# Exclusive scalar meson production: from high to intermediate energies

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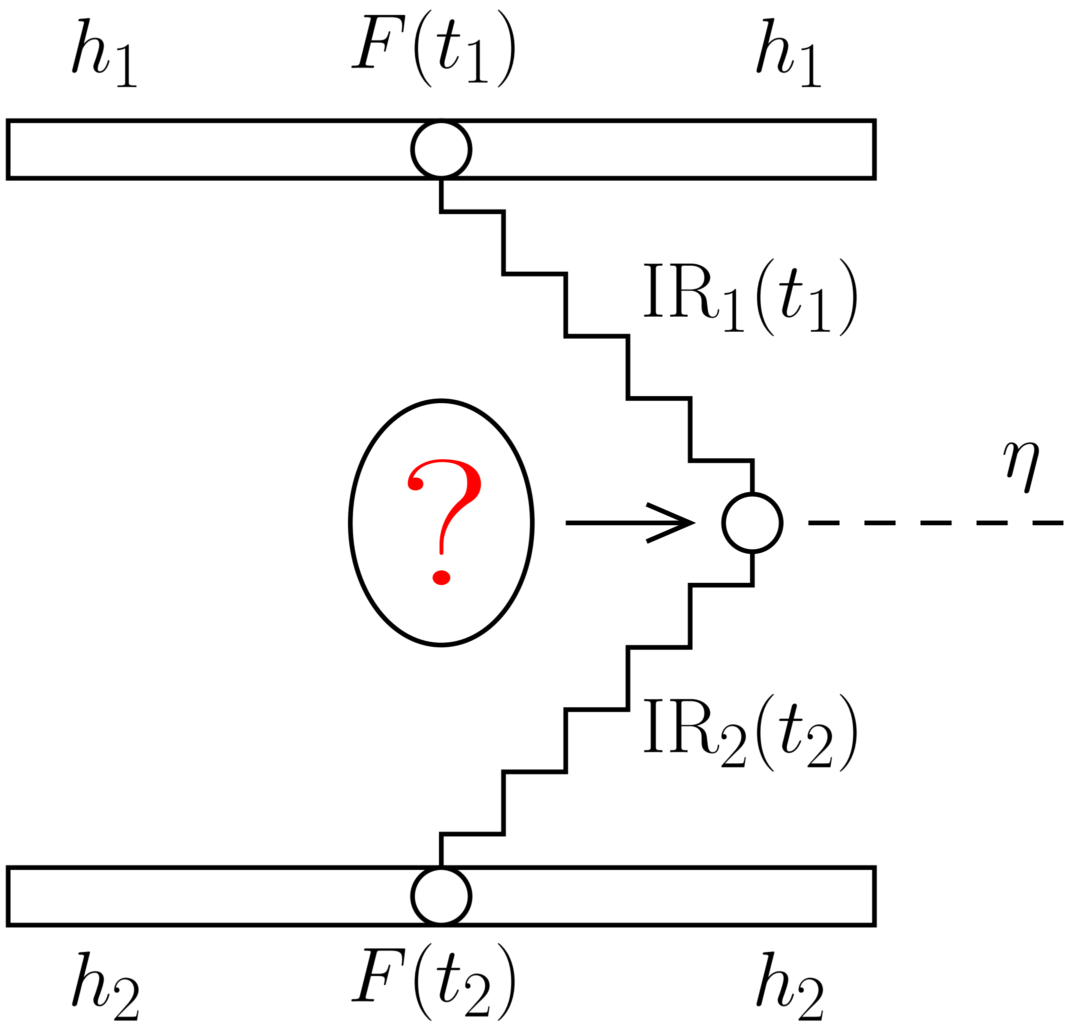
# Introduction

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.

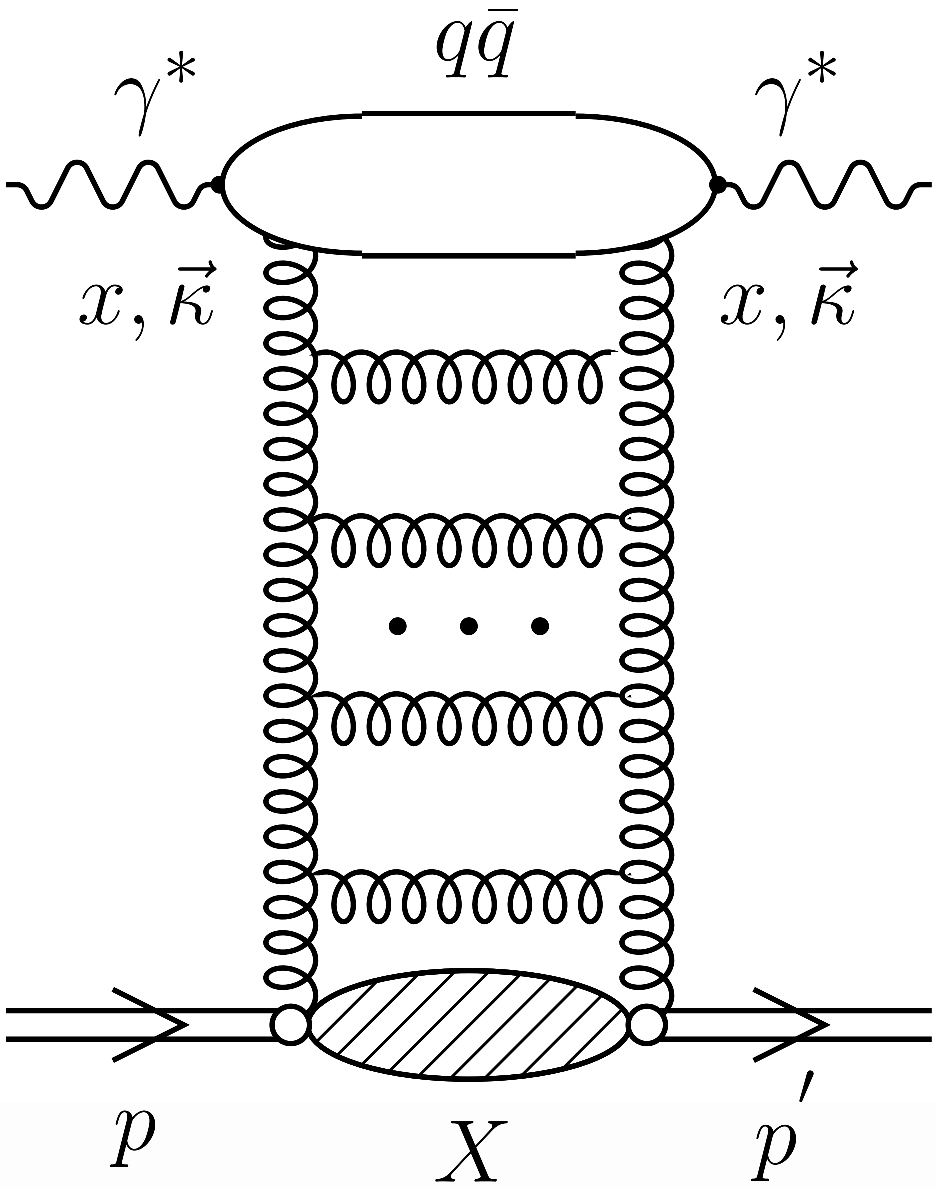
- (a) Search for Higgs primary task for LHC.
  Diffractive production of the Higgs an alternative to inclusive production (background reduction).
  A new QCD mechanism proposed recently by Khoze-Martin-Ryskin.
  Not possible to measure Higgs at present.
  Replace Higgs by a meson (scalar, pseudoscalar)
- (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

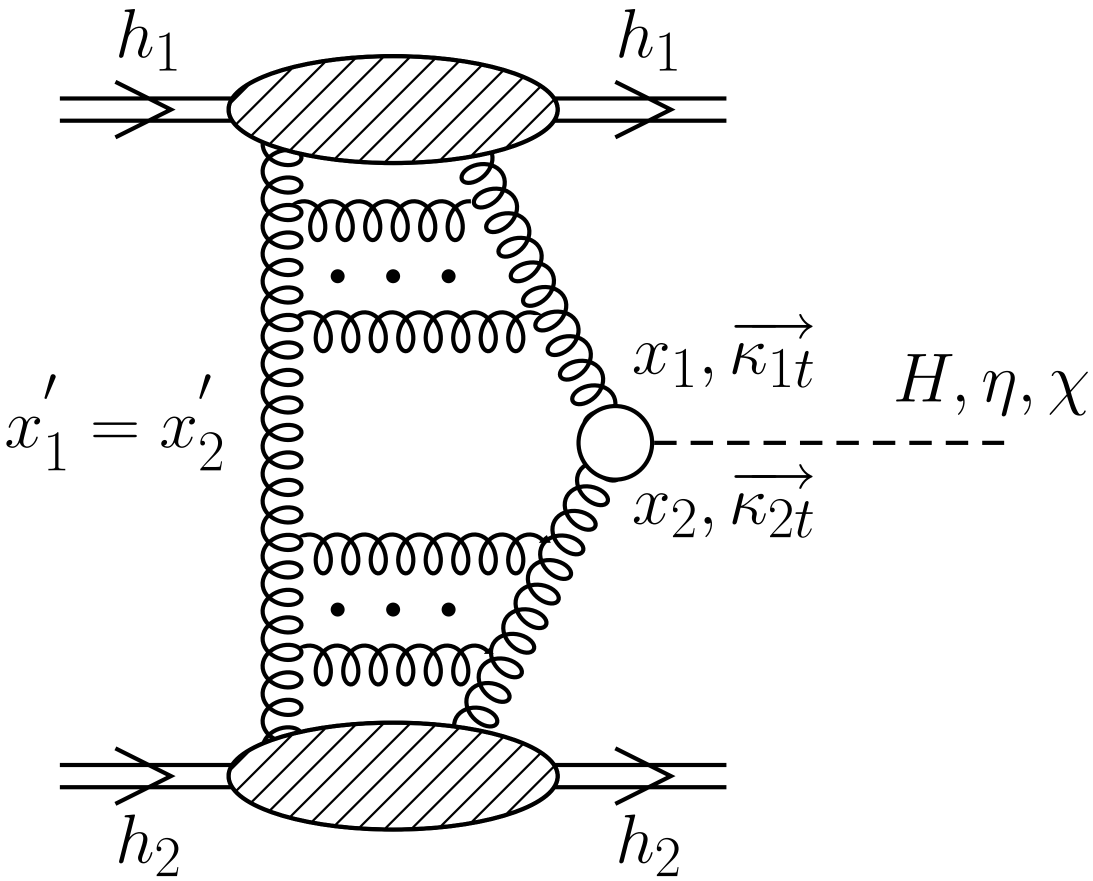


# QCD motivation

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



# QCD mechanism



# QCD mechanism

Khoze-Martin-Ryskin (Higgs production) (H $\to \chi_c(0)$)

$$\mathcal{M}^{g^*g^* \to \chi_c(0)}_{pp \to p\chi_c(0)p} = i\,\pi^2\, s \int d^2 k_{0,t} \quad V(k_1, k_2, P_M) \tag{1}$$

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

$f_g^{off}(...)$ – 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

$$\mathcal{P}_{S=1,S_z} = \frac{1}{2m}(\hat{k}_2 - m)\frac{\hat{\epsilon}(S_z)}{\sqrt{2}}(\hat{k}_1 + m)\ . \qquad (10)$$

$$\begin{aligned}\mathrm{Tr}(\Psi\,\mathcal{P}_{S=1,S_z}) &= -\delta^{c_1 c_2}\frac{\epsilon^{\rho}(S_z)}{\sqrt{2N_c}}\frac{g^2}{4m}\,\mathrm{Tr}\Big\{\Big(\gamma_\nu\frac{\hat{q}_1 - \hat{k}_1 - m}{(q_1-k_1)^2 - m^2}\gamma_\mu - \gamma_\mu\frac{\hat{q}_1 - \hat{k}_2 + m}{(q_1-k_2)^2 - m^2}\gamma_\nu\Big) \times \\ &\times \quad (\hat{k}_2 - m)\gamma_\rho(\hat{k}_1 + m)\Big\}. \qquad (11)\end{aligned}$$

$$\int \frac{d^3\mathbf{q}}{(2\pi)^3} q^{\sigma}\Phi_{L=1,L_z}(\mathbf{q}) = -i\sqrt{\frac{3}{4\pi}}\epsilon^{\sigma}(L_z)\mathcal{R}'(0), \qquad (12)$$

$$\mathcal{T}^{\sigma\rho}_{J=0} \equiv \sum_{L_z, S_z}\langle 1, L_z; 1, S_z|0,0\rangle\,\epsilon^{\sigma}(L_z)\epsilon^{\rho}(S_z) = \sqrt{\frac{1}{3}}\Big(g^{\sigma\rho} - \frac{P^{\sigma}P^{\rho}}{M^2}\Big) \qquad (13)$$

# QCD formalism

Our vertex (off-shell)

$$V_{J=0}^{c_1 c_2}(q_1, q_2) = 8ig^2 \frac{\delta^{c_1 c_2}}{M} \frac{\mathcal{R}'(0)}{\sqrt{\pi M N_c}} \frac{3M^2(q_{1,t}q_{2,t}) + 2q_{1,t}^2 q_{2,t}^2 - (q_{1,t}q_{2,t})(q_{1,t}^2 + q_{2,t}^2)}{(M^2 - q_{1,t}^2 - q_{2,t}^2)^2}. \quad (14)$$

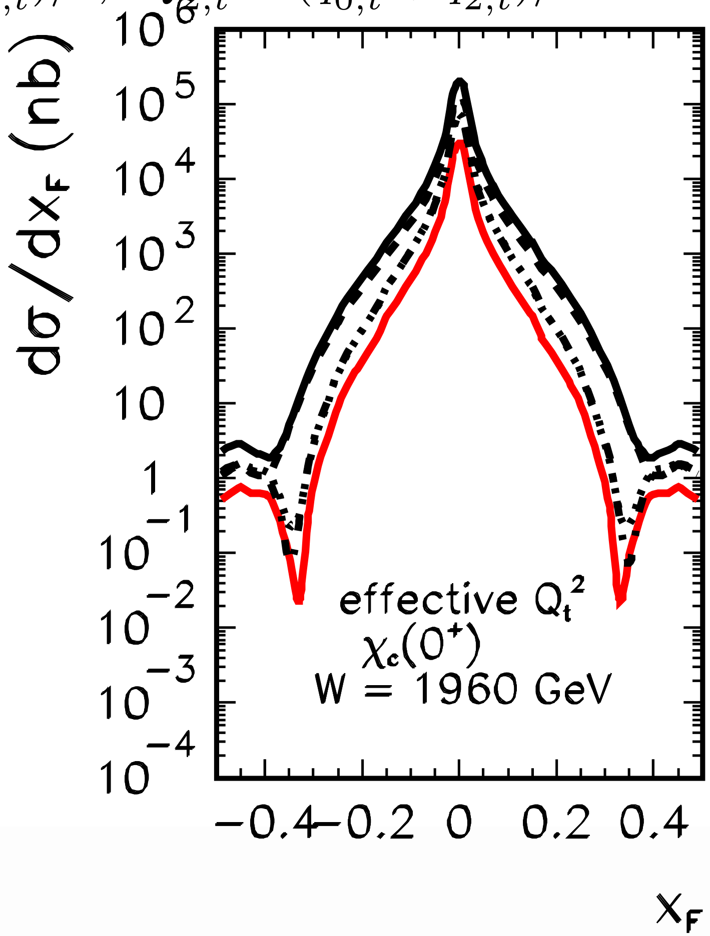
KMR vertex (on-shell)

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

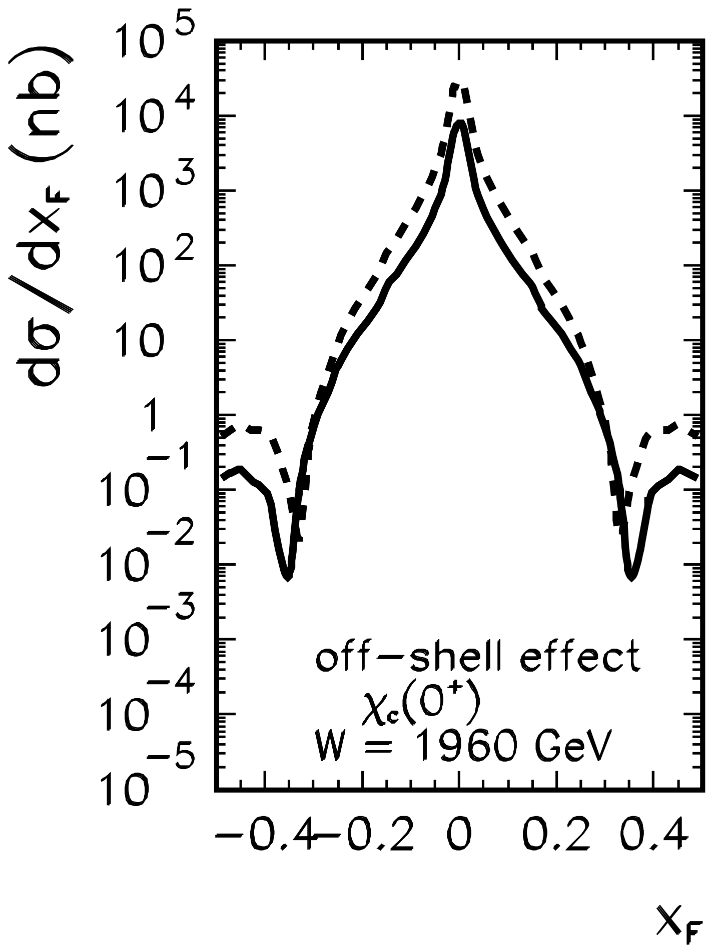
$$= i\delta^{c_1 c_2} \cdot 8g^2 \sqrt{\frac{3}{\pi M}} \frac{\mathcal{R}'(0)}{M^3} \cdot (q_{1,t}q_{2,t}). \quad (15)$$

# Uncertainties for KMR UGDFs

- 1) $Q_{1,t}^2 = \min(q_{0,t}^2, q_{1,t}^2)$, $Q_{2,t}^2 = \min(q_{0,t}^2, q_{2,t}^2)$ ,
- 2) $Q_{1,t}^2 = \max(q_{0,t}^2, q_{1,t}^2)$, $Q_{2,t}^2 = \max(q_{0,t}^2, q_{2,t}^2)$ ,
- 3) $Q_{1,t}^2 = q_{1,t}^2$, $Q_{2,t}^2 = q_{2,t}^2$ .
- 4) $Q_{1,t}^2 = q_{0,t}^2$, $Q_{2,t}^2 = q_{0,t}^2$ ,
- 5) $Q_{1,t}^2 = (q_{0,t}^2 + q_{1,t}^2)/2$, $Q_{2,t}^2 = (q_{0,t}^2 + q_{2,t}^2)/2$ .

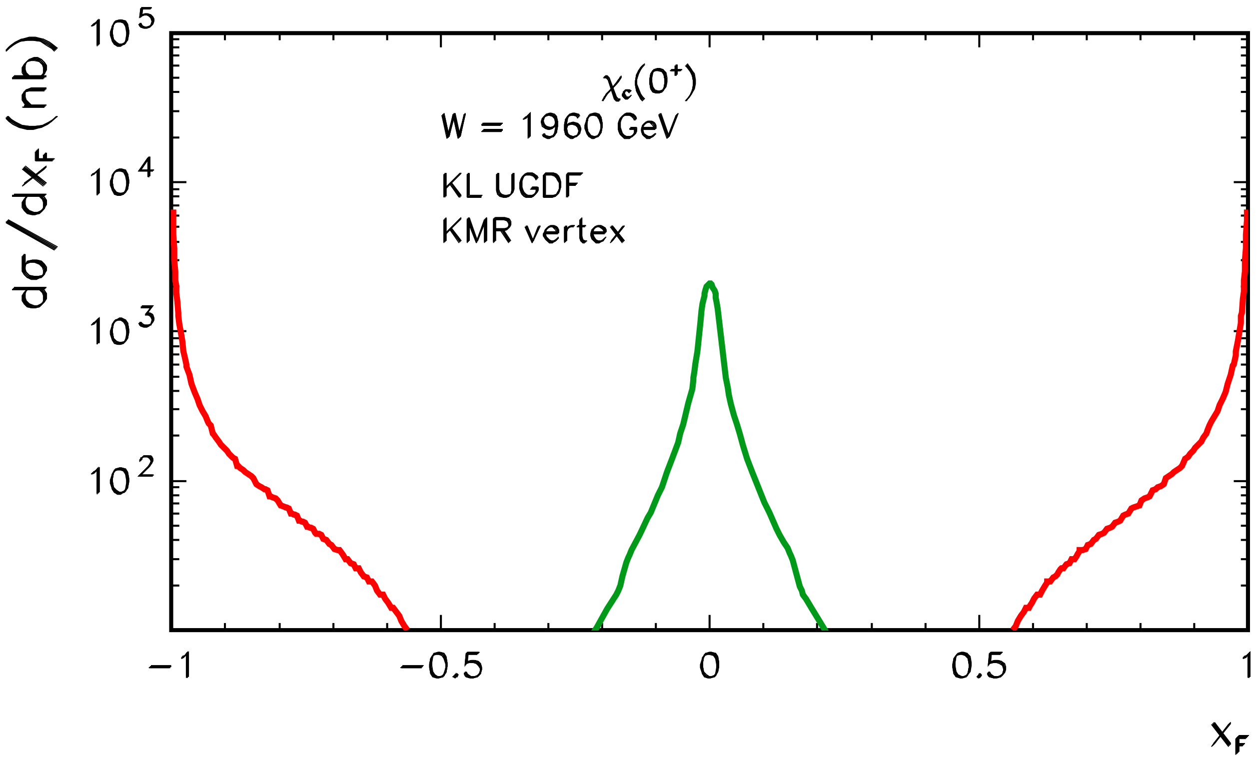


# off-shell versus on-shell



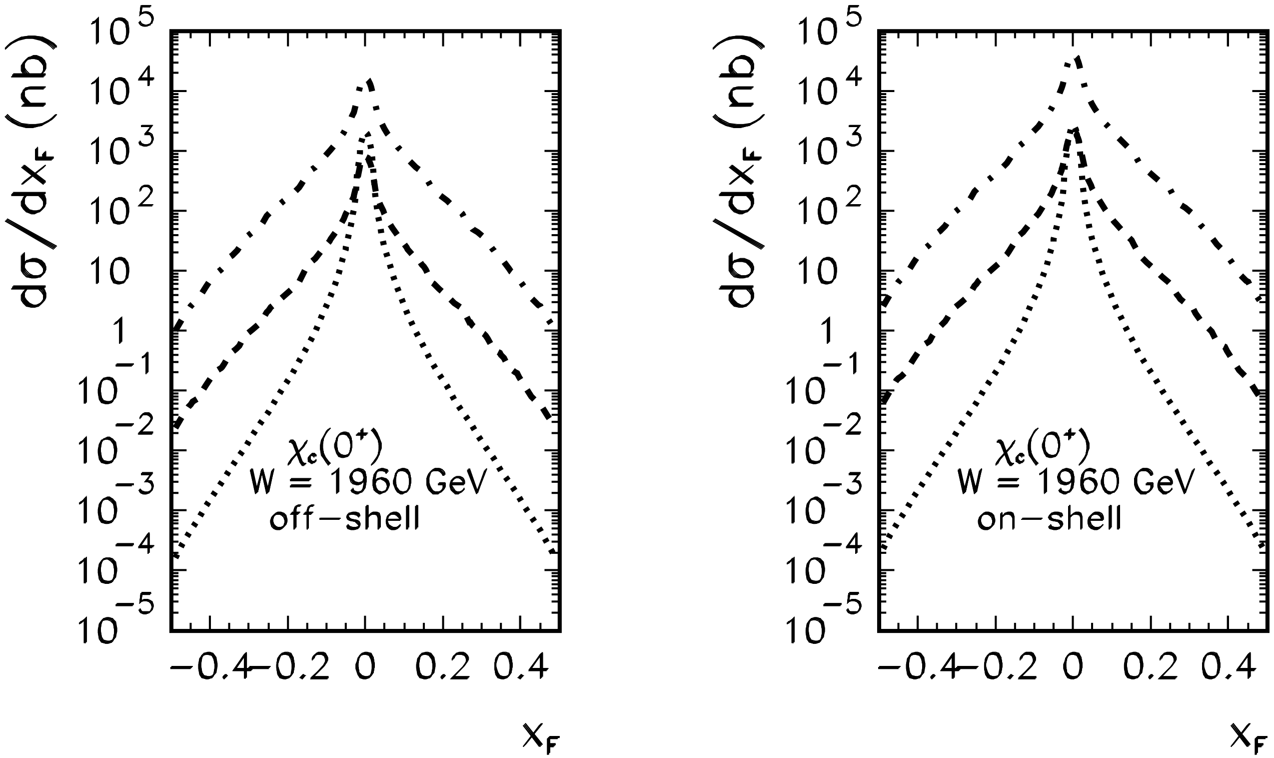

dashed line: on-shell, solid line: off-shell.

# Diffractive production = central production



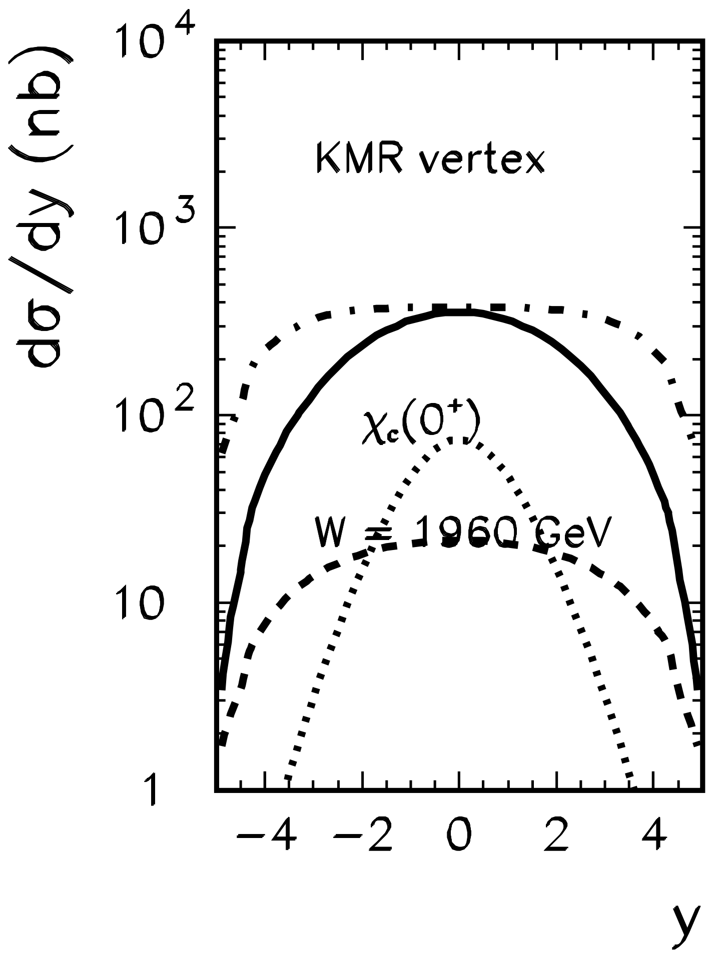

gap in longitudinal momenta between $\chi_c(0)$ and outgoing protons

# Other UGDFs




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

# Rapidity distribution




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

# 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 $\Phi$)) for QCD diffraction.
- $\sigma$(photon-photon) $\ll$ $\sigma$(QCD diffraction).
- Different shapes of both components.
- Sizeable but not dominant contribution for exclusive $J/\psi$ production via $\chi_c(0) \rightarrow J/\psi\gamma$.

# Scalar glueball $f_0(1500)$ production

Many theoretical calculations (including lattice QCD) predicted existence of glueballs with $M > 1.5$ GeV.
$f_0(1500)$ is one of the candidates.

Short history:

- $f_0(1500)$ discovered by the Crystall Barrel Collaboration in proton-antiproton annihilation
- Observed by the WA102 Collaboration in central production $pp \to pp f_0(1500)$
- Observed at BES in $J/\psi \to f_0(1500) + \gamma$

based on work with P. Lebiedowicz, a paper in preparation

# Exclusive production of $f_0(1500)$

Close and Kirk – a phenomenological model.
In their language the pomerons (transverse and longitudinal) are the effective degrees of freedom.
The Close-Kirk amplitude:

$$\mathcal{M}(t_1, t_2, \phi') = a_T \exp\left(\frac{b_T}{2}(t_1 + t_2)\right) + a_L \frac{\sqrt{t_1 t_2}}{\mu^2} \exp\left(\frac{b_L}{2}(t_1 + t_2)\right) \; cos( \tag{16}$$

Comment on their approach:

- No explicit $f_0(1500)$-rapidity,
- No absolute normalization.

# Exclusive production of $f_0(1500)$

We consider processes:

$$\begin{aligned} p + p &\rightarrow p + f_0(1500) + p \ \ (J-PARC) \,, \\ p + \bar{p} &\rightarrow p + f_0(1500) + \bar{p} \ \ (PANDA) \,, \\ p + \bar{p} &\rightarrow n + f_0(1500) + \bar{n} \ \ (PANDA) \,, \end{aligned} \tag{17}$$

Our approach:

- Explicit rapidity dependence,
- Absolute normalization

Let us concentrate on 3.5 GeV $< W <$ 50 GeV

# Our approach to exclusive $f_0(1500)$ production

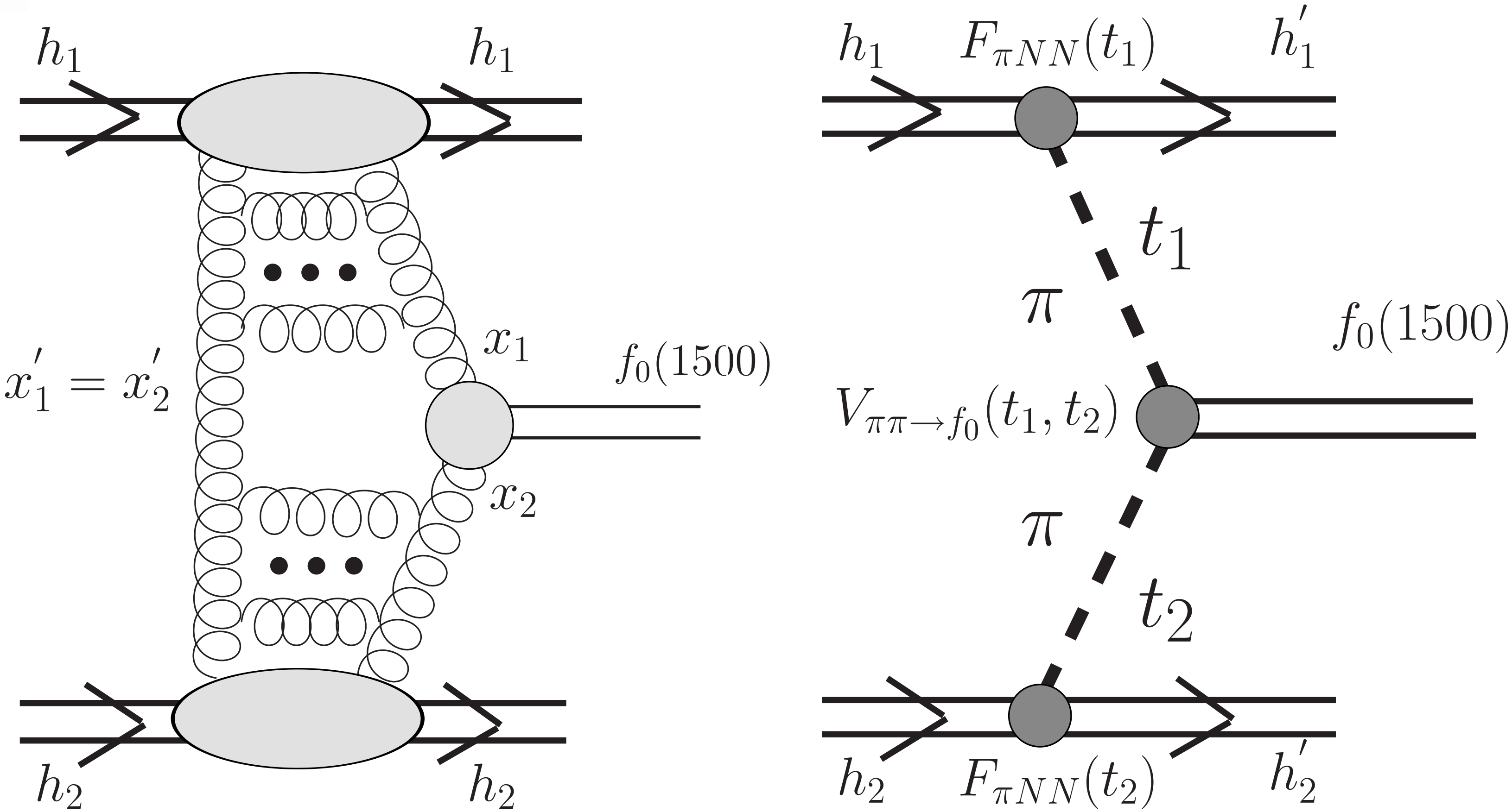



Figure 1: QCD mechanism vs MEC mechanism

# Diffractive amplitude, part1

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

In the original Khoze-Martin-Ryskin (KMR) approach the amplitude is written as

$$\mathcal{M} = N \int \frac{d^2 q_{0,t} P[f_0(1500)]}{q_{0,t}^2 q_{1,t}^2 q_{2,t}^2} f_g^{KMR}(x_1, x_1', Q_{1,t}^2, \mu^2; t_1) f_g^{KMR}(x_2, x_2', Q_{2,t}^2, \mu^2; t_2) \, , \quad (19)$$

where only one transverse momentum is taken into account somewhat arbitrarily as

$$Q_{1,t}^2 = \min\{q_{0,t}^2, q_{1,t}^2\} \, , \qquad Q_{2,t}^2 = \min\{q_{0,t}^2, q_{2,t}^2\} \, , \quad (20)$$

and the normalization factor $N$ can be written in terms of the $f_0(1500) \to gg$ decay width.

# Diffractive amplitude, part2

In the general case we do not know off-diagonal UGDFs.
R.Pasechnik, O.Teryaev and A.S. proposed a prescription:

$$\begin{aligned} f_{g,1}^{off} &= \sqrt{f_g^{(1)}(x_1', q_{0,t}^2, \mu_0^2) \cdot f_g^{(1)}(x_1, q_{1,t}^2, \mu^2)} \cdot F_1(t_1)\,, \\ f_{g,2}^{off} &= \sqrt{f_g^{(2)}(x_2', q_{0,t}^2, \mu_0^2) \cdot f_g^{(2)}(x_2, q_{2,t}^2, \mu^2)} \cdot F_1(t_2)\,, \end{aligned} \tag{21}$$

where $F_1(t_1)$ and $F_1(t_2)$ are isoscalar nucleon form factors.

$$F_1(t_{1,2}) = \frac{4m_p^2 - 2.79\, t_{1,2}}{(4m_p^2 - t_{1,2})(1 - t_{1,2}/071)^2}\,. \tag{22}$$

Even at intermediate energies ($W$ = 10-50 GeV) typical $x_1' = x_2'$ are relatively small ($\sim$ 0.01). $x_1, x_2 \sim M_{f_0}/\sqrt{s}$ are not too small (typically $> 10^{-1}$). Therefore here we cannot use the small-$x$ models of UGDFs.

# Diffractive amplitude, part3

Gaussian smearing of the collinear distribution seems a reasonable solution:

$$\mathcal{F}_g^{Gauss}(x, k_t^2, \mu_F^2) = x g^{coll}(x, \mu_F^2) \cdot f_{Gauss}(k_t^2) \;, \tag{23}$$

where $g^{coll}(x, \mu_F^2)$ are standard collinear (integrated) gluon distribution and $f_{Gauss}(k_t^2)$ is a Gaussian two-dimensional function

$$f_{Gauss}(k_t^2) = \frac{1}{2\pi\sigma_0^2} \exp\left(-k_t^2/2\sigma_0^2\right)/\pi \;. \tag{24}$$

Above $\sigma_0$ is a free parameter. Summarizing, we propose:

$$f(x, x', k_t^2, k_t'^2, t) = \sqrt{f_{small-x}(x', k_t'^2) f_{Gauss}(x, k_t^2, \mu^2)} \cdot F(t) \;, \tag{25}$$

where $f_{small-x}(x', k_t'^2)$ is one of the typical small-$x$ UGDFs.

# Pion-pion MEC amplitude

$$\overline{|\mathcal{M}|^2} = \frac{1}{4} \quad [(E_1+m)\left(E_1'+m\right)\left(\frac{\mathbf{p}_1^2}{(E_1+m)^2} + \frac{\mathbf{p}_1^{\prime 2}}{(E_1'+m)^2} - \frac{2\mathbf{p}_1\cdot\mathbf{p}_1'}{(E_1+m)(E_1'+m)}\right)]\cdot 2$$

$$\frac{g^2_{\pi NN} \cdot T_k}{(t_1-m_\pi^2)^2} F^2_{\pi NN}(t_1) \cdot |C_{f_0(1500)\to\pi\pi}|^2 \, V^2_{\pi\pi\to f_0(1500)}(t_1,t_2) \cdot \frac{g^2_{\pi NN} \cdot T_k}{(t_2-m_\pi^2)^2} F^2_{\pi N}$$

$$[(E_2+m)\left(E_2'+m\right)\left(\frac{\mathbf{p}_2^2}{(E_2+m)^2} + \frac{\mathbf{p}_2^{\prime 2}}{(E_2'+m)^2} - \frac{2\mathbf{p}_2\cdot\mathbf{p}_2'}{(E_2+m)(E_2'+m)}\right)]\cdot 2$$

.

$g_{\pi NN}$ is the pion nucleon coupling constant ($\frac{g^2_{\pi NN}}{4\pi}$ = 13.5)
The isospin factor $T_k$ equals 1 for the $\pi^0\pi^0$ fusion and equals 2 for the $\pi^+\pi^-$ fusion.
In the case of $p-p$ collisions only $\pi^0\pi^0$ fusion. In the case of $p-\bar{p}$ collisions both $\pi^0\pi^0$ and $\pi^+\pi^-$.

# Pion-pion MEC amplitude

In central heavy meson production – large $t_1$ and $t_2 \to$ extended nature of the particles involved. This is incorporated via $F_{\pi NN}(t_1)$ or $F_{\pi NN}(t_2)$.

The normalization constant $|C|^2$ can be calculated from the partial decay width

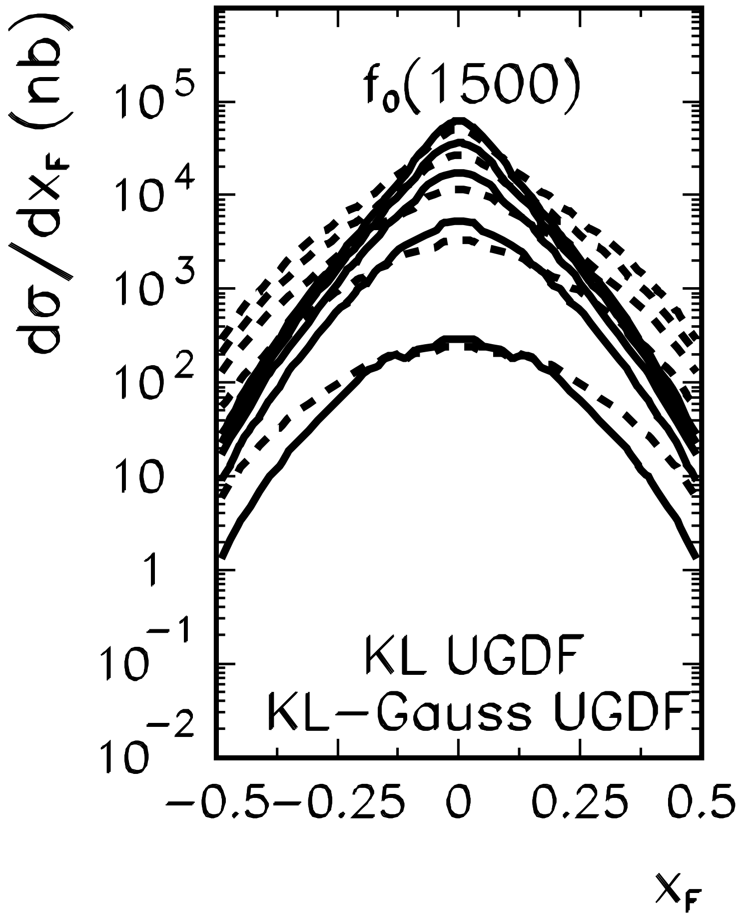
$$|C_{f_0(1500)\to\pi\pi}|^2 = \frac{8\pi\ 2M_{f_0}^2 \Gamma_{f_0(1500)\to\pi^0\pi^0}}{\sqrt{M_{f_0}^2 - 4m_\pi^2}}\,, \qquad (27)$$

where $\Gamma_{f_0(1500)\to\pi^0\pi^0} = 0.109 \cdot BR(f_0(1500) \to \pi\pi) \cdot 0.5$ GeV.

The branching ratio is $BR(f_0(1500) \to \pi\pi)$ = 0.349 (PDG).

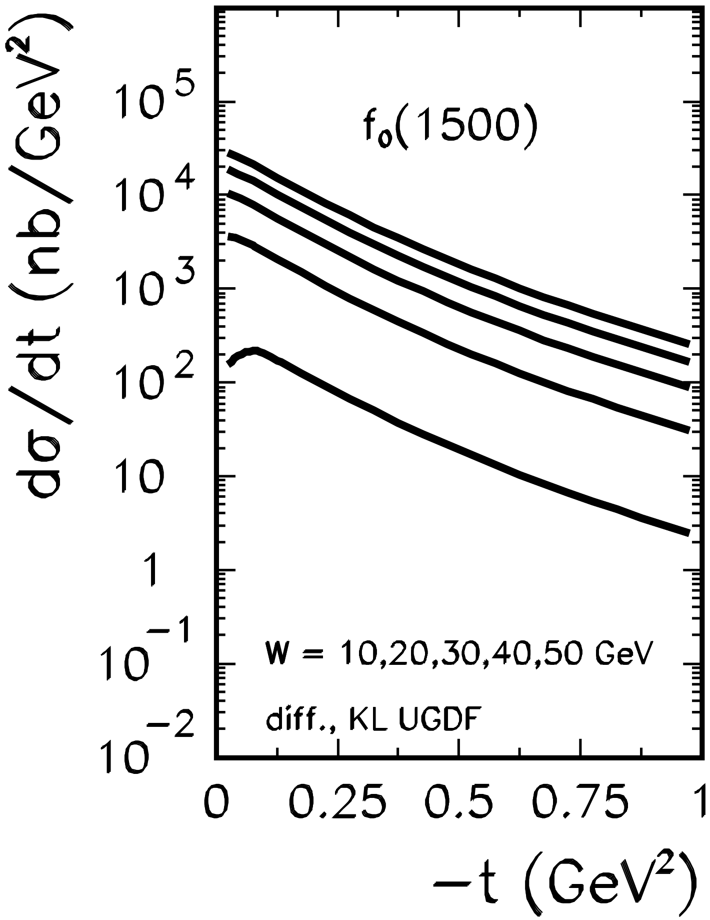
The off-shellness of pions is also included for the $\pi\pi \to f_0(1500)$ transition through the extra $V_{\pi\pi\to f_0(1500)}(t_1, t_2)$ form factor.

# Diffractive component, part1



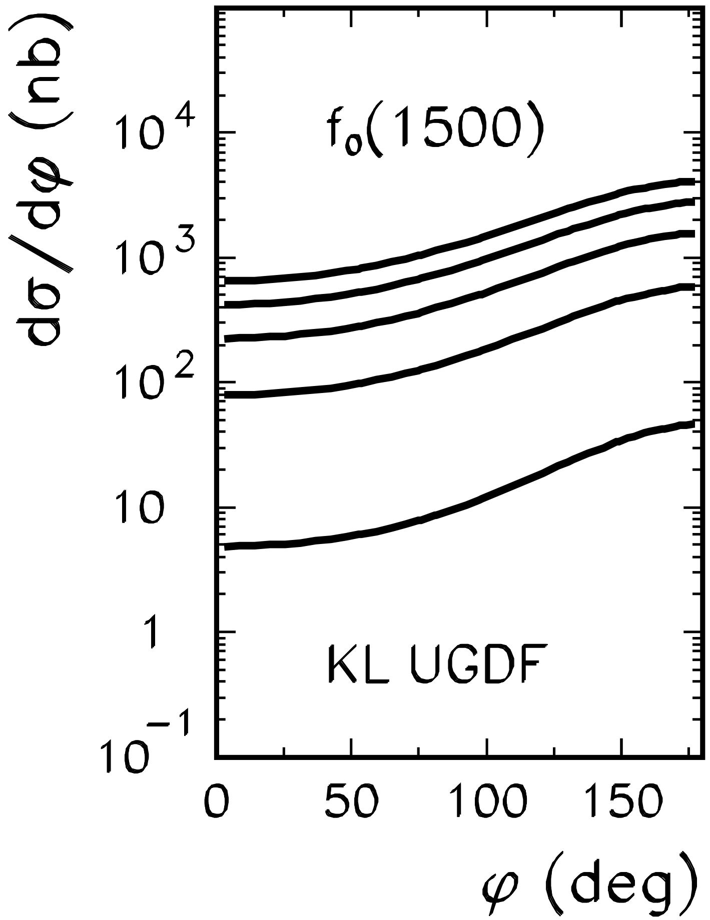

W = 10, 20, 30, 40, 50 GeV. Kharzeev-Levin UGDF (solid line) and the mixed distribution KL$\otimes$ Gauss (dashed line).

# Diffractive component, part2



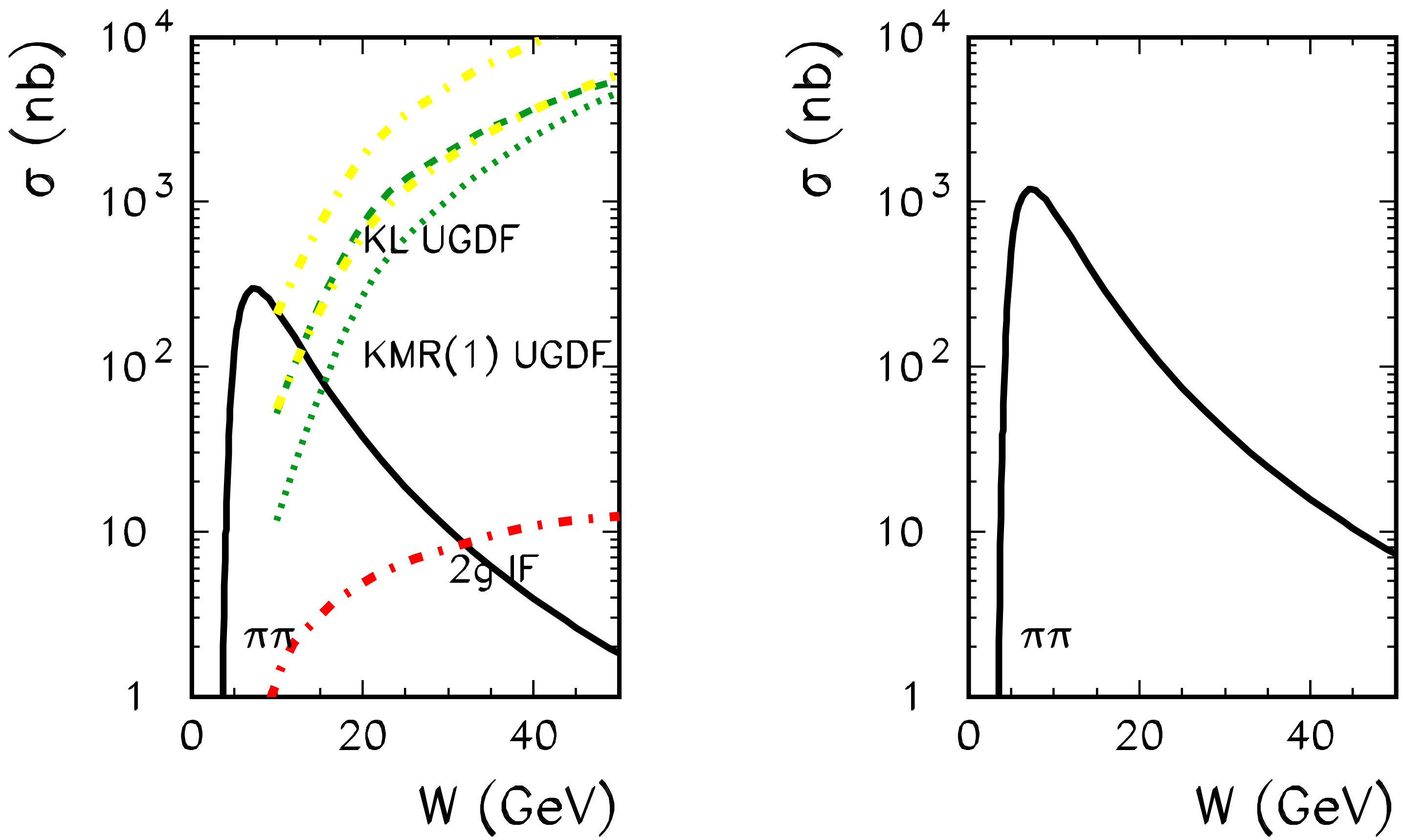

$t = t_1 = t_2$. Kharzeev-Levin UGDF.
$W$ = 10, 20, 30, 40, 50 GeV.

# Diffractive component, part3



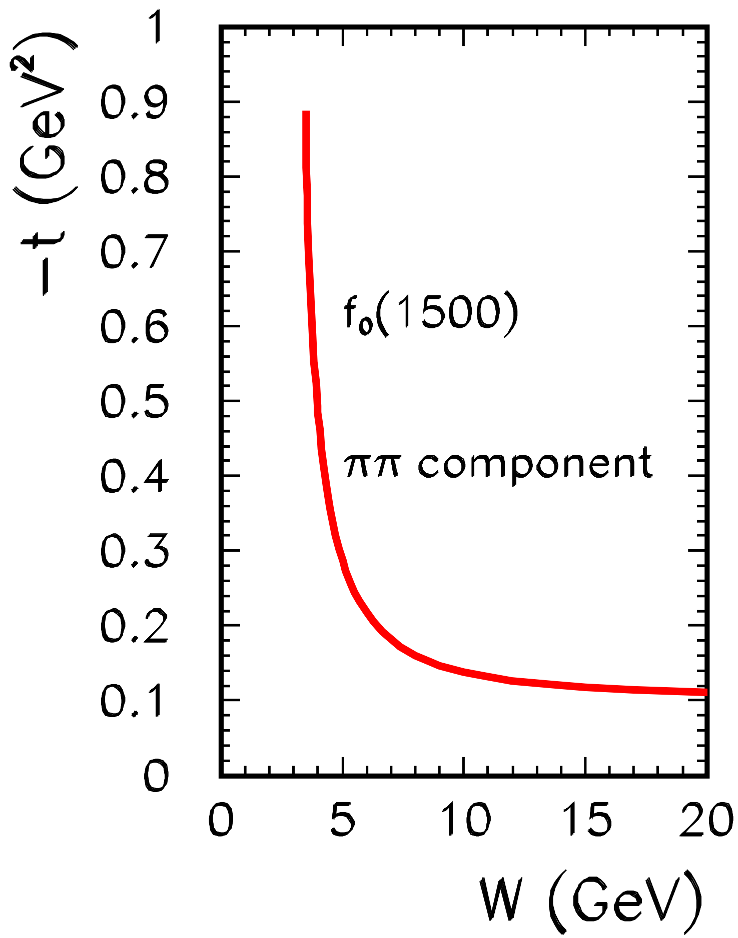

$W$ = 10, 20, 30, 40, 50 GeV. KL UGDF.

# Energy dependence



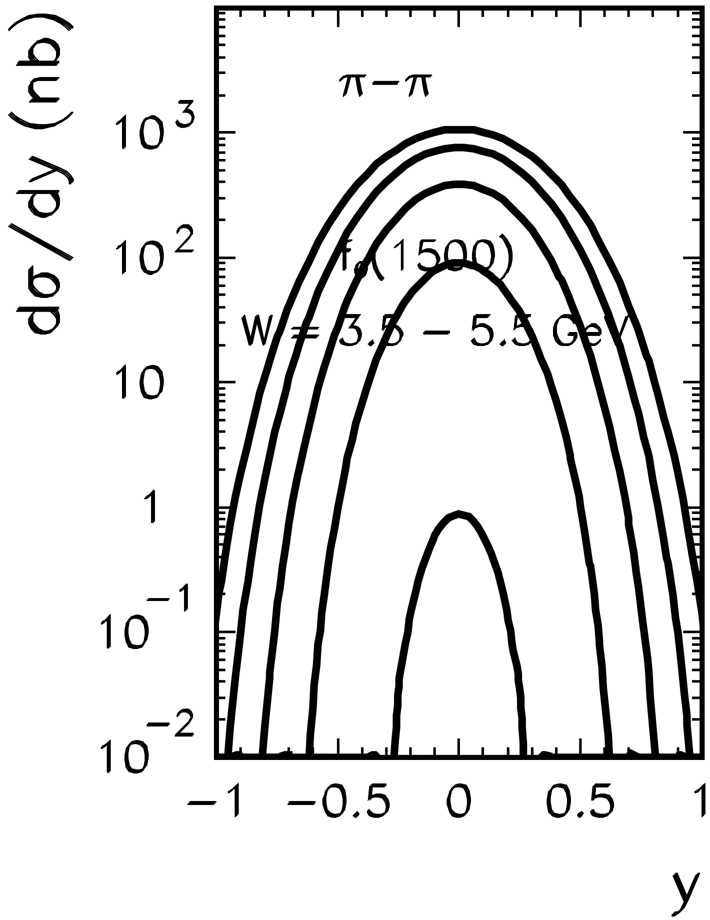

$p\bar{p} \to p\bar{p} f_0(1500)$ (left panel) and $p\bar{p} \to n\bar{n} f_0(1500)$ (right panel).

# Momentum transfer



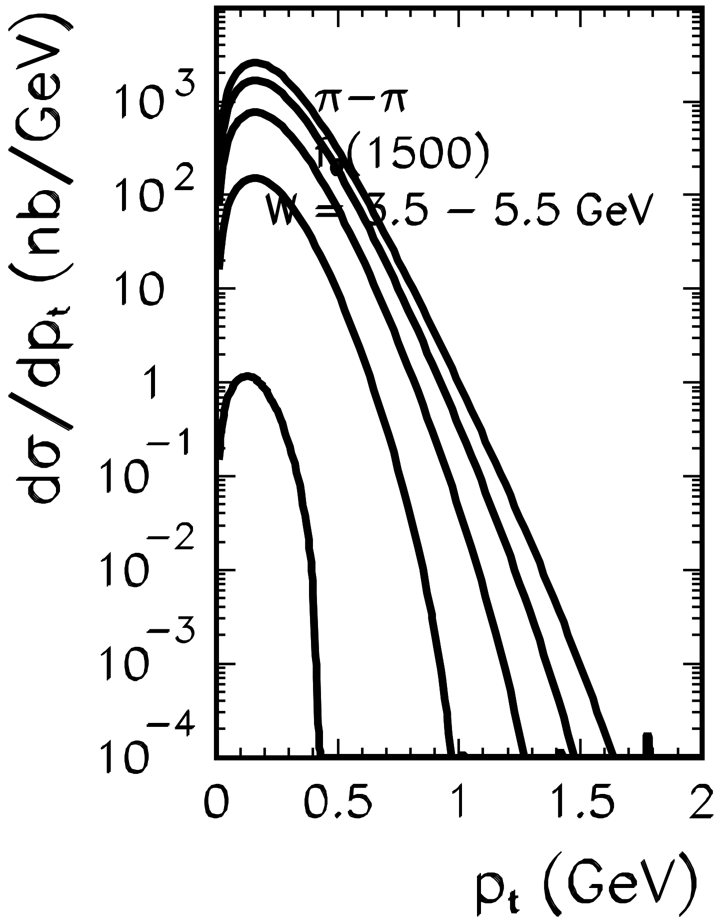

Average value of $< t_1 >=< t_2 >$.

# Predictions for PANDA, part1



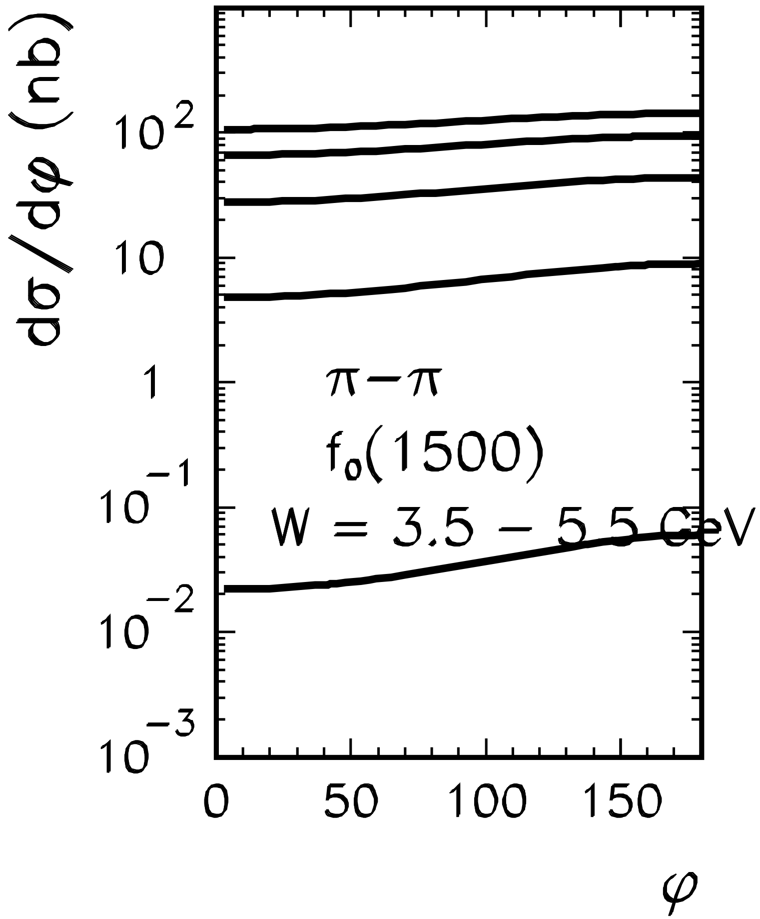

$p\bar{p} \to n\bar{n} f_0(1500)$. W = 3.5, 4.0, 4.5, 5.0, 5.5 GeV.

# Predictions for PANDA, part2



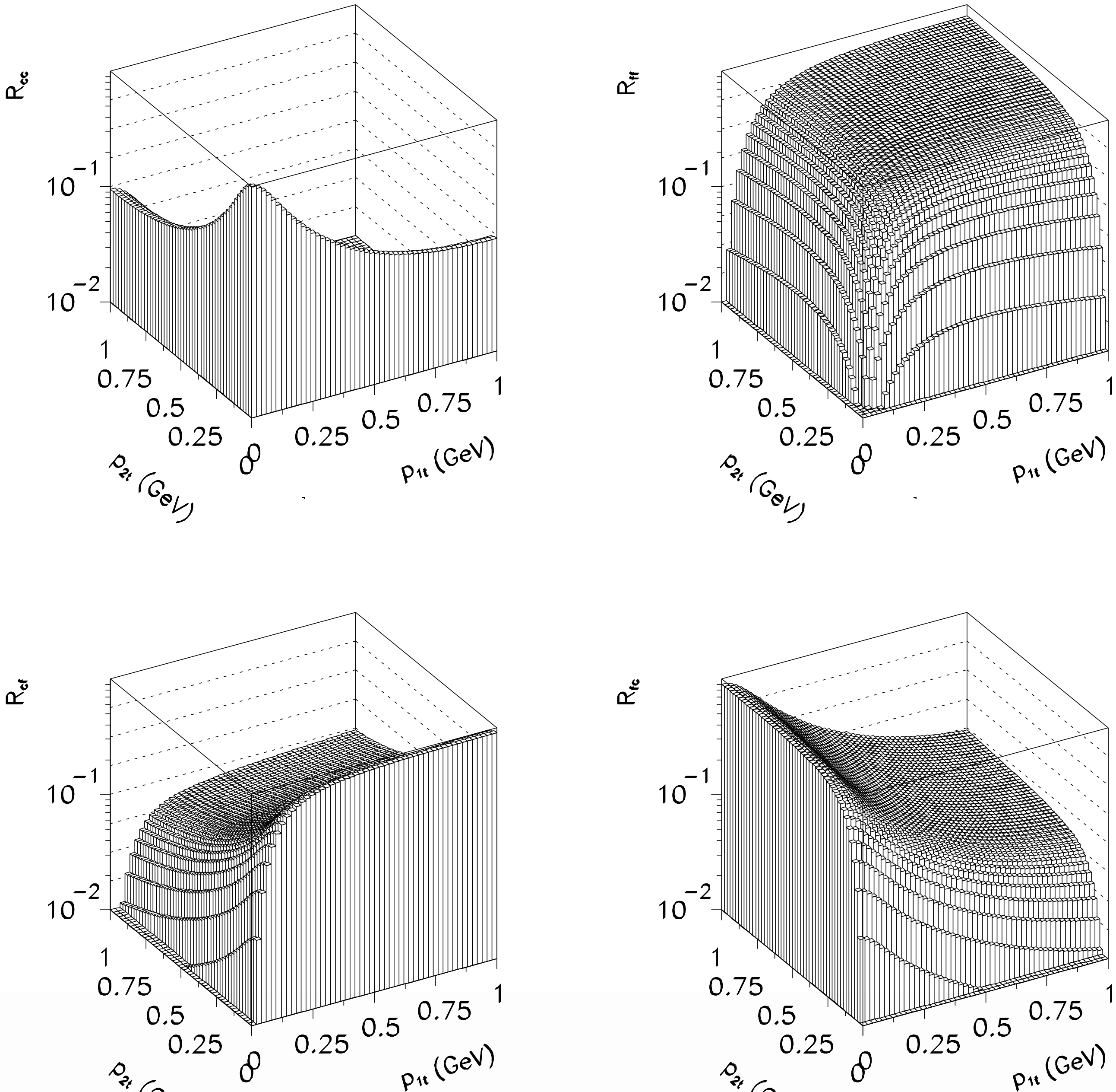

Transverse momentum distribution of neutrons or antineutrons. $p\bar{p} \to n\bar{n}f_0(1500)$. W = 3.5, 4.0, 4.5, 5.0, 5.5 GeV.

# Predictions for PANDA, part3




Azimuthal angle between neutron and antineutron in the reaction $p\bar{p} \to n\bar{n} f_0(1500)$. W = 3.5, 4.0, 4.5, 5.0, 5.5 GeV.

# Helicity decomposition



# Summary of the glueball part

- We have estimated differential cross section for exclusive $f_0(1500)$ production.
- Diffractive QCD mechanism (dominance at higher energies) and pion-pion fusion (dominance close to threshold).
- Experiments with PANDA and at J-PARC(?) could verify the predictions.
- Simultaneous analysis of:
  (a) $pp \to pp f_0(1500)$
  (b) $p\bar{p} \to p\bar{p} f_0(1500)$
  (c) $p\bar{p} \to n\bar{n} f_0(1500)$
  would help to disantangle the mechanism of the reaction.
- $f_0(1500) \to \pi\pi$. Continuum in the $\pi\pi$ channel?
- Planning experiments requires a dedicated Monte Carlo simulation of the apparatus.