EXPLORING RESONANCE BEHAVIOR IN PROTON DIFFRACTION WITH MONTE CARLO EVENT GENERATION IN PYTHIA8

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The dual-amplitude model of the diffractive scattering of protons is implemented in Pythia8 Monte Carlo event generator, which allows to describe resonance production at low diffractive masses. The model includes the baryon N^+ resonances at low M_X^2 using a complex non-linear baryon Regge trajectory, the Roper resonance is also included using Breit-Wigner formula. At high M_X^2 the model provides smooth M_X^2 - dependency. The results are compared with the available diffraction models in Pythia8.

PACS: 11.55.-m, 11.55. Jy, 02.70. Uu, 02.70.-c

As is known from many experimental results in high-energy hadron scattering, most events are localized within the small momentum transfer region [1]. The combination of high energies and small momentum transfers creates conditions for the realization of diffraction processes [2, 3]. The main types of diffractive processes are single diffraction (SD), in which one of the incoming protons dissociates, double diffraction (DD), in which both protons dissociate and central diffraction (CD) or double-Pomeron exchange where neither proton dissociates (Fig. 1).

Let's consider the simplest of these three processes - the single diffraction. The primary theoretical approach to explaining single diffraction dissociation relies on Regge theory and the hypothesis of Pomeron exchange. In this model, the Pomeron is a theoretical construct, which does not carry charge, color, or flavor. It allows the exchange of momentum between particles without breaking them apart.

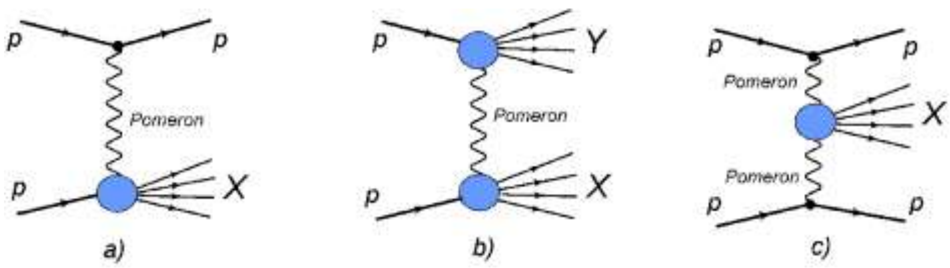

Fig.1 a) single diffraction (SD), b) double diffraction (DD) and c) central diffraction (CD), where p – is proton, X(Y) – is a system of secondary hadrons

In the model we are considering, double differential cross section is obtained from the elastic process using Regge factorization

$$\frac{d^2\sigma}{dtdM_X^2}\left(s,t,M_X^2\right)=\frac{1}{2}F_p^2\left(t\right)F_{inel}^2\left(t,M_X^2\right)\left(\frac{s}{M_X^2}\right)^{2\left(\alpha_p(t)-1\right)}, \tag{1}$$

where $\alpha_p\left(t\right)=1.075+0.34t$ – is the Pomeron trajectory, $F_p\left(t\right)=\dfrac{4m_p^2-2.9t}{4m_p^2-t}\left(1-t/0.71\right)^{-2}$ – elastic proton form-factor, $F_{inel}\left(t,M_X^2\right)$ – the nucleon structure function, s – is the square of the center-of-mass energy of the collision, t – is the momentum transfer between colliding particles, M_X – is the mass of the diffractive system. The most challenging building block of the expression (1) is the nucleon structure function, which describes the Pomeron-proton vertex. This structure function can be constructed from the similarity between the Pomeron-proton diffractive process and deep inelastic scattering (DIS), where Pomeron is associated with virtual photon [4]. This provides us with the following expression for inelastic structure function

$$F_{inel}^2\left(t,M_X^2\right)=AK_f\left(t,M_X^2\right)\sigma_T^{Pp}\left(M_X^2,t\right), \tag{2}$$

where $K_f\left(t,M_X^2\right)=\dfrac{x_B\left(1-x_B\right)^2}{\left(M_X^2-m_p^2\right)\left(1-4m_p^2x_B^2/t\right)^{3/2}}$ – kinematic factor taken from DIS, A – is the model parameter, $x_B=-t/\left(M_X^2-m_p^2-t\right)$ – is the Bjorken variable, $\sigma_T^{Pp}\left(M_X^2,t\right)$ – the total $Pp\to X$ cross-section.

The core idea of the model is the connection $\sigma_T^{Pp}\left(M_X^2,t\right)$ to the direct channel resonance decomposition of the dual amplitude. For this we use unitary condition and Veneziano duality [5]. Finally the $\sigma_T^{Pp}\left(M_X^2,t\right)$ take the form

$$\sigma_T^{Pp}\left(M_X^2,t\right)=\mathrm{Im}\,A\left(M_X^2,t\right)\sim\mathrm{Im}\sum_{n\in 0,1,\ldots}\frac{\left[f(t)\right]^{2(n+1)}}{2n+0.5-\alpha_{N^*}\left(M_X^2\right)},\qquad(3)$$

where $f(t)=e^{b_{res}t}$ – is the form factor appearing in $Pp\to Pp$ process, $\alpha_{N^*}\left(M_X^2\right)$ – is a complex Regge trajectory, which encapsulates the contributions of various baryon resonances to the scattering amplitude (see Figs. 2, 3).

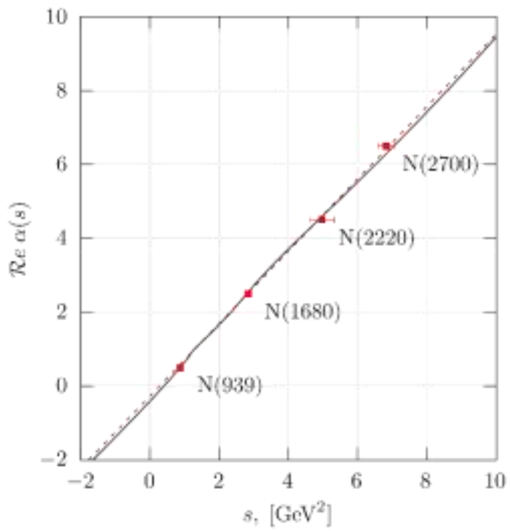

Fig. 2 $\mathrm{Re}\,\alpha$ *relates the mass of the baryon* M *and its angular momentum* J

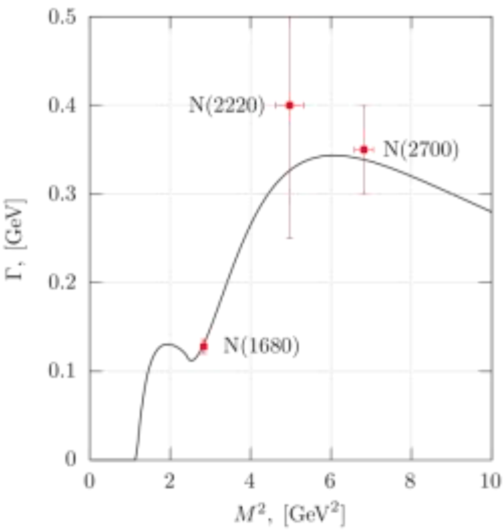

Fig. 3, $\mathrm{Im}\,\alpha$ *provides the Breit-Wigner widths* Γ *of the resonances*

The trajectory used in the model includes the following N resonances: N (1680), N (2220), N (2700) [6,7]. Roper resonance N (1440) is the first radially excited state of the nucleon. It does not lie on this trajectory. The contribution of Roper resonance to (3) is included separately using Breit-Wigner formula:

$$\sigma_T^{Pp}\left(M_X^2,t\right)=\left(\sum_{res\in\alpha_{N^*}}\ldots\right)+b\frac{f^2(t)M_R\Gamma_R/2}{\left(M_X^2-M_R^2\right)+\left(\Gamma_R/2\right)^2},\qquad(4)$$

where b – is another model parameter, $M_R\approx 1.37$ GeV is the Roper mass, $\Gamma_R\approx 0.18$ GeV is the Roper Breit-Wigner width.

The structure function (2) also includes the term corresponding to non-resonance contributions

$$F_{inel}^2\left(t,M_X^2\right)=AK_f\left(t,M_X^2\right)\sigma_T^{Pp}\left(M_X^2,t\right)+c_{bg}\sigma_{bg}\left(M_X^2,t\right).\qquad(5)$$

It has the form

$$\sigma_{bg}\left(M_X^2,t\right)=\frac{e^{b_{bg}t}}{\left[M_X^2-\left(m_p+m_\pi\right)^2\right]^{\zeta}+M_X^{2\eta}},\qquad(6)$$

where c_{bg},b_{bg},ζ,η – are model parameters, fitted to the experimental data [5].

We implemented the model in Pythia8 Monte Carlo event generator for such reasons. Firstly, it is necessary to compare the model with other diffraction models that have already been implemented. At the same time, it is important to consider how well the model aligns with experiments and its real-world applicability. Finally, the model should be made available to the broader scientific community.

Let's consider available diffraction models in Pyphia8: SaS/DL (Schuler & Sjöstrand/Donnachie & Landshoff), MBR (Minimum Bias Rockfeller), ABMST

(Appleby & Barlow & Molson & Serluca & Toader) and User parametrization (quite limited approach). The model considered in this article was noted as JK model (Jenkovszky & Kuprash). The proposed model (JK model) describes resonances at low M_X^2, whereas other models (SaS/DL, MBR) do not exhibit such resonances (see Fig. 4).

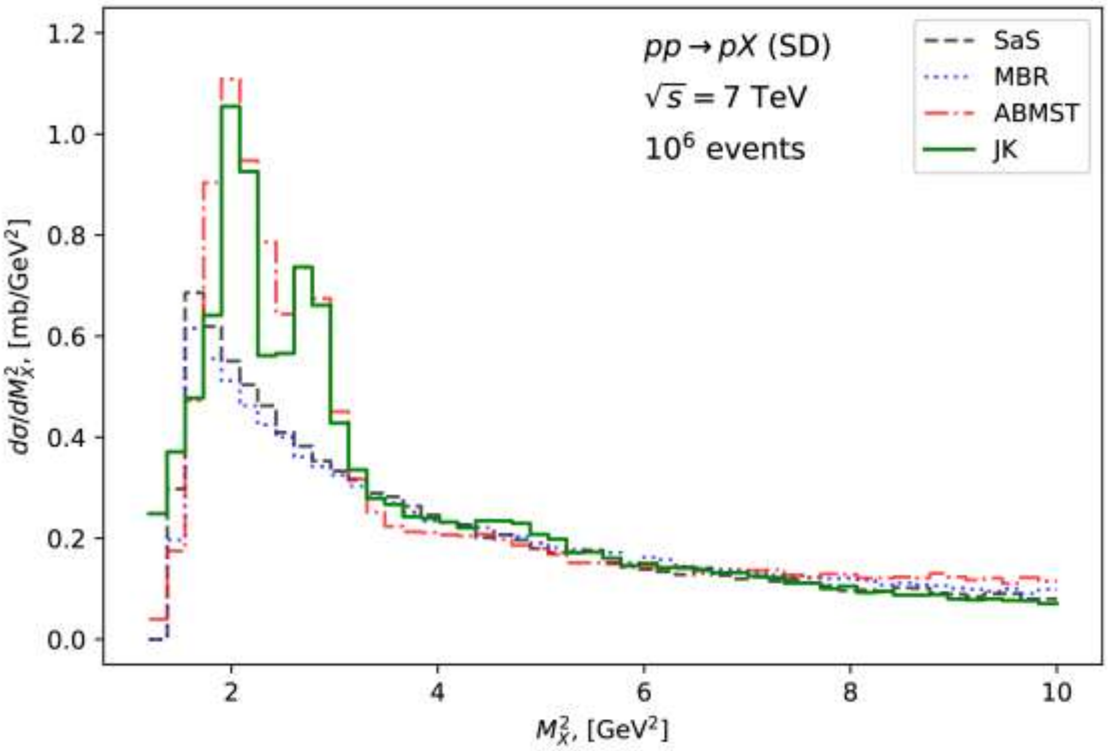

Fig. 4. Comparison of existing diffraction models in Pythia 8 with the JK model

In the JK and ABMST models peaks appear in the resonance region, but the ABMST model accounts for these resonances using the Breit-Wigner formula, tuned at low s. If we compare the generation and calculation they match (Fig. 5).

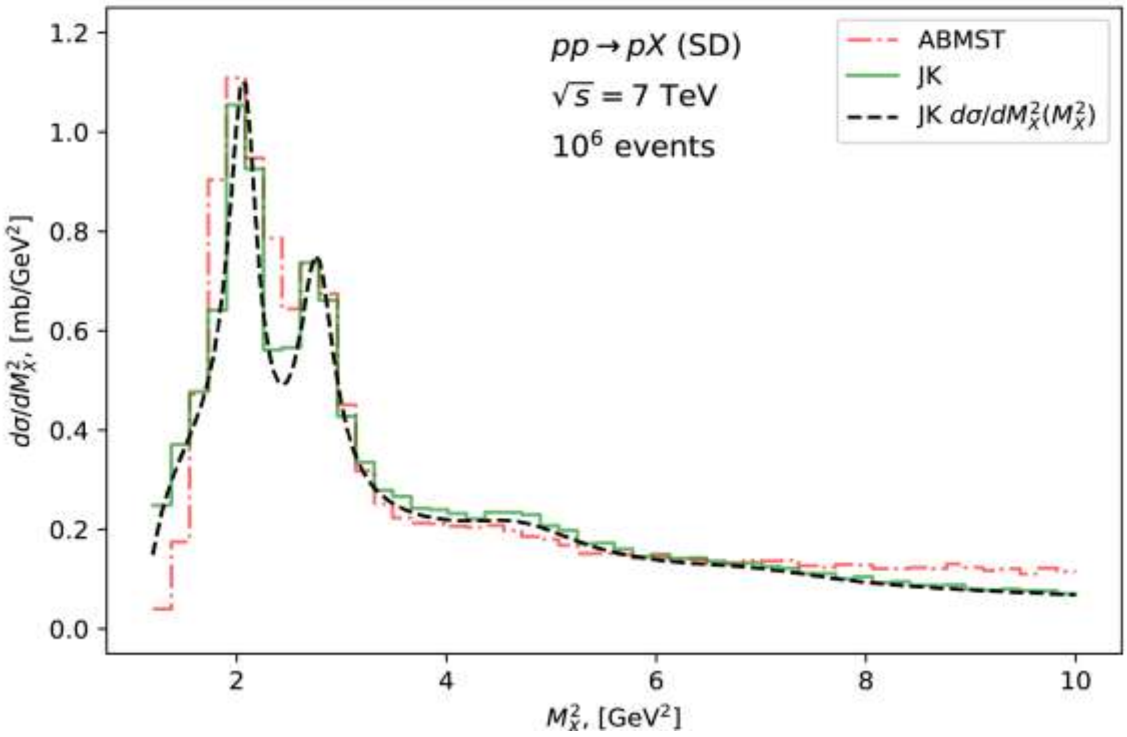

Fig. 5. Comparison of the calculated JK model (dashed line) and the JK and ABMST generation (green and red lines)

As seen in the Figs. 4 and 5, the ABMST model also has peaks in the resonance region, but the differences between these models will be shown later.

Let's consider the differential cross-section with respect to the rapidity gap (see Fig. 6). Rapidity gap – is a region in the detector with very few or no particles.

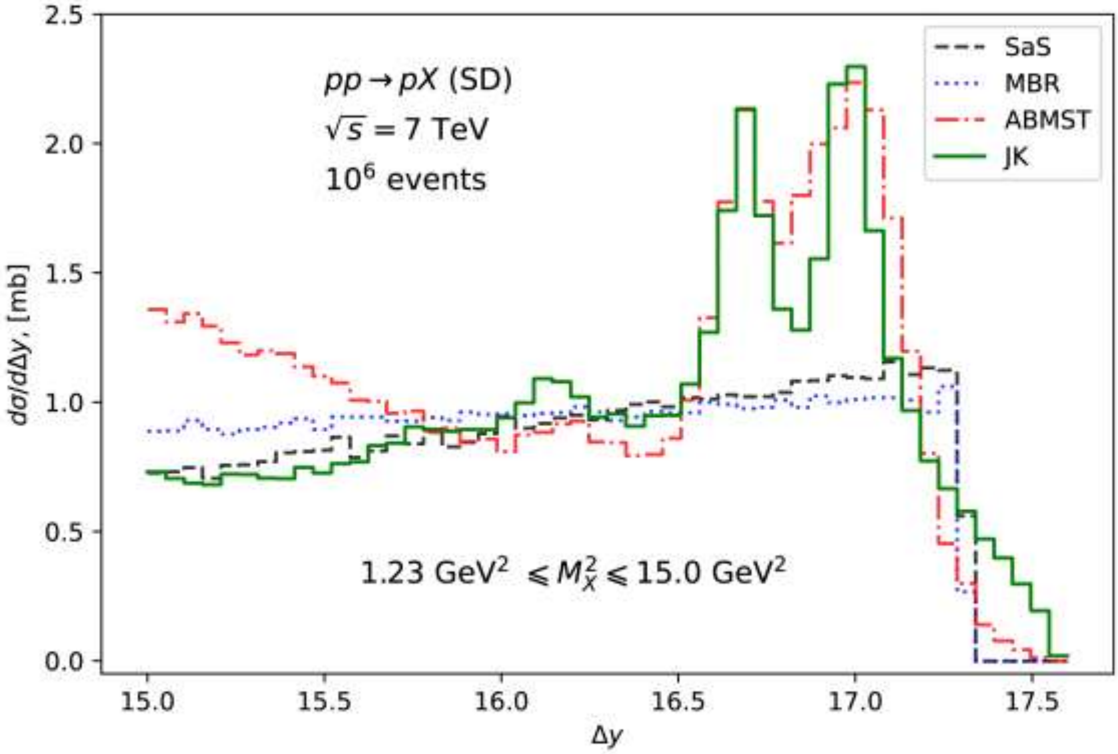

Fig. 6. Comparison of existing diffraction models in Pythia 8 with the JK model, where $\Delta y = -\ln \xi, \xi = M_X^2 / s$

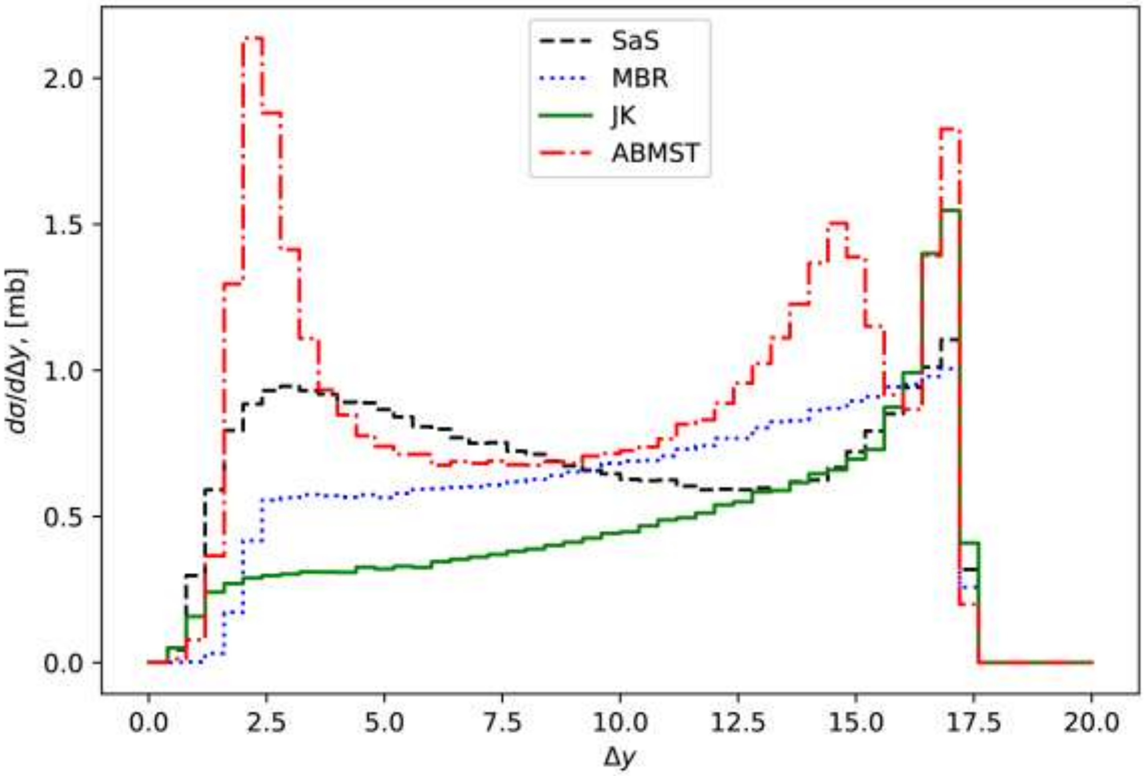

Fig. 7. Comparison of existing diffraction models in Pythia 8 with the JK model for $0 \le \Delta y \le 20.0$

Fig. 7 shows that the ABMST model has peaks in the region where all other models do not show such peaks. Also, integrated SD cross-section was generated with Pyphia8 (Table).

Integrated SD cross-section

Model	σ_{SD}
SaS	12.38 mb
MBR	10.91 mb
ABMST	15.84 mb
JK	8.38 mb

CONCLUSIONS

There are three available diffraction models in Pythia8. The SaS and MBR (default model) do not describe resonances at low M_X^2, which can be seen from the obtained histograms. These models provide smooth behavior of differential cross-section $d\sigma / dM_X^2$ in the resonance region (M_X < 4 GeV). The ABMST model describes the resonances at low M_X^2 using Breit-Wigner formula, however, it is tuned at low s. Moreover, the JK model we implemented in Pythia8 describes the resonances at low M_X^2 using complex non-linear baryon Regge trajectory and provides smooth M_X^2 – dependency at high M_X^2 like SaS and MBR models.

ACKNOWLEDGEMENT

This research has received funding through the EURIZON project, which is funded by the European Union under grant agreement No.871072.

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