2023

Lévy stable model for the small momentum transfer region of elastic proton-proton collisions at LHC energies. — In our earlier studies, the Real extended Bialas-Bzdak (ReBB) model turned out to be an efficient tool in a model-dependent discovery of odderon exchange in the TeV energy range, but in a limited √s and −t range. The validity range of the ReBB model in √s does not include 13 TeV, possibly due to a significant hollowness effect observed at that energy. The validity range of the ReBB model in −t includes the minimum−maximum structure of the differential cross-section, but does not include the significant non-exponential behavior at low −t values. To overcome these shortcomings of the ReBB model, we have introduced the Lévy α-stable generalized Real Extended Bialas–Bzdak (LBB) model [1]. In the low four-momentum transfer region, based on our novel approximations and the idea of the Levy-α-stable-shaped inelastic scattering probability suggested by the LBB model, we deduced and fitted a highly simplified Levy α-stable model of the proton-proton differential cross section to the measured data at √s = 8 TeV. Our simple model represents the low-|t| experimental data in a statistically acceptable manner. This is a promising prospect for future applications of the Lévy α-stable generalized Real Extended Bialas–Bzdak (LBB) model and for the clarification of an on-going debate in the literature about the possible signals of odderon-exchange at low-t values [1]. We have also confirmed our earlier results on a statistically significant observation of odderon exchange in conference reports, using both model-independent [2] as well as model-dependent methods [3] in the full -t region of the newly published elastic proton-proton scattering data at 8 TeV.

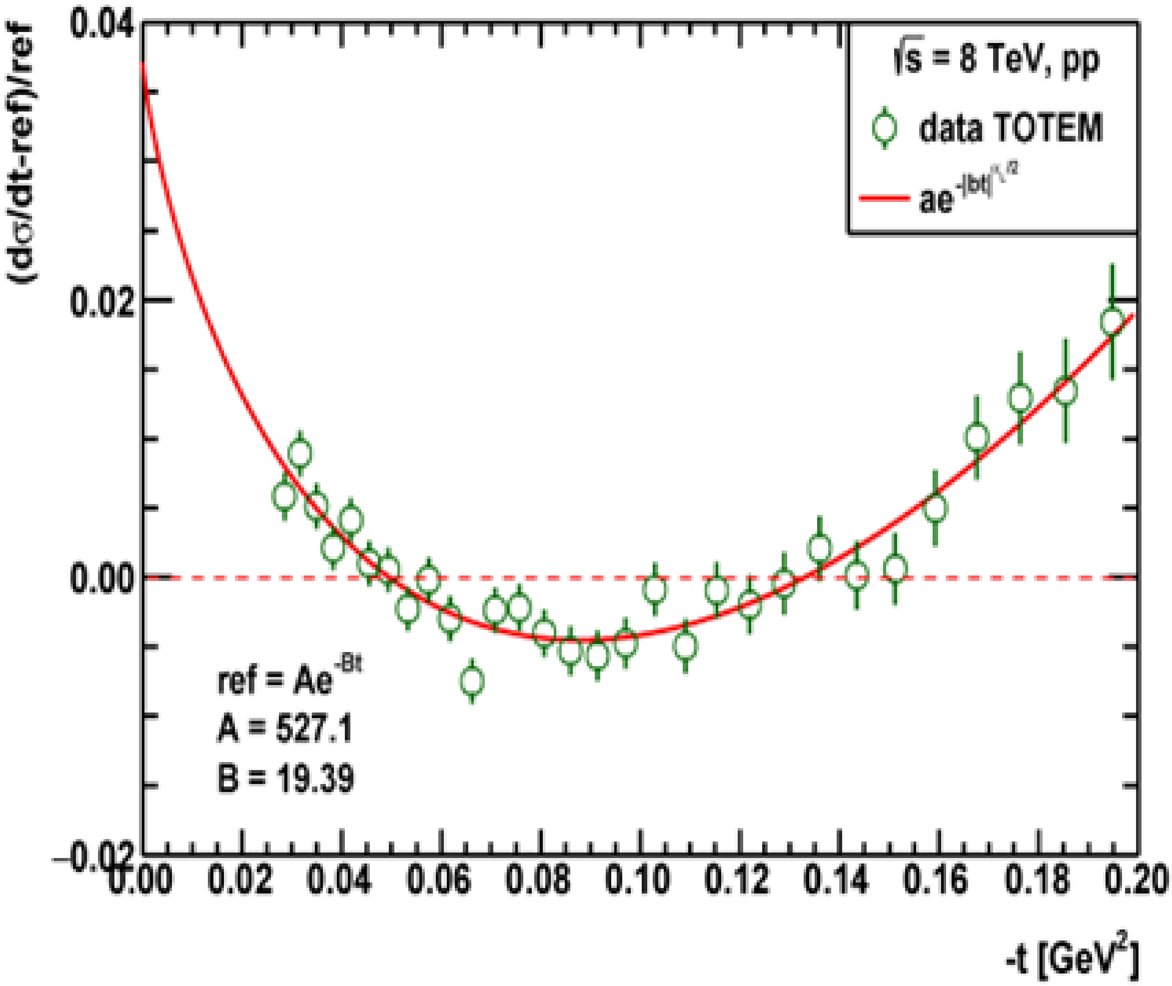

Figure 1. Description of the differential cross-section of elastic proton-proton scattering data in the

low four-momentum transfer (-t) region at s = 8 TeV using a simple Levy form is shown as a solid red, as compared to the null effect using a reference exponential (dashed line).

First publications from a common CMS and TOTEM data analysis and new limits on anomalous quartic gauge couplings. — The TOTEM group from Wigner has specialized not only in the search for odderon exchange but participated in the joint CMS – TOTEM project on precision proton spectrometer and in common CMS and TOTEM publications. In particular, F. Nemes was responsible for LHC optics calibration from TOTEM and PPS data and during 2023 he also became an expert in alignment studies in TOTEM and CMS PPS. The first physics publication of the joint CMS and TOTEM datataking was building on this expertise, the topic was a search for beyond standard model physics, in particular anomalous quartic gauge couplings. No beyond standard model physics signals were found in this search, which has been performed for exclusive high-mass $\gamma\gamma \to$ WW and $\gamma\gamma \to$ ZZ production in proton-proton collisions using intact forward protons reconstructed in near-beam Roman Pot detectors, with both weak bosons decaying into boosted and merged jets. The analysis was based on a sample of proton-proton collisions collected by the CMS and TOTEM experiments at $\sqrt{s}$ = 13 TeV, corresponding to an integrated luminosity of 100 fb^{-1}. Upper limits were set on the pp $\to$ pWWp and pp $\to$ pZZp cross sections in a fiducial region defined by the diboson invariant mass m(VV) > 1 TeV (with V = W, Z) and proton fractional momentum loss $0.04 < \xi < 0.20$. [4].

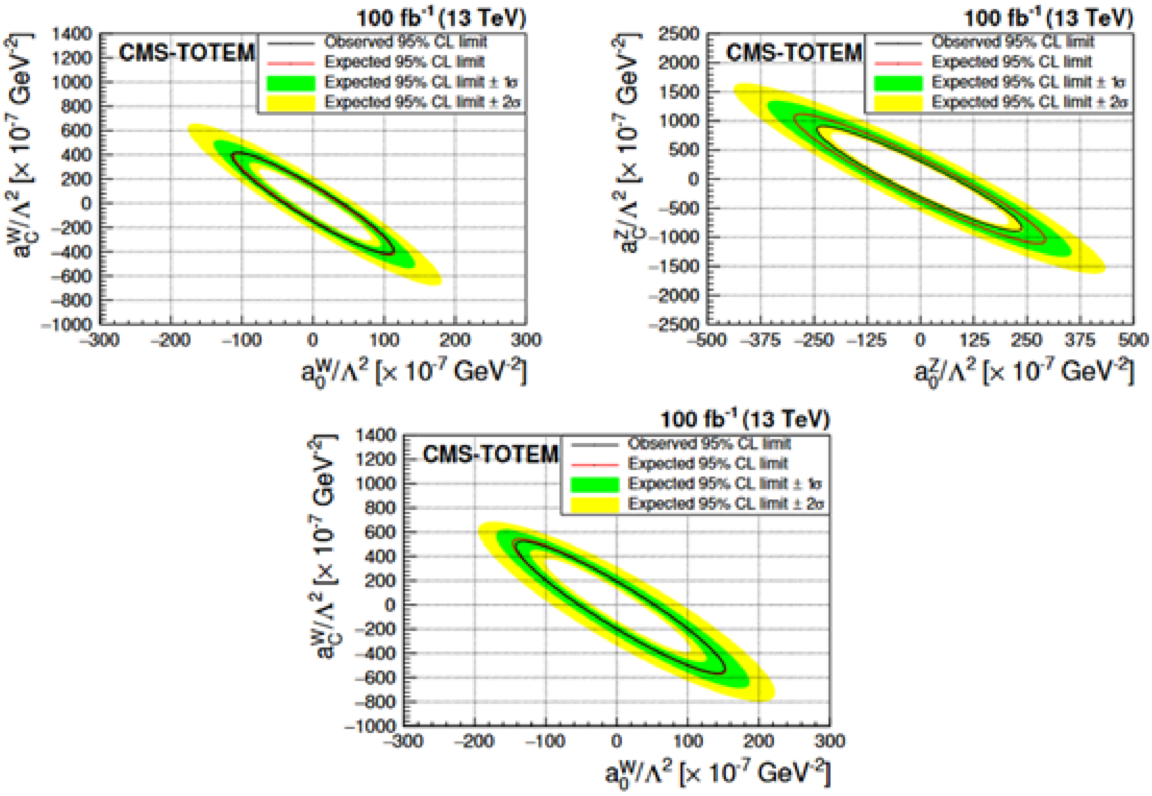

Figure 2. First published results, with significant contributions from the TOTEM group of Wigner, on a search for anomalous quartic gauge couplings in a combined CMS and TOTEM data analysis. No Beyond the Standard Model signal is found, but new upper limits were set on the pp → pWWp and pp → pZZp cross sections [4].

References:

[1] DOI: 10.3390/universe9080361

[2] DOI: 10.5506/APhysPolBSupp.16.5-A2

[3] DOI: 10.5506/APhysPolBSupp.16.5-A10
[4] DOI: JHEP07(2023)229

2022

A new and exact, spherical solution of viscous fireball hydrodynamics. — We have found a new family of analytic, exact solutions of non-relativistic Navier–Stokes hydrodynamics in 1 + 3 dimensions. In these solutions, the velocity field is spherically symmetric Hubble flow, so the effect of shear viscosity cancels, and we assumed that the heat conduction is negligible. This article was selected by the journal as a Feature Article in the MDPI Journal Entropy [1 (https://www.mdpi.com/1099-4300/24/4/514)]. With these features, we have provided exact and analytic solutions for the cases of homogeneous and inhomogeneous pressure as well, as illustrated on Fig. 1. We have shown that the approach to "perfection" is not specific to relativistic kinematics, but seems to be a more general phenomenon, valid for certain exact, 1 + 3 dimensional, spherically symmetric, parameteric solutions of the Navier–Stokes equations. Generalisations of these results to the case of spheroidal and ellipsoidal as well as multipole solutions are in progress but will be discussed in separate manuscripts. For more information please visit the homepage of the Zimányi School: Hydrodynamics and Thermodynamics in Relativistic Heavy Ion Collisions (https://www.mdpi.com/journal/entropy/special_issues/hydrodynamics_thermodynamics).

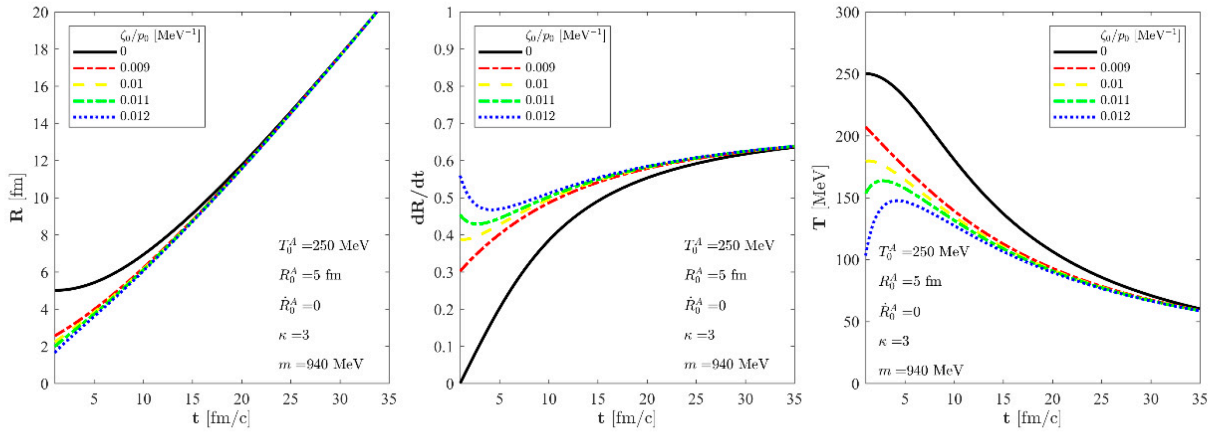

Figure 1. The dashed blue, the dotted--dashed green, the dashed yellow, and the dotted--dashed red lines correspond to our new viscous solution of non-relativistic Navier-Stokes equations for different values of the kinematic bulk viscosity, but for the same, asymptotically perfect fluid, spherically expanding fireball solution.

Odderon exchange is a certainty. — During 2022, the TOTEM Collaboration at CERN LHC published its final data on the diffractive minimum and maximum measurements in elastic proton-proton collisions at √s = 8 TeV [2 (https://link.springer.com/article/10.1140/epjc/s10052-022-10065-x)]. Within the framework of the Real Extended Bialas-Bzdak model, we have evaluated the impact of these new data on the statistical significance of the observation of Odderon exchange [3]. Our published results were also disseminated in well received conference presentations [4 (https://arxiv.org/abs/2211.17079)], and summarized in Table 1. Thus Odderon exchange is, in any practical terms, not a probability, but a certainty at the TeV energy scale. This feature is highighted, unusually, even in the title of the published paper [3 (https://link.springer.com/article/10.1140/epjc/s10052-022-10770-7)].
The Hungarian contribution to the discovery of Odderon exchange was also highlighted in a recent

study book [5], that appeared in the beginning of 2022. The publication of this textbook in Hungarian language [5] was supported by the Domus Publishing Programme of the Hungarian Academy of Sciences.

$\sqrt{s}$ (TeV)	χ^2	NDF	CL	significance (σ)
1.96	24.283	14	0.0423	2.0
2.76	100.347	22	5.6093×10^{-12}	6.8
7	2811.46	58	$< 7.2853 \times 10^{-312}$	>37.7
8	426.553	25	1.1111×10^{-74}	≥18.2

Table 1. Summary of the model-dependent significances of Odderon exchange from Refs. [3 (https://link.springer.com/article/10.1140/epjc/s10052-022-10770-7),4 (https://arxiv.org/abs/2211.17079)]. The significances as well as their combinations [3 (https://link.springer.com/article/10.1140/epjc/s10052-022-10770-7),4 (https://arxiv.org/abs/2211.17079)] are much higher than 5 σ, the conventional statistical threshold for a discovery in high energy particle and nuclear physics.

References:
[1] DOI: 10.3390/e24040514 . Feature paper, that represents the most advanced research with significant potential for high impact in the field. By G. Kasza, L. P. Csernai and T. Csörgő.
[2] DOI: 10.1140/epjc/s10052-022-10065-x By TOTEM Collaboration (T. Csörgő, F. Nemes ...)
[3] DOI: 10.1140/epjc/s10052-022-10770-7 By I. Szanyi and T. Csörgő
[4] DOI: 10.48550/arXiv.2211.17079 by I. Szanyi and T. Csörgő (Diffraction and Low-x 2022)
[5] Jenkovszky László, Spenik Sándor, Szanyi István és Turóci-Sütő Jonán: Rugalmas és diffraktív szórás az LHC korában: A Pomeron, az Odderon és a Gluonlabdák (a textbook in Hungarian language, published by Ungvár- Budapest, Autdoor Shark kiadó, 2021 (2022), pp. 152). Supported by the "MTA Domus Könyvkiadási Pályázat" of the Hungarian Academy of Sciences. This is the first book on this topic in Hungarian. Lectored by Tarics, Zoltán.

2021

After 48 years of particle physics research, the elusive quasi-particle called odderon has been discovered in 2021.

In February 2021, three members of the Femtoscopy Research Group of Wigner RCP together with another Hungarian colleague of MATE Institute of Physics KRC, Gyöngyös and one Swedish scientists from the University of Lund, Lund, Sweden, published a statistically significant, greater than 5 σ evidence for the exchange of the elusive odderon [1 (https://doi.org/10.1140/epjc/s10052-021-08867-6)]. This paper was a meta-analysis of already published, public domain experimental data measured by the D0 and TOTEM collaborations, utilizing a new scaling method, invented by the Hungarian-Swedish team [1 (https://doi.org/10.1140/epjc/s10052-021-08867-6)]. This scaling analysis observed that in a limited center of mass energy range, that includes the D0 energy of 1.96 TeV and the TOTEM energies of 2.76 and 7 TeV, elastic proton-proton scattering data feature a data collapsing or scaling behaviour within the experimental uncertainties, independently of the energy of the collision [1 (https://doi.org/10.1140/epjc/s10052-021-08867-6)]. It thus utilized a direct data-to-data comparison and showed that energy independent scaling function of elastic proton-proton collisions is significantly different from the scaling function of elastic proton-antiproton collisions, hence providing a statistically significant signal for the exchange of the elusive odderon.

Fig. 1. indicates that the odderon can be illustrated as an anti-symmetric combination of two colored rings, both formed from three gluons. Fig. 2. indicates that the asymmetry parameter of the proton-antiproton versus proton-proton elastic scattering is significantly different from a vanishing value, as a consequence of a statistically significant odderon exchange..

The Hungarian-Swedish paper on the odderon discovery, published in February 2021, has been followed in July 2021 by a theoretical paper [2 (https://doi.org/10.1140/epjc/s10052-021-09381-5)] by two members of the Wigner Femtoscopy Research Group, increasing the statistical significance of odderon observation to at least 7.08 σ signal [2 (https://doi.org/10.1140/epjc/s10052-021-09381-5)]. This paper utilized a previously published theoretical model, the so-called real-extended Bialas-Bzdak model, to extrapolate not only the elastic proton-proton scattering data from the LHC energies to the D0 energy of 1.96 TeV but also to extrapolate the elastic proton-antiproton scattering data from 0.546 and 1.96 TeV to the LHC energies of 2.76 TeV and 7 TeV. Evaluating the proton-proton data with a model increased the uncertainty and decreased the odderon signal from proton-proton scattering data alone, but this decrease was well over-compensated with the ability of the model to evaluate theoretically the proton-antiproton scattering at the LHC energies, leading to an overall increase of the statistical significance from 6.26 to 7.08 σ signal.

In August 2021, the D0 and TOTEM Collaborations published an experimental paper, with an at least 5.2 σ signal for odderon exchange [3 (https://doi.org/10.1103/physrevlett.127.062003)]. This significance was achieved by combining a 3.4 σ signal for odderon exchange at large scattering angles at 1.96 TeV with a 3.4 - 4.6 σ signal, from measurements at nearly vanishing scattering angles at 13 TeV. Thus the D0-TOTEM result on odderon exchange is an experimental observation, obtained by extrapolating already published and newly measured TOTEM experimental data on elastic proton-proton collisions at 2.76, 7, 8 and 13 TeV to the D0 energy of 1.96 TeV at large scattering angles and combining it with TOTEM experimental data at 13 TeV at small scattering angles.

The discovery of the odderon in February 2021 [1 (https://doi.org/10.1140/epjc/s10052-021-08867-6)] has been recognized by CORDIS, the Community Research and Development Information Service of the European Commission as milestone result achieved at CERN [4 (https://cordis.europa.eu/article/id/429667-particle-physics-milestone-achieved-at-cern)]. The experimental observation of the odderon by D0 and TOTEM Collaborations, including members of the Femtoscopy Research Group of Wigner RCP, has been reported in a Nature Reviews Physics article in September 2021 [5 (https://doi.org/10.1038/s42254-021-00375-6)]. The D0-TOTEM observation of odderon exchange was selected in December 2021 as the first listed physics result among the highlighted physics [6 (https://home.cern/news/news/knowledge-sharing/relive-2021-cern)]. Members of the Femtoscopy Research Group co-authored all the three odderon discovery papers [1 (https://doi.org/10.1140/epjc/s10052-021-08867-6), 2 (https://doi.org/10.1140/epjc/s10052-021-09381-5), 3 (https://doi.org/10.1103/physrevlett.127.062003)].

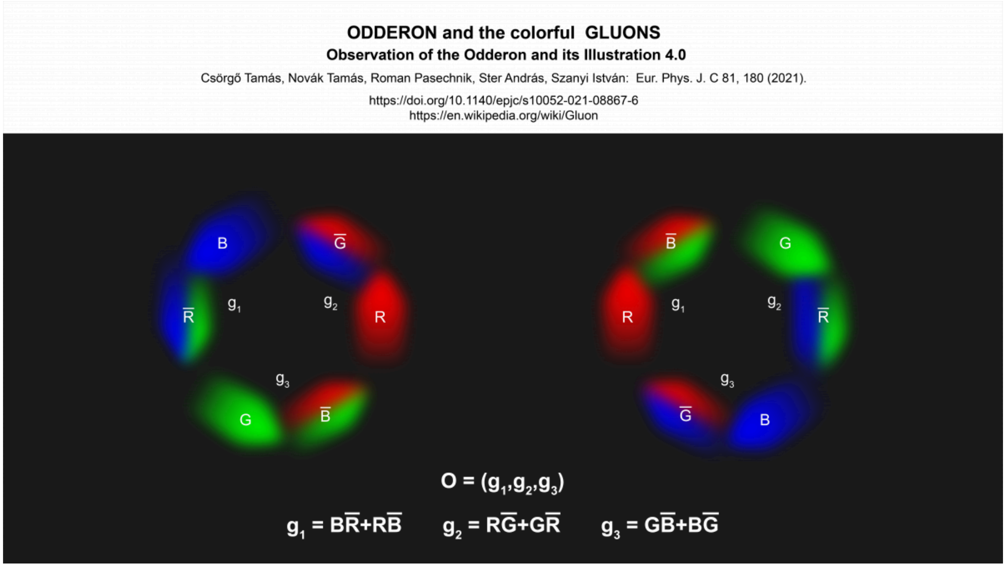

Figure 1. After 48 years of physics research, the elusive odderon has been discovered, with a statistical significance of at least 6.26 σ in February 2021 [1 (https://doi.org/10.1140/epjc/s10052-021-08867-6)] based on a meta-analysis of public domain D0 and TOTEM data.

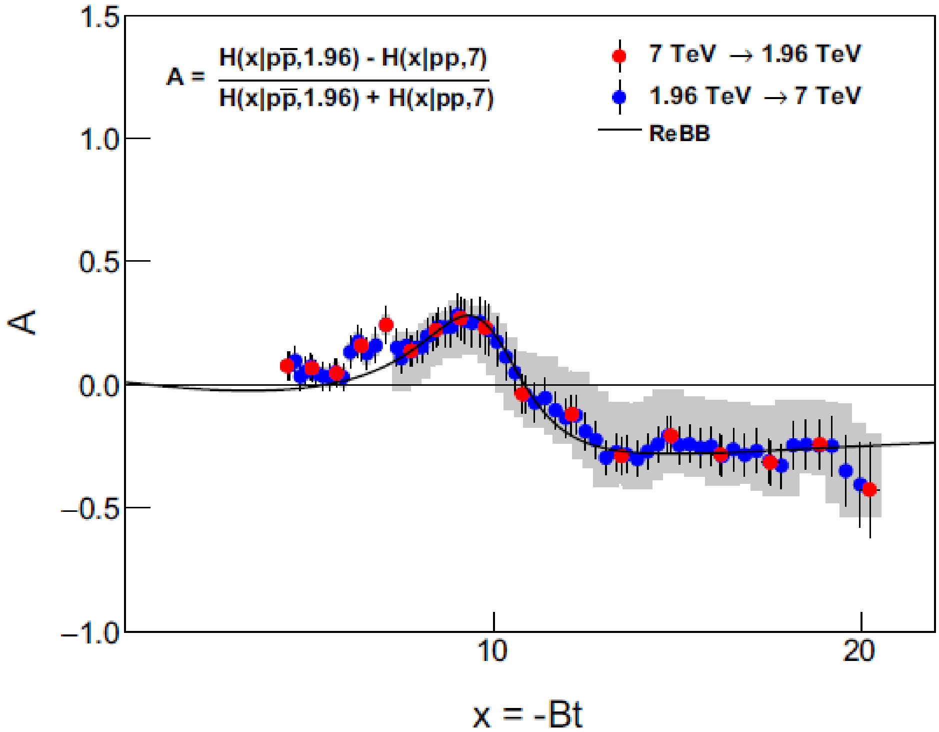

Figure 2. Within experimental errors, the asymmetry parameter A of elastic proton-antiproton versus proton-proton collisions does not vanish, indicating a statistically significant signal of the odderon exchange.

2020

Emptiness of the proton — black ring limit instead of black disc limit

Recently we have developed a Lévy imaging method and in 2020 we have applied this method to extract an important physics information on proton structure at high energies and ultra-low momentum transfers directly from elastic proton-proton scattering data. Such a model-independent method was applied to probe the internal structure of the proton and quantify its inelasticity profile in the impact parameter space emerging in proton-proton collisions at the highest available colliding energy of √s=13 TeV. The inelasticity profile function and its error band for the proton and its substructure have been reconstructed at different energies and the proton hollowness (or "black-ring") effect with more than a 5σ discovery level significance has been found at 13 TeV, as illustrated on Fig. 1.

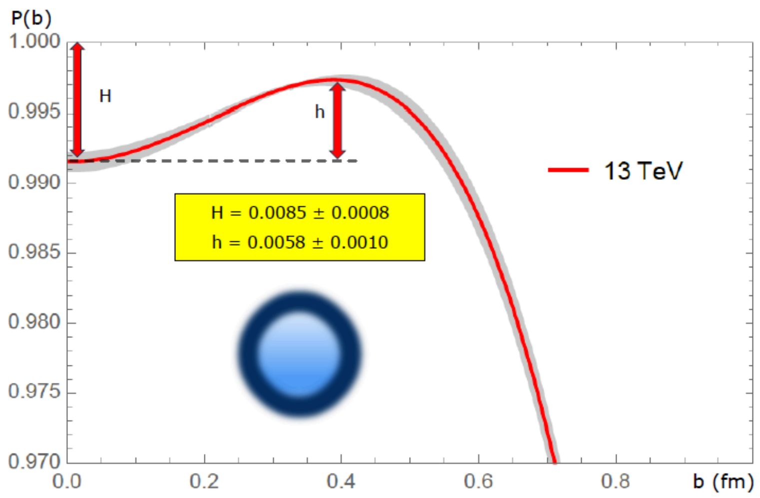

Figure 1. Protons appear as black rings at the top LHC energy of √s = 13 TeV. In a collaboration with the University of Lund, Lund, Sweden, we found a statistically significant, more than a 5σ hollowness effect, namely that in the center of the protons at such a high collision energy becomes more transparent for inelastic collisions as compare to the edge of the protons at the same energies, for details see Ref. 1. (https://epjc.epj.org/articles/epjc/abs/2020/02/10052_2020_Article_7681/10052_2020_Article_7681.html)

Other highlighted results of the Femtoscopy Research Group — Our group is active both in theoretical and in experimental investigations of both elementary particle physics and heavy ion physics. During 2020, our main focus was to prepare the discovery of the Odderon: a crossing-odd component of elastic proton-proton scattering at asymptotically high energies. Together with the TOTEM Collaboration, we have published the differential cross-section of elastic pp collisions at √s = 2.76 TeV and observed a persistent diffractive minimum – maximum structure [2]. (https://link.springer.com/article/10.1140/epjc/s10052-020-7654-y?fbclid=IwAR393lv0sHHPvzL3Xp83M0fTnTExDEZJ5M0AcmDtS5GbGZ6vHwgCYhnC75I) This paper concluded that the last step to be done to for a statistically significant Odderon discovery is to close the energy gap between 2.76 TeV proton-proton and 1.96 TeV proton-antiproton collisions. The experimenal as well as the theoretical papers that reveal this signal have been submitted for a publication during 2020. F. Nemes was a corresponding author for this important experimental milestone paper [2]. (https://link.springer.com/article/10.1140/epjc/s10052-020-7654-y?fbclid=IwAR393lv0sHHPvzL3Xp83M0fTnTExDEZJ5M0AcmDtS5GbGZ6vHwgCYhnC75I)

2019

The Femtoscopy Research Group is actively participating both in **theoretical and experimental research**. The PHENIX experiment at the RHIC accelerator is in the data analysis phase at Brookhaven National Laboratory. One of our **PHENIX** results, published online in Nature Physics already in December 2018, was selected as the cover page story of Nature Physics in March 2020. The **TOTEM** experiment at Large Hadron Collider (LHC) at CERN continued its preparations for

Run-3 and its data analysis programme as well. During 2019, we have achieved important theoretical results, as well as experimental results both in in the PHENIX and in the TOTEM experiments.

In our **theoretical femtoscopy related research**, related to proton-proton and heavy ion physics at RHIC and LHC,

- We have published in EPJ C our first results on a model-independent Levy series expansion, that revealed an important model-independent difference between the four-momentum-transfer dependent nuclear slope parameter B(t) in proton-proton and in proton-antiproton elastic collisions at LHC. This result is **a clear-cut Odderon effect, indicating the discovery of a new quasi-particle at LHC**, a vector glueball - a quarkless bound state of odd, predominantly 3, number of gluons.

In our **experimental femtoscopy research in the CERN LHC experiment TOTEM**, during 2019 we have made significant contributions to the

- TOTEM publication of the differential cross-section of elastic proton-proton (pp) collisions at 13 TeV. [1] (https://doi.org/10.1140/epjc/s10052-019-7346-7)
- measurement of the differential cross-section of elastic pp collisions at 2.76 TeV, and to the
- recalibration of the LHC optics with elastic pp scattering in the PPS project of CMS
- for his innovative, original and careful determination of the LHC optics from the PPS data, a key ingredient for all analyses based on PPS information in CMS and TOTEM, F. Nemes received the **2019 CMS Achievement Award** [https://cms.cern/content/achievement-awards-2019 (https://cms.cern/content/achievement-awards-2019)]

In our **PHENIX related femtoscopy research**, we have made two important discoveries in 2019:

- In p+Au, d+Au and ^{3}He+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV feature **droplets of a perfect fluid with three distinct geometries** on the femtometer scale, thus tiny droplets of strongly interacting quark gluon plasma can be engineered. This PHENIX result was published in online in December 2018 in **Nature Physics**, however we mention it again as this result became a Nature Physics cover story in March 2019. [https://www.nature.com/nphys/volumes/15/issues/3 (https://www.nature.com/nphys/volumes/15/issues/3)][2] (https://doi.org/10.1038/s41567-018-0360-0)

2018

The Femtoscopy Research Group is actively participating both in **theoretical and experimental research.** The **PHENIX** experiment at the RHIC accelerator is in the data analysis phase at Brookhaven National Laboratory publishing in Nature Physics in 2018, while the **TOTEM** experiment at Large Hadron Collider (LHC) at CERN continued its data taking and data analysis as well. During 2018, we have achieved important breakthroughs in theory, as well as in PHENIX and also in TOTEM.

In our **theoretical femtoscopy related research**, related to proton-proton and heavy ion physics at RHIC and LHC,

- We have written a series of four manuscripts on a new family of exact solutions of 1+1 dimensional relativistic fireball hydrodynamics with acceleration and realistic equation of state.
- As applications, we have evaluated the pseudorapidity distributions, the longitudinal HBT radii and the initial energy density in proton-proton and heavy ion collisions at RHIC and LHC.

We have reached a **break-through** in our **theoretical femtoscopy** research related to imaging of the **internal structure of the protons** at LHC energies. With our model-independent Lévy imaging method,

- We have reconstructed the scattering amplitude of high-energy proton-proton elastic scattering processes and determined the excitation function of the shadow profile P(b) of elastic proton-proton and proton-antiproton collisions at the TeV scale.
- **We have identified** significant differences of the four-momentum transfer dependence of the elastic slope B(t) between proton-proton and proton-antiproton collisions, **a clear-cut Odderon effect, indicating the discovery of a new quasi-particle at LHC**, a vector glueball - a quarkless bound state of odd, predominantly 3, number of gluons.

In our **experimental femtoscopy research in the CERN LHC experiment TOTEM**, we have made significant contributions to the

- measurement of the differential cross-section of elastic proton-proton (pp) collisions at 13 TeV
- measurement of the differential cross-section of elastic pp collisions at 2.76 TeV, and to the
- publication of the first measurements of the pp total cross-section at 13 TeV.
- For these achievements, the **Hungarian TOTEM group** received the **2018 TOTEM Achievement Award** and F. Nemes the **2018 TOTEM Publication Award.**

In our **PHENIX related femtoscopy research**, we have made two important discoveries in 2018:

- In p+Au, d+Au and ^{3}He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV feature **droplets of a perfect fluid with three distinct geometries** on the femtometer scale, thus tiny droplets of strongly interacting quark gluon plasma can be engineered. This PHENIX result was published in **Nature Physics**.
- In 0-30% central Au+Au collision at 200 GeV, the shape of the Bose-Einstein correlation function is significantly different from the Gaussian shape, however, the Levy form describes these data precisely. The PHENIX paper on **Levy stable Bose-Einstein correlations** in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions indicated results that are not inconsistent with a **significant mass drop of h' mesons**.

2017

The Femtoscopy Research Group is actively participating in theoretical research and in experimental research in the PHENIX experiment at the RHIC accelerator, Brookhaven National Laboratory and in the TOTEM experiment at Large Hadron Collider (LHC) at CERN. We have achieved important breakthroughs in each research direction during 2017:

In our **theoretical femtoscopy related research**, we have discovered

- new families of exact solutions of 1+3 dimensional, rotating, multi-component, nonrelativistic fireball hydrodynamics;
- new families of exact solutions of accelerating 1+1 dimensional, relativistic perfect fluid hydrodynamics with realistic equations of state;
- new families of perturbative solutions of accelerating, viscous 1+1 dimensional relativistic viscous hydrodynamics.

During the academic year we have organized and participated in an extremely large number of conferences where most of these new results were presented, and we started to write-up these results in conference proceedings and manuscripts submitted for a publication. We expect that most of the new solutions will be published subsequently during 2018.

In our **TOTEM related femtoscopy research**, we have discovered

- new structures in the excitation function of the total cross section, the rho and the B parameter of elastic proton-proton scattering. This result is interpreted as the discovery of the Odderon (or vector glueball, a 3-gluon bound state).

In our **PHENIX related femtoscopy research**, we have discovered

- that d+Au collisions and 3He+Au collisions feature perfect fluid properties down to as low nucleon-nucleaon center of mass energies as 19.6 GeV. T. Csörgő acted as the Chairman of the Internal Review Committee on this publication.
- in 0-30% Au+Au collision at 200 GeV, the shape of the Bose-Einstein correlation function is significantly different from the usual Gaussian shape. The Levy form however describes the data, opening a new series of papers. The manuscript was submitted for a publication and several Levy related Bose-Einstein corrrelation measurements were presented by members of the Hungarian PHENIX group at conferences during 2017, with publications to appear in 2018.