Υ polarization in k_T factorization

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JETP Lett. **88** (2008), arXiv:0810.4928 [hep-ph]; arXiv:0707.0253 [hep-ph]

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1. Introduction

The production mechanism of heavy quarkonium involves the physics of both short and long distances and so appeals to both perturbative and nonperturbative methods of QCD.
The creation of a heavy quark pair $Q\bar{Q}$ proceeds via the photon-gluon or gluon-gluon fusion referring to small distances of the order of $1/(2m_Q)$, while the formation of the colorless final state refers to longer distances of the order of $1/[m_Q\,\alpha_s(m_Q)]$.
$\Rightarrow$ The production of heavy quarkonium states is under control of perturbative QCD but, on the other hand, is succeeded by nonperturbative emission of soft gluons.
This feature gives rise to two competing theoretical approaches known as the color-singlet model

C.-H. Chang, Nucl. Phys. B 172 (1980) 425;
R. Baier, R. Rückl, Phys. Lett. B 102 (1981) 364;
S. Gershtein, A. Likhoded, S. Slabospitsky, Sov. J. Nucl. Phys. 34 (1981) 128;
E.L. Berger, D. Jones, Phys. Rev. D 23 (1981) 1521.

and color-octet model (NRQCD)

G.T. Bodwin, E. Braaten, P. Lepage, Phys. Rev. D 51 (1995) 1125;

E. Braaten, S. Fleming, Phys. Rev. Lett. 74 (1995) 3327;
P. Cho, A.K. Leibovich, Phys. Rev. D 53 (1996) 150; 6203.

In the COM the formation of a meson starts from a color-octet $Q\bar{Q}$ pair and proceed via the emission of soft nonperturbative gluons.

The COM was introduced to overcome the discrepancy between the large J/ψ production cross section measured in pp interactions at the Tevatron and the results of theoretical calculations based on the standard pQCD.

The problem was apparently solved by attributing the discrepancy to the hypothetical contributions from the intermediate CO states, which must obey certain hierarchy in powers of the relative velicity of the quarks in a bound system.

However, the numerical estimates of these contributions extracted from the analysis of Tevatron data are at odds with the HERA data, especially as far as the inelasticity parameter $z = E_\psi/E_\gamma$ is concerned:

B. Kniehl, L. Zwirner, Nucl. Phys. B 621 (2002) 337.

The CSM has a well defined applicability range and has already demonstrated its predictive power in describing the J/ψ production at HERA, both in the collinear

M. Kraämer, Nucl. Phys. B 459 (1996) 3,

and the k_T-factorization approaches:

S.P. Baranov, N.Z., J. Phys. G 29 (2003) 1395;
A.V. Lipatov, N.Z., Eur. Phys. J. C 27 (2003) 87.

As it was shown in the analysis of ZEUS data, there is no need in the CO contribution, neither in the collinear nor in the k_T-factorization approaches at HERA:

ZEUS Collaboration, S. Chekanov et al. Eur. Phys. J. C 44 (2005) 13.

In the k_T-factorization approach, the values of the color-octet contributions obtained as fits of the Tevatron data appear to be substantially smaller than the ones in the collinear scheme, or even can be neglected at all:

Ph. Hägler, R. Kirschner, A. Shäfer, L. Szymanowski, O.V. Teryaev, Phys. Rev. D 63 (2001) 077501; Phys. Rev. Lett. 86 (2001) 1446;
F. Yuan, K.-T. Chao, Phys. Rev. D 63 (2001) 034006;
S.P. Baranov, Phys. Rev. D 66 (2002) 114003;
B. Kniel, D.Vasin, A. Saleev, Phys. Rev. D 73 (2006) 074022; 74 (2006) 014024.

Our goal to show once again that measurement the polarizaton of quarkonium states produced at high energies may serve as an important and crucial test discriminating the different theoretical concepts.

The first attempts to solve the quarkonium polarization problem within the k_T-factorization approach were made in the papers

S.P. Baranov, Phys. Lett. B 428 (1998) 377;
S.P. Baranov, A.V. Lipatov, N.Z., in Proceedings of DIS 2001, hep-ph/0106299

for ep collisions and in Refs.

F. Yuan, K.-T. Chao, Phys. Rev. Lett. 87 (2001) 022002; Phys. Rev. D 63 (2001) 034017

for pp collisions.

It was emphasized that the off-shellness of the initial gluons, the intrinsic feature of the k_T-factorization approach, has an immediate consequence (by analogy with longitudinal photons) in the longitudinal polarization of the final state J/ψ mesons.

The theoretical predictions have stimulated experimental investigation of J/ψ spin alignment at the collider HERA. The first results obtained by the collaborations H1 and ZEUS have been described in Refs.

S.P. Baranov, N.Z., J. Phys. G 29 (2003) 1395;
A.V. Lipatov, N.Z., Eur. Phys. J. C 27 (2003) 87.

These results have qualitatively confirmed the predictions on the dominance of longitudinal polarization.
The preliminary results on the J/ψ and ψ' polarization at the Tevatron also point to logitudinal polarization with the average value of spin alignment parameter $\alpha \approx -0.2$ over the whole range of J/ψ transverse momentum p_T and $\alpha \approx -0.5$ at high p_T for prompt ψ':

E537 Collab., C. Akerlof et al,, Phys. Rev. D 48 (1993) 5067;
CDF Collab., T. Affolder et al. Phys. Rev. Lett. 85 (2000) 2886;
B.C. Reisert, talk at DIS'07 Workshop, Munich, 2007.

In the NRQCD approach the gluon fragmentation mechanism leads to strong transverse polarization. Including the next-to-leading QCD corrections makes the transverse polarization even stronger.
The only way out - to increase the fraction of unpolarized color-octet channels, which, however, violates the expected NRQCD hierarchy!

2. Theoretical framework

Our goal is to derive theoretical predictions on the polarization of Υ mesons at Tevatron and LHC.
In the k_T-factorization approach the cross section of a physical process is calculated as a convolution of the partonic cross section $\hat{\sigma}$ and the u.g.d. $\mathcal{F}_g(x, k_T^2, \mu^2)$, which depend on both the longitudinal momentum fraction x and transverse momentum k_T:

$$\sigma_{pp} = \int \mathcal{F}_g(x_1, k_{1T}^2, \mu^2)\, \mathcal{F}_g(x_2, k_{2T}^2, \mu^2)\, \hat{\sigma}_{gg}(x_1, x_2, k_{1T}^2, k_{2T}^2, ...)\, dx_1\, dx_2\, dk_{1T}^2\, dk_{2T}^2.$$

In accord with the BFKL prescriptions the off-shell gluon spin density matrix is taken in the form

$$\overline{\epsilon_g^{\mu} \epsilon_g^{*\nu}} = p_p^{\mu} p_p^{\nu} x_g^2 / |k_T|^2 = k_T^{\mu} k_T^{\nu} / |k_T|^2.$$

E.A. Kuraev, L.N. Lipatov, V.S. Fadin, Sov. Phys. JETP 45 (1977) 199;
Ya. Balitsky, L.N. Lipatov, Sov. J. Nucl. Phys. 28 (1978) 822;
L.V. Gribov, E.M. Levin, M. G. Ryskin, Phys. Rep. 100 (1983) 1.

In order to estimate the degree of theoretical uncertainty connected with the choice of u.g.d., we use two different parametrizations, which are known to show the largest difference with each other.
The first u.g.d. is derived from the ordinary (collinear) density $G(x, \mu^2)$ by differentiating it with respect to μ^2 and setting $\mu^2 = k_T^2$. $G(x, \mu^2)$ is the LO GRV set (the dGRV parametrisation).
The other u.g.d. is obtained as a solution of leading order BFKL equation in the double-logarithm approximation. Technically, it is calculated as the convolution of the ordinary g.d. with some universal weight factor (the JB parametrisation):

J. Blümlein, J. Phys. G. 19 (1993) 1623; DESY 95-121 (1995).

The production of Υ mesons in pp collisions can proceed via either direct gluon-gluon fusion or the production of P-wave states χ_b followed by their radiative decays $\chi_b \to \Upsilon + \gamma$.
The direct mechanism corresponds to the partonic subprocess $g + g \to \Upsilon + g$. The production of P-wave mesons is given by $g + g \to \chi_b$, and there is no emittion of any additional gluons.
We see no need in taking the color-octet contributions into consideration.

The polarization state of a vector meson is characterized by the spin alignment parameter α which is defined as a function of any kinematic variable as

$$\alpha(\mathcal{P}) = (d\sigma/d\mathcal{P} - 3d\sigma_L/d\mathcal{P})/(d\sigma/d\mathcal{P} + d\sigma_L/d\mathcal{P}),$$

where σ is the reaction cross section and σ_L is the part of cross section corresponding to mesons with longitudinal polarization (zero helicity state). The limiting values $\alpha = 1$ and $\alpha = -1$ refer to the totally transverse and totally longitudinal polarizations. We will be interested in the behavior of α as a function of the Υ transverse momentum: $\mathcal{P} \equiv |\mathbf{p}_T|$.

The experimental definition of α is based on measuring the angular distributions of the decay leptons

$$d\Gamma(\Upsilon \to \mu^+\mu^-)/d\cos\theta \sim 1 + \alpha\cos^2\theta,$$

where θ is the polar angle of the final state muon in the meson rest frame.
When considering the polarization properties of $\Upsilon(1S)$ mesons originating from radiative decays of P-wave states, we rely upon the dom-

inance of electric dipole $E1$ transitions. The corresponding invariant amplitudes have been done in

P. Cho, M. Weise, S. Trivedi, Phys. Rev. D51 (1995) R2039.

Then the following relations between the production cross sections for different helicity states have been obtained:

$$
\begin{aligned}
\sigma_{\Upsilon(h=0)} &= B_{(\chi_1 \to \Upsilon\gamma)} \left[\frac{1}{2}\, \sigma_{\chi_1(|h|=1)} \right] \\
&+ B_{(\chi_2 \to \Upsilon\gamma)} \left[\frac{2}{3}\, \sigma_{\chi_2(h=0)} + \frac{1}{2}\, \sigma_{\chi_2(|h|=1)} \right] \\
\sigma_{\Upsilon(|h|=1)} &= B_{(\chi_1 \to \Upsilon\gamma)} \left[\sigma_{\chi_1(h=0)} + \frac{1}{2}\, \sigma_{\chi_1(|h|=1)} \right] \\
&+ B_{(\chi_2 \to \Upsilon\gamma)} \left[\frac{1}{3}\, \sigma_{\chi_2(h=0)} + \frac{1}{2}\, \sigma_{\chi_2(|h|=1)} \right. \\
&\qquad \left. + \, \sigma_{\chi_2(|h|=2)} \right].
\end{aligned}
$$

The dominance of electric dipole transitions (at least for the charmonium family) is supported by the recent experimental data:

M. Ambrogiani et al. (E385 Collab.), Phys. Rev. D65 (2002) 052002.

The other essential parameters were taken as follows: the b-quark mass $m_b = m_\Upsilon/2 = 4.75$ GeV; the Υ meson wave function $|\Psi_\Upsilon(0)|^2 = 0.4$ GeV^3 (known from the leptonic decay width $\Gamma_{l^+l^-}$); the wave function of P-wave states $|\Psi'_\chi(0)|^2 = 0.12$ GeV^5 (taken from the potential model); the radiative decay branchings $Br(\chi_{b,J} \to \Upsilon\gamma) = \mathbf{0.06,\ 0.35,\ 0.22}$ for $(J = 0, 1, 2)$, the renormalization and factorization scale $\mu^2 = m_\Upsilon^2 + p_T^2$.

3. Numerical results

The results of our calculations for $\Upsilon(1S)$ Tevatron energies are displayed in Figs. 1.

The left panel show the predicted transverse momentum distribution. Dash-dotted histograms are for JB gluons, dashed histograms are for derivative of GRV gluons.

The right panel in Figs. 1 show the behavior of the spin alignment parameter α for $\Upsilon(1S)$ mesons produced in the direct subprocess and direct and added $\Upsilon(1S)$ from χ decays in comparison with $D\oslash$ experimental data:

V.M. Abazov *et al.* (D⊘ Collab.), Phys.Rev.Lett. 101 (2008) 182004.

In Fig. 3 we show the rapidity distribution for Υ(1S) production in more wide rigion than the $D\oslash$ experimental data, and behaviour of the alignment parameter α as fuction of rapidity.

We see that α becomes positive at large y. We propose to measure the double differential cross sections of quarkonium productions.

Recently, in the framework of standard pQCD the results of theoretical caclulations of the NLO and NNLO order corrections to colour singlet (CS) quarkonium production have been obtained:

P. Artoisent *et al.*, Phys. Rev. Lett. 101 (2008) 152001.

In the region of moderate p_T ($p_T \geq 10$ GeV), these corrections enhance the color singlet production rate by one order of magnitude and even larger.
These new results are in much better agreement with the k_T-factorization predictions than it was seen for leading order collinear calculations.

4. Conclusions

- **We have considered the production of Υ mesons in high energy pp collisions in the k_T-factorization approach.**
- **We have derived predictions on the spin alignment parameter $\alpha(p_T)$.**
- **We point out that the predicted value of $\alpha(p_T)$ is negative in the whole observable range of p_T and shows variations from $\alpha \simeq (-0.2)$ to $\alpha \simeq (-0.7)$ depending on the hypothesis assumed for the decays $\chi_b \to \Upsilon(1S)+\gamma$.**
- **At the LHC energies, the theoretical predictions possess less sensitivity to the choice of unintegrated gluon distributions.**
- **The purest probe is provided by the polarization of $\Upsilon(3S)$ mesons. In that case, the predictions are free from uncertainties coming from the unknown properties of χ_b decays.**

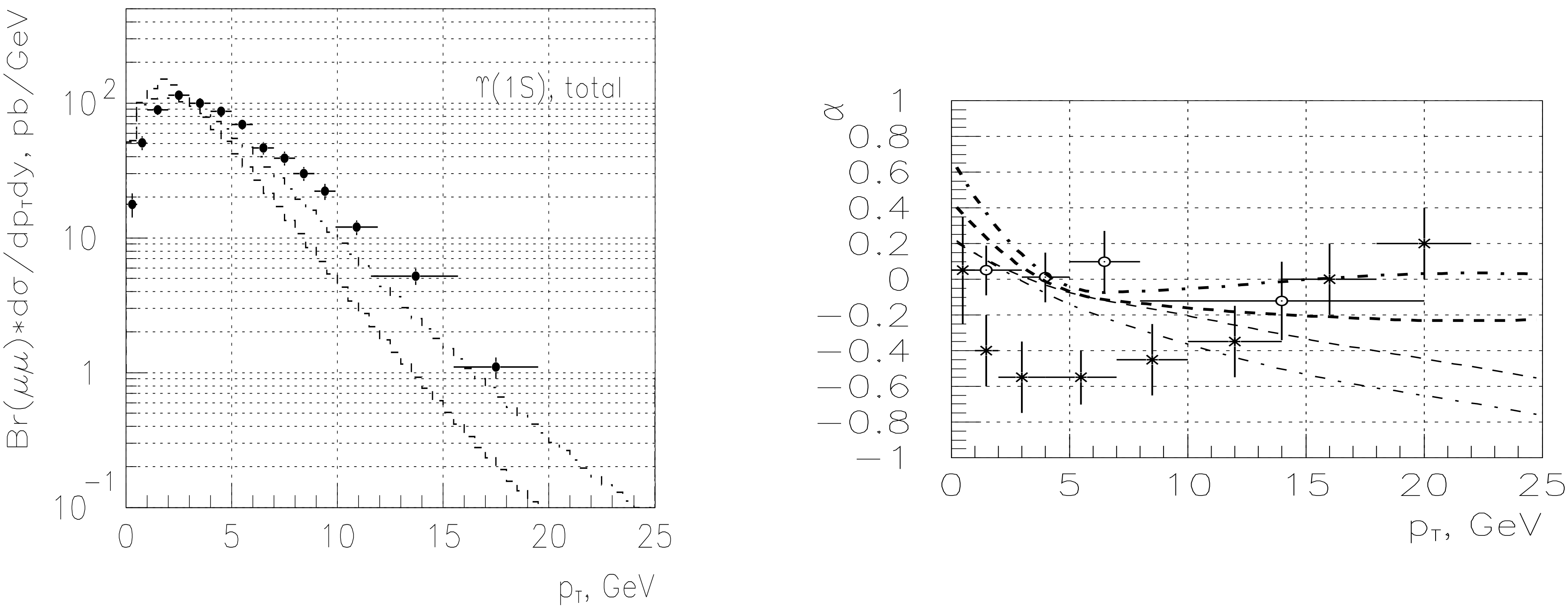

Figure 1: *Predictions on the production of* $\Upsilon(1S)$ *mesons at the Tevatron: differential cross section (left panel): dash-dotted histograms are JB gluons, dashed - dGRV gluons; the spin alignment parameter (right panel) as function of* p_T*: thin lines correspond to the direct contribution only; thick lines - with the feed-down from* χ_b *states added. Exp. data: D. Acosta et al. (CDF), PRL* **88** *(2002) 161802 (left panel); V.M. Abazov et al. (D⊘) PRL* **101** *(2008) 182004 (righ panel).*

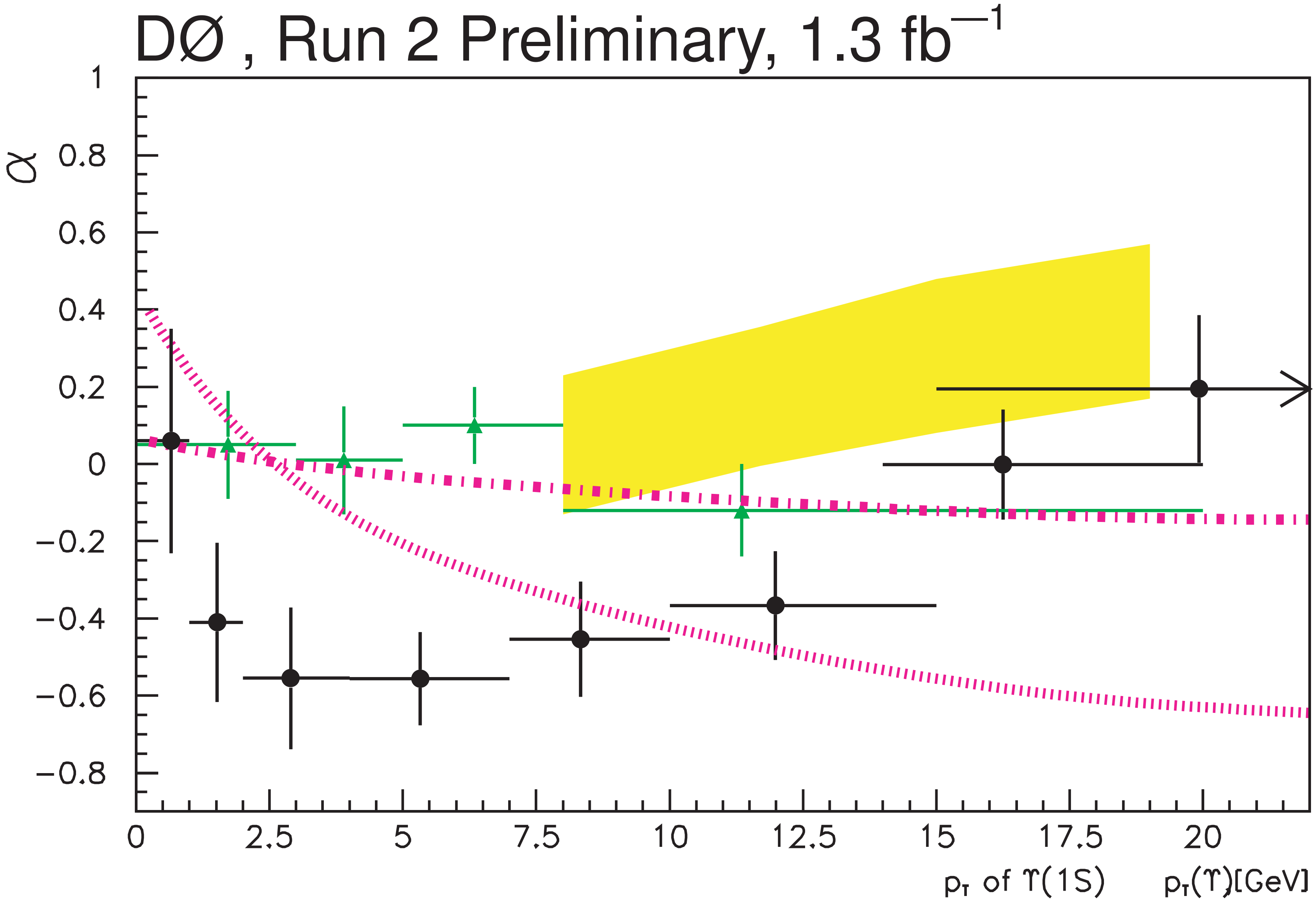

Figure 2: *Predictions on the production of* Υ *(1S) at Tevatron taken from D*∅ *paper.*

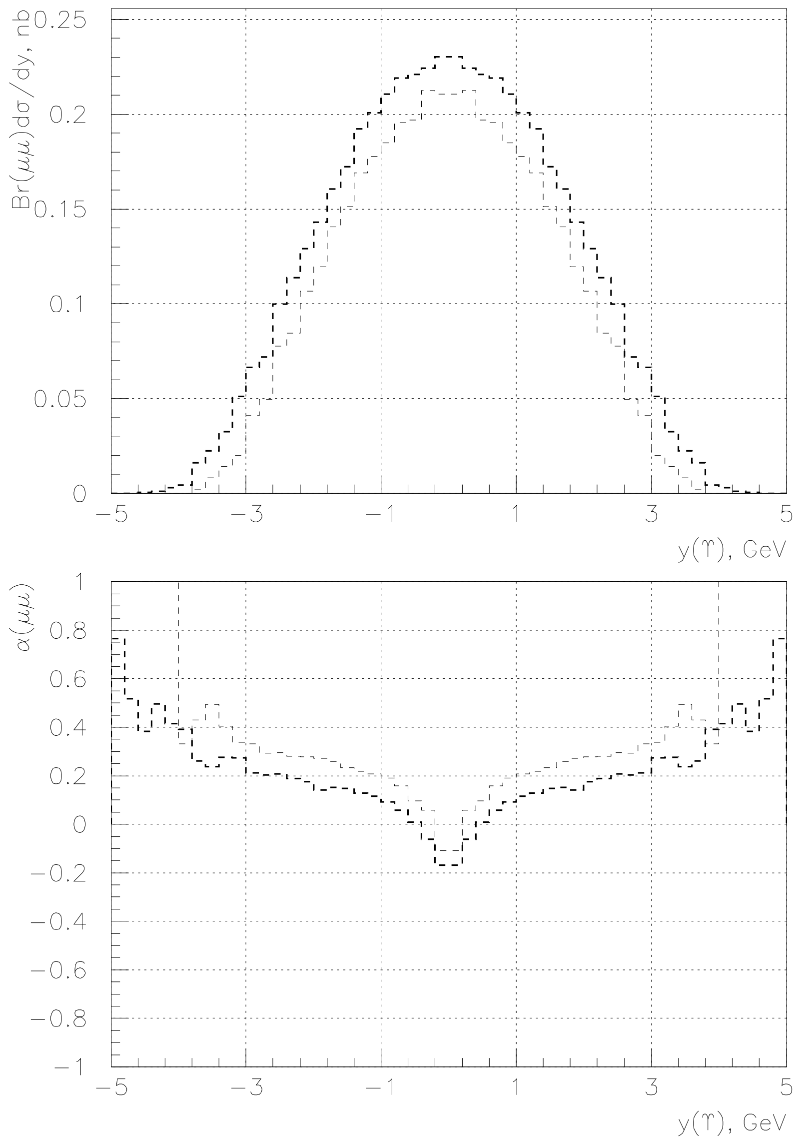

Figure 3: *Predictions on the production of Υ (1S) at Tevatron.*

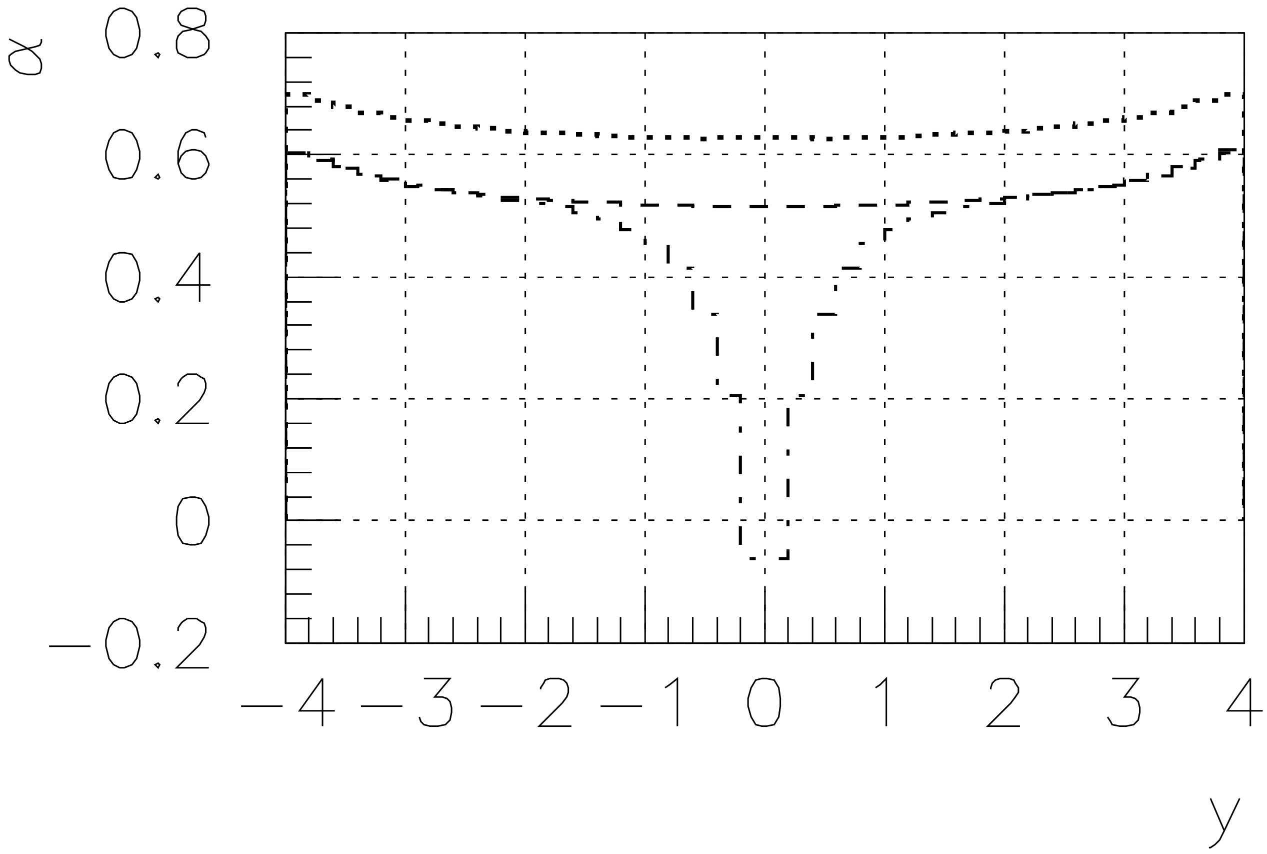

Figure 4: *Predictions on the parameter* α *in the different helicity frames* (χ_b *contribution only with JB gluon density): dash-dotted histograms - recoil system, dashed histograms - taget system (equivalent to GJ system), dotted histograms - Collins-Soper system.*

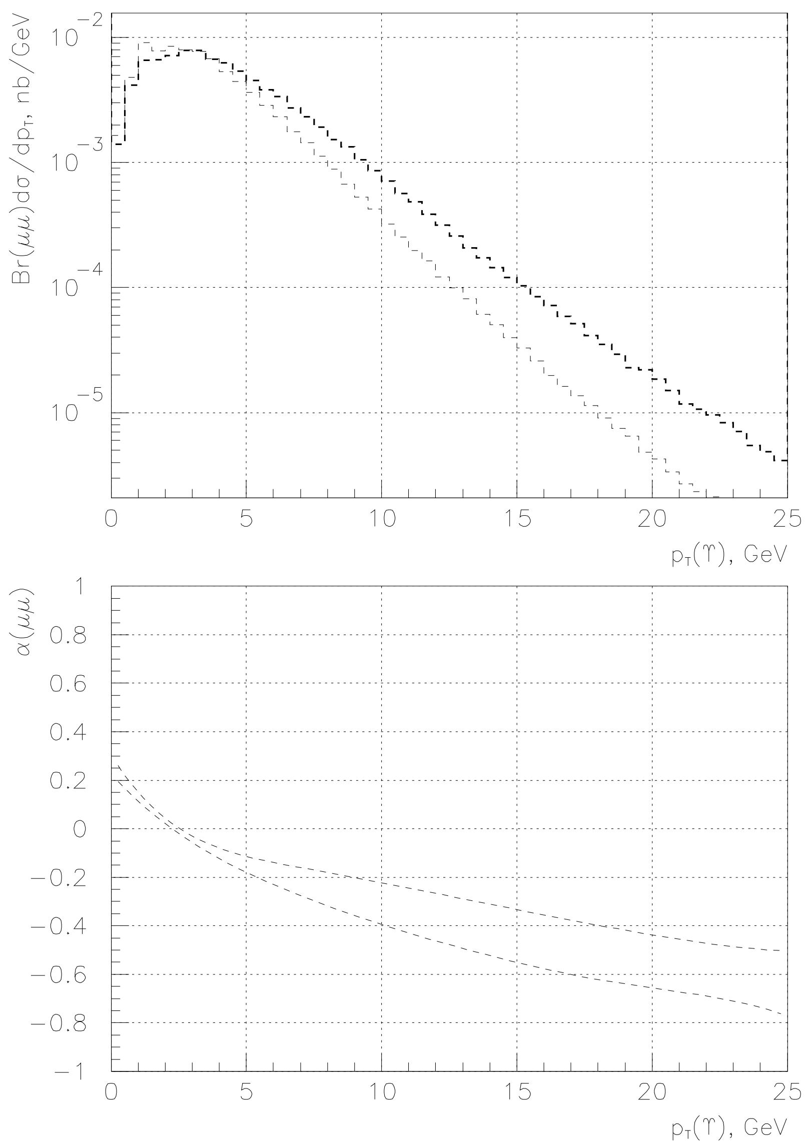

Figure 5: *Predictions on the production of* Υ *(3S) at Tevatron.*

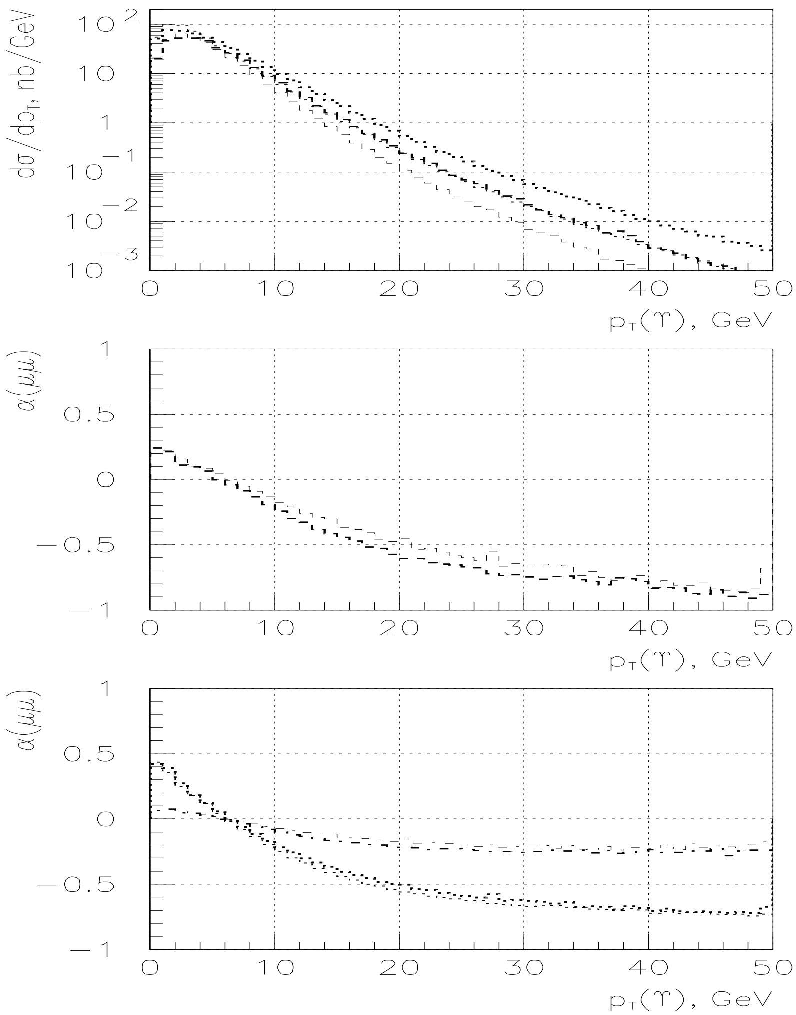

Figure 6: *Predictions on the production of* Υ *(1S) at LHC: Thick lines, JB parametrization; thin lines, dGRV parametrization.* **Upper panel:** *Transverse momentum distribution.* **Central panel:** *Spin alignment parameter* α *for the direct contribution only.* **Lower panel:** *Spin alignment parameter* α *with feed-down from* χ_b *decays taken into account. Dotted lines, the quark spin conservation hypothesis; dash-dotted lines, the full depolarization hypothesis.*