Review of diffraction at the LHC

Robert Ciesielski
(The Rockefeller University)

EDS-Blois 2015, the 16th Conference on Elastic and Diffractive Scattering
29 June – 4 July, 2015, Borgo, Corsica
Outline

Diffraction at the LHC

- Inclusive measurements
- Hard diffraction
- Exclusive processes

Will only minimally cover HERA results, as they will be discussed on Thursday by:
  - Alice Valcarova - Hard diffraction at HERA
  - Marta Ruspa - Exclusive processes at HERA
Motivation

- Measure fundamental quantities in HEP: total, elastic, diffractive cross sections
- Understand mechanism of diffractive processes
- Study interplay between soft and hard physics
  - Test phenomenological models in soft regime
  - Test pQCD in hard regime
- Search for new phenomena
  - BFKL dynamics
  - Saturation
  - Exotic QCD states, e.g. glueballs
  - BSM physics
Main processes contributing to the total pp cross section

Non-diffractive

\[ pp \rightarrow X \] (exponentially-suppressed rapidity gap)

Elastic

\[ pp \rightarrow pp \]

Single dissociation (SD)

\[ pp \rightarrow Xp, \ pp \rightarrow pY \]

Double dissociation (DD),

\[ pp \rightarrow XY \]

or double-Pomeron exchange (DPE)

Central diffraction (CD)

\[ pp \rightarrow pXp \]

Diffractive processes (SD, DD, CD) – about 20-30% of total-inelastic cross section. Large rapidity gap (LRG) present in the final state.
Elastic scattering @7 TeV

Proton tagging at z=±220 m (TOTEM RP) and z=±240 m (ATLAS-ALFA)

EPL 95 (2011) 41001, EPL 101 (2013) 21001

\[
\frac{d\sigma_{el}}{dt} = \left. \frac{d\sigma_{el}}{dt} \right|_{t=0} e^{-B|t|}
\]

ATLAS: \( B = 19.7 \pm 0.3 \text{ GeV}^{-2} \)
TOTEM: \( B = 19.9 \pm 0.3 \text{ GeV}^{-2} \)

NPB 889 (2014) 486

**Forward peak, exponential in |t|**
**Power low dependence at higher |t|**
**Dip position (\( R_p^2/4 \)) moves to lower |t| with energy**
Optical theorem and total pp cross section

From elastic observables:

\[ \sigma_{\text{tot}}^2 = \frac{1}{L} \frac{16\pi}{1 + \rho^2} \left| \frac{dN_{\text{el}}}{dt} \right|_{t \to 0} \]

\[ \rho = \frac{\Re(f_{1}(t))}{\Im(f_{1}(t))} \bigg|_{t \to 0} = 0.14 \]

\( \rho \) independent:

\[ \sigma_{\text{tot}} = \frac{1}{L} (N_{\text{el}} + N_{\text{inel}}) \]

Luminosity independent:

\[ \sigma_{\text{tot}} = \frac{16\pi}{1 + \rho^2} \frac{dN_{\text{el}}/dt}{N_{\text{el}} + N_{\text{inel}}} \]

All three methods in agreement.

For an evolution of theory predictions before and after the LHC data, see Errol Gotsman's talk at DIFFRACTION 2014
Elastic at low and very low $|t|$ - TOTEM

- High statistics dataset ($\beta^*=90\text{m, 2012}$), 7 Mevt, $0.027 \text{ GeV}^2 < |t| < 0.2 \text{ GeV}^2$ (Coulomb effects negligible)

Relative deviation from exponential fit with

$$B(t) = b_0$$
$$B(t) = b_0 + b_1 t$$
$$B(t) = b_0 + b_1 t + b_2 t^2$$

Pure exponential dependence excluded at 7.2 s significance.

- Very-low $|t|$ dataset ($\beta^*=1000\text{m, 2012}$), $|t| > 6 \times 10^{-4} \text{ GeV}^2$

Constrain models of Coulomb-nuclear interference (nuclear phase $\Psi$, B(t))

See e.g. Mario Deile at DIS 2015

R. Ciesielski, Review of diffraction
Diffractive results

Kinematic limit @7 TeV: $\eta = \pm 0.5 \times \log(s/m^2) \approx \pm 10$

Detector coverage:

$M_x (SD)$: $\sim 3.4 \sim 12$. $\sim 1100$ GeV

CMS, ATLAS central detector

TOTEM

R. Ciesielski, Review of diffraction
Diffractive events at high values of $\Delta \eta^F$
For $\Delta \eta^F > 3$ measured $\sim 1$ mb per unit of $\Delta \eta^F$
Test of diffraction models
No SD/DD separation possible

Similar results from CMS.
In addition, CMS uses CASTOR calorimeter (-6.6<$\eta$<-5.2) to separate SD/DD for events with $\Delta \eta^F > 4$. 

R. Ciesielski, Review of diffraction
Diffractive results from CMS

For $12 < M_X < 394$ GeV

- Forward rapididity gap
- CASTOR ($-6.6 < \eta < -5.2$)
- $3.2 < M_X < 12$ GeV

Test of diffraction (and hadronization) models

PYTHIA8-MBR describes all aspects of the data

Details of PYTHIA8-MBR model in K. Goulianos talk

CMS-FSQ-12-005, arXiv:1503.08689
SD cross section from CMS

From background-subtracted (with small uncertainties) CASTOR-tag sample:

\[
\sigma^{SD_{vis}} = 4.06 \pm 0.04 \left( \text{stat} \right)^{+0.69}_{-0.63} \left( \text{syst} \right) \text{mb} \quad -5.5 < \log_{10} \xi_X < -2.5 \quad (12 < M_X < 394 \text{ GeV})
\]

Extrapolated to the not observed region with PYTHIA8-MBR:

(from yellow to khaki on plots below)

\[
\sigma^{SD} = 8.84 \pm 0.08 \left( \text{stat} \right)^{+1.49}_{-1.38} \left( \text{syst} \right)^{+1.17}_{-0.37} \left( \text{extr} \right) \text{mb} \quad \xi_X(Y) < 0.05
\]

Large model variations, PYTHIA8-MBR describes the data in the visible region

used in EPJC 73 (2013) 2456
**SD cross section from TOTEM**

Proton tag + combinations of T1 (3.1 < |η| < 4.7) and T2 (5.3 < |η| < 6.5) detectors to select different Mx bins

---

**Integrated SD cross section @ 7 TeV**

\[
\sigma_{SD} = 6.5 \pm 1.3 \text{ mb} \\
(3.4 < M_{SD} < 1100 \text{ GeV})
\]

See e.g. Mirko Berretti talk at DIFFRACTION 2014
DD cross section from CMS and TOTEM

CMS-FSQ-12-005, arXiv:1503.08689

**DD cross section from CMS and TOTEM**

**forward gap with CASTOR tag**

\[
\sigma_{DD vis}^{\text{CASTOR}} = 1.06 \pm 0.02 \text{(stat)} \pm 0.12 \text{(syst)} \text{mb}
\]

**central gap**

\[
\sigma_{DD vis}^{\text{CG}} = 0.56 \pm 0.01 \text{(stat)} + 0.15 \text{(syst)} \text{mb}
\]

and

extrapolated to \(\Delta\eta > 3\) with PYTHIA8-MBR:

\[
\sigma^{DD} = 5.17 \pm 0.08 \text{(stat)} + 0.55 \text{(syst)} + 1.62 \text{(extr)} \text{mb}
\]

**TOTEM (T2 on both sides, no T1, 3.4 < M_{X/Y} < 8 GeV)**

\[
\sigma_{DD(4.7<|\eta_{\min}|<6.5)} = 120 \pm 25 \mu\text{b}
\]

R. Ciesielski, Review of diffraction
SD and DD cross sections weakly rising with energy

TOTEM SD:
6.5 ± 1.3 mb – SD cross section for 3.4 < M_x < 1.1 GeV

+ 2.62 ± 2.17 mb - T2-invisible cross section for M_x < 3.4 GeV (SD dominated)

9.12 ± 2.53 mb for ξ<0.025 (extrapolation to ξ<0.05 compensated by DD in T2-invisible cross section)

in agreement with extrapolated CMS SD cross section.
Central and forward $dN_{ch}/d\eta$

The first common CMS+TOTEM runs (2012, @8 TeV) and publication
Trigger based on activity in T2

Multiplicity of SD-enhanced events significantly smaller than inclusive ones
No prediction able to describe $dN_{ch}/d\eta$ in the entire $\eta$ range
Data can help constrain modelling of hadronic final state and diffractive scattering

Direct measurements of charged multiplicity spectra in proton dissociation systems?
Double- and Multi-gaps at the LHC?

Will we measure them, as CDF did?
Fine-tuning of hadronization models, multiplicity spectra, etc.
Hard diffraction at LHC
Diffractive dijets

Factorization breaking: NLO predictions based on HERA diffractive PDFs overestimate Tevatron diffractive dijet cross sections by ~0(10). Suppression factor $|S|^2$ due to rescattering effects.

Inclusive dijet cross section in 3 bins of $\xi$

Data/MC in the lowest $\xi$ bin (0.0003< $\xi$<0.002):
- 0.21 ±0.07 (LO - POMPYT POMWIG)
- 0.14 ±0.05 (NLO - POWHEG)

After proton-dissociation correction:
- 0.12 ±0.05 (LO)
- 0.08 ±0.04 (NLO).

Combined CMS+TOTEM analysis in progress

Proton tagging with TOTEM Roman Pots
No ND and p-diss background
Demonstrated good control of the background (PU and beam related)
Measurement of the $t$ dependence of the cross section

Plans for other measurements with p-tag @13 TeV (diffractive dijets, W, Z, J/psi)

CMS-PAS-FSQ-14-001, TOTEM-NOTE-2014-02
Jet-gap-jet events

Jets separated by a large rapidity gap, color singlet exchange (CSE)
BFKL dynamics, rescattering processes
Events with gaps ~1% at Tevatron (CDF, D0)

Charged multiplicity for $|\eta|<1$:
Clear excess of gap events over PYTHIA6 prediction (LO DGLAP),
described by HERWIG (LL-BFKL, Mueller-Tang model)

D0 data, compared to Enberg, Ingelman, Motyka model (NLL BFKL + MPI+SCI)
PLB 524 (2002) 273
Jet-gap-jet events

Gap/CSE fraction := ratio of events in the lowest multiplicity bins to all events
Modest increase with jet energy and rapidity separation $\Delta \eta$

A factor $\sim 2$ suppression w.r.t. to 1.8 TeV data
observed earlier: $2.5 \pm 0.9$ (D0) and $3.4 \pm 1.2$ (CDF)
decrease with $\sqrt{s} = 0.63 \rightarrow 1.8$ TeV

Preliminary predictions of Ekstedt, Enberg, Ingelman, Motyka with two models for SCI - color exchange between partons (old SCI) or strings (new SCI): good description of gap fractions vs $\Delta \eta$
CEP in pp collisions

QED

Photo production

Double pomeron exchange

R. Ciesielski, Review of diffraction
π⁺π⁻ production in DPE

DPE (no valence quarks, spin selector) - production of isoscalars with $J^{PC} = 0^{++}, 2^{++}, ...$, including glueballs

STAR @200 GeV: pions with p-tagging
Resonance structure similar to that seen at ISR @63 GeV
$f_0(600)$, shoulder from $f_0(980)$ interference,
some structure around 1.2-1.6 GeV

Increased statistics (30-40 times) expected from 2015 runs

See e.g. Jacek Turnau at DIS 2014

CDF @0.9 and 1.96 TeV: dipions and no other activity in $|\eta| > 5.9$
Resonance structure for $M(\pi\pi) > 1$ GeV
$f_2(1270)$, shoulder from $f_0(1370)$ interference, some structure around 1.4-2.4 GeV,
data falls monotonically above 2.4 GeV

The cross section ratio $R(0.9:1.96) = 1.28$ for $1 < M(\pi\pi) < 2$ GeV
consistent with Regge phenomenology ($\sim 1/\ln(s)$)

At LHC: ongoing CMS+TOTEM and ALICE analyses

R. Ciesielski, Review of diffraction
Exclusive production of charmonium pairs in DPE

First observation of the central exclusive production of $J/\Psi + J/\Psi$ and $J/\Psi + \Psi(2S)$ pairs.

Four tracks, at least 3 muons

$57 J/\Psi + J/\Psi$ candidates
$7 J/\Psi + \Psi(2S)$ candidates

Cross section for elastic $J/\Psi + J/\Psi$ production: $24 \pm 9$ pb
In agreement with predictions of Harland-Lang, Khoze, Ryskin, Stirling: 8 pb
(large theoretical uncertainties, factor of 2-3)
Reminder: $\gamma p \rightarrow V p$ at HERA

Harvest of VM results at HERA
Observed transition from soft to hard with a hard scale ($M_V, Q^2, t$)
In the hard regime, validated pQCD description

$\sigma \sim [xg(x, \mu^2)]^2$ Sensitive to gluon saturation at very low $x$ (high $W$)

$W_5$, $\delta=0.2$
Regge with soft IP

$W_5$, $\delta=0.7-1.2$
Gluons at low-$x$ ($W^2=1/x$)

V mass provides hard scale
Reminder: $\gamma p \rightarrow Vp$ at HERA

Exclusive production of $J/\Psi$
(photoproduction and DIS)

Cross sections as a function of $W$ in bins of $Q^2$
compared to pQCD predictions (MRT model)
with different gluon PDFs.

Sensitivity to gluon PDFs at low $x$!

HERA data used by MNRT group to extract gluon PDFs and provide predictions for the LHC
Photoproduction of $J/\Psi$ and $\Psi(2S)$ in pp

Two muons with $p_T>400$ MeV and no other activity
Inelastic background subtracted by fitting $p_T^2$ spectra
For $J/\Psi$: feed down from $X_c$ and $\Psi(2S)$ - 8% and 2.5%

Extracted $b$ slopes of the exponential $p_T^2$ dependence
Measured cross section as a function of VM rapidity

Comparison to predictions of JMRT model
NLO in better agreement

Data also described by saturation models

LHCb sensitivity $\propto 10^{-5}$
Photoproduction of $J/\Psi$ and $\Psi(2S)$ in $pp$

Comparison to HERA data

Emitter/target ambiguity

Assume $\sigma(W)$ and extract $\sigma(W)$ according to:

$$\sigma_{J/\psi p}(W) = 81(W/90\text{GeV})^{0.67}$$

$$\frac{d\sigma}{dy}_{pp\rightarrow pJ/\psi p} = r_+ k_+ \frac{dn}{dk_+} \sigma_{J/\psi p}(W^+) + r_- k_- \frac{dn}{dk_-} \sigma_{J/\psi p}(W^-)$$

LHCb data in agreement with the extrapolation of the fit to the H1 data.
Photoproduction of $J/\Psi$ in p-Pb

Pb: rich source of photons (flux~$Z^2$), negligible Xc background

$W^-$ from Pb-p, $W^+$ from p-Pb

ALICE data compared to HERA and LHCb data, and to theory predictions

The result of a fit with $\sigma \propto W_{\gamma p}^\delta$

consistent with HERA measurements

<table>
<thead>
<tr>
<th></th>
<th>ZEUS</th>
<th>H1</th>
<th>ALICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta$</td>
<td>$0.69 \pm 0.04$</td>
<td>$0.67 \pm 0.03$</td>
<td>$0.68 \pm 0.06$</td>
</tr>
</tbody>
</table>

LHCb solutions consistent with ALICE power-law fit

Data described by the JMRT model at LO and NLO, and saturation models
Photoproduction of Y in pp

Two muons with $p_T > 400$ MeV, $2<|\eta|<4.5$ and no other activity
Inelastic background subtracted by fitting $p_T^2$ spectra
Feed down from $X_b(m_P) \rightarrow Y(n_S)\gamma$ - 20-50%

Measure cross section as a function of VM rapidity

Comparison to predictions of JMRT model.
NLO in better agreement

W+ solution dominant
W- neglected

Run-2 @LHCb: HERSCHEL high rapidity shower counters to reduce inelastic background.
Photoproduction of $J/\Psi$ in Pb-Pb collisions

Is the nucleus gluon field equivalent to those of $A$ nucleons? → hunting for shadowing

\[ \frac{d\sigma_{\gamma A \rightarrow J/\Psi A}}{dt} \bigg|_{t=0} = \xi_{J/\Psi} \left( \frac{16\pi^3\alpha_s^2\Gamma_{l+l^-}}{3\alpha M_{J/\Psi}^5} \right) \left[ xG_A(x, \mu^2) \right]^2 \]

Direct evidence for shadowing

Data can improve ~100% uncertainty

Exclusive $\gamma\gamma \rightarrow e^+e^-$ production

QED prediction for exclusive production has an uncertainty of $\sim 2\%$

Suppression due to rescattering effects expected in pp collisions

Fits to dielectron and dimuon acoplanarity spectra with elastic and p-dissociation templates.
Templates from HERWIG++ (cross section from Equivalent Photon Approximation (EPA) = LO QED).

\[
\begin{align*}
R_{\gamma\gamma \rightarrow e^+e^-}^{\text{excl.}} &= 0.863 \pm 0.070 \text{ (stat.)} \\
R_{\gamma\gamma \rightarrow e^+e^-}^{\text{s-diss.}} &= 0.759 \pm 0.080 \text{ (stat.)} \\
R_{\gamma\gamma \rightarrow \mu^+\mu^-}^{\text{excl.}} &= 0.791 \pm 0.041 \text{ (stat.)} \\
R_{\gamma\gamma \rightarrow \mu^+\mu^-}^{\text{s-diss.}} &= 0.762 \pm 0.049 \text{ (stat.)}
\end{align*}
\]

A suppression of about 20\% is measured

In agreement with predictions of Dyndal and L. Schoeffel

Similar observation by CMS: $R_{\gamma\gamma \rightarrow e^+e^-}^{\text{excl.}} = 0.91 \pm 0.03$ and $R_{\gamma\gamma \rightarrow \mu^+\mu^-}^{\text{s-diss.}} = 0.72 \pm 0.02$ for $p_T^{\mu} > 20 \text{ GeV}, |\eta^\mu| < 2.4$

PLB 741 (2015) 66

JHEP 07 (2013) 116
Exclusive $\gamma\gamma \rightarrow WW$ production, limits on aQGC

Update of 7 TeV ($L=5 \text{ fb}^{-1}$) analysis with $L=20 \text{ fb}^{-1} @ 8 \text{ TeV}$

Effective Lagrangian with two additional dimension 6 terms:

$$\mathcal{L}_6^0 = \frac{e^2}{16 \cos^2 \Theta_W} \frac{a_0^W}{\Lambda^2} F_{\mu \nu} F^{\mu \nu} W^+ W^- - \frac{e^2}{16 \cos^2 \Theta_W} \frac{a_0^Z}{\Lambda^2} F_{\mu \nu} F^{\mu \nu} Z^\alpha Z^\alpha$$

$$\mathcal{L}_6^C = \frac{-e^2}{16 \cos^2 \Theta_W} \frac{a_C^W}{\Lambda^2} F_{\mu \alpha} F^{\mu \beta} (W^+ W^- + W^- W^+) - \frac{e^2}{16 \cos^2 \Theta_W} \frac{a_C^Z}{\Lambda^2} F_{\mu \alpha} F^{\mu \beta} Z^\alpha Z^\beta$$

Parameteres $a_0^W$ and $a_C^W$, $\Lambda$ – scale for new physics

In $e\mu$ channel for $p_T(e\mu)>30 \text{ GeV}$: 13 events observed (SM: 8.8 events)

For $\Lambda=500 \text{ GeV}$ new constrains on aQGC 25% better than @7 TeV
(limits at @7 TeV 20 times better than Tevatron and $\sim O(100)$ than LEP)

~10x better limits if proton tagging and high Lumi
→ see CT-PPS talk by Margerita Obertino
Summary

● Total, elastic and diffractive cross sections measured - important input for phenomenological models, MC tuning, and cosmic ray physics

● Hard diffraction results
  • BFKL color singlet exchange measured for the first time at the LHC
  • Hard diffraction still little studied at the LHC, proton tagging (CMS+TOTEM, CT-PPS, AFS) is crucial for expanding number of channels e.g. diffractive dijets, W, Z, J/Ψ

● Rich program for exclusive processes
  • HERA's vector mesons in full swing at increased energy (+ forward detectors to further reduce backgrounds, e.g. HERSCHEL @LHCb)
  • Saturation effect not yet seen
  • First observation of exclusive production of charmonium pairs in DPE
  • Exotic QCD states not yet seen, need more statistics
  • World most stringent limits on aQGC. And will get even better!

Looking forward to Run 2 data.
Elastic/Total pp cross section from ATLAS

\[ \sigma_{\text{tot}}^2 = \frac{1}{L} \frac{16\pi}{1 + \rho^2} \left. \frac{dN_{\text{el}}}{dt} \right|_{t \to 0} \]

\[ \rho = \frac{\text{Re}(f_{\text{el}})}{\text{Im}(f_{\text{el}})} \bigg|_{t \to 0} = 0.14 \]

ALFA - tracking detectors with scintillating fibers at \( z = \pm 240 \text{ m} \)
\( \beta^* = 90 \text{ m} \) optics, 700 kevts

\[ d\sigma_{\text{el}} / dt [\text{mb/GeV}^2] \]
\[ \frac{d\sigma_{\text{el}}}{dt} [\text{mb/GeV}^2] \]
\[ \frac{d\sigma_{\text{el}}}{dt} [\text{mb/GeV}^2] \]

Exponential fit for \( 0.01 < |t| < 0.1 \text{ GeV}^2 \)

ATLAS: \( \sigma_{\text{tot}} = 95.4 \pm 1.4 \text{ mb} \quad B = 19.7 \pm 0.3 \text{ GeV}^{-2} \)

TOTEM: \( \sigma_{\text{tot}} = 98.6 \pm 2.2 \text{ mb} \quad B = 19.9 \pm 0.3 \text{ GeV}^{-2} \)
Diffractive results from CMS

SD/DD separation with CASTOR (-6.6<\eta<-5.2)

\[ \Delta \eta^F > 4 \approx \eta_{\min} > -1 \]

All with \( \eta_{\min} > -1 \)

no CASTOR-tag (SD dominated)  \hspace{2cm} CASTOR-tag (DD dominated)

\[ \xi_X = \frac{M^2_X}{S} \]
CMS+TOTEM, CT-PPS future plans

Two Upgrade Technical Design Reports

Operation at low $\beta^*$ (< 1 m),
high luminosity, standard runs

Operation at high $\beta^*$ (19 m, 90 m, > 1 km),
Low - medium luminosity, special runs

CMS-TOTEM Precision Proton Spectrometer (CT-PPS)

High statistics CEP:
DPE exclusive dijets,
photon-photon WW and
BSM EWK couplings.
2016-2017

Timing Measurements in the Vertical Roman Pots of the TOTEM Experiment

Diffractive processes with TOTEM+CMS,
e.g.: SD J/Psi, Y, W, Z, dijet
DPE dijets, hadron spectroscopy (gluballs)
2015-2016

Similar physics program for ATLAS-ALFA and AFP (ATLAS Forward Physics) project
Future prospects

- **HERSCHEL**: High Rapidity Shower Counter
- Increase size of rapidity gap (to ±9). Reduce inelastic backgrounds.
- Trigger for hadrons, photons, electrons as well as muons.
- Exclusive $\Lambda$, $D$, low mass resonances in analysis of continuum, glueballs, .....

See e.g. R. Wallace at DIS 2015
Dijet events with jet veto from ATLAS

Gap := jet veto \( (p_T>20 \text{ GeV}) \) for dijets with \( p_T > 70 \text{ GeV} \). Generally described by POMHEG+PYTHIA (NLO DGLAP)
VM production in Pb-Pb and e-Pb collisions

Other VM at LHC in Pb-Pb

Very strong shadowing and no-nuclear-effect disfavored. But more statistics and more theoretical effort required (e.g. uncertainty of $\Psi(2S)$ wave function).

Vector meson are a key tool to study saturation at EIC: $\Phi$ meson well suited for this job.

T. Ullrich

A. Rezaeian