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PARTON DISTRIBUTIONS FROM $W^{\pm}$ AND Z PRODUCTION IN POLARIZED pp AND pn COLLISIONS AT RHIC

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Abstract

We study the production of $W^{\pm}$ and Z gauge bosons in proton-proton and proton-neutron collisions up to a center-of-mass energy $\sqrt{s} = 0.5\ TeV$, in connection with the realistic possibility of having proton-deuteron collisions at RHIC with a high luminosity. We stress the importance of measuring unpolarized cross sections for a better determination of the flavor asymmetry of the sea quarks. Since polarized proton beams will be available at RHIC, we evaluate several spin-dependent observables like, double helicity asymmetries A_{LL} as a test of the sea quark polarization, double transverse spin asymmetries A_{TT} as a practical way to determine a new structure function, the nucleon transversity distribution $h_1(x)$, and parity-violating asymmetries A_L as a further test of our present knowledge of polarized parton distributions.

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1. INTRODUCTION

A Relativistic Heavy Ion Collider (RHIC) is now under construction at Brookhaven National Laboratory and, already more than two years ago, it was realized that one should propose a very challenging physics programme[1], provided this machine could be ever used as a polarized pp collider. Of course all these considerations relie on the foreseen key parameters of this new facility, i.e. a luminosity of $2.10^{32} cm^{-2} sec^{-1}$ and an energy of $50 - 250\ GeV$ per beam with a polarization of about 70%. Since then, the RHIC Spin Collaboration (RSC) has produced a letter of intent[2] and has undertaken several serious studies in various areas which have led to a proposal[3] which has now been fully approved.

Among the very many basic hadronic reactions which will be studied in this experimental programme, we recall that jet production and direct photon production are sensitive to the size of the gluon polarization, whereas Drell-Yan lepton pair production will allow to determine the magnitude and the sign of the sea quark polarization[1,4]. Recent measurements of proton and neutron F_2 structure functions by the NMC at CERN[5] have yielded a violation of the Gottfried sum rule[6] whose most natural interpretation is the evidence for a flavor asymmetry in the light sea quarks (i.e. $\bar{d}(x) > \bar{u}(x)$). In a recent paper[7], we have shown that this can be studied further in the production of $W^{\pm}$ and Z bosons in a proton-proton collider because it is dominated by quark-antiquark annihilation and therefore sensitive to the sea distributions. It was stressed that in the central region the predicted unpolarized cross sections can vary by a large factor depending on, whether or not, one assumes a flavor symmetric sea. The measurement of charge asymmetries in the W^+ and W^- production was also suggested as an interesting possibility[8]. Parity violating asymmetries with either one beam polarized A_L or with two beams polarized A_{LL}^{PV} have been calculated[7] and we showed that their measurement, will give us a good calibration of the polarization of quarks and antiquarks, for both u and d. In this paper we are further investigating $W^{\pm}$ and Z bosons production and, in particular, we emphasize some new possibilities if one can measure simultaneously proton-proton and proton-neutron collisions, assuming the feasibility of tagging the spectator in proton-deuteron interactions[9]. We will also consider several spin dependent observables, with longitudinally and transversely polarized proton beams, which contain useful information on the polarized parton distributions.

The paper is organized as follows. In section 2 we compare unpolarized cross sections in pp and pn collisions and we show it allows a much improved determination of flavor asymmetry of the sea quarks. In section 3 we evaluate double helicity asymmetries A_{LL} for pp collisions with both proton beams polarized and parity violating asymmetries A_L for pn collisions with only one proton beam longitudinally polarized. Finally in section 4 we consider the situation of pp collisions with both proton beams transversely polarized and we will see that only in the case of Z production, one can extract the new structure function $h_1(x)$ [10], the *transversity* distribution, which indeed measures the correlation between the left-handed and the right-handed quarks in a transversely polarized proton. We will give our concluding remarks in section 5.

2. UNPOLARIZED CROSS SECTIONS

Let us recall that the differential cross section for the reaction

$$pp \to W^{\pm} + \text{ anything} \tag{1}$$

can be computed directly in the Drell-Yan picture in terms of the *dominant* quark-antiquark fusion reactions $u\bar{d} \to W^+$ and $\bar{u}d \to W^-$ and we have for the Standard Model W^+ production

$$\frac{d\sigma_{pp}^{W^+}}{dy} = G_F \pi \sqrt{2} \tau \cdot \frac{1}{3} \left[u(x_a, M_W^2) \bar{d}(x_b, M_W^2) + (u \leftrightarrow \bar{d}) \right] \tag{2}$$

with

$$G_F = \frac{\pi \alpha}{\sqrt{2} M_W^2 \sin^2 \theta_W} \;, \; x_a = \sqrt{\tau} e^y \;, \; x_b = \sqrt{\tau} e^{-y} \;, \text{ and } \tau = M_W^2/s \;.$$

Here $\sin^2 \theta_W$ is the weak mixing angle and quark flavors are interchanged in eq.(2) for W^- production. Clearly these y distributions are symmetric under $y \to -y$. For the reaction

$$pn \to W^{\pm} + \text{ anything} \tag{3}$$

under the assumption of isospin invariance for the nucleon, i.e. $u_p(x) = d_n(x) = u(x)$, etc... (also for antiquarks), one has for W^+ production

$$\frac{d\sigma_{pn}^{W^+}}{dy} = G_F \pi \sqrt{2} \tau \cdot \frac{1}{3} \left[u(x_a, M_W^2) \overline{u}(x_b, M_W^2) + \overline{d}(x_a, M_W^2) d(x_b, M_W^2) \right] \tag{4}$$

which is no longer symmetric under $y \to -y$ and it simply follows that for W^- production one has

$$\frac{d\sigma_{pn}^{W^-}}{dy}(y) = \frac{d\sigma_{pn}^{W^+}}{dy}(-y) \ . \tag{5}$$

All these cross sections will strongly be dependent on the antiquark distributions whose present determination is more uncertain than that of $u(x)$ and $d(x)$. Following ref.[7] we will take the valence quarks $u_v(x, Q^2)$ and $d_v(x, Q^2)$ from ref.[11] with the appropriate evolution from $Q^2 = 4$ GeV^2 to $Q^2 = M_W^2$. We will assume that the antiquark and sea quark distributions go like $(1-x)^{10}$, flavor symmetry breaking being obtained by taking

$$x\delta\overline{q}(x) = x\overline{u}(x) - x\overline{d}(x) = ax^b(1-x)^{10} \tag{6}$$

with $a = -0.22$ and $b = 0.45$. For our calculations we have used $M_W = 80.22\ GeV$, the latest value given in the Particle Properties Data Booklet. This value is lower than the one used in ref.[7] and it leads to slightly larger predictions for pp collisions. The results are shown in figs. 1 and 2 for two different center of mass energies $\sqrt{s} = 350$ and $500\ GeV$, the lower one being the maximum energy in pn collisions when the proton and the deuteron beam momenta are $250\ GeV/c$. Given the luminosity mentioned above, we see that one expects a fairly large event rate for all these cases. As in ref.[7] we could have studied the sensitivity of these cross sections to various choices of the antiquark distributions, but in order to avoid some uncertainties related to their absolute normalization and to pin down the flavor asymmetry of the sea we introduce the following quantity

$$R_W = \frac{d\sigma_{pp}^{W^+}/dy - d\sigma_{pn}^{W^+}/dy + d\sigma_{pp}^{W^-}/dy - d\sigma_{pn}^{W^-}/dy}{d\sigma_{pp}^{W^+}/dy + d\sigma_{pn}^{W^+}/dy + d\sigma_{pp}^{W^-}/dy + d\sigma_{pn}^{W^-}/dy} \ . \tag{7}$$

In terms of parton distributions, it simply reads

$$R_W = -\frac{\delta q(x_a)\delta\overline{q}(x_b) + (x_a \leftrightarrow x_b)}{\sigma q(x_a)\sigma\overline{q}(x_b) + (x_a \leftrightarrow x_b)} \tag{8}$$

where $\binom{\sigma}{\delta} q(x) = u(x) \pm d(x)$ and similarly for antiquarks. Clearly R_W is symmetric under $y \to -y$ and $R_W = 0$ if the sea is flavor symmetric, i.e. $\overline{u}(x) = \overline{d}(x)$ that is $\delta\overline{q}(x) \equiv 0$. The result of the calculation for our choice of the flavor symmetry breaking (see eq.(6)) is shown in fig.3 for two different energies and it provides a very clear test for the antiquark distributions. We find that R_W is positive which is due to the fact that for our choice $\delta\overline{q}(x) < 0$, because $\overline{d}(x) > \overline{u}(x)$.

In the case of Z production, similar calculations can be done in the Drell-Yan picture in terms of $u\overline{u}$ and $d\overline{d}$ annihilations. For pp collisions we have

$$\frac{d\sigma^Z_{pp}}{dy} = \frac{G_F \pi\tau}{\sqrt{2}} \cdot \frac{1}{3} \sum_{i=u,d} (a_i^2 + b_i^2) \left[q_i(x_a, M_Z^2)\overline{q}_i(x_b, M_Z^2) + (x_a \leftrightarrow x_b)\right] \tag{9}$$

where a_i and b_i denote the vector and axial vector coupling constants of the quark i to the Z boson. For pn collisions one obtains the corresponding expression $d\sigma^Z_{pn}/dy$ by making the appropriate substitutions as above for the case of $W^\pm$ production. The results are shown in figs.4 and 5 for $M_Z = 91.173\ GeV$ at two different energies where we see, as expected, a symmetric distribution for pp and asymmetric for pn collisions.

Let us also consider a quantity which is less sensitive to absolute normalization uncertainties i.e.

$$R_Z = \frac{d\sigma^Z_{pp}/dy - d\sigma^Z_{pn}/dy}{d\sigma^Z_{pp}/dy + d\sigma^Z_{pn}/dy} \tag{10}$$

and which reads in terms of the parton distributions taken at $Q^2 = M_Z^2$

$$\begin{aligned} R_Z = \{ & (a_u^2 + b_u^2) \left[u(x_a)\delta\overline{q}(x_b) + \overline{u}(x_a)\delta q(x_b)\right] \\ & -(a_d^2 + b_d^2) \left[d(x_a)\delta\overline{q}(x_b) + \overline{d}(x_a)\delta q(x_b)\right] \} \, / \\ & \sum_{i=u,d} (a_i^2 + b_i^2) \left[q_i(x_a)\sigma\overline{q}(x_b) + \overline{q}_i(x_a)\sigma q(x_b)\right] \end{aligned} \tag{11}$$

In this case, even for $\delta\overline{q} \equiv 0$ we don't have $R_Z = 0$, because the couplings of u and d quarks are different and we find R_Z negative because $\left(a_d^2 + b_d^2\right) > \left(a_u^2 + b_u^2\right)$. The results are given in figs. 6a and b for two different energies where the dashed curves correspond to $\delta\overline{q} \equiv 0$ and solid curves to our choice of the flavor symmetry breaking (see eq. (6)). Although the Z production will be less copious this comparison between pp and pn collisions will also allow to discriminate between $\delta\overline{q} \equiv 0$ and $\delta\overline{q} \neq 0$.

3. HELICITY ASYMMETRIES WITH LONGITUDINALLY POLARIZED PROTON BEAMS

Since RHIC will be built to be used as a polarized pp collider, let us now investigate what we can learn from the measurement of various spin-dependent observables. We first start with one longitudinally polarized proton beam and we consider the parity-violating helicity asymmetry defined as

$$A_L = \frac{d\sigma_- - d\sigma_+}{d\sigma_- + d\sigma_+} \; . \tag{12}$$

Here σ_h denotes the cross section where the initial proton has helicity h. This asymmetry will be expressed in terms of the parton helicity asymmetries $\Delta f(x, Q^2) = f_+(x, Q^2) - f_-(x, Q^2)$ where $f_\pm(x, Q^2)$ denote the parton distributions in a polarized nucleon either with helicity parallel (+) or antiparallel (−) to the parent nucleon helicity. In the Standard Model the W is a purely left handed current and this asymmetry reads simply, for W^+ production in pp collisions,

$$A_L(y) = \frac{\Delta u\left(x_a, M_W^2\right) \overline{d}\left(x_b, M_W^2\right) - \left(u \leftrightarrow \overline{d}\right)}{u\left(x_a, M_W^2\right) \overline{d}\left(x_b, M_W^2\right) + \left(u \leftrightarrow \overline{d}\right)} \tag{13}$$

assuming the proton a is polarized. For W^- production quark flavors are interchanged. This asymmetry, together with two other parity-violating helicity asymmetries related to it, have been studied in ref. [7], so here we will rather consider the case of pn collisions which will be also combined with some of our previous results on pp collisions from ref. [7]. For W^+ production in pn collisions one has

$$A_L(y) = \frac{\Delta u\left(x_a, M_W^2\right) \overline{u}\left(x_b, M_W^2\right) - \Delta\overline{d}\left(x_a, M_W^2\right) d\left(x_b, M_W^2\right)}{u\left(x_a, M_W^2\right) \overline{u}\left(x_b, M_W^2\right) + \overline{d}\left(x_a, M_W^2\right) d\left(x_b, M_W^2\right)} \tag{14}$$

assuming the proton is polarized(1). In order to calculate these asymmetries we have to use a model for the various partons (valence quark, sea quark, antiquark) helicity asymmetries Δu_v, Δu_s, $\Delta\overline{u}$, Δd_v, Δd_s, $\Delta\overline{d}$ compatible with polarized deep inelastic scattering data. We recall that in leptoproduction with both lepton and nucleon longitudinally polarized, one extracts the structure function $g_1(x) = 1/2\sum_i e_i^2\,[\Delta q_i(x) + \Delta\overline{q}_i(x)]$ which is, so far, our unique source of information on the quark and antiquark helicity asymmetries. Many parametrizations have been proposed in the litterature, but following ref. [7] we will adopt a recent suggestion[12] to construct polarized quark distributions from unpolarized quark distributions, based on the extensive use of the Pauli exclusion principle. In this approach(2) one successfully relates the violation of the Gottfried sum rule to the Ellis-Jaffe sum rule[14] defect reported earlier by the EMC in the proton case[15]. So concerning the valence distributions we will take

$$\Delta u_v(x) = u_v(x) - d_v(x) \quad \text{and} \quad \Delta d_v(x) = -1/4\; d_v(x), \tag{15}$$

whereas for sea quark, and antiquark, assuming that $\Delta q_s(x) = \Delta\overline{q}_s(x)$, for the $\overline{u}$'s we will take following ref. [7]

$$\Delta\overline{u}(x) = \overline{u}(x) - \overline{d}(x) \equiv \delta\overline{q}(x) \tag{16a}$$

which leads to a large negative $\overline{u}$ polarization. Concerning the $\overline{d}$'s, in ref. [7] their polarization was taken to be small and positive, but our analysis[13] of the recent SLAC data on polarized neutron deep inelastic scattering[16] is consistent with

$$\Delta\overline{d}(x) \equiv 0, \tag{16b}$$

and this will be assumed from now on. We show in fig. 7 our choice of the various parton polarizations $\Delta q/q$ taken at $Q^2 = M_W^2$. Returning now to A_L, we show the results of our calculations for pn collisions in figs 8a, b at two

(1) In the proton-deuteron collisions we assume that only the proton beam is polarized, because it is not clear to us that it will be possible to have polarized deuteron beams.

(2) For a more recent work on the description of quark distributions in terms of Fermi-Dirac distributions see also ref. [13].

different energies and we observe that there is very little energy dependence. The general trend of A_L is similar to what we obtained in ref. [7] for pp collisions. It can be understood from eq. (14) and we see that for $y=-1$, A_L is sensitive to the antiquark polarizations since

$$A_L^{W^+} \sim -\frac{\Delta\overline{d}}{\overline{d}} \quad \text{and} \quad A_L^{W^-} \sim -\frac{\Delta\overline{u}}{\overline{u}} \tag{17}$$

whereas for $y=+1$, it is sensitive to the quark polarizations since

$$A_L^{W^+} \sim \frac{\Delta u}{u} \quad \text{and} \quad A_L^{W^-} \sim \frac{\Delta d}{d}\,. \tag{18}$$

So it is easy from fig. 7 to anticipate the results shown in figs. 8a, b and in particular if $\Delta\overline{d}$ is not equal to zero, it will clearly show up in $A_L^{W^+}$ near $y=-1$. From the measurement of the cross section $d\sigma/dy$ and the parity-violating asymmetry A_L for the four cases $pp \to W^\pm$ and $pn \to W^\pm$ one can obtain a quantity which is less sensitive to absolute normalization uncertainties, that is

$$a_L^W = \frac{(A_L d\sigma/dy)_{pp}^{W^+} - (A_L d\sigma/dy)_{pn}^{W^+} + (A_L d\sigma/dy)_{pp}^{W^-} - (A_L d\sigma/dy)_{pn}^{W^-}}{d\sigma_{pp}^{W^+}/dy + d\sigma_{pn}^{W^+}/dy + d\sigma_{pp}^{W^-}/dy + d\sigma_{pn}^{W^-}/dy}\,. \tag{19}$$

In terms of parton distributions taken at $Q^2 = M_W^2$ it simply reads

$$a_L^W = -\frac{\sigma\Delta q(x_a)\delta\overline{q}(x_b) + \sigma\Delta\overline{q}(x_a)\delta q(x_b)}{\sigma q(x_a)\sigma\overline{q}(x_b) + (x_a \leftrightarrow x_b)} \tag{20}$$

where $\sigma\Delta q(x) = \Delta u(x) + \Delta d(x)$ and similarly for antiquarks. So in a situation where the sea is flavor symmetric i.e. $\delta\overline{q}(x) \equiv 0$ *and* the antiquarks are unpolarized i.e. $\Delta\overline{q}(x) \equiv 0$, one has $a_L^W \equiv 0$. Our results are shown in figs. 9a, b for two different energies. The solid curve corresponds to $\delta\overline{q}(x) \neq 0$ and $\Delta\overline{q}(x) \neq 0$ so a_L^W is positive and lies between 5% and 15%. However if we assume flavor symmetry breaking for the sea i.e. $\delta\overline{q}(x) \neq 0$, but unpolarized antiquarks $\Delta\overline{q}(x) = 0$, we get the small dashed curve, which compared to the solid curve exhibits clearly the sensitivity to $\Delta\overline{q}(x)$ near $y=-1$. Finally one can also consider the case where $\delta\overline{q}(x) = 0$ so $\Delta\overline{u}(x) = 0$ and $\Delta\overline{d}(x) \neq 0$ at variance with eq. (16b), then we would have $a_L^W \neq 0$ and of opposite sign to $\Delta\overline{d}(x)$.

We now turn to the case of Z production where similar calculations can be done. For A_L we obtain the following expression

$$A_L = \frac{\left[2a_u b_u \Delta u(x_a)\overline{d}(x_b) + 2a_d b_d \Delta d(x_a)\overline{u}(x_b)\right] - (q \leftrightarrow \overline{q})}{\left[(a_u^2 + b_u^2)\, u(x_a)\overline{d}(x_b) + (a_d^2 + b_d^2)\, d(x_a)\overline{u}(x_b)\right] + (q \leftrightarrow \overline{q})} \ . \tag{21}$$

The results are shown in fig. 10 at two different energies. We get large positive values near $y = +1$, whereas it is almost zero near $y = -1$, at variance with the case of pp collisions where it was also large and positive near $y = -1$[7] and this is related to the fact that $\overline{d}(x) > \overline{u}(x)$ as we will see now. Like for $W^{\pm}$ production combining pp and pn measurements, we now consider the following quantity

$$a_L^Z = \frac{(A_L d\sigma/dy)_{pp}^Z - (A_L d\sigma/dy)_{pn}^Z}{d\sigma_{pp}^Z/dy + d\sigma_{pn}^Z/dy} \ . \tag{22}$$

In terms of the parton distributions taken at $Q^2 = M_Z^2$ it simply reads

$$a_L^Z = \frac{\left[2a_u b_u \Delta u(x_a) - 2a_d b_d \Delta d(x_a)\right]\left[\overline{u}(x_b) - \overline{d}(x_b)\right] - (q \leftrightarrow \overline{q})}{\left[(a_u^2 + b_u^2)\, u(x_a) + (a_d^2 + b_d^2)\, d(x_a)\right]\left[\overline{u}(x_b) + \overline{d}(x_b)\right] + (q \leftrightarrow \overline{q})} \ . \tag{23}$$

Clearly in a situation where the sea is flavor symmetric *and* the antiquarks are unpolarized one has $a_L^Z \equiv 0$. We show our results in figs 11a, b for two different energies. The solid curve corresponds to $\delta\overline{q}(x) \neq 0$ and $\Delta\overline{q}(x) \neq 0$ so a_L^Z is around +10% near $y = -1$ and reflects the trend of A_L in pp collisions whereas a_L^Z is around -10% near $y = +1$ and is driven by A_L in pn collisions. For unpolarized antiquarks $\Delta\overline{q}(x) = 0$, we get the small dashed curve which goes to zero near $y = -1$ as A_L in pp collisions for this case, but it follows the solid curve near $y = +1$. Finally we can also consider the case where $\delta\overline{q}(x) = 0$, so $\Delta\overline{u}(x) = 0$ and $\Delta\overline{d}(x) \neq 0$; then we would have $a_L^Z \neq 0$ and with the sign of $\Delta\overline{d}(x)$.

Before closing this section let us consider, in pp collisions where both proton beams are polarized, another observable which is very sensitive to antiquark polarizations, that is the parity-conserving double helicity asymmetry A_{LL} defined as

$$A_{LL} = \frac{d\sigma_{++} + d\sigma_{--} - d\sigma_{+-} - d\sigma_{-+}}{d\sigma_{++} + d\sigma_{--} + d\sigma_{+-} + d\sigma_{-+}} \ . \tag{24}$$

Here $\sigma_{h_1 h_2}$ is the cross section where the initial protons have helicities h_1 and h_2. This asymmetry, in W^+ production, reads simply

$$A_{LL}(y) = -\frac{\Delta u\left(x_a,\ M_W^2\right) \Delta \overline{d}\left(x_b,\ M_W^2\right) + (u \leftrightarrow \overline{d})}{u\left(x_a,\ M_W^2\right) \overline{d}\left(x_b,\ M_W^2\right) + (u \leftrightarrow \overline{d})} \ . \tag{25}$$

For W^- production quark flavors are interchanged. It is clear that $A_{LL}(y) = A_{LL}(-y)$ and that $A_{LL} \equiv 0$ if the antiquarks are not polarized, i.e. $\Delta\overline{u}(x) = \Delta\overline{d}(x) \equiv 0$. Similarly for Z production we find

$$A_{LL}(y) = -\frac{\sum\limits_{i=u,d} \left(a_i^2 + b_i^2\right) \left[\Delta q_i\left(x_a,\ M_Z^2\right) \Delta \overline{q}_i\left(x_b,\ M_Z^2\right) + (x_a \leftrightarrow x_b)\right]}{\sum\limits_{i=u,d} \left(a_i^2 + b_i^2\right) \left[q_i\left(x_a,\ M_Z^2\right) \overline{q}_i\left(x_b,\ M_Z^2\right) + (x_a \leftrightarrow x_b)\right]} \tag{26}$$

which will vanish for unpolarized antiquarks. We show in figs 12a, b our predictions for the three cases at two different energies and we now try to understand these results. Clearly as a consequence of eq. (16b) $A_{LL} \equiv 0$ for W^+ production but if $\Delta\overline{d}(x) \neq 0$, it would be non-zero and of opposite sign to $\Delta\overline{d}(x)$. For W^- production for $y = 0$ we get $A_{LL} = -\frac{\Delta d}{d}\frac{\Delta\overline{u}}{\overline{u}}$ evaluated at $x = M_W/\sqrt{s}$ which gives around $+10\%$ according to fig. 7. From the trend of the d and $\overline{u}$ polarizations shown in fig. 7 we also expect A_{LL} to be almost constant for $-1 < y < +1$. Finally for Z production as a consequence of eq. (16b) A_{LL} does not depend on the d quark polarization. For $y \simeq \pm 1$ one has approximately $A_{LL} \sim -\frac{\Delta u(x_a)}{u(x_a)}\frac{\Delta\overline{u}(x_b)}{\overline{u}(x_b)}$ evaluated at $x_a \sim 0.65$ and $x_b \sim 0.10$ for $\sqrt{s} = 350\ GeV$ that is, according to fig. 7, $A_{LL} \sim +40\%$. For $\sqrt{s} = 500\ GeV$ we get $A_{LL} \sim +25\%$. The values at $y = 0$ are smaller because of the maximum of the unpolarized cross section.

4. DOUBLE SPIN TRANSVERSE ASYMMETRY WITH POLARIZED PROTON BEAMS

So far we have considered collisions involving only longitudinally polarized proton beams, but of course at RHIC transversely polarized protons will be available as well[3]. This new possibility is extremely appealing because of recent progress in understanding transverse spin effects in QCD, both at leading twist[10] and higher twist levels[17]. For the case of the nucleon's helicity, its distribution among the various quarks and antiquarks can be obtained in polarized deep inelastic scattering from the measurement of the structure function $g_1(x)$ mentioned above. However this is not possible for the *transversity* distribution $h_1(x)$ which describes the state of a quark (antiquark) in a transversely polarized nucleon. The reason is that $h_1(x)$, which measures the correlation between right-handed and left-handed quarks, decouples from deep inelastic scattering. Indeed like $g_1(x)$, $h_1(x)$ is leading - twist and it can be measured in Drell-Yan lepton-pair production with both initial proton beams transversely polarized[10]. Other possibilities have been suggested[18] but in the framework of this paper, we will propose a practical way to determine $h_1(x)$ using gauge boson production in *pp* collisions with protons transversely polarized. Let us consider the double spin transverse asymmetry defined as

$$A_{TT} = \frac{d\sigma_{\uparrow\uparrow} - d\sigma_{\uparrow\downarrow}}{d\sigma_{\uparrow\uparrow} + d\sigma_{\uparrow\downarrow}} \tag{27}$$

where $\sigma_{\uparrow\uparrow}(\sigma_{\uparrow\downarrow})$ denotes the cross section with the two initial protons transversely polarized in the same (opposite) direction. Assuming that the underlying parton subprocess is quark-antiquark annihilation, we easily find for Z production

$$A_{TT} = \frac{\sum\limits_{i=u,d} \left(b_i^2 - a_i^2\right) \left[h_1^{q_i}(x_a) h_1^{\overline{q}_i}(x_b) + (x_a \leftrightarrow x_b)\right]}{\sum\limits_{i=u,d} \left(a_i^2 + b_i^2\right) \left[q_i(x_a)\overline{q}_i(x_b) + (x_a \leftrightarrow x_b)\right]} \,. \tag{28}$$

This result generalizes the case of lepton-pair production[10] through an off shell photon $\gamma^\star$ and corresponding to $b_i = 0$ and $a_i = e_i$, the electric charge of q_i. For $W^\pm$ production, which is pure left-handed and therefore does not allow right-left interference, we expect $A_{TT} = 0$, since in this case $a_i^2 = b_i^2$. This result is worth checking experimentally.

We recall that $h_1(x)$ has never been measured, so to evaluate A_{TT} one has to make an assumption on the possible magnitude of $h_1(x)$ for quarks and antiquarks. According to the MIT bag model[10] one expects relativistic effects to increase the magnitude of $h_1(x)$ and since in the non relativistic quark model one has

$$h_1^q(x) = \Delta q(x) \tag{29}$$

we will speculate that eq. (29) holds for quarks and antiquarks. The results of our calculations are shown in fig. 13 at two different energies and we see that A_{TT} has a similar trend as A_{LL} in figs. 12a, b, as a consequence of eq. (29). Clearly this prediction is only a guide for a future experiment at RHIC which will indeed lead to the actual determination of $h_1(x)$.

5. CONCLUDING REMARKS

We have seen that $W^\pm$ and Z production in pp and pn collisions at RHIC up to $\sqrt{s} = 500\ GeV$ will provide an extremely valuable source of information on parton distributions. The high luminosity of the machine will allow copious production of these gauge bosons and the precise measurement of unpolarized cross sections will answer unambigously the relevant question of flavor symmetry breaking of the light sea quarks (or antiquarks) of the nucleon. Since polarized proton beams will be available at RHIC with a high polarization, it will be possible to use longitudinally polarized beams to measure parity-violating asymmetries A_L. These asymmetries are large and contain clear signatures of the properties (magnitude and sign) of parton polarizations and it will greatly improve the calibration of light quark and antiquark polarized distributions. The absence of antiquark polarizations implies a vanishing double helicity asymmetry A_{LL}, which is rather easy to test. Of course, all these informations will be complementary to the data extracted from polarized deep inelastic scattering experiments both on proton and neutron targets and will supply a detailed knowledge of the quark spin structure of the nucleon. Finally the use of transversely polarized proton beams for Z production in pp collisions will allow the first determination of the transversity distribution $h_1(x)$ for quarks and antiquarks, which is so far totally unknown. To conclude, we hope the arguments given above are strong enough to make gauge boson production a vital part of the future experimental programme at RHIC with polarized proton beams.

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FIGURE CAPTIONS

Fig. 1a $d\sigma/dy$ versus y for W^+ and W^- production in pp collisions at $\sqrt{s} = 350\ GeV$.

Fig. 1b Same as (a) at $\sqrt{s} = 500\ GeV$.

Fig. 2 $d\sigma/dy$ versus y for W^+ production in pn collisions at $\sqrt{s} = 350$ and $500\ GeV$. W^- cross section is obtained by symmetry around $y = 0$.

Fig. 3 The ratio R_W (see eq. (7)) versus y at $\sqrt{s} = 350$ and $500\ GeV$.

Fig. 4 $d\sigma/dy$ versus y for Z production in pp collisions at $\sqrt{s} = 350$ and $500\ GeV$.

Fig. 5 $d\sigma/dy$ versus y for Z production in pn collisions at $\sqrt{s} = 350$ and $500\ GeV$.

Fig. 6a The ratio R_Z (see eq. (10)) versus y at $\sqrt{s} = 350\ GeV$. Dashed curve corresponds to $\delta\overline{q} = 0$, solid curve corresponds to the choice in eq. (6).

Fig. 6b Same as (a) at $\sqrt{s} = 500\ GeV$.

Fig. 7 Parton polarizations $\Delta q/q$ versus x taken at $Q^2 = M_W^2$ following eqs. (15, 16a, 16b).

Fig. 8a The parity-violating helicity asymmetry A_L versus y for W^+ and W^- production in pn collisions at $\sqrt{s} = 350\ GeV$.

Fig. 8b Same as (a) at $\sqrt{s} = 500\ GeV$.

Fig. 9a The ratio a_L^W (see eq. (20)) versus y at $\sqrt{s} = 350\ GeV$. Solid curve, $\delta\overline{q}(x) \neq 0$ and $\Delta\overline{q}(x) \neq 0$. Small dashed curve, $\delta\overline{q}(x) \neq 0$ and $\Delta\overline{q}(x) = 0$.

Fig. 9b Same as (a) at $\sqrt{s} = 500\ GeV$.

Fig. 10 The parity-violating helicity asymmetry A_L versus y for Z production in pn collisions at $\sqrt{s} = 350$ and $500\ GeV$.

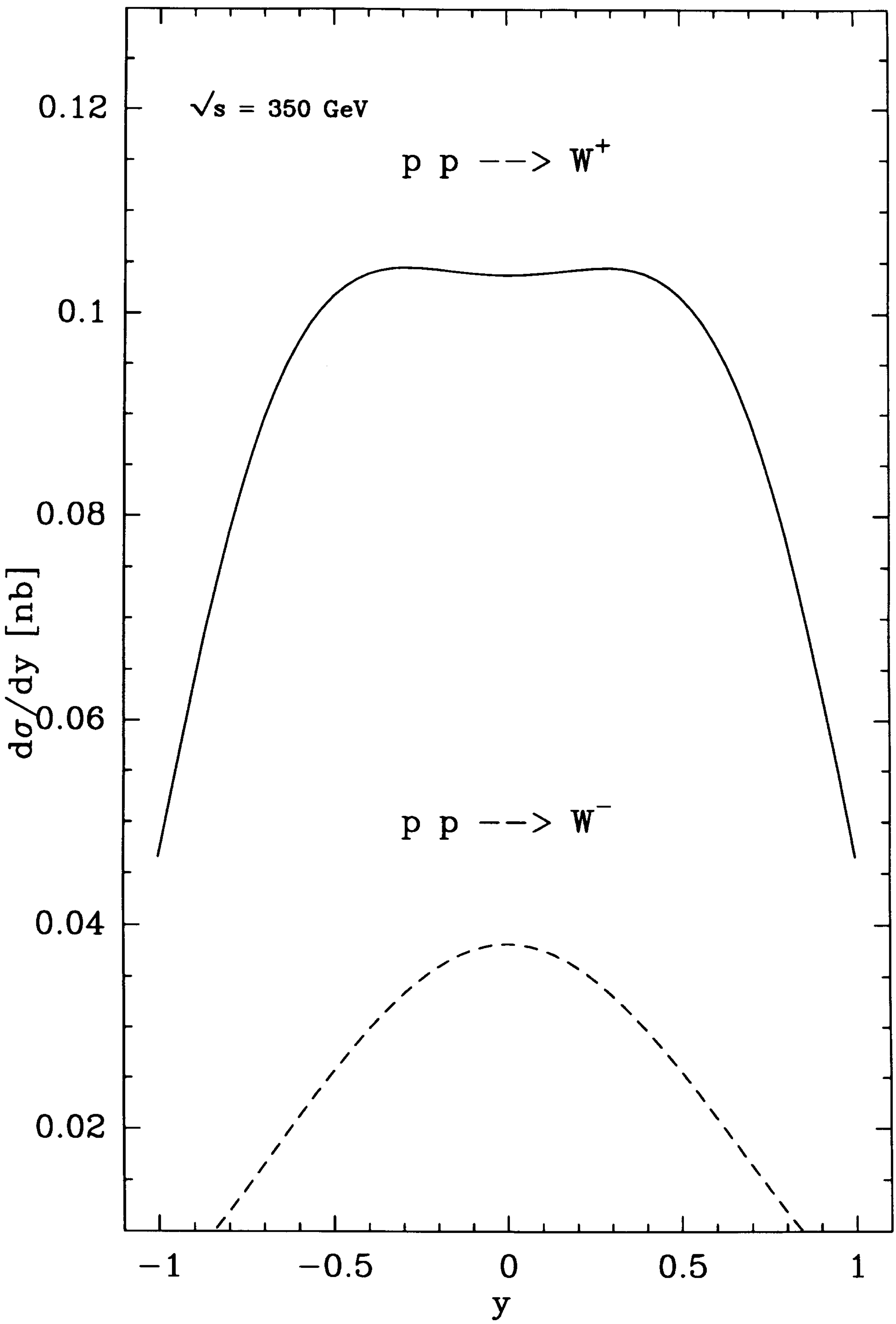
Fig. 11a The ratio a_L^Z (see eq. (22)) versus y at $\sqrt{s} = 350\ GeV$. Solid curve, $\delta\overline{q}(x) \neq 0$ and $\Delta\overline{q}(x) \neq 0$. Small dashed curve, $\delta\overline{q}(x) \neq 0$ and $\Delta\overline{q}(x) = 0$.

Fig. 11b Same as (a) at $\sqrt{s} = 500\ GeV$.

Fig. 12a Parity-conserving double helicity asymmetry A_{LL} versus y for $W^{\pm}$ and Z production in pp collisions at $\sqrt{s} = 350\ GeV$.

Fig. 12b Same as (a) at $\sqrt{s} = 500\ GeV$.

Fig. 13 Double spin transverse asymmetry A_{TT} versus y for Z production in pp collisions at $\sqrt{s} = 350$ and $500\ GeV$.



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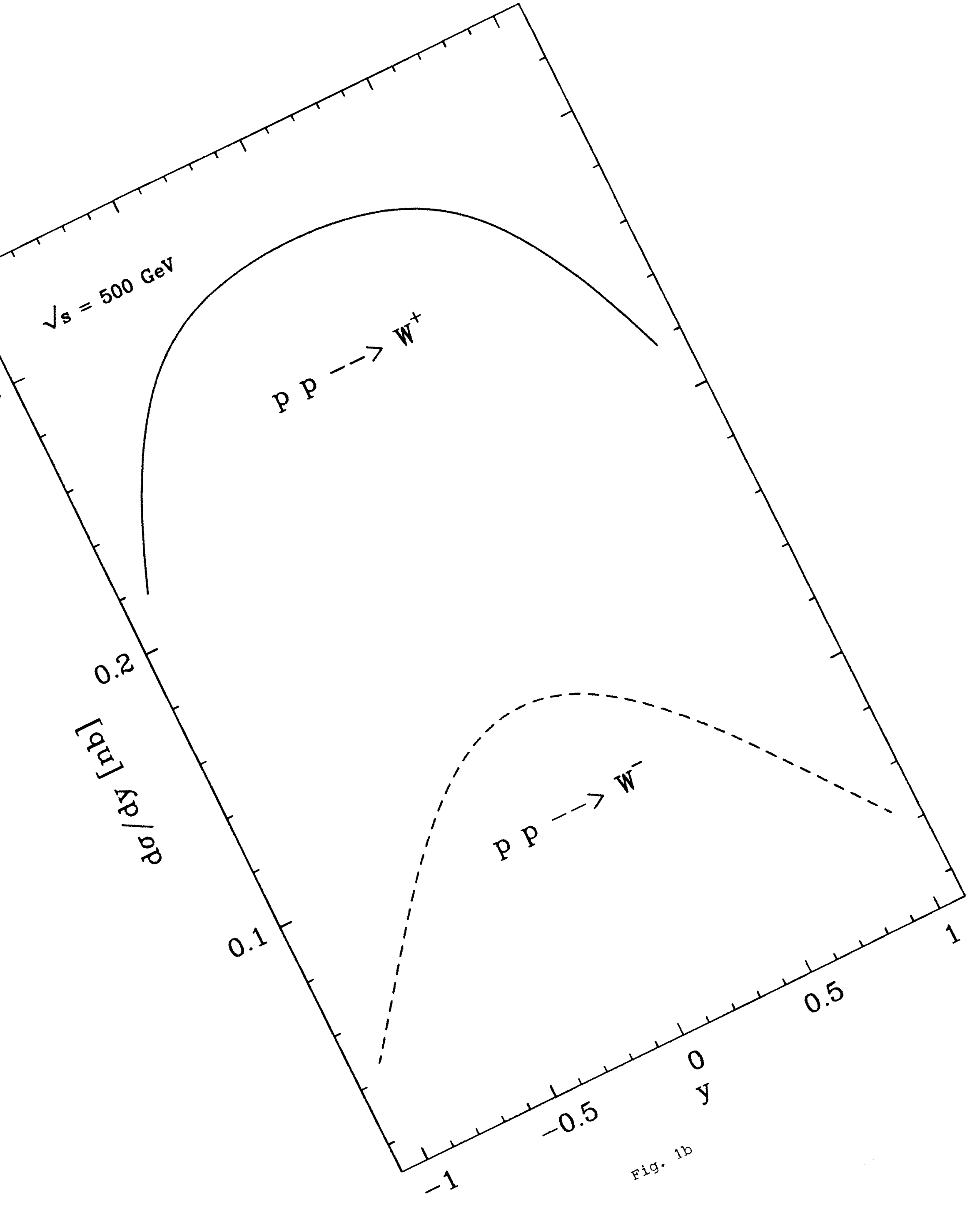

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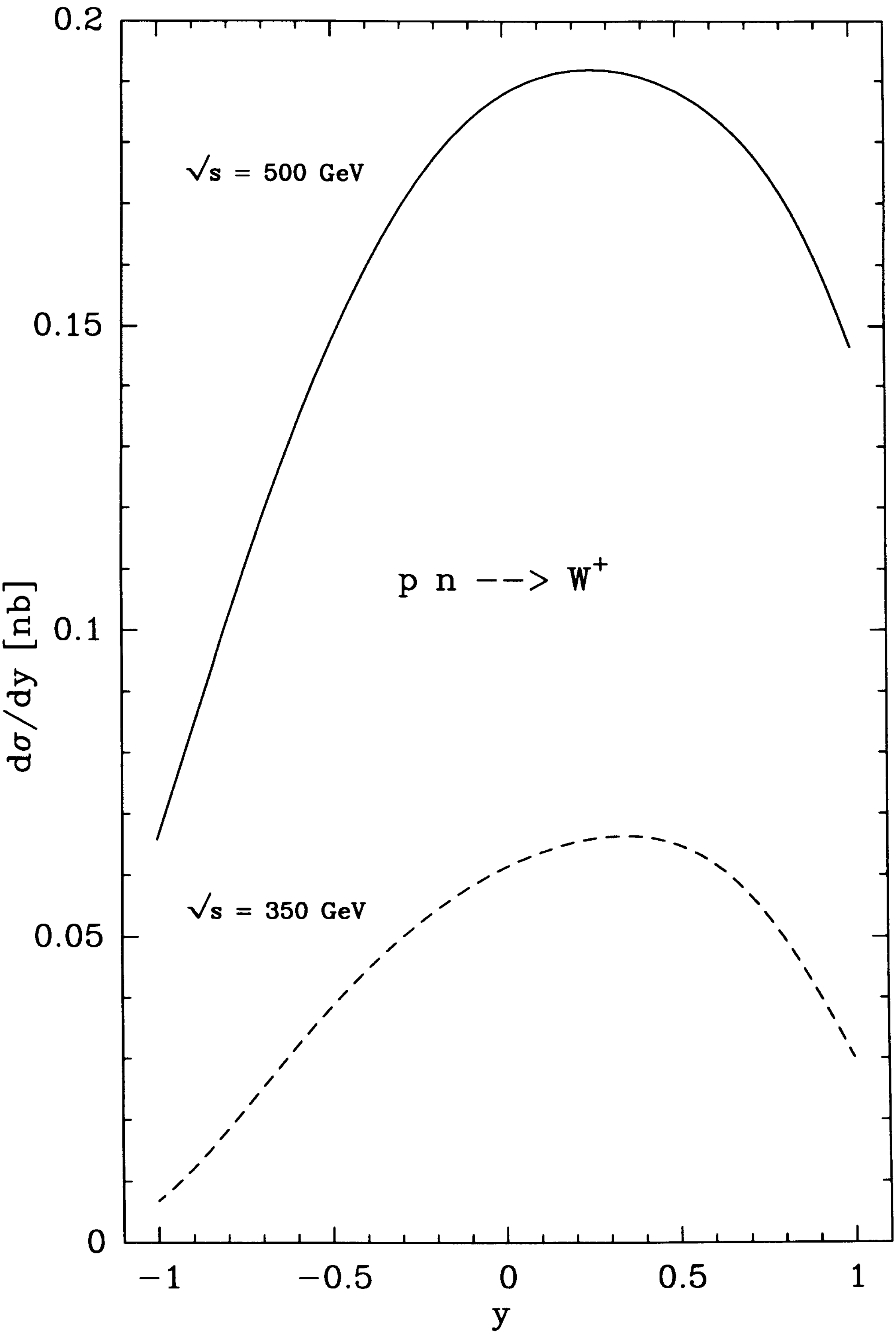

0.2
0.15
0.1
0.05
0
$d\sigma/dy$ [nb]
$\sqrt{s}$ = 500 GeV
p n --> W^+
$\sqrt{s}$ = 350 GeV
−1
−0.5
0
0.5
1
y

Fig. 2

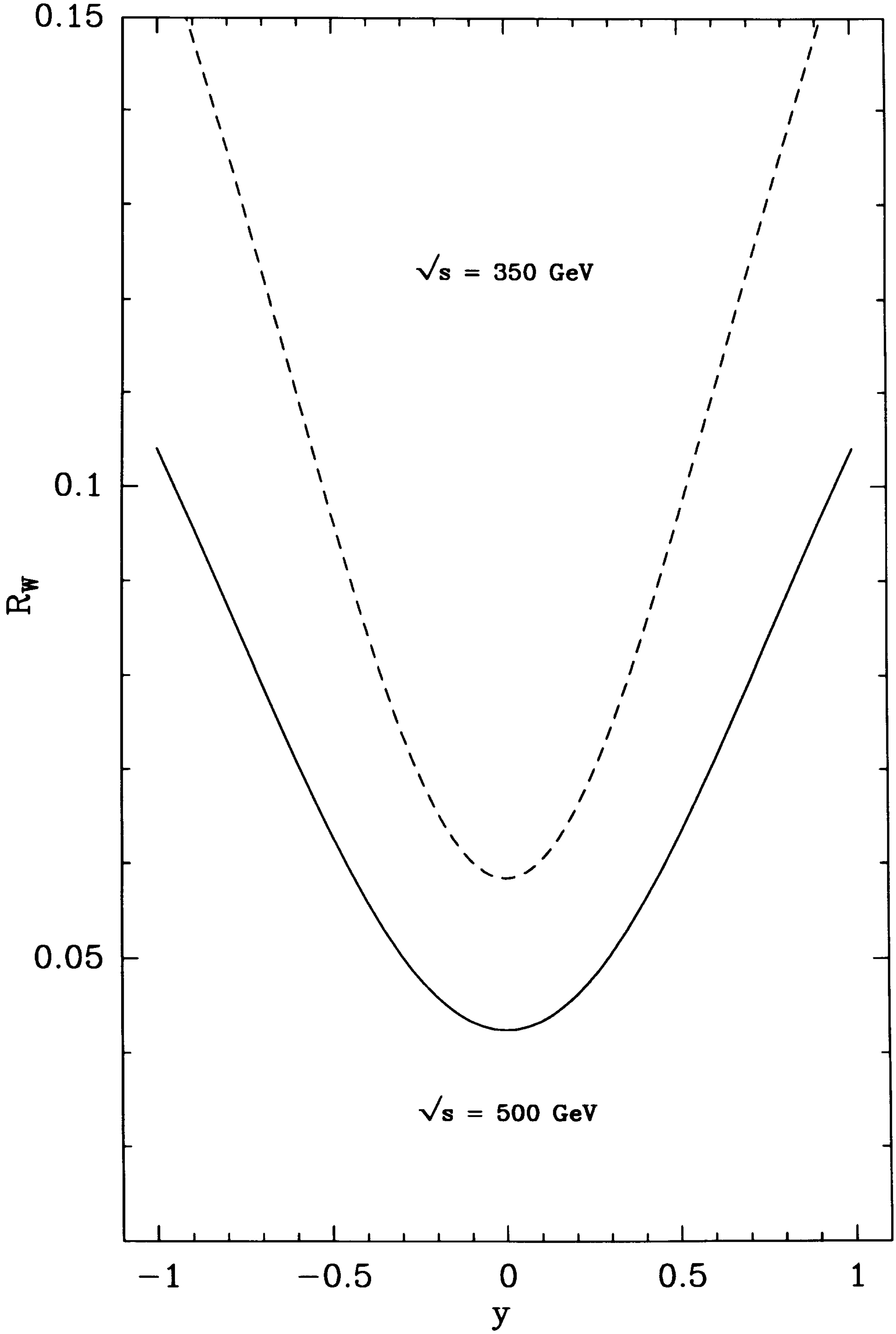


Fig. 3

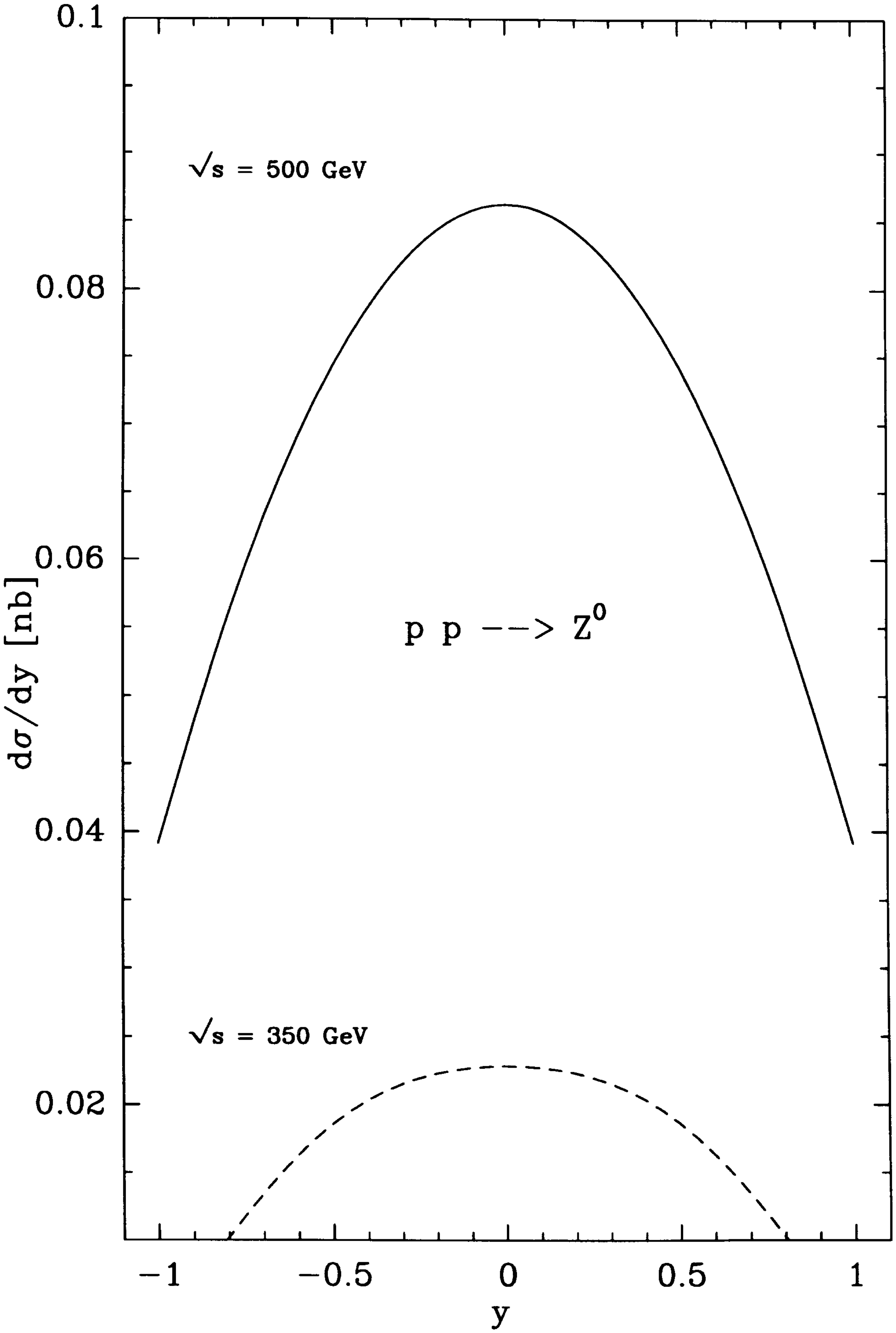
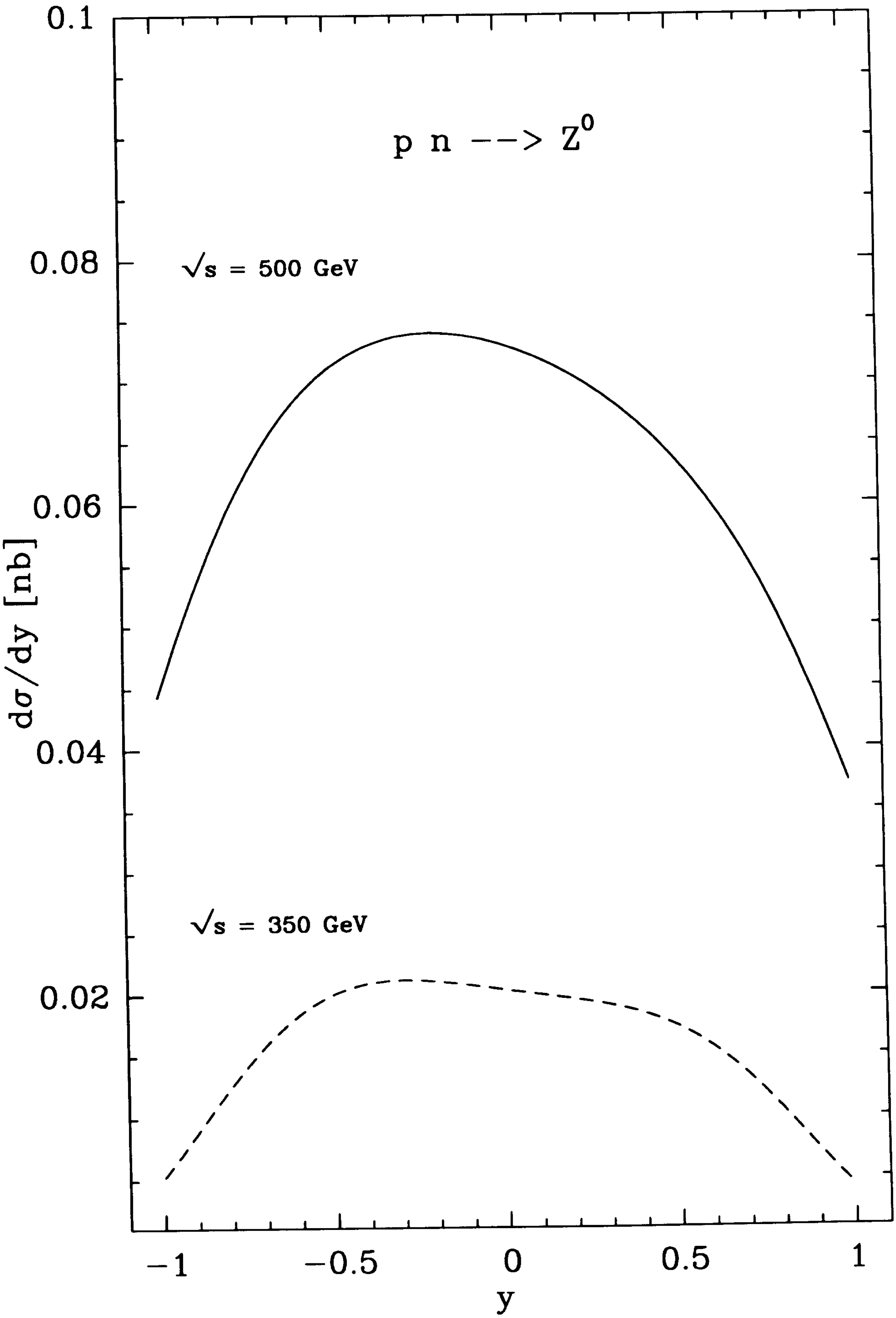


Fig. 4



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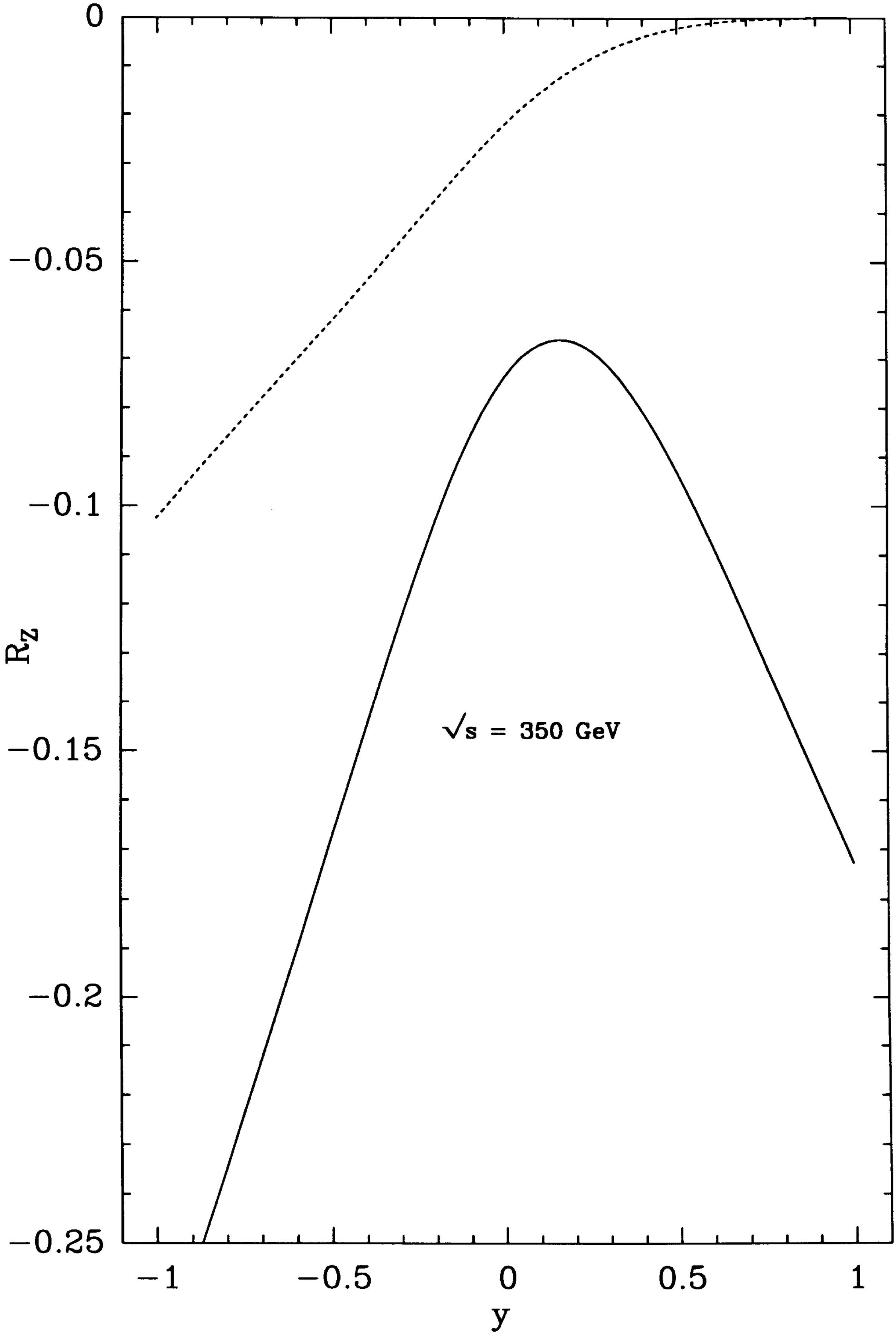


Fig. 6a

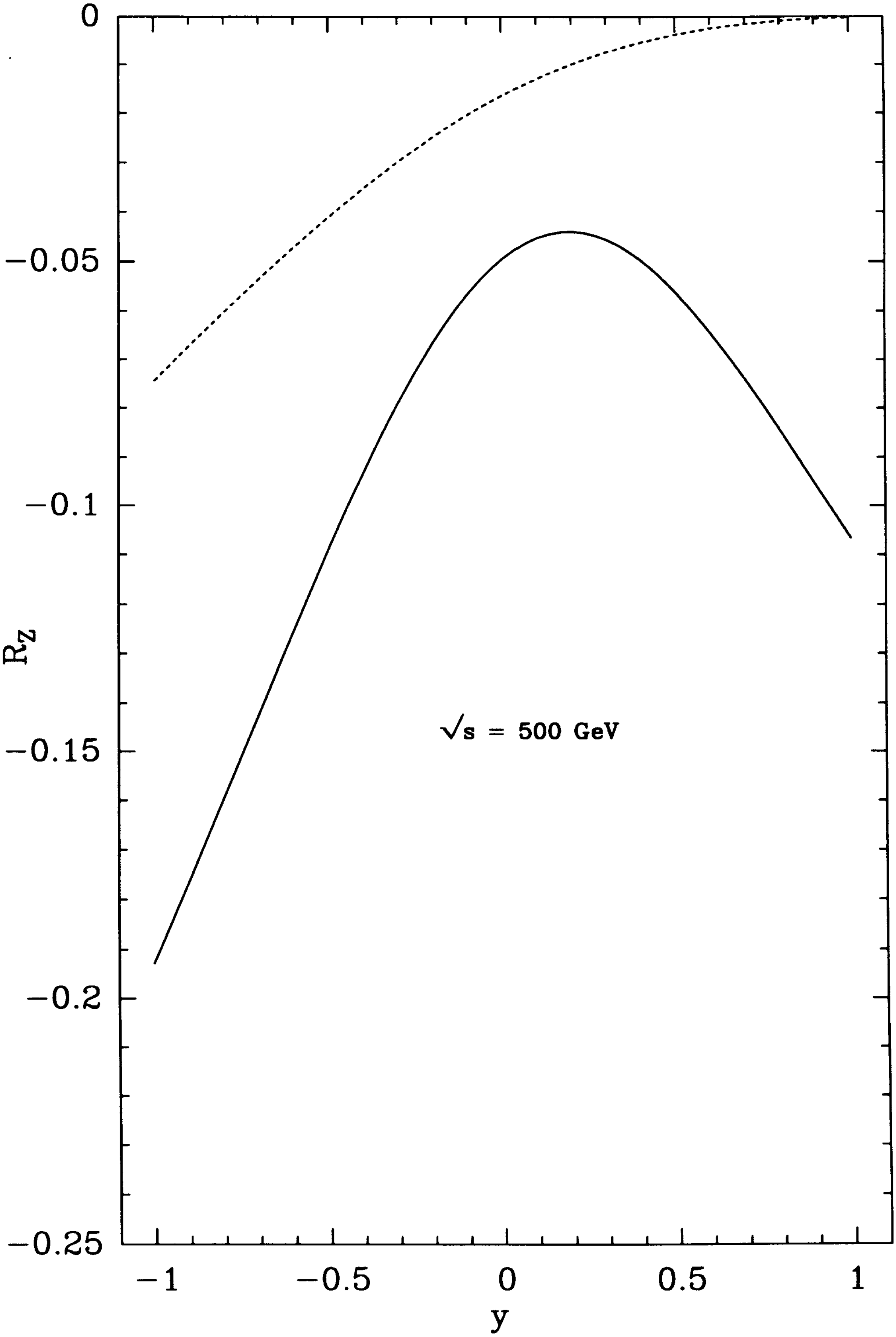


Fig. 6b

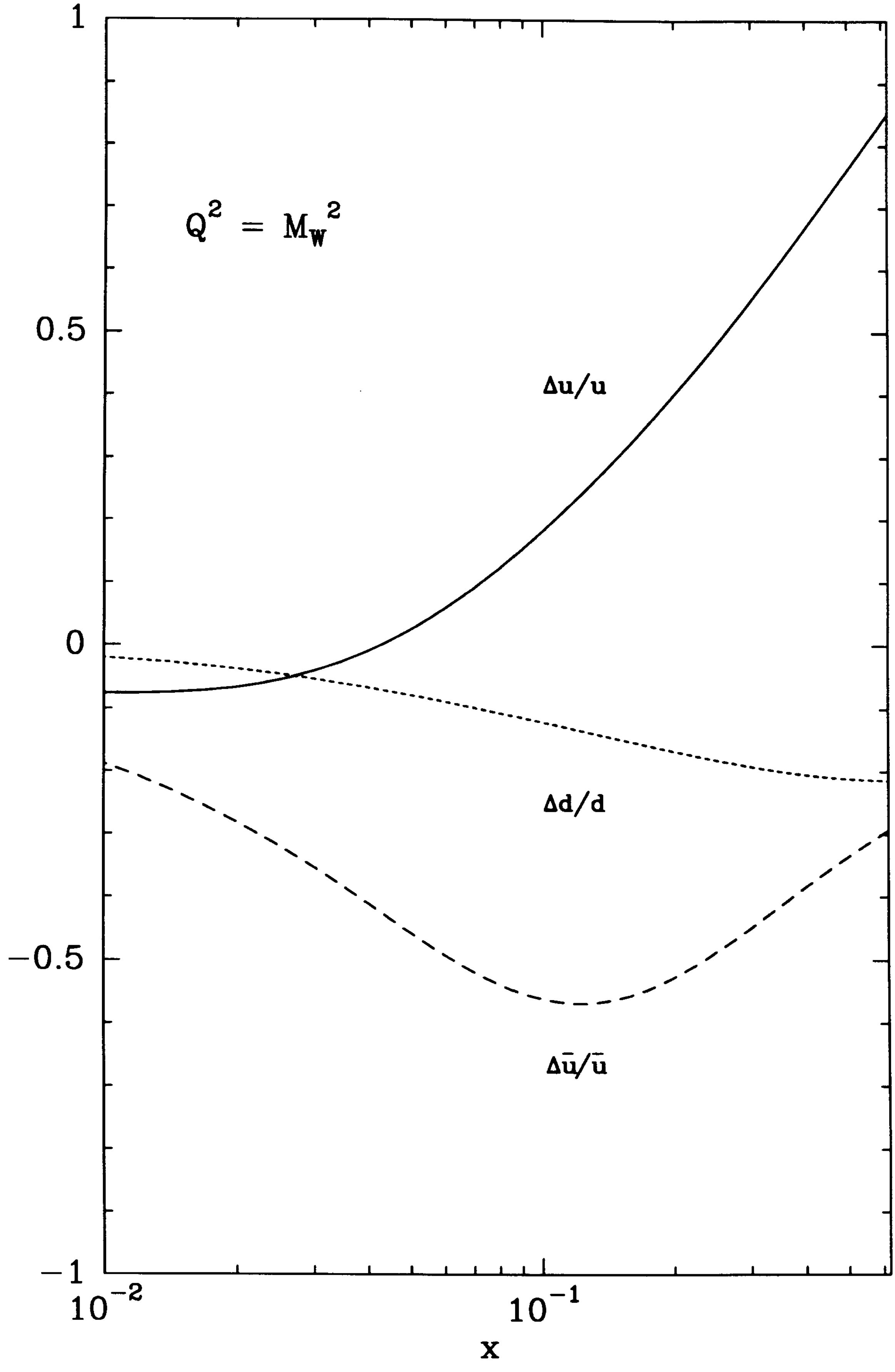


Fig. 7

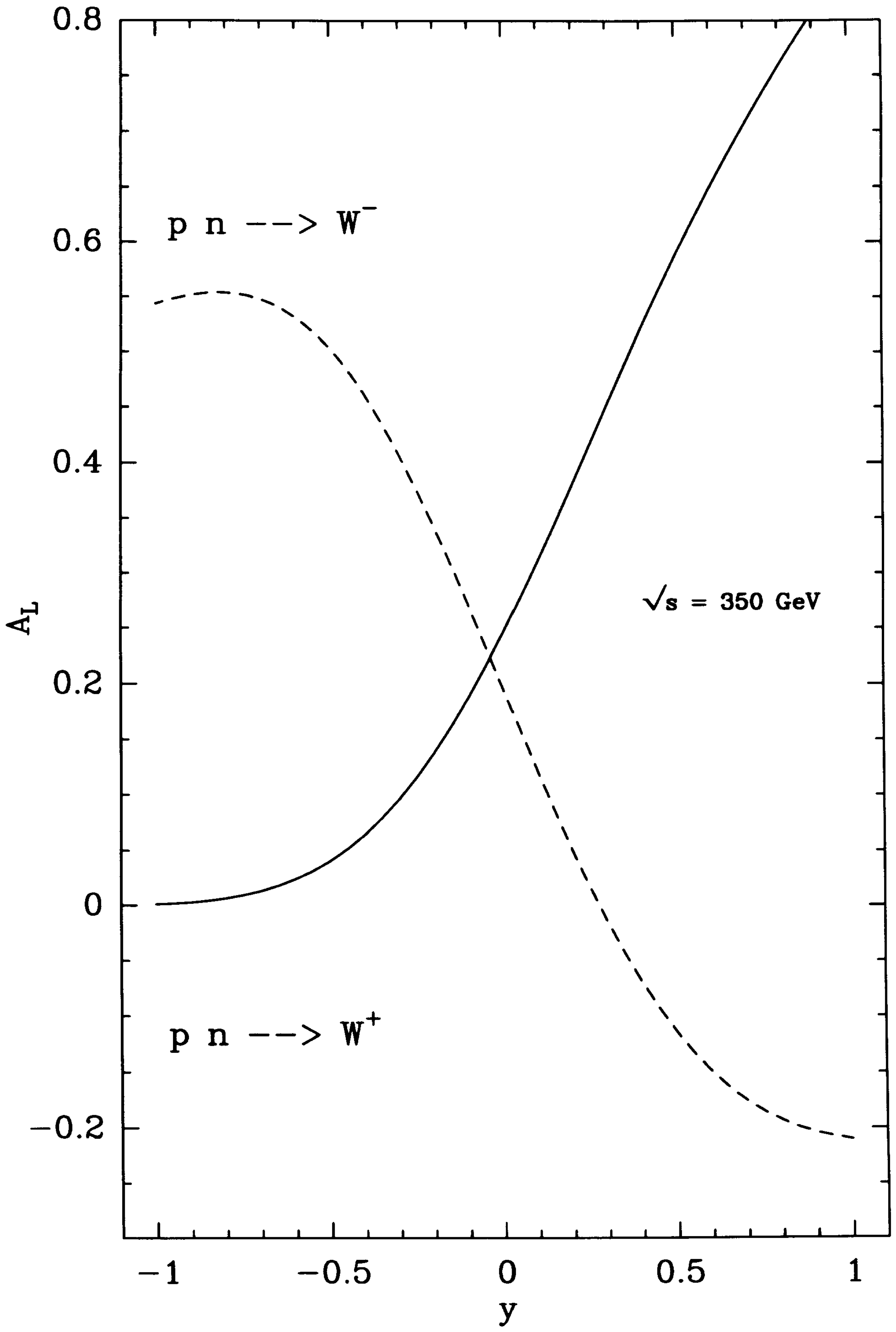
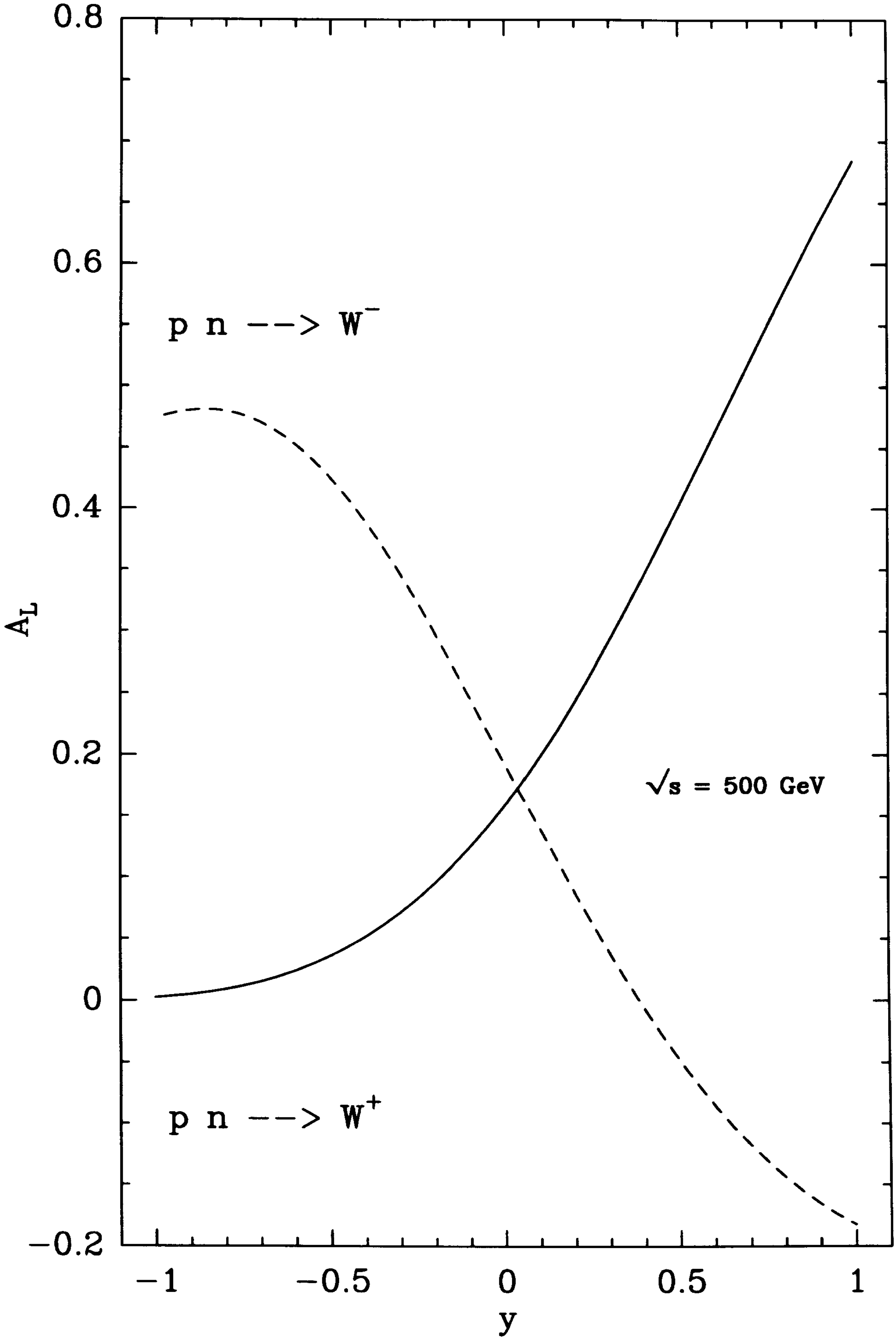


Fig. 8a



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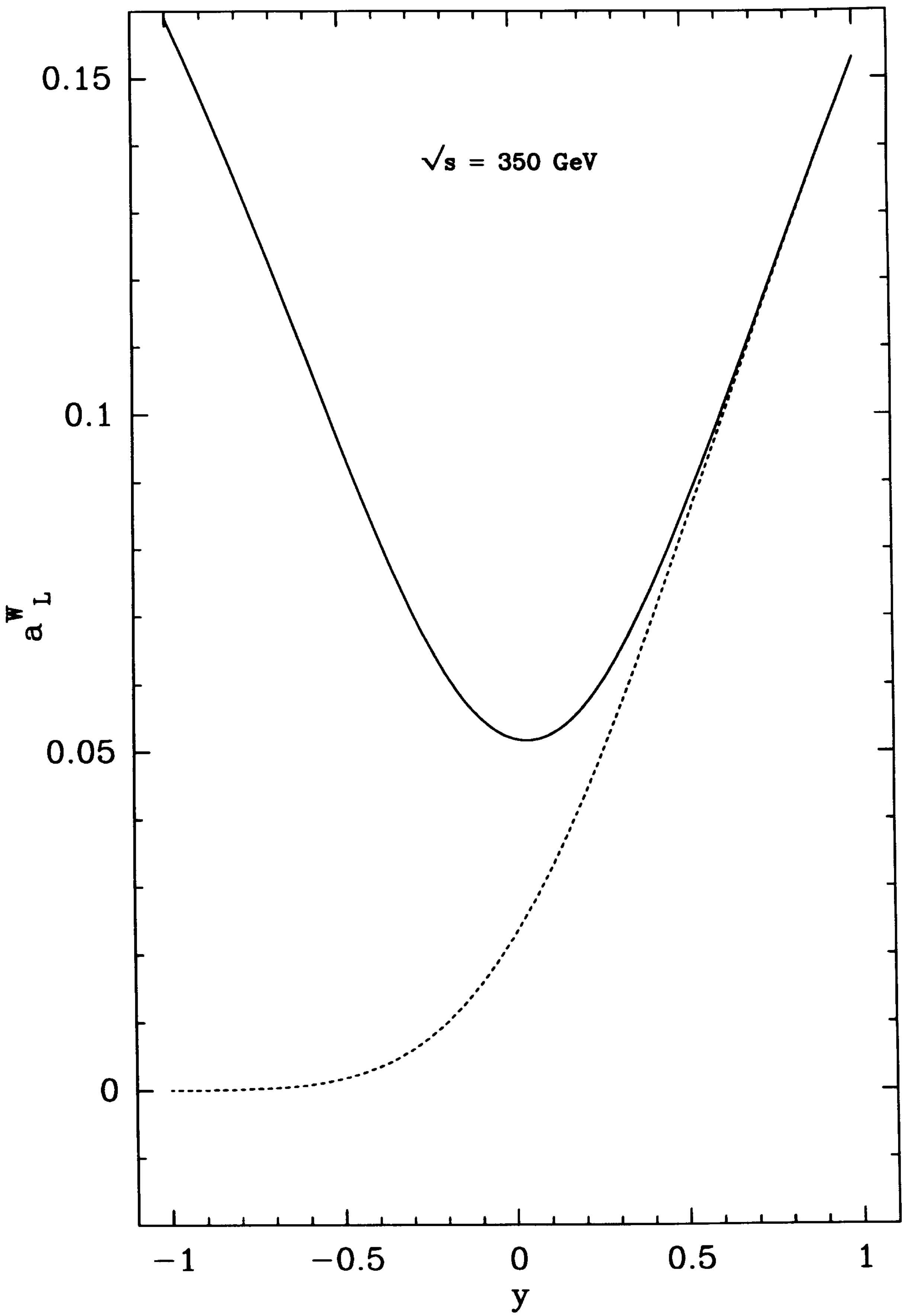

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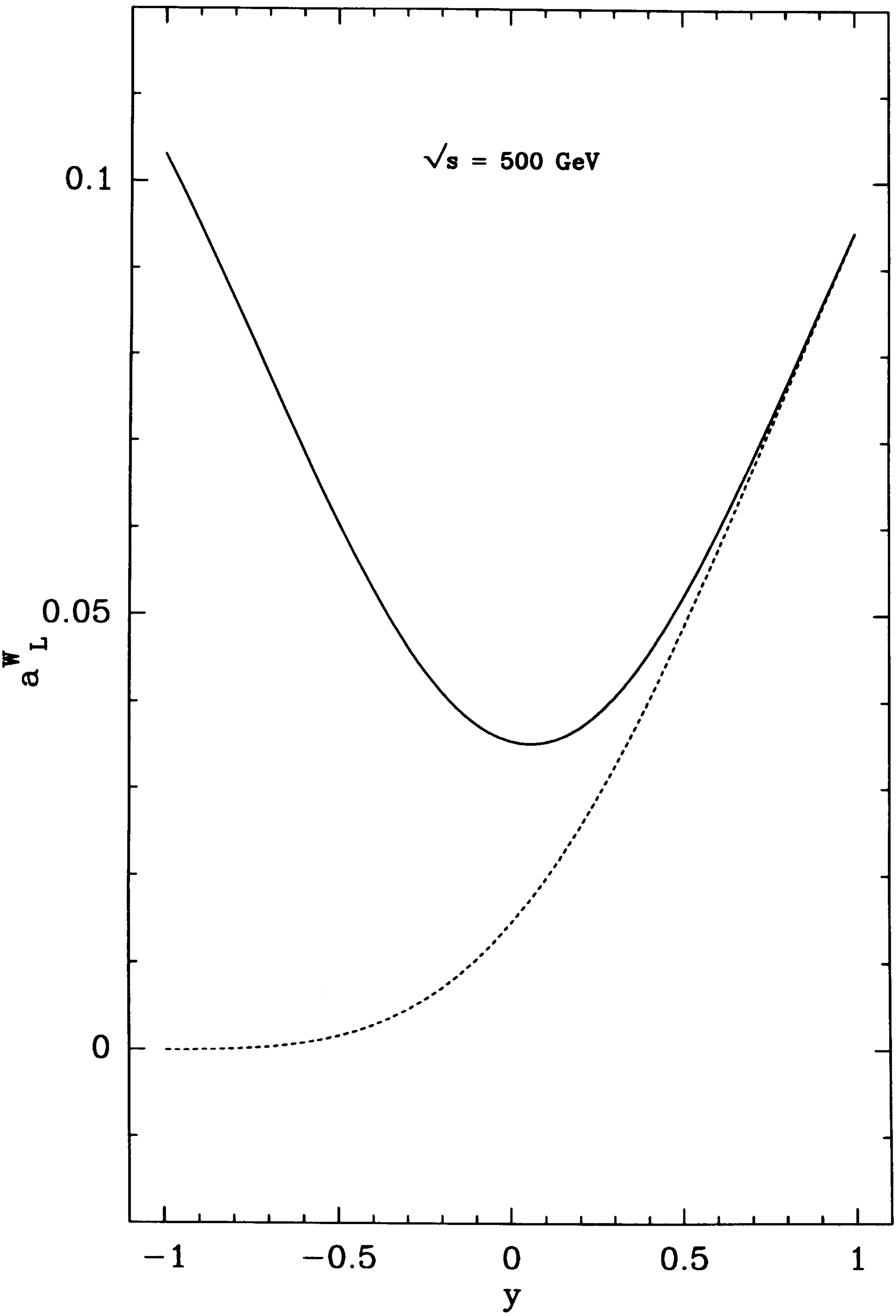

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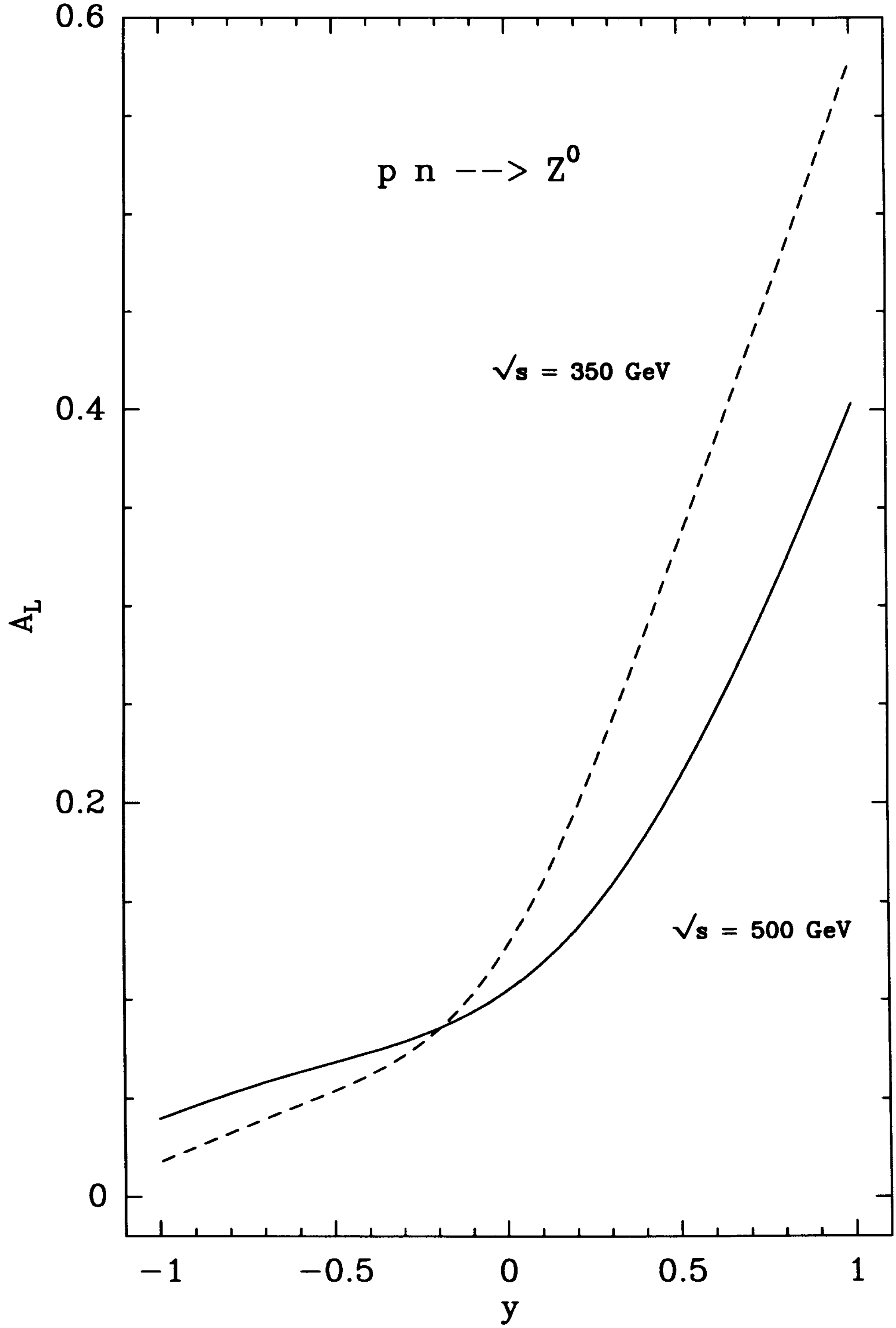


Fig. 10

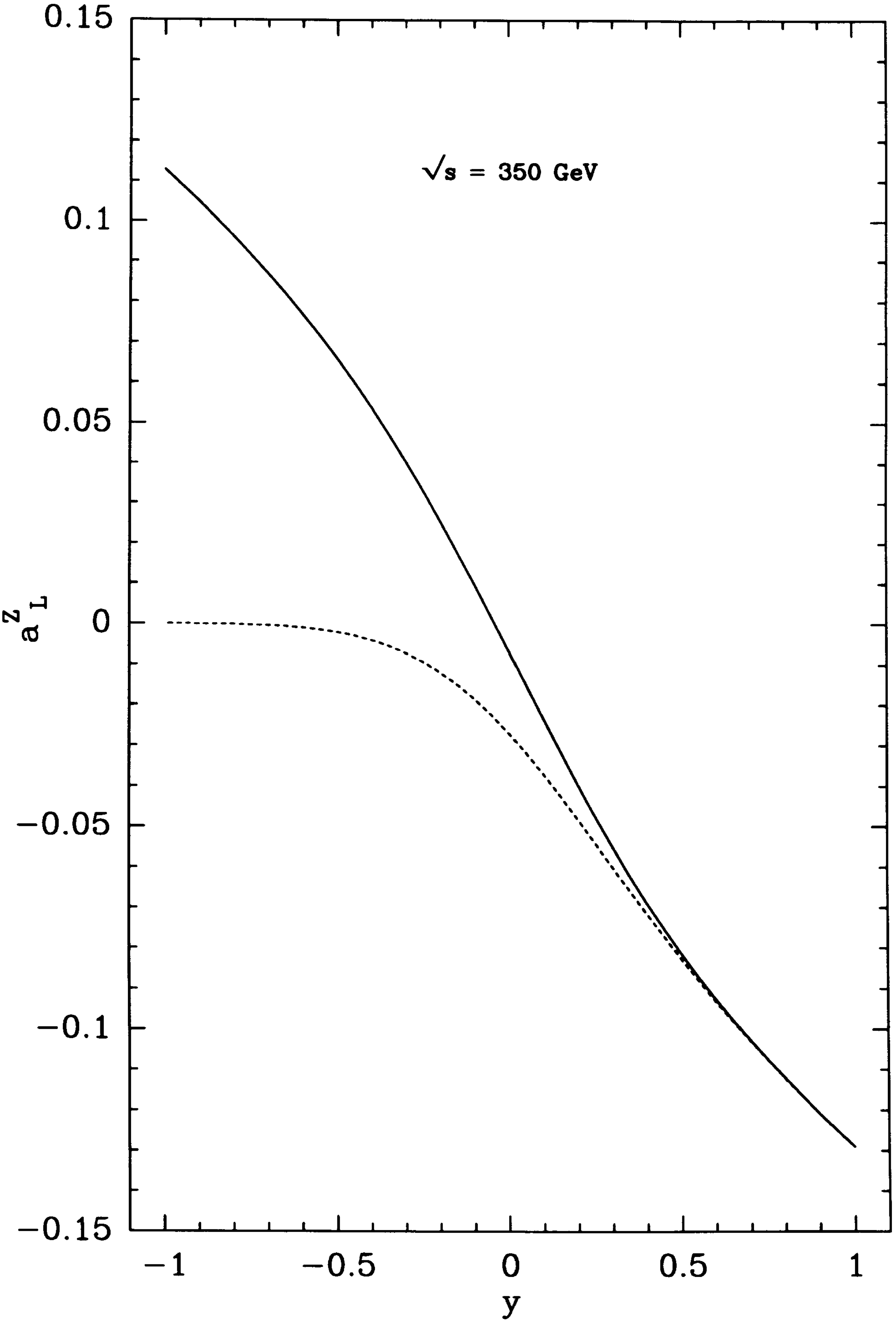
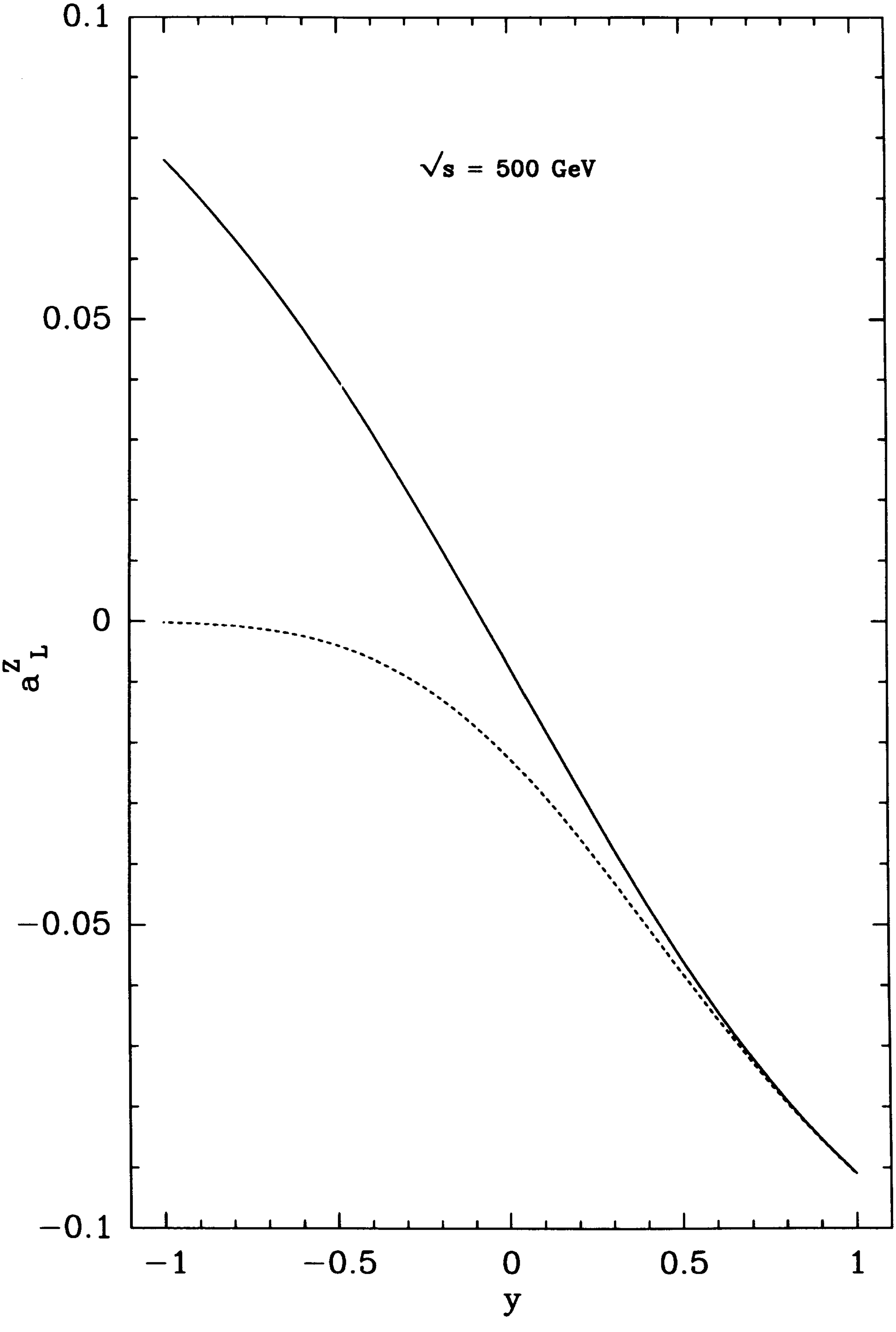


Fig. 11a



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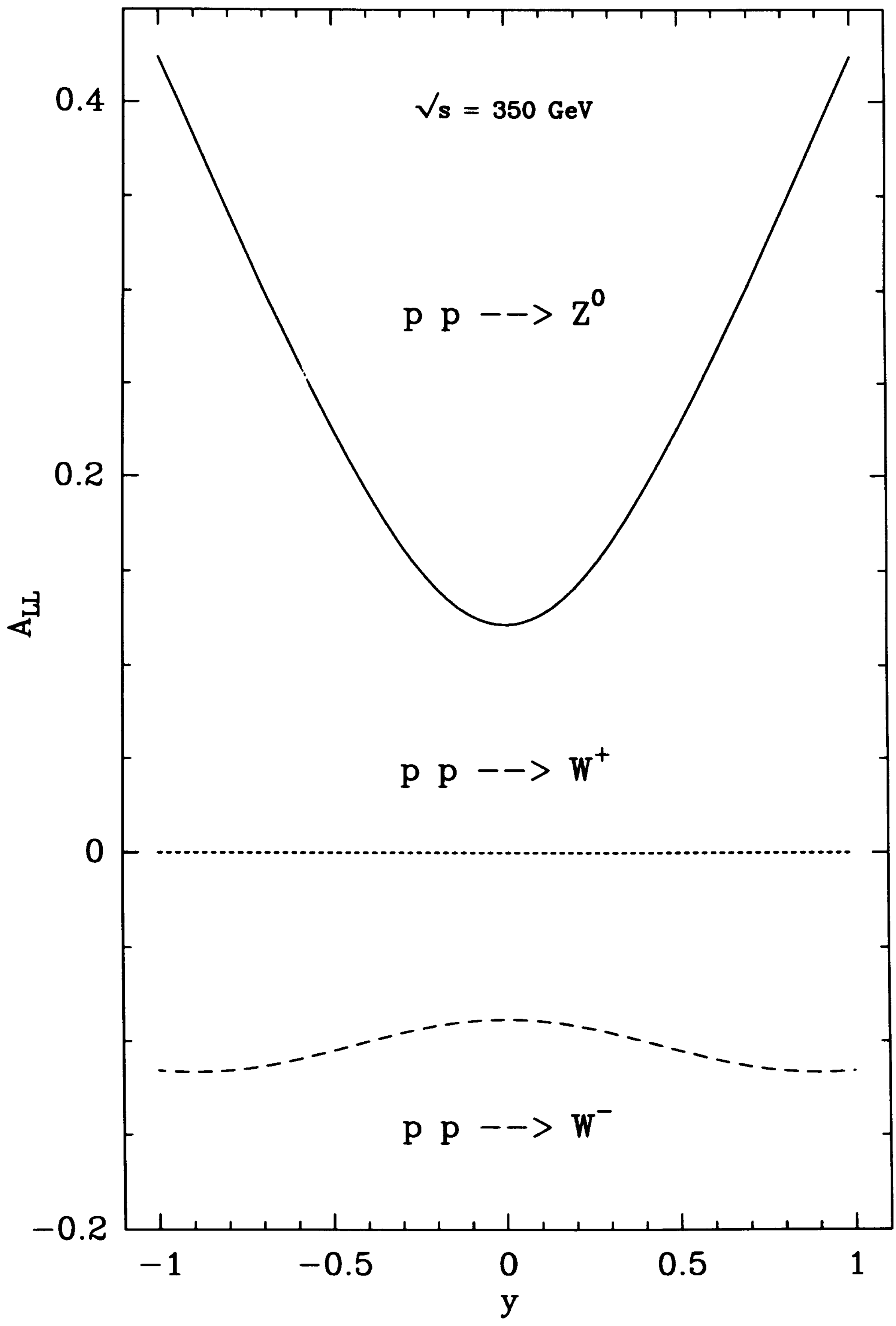

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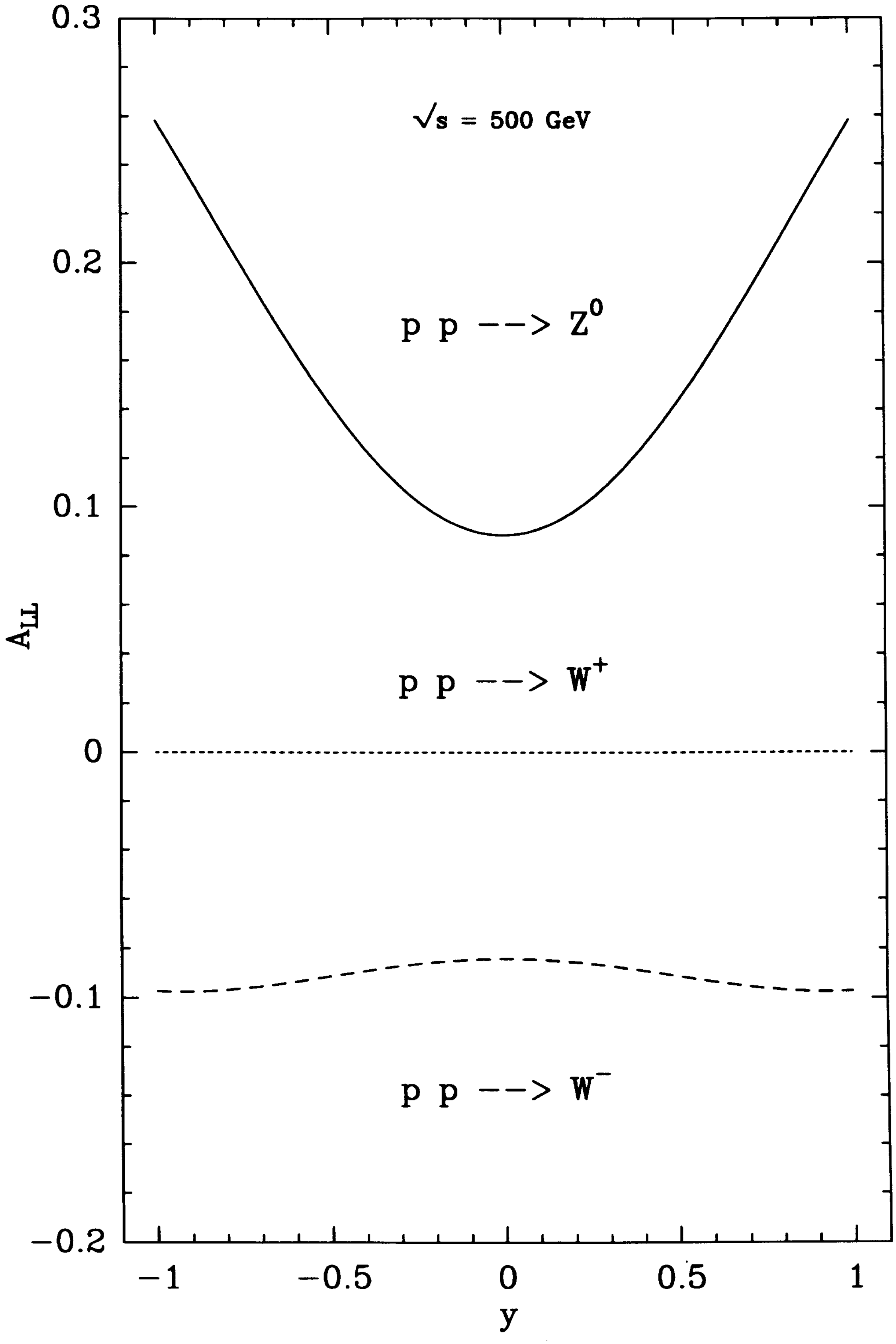

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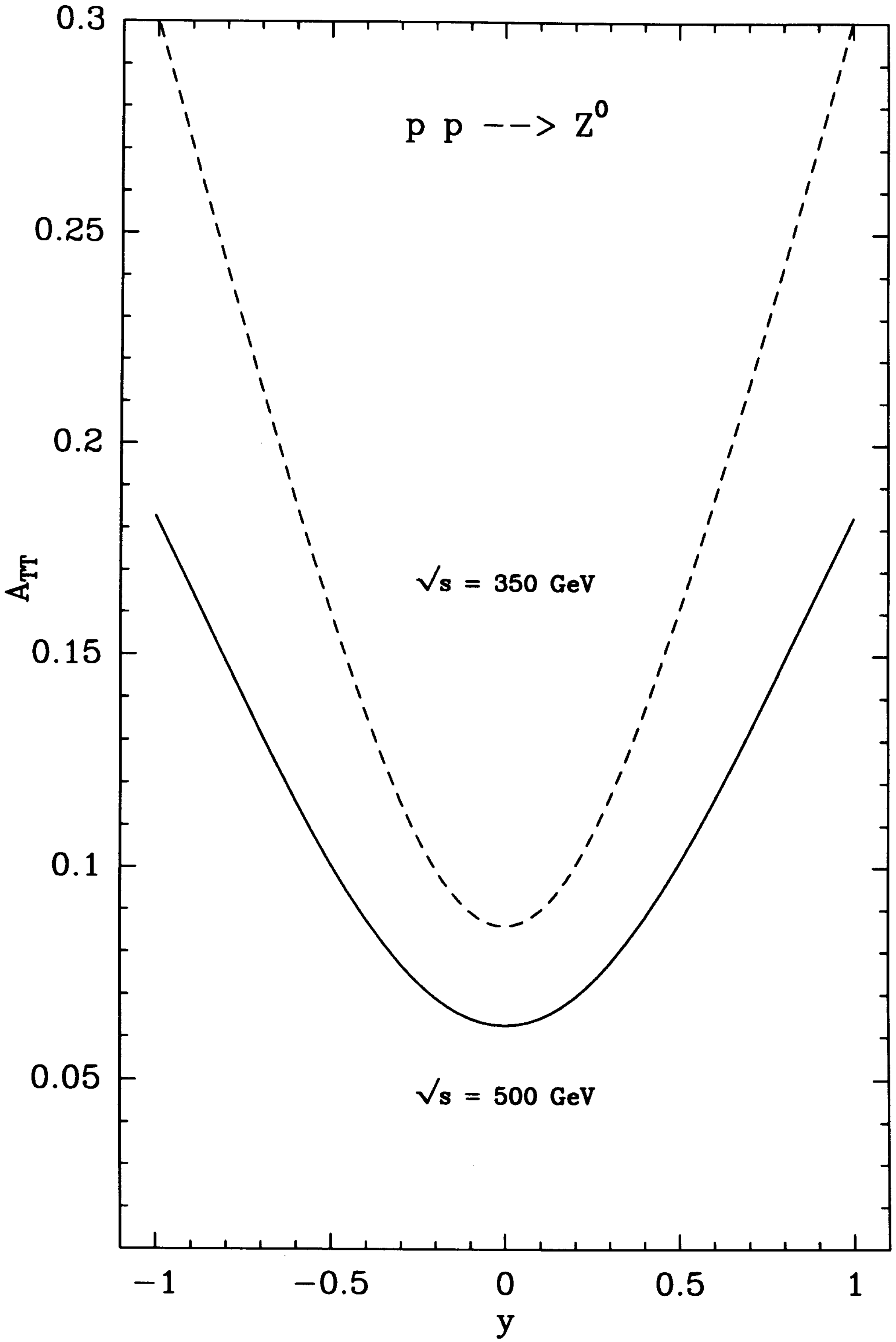

Fig. 13