Heavy Quark and Quarkonium Production at LEP2: k_T-Factorization versus Data

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O U T L I N E

1. **Motivation**
2. **Ingredients of the k_T-factorization approach**
3. **Numerical results**
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1. Motivation

We would like to obtain predictions for c.s. of different H.Q. and Higgs production processes at LHC

Why k_T-factorization or semi-hard approach (SHA)?

1) At LHC energies the H.Q. and Qurkonium production - SH processes.

By definition in these processes we have a hard scale μ

$$\mu^2 \sim p_T^2 \sim M_T^2 = M^2 + p_T^2, \; M \sim M_Q,$$

which is large as compared to the Λ_{QCD} but μ is much less than the total c.m.s. energy $\sqrt{S}$ of a process:

$$\Lambda_{QCD} \ll \mu \ll \sqrt{S}.$$

In such case $M^2/S \sim x << 1$ and we have deal with hard processes in small x region.

2) It means the pQCD expansion any observable quantity in α_s contains large coefficients $(\ln^n(S/M^2)) \sim (\ln^n(1/x))$ (besides the usual R.G. ones $(\ln^n(\mu^2/\Lambda^2_{QCD})))$.
The resummation of these terms $(\alpha_s(\ln(1/x))^n$ $(\sim 1$ at $x \to 0)$ results in the so called unintegrated parton distribution $F_i(x, \vec{k}_T^2)$ - the probability to find a parton i carring the longitudinal moment. fraction x and transverse momentum $\vec{k}_T$.

If the terms $(\alpha_s \ln(\mu^2/\Lambda^2_{QCD}))^n$ and DL terms $(\alpha_s \ln(\mu^2/\Lambda^2_{QCD}) \ln(1/x))^n$ are also resummed, then the unintegrated parton distributions (u.p.d.) depends on the probing scale μ: $A(x, \vec{k}_T^2, \mu^2)$.

The (u.p.d.) obey certain evolution equations:

- **BFKL: E.A. Kuraev, L.N. Lipatov, V.S. Fadin, Sov. Phys. JETP 44 (1976) 443, 45 (1977) 199; Y.Y. Balitskii, L.N. Lipatov, Sov. J. Nucl. Phys. 28 (1978) 822.**
- **CCFM: M. Ciafaloni, Nucl. Phys. B 296 (1988) 49;**
  S. Catani, F. Fiorani, G. Marchesini, Nucl. Phys. B336 (1990) 18;
  G. Marchesini, Nucl. Phys. B445 (1995) 49.

The u.p.d. are related to the conventional DGLAP densities once the k_T dependence is integrated out. For example, the u.g.d. reduce to the conventional gluon density with the help of

$$\int_0^{Q^2} F_g(x, \vec{k}_T^2) d\vec{k}_T^2 \sim xG(x, Q^2).$$

3) LO+NLO calculations for H.Q. production have some problems:

- **very large discrepancy (by more than an order of magnitude) between the pQCD predictions (with CSM) and existing exp. data for quarkonium production at Tevatron was resolved with help of colour-octet CO contribution in the framework NRQCD. BUT NRQCD does not discribe:**
- $J/\psi, \psi'$ **and** Υ **polarization at Tevatron**
- **the z-distribution of** J/ψ **at HERA.**
- **To produce the** $b\bar{b}$ **correlations at Teavatron in pQCD one usually intoduces the promordial** k_T **of initial partons. The size of that** k_T **cannot be predicted within model itself and is required to be** $k_T \sim$**1 - 3 GeV (instead** k_T **of the order** $\Lambda_{QCD} \sim 300$ **MeV) to fit the data.**

  What will be at LHC?

  Will we need LO + NLO + NNLO +... or the better to have a resummation procedure?

4) At LHC energies we will run into so called Color Glass Condesate (CGC):

M. Gyulassy, L. McLerran, nucl-th/0405013

It is an equilibrium-like system of partons with some definite value of the average transverse momentum k_T and the corresponding saturation scale $Q_s(x)$:

E. Levin, in *THERA Book*, DESY 01-123F vol 4, DESY-LC-REV-2001-062, p.160.

It is $Q_s^2(x, A) \sim x^{-\lambda} A^{\delta}$ with $\lambda \sim 0.3, \delta \sim 1/3$:

E. Iancu, hep-ph/0408228

At LHC energies CGC may be at $x \sim 10^{-3}$. In preasymtotic region $k_T \geq Q_s$ the k_T- factorization approach is applicable:

F. Gelis, R. Venugopalan, Phys. Rev. D69 (2004) 014019,
D. Kharzeev, K. Tuchin, Nucl. Phys. A735 (2004) 248.
R. Baier, A.H. Mueller, D. Schiff, Nucl. Phys. A741 (2004) 358,

$->$ **We used the semi-hard (SHA)**

**L. Gribov, E. Levin, M. Ryskin,
Phys. Rep. 100 (1983) 1;
E. Levin, M. Ryskin, Y. Shabelski, A. Shuvaev,
Sov. J. Nucl. Phys. 53 (1991) 657**

or k_T-factorization approach

**S. Catani, M. Ciafaloni, F. Hautmann,
Nucl. Phys. B 366 (1991) 135;
J. Collins, R. Ellis, Nucl. Phys. B 360 (1991) 3**

to discribe exp. data on:

- **charm quark photoproduction at HERA**
- **J/ψ production in photo- and electroproduction at HERA with CSM and COM**
- **D^* photoproduction and DIS**
- **charm contribution to the s.f. $F_2^c(x, Q^2), F_L^c, F_L$**
- **$b\bar{b}$ production at Tevatron**

Here I want to present the results for

- **charm, D^* and J/ψ production in two-photon collisions at LEP2**

A.V. Lipatov, N. Z., DESY 05-027, hep-ph/0412275

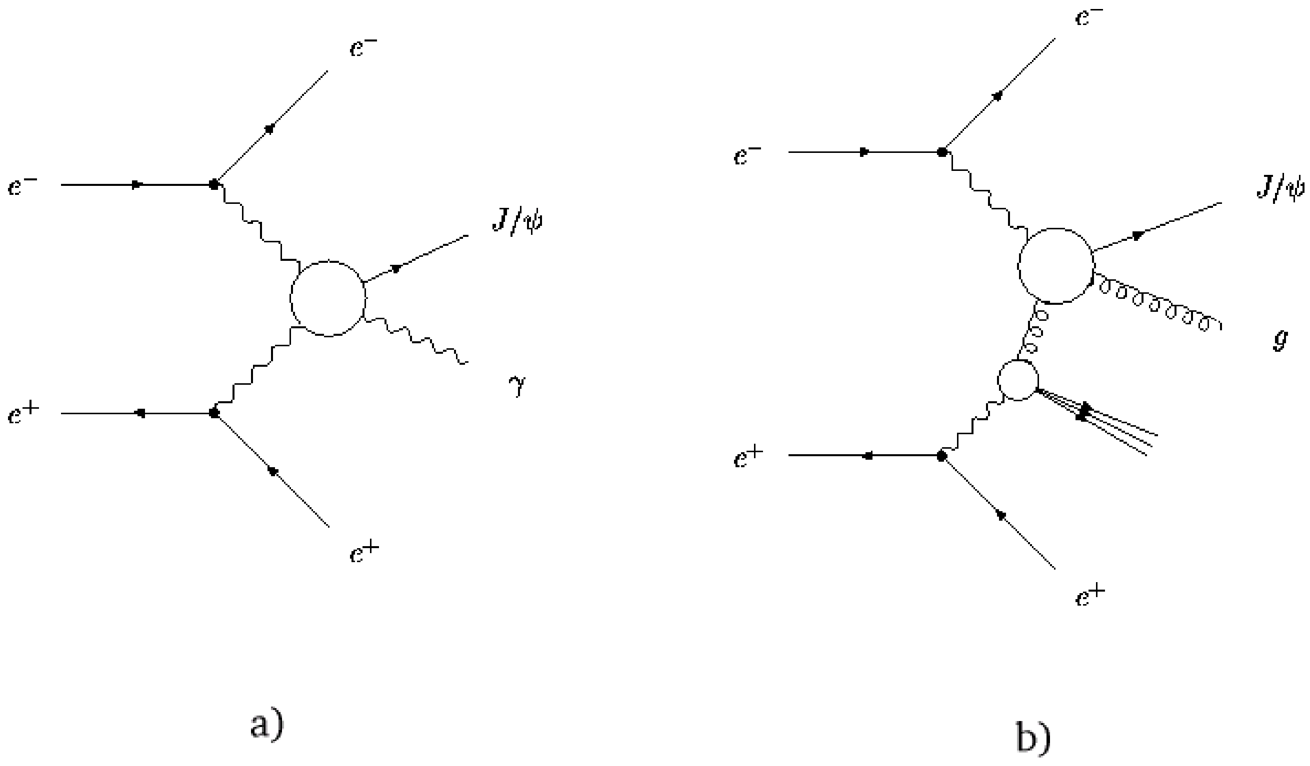
The main goals of this study

- **to investigate whether the inclusive heavy quark, D^*, and J/ψ production at LEP2 can be explained in the traditional CS model by using k_T-factorization and the CCFM-based u. g. d. in a photon**
- **to use this the CCFM-based unintegrated gluon distribution to predict cross sections for different processes at LHC.**

2. Ingredients of the k_T-factorization (SHA)

1) Off-mass shell matrix elements

In $\gamma\gamma$ collisions heavy quark and quarkonium can be produced by one of the three mechanisms: **direct** production (Fig. 1a), photoproduction by **resolved** photon (Fig. 1b) and by double resolved process (they give a much smaller contribution and will not taken into account in our analysis)



The QCD motivated cross section is $e^+ e^- \to e^+ e^- J/\psi\, X$ is given by

$$d\sigma(e^+ e^- \to e^+ e^- J/\psi\, X) = \int f_{\gamma/e}(x_1) dx_1 \int f_{\gamma/e}(x_2) dx_2\, d\hat{\sigma}(\gamma\gamma \to J/\psi\, X),$$

where we use the WW approximation for the bremsstrahlung photon distribution from an electron:

$$f_{\gamma/e}(x) = \frac{\alpha}{2\pi}\left(\frac{1+(1-x)^2}{x} \ln\frac{Q^2_{\rm max}}{Q^2_{\rm min}} + 2m_e^2 x \left(\frac{1}{Q^2_{\rm max}} - \frac{1}{Q^2_{\rm min}}\right)\right)$$

with $Q^2_{\rm min} = m_e^2 x^2/(1-x)^2$ **and** $Q^2_{\rm max} = (E\theta)^2(1-x) + Q^2_{\rm min}$. **Here** $x = E_\gamma/E_e$, $E = E_e = \sqrt{s}/2$, $\theta = 32\,{\rm mrad}$ **is the angular cut that ensures the photon is real, and** $\sqrt{s} = 197\,{\rm GeV}$.

The single-resolved contribution to the $\gamma\gamma \to Q\bar{Q}$ process in the k_T-factorization approach has the following form:

$$d\sigma_{1-\mathrm{res}}(\gamma\gamma \to Q\bar{Q}) =$$
$$\int \frac{dx}{x}\mathcal{A}_\gamma(x, \mathbf{k}_T^2, \mu^2) d\mathbf{k}_T^2 \frac{d\phi}{2\pi} d\hat{\sigma}(\gamma g^* \to Q\bar{Q}),$$

where $\hat{\sigma}(\gamma g^* \to Q\bar{Q})$ is the heavy quark production cross section via an off-shell gluon from photon.

The expression (1) can be easily rewritten as

$$\frac{d\sigma_{1-\mathrm{res}}(\gamma\gamma \to Q\bar{Q})}{dy_2 d\mathbf{p}_{2T}^2} =$$
$$\int \frac{1}{16\pi(xs)^2(1-\alpha_2)}\mathcal{A}_\gamma(x, \mathbf{k}_T^2, \mu^2)|\bar{\mathcal{M}}|^2(\gamma g^* \to Q\bar{Q}) d\mathbf{k}_T^2 \frac{d\phi}{2\pi}\frac{d\phi_2}{2\pi},$$

where $|\bar{\mathcal{M}}|^2(\gamma g^* \to Q\bar{Q})$ is the off-shell m.e., $s = (p_\gamma^{(1)} + p_\gamma^{(2)})^2$ is the total c.m. frame energy, y_2 and ϕ_2 are the rapidity and the azimuthal angle of the produced heavy quark with mass m_Q, $\alpha_2 = m_{2T}\exp(y_2)/\sqrt{s}$ and $m_{2T}^2 = m_Q^2 + \mathbf{p}_{2T}^2$.

For partonic cross section $d\hat{\sigma}(\gamma\gamma \to J/\psi\, X)$ we will use expression obtained earlier

A.V. Lipatov, N.Z., Eur. Phys. J C27 (2003) 87,

because the 1-res processes are analogous to those contributing to the lepto- or photoproduction processes at HERA. The unintegrated gluon distributions in the proton should be replaced by ones in the photon.

2) Unintegrated gluon distribution in photon

CCFM evolution equation formulated for the **proton** has been solved numerically or analytically in different ways:

H. Jung, G. Salam, Eur. Phys. J. C19 (2001) 351,
M.A. Kimber, A.D. Martin, M.G. Ryskin, Phys. Rev., D63 (2001) 114027,
J. Kwiecinski, Acta Phys. Polon. B33 (2002) 1809.

Unintegrated gluon distribution in a photon $\mathcal{A}_\gamma(x, q_T^2, \mu^2)$ can be constructed by the similar method

A. Gawron, J. Kwiecinski, Acta Phys. Polon. B34 (2003) 133,
L. Motyka, N. Timneanu, Eur. Phys. J. C27 (2003) 73.

Recently the unintegrated gluon distribution in a photon $\mathcal{A}_\gamma(x, \mathbf{k}_T^2, \mu^2)$ was obtained using the full CCFM evolution equation

M. Hansson, H. Jung, L. Jönsson, hep-ph/0402019.

It was shown that the full CCFM evolved effective (integrated over $\mathbf{k}_T^2$) distribution is much higher than the usual DGLAP-based gluon density at $x < 10^{-1}$.

Here we study heavy flavor production at LEP2 in more detail using the full CCFM-evolved u.g.d. We investigate the total and differential heavy quark cross section (namely pseudo-rapidity and transverse momenta distributions of the D^*-meson) and compare our theoretical results with the recent experimental data taken by the L3, OPAL, ALEPH Collab. and DELPHI Collab. for J/ψ in $\gamma\gamma$ collisions at LEP2:

M. Acciari *et al.* **(L3 Collaboration), Phys. Lett.,B503, 10 (2001),**
M. Acciari *et al.* **(L3 Collaboration), Phys. Lett. B514, 19 (2001),**
P. Achard *et al.* **(L3 Collaboration), Phys. Lett. B535, 59 (2002),**
G. Abbiendi *et al.* **(OPAL Collaboration), Eur. Phys. J. C16, 579 (2000),**
ALEPH Collaboration, Eur. Phys. J. C28, 437 (2003).
J. Abdallah *et al.* **(DELPHI Collab., Phys. Lett. B565, 76 (2003).**

3. Numerical results

First of all, we performed the integration of the u.g.d. $\mathcal{A}_\gamma(x, k_T^2, \mu^2)$ over the gluon transverse momenta $\mathbf{k}_T^2$ to obtain the effective gluon density in a photon

$$xg_\gamma(x, \mu^2) \sim \int\limits_0^{\mu^2} \mathcal{A}_\gamma(x, \mathbf{k}_T^2, \mu^2) d\mathbf{k}_T^2.$$

The effective density $xg_\gamma(x, \mu^2)$ can be compared with the experimental data taken by H1 collaboration at HERA:

C. Adloff *et al.* (H1 Collaboration),
Eur. Phys. J. C10 (1999) 363;
Phys. Lett. B483 (2000) 36.

As seen in Figs. 1 and 2 this gluon distribution agrees well with the existing data extracted from hard dijet photoproduction (at $p_T^2 = 38\,\mathrm{GeV}^2$ and $p_T^2 = 74\,\mathrm{GeV}^2$).

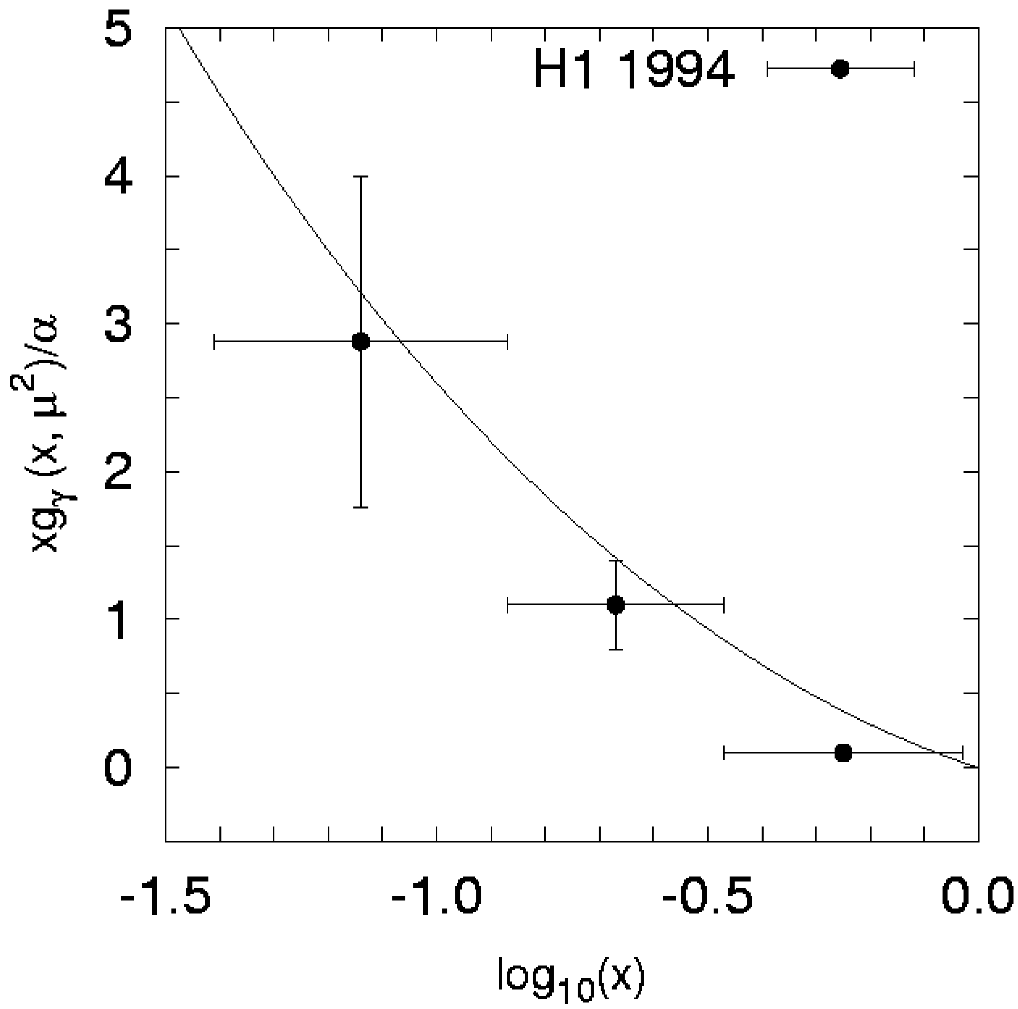


Figure 1: The effective gluon distribution $xg_\gamma(x, \mu^2)$ in the photon as a function of $\log_{10} x$ at $\mu^2 = 38\,\mathrm{GeV}^2$. The experimental data are taken by the H1 Collab. using hard dijets production.

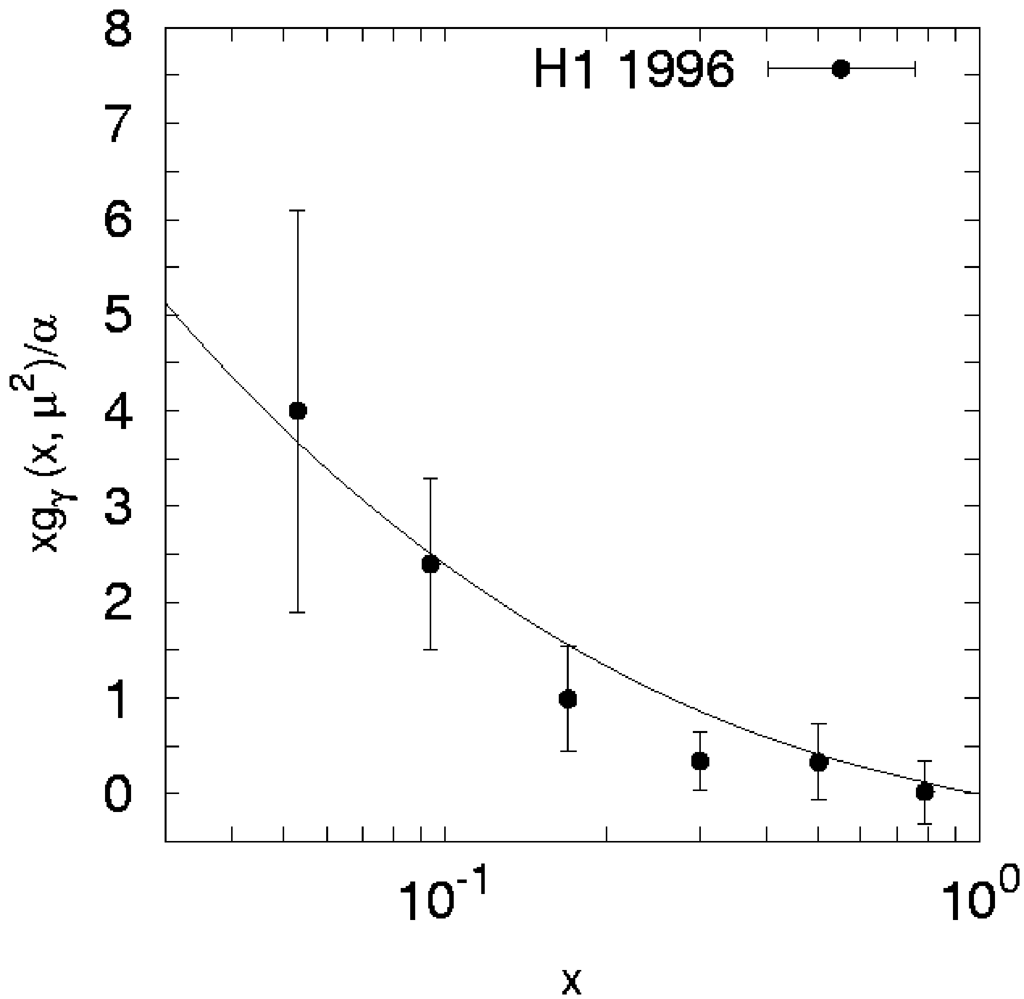


Figure 2: The effective gluon distribution $xg_\gamma(x, \mu^2)$ in the photon as a function of $\log_{10}x$ at $\mu^2 = 74\,\text{GeV}^2$. The experimental data are taken by the H1 Collab. using hard dijets production.

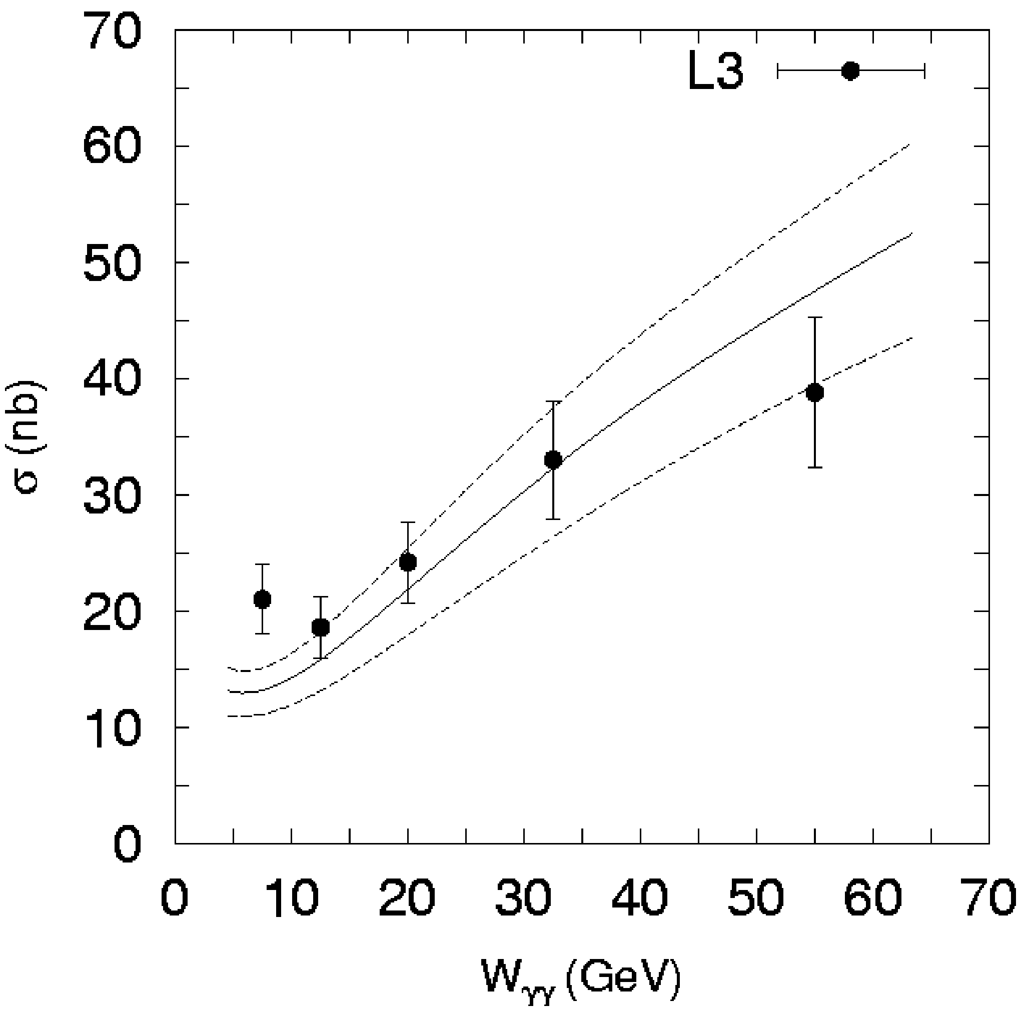


Figure 3: The open charm total c. s. $\sigma(\gamma\gamma \to c\bar{c} + X)$ as a function of $W_{\gamma\gamma}$ at $\sqrt{s} = 189 - 202$ GeV. The solid line corresponds to $m_c = 1.4$ GeV, upper and lower dashed lines - $m_c = 1.3$ GeV and $m_c = 1.5$ GeV. The experimental data are taken by the L3 Collab.

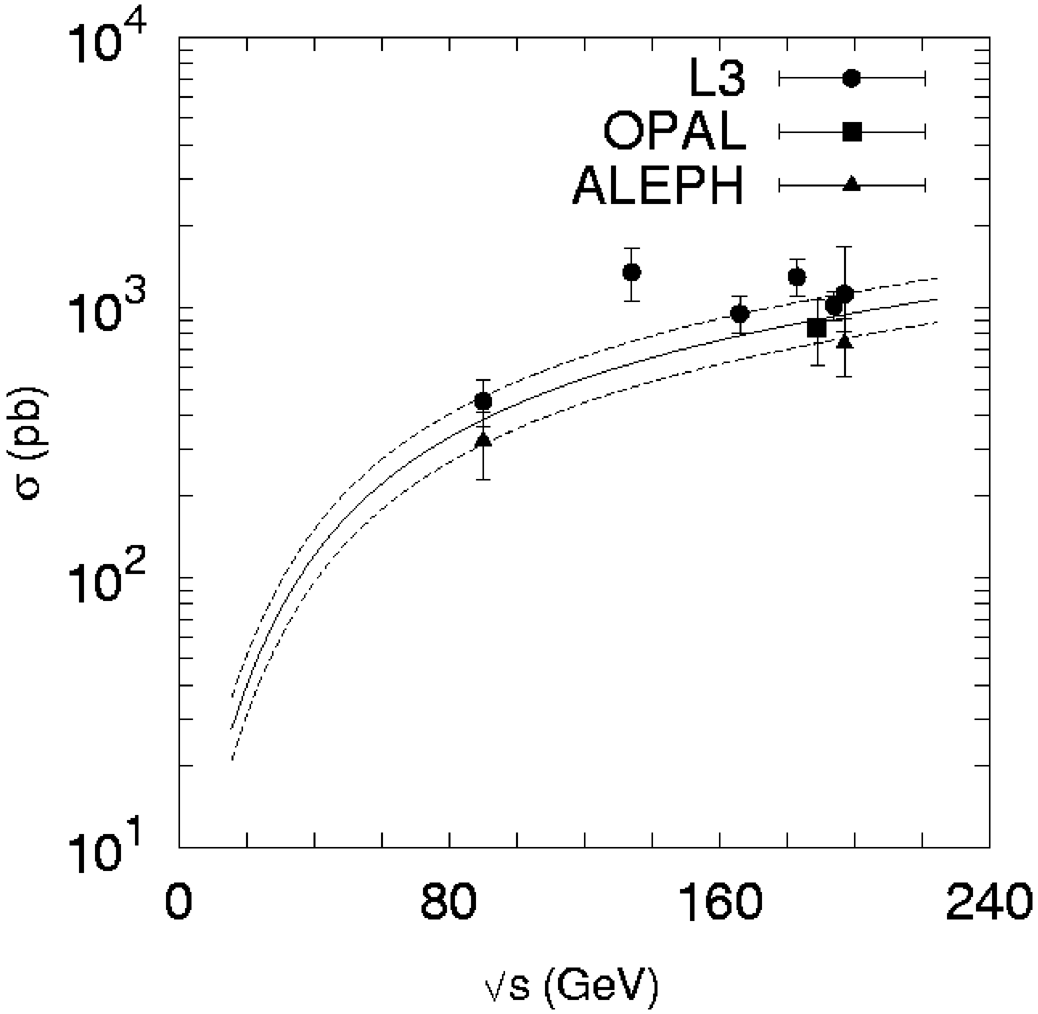


Figure 4: The open charm total c. s. $\sigma(e^+e^- \to e^+e^-c\bar{c} + X)$ as a function of the e^+e^- c.m. energy $\sqrt{s}$. All curves are the same as Fig. 3. The exp. data are taken by L3, OPAL and ALEPH Collab.

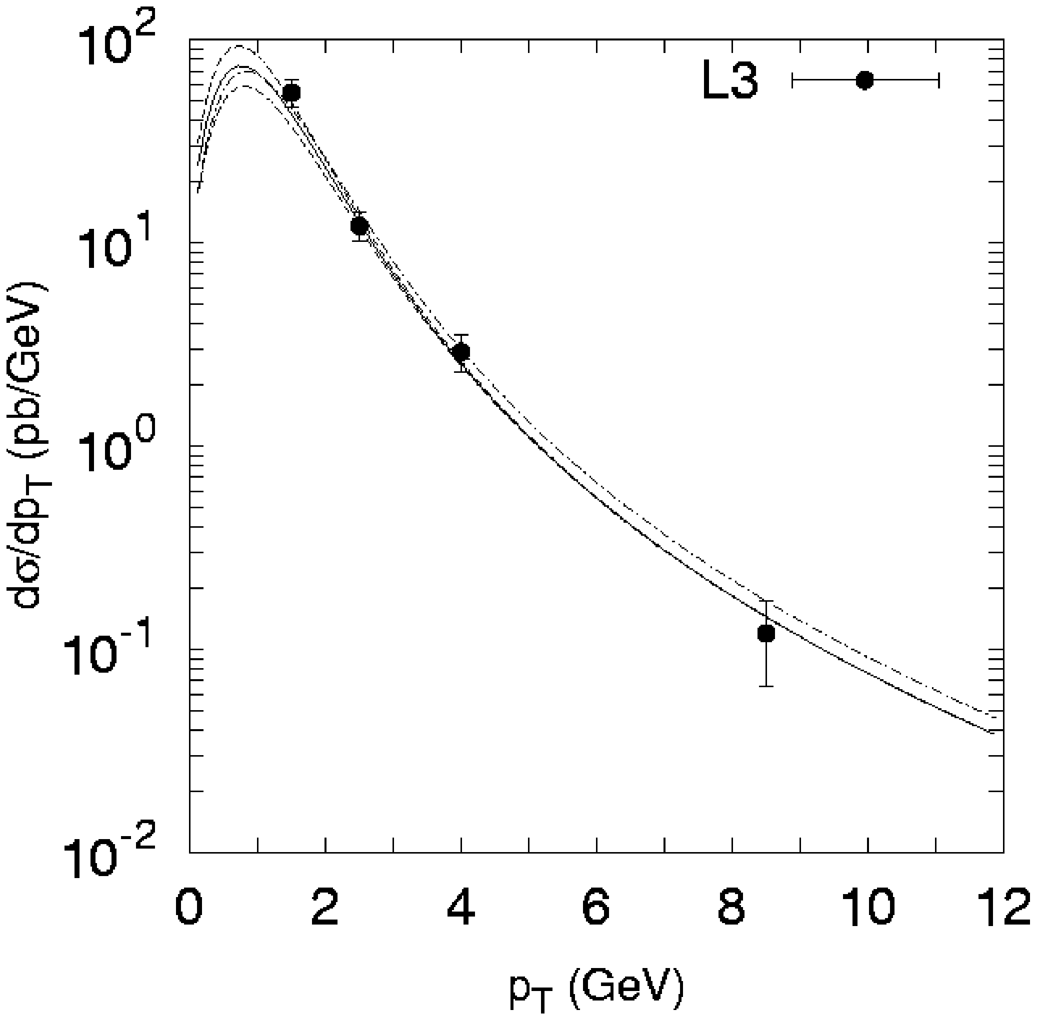


Figure 5: The diff. c.s. $d\sigma/dp_T$ for inclusive D^* production at $|\eta| < 1.4$. The solid and both dashed curves here are the same as in Fig. 3 (calculated with the default value $\epsilon_c = 0.06$), dash-dotted curve correspond to $\epsilon_c = 0.031$ and $m_c = 1.4$ GeV. The exp. data are from L3 Collab..

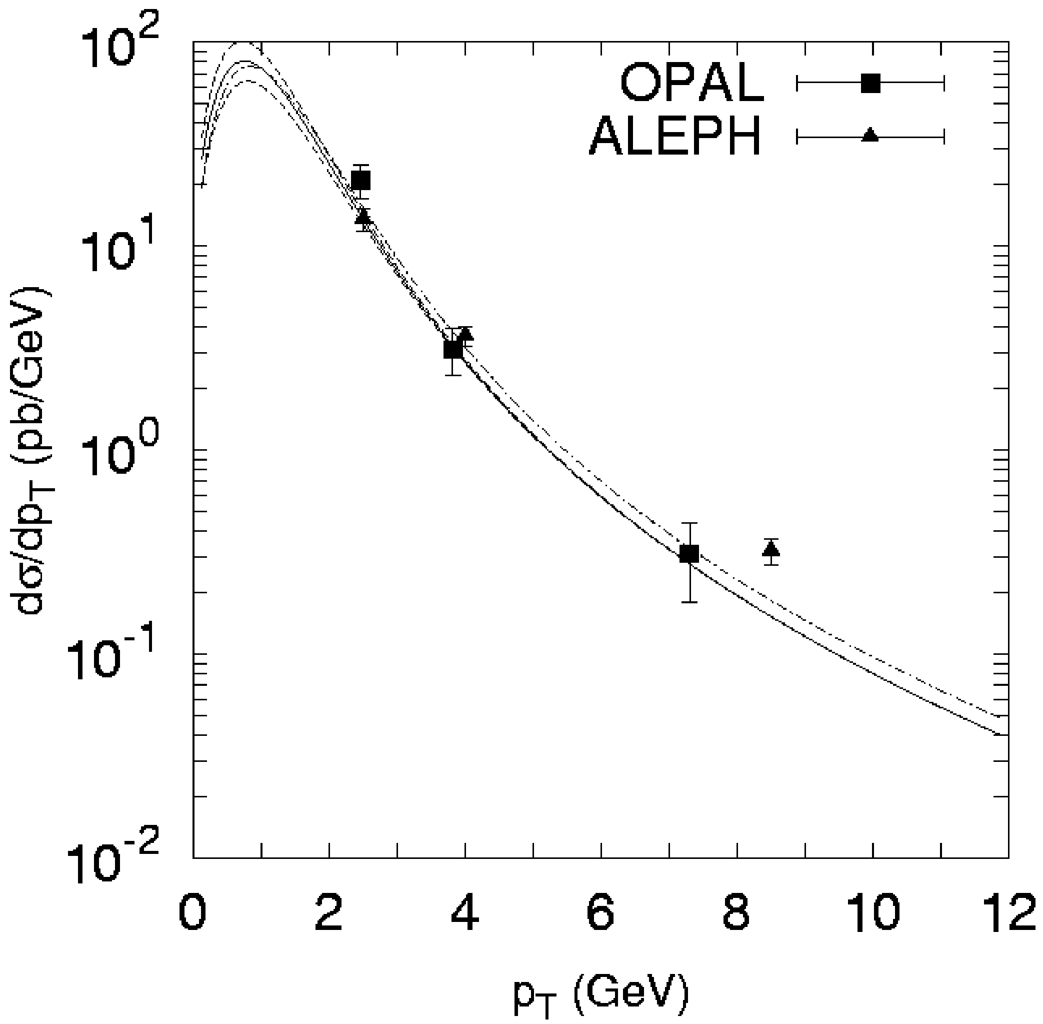


Figure 6: The diff. c. s. $d\sigma/dp_T$ for inclusive D^* production at $|\eta| < 1.5$. All curves are the same as in Fig. 5. The experimental data are from OPAL and ALEPH Collab..

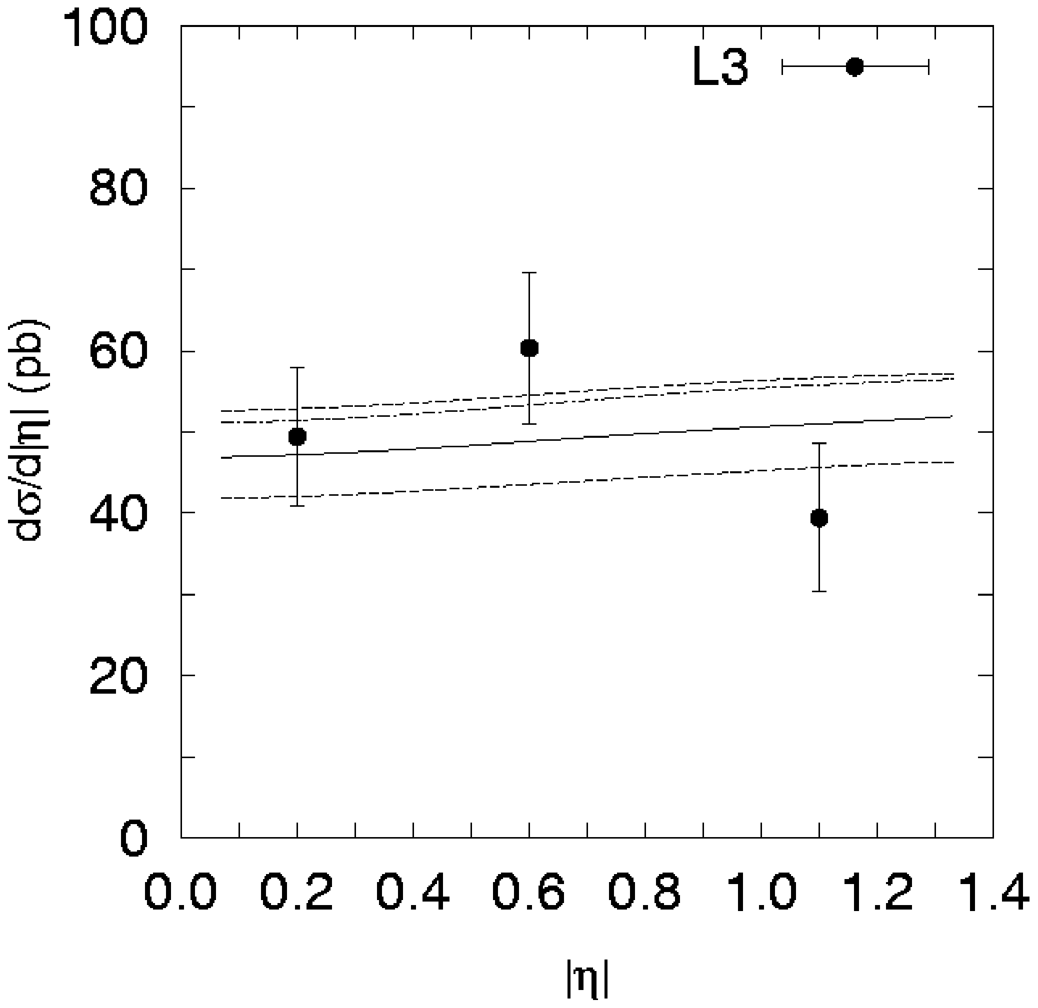


Figure 7: The diff. D^* c. s. $d\sigma/d|\eta|$ for the process $e^+e^- \to e^+e^- D^* + X$ at $1 < p_T < 12$ GeV. All curves are the same as in Fig. 5. The exp. data are from L3 Collab..

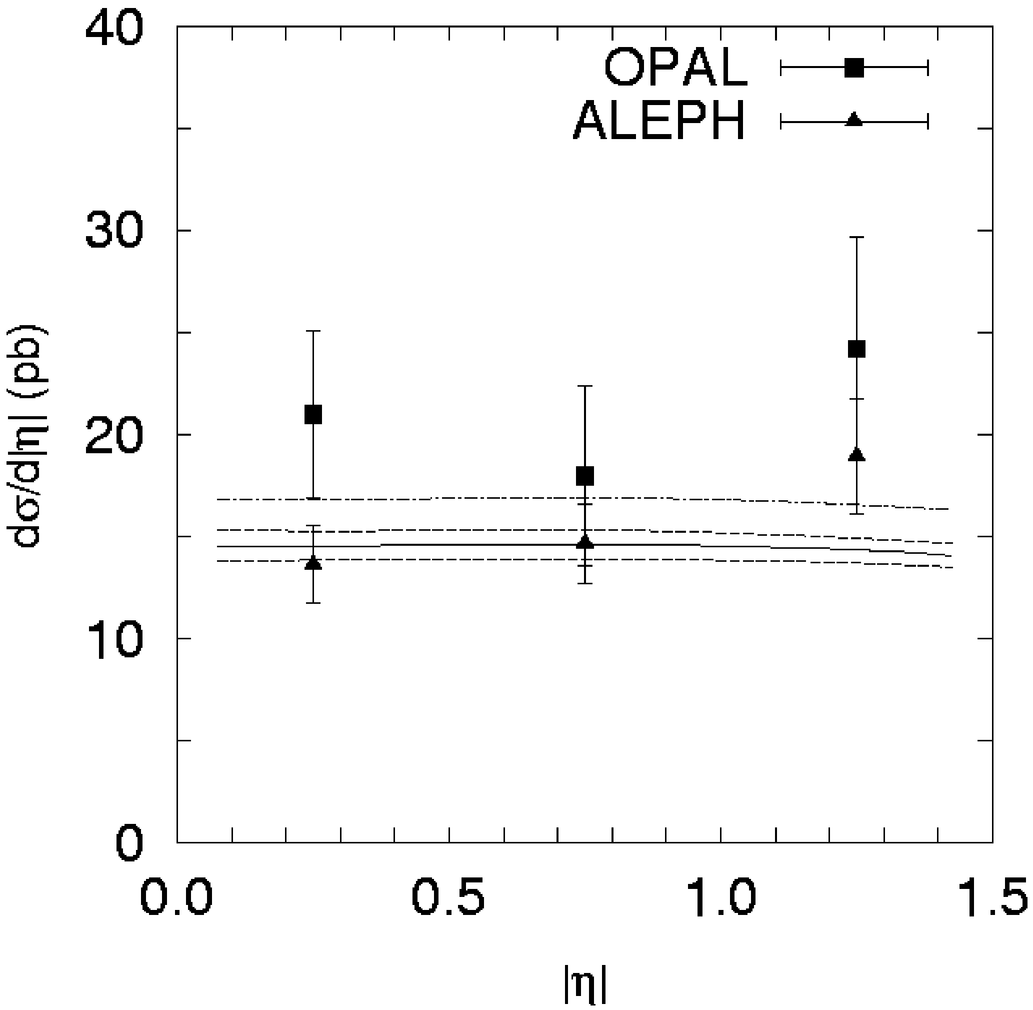


Figure 8: The diff. D^* c. s. $d\sigma/d|\eta|$ for the process $e^+e^- \to e^+e^-D^* + X$ at $2 < p_T < 12$ GeV. All curves are the same as in Fig. 5. The exp. data are from OPAL and ALEPH Collab.

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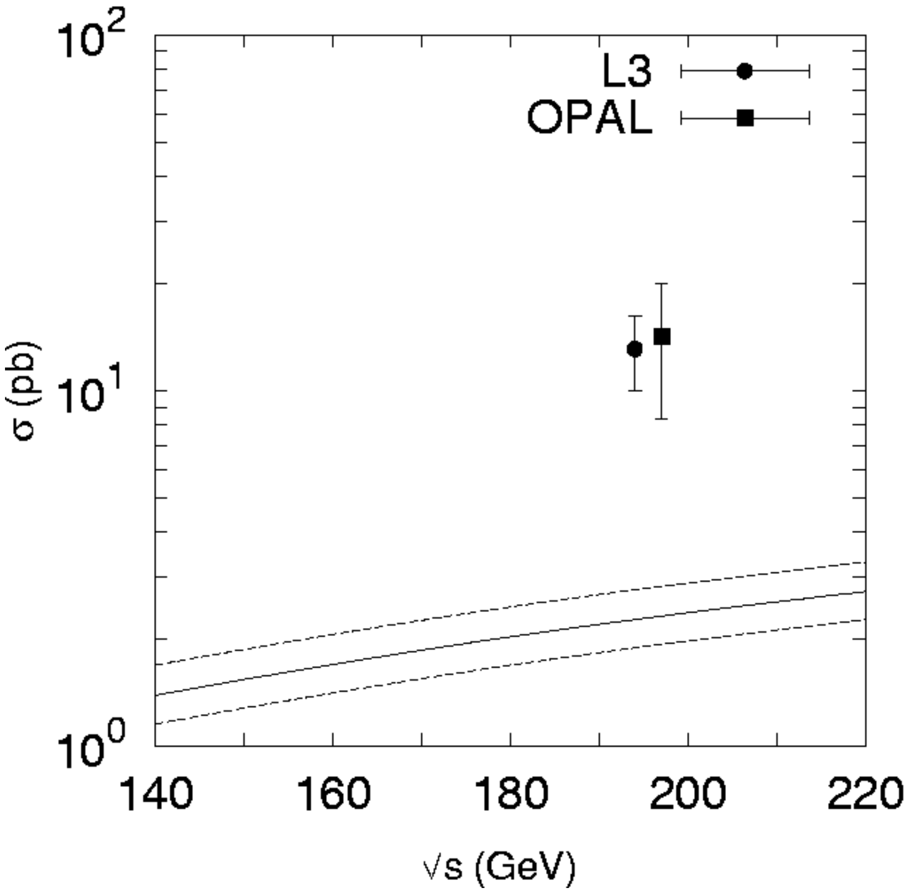

Figure 9: The bottom total c. s. $\sigma(e^+e^- \to e^+e^- b\bar{b} + X)$ **as a function of the** e^+e^- **c. m. energy** $\sqrt{s}$**. The solid line corresponds to the** $m_b = 4.75$ **GeV, upper and lower dashed lines correspond to the** $m_b = 4.5$ **GeV and** $m_b = 5.0$ **GeV. The exp. data are from L3 and OPAL Collab.**

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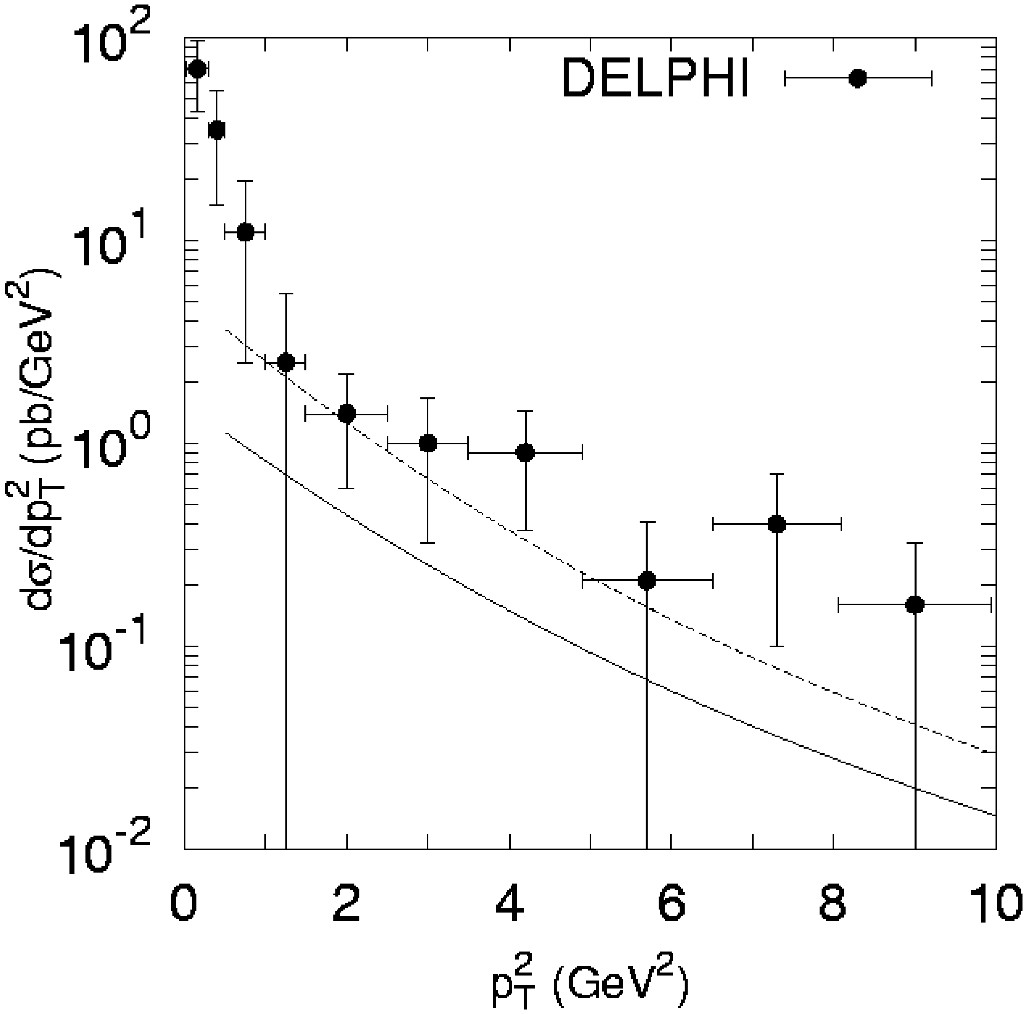

Figure 10: The c. s. $d\sigma/dp^2_{\psi T}$ of $e^+e^- \to e^+e^- J/\psi + X$ measured by DELPHI Collab. at $2 < y_\psi < 2$ as a function of $p^2_{\psi T}$ is compared with the k_T-factorization calculations in the CS model.The solid line corresponds to the $m_c = 1.55$ GeV and $\Lambda_{\rm QCD} = 200$ MeV, dashed line corresponds to the $m_c = 1.4$ GeV and $\Lambda_{\rm QCD} = 340$ MeV.

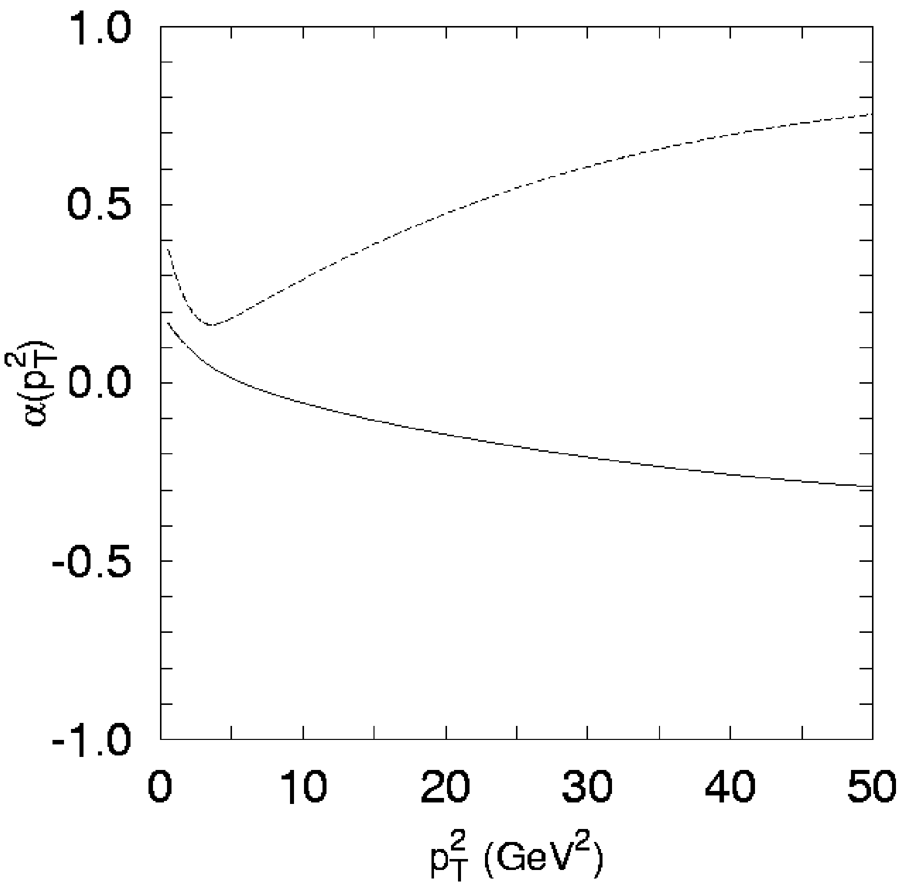

Figure 11: The $p^2_{\psi T}$ dependence of the spin alignment parameter α for the inclusive J/ψ production. The solid line corresponds to the k_T-factorization predictions, dashed line corresponds to the collinear leading order pQCD calculations with the GRV (LO) gluon density in a photon.

5. Summary

- **We studied H.Q. production at CERN LEP2 with k_T-factorization.**
- **CCFM u.g.d. in a photon (similar J2003set1) describes the all exp. data (except $b\bar{b}$-production).**
- **We hope to obtain the correct predictions at LHC.**