Diffractive production of mesons

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Abstract. The interest in the study of diffractive meson production is discussed. The description of diffraction within Regge phenomenology is presented, and the QCD-based understanding of diffractive processes is given. Central production is reviewed, and the corresponding main results from the COMPASS experiment and from the experiments at the ISR, RHIC, TEVATRON and LHC collider are summarised.

1 Introduction

The production of mesons is interesting for a variety of reasons. First, meson production at a hard scale has a description within perturbative Quantum-Chromo-Dynamics (QCD) with quarks and gluons being the relevant degrees of freedom. For meson production at a soft scale, hadronic degrees of freedom need to be invoked. Here, Regge phenomenology has been the traditional framework with Regge trajectories representing the hadronic states. Second, diffractive meson production is of particular interest as a tool to investigate the role of multi-gluon colour-singlet exchanges in strong interactions. The dynamics of these multi-gluon singlet exchanges is so far only poorly understood within QCD. Third, the fusion of multi-gluon objects is a gluon-rich environment, with very much suppressed quark degrees-of-freedom. It is therefore anticipated that the hadronisation of these multi-gluon objects populates preferentially gluon-rich hadronic bound states, glueballs and hybrids.

The above issues can be addressed by studying central meson production at hadron colliders. Experimentally, central production is characterised by the very forward scattered beam particle, or remnants thereof, and by gaps in rapidity between the beam particle and the mid-rapidity system. A gap is characterised by the property that no particles are produced within this rapidity interval. Centrally produced systems are hence often characterised as double-gap events due to the presence of two gaps, one on either side of mid-rapidity. The study of centrally produced systems at different centre-of-mass energies reveals the contribution of colour-singlet quark and colour-singlet gluon exchanges. These two different exchanges have a different energy dependence, as will be discussed below.

The study of glueballs and hybrids is based on the analysis of centrally produced resonances decaying into pion or kaon pairs. A Partial Wave Analysis (PWA) of the decay distributions of these pion and kaon pairs reveals the quantum numbers J^{PC} of the decaying state. States with quantum numbers $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$ cannot be $q\bar{q}$-mesons, hence are of high interest for hadron spectroscopy. Such exotic states can be of tetraquark nature ($q\bar{q} + \bar{q}q$), or gluonic hybrids ($q\bar{q} + $ gluon). In addition, such a decomposition into states of known quantum numbers will bring new information on the existence of super-numerous states in the scalar sector [1].

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2 Diffraction

The phenomenon of diffraction has been known in optics for a long time due to the systematic studies by Joseph von Fraunhofer (1787-1826) and Augustin-Jean Fresnel (1788-1827). The reconstruction of the diffraction figure based on Maxwell's equation was achieved by Gustav Kirchhoff (1824-1887). A plane wave of light passing through a circular hole or a slit will form a diffraction pattern on a screen located behind the hole or slit. This pattern consists of a series of diffraction maxima and minima, which can be understood to arise from Huygens principle describing the wave propagation. The first use of the term diffraction in nuclear high-energy physics was introduced by Landau and Pomeranchuk (1953). Good and Walker formulated an anticipation in 1960:

"A phenomenon is predicted in which a high-energy beam particle undergoing diffraction scattering from a nucleus will acquire components corresponding to various products of the virtual dissociations of the incident particle. These diffraction-produced systems would have a characteristic extremely narrow distribution in transverse momentum, and would have the same quantum numbers as the initial particle."

Diffractive reactions in hadronic collisions can be characterised by two equivalent formulations:

- a reaction in which no quantum numbers are exchanged between the colliding particles is, at high energy, a diffractive reaction;

- a diffractive reaction is characterised by a large, non-exponentially suppressed, rapidity gap in the final state.

In the Regge framework, hadronic interactions are described by an exchange of objects, the Reggeons, which are characterised by their so-called trajectory. Hadronic interactions at high energies are dominated by the Pomeron trajectory. The different contributions of Reggeon and Pomeron exchanges are clearly visible in the energy dependence of hadronic cross sections [2]. A variety of event topologies can result from these exchanges.
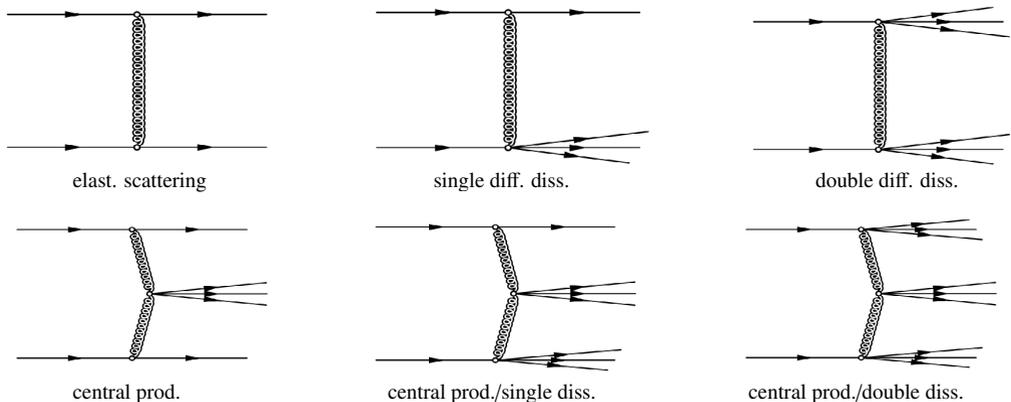

Figure 1. Diffractive event topologies.

Figure 1 displays event topologies with rapidity gaps. In addition to the Reggeon/Pomeron exchanges discussed above, photon and $W^{\pm}$-exchanges contribute to these topologies. Due to the large photon flux present in heavy-ion beams, in particular photon contributions need to be taken into account with heavy-ion beams. Reggeon/Pomeron and photon exchanges contribute, however, differently in pp, pA and AA-collisions. A systematic study of meson production in these systems is therefore mandatory for a comprehensive understanding of the underlying production mechanisms.

3 Central production

The topologies in the lower part of Figure 1 are of particular interest for the study of diffractive meson production. The hadronisation of two Reggeon/Pomeron exchanges can take place with and without dissociation of the beam particle as shown in the three bottom diagrams. In the case of approximate energy sharing between the two exchanges, the central system will be formed close to mid-rapidity.

In the Regge regime ($\sqrt{s} \to \infty$, $\sqrt{|t|} \leq 1$ GeV, t = square of four-momentum transfer), the modeling of such reactions is based on exchanges of the Pomeron and Reggeons f_2, a_2, ω, ρ. A fundamental question is the nature of the Pomeron. Recent theoretical work resulted in the formulation of a model combining general rules of Quantum Field Theory (QFT) with Regge theory. This model aims at giving simple rules for calculating exchange amplitudes compatible with QFT. First results within this model include new insights into the meaning of Vector-Dominance relations, relations between particle-particle-particle and Reggeon-particle-particle vertices, and the appearance of the Pomeron as an effective rank-two tensor exchange [3]. A report on exclusive central diffractive production of scalar, pseudoscalar and vector mesons within this model is given at this conference [4]. An investigation of exclusive photoproduction of J/Ψ and Ψ' is presented at this conference [5].

Early searches for double-gap-topology events were carried out at the Serpukov accelerator at $\sqrt{s} = 11.5$ GeV. All the events found were consistent with single-diffractive dissociation, and hence only an upper limit on the central exclusive cross-section could be derived [6].

3.1 Central production at the ISR

The first observation of double-gap events was achieved by the ARCGM Collaboration at the Intersecting Storage Ring (ISR) at CERN [7]. This experiment measured the forward protons and had full angular coverage with scintillation counters. Measurements of centrally produced $\pi^+\pi^-$-pairs were accomplished at the ISR by the CCHK Collaboration at $\sqrt{s} = 31$ GeV [8], and later by the Axial Field Spectrometer Collaboration with much improved statistics at $\sqrt{s} = 63$ GeV [9].
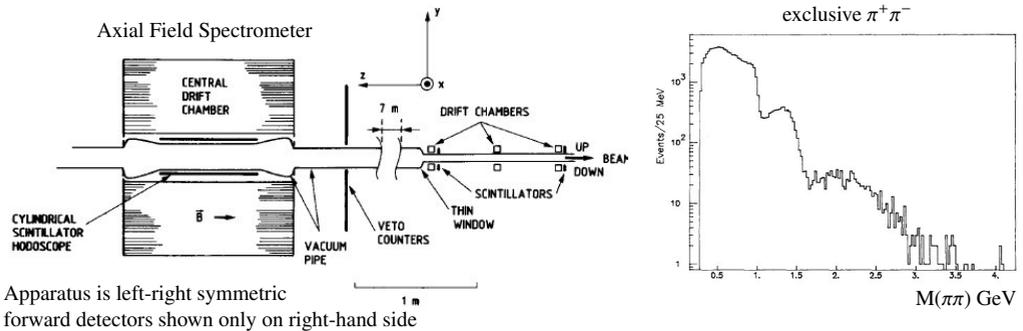

Figure 2. The Axial Field Spectrometer at the ISR (taken from Ref. [9]).

Figure 2 shows the Axial Field Spectrometer setup on the left. The central detector consists of a drift chamber and of cylindrical scintillator hodoscopes. The information from the Veto counters establishes the rapidity gap. In forward direction, drift chambers and scintillators register the forward-scattered beam particles. On the right side of Figure 2, the invariant-mass spectrum of pion pairs measured at mid-rapidity is shown. Clear peaks associated to resonances are seen. Due to the quantum numbers $J^{PC} = 1^{--}$, the ρ-resonance can be produced when a Reggeon exchange is involved, but not in pure Pomeron-Pomeron exchange. The absence of the ρ-signal in this spectrum is therefore evidence that Reggeon exchanges contribute very little at the energy of $\sqrt{s} = 63$ GeV.

3.2 Central production at the COMPASS experiment

COMPASS is a fixed-target experiment at the CERN SPS accelerator. The experimental setup consists of a two-stage magnetic spectrometer, of tracking detectors for momentum reconstruction and of calorimeters and RICH detectors for particle identification. The data taken by COMPASS in the years 2008 and 2009 allow the analysis of central meson production. A comparison of the COMPASS data at $\sqrt{s}$ = 18.9 GeV to the data at the ISR experiments clearly shows the gradual disappearance of the centrally produced ρ-signal in the energy range from $\sqrt{s}$ = 12.7 GeV to $\sqrt{s}$ = 63 GeV, and hence is evidence for the interplay between Reggeon and Pomeron exchanges. The present status of the COMPASS partial wave analysis of centrally produced pion and kaon pairs is presented at this conference [10].

3.3 Central production at STAR

The STAR experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven consists of a Time Projection Chamber (TPC), a silicon vertex tracker, electromagnetic calorimetry and scintillator paddles for time-of-flight measurements. The central TPC with a pseudorapidity coverage $-1 < \eta < 1$ allows the measurement of the central system, while the rapidity gap is defined by the information of the Forward TPC (FTPC, $2.5 < |\eta| < 4.2$) and the beam-beam counters (BBC, $3.8 < |\eta| < 5.2$). In addition, Roman Pots installed at a distance of 55.5 m and 58.5 m from the interaction region allow the measurement of the forward-scattered protons. In Phase I of STAR running at $\sqrt{s}$ = 200 GeV, the acceptance of the Roman Pots allowed the measurement of forward protons in the range $0.003 < |t| < 0.035$ GeV^2. In accepted events, the kinematics of all the final-state particles is known. This information of the final state can be used to efficiently remove non-exclusive background by imposing a condition on the transverse momentum balance $p_T^{miss} < 0.02$ GeV. The STAR analysis of central production from data taken in 2009 resulted in 380 clean events, yielding differential cross sections in the invariant mass and rapidity of the centrally produced pion pairs [11].

3.4 Central production at the TEVATRON

The Tevatron collider at Fermilab provided proton-antiproton collisions in Run I (1992-1996) at energies $\sqrt{s}$ = 546, 630 and 1800 GeV. In this Run, the Collider Detector (CDF) had Roman Pots installed, and was thereby able to record elastically and inelastically scattered protons and antiprotons. From these data, the elastic and the total cross section could be derived. Unfortunately, these Roman Pots were removed before central production could be measured in coincidence with the forward beam particles. In Run II (2004-2011), the CDF Collaboration installed a new Roman Pot for measuring antiprotons, and scintillation counters were installed as beam shower counters in the range $5.4 < |\eta| < 7.4$. In conjunction with miniplug calorimeters, a rapidity gap $\Delta\eta > 3.8$ could be required on either side of mid-rapidity. The data were analysed by imposing this gap condition in addition to the Roman Pot information. From this analysis, results were derived for diffractive dijet and diffractive W-boson production, exclusive $\gamma\gamma$ and exclusive χ_c-production[12, 13].

The CDF Collaboration implemented special triggers during the Tevatron energy scan running at $\sqrt{s}$ = 300 and 900 GeV in September of 2011. These triggers included zero-bias and minimum-bias conditions, a jet trigger, a lepton trigger as well as a Gap-X-Gap trigger for the double gap topology [14]. The present status of the ongoing analysis is presented at this conference [15].

3.5 Central production at the LHC

3.5.1 Central production at ALICE

The ALICE experiment at the Large Hadron Collider (LHC) at CERN consists of a central barrel, a muon spectrometer and of additional detectors for trigger and event classification purposes. The low transverse-momentum threshold of the central barrel gives ALICE a unique opportunity to study the low-mass sector of central exclusive production at the LHC.

The ALICE Collaboration has taken data in proton-proton, proton-lead as well as lead-lead collisions in Run I of the LHC. In the years 2010-2011, ALICE recorded zero-bias and minimum-bias data in pp-collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV. Events with double-gap topology are contained in the minimum-bias trigger, hence central diffractive events were analysed from the minimum bias data sample. The multiplicity distributions of the double and no-gap events clearly show different behaviour, as discussed in Ref. [16].

In lead-lead collisions, exclusive photoproduction of vector mesons is of particular interest. The vector meson production cross-section depends on the nuclear gluon distribution, hence allows the study of nuclear gluon-shadowing effects at values of Bjorken-x $\sim 10^{-3}$ and $\sim 10^{-2}$ for data taken in the ALICE central barrel and the muon spectrometer, respectively. A report on the ALICE results in coherent photo-production of ρ^0-mesons in ultra-peripheral lead-lead collisions is given at this conference [17].

3.5.2 Central production at LHCb

The LHCb experiment consists of a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, of a tracking system surrounding the interaction region (VELO), and three stations of silicon-strip detectors and straw drift-tubes placed downstream of the magnet. Charged hadrons are identified using two ring-imaging Cherenkov detectors. Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad (SPD) and pre-shower detectors, an electromagnetic and hadronic calorimeter. Rapidity gaps can be established by the VELO detector. A requirement of exactly two muon tracks within the spectrometer acceptance hence allows the study of exclusive quarkonia production[18].
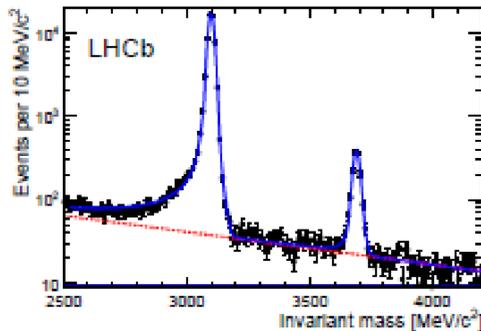

Figure 3. Mass spectrum of exclusively produced dimuons (taken from Ref. [18]).

Figure 3 shows the dimuon invariant-mass spectrum measured in the acceptance of LHCb. Clearly visible are the J/Ψ and the Ψ(2S) signals, as well as a continuum arising from $\gamma\gamma \to \mu^+\mu^-$. From these data, cross sections for exclusive production of J/Ψ and Ψ(2S) can be derived [18].

3.5.3 Exclusive production at CMS

The Compact Muon Solenoid (CMS) experiment consists of a silicon tracker with pseudorapidity coverage $|\eta| < 2.5$, of electromagnetic and hadronic calorimeters in the range $|\eta| < 3$ and of a forward hadronic calorimeter with coverage $2.9 < |\eta| < 5.2$. The CASTOR detector extends the CMS coverage on one side to the region $5.3 < |\eta| < 6.6$. An overview of the CMS results on exclusive production is given at this conference [19].

4 Conclusion

A wealth of data is available for central meson production at hadron colliders, from the early low energies of the ISR to the presently highest energies of the LHC. A partial wave analysis of the decay distributions of pion and kaon pairs reveals the quantum numbers of the centrally produced resonances. Such information allows the study of exotic mesonic states, a topic of fundamental interest in meson spectroscopy.

Acknowledgements

References

[1] W. Ochs, J.Phys. **G40**, 043001 (2013).

[2] A. Donnachie, P.V. Landshoff, Phys. Lett. **B727** 500 (2013).

[3] C. Ewerz, M. Maniatis, O. Nachtmann, Annals Phys. **342** 31 (2014).

[4] P. Lebiedowicz, Exclusive central diffractive production of scalar, pseudoscalar and vector mesons, these proceedings.

[5] A. Cisek, Exclusive photoproduction of J/Ψ and Ψ' mesons in pp-collisions, these proceedings.

[6] D. Denegri et al., Nucl. Phys. **B98** 189 (1975).

[7] L. Baksay et al., Phys. Lett. **B61** 89 (1976).

[8] M. Della Negra et al., Phys. Lett. **B65** 394 (1976).

[9] T. Akesson et al., Nucl. Phys. **B264** 154 (1986).

[10] F. Haas, The COMPASS Hadron Program, these proceedings.

[11] J. Turnau for the STAR Collab., Central Exclusive Production of $\pi^+\pi^-$ pairs in pp-collisions at $\sqrt{s}$ = 200 GeV, DIS2014, XXII. Int. Workshop on Deep-Inel. Scattering, Warsaw, apr 28, 2014.

[12] T. Aaltonen et al., Phys. Rev. Lett. **99** 242002 (2007).

[13] T. Aaltonen at al., Phys. Rev. Lett. **102** 242001 (2009).

[14] C. Mesropian, Diffraction at the Tevatron, WE-Heraeus-School, Heidelberg, sept 2-6, 2013.

[15] M. Zurek, Exclusive Central Meson Production in Proton Antiproton Collisions at the Tevatron at $\sqrt{s}$ = 1960 GeV and 900 GeV, these proceedings.

[16] R. Schicker, Central Diffraction in ALICE, in *Proc. 14th Workshop on Elastic and Diffractive Scattering,* Qui Nhon, 2011, eds. M. A. Rotondo and Ch. Tan (SLAC-eConf-C111215).

[17] Ch. Mayer, Coherent photo-production of ρ^0 mesons in ultra-peripheral Pb+Pb collisions at the LHC, measured by ALICE, these proceedings.

[18] R. McNulty, Int.J.Mod.Phys.A **29** 1446003 (2014).

[19] G. Silveira, Exclusive production in CMS, these proceedings.