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SOLENOIDAL DETECTOR NOTES

COMPARISON OF MUON MOMENTUM RESOLUTION FOR THE SOLENOIDAL DETECTOR VERSUS MUON MOMENTUM RESOLUTION FOR EXTERNAL-ONLY MUON SYSTEMS

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Comparison of Muon Momentum Resolution for the Solenoidal Detector Versus Muon Momentum Resolution for External-Only Muon Systems

I became intrigued with comparing the ability of the Solenoid Detector to measure the momentum of muons with that of an external-only muon momentum type detector, such as e.g. EMPACT or L*. I wrote a simple Monte Carlo program to simulate the muon EM and hadron dE/dX loss energy deposition in traversing the EM and hadron calorimeter, then making an external momentum measurement on the muon after exiting the calorimeter. I allowed the same intrinsic momentum resolution for the external muon system as for the overall muon momentum resolution for the Solenoid Detector for offline analysis, i.e. applying the beam constraint, using the silicon, central tracking chamber and barrel muon toroid system, dPt/Pt ~ 0.18*Pt (TeV/c).

The precision measurement of the momentum (and charge sign) of muons in a solenoidal magnetic field and especially before traversing appreciable amounts of detector material (e.g. the calorimeter) has significant advantages to the method of external-only muon momentum measurement. It is a straightforward argument to demonstrate that the OPTIMUM mass resolution for any particle state, e.g. W or Z0 which has muons in the final state is achieved by measuring the muon momentum with high precision BEFORE traversing substantial amounts of detector material, rather than by measuring the muon momentum with the same, or even more precise momentum resolution AFTER traversing the same detector material. This is simply due to the fact that in the latter scheme, the overall muon momentum resolution, even for infinitely precise post-material measurement of the muon momentum is dominated by the ability to precisely correct back for the effects of traversing the detector material (the calorimeter) upstream of the muon momentum measurment. This is due to the effect of event-by-event FLUCTUATIONS in the total dE/dX energy loss of the muon in traversing the detector material (from multiple coulomb scattering and for high-Pt muons, QED external radiative effects). The initial muon momentum Pt_i is related to the externally measured muon momentum Pt_e by:

$$Pt_i = Pt_e + Eem + Ehad$$

Where Eem, Ehad are the true (not observed/measured) dE/dX muon energy loss depositions in the EM and hadron calorimeter towers. The overall muon momentum resolution in this latter scheme is given by:

$$Sigma_Pt_i = Sigma_Pt_e \ (+)\ Sigma_EM \ (+)\ Sigma_Had$$

Where Sigma_Pt_e = Kp*(Pt_e**2) is the intrinsic momentum resolution associated with the external (only) measurement of the muon's momentum AFTER exiting the EM + hadron calorimeter; Sigma_EM and Sigma_Had are the sigmas associated with the intrinsic fluctuations on the mean muon dE/dX loss energy depositions, <EM> and <Had> in the EM and hadron calorimeters, respectively. If a constant correction to the observed/ muon Pt (as measured in the external muon system (e.g. an air-core barrel toroid) is applied to infer the initial muon momentum, i.e. BEFORE entering the calorimeter:

$$Measured\ Pt_i = Pt_e + \langle EM\rangle + \langle Had\rangle$$

Then the muon momentum resolution for the scheme of external muon

momentum measurement IS in fact (on the surface) competitive (in the mean) with the muon momentum resolution as measured using a solenoidal magnetic field and central tracking chamber, if the intrinsic muon momentum resolutions of the external and internal muon systems are the same. One might worry here about tails of the energy loss distribution in using this method. However, one can make cuts on the OBSERVED EM and hadron muon dE/dX loss energy depositions to regulate these fluctations to some degree. However, making cuts on the energy deposition in the EM and hadron towers associated with the muon has significant complications - e.g. associated with energy resolution smearing effects, luminosity-dependent AND muon Pt-dependent EM and hadron energy deposition contributions from the underlying event and/or near-by jets in the event and collinear radiation accompanying the muon (see below). Note that in order to accurately determine the momentum scale in this method, it is extremely important that these mean corrections <EM> and <Had> to the muon's observed momentum be extremely well-understood, not only as a function of muon Pt, but also e.g. as a function of where the muons go in eta and phi, through different portions of the detector, and also be extremely well-understood in terms of the other physical effects just discussed. Controlling systematics associated with the muon momentum scale for external-only muon momentum measurement will require a very significant amount of effort if e.g. precision measurements of particle masses are to be extracted from the data.

Note also that if the OBSERVED EM and hadron muon dE/dX loss energy depositions are used to apply corrections to the externally measured muon Pt on an event-by-event basis, i.e.

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Measured Pt_i    = Pt_e + EM_obs + Had_obs
with:
Sigma_Pt_e/Pt_e = Kp*Pt_e
Sigma_Eem/Eem   = Kem/Sqrt(Eem)    (+) Kb_em
Sigma_Ehad/Ehad = Khad/Sqrt(Ehad)  (+) Kb_had
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then because the energy resolution of the EM and hadron calorimeters are typically rather poor at low energy, the use of this information actually (significantly) degrades the overall muon momentum resolution for external-only muon momentum measurement. The effect on the fractional momentum resolution is largest at low Pt, where the momentum measurement of the external muon system is also required to have extremely good momentum resolution for muon triggering purposes, precisely where the rate, and the backgrounds are the largest!

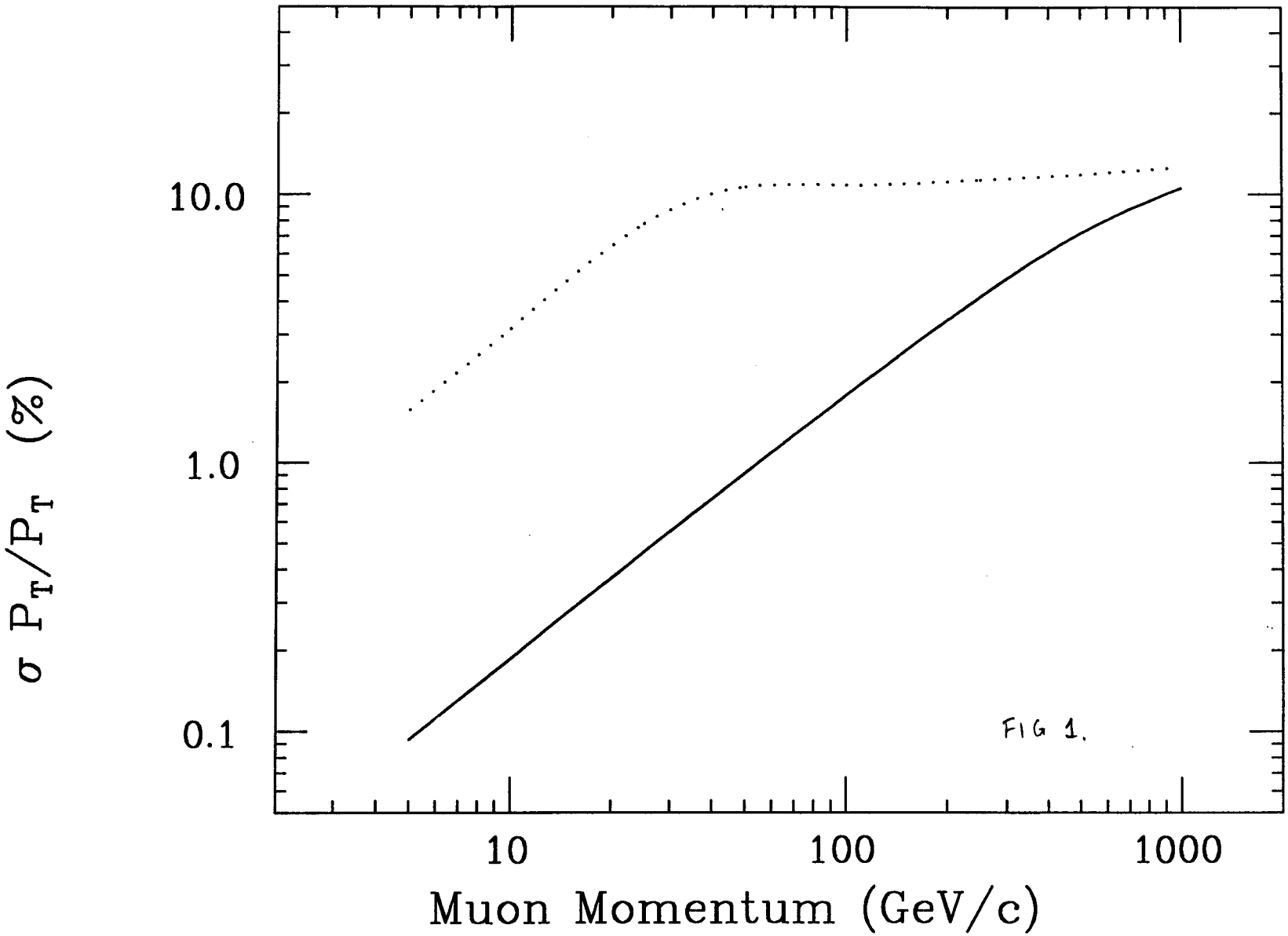
An additional consideration is that for precision measurements of e.g. particle masses, such as W and Z0 from W -> mu nu and Z0 -> mu+mu-, radiative corrections from inner bremsstrahlung at the 80-90 GeV/c2 mass scale affect the absolute determination of the mass at the ~0.1% and ~0.2% level, respectively for reasonable cuts on muon variables. Most of this (E1) radiation is (nearly) collinear with the muon leg, and the magnitude of this radiation can be considerable. Use of a solenoidal magnetic field to bend the high-Pt muon over a radius of ~ 2m, coupled with reasonable spatial resolution (1-2 mm) for showers in the EM calorimeter can actually separate the radiation from the muon at the radius of the EM calorimeter and help to distinguish internal radiation emitted in the decay of the high-mass particle to muon(s) from (external) muon interactions in the detector material. Quantitative and detailed understanding of internal radiative effects in the decays of W and Z0 is needed for obtaining precision measurements of both their masses AND widths at hadron colliders. If heavier gauge bosons, e.g. W' and Z' exist, the effects of inner bremsstrahlung on the mass determination of such particle states becomes even more important as their masses increase. For new particle states that may be discovered, which may have no sound theoretical prediction, a sound understanding of the effect of internal bremsstrahlung on the natural width/line shape will be crucial. Making explicit cuts on "minimum

ionizing" energy deposition in the EM and hadron calorimeters traversed by the muon(s) produced in the decay of such a massive parent particle dramatically affects the impact of the radiative corrections on the parent mass AND width determination. The ability to clearly decouple internal radiation from external muon bremsstrahlung in the calorimeter will help enormously in this matter, based on CDF experience.

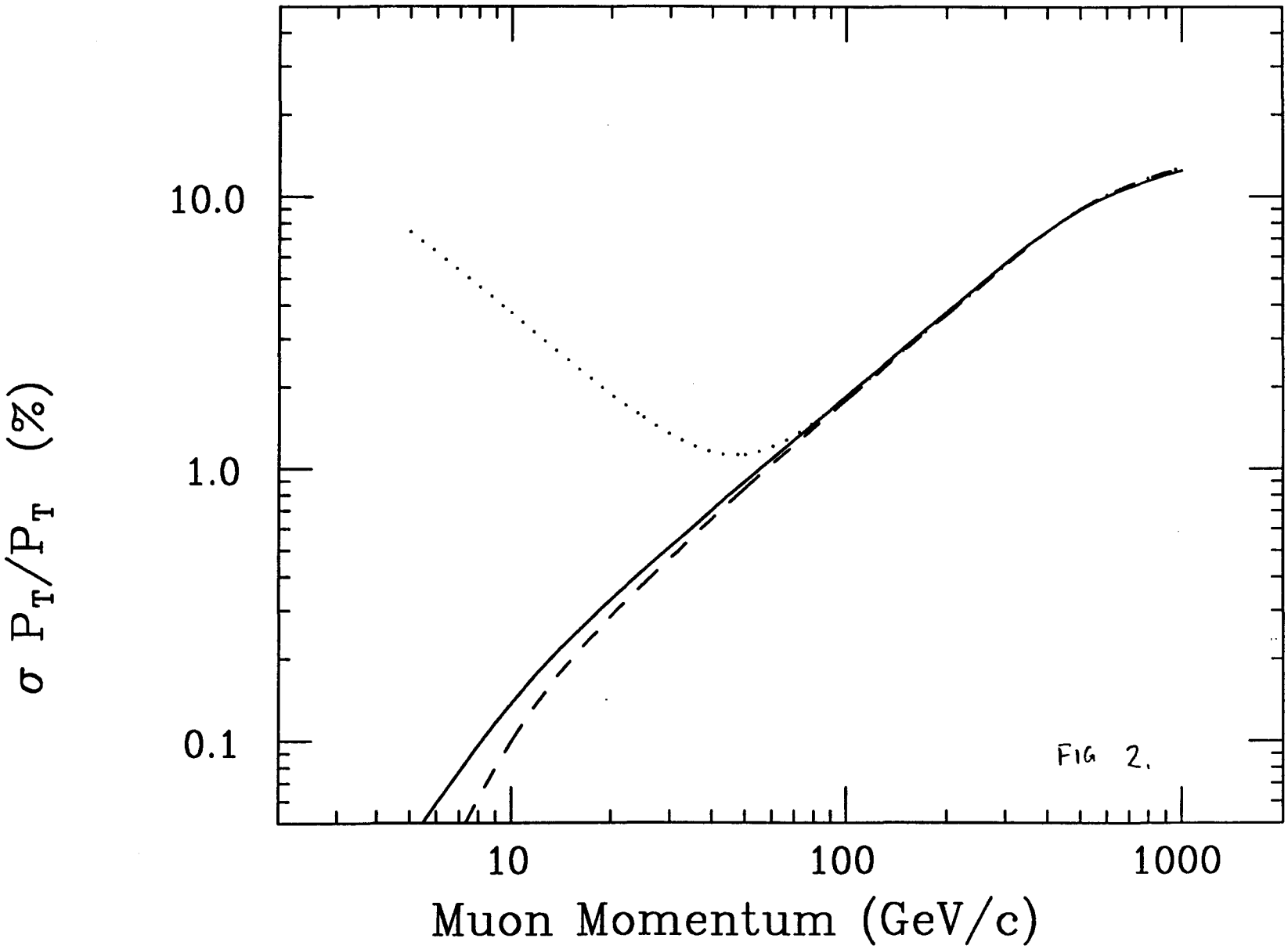
The following plots show the results comparing "Us vs. Them". The first figure is for the Solenoid Detector, for offline momentum resolution and the online momentum resolution at the trigger level, assuming that the last superlayer of the central tracking chamber is used in conjunction with the barrel muon toroid system. The constants for the momentum resolutions for these two cases were determined from studies done by Jim Wiss. The second figure is for an external-only muon system, such as e.g. EMPACT or L*, which shows the intrinsic momentum resolution for measuring the muon momentum AFTER exiting the calorimeter, as well as curves for constant correction for dE/dX energy loss by the muon (systematic uncertainties not included!!!) and for event-by-event corrections, which can be seen to actually destroy the external-only momentum resolution below Pt_mu ~ 50 GeV/c. The third figure is an overlay of the first and second figure. The fourth figure is actual muon data for EM and hadron energy deposition in the CDF calorimetry in the tower traversed by the muon, and the energy deposition in the 8 neighboring towers around the muon tower. The final set of figures shows some of the details associated with the Monte Carlo program used to simulate these effect and to obtain the results in the first three figures, for (initial) muon Pt = 100 GeV/c (one data point on the curves in figures 1-3).

It can be seen that the external-only muon momentum measurement on the surface, appears to be competitive with our method for the Solenoid Detector, if constant corrections for dE/dX muon energy loss in the EM and hadron calorimeters are applied to the observed muon momentum, to infer the original muon momentum. However we stress that the SYSTEMATICS on the external-only muon momentum measurement (and therefore the overall momentum scale, as well as e.g. the muon trigger efficiency vs. Pt, event reaction type, etc.) are likely to be significantly larger than for the Solenoid Detector. These aspects and details must be extremely well understood in order to determine which detector scheme, in the final analysis, actually is superior to the other. I am willing to "bet" that it is the Solenoid Detector, based on our experience at CDF.

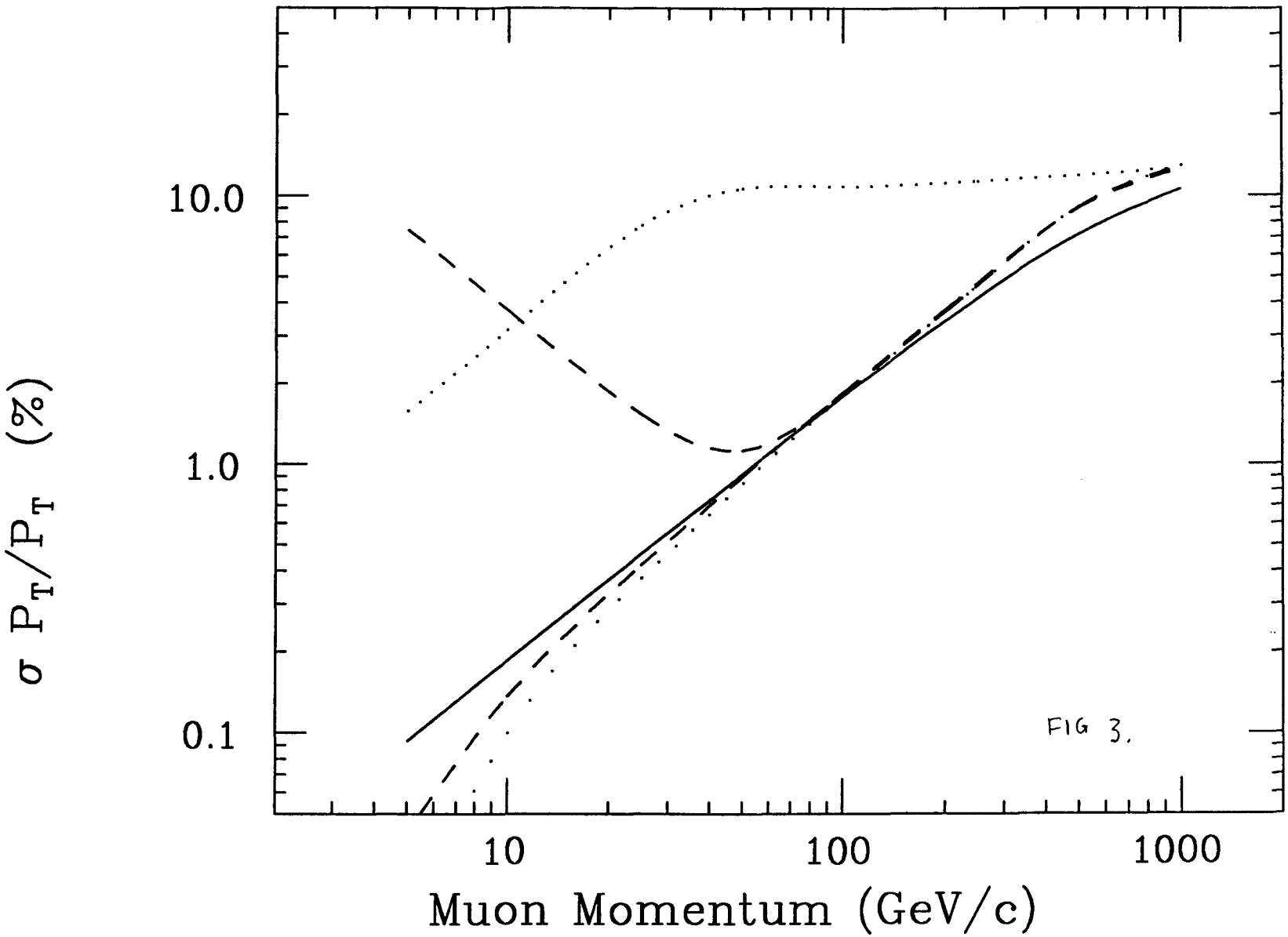
Solenoid Detector Muon P_T Resolution



EMPACT Detector Muon P_T Resolution



SSC Detector Muon P_T Resolution



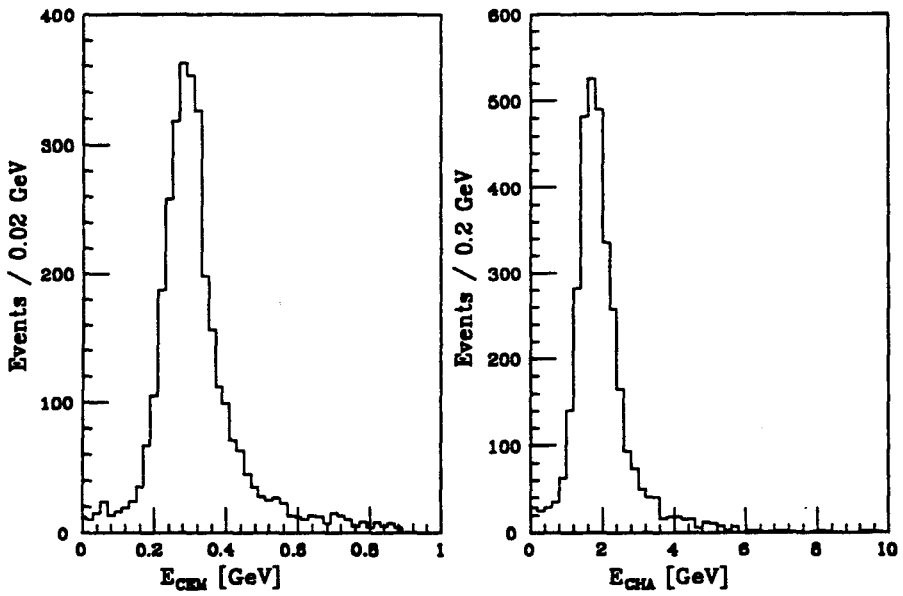


Figure 14: Energy deposition by 57 GeV/c testbeam muons in the central calorimeters.

FIG. 4.