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A determination of α_{strong} with transversally polarized beams at LEP1

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ABSTRACT

We propose a new and rather unbiased way of determining the value of the strong coupling constant α , if transversally polarized electron-positron beams were available at LEP1. The ratio of azimuthal asymmetries for the production of hadrons to muons in e^+e^- annihilation is independent of any cut-off procedure and is very sensitive to the value of α_s . Moreover we show that on top of Z resonance, it is free from any ambiguity stemming from Standard Model unknown parameters or the possible presence of New Physics.

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1 Introduction

The huge number of Z vector bosons that will be accumulated in the four LEP detectors in a very near future, will allow very high precision measurements providing a test of the electroweak sector of the (minimal) Standard Model to the level of its quantum corrections [1]. These high statistics will also be used to look at the strong sector of the theory. Indeed, one a priori knows that due to the purity of the initial state, e^+e^- annihilation at high energies and far from flavor production thresholds is the best place to test perturbative QCD and to determine without any ambiguity the value of its only free parameter α_s [2].

The "cleanest" way of determining the strong coupling constant α_s is to measure the ratio R_h of hadronic to muonic events [2,3]. This is due to the fact that, since at high energies and far from quark flavor production thresholds the produced partons are converted into hadrons with unit probability, no hadronization effects have to be considered. Unfortunately, the α_s correction to the ratio R_h is very small as it only amounts to $\simeq 0.04$ at $\sqrt{s} \simeq M_Z$. Since the experimental error on R_h is expected to be around 0.5–1% at LEP1 [3], one gets a measurement of α_s with an accuracy which is at best of the order of ~ 10 –20%.

The situation becomes worse if one moves from the minimal Standard Model and consider the possibility that some effects due to a new kind of physics beyond it, might show up on Z resonance. Since besides the Z mass which will be used as input parameter, R_h will be the most precisely measurable observable at LEP1, it will be the first to feel any deviation due to some kind of New Physics. This has been illustrated in [4] for the case of new vector bosons originating from an extended gauge structure or from alternative models like those inspired by compositeness. In the latter reference, it has been shown that the additional parameters of the new Z' cannot be constrained by other precision measurements at LEP1, to the level where they have no visible effect on the ratio R_h .

Thus clearly, when attempting to extract a relatively precise value of α_s from the ratio R_h , one has to assume that the minimal version of the Standard Model is correct.

There are also alternative ways of determining the value of α_s in e^+e^- annihilation. One can for instance consider the so-called "three-jet" like quantities [3]. These have been very useful in the past to make important qualitative tests of perturbative QCD and, with the help of the enormous number of hadronic events which will be produced at LEP1 could reach a more quantitative level. In general these quantities are meaningfully defined only through the introduction of a cut-off parameter (e.g the invariant mass of two jets in the case of jet cross-sections). In this case the situation becomes less transparent since this additional parameter often appears as a source of problems. For instance in the case of the "three jet" cross-section [5], the correction is very large for small values of this cut-off and one needs to compute higher order terms to make the QCD prediction reliable. On the other hand if the cut-off is large one has to take into account the non leading terms (which is technically difficult) and even in this case the whole QCD correction is so small that the extracted value of α_s hardly

competes with the measurement of the latter via the inclusive quantity R_h . Moreover one has to deal with non perturbative effects and thus rely on models for quark and gluon fragmentation.

In the present paper, we would like to point at another possibility of determining the value of the QCD coupling constant α_s , if the initial electron/positron beams were suitably transversally polarized at LEP1. As we shall show, the ratio of azimuthal asymmetries of hadron to muon production $R_{\perp}^{\text{had}}$ is inclusive (in the sense that it is independent of any cut-off procedure), completely free of pure electroweak physics "backgrounds" and particularly sensitive to the value of the strong coupling constant.

2 Transverse Asymmetry

The characteristic feature of transversally polarized electron/positron beams is to generate an azimuthal angular dependence of the cross-section $e^+e^- \rightarrow \text{fermions}$. To carry on our investigation of the properties of the transverse asymmetry we consider the general inclusive process

$$e^+(l', P'_{\perp}) e^-(l, P_{\perp}) \rightarrow q + X \quad X \equiv q \text{ or } q + g$$

where $P'_{\perp}$ and $P_{\perp}$ are the transverse polarizations of the initial leptons. Through $\alpha, \beta = \gamma$ or Z exchange, the differential cross-section in the e^+e^- CM frame, with the polar angle θ and the azimuthal angle ϕ specifying the direction of the quark with respect to the incoming electron, can be written as [6]

$$\begin{aligned} \frac{d\sigma}{d\Omega} = & \frac{\alpha^2}{4s} \beta_q \left\{ (V_{\alpha} V_{\beta}^* + A_{\alpha} A_{\beta}^*) [(1 + \cos^2 \theta) \sigma_U + 2 \sin^2 \theta \sigma_L] + 2(V_{\alpha} A_{\beta}^* + A_{\alpha} V_{\beta}^*) \cos \theta \sigma_F \right. \\ & \left. + P_{\perp} P'_{\perp} [(V_{\alpha} V_{\beta}^* - A_{\alpha} A_{\beta}^*) \cos 2\phi + i(V_{\alpha} A_{\beta}^* + A_{\alpha} V_{\beta}^*) \sin 2\phi] \sin^2 \theta (\sigma_U - 2\sigma_L) \right\} \quad (1) \end{aligned}$$

with:

$$V_{\gamma}(A_{\gamma}) = v_e^{\gamma}(a_e^{\gamma}) \quad V_Z(A_Z) = \frac{v_e^Z(a_e^Z)}{1 - M_Z^2/s + i\Gamma_Z M_Z/s} \quad (2)$$

where v_f, a_f ($f = l, q$) are the coefficients of the fermionic vertex $\gamma_{\mu}(v_f - a_f \gamma_5)$ and β_q the usual threshold factor which, in terms of the CM energy squared $s = (l + l')^2$ and the quark mass m_q reads:

$$\beta_q = \sqrt{1 - 4 \frac{m_q^2}{s}} = \sqrt{1 - \mu^2} \quad (3)$$

The transverse asymmetry for a given quark q will be defined as the relative magnitude of the $\cos 2\phi$ term:

$$A_{\perp}^q(s) = 2 \frac{\int d\Omega \left(\frac{d\sigma}{d\Omega} \right) \cos 2\phi}{\int d\Omega \left(\frac{d\sigma}{d\Omega} \right)} \quad (4)$$

Since this asymmetry is by definition a ratio, it is obviously independent of the overall normalization. At energies around the Z peak, ignoring the very small intermediate photon contribution, it simplifies to (we drop the index Z in the coefficients a_f, v_f):

$$A_{\perp}^q(s \simeq M_Z^2) = \frac{P_{\perp} P'_{\perp}}{2} \frac{v_q^2 - a_q^2}{v_q^2 + a_q^2} \frac{\sigma_U - 2\sigma_L}{\sigma_U + \sigma_L} \quad (5)$$

where at this level the two parton cross-sections σ_U and σ_L read:

$$\sigma_U^q = v_q^2 + \beta_q^2 a_q^2 \quad \sigma_L^q = \frac{1}{2}(1 - \beta_q^2) v_q^2 \quad (6)$$

In this Born approximation and for light ($\beta_q \simeq 1$) quarks, it turns out that the transverse asymmetry is completely independent of the final state couplings (a property shared with the celebrated left-right polarization asymmetry on Z resonance) so that one can sum over all quark flavours and write:

$$A_{\perp}^{\text{had}}(s = M_Z^2) = \frac{P_{\perp} P'_{\perp}}{2} \frac{v_e^2 - a_e^2}{v_e^2 + a_e^2} \quad (7)$$

two welcome advantages being the enormous gain in statistics and the absence of the, experimentally very hard, problem of identifying a given quark flavor¹. Mass effects do not alter this important property of the asymmetry, since the contribution of the b mass amounts to a mere 0.1% and thus, can be safely neglected if the experimental accuracy in the measurement of $A_{\perp}$ were at the 1% level.

Since the degree of the transverse polarization of the initial leptons might be a source of experimental uncertainty, one can get rid of it by considering the ratio of the asymmetry for hadrons and the one for muons. Note that in this ratio, all the systematic errors which are common to hadrons and muons, will be washed out (or at least drastically reduced) in much the same way as for the ratio R_h . Assuming e - μ universality, one has then in the Born approximation and to the above considered accuracy:

$$R_{\perp}^{\text{had}} \equiv A_{\perp}^{\text{had}}(s \simeq M_Z^2) / A_{\perp}^{\mu^+ \mu^-}(s \simeq M_Z^2) = 1 \quad (8)$$

which appears to be independent of the initial state couplings as well. This property of being independent of the initial and final state couplings is very important since it makes this particular asymmetry insensitive to "genuine" electroweak effects. To make this statement more clear, let us review all the possible effects which might lead to a departure of $R_{\perp}^{\text{had}}$ from the value 1.

We shall first discuss the QED corrections as they are rather standard and also because in practice they are detector dependent. The transverse asymmetry $A_{\perp}$ has a very smooth energy dependence around the Z peak. As one can see from Fig.1, it

¹Note that there is still the need of distinguishing between quark and gluon jets, which might be experimentally difficult to perform to the required accuracy. An alternative, that we shall discuss later, is to define the reference axis as the thrust axis.

is practically flat between $M_Z - 2.5$ GeV and $M_Z + 2.5$ GeV, as opposed for instance to the forward-backward asymmetry for muon production on Z resonance, and even to the ratio R_h . This important feature will strongly reduce the uncertainties due to the photonic corrections. Final state QED corrections can be copied from the QCD ones (that we shall discuss later). Their effect is, though, very small ($\sim 0.2\%$) and can be safely neglected.

In the minimal version of the Standard Model (with three generations of fermions and one Higgs doublet) the effect of the "genuine" one loop corrections, and thus the effects of the unknown top and Higgs masses, appears in two ways on top of the Z [1]. The so-called oblique corrections (due to the vacuum polarization functions of the gauge bosons) which are universal and form the bulk of the radiative corrections, can be incorporated by shifting the value of the fine structure constant α and the weak mixing angle $\sin^2 \theta_W$. Note that these corrections contain terms which are quadratic in the unknown top quark mass and would lead to a very large "theoretical uncertainty". The direct corrections, on the other hand, are process dependent. They originate from vertex, fermion self energies and box corrections, and alter the couplings of the fermions to the Z boson:

$$v_f \gamma_\mu + a_f \gamma_5 \gamma_\mu \longrightarrow v_f [1 + F_f^V] \gamma_\mu + a_f [1 + F_f^A] \gamma_5 \gamma_\mu + \frac{i F_f^M}{2m_f} \sigma_{\mu\nu} q^\nu$$

The magnetic type coupling F_f^M is the only term which can alter the asymmetry. However, since it is of order α and always proportional to the fermion masses which are very small compared to the Z mass, no effect from the latter is to be expected in the Standard Model [7]. The two form factors F_f^V and F_f^A can be, in principle, sizeable (especially in the case of the b quark where terms that are quadratic in the top quark mass also show up) but factorize in a_f and v_f . Since $R_{\perp}^{\text{had}}$ is independent of these couplings, and thus independent of α and $\sin^2 \theta_W$, all purely electroweak radiative corrections both direct and oblique, disappear.

This feature can be generalized to all possible manifestations of New Physics which appear via radiative corrections (among these, additional fermion families, the supersymmetric extension of the Standard Model ...etc) or have formally the same structure (for instance, unconventional Higgs representations which translate in a deviation of the ρ parameter from 1) and which do not lead to the alteration of the (axial-) vector type of the coupling of the standard fermions to the Z boson.

In the case of a possible new vector boson Z' , the analysis can be done following the general trend illustrated in ref. [8], i.e considering both models with an enlarged gauge structure and alternative models with composite vector bosons or new Z' originating from a strongly interacting electroweak sector. In all cases it has been shown that the only effects of these new bosons, is to rescale the Z -fermions couplings leaving their (axial-) vectorial character unchanged. This is exactly what radiative corrections do and we have shown that the transverse asymmetry is free of the latter corrections.

The only potential source of alteration may come from new physics leading to large anomalous magnetic moments for the fermions. This would be the case if e.g the fermions were composite objects. But in general one assumes a chiral protection so that the effect is of order m_f^2/Λ^2 where Λ is the compositeness scale which is severely constrained by the $(g-2)_\mu$ [9] for muons and by collider data [10,11] for light quarks and no effect in $R_\perp^{\text{had}}$ is to be expected. This cannot be readily extrapolated to the case of the b quark which, in several models plays a special role. Nevertheless, a large magnetic type coupling of the b quark can be tightly constrained by other precision measurements on Z resonance [12] and its effect on the averaged transverse asymmetry can only be marginal.

Thus, the transverse asymmetry $R_\perp^{\text{had}}$ is free of all effects stemming from the purely electroweak sector and the standard QED effects are well under control. It is however, strongly affected by QCD radiative corrections to which we turn our attention now.

3 QCD Corrections

To incorporate gluonic corrections one has to consider the diagrams given in Fig.2. With the definition of the reference axis as being the quark axis, the QCD corrections to the parton cross sections σ_U and σ_L have been computed in ref. [13] for massive final quarks and later in [14]. Performing an expansion in powers of μ one gets simple analytic formulae for the QCD contribution [15] to be added to the tree level expression (6):

$$\begin{aligned}\sigma_U^1 &= \frac{\alpha_s}{\pi}(v_q^2 + a_q^2) \left[\frac{1}{3} + \mu \frac{\pi^2}{6} + \mu^2 \left(\frac{11}{3} + t \right) - 2\mu^2 \frac{1}{1 + v_q^2/a_q^2} \left(1 + \log \frac{\mu^2}{4} \right) \right] \\ \sigma_L^1 &= \frac{\alpha_s}{\pi}(v_q^2 + a_q^2) \left[\frac{2}{3} - \mu \frac{\pi^2}{6} - \mu^2 \left(\frac{2}{3} + t \right) - \mu^2 \frac{1}{1 + v_q^2/a_q^2} \left(\frac{5}{3} + \log \frac{\mu^2}{4} \right) \right] \\ t &= \frac{\pi^2}{9} + \frac{1}{3} \log 2 + \frac{47}{12} \log \frac{\mu^2}{4}\end{aligned}\tag{9}$$

Retaining only the leading term in the μ expansion, one gets for the transverse asymmetry of a given quark :

$$R_\perp^q = 1 - 2 \left(1 - \mu \frac{\pi^2}{4} \right) \frac{\alpha_s}{\pi} \xrightarrow{\beta_q \rightarrow 1} 1 - 2 \frac{\alpha_s}{\pi}\tag{10}$$

The exact coefficients of $\frac{\alpha_s}{\pi}$, including the subleading terms are displayed for the different quark flavors in Tab.1 . One notices that these coefficients are rather large (~ -2) and that mass effects, contrarily to the tree level case where they played a negligible role, are very important since the correction decreases by roughly a factor $\frac{3}{4}$ when going from the massless case to the case of a massive b quark.

This then gives for the averaged transverse asymmetry $R_{\perp}^{\text{had}}$ defined in eq. (8):

$$R_{\perp}^{\text{had}} = 1 - 1.9 \frac{\alpha_s}{\pi} \quad (11)$$

Note that one can improve the sensitivity in α_s by considering the θ dependence of the asymmetry. From eqs. (1) and (9) restricting to the massless case for simplicity one has:

$$R_{\perp}^q(\theta) = \frac{(1 - \frac{8}{3} \frac{\alpha_s}{\pi})(1 + \cos^2 \theta)}{1 + (1 - \frac{8}{3} \frac{\alpha_s}{\pi}) \cos^2 \theta} \quad (12)$$

which for values of θ close to $\frac{\pi}{2}$ enhances the coefficient of $\frac{\alpha_s}{\pi}$ to $-8/3$. This however would require very high statistics.

Since the asymmetry is defined through the quark direction, one needs to distinguish between gluon and quark jets². This should be feasible since the former are expected to have a much higher multiplicity and a larger width [16]. Alternatively, one can use the very recent method proposed in [18], where it is claimed that the distinction could be done in a very efficient way.

Nevertheless, if it turns out that the separation between quark and gluon jets is a source of a too large experimental error, it will be much more convenient to define the reference axis as being the thrust axis for which this separation is not required. The price to pay, though, is a decrease of the coefficient of $\frac{\alpha_s}{\pi}$.

Indeed, using the latter definition, we computed the QCD corrections to the transverse asymmetry, retaining again the actual quark masses, and we found that changing the reference axis has quite a large impact, since the corrections are now by a factor $\sim \frac{3}{4}$ smaller. The details of the calculation³ will be given elsewhere and here we shall simply summarize our results by means of Tab.2.

Averaging over the five flavors, leads then to a correction:

$$R_{\perp}^{\text{had}} = 1 - 1.42 \frac{\alpha_s}{\pi} \quad (13)$$

This last equation, together with eq.(11), shows that the ratio of the transverse asymmetry for hadrons to muons is rather sensitive to the value of the QCD coupling constant α_s , and thus can be seen as a measurement of this parameter with a precision that will depend on the experimental error. If the latter were of order one percent, the value of α_s could be determined with an accuracy of 10-15%, depending on the choice of the reference axis and the possibility of using the θ distribution. If $R_{\perp}^{\text{had}}$ is not affected by additional errors, this accuracy would be comparable to that from R_h or (and in some cases even better than) that from alternative possibilities [3].

²Quarks and antiquarks jets have the same topology, but the asymmetry is not affected by their exchange.

³Note that in the massless case, our result agrees with the one quoted in [19] once we use the correct differential parton cross section given in the erratum and integrate over the last variable.

Let us now, review the potential uncertainties which might affect this particular asymmetry. Besides the experimental error that we shall assume to be of order 1%, there are uncertainties coming from higher order QCD corrections and from non perturbative effects. For the latter, since the involved physical scale is a typical hadron mass which can be considered to be small compared to the very large momentum transfer in e^+e^- annihilation, one expects that the effect of the primary parton fragmentation is power suppressed with some power of $1\text{GeV}/O(M_Z)$ [3]. To have an idea about the size of this effect we shall attempt to make in what follows, a rough estimate. The main effect of the fragmentation of the primary partons will be to alter their initial direction and energy, leading to an uncertainty on the identification of the reference axis [16]. For instance the direction of the primary parton is no longer the direction of the jet (which can be identified as the one of its most energetic particle), the difference being of the order of a few degrees [17]. Assuming that, when reconstructing the polar and the azimuthal angles of the initial quark or gluon, an uncertainty $\Delta\theta$ and $\Delta\phi$ is generated, this migrates to the asymmetry in the following way (we consider only the numerator of eq.(4), the denominator being simply the total number of events):

$$|\delta R_{\perp}^{\text{had}}| \simeq \frac{1}{2} [(\Delta\theta)^2 + (\Delta\phi)^2] \quad (14)$$

This shows that the error on the asymmetry is only quadratic in $\Delta\theta$ and $\Delta\phi$ and that for reasonable values of the latter, say smaller than 3° , is of the order of a few per mille and thus completely negligible.

Another potential source of uncertainties would be the misidentification of the most energetic parton and thus, the thrust axis if it is chosen as the reference axis. This would occur for instance if the three jets have approximately the same energy. Since the total energy of the three jets corresponds to the very well known energy of the initial e^+e^- pair, this error (which is mainly due to losses of particles [16]) should be small. We have checked that the assignment of the reference axis to the wrong parton, provided that the difference between the quark and gluon energies is less than a few ($\simeq 2$) GeV, generates an error which can safely be neglected in the asymmetry.

Thus, from these naive estimates, one would expect that non-perturbative effects are well below the experimental accuracy that we are envisioning for our observable. These arguments, though, have to be carefully checked with a realistic Monte Carlo simulation.

The last point is that to extract in a meaningful way the value of α_s (and thus the value of Λ_{MS}) from the transverse asymmetry, one needs to compute the next order QCD radiative corrections. Part of this calculation, i.e the contributions of the virtual corrections and the three parton matrix elements, is already available in the literature [5]. The remaining part, which consists in the contribution of the four parton matrix elements, is presently being performed [20].

4 Conclusion

In this paper, we have shown that a suitable transverse polarization of the initial electron/positron beams at LEP1 provides a measurement of the ratio of azimuthal asymmetries for hadron to muon production which is strongly dependent on the value of the coupling constant α_s . This ratio is completely insensitive to the electroweak sector of the theory, and thus to the unknown parameters of the Standard Model or to any kind of New Physics beyond it. Moreover it is independent of any cut-off procedure and we expect that it is only marginally sensitive to the effects of the hadronization of the initial quarks and gluons. These properties make this particular asymmetry $R_{\perp}^{\text{had}}$ a genuine and powerful way of measuring the QCD coupling α_s with the only possible uncertainty that would be coming from the experimental error. If the latter were of the order, say of one percent, it could provide a value for α_s with an accuracy of 10–15%. This value is well comparable with those which would be provided by a measurement of R_h or by alternative, and we believe less unbiased possibilities [3], at the same experimental accuracy.

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TABLE CAPTIONS:

Tab. 1 Coefficients of α_s/π of the transverse asymmetry $R_{\perp}^{\text{had}}$ in the case where the reference axis is the quark axis. The Z mass is taken to be $M_Z = 91.1$ GeV.

Tab. 2 Coefficients of α_s/π of the transverse asymmetry $R_{\perp}^{\text{had}}$ in the case where the reference axis is the thrust axis. The Z mass is taken to be $M_Z = 91.1$ GeV.

FIGURE CAPTIONS:

Fig. 1 Energy dependence of the transverse asymmetry around the Z resonance. The asymmetry is practically flat in the region between $M_Z - 2.5$ GeV and $M_Z + 2.5$ GeV.

Fig. 2 Feynman diagrams contributing to the first order QCD corrections to $e^+e^- \rightarrow q\bar{q}$.

Table 1:

$q \rightarrow$	u, d	s	c	b
Mass (GeV)	< 0.1.	0.5	1.5	4.5
Coeff.	-2	-1.98	-1.85	-1.57

Table 2:

$q \rightarrow$	u, d	s	c	b
Mass (GeV)	< 0.1.	0.5	1.5	4.5
Coeff.	-1.46	-1.45	-1.42	-1.30

Fig. 1

Fig. 2