Measurements of diffraction in p-p collisions in CMS

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on behalf of the CMS collaboration

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**Outline**

- **Measurement of soft diffractive SD and DD cross sections and forward rapidity gap cross section at 7 TeV**  
  *CMS PAS FSQ-12-005*  
  *NEW!*

- **Evidence for hard diffractive di-jet prediction at 7 TeV**  
  *CMS-FWD-10-004, PRD 87 (2013) 012006*  
  *arXiv:1209.1805*

- **CMS+TOTEM event displays of high-pT jets with two leading protons at 8 TeV**  
  *CMS-DP-2013-004,CMS-DP-2013-006*  
  *NEW!*
CMS detector

- Tracking
  \(|\eta| < 2.4\), \(p_T\) down to \(~100\) MeV
- Calorimetry
  - Electromagnetic calorimeter \(|\eta| < 3.0\)
  - Hadronic calorimeter (HB, HE, HF) \(|\eta| < 5.0\)
- Forward detectors:
  - HF, hadron forward calorimeter (10m from IP) \(3 < |\eta| < 5\)
  - BSC, beam scintillator counters (in front of HF) \(3.2 < |\eta| < 4.7\)
  - CASTOR calorimeter (one side only) \(-6.6 < \eta < -5.2\)
  - FSC (Forward Shower Counters) \(6 < |\eta| < 8\)
  - ZDC (zero degree calorimeter) \(|\eta| > 8.1\)
Soft diffractive cross sections

First CMS measurement of inclusive diffractive cross sections.

Using Large Rapidity Gap (LRG) signatures.

SD and DD separated with CASTOR (-6.6 < η < -5.2).

- Low-PU 2010 data at √s = 7 TeV.
- Minimum-Bias trigger (hit in either of BSCs).
- Based on Particle Flow objects (tracking+calorimetry).
- At least 2 PF objects in the BSC acceptance.
- No vertex requirement (to retain M_X < 100 GeV).

Minimum-Bias sample in the central CMS detector (-4.7 < η < 4.7).

MC simulations:

- **PYTHIA8-4C**: diffraction with Schuler&Sjostrand model from PYTHIA6. Tune 4C - additional scaling of SD and DD downwards by 10% and 12%.
- **PYTHIA8-MBR (*)&**: diffraction with MBR model. Pomeron intercept ε=0.08 and additional scaling of DD downwards by 15%.

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* MBR (Minimum-Bias Rockefeller) – implemented in Pythia8.165. Regge-based model with renormalized flux, developed for and successfully tested at CDF. Hadronization model tuned to describe diffractive masses at lower energies. More details in Dino's talk on Tuesday and in 'Recent developments on diffraction in Pythia8' talk at MPI2012@CERN.

DIS 2013, R. Ciesielski  [http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=184925]
Soft diffractive cross sections

Experimental topologies of diffractive events with LRG

SD1 type – gap on +side
SD2 type – gap on -side
DD type – central gap

CMS Preliminary, √s = 7 TeV, L = 16.2 μb⁻¹

η_{max} (η_{min}) - highest (lowest) η of the particle reconstructed in the central detector.
η₀^{max} (η₀^{min}) - closest-to-zero positive (negative) η of the particle in the central detector. ∆η₀ = η₀^{max} – η₀^{min}.

All types - measure forward-rapidity-gap cross section (and compare to ATLAS)
No separation of SD and low-mass DD events.

SD2 type, η_{min} >-1 selection
+ CASTOR (to separate SD/DD events) - measure SD and DD cross sections
CASTOR only on -side.

DD type, ∆η₀ >3 selection - measure DD cross section

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Soft diffractive cross sections

Separation of SD/DD events with CASTOR

SD2-type $+$ $\eta_{\text{min}} > -1$ selection - SD events and DD events with low-mass hadronic system escaping detection in the central detector → CASTOR tag to select the sample enhanced in DD events and calculate SD and DD cross sections.

CASTOR calorimeter – layers of tungsten absorber and quartz plates.
12 longitudinal modules and 16 azimuthal sectors.
Sensitivity: $0.5 < \log_{10}(M_Y/\text{GeV}) < 1.1$ ($3.2 < M_Y < 12 \text{ GeV}$).

CASTOR tag – signal above threshold (1.48 GeV) in at least one of 16 sectors (summed over the first 5 modules).
Soft diffractive cross sections

Kinematic phase space (diffractive-mass range) after all selections.

- **Generator level SD process**
- **SD2-type events with the $\eta_{\text{min}}>-1$ selection (forward gap) and no CASTOR tag:**
  
  $12 < M_X < 394$ GeV

- **Generator level DD process**
- **DD-type events with the $\Delta \eta^0 > 3$ selection (central gap):**
  
  $\Delta \eta > 3$, $M_X > 10$ GeV, $M_Y > 10$ GeV

- **SD2-type events with the $\eta_{\text{min}} > -1$ selection (forward gap) and a CASTOR tag:**
  
  $12 < M_X < 394$ GeV, $3.2 < M_Y < 12$ GeV

Two complementary measurements of DD.
Soft diffractive cross sections

Detector-level distribution of fractional proton momentum loss, $\zeta$. CASTOR tag performance.

SD2 with an $\eta_{\text{min}} > -1$ selection.

SD and DD cross sections measured as a function of $\zeta$.

$$\zeta = \frac{\sum(E^i + p_{z}^i)}{M_X^2} \sim \frac{-1}{s}$$

$\zeta$ reconstructed from PF objects, corrected for particles lost in the beam hole or below PF thresholds (MC-based $\zeta$-dependent correction).

The DD contribution to the no-CASTOR tag sample reduced to $\sim$20% (dominant background). DD simulation validated with the CASTOR tag sample.

PYTHIA8-MBR gives a better description of the data and is used to extract cross section. PYTHIA8-4C used for systematic checks (hadronization, diffraction model).
Soft diffractive cross sections

SD and DD cross sections (bin-by-bin correction)

Results compared to predictions of theoretical models used in PYTHIA8-MBR, PYTHIA8-4C and PYTHIA6:

- PYTHIA8 MBR shown for two values of the Pomeron trajectory ($\alpha(t) = 1 + \epsilon + \alpha'(t)$), $\epsilon = 0.08$ and $\epsilon = 0.104$. Both describe the measured SD cross section well. The DD data favour the smaller value of $\epsilon$.

- The Schuler&Sjostrand model used in PYTHIA8-4C and PYTHIA6 describes the DD cross section, but fails to describe the falling behavior of the SD data.

The SD cross section integrated over $-5.5 < \log_{10} \xi < -2.5$:

$\sigma^{SD}_{vis} = 4.27 \pm 0.04$ (stat.) $^{+0.65}_{-0.58}$ (syst.) mb

12 < $M_X$ < 394 GeV

MC-based background subtraction (see previous slide). acc – acceptance (pileup correction included, ~7%). Hadron level – generated masses.

Error bars dominated by systematic uncertainties (HF energy scale and hadronization+diffraction model uncertainties dominate).
Soft diffractive cross sections

**DD cross section with central LRG (bin-by-bin correction)**

\[ \frac{d\sigma^{DD}}{d\Delta\eta} = \frac{N^{\text{data}} - (N_{\text{ND}} + N_{\text{SD}} + N_{\text{CD}})^{\text{MC}}}{\text{acc} \cdot \mathcal{L} \cdot (\Delta\eta)_{\text{bin}}} \]

MC-based background subtraction, ND dominant.

acc – acceptance (pileup correction included, extrapolation from \(\Delta\eta > 3\) to \(\Delta\eta > 3\)).

Hadron level – generated masses, \(\Delta\eta = -\log(M_X^2 M_Y^2 / s s)\).

Results compared to predictions of theoretical models used in PYTHIA8-MBR, PYTHIA8-4C and PYTHIA6. The predictions are in agreements with the data.

The DD cross section integrated in the region \(\Delta\eta > 3\), \(M_X > 10\) GeV, \(M_Y > 10\) GeV:

\[ \sigma^{DD}_{\text{vis}} = 0.93 \pm 0.01 \text{ (stat.)}^{+0.26}_{-0.22} \text{ (syst.) mb} \]
Forward rapidity gap defined as $\Delta \eta^F = \text{Max}(4.7 - \eta_{\text{max}}, 4.7 + \eta_{\text{min}})$.

Bayesian unfolding. Hadron level: stable FS particles with $p_T > 200$ MeV, $|\eta| < 4.7$. Migration matrix from PYTHIA8-MBR.

Cross section limited to $\Delta \eta^F < 8.4$ (small trigger efficiency uncertainty) Different run than for SD/DD cross sections.

Detector-level $\Delta \eta^F$ distribution.
Hadron-level comparison of the forward rapidity gap cross section to predictions of PYTHIA8-MBR ($\epsilon=0.08$ and $\epsilon=0.104$), PYTHIA8-4C and PYTHIA6-Z2* simulations.

Exponentially falling ND contribution dominant for $\Delta\eta^F<3$, above this value cross section weakly changing with $\Delta\eta^F$.

Sensitivity to model dependence.
PYTHIA8-MBR ($\epsilon=0.08$) – best description within uncertainties.
Forward-rapidity gap cross section

Comparison to the ATLAS measurement (EPJ C72 (2012) 1926).

Different hadron level definition: $|\eta|<4.7$ (CMS) vs $|\eta|<4.9$ (ATLAS) – up to 5% effect.
Different MC sample used for unfolding – ~10% effect.
Agreement with ATLAS within uncertainties.
CMS extends the ATLAS measurement by 0.4 unit of gap size.
Diffractive dijets

- Analysis based on 2010 data (2.7 nb\(^{-1}\)) with negligible PileUp
- Single-jet trigger, anti-kt 0.5, vertex.
- At least 2 jets with \(p_T > 20\) GeV and \(|\eta| < 4.4\)
- Based on Particle Flow objects (tracking+calorimetry)

Large Rapidity Gap (LRG): require most forward (or backward) PF object in the event to satisfy \(\eta_{\text{max}} < 3\) (or \(\eta_{\text{min}} > -3\)).

Corresponds to no individual energy deposit above 4 GeV in HF+ (or HF-). Rapidity gap of 1.9 units in the central CMS detector.

LRG data described by a combination of diffractive (POMPYT) and non-diffractive (PYTHIA6 Z2) samples. Relative fraction from the fit to the data.
Inclusive di-jet cross section extracted in 3 bins of $\xi$.

For single-diffractive events $\xi$ approximates proton fractional momentum loss.

$$\tilde{\xi} = \frac{\sum (E^i \pm p^i_z)}{\sqrt{s}} \approx \frac{M_X^2}{s}$$

$\xi$ reconstructed from PF objects.

$\xi^+ (\xi^-)$ corresponds to the gap on positive (negative) side.

Excess of events in low-$\xi$ region wrt non-diffractive PYTHIA6 and PYTHIA8 MC.

POMPYT and POMWIG (LO) diffractive MCs and NLO calculations from POMWEG, using diffractive PDFs, are a factor $\sim 5$ above the data in the lowest-$\xi$ bin.

Data/MC suppression factor is: 0.21 $\pm$ 0.07 (LO MC) 0.14 $\pm$ 0.05 (NLO MC).

After proton-dissociation correction, the ratio can be interpreted in terms of rapidity-gap survival probability of 0.12 $\pm$ 0.05 (LO MC) and 0.08 $\pm$ 0.04 (NLO MC).
Low-PU 90m β* runs with common TOTEM-CMS trigger.

Separate data taking with bidirectional exchange of trigger information (TOTEM RP and T2 triggers to CMS, CMS combined di-jet and lepton/gamma trigger to TOTEM).

Offline event synchronisation with orbit & bunch number matching.

Data sample recorded with 'L1_DoubleJet20' trigger (CMS).

Event selection required at least two jets with $p_T > 20$ GeV (anti-$k_T$, $R=0.5$ jets)

Forward Shower Counters (FSC) empty, 6<$|\eta|<$8.

Reconstructed proton tracks (TOTEM Roman Pots) on both sides of IP (non-elastic)
**CMS+TOTEM detectors**

**Common data taking during low-PU runs in 2012**

- CMS: $|\eta| < 5$
- T2: $5.3 < |\eta| < 6.5$
- FSC: $6 < |\eta| < 8$
- Roman Pots: diffractive protons

**Unique setup, very large $\eta$ coverage:**

- **Forward Shower Counters**
  - 59 - 114 m

- **TOTEM T2**
  - In front of CASTOR
  - 220 m
Run 198903 Event 3478279

Leading three jets $E_T = 65, 45, 27$ GeV
proton $\Delta p/p = -0.01$ (z+)
proton $\Delta p/p = -0.1$ (z-)
$M(pp, TOTEM) = 244$ GeV
$M(CMS) = 219$ GeV
$\Sigma \ p_T (CMS) = 3.4$ GeV
FSC empty in both sides

ECAL/HCAL $E_T > 200$ MeV
Track $p_T > 1$ GeV
Run 198903 Event 3478279
Run 198903 Event 3478279

TOTEM T2 Telescope

Number of Tracks: 3
Run 198903 Event 3478279

TOTEM Event 15322
Clean dijet event in otherwise empty detector.
Forward protons in RPs.
Clean "Mercedes" event in otherwise empty detector.
Forward protons in RPs.
Summary

- Inclusive SD and DD diffractive cross sections measured at 7 TeV:
  - $\sigma_{SD}^{vis} = 4.27 \pm 0.04 \text{ (stat.)}^{+0.65}_{-0.58} \text{ (syst.)} \text{ mb for } -5.5 < \log_{10} \xi < -2.5$
  - $\sigma_{DD}^{vis} = 0.93 \pm 0.01 \text{ (stat.)}^{+0.26}_{-0.22} \text{ (syst.)} \text{ mb for } \Delta\eta > 3, M_{X} > 10 \text{ GeV, } M_{Y} > 10 \text{ GeV}$

  - Forward rapidity gap cross section compared to ATLAS measurement. CMS extends the ATLAS measurement by 0.4 unit of gap size.

- Inclusive di-jet cross section measured as a function of $\zeta$ (fractional proton momentum loss, SD) at 7 TeV:
  - Excess of events over non-diffractive MC predictions at lower $\zeta$.
  - Gap-survival probability of 0.08-0.12 (LO/NLO MC) measured for $0.0003 < \zeta < 0.002$.

- CMS+TOTEM high-p$_{T}$ jet event displays with two protons detected in the TOTEM RP.
  Ongoing CMS+TOTEM analyses: dN/d$\eta$ with CMS tracker + T2, SD di-jets with proton, soft semi-hard CD, etc.

New results on the way. Check the latest CMS results at: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ