Experimental High Energy Physics

FINAL REPORT

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1 Diffraction and low-x QCD

A. Diffractive and exclusive production at CDF. In previous funding periods we studied several diffractive processes at Fermilab during the Tevatron Collider Run I (see summary in [1]):

SD	single diffraction/dissociation	$\bar{p}p \to \bar{p} + G + X_p$,
DD	double diffraction/dissociation	$\bar{p}p \to X_{\bar{p}} + G + X_p$,
DPE or CD	double Pomeron exchange or central dissociation	$\bar{p}p \to \bar{p} + G + X_c + G + p$,
SDD	single plus double diffraction/dissociation	$\bar{p}p \to \bar{p} + G + X_c + G + X_p$,

where $X_{\bar{p}}$, X_p and X_c are regions with final-state particles and G is a pseudorapidity gap (region of pseudorapidity devoid of particles), presumed to be formed by a color-singlet partonic exchange with vacuum quantum numbers, referred to as Pomeron ($I\!P$) exchange. In this funding period, we concentrated on measuring diffractive W/Z and *dijet* production.

1) Diffractive W/Z production. In Run I, we measured the fraction of diffractively produced events in inclusive dijet, W boson, b quark and J/ψ event samples at $\sqrt{s} = 1800$ GeV, and found it to be in all cases $\sim 1\%$ (see [1]). Since diffractive dijets can be produced via quarks or gluons, whereas to leading order a diffractive W is produced via a quark in the Pomeron, combining cross section measurements of diffractive dijet production and diffractive W production allowed us to determine the quark/gluon content of the Pomeron [2]. This result, however, was brought into question by a measurement by the D0 collaboration [3], which reported a diffractive W fraction of up to 4 times larger than the CDF result depending on the theory model used to determine the *gap survival* probability, defined as the likelihood that the diffractive rapidity gap would not be filled by products of additional parton-parton interactions in the same $\bar{p}p$ collision. An observation of an anomalously high diffractive W/Z production rate could be evidence for beyond-standard-model theories, such as that of Ref. [4] in which the Pomeron couples strongly to the electroweak sector through a pair of *sextet* quarks. We therefore decided to measure diffractive W and Z production by tagging diffractive events by the recoil $\bar{p}$ and measuring directly its momentum loss, ξ, and 4-momentum-transfer squared, t, using a Roman-Pot spectrometer (RPS). The following results were found [5]:

- SD/ND ratios for SD events within $0.03 < \xi < 0.10$ and $-t < 0$ GeV^2:

  $\mathrm{R}_{\mathrm{W}}^{\mathrm{sd/nd}} = [1.00 \pm 0.05\,(\mathrm{stat.}) \pm 0.10(\mathrm{syst.})]\%,\ \mathrm{R}_{\mathrm{Z}}^{\mathrm{sd/nd}} = [0.88 \pm 0.21(\mathrm{stat.}) \pm 0.08(\mathrm{syst.})]\%.$

  The $\mathrm{R}_{\mathrm{W}}^{\mathrm{sd/nd}}$ value confirms the CDF Run I rapidity-gap-based result [2].
- $\mathrm{M_W}$ is measured from fully reconstructed diffractive W events by obtaining p_z^ν for $W \to \mu/e+\nu$ from the difference between $\xi_{\bar{p}}^{\mathrm{RPS}}$ and its calorimetric value $\xi_{\bar{p}}^{\mathrm{CAL}}$:

  $\xi_{\bar{p}}^{\mathrm{CAL}} = \sum_{i=1}^{N_{\mathrm{towers}}} \frac{E_{\mathrm{T}}^i}{\sqrt{s}} e^{-\eta^i},\ \xi_{\bar{p}}^{\mathrm{RPS}} - \xi_{\bar{p}}^{\mathrm{CAL}} = \sum_{i=1}^{N_{\mathrm{towers}}} \frac{\not{E}_T^i}{\sqrt{s}} e^{-\eta^\nu},\ p_z^\nu = \not{E}_T / \tan\left[2\tan^{-1}\left(e^{-\eta^\nu}\right)\right].$

  The measured value of $\mathrm{M_W^{diff}} = 80.9 \pm 0.7$ GeV agrees with our inclusive measurement of $\mathrm{M_W} = 80.387 \pm 0.019$ GeV [6], supporting our method of extracting the diffractive fraction.
- No candidates for exclusive Z production were observed, consistent with the upper bound for exclusive Z production within the standard model (SM) [7].

2) Diffractive dijet production. Measurement of the SD structure function, $F_{jj}^{SD}(x, Q^2, \xi, t)$.

Question. Is the result compatible with predictions based on the diffractive parton distribution function measured by the H1 and ZEUS experiments at the DESY HERA *e-p* collider?

Answer. Yes; this measurement confirmed our Run I result; a $\sim 30\%$ discrepancy that existed between CDF and H1 measurements was resolved by a revised H1 analysis; the CDF result is now consistent with HERA measurements; the slope parameter of the t distribution has been measured over a Q^2 range of $10^2 - 10^4$ GeV^2 and found to be nearly constant and consistent with the slope measured in soft diffraction; within the range accessible to the diffractive process the diffractive structure function of the (anti)proton is similar to the inclusive structure function.

Physics significance of results. These results, together with those of the W/Z measurements, point to a QCD-based interpretation of the diffractive exchange, as explained in [1].

B. Diffraction at CMS. We implemented a Monte Carlo simulation for diffractive processes in PYTHIA8.165 and measured soft diffraction cross sections at $\sqrt{s} = 7$ TeV at the LHC.

1) Simulation of diffractive processes. The available MC simulations have been found inadequate to predict cross sections and final-state distributions for minimum-bias (MB) and diffractive processes using the same tuning parameters at all energies at the LHC. In CDF, we use the Minimum Bias Rockefeller (MBR) simulation as a stand-alone MC event generator with gap cross sections based on RENORM predictions and a final state modeled phenomenologically. We have updated the total, elastic, and diffractive (SD, DD, CD/DPE) cross sections used in MBR and, working with PYTHIA experts, implemented MBR as an option [8] in PYTHIA8.165. This version is already used in several CMS analyses.

2) Measurement of the single/double-diffractive and rapidity gap cross sections. We have measured individually the SD and DD cross sections at $\sqrt{s} = 7$ TeV, as well as the cross section for events with a Large pseudoRapidity Gap (LRG), over a wide range of parameter space. As diffraction constitutes $\sim 30\%$ of $\sigma_{\rm inel}$, these measurements are crucial for a proper modeling of MB events and can be used to improve the simulation of the underlying event, pileup events, and measurements of LHC machine luminosity.

Method. We used the rapidity-gap signature to trigger on and/or select diffractive events. This method presents ambiguities, since a given event sample contains a mixture of SD, DD, and DPE/CD events. In the various analyses of diffractive events at LHC, comparisons with expectations from MC simulations are used, which render the extraction of cross sections model-dependent. In our analysis, we substantially reduce model-dependent effects by simultaneously measuring SD, DD, and DPE/CD rates with two detector configurations of different η coverage, $-5 < \eta < 5$ and $-6.6 < \eta < -5.2$, in which the various diffractive components contribute with different acceptances. In practice, this is achieved by including or excluding the very forward region covered by the CMS CASTOR calorimeter.

Results. We have analyzed $\sqrt{s} = 7$ TeV data using PYTHIA8-MBR for estimating acceptance and systematic effects. Our results have been made public [9] and a paper is in preparation. The results are in good agreement with the MBR predictions.

2 Search for supersymmetry and new physics at the LHC

Supersymmetry search: The search for supersymmetry (SUSY) was one of the main reasons to build the Large Hadron Collider (LHC). Over the period 2009-2012 we played a significant role in this search, using the classic signature of momentum imbalance in multijet events. To minimize dependence on event generators and detector simulation, all SM contributions were determined directly from collider data. In addition to guiding the whole analysis, we worked on sensitivity studies, analysis design, measurement of the Z+jet background, and interpretation of the observation within the Constrained Minimal SuperSymmetric extension of the SM (CMSSM).

Using 36 pb^{-1} of 7 TeV data from 2010 [10], we searched for SUSY in the CMSSM framework, which is described by four free parameters if the sign of the Higgsino mass μ is fixed. The parameters are a scalar mass m_0, a gaugino mass $m_{1/2}$, a trilinear coupling A_0, all expressed at the grand unification scale, and the ratio of the vacuum expectation values of two Higgs fields, $\tan\beta$. Prior to LHC, Tevatron experiments excluded $m_0 < 400$ GeV for $m_{1/2} = 0$ GeV and $m_{1/2} < 150$ GeV for $m_0 = 0$ GeV. With the 2010 CMS data we extended this exclusion to 1 TeV and 320 GeV respectively. With the full 5 fb^{-1} [11] of 7 TeV CMS data, we extended these exclusions to 3 TeV and 600 GeV respectively. These limits correspond to a squark mass of 1.2 TeV for all gluino masses, and a gluino mass of 800 GeV for any squark mass. Combined with other experimental constraints and theoretical considerations, these results force one to conclude that the CMSSM is not a viable model.

The results are also presented in terms of simple topologies [12]. We studied the final states $\tilde{q}\tilde{q} \rightarrow qq\chi_0^1\chi_0^1$ where $\tilde{q}$ is a light squark, $\tilde{g}\tilde{g} \rightarrow q\bar{q}q\bar{q}\chi_0^1\chi_0^1$, and $\tilde{g}\tilde{g} \rightarrow t\bar{t}t\bar{t}\chi_0^1\chi_0^1$. Assuming the first two squark generations to be degenerate, the full 19.5 fb^{-1} of 8 TeV CMS data allow us to exclude light squark masses below 0.75 TeV and gluino masses below 1.1 TeV, for a massless χ_0^1 [13].

Our results have been used by several phenomenologists to constrain various SUSY models, such as the NMSSM [16]; they were a major driving force [14] in constraining the pMSSM [15].

In 2012 we also worked on a search for top-squark pair production using events with one or more reconstructed top quarks. The analysis is in the CMS approval stage. Following the generic Jet+$\not{E}_{\text{T}}$ search, all major backgrounds are determined directly from data. We will be able to exclude a top squark mass below 650 GeV for a massless χ_0^1. This search is very important in determining whether SUSY can solve the little hierarchy problem without any contrived cancellations.

Dark matter search: Numerous astrophysical measurements, such as the rotational speed of galaxies and gravitational lensing, suggest that approximately 80% of the matter density of the Universe is non-luminous. Understanding the nature of this dark matter is one of the most important fundamental questions confronting both astrophysics and particle physics. The best candidates put forth to explain the nature of this type of matter are stable weakly interacting particles (WIMPs). Previously, searches for dark matter at the LHC proceeded within the context of a new physics theory, such as SUSY, where the lightest SUSY particle is neutral and stable and thus a good dark matter candidate. Recently, a more model independent approach has been proposed, in which the coupling between SM particles and dark-matter states is assumed to be mediated by a particle that is very heavy and not accessible to the LHC. The pair production of WIMPs via a heavy mediator can be probed using the signature of a single high-p_T jet and no other visible energy in the event, a monojet. We searched for WIMPs using 5 fb^{-1} of 7 TeV data [17] and 19.5 fb^{-1} of CMS data at 8 TeV [18]. The limits are competitive and complementary to those from direct detection experiments. The limits on the spin dependent cross section are the most stringent for a large range in dark matter mass, whilst for spin independent interactions the collider limits extend the sensitivity to the low mass region, where direct-detection experiments are not as sensitive due to energy-threshold effects. These results excited the particle physics and astrophysics communities, and we were invited to present them at numerous international conferences, such as Moriond Cosmology and ICHEP, and also at workshops dedicated to bringing together the dark matter community.

Large extra dimensions search: The monojet topology can also be used to constrain large extra dimensions in the context of the ADD model [19], which postulates extra spatial dimensions to explain the difference between the electroweak and Planck scales. This model produces a monojet signature if a graviton is emitted in association with a jet and subsequently escapes into the extra dimensions, thus resulting in missing transverse energy. The consistency between the observed number of events and the expected background is used to set limits on the ADD parameter M_D as a function of the number of extra dimensions [20, 17]. The limits represent a significant improvement over previous limits. Our results have been used by the theoretical community to set limits on Higgs decay to invisible particles [21] and on the production of top squarks in compressed SUSY scenarios [22, 23].

Jet shape measurement: The jet transverse momentum profile (shape), transverse size, and charged-hadron multiplicity are sensitive to multiple parton emissions from the primary outgoing parton and provide a powerful test of the parton showering approximation of QCD. Recently there have been many methods proposed to search for heavy particles by studying the substructure of jets formed by their decay products. We measured jet shapes using $36\,\mathrm{pb}^{-1}$ of 7 TeV data [24], and these measurements are being used to validate and tune the PYTHIA8 event generator [25].

3 Statistical issues in data analysis

As member of the CMS Statistics Committee we helped provide the following services:

• **Rapid-response shifts:** Twice a year, each regular member of the committee takes a three-week shift during which he or she responds to queries from CMS collaborators.

• **CMS paper draft sign-off:** Committee members take turns verifying the statistical soundness of CMS physics papers. The burden is approximately 20 papers per member per year.

• **Review of analysis questionnaires:** The committee prepared a detailed statistics questionnaire to be filled out by collaborators planning a physics analysis. Each committee member reviews all the questionnaires coming from one of the CMS physics analysis groups.

• **Committee meetings:** The committee meets regularly to discuss unresolved issues. These meetings are open to CMS collaborators, and minutes are posted on the committee's Twiki pages [26].

• **CMS-ATLAS coordination:** A subset of the CMS committee met several times with ATLAS representatives to hammer out a joint agreement on statistical methods.

We also belonged to the CDF statistics committee. This committee no longer meets regularly but still provides advice and recommendations to CDF collaborators who solicit it.

In addition to the above service items, we worked on a number of projects aimed at developing new data analysis methods or improving existing ones. Chief among these are:

• **Bayesian reference analysis:** Bayesian applications in high energy physics typically seek to use noninformative priors for parameters of interest. *Reference* priors are noninformative in a well-defined sense that is grounded in information theory. Their formulation is independent of parametrization, avoids various paradoxes, and leads to proper posteriors with good frequentist coverage. We applied this methodology to cross section measurements and provided analytical forms for the reference prior [27] as well as software [28]. More recently we computed reference priors for a search for contact interactions using inclusive jet data [29].

• **Bootstrap methods:** A difficulty of HEP measurements is that often no fully analytical representation of the likelihood function exists. In a frequentist approach this is remedied by investigating large ensembles of Monte Carlo simulated "toy experiments". It has recently come to light that this corresponds to a bona fide statistical methodology known as the bootstrap, that there are known limitations to its applicability, and that many techniques exist to refine its coverage accuracy and endow the resulting inferences with desirable properties such as invariance under reparametrization and respect of physical boundaries. Results of an initial investigation of the applicability of the bootstrap to HEP measurements were presented at the PhyStat conference on "Progress on Statistical Issues in Searches" at SLAC in June 2012 [30].

• **Simple-versus-simple hypothesis testing:** A measurement will occasionally present itself as a test between two hypotheses, for example whether the particle currently known as the top quark has electric charge $+2/3$ or $-4/3$, or whether the recently observed Higgs boson is scalar or pseudo-scalar. We studied several issues associated with this type of measurement and presented a summary at a workshop at CERN in February 2013 [31]. Some of the ideas presented there were applied to the top quark [32] and Higgs [33] examples.

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4 List of papers that acknowledge DOE support

In the following papers the Rockefeller group made major contributions, as described in the main body of the report. With the exception of paper #15 below, all listed papers received support from various other agencies besides DOE, as described in the Acknowledgments section of each individual paper.

1. T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **86**, 032009 (2012).
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