The Backward Silicon Tracker and Deep Inelastic Scattering at H1

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Silicon detectors provide a high spatial resolution, so they are well suited for precise measurements of tracks from particles. The alignment and the calibration of the detectors are important for further studies, for example for the measurement of the structure functions of the proton in Deep Inelastic Scattering (DIS). The H1 experiment at the HERA accelerator is a great tool to study DIS. Different methods were employed to find potential sources of error in the two detectors used in this study, the Spaghetti Calorimeter (Spacal) and the Backward Silicon Tracker (BST).

1 Introduction

1.1 *Kinematics of Deep Inelastic Scattering (DIS)*

At high energies electrons can resolve the structure of protons because of the small de Broglie wavelength, i.e. deep within the proton. Because of these high energy the protons will be disrupted (hadronic final state) and that's why it is also called inelastic. One can see a lowest order Feynman graph in the following picture:

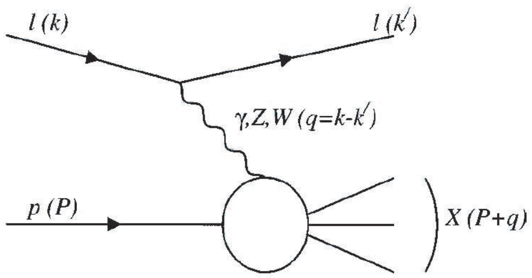

Fig. 1: *Deep Inelastic Scattering*

The kinematics of these events are described in the most convenient way by the following variables[1]:

$$
\begin{aligned}
s &= (k+P)^2 \\
Q^2 &= -q^2 = -(k-k')^2 > 0 \\
x &= \frac{Q^2}{2P\cdot q} \\
y &= \frac{q\cdot P}{k\cdot P}
\end{aligned}
$$

$\sqrt{s}$ is the center of mass energy.

Of course k (k')and P are the four momenta of the incoming (outgoing) electron and proton.

x is the fraction of the proton momentum taken by the parton which is hit by the exchanged boson.

y corresponds to the fraction of the lepton energy that was transmitted to the proton. Hence one calls it "inelasticity" variable.

Both variables x and y have a range between 0 and 1.

With these variables one gets the well known form for the DIS cross section for the inclusive reaction e + p → e + X. That means one has an outgoing electron and a hadronic final state which can be anything.

$$\frac{d^2\sigma}{dxdQ^2} = \kappa(F_2(x,Q^2) - f(y)F_L(x,Q^2)) \quad (1)$$

with

$$f(y) = \frac{y^2}{Y_+} \quad (2)$$

$$\kappa = \frac{2\pi\alpha^2 Y_+}{Q^4 x} \quad (3)$$

$$Y_+ = 2(1-y)+y^2 \quad (4)$$

The structure function F_2 is related to the quark content of the proton and the longitudinal structure function F_L is expected to be zero in first order for spin $\frac{1}{2}$ quarks.

1.2 Reconstruction of Kinematic Variables

The kinematics are determined by 2 quantities. One possible method for reconstructing the kinematic variables is the electron method. Next to the known momenta of the incoming protons and electrons one basically measures the energy and the scattering angle of the outgoing lepton to calculate the above mentioned kinematic variables x, y and Q^2. One also uses the following relations instead of calculating with four momenta:

$$Q^2 = 4E_e E'_e \cos^2\left(\frac{\theta_e}{2}\right) \quad (5)$$

$$y = 1 - \frac{E'_e}{E_e}\sin^2\left(\frac{\theta_e}{2}\right) \quad (6)$$

$$Q^2 = x \cdot y \cdot s \quad (7)$$

1.3 Structure Functions

So if one measures the cross section in x, y and Q^2 one has direct access to the structure functions. With the structure functions one is able to check predictions of the Standard Model. Formula (1) offers the possibility to measure the longitudinal structure function F_L using the "Rosenbluth separation"[2].

$$\sigma_r = F_2(x,Q^2) - f(y)\cdot F_L(x,Q^2) \quad (8)$$

$$f(y) = \frac{y^2}{2(1-y)+y^2} \quad (9)$$

At small y the influence of F_L is negligible and on gets F_2. Staying at fixed x and Q^2 one changes the value y by changing s (9)). At lower s the influence of F_L increases and the difference in σ_r corresponds to F_L.

The given definition (2) of $f(y)$ shows that it is zero for $y = 0$ and one for y=1. Hence one extrapolates σ_r to $f(y) = 0$ and $f(y) = 1$ and the difference of these two values will be F_L.

2 HERA

2.1 The H1 Detector

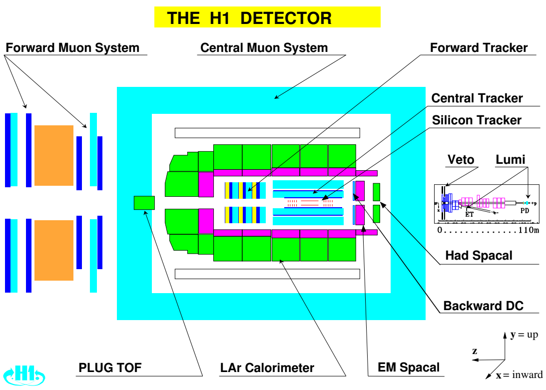

Fig. 2: *The H1 detector*

The Hadron-Electron-Ring-Anlage HERA in Hamburg has two 6.3 km long storage rings to accelerate protons up to 920 GeV and electrons up to 30 GeV (or positrons). With H1 (in the north hall) and ZEUS (in the south hall) it has two large detectors, which use HERA in its e-p colliding mode.

H1 was designed as a general purpose detector to study high-energy physics at HERA.

The most important parts of the detector for this study are the following. One has the Central Tracker close to the beam pipe to reconstruct the vertex coordinates. In the backward direction (see the H1 coordinate system) one finds the Backward Silicon Tracker (BST) which is designed to measure small scattering angles θ_e with high spatial resolution.

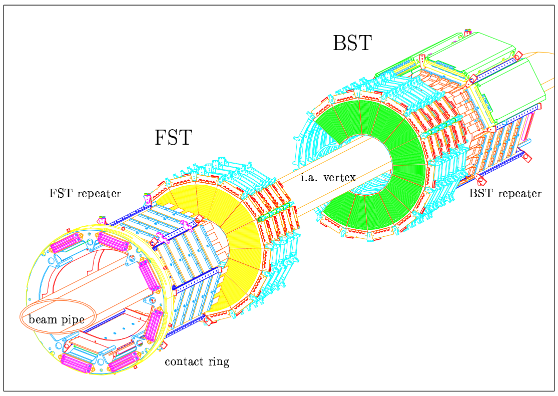

Fig. 3: *The Forward and Backward Silicon Tracker*

The so called Spaghetti Calorimeter (Spacal) is located behind the silicon detector, hence Spacal is a powerful tool to measure energy and space coordinates of particles that passed the silicon detector.

2.2 The H1 Coordinate System

The incoming proton direction is defined to be the positive z-axis and that's why the polar angle θ is measured with respect to this axis.

2.3 The Backward Silicon Tracker

Because of their good spatial resolution silicon detectors are very useful tools to measure tracks of charged particles. The operating principle is similar to a photo diode. One can see how it works schematically in the following picture.

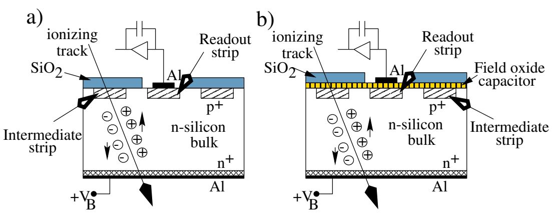

Fig. 4: *Detection principle*

Electron hole pairs are created by ionization and the charges are collected at their correspondent electrodes and the signal can be read out.

The BST, which will be the main object in the following sections, consists of 6 planes, each having two wheels the "u"- and "v"- coordinates. One needs these two wheels because each module measures the track in one spatial dimension (see fig. 5). So with two crossed wheels one gets a point in the x-y plane. Due to the 6 planes which are located from approximately -39 cm to -60 cm one is able to reconstruct a track going through the BST.

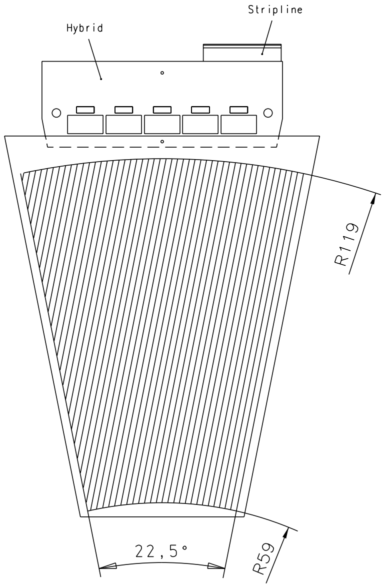

Fig. 5: *Single BST module*

The whole BST covers a range in Φ of only 270° because the beam pipe became elliptical with the HERA II setup. The range in θ is between 163° and 174°, which makes the BST predestined to measure electrons in DIS events at small deflection angles (corresponding to small Q^2). Its R range is from 6 cm to 12 cm (fig.5).

2.4 Analysis Tools

The H1 OO Analysis Environment [3] and the ROOT Framework [4] were used to evaluate MC (inclusive DIS with Djangoh Generator) and H1 Data from 2004 in the C++ language.

3 Alignment of the Spacal

An important task is to find quantitative information about the alignment of the subdetectors to each other.

One method is to select QED Compton events which means that one has detected an electron and a photon in the Spacal with approximately 180° difference in Φ. So $\cos(\Phi_1 - \Phi_2) < -0.9$ was required. Hence one assumes that both particles moved in opposite directions and one simply reconstructs this line in a 2-D histogram on the X-Y-plane. Lines of different events will intersect on the vertex position. The energy of both particles should be close to the beam energy of 27.5 GeV and due to that the selection $E = E_1 + E_2 > 25\,\mathrm{GeV}$ was made.

The result is shown in fig.6 and one sees an approximate misalignment of 0.25 cm in x and -0.2 cm in y.

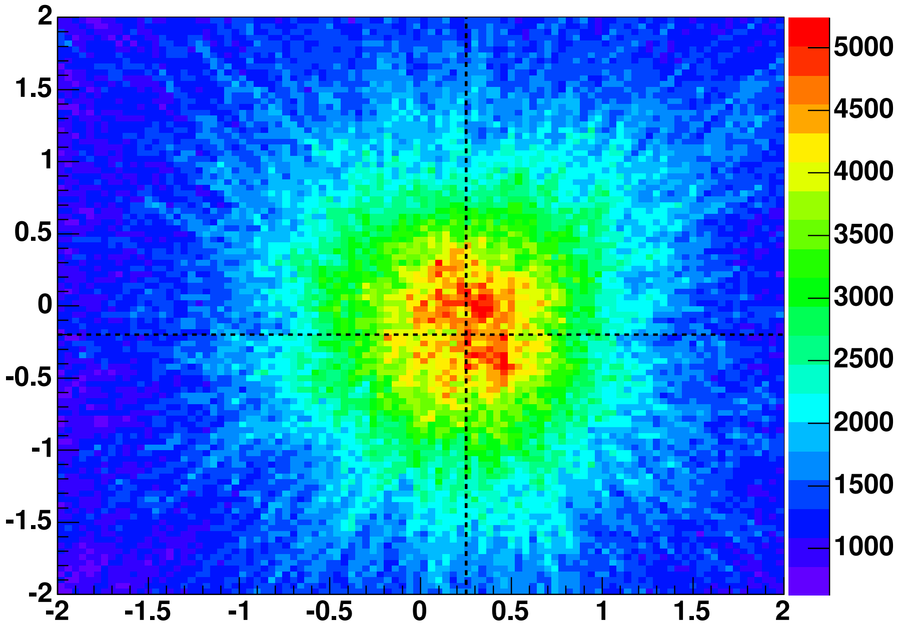

Fig. 6: *Misalignment in x-y plane, values in cm*

4 Measurements with the BST

4.1 Hit Efficiency of the BST

To find out how effective the reconstruction with the BST works, the above mentioned Spaghetti Calorimeter (Spacal) was used. A straight line approximation between vertex and cluster was used to calculate if a particle went through the BST or not. That's why high energy electrons with more than 15 GeV were selected. The events were required to have a central vertex between −30 cm and +30 cm and the error in the z-vertex was required to be smaller than 2 cm.

In the following figures one sees the efficiency of chosen example modules (like fig. 5). For the whole BST with 12 discs with each 12 sectors in Φ one gets 144 diagrams which provide detailed efficiency information in R-Φ plane. One finds as expected very efficient results for MC. The ratio of measured and expected hits is everywhere very close to 1.

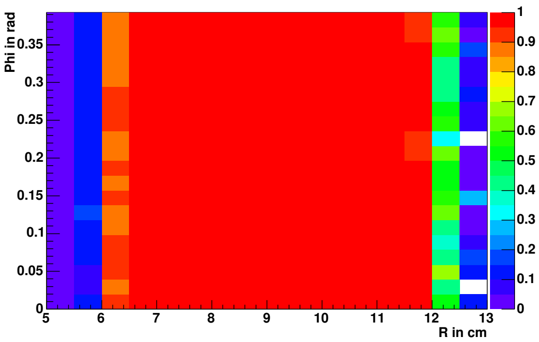

Fig. 7: *Example of a well working module for Monte Carlo*

The results for Data are different. One finds now modules which were working well and also some modules not working on the whole active area. The efficiency of well working modules is between 0.7 and 0.9 in the central region of the module.

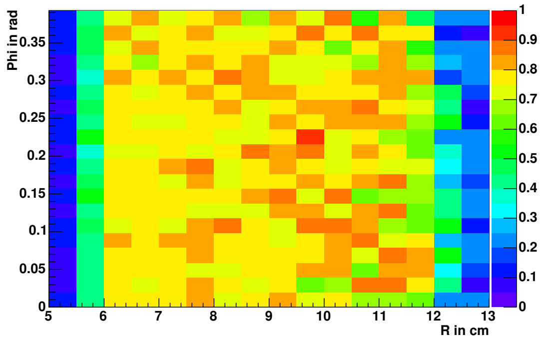

Fig. 8: *Well working BST module data 2004*

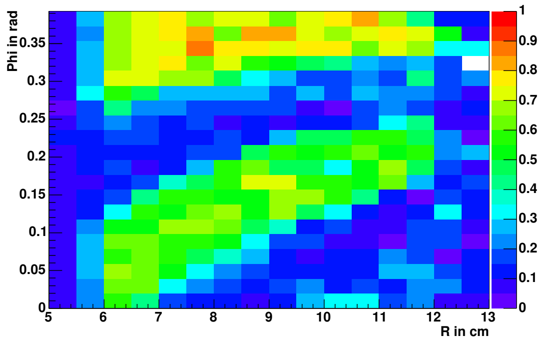

Fig. 9: *Only partially working BST module data 2004*

A further result of this study one can see in the following figures. One assigns a unique number to each module and checks the total efficiency. The ratio between measured and expected hits for MC is shown on fig.10 and data on fig.11 with the condition that the electron should pass the module between a radius of 6.5 and 11.5 cm.

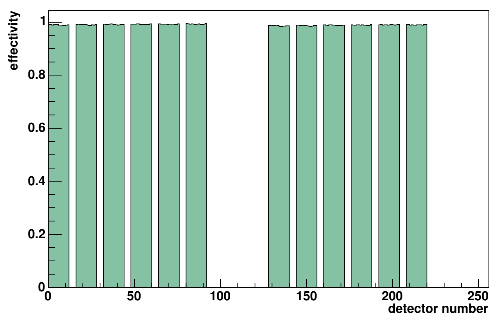

Fig. 10: *Efficiency for Monte Carlo Data*

Thus for MC the BST works with very high efficiency in all modules.

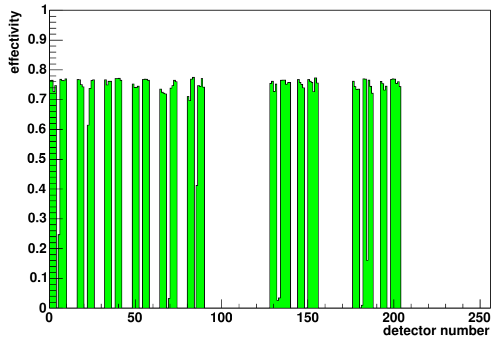

Fig. 11: *Efficiency for data 2004*

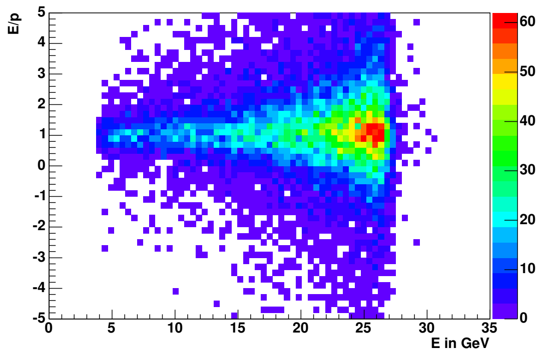

Fig. 12: *E - E/p diagram for Monte Carlo*

For data 2004 one sees only 10 of the twelve wheels (6 in the first half of fig.11 and 4 in the second half) because one of them wasn't installed and the other obviously had a read out problem. Another problem is that there are two modules for each wheel which also didn't transmit a signal.

4.2 Track Reconstruction

Due to the magnetic field of H1 parallel to the z-axis the scattered lepton describes a helix. Such a helix can be fully described by 5 parameters κ (inverse radius), θ, Φ, dca (distance closest approach), z_0.

With the help of the official H1 BST track reconstruction one gets a list of tracks. From this list the best track was chosen by minimizing the difference between the extrapolated track from the BST and cluster in the Spacal. Furthermore a cut on this difference $< 2\,\mathrm{cm}$ could ensure that it is the electron from DIS.

And it is very illustrating to show a histogram with energy from Spacal over momentum from BST in dependence of energy from Spacal to see how good the measurement of the momentum works with increasing energies. Due to Einstein's famous relativistic relation $E^2 = m^2 + p^2$ and the negligible masses at high energies it simplifies to $E = p$, and the ration between E and p should be one in the range electron energies (5-30GeV). Except for the energy cut the same cuts as in section 4.1 were used plus the acceptance condition that at least four BST wheels were hit. That works quite well for Monte Carlo simulations (see fig.12).

The expected behavior, that the momentum measurement gets worse with increasing energy is obvious. Its more difficult to measure the momentum due to the increasing radius of the leptons in the magnetic field.

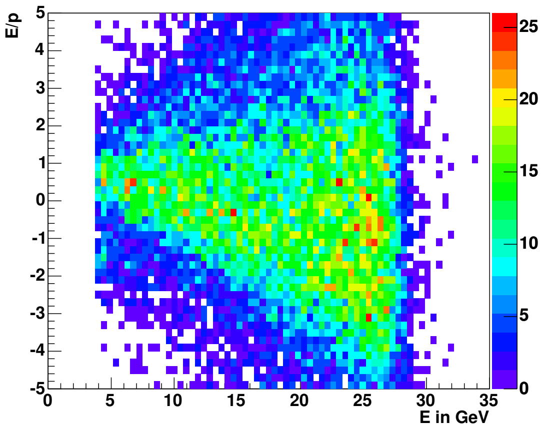

Fig. 13: *E - E/p diagram for Data*

The expected results of $\frac{E}{p} = 1$ is not reproduced for data (see fig.13) because the alignment is probably too bad.

4.3 Energy Dependence of Track Efficiency

In the best case one also would like to get the reconstruction of tracks with the BST independent of energy. BST tracks were selected like in section 4.2. Then this histogram was divided by a histogram without BST track requirement and the result is shown for MC (fig.14) and for data (fig.15).

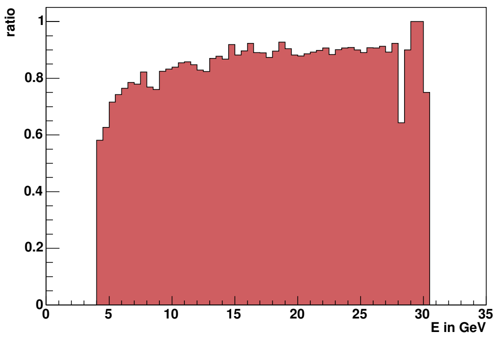

Fig. 14: *Efficiency of reconstruction with BST in Energy resolution (MC)*

The result shows that the track reconstruction is not energy independent. While high energies have an efficiency of about 90% below 15 GeV the efficieny drops to about 60%.

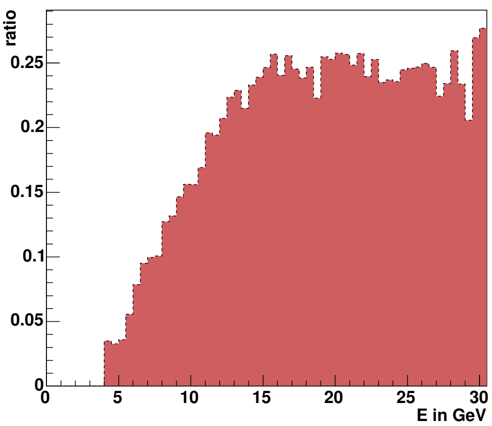

Fig. 15: *Efficiency of reconstruction with BST in Energy resolution (Data)*

For data the same effect is present for decreasing energy but even at high energies the efficiency of about 25% is very low. Reasons are the misalignment and the inefficiences of some modules (see previous sections).

Another interesting plot to look is at the energy with and without BST track requirement.

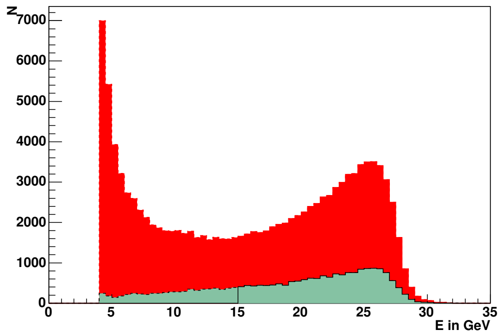

Fig. 16: *All events in BST acceptance (red) and events with reconstructed BST track (green)*

Obviously many low energetic background events are not passed by the cut and so one has at low energies a powerful tool to avoid background.

4.4 Pipe Line Counter Dependence of Track Efficiency

Under the same assumptions one checks the dependence on pipe line number. Because approximately every 96 ns HERA collides a package of electrons and protons the events are put in a "pipeline" and with different triggers the non background events are chosen. Every event gets its own pipe line number and except from statistical fluctuations efficiency should be independent from that number. Of course this only makes sense with data because MC has no triggers.

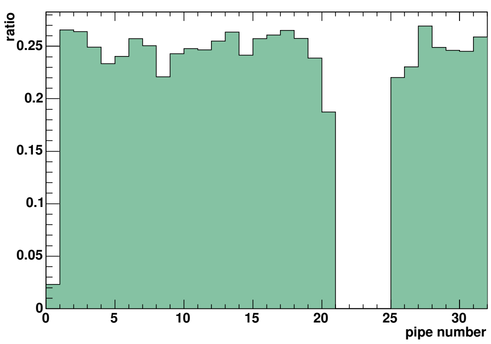

Fig. 17: *Efficiency of reconstruction with BST in pipe number resolution (Data)*

Obviously the readout doesn't work with pipe numbers from 21 to 24 which is a potential source of loosing data.

4.5 Comparison of Generated Quantities from MC with Reconstructed Values

Now it would be very illuminating to compare with measured kinematic variables with the generated variables from MC. There are at least the two most important ones, the energy and the scattering angle θ of the scattered lepton. Like mentioned in the first paragraph one uses them to calculate the kinematic variables (x, y, Q^2) with the electron method. To measure the energy one uses the Spacal and on the next figure one has the difference of the generated energy variable to the energy from Spacal.

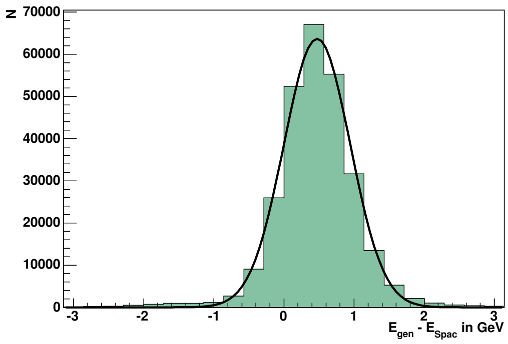

Fig. 18: *Difference of generated energy to energy from Spacal*

The deviation in mean value is due to badly calibrated Spacal in MC simulation. The σ of the Gaussian fit is about 0.47 GeV and that is compatible with the resolution of the Spacal which is given quantitatively by the following formula:

$$\frac{\sigma}{E} = \frac{7\%}{\sqrt{E/GeV}} \oplus 1\%\,, \qquad (10)$$

where $\oplus$ means quadratic summation.

At an average energy of about 25 GeV one gets $\sigma = 0.43\,\text{GeV}$ which is close to the measured value.

The next figure shows the difference between the generated scattering angle to the angle measured with the BST.

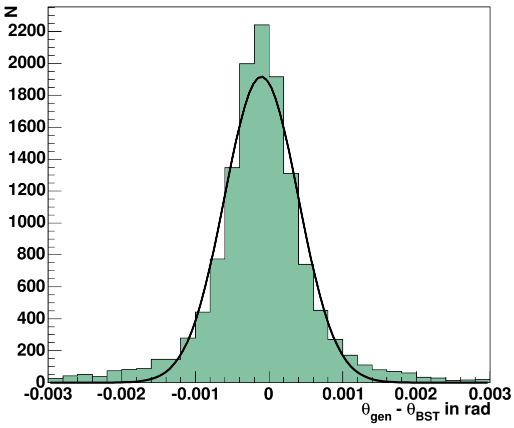

Fig. 19: *Difference of generated scattering θ to θ from BST*

With a Gaussian fit (black line) it was calculated that the θ measurement with the BST has a σ of about 0.5 mrad.

Acknowledgments

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[3] The H1 OO Project Team, Introduction to the H1 OO Analysis Environment

[4] ROOT - An Object-Orientated Data Analysis Framework, Users Guide 4.08