Diffractive production of $\chi_c(\mathbf{0}^+)$ (in pp and $p\bar{p}$ collisions)

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Our recent works

Recently we have calculated differential cross sections in:

- $pp \to pp\eta'$
- $pp \to ppJ/\psi$ Wolfgang Schäfer
- $pp \to pp\chi_c(0)$ this talk

based on:

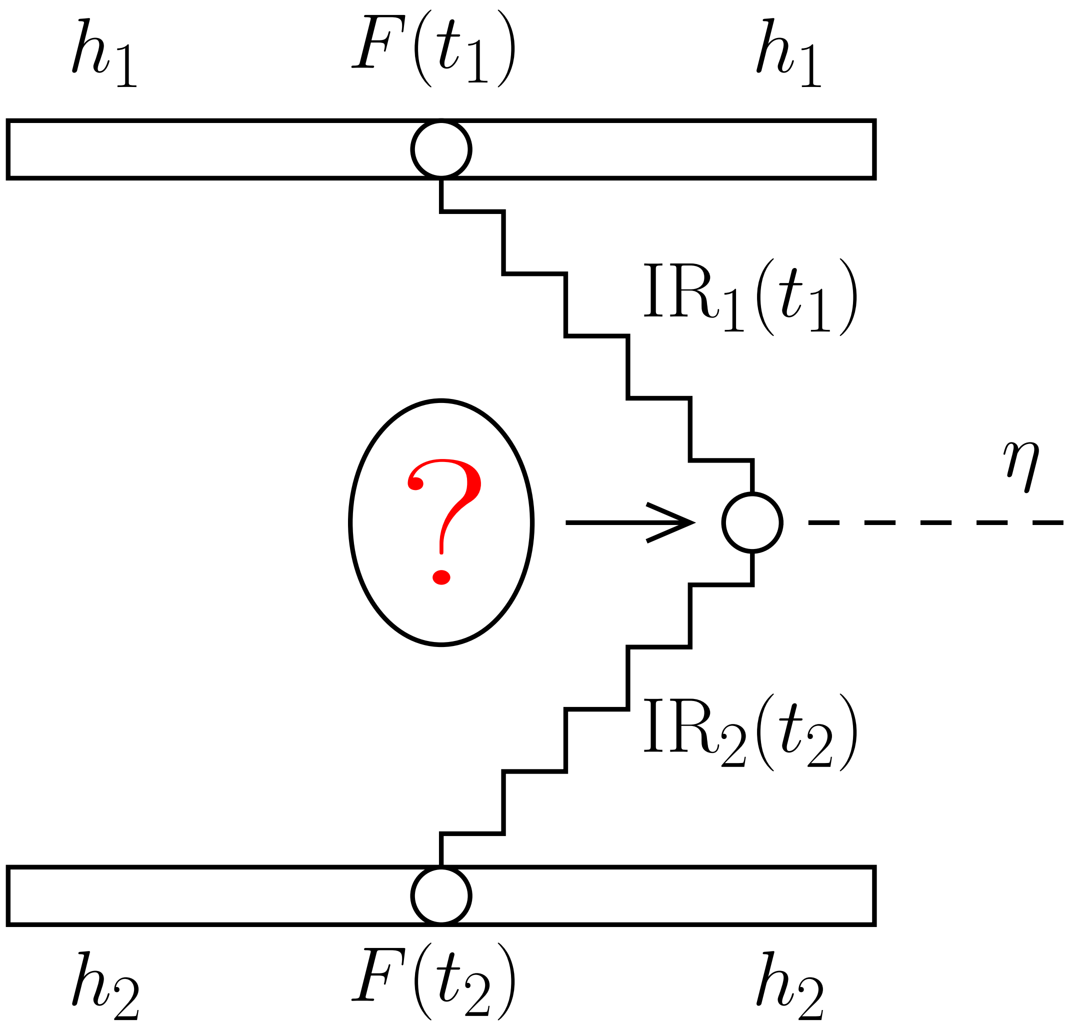
- A. Szczurek, R. Pasechnik and O. Teryaev, hep-ph/0608302, Phys. Rev. **D75**, 054021 (2007)
- W. Schäfer and A. Szczurek, Arxiv:0705.2887, in print in Phys. Rev. **D**
- R. Pasechnik, A. Szczurek and O. Teryaev, Arxiv:0709.0857

Introduction

Exclusive reaction: $pp \to pXp$ ($X = \eta', \eta_c, \eta_b, \chi_c, \chi_b$).
At high energy - one of many open channels (!)
$\to$ rapidity gaps.

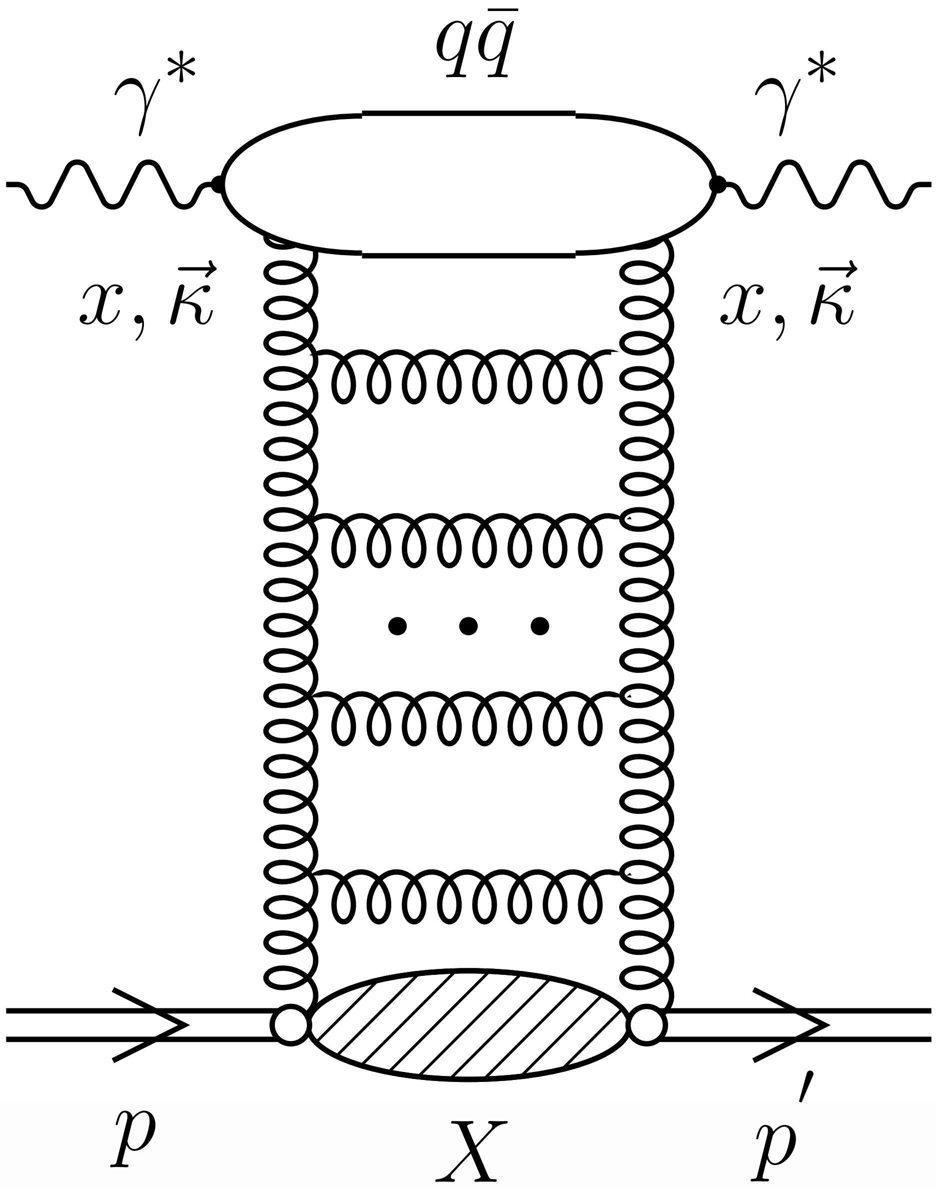
- (a) Search for Higgs primary task for LHC.
  Diffractive production of the Higgs an alternative to inclusive production (background reduction).
  A new QCD mechanism proposed recently by Khoze-Martin-Ryskin.
  Not possible to measure Higgs at present.
  Replace Higgs by a meson (scalar, pseudoscalar)
- (b) The mechanism of the exclusive production of mesons at high energy is not well known in detail.
- (c) Possibility to study differential distributions.

pre-QCD mechanism

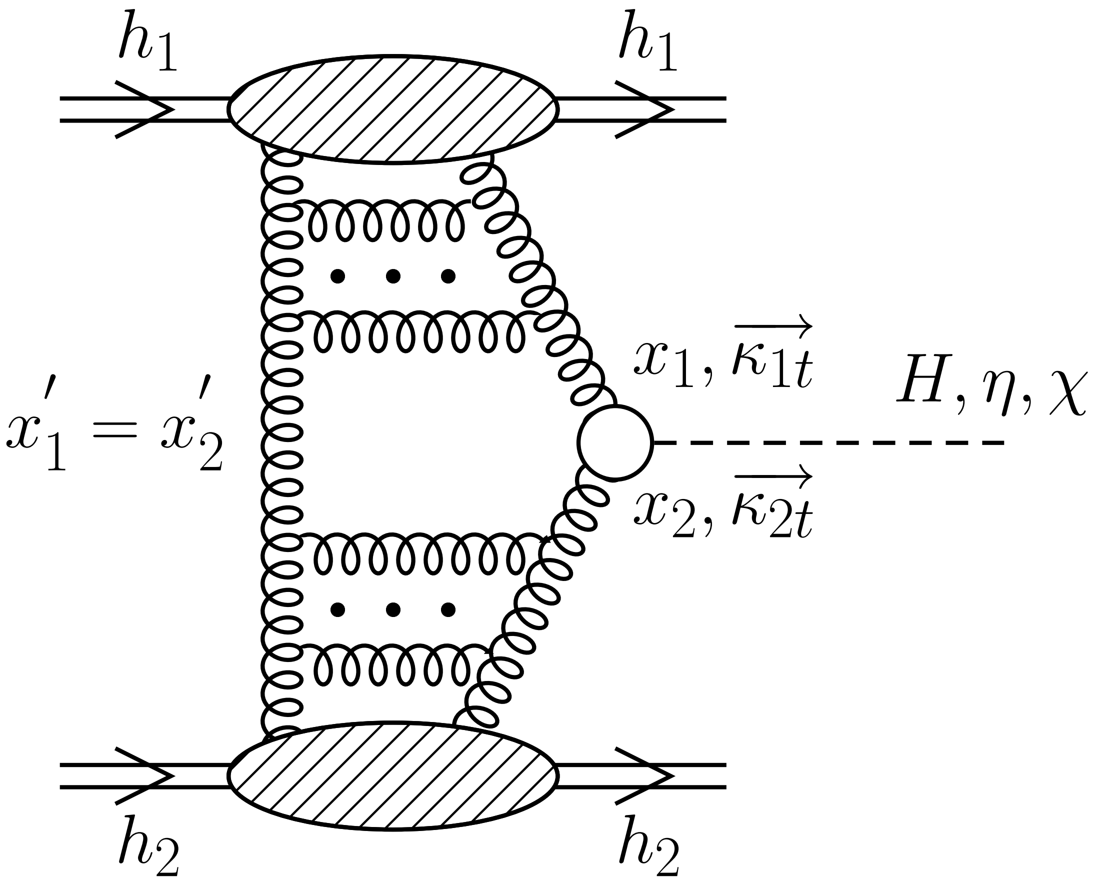


QCD motivation

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

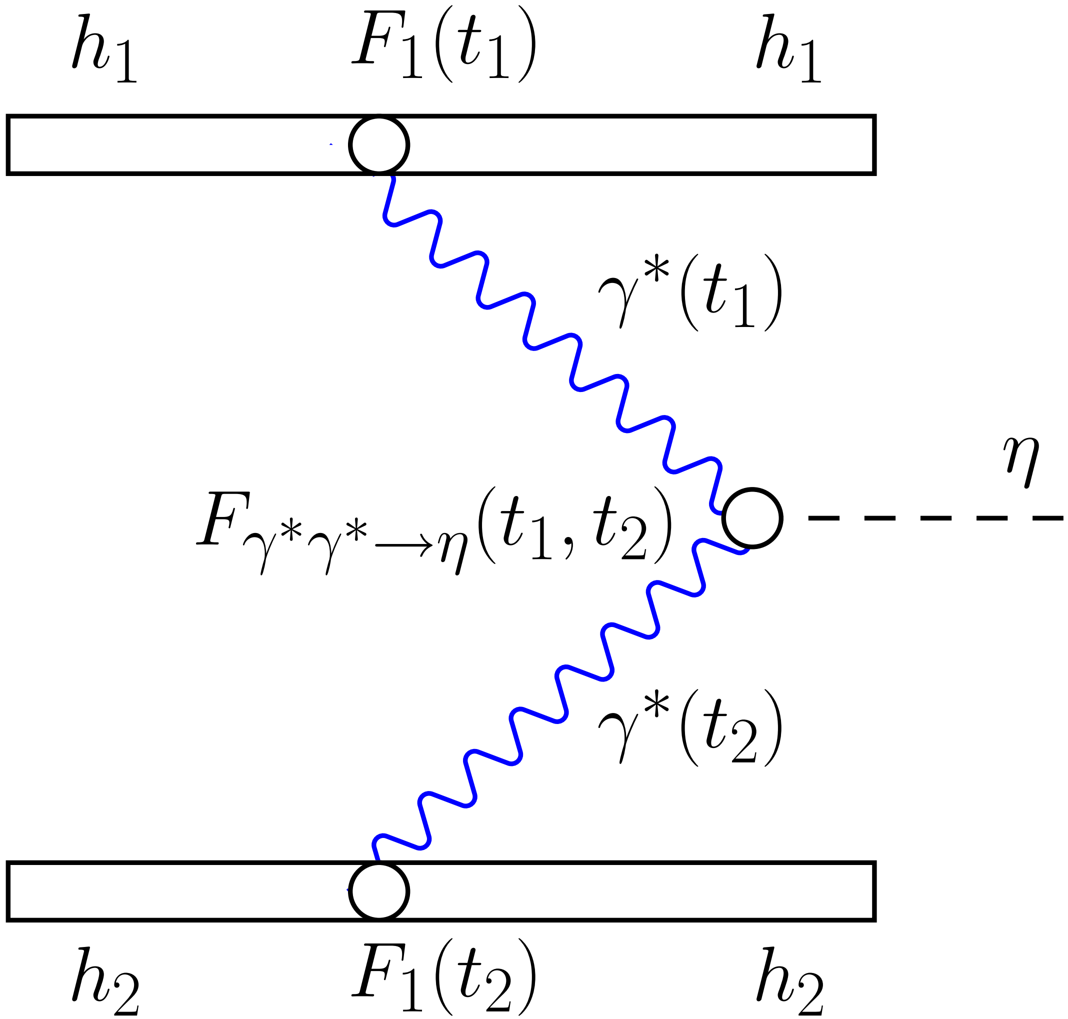


QCD mechanism



Asymmetry initial-final state.

QED mechanism



QCD mechanism

Khoze-Martin-Ryskin (Higgs production) (scalar $\to$ pseudoscalar)

$$\mathcal{M}^{g^* g^* \to \eta'}_{pp \to p\eta' p} = i\,\pi^2\, s \int d^2 k_{0,t} \quad V(k_1, k_2, P_M) \tag{1}$$

$$\frac{f_g^{off}(x_1, x_1', k_{0,t}^2, k_{1,t}^2, t_1) \quad f_g^{off}(x_2, x_2', k_{0,t}^2, k_{2,t}^2, t_2)}{k_{0,t}^2\, k_{1,t}^2\, k_{2,t}^2}\,. \tag{2}$$

$f_g^{off}(\ldots)$ – off-diagonal gluon unintegrated distributions

Off-diagonal unintegrated gluon distributions – ?

$$f_g^{off}(x_1, x_1', k_{0,t}^2, k_{1,t}^2, t_1) = \sqrt{f_g^{(1)}(x_1', k_{0,t}^2) \cdot f_g^{(1)}(x_1, k_{1,t}^2)} \cdot F_1(t_1) \tag{3}$$

$$f_g^{off}(x_2, x_2', k_{0,t}^2, k_{2,t}^2, t_2) = \sqrt{f_g^{(2)}(x_2', k_{0,t}^2) \cdot f_g^{(2)}(x_2, k_{2,t}^2)} \cdot F_1(t_2) \tag{4}$$

QCD formalism

$$\mathcal{M}^{g^* g^*} = \frac{s}{2} \cdot \pi^2 \frac{1}{2} \frac{\delta_{c_1 c_2}}{N_c^2 - 1} \int d^2 q_{0,t} V_J^{c_1 c_2} \frac{f_{g,1}^{off}(x_1, x_1', q_{0,t}^2, q_{1,t}^2, t_1) f_{g,2}^{off}(x_2, x_2', q_{0,t}^2, q_{2,t}^2, t_2)}{q_{0,t}^2 \, q_{1,t}^2 \, q_{2,t}^2} . \tag{5}$$

$$V_J^{c_1 c_2} = \mathcal{P}(q\bar{q} \to \chi_{cJ}) \bullet \Psi_{ik}^{c_1 c_2}(k_1, k_2) \; , \tag{6}$$

$$V_{J,\,\mu\nu}^{c_1 c_2}(q_1, q_2) = \mathcal{P}(q\bar{q} \to \chi_{cJ}) \bullet \Psi_{ik,\,\mu\nu}^{c_1 c_2}(k_1, k_2) =$$

$$2\pi \cdot \sum_{i,k} \sum_{L_z, S_z} \frac{1}{\sqrt{m}} \int \frac{d^4 q}{(2\pi)^4} \delta\left(q^0 - \frac{\mathbf{q}^2}{M} \right) \times$$

$$\times \Phi_{L=1, L_z}(\mathbf{q}) \cdot \langle L = 1, L_z; S = 1, S_z | J, J_z \rangle \, \langle 3i, \bar{3}k | 1 \rangle$$

$$\mathrm{Tr} \left\{ \Psi_{ik,\,\mu\nu}^{c_1 c_2} \mathcal{P}_{S=1, S_z} \right\} ,$$

QCD formalism

$$\Psi^{c_1,c_2}_{i,k}(k_1,k_2) \quad = \quad -g^2\left(t^{c_1}_{ij}t^{c_2}_{jk}b(k_1,k_2) - t^{c_2}_{kj}t^{c_1}_{ji}\bar{b}(k_2,k_1)\right) \qquad (10)$$

$$b(k_1,k_2) = \gamma^- \frac{\hat{q}_1 - \hat{k}_1 - m}{(q_1-k_1)^2 - m^2}\gamma^+ - \frac{\gamma_\beta \Gamma^{+-\beta}(q_2,q_1)}{(k_1+k_2)^2}\,, \qquad (11)$$

$$\bar{b}(k_1,k_2) = \gamma^+ \frac{\hat{q}_1 - \hat{k}_1 + m}{(q_1-k_1)^2 - m^2}\gamma^- - \frac{\gamma_\beta \Gamma^{+-\beta}(q_2,q_1)}{(k_1+k_2)^2}\,. \qquad (12)$$

$$\mathcal{P}_{S=1,S_z} = \frac{1}{2m}(\hat{k}_2 - m)\frac{\hat{\epsilon}(S_z)}{\sqrt{2}}(\hat{k}_1 + m)\,. \qquad (13)$$

$$\int \frac{d^3\mathbf{q}}{(2\pi)^3} q^\sigma \Phi_{L=1,L_z}(\mathbf{q}) = -i\sqrt{\frac{3}{4\pi}}\epsilon^\sigma(L_z)\mathcal{R}'(0), \qquad (14)$$

QCD formalism

Our vertex (off-shell)

$$V_{J=0}^{c_1 c_2}(q_1, q_2) = 8ig^2 \frac{\delta^{c_1 c_2}}{M} \frac{\mathcal{R}'(0)}{\sqrt{\pi M N_c}} \frac{3M^2(q_{1,t}q_{2,t}) + 2q_{1,t}^2 q_{2,t}^2 - (q_{1,t}q_{2,t})(q_{1,t}^2 + q_{2,t}^2)}{(M^2 - q_{1,t}^2 - q_{2,t}^2)^2}. \quad (19)$$

KMR vertex (on-shell)

$$V_{J=0}^{c_1 c_2}[M \gg q_{1,t},\, q_{2,t}] \simeq 8ig^2 \delta^{c_1 c_2} \frac{\mathcal{R}'(0)}{M^3} \frac{1}{\sqrt{\pi M N_c}} \left\{ 3(q_{1,t}q_{2,t}) \right\} =$$

$$= i\delta^{c_1 c_2} \cdot 8g^2 \sqrt{\frac{3}{\pi M}} \frac{\mathcal{R}'(0)}{M^3} \cdot (q_{1,t}q_{2,t}). \quad (20)$$

Phase space and kinematics (part 1)

$$d\sigma = \frac{1}{2s}\overline{|\mathcal{M}|^2} \cdot d^3PS\,. \qquad (21)$$

$$d^3PS = \frac{d^3p_1'}{2E_1'(2\pi)^3}\frac{d^3p_2'}{2E_2'(2\pi)^3}\frac{d^3P_M}{2E_M(2\pi)^3} \cdot (2\pi)^4\delta^4(p_1 + p_2 - p_1' - p_2' - P$$

$$d^3PS = \frac{1}{2^8\pi^4}dt_1dt_2d\xi_1d\xi_2d\Phi\;\delta\left(s(1-\xi_1)(1-\xi_2) - m_{\eta'}^2\right)\;, \qquad (23)$$

$$d^3PS = \frac{1}{2^8\pi^4}dt_1dt_2\frac{dx_F}{s\sqrt{x_F^2 + 4(m_{\eta'}^2 + |\mathbf{P}_{M,t}|^2)/s}}\,d\Phi \qquad (24)$$

Phase space and kinematics (part 2)

$$x_F \to 0 \;\; then \;\; J \approx \frac{1}{\sqrt{x_F^2 + 4m_{\eta'}^2/s}} \to \frac{\sqrt{s}}{2m_{\eta'}} \tag{25}$$

$$d^3PS = \frac{1}{2^8 \pi^4 \, s} dt_1 dt_2 dy d\Phi \, . \tag{26}$$

$$\xi_{1,2} \approx 1 - \frac{1}{2}\sqrt{x_F^2 + \frac{4m_{\eta'}^2}{s}} \mp \frac{x_F}{2} \, . \tag{27}$$

$$\xi_{1,2} \approx 1 - \frac{m_{\eta'}}{\sqrt{s}} \exp(\pm y) \, . \tag{28}$$

$$t_{1,2} = -\frac{p_{1/2,t}'^2}{\xi_{1,2}} - \frac{(1-\xi_{1,2})^2 m_p^2}{\xi_{1,2}} \, . \tag{29}$$

Unintegrated gluon distributions (part 1)

Gaussian smearing

$$\mathcal{F}_{naive}(x,\kappa^2,\mu_F^2) = x g^{coll}(x,\mu_F^2) \cdot f_{Gauss}(\kappa^2) \; , \qquad (31)$$

$$f_{Gauss}(\kappa^2) = \frac{1}{2\pi\sigma_0^2} \exp\left(-\kappa_t^2/2\sigma_0^2\right)/\pi \; . \qquad (32)$$

BFKL UGDF

$$-x\frac{\partial f(x,q_t^2)}{\partial x} = \frac{\alpha_s N_c}{\pi} q_t^2 \int_0^\infty \frac{dq_{1t}^2}{q_{1t}^2}\left[\frac{f(x,q_{1t}^2)-f(x,q_t^2)}{|q_t^2-q_{1t}^2|} + \frac{f(x,q_t^2)}{\sqrt{q_t^4+4q_{1t}^4}}\right] \qquad (33)$$

Unintegrated gluon distributions (part 2)

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

$$\alpha_s \mathcal{F}(x,\kappa_t^2) = \frac{3\sigma_0}{4\pi^2} R_0^2(x) \kappa_t^2 \exp(-R_0^2(x)\kappa_t^2) \ , \tag{34}$$

$$R_0(x) = \left(\frac{x}{x_0}\right)^{\lambda/2} \frac{1}{GeV} \ . \tag{35}$$

Parameters adjusted to HERA data for F_2.

Kharzeev-Levin gluon saturation

$$\mathcal{F}(x,\kappa^2) = \begin{cases} f_0 & \text{if } \kappa^2 < Q_s^2, \\ f_0 \cdot \frac{Q_s^2}{\kappa^2} & \text{if } \kappa^2 > Q_s^2. \end{cases} \tag{36}$$

f_0 adjusted by Szczurek to HERA data for F_2.

KMR UGDF

$$f_g^{KMR}(x,x',Q_t^2,\mu^2;t) = f_g^{KMR}(x,x',Q_t^2,\mu^2)\exp(b_0 t) \quad (37)$$

$$f_g^{KMR}(x,x',Q_t^2,\mu^2) = R_g \frac{\partial}{\partial \ln Q_t^2}\left[\sqrt{T(Q_t^2,\mu^2)}xg(x,Q_t^2)\right] . \quad (38)$$

$$T(Q_t^2,\mu^2) = \exp\left(-\int_{Q_t^2}^{\mu^2}\frac{\alpha_s(k_t^2)}{2\pi}\frac{dk_t^2}{k_t^2}\int_0^{1-\Delta}[zP_{gg}(z)+\sum_q P_{qg}(z)]dz\right) ; \quad (39)$$

KMR UGDF

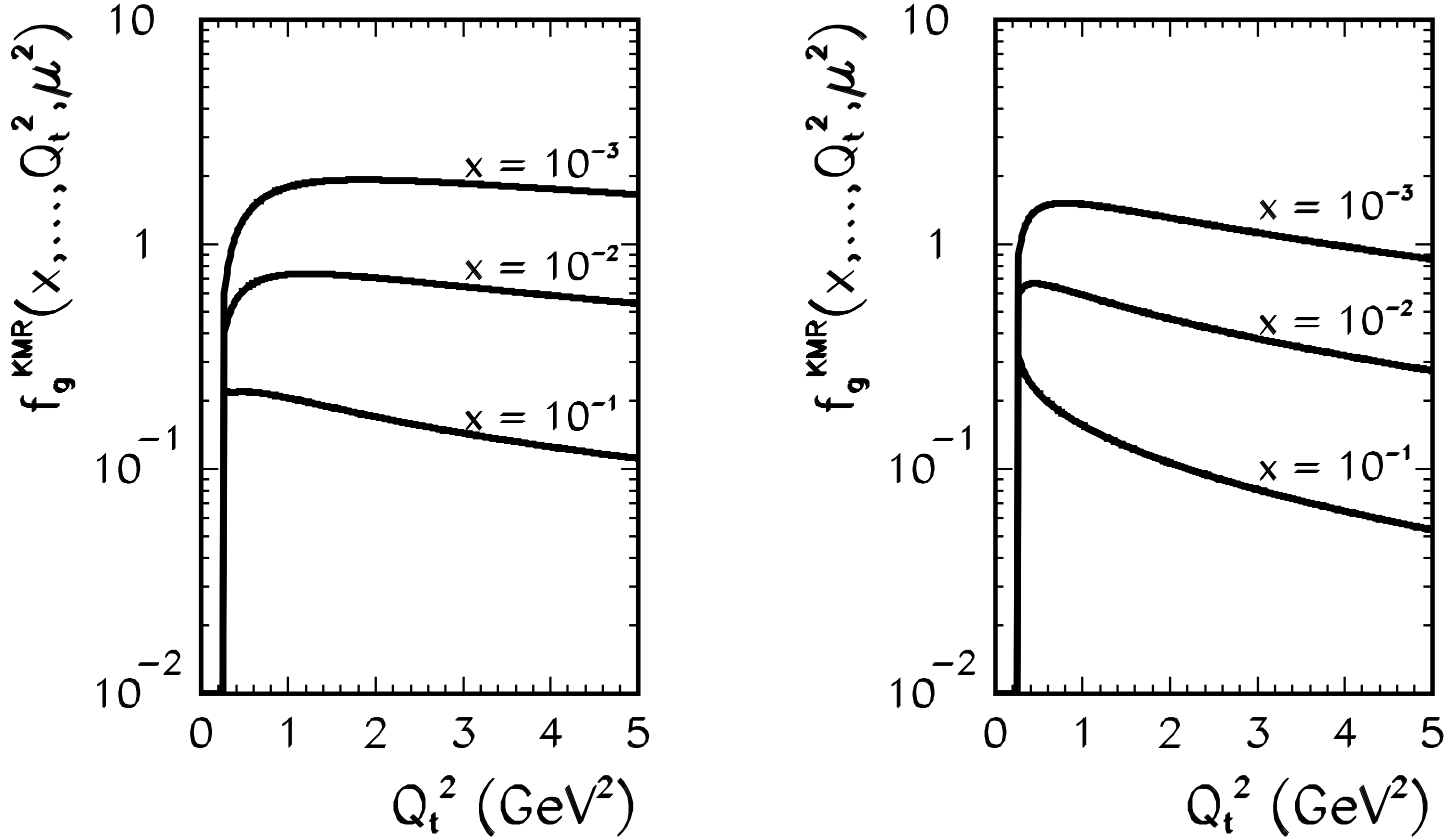


Figure 1: $\mu^2 = M_\chi^2$ (left panel) and $\mu^2 = (M_\chi/2)^2$ (right panel).

Photon-photon fusion

$$\mathcal{M}_{\lambda_1,\lambda_2,\lambda'_1,\lambda'_2} = \pm e^2 \{\overline{u}(p'_1,\lambda'_1)[F_1(t_1)\gamma^{\nu} \pm i\frac{\sigma^{\nu\nu''}}{2m_N} q_{1,\nu''} F_2(t_1)] u(p_1,\lambda_1)\} \frac{g_{\nu\nu'}}{t_1} V^{\gamma^*\gamma^*\to\chi_{cJ}}_{\mu'\nu'}(q_1,q_2) \frac{g_{\mu\mu'}}{t_2} \{\overline{u}(p'_2,\lambda'_2)[F_1(t_2)\gamma^{\mu} \pm i\frac{\sigma^{\mu\mu''}}{2m_N} q_{1,\mu''} F_2(t_2)] u(p_2,\lambda_2)\} \quad (40)$$

After some algebra:

$$\mathcal{M}^{\gamma^*\gamma^*} \approx -i\, 4s \left(\frac{4e^2}{3}\right)^2 \frac{\mathcal{R}'(0)}{M} \sqrt{\frac{N_c}{\pi M}} \frac{F_1(t_1)}{t_1} \frac{F_1(t_2)}{t_2} \frac{3M^2(q_{1,t}q_{2,t}) + 2t_1t_2 - (q_{1,t}q_{2,t})(t_1+t_2)}{(M^2-t_1-t_2)^2}, \quad (41)$$

Equivalent Photon Approximation

$$\sigma = \int dz_1 dz_2 \left(\frac{dn}{dz_1}(z_1) \frac{dn}{dz_2}(z_2) \sigma(\gamma\gamma \to \chi_c(0)) \right) . \tag{42}$$

$$\sigma(\gamma\gamma \to \chi_c(0)) \approx \frac{4\pi^2}{M_R^2} \Gamma_{\chi_c(0)\to\gamma\gamma} \delta(M - M_R) . \tag{43}$$

$$\begin{aligned} x_F &= z_1 - z_2 \\ M &= \sqrt{s z_1 z_2} . \end{aligned} \tag{44}$$

Equivalent Photon Approximation

$$\frac{d\sigma}{dx_F dM} = \frac{2M}{s(z_1+z_2)} \frac{dn}{dz_1}(z_1) \frac{dn}{dz_2}(z_2) \frac{4\pi^2}{M_R^2} \Gamma_{\chi_c(0)\to\gamma\gamma} \delta(M-M_R) \; . \tag{45}$$

$$\frac{d\sigma}{dx_F} = \frac{2M_R}{s(z_1+z_2)} \frac{dn}{dz_1}(z_1) \frac{dn}{dz_2}(z_2) \frac{4\pi^2}{M_R^2} \Gamma_{\chi_c(0)\to\gamma\gamma} \; , \tag{46}$$

where

$$\begin{aligned} z_1 &= \frac{1}{2}x_F + \frac{1}{2}\sqrt{x_F^2 + 4M_R^2/s} \; , \\ z_2 &= -\frac{1}{2}x_F + \frac{1}{2}\sqrt{x_F^2 + 4M_R^2/s} \; . \end{aligned} \tag{47}$$

The analytical flux factors of Drees and Zeppenfeld are taken

Pomeron-Pomeron fusion

$$\mathcal{M}_{pp\to pp\,\chi_{cJ}}^{\mathbb{P}\mathbb{P}\to\chi_{cJ}} \approx A_R(s_1,t_1)(p_1+p_1')^{\nu}\, V_{\mu\nu}^{\mathbb{P}\mathbb{P}\to\chi_{cJ}}(k_1,k_2)\,(p_2+p_2')^{\mu} A_R(s_2,t_2)\ . \tag{48}$$

$A_R(s_{1/2},t_{1/2})$ are so-called Regge propagators.

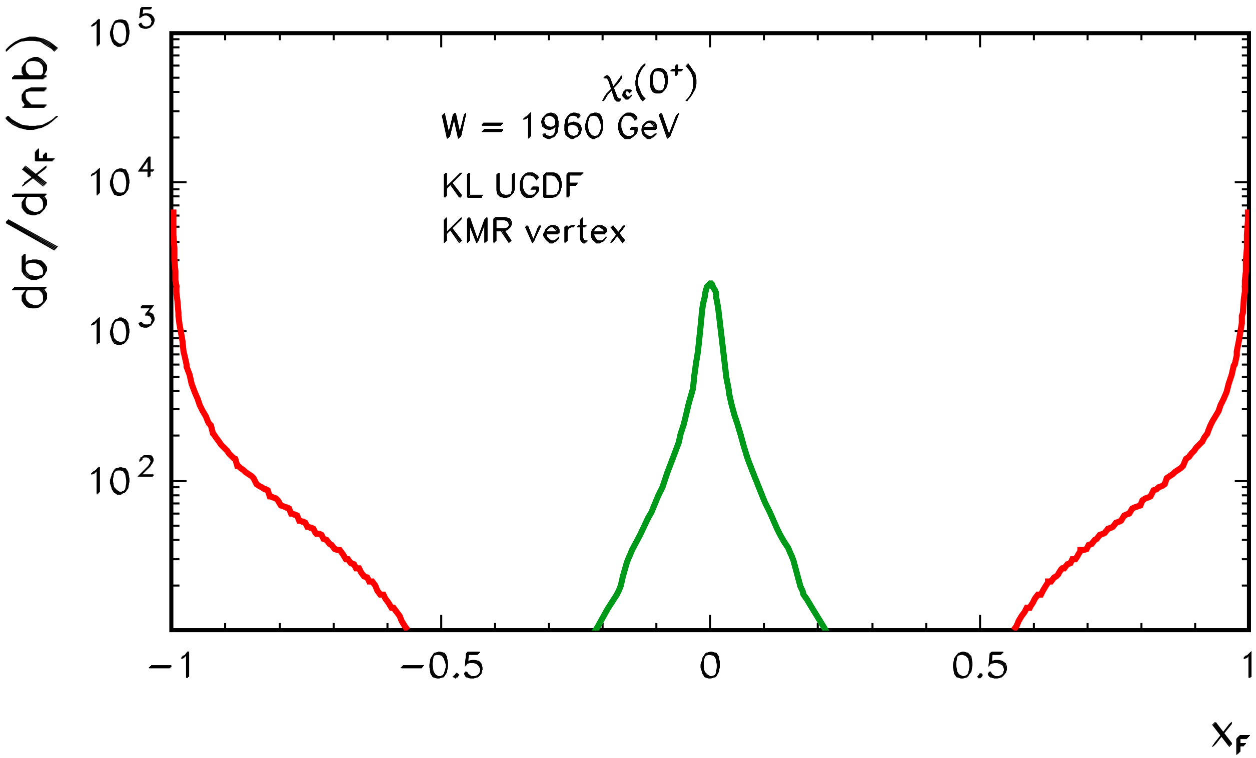
$$A_R(s_{1/2},t_{1/2}) = r_c \frac{C_{\mathbb{P}}}{3}\left(\frac{s_{1/2}}{s_0}\right)^{\delta} F_1^{\mathbb{P}}(t_{1/2})\ . \tag{49}$$

$C_{\mathbb{P}}$ - Donnachie-Landshoff

$F_1^{\mathbb{P}}(t_{1/2})$ describe helicity-preserving coupling of the pomeron to the nucleon. Dirac EM form factors of the proton.

$r_c \sim 0.2$

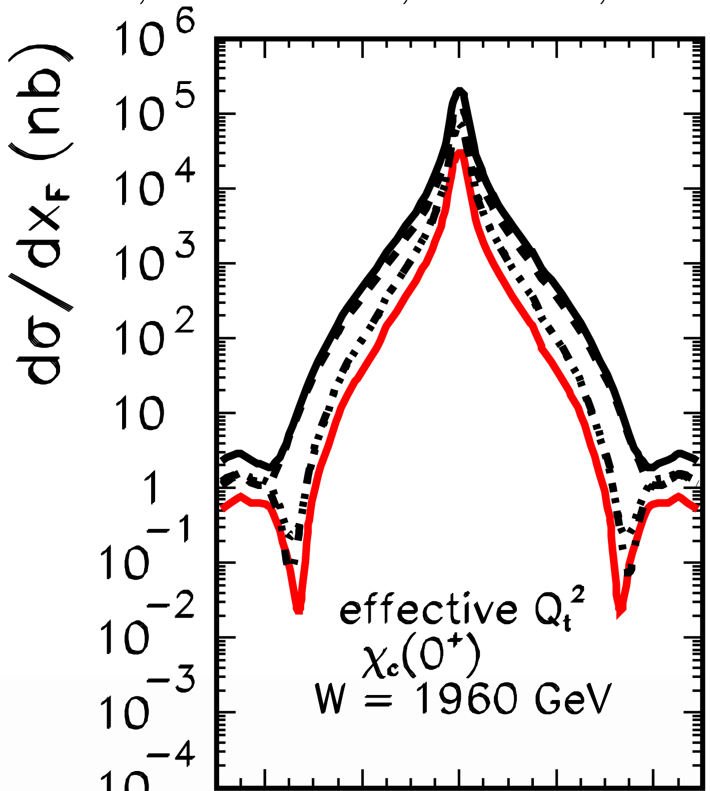
Diffractive production = central production



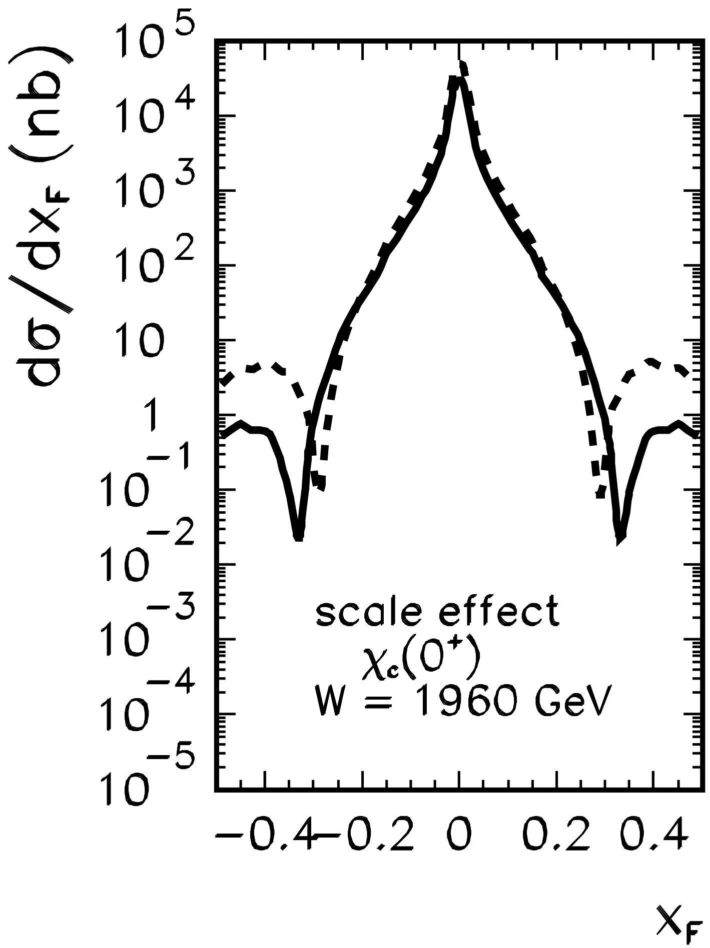
gap in longitudinal momenta between $\chi_c(0)$ and outgoing protons

Uncertainties for KMR UGDFs

- 1) $Q^2_{1,t} = \min(q^2_{0,t}, q^2_{1,t}), \quad Q^2_{2,t} = \min(q^2_{0,t}, q^2_{2,t})$,
- 2) $Q^2_{1,t} = \max(q^2_{0,t}, q^2_{1,t}), \quad Q^2_{2,t} = \max(q^2_{0,t}, q^2_{2,t})$,
- 3) $Q^2_{1,t} = q^2_{1,t}, \quad Q^2_{2,t} = q^2_{2,t}$.
- 4) $Q^2_{1,t} = q^2_{0,t}, \quad Q^2_{2,t} = q^2_{0,t}$,
- 5) $Q^2_{1,t} = (q^2_{0,t} + q^2_{1,t})/2, \quad Q^2_{2,t} = (q^2_{0,t} + q^2_{2,t})/2$.



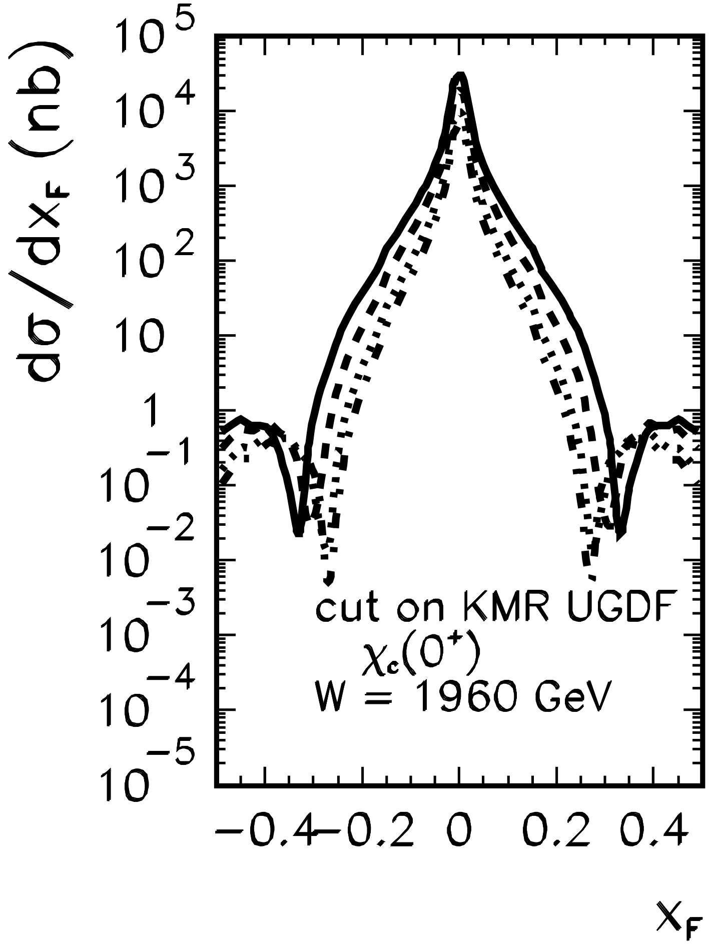
Uncertainties for KMR UGDFs



The solid line: $\mu^2 = M_\chi^2$

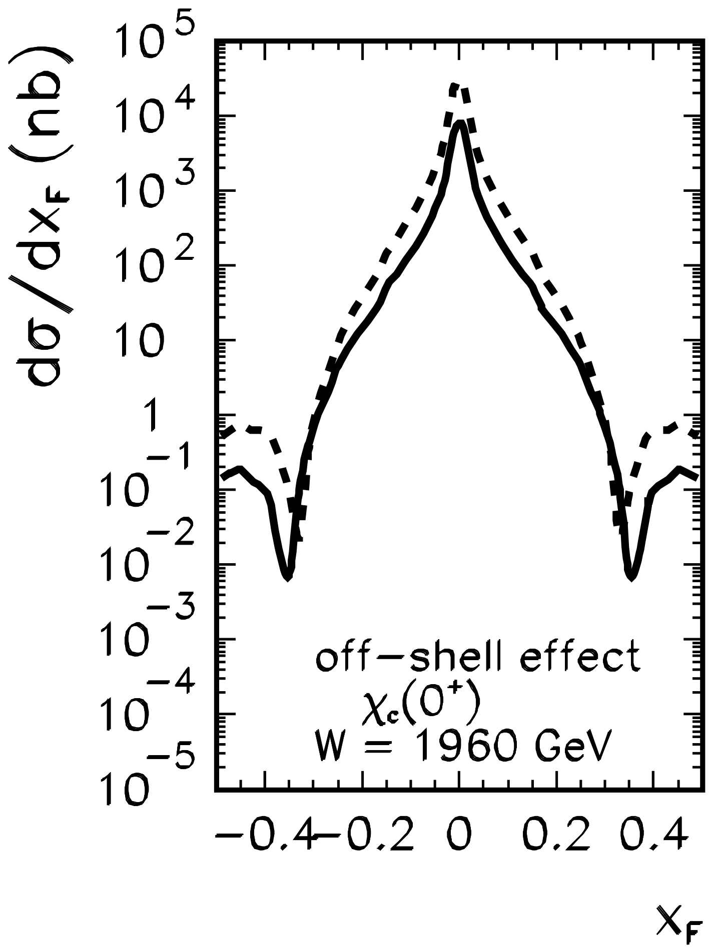
the dashed: $\mu^2 = M_\chi^2/4$.

Uncertainties for KMR UGDFs



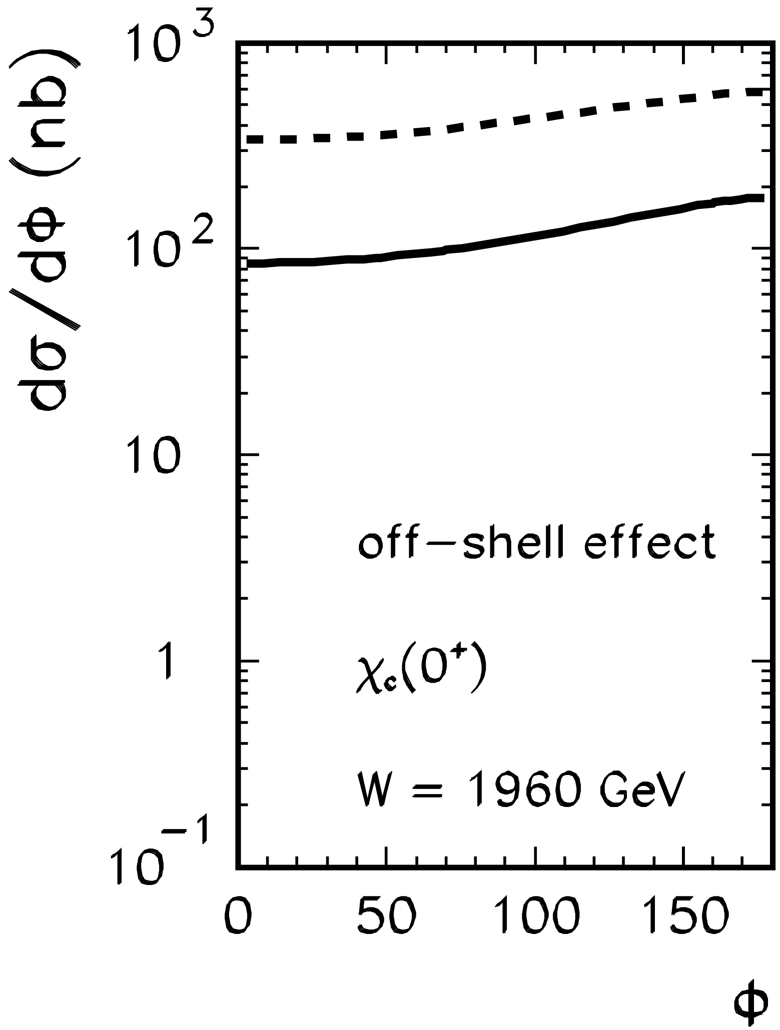
solid: Q^2_{cut} = 0.26 GeV^2, dashed: Q^2_{cut} = 0.5 GeV^2,
dotted: Q^2_{cut} = 0.8 GeV^2, dash-dotted: Q^2_{cut} = 1.0 GeV^2.

off-shell versus on-shell



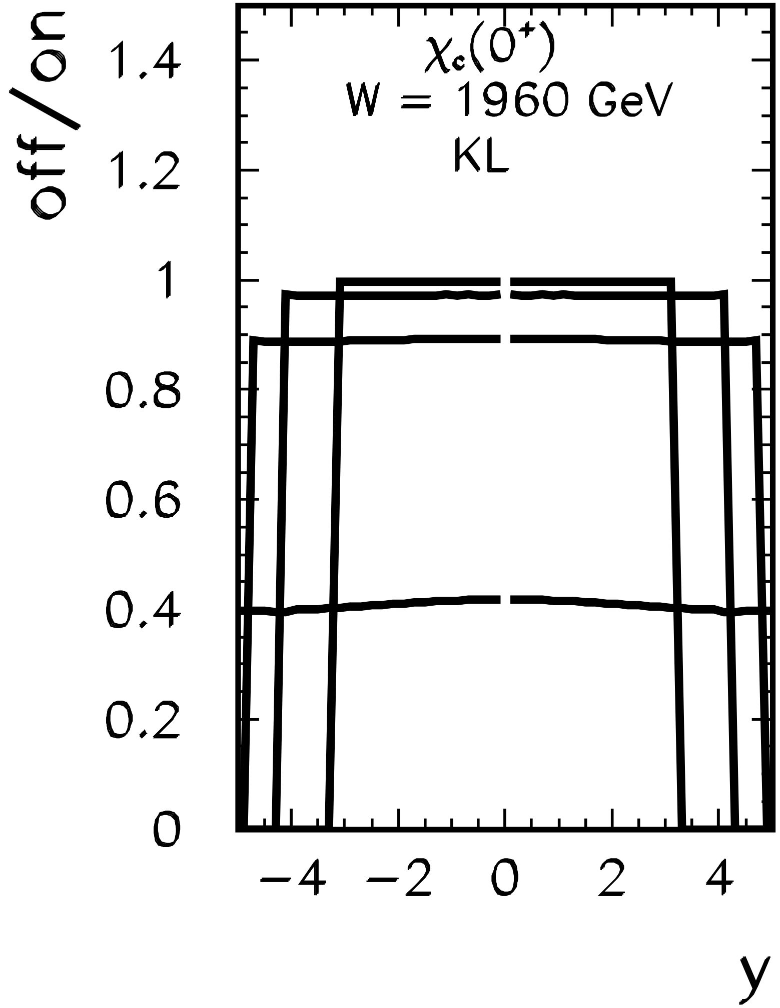
dashed line: on-shell, solid line: off-shell.

off-shell versus on-shell



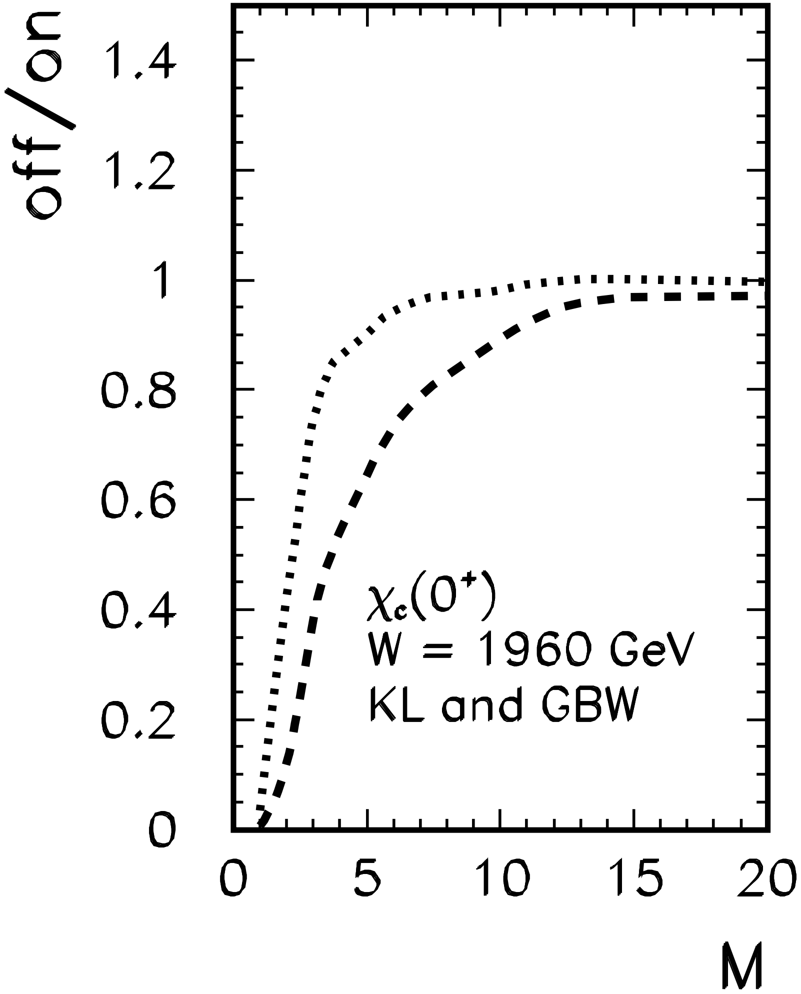
dashed line: on-shell, solid line: off-shell case.

off-shell versus on-shell



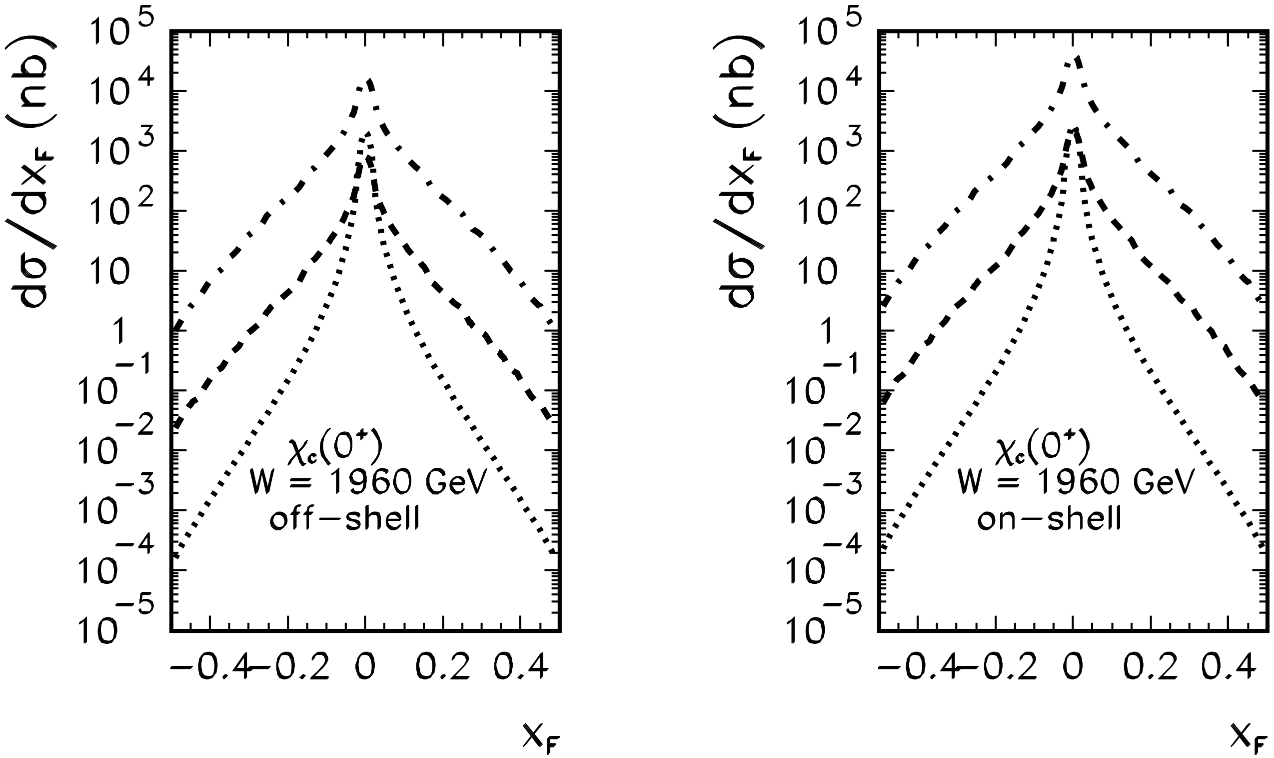
meson mass M = 3.41, 10, 20, 50 GeV

off-shell versus on-shell



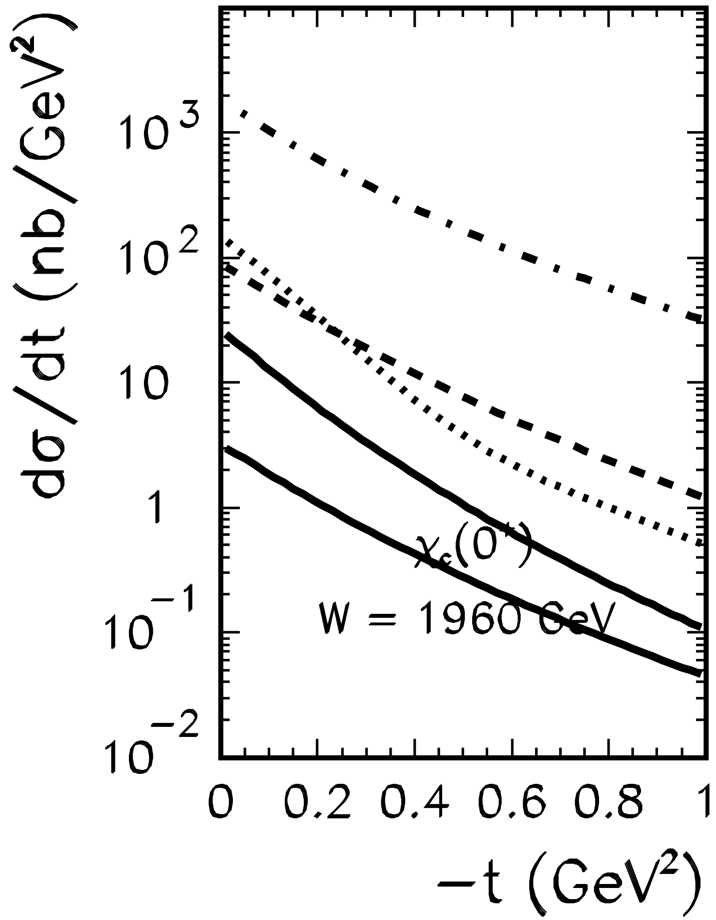
dashed: KL, dotted: GBW

Other UGDFs



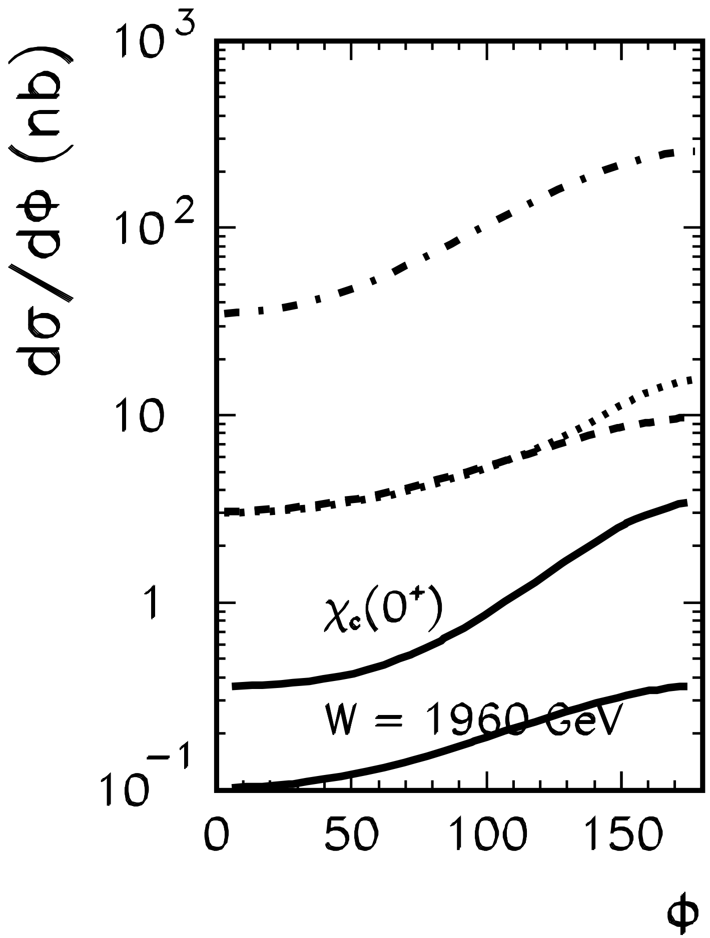
KL–dashed, GBW–dotted, BFKL–dash-dotted

Other UGDFs



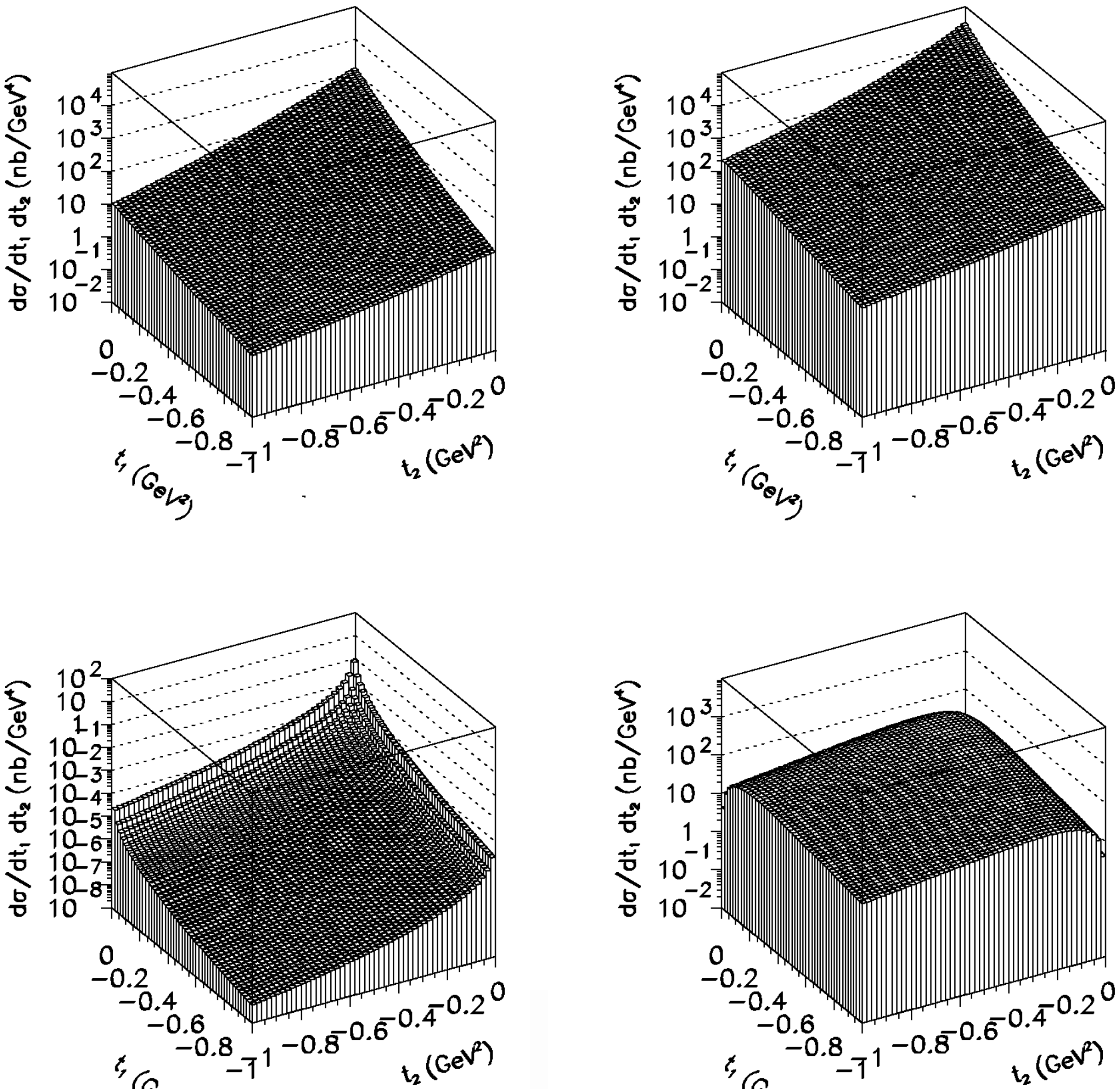
The solid line: Gaussian distributions with σ_0 = 0.5/1.0 GeV.

Other UGDFs

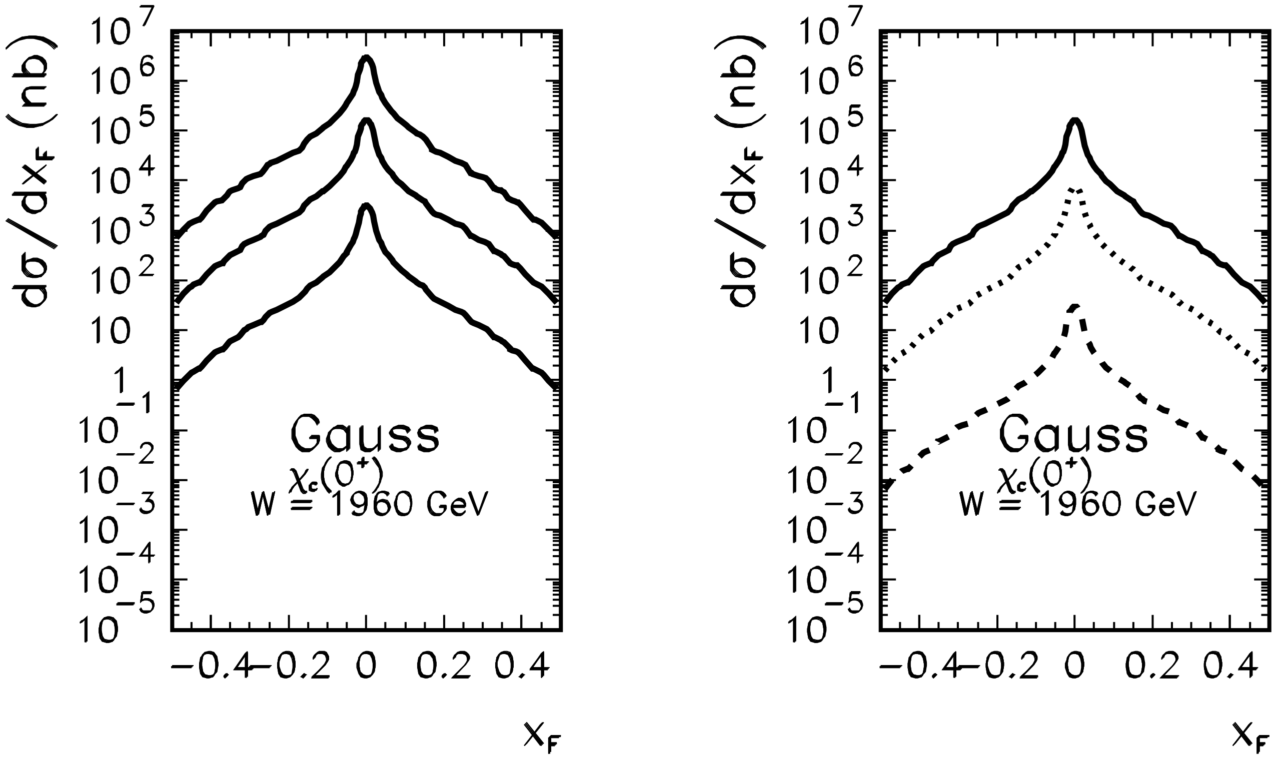


The solid line: the Gaussian distributions with σ_0 = 0.5/1.0 GeV

$t_1 \times t_2$ correlations

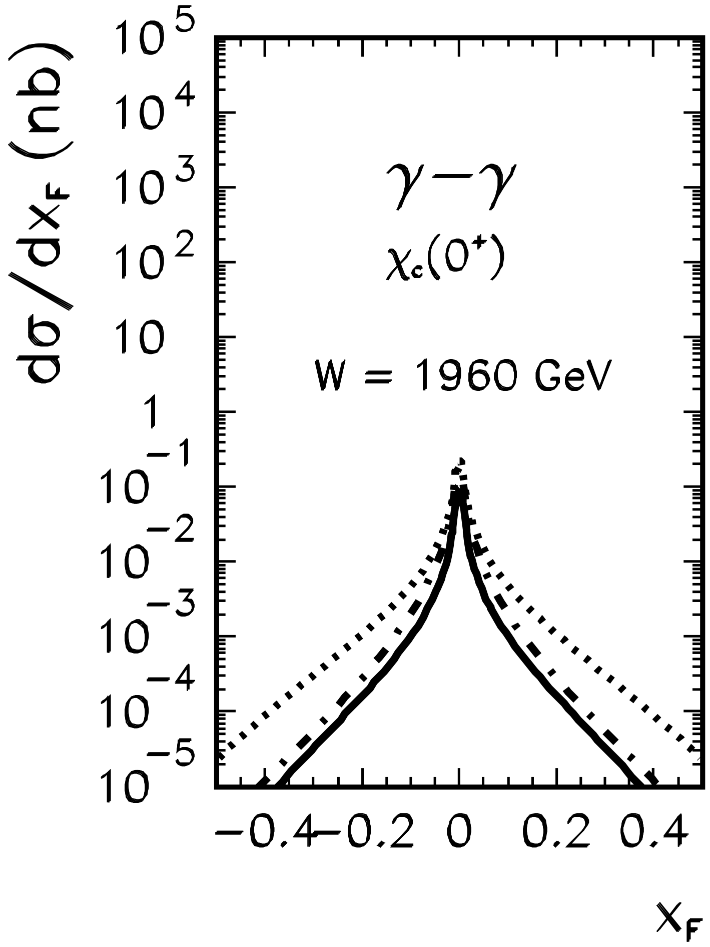


Gaussian UGDF



Left panel: σ_0 = 0.5, 1, 2 GeV and $\mu_0^2 = \mu^2 = M_\chi^2$. Right panel σ_0 = 1 GeV and different scales (1: solid, 2: dashed and 3: dotted).

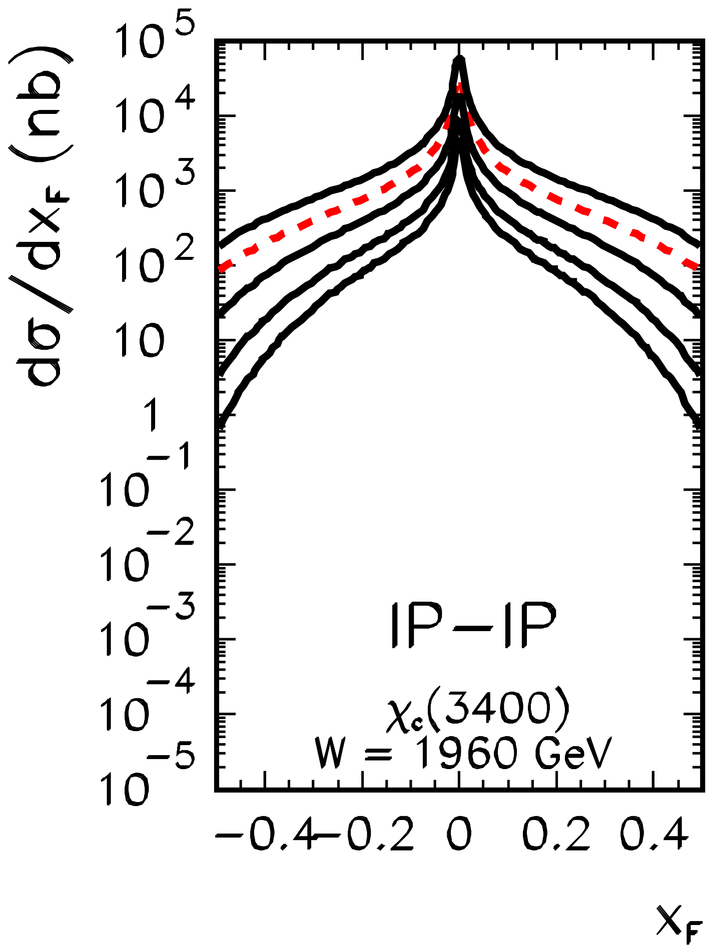
Photon-photon fusion



(50)

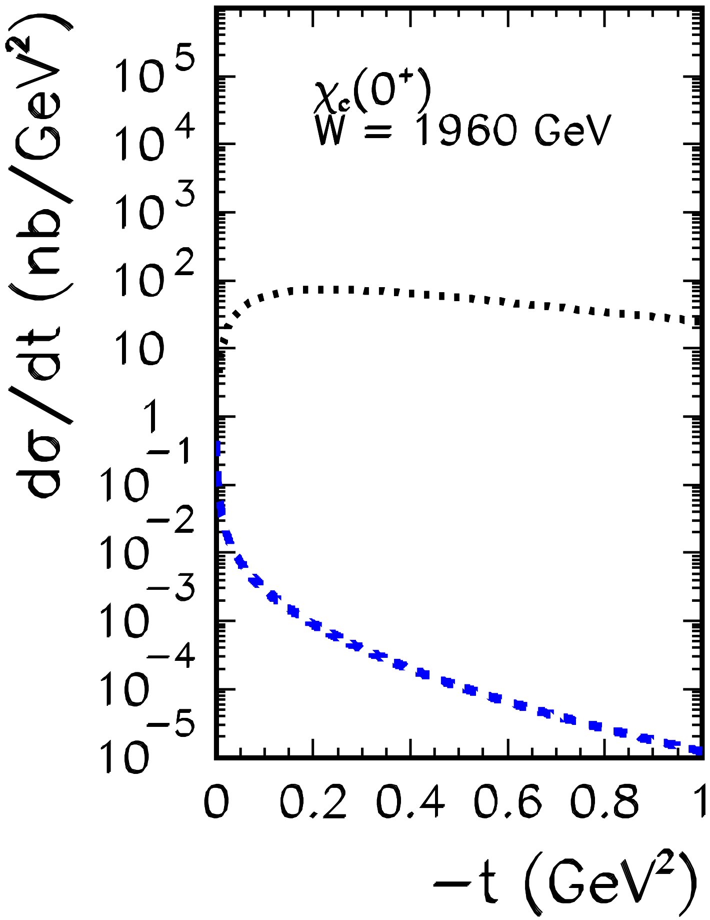
Solid line: the best approximation, Dotted and dashed dotted lines: EPA approach with different flux factors.

Pomeron-pomeron fusion



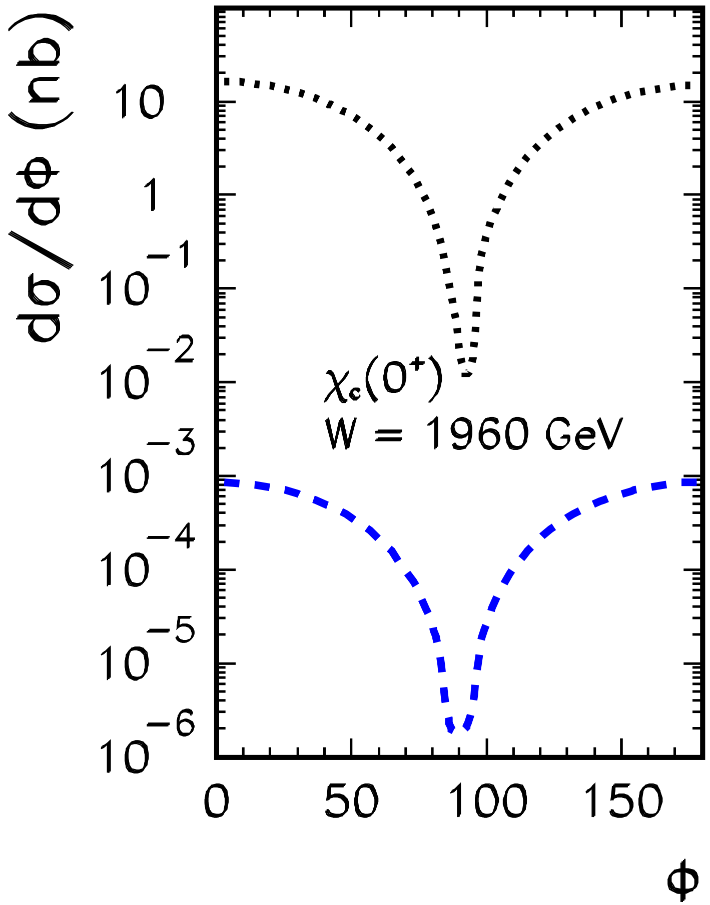
B = 5, 10, 15, 20 GeV^{-2} (from top to bottom) of the exponential form factor. The dashed line: dipole (electromagnetic) form factor.

Photon-photon vs pomeron-pomeron



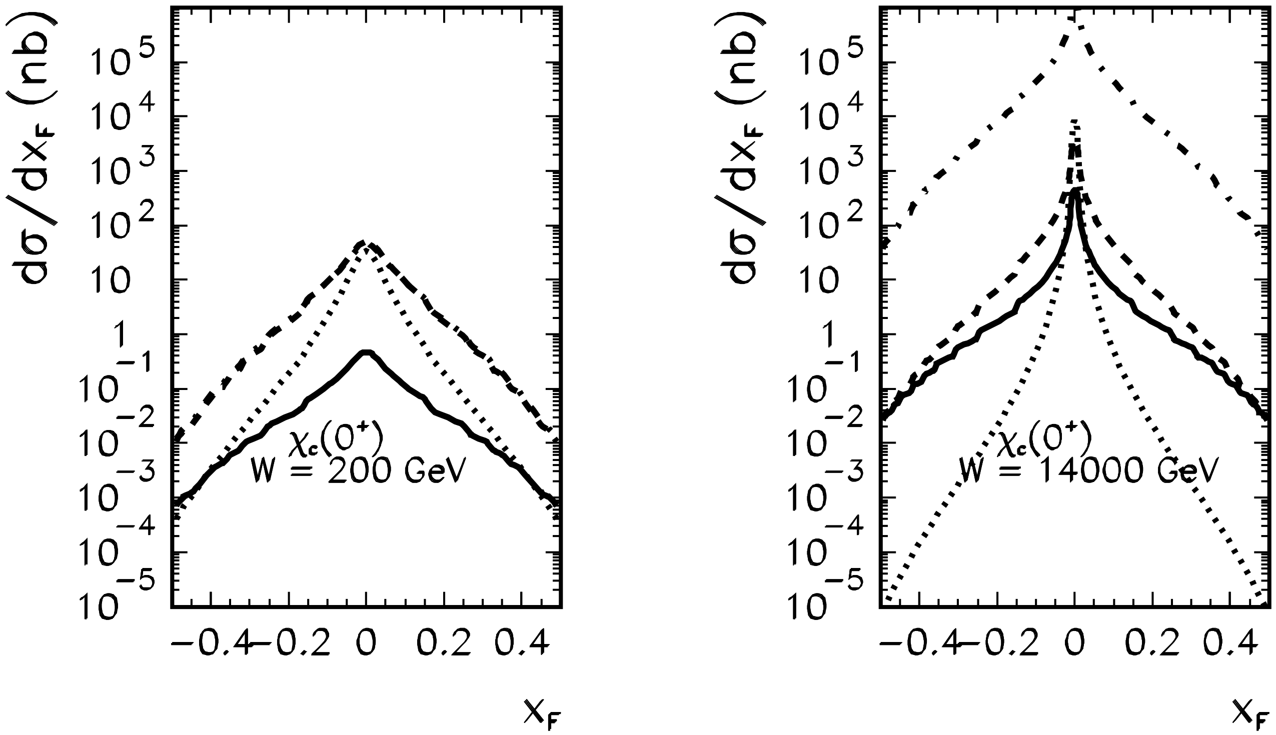
The two-photon (dashed, blue) and two-pomeron (dotted).

Photon-photon vs pomeron-pomeron



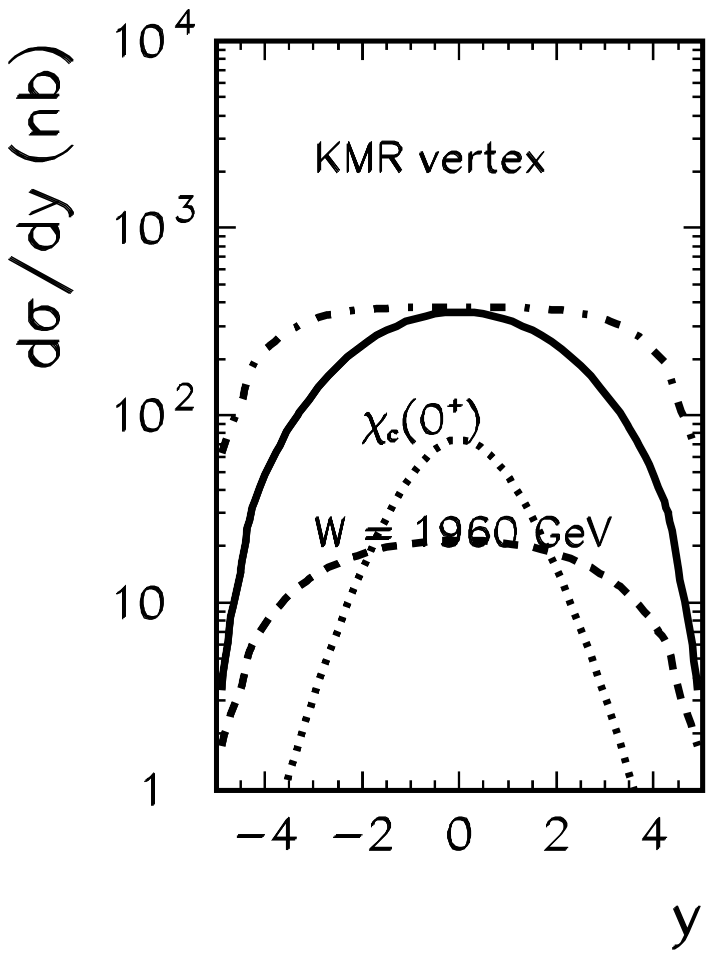
Two-photon (dashed, blue) and two-pomeron (dotted).

Energy dependence, RHIC and LHC



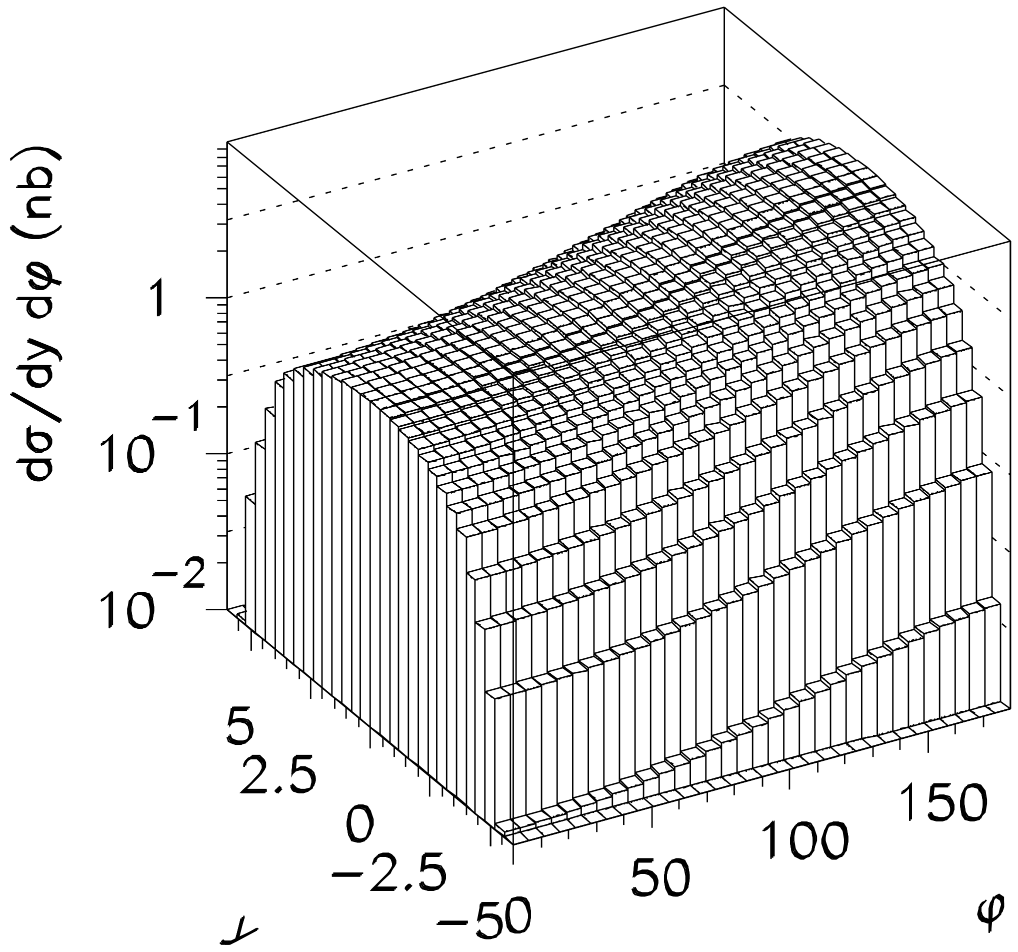
Different UGDFs.

Rapidity distribution



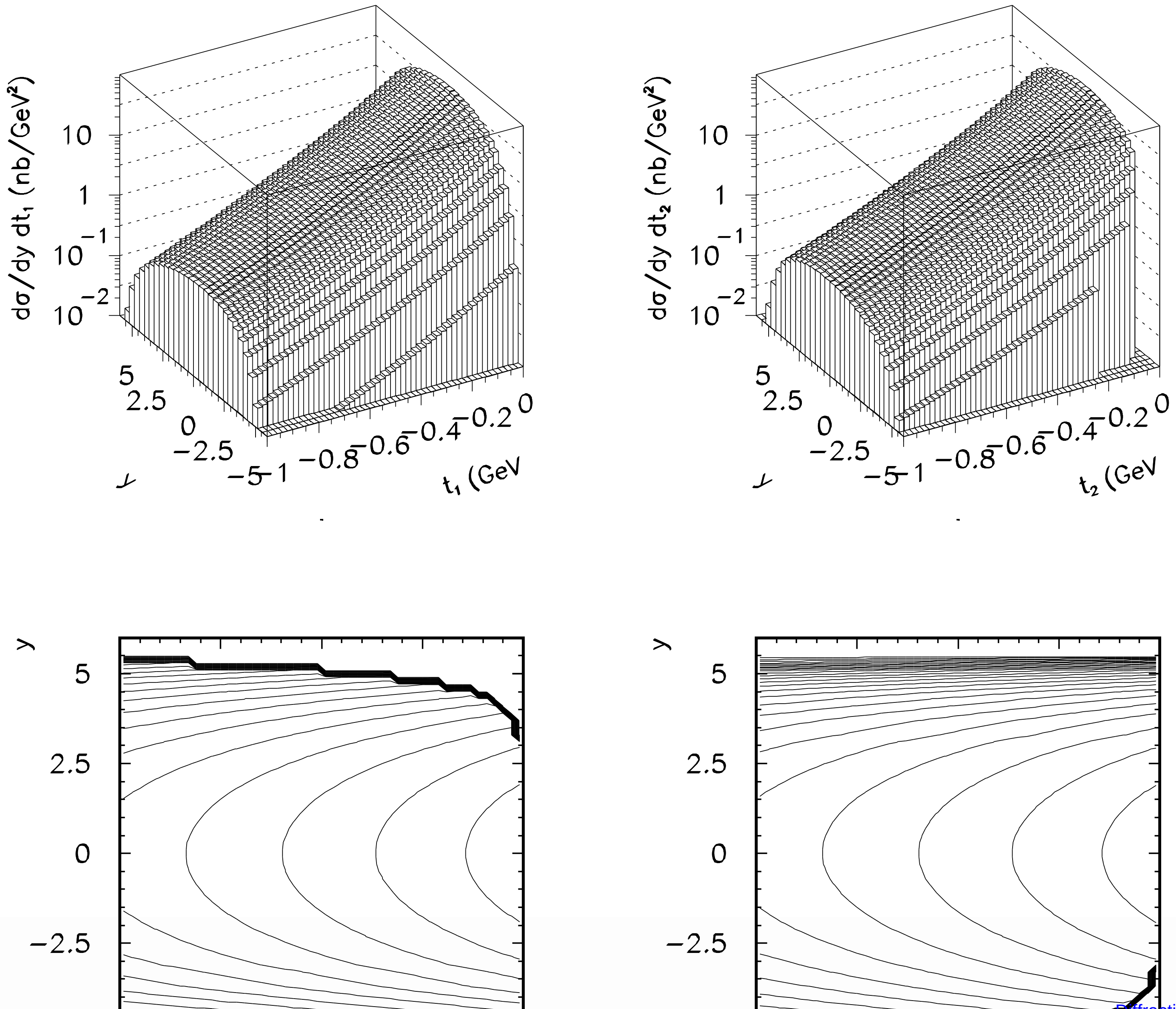
KL–dashed, GBW–dotted, BFKL–dash-dotted

Correlations 1

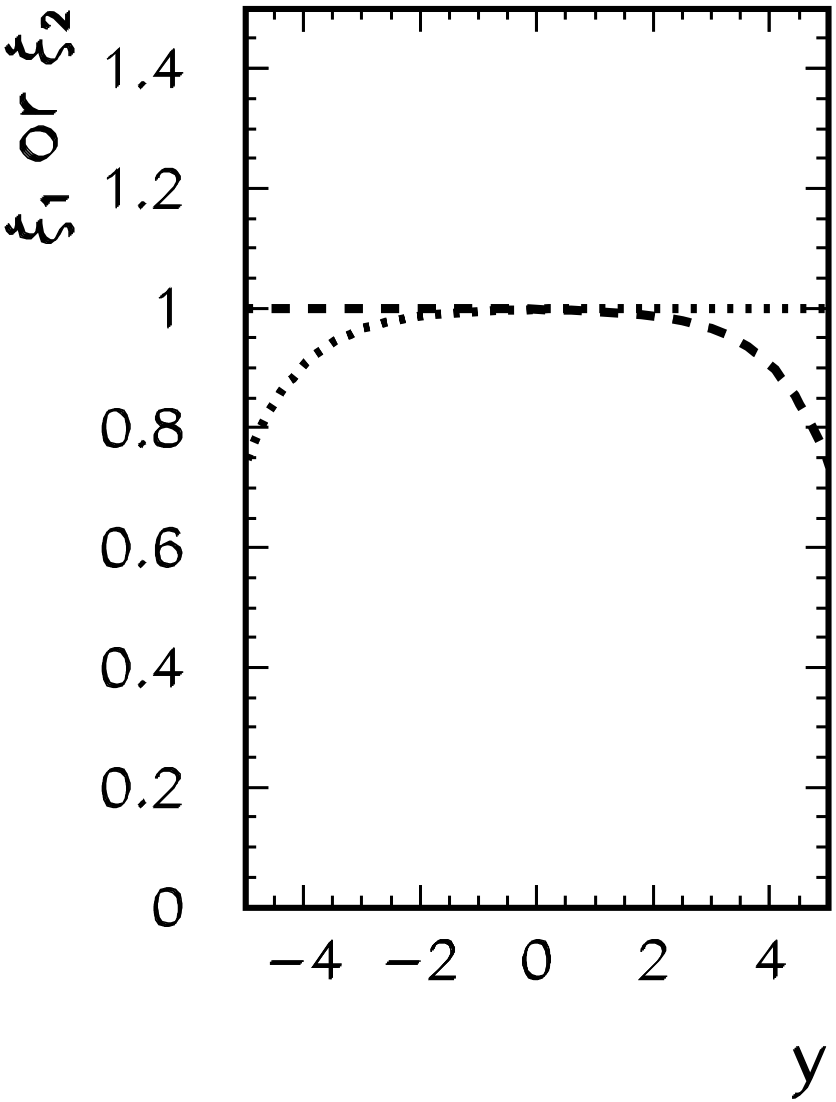


no visible dependence of azimuthal correlations on rapidity!

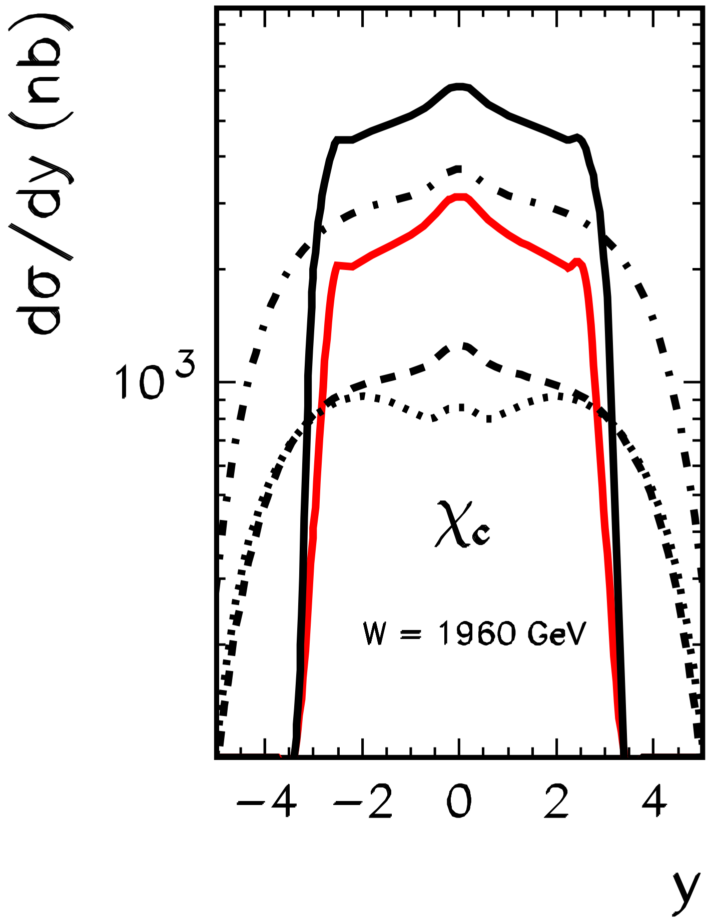
Correlations 2



Correlations 3



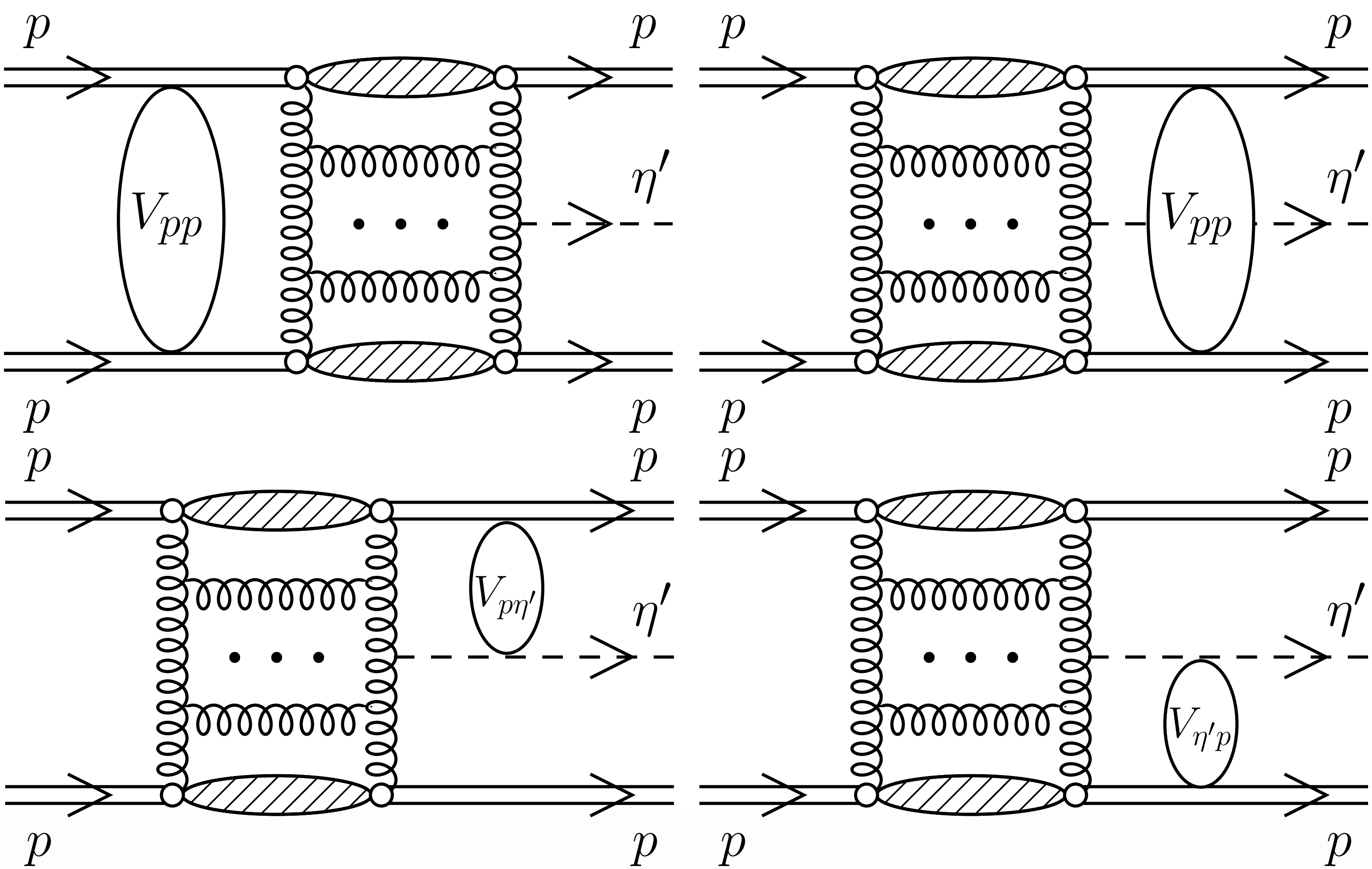
Exclusive vs inclusive production



KL–dashed, GBW–dotted, BFKL–dash-dotted

Outlook, absorption corrections

I was talking about bare amplitudes.
There are ISI and FSI effects destroying rapidity gaps.
Must be included (!)



Conclusions

- Big uncertainties in the Khoze-Martin-Ryskin approach.
- Huge sensitivity to the choice of UGDFs.
- Large off-shell effects.
- Different shapes for $\frac{d\sigma}{dx_F}$ ($\frac{d\sigma}{dy}$) for different UGDFs.
- Strong deviations from (1+cos(2 Φ)) for QCD diffraction.
- σ(photon-photon) $\ll$ σ(QCD diffraction).
- Different shapes of both components.
- Sizeable but not dominant contribution for exclusive J/ψ production via $\chi_c(0) \to J/\psi\gamma$.