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QCD corrections to forward-backward charge asymmetries in l^-l^+j production at hadron colliders

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The large cross sections for gauge boson production at the Fermilab Tevatron and the CERN Large Hadron Collider (LHC) might give a chance to determine the electroweak parameters with high precision. We calculated two different forward-backward charge asymmetries (A_{FB}^{CS} and A_{FB}^{j}) of lepton pairs in events with a large transverse momentum jet $p\overset{(-)}{p} \to Z, \gamma^* + j \to e^- e^+ + j$ at next-to-leading order (NLO), $\mathcal{O}(\alpha_s)$ corrections, making use of the Monte Carlo programs MCFM [1] and ALPGEN [2]. These observables could provide a new determination of the weak mixing angle $\sin^2\theta_{\rm eff}^{\rm lept}(M_Z^2)$ with a statistical precision for each lepton flavour of $\sim 10^{-3}$ (7×10^{-3}) at LHC (Tevatron). If b jets are identified, a new asymmetry with respect to the b quark (A_{FB}^{b}) can also be measured with a statistical precision of $\sim 2\times10^{-3}$ (4×10^{-2}) at LHC (Tevatron). Finally, we comment on the dependence of our results on various sources of uncertainties and compare, in the case of A_{FB}^{b}, the exact result with an approximation that might be more suitable when performing a realistic experimental analysis.

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1. The definition of the forward-backward charge asymmetries

As explained in [3], the optimal observable to quantify possible correlations in the direction of emission of the final state lepton in the process $p\overset{(-)}{p} \to Z,\gamma^* + j \to e^-e^+ + j$, is a forward-backward asymmetry:

$$\mathrm{A_{FB}} = \frac{F-B}{F+B} \quad \text{with } F = \int_0^1 \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta}\mathrm{d}\cos\theta \text{ and } B = \int_{-1}^0 \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta}\mathrm{d}\cos\theta\,.$$

One can consider two possible angles:

$$\cos\theta_{\mathrm{CS}} = \frac{2(p_z^{e^-}E^{e^+} - p_z^{e^+}E^{e^-})}{\sqrt{(p^{e^-}+p^{e^+})^2}\sqrt{(p^{e^-}+p^{e^+})^2+(p_T^{e^-}+p_T^{e^+})^2}} \quad \text{or} \quad \cos\theta_j = \frac{(p^{e^-}-p^{e^+})\cdot p^j}{(p^{e^-}+p^{e^+})\cdot p^j}\,,$$

where the four-momenta are measured in the laboratory frame and $p_T^\mu \equiv (0, p_x, p_y, 0)$. The Collins-Soper angle θ_{CS} is, on average, the angle between e^- and the initial quark direction, while θ_j is the angle between e^- and the direction opposite to the jet in the e^-e^+ rest frame [4].

Different asymmetries can then be defined, according to the scheme given in Table 1. The

Collider	Asymmetry	Definition
$p\bar{p}$	$A_{\mathrm{FB}}^{\mathrm{CS}}$	$\cos\theta = \cos\theta_{\mathrm{CS}}$
pp	$A_{\mathrm{FB}}^{\mathrm{CS}}$	$\cos\theta = \cos\theta_{\mathrm{CS}} \times \frac{\lvert p_z^{e^+}+p_z^{e^-}+p_z^j\rvert}{p_z^{e^+}+p_z^{e^-}+p_z^j}$
$p\bar{p}$	A_{FB}^{j}	$\cos\theta = \cos\theta_j \times \frac{\lvert p_z^{e^+}+p_z^{e^-}+p_z^j\rvert}{p_z^{e^+}+p_z^{e^-}+p_z^j}$
pp	A_{FB}^{j}	$\cos\theta = \cos\theta_j$
$p\bar{p}$	A_{FB}^{b}	$\cos\theta = \cos\theta_j \times (-\mathrm{sign}(Q_b))$
pp	A_{FB}^{b}	$\cos\theta = \cos\theta_j \times (-\mathrm{sign}(Q_b))$

Table 1: The definitions of the various asymmetries at the pp and $p\bar{p}$ colliders.

extra phase factors in the definitions of Table 1 ensure non vanishing asymmetries. Notice that, in the case of $\mathrm{A_{FB}^b}$, one must detect the charge of the produced b jet.

2. Numerical results and conclusions

The effect of including NLO $\mathscr{O}(\alpha_s)$ corrections in the production rates is given in Table 2, while the corresponding change in the asymmetries is depicted in Figure 1. A measurement of such asymmetries can be directly translated into a determination of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}(M_Z^2)$. The precision reach $\delta\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ is given in Table 3, assuming an integrated Luminosity L of 100 (10) fb^{-1} at LHC (Tevatron). The size of the NLO corrections is moderate, except for σ^{Vb} at Tevatron in Table 2 and in the two b asymmetries of Figure 1. This is mainly due to the new $q\bar{q}$ subprocess appearing at the NLO. In Table 3 we assumed a b-tagging efficiency ε of 100 % and no contamination ω in disentangling b and $\bar{b}$ jets. Taking ε and ω into account means in practice dividing $\delta\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ coming from the Vb events by $\sqrt{\varepsilon}(1-2\omega)$. A typical realistic value for ε is 50 % while ω can be estimated as follows. Once the forward and backward hemispheres are identified, event by event, with some criterion, the charge separation δ_b^{exp} of the average charges measured in both

Contributing process	LHC LO	LHC NLO	Tevatron LO	Tevatron NLO
$g\overset{(-)}{q} \to V j(j)$	44.3	53.4	3.40	4.77
$q\bar{q} \to V j(j)$	8.4	} 3.7	4.61	} 2.76
$\overset{(-)}{q}\overset{(-)}{q} \to V j(j)$	–		–	
$gg \to V j(j)$	–		–	
Total	52.7	57.1	8.01	7.53
$gb \to Vb(g)$	1.81	} 1.81	0.038	} 0.049
$gg \to Vb(\bar{b})$	–		–	
$\overset{(-)}{q} b \to Vb(\overset{(-)}{q})$	–		–	
$q\bar{q} \to Vb(\bar{b})$	–	0.06	–	0.025
Total	1.81	1.87	0.038	0.074

Table 2: Estimates for the $e^- e^+ j$ and $e^- e^+ b$ cross sections at LHC ($\sqrt{s} = 14$ TeV) and Tevatron ($\sqrt{s} = 1.96$ TeV) in pb. The jet transverse momenta are required to be larger than 50 (30) GeV at LHC (Tevatron) and all pseudorapidities $|\eta|$ smaller than 2.5. The p_t of the leptons is larger than 20 GeV. The separations in the pseudorapidity-azimuthal angle plane satisfy $\Delta R > 0.4$ and $M_{e^- e^+}$ is within the range $[75, 105]$ GeV. $\overset{(-)}{q}$ means summing over q and $\bar{q}$ contributions and $V \equiv Z, \gamma^*$.

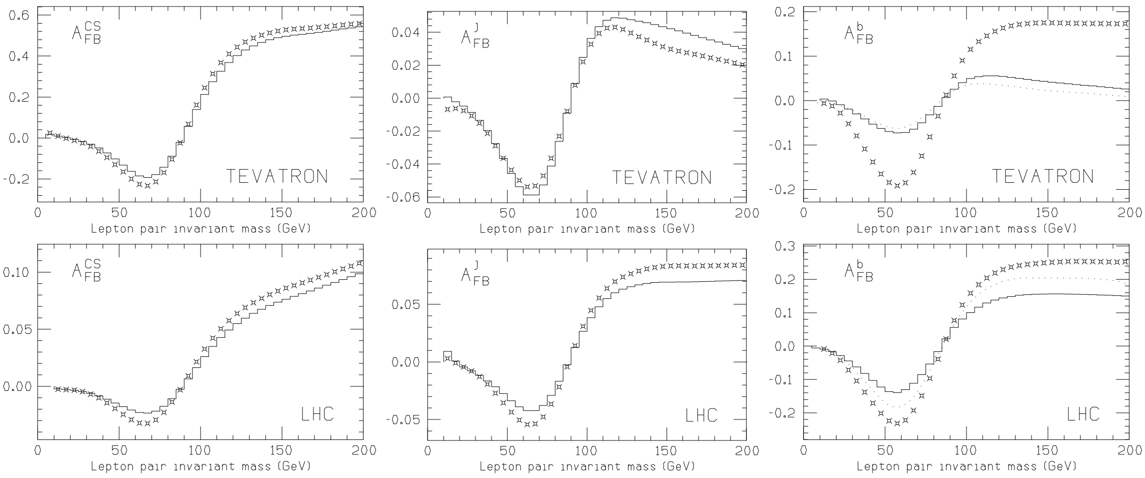

Figure 1: NLO (solid histogram) and LO (points) asymmetries at Tevatron and LHC. The dotted lines refer to the approximation of using only ALPGEN, as described in the text, with $m_b = 4.62$ GeV.

hemispheres can be determined: $\delta_b^{exp} =< Q_b >_F - < Q_b >_B$. A simple calculation yields, for small asymmetries, a relation among δ_b^{exp}, the bare quark charge Q_b and ω: $\delta_b^{exp} = 2Q_b(1-2\omega)$. Using $Q_b = -\frac{1}{3}$, together with the experimental LEP value $\delta_b^{\rm exp} = -0.21$ [5], gives $\omega \sim 0.34$. This loss of precision is partly compensated by the fact that the Table refers to b production only; adding $\bar{b}$ doubles the available statistics. At any rate approaching the quoted precisions will be an experimental challenge.

Another source of uncertainty, that is not accounted for in Table 3, is the dependence of the asymmetries on the chosen set of parton densities. We investigated it by recomputing them with

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LO / NLO	σ(pb)		$\mathrm{A_{FB}}$	$\delta\mathrm{A_{FB}}$	$\delta \sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$
LHC	$\sigma^{Vj} = 53$	$A_{\mathrm{FB}}^{\mathrm{CS}}$	8.7×10^{-3}	4.4×10^{-4}	1.3×10^{-3}
	57		6.8×10^{-3}	4.2×10^{-4}	1.3×10^{-3}
		A_{FB}^{j}	1.2×10^{-2}	4.4×10^{-4}	8.8×10^{-4}
			1.1×10^{-2}	4.2×10^{-4}	1.1×10^{-3}
	$\sigma^{Vb} = 1.8$	A_{FB}^{b}	7.5×10^{-2}	2.3×10^{-3}	8.7×10^{-4}
	1.9		4.9×10^{-2}	2.3×10^{-3}	1.4×10^{-3}
Tevatron	$\sigma^{Vj} = 8.0$	$A_{\mathrm{FB}}^{\mathrm{CS}}$	6.4×10^{-2}	3.5×10^{-3}	1.4×10^{-3}
	7.5		5.5×10^{-2}	3.6×10^{-3}	1.7×10^{-3}
		A_{FB}^{j}	9.9×10^{-3}	3.5×10^{-3}	8.1×10^{-3}
			1.1×10^{-2}	3.6×10^{-3}	7.2×10^{-3}
	$\sigma^{Vb} = 0.04$	A_{FB}^{b}	5.5×10^{-2}	5.1×10^{-2}	2.5×10^{-2}
	0.07		2.7×10^{-2}	3.7×10^{-2}	4.7×10^{-2}

Table 3: 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 first row of each entry is the LO result, while the second one is the NLO. The integrated luminosity and the cuts can be found in the text. The statistical precisions are also given.

different parton distribution sets in the classes `cteq` and `mrst`. By doing so, variations of the asymmetries of the order of 10% can be easily observed around the Z peak at both colliders. This important dependence on the parton densities can be considered as an extra handle provided by the asymmetry measurements in constraining the parton distribution functions. Conversely, with a more precise knowledge of them, the charge asymmetries can be used for precision measurements.

Although a complete NLO result is essential to predict the correct production rates, a realistic experimental analysis is better performed with a tree level program allowing an easier interface with parton shower and hadronization packages [2]. While this looks feasible in the Vj case, the stronger impact of the NLO corrections seems to prevent this possibility for the Vb production process. A possible way out is using a program as ALPGEN and produce the Vb final state only through the tree level $gg \to Vb(\bar{b})$ and $q\bar{q} \to Vb(\bar{b})$ subprocesses. The former rate is finite when computed with $m_b \neq 0$. As a result of such approximation one gets the dotted lines of Figure 1, that provide a good approximation to the exact asymmetries around the Z peak. As a drawback of this approach wrong rates are obtained, namely $\sigma^{Vb} = 1.0$ (0.04) pb at LHC (Tevatron) to be compared with the NLO numbers in Table 3. Therefore a K factor should be included. A rather easy way to achieve this is using a fake b mass. We checked that with $m_b \sim 1$ GeV the correct Vb production rate is reproduced at Tevatron, leaving the corresponding asymmetry nearly unchanged.

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