Bounding $W - W'$ Mixing with Spin Asymmetries at RHIC

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The W boson can obtain a small right-handed coupling to quarks and leptons through mixing with a hypothetical W' boson that appears in many extensions of the standard model. Measuring or even bounding this coupling to the light quarks is very challenging. Only one model independent bound on the absolute value of the complex mixing parameter has been obtained to date. Here we discuss a method sensitive to both the real and CP-violating imaginary parts of the coupling, independent of assumptions on the new physics, and demonstrate quantitatively the feasibility of its measurement at RHIC.

As is well known, the observed asymmetry between matter and antimatter in the Universe requires one or more new sources of CP violation, which is one of the main reasons why physics beyond the standard model (SM) is expected. One such source can arise from a heavier version of the W boson of the weak interaction, generically called W' boson, which appears in many extensions of the SM. From experimental searches it is known that its mass would have to be larger than at least 700 GeV [1,2]. Direct searches for this hypothetical particle thus require TeV range colliders such as Fermilab's Tevatron or CERN's Large Hadron Collider. Although the 0.5 TeV center of mass energy of the proton-proton collisions at BNL's Relativistic Heavy Ion Collider (RHIC) is too small to observe the W' boson directly, it could still be probed through its mixing with the W boson. This possibly CP-violating mixing causes a right-handed coupling of the W boson to the fermions of which the size and CP-violating phase are flavor dependent and *a priori* independent of the W' mass. Neither Tevatron nor LHC will be able to set competitive, model independent bounds on this particular coupling to the light quarks, which requires accurate selection of definite helicity states. As will be discussed, RHIC does have the capability to measure or bound this coupling, including its CP-violating part. The ability to control the polarization states of the colliding protons at RHIC offers a unique advantage that compensates for the lower energy. This allows one to filter out dominant SM contributions to become directly sensitive to new physics [3–6]. Here we will outline the relevant observables and the possibility to measure them at RHIC specifically. We will leave the calculational details for a future publication, highlighting here only certain aspects and results in order to expedite the experimental investigation. In 2009 RHIC had its first polarized proton collisions at 0.5 TeV, which has already delivered the first nonzero measurement of a parity-violating single longitudinal spin asymmetry in W production [7]. The measurements discussed here require extensive running with transversely polarized beams, like for the planned polarized Drell-Yan measurements [8,9].

The process under consideration is that of W-boson production from the collision of two transversely polarized protons. In the SM the coupling of the W boson to the quarks is purely of $V - A$ character: i.e., it couples only to left-handed quarks. If the coupling is not purely $V - A$, for instance due to some as yet unknown physics beyond the SM, the cross section for the collision of two protons polarized transversely with respect to their momenta ceases to be spherically symmetric around the collision axis.

If the produced W boson decays into an electron (or muon) and its associated neutrino, then the electron direction can exhibit a $\cos2\phi$ and $\sin2\phi$ distribution with respect to the direction set by the spins, cf. Fig. 1. The $\sin2\phi$ asymmetry is of particular interest since it probes CP violation beyond the SM, as was pointed out ten years ago in Ref. [5]. Here we will demonstrate quantitatively the feasibility of measuring these asymmetric distributions at RHIC and discuss several essential issues, such as the required accuracy, the optimal experimental cuts, SM background contributions, independence of assumptions on the new physics, and the uncertainty from the transversely polarized quarks and antiquarks distributions.

The reason for the asymmetries in the ϕ distribution is the following. Quarks in a transversely polarized proton are
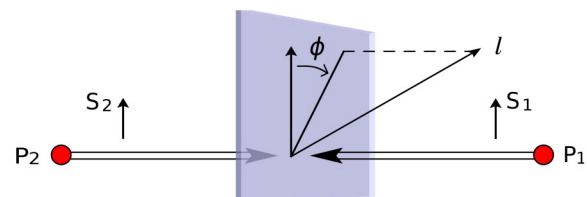

FIG. 1 (color online).   A leptonic decay of a W boson produced in a transversely polarized proton collision. The transverse momentum of the outgoing lepton l defines the azimuthal angle ϕ with respect to the transverse spins S_1, S_2 of the colliding protons.

also to some extent transversely polarized, with a probability described by the so-called transversity distribution [10]. A cross section is only sensitive to transverse polarization through the interference of left- and right-handed chirality states. Since the SM $V - A$ coupling of the W boson to the quarks only occurs for fixed (left-handed) chirality, no sensitivity to transverse polarization occurs in W-boson production [11], except through extremely small higher order quantum corrections. As a consequence, double transverse spin asymmetries will be negligibly small in the SM. Nonzero asymmetries would indicate a coupling of the W boson to right-handed quarks. This can, e.g., arise from the mixing with a hypothetical W' boson. Such a boson arises in theories in which a $SU(2)_R \otimes SU(2)_L$ gauge group is spontaneously broken to $SU(2)_L$ at some scale higher than the electroweak symmetry breaking scale. Examples are left-right symmetric models [12,13], Little(st) Higgs models [14], SUSY $SO(10)$ [15] and SUSY E_6 [16] models. Here we will consider a general model which is not specific to any of these scenarios. It consists of a W_L- and W_R-boson coupling to left- and right-handed particles with strength g_L and g_R, respectively. These states will mix to form two mass eigenstates

$$
\begin{aligned}
W_1^- &= \cos\zeta W_L^- - e^{i\omega}\sin\zeta W_R^-, \\
W_2^- &= \sin\zeta W_L^- + e^{i\omega}\cos\zeta W_R^-,
\end{aligned}
\tag{1}
$$

where W_1 is identified with the observed W boson and W_2 with the W' boson. Strictly speaking, new physics could lead to an effective coupling of the SM W boson to the right-handed quarks and leptons, without the existence of a W' boson. However, this scenario is also covered by letting $M_{W_2} \to \infty$, while keeping ζ fixed. Moreover, as far as a renormalizable extension of the SM is concerned, the W' boson is the least exotic option. A nonzero value of ζ will cause the aforementioned $\cos 2\phi$ asymmetry to appear and if also ω is nonzero, this will reveal itself through a $\sin 2\phi$ asymmetry.

Bounds on the mixing angle ζ are often derived by measuring the right-handed coupling of the W boson to leptons. In any process a vanishing right-handed coupling to the leptons can result from the right-handed neutrino, being too heavy to be produced. Therefore, it is important to test the right-handed coupling of the W boson to leptons and quarks independently. The method discussed here measures the right-handed coupling to quarks and is therefore independent from the as yet unknown right-handed neutrino mass. Also, since the coupling (including the phase) can be different for every generation of quarks, there is no reason why that coupling in the light quark sector should be the same as for the heavier quarks. In view of family symmetry studies, it is important to measure the couplings for all three families separately. Here we will focus on the light quarks, which always suffer from additional uncertainties from nonperturbative strong interaction effects.

The strongest bound available on ζ for quarks is, according to the Particle Data Group [17], $\zeta < 0.003$ [18]. This bound from neutron β decay is obtained under a very strong assumption: manifest left-right symmetry. This assumes Dirac-type neutrinos, an equal coupling constant for the left and right $SU(2)$ gauge group, equal unitary left and right Cabibbo-Kobayashi-Maskawa (CKM) matrices and no complex mixing, i.e. $\omega = 0$. These assumptions have been questioned in Ref. [19] and the resulting bound should not be taken at face value. The method discussed here is independent of any of these assumptions. The best bound available *without* assumptions of light right-handed neutrinos or manifest left-right symmetry is $\zeta < 0.04$ [20]. This has been measured in νN deep inelastic scattering (DIS), which is in fact the *only* way in which a model independent bound on ζ has been obtained. Recently, there has been much discussion about the determination of $\sin^2\theta_W$ from νN DIS [21], where doubts about the employed nuclear parton densities have been raised [22,23]. Also, the strange quark can play a significant role (cf., e.g., [24]), such that it involves two generations in contrast to neutron β decay. This together with the fact that there is just one model independent bound begs confirmation.

Most observables sensitive to $W - W'$ mixing only allow one to constrain or measure ζ. The best and possibly only bound on ω can be obtained from the bound of Ref. [25] on imaginary couplings in neutron β decay. Under the assumptions that the SM contributions do not lead to imaginary parts and that the right-handed neutrino mass is larger than $m_n - m_p - m_e \approx 0.8$ MeV, one obtains $2\zeta \sin\omega = 0.0012(19)$, which together with the best bound on ζ translates into $\omega < 0.03$ (for W^- bosons). The $\sin 2\phi$ asymmetry at RHIC will be capable of determining or bounding the *CP*-violating phase ω for the light quarks without these assumptions, albeit not down to such low values. Nevertheless, it would be worthwhile to obtain an independent bound on ω, free of right-handed neutrino mass assumptions.

Now we turn to the asymmetry estimates. In lowest order in the electroweak and strong coupling constants α and α_s, the observable under consideration becomes a product of transversely polarized quark and antiquark distributions (denoted by h_1^q and $h_1^{\bar{q}}$) convoluted with the process of quark-antiquark annihilating into a W boson. A first determination of the transversity distribution for up and down quarks was obtained recently using semi-inclusive deep inelastic scattering and electron-positron annihilation data [26]. Given the considerable uncertainties in this determination, below we will simply take $h_1^q(x) = f_1^q(x)/2$, which is slightly above the best fit, but certainly compatible with it within errors and is in reasonable agreement with lattice results for the integral over the momentum fraction x that requires somewhat larger h_1 [27]. Here f_1 denotes the unpolarized quark distribution. From Ref. [28] it can be concluded that for the relevant x values

($x \sim 0.2$) in W production at RHIC at 0.5 TeV, the ratio $h_1^q(x)/f_1^q(x)$ has little scale dependence.

The absence of experimental data on the antiquark transversity $h_1^{\bar{q}}$ prevents making absolute predictions for the asymmetries discussed here, but for estimates we will use $h_1^{\bar{q}}(x) = f_1^{\bar{q}}(x)/2$, which allows for easy rescaling of the results in the future. This choice is below its maximally allowed value given by the Soffer bound $|h_1^{\bar{q}}(x)| \leq \frac{1}{2}[f_1^{\bar{q}}(x) + g_1^{\bar{q}}(x)]$, where g_1 denotes the helicity distribution. The assumption $h_1^{\bar{q}}(x) = f_1^{\bar{q}}(x)/2$ may nevertheless be an overestimate, since the scale dependence of the ratio $h_1^{\bar{q}}(x)/f_1^{\bar{q}}(x)$ is not negligible. It decreases by about a factor of 2 from low energy hadronic scales to the relevant energy scale set by the W mass [28]. Fortunately, at RHIC the product $h_1^q(x_1)h_1^{\bar{q}}(x_2)$ can be measured from a spin asymmetry in the Drell-Yan process [10,28]. Hence, the uncertainty in the asymmetry bounds below coming from the transversity distributions can in principle be eliminated from the analysis.

We will look at both positively and negatively charged W-boson production. We restrict our study to their leptonic decay, which means the W momentum cannot be determined. The three independent kinematic variables that can be measured are chosen to be the transverse momentum of the charged lepton l_T, its rapidity Y and the angle ϕ in the plane perpendicular to the beam axis. We will not give the full differential cross section here (cf. [29]), but immediately turn to the asymmetries between the processes with parallel and antiparallel proton spins, given by the cross sections $d\sigma^{\uparrow\uparrow}$ and $d\sigma^{\uparrow\downarrow}$, respectively. We define symmetric and antisymmetric cross sections as $d\sigma \equiv \frac{1}{2}(d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow})$ and $\delta d\sigma \equiv \frac{1}{2}(d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow})$. The latter cross section is a function of ϕ. We define two independent transverse spin asymmetries that select the $\cos 2\phi$ and $\sin 2\phi$ contributions respectively, by appropriate integration over the azimuthal angle

$$A_{TT} \equiv \frac{(\int_{-\pi/4}^{\pi/4} - \int_{\pi/4}^{3\pi/4} + \int_{3\pi/4}^{5\pi/4} - \int_{5\pi/4}^{7\pi/4})d\phi\, \delta d\sigma}{\int_0^{2\pi} d\phi\, d\sigma},$$

$$A_{TT}^{\perp} \equiv \frac{(\int_0^{\pi/2} - \int_{\pi/2}^{\pi} + \int_{\pi}^{3\pi/2} - \int_{3\pi/2}^{2\pi})d\phi\, \delta d\sigma}{\int_0^{2\pi} d\phi\, d\sigma}. \quad (2)$$

The asymmetries depend on the center of mass energy and the cuts imposed on the Y and l_T integrations. Transversely polarized proton-proton collisions are only planned at RHIC, therefore, the center of mass energy is chosen to be 0.5 TeV. The parton distribution functions f_1 are taken from the CTEQ5 LO pdf set [30]. Strange quark contributions are small and will be neglected.

The asymmetries for $W^{\pm}$ production (indicated by a $\pm$ superscript) are now given by

$$A_{TT}^{\pm} = A^{\pm}\zeta_g \cos\omega, \quad \text{and,} \quad A_{TT}^{\perp\pm} = B^{\pm}\zeta_g \sin\omega, \quad (3)$$

for both beams fully transversely polarized. Here the complex phase δ_{ud} of the right-handed CKM-matrix element,

$V_{ud}^R = e^{i\delta_{ud}}|V_{ud}^R|$, that cannot be distinguished from ω, is absorbed into ω. Also, the ratio of left and right coupling constants and CKM-matrix elements is conventionally absorbed into $\zeta_g \equiv \zeta g_R|V_{ud}^R|/g_L|V_{ud}^L|$. Only terms up to first order in ζ_g are kept.

In Table I the values of $A^{\pm}$ and $B^{\pm}$ are given in leading order (LO) approximation. The coefficient B is antisymmetric in Y; therefore, it is calculated for *half* the indicated rapidity interval. One can still use both forward and backward events by taking into account this minus sign; therefore, the cross section is calculated for the *full* rapidity range. The indicated range is covered by the central detector of the STAR experiment at RHIC. To optimize the discovery potential, i.e., the ratio of the expected asymmetry to the expected statistical error, for B the most central region is excluded as it vanishes at zero rapidity. The l_T range has a lower cutoff, as the asymmetry decreases at low l_T. The optimal values are given in the table. At next-to-leading order the cross sections are typically 25%–40% larger.

Crucial for the possibility to measure or exclude new physics, is the expected accuracy in the determination of the double spin asymmetries. Translating the best model independent bound on the right-handed coupling of the W boson to the light quarks [20], $\zeta_g < 0.04$, into the asymmetries results in $|A_{TT}^+| < 0.9\%$ and $|A_{TT}^{\perp+}| < 0.6\%$. If at RHIC the original design integrated luminosity of 800 pb^{-1} and polarizations $\mathcal{P}_1$ and $\mathcal{P}_2$ of 70% are achieved [8], we estimate (in agreement with [31]) the error in the spin asymmetry $\delta A_{TT} = 1/(\mathcal{P}_1\mathcal{P}_2\sqrt{L\sigma})$ to be on the percent level. If a bound of $|A_{TT}^+| < 1\%$ and $|A_{TT}^{\perp+}| < 1\%$ in W^+ production would be obtained, then the bounds on the mixing become $|\zeta_g \cos\omega| < 4.5\%$ and $|\zeta_g \sin\omega| < 6.3\%$, showing that RHIC can deliver competitive bounds, see Fig. 2. Of course, the main uncertainty in these numbers comes from the unknown magnitude of the antiquark transversity distribution, which we emphasize can be determined simultaneously at RHIC from an independent asymmetry measurement.

We end with a discussion of the expected background. Deviations from the SM $V - A$ coupling may be generated effectively in higher orders in α or α_s, for instance by the exchange of a Higgs boson or gluon between the annihilating $q\bar{q}$ pair. Such higher order corrections are all sup-

TABLE I. Coefficients and cross section at $\sqrt{s} = 0.5$ TeV, rapidity range $|Y| \leq 1$ and transverse momentum interval $31 \leq l_T \leq 45$ GeV for $A^{\pm}$ and σ_1, $0.3 \leq |Y| \leq 1$ and $35 \leq l_T \leq 45$ GeV for $B^{\pm}$ ($Y > 0$) and σ_2.

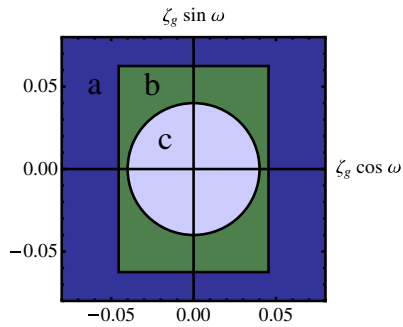|	W^+	W^-	$W^+ + W^-$
A	-0.22	-0.28	-0.23
B	0.16	-0.12	0.10
σ_1[pb]	40	10	51
σ_2[pb]	18	5.3	23

FIG. 2 (color online). Example exclusion plot of ζ_g and ω if the asymmetries $|A_{TT}^+|$ and $|A_{TT}^{\perp+}|$ will be bounded by 1%. The region (a) would be excluded by both the best existing model independent bound [20] *and* the new asymmetry measurements, region (b) would be excluded by the existing bound, and region (c) would be allowed by both measurements.

pressed by a factor of $\alpha_{(s)} m_u m_d / M_W^2$ producing unmeasurably small asymmetries. Higher twist QCD corrections and partonic transverse momentum effects beyond collinear factorization may also generate (residual) double transverse spin asymmetries within the SM [32], but are suppressed by at least a factor of M_p^2/M_W^2 [29]. Therefore, in the SM double transverse spin asymmetries in W-boson production are at most of the 10^{-4} level.

We expect the largest experimental background to come from misidentified events. This can be caused by missing a lepton from a neutral current event interpreted as a neutrino from a charged current event. The cross section for such a missing lepton with $|Y| > 1$ is in the order of a picobarn, leading to false A_{TT} asymmetries smaller than 10^{-3}. For $A_{TT}^{\perp}$ the only neutral current contribution comes from the interference of photon and Z-boson contributions. It is proportional to the Z-boson width. Again this contribution can be safely ignored. Another type of misidentified event can come from heavy quark decays, but this background is largely removed together with the cuts that remove dijet events [7].

In conclusion, without background to worry about, the double transverse spin asymmetry in leptonic decays from W bosons produced in polarized proton-proton collisions is a very clean and promising way to study *separately* the mixing angle and CP-violating phase arising from a hypothetical W' boson. We have estimated the size of the asymmetries, without any model dependent assumptions regarding the right-handed sector. These estimates do depend on an assumption about the unknown distribution of transversely polarized antiquarks, but this can be determined simultaneously through a measurement of the polarized Drell-Yan process. We find that at RHIC, which is the only high energy polarized proton collider, competitive bounds may be set if design goals will be reached at 0.5 TeV. Since there is only one model independent bound on the $W - W'$ mixing angle, this is a highly desirable measurement.

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