Model-independent Odderon results based on TOTEM data on elastic proton-proton scattering at 8 TeV*

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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 the background region with a new gating method. In the signal region, we find that the statistical significance of 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.

1. Introduction

The Odderon by now is an almost a 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 a statistically significant, at least 5 σ level observational evidence of the theoretically predicted Odderon exchange from experimental data were lacking[1]. Recent data from the TOTEM Collaboration at 2.76 TeV, 7 TeV, 8 TeV and 13 TeV [3, 4, 5] 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 [6] at Tevatron, the largest collider for proton-antiproton collisions so

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[1] Nicolescu was not only proposing the Odderon in 1973 [1], but in 1975, he also contributed to coining the Odderon name [2].

far. Both the Tevatron and the LHC provided collisions at the TeV energy scale, where the dominant exchanges are the gluonic Pomeron and Odderon exchanges, while the contribution of hadronic reggeon exchanges are suppressed below the experimental errors [7]. Consequently the Odderon exchange has been searched for, as an odd component of elastic scattering amplitude which changes sign under crossing [8, 9, 10].

Odderon exchange is a well established phenomenon in Quantum Chromodynamics (QCD) not only in the original Regge phenomenological framework. Let us mention some of the papers on this topic. In 1980 Kwiecinski and Praszalowicz proposed an integral equation for the C-odd three gluon system [11]. A new Odderon intercept was evaluated in a paper by Janik and Wosiek in 1999 [12]. The reggeized three-gluon exchange in QCD was proposed by Bartels, Lipatov, and Vacca in 2000 [13] and recently in 2020 the Odderon in QCD with running coupling constant was studied by Bartels, Contreras, and Vacca [14]. The usual illustration in QCD in leading order for the Pomeron is the exchange of bound states of at least two (even number of) gluons, while Odderon exchange corresponds to exchange of bound (color white) states of odd (at least three) number of gluons.

Currently there are at least four published papers [9, 10, 15, 16] 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 [9]. 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 [9]. The resulting significance of Odderon-exchange was found to be at least 6.26σ [9], which seems to be the first published, greater than 5 σ observation of Odderon-exchange. Its results were based on a re-analysis of previously published, public domain experimental data of the D0 and TOTEM collaborations, Refs. [6, 17, 18] measured at $\sqrt{s} = 1.96$, 2.76, and 7.0 TeV, respectively. We follow here the conventions, definitions, notations and methods of Ref. [9], extending it to the analysis of new data on elastic pp collisions at 8.0 TeV [19], as illustrated in Fig. 1.

The second proof of a discovery level Odderon exchange was published in July 2021, based on extrapolations of both pp and $p\bar{p}$ differential cross-sections with the help of the Real Extended Bialas-Bzdak model [20, 21], leading to a significance of at least 7.08σ [10]. 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 [22].

The third observation of 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 [15]. In

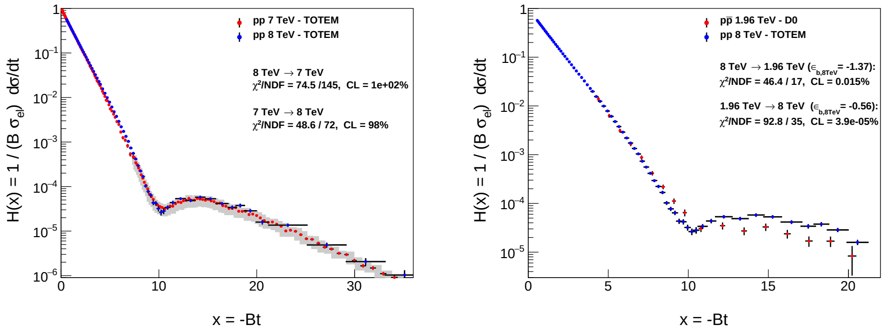

Fig. 1. Left panel compares the $H(x, s_i|pp)$ scaling functions at $\sqrt{s_1} = 7$ TeV [18, 9] and $\sqrt{s_2} = 8$ TeV [19], corresponding to an agreement with a confidence level of CL $\geq$ 98%. Right panel compares the $H(x, s_2|pp)$ with the $H(x, s_3|p\bar{p})$ scaling functions at $\sqrt{s_3} = 1.96$ TeV [6, 9], 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.

contrast to the publications of Refs. [9, 10], that were based on a re-analysis of previously published experimental data already in the public domain, the D0-TOTEM paper [15] was based on new experimental data, in particular new pp data points on the differential cross-section of elastic scattering at 8 TeV and one new datapoint at 2.76 TeV. Another difference was that the D0-TOTEM paper [15] 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. [10] 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. [9] utilized all the 17 published D0 points. Thus the different domains of validity of the three different methods applied in Refs. [9, 10] and [15] alone explain, why the published significances of Odderon-exchange were also different: at least 6.26, 7.08 and 5.2 σ, respectively. In addition, the scaling analysis of Ref. [9] and the D0-TOTEM analysis of Ref. [15] did not utilize the UA4 data on elastic collisions $p\bar{p}$ at $\sqrt{s} = 0.546$ TeV [22], in contrast to Ref. [10]. Furthermore, neither the scaling analysis of Ref. [9], nor the ReBB model dependent analysis of Ref. [10] utilized the TOTEM datasets on elastic pp scattering as measured at 8.0 and 13.0 TeV [15, 19, 23], in contrast to the above mentioned D0-TOTEM paper of Ref. [15].

In March 2022, the TOTEM Collaboration published its 8 TeV data on elastic pp differential cross-section [19] 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 in practical terms it amounts practically to a certainty [16]. Thus in September 2022, the fourth published paper reported the observation of Odderon-exchange at TeV energies with a discovery level, greater than 5σ statistical significance [16]. These model-dependent results were summarized in the conference contribution of Ref. [24].

2. H(x) 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 TeV, 2.76 TeV, 7 TeV 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 TeV, 7 TeV and 8 TeV. These datasets pairwise agree at a confidence level (CL) of at least 98% .

$\sqrt{s}$ (TeV)	signal (CL, %)
8.0 vs 7.0	≥ 98
8.0 vs 2.76	≈ 100
7.0 vs 2.76	≈ 100

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

$\sqrt{s}$ (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

Table 2. Pairwise comparision 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 indicate, that these scaling functions are 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 5 σ.

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 TeV, 7.0 TeV 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 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 TeV, 7.0 TeV and 1.96 TeV reaches above 7.0σ. This is achieved with a full utilization of all the 17 D0 points and without any model-dependent input to this analysis.

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 $\sqrt{s_i} = 8.0$ TeV, 7.0 TeV and 2.76 TeV and $\sqrt{s_j} = 1.96$ TeV, which provides a statistically significant signal for Odderon exchange. However, in ref. [9], 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 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 region, 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.

$\sqrt{s}$ (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. Closing gates separate the signal and the background region of Odderon exchange at $\sqrt{s_1} = 7$ TeV 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.

We utilize the method of closing gates that is suitable to separate the signal and background regions of 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 greater increase of the signal for 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 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 TeV 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 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 also indicates, that outside the signal region, the backgrounds of the $H(x,s|pp)$ scaling functions of elastic pp collisions at 7 TeV 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 the 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 $H(x)$ scaling functions of pp and $p\bar{p}$ collisions agree, with a less than 2σ statistical significance of difference.

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