Neutral current interference in the TeV region: The experimental sensitivity at the CERN LHC

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(Received 12 August 1996)

The possibilities to measure lepton forward-backward asymmetries at the CERN LHC in the reaction $pp(q_i\overline{q_i})\rightarrow l^+l^-$ are studied for dilepton events with masses above 400 GeV. It is shown that such measurements allow accurate tests of the neutral current interference structure up to about 2 TeV center-of-mass energies. The sensitivity of asymmetries at the LHC to new physics is demonstrated within the context of quark compositeness and exotic Z' scenarios. [S0556-2821(97)01301-5]

PACS number(s): 13.60.Fz, 13.85.Qk

I. INTRODUCTION

Measurements of forward-backward charge asymmetries A_{FB} are traditionally a domain of e^+e^- collider experiments. Evidence for γ-Z interference came from the observation of the nonzero value of A_{FB} in the reaction $e^+e^-\rightarrow\mu^+\mu^-$ at the DESY e^+e^- collider PETRA around 1982 or 1983 [1]. Furthermore, A_{FB} measurements with quarks and leptons at the Z peak provide precise $\sin^2\theta_W$ determinations [2]. The sensitivity of A_{FB} measurements to new physics such as additional Z' bosons or compositeness has been shown in great detail for future high energy e^+e^- collider experiments [3]. Lepton asymmetries in the reaction p-$\overline{p}\rightarrow e^+e^-(\mu^+\mu^-)$ can be defined with respect to the proton direction. Such asymmetry measurements [4] are currently less precise than the corresponding e^+e^- results have so far only been performed close to the Z resonance.

High mass dilepton events in p-p collisions originate from the annihilation of valence quarks with sea antiquarks or from the annihilation of sea quarks with sea antiquarks. As the valence quarks have on average a much larger momentum than the sea anitquarks, the boost direction of the dilepton system approximates the quark direction. A lepton asymmetry can thus be expected with respect to the boost direction. In contrast, dilepton events which originate from the annihilation of quark pairs from the sea must be symmetric.

The sensitivity of A_{FB} measurements to Z' bosons at future multi-TeV p-p and p-$\overline{p}$ has been discussed by several authors [5]. In particular Langacker *et al.* have studied the sensitivity of on-resonance asymmetries to the couplings of hypothetical new bosons at future multi-TeV hadron colliders. Such on-resonance asymmetry measurements at the CERN Large Haron Collider (LHC) were simulated in detail for the 1990 workshop in Aachen [6] and also for the design studies of ATLAS [7] and CMS [8]. The possibility of an asymmetry measurement at the Z peak with a dedicated LHC experiment has also been discussed [9].

However, asymmetries from continuum dilepton events at very high energy pp colliders as an additional tool to study the neutral current interference have so far only been studied theoretically. Rosner has investigated the sensitivity of lepton asymmetries with on-resonance, off-resonance, and continuum dilepton events at the superconducting supercollider (SSC). He concluded that the combination of these dilepton asymmetries, if experimentally accessible, should provide the best sensitivity to new physics in neutral current reactions [10].

The aim of this paper is to demonstrate that dilepton asymmetries can indeed be exploited experimentally and to show the achievable accuracy of such a measurement at the LHC. Consequently, dilepton asymmetries should be considered as an additional accurate tool to study the TeV center of mass domain. The study assumes the expected experimental capabilities of the LHC experiments ATLAS [7] and CMS [8] and an expected integrated yearly luminosity of up to 100 fb^{-1} per experiment. The simulation of such an asymmetry measurement at the LHC and its sensitivity to a few new physics examples is described in the following.

II. ASYMMETRIES IN REACTIONS WITH QUARK AND LEPTON PAIRS

The reaction $pp(q_i\overline{q_i})\rightarrow e^+e^-$ and $pp(q_i\overline{q_i})\rightarrow\mu^+\mu^-$, as well as the inverse reaction $e^+e^-\rightarrow q_i\overline{q_i}$ are described by the exchange of neutral vector bosons. Within the standard model the couplings of the photon and the Z to quarks and leptons are known and precise calculations for the interference between the photon and the Z exist. γ-Z interference results in large forward-backward asymmetries for center-of-mass energies well above the Z peak. For center-of-mass energies above 250 GeV, essentially constant asymmetries of about 61% are expected for the above reactions with up-type and down-type quarks. New phenomena in the TeV range, such as Z' bosons [5] or contact interactions between quarks and lepton due to compositeness [11], might considerably modify this picture. Fermion asymmetry measurements at high center of mass energies are consequently an excellent tool to search for and perhaps study such new phenomena.

Asymmetries with quarks and leptons in the final state up to $m_{\ell\ell}$ $(=\sqrt{s})\approx 200$ GeV will be measured in detail at CERN e^+e^- collider LEP II and the region of perhaps up to $m_{\ell\ell}\approx 500$ GeV will be investigated at the upgraded Fermilab Tevatron $p\overline{p}$ collider [12]. To exploit the higher energies at the LHC, we concentrate in this study on high mass dilepton events ($m_{\ell\ell}<400$ GeV).

In pp collisions, unlike in e^+e^- collider experiments, the center of mass frame is different from the laboratory frame.

However, the four-momenta of the dilepton system are measured and one can calculate the lepton (electron or moun) angle θ^* in the dilepton center of mass frame. The lepton asymmetry A_{FB}^{ℓ} is defined from the angular distribution $\cos\theta^*$ with respect to the quark direction and can be obtained best with an unpinned maximum likelihood fit to the $\cos\theta^*$ distribution given by

$$\frac{d\sigma}{d\ \cos\theta^*} \propto 3/8(1+\cos^2\theta^*)+A_{\mathrm{FB}}^{\ell}\cos\theta^*. \tag{1}$$

To simulate an asymmetry measurement with dilepton events at the LHC (with 14 TeV pp collisions) the PYTHIA Monte Carlo program [13] is used. The PYTHIA dilepton event generators allow one to simulate the standard model predictions with a photon and a Z exchange as well as modifications due to compositeness [14] or the possibilities of the additional exchange of a Z' including the interference between, γ, Z, and Z' [15].

For the standard model simulation of dilepton events with a mass larger than 400 GeV, one finds that about 70% originate from the annihilation of $u\bar{u}$ quarks, 21% from $d\bar{d}$ quarks, and about 9% are from the annihilation of $s\bar{s}$, $c\bar{c}$, and $b\bar{b}$ sea quarks. Uncertainties from the quark flavor composition are not important for comparisons of a measurement with the standard model as essentially identical lepton asymmetries are predicted for the annihilation of $u\bar{u}$ and $d\bar{d}$ quark pairs and dilepton masses above 400 GeV. However, at a pp collider, observable asymmetries must come from those dilepton events which originate from the annihilation of a valence quark (u and d quarks) and the corresponding sea-antiquark. The fraction of events which will show measurable asymmetries depends therefore on the mass and on the boost of the dilepton system.

As a first step of the simulation, the charge asymmetries are determined with respect to the quark direction taken from the generator. Using this approach lepton asymmetries of $\approx$61% are obtained from the fit to the $\cos\theta^*$ distribution of dilepton events and the standard model simulation. The asymmetry is essentially independent of the mass and rapidity of the lepton system. If instead a random assignment for the quark direction is used, the angular distribution of the leptons is well described by a $1+\cos^2\theta^*$ function with an asymmetry of zero.

As the original quark direction is not known in pp collisions one has to extract it from the kinematics of the dilepton system. For this analysis, the quark direction is taken from the boost direction of the dilepton system with respect to the beam axis (the z axis). The correctness of this assignment is studied as a function of the dilepton rapidity $y=\frac{1}{2}\ \ln[(E+p_z)/E-p_z)]$. The rapidity distribution for dilepton events with masses above 400 GeV is shown in Fig. 1(a) for all dilepton events and for the subsample of events where the signs of the boost direction and the quark direction agree. As shown in Fig. 1(b), the fraction of events with a correctly assigned quark direction increases as a function of the rapidity. For small rapidities ($|y|<0.2$) essentially all dilepton events originate from the annihilation of sea quarks with sea antiquarks and an almost random assignment is made for the

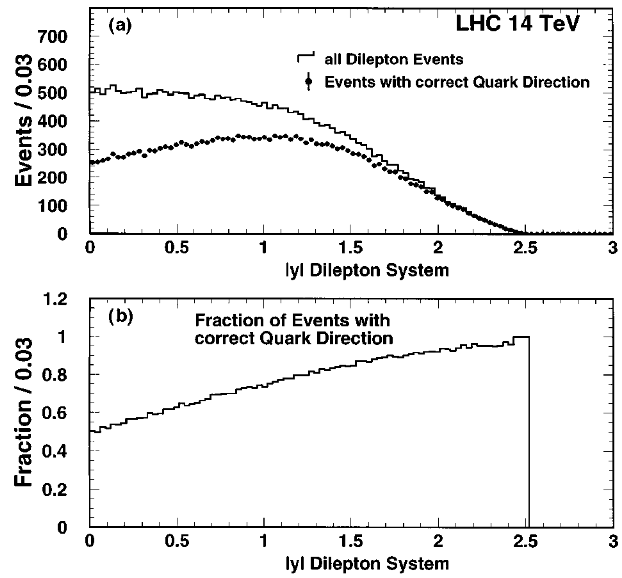

FIG. 1. Rapidity $|y|$ distribution of the dilepton system with respect to the beam direction for all events and the subsample where the sign of the rapidity agrees with the quark direction (a). The fraction of events with a correctly assigned quark direction is shown in (b).

quark direction. The fraction of events with a correctly assigned quark direction increases to move than 80% at a rapidity of 1.

Uncertainties in the quark direction assignment and in the fraction of events which originate from the annihilation of sea-quark pairs have been studied with a variety of structure functions [16] as implemented in PYTHIA. From this study we find that for dilepton masses above 400 GeV these uncertainties are essentially negligible compared to the achievable statistical precsions of the A_{FB}^{ℓ} measurements. However, the dilepton masses below 200 GeV, the uncertainties are more important for asymmetry measurements and require special attention. At this center of mass energy range will already be covered by LEP II, we concentrate in the following only on dilepton events with high mass.

III. SIMULATION OF AN ASYMMETRY MEASUREMENT

According to the design characteristics of ATLAS [7] and CMS [8] high identification efficiency for isolated electrons and muons with excellent energy and momentum resolutions are expected down to pseudorapidities of $|\eta|<2.5$ and for the highest LHC luminosities ($10^{34}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$). For example, using the beam spot constraint, the momentum resolution for 1 TeV muons and electrons should be better than 10% and no charge confusion is expected up to much higher momenta. With this accuracy, dilepton mass resolutions of better than 5–10% for dimuon events and 1–2% for dielectron events can be expected for masses of about 1 TeV.

For this study, PYTHIA events of the type $pp\rightarrow e^+e^-(\gamma)$ and $pp\rightarrow\mu^+\mu^-(\gamma)$ are simulated at a center of mass energy of 14 TeV. The produced leptons are in general isolated and are essentially back to back in the plane transverse to the beam direction. Dilepton events, either dielectron or dimuon events, are accepted if the following criteria are satisfied:

TABLE I. The standard model predictions, using two different structure functions, for the number of accepted dilepton events, assuming 100% lepton identification for the used geometrical selection with an integrated luminosity of 100 fb^{-1} and different mass bins. The expected asymmetries with their statistical errors for the different mass and rapidity intervals are also given.

Mass ($\ell^+\ell^-$) [TeV]	Number of events (for 100 fb^{-1})	A_{FB}^{ℓ} $\|y\|<0.4$	A_{FB}^{ℓ} $0.4<\|y\|<0.8$	A_{FB}^{ℓ} $\|y\|>0.8$
Structure Function CTEQ2L				
0.40–0.50	14100	0.05±0.02	0.16±0.02	0.34±0.01
0.50–0.75	10300	0.05±0.02	0.18±0.02	0.37±0.01
0.75–1.00	2270	0.05±0.04	0.24±0.04	0.43±0.03
1.00–1.25	723	0.10±0.06	0.30±0.06	0.46±0.05
1.25–1.50	261	0.09±0.10	0.31±0.10	0.48±0.08
1.50–2.00	155	0.08±0.12	0.37±0.21	0.49±0.28
>2.00	42	0.16±0.21	0.37±0.21	0.49±0.28
Structure function EHLQ set 1				
0.40–0.50	12150	0.05±0.02	0.15±0.02	0.32±0.01
0.50–0.75	9040	0.05±0.02	0.19±0.02	0.37±0.01
0.75–1.00	2050	0.04±0.04	0.25±0.04	0.43±0.03
1.00–1.25	619	0.10±0.06	0.32±0.06	0.47±0.05
1.25–1.50	239	0.10±0.10	0.35±0.10	0.53±0.08
1.50–2.00	140	0.14±0.12	0.38±0.13	0.51±0.11
>2.00	44	0.15±0.21	0.43±0.22	0.59±0.21

The minimum p_t of each charged lepton should be larger than 20 GeV; the pseudorapidity $|\eta|$ of each lepton should be smaller than 2.5; he two leptons must have opposite charge; the two leptons should be back to back in the plane transverse to the beam direction with an opening angle between the two leptons of more than 160°, the dilepton mass has to be larger than 400 GeV.

Especially for dilepton pairs with masses in the TeV region these criteria seem to be sufficient to select essentially background-free events. However, if required by backgrounds, isolation criteria for electrons an muons and veto criteria against events which have a large jet activity can be applied without a significant loss in statistics.

For an integrated luminosity of 100 fb^{-1} about 2.8×10^4 dilepton events with a mass above 400 GeV are accepted with these criteria. Table I shows the number of expected events for different mass intervals. For a real experiment the number of events will be further reduced by the imperfect geometrical detector coverage and lepton detection efficiencies ϵ. The number of events given in Table I should be multiplied by ϵ^2 and the estimated asymmetry errors will increase by roughly $1/\epsilon$. Accurate efficiency estimates are difficult to make, but values of 90% and more have been used for other simulations [17].

As discussed in Sec. II, the lepton asymmetry is obtained from the $\cos\theta^*$ distribution in the dilepton center of mass frame. The $\cos\theta^*$ distribution for dilepton masses between 0.75 TeV and 1.25 TeV and an absolute rapidity of more than 0.8 is shown in Fig. 2(a) before and after the selection criteria are applied. As expected, the used lepton selection criteria effect only large $|\cos\theta^*|$ values.

Lepton asymmetries are now determined from the $\cos\theta^*$ distribution of the negatively charged lepton with respect to the boost direction of the dilepton system along the z axis. For various dilepton mass and rapidity intervals, the $\cos\theta^*$ distribution is fitted using the unbinned maximum likelihood method. These lepton asymmetries are shown in Fig. 2(b) as a function of the dilepton mass (using about 10 times the integrated luminosity expected per experiment). Large and statistically significant asymmetries are found for large dilepton rapidities up to masses of about 2 TeV.

The extracted asymmetries are smaller than the ones expected from the standard model and depend on the mass and

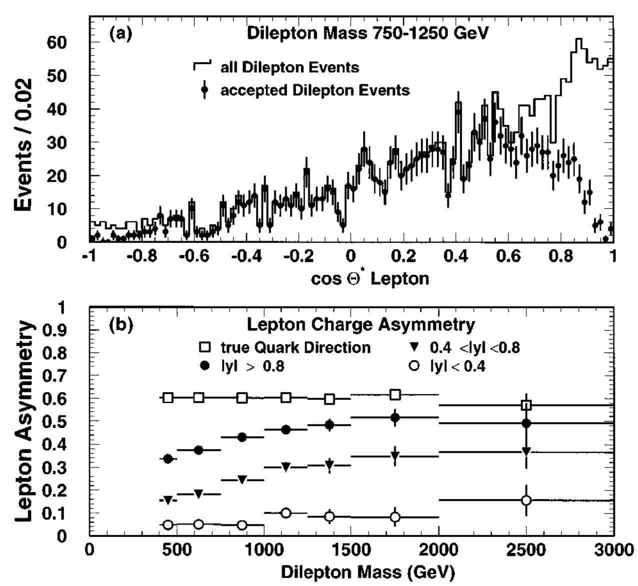

FIG. 2. (a) The standard model predictions for the $\cos\theta^*$ distribution of the negatively charge lepton with and without acceptance criteria for a mass of the dilepton system in the interval 0.75–1.25 TeV and an absolute rapidity of the dilepton system larger than 0.8. Asymmetries for different dilepton mass and rapidity intervals are shown in (b).

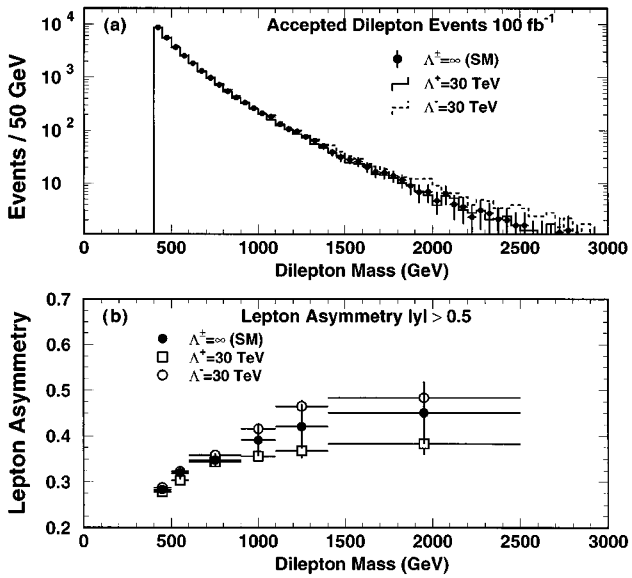

FIG. 3. Expected dilepton mass distributions (a) and lepton symmetries (b) for the standard model and for quark compositeness with different $\Lambda^{\pm}$ values.

rapidity of the dilepton system. This difference comes from two sources, the contributions from events which originate from the annihilation of sea quarks which must have zero asymmetry and from the cases where the valence quark carries a smaller momentum than the sea antiquark. Both contributions reduce the asymmetries and can be considered as random background. This background is especially important for low dilepton masses.

Possible uncertainties from these backgrounds were studied and found to be much smaller than the obtainable statistical errors from an integrated luminosity of 100 fb^{-1}. The expected standard model asymmetries, uncorrected for backgrounds, with statistical errors assuming an integrated luminosity of 100 fb^{-1} are given in Table I. In order to study the sensitivity to structure function uncertainties we have simulated dilepton pair production also with rather old structure functions. As can be seen from Table I, the cross section predictions show a considerable spread of up to 15% for the used structure functions. In contrast the asymmetries are found to be quite insensitive to the structure function choice. Of course, a satisfactory interpretation of any asymmetry measurement requires the simultaneous description of asymmetries and dilepton cross section.

It is interesting to compare the estimated accuracy of asymmetry measurements at the LHC with measurable quark asymmetries at a high energy linear e^+e^- collider. The most accurate and efficient asymmetry measurements with quarks in the final state can be obtained for the reaction $e^+e^- \rightarrow b\bar{b}$. To obtain asymmetry errors at $m_{\ell\ell} \approx 1$ TeV of about 2–3%, at least 1000 accepted and tagged b events are required. The cross section for the reaction $e^+e^- \rightarrow b\bar{b}$ at 1 TeV center of mass energy is approximately 100 fb. Assuming an optimistic efficiency of about 10% to identify b events and measure correctly the charge of b flavored jets, one can estimate the required LHC equivalent yearly luminosity to be about 100 fb^{-1}, corresponding to an average luminosity of 10^{34} sec^{-1} cm^{-2}.

IV. A_{FB}^{ℓ} AND EXOTICA

We now discuss the sensitivity of the A_{FB}^{ℓ} measurements at the LHC with respect to two different exotic physics scenarios as implemented in PYTHIA. These are (a) composite models according to the model by Eichten *et al.* [11] and (b) a heavy Z' with quark and lepton couplings identical to the standard model Z [15]. To demonstrate the sensitivity of asymmetry measurements two extreme scenarios for the total Z' width have been used. The width has been modified by changing the decay rate $Z' \rightarrow W^+W^-$ to very large values. For various other Z' scenarios with their detailed lepton asymmetry predictions we refer to the literature [18]. The different model predictions for dilepton event rates are determined with the above selection criteria. For the asymmetries

TABLE II. Accepted number of dilepton events and expected asymmetries for $|y|$ larger than 0.5 for different compositeness scales $\Lambda^{\pm}$, corresponding to an integrated luminosity of 100 fb^{-1}. For the standard model (Λ^{∞}) the statistical errors of the asymmetry results are also given.

Mass ($\ell^+\ell^-$) [TeV]	Number of events (100 fb^{-1})				
	Λ^{∞}	$\Lambda^+=20$ TeV	$\Lambda^+=30$ TeV	$\Lambda^-=20$ TeV	$\Lambda^-=30$ TeV
0.4–0.5	14100	13940	14020	14380	14118
0.5–0.6	6200	6127	6137	6462	6351
0.6–0.9	5755	5591	5655	6180	5923
0.9–1.1	978	885	940	1152	1023
1.1–1.4	525	466	487	674	559
1.4–3.0	267	320	257	558	353
			$A_{\mathrm{FB}}^{\ell}(\lvert y\rvert>0.5)$		
0.4–0.5	0.283±0.010	0.270	0.279	0.291	0.288
0.5–0.6	0.320±0.015	0.296	0.310	0.323	0.324
0.6–0.9	0.345±0.015	0.325	0.344	0.373	0.359
0.9–1.1	0.392±0.035	0.342	0.356	0.434	0.416
1.1–1.4	0.421±0.048	0.321	0.368	0.498	0.465
1.4–3.0	0.451±0.068	0.345	0.383	0.554	0.484

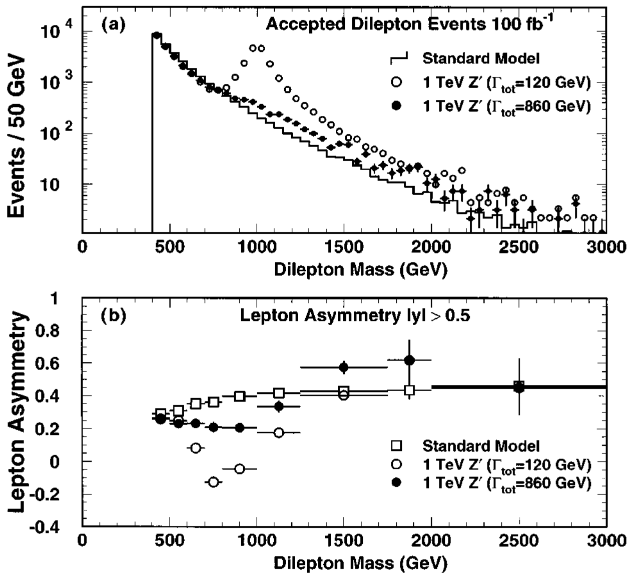

FIG. 4. (a) Expected dilepton mass distributions (a) and asymmetries (b) for the standard model and for two exotic Z' scenarios.

it is further required that the dilepton rapidities $|y|$ be larger than 0.5.

The compositeness scenario is simulated such that u and d quarks are composite with a scale $\Lambda^{\pm}$, the sign indicating either a positive or a negative interference term. As a result of the contact interaction one expects a flattening of the steeply falling dilepton mass distribution as shown in Fig. 3(a) for $\Lambda^{\pm}$ of 30 TeV and for the standard model ($\Lambda^{\pm}=\infty$). Detailed discussions of these cross section changes can be found in [11]. In Table II, dilepton event rates and asymmetries are given for different masses and $\Lambda^{\pm}$ scales. The central values for the different models have been obtained from a high statistic simulation equivalent to about 1000 fb^{-1}. Taking dilepton cross section uncertainties of up to 20% into account, the event rate with masses above 1 TeV alone will perhaps not be significant enough to observe compositeness with $\Lambda^{\pm}$ scales of about 25–30 TeV. However, the asymmetries, as shown in Fig. 3(b) and Table II will improve the sensitivity to compositeness phenomena considerable. The combination of cross section and asymmetry measurements should thus allow one to increase the sensitivity at the two σ level to $\Lambda^{\pm}$ values of almost 30 TeV.

The sensitivity of off- and on-resonance lepton asymmetry measurements to a Z' is demonstrated with two extreme scenarios. For this study a Z' with a mass of 1 TeV and a width of either $\approx$120 GeV or of $\approx$860 GeV is used. The resulting dilepton mass distributions from the exchange of a photon, Z, and $Z'$are compared in Fig. 4(a) with the ones from the standard model with photon and Z exchange only. Clear mass peaks will demonstrate the presence of such a Z' boson up to a few TeV. Only for a very broad Z' might the dilepton cross section measurement alone not be sufficient. However, lepton asymmetries even far away from the Z' peak, as shown in Fig. 4(b), reveal large deviations from standard model scenarios. We have also studied the continuum asymmetries for higher Z' masses with a relatively large width and find significant deviations from the standard model neutral current structure up to masses of about 2.5 TeV.

V. SUMMARY

We have demonstrated the feasibility of lepton forward-backward asymmetry measurements with dilepton continuum events at the LHC. Such measurements, assuming the expected performance of ATLAS and CMS, appear to be almost straightforward. For an integrated luminosity of 100 fb^{-1}, lepton asymmetry measurements will allow an accurate study of neutral current interference effects up to dilepton masses of about 2 TeV. The obtainable asymmetry accuracy is comparable with the ones at a 1 TeV linear e^+e^- collider with quark final states and an integrated luminosity of about 100 fb^{-1}.

From a study of two different exotic scenarios, quark compositeness or exotic Z' models, we conclude that continuum lepton asymmetries at the LHC can be considered as an additional and accurate experimental tool to observe and study new physics in the TeV center of mass energy domain.

ACKNOWLEDGMENTS

I am grateful to E. Richter-Was for many detailed discussions about this analysis and her critical comments on the manuscript. I also would like to thank F. Pauss for several stimulating discussions and F. Behner for his suggestions on how to write an efficient fitting program.

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