MODEL-INDEPENDENT ODDERON RESULTS BASED ON TOTEM DATA ON ELASTIC PROTON–PROTON SCATTERING AT 8 TeV*

Tamás Csörgő[a,b,†], Tamás Novák[b], Roman Pasechnik[c]
András Ster[a], István Szanyi[a,b,d]

[a]Wigner RCP, HAS, 1525 Budapest 114, P.O. Box 49, Hungary
[b]MATE Institute of Technology, KRC, 3200 Gyöngyös, Mátrai út 36, Hungary
[c]Department of Physics, Lund University, 223 63 Lund, Sweden
[d]Eötvös University, 1117 Budapest, Pázmány P. s. 1/A, Hungary

Received 12 January 2023, accepted 7 February 2023,
published online 25 May 2023

We complete the model-independent analysis of the scaling properties of the differential cross section of elastic proton–proton cross sections, including new TOTEM data published in 2022 at $\sqrt{s} = 8$ TeV. We separate the signal and background regions with a new gating method. In the signal region, we find that the statistical significance of the Odderon exchange from the combined 7.0 and 8.0 TeV pp data of TOTEM and the 1.96 TeV $p\bar{p}$ data of D0 is at least 7.32σ. In the background region, the scaling functions of elastic proton–proton data at 7 and 8 TeV, and that of elastic proton–antiproton scattering data at 1.96 TeV agree with a statistical significance not larger than 1.93σ.

DOI:10.5506/APhysPolBSupp.16.5-A2

1. Introduction

The Odderon by now is an almost 50 years old scientific puzzle. The possible existence of the Odderon exchange was proposed by Lukaszuk and Nicolescu in 1973 [1], but until 2021, publications of statistically significant, at least 5σ level observational evidence of the theoretically predicted Odderon exchange from experimental data were lacking. Recent data from the TOTEM Collaboration at 2.76, 7, 8, and 13 TeV [2–4] at the Large Hadron Collider (LHC) allowed for the discovery of the Odderon exchange when combined with data of the D0 experiment at 1.96 TeV [5] at Tevatron. Both the Tevatron and LHC provided collisions at the TeV energy scale, where

* Presented at the Diffraction and Low-x 2022 Workshop, Corigliano Calabro, Italy, 24–30 September, 2022.

† Coresponding author: `tcsorgo@cern.ch`

the dominant exchanges are the gluonic Pomeron and Odderon exchanges, while the contribution of hadronic Reggeon exchanges is suppressed below the experimental errors [6]. Consequently, the Odderon exchange has been searched for as an odd component of elastic scattering amplitude which changes sign under crossing [7–9].

Currently, there are at least four published papers [8–11] that present statistically significant observations of the Odderon. A model-independent and data-driven statistical method that utilized the $H(x)$ scaling property of pp elastic scattering was published in February 2021 [8]. This method is based on a direct data-to-data comparison, without theoretical inputs, hence it is a truly model-independent method, however, the domain of the validity of this method has been determined so far only model-dependently [8]. The resulting significance of the Odderon exchange was found to be at least 6.26σ [8], which seems to be the first published, greater than 5σ observation of the Odderon exchange. This discovery paper [8] was based on a re-analysis of previously published, public-domain experimental data of the D0 and TOTEM collaborations, Refs. [3, 5, 12], measured at $\sqrt{s} = 1.96$, 2.76, and 7.0 TeV, respectively. We follow here the conventions, definitions, notations, and methods of Ref. [8], extending it to the analysis of new data on elastic pp collisions at 8.0 TeV [13], as illustrated in Fig. 1.

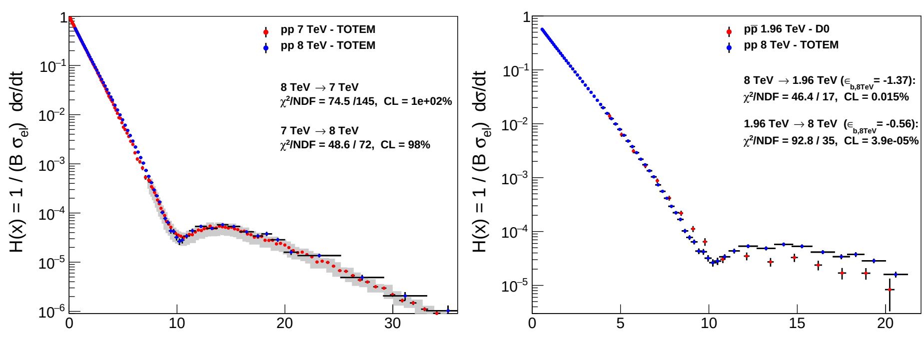

Fig. 1. Left panel compares the $H(x, s_i|pp)$ scaling functions at $\sqrt{s_1} = 7$ TeV [8, 12] and $\sqrt{s_2} = 8$ TeV [13], corresponding to an agreement with a confidence level of C.L. $\geq 98\%$. Right panel compares the $H(x, s_2|pp)$ with the $H(x, s_3|p\bar{p})$ scaling functions at $\sqrt{s_3} = 1.96$ TeV [5, 8], corresponding to a disagreement, indicating an Odderon signal of at least 3.74σ, when all the 17 D0 $p\bar{p}$ datapoints at $\sqrt{s_3} = 1.96$ TeV are compared with pp data in the same $x = -tB$ range at $\sqrt{s_2} = 8$ TeV.

The second proof of a discovery level Odderon exchange was published in July 2021, based on extrapolations of both the pp and $p\bar{p}$ differential cross sections with the help of the Real Extended Bialas–Bzdak model [14, 15], leading to a significance of at least 7.08σ [9]. In addition to the above-mentioned datasets, this analysis also utilized the $p\bar{p}$ elastic scattering data at $\sqrt{s} = 0.546$ TeV, measured by the UA4 experiment at the SPS collider [16].

The third observation of the Odderon exchange was the result of a joint analysis of the D0 and TOTEM experimental collaborations, leading to a statistical significance of at least 5.2σ, as published in August 2021 [10]. In contrast to the publications of Refs. [8, 9], that were based on a re-analysis of previously published experimental data already in the public domain, the D0–TOTEM paper [10] was based on new experimental data. Another difference was that the D0–TOTEM paper [10] was limited to the diffractive interference region, utilizing 8 D0 points out of all the publicly available 17 D0 datapoints, while the ReBB model of Ref. [9] included 14 out of the 17 D0 points in the domain of validity of its model-dependent Odderon search. In contrast, the model-independent scaling study of Ref. [8] utilized all the 17 published D0 points.

In March 2022, the TOTEM Collaboration published its 8 TeV data on elastic pp differential cross section [13] in an extended kinematic range. These data have been used in an updated Real Exendent Bialas–Bzdak model to find that the statistical significance of the observation of Odderon exchange is so large that it amounts practically to a certainty [11].

2. $H(x|pp)$ scaling and Odderon exchange at 8 TeV

In this section, we demonstrate that for elastic pp collisions, $H(x, s|pp) = H(x|pp)$ becomes independent of s, the square of the centre-of-mass energy in a limited, but large enough energy region, that includes 1.96, 2.76, 7, and 8 TeV. Table 1 summarizes the results of the pairwise comparison of the $H(x, s_i|pp)$ scaling functions for $s_i = 2.76$, 7, and 8 TeV. These datasets pairwise agree at a confidence level (C.L.) of at least 98%.

Table 1. Pairwise comparison of the $H(x, s_i|pp)$ scaling functions for $\sqrt{s_i} = 8.0$, 7.0, and 2.76 TeV indicates that these scaling functions are energy-independent with a confidence level of at least 98%.

$\sqrt{s}$ [TeV]	signal (C.L., %)
8.0 *vs.* 7.0	≥ 98
8.0 *vs.* 2.76	≈ 100
7.0 *vs.* 2.76	≈ 100

Table 2 shows the comparison of the $H(x, s_i|pp)$ scaling functions with the $H(x, s_j|p\bar{p})$ scaling functions for $\sqrt{s_i} = 8.0$, 7.0, and 2.76 TeV, and $\sqrt{s_j} = 1.96$ TeV. These pp and $p\bar{p}$ scaling functions are significantly different, except for the standalone comparison of the 2.76 TeV pp and the 1.96 TeV $p\bar{p}$ dataset. The last two lines show the lower estimate for the minimal combined significances of these pp data for an energy-independent $H(x|pp)$ as compared to the data on the $H(x, s_j|p\bar{p})$ function at $\sqrt{s_j} = 1.96$ TeV. The combined significances are safely above the discovery threshold of 5σ. If the 2.76 TeV pp dataset is not considered, the combined significance of the signal of Odderon exchange from the data measured at 8.0, 7.0, and 1.96 TeV exceeds 7.0σ. This is achieved with the full utilization of all the 17 D0 points and without any model-dependent input to this analysis.

Table 2. Pairwise comparison of the $H(x, s_i|pp)$ with the $H(x, s_j|p\bar{p})$ scaling functions for $\sqrt{s_i} = 8.0$, 7.0, and 2.76 TeV, and $\sqrt{s_j} = 1.96$ 2.76 TeV indicates that these scaling functions are clearly different, except for the comparison of the 2.76 TeV pp and the 1.96 TeV $p\bar{p}$ dataset. The combined significances are well above 5σ.

$\sqrt{s}$ [TeV]	Odderon signal [σ]
8.0 *vs.* 1.96	≥ 3.74
7.0 *vs.* 1.96	≥ 6.26
2.76 *vs.* 1.96	≥ 0.01
8.0 & 7.0 *vs.* 1.96	≥ 7.07
8.0 & 7.0 & 2.76 *vs.* 1.96	≥ 5.77

So far, we have demonstrated that for elastic $p\bar{p}$ collisions, $H(x, s_i|pp) \neq H(x, s_j|p\bar{p})$ for $\sqrt{s_i} = 8.0$, 7.0, and 2.76 TeV, and $\sqrt{s_j} = 1.96$ TeV, which provides a statistically significant signal for the Odderon exchange. However, in Ref. [8], we utilized the Real Extended Bialas–Bzdak model to show that the pp $H(x, s|pp)$ scaling function remains energy-independent even at $\sqrt{s} = 1.96$ TeV. To complete a statistically significant and model-independent proof of the Odderon exchange, we now show that $H(x, s_j|pp) = H(x|pp)$ is energy-independent also at $\sqrt{s_j} = 1.96$ TeV. Given that there are no pp data measured at 1.96 TeV, we separate the Odderon signal and background regions, and show that $H(x, s_j|p\bar{p}) = H(x|pp)$ is energy-independent at 1.96 TeV — if the comparison is limited to the background region, *i.e.* outside the Odderon signal region.

We utilize the method of closing gates that is suitable to separate the signal and background regions of the Odderon exchange. This method starts with the utilization of the full D0 dataset, then considers removing either the leftmost or the rightmost D0 datapoint, evaluating the expected increase in the signal in both cases. The next step is to gate out that of the leftmost or the rightmost datapoint that results in a smaller increase of the signal for the Odderon exchange. This procedure is iterated step by step until the significance is maximized. The remaining $17 - n - m$ datapoints of D0 are considered the signal region and the gated out $n + m$ datapoints of D0 correspond to the background region of the Odderon exchange.

When comparing the $H(x, s_i|pp)$ with the $H(x, s_j|p\bar{p})$ scaling functions, the best signal region is found at $(n, m) = (3, 2)$, corresponding to a statistical significance of the Odderon signal that is increased from 6.26σ to 6.33σ, while for the same (n, m) selection, the background regions at 1.96 and 7 TeV agree: the significance of their difference is 1.70σ only, less than an indication of a difference that starts at 3.0σ in our terminology. For the same $(3, 2)$ gating, the comparison of 8 TeV pp and 1.96 TeV $p\bar{p}$ datasets yields a signal significance that increases from 3.55σ to 4.03σ, while the backgrounds between the pp and the $p\bar{p}$ scaling functions agree at 1.04σ. The combined significances for the signal and the background are shown for the same $(3, 2)$ gating in the third line of Table 3, indicating that the backgrounds agree within 1.94σ, while the combined significance of the Odderon exchange increases to 7.32σ. The last line shows that the gated signal from the 8 TeV *versus* 1.96 TeV comparison can be further increased to 4.55σ with the gate position at $(6, 1)$, where the backgrounds also agree at 0.13σ.

Table 3. Closing gates separate the signal and background regions of the Odderon exchange at $\sqrt{s_1} = 7$ and 8 TeV. The first n and the last m of the 17 D0 $p\bar{p}$ points are taken as background, at low $-t$ and large $-t$, respectively. The remaining $17 - n - m$ datapoints of D0 constitute the signal region.

$\sqrt{s}$ [TeV]	n	m	signal [σ]	background [σ]
1.96 *vs.* 7.0	3	2	6.33	1.70
1.96 *vs.* 8.0	3	2	4.03	1.04
1.96 *vs.* 7.0 *vs.* 8.0	3	2	7.32	1.93
1.96 *vs.* 8.0	6	1	≥ 4.55	0.13

Table 3 also indicates that outside the signal region, the backgrounds of the $H(x, s|pp)$ scaling functions of elastic pp collisions at 7 and 8 TeV agree with the same region of elastic $p\bar{p}$ collisions at 1.96 TeV. Even for the combined dataset and for slightly different selections of the background region, these pp and $p\bar{p}$ backgrounds agree within less than 2.0σ deviations. This is possible only if the $H(x, s|pp) = H(x|pp)$ energy-independent scaling relation includes the center-of-mass energy of $\sqrt{s_j} = 1.96$ TeV.

3. Summary

We have completed, without any model-dependent ingredients, the proof that at the TeV energy scale, the $H(x, s_i|pp)$ scaling functions are independent of the center-of-mass colliding energy at $\sqrt{s_i} = 1.96$, 2.76, 7.0, and 8.0 TeV. We have separated the signal and background regions of this scaling using the method of closing gates. The exact location of the gating does not influence the qualitative conclusion that in the signal region, the combined statistical significance of the Odderon exchange is at least 7.0σ, safely above the 5σ discovery threshold. In the background region, the energy-independent $H(x|pp)$ scaling function agrees with the $H(x|p\bar{p})$ function at $\sqrt{s} = 1.96$ TeV, with a less than 2σ statistical significance of difference.

We thank A. Papa and his team for their hospitality and for organizing an inspiring and useful meeting at Corigliano Calabro, Italy. Our research has been supported by the Hungarian NKFI grants K133046 and 2020-2.2.1-ED-2021-00181 and the ÚNKP-22-3 New National Excellence Program, by the Swedish Research Council grants Nos. 621-2013-4287 and 2016-05996 as well as by the European Research Council (ERC) under the EU's Horizon 2020 research and innovation programme (agreement No. 668679).

REFERENCES

[1] L. Lukaszuk, B. Nicolescu, *Lett. Nuovo Cim.* **8**, 405 (1973).
[2] TOTEM Collaboration (G. Antchev *et al.*), *Eur. Phys. Lett.* **101**, 21004 (2013).
[3] TOTEM Collaboration (G. Antchev *et al.*), *Eur. Phys. J. C* **80**, 91 (2020).
[4] TOTEM Collaboration (G. Antchev *et al.*), *Eur. Phys. J. C* **79**, 861 (2019).
[5] D0 Collaboration (V.M. Abazov *et al.*), *Phys. Rev. D* **86**, 012009 (2012).
[6] W. Broniowski, L. Jenkovszky, E. Ruiz Arriola, I. Szanyi, *Phys. Rev. D* **98**, 074012 (2018).
[7] A. Ster, L. Jenkovszky, T. Csörgő, *Phys. Rev. D* **91**, 074018 (2015).
[8] T. Csörgő, *et al.*, *Eur. Phys. J. C* **81**, 180 (2021).
[9] T. Csörgő, I. Szanyi, *Eur. Phys. J. C* **81**, 611 (2021).
[10] TOTEM and D0 collaborations (V.M. Abazov *et al.*), *Phys. Rev. Lett.* **127**, 062003 (2021).
[11] I. Szanyi, T. Csörgő, *Eur. Phys. J. C* **82**, 827 (2022).
[12] TOTEM Collaboration (G. Antchev *et al.*), *Eur. Phys. Lett.* **101**, 21002 (2013).
[13] TOTEM Collaboration (G. Antchev *et al.*), *Eur. Phys. J. C* **82**, 263 (2022).
[14] A. Bialas, A. Bzdak, *Acta Phys. Pol. B* **38**, 159 (2007).
[15] F. Nemes, T. Csörgő, M. Csanád, *Int. J. Mod. Phys. A* **30**, 1550076 (2015).
[16] UA4 Collaboration (M. Bozzo *et al.*), *Phys. Lett. B* **155**, 197 (1985).