Fermi National Accelerator Laboratory

**FERMILAB-Conf-96/063**

# Hyperon Beam Physics

Peter S. Cooper

*Fermi National Accelerator Laboratory*
*P.O. Box 500, Batavia, Illinois 60510*

March 1996

Submitted to the Proceedings of *(Baryons '95) 7th International Conference on the Structure of Baryons*, Santa Fe, New Mexico, October 3-7, 1995

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

# Hyperon Beam Physics

Peter S. Cooper
*Fermi National Accelerator Laboratory, Batavia, IL 60510*

## 1. Introduction

I review the present status and recent results in hyperon physics concentrating on results from high energy hyperon beam experiments performed at Fermilab over the past several years. I will focus on hyperon production polarization, precision hyperon magnetic moment measurements and radiative decay studies. Modern charged hyperon beam experiments are characterized by~100m long apparatus and hyperon beams with $\gamma_Y$~100 and hyperon fluxes in the 1-100 KHz range. The capabilities of such experiment is shown in Fig. 1 [1] where the analysis of $\Sigma^+$ decays from one month of data in Fermilab E761 is displayed.

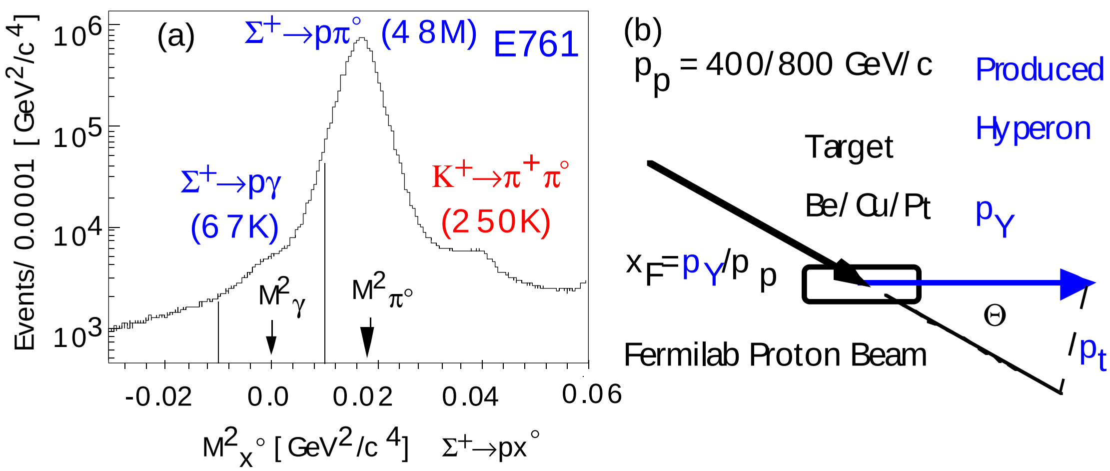


Figure 1. (a) Recent data on $\Sigma^+$ decay from E761. (b) Hyperon beam production geometry.

## 2. Hyperon Production Polarization

Inclusive polarization of $\Lambda^\circ$ produced by unpolarized 400 GeV/c protons was discovered in 1976 by Fermilab E8 [2]. This was a great surprise and has lead to 20 years of polarized hyperon physics. Quantities measured included the kinematic dependence ($x_F$, $p_t$) of the production polarization of both hyperons and anti-hyperons, hyperon magnetic moments and asymmetry parameters in semi-leptonic ($\Sigma^- \to ne^- \bar{\nu}$) and radiative ($\Sigma^+ \to p\gamma$, $\Xi^- \to \Sigma^-\gamma$) decays.

Hyperons can be strongly produced with a finite polarization only normal to the scattering plane shown in Fig 1b. Reversing targeting angle [Θ] reverses the polarization. This gives a powerful tool for separating polarization effects from instrumental biases.

The results of the experiments before the last round (E761, E756, E800) yielded a picture of production polarization shown in Fig 2. Both signs of polarization are observed, the polarization increases approximately linearly with $p_t$ until $p_t$=1 GeV/c then levels off. The polarization increases strongly with $x_F$ at fixed $p_t$. Anti hyperons [ $\bar{\Lambda}°$] are not produced polarized. The magnitude of polarization seems correlated with the number of valence quarks shared by the incident proton and produced hyperon: $|P(\Lambda°)|=|P(\Sigma^+)| =|P(\Sigma^-)|$ ~20%, $|P(\Xi°)|= |P(\Xi^-)|$ ~10%, $|P(\bar{\Lambda}°)|=|P(\Omega^-)|$ ~0%

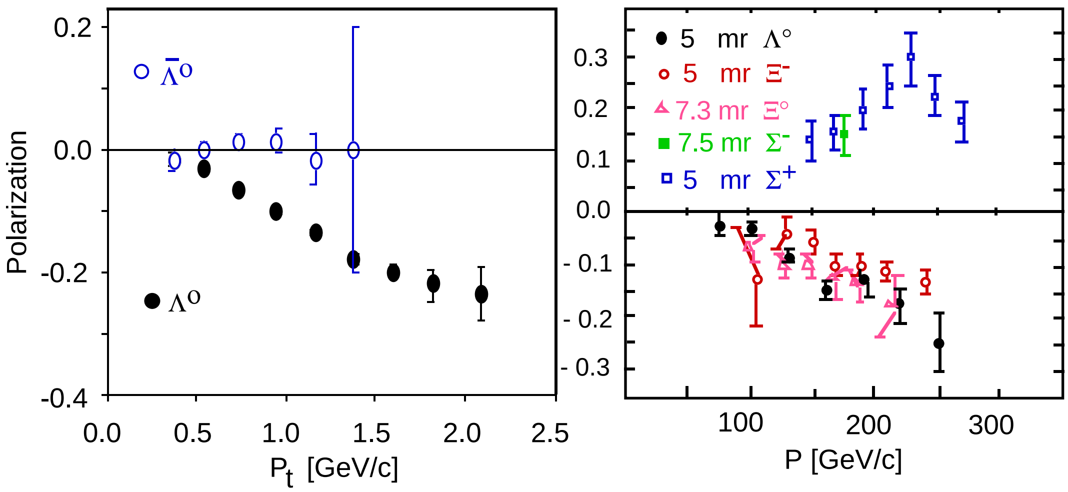


Figure 2. Λ° and $\bar{\Lambda}°$ Polarization vs. $P_t$., hyperon polarization vs. P.

PQCD predicts that all such production polarizations should be zero, but PQCD can't reliably calculate these effects for $p_t$< ~5 GeV/c Several models have been built to attempt to describe these phenomena. These models incorporate the phenomenology above. Unfortunately, most of what is above is wrong. The models don't deal with this gracefully.

## 3. New Production Polarization Results

Both E756 [3] and E761 [4] (Fig. 3) find that anti hyperons are produced with polarization similar in magnitude and sign to the corresponding hyperons. The polarization shows a significant dependence on the incident proton momentum. Comparing $p_p$ = 800 GeV/c relative to 400 GeV/c we find that (Fig. 4 ) ($\Xi^-$[3]; $\Sigma^+$[4]; $\Lambda^\circ$[5],

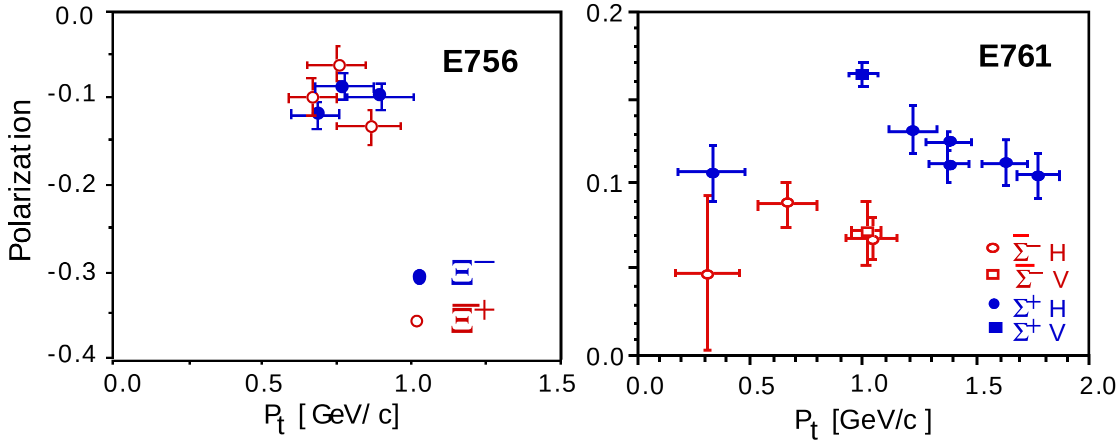


Figure 3. $\Xi^-$ and $\bar{\Xi}^+$ polarization from E756., $\Sigma^+$ and $\bar{\Sigma}^-$ polarization from E761.

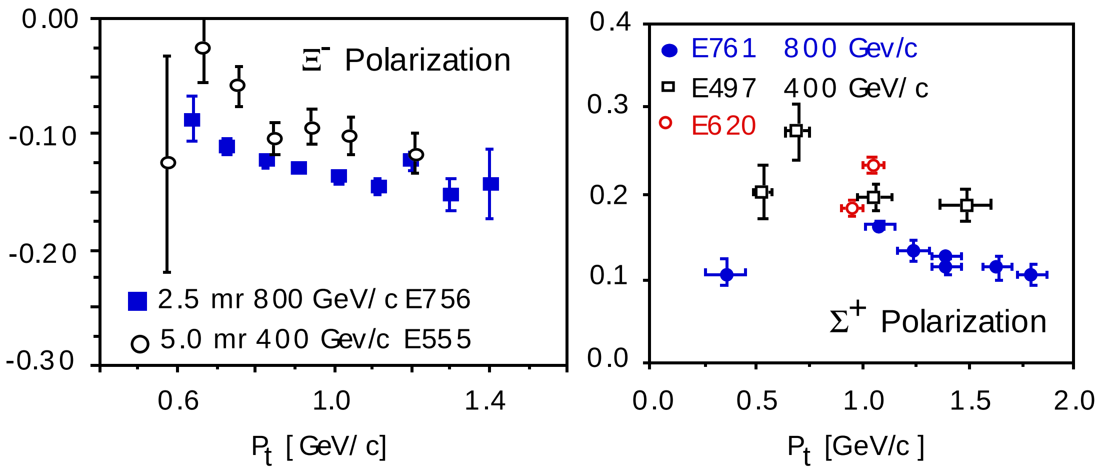


Figure 4. Energy dependence of $\Xi^-$ and $\Sigma^+$ polarization.

$\Sigma^-$[6]) polarization magnitudes (increase; decrease; are unchanged). High statistics studies show (Fig 5.) that the $\Sigma^+$ polarization at fixed $x_F$ goes through a maximum as a function of $p_t$ at $p_t$=1 GeV/c and then decreases measurably [4, 7]. Is it going to zero now as PQCD says? $\Lambda^\circ$ polarization is constant as a function of $p_t$ for fixed $x_F$.

Hyperon production polarizations show a rich and complicated structure. The picture from the previous generation of experiments has proven to be too simple. The models based upon that simple

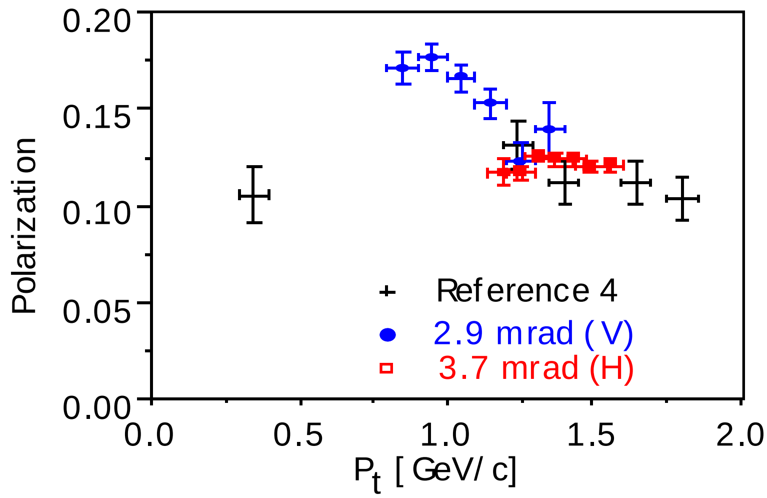


Figure 5. Pt dependence of $\Sigma^+$ polarization from E761.

picture can't describe the energy, anti-hyperon and $p_t$ dependence we observe. PQCD is no help and might just be wrong in this case. We lack even the simplest phenomenological model or picture of what is going on. We have no guidance as to what experiment to do next.

**4. Hyperon Magnetic Moments**

The simple $SU_6$ additive quark model assumes fixed moments for each flavor of quark and no orbital angular momentum. It predicts all the moments in terms of the measured moments of (p, n, $\Lambda^\circ$) which fix the (u, d, s) quark moments. Fermilab E800 has recently published [8] a precision magnetic moment for the $\Omega^-$. This result, together with recent $\Sigma^+$ [9] and $\Xi^-$ [10] measurements, completes the set of measurements at the ~<1% level. This new result and the PDG [11] averages for the other moments are shown in Table I. The deviations from the $SU_6$ model are at the 5-10% level as expected for an $SU_3$ based model. These deviations are very well measured (~10 $\sigma$). No more advanced model seems to do much better than simple $SU_6$. This is an experimentally finished program until somebody can build a better baryon model.

Table I - Hyperon magnetic moments [NM]

| Hyperon | Moment [8, 11] | Quark Model | Difference |
|---|---|---|---|
| p | +2.792847 | fixed | ___ |
| n | -1.913043 | fixed | ___ |
| $\Lambda^\circ$ | -0.613(04) | fixed | ___ |
| $\Sigma^+$ | +2.458(10) | +2.67 | -0.210(10) |
| $\Sigma^\circ \to \Lambda^\circ$ | -1.610(80) | -1.63 | +0.020(80) |
| $\Sigma^-$ | -1.160(25) | -1.09 | -0.070(25) |
| $\Xi^\circ$ | -1.250(14) | -1.43 | +0.177(14) |
| $\Xi^-$ | -0.651(03) | -0.47 | -0.161(03) |
| $\Omega^-$ | **-2.024(56)** | -1.84 | -0.184(56) |

## 5. Cabibbo Fits to the Hyperon Beta Decays

The fits of the rates and asymmetry parameters of the hyperon $\beta$ decays to the Cabibbo model give one of two measures of the $V_{us}$ CKM matrix element ($V_{us}=\sin\theta_C$) and a direct determination of the F and D parameters with have recently gained importance in understanding nucleon spin structure. Since the last global fits were done in 1984 [12] 5 of the 10 measurements fit have improved by more than a factor of 2. The neutron lifetime measurement has improved by x5.5 and shifted -3.5 $\sigma_{old}$. I have refit the new measurements using, as much as possible, the '84 formalism. Two of the rates [$\Sigma^- \to \Lambda^\circ, \Xi^- \to \Lambda^\circ$] are off by more than 3$\sigma$ from the new fits. Dropping these gives a reasonable fit with a value of the Cabibbo angle consistent with its other determination from $K_{e3}$ decay.

Table II - Cabibbo fits to hyperon $\beta$ decays

| parameter | 84 Fits | Ke3 | This work |
|---|---|---|---|
| $\sin\theta_C$ | 0.2310(30) | 0.2196(23) | 0.2202(17) |
| F / D | 0.6310(250) | | 0.5632(29) |
| $\chi^2 / \nu$ | 8.8/6 | | 10.3/5 |

The quality of this fit (CL=7%) is dominated by ~1.5 $\sigma$ inconsistencies between the rate and asymmetry measurements for two modes [$\Sigma^- \to n$, $n \to p$]. The resulting uncertainties are much smaller the ~10% one expects from an $SU_3$ based theory. The Cabibbo angle determined is consistent with the value measured from $K_{e3}$, in contrast with the '84 fits. It is as if the $SU_3$ symmetry of the axial vector weak current which underlies the Cabibbo model is a much better symmetry than the mass spectrum of the baryon octet.

## 6. Radiative hyperon decays

Hyperon radiative decays represent a class of baryon decays which require contributions from both the weak and electromagnetic interactions. Hara proved in 1964 [13] that the asymmetries in radiative hyperon decay vanish in the $SU_3$ limit assuming only CP invariance and left handed currents in the weak interaction. Contrary to this prediction, a new measurement of the $\Sigma^+ \to p\gamma$ asymmetry performed in 1987 at KEK [14] confirmed two older bubble chamber measurements; with 190 events this asymmetry parameter was found to be -0.86±0.13(stat)±0.04(syst).

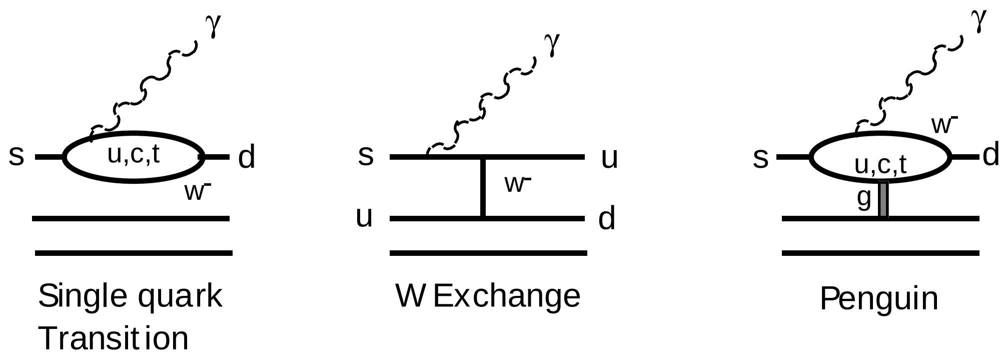


Figure 6. Quark Level Feynman diagrams for the processes contributing to hyperon radiative decays.

These observations raised a wide interest among theorists [15] The classes of diagrams which contribute to these processes are shown in Fig. 6. The W exchange diagram can only contribute to radiative decays with a valence *u* quark in the initial state like $\Sigma^+ \to p\gamma$. Various models were investigated. None of these models could describe satisfactorily both the large negative asymmetry and the observed rate of the $\Sigma^+ \to p\gamma$ decay. This became possible only recently in the form of a QCD sum rule model [16].

We mounted our most recent hyperon beam experiment, E761, to study this problem with high statistical precision and excellent control of systematic uncertainties. The biggest experimental problem in studying the $\Sigma^+$ radiative decay is the 400 times larger hadronic background ($p\pi^\circ$) channel which differs by the addition of one more photon in the final state, and has an asymmetry of -0.98. Our signals

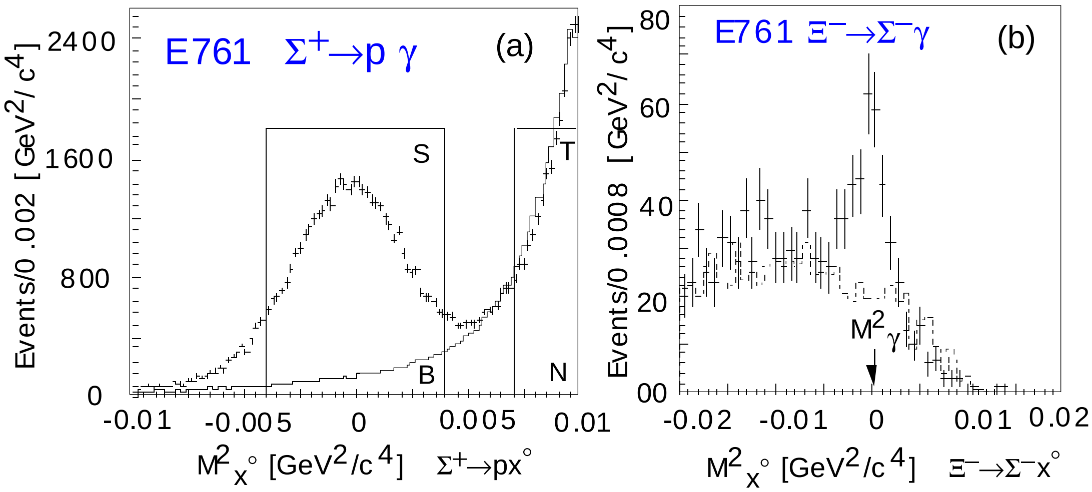


Figure 7. E761 Radiative Decay results; (a) $\Sigma^+ \to p\gamma$ , (b) $\Xi^- \to \Sigma^-\gamma$.

Table III - Previous world radiative decay data and E761 results

| decay | parameter | PDG [11] | events | E761 | events |
|---|---|---|---|---|---|
| $\Lambda^\circ \to n\gamma$ | Br [x10$^{-3}$] | 1.02 (33) | 24 | ______ | |
| $\Sigma^+ \to p\gamma$ | Br [x10$^{-3}$] | 1.250 (70) | 899 | 1.198 (77) | 31901 |
| | $\alpha_\gamma$ | -0.83 (12) | 297 | -0.72 (10) | 34754 |
| $\bar{\Sigma}^- \to \bar{p}\gamma$ | Br [x10$^{-3}$] | ______ | | 1.42 (20) | |
| $\Xi^\circ \to \Lambda^\circ\gamma$ | Br [x10$^{-3}$] | 1.06 (16) | 116 | ______ | |
| | $\alpha_\gamma$ | +0.43 (44) | 87 | ______ | |
| $\Xi^\circ \to \Sigma^\circ\gamma$ | Br [x10$^{-3}$] | 3.56 (43) | 85 | ______ | |
| | $\alpha_\gamma$ | +0.20 (32) | 85 | ______ | |
| $\Xi^- \to \Sigma^-\gamma$ | Br [x10$^{-3}$] | 0.230 (100) | 9 | 0.122 (23) | 211 |
| | $\alpha_\gamma$ | ______ | | +1.0 (1.3) | |
| $\Omega^- \to \Xi^-\gamma$ | Br [x10$^{-3}$] (90% CL) | < 2.2 | | < 0.46 | <2.3 |

are shown in Figs. 1 and7a. We also made the first high statistics observation of the $\Xi^- \to \Sigma^- \gamma$ radiative decay [17] shown in Fig 7b. Our contributions to the world radiative hyperon decay [11] data [1,17-19] are shown in Table III. We are forced to conclude that Hara's theorem, for all its elegance, is wrong in the case of the $\Sigma^+ \to p\gamma$. That asymmetry is large and negative. Recent theoretical work [20] has begun to make new progress in explaining the physics of this sector.

## 7. Summary

More than 20 years of hyperon beam physics has pushed several conventional topics to near theoretical exhaustion. Polarization is still a mystery - now even more baroque then ever. All the magnetic moments are now well measured. Revisiting semi-leptonic decays may help us determine SM parameters better. Hyperon radiative decay are still a challenge on both the experimental and theoretical fronts. The possibility of observing CP violation in the hyperon sector is being actively pursued by the HyperCP experiment (E871) now preparing to take data at Fermilab. The author gratefully acknowledges the work of eight former graduate students who have produced much of the E761 physics reported here. The errors in this manuscript are the sole property of the author.


<u>References</u>

1 M. Foucher, et.al., *Phys.Rev.Lett.* **68**,(1992) 3004.
2 G. Bunce, et.al., *Phys.Rev. Lett.* **36**, (1976) 1113.
3 P. M. Ho , et.al., *Phys.Rev. D* **44**, (1991) 3402.
4 A. Morelos, et.al., *Phys.Rev.Lett.* **71**,(1993) 2172.
5 B Lundberg , et.al., *Phys.Rev. D* **40**, (1989) 3557.
6 Steven Timm, Ph.D. Thesis, Carnegie Mellon University,1995. (unpublished).
7 A. Morelos, et.al., *Phys.Rev. D* **52,** (1995) 3777.
8 N. B. Wallace, et.al., *Phys.Rev. Lett.* **74**, (1995) 3732.
9 A. Morelos, et.al., *Phys.Rev. Lett.* **71**, (1993) 3417.
10 J.Duryea, et.al., *Phys.Rev. Lett.* **68**, (1992) 768.
11 J.M. Gaillard and G. Sauvage, *Ann. Rev. Nucl. Part. Sci.* 34, (1984) 351.
12 Y. Hara, *Phys. Rev. Lett.* **12**, (1964) 378.
13 M. Kobayashi, et.al., *Phys. Rev. Lett.* **59**, (1987) 868 .
14 N. Vasanti *Phys. Rev. D* **13**, 1889 (1976), F.J. Gilman and M.B. Wise, *Phys. Rev. D.* **19**, (1979) 976, Y.I. Kogan and M.A. Shiftman, *Sov. J.Nucl. Phys.* **38**, (1983) 628, M.D. Scadron and M. Visinescu, *Phys. Rev.D.* **28**, (1983) 1117, M.K. Gaillard, X.Q. L1 and S. Rudaz, *Phys. Letters* **158B**, (1985) 158, D. Palle, *Phys. Rev. D.* **36**, (1987) 2863, C. Goldman and C.O. Escobar, *Phys. Rev. D* .**40**, (1989) 106, P. Zenczykowski, *Phys Rev ,D* 44 (1991) 1485.
15 I.I. Balitsky, V.M. Braun, A.V. Kolesnichenko, N*ucl. Phys. B.* **312**,(1989) 509.
16 Particle Data Group, *Phys. Rev. D.* **50** , (1994) 1173.
17 T. Dubbs, et.al.,*Phys.Rev. Lett.* **72**, (1994) 808 .
18 S. Timm, et.al., *Phys.Rev. D* **51,** (1995) 4632.
19 I. Albuquerque, et.al., *Phys.Rev. D* **50,** (1994) 18.
20 J. Lach and P. Zenczykowski, *Int. J. Mod. Phys.* A**10**, (1995), 3817 and references therein.