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ASYMMETRY OF JET PRODUCTION IN POLARIZED *pp*-COLLISIONS AT RHIC AND SIGN OF ΔG

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1. Introduction

Both spin-dependent and spin-independent parton distributions in the nucleon are of universal nature, hence the direct measure of them is one of the actual problem of the high energy spin physics. Deep-inelastic lepton-nucleon scattering allows us to obtained information on quark distributions but such information is not sufficient to resolve 'spin crisis'(see [1] and references therein). It is necessary to know a gluon contribution to proton spin. Therefore future research programs at the RHIC [2], HERA [3] and LHC colliders plan to perform experiments with polarized proton beams to study the spin-dependent gluon-distributions $\Delta G(x, Q^2)$.

The study of the asymmetry of jet and direct γ-production in $\vec{p}-\vec{p}$ collisions is more perspective for the purposes. Theoretical basis of the analysis of the processes is the theory of strong interaction - Quantum Chromodynamics. High energy of colliding beams and high momentum transferred give possibility to perform the calculations in the framework of perturbative QCD.

In the framework of the parton model the basic subprocesses for jet production in the pp collision are $qq \to qq$, $qg \to qg$, $gg \to gg$. Their contributions to asymmetry A_{LL} depend on a chosen kinematic region. Therefore the main question is to find the kinematical region more suitable for measuring of $\Delta G(x, Q^2)$. For the direct photon production a main subprocess is the Compton $qg \to \gamma q$ scattering. Note that the measure of ΔG by means of jet asymmetry is connected with larger background than in the case of prompt photon production, but the statistical power is much higher [4].

Up to now, there exists neither a running experiment to directly measure the polarized gluon distribution nor does the variety of indirect analyses give a unique result. Hence there is no completely convincing argument on the shape and sign of $\Delta G(x, Q^2)$ yet, although a recent NLO analysis [5] clearly favors a positive sign. However, recent calculations in the context of a non-relativistic quark model and the bag model, respectively, [6] indicate that the integral over $\Delta G(x, Q^2)$ might be negative too. Both positive and negative values of the sign of $\Delta G(x, Q^2)$ over a wide kinematical range $10^{-3} < x < 1$ were considered in [7]. The possibility to draw conclusions on the sign of the spin-dependent gluon distribution, $\Delta G(x, Q^2)$, from existing polarized DIS data have been studied in [8]. The result of the DIS data analysis [8] on g_1^n strongly supports the conclusion that the sign of $\Delta G(x, Q^2)$ should be positive. Nevertheless the additional confirmations on sign of ΔG are required and the experiments for direct measuring of the $\Delta G/G$ are necessary.

The aim of the present paper is to study the dependence of asymmetry of jet and dijet production in $\vec{p}-\vec{p}$ collisions on different gluon distributions ΔG, and especially as a function of sign of ΔG, and made predictions of sign of A_{LL} for the future experiment planed at RHIC [9].

2. Spin-Dependent Gluon Distribution

The 3 sets of spin-dependent parton distributions [7] and [10] are used to calculate the jet asymmetry A_{LL}. First set is based on work of Altarelli and Stirling [10] and include a scenario with large gluon polarization Δg. Second and third ones have been obtained by the phenomenological method [7] including some constraints on the signs of valence and sea quark distributions, taking into account the axial gluon anomaly and utilizes results on integral quark contributions to the nucleon spin. Based on the analysis of experimental data on deep-inelastic data on structure function g_1 the parametrization of spin-dependent parton distributions for both positive and negative sign of ΔG have been constructed. We would like to note the both sets of distributions describe experimental data very well. We shall denote $\Delta G^{>0}$ and $\Delta G^{<0}$ sets of spin-dependent parton distributions obtained in [7] with positive and negative sign of ΔG, respectively. It was shown in [11] that phenomenological method reproduces the main features of the NLO QCD Q^2-evolution of proton, deuteron and neutron structure function g_1. Therefore the constructed spin-dependent quark and gluon distributions can be reasonably used to study a asymmetry of jet production in $\vec{p}-\vec{p}$ collisions too.

Figure 1(a) shows the dependence of the ratio $\Delta G(x,Q^2)/G(x,Q^2)$ on x at $Q^2 = 100\ (GeV)^2$ for gluon distributions [10] and $\Delta G^{>0}$ [7]. The curve [10] increases with x and then decreases to zero. The behaviour is due to the structure of the ratio $\Delta G/G \sim x^{\alpha}(1-x)^{\beta}$. The monotonous increase of a second curve with x connects to other asymptotic of the ratio $\Delta G/G \sim x^{\delta}$ at $x \to 1$.

Figure 1(b) shows the dependence of the ratio $\Delta G(x,Q^2)/G(x,Q^2)$ on x at $Q^2 = 100\ (GeV)^2$ for gluon distributions $\Delta G^{>0}$ and $\Delta G^{<0}$ [7].

We would like to note that integral contributions of gluons to the proton's spin is practically the same in all the parameterizations ($\Delta g \simeq 2$) so the difference in asymmetry should reflects the difference in shape of distributions (and sign of ΔG) used.

3. Asymmetry of Jet Production

The cross section for jet production in polarized $p-p$ collisions is given by a convolution of the partonic cross section and the polarized parton distributions, summed over all partonic subprocesses contributing to the reaction $p+p \longrightarrow jet + X$. Then, the double spin asymmetry is defined through the difference of cross sections (numbers of jets) for antiparallel ($\uparrow\downarrow$) and parallel ($\uparrow\uparrow$) spins of colliding protons:

$$A_{LL} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} = \frac{N_{jet}^{\uparrow\downarrow} - N_{jet}^{\uparrow\uparrow}}{N_{jet}^{\uparrow\downarrow} + N_{jet}^{\uparrow\uparrow}}, \quad (1)$$

with the error:

$$\delta A_{LL} \simeq \frac{1}{\sqrt{N_{jet}^{\uparrow\downarrow} + N_{jet}^{\uparrow\uparrow}}}. \quad (2)$$

For detailed study of jets and dijets asymmetry at STAR we have used the Monte Carlo code SPHINX [12] which is 'polarized' version of PYTHIA [13].

Jet reconstruction was done by the JETSET-subroutine LUCELL [13]. This routine defines jets in the two-dimensional (η,ϕ)-plane, η being pseudorapidity and ϕ the azimuthal angle. STAR detector covers full space in azimuth and pseudorapidity region $-1 < \eta < 2$. In order to have segmentation expected at STAR

($\Delta\eta \times \Delta\phi = 0.1 \times 0.1$) we used 30 η-bins and 60 ϕ-bins in our calculation procedure. The values of LUCELL-subroutine parameters $E_{\perp}^{cell}$ and $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ were $E_{\perp}^{cell} = 1.5\ GeV$ and $R = 0.7$.

The expected resolution of the STAR Electromagnetic Calorimeter $\Delta E/E \simeq 0.16/\sqrt{E}$ was also taken into account [4]. To obtain total rates ($Rate = \sigma \cdot \mathcal{L}$) of jets and dijets at STAR we take into account designed luminosity at RHIC, $\mathcal{L} = 8 \times 10^{31} cm^{-2}s^{-1}$ at $\sqrt{s} = 200\ GeV$ ($\mathcal{L} = 2 \times 10^{32} cm^{-2}s^{-1}$ at $\sqrt{s} = 500\ GeV$) and effective run time of 100 days with 50% efficiency. The polarization of both beams was fixed at the value $P = 0.7$.

As an example, the jet and dijets rates for STAR detector at two different energies are presented in Tables 1(a) and 1(b).

Figure 2 shows the dependence of the cross section of jet production as a function of pseudorapidity η at colliding energy $\sqrt{s} = 500\ GeV$ and for 3 different cuts on transverse energy of the jet. As can be seen, with increasing transverse energy of jet the contribution of jet events from EndCap Calorimeter decrease. However, at lower jet transverse energies, the cross section for jet production in EndCap Calorimeter region is practically the same as in the Barrel Calorimeter region. Because of this, the End Cap Calorimeter will be very important for studying the low x-region, where the gluons play the major role.

Table 1. Jet and dijets rates in $\vec{p}-\vec{p}$ collisions at $\sqrt{s} = 200\ GeV$ (a) and $\sqrt{s} = 500\ GeV$ (b) as a function of the jet transverse energy E_T. The spin-dependent PDF's $\Delta G^{<0}$ [7] were used for calculation of the cross section. (50% efficiency was assumed for estimating the jet and dijets rate for 100 days of RHIC work).

E_T^{jet} (GeV)	Jet Rate (Hz/GeV)	Jet Rate $1/(100days * GeV)$	E_T^{dijets} (GeV)	Dijets Rate (Hz/GeV)	Dijets Rate $1/(100days * GeV)$
10	26	$1.1 \cdot 10^8$	20	5.8	$2.5 \cdot 10^7$
15	9	$3.9 \cdot 10^7$	25	2.2	$9.6 \cdot 10^6$
20	1	$4.4 \cdot 10^6$	30	0.9	$4 \cdot 10^6$
25	0.17	$7.4 \cdot 10^5$	40	0.15	$6.4 \cdot 10^5$
30	0.04	$1.6 \cdot 10^5$	50	0.03	$1.3 \cdot 10^5$
35	0.008	$3.4 \cdot 10^4$	60	0.005	$2.3 \cdot 10^4$
40	0.002	8436	70	$1.4 \cdot 10^{-3}$	5968
45	$4.6 \cdot 10^{-4}$	2000	80	$3.5 \cdot 10^{-4}$	1524
50	$1.2 \cdot 10^{-4}$	535	90	$9.2 \cdot 10^{-5}$	400
60	$4.9 \cdot 10^{-6}$	21	100	$2.3 \cdot 10^{-5}$	99

Table 1(b)

E_T^{jet} (GeV)	Jet Rate (Hz/GeV)	Jet Rate $1/(100days * GeV)$	E_T^{dijets} (GeV)	Dijets Rate (Hz/GeV)	Dijets Rate $1/(100days * GeV)$
10	1157	$5 \cdot 10^9$	20	56	$2.4 \cdot 10^8$
20	46	$2 \cdot 10^8$	30	20	$8.8 \cdot 10^7$
30	2.6	$1.1 \cdot 10^7$	40	5	$2.1 \cdot 10^7$
40	0.46	$2 \cdot 10^6$	50	1.3	$5.7 \cdot 10^6$
50	0.08	$3.6 \cdot 10^5$	60	0.4	$1.7 \cdot 10^6$
60	0.02	$9.3 \cdot 10^4$	70	0.17	$7.3 \cdot 10^5$
70	0.006	26504	90	0.03	$1.3 \cdot 10^5$
80	0.002	7834	110	$7.5 \cdot 10^{-3}$	32423
90	$5 \cdot 10^{-4}$	2315	130	$1.9 \cdot 10^{-3}$	8277
100	$2 \cdot 10^{-4}$	1028	150	$5.8 \cdot 10^{-4}$	2515

4. Results of Monte Carlo simulations

Figure 3 shows the dependence of A_{LL} on the jet transverse energy E_T at $\sqrt{s} = 200\ GeV$. Points (open and black boxes) are simulation results with spin-dependent PDF [10] and $\Delta G^{>0}$ [7]. Errors on the figure are statistical only. One can see from Fig.3 that the absolute value of A_{LL} for both set of PDF is less than 5% at $E_T < 35\ GeV$. At higher transverse energy $E_T > 35\ GeV$ the asymmetry calculated with PDF $\Delta G^{>0}$ increases with E_T.

Dijet production in $p-p$ collisions allows to study so-called 'back-to-back' jets and to extract more correctly information on the dominant parton subprocess. In our simulations, the dijets were considered to be found if back-to-back deviations for the two jets don't exceed 30^o. The error of the efficiency of the jet finder is estimated [14] to be at the level of 10 % for $E_T \simeq 30\ GeV$.

Figure 4 demonstrates the dependence of the asymmetry A_{LL} of dijet production in the $\vec{p}-\vec{p}$ collisions on the dijet transverse energy E_T at $\sqrt{s} = 200\ GeV$. The pseudorapidity range of jet production covers $-1 < \eta < 2$. Points (open and black boxes) are simulation results with spin-dependent PDF [10] and $\Delta G^{>0}$ [7]. Errors on the figure are statistical only. One can see from Fig.4 that the absolute value of A_{LL} for PDF[10] is practically constant ($\simeq (4-5)\%$) up to $E_T = 60\ GeV$. At higher transverse energy range $E_T > 60\ GeV$ the asymmetry decreases with E_T. The asymmetry calculated with PDF $\Delta G^{>0}$ [7] is small ($< 2\%$) at $E_T < 60\ GeV$ and increases up to (15-20)% at $E_T > 90\ GeV$.

We can consider 3 characteristic regions on both the Figures 3 and 4. In the low E_T region ($E_T < 20\ GeV$ for jets and $E_T < 50\ GeV$ for dijets) the value of the asymmetry A_{LL}^{Al-St} obtained with parametrization [10] is larger than the asymmetry A_{LL}^{Tok} obtained with parametrization $\Delta G^{>0}$ [7]. The contribution of $g-g$ scattering for A_{LL}^{Al-St} is 3 times higher than for A_{LL}^{Tok}. One can see from the Fig.1a that the ratio $\Delta G/G$ calculated with PDF [10] is larger than $\Delta G/G$ calculated with PDF $\Delta G^{>0}$ [7] at low x, so the behaviour of the asymmetry A_{LL} is reasonable. Moreover, it seems that this difference can be separated experimentally. On the basis of the obtained results we can conclude that, the information about ΔG could be extracted from (relatively) low E_T asymmetry values.

In the intermediate E_T region ($20 < E_T < 40\ GeV$ for jets and $50 < E_T < 70\ GeV$ for dijets) the asymmetry A_{LL}^{Al-St} decreases and the asymmetry A_{LL}^{Tok} increases. The main contribution comes from $q-g$ scattering and $A_{LL} \sim \Delta G/G \cdot \Delta q/q \cdot a_{LL}$. So the difference of the Δq parametrizations $\Delta G^{>0}$ [7] and [10] becomes equally important as ΔG. This region gives us mixed information about ratio $\Delta G/G \cdot \Delta q/q$. The ratio $\Delta G/G$ for parametrization [10] decreases with x at $x > 0.2$ which results in the decreasing of asymmetry value A_{LL}. The asymmetry A_{LL}^{Tok} increases with E_T. The behaviour of A_{LL}^{Tok} is due to the growth of the ratio $\Delta G/G$ with x.

In the high E_T region ($E_T > 40\ GeV$ for jets and $E_T > 70\ GeV$ for dijets) the asymmetry $A_{LL}^{Al-St} \simeq 0$ and A_{LL}^{Tok} increases with E_T and reaches (15-20)% for jet and dijets production at $E_T > 50$ and $E_T > 90\ GeV$, respectively. The main contribution comes in both cases $\Delta G^{>0}$ [7] and [10]) from $q-q$ scattering, so the resulting asymmetries reflect the difference between the Δq quark distributions. This region is very interesting because of possibility for checking the universality of factorization of spin-dependent PDF which are extracted from the results of DIS experiments.

Figure 5 shows the dependence of A_{LL} on the jet transverse energy E_T at $\sqrt{s} = 200\ GeV$ but for spin-dependent PDF with different sign of gluon distributions, $\Delta G^{>0}$ and $\Delta G^{<0}$ [7]. The asymmetry calculated with PDF $\Delta G^{>0}$ increases with E_T, while the asymmetry calculated with PDF $\Delta G^{<0}$ is practically equal to zero in the whole region.

Figure 6 shows the dependence of the asymmetry A_{LL} of dijet production in the $\vec{p}-\vec{p}$ collisions on the dijet transverse energy E_T at $\sqrt{s} = 200\ GeV$ for the same combination of spin-dependent PDF's ($\Delta G^{>0}$ and $\Delta G^{<0}$[7]).

On the basis of these results we can conclude that, the measurements of the jet and dijets asymmetry at $\sqrt{s} = 200\ GeV$ can give us information about the sign of ΔG.

However, the main results could be obtained at higher colliding energy $\sqrt{s} = 500\ GeV$. The dependence of A_{LL} on the jet transverse energy E_T at $\sqrt{s} = 500\ GeV$ for spin-dependent PDF's $\Delta G^{>0}$ and $\Delta G^{<0}$[7] are presented in Figure 7. In the low E_T region ($E_T < 30\ GeV$) the values of the asymmetry A_{LL} are the same for both positive and negative sign of ΔG. It reasonable behaviour if keep in mind Figure 1(b) and the fact that the contribution of $g-g$ scattering dominate in this kinematical region (so, the factor $\Delta G(x,Q^2)/G(x,Q^2)$ enter twice the formula for asymmetry). In the intermediate E_T region ($30 < E_T < 65\ GeV$), there is a clear difference between asymmetry values for positive and negative sign of ΔG. If we combine, these results with the results obtained by using the third parametrization [10], that is presented in Figure 8, we conclude that the information about ΔG could be extracted from this experimental data, because in the low E_T region the value of the asymmetry A_{LL}^{Al-St} obtained with parametrization [10] is larger than the asymmetry A_{LL}^{Tok} obtained with both parametrizations [7].

Finally, if we assume that the one of the parametrizations used estimates well

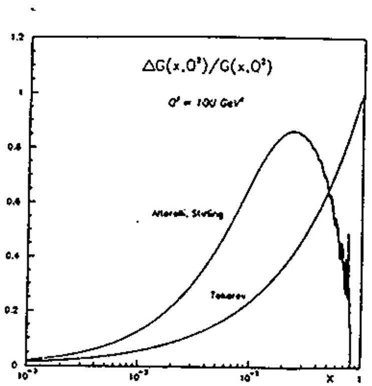

Figure 1(a)
The ratio of polarized and unpolarized gluon distributions as a function of x for two different parametrizations $\Delta G^{>0}$ [7] and [10] at Q^2=100 GeV².

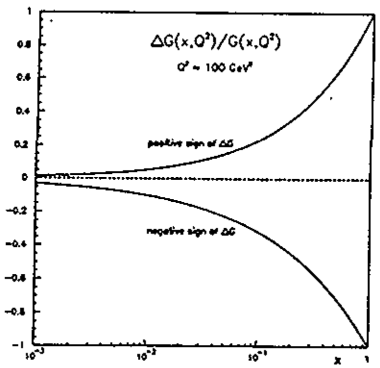

Figure 1(b)
The ratio of polarized and unpolarized gluon distributions as a function of x for two different parametrizations $\Delta G^{>0}$ [7] and $\Delta G^{<0}$ [7] at Q^2=100 GeV².

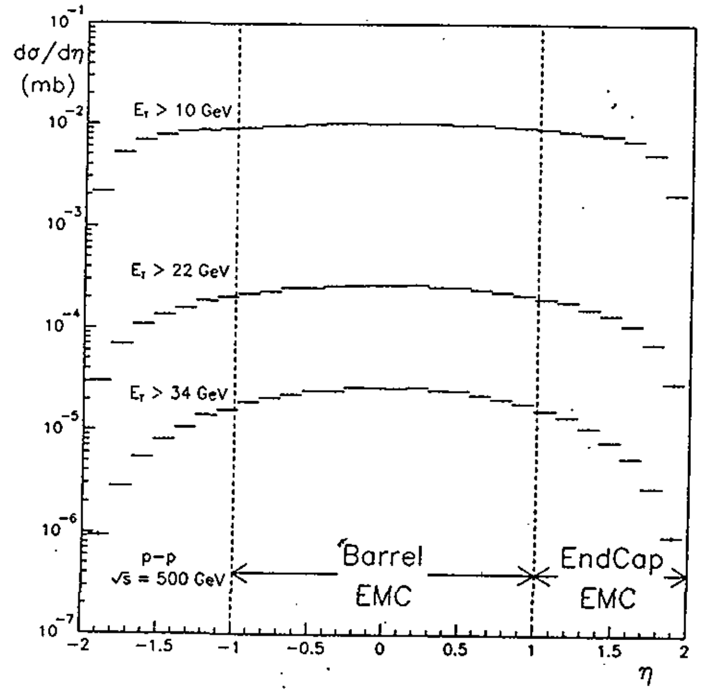

Figure 2. The dependence of the cross section of jet production as a function of pseudorapidity η at colliding energy $\sqrt{s} = 500\ GeV$ for 3 different cuts on transverse energy of the jet.

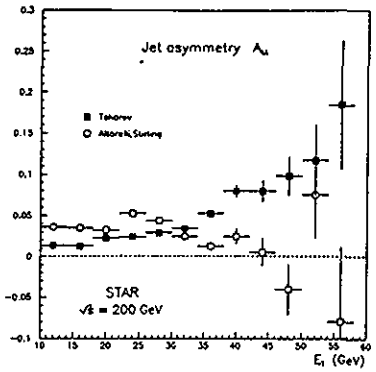

Figure 3.
Asymmetry of jet production A_{LL} in polarised pp collisions at $\sqrt{s} = 200$ GeV for two different sets of spin-dependent PDFs ($\Delta G^{>0}$ [7] and [10]) as a function of jet transverse energy E_T. The errors indicated are statistical only, based on the expected luminosity of RHIC and the properties of the STAR detector.

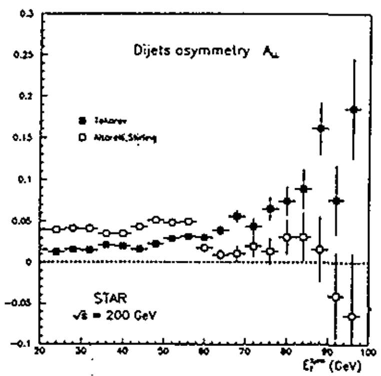

Figure 4.
Asymmetry of dijet production A_{LL} in polarised pp collisions at $\sqrt{s} = 200$ GeV for two different sets of spin-dependent PDFs ($\Delta G^{>0}$ [7] and [10]) as a function of dijet transverse energy E_T. The errors indicated are statistical only, based on the expected luminosity of RHIC and the properties of the STAR detector.

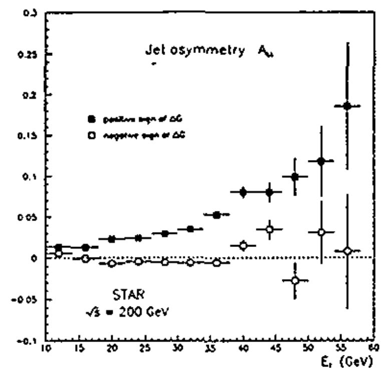

Figure 5.
Asymmetry of jet production A_{LL} in polarised pp collisions at $\sqrt{s} = 200$ GeV for two different sets of spin-dependent PDFs ($\Delta G^{>0}$ [7] and $\Delta G^{<0}$ [7]) as a function of jet transverse energy E_T. The errors indicated are statistical only, based on the expected luminosity of RHIC and the properties of the STAR detector.

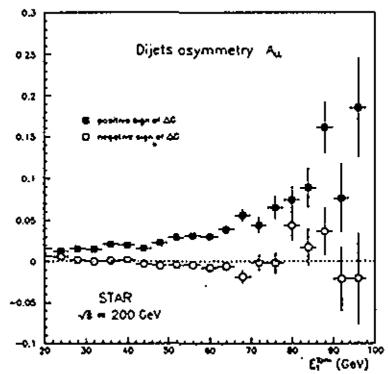

Figure 6.
Asymmetry of dijet production A_{LL} in polarised pp collisions at $\sqrt{s} = 200$ GeV for two different sets of spin-dependent PDFs ($\Delta G^{>0}$ [7] and $\Delta G^{<0}$ [7]) as a function of dijet transverse energy E_T. The errors indicated are statistical only, based on the expected luminosity of RHIC and the properties of the STAR detector.

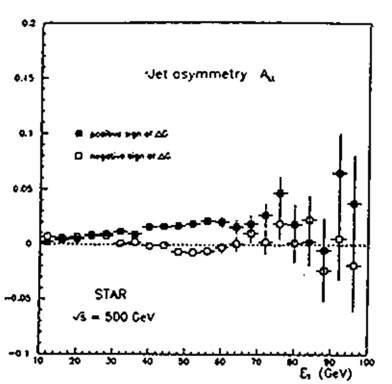

Figure 7.
Asymmetry of jet production A_{LL} in polarised pp collisions at $\sqrt{s} = 500$ GeV for two different sets of spin-dependent PDFs ($\Delta G^{>0}$ [7] and $\Delta G^{<0}$ [7]) as a function of jet transverse energy E_T. The errors indicated are statistical only, based on the expected luminosity of RHIC and the properties of the STAR detector.

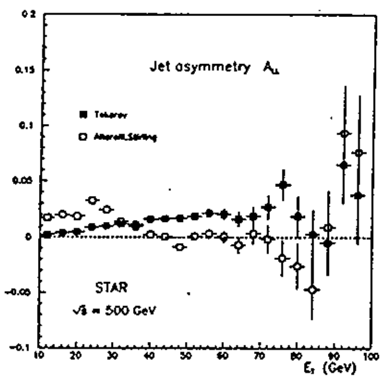

Figure 8.
Asymmetry of jet production A_{LL} in polarised pp collisions at $\sqrt{s} = 200$ GeV for two different sets of spin-dependent PDFs ($\Delta G^{>0}$ [7] and $\Delta G^{<0}$ [7]) as a function of dijet transverse energy E_T. The errors indicated are statistical only, based on the expected luminosity of RHIC and the properties of the STAR detector.

the spin dependent PDF's (especially $\Delta G(x,Q^2)$) the measurements of jet and dijets asymmetry at STAR will give us the definite answer about the sign and the shape of spin dependent gluon distribution ΔG.

5. Conclusions

The asymmetry of jet and dijets production A_{LL} in $\vec{p}-\vec{p}$ collisions at high energies was studied. The observable is expressed in the parton model via the $q-q$, $q-g$ and $g-g$ cross sections for different helicity and spin-dependent parton Δq and gluon ΔG distributions. The Monte Carlo simulation of A_{LL} taking into account parameters of the STAR EMC detector was made. Dependence of A_{LL} on jet transverse energy E_T for different parametrization of ΔG was studied. It was found that the value of A_{LL} is less than 5% at $E_T < 30$ GeV and $E_T < 50$ GeV for jet and dijets production, respectively. The asymmetry A_{LL} is sensitive for ΔG at lower E_T values and can give us information about the sign and shape of the $\Delta G(x,Q^2)$. At higher E_T range the asymmetry is sensitive for Δq and reaches (15-20)% for the jet and the dijets production at $E_T > 50$ and $E_T > 90$ GeV, respectively. The obtained results can be verified in future experiments with polarized protons planed at RHIC.

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