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Properties of the $b\bar{b}g$ Vertex *

R. Plano
U.S. Department of Energy, Germantown, MD 20874, USA
on leave from Rutgers University, Piscataway, NJ 08855

Representing The SLD Collaboration**
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Abstract

We have used the unique strengths of the SLAC Linear Collider (SLC) and the SLD detector to study some important properties of the $b\bar{b}g$ vertex. Using the excellent impact parameter resolution to identify and tag jets produced by light quarks, by charmed quarks, or by bottom quarks, we have measured the lack of dependence of the strong coupling α_s on quark flavor to within 1.6% (uds), 7.9% (c), and 3.1% (b). We have set an upper limit of less than 7% on an anomalous chromomagnetic coupling at the $b\bar{b}g$ vertex. Finally we have shown the parity violation and symmetry properties of the $b\bar{b}g$ vertex agree with QCD calculations to the 10% level.

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1 Introduction

The $q\bar{q}g$ vertex observed in three-jet hadronic decays of the Z^0 gauge boson produced in e^+e^- collisions is well identified and measured by the SLD detector, and sensitive to a variety of new physics. These studies are made possible by the strengths, some unique, of the SLC/SLD accelerator/detector combination [1].

These strengths include:

- A micron-sized interaction region whose position is stable and measurable to 7 microns.
- High and well-known e^- beam polarization which averaged 72% for the data presented here (1993-95 runs).
- An excellent vertex detector with 130 million pixels [2]. This, combined with the central drift chamber [3] and the small and stable interaction region permits the determination of impact parameters in a plane perpendicular to the beam axis to an accuracy of $11 \oplus 70/(p_\perp \sqrt{\sin\theta})$ μm. θ is the angle between the track and the beam axis and $p_\perp$ is the component of the track's momentum perpendicular to the beam axis.
- Good particle identification, provided especially by the Cerenkov Ring-Imaging Detector (CRID) [4].

As exploited in the analyses described in this paper, these features allow efficient identification of individual jets as originating from light (uds), charmed (c), or bottom (b) quarks. This efficiency is the basis of a sensitive test of the flavor independence of the strong coupling.

Further, $q\bar{q}g$ events with explicit tagging of the jet originating from the quark, the jet from the antiquark, and the jet from the gluon allows detailed studies of the structure of these events. The studies reported here include:

- An improved study of the flavor independence of the strong interactions.
- A new study of the gluon energy spectrum which is sensitive to anomalous couplings.
- A new study of parity violation in $e^+e^- \to Z^0 \to b\bar{b}g$ events [5].
- New studies of T_N and CP symmetry properties.

It is worth noting that the b quark is the heaviest quark accessible at Z^0 energies and so is most sensitive to new physics beyond the standard model. These studies are also useful as an important input to electroweak studies including determination of R_b and A_b ($Z^0 \to b\bar{b}$ branching ratios and asymmetries).

2 Flavor Independence of α_s

An interesting check of the Quantum Chromodynamics (QCD) can be carried out by testing whether the strong coupling constant, α_s, is the same for all quark flavors. We have separated events into flavor categories based on N_{sig}, the number of "significant tracks" per event, those tracks with impact parameters in the plane perpendicular to the beam differing from zero by more than three standard deviations ($b/\sigma_b > 3$).

Fig. 1 shows the distributions of N_{sig} for selected hadronic events in the data, as well as from Monte Carlo generated events, which match the data well. The Monte Carlo simulation indicates that the lowest bin $N_{sig} = 0$ contains predominately light (uds) flavor events and that the higher bins are predominately b-flavor events. For fitting, the events were divided into five flavor-tagged samples, one for each of the four lower N_{sig} bins, and the fifth for $N_{sig} > 3$.

Events were classified as 2- or 3-jet events (where 3-jet events included all events with more than two jets) using each of six jet finding algorithms in turn [6]. Tagging efficiencies and sample purities for a typical algorithm are shown in the table in Fig. 1 for 2- and 3-jet events separately.

True relative rates for multijet production in events of each flavor (uds, c, b) were extracted by a maximum likelihood fit to the number of 2- and 3-jet events in each tagged sample, correcting for hadronization effects, detector losses, and tagging biases. The ratio of the strong coupling of each quark type to the average coupling was then calculated, accounting for quark mass effects, and averaged over the six jet-finding algorithms.

The final result, compared to other experiments, is shown in Fig. 2. There is good agreement among the experiments, with no evidence for dependence of the strong coupling on quark flavor. This result is the most precise of those experiments which measure the rates for all three flavors.

3 Search for an Anomalous Chromomagnetic Coupling at the $b\bar{b}g$ Vertex

For this investigation, it is necessary to isolate $b\bar{b}g$ events and identify the gluon jet. To accomplish this, three jet events were selected, the energies of the three jets recalculated using their measured angles to improve the energy resolution, and then ordered such that $E_1 > E_2 > E_3$. Events with exactly two jets tagged as b or $\bar{b}$ by having $\geq$ 2 significant tracks in both jets were retained; the untagged jet in each event was assigned as the gluon jet. The correctness of the tag depended on the energy ordering of the $b/\bar{b}$ tagged jets; 95% for jets 1 and 2, 84% for jets 1 and 3, and 52% if jets 2 and 3 (the two lowest energy jets) were the $b/\bar{b}$ tagged jets. The gluon energy distribution was then fit using a Lagrangian with a 'chromomagnetic' moment term, κ:

$$\mathcal{L}^{b\bar{b}g} = g_s \bar{b} T_a \{\gamma_\mu + \frac{i\sigma_{\mu\nu}k^\nu}{2m_b}(\kappa - i\tilde{\kappa}\gamma_5)\} b G_a^\nu \tag{1}$$

The 'chromoelectric' term proportional to $\tilde{\kappa}$ was neglected; it would give rise to CP-violating effects and is expected to be very small. The data and curves [7] showing the sensitivity to κ are shown in Fig. 3. The fit gives $\kappa = -0.03 \pm 0.06 \pm 0.02$ with $\chi^2 = 1.39$ per degree of freedom. The data are consistent with QCD and show no evidence for an anomalous coupling.

4 Parity Violation in $Z^0 \to b\bar{b}g$.

The expected angular distribution of the b-quark in $Z^0 \to b\bar{b}g$ events produced in e^+e^- interactions where the e^- polarization is P_e is:

$$\frac{d\sigma}{dx} = (1 - P_e A_e)(1 + \alpha x^2) + 2A_P(P_e - A_e)x$$

Here $x = \cos\theta$ where θ is the polar angle of the b-jet axis, $A_e \approx 0.161$, $A_P = 0.93A_b \approx 0.87$, where $A_b = 0.94$ in the Standard Model and 0.93 is a QCD correction[5]. $P_e = 0.72$ for this data.

For this analysis and for the symmetry tests in the next section, the same procedure is used. 3-jet events are selected and the energies calculated using the measured angles. At least one jet must have a reconstructed secondary vertex with a P_t corrected mass [8] $M_{P_t} > 1.5$ GeV/c^2. This procedure results in a sample of 3420 events which contains 63% of the $b\bar{b}g$ events with a purity of 87%. To decide which jet is the b-jet – necessary for the parity violation measurement and the CP odd test in the next section – the momentum weighted jet charge is used:

$$Q_{jet} = \Sigma q_i \left| \vec{p_i} \cdot \hat{P_j} \right|^{0.5}$$

Here $\hat{P_j}$ is the unit vector along jet j, and q_i, p_i are the charge and momentum of the i^{th} track associated with jet j. We then examine $Q_{diff} = Q_1 - Q_2 - Q_3$. If Q_{diff} is negative(positive), jet 1 is tagged as the b-jet ($\bar{b}$-jet).

Fig. 4 shows the left-right-forward-backward asymmetry in the polar angle of the b-jet relative to the e^- beam polarization. A fit to the data gives $A_P = 0.987 \pm 0.093 \pm 0.072$ [12] where 0.87 is expected. Again the results are fully consistent with the Standard Model.

5 Symmetry Tests in $Z^0 \to b\bar{b}g$.

Two T-odd angular correlations between the three-jet plane and the Z^0 spin are studied in a measurement sensitive to physics beyond the standard model. The test is made by examining the angular distribution of the normal to the 3-jet plane relative to the spin vector of the Z^0:

$$\frac{d\sigma}{dy} = (1 - P_e A_e)(1 - \frac{1}{3}y^2) + 2A_T(P_e - A_e)y$$

Here $y = \cos\omega = \vec{\sigma_Z} \cdot \hat{n}$ where $\vec{\sigma_Z}$ is the spin of the Z^0, which is in the direction of the electron polarization, and $\hat{n}$ is a normal to the 3-jet plane.

The data are analyzed similarly to the previous analysis, with one addition relevant to the CP odd asymmetry for which both the b-jet and $\bar{b}$-jet must be identified. Jet 3 is tagged as the gluon jet (meaning jet 2 is a b- or $\bar{b}$-jet) unless jet 2 had no significant track and jet 3 had at least one, in which case jet 2 was tagged as the gluon-jet.

If the normal to the 3-jet plane is chosen to be $\hat{n} \sim \vec{p_1} \times \vec{p_2}$ (energy ordered), a CP-even angular asymmetry results. If, however, $\hat{n} \sim \vec{p_b} \times \vec{p_{\bar{b}}}$ (flavor ordered), a CP-odd angular asymmetry results. The selection procedure described above produces the correct sense for the normal to the three jet plane 67% of the time in the CP-odd case and 76% in the CP-odd case.

The results of the fits are $A_T^+ = -0.002 \pm 0.027$ and $A_T^- = -0.011 \pm 0.053$, where A_T^+ describes the CP-even asymmetry and A_T^- describes the CP-odd asymmetry. 95% confidence limits are $-0.056 < A_T^+ < 0.051$ and $-0.115 < A_T^- < 0.093$, again consistent with predictions of the Standard Model and QCD, which predicts $|A_T| \leq 10^{-5}$ [9].

6 Summary

The excellent b and $\bar{b}$ jet tagging capabilities of the SLC/SLD experiment, especially for softer jets, allows a detailed study of the $q\bar{q}g$ structure. These capabilities make the following results possible:

- Updated tests of the flavor independence of α_s limiting the dependence to a few percent [10],
- A new measurement of the gluon energy spectrum in $Z^0 \to b\bar{b}g$ yielding a 95% confidence level constraint on an anomalous chromomagetic contribution of $-0.15 < \kappa < 0.09$ [11].
- A new test of parity violation in $Z^0 \to b\bar{b}g$ yielding $A_P = 0.987 \pm 0.093 \pm 0.072$ in agreement with the Standard Model,
- A new test of two asymmetries, sensitive to new physics, limits CP-even and CP-odd asymmetries, both T_N-odd to less than 5.6% and 11.5% respectively at the 95% confidence level [12].

With increased data from the upcoming run exploiting an improved vertex detector [13], it is hoped that these errors can be reduced significantly.

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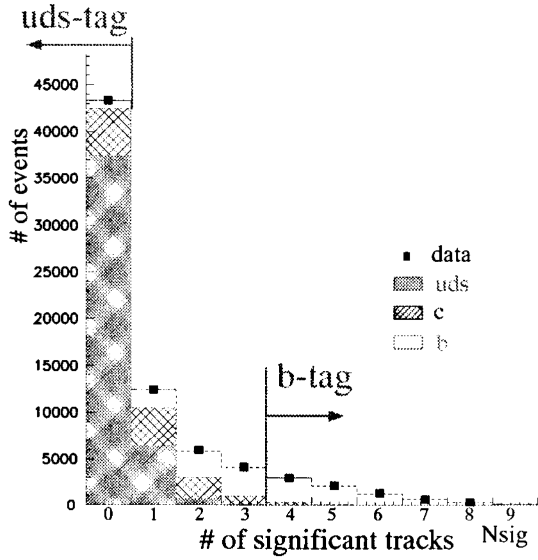
**List of Authors

K. Abe,(19) K. Abe,(30) T. Akagi,(28) N.J. Allen,(4) W.W. Ash,(28)† D. Aston,(28)
K.G. Baird,(24) C. Baltay,(34) H.R. Band,(33) M.B. Barakat,(34) G. Baranko,(9)
O. Bardon,(15) T. L. Barklow,(28) G.L. Bashindzhagyan,(18) A.O. Bazarko,(10)
R. Ben-David,(34) A.C. Benvenuti,(2) G.M. Bilei,(22) D. Bisello,(21) G. Blaylock,(16)
J.R. Bogart,(28) B. Bolen,(17) T. Bolton,(10) G.R. Bower,(28) J.E. Brau,(20)
M. Breidenbach,(28) W.M. Bugg,(29) D. Burke,(28) T.H. Burnett,(32) P.N. Burrows,(15)
W. Busza,(15) A. Calcaterra,(12) D.O. Caldwell,(5) D. Calloway,(28) B. Camanzi,(11)
M. Carpinelli,(23) R. Cassell,(28) R. Castaldi,(23)(a) A. Castro,(21) M. Cavalli-Sforza,(6)
A. Chou,(28) E. Church,(32) H.O. Cohn,(29) J.A. Coller,(3) V. Cook,(32) R. Cotton,(4)
R.F. Cowan,(15) D.G. Coyne,(6) G. Crawford,(28) A. D’Oliveira,(7) C.J.S. Damerell,(25)
M. Daoudi,(28) N. de Groot,(28) R. De Sangro,(12) R. Dell’Orso,(23) P.J. Dervan,(4)
M. Dima,(8) D.N. Dong,(15) P.Y.C. Du,(29) R. Dubois,(28) B.I. Eisenstein,(13) R. Elia,(28)
E. Etzion,(33) S. Fahey,(9) D. Falciai,(22) C. Fan,(9) J.P. Fernandez,(6) M.J. Fero,(15)
R. Frey,(20) T. Gillman,(25) G. Gladding,(13) S. Gonzalez,(15) E.L. Hart,(29) J.L. Harton,(8)
A. Hasan,(4) Y. Hasegawa,(30) K. Hasuko,(30) S. J. Hedges,(3) S.S. Hertzbach,(16)
M.D. Hildreth,(28) J. Huber,(20) M.E. Huffer,(28) E.W. Hughes,(28) H. Hwang,(20)
Y. Iwasaki,(30) D.J. Jackson,(25) P. Jacques,(24) J. A. Jaros,(28) Z. Y. Jiang,(28)
A.S. Johnson,(3) J.R. Johnson,(33) R.A. Johnson,(7) T. Junk,(28) R. Kajikawa,(19)
M. Kalelkar,(24) H. J. Kang,(26) I. Karliner,(13) H. Kawahara,(28) H.W. Kendall,(15)
Y. D. Kim,(26) M.E. King,(28) R. King,(28) R.R. Kofler,(16) N.M. Krishna,(9)
R.S. Kroeger,(17) J.F. Labs,(28) M. Langston,(20) A. Lath,(15) J.A. Lauber,(9)
D.W.G.S. Leith,(28) V. Lia,(15) M.X. Liu,(34) X. Liu,(6) M. Loreti,(21) A. Lu,(5)
H.L. Lynch,(28) J. Ma,(32) G. Mancinelli,(24) S. Manly,(34) G. Mantovani,(22)
T.W. Markiewicz,(28) T. Maruyama,(28) H. Masuda,(28) E. Mazzucato,(11)
A.K. McKemey,(4) B.T. Meadows,(7) R. Messner,(28) P.M. Mockett,(32) K.C. Moffeit,(28)
T.B. Moore,(34) D. Muller,(28) T. Nagamine,(28) S. Narita,(30) U. Nauenberg,(9) H. Neal,(28)
M. Nussbaum,(7)† Y. Ohnishi,(19) N. Oishi,(19) D. Onoprienko,(29) L.S. Osborne,(15)
R.S. Panvini,(31) C.H. Park,(27) H. Park,(20) T.J. Pavel,(28) I. Peruzzi,(12)(b) M. Piccolo,(12)
L. Piemontese,(11) E. Pieroni,(23) K.T. Pitts,(20) R.J. Plano,(24) R. Prepost,(33)
C.Y. Prescott,(28) G.D. Punkar,(28) J. Quigley,(15) B.N. Ratcliff,(28) T.W. Reeves,(31)
J. Reidy,(17) P.L. Reinertsen,(6) P.E. Rensing,(28) L.S. Rochester,(28) P.C. Rowson,(10)
J.J. Russell,(28) O.H. Saxton,(28) T. Schalk,(6) R.H. Schindler,(28) B.A. Schumm,(6)
J. Schwiening,(28) S. Sen,(34) V.V. Serbo,(33) M.H. Shaevitz,(10) J.T. Shank,(3)
G. Shapiro,(14) D.J. Sherden,(28) K.D. Shmakov,(29) C. Simopoulos,(28) N.B. Sinev,(20)
S.R. Smith,(28) M.B. Smy,(8) J.A. Snyder,(34) H. Staengle,(8) P. Stamer,(24) H. Steiner,(14)
R. Steiner,(1) M.G. Strauss,(16) D. Su,(28) F. Suekane,(30) A. Sugiyama,(19) S. Suzuki,(19)
M. Swartz,(28) A. Szumilo,(32) T. Takahashi,(28) F.E. Taylor,(15) E. Torrence,(15)
A.I. Trandafir,(16) J.D. Turk,(34) T. Usher,(28) J. Va’vra,(28) C. Vannini,(23) E. Vella,(28)
J.P. Venuti,(31) R. Verdier,(15) P.G. Verdini,(23) D.L. Wagner,(9) S.R. Wagner,(28)
A.P. Waite,(28) S.J. Watts,(4) A.W. Weidemann,(29) E.R. Weiss,(32) J.S. Whitaker,(3)
S.L. White,(29) F.J. Wickens,(25) D.C. Williams,(15) S.H. Williams,(28) S. Willocq,(28)

R.J. Wilson,(8) W.J. Wisniewski,(28) M. Woods,(28) G.B. Word,(24) J. Wyss,(21)
R.K. Yamamoto,(15) J.M. Yamartino,(15) X. Yang,(20) J. Yashima,(30) S.J. Yellin,(5)
C.C. Young,(28) H. Yuta,(30) G. Zapalac,(33) R.W. Zdarko,(28) and J. Zhou(20)

(1)*Adelphi University, Garden City, New York 11530*
(2)*INFN Sezione di Bologna, I-40126 Bologna, Italy*
(3)*Boston University, Boston, Massachusetts 02215*
(4)*Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*
(5)*University of California at Santa Barbara, Santa Barbara, California 93106*
(6)*University of California at Santa Cruz, Santa Cruz, California 95064*
(7)*University of Cincinnati, Cincinnati, Ohio 45221*
(8)*Colorado State University, Fort Collins, Colorado 80523*
(9)*University of Colorado, Boulder, Colorado 80309*
(10)*Columbia University, New York, New York 10027*
(11)*INFN Sezione di Ferrara and Università di Ferrara, I-44100 Ferrara, Italy*
(12)*INFN Lab. Nazionali di Frascati, I-00044 Frascati, Italy*
(13)*University of Illinois, Urbana, Illinois 61801*
(14)*E.O. Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720*
(15)*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
(16)*University of Massachusetts, Amherst, Massachusetts 01003*
(17)*University of Mississippi, University, Mississippi 38677*
(18)*Moscow State University, Institute of Nuclear Physics 119899 Moscow, Russia*
(19)*Nagoya University, Chikusa-ku, Nagoya 464 Japan*
(20)*University of Oregon, Eugene, Oregon 97403*
(21)*INFN Sezione di Padova and Università di Padova, I-35100 Padova, Italy*
(22)*INFN Sezione di Perugia and Università di Perugia, I-06100 Perugia, Italy*
(23)*INFN Sezione di Pisa and Università di Pisa, I-56100 Pisa, Italy*
(24)*Rutgers University, Piscataway, New Jersey 08855*
(25)*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX United Kingdom*
(26)*Sogang University, Seoul, Korea*
(27)*Soongsil University, Seoul, Korea 156-743*
(28)*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309*
(29)*University of Tennessee, Knoxville, Tennessee 37996*
(30)*Tohoku University, Sendai 980 Japan*
(31)*Vanderbilt University, Nashville, Tennessee 37235*
(32)*University of Washington, Seattle, Washington 98195*
(33)*University of Wisconsin, Madison, Wisconsin 53706*
(34)*Yale University, New Haven, Connecticut 06511*
† *Deceased*
(a)*Also at the Università di Genova*
(b)*Also at the Università di Perugia*



	uds 2jet(3jet)%	charm	bottom
eff.	84.8(80.4)	57.8(52.7)	45.0(34.1)
purity	86.7(83.0)	33.2(28.0)	95.2(94.5)

Figure 1: Number of significant tracks per event in the data compared with the number predicted by a Monte Carlo calculation for uds, c, and b events; the agreement is very good.

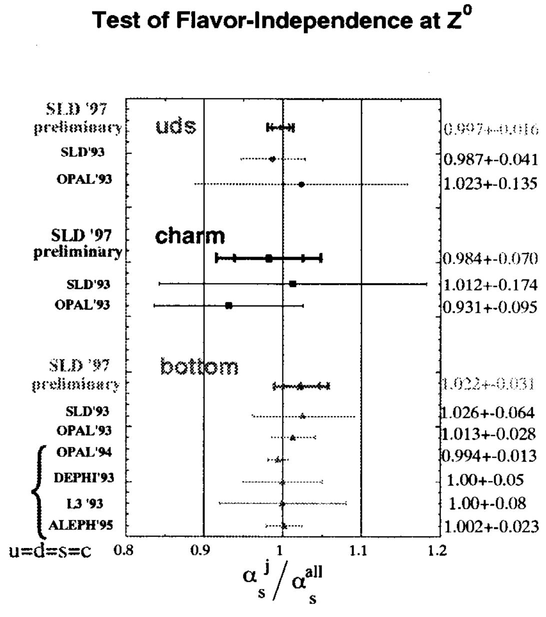


Figure 2: SLD and LEP results on flavor-independence at the Z^0.

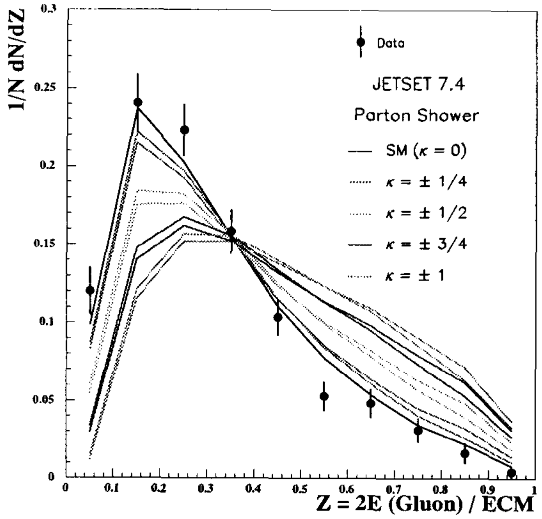


Figure 3: The measured normalized gluon energy spectrum compared with the result of a QCD calculation including several possible values for the chromomagnetic contribution, described by κ. The calculation differs from the data increasingly as the magnitude of κ increases. $\kappa = 0$ is a good fit.

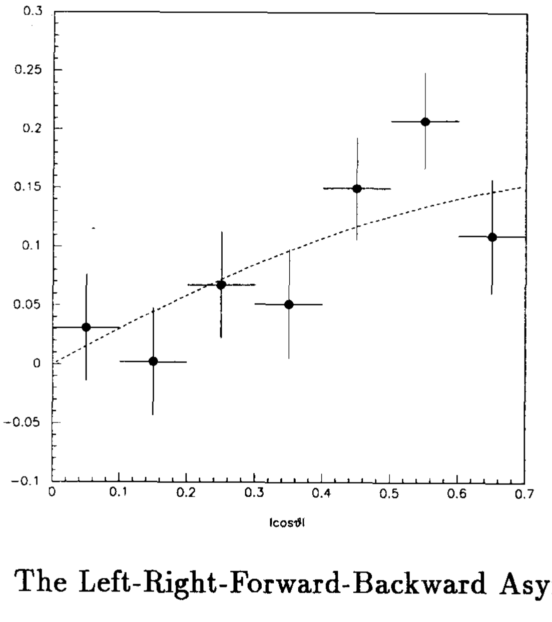


Figure 4: The Left-Right-Forward-Backward Asymmetry