Inclusive production of J/ψ in proton-proton collisions at RHIC

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Plan of the talk

- Introduction/Motivation
- Theoretical approach(es)
- Unintegrated gluon distributions
- Results
- Conclusions

based on:
S. Baranov and A. Szczurek,
a paper in preparation

Introduction/Motivation

J/ψ suppression as evidence of quark-gluon plasma. The measure of the suppression:

$$R_{J/\psi}(y,p_t) = \frac{\frac{d\sigma_{AA\to J/\psi X}}{dyd^2p_t}(y,p_t)}{N_{coll}\frac{d\sigma_{pp\to J/\psi X}}{dyd^2p_t}(y,p_t)} \tag{1}$$

However, even the elementary reaction is not fully understood.

- The collinear pQCD does not give a good description of J/ψ production in elementary reactions.
- The way out – color-octet contribution (fitted to the data). Polarization observables in conflict with the color-octet "explanation".
- k_t-factorization explains the elementary production at the Tevatron energy.

Introduction/Motivation

pQCD motivation:
Dynamics of gluon/parton ladders – a theoretical chalange.

The QCD dynamics (collinear, k_t-factorization) is usually investigated for inclusive reactions:

- γ^*-proton total cross section (or F_2)
- Inclusive production of jets
- Inclusive production of mesons (pions)
- Inclusive production of open charm, bottom, top
- Inclusive production of direct photons
- Inclusive production of quarkonia

Introduction/Motivation

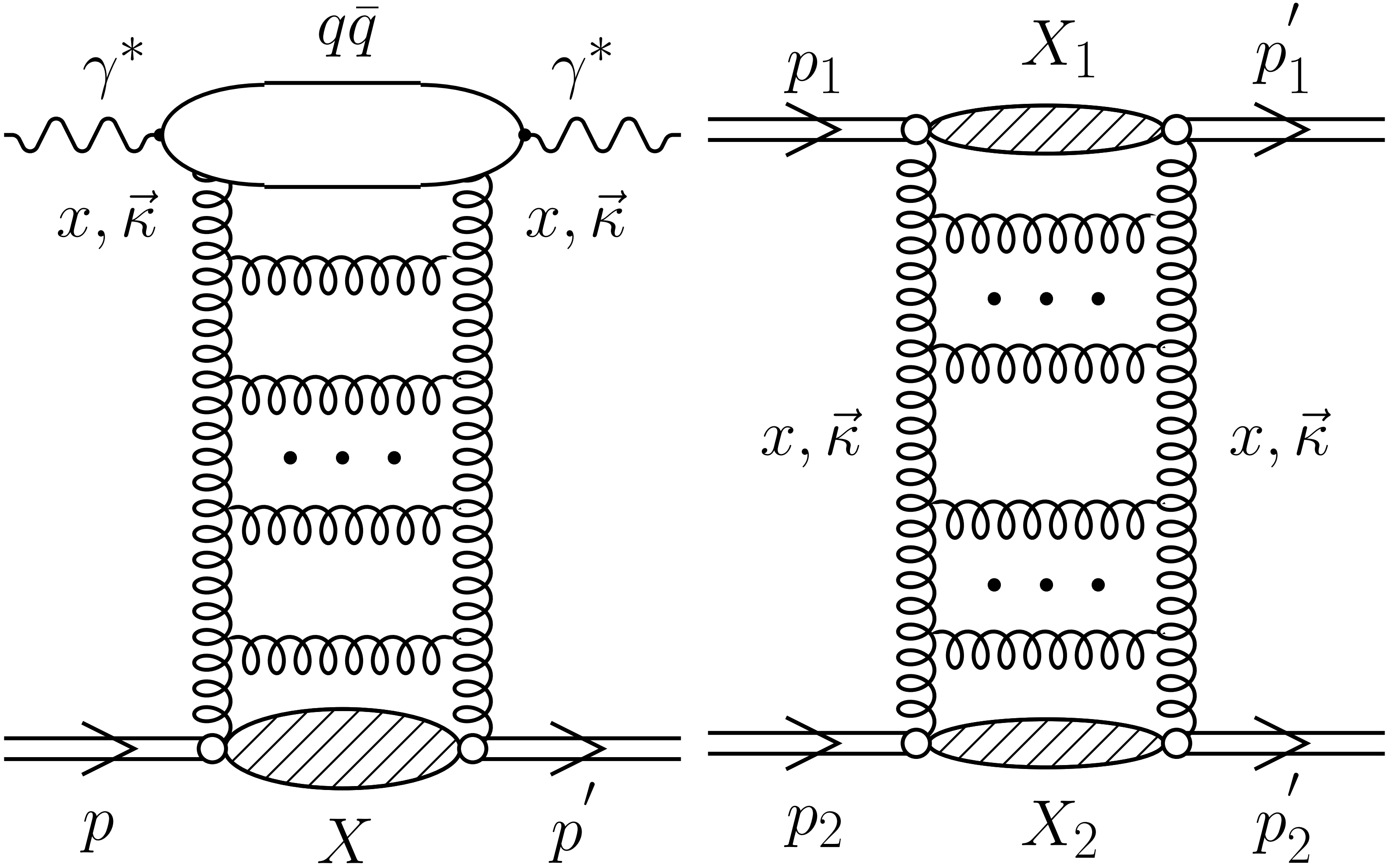
Very interesting are:

- Dijet correlations (Leonidov-Ostrovsky, Bartels et al.)
- $Q\bar{Q}$ correlations (Luszczak-Szczurek)
- γ^* – jet correlations (Pietrycki-Szczurek)
- jet – J/ψ correlations (Baranov-Szczurek)
- Exclusive reactions: $pp \to pXp$ where $X = J/\psi, \chi_c, \chi_b, \eta', \eta_c, \eta_b$ (Matrin-Khoze-Ryskin, Szczurek-Pasechnik-Teryaev)

They contain much more information about QCD ladders.

QCD motivation

HERA $\gamma^* p$ total cross section ($F_2(x, Q^2)$)



Unintegrated gluon distributions (part 1)

Gaussian smearing

$$\mathcal{F}_{naive}(x,\kappa^2,\mu_F^2) = xg^{coll}(x,\mu_F^2)\cdot f_{Gauss}(\kappa^2)\ , \tag{2}$$

$$f_{Gauss}(\kappa^2) = \frac{1}{2\pi\sigma_0^2}\exp\left(-\kappa_t^2/2\sigma_0^2\right)/\pi\ . \tag{3}$$

BFKL UGDF

$$-x\frac{\partial f(x,q_t^2)}{\partial x} = \frac{\alpha_s N_c}{\pi} q_t^2 \int_0^\infty \frac{dq_{1t}^2}{q_{1t}^2}\left[\frac{f(x,q_{1t}^2)-f(x,q_t^2)}{|q_t^2-q_{1t}^2|} + \frac{f(x,q_t^2)}{\sqrt{q_t^4+4q_{1t}^4}}\right] \tag{4}$$

Unintegrated gluon distributions (part 2)

Golec-Biernat-Wuesthoff saturation model
from dipole-nucleon cross section to UGDF

$$\alpha_s \mathcal{F}(x, \kappa_t^2) = \frac{3\sigma_0}{4\pi^2} R_0^2(x) \kappa_t^2 \exp(-R_0^2(x)\kappa_t^2) \; , \tag{5}$$

$$R_0(x) = \left(\frac{x}{x_0}\right)^{\lambda/2} \frac{1}{GeV} \; . \tag{6}$$

Parameters adjusted to HERA data for F_2.

Kharzeev-Levin gluon saturation

$$\mathcal{F}(x, \kappa^2) = \begin{cases} f_0 & \text{if } \kappa^2 < Q_s^2, \\ f_0 \cdot \frac{Q_s^2}{\kappa^2} & \text{if } \kappa^2 > Q_s^2. \end{cases} \tag{7}$$

f_0 adjusted by Szczurek to HERA data for F_2.

Kwiecinski parton distributions

QCD-most-consistent approach – CCFM.

For LO ($2 \to 1$) processes convenient to use UPDFs in a space conjugated to transverse momentum (Kwieciński et al.)

$$\tilde{f}(x, b, \mu^2) = \frac{1}{2\pi} \int d^2\kappa \exp\left(-i\vec{\kappa}\cdot\vec{b}\right) \mathfrak{F}(x, \kappa^2, \mu^2)$$

$$\mathfrak{F}(x, \kappa^2, \mu^2) = \frac{1}{2\pi} \int d^2 b \exp\left(i\vec{\kappa}\cdot\vec{b}\right) \tilde{f}(x, b, \mu^2)$$

The relation between

Kwieciński UPDF and the collinear PDF:

$$xp_k(x, \mu^2) = \int_0^\infty d\kappa_t^2 f_k(x, \kappa_t^2, \mu^2)$$

Kwiecinski parton distributions

At $b = 0$ the functions f_j are related to the familiar integrated parton distributions, $p_j(x, Q)$, as follows:

$$f_j(x, 0, Q) = \frac{x}{2} p_j(x, Q).$$

$$\begin{aligned} p_{NS} &= u - \bar{u}, \quad d - \bar{d}, \\ p_S &= \bar{u} + u + \bar{d} + d + \bar{s} + s + ..., \\ p_{\text{sea}} &= 2\bar{d} + 2u + \bar{s} + s + ..., \\ p_G &= g, \end{aligned}$$

where $\ldots$ stand for higher flavors.

Kwiecinski equations

for a given impact parameter:

$$\frac{\partial f_{NS}(x,b,Q)}{\partial Q^2} = \frac{\alpha_s(Q^2)}{2\pi Q^2}\int_0^1 dz\, P_{qq}(z)\Big[\Theta(z-x)\, J_0((1-z)Qb)\, f_{NS}\left(\frac{x}{z},b,Q\right) - f_{NS}(x,b,Q)\Big]$$

$$\frac{\partial f_{S}(x,b,Q)}{\partial Q^2} = \frac{\alpha_s(Q^2)}{2\pi Q^2}\int_0^1 dz\Big\{\Theta(z-x)\, J_0((1-z)Qb)\Big[P_{qq}(z)\, f_S\left(\frac{x}{z},b,Q\right) + P_{qg}(z)\, f_G\left(\frac{x}{z},b,Q\right)\Big] - [zP_{qq}(z)+zP_{gq}(z)]\, f_S(x,b,Q)\Big\}$$

$$\frac{\partial f_{G}(x,b,Q)}{\partial Q^2} = \frac{\alpha_s(Q^2)}{2\pi Q^2}\int_0^1 dz\Big\{\Theta(z-x)\, J_0((1-z)Qb)\Big[P_{gq}(z)\, f_S\left(\frac{x}{z},b,Q\right) + P_{gg}(z)\, f_G\left(\frac{x}{z},b,Q\right)\Big] - [zP_{gg}(z)+zP_{qg}(z)]\, f_G(x,b,Q)\Big\}$$

Nonperturbative effects

Transverse momenta of partons due to:

- perturbative effects
  (solution of the Kwieciński- CCFM equations),
- nonperturbative effects
  (intrinsic momentum distribution of partons)

Take factorized form in the b-space:

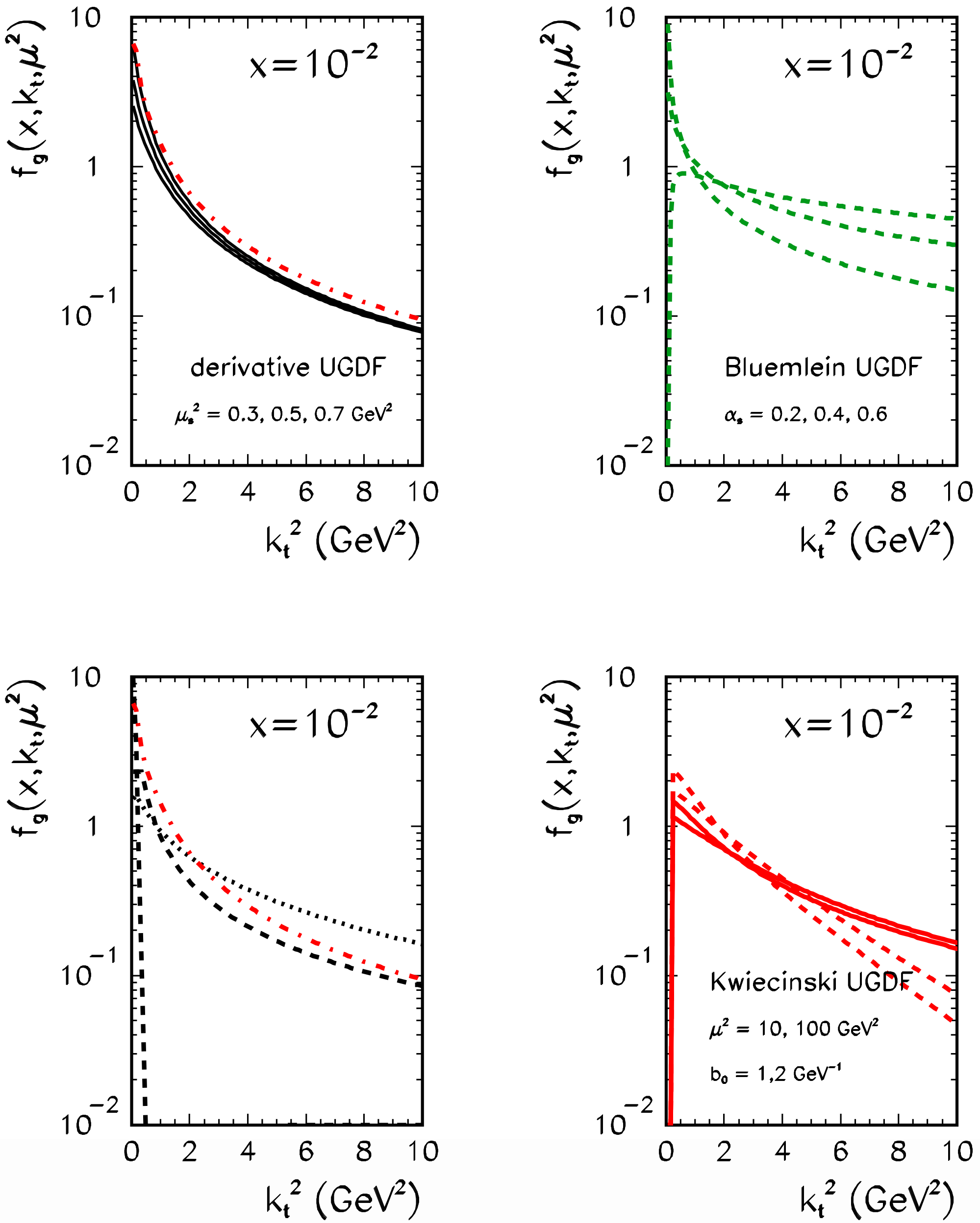
$$\tilde{f}_q(x,b,\mu^2) = \tilde{f}_q^{CCFM}(x,b,\mu^2) \cdot F_q^{np}(b) \ .$$

We use a flavour and x independent form factor

$$F_q^{np}(b) = F^{np}(b) = \exp\left(\frac{-b^2}{4b_0^2}\right)$$

May be too simplistic ?

Unintegrated gluon distributions (comparison)



Processes included

- 1) direct singlet production

$$g + g \to J/\psi + g; \tag{8}$$

- 2) direct production of ψ' meson

$$g + g \to \psi' + g \quad and \quad \psi' \to J/\psi \tag{9}$$

- 3) direct production of χ_c mesons

$$g + g \to \chi_{cJ} \quad and \quad \chi_c \to J/\psi + \gamma \tag{10}$$

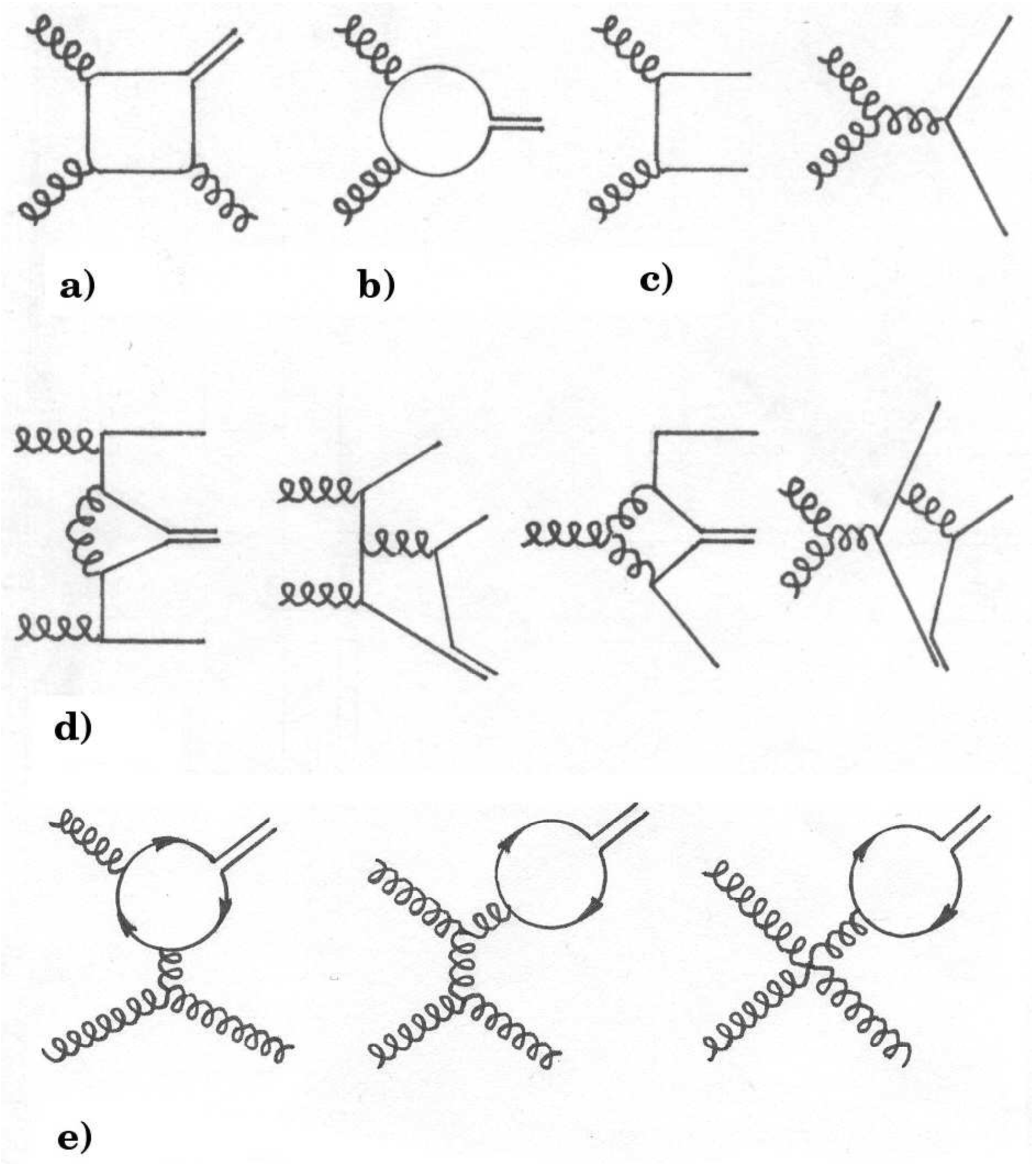
- 4) production of b quarks and antiquarks

$$g + g \to b + \bar{b} \quad and \quad b \to B \quad and \quad B \to J/\psi + X \tag{11}$$

- 5) associate production

$$g + g \to J/\psi + c + \bar{c} \tag{12}$$

Processes included



k_t-factorization approach

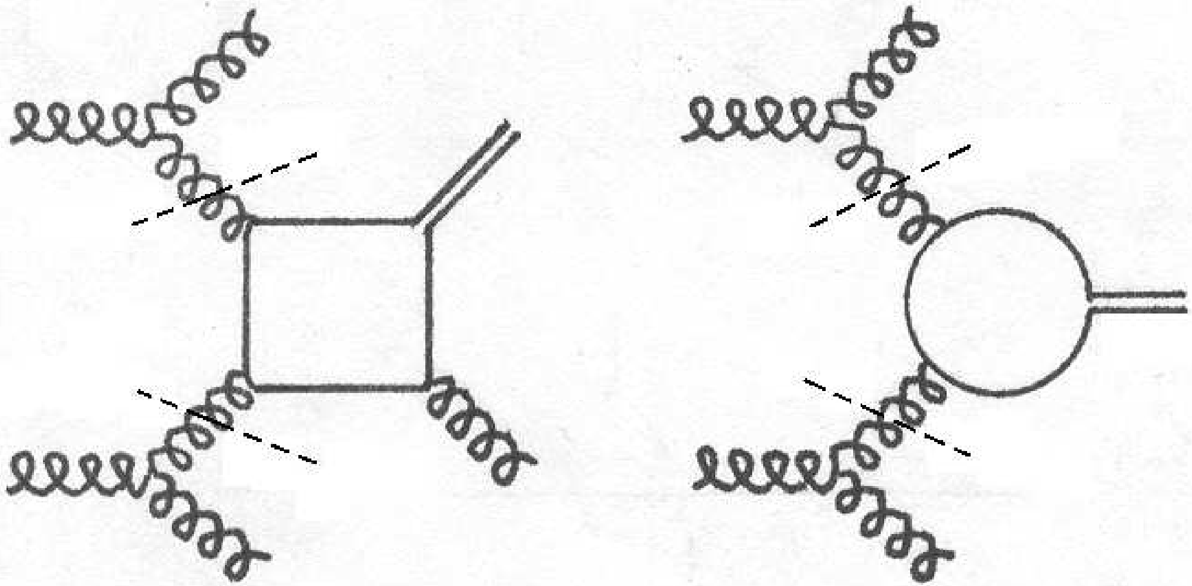


Figure 2: Application of the k_t-factorization approach.

How the cross sections are calculated

NR pQCD methods

operators $J(S,L)$, which guarantee the proper quantum numbers of the $c\bar{c}$ state under consideration.

$$J(^1S_0) \equiv J(S{=}0, L{=}0) \quad = \quad \gamma_5 \, (\not{p}_c + m_c)/m_\psi^{1/2} \tag{13}$$

$$J(^3S_1) \equiv J(S{=}1, L{=}0) \quad = \quad \not{\epsilon}(S_z) \, (\not{p}_c + m_c)/m_\psi^{1/2} \tag{14}$$

$$J(^3P_J) \equiv J(S{=}1, L{=}1) \quad = \quad (\not{p}_{\bar{c}} - m_c) \;\; \not{\epsilon}(S_z) \, (\not{p}_c + m_c)/m_\psi^{3/2} \tag{15}$$

$m_c = m_\psi/2$,
$p_c = p_\psi/2 + q, \;\; p_{\bar{c}} = p_\psi/2 - q$

- matrix elements multiplied by $\Psi(q)$,
- integration with respect to q,
- expansion in q

$$\mathcal{M}(q) = \mathcal{M}|_{q=0} + (\partial\mathcal{M}/\partial q^\alpha)|_{q=0} q^\alpha \; + \; \ldots \tag{16}$$

How the cross sections are calculated

For the direct production mechanism:

$$d\sigma(pp \to \psi X) = \frac{\pi \alpha_s^3 \, |\mathcal{R}(0)|^2}{\hat{s}^2} \frac{1}{4} \sum_{\text{spins}} \frac{1}{64} \sum_{\text{colors}} |\mathcal{M}(gg \to \psi g)|^2$$

$$\times \mathcal{F}_g(x_1, k_{1T}^2, \mu^2)\, \mathcal{F}_g(x_2, k_{2T}^2, \mu^2)\; dk_{1T}^2\, dk_{2T}^2\, dp_{\psi T}^2\, dy_3\, dy_\psi\, \frac{d\phi_1}{2\pi}\, \frac{d\phi_2}{2\pi}\, \frac{d\phi}{2\pi}$$

where ϕ_1, ϕ_2 and ϕ_3 are the azimuthal angles of the initial and final gluons, and y_ψ and ϕ_ψ the rapidity and the azimuthal angle of J/ψ particle.

$$\begin{aligned} (k_1 + k_2)_{E+p_{||}} = x_1\sqrt{s} &= m_{\psi T}\exp(y_\psi) \;\; + \; |k_{3T}|\exp(y_3), \\ (k_1 + k_2)_{E-p_{||}} = x_2\sqrt{s} &= m_{\psi T}\exp(-y_\psi) + |k_{3T}|\exp(-y_3), \end{aligned} \qquad (20)$$

$m_{\psi T} = (m_\psi^2 + |p_{\psi T}|^2)^{1/2}$.

$|\mathcal{R}_{J/\psi}(0)|^2 = 0.8$ GeV^3 for J/ψ, $|\mathcal{R}_{\psi'}(0)|^2 = 0.4$ GeV^3 for ψ'.

How the cross sections are calculated

For the production of χ_c mesons

$$d\sigma(pp \to \chi_{cJ} X) = \frac{12\pi^2\alpha_s^2\, |\mathcal{R}'(0)|^2}{\hat{s}^2} \frac{1}{4} \sum_{\text{spins}} \frac{1}{64} \sum_{\text{colors}} |\mathcal{M}'(gg \to \chi_{cJ})_{q=}$$

$$\times \mathcal{F}_g(x_1, k_{1T}^2, \mu^2)\, \mathcal{F}_g(x_2, k_{2T}^2, \mu^2)\; dk_{1T}^2\, dk_{2T}^2\, dy_\chi \frac{d\phi_1}{2\pi} \frac{d\phi_2}{2\pi}. \quad (2$$

$|\mathcal{R}'_\chi(0)|^2 = 0.075$ GeV^5 (potential models).
$Br(\chi_{cJ} \to J/\psi\gamma)$ = 0.006, 0.35, and 0.135 for J = 0, 1, 2.
For the production of beauty quarks

$$d\sigma(pp \to b\bar{b}X) = \frac{4\pi\alpha_s^2}{\hat{s}^2} \frac{1}{4} \sum_{\text{spins}} \frac{1}{64} \sum_{\text{colors}} |\mathcal{M}(gg \to b\bar{b})|^2$$

$$\times \mathcal{F}_g(x_1, k_{1T}^2, \mu^2)\, \mathcal{F}_g(x_2, k_{2T}^2, \mu^2)\; dk_{1T}^2\, dk_{2T}^2\, dp_{bT}^2\, dy_b\, dy_{\bar{b}} \frac{d\phi_1}{2\pi} \frac{d\phi_2}{2\pi} \frac{d\phi_b}{2\pi} \quad (22$$

How the cross sections are calculated

For the charm-associated production:

$$d\sigma(pp \to \psi c\bar{c}X) = \frac{\alpha_s^4}{4\hat{s}^2} |\mathcal{R}(0)|^2 \frac{1}{4} \sum_{\text{spins}} \frac{1}{64} \sum_{\text{colors}} |\mathcal{M}(gg \to \psi c\bar{c})|^2$$

$$\times \mathcal{F}_g(x_1, k_{1T}^2, \mu^2)\, \mathcal{F}_g(x_2, k_{2T}^2, \mu^2)\, dk_{1T}^2 dk_{2T}^2 dp_{\psi T}^2 dp_{cT}^2 dy_\psi dy_c dy_{\bar{c}} \frac{d\phi_1}{2\pi} \frac{d\phi}{2\pi}$$

Parton level matrix elements $|\mathcal{M}(gg \to \psi c\bar{c})|^2$ (Baranov)

Contributions of different processes

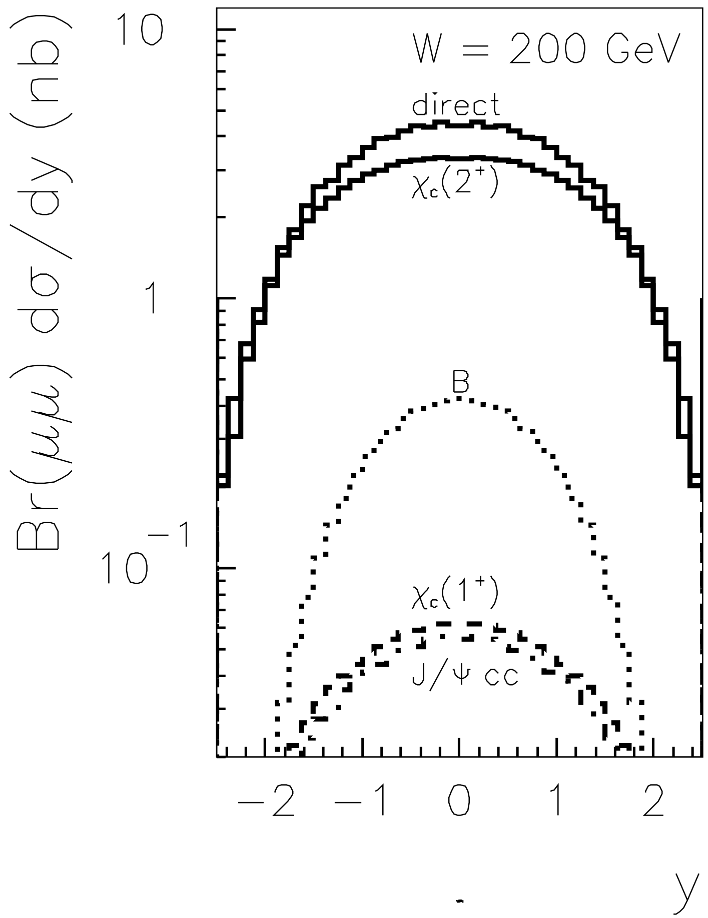


Figure 3: Monte Carlo method, “derivative UGDF”.

Contributions of different processes

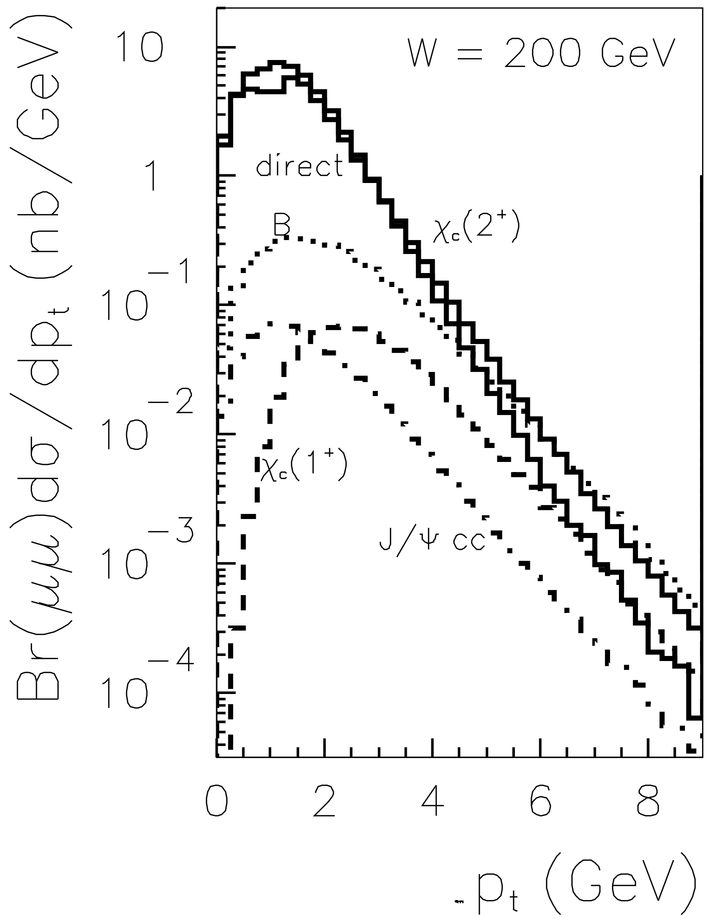
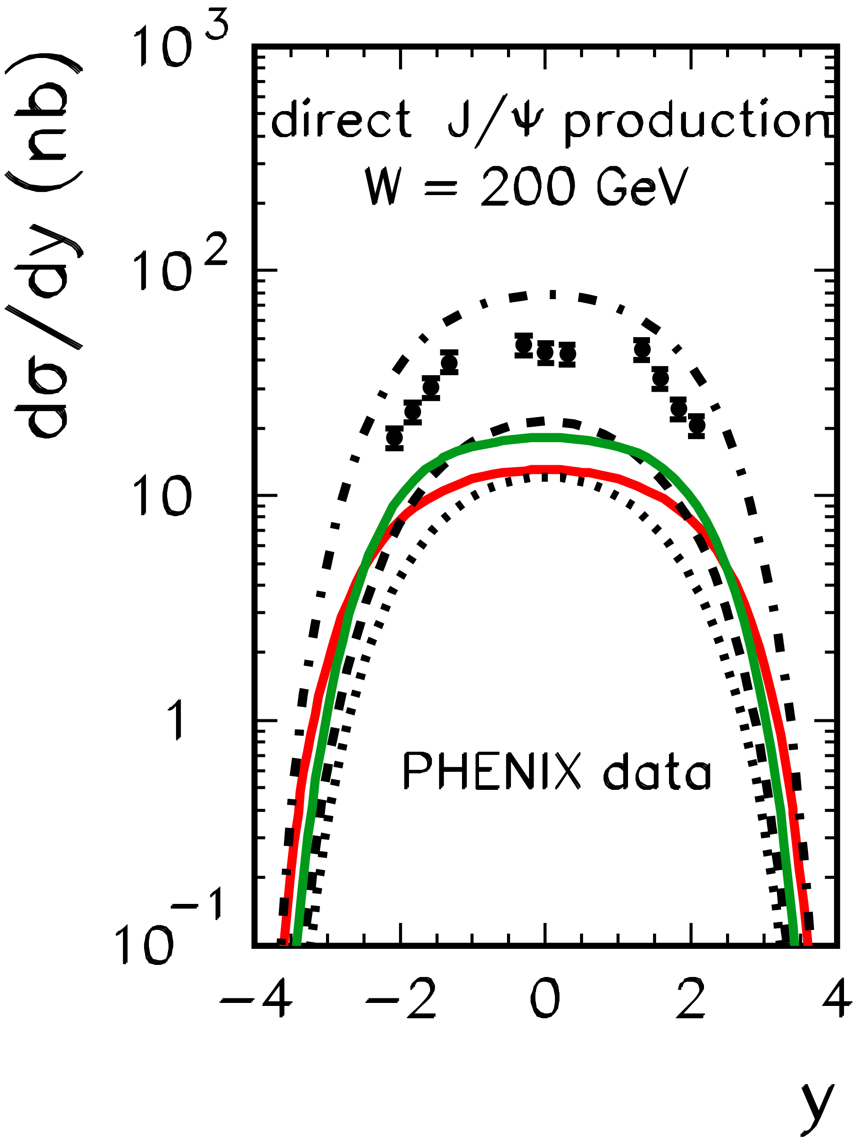


Figure 4: “derivative UGDF”, the full range of rapidity, Monte Carlo method.

Direct color-singlet production



Direct singlet production

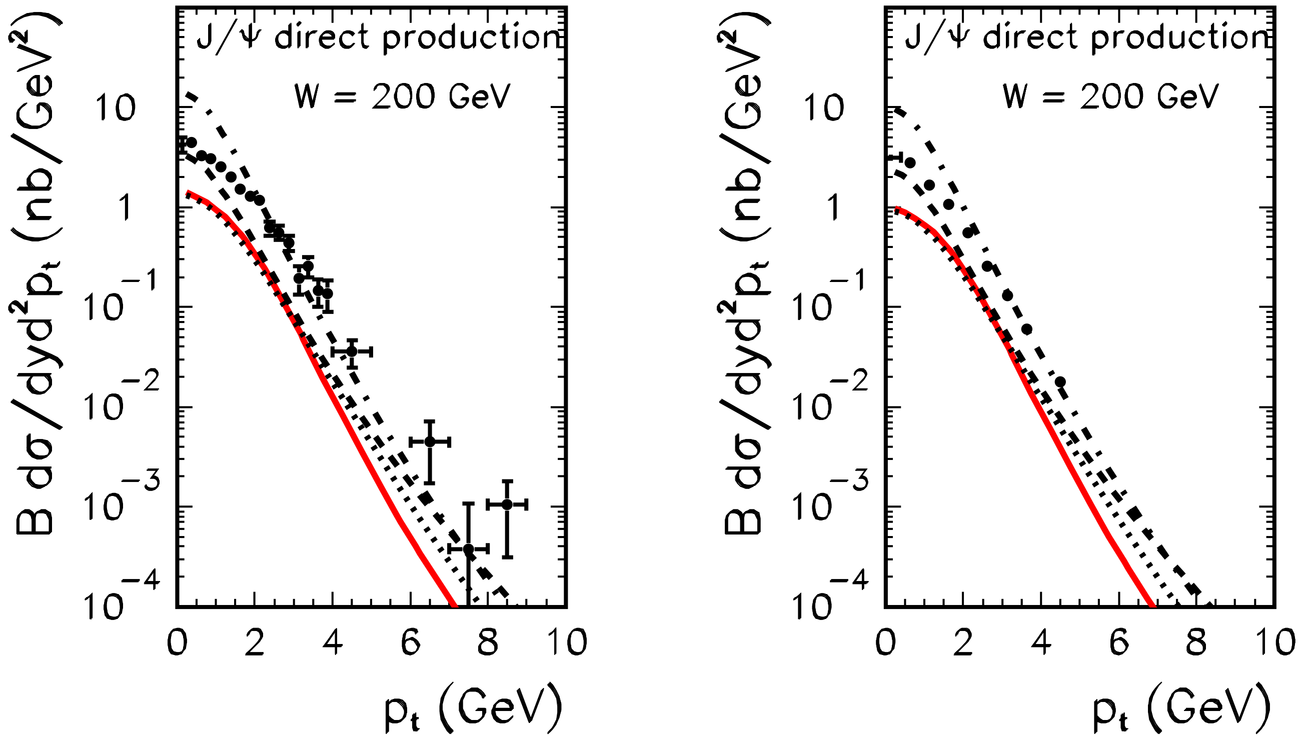
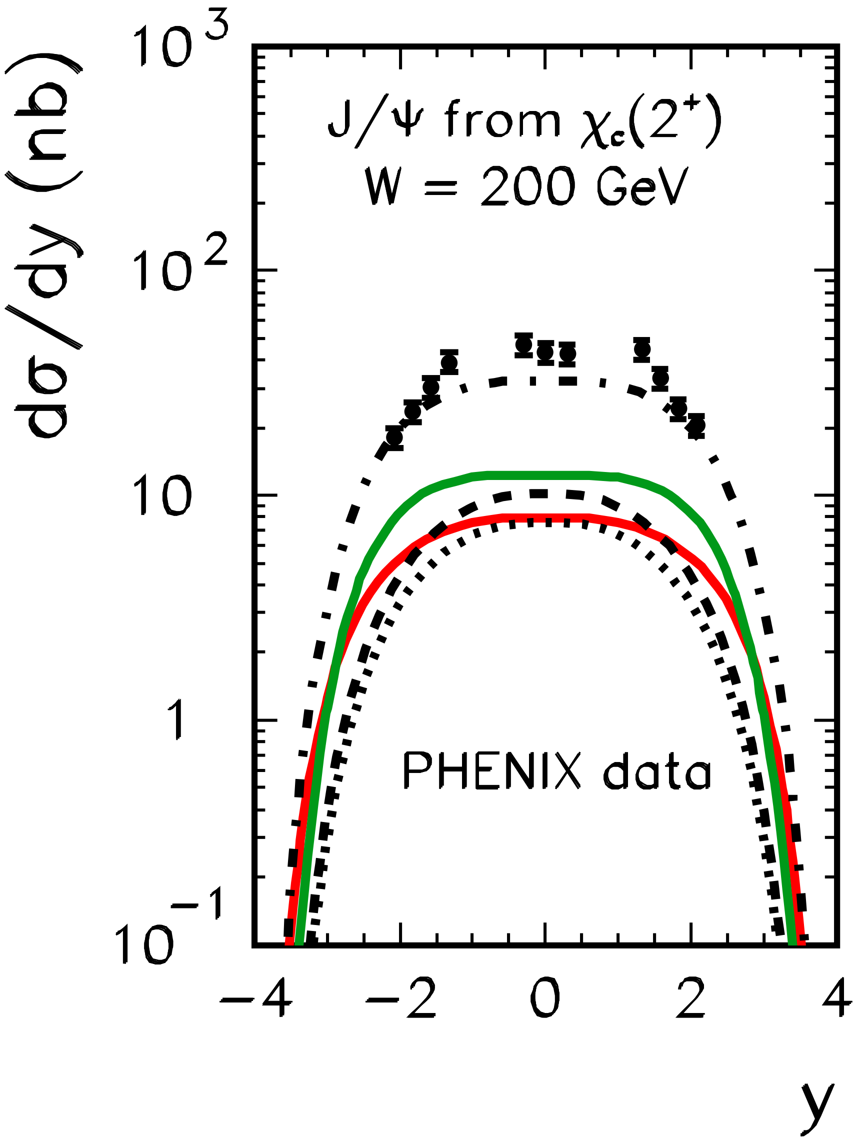


Figure 6: (a) -0.35 $< y <$ 0.35 (left panel),
(b) 1.2 $< |y| <$ 2.2 (right panel).

Direct χ_c meson production



Direct χ_c meson production

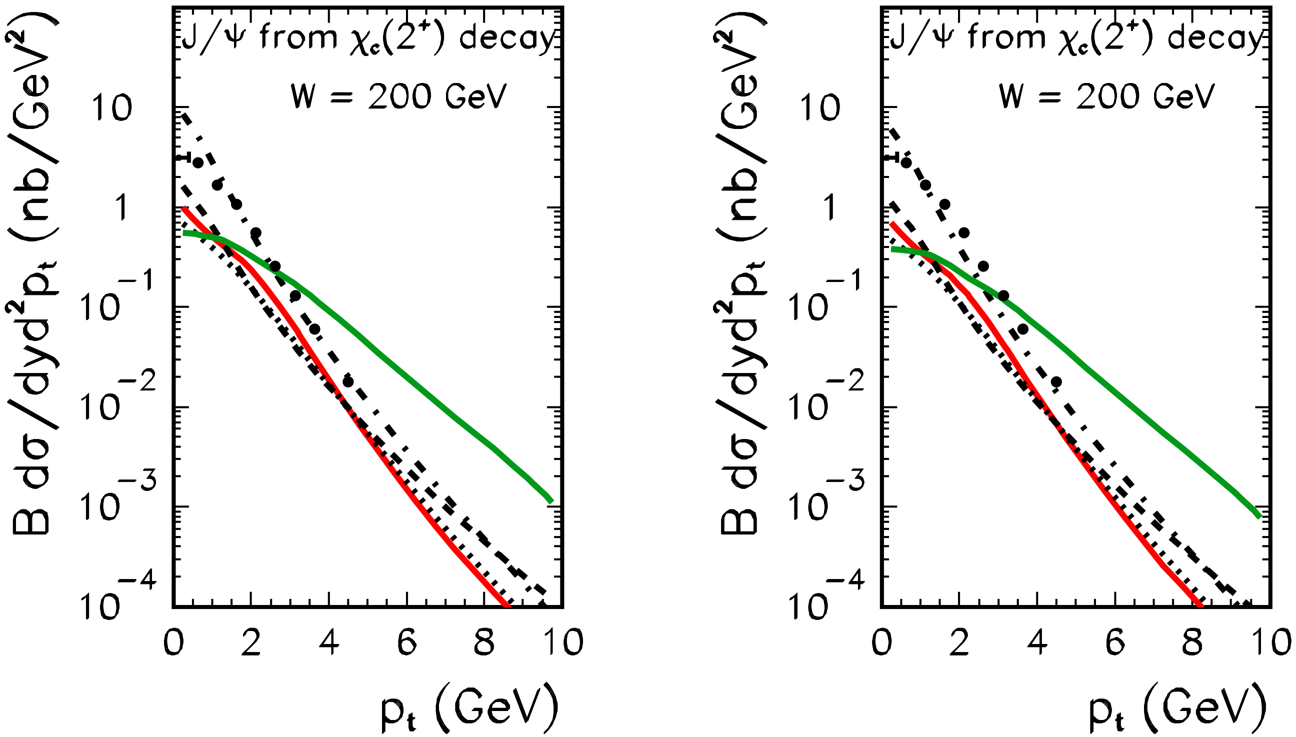
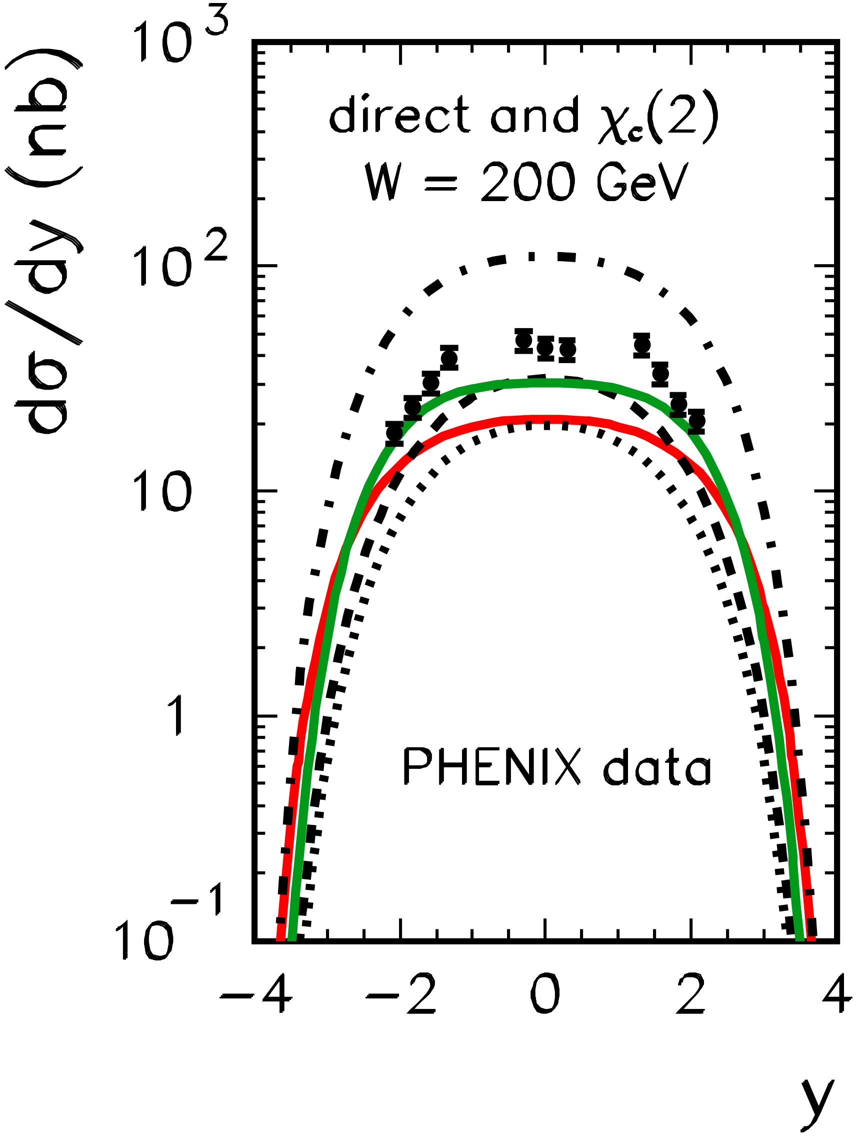


Figure 8: (a) -0.35 $< y <$ 0.35 (left panel),
(b) 1.2 $< |y| <$ 2.2 (right panel).

Sum of dominant mechanisms



Sum of dominant mechanisms

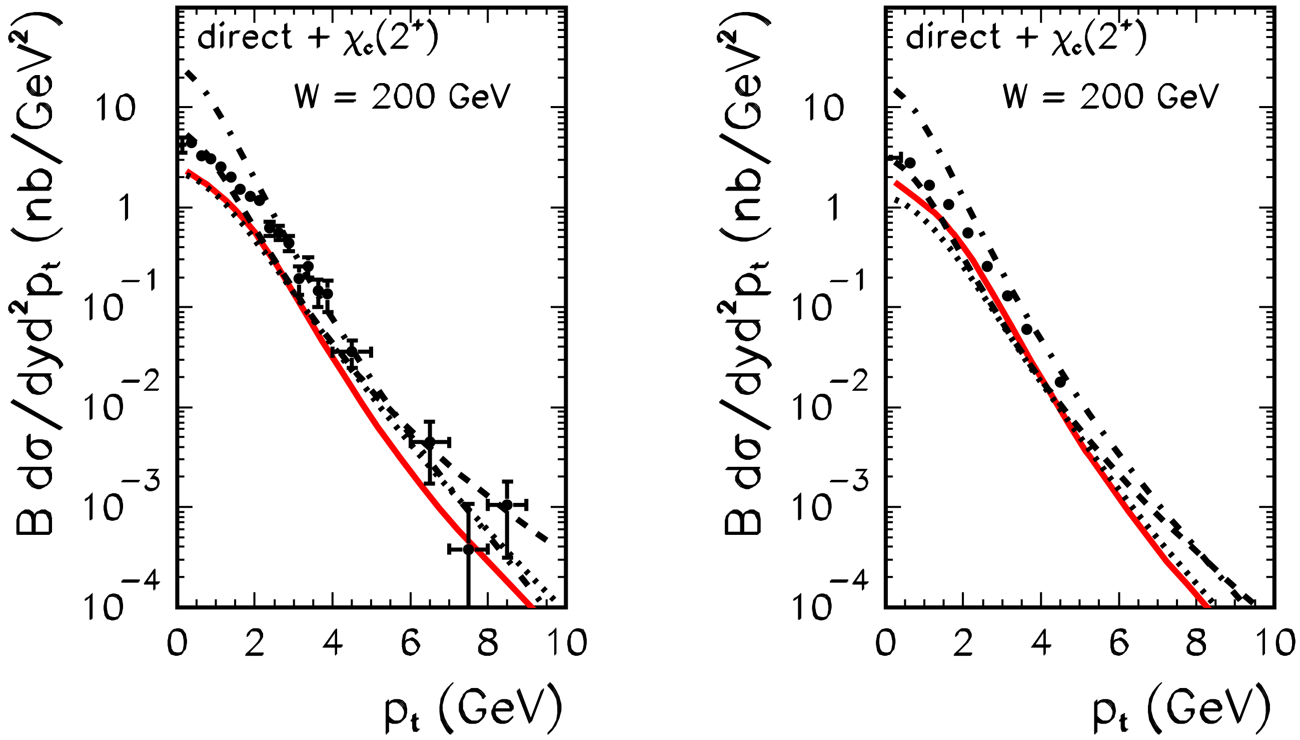


Figure 10: (a) -0.35 $< y <$ 0.35 (left panel),
(b) 1.2 $< |y| <$ 2.2 (right panel).

Kwiecinski UGDF

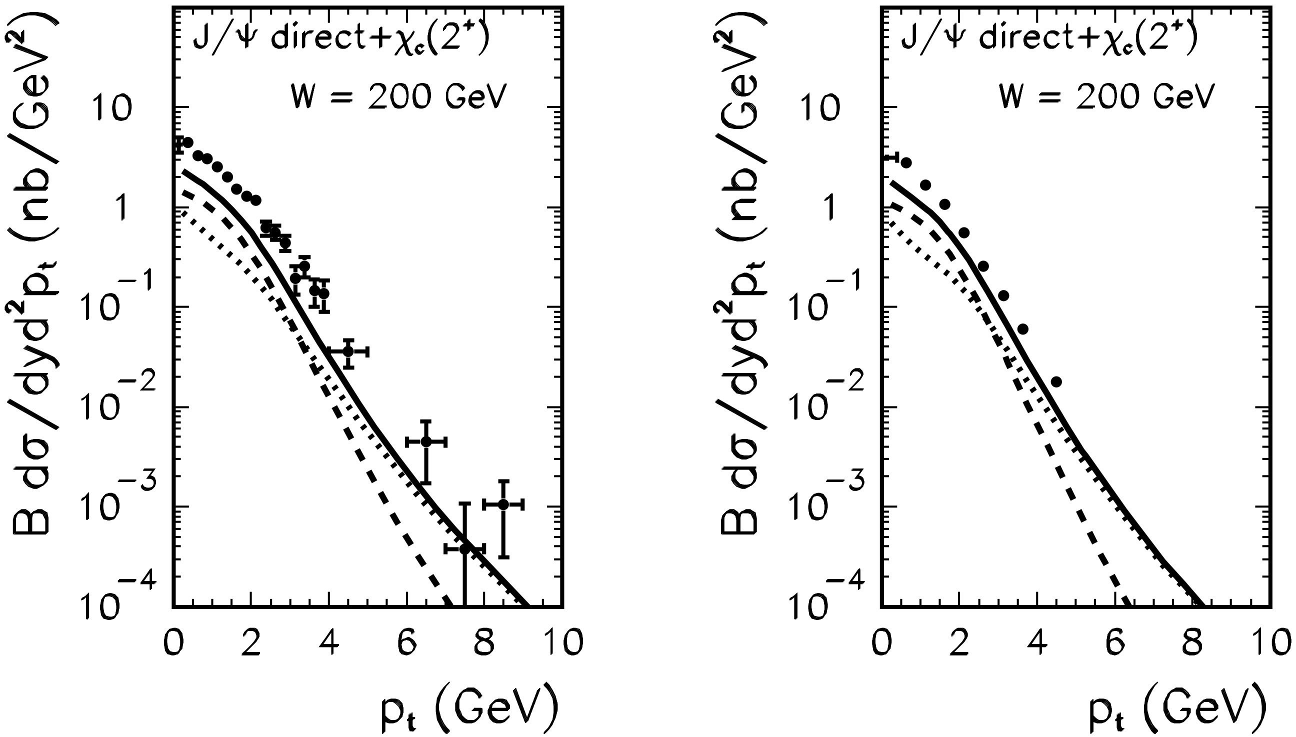


Figure 11: Kwieciński UGDF with running scale.

(a) (-0.35 $< y <$ 0.35)

(b) (1.2 $< y <$ 2.2).

direct – dashed line, $\chi_c(2^+)$-decay – dotted line and the sum

Kwiecinski UGDF

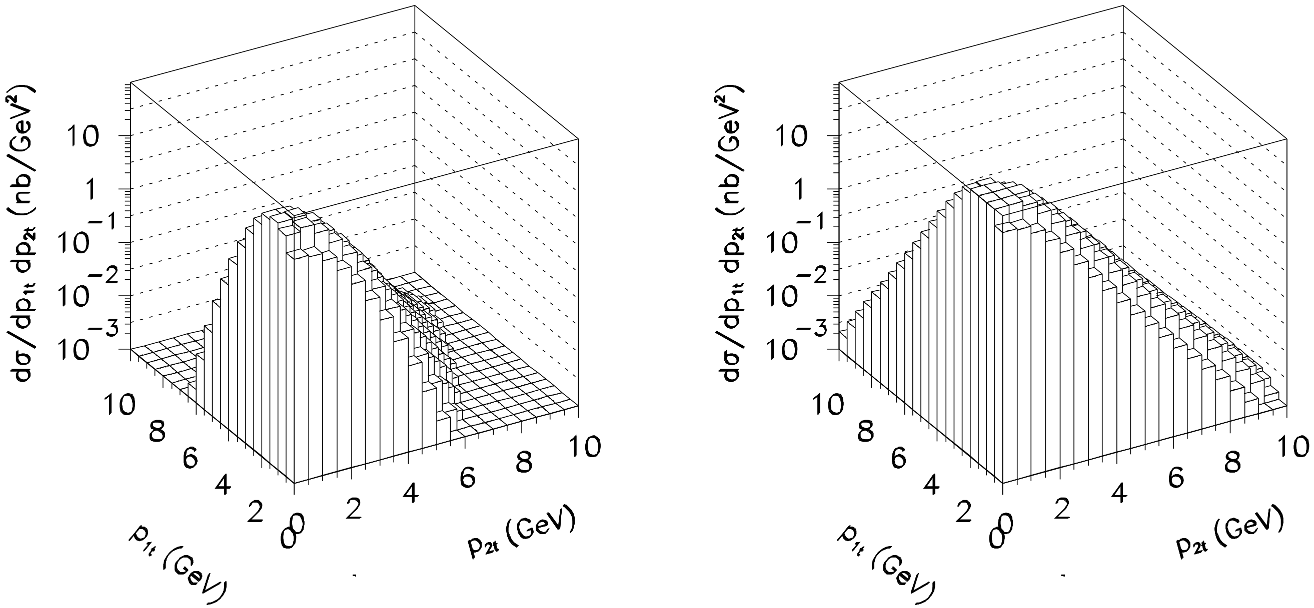
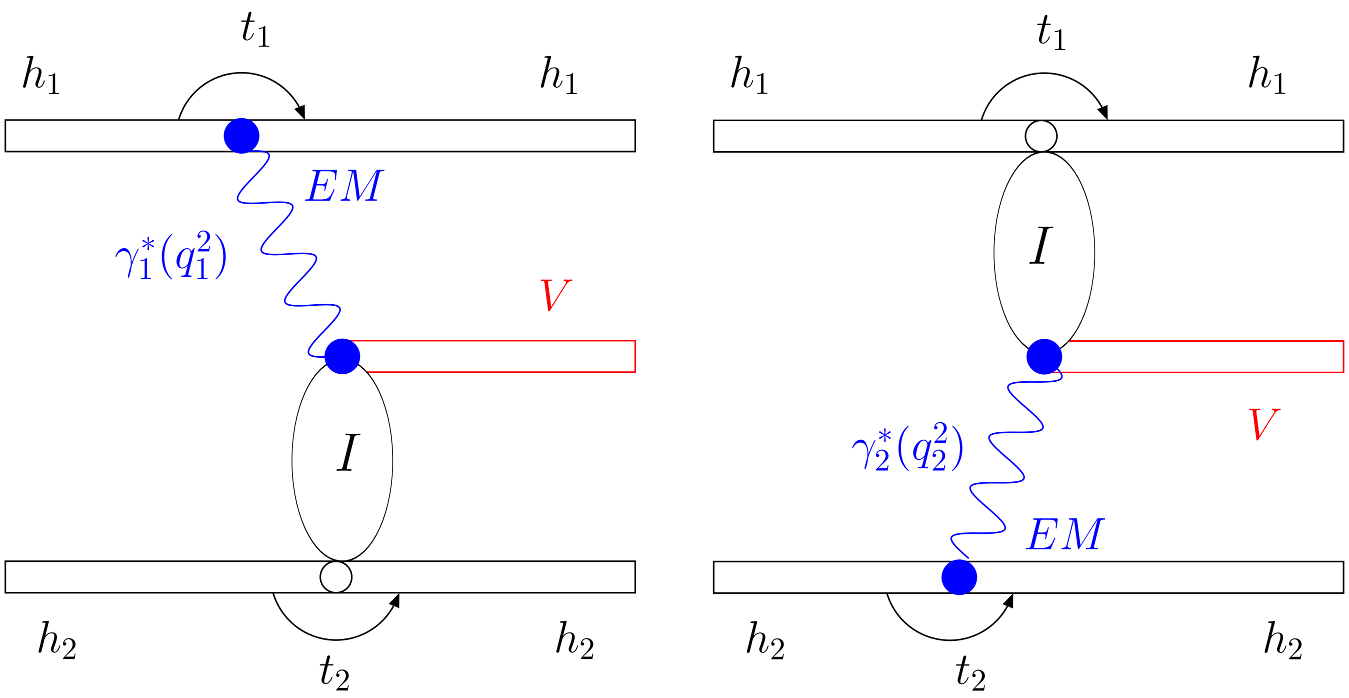


Figure 12: $p_{J/\psi,t} \times p_{g,t}$.

left panel: μ^2 = 10 GeV^2

right panel: μ^2 = 100 GeV^2.

Exclusive photoproduction of J/ψ



Schäfer, Szczurek

Exclusive photoproduction of J/ψ

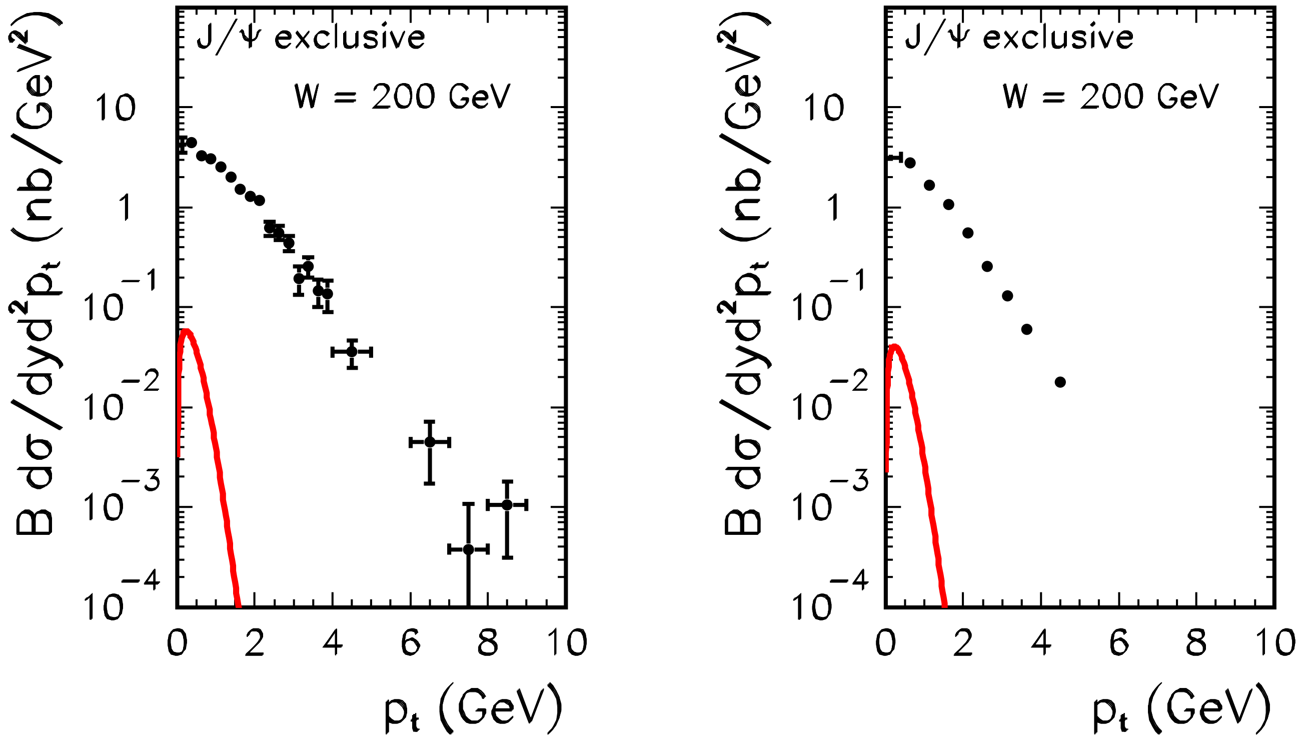
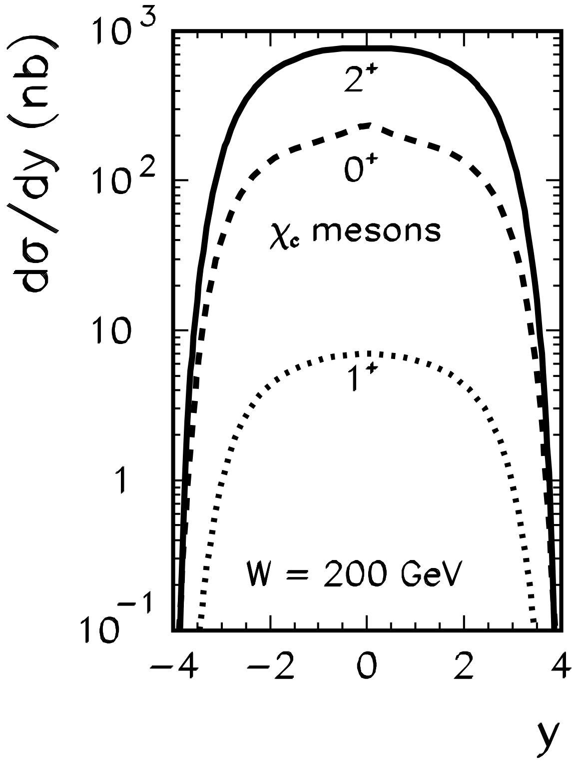


Figure 13: left panel for (-0.35 $< y <$ 0.35) right panel for (1.2 $< y <$ 2.2).

Predictions for χ_c production



BR($\chi_c(0^+) \to \pi^+\pi^-$) = (7.5 $\pm$ 2.1) $\times$ 10^{-3},
BR($\chi_c(0^+) \to K^+K^-$) = (7.1 $\pm$ 2.4) $\times 10^{-3}$,
BR($\chi_c(2^+) \to \pi^+\pi^-$) = (1.9 $\pm$ 1.0) $\times 10^{-3}$,
BR($\chi_c(2^+) \to K^+K^-$) = (1.5 $\pm$ 1.1) $\times 10^{-3}$.

Summary/Conclusions

- The distributions of J/ψ in y and p_t were calculated in the k_t-factorization approach.
- Different UGDFs were used. The results depend on UGDFs.
- The contributions from direct color-singlet and radiative $\chi_c(2^+)$ decays dominate the inclusive cross section.
- There is no much room for color-octet contribution.
- The analysis of kinematical correlations of J/ψ - jet was proposed.