Forward-backward asymmetries of lepton pairs in events with a large transverse momentum jet at hadron colliders

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Abstract

We discuss forward-backward charge asymmetries for lepton pair production in association with a large transverse momentum jet at hadron colliders. The measurement of the lepton charge asymmetry relative to the jet direction $A_{FB}^L$ gives a new determination of the effective weak mixing angle $\sin^2 \theta_{\text{eff}}^\text{lept} (M_Z^2)$ with in principle a statistical precision after cuts of $10^{-3}$ $(8 \times 10^{-3})$ at LHC (Tevatron), due to the large cross section of the process with initial gluons. The identification of $b$ jets also allows for the measurement of the bottom quark $Z$ asymmetry $A_{FB}^b$ at hadron colliders although with a lower precision than at LEP, the resulting statistical precision for $\sin^2 \theta_{\text{eff}}^\text{lept} (M_Z^2)$ being $\sim 9 \times 10^{-4}$ $(2 \times 10^{-2}$ at Tevatron).

PACS: 13.85.-t, 14.70.-e

Keywords: Hadron-induced high- and super-high-energy interactions, Gauge bosons.
The possibility of using hadron colliders to perform precision tests of the electroweak Standard Model (SM) is a challenge for the Fermilab Tevatron and the CERN Large Hadron Collider (LHC) experiments [1, 2]. Indeed, the large neutral gauge boson production cross section can allow for a precise determination of the effective weak mixing angle $\sin^2 \theta_{\text{eff}}^{\text{lept}}$, the optimum observable being the forward-backward charge asymmetry of lepton pairs $A_{\text{FB}}$ in the Drell-Yan process $q\bar{q} \rightarrow \gamma, Z \rightarrow l^- l^+$, with $l = e$ or $\mu$ [3, 4]. The Collider Detector Facility (CDF) Collaboration has reported a measurement of $A_{\text{FB}} = 0.070 \pm 0.016$ for $e^- e^+$ pair invariant masses between 75 and 105 GeV at the Fermilab Tevatron Run I [5]. The expected precision to be reached at Run II with an integrated luminosity of 10 fb$^{-1}$ has been estimated to be $\sim 0.1\%$, corresponding to a precision for $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ of $\sim 0.05\%$ [3]. At LHC with an integrated luminosity of 100 fb$^{-1}$ the asymmetry precision will be further improved by a factor $\sim 6$ and the weak mixing angle one by a factor $\sim 3$. This is comparable to the global fit precision at LEP, but for instance a factor $\sim 2$ better than the weak mixing angle precision obtained from the bottom forward-backward asymmetry at the Z pole alone [7].

The associated production of a neutral gauge boson $V = \gamma, Z$ (with $V \rightarrow l^- l^+$) and a jet has also a large cross section, especially at LHC, thus can also allow for a precise determination of the effective weak mixing angle. This Next to Leading Order (NLO) correction to $V$ production is a genuine new process when the detection of the extra jet is required. In particular, gluons can be also initial states, and the large gluon content of the proton at high energy tends to make the $V$ and $Vj$ production cross sections of similar size. A neutral gauge boson with an accompanying jet is produced at tree level by $qq$ and $g (\bar{q})$ collisions, amounting the latter to $\sim 83\%$ ($\sim 48\%$) of the total $Vj$ cross section at LHC, $\sqrt{s} = 14$ TeV (Tevatron, $\sqrt{s} = 2$ TeV), for the cuts below. In this Letter we point out that the forward-backward charge asymmetry of the lepton pairs can be measured in this process either relative to a direction fixed by the initial state $A_{\text{FB}}^j$ as in the Drell-Yan case, or relative to the final jet direction $A_{\text{FB}}^j$. The former is adapted to obtain the asymmetry from the events $q\bar{q} \rightarrow Vg \rightarrow l^- l^+ g$, and the latter from $g (\bar{q}) \rightarrow V (\bar{q}) \rightarrow l^- l^+ (\bar{q})$. Both asymmetries give similar precision for $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ at LHC but not at Tevatron, where $A_{\text{FB}}$ gives a precision almost one order of magnitude higher. However, $A_{\text{FB}}^j$ also allows for the measurement of flavour asymmetries. Thus, if we require the final jet to be a $b$ quark, we can make a new measurement of $A_{\text{FB}}^b$. This is especially interesting given its observed deviation at the Z pole from the SM prediction, $2.9 \sigma$ [4]. Although the precision in principle expected
at LHC, $8.9 \times 10^{-4}$, is lower than the one reported by LEP, $3.1 \times 10^{-4}$, it is similar to the difference between the central values of $\sin^2 \theta^\text{lept}_{\text{eff}}$ resulting from $A_{\text{FB}}^b$ at the $Z$ pole and the global fit to all data.

In the following we discuss these asymmetries and estimate the expected statistical precision at LHC and Tevatron. Here we present tree level results with no detailed detector simulation, although any attempt to fit real data demands including electromagnetic and strong as well as electroweak radiative corrections [6]. Although large, these corrections, which are expected to modify the predicted asymmetries appreciably, are NLO. Particularly worrisome is a priori the production of a neutral gauge boson with two jets. The phase space region where one of them is too soft or collinear dominates the total cross section. The corresponding logarithmic behaviour then compensates for the corresponding extra $\alpha_s$ suppression factor. However, this leading contribution must be included in the Parton Distribution Functions (PDF) and then subtracted from the $V_j j$ cross section to avoid double counting, the resulting correction being actually NLO [8]. This process is also further enhanced at high energy for it has gluon fusion contributions. However, at LHC energies these are still smaller than the $V_j j$ cross section. A detailed calculation of the NLO corrections is in progress. The simulation of the experimental set up is also an essential ingredient to describe the observed asymmetries. We will try to mimic the experimental conditions in our parton calculation, but a real simulation is eventually needed.

In Drell-Yan production of lepton pairs the forward-backward charge asymmetry has to be measured relative to the initial quark direction. In $p\bar{p}$ collisions this is identified with the direction of the proton because it has more quarks than antiquarks.

$$A_{\text{FB}} = \frac{F - B}{F + B}$$

(1)

with

$$F = \int_0^1 \frac{d\sigma}{d \cos \theta_{\text{CS}}} d \cos \theta_{\text{CS}}, \quad B = \int_{-1}^0 \frac{d\sigma}{d \cos \theta_{\text{CS}}} d \cos \theta_{\text{CS}}$$

(2)

and

$$\cos \theta_{\text{CS}} = \frac{2(p_2^- E^{t+} - p_2^{t+} E^{t^-})}{\sqrt{(p_2^- + p_2^{t+})^2} \sqrt{(p_2^- + p_2^{t+})^2 + (p_T^- + p_T^{t+})^2}},$$

(3)

where $\theta_{\text{CS}}$ is the Collins-Soper angle [9]. The four-momenta are measured in the laboratory frame and $p_T^\mu \equiv (0, p_x, p_y, 0)$. In $pp$ colliders the quark direction is fixed by the rapidity
of the lepton pair. This implies defining $\cos \theta_{CS}$ with an extra sign factor $\frac{|p_l^- + p_l^+|}{|p_l^- - p_l^+|}$. In $Vj$ production one can use the same asymmetry $A_{FB}$ or define a new one relative to the final jet, $A_{j FB}$. In this last case the corresponding angle $\theta$ in Eq. (2) is defined for $pp$ collisions as the angle between $l^-$ and the direction opposite to the jet in the $l^-l^+$ rest frame,

$$\cos \theta = \frac{(p_l^- - p_l^+) \cdot p_j}{(p_l^- + p_l^+) \cdot p_j}. \quad (4)$$

The corresponding asymmetry which is suited to $g^{(-)}q$ collisions does not vanish because the proton contains many more quarks than antiquarks. However, in $p\bar{p}$ colliders there are produced as many quarks as antiquarks and this asymmetry vanishes unless some difference is made between them. Hence, $\cos \theta$ is defined with an extra sign factor $\frac{|p_l^-|}{p_l^+}$, $p = p_l^- + p_l^+ + p_j$, which corresponds to assume that the largest rapidity parton is a (anti)quark if it is along the (anti)proton direction. Besides, $Vj$ events also allow for measuring a flavour asymmetry if the final jet is identified and its charge determined, as in the case of $Vb$ production and $A_{FB}^b$. For these events $A_{FB}$ is less significant. In order to obtain $A_{FB}^b$ in $pp$ or $p\bar{p}$ colliders one must use $\cos \theta$ in Eq. (4) but multiplied by a $+(-)$ sign for $b$ (anti)quarks, $-\text{sign}(Q_b)$ with $Q_b$ the $b$ charge.

Let us present our numerical results for $l^-l^+j$ and $l^-l^+b$ at LHC and Tevatron in turn. We work in the effective Born approximation [2] and use the MRST parton distribution functions [10]. The K factors for LHC and Tevatron, 1.1 and 1.2, respectively [11], are not included. Otherwise they would slightly improve our statistical precision estimates. Besides, we only count electron pairs. For muons the main differences would be the pseudorapidity coverage [12, 13] and the size of the radiative corrections involving the lepton mass [6], which are not considered here anyway. A realistic simulation should include the detector acceptances and efficiencies. We imitate the experimental set up at LHC (Tevatron) smearing the lepton and jet energies using values based on the CDF specifications [14]

$$\frac{\Delta E_e}{E_e} = \frac{10(20){\%}}{\sqrt{E_e}} + 0.3(2)\%, \quad \frac{\Delta E_j}{E_j} = \frac{50(80){\%}}{\sqrt{E_j}} + 3(5)\%, \quad (5)$$

with $E$ in GeV, and requiring that the momenta $p$, pseudorapidities $\eta$ and separation in the pseudorapidity - azimuthal angle plane $\Delta R$ satisfy

$$p^e_l = \sqrt{p_T^2} > 20 \text{ GeV}, \quad p^j_l = \sqrt{p_T^2} > 50 (30) \text{ GeV},$$

$$|\eta^e,j| < 2.5, \quad \Delta R_{e,j} > 0.4, \quad (6)$$
respectively, unless otherwise stated. In Figure 1 (a) we plot the \( pp \rightarrow V_j \rightarrow e^-e^+j \) cross section, with \( V = \gamma, Z \) and the cuts above for LHC, as function of \( M_{e^-e^+} = \sqrt{(p^- + p^+)^2} \) (upper curves). The distributions with (solid) and without (dashed) smearing are overlapped, no difference being apparent. In Figure 2 (a) we show the corresponding charge asymmetries, \( A_{FB} \) relative to the initial parton and \( A^b_{FB} \) to the final jet. Both give similar results, although the former is adapted to the \( q\bar{q} \) collisions and the latter to the \( g \rightarrow \bar{q} \) ones.

We do not include hadronization neither detector simulation which, as the smearing, mainly affect the asymmetries, in particular due to the fact that the directions of the jets are related but not equal to the directions of the parent partons. In the Figures we also show the \( pp \rightarrow V^b \rightarrow e^-e^+b \) cross section, assuming a \( b \)-tagging efficiency of 50 \% \cite{12}, and the corresponding asymmetry \( A^b_{FB} \), assuming no charge misassignment (thick lines). The cross section is a factor 30 smaller in this case, but the asymmetry is much larger because only \( g \rightarrow b \) collisions contribute. As explained NLO corrections are not included but they are eventually needed to describe the data. In Figure 1 we also plot the top pair background, \( p \bar{p} \rightarrow t \bar{t} \rightarrow W^+W^-b \bar{b} \rightarrow \nu_e \bar{\nu}_e e^-e^-b \bar{b} \) \cite{15}, and consider the case of losing one \( b \). We assume the same \( b \)-tagging efficiency and that the second \( b \) jet is missed if \( p^b_t < 50 \text{ GeV} \). We also require that the total transverse momentum \( p_t < 20 \text{ GeV} \), \( p = p^- + p^+ + p^b \). The resulting distribution is rather flat and the smearing makes no difference. In the \( M_{e^-e^+} \) interval between 75 and 105 GeV the signal is 200 times larger, \( \sigma^{Vb} = 1.7 \text{ pb} \) whereas \( \sigma^{t\bar{t}} = 0.008 \text{ pb} \). This background is further reduced by a factor 1.25 if the \( b \) jet is only missed if \( p^b_t < 20 \text{ GeV} \). So, we neglect it in the following. In any case its mixed \( e\mu \) decays can also provide a further handle on \( t\bar{t} \). In Figures 1 and 2 (b) we plot the same cross sections and asymmetries but for Tevatron. At 2 TeV the \( q\bar{q} \) collisions dominate and the asymmetry adapted to these events \( A_{FB} \) is much larger. The applied smearing and cuts are given in Eqs. (3,4). In particular, for the \( t\bar{t} \) background we mimic the missed \( b \) by demanding \( p^b_t < 30 \text{ GeV} \) and also require \( p_t < 20 \text{ GeV} \). In such conditions we find that the \( Vb \) signal is 700 times larger in the \( M_{e^-e^+} \) range between 75 and 105 GeV, \( \sigma^{Vb} = 58 \text{ fb} \) whereas \( \sigma^{t\bar{t}} = 0.08 \text{ fb} \). Other \( W \) pair backgrounds like \( p \rightarrow W^+W^-j, W^+W^-b \) or \( W^+W^-jj, W^+W^-b \) with only one jet detected, which can be large a priori, can be further reduced requiring small total transverse momentum.
Near the $Z$ pole, $M_{e^-e^+} \sim M_Z$, the asymmetries can be approximated by

$$A = b(a - \sin^2 \theta_{\text{eff}}^{\text{lept}} (M_Z^2)),$$

translating then their measurement into a precise determination of $\sin^2 \theta_{\text{eff}}^{\text{lept}} (M_Z^2)$. In the Table we collect the asymmetry estimates and their statistical precision, the corresponding $b$ and $a$ values in Eq. (7) and the precision reach $\delta \sin^2 \theta_{\text{eff}}^{\text{lept}}$ of LHC and Tevatron for $M_{e^-e^+}$ in the range $[75, 105]$ GeV and two sets of cuts. The first set has been used throughout the paper and is given in Eq. (8), whereas the second one requires a smaller minimum jet transverse momentum, $p_{jt}^j > 20$ (10) GeV at LHC (Tevatron). These less stringent cuts increase the number of events, and then improve the statistical precision by 10 to 50% depending on the asymmetry and collider. We have not tried to optimize them at this stage, but it will have to be done when dealing with real data and the experimental inefficiencies are known. The cross sections are also gathered in the Table. All the estimates include the smearing in Eq. (8). The results without smearing are very similar, except for the $A_{FB}^j$ asymmetry and the second set of cuts for which $A_{FB}^j$ is 20% smaller (larger) at LHC (Tevatron).

We have assumed throughout the paper a ($-$) $b$-tagging efficiency $\epsilon$ of 50%. This is too optimistic, especially because we assume no contamination $\omega$, and in particular no charge misidentification. The statistical precisions $\delta A$ and $\delta \sin^2 \theta_{\text{eff}}^{\text{lept}}$ are proportional to $\epsilon^{-\frac{1}{2}}$, and the asymmetries $A$ and coefficients $b$ in Eq. (7) to $1 - 2\omega$. This means in particular that the contamination multiplies $\delta \sin^2 \theta_{\text{eff}}^{\text{lept}}$ by $(1 - 2\omega)^{-1}$. Hence, if we only consider semileptonic $b$ decays, implying $\epsilon \sim 0.1$ and $\omega \sim 0$, $\delta A$ and $\delta \sin^2 \theta_{\text{eff}}^{\text{lept}}$ increase by a factor $\sim 2$. In practice we must try to maximize the quality factor $Q = \epsilon (1 - 2\omega)^2$ [10]. The statistical precisions given in the Table are certainly optimistic for systematic errors are also sizeable. To approach the quoted precisions will be an experimental challenge.

In summary, we have pointed out that the large $Vj$ production cross section at hadron colliders and the possibility of measuring the lepton asymmetries relative to the final jet allow for a precise determination of the effective electroweak mixing angle. If there is an efficient $b$-tagging and charge identification, these events with a $b$ jet also allow for a new determination of $A_{FB}^j$. The corresponding statistical precisions are collected in the Table. As in Drell-Yan production [17], this process is also sensitive to new physics for large $M_{e^-e^+}$, especially to new gauge bosons.
Acknowledgments

We thank J.A. Aguilar Saavedra, A. Bueno, R. Pittau and J. Santiago for useful comments. This work was supported in part by MCYT under contract FPA2000-1558, Junta de Andalucía group FQM 101 and the European Community’s Human Potential Programme under contract HPRN-CT-2000-00149 Physics at Colliders.

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FIG. 1: Leading order $e^-e^+ j$ ($Vj$) and $e^-e^+ b^{-}$ ($Vb$ and $t\bar{t}$) cross sections as function of $M_{e^-e^+}$ for the processes, cuts and efficiencies discussed in the text at LHC (a) and Tevatron (b).
FIG. 2: Forward-backward electron asymmetries defined in the text as function of $M_{e^- e^+}$ for $e^- e^+ j$ ($A_{FB}^e$ and $A_{FB}^j$) and $e^- e^+ b$ ($A_{FB}^b$) events in Figure 1 at LHC (a) and Tevatron (b). The $t\bar{t}$ background is not included.
|         | $\sigma$ (pb) | A | $\delta$A | b | a | $\delta \sin^2 \theta_{\text{eff}}$ |
|---------|---------------|---|-----------|---|---|----------------------------------|
| LHC     |               |   |           |   |   |                                  |
| $p_t^j > 50$ GeV | $\sigma^V_j = 49$ | $A_{FB}^V$ | $1.760 \times 10^{-3}$ | $4.5 \times 10^{-4}$ | $0.346$ | $0.2491 \times 10^{-3}$ |
|         | $A_{FB}^j$   |   |           |   |   |                                  |
|         | $A_{FB}^b$   |   |           |   |   |                                  |
| $p_t^j > 20$ GeV | $\sigma^V_j = 167$ | $A_{FB}^V$ | $5.9 \times 10^{-3}$ | $2.4 \times 10^{-4}$ | $0.357$ | $0.2469 \times 10^{-4}$ |
|         | $A_{FB}^j$   |   |           |   |   |                                  |
|         | $A_{FB}^b$   |   |           |   |   |                                  |
| Tevatron |               |   |           |   |   |                                  |
| $p_t^j > 30$ GeV | $\sigma^V_j = 9.7$ | $A_{FB}^V$ | $0.06$ | $1.3 \times 10^{-3}$ | $2.187$ | $0.2499 \times 10^{-4}$ |
|         | $A_{FB}^j$   |   |           |   |   |                                  |
|         | $A_{FB}^b$   |   |           |   |   |                                  |
| $p_t^j > 10$ GeV | $\sigma^V_j = 39$ | $A_{FB}^V$ | $0.21$ | $1.6 \times 10^{-3}$ | $3.005$ | $0.2463 \times 10^{-4}$ |
|         | $A_{FB}^j$   |   |           |   |   |                                  |
|         | $A_{FB}^b$   |   |           |   |   |                                  |

TABLE I: Estimates for the $e^- e^+ j$ and $e^- e^+ b$ cross sections and asymmetries defined in the text with $M_{e^- e^+}$ in the range $[75, 105]$ GeV. The statistical precisions are also given. The integrated luminosity as well as the smearing, cuts and tagging efficiency can be found in the text.