MASS RESOLUTION FOR HEAVY HIGGS PARTICLE SEARCH

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4 Oct 1990

Abstract

The dependence of the reconstructed Higgs particle mass resolution on the muon momentum measurement is studied for the $H^0 \to 2Z^0 \to 4\mu$ channel. The known mass of the Z^0 is used as a constraint to correct the muon momenta. Results are presented for magnetic spectrometers with any combination of air and iron components.

1 Introduction: Detector Types

The most promising signature for the search of a "heavy" ($m_{H^0} \geq 2m_{Z^0}$) Higgs particle is its decay to four charged leptons, especially

$$H^0 \;\; \to \;\; Z^0 + Z^0 \;\; \to \;\; \mu^+ + \mu^- + \mu^+ + \mu^- \tag{1}$$

since muons can be identified readily. On the other hand, their momentum measurement, done with a magnetic spectrometer, would require a huge effort if high accuracy at high momentum is needed. Therefore, the question of neccessary muon momentum resolution for the Higgs search is at the root of any detector design. The main irreducible background consists of the QCD process $qq \to Z^0 Z^0 X$ with two real Z^0, which cannot be removed by cuts in $m_{\mu\mu}$, the reconstructed mass of the Z^0. The Higgs signal must thus show up as a narrow mass peak over a wider background. Hence, the *scale* for the optimal measurement accuracy is determined by the *natural width* of the Higgs particle itself, which varies as $\sim m^3_{H^0}$ from a few GeV at $m_{H^0} = 200$ GeV to ≈ 250 GeV at $m_{H^0} = 800$ GeV.

A magnetic spectrometer measures the tiny bending of the muon track in the magnetic field. This sagitta is a measurement of $1/p_\mu$, where p_μ is the muon momentum. A detector having a constant resolution for the sagitta measurement has thus a *constant error* $\sigma(1/p_\mu)$, or $\sigma(p_\mu)/p_\mu$ proportional to p_μ. On the other hand, massive spectrometers using magnetized iron have an additional uncertainty arising from multiple scattering of the muon in the iron. Since this random deflection from multiple scattering has the same energy dependence as the magnetic deflection, the effective momentum resolution in a massive magnetized iron spectrometer is nearly a *constant error* $\sigma(p_\mu)/p_\mu$ *independent of energy.*

Other detector designs may feature a mixture of both types of response. This is the case when a part of the magnetic field is in iron and a part in air, or when the magnetic field in iron is raised above its saturation value, thus increasing the magnetic deflection without increase of multiple scattering.

In this work we present the Higgs mass resolution obtainable with any type of spectrometer characterized by the two components of constant $\sigma(1/p_\mu)$ and constant $\sigma(p_\mu)/p_\mu$. This allows a direct appreciation of the detector performance and an objective comparison of basic detector designs. A real detector will very likely have a momentum resolution depending not only on the

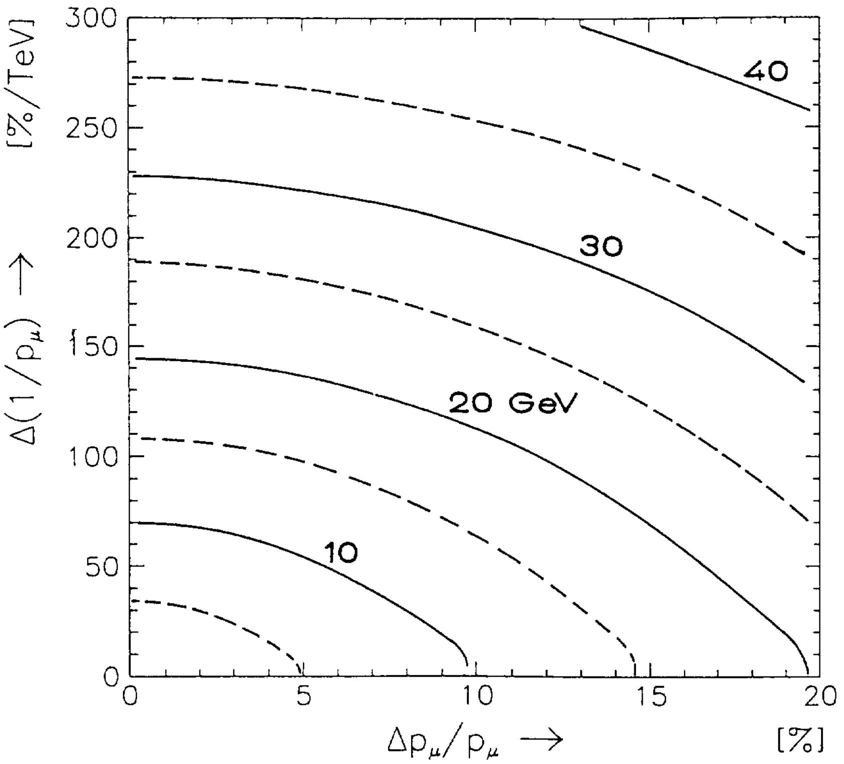

Figure 1: Resolution of the reconstructed Higgs mass, for any combination of muon momentum resolutions $\Delta(p_\mu)/p_\mu$ and $\Delta(1/p_\mu)$. This resolution contains the contribution from measurement errors only, and is significantly larger than the natural width Γ_{H^0}. Here m_{H^0} = 200 GeV was used and *no fit* of the muon momenta was attempted.

momentum, but also on the direction of flight of the muon. Here, for simplicity, the momentum resolution was assumed to be independent of the direction of flight.

2 Generation of Events

Events of reaction (1) were generated for the LHC energy $\sqrt{s}$ = 16 TeV. In order to make the effect of the measurement accuracy more apparent, the events were generated for a natural width of the Higgs particle set to zero. Therefore, the mass distributions shown here have a *width reflecting the experimental resolution only.* The muon momenta were smeared randomly with two gaussian widths $\sigma_1 = \sigma(p_\mu)/p_\mu$ and $\sigma_2 = \sigma(1/p_\mu)$. These errors $\Delta_1 p_\mu$ and $\Delta_2 p_\mu$ were added in quadrature. Since the direction of flight of the muon is well determined it was kept unchanged.

The resulting resolution of m_{H^0} is shown in fig. 1 for m_{H^0} = 200 GeV. It displays lines of constant $\sigma(m_{H^0})$, obtained from a gaussian fitted to the reconstructed Higgs mass distribution, as a function of both components of the muon resolution. At first sight it does not look too promising, for e.g. a present central detector featuring $\sigma_2 \approx 0.5\%/\text{GeV} = 500\%/\text{TeV}$, or for an iron spectrometer with $\sigma_1 \approx 17\%$.

3 Fit of Muon Momentum

To improve the measurement accuracy, the condition $m_{\mu\mu} = m_{Z^0}$ was used to correct the observed raw muon momenta. A second condition is needed to fix the two Δp; we have chosen to require $\sum(\Delta p/\sigma)^2$ minimal. The expected error σ of the muon momentum p was taken to be $\sigma(p) = \sqrt{\sigma_1^2 + \sigma_2^2}$. A fit was done for each muon pair. The effect of this fit on the reconstructed

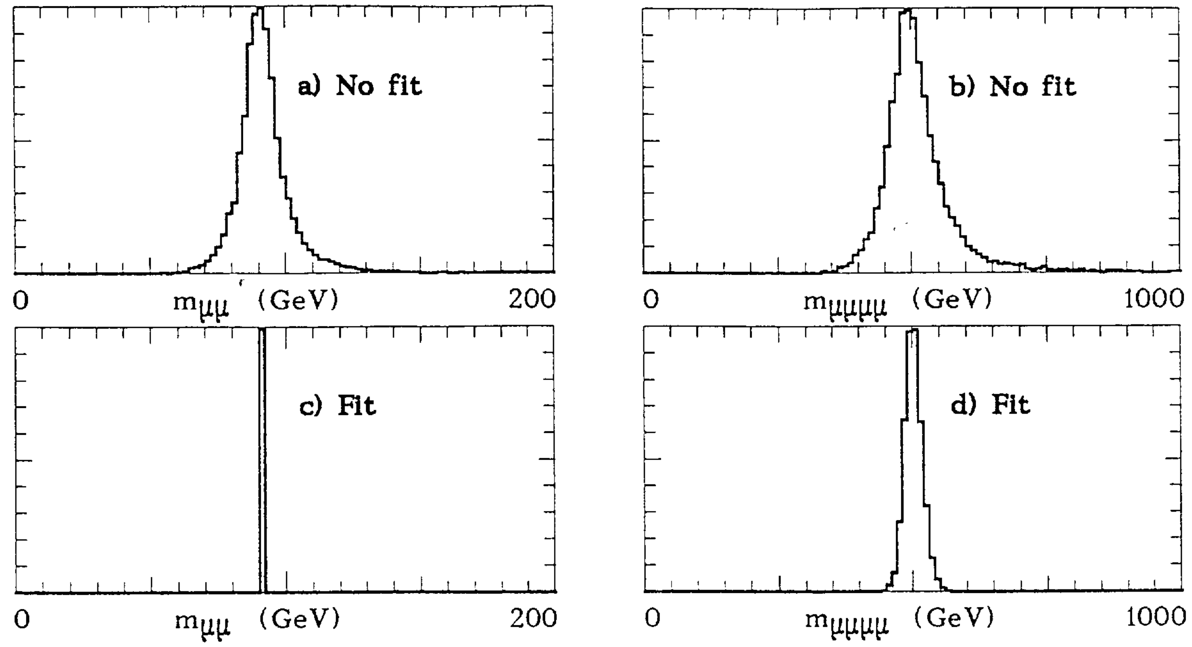

Figure 2: Reconstructed masses for $m_{H^0} = 500$ GeV, $\Gamma_{H^0} = 0, \Delta p_\mu/p_\mu = 50\% \times (p_\mu/\mathrm{TeV})$. In a) and b) the raw momenta were used, while in c) and d) the momenta were fitted to match $m_{\mu\mu} = m_{Z^0}$. The fit reduces the experimental width $\sigma(m_{H^0})$ from 46 to 16 GeV.

Z^0 and H^0 mass is illustrated in fig. 2: part a) shows a raw $m_{\mu\mu}$distribution and the resulting $m_{\mu\mu\mu\mu}$ (part b)), while parts c) and d) show the analogue distributions after $m_{\mu\mu} = m_{Z^0}$ has been fitted for both muon pairs. As expected, the improvement is considerable.

A natural limitation is imposed to this fit by the Z^0 width $\Gamma_{Z^0} \approx 2.5$ GeV itself: since for the fit $m_{\mu\mu} = m_{Z^0}$ one uses the central value of m_{Z^0}, an error of order Γ_{Z^0} is always present. If a detector would have a better resolution, this type of fit should of course be avoided. The effect of the Z^0 width on the H^0 mass, reconstructed with the fit above, is a minimum width of 4, 10, ≈20 GeV for $m_{H^0} = 200, 500, 800$ GeV respectively. However, this unavoidable width is much smaller than the natural width of the Higgs particle, except for the lowest value $m_{H^0} = 200$ GeV.

It should be noted that this procedure cannot produce an artificial $m_{Z^0Z^0}$ mass peak for the QCD background events $qq \rightarrow Z^0Z^0X$, since their $m_{Z^0Z^0}$ distribution has no peak.

4 Wrong Pairings

For a high momentum particle the reconstruction of its track might sometimes be poor and just give a lower bound for the momentum, thus leaving the sign of its electric charge unmeasured. When the sign of the electric charge of at least three of the four observed muons is known, there are *two* possible combinations to form two Z^0 particles from pairs of muons. If less than three charges are known, *three* such pairings may become possible. Thus there are always (at least) two pairings to be considered.

It turns out that this ambiguity does not spoil the Higgs signal. The invariant mass distribution of $m_{\mu\mu}$ for the wrong pairings is wide (fig. 3a). Here the Z^0 mass fit will not improve the measured muon momenta, but rather distort them further. The resulting $m_{Z^0Z^0}$ distribution has a maximum always near its lower kinematical limit (fig. 3d). One might thus suspect that inclusion of such wrong pairings becomes disturbing for a Higgs mass near 200 GeV, but even here it will not jeopardize the recognition of the much narrower peak for the correct pairings.

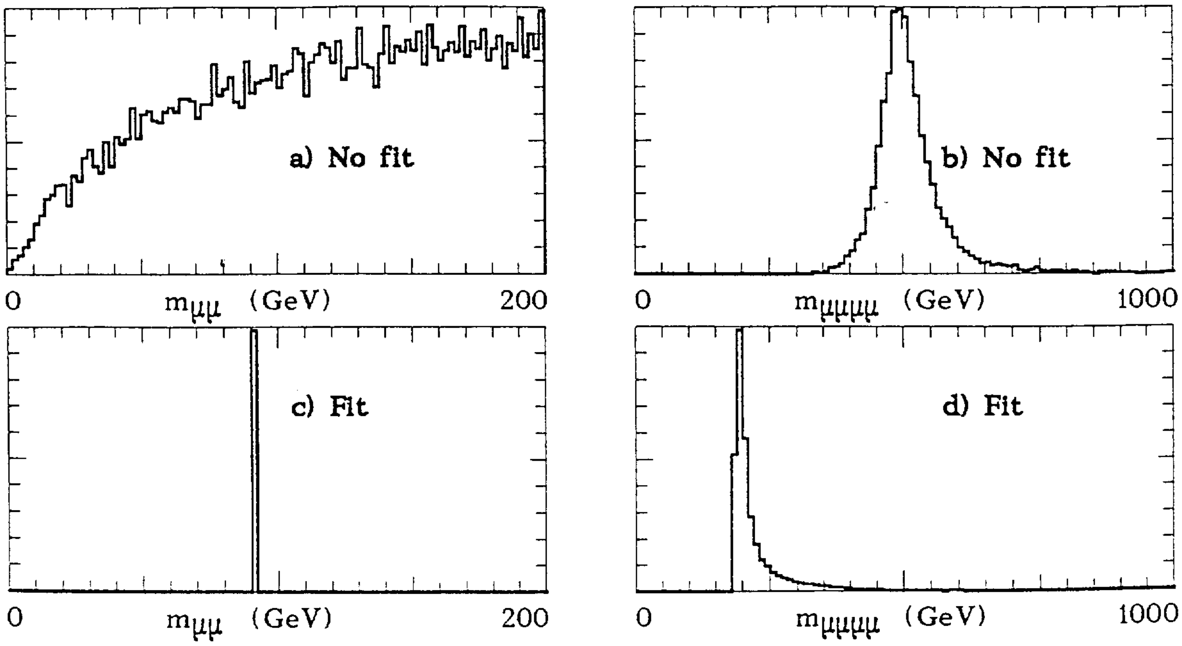

Figure 3: Reconstructed masses for the **wrong $\mu\mu$ pairings**; same conditions as for fig. 2. The $m_{\mu\mu}$reconstructed from the raw muon momenta a) are much higher than m_{Z^0} (50% of the events are in the overflow region of this histogram). Therefore, the fit to m_{Z^0} c) would cause the reconstructed four muon invariant mass d) to concentrate at the lower kinematical bound. The wrong pairings (fig. 3d) are thus clearly distinguishable from the correct pairings (fig. 2d).

Furthermore we compared the raw value $\Delta^2 = (m_{\mu_1\mu_2} - m_{Z^0})^2 + (m_{\mu_3\mu_4} - m_{Z^0})^2$ for each pairing. With the very simple rule of choosing the pairing with the lowest Δ^2, the correct pairing is tagged with about 92% (85%) efficiency for two (three) pairings for a momentum resolution of 100%×(p/TeV) and $m_{H^0} = 200$ GeV. For higher masses this tagging improves; for $m_{H^0} = 500$ GeV this efficiency is 99.5% (99%). This worst case selection (from three possible pairings) was applied to calculate the experimental resolution in m_{H^0} for the final curves in fig. 4–6.

5 Results

The fit procedure, including the "worst case selection" of pairings as described above, was repeated for the full range of detector resolutions. The resulting Higgs mass resolutions are summarized in fig. 4–6 for $m_{H^0} = 200$, 500 and 800 GeV. These curves show, for any mixture of air-type ($\sigma(1/p_\mu) = C^{te}$) and of iron-type ($\sigma(p_\mu)/p_\mu = C^{te}$) spectrometer behaviour, the error on m_{H^0} resulting from measurement errors only. The natural width of the Higgs particle is given for each figure. A good detector should match this resolution, or be slightly better.

It turns out, that a relatively "modest" muon momentum resolution is sufficient to measure the mass peak of the Higgs particle for the whole range of Higgs masses from 200 to 800 GeV considered here. The most stringent requirement is for the lightest Higgs (fig. 4): if one accepts a measurement width of $\sigma(m_{H^0}) \approx 5$ GeV, the needed muon momentum resolution is about 14% for an iron-type spectrometer (or 130%/TeV for an air-type spectrometer, or any suitable combination of both spectrometer types).

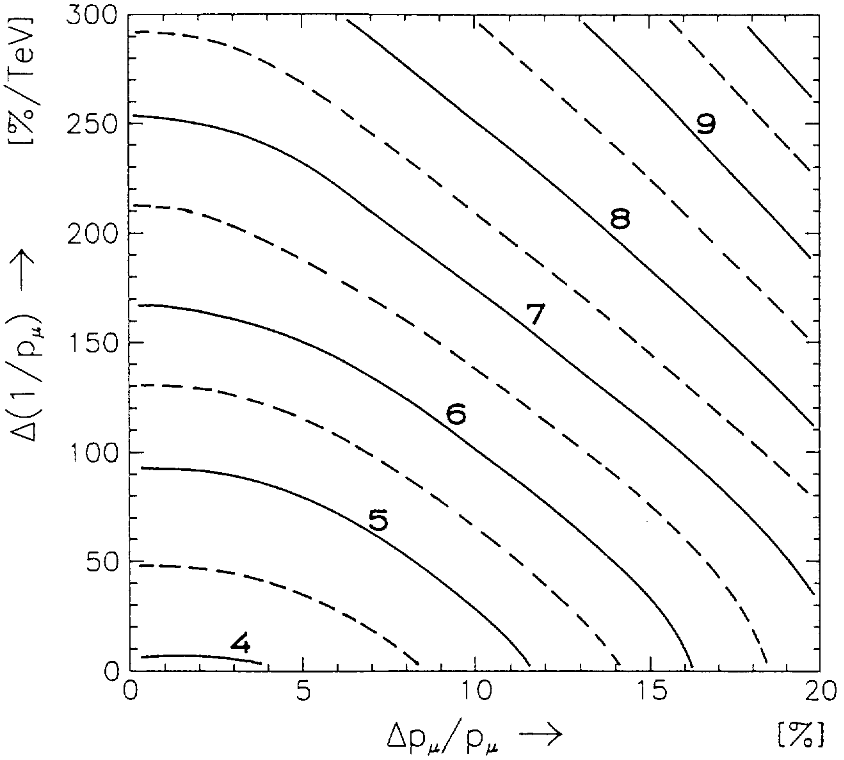

Figure 4: Resolution of the reconstructed Higgs mass, for any combination of muon momentum resolutions $\Delta(p_\mu)/p_\mu$ (massive spectrometer) and $\Delta(1/p_\mu)$ (air spectrometer). As in all figures, the natural width of the Higgs particle is set $\equiv 0$. Hence, the line width shown reflects the contribution from measurement errors alone. The muon momenta were fitted to reproduce m_{Z^0}. Note that for a very good detector (lowest value on picture) a better mass resolution is achieved without the Z^0 mass constraint. A mass $m_{H^0} = 200$ GeV was assumed here. For comparison, the natural width of the Higgs is 1.4 GeV.

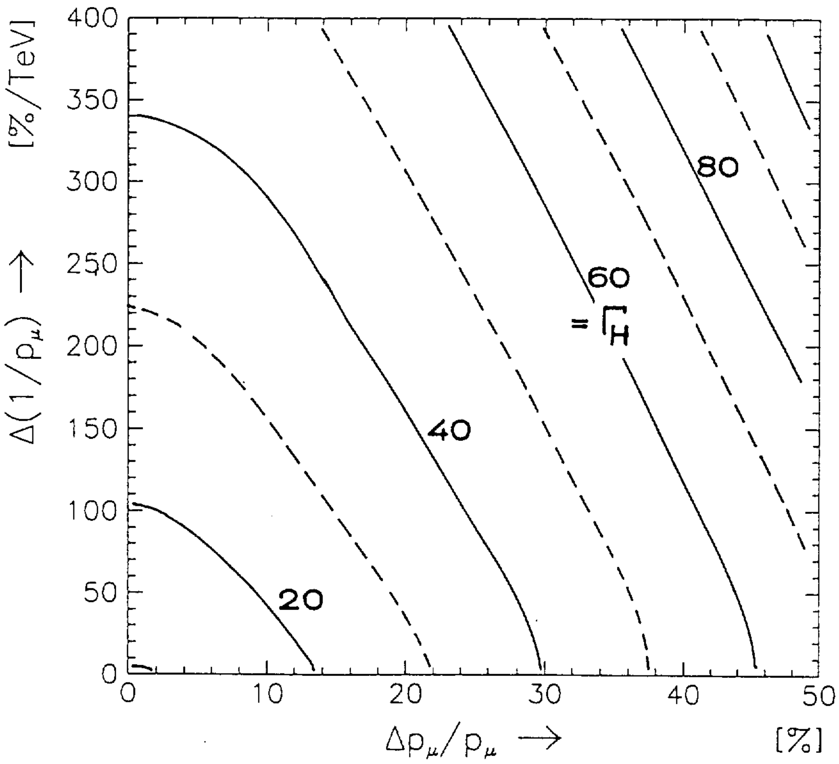

Figure 5: Reconstructed Higgs mass resolution resulting from measurement errors, as in fig. 4, but here for $m_{H^0} = 500$ GeV. The natural Higgs width is $\Gamma_{H^0} = 60$ GeV.

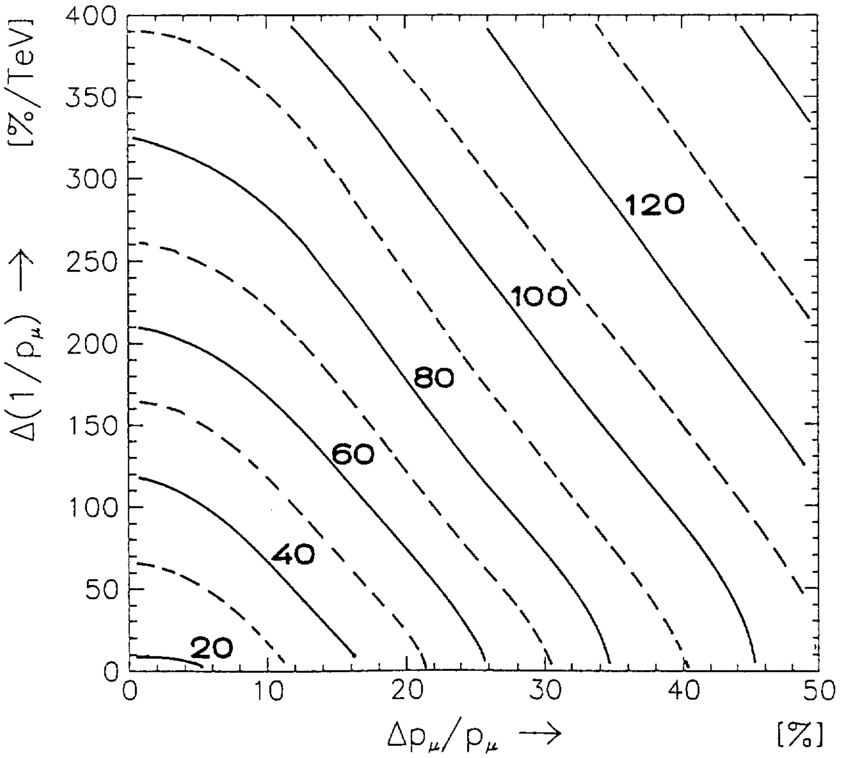

Figure 6: Reconstructed Higgs mass resolution resulting from measurement errors, as in fig. 4, but here for $m_{H^0} = 800$ GeV. The natural Higgs width is $\Gamma_{H^0} = 246$ GeV.