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A METHOD FOR *CP*-ASYMMETRIES MEASUREMENTS IN $B_D \to \pi^+\pi^-$ DECAY

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Abstract

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Both, A_{mix} and A_{dir} CP asymmetries in $B_d^0 \rightarrow \pi^+\pi^-$ decays can be measured at LHC without particle identification using a fitting procedure of two hadrons effective mass spectra. In an experiment like CMS statistical errors of about 0.20 can be obtained after about 1/2 year of data taking at LHC with luminosity $2.10^{33} cm^{-2} sec^{-1} (L_{int} = 10 fb^{-1})$.

Аннотация

Роинишвили В.Н. Метод измерения CP-асимметрий при распаде $B_d \rightarrow \pi^+\pi^-$: Препринт ИФВЭ 2003–29. – Протвино, 2003. – 11 с., 7 рис., библиогр.: 11.

Обе CP-асимметрии A_{mix} и A_{dir} при распаде $B_d \rightarrow \pi^+\pi^-$ могут быть измерены на LHS без идентификации частиц, используя процедуру фитирования спектра эффективных масс двух адронов. Для эксперимента типа CMS статистическая ошибка составит около 0.2 за 1/2 года набора статистки при светимости $2 \cdot 10^{33}$ см$^{-2}$ сек $^{-1}$ $(L_{int} = 10 fb^{-1})$.

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1. Introduction

The study of CP-violation effects in B decays is an important goal of experiments at LHC providing also ways to test SM predictions. CP-violation in B_d^0-decay leads to a difference between the rates of B_d^0 and $\bar{B}_d^0$ decay into a CP eigenstate f (for details see for example [1]). In terms of the normalized proper time $\tau = \Gamma t$ and the mixing parameter $x_d = \Delta m/\Gamma$ (t is the proper time of flight of B_d, Γ is the decay width and Δm is the mass difference between the B_d^0 mass eigenstates) the time-dependent CP-asymmetry can be written as:

$$A(\tau) = \frac{N(B_d^0 \to f;\tau) - N(\bar{B}_d^0 \to f;\tau)}{N(B_d^0 \to f;\tau) + N(\bar{B}_d^0 \to f;\tau)} = A_{dir} cos(x_d \tau) + A_{mix} sin(x_d \tau), \tag{1}$$

where A_{dir} is the asymmetry arising directly from the decay amplitudes and A_{mix} the asymmetry from intereference effects between $B_d^0 - \bar{B}_d^0$ mixing and decay processes respectively. For $f \equiv J/\psi K_s$, A_{dir} is expected to be very small and $A_{mix} = sin(2\beta)$, where β is the angle in the unitarity triangle of the CKM matrix. For $f \equiv \pi^+\pi^-$ the asymmetry A_{dir} is not negligible anymore and both terms in (1) are significant. In the following it will be shown how these asymmetries for $f \equiv \pi^+\pi^-$ could be measured at LHC with a detector similar to CMS [2], even without particle identification.

2. The method

2.1. *Extraction of $B_d^0/\bar{B}_d^0 \to \pi^+\pi^-$ asymmetries*

The main problems when studying the $B_d^0 \to \pi^+\pi^-$ decay are: the small branching ratio $Br(B_d^0 \to \pi^+\pi^-)$ (less than 10^{-5}) and the large background from other two body B^0 decays when no particle identification is available.

It is clear that without particle identification it is impossible to obtain a pure sample of $B_d^0 \to \pi^+\pi^-$ events, especially to separate $B_d^0 \to \pi^+\pi^-$ from $B_s^0 \to K^+K^-$ (see Fig. 3). However, for CP asymmetries measurements it is not crucial [3]. The asymmetry in the $B^0 \to K\pi$ decay is expected to be small: Ali et al. [4] predict a value between 0.037 and 0.106 and the measured value by CLEO [5] is -0.04 ± 0.16. In this paper we assume a zero value.

Asymmetries which could arise from $B_s^0 \to K^+K^-$ decays will be very much diluted for time-integrated asymmetries in a wide τ range because of the large value of the mixing parameter for B_s^0 : $x_s > 20$ (dilution factor is $\sim\frac{x_s}{1+x_s^2}$). Thus the difference $\Delta = N(B_d^0 \to \pi^+\pi^-) - N(\bar{B}_d^0 \to \pi^+\pi^-)$ will be equal:

$$\Delta = N(B^0 \to h^+h^-) - N(\bar{B}^0 \to h^+h^-) \tag{2}$$

in the limits of statistical errors and for a time integrated interval larger than the B_s^0 oscillation time.

To determine the asymmetries $A = \Delta/N_{\pi^+\pi^-}$ it is necessary to know also the denominator — the total number of $B \to \pi^+\pi^-$ events:

$$N_{\pi^+\pi^-} = N(B_d^0 \to \pi^+\pi^-) + N(\bar{B}_d^0 \to \pi^+\pi^-). \tag{3}$$

The way proposed in this article is to extract the number of $N_{K\pi}^d = N(B_d^0 \to K\pi)$ events from the effective mass spectrum of two hadrons of $B^0 \to h^+h^-$ and to correct it with the known ratio $R_d = Br(B_d^0 \to \pi^+\pi^-)/Br(B_d^0 \to K\pi)$:

$$N_{\pi^+\pi^-} = N_{K\pi}^d \times R_d. \tag{4}$$

This is possible because the $K\pi$ signal from B_d^0 dominates in Fig. 3 and can be separated from other two body decays of B^0 thanks to the rather good effective mass resolution of CMS (40 MeV for $B_{d,s}^0$). The procedure consists in fitting the effective mass spectrum of two hadrons by the expression:

$$N(m_{hh}) = (N_{\pi\pi} + N_{KK}) \times F_{\pi\pi}^d(m_{hh}) + N_{K\pi}^d \times F_{K\pi}^d(m_{hh}) + N_{K\pi}^s \times F_{K\pi}^s(m_{hh}), \tag{5}$$

with three free parameters $(N_{\pi\pi} + N_{KK})$, $N_{K\pi}^d$ and $N_{K\pi}^s$. The normalized resolution functions $F(m_{hh})$ describe the shapes of the effective mass spectra of two hadrons including experimental resolutions. For example $F_{K\pi}^d(m_{\pi\pi})$ represents the shape of the effective mass spectrum for $B_d^0 \to K\pi$ decay if the value of the pion mass is used instead of the mass of the kaon. The functions F can be evaluated by a Monte-Carlo (MC) simulation. The detected samples of $J/\Psi \to \mu^+\mu^-$ and $\Upsilon \to \mu^+\mu^-$ also can be used to study distortions of the shape of the effective mass spectra in the range between 3 GeV and 10 GeV when the mass of a pion or a kaon is used instead of the mass of a muon. As MC shows $F_{\pi\pi}^d \cong F_{KK}^s$ (App. 1), this is why the sum of $N_{\pi\pi}$ and N_{KK} appeares in (5). Any contribution from the $\Lambda_b \to$ proton π decays is ignored because it is small and the maximum of $F_{p\pi}^{\Lambda_b}(m_{\pi\pi})$ is rather far from the value of the mass of B_d^0. Their inclusion would not have changed the final results significally.

2.2. *A_{mix} and A_{dir} definition from time-integrated asymmetries*

It has been mentioned that to avoid possible CP asymmetries arising from the $B_s^0 \to KK$ decays one has to measure time-integrated asymmetries. From (1) the time-integrated asymmetry in the range $\tau_l \le \tau \le \infty$ (in practice the lower limit of integration τ_l should be taken greater then 0 in order to select B particles with reduced background):

$$A(\tau \ge \tau_l) = A_{mix} \times Is(\tau_l) + A_{dir} \times Ic(\tau_l), \tag{6}$$

where $Is(\tau_l)$ denotes $e^{\tau_l}\int_{\tau_l}^{\infty} e^{-\tau} sin(x_d\tau)d\tau$ and $Ic(\tau_l)$ denotes $e^{\tau_l}\int_{\tau_l}^{\infty} e^{-\tau} cos(x_d\tau)d\tau$.

For

$$\tau_l \equiv \tau_m = \frac{arctan(1/x_d)}{x_d} \quad (\tau_m = 1.37\ for\ x_d = 0.7) \tag{7}$$

the second integral in (6) vanishes - $Ic(\tau_m) = 0$. This range $\tau_m \leq \tau \leq \infty$ is adequate for A_{mix} measurement since

$$A(\tau \geq \tau_m) = A_{mix} \times Is(\tau_m) \tag{8}$$

contains only one free parameter A_{mix}. The direct asymmetry A_{dir} can then be measured using the full available range of τ - with fixed A_{mix} obtained from (8) - by the expression:

$$A(\tau \geq \tau_l) = A_{mix}^{fix} \times Is(\tau_l) + A_{dir} \times Ic(\tau_l), \tag{9}$$

which contains again only one free parameter A_{dir}.

2.3. B^0 *flavor definition*

For B^0 flavor tagging the conventional method is based on the definition of the flavor of the associated b-quark through the $b \to lepton$ (l) decay chain. The B^0 is produced in association mainly with a high transverse momentum (p_t^l) positively charged lepton, whilst $\bar{B}^0$ — with a negative one. This method has a good purity for B^0 flavor definition. The dilution factor for asymmetries because of wrong tagging (D_w) is in the range $0.4 - 0.7$. The main contribution to the wrong tagging is due to the cascade decays $b \to c \to l$, which can be reduced by increasing the p_t^l threshold. MC simulation shows, that $D_w = 0.67$ for the first level trigger cut of CMS for muons $p_t^\mu(trigger) \geq 14\ GeV/c$. The measured asymmetries must be corrected by the factor $\frac{1}{D_w}$.

The method of lepton tagging makes it possible to trigger on beauty events using high p_t^l leptons.

3. Application of the method to simulated events

3.1. *Events simulation and selection*

PYTHIA 5.7 and JETSET 7.3 were used to generate $B^{'}s$ in the reaction $pp \to B/\bar{B} + \mu....$ at $\sqrt{s} = 14.0\ TeV$.

For the branchig ratio $Br(B_d^0 \to K\pi)$ and the ratio R_d weighted average values(CLEO [6], BaBar [7], Belle [8]), were used:

$$Br(B_d^0 \to K\pi) = 1.510^{-5} \quad and \quad R_d = 0.4. \tag{10}$$

There are no experimental data for B_s decays into two hadrons, therefore it was assumed:

$$Br(B_s^0 \to KK) = Br(B_d^0 \to K\pi) \quad and \quad R_s = \frac{Br(B_s^0 \to K\pi)}{Br(B_s^0 \to KK)} = R_d\ , \tag{11}$$

because the same $b \to s/d$ transmition for both B_d and B_s decays (see for exaple R.Fleisher [9], who claims that $Br(B_s^0 \to KK) \approx Br(B_d^0 \to K\pi) \times \frac{\tau_{B_s}}{\tau_{B_d}}$).

CP-violation with input values $A_{mix}^{input} = -1.0$ and $A_{dir}^{input} = 1.0$ was included according to the measured values $A_{mix} = -1.21^{+0.38}_{-0.27}$ and $A_{dir} = 0.94^{+0.25}_{-0.31}$ (KEK, Belle [10]).

The CMS TRACKER [11] acceptance and experimental resolutions are used.

The events which satisfy the following criteria were selected:

- one muon with $p_t^\mu(trigger) \geq 14$ GeV/c. With such a trigger rather a lot of events with lower p_t^μ are still accepted (App. 2);

- at least one pair of particles($p_t^{particle} \geq 2.5$ GeV/c) with opposite charges and with 5.0 GeV $\leq M_{pair} \leq 5.5$ GeV. The vertex of the pairs (secondary vertex) must be separated from the primary one by a distance in the transverse plane corresponding to $\tau \geq 0.5$;
- some other cuts to reduce backgrounds(on isolation, on the angle between the B^0 motion and the vector which connects the primary vertex with the secondary one,...).

If there is more than one pair in an event, it is the pair with the highest transverse momentum which was chosen as the B^0 candidate (B^0 in the following).

To take the combinatorial background into account, generated events from $pp \to b/\bar{b} + \mu...$ were added with an appropriate weight and with the same selection.

After cuts and for $10 fb^{-1}$ of integrated luminosity(1/2 year of LHC at $2.10^{33} cm^{-2} s^{-1}$) a sample with about 6000 of two body B^0 decay events with $\tau \geq 0.5$ and with about 4 times more background events was left in the mass range 5.0 GeV $\leq m_{h^+h^-} \leq 5.5$ GeV.

The μ tagging method was applied to determine the B flavor.

3.2. A_{mix}, $R_A = \frac{A_{dir}}{A_{mix}}$ *and* A_{dir} *"measurements"*

$\underline{A_{mix}}$. In Fig. 1 the effective mass spectra of two hadrons taken as pions are plotted for negative tagging muons(+) — mainly $\bar{B}^0$ decays, and positive ones($\circ$) — mainly B^0 decays, for two τ ranges $\tau \geq 0.5$ and $\tau \geq 1.37$. The difference between the two spectra for $\tau \geq 1.37$ (Fig. 2), which is appropriate for A_{mix}, was fitted by the function:

$$\Delta(\tau \geq 1.37) \times F^d_{\pi\pi}(m_{\pi\pi}) \tag{12}$$

with one free parameter $\Delta(\tau \geq 1.37)$. The fitted value $\Delta(\tau \geq 1.37) = -364 \pm 58$ represents the "observation" of CP -violation due to the mixing with a statistical significance of about 6 standard deviations.

For the magnitude of A_{mix} it is necessary to define $N^d_{K\pi}(\tau \geq 1.37) = N^d_{K\pi}(\tau \geq 0.5) \times exp(-1.37 + 0.5)$ and correct it by the factor R_d as was mentioned in chapter 2. To this purpose the background subtracted effective mass spectrum of two hadrons for $\tau \geq 0.5$ (Fig. 3) was fitted by the function:

$$\begin{aligned}&[N_{\pi\pi}(\tau \geq 0.5) + N_{KK}(\tau \geq 0.5)] \times F^d_{\pi\pi}(m_{\pi\pi}) + \\ &\qquad + N^d_{K\pi}(\tau \geq 0.5) \times F^d_{K\pi}(m_{\pi\pi}) + N^s_{K\pi}(\tau \geq 0.5) \times F^s_{K\pi}(m_{\pi\pi}),\end{aligned} \tag{13}$$

with three free parameters $[N_{\pi\pi}(\tau \geq 0.5) + N_{KK}(\tau \geq 0.5)]$, $N^d_{K\pi}(\tau \geq 0.5)$ and $N^s_{K\pi}(\tau \geq 0.5)$.

In Fig. 3 crosses(+) correspond to the observed effective mass spectrum for $B^0 \to h^+h^-$ events. Open circles ($\circ$) are related to the $B^0_d \to K\pi$ events defined by MC. The curve represents the result of the fit — $N^d_{K\pi}(\tau \geq 0.5) \times F^d_{K\pi}(m_{\pi\pi})$. As it can be seen the quality of the fit is not bad. The fitted number of $B^0_d \to K\pi$ events is $N^d_{K\pi}(\tau \geq 0.5) = 3758$ whilst the generated number was 3394.

The asymmetry A_{mix} can be expressed:

$$A_{mix} = \frac{\Delta(\tau \geq 1.37)}{N^d_{K\pi}(\tau \geq 0.5) \times exp(-1.37 + 0.5) \times R_d \times D_w} \times \frac{1}{Is(1.37)}. \tag{14}$$

Inserting $Is(1.37) = 0.82$ and "measured" values of $\Delta(\tau \geq 1.37)$ and $N^d_{K\pi}(\tau \geq 0.5)$ for the value of "measured" CP asymmetry because of mixing we get:

$$A^{mes}_{mix} = -1.05. \tag{15}$$

$\underline{R_A \text{ and } A_{dir}}$. From (8) and (9) one can get a formula for the evaluation of the ratio

$$R_A \equiv \frac{A_{dir}}{A_{mix}} = < Y > \times exp(-1.37 + 0.5) \times \frac{Is(1.37)}{Ic(0.5)} - \frac{Is(0.5)}{Ic(0.5)}, \tag{16}$$

where

$$Y(m) = \frac{\Delta_{h^+h^-}(m,\ \tau \geq 0.5)}{\Delta_{h^+h^-}(m,\ \tau \geq 1.37)}, \quad \Delta(m,\tau) = N^{\mu^+-tag}(m,\tau) - N^{\mu^--tag}(m,\tau). \tag{17}$$

Note that ratio R_A does not contain neither branching ratios or dilution factor and therefore has a small systematic error.

Fig. 4 shows obtained Y distribution. The weighted mean value of Y in the mass range of B_d^0 is $< Y >= 0.64$. Inserting this value and $Is(1.37)$, $Is(0.5) = 0.67$, $Ic(0.5) = 0.47$ we get from (16):

$$R_A^{mes} = -0.96\ . \tag{18}$$

Using this value of R_A^{mes} and the value of A_{mix} from (15) we obtain the "measured" asymmetry A_{dir}:

$$A_{dir}^{mes} = R_A^{mes} \times A_{mix}^{mes} = 1.01\ . \tag{19}$$

3.3. *Precision of A_{mix}, R_A and A_{dir} "measurements"*

To take into account statistical fluctuations of the branching ratios and the dilution factor as well as some nonstability of the fitting procedures, 72 independent samples of signals and backgrounds were generated. All results obtained above and the figures are related to the one particular sample out of these 72. The results of A_{mix}, R_A and A_{dir} "measurements" for 72 samples are plotted in Fig. 5.

For the standard deviation of distributions in Fig. 5 we get:

$$\sigma_{A_{mix}} = 0.22, \quad \sigma_{R_A} = 0.19 \ \ and \ \ \sigma_{A_{dir}} = 0.23\ . \tag{20}$$

Comments on systematic errors. The central values for A_{mix}, R_A and A_{dir} are -1.02, -1.04 and 1.05 respectively and indicate that systematic shifts are of order a few percents (remember that the input values were -1, -1 and 1). But the main systematic error for A_{mix} and A_{dir} comes from the precision of R_d, which will be hopefully not to low at the LHC starting time. The systematic errors for R_A are expected to be small, because for this ratio both R_d and D_w cancel.

4. Conclusion

The CP asymmetries in $B_d^0 \to \pi^+\pi^-$ decays A_{mix} and A_{dir} can be measured without particles identification using the method proposed here and based on the fitting procedure of two hadrons effective mass spectra. For a setup like CMS statistical errors about 0.2 can be obtained with the first level trigger cut $p_t^\mu \geq 14.GeV/c$. An integrated luminosity of about $10 fb^{-1}$ will be needed.

The main systematical error depends on the knowlenge of the ratio of branchig ratios $R_d = Br(B_d^0 \to \pi^+\pi^-)/Br(B_d^0 \to K\pi)$. For the ratio of asymmetries $R_A = \frac{A_{dir}}{A_{mix}}$ the systematical error is some few percents.

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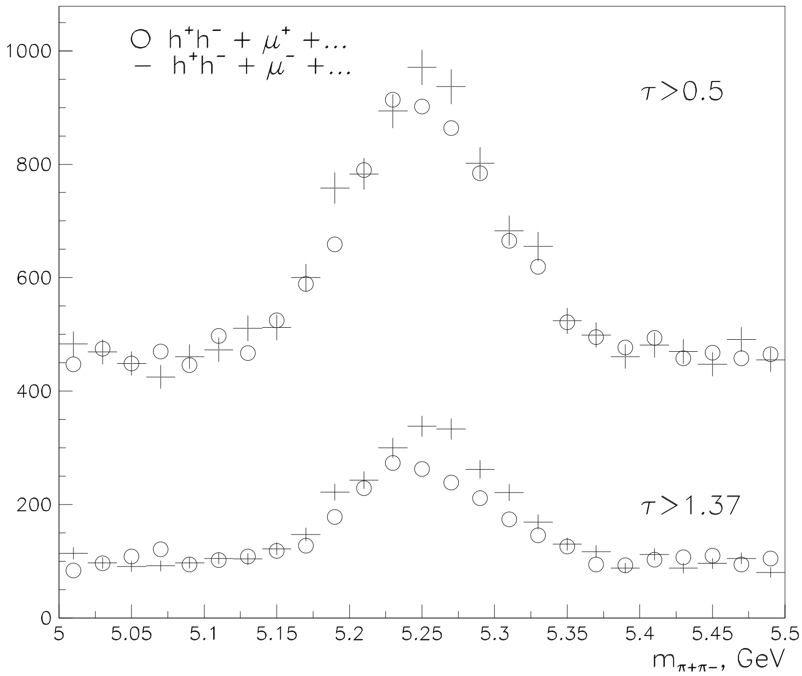


Figure 1. Effective mass distributions for h^+h^- from $B^0 \to h^+h^-$ decay with negative (+) and positive ($\circ$) tagging muons ($m_h = m_\pi$). The upper plots for $\tau > 0.5$, the lower ones for $\tau > 1.37$.

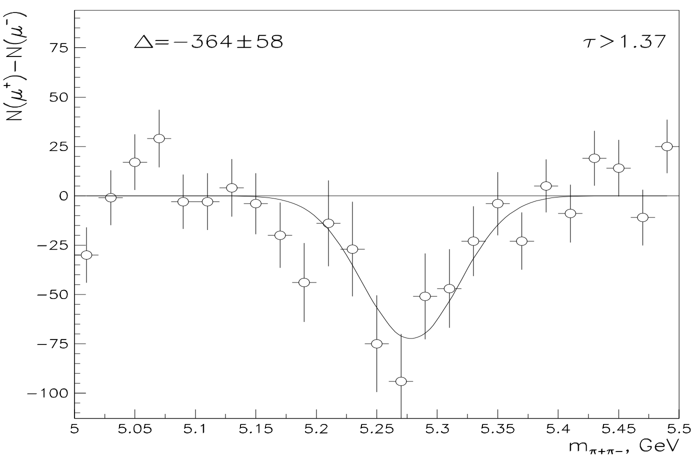


Figure 2. Difference between effective mass spectra of events with positive tagging muons and negative ones for $\tau > 1.37$. The curve is the result of the fit by the function: $\Delta(\tau \geq 1.37) \times F^d_{\pi\pi}(m_{\pi\pi})$.

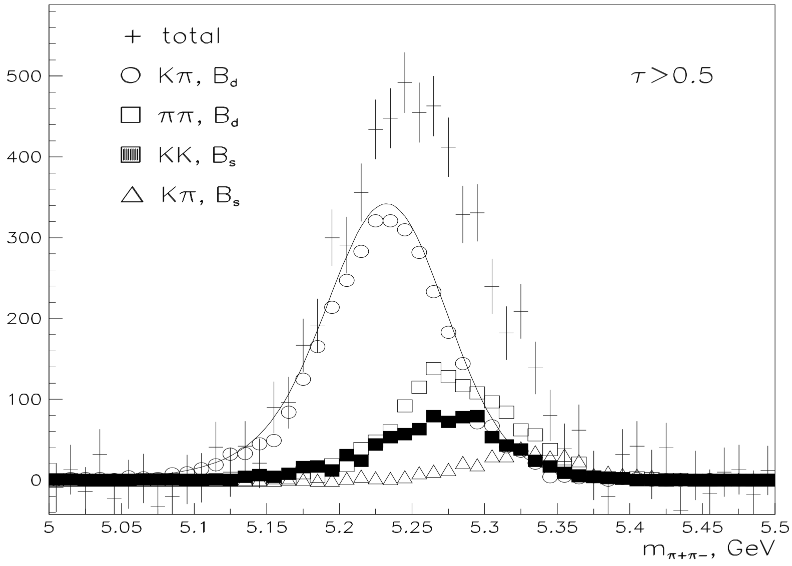


Figure 3. The backround substracted effective mass distributions of h^+h^- from $B^0 \to h^+h^-$ $(m_h = m_\pi)$ for $\tau > 0.5$. The histogram with error bars coresponds to the "experimentally" observed spectrum. The other markers show the decomposition of this spectrum into separate decay channels obtained by MC. The curve is the result of the fit by (13)(see text) — $N^d_{K\pi}(\tau \geq 0.5) \times F^d_{K\pi}(m_{\pi\pi})$.

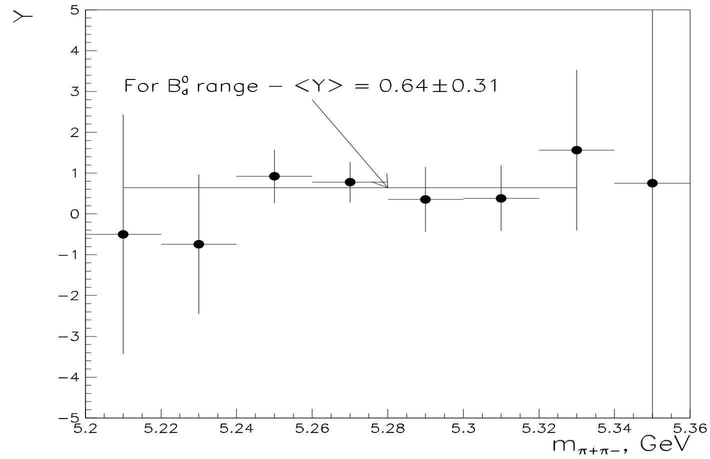


Figure 4. $Y(m) = \frac{\Delta_{h^+h^-}(m,\ \tau \geq 0.5)}{\Delta_{h^+h^-}(m,\ \tau \geq 1.37)}$ distribution. $\Delta(m,\tau) = N^{\mu^+-tag}(m,\tau) - N^{\mu^--tag}(m,\tau)$.

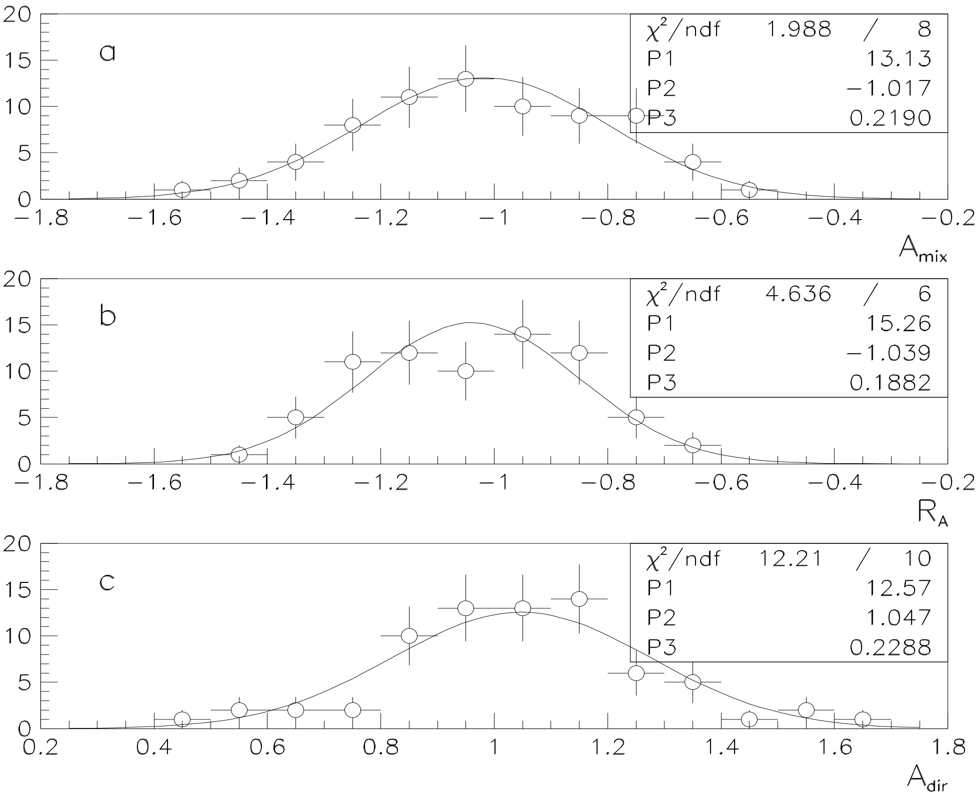
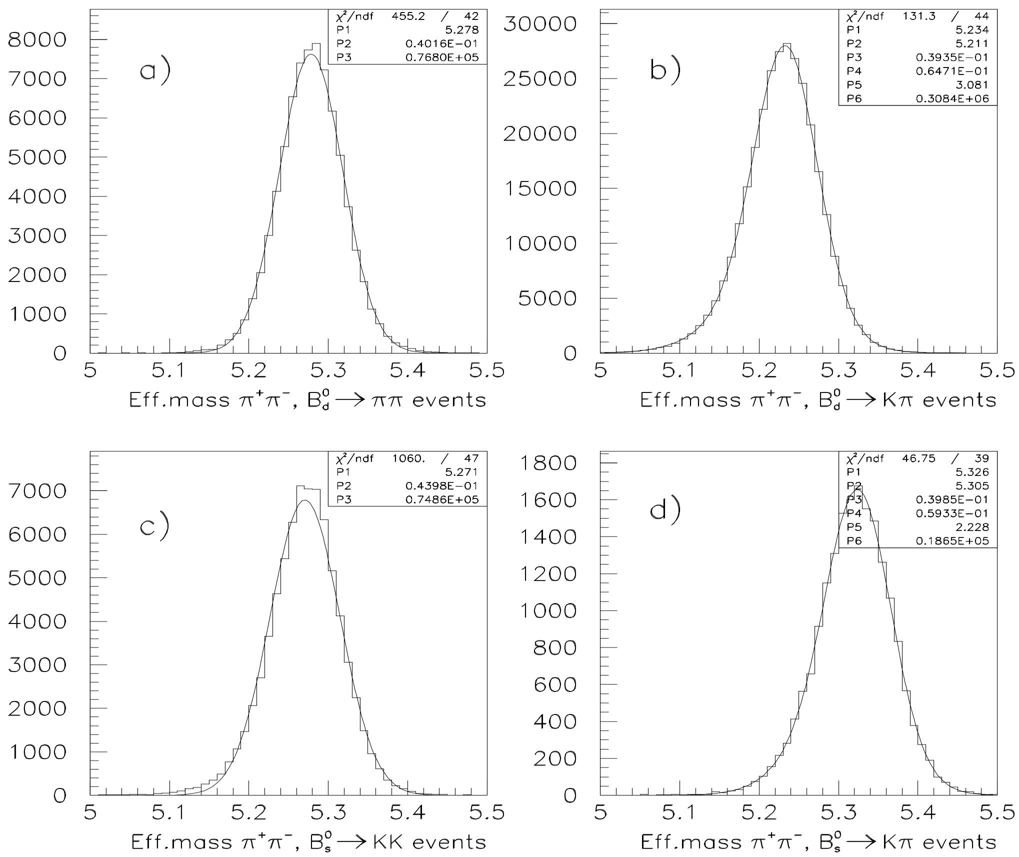


Figure 5. The "measured" values of A_{mix}(a), R_A(b) and A_{dir}(c) for 72 generated samples.

Appendix 1

<u>*Resolution functions*</u>. The following figures show how the effective mass spectra for $B^0 \to h^+h^-$ defined by Monte Carlo simulation, will look like if all hadrons are assumed to be pions. For this figure the CMS Tracker acceptance and resolutions are used. Figures a), b), c) and d) are related to the $B_d^0 \to \pi^+\pi^-$, $B_d^0 \to K^\pm\pi^\mp$, $B_s^0 \to K^+K^-$ and $B_s^0 \to K^\pm\pi^\mp$ respectively. The curves are the results of the fits with single gaussian distribution for $\pi\pi$ and KK decays and sum of two gaussians for $K\pi$ decays.

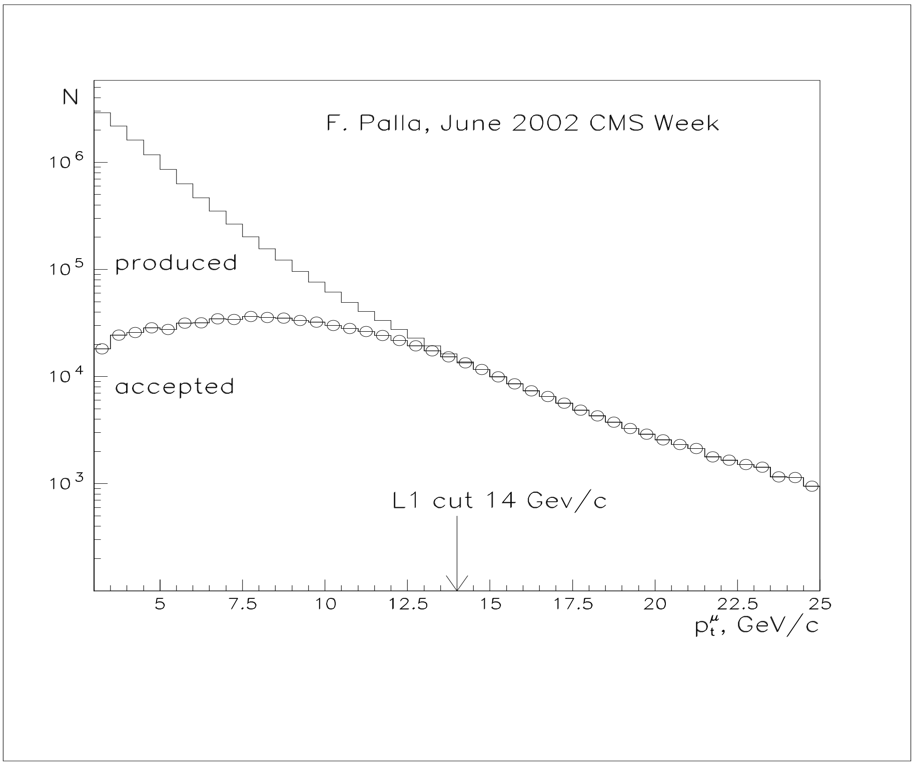


The obtained central values and widths($\simeq 40\ MeV$) for $\pi\pi$ and KK events are very close to each other and thus can not be separeted kinematicaly. The central values for $K\pi$ events are shifted from the value of B_d^0 mass by about 40 MeV and thus can be separeted from other decays.

For the resolution functions $F^d_{\pi\pi}(m_{hh})$ and $F^s_{KK}(m_{hh})$ we use the normalized fitted distribution for $\pi\pi$ events (fig.a). For the funcions $F^d_{K\pi}(m_{hh})$ and $F^s_{K\pi}(m_{hh})$ we use the normalized fitted distribution for $K\pi$ events (fig.b and fig.d respectively).

Appendix 2

The following figure shows genareted p_t^μ distribution (histogram) and obtained spectrum(∘) after the CMS first level trigger cut $-$ $p_t^\mu(trigger) > 14GeV$, according to the results of F.Palla (CMS week, June 2002). As one can see a lot of events with $p_t^\mu < 14GeV$ are accepted.



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