Exclusive Diffractive Resonance Production in Proton-Proton Collisions at the LHC

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Abstract. A model for exclusive diffractive resonance production in proton-proton collisions at LHC energies is presented. This model is based on the convolution of the Donnachie-Landshoff parameterisation of Pomeron flux in the proton with the Pomeron cross section for resonance production. The hadronic cross section for f₀(980) and f₂(1270) production at midrapidity is given differentially in mass and transverse momentum of the resonance. The proton fractional longitudinal momentum loss is presented.

INTRODUCTION

Central production has been studied at the energies \( \sqrt{s} = 12.7-63 \text{ GeV} \) of the Intersecting Storage Ring (ISR) at CERN, at the SPS by the COMPASS Collaboration, at the Tevatron by the CDF Collaboration, at RHIC by the STAR Collaboration, and at the LHC by the ALICE and LHCb Collaborations. At all these energies, pronounced resonance structures are seen in the two-pion invariant mass spectra at values \( m_{\pi\pi} < 2 \text{ GeV}/c^2 \). The analysis of central production events recorded by complex detector systems necessitates the simulation of such events by Monte Carlo generators. The purpose of the study presented here is the formulation of such an event generator in the low mass resonance region \( m_{\pi\pi} < 2 \text{ GeV}/c^2 \) where the perturbative QCD formalism is not applicable.

CENTRAL PRODUCTION AT HADRON COLLIDERS

The pion-pair invariant mass spectra measured by the COMPASS [1], the CDF [2] and the ALICE Collaboration [3] are shown in Figure 1. Clearly visible in all the three spectra are the \( f_2(1270) \) resonance, and the \( \rho(770) \) and \( f_0(980) \).

FIGURE 1. Invariant pion pair masses from the COMPASS Collaboration on the left, the CDF Collaboration in the middle, and the ALICE Collaboration on the right.
resonance in the COMPASS data. The invariant mass spectra of the CDF and the ALICE measurements are seriously distorted at low masses due to the single track $p_T$-threshold. These mass spectra contain only the pion pairs with transverse momenta of approximately $p_T > 0.5$ and 0.8 GeV/c for the ALICE and CDF measurements, respectively. The missing acceptance of resonances in the low-$p_T$ region can, however, be modelled with the help of an event generator tuned to the visible part of the $p_T$-spectrum.

EXCLUSIVE DIFRACTIVE RESONANCE PRODUCTION

The model for exclusive resonance production is developed in two steps. In the first step, the amplitude for Pomeron-Pomeron scattering to mesonic states is formulated, and the corresponding cross section is derived [4]. In the second step, this Pomeron-Pomeron cross section is convoluted with the Pomeron distribution in the proton in order to get the resonance production cross section at hadron level.

The Dual Resonance Model of Pomeron-Pomeron Scattering

The amplitude for Pomeron-Pomeron scattering to mesonic states is defined by the dual amplitude with Mandelstam analyticity (DAMA) [5]. From the direct-channel pole decomposition of this amplitude, the cross section of Pomeron-Pomeron scattering producing low-mass resonances is derived by use of the optical theorem. The Pomeron-Pomeron channel, $PP \rightarrow M^2$, has couplings to the Pomeron and $f$ channels as defined by conservation of quantum numbers [4].

![FIGURE 2. The Pomeron-Pomeron total cross section as function of the resonance mass (figure from Ref. [4]).](image)

In Figure 2, the contributions of the $f_0(500)$ resonance, the $f_1$, $f_2$ and the Pomeron trajectory, and of the background to the Pomeron-Pomeron total cross section are shown. The contribution of the $f_0(500)$ resonance, indicated by the dashed cyan line, is calculated by taking the central values for the mass and the width of this resonance, $M_0 = 475$ MeV and $\Gamma = 550$ MeV, respectively. The contribution of the $f_1$ trajectory shown by the solid green line clearly shows the $f_0(980)$ resonance. The contribution of the $f_2$ trajectory, displayed by the dashed blue line, shows peaks for the $f_2(1270)$ and the $f_4(2050)$ resonances.

The Cross Section at Hadron Level

The cross section at hadron level can be derived by using the definition of a cross section element

$$d\sigma = \frac{|M|^2}{\text{flux}} dQ,$$

with $M$ the invariant amplitude of the process, $dQ$ the Lorentz-invariant phase space, and the flux in the denominator representing the flux factor. Equation (1) can be rewritten as

$$|M|^2 dQ = \text{flux}_{prot} d\sigma_{prot} = \text{flux}_{Pom} F_{Pom}^{prot} d\sigma_{Pom}.$$

(2)
In Equation (2), the quantity $F_{\text{Pom}}^{\text{prot}}$ represents the distribution of Pomerons in the proton. The flux factor for collinear two-body collision of particle A and B is given by \cite{6}

$$\text{flux} = 4. \ast \left(\frac{p_A \cdot p_B}{2} - m_A^2 m_B^2\right)^{1/2}. \quad (3)$$

From Equation (2), a cross section element at hadron level is defined as

$$d\sigma_{\text{prot}} = \frac{\text{flux}_{\text{Pom}}}{\text{flux}_{\text{prot}}} F_{\text{Pom}}^{\text{prot}} d\sigma_{\text{Pom}}. \quad (4)$$

The distribution of Pomerons in the proton, $F_{\text{Pom}}^{\text{prot}}$, can be expressed as function of $t$ and $\xi$, $F_{\text{Pom}}^{\text{prot}} = F_{\text{Pom}}^{\text{prot}}(t, \xi)$, with $t$ the 4-momentum transfer to the proton, and $\xi$ the fractional longitudinal momentum loss of the proton, $\xi = 1 - x_F$.

An analysis of the Pomeron structure function arrives at the distribution of Pomerons in the proton parameterised in the following form (averaged over azimuthal angle $\phi$) \cite{7}

$$F_{\text{Pom}}^{\text{prot}}(t, \xi) = \frac{9\alpha^2}{4\pi^2} \left[F_1(t)\right]^2 \xi^{1-2\alpha(t)}, \quad (5)$$

with $\beta_0 = 1.8 \text{ GeV}^{-1}$, $F_1(t)$ the elastic form factor, and $\alpha(t)$ the Pomeron trajectory $\alpha(t) = 1 + \varepsilon + \alpha' t$ with $\varepsilon \sim 0.085$, $\alpha' = 0.25 \text{ GeV}^{-2}$.

The total cross section for exclusive resonance production at hadron level is expressed as

$$\sigma_{pp} = \iint \text{flux}_{\text{Pom}} F_{\text{Pom}}^{\text{prot}}(t_A, \xi_A, \phi_A) F_{\text{Pom}}^{\text{prot}}(t_B, \xi_B, \phi_B) \sigma_{pp}(M_x, t_{AB}) dt_A d\xi_A d\phi_A dt_B d\xi_B d\phi_B. \quad (6)$$

With a kinematic transformation $(t_A, \xi_A, t_B, \xi_B) \rightarrow (u_+, u_-, v_+, M_x, p_{T,x})$ with Jacobian $J$, the cross section becomes

$$\sigma_{pp} = \iint \text{flux}_{\text{Pom}} F_{\text{Pom}}^{\text{prot}} F_{\text{Pom}}^{\text{prot}} \frac{p_{T,x} dt_{p_{T,x}}}{\sqrt{F^2 - (p_{T,x}^2 - G)^2}} \frac{\sigma_{pp}(M_x, u_+, u_-, v_+) M_x J dM_x d\varepsilon d\varepsilon d\varepsilon d\varepsilon}{\sqrt{H^2 - (\frac{\varepsilon_+ + M_x^2}{2\gamma})^2}}, \quad (7)$$

with $M_x$ and $p_{T,x}$ the mass and transverse momentum of the meson state, respectively, and $F, G$ and $H$ known functions of the new variables $u_+, u_-, v_+$.

From Equation (7), the double differential cross section is defined as

$$\frac{d\sigma_{pp}}{dM_x dp_{T,x}} = \iint \text{flux}_{\text{Pom}} F_{\text{Pom}}^{\text{prot}} F_{\text{Pom}}^{\text{prot}} \frac{p_{T,x}}{\sqrt{F^2 - (p_{T,x}^2 - G)^2}} \frac{\sigma_{pp}(M_x, u_+, u_-, v_+) M_x J dM_x d\varepsilon d\varepsilon d\varepsilon d\varepsilon}{\sqrt{H^2 - (\frac{\varepsilon_+ + M_x^2}{2\gamma})^2}}. \quad (8)$$

**FIGURE 3.** The differential cross section for resonance production by $f_1$ trajectory on the left, and by $f_2$ trajectory on the right.
The triple differential cross section \( \frac{d^3\sigma}{dM dp_T dx} \) is shown in units of \( \text{mb GeV}^{-2}c^3 \) on the left of Figure 3 for resonance production by \( f_1 \) trajectory at midrapidity. The corresponding differential cross section for the \( f_2 \) trajectory is shown on the right.

**FIGURE 3.** The proton fractional longitudinal momentum loss for \( f_0(980) \) production.

The proton fractional longitudinal momentum loss \( \xi \) for \( f_0(980) \) production at a center-of-mass energy \( \sqrt{s} = 14 \text{ TeV} \) is shown in Figure 4. Values of \( \xi \) in the range \( 1-6 \times 10^{-4} \) are reached. Such low \( \xi \)-values underline the interest of central diffractive production studies in the low-mass region for examining the Pomeron distribution in the proton at low values of Bjorken-\( x \). In this kinematical range, the onset of gluon saturation is one of the central issues for studying QCD induced dynamics at the LHC.

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