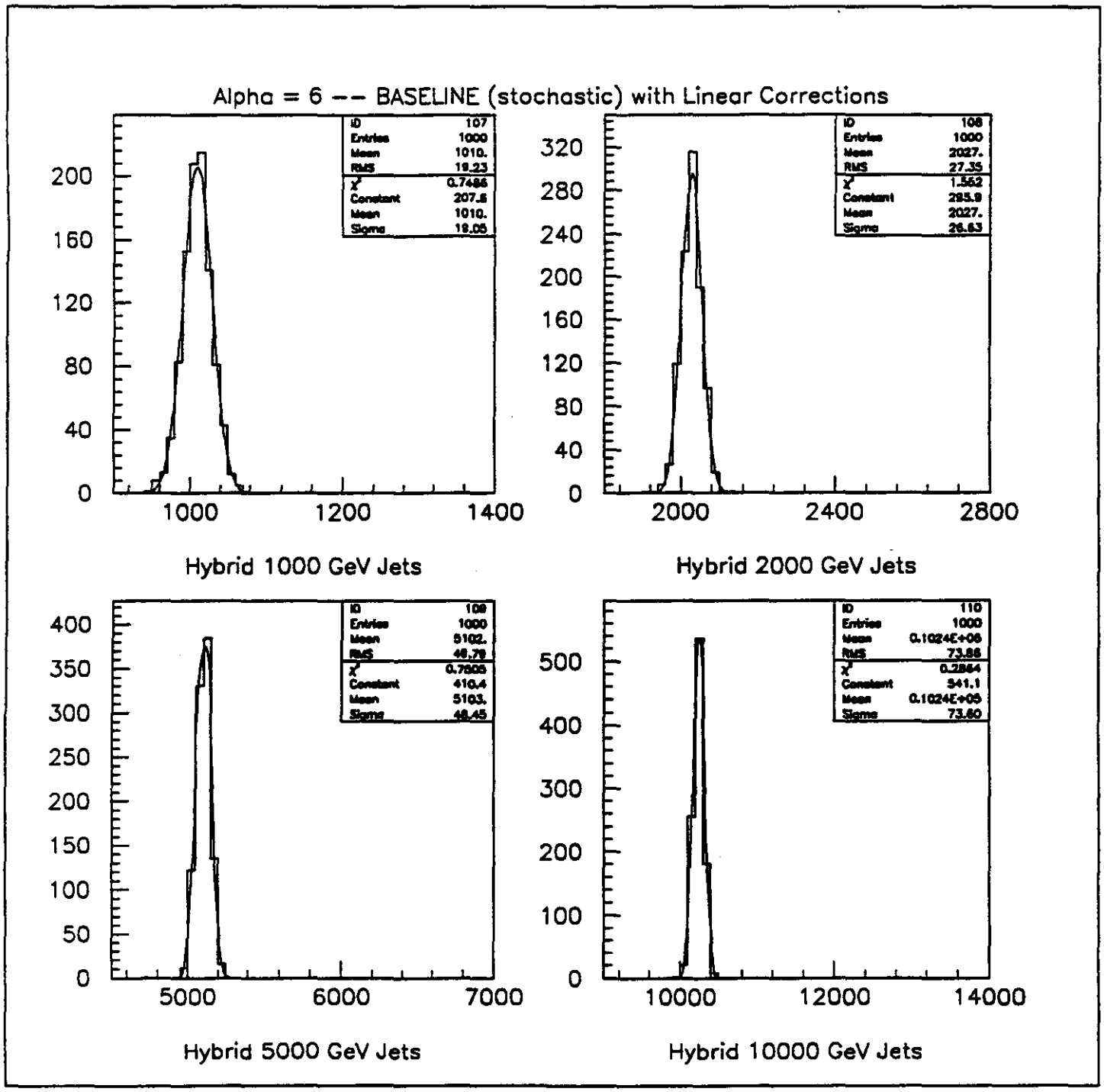

Alpha = 6 -- BASELINE (stochastic) with Linear Corrections
ID 107
Entries 1000
Mean 1010.
RMS 19.23
χ² 0.7486
Constant 207.6
Mean 1010.
Sigma 19.05
Hybrid 1000 GeV Jets
ID 108
Entries 1000
Mean 2027.
RMS 27.35
χ² 1.562
Constant 293.9
Mean 2027.
Sigma 26.63
Hybrid 2000 GeV Jets
ID 109
Entries 1000
Mean 5102.
RMS 48.79
χ² 0.7605
Constant 410.4
Mean 5103.
Sigma 48.45
Hybrid 5000 GeV Jets
ID 110
Entries 1000
Mean 0.1024E+05
RMS 73.86
χ² 0.2864
Constant 541.1
Mean 0.1024E+05
Sigma 73.60
Hybrid 10000 GeV Jets

Figure 11

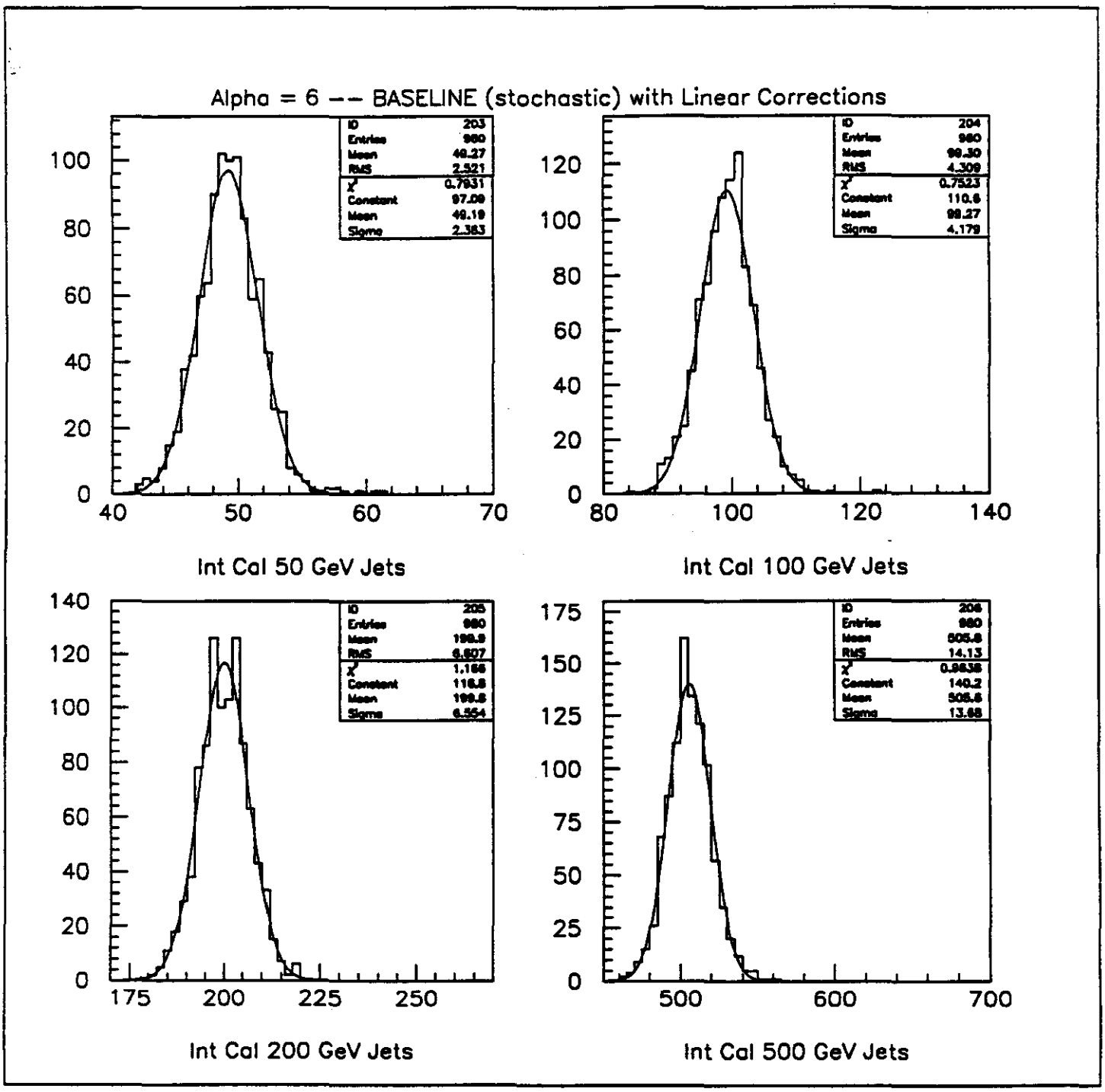

Alpha = 6 -- BASELINE (stochastic) with Linear Corrections
ID 203
Entries 980
Mean 49.27
RMS 2.521
χ² 0.7931
Constant 97.09
Mean 49.19
Sigma 2.383
Int Cal 50 GeV Jets
ID 204
Entries 980
Mean 99.30
RMS 4.309
χ² 0.7523
Constant 110.6
Mean 98.27
Sigma 4.179
Int Cal 100 GeV Jets
ID 205
Entries 980
Mean 199.9
RMS 6.607
χ² 1.166
Constant 116.8
Mean 199.8
Sigma 6.554
Int Cal 200 GeV Jets
ID 206
Entries 980
Mean 505.8
RMS 14.13
χ² 0.9838
Constant 140.2
Mean 505.6
Sigma 13.88
Int Cal 500 GeV Jets

Figure 12

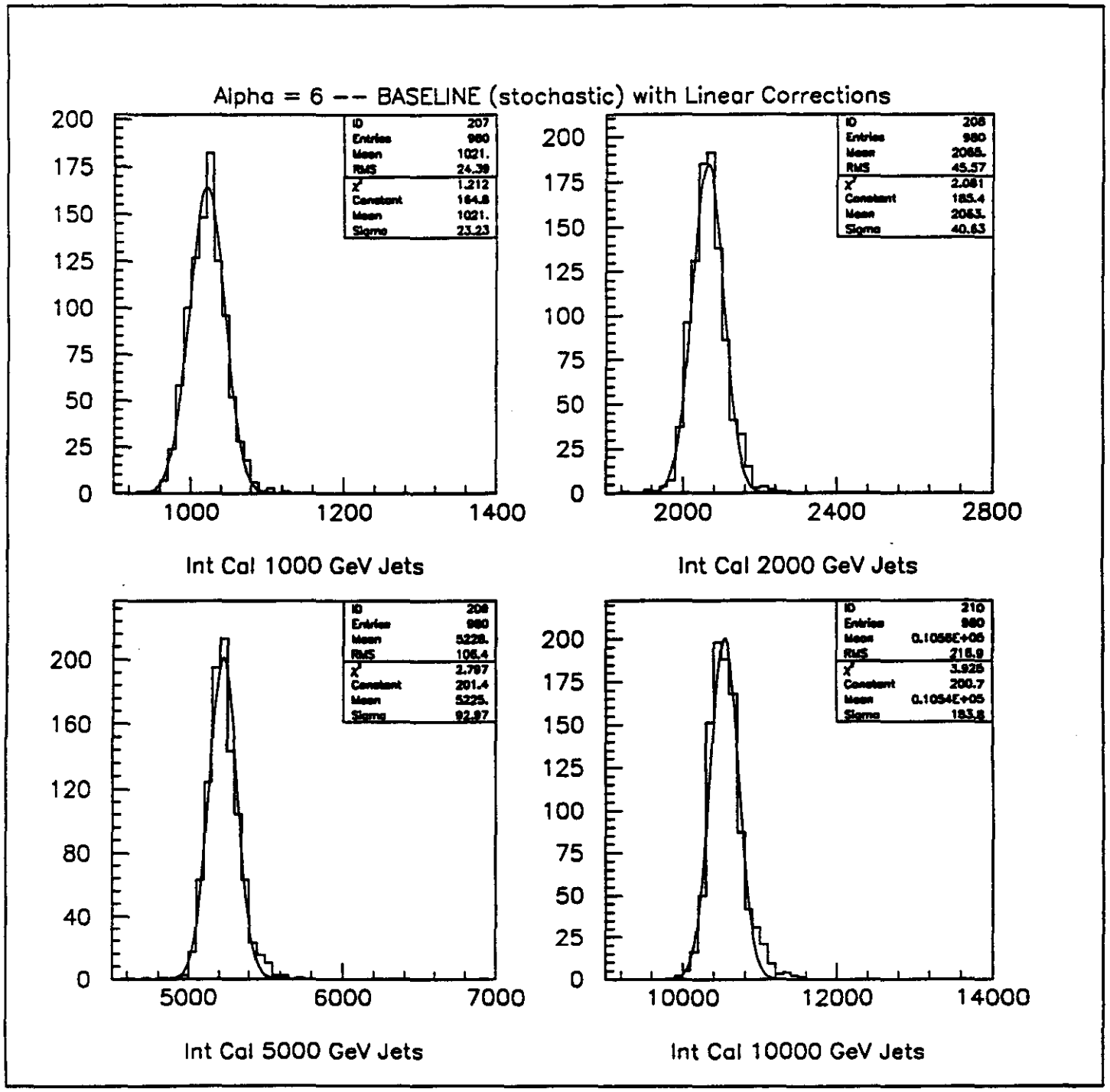

Alpha = 6 -- BASELINE (stochastic) with Linear Corrections
ID 207
Entries 980
Mean 1021.
RMS 24.39
χ² 1.212
Constant 164.8
Mean 1021.
Sigma 23.23
Int Cal 1000 GeV Jets
ID 208
Entries 980
Mean 2065.
RMS 45.57
χ² 2.081
Constant 185.4
Mean 2063.
Sigma 40.63
Int Cal 2000 GeV Jets
ID 209
Entries 980
Mean 5228.
RMS 106.4
χ² 2.787
Constant 201.4
Mean 5225.
Sigma 92.97
Int Cal 5000 GeV Jets
ID 210
Entries 980
Mean 0.1058E+05
RMS 216.9
χ² 3.925
Constant 200.7
Mean 0.1054E+05
Sigma 183.8
Int Cal 10000 GeV Jets

Figure 13