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Double J/ψ production: a probe of gluon polarization?

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Abstract

We consider the process of direct simultaneous production of two J/ψ particles and discuss the possibility that it can be used as a tool to measure the gluon polarization in the colliding particles.

1 Introduction

Hadron-hadron and photon-hadron collisions at high energies offer the possibility for a detailed study of parton distributions inside a proton or the hadronic components of a photon (resolved photon). At present most interest lies in the measurement of the parton distributions at low x, with x being the momentum fraction of a proton or photon carried by a parton. The present knowledge of the parton distributions at low x, and especially the knowledge of polarized parton densities inside the proton or photon, is small. Note that quark helicities are obtainable from neutrino experiments while information about the gluon polarization can only be obtained from lepton-hadron [1] or hadron-hadron experiments.

In this paper we present a calculation of double J/ψ production via

$$g + g \to J/\psi + J/\psi \tag{1}$$

and

$$q + \bar{q} \to J/\psi + J/\psi. \tag{2}$$

These processes have a very clear signature and are sensitive to the polarization of the incoming partons: different polarization states of the initial partons lead to different angular distributions of the outgoing J/ψ's in the center-of-mass frame of the partonic subprocess. It is the most striking feature of double J/ψ production, that the *cm* frame can be obtained easily since the final state, the two J/ψ's, is completely known experimentally.

The outline of this paper is the following: first we present the calculation of the matrix elements for processes (1) and (2). Then we give results for the total cross section for both pp and ep colliders at different *cm* energies. Finally we turn to the question of the measurement of the polarization state of the incoming partons.

2 The Model

In the non-relativistic color singlet model [2] a J/ψ particle can be produced from a pair of charmed quarks, when the quarks both move with exactly half of the momentum of the J/ψ. Care has to be taken that the $c\bar{c}$ forming the J/ψ are in a color singlet state. This model has been used to calculate J/ψ decays and J/ψ photo- and hadroproduction. The cross section depends on the wave function of the J/ψ at the origin $|\psi(0)|^2$. This wave function is usually extracted from the leptonic decay width of the J/ψ:

$$\Gamma^0_{ll} = 16\pi e_q^2 \alpha_{em}^2 \frac{|\psi(0)|^2}{M^2_{J/\psi}}$$

The partonic cross section for the process $a + b \to J/\psi + J/\psi$ with a, b standing for $g + g$ or $q + \bar{q}$ is given by:

$$\frac{d\hat{\sigma}(a + b \to J/\psi + J/\psi)}{d\cos(\theta)} = \frac{\pi^3 \alpha_s^4 (1 - 4M^2_{J/\psi}/\hat{s})^{1/2} |\psi(0)|^4}{144 \hat{s} M^2_{J/\psi}} \sum_{a_1, a_2, \epsilon_1, \epsilon_2} |\mathcal{M}|^2. \tag{3}$$

where $\hat{s}$ is the invariant mass of the subprocess and $|\mathcal{M}|^2$ is the matrix element for the subprocess. The experimentally measurable cross section reads:

$$d\sigma(A + B \to J/\psi + J/\psi + X) = \int dx_1\, dx_2\, f_{a/A}(x_1)\, f_{b/B}(x_2)\, d\hat{\sigma}(a + b \to J/\psi + J/\psi) \tag{4}$$

where A and/or B may be a hadron, photon or lepton, and $f(x_i)$ represent the parton distribution functions of the colliding particles. In photoproduction only the resolved photon contributes because of color conservation.

The complete set of Feynman diagrams for $g + g \to J/\psi + J/\psi$ and $q + \bar{q} \to J/\psi + J/\psi$ is shown in Fig. 1 and Fig. 2 respectively. For the production of two J/ψ's two $c\bar{c}$ pairs are needed. One $c\bar{c}$ pair is produced by gg-fusion and the other by the internal gluon line. Moreover within the non-relativistic color singlet model for J/ψ production [2] the internal gluon line in the diagrams is needed to prevent a unphysical restriction of the momentum space.

First we present the calculation for process (1). Let k_1 and k_2 be the 4-momenta of incoming gluons, a_1 and a_2 their polarization vectors, $P_{\psi 1}, P_{\psi 2}$ and ϵ_1, ϵ_2 the momenta and the polarization vectors of outgoing J/ψ's, and m the mass of a charmed quark with $m = \frac{M_{J/\psi}}{2}$. With the notations

$$J_1 = \not{\epsilon}_1(m + \not{p}_1), \quad J_2 = \not{\epsilon}_2(m + \not{p}_2), \qquad p_1 = P_{J/\psi 1}/2, \quad p_2 = P_{J/\psi 2}/2, \quad \hat{s} = 2(k_1 k_2),$$

the matrix elements for the diagrams of Fig. 1 read as follows:

$$\begin{aligned}
\mathcal{M}_a &= tr\{J_1 \gamma_\mu J_2 \not{a}_2 (m - \not{k}_2 + \not{p}_2) \gamma_\mu (m + \not{k}_1 - \not{p}_1) \not{a}_1\} \;/(\hat{s}(k_2 p_2)(k_1 p_1)) && (5)\\
\mathcal{M}_b &= tr\{J_1 \gamma_\mu J_2 \not{a}_2 (m - \not{k}_2 + \not{p}_2) \not{a}_1 (m - 2\cdot \not{p}_1 - \not{p}_2) \gamma_\mu\} \;/(-\hat{s}^2(k_2 p_2)/4) && (6)\\
\mathcal{M}_c &= tr\{J_1 \gamma_\mu J_2 \gamma_\mu (m + 2\cdot \not{p}_2 + \not{p}_1) \not{a}_2 (m + \not{k}_1 - \not{p}_1) \not{a}_1\} \;/(-\hat{s}^2(k_1 p_1)/4) && (7)\\
\mathcal{M}_d &= tr\{J_1 \gamma_\mu (m + \not{k}_2 - \not{p}_2) \not{a}_2 J_2 \gamma_\mu (m + \not{k}_1 - \not{p}_1) \not{a}_1\} \;/(-\hat{s}(k_2 p_2)(k_1 p_1)) && (8)\\
\mathcal{M}_e &= tr\{J_1 \gamma_\mu (m + \not{k}_2 - \not{p}_2) \not{a}_2 J_2 \not{a}_1 (m - \not{k}_1 + \not{p}_2) \gamma_\mu\} \;/(-\hat{s}(k_1 p_2)(k_2 p_2)) && (9)\\
\mathcal{M}_f &= tr\{J_1 \gamma_\mu J_2 \gamma_\nu (m + \not{k}_1 - \not{p}_1) \not{a}_1\}\, G^{(3)}(k_2^{a_2}, q_-^\nu, -q_+^\mu) \;/(\hat{s}^2(k_1 p_1)/8) && (10)\\
\mathcal{M}_g &= tr\{J_1 \gamma_\mu J_2 \not{a}_1 (m - \not{k}_1 + \not{p}_2) \gamma_\nu\}\, G^{(3)}(k_2^{a_2}, q_-^\nu, -q_+^\mu) \;/(\hat{s}^2(k_1 p_2)/8) && (11)\\
\mathcal{M}_h &= tr\{J_1 \gamma_\mu J_2 \gamma_\nu\}\, G^{(3)}(k_1^{a_1}, -q_-^\lambda, -q_+^\mu)\, G^{(3)}(k_2^{a_2}, q_-^\lambda, -q_+^\nu) \;/(-\hat{s}^3/64) && (12)\\
\mathcal{M}_i &= tr\{J_1 \gamma_\mu J_2 \gamma_\nu\}\, G^{(4)}_{a_1 a_2 \mu\nu} \;/(\hat{s}^2/16) && (13)
\end{aligned}$$

Here $q_+ = (k_1 + k_2)/2, \; q_- = (k_1 - k_2)/2$ and $G^{(3)}$ and $G^{(4)}$ are the standard QCD three- and four-gluon couplings:

$$\begin{aligned}
G^{(3)}(p^a_\lambda, q^b_\mu, r^c_\nu) &= -g\, f^{abc}((p-q)_\nu g_{\lambda\mu} + (q-r)_\lambda g_{\mu\nu} + (r-p)_\mu g_{\nu\lambda}), && (14)\\
G^{(4)}(^{a\,b\,c\,d}_{\lambda\mu\nu\sigma}) &= -ig^2\, f^{abe} f^{cde}(g_{\lambda\nu} g_{\mu\sigma} - g_{\lambda\sigma} g_{\mu\nu}) \\
&\quad -ig^2\, f^{ace} f^{bde}(g_{\lambda\mu} g_{\nu\sigma} - g_{\lambda\sigma} g_{\mu\nu}) \\
&\quad -ig^2\, f^{ade} f^{cbe}(g_{\lambda\nu} g_{\mu\sigma} - g_{\lambda\mu} g_{\nu\sigma}) && (15)
\end{aligned}$$

The appropriate color factors are:

$$C_a = C_d = \frac{-1}{12}, \quad C_b = C_c = C_e = \frac{2}{3}, \quad C_f = -C_g = \frac{3}{4}, \quad C_h = C_i = \frac{3}{4}.$$

The matrix element for process (2) (Fig. 2) reads:

$$\mathcal{M}_{q\bar{q}} = tr\{J_1 \gamma_\mu J_2 \gamma_\nu\}\, \bar{u}(k_2)(\gamma_\mu \not{J}_- \gamma_\nu + \gamma_\nu \not{J}_- \gamma_\mu) u(k_1) \,/(-\hat{s}^3/64), \qquad (16)$$

$u(k_i)\bar{u}(k_i) = \frac{1}{2}\not{k}_i(1 + a_i\gamma_5)$, $\; i = 1, 2$, and $a_i = \pm 1$ define the helicities of the annihilating light quarks.

We performed the summation over all physical polarization states (two for each gluon or for each quark and three for each J/ψ) by substituting explicitly the polarization vectors in the

matrix element squared. Therefore ghost diagrams are not needed. The analytical expressions for $|\mathcal{M}|^2$ in terms of the 4-momenta dot-products were obtained with the REDUCE [3] program and are too long to be presented in this paper. [1]

3 Results

The unpolarized cross sections for processes (1) and (2) are calculated using $\alpha_s = 0.3$, $|\psi(0)|^2 = 0.038$ GeV^3, and the unpolarized parton distributions of Duke Owens [4]. In the case of photoproduction we use the parametrization of [5] for the parton contents of a photon. In Fig. 3 we show the cross section for processes (1) and (2) separately as a function of $\sqrt{s}$ for pp- and $p\bar{p}$ colliders. The corresponding results for ep scattering [2] are shown in Fig. 4. In

	gg (1)	$q\bar{q}$ (2)
HERA ep $\sqrt{s} = 314$ GeV	0.4 pb	0.03 pb
LEP-LHC ep $\sqrt{s} = 1.3$ TeV	3.0 pb	0.074 pb
LHC pp $\sqrt{s} = 16$ TeV	5.3 nb	0.11 nb

Table 1: Expected cross section for ep and pp colliders for process (1) and (2).

Tab. 1 we give the expected cross section for HERA (ep at $\sqrt{s} = 314$ GeV), LEP-LHC (ep at $\sqrt{s} = 1.3$ TeV) and LHC (pp or $p\bar{p}$ at $\sqrt{s} = 16$ TeV) for (1) and (2). Our calculation of the total cross section is in qualitative agreement with the previous results of [7] but they only give matrix elements summed over all the polarization states. From Tab. 1 and Figs. 3,4 we conclude that process (2) gives only a small contribution to (1) both for pp and ep colliders at high energies. Therefore we can use process (1) for a study of the polarization of the initial gluons. However at HERA energy the total cross section is quite low.

In Fig. 5 we show the gluon distribution $xG(x) = xG\uparrow + xG\downarrow$ and $x\Delta G(x) = xG\uparrow - xG\downarrow$, where $\uparrow$ means polarization parallel to the polarization of the proton and $\downarrow$ means antiparallel. The parametrization of $x\Delta G(x)$ is taken from [8] [3]. The angular distribution of the final state J/ψ's for process (1) in the partonic cm-frame for different polarization states of the initial gluons are shown in Fig. 6 and Fig. 7. Both J/ψ's can be observed experimentally using the leptonic decay modes, the momenta are well known and a boost from the lab-frame to the partonic cm-frame can be performed easily on an event by event basis. Since the angular distributions are very different for various initial state polarizations, we have an easy and unique method to measure the polarization of gluons inside protons and photons. Even if we sum over all the polarization states of one of the initial gluons, the method works well. This can be seen in Fig. 8 where we summed over all the polarization states of one of the gluons. There is still the possibility to measure the gluon polarization inside the proton.

Some remarks on possible background processes are needed:

- First is the $B\bar{B}$ production with the subsequent decay into J/ψ's. With the branching ratio $Br(B \to J/\psi X) \simeq 1\%$ the cross section becomes comparable with direct double J/ψ production. However this background can be reduced drastically since the decay

[1] The FORTRAN expressions for $|\mathcal{M}|^2$ can be obtained from the authors on request.
[2] For ep scattering we use a new version of EPJPSI [6].
[3] The FORTRAN code was provided by S.Güllenstern and A.Schäfer [9].

$B \to J/\psi X$ is accompanied by hadronic activity. Moreover in process (1) and (2) there is exact transverse momentum balance between the two J/ψ's, whereas for $B \to J/\psi X$ this is not the case. Even with initial state gluon radiation (parton shower) the transverse momentum balance holds for (1) and (2), only the higher order process $a + b \to J/\psi + J/\psi + g$ will destroy $p_\perp$ balance.

- A considerable part of the J/ψ's might be produced via $\chi_{0,1,2}$ decays. This process needs a detailed analysis which we are going to perform later.

Finally we note that all the calculations presented here are valid for all (1^{--}) states and therefore also double Υ production can be searched for. The simple event signature remains unchanged whereas there are several advantages due to the higher mass:

- higher energy of the decay leptons
- background of Top-meson decay (in analogy to $B \to J/\psi X$) is totally negligible
- χ_b decays might be better observed due to larger mass difference compared to χ_c
- the use of perturbative QCD is on more solid grounds.

In Fig. 9 we present the cross section for pp and $p\bar{p}$ colliders as a function of $\sqrt{s}$ for double Υ production.

We would like to point out the advantage of the process considered, that one can extract the gluon polarization from a single experiment, in contrast to other proposals [10], which are based on a comparison of total rates in two differently polarized beams.

Acknowledgments

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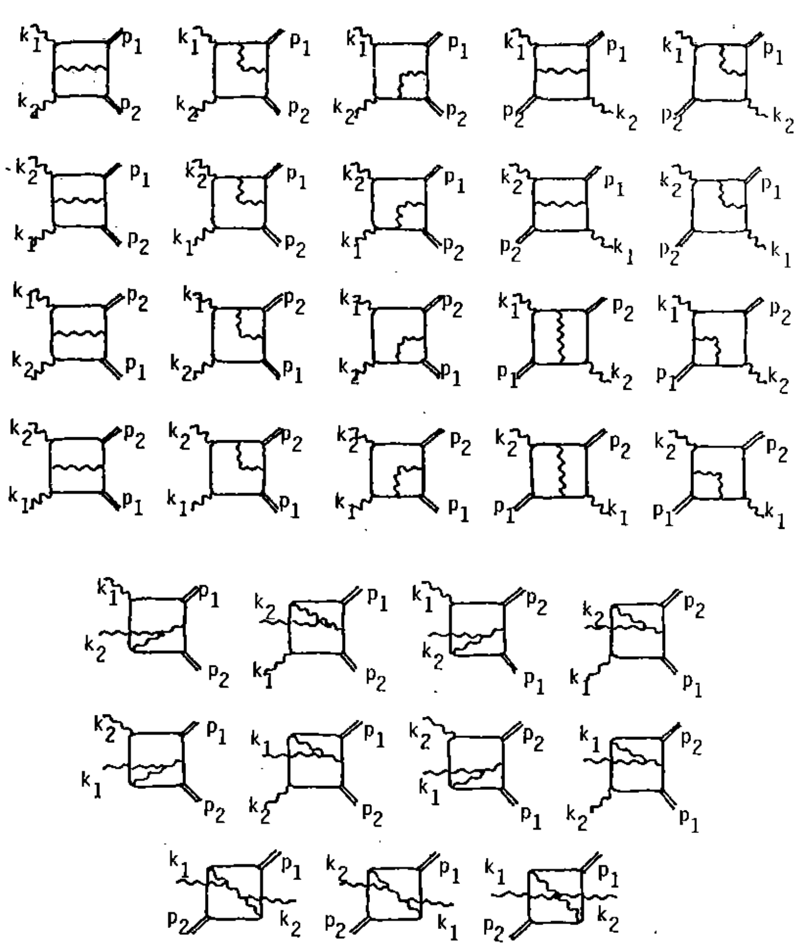

Figure 1: Feynman diagrams contributing to the double J/ψ production by gluons.

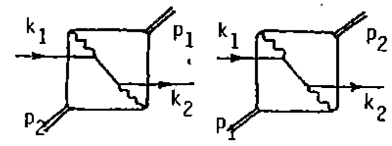

Figure 2: Feynman diagrams representing the $\bar{q}q$ annihilation subprocess.

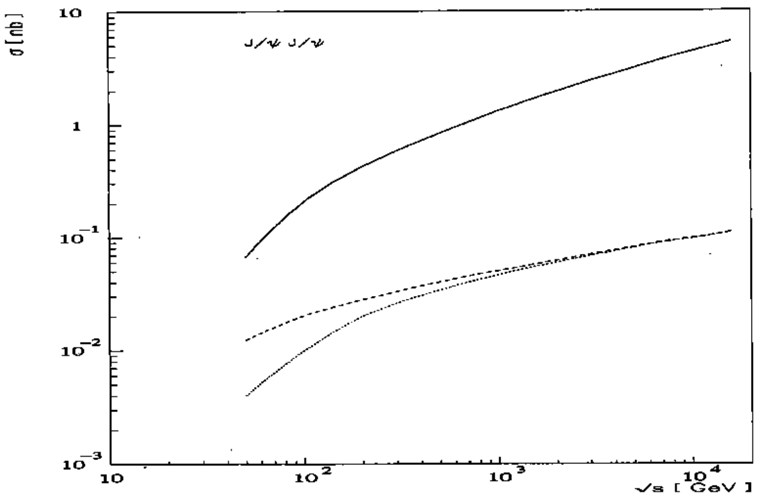

Figure 3: The energy dependence of the double J/ψ production cross-sections: solid line gluon-gluon fusion, dashed line $\bar{q}q$ annihilation in $\bar{p}p$ collisions and dotted line $\bar{q}q$ annihilation in pp collisions.

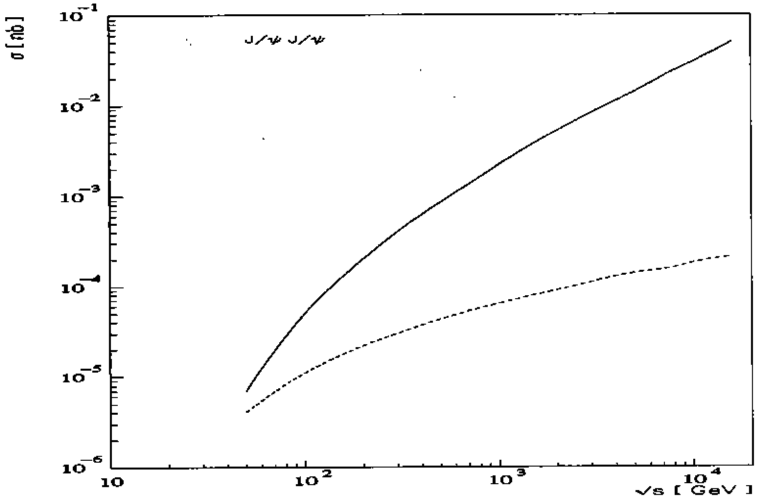

Figure 4: The energy dependence of the double J/ψ production cross-sections in ep collisions: solid line gluon-gluon fusion and dashed line $\bar{q}q$ annihilation in ep collisions.

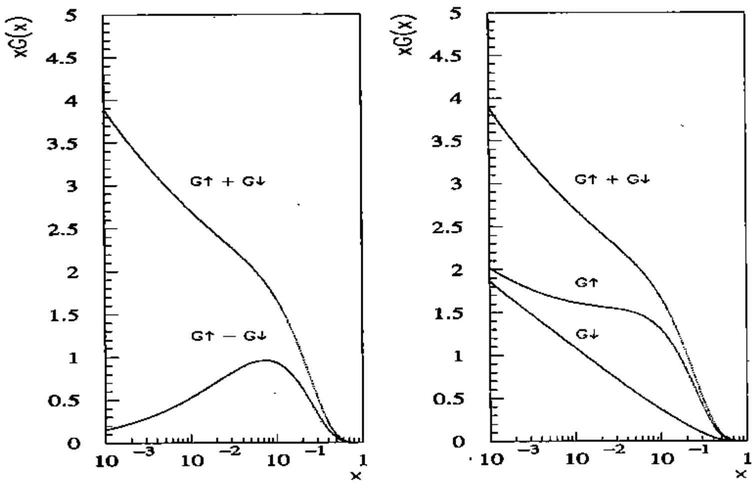

Figure 5: $xG(x) = xG(x)\uparrow + xG(x)\downarrow$ [4] and $x\Delta G(x) = xG(x)\uparrow - xG(x)\downarrow$ [8] as used in the calculation.

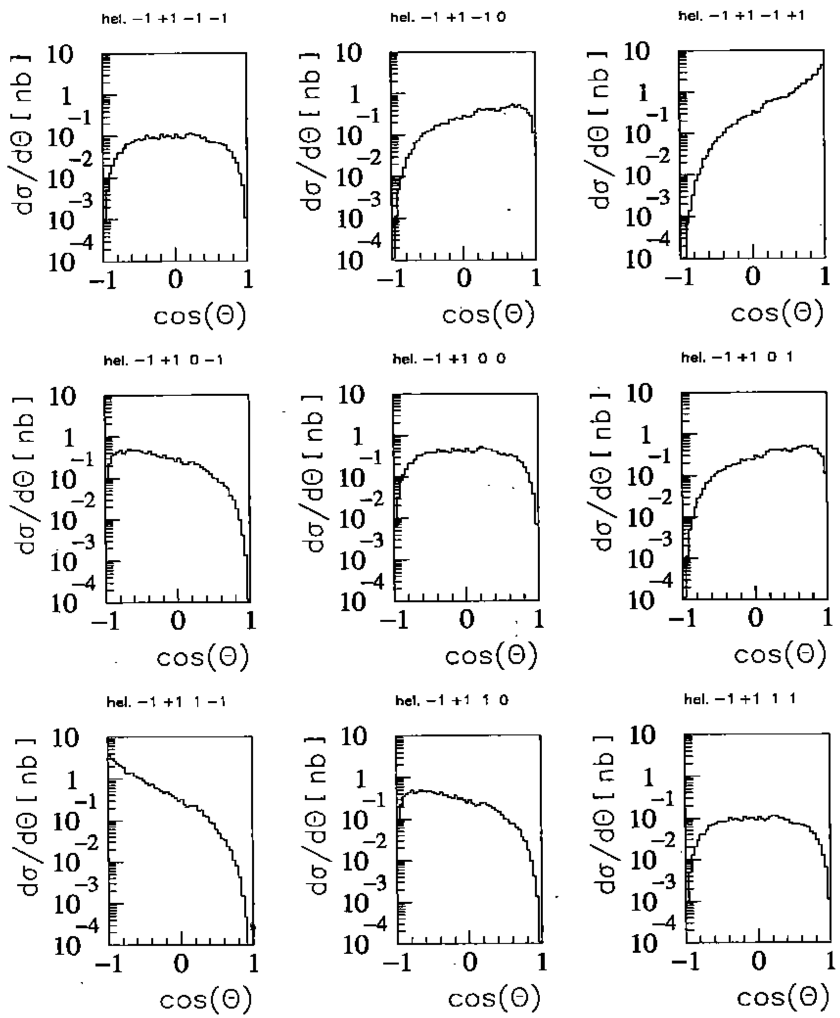

Figure 6: Angular distributions ($d\sigma/d\cos\theta$ [nb]) of the J/ψ's with respect to the beam axis in the gluon-gluon c.m.s. The sequence of numbers on top of each small figure gives the helicities of the initial gluons and the helicities of the final J/ψ's. Only 18 of 36 different helicity combinations are shown. The others are identical to the shown ones with all the helicities reversed (space parity symmetry).

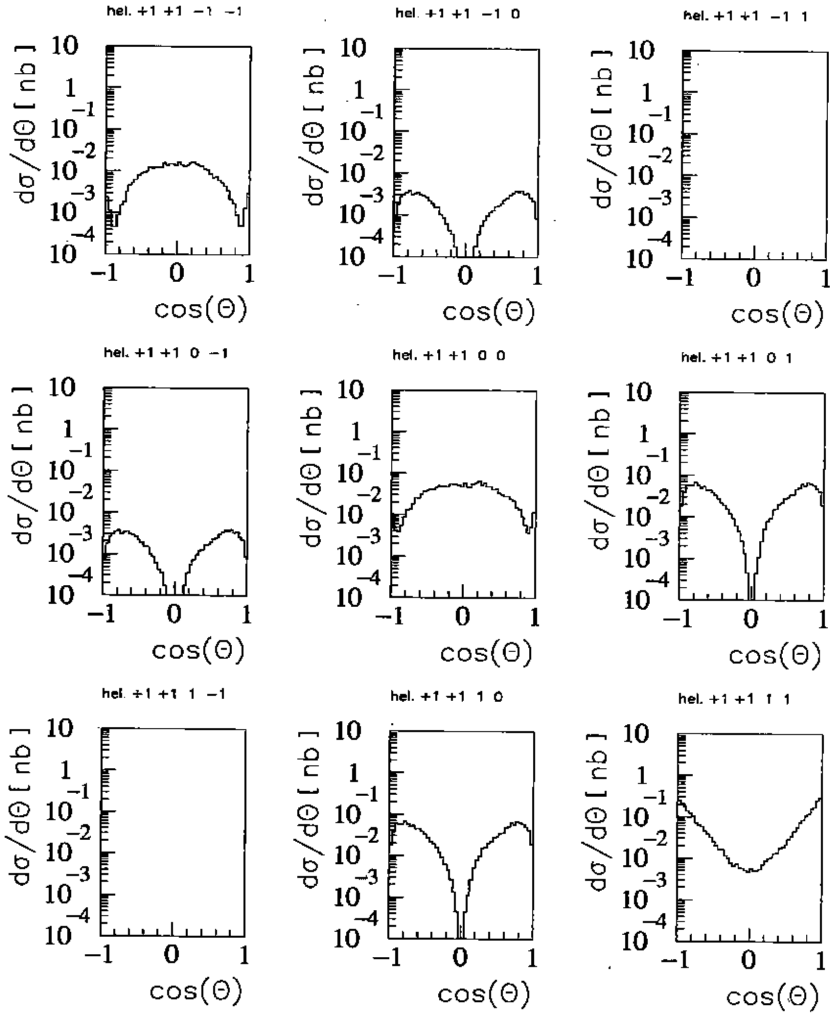

Figure 7: Angular distributions ($d\sigma/d\cos\theta$ [nb]) of the J/ψ's with respect to the beam axis in the gluon-gluon c.m.s. The sequence of numbers on top of each small figure gives the helicities of the initial gluons and the helicities of the final J/ψ's. Only 18 of 36 different helicity combinations are shown. The others are identical to the shown ones with all the helicities reversed (space parity symmetry).

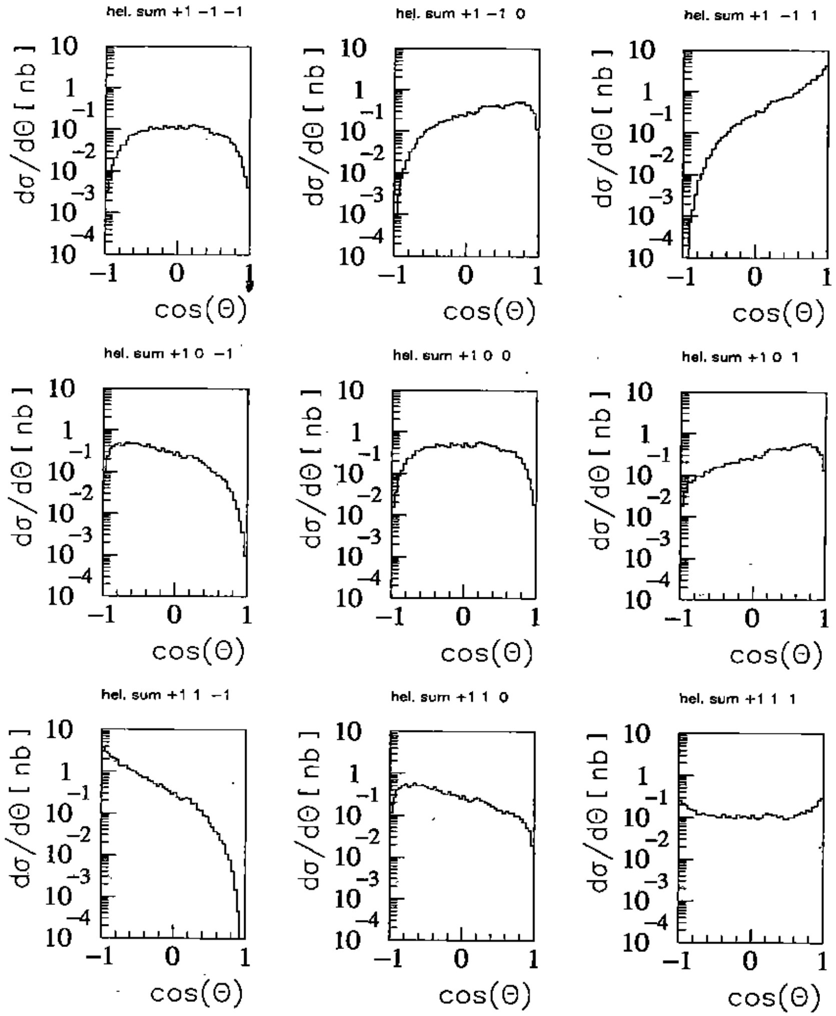

Figure 8: Angular distributions ($d\sigma/d\cos\theta$ [nb]) of the J/ψ's with respect to the beam axis in the gluon-gluon c.m.s. where we have summed over the polarization states of one of the incoming gluons.

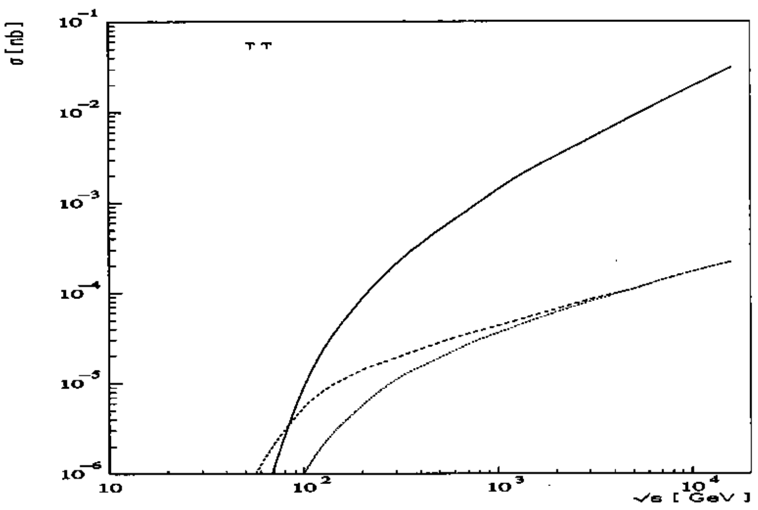

Figure 9: The energy dependence of the double Υ production cross-sections: solid line gluon-gluon fusion, dashed line $\bar{q}q$ annihilation in $\bar{p}p$ collisions and dotted line $\bar{q}q$ annihilation in pp collisions.