Diffractive and Exclusive Measurements at CMS

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on behalf of the CMS Collaboration
Outline

- CMS detector and forward instrumentation

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ
**CMS detector**

- **Tracker**: $|\eta| < 2.4$, $p_T > 100$ MeV

- **Calorimeters**: $|\eta| < 3$ (barrel and endcap)
  
  - Electromagnetic calorimeter ECAL
  - Hadronic calorimeter HCAL
CMS detector forward instrumentation

- **Hadron Forward calorimeter (HF):** $2.9 < |\eta| < 5.2$ (10 m from IP)
- **Beam Scintillator Counters BSC:** $3.2 < |\eta| < 4.7$ (in front of HF)
- **CASTOR calorimeter:** $-6.6 < |\eta| < -5.2$ (14.4 m from IP, one side only)
- **Forward Shower Counters FSC:** $6 < |\eta| < 8$ (59-114 m from IP)
- **Zero Degree calorimeter:** $|\eta| > 8.1$ (140 m from IP)
Two generic type of processes contribute to the production of most of the final state particles at LHC energies:

- Semi-hard multi parton scattering with exchanged momenta of a few GeV and subsequent fragmentation of quarks and gluons into hadrons

- Diffractive scattering in more peripheral pp interactions

Particle yields and their kinematic along the rapidity range → better understanding of mechanism of hadron production in high-energy hadronic interactions and notably of the relative roles of soft-hard scattering
About diffractive and...

- Energy of scattered protons ≈ beam energy (within a few %)
  - Pomeron exchange (IP), Large Rapidity Gap (LRG)
- If $X =$ anything:
  - Measure fundamental quantities of soft QCD
    - Contributes significantly to pile-up, underlying event (SD ~ 15 mb, DD ~ 10 mb)
- If $X$ includes jets, W's, Z's:
  - Hard processes, calculable in perturbative QCD
  - Measure proton structure, QCD at high parton densities, discovery physics
...exclusive reactions

Study the reaction

\[ pp \rightarrow p^{(*)}Xp^{(*)} \]

where numerous production mechanisms can contribute to produce the central system

\[ X = e^+e^-, \mu^+\mu^-, \gamma\gamma, W^+W^-, \ldots \]
Outline

- CMS detector and forward instrumentation
- Single and double diffractive cross sections at $\sqrt{s} = 7$ TeV
  [CMS PAS FSQ-12-005]
- Forward rapidity gap cross section at $\sqrt{s} = 7$ TeV
  [CMS PAS FSQ-12-005]
- Pseudorapidity distribution of charged particles at $\sqrt{s} = 8$ TeV
- Two-photon production of $W^+W^-$ pairs
  [CMS PAS FSQ-12-010, arXiv:1305.5596]

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ
Soft diffractive cross sections
Event selection

- Based on Large Rapidity Gap (LRG) tagging
- Single and double diffractive contributions separated with CASTOR tag (-6.6 < |η| < -5.2)

Sample
16.2 µb⁻¹ low pileup (µ=0.14) data at √s = 7 TeV

Selection
minimum bias trigger (hit in either of the BSCs)
at least 2 PF in the BSC acceptance
no vertex requirement (to retain M_X < 100 GeV)
LRG cut based on Particle Flow (PF) objects

Monte Carlo
acceptance+background: PYTHIA8-MBR, diffraction with Minimum Bias Rockefeller model
systematics: PYTHIA8-4C, diffraction with Schuler & Sjostrand model from PYTHIA6
Experimental topologies

- 3 experimental topologies based on the position of the LRG

**GAP ON POSITIVE SIDE**

- CMS Preliminary $\sqrt{s} = 7$ TeV, $L = 16.2 \mu$b$^{-1}$

**GAP ON NEGATIVE SIDE**

- CMS Preliminary $\sqrt{s} = 7$ TeV, $L = 16.2 \mu$b$^{-1}$

**CENTRAL GAP**

- CMS Preliminary $\sqrt{s} = 7$ TeV, $L = 16.2 \mu$b$^{-1}$

$\eta_{\text{max}}$ ($\eta_{\text{min}}$): highest (lowest) $\eta$ of the particle candidates in $|\eta| < 4.7$

$\Delta\eta^0$: difference between the closest-to-zero positive ($\eta_{\text{max}}^0$) and negative ($\eta_{\text{min}}^0$) $\eta$ of the particle candidates in $|\eta| < 4.7$

![](image)

- sample SD1
- sample SD2
- sample DD

- dominated by SD and DD events
- dominated by DD events
Experimental topologies

- 3 experimental topologies based on the position of the LRG

**GAP ON POSITIVE SIDE**

- CMS Preliminary $\sqrt{s} = 7$ TeV, $L = 16.2 \mu$b$^{-1}$

- Events

<table>
<thead>
<tr>
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**GAP ON NEGATIVE SIDE**

- CMS Preliminary $\sqrt{s} = 7$ TeV, $L = 16.2 \mu$b$^{-1}$

- Events

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**CENTRAL GAP**

- CMS Preliminary $\sqrt{s} = 7$ TeV, $L = 16.2 \mu$b$^{-1}$

- Events

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**CASTOR used to tag the undetected low mass system in $-6.7 < \eta < -5.2$**
Detector level $\xi$ distributions

$$\xi = \frac{M_X^2}{s} = \frac{\sum (E_i' + p_i')}{\sqrt{s}}$$

proton fractional momentum loss reconstructed from particle candidates in $|\eta| < 4.7$

**COMPARISON to PYTHIA8-MBR**

CMS Preliminary $\sqrt{s} = 7$ TeV, $L = 16.2 \mu$b$^{-1}$

- (a) sample SD2 no CASTOR tag
- (b) sample SD2 CASTOR tag
- (c) sample SD2 CASTOR tag

CASTOR used to tag the undetected low mass system

- $-6.7 < \eta < -5.2$
- $3.2 < M < 12$ GeV
SD and DD cross sections vs $\xi$

- MBR model for 2 values of the Pomeron intercept $\alpha_{IP}(0)$ (1.08 e 1.104)

- Same implementation of Schuler & Sjostrand model in PYTHIA8-4C and PYTHIA6

$\rightarrow$ SD data well described by either versions of the MBR model, but DD cross section better described by smaller intercept

$\rightarrow$ Schuler&Sjostrand model cannot describe the falling behaviour of SD cross section

$\rightarrow$ Single diffractive cross section integrated over $-5.5 < \log \xi < -2.5$:

$$\sigma_{vis}^{\text{SD}} = 4.27 \pm 0.04(\text{stat.}) + 0.65/-0.58(\text{syst.}) \text{ mb for } 1.1 < \log(M_X/\text{GeV}) < 2.6$$
**DD cross section vs Δη**

\[ \Delta \eta = -\ln \xi \quad \xi = \frac{M_X^2 \cdot M_Y^2}{s \cdot m_p^2} \]

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

- MBR model for 2 values of the Pomeron intercept \(\alpha_{IP}(0)\) (1.08 e 1.104)
- Same implementation of Schuler & Sjostrand model in PYTHIA8-4C and PYTHIA6

\(\rightarrow\) Agreement with data

\(\rightarrow\) Double diffractive cross section integrated over \(\Delta \eta > 3, M_X > 10 \text{ GeV}, M_Y > 10 \text{ GeV}:\)

\[ \sigma_{vis}^{DD} = 0.93 \pm 0.01(\text{stat.}) + 0.26/-0.22(\text{syst.}) \text{ mb} \]
Forward rapidity gap cross section
Event selection

- Inclusive measurement, no separation of SD and DD

Sample
16.2 \( \mu b^{-1} \) low pileup (\( \mu = 0.14 \)) data at \( \sqrt{s} = 7 \) TeV

Selection
minimum bias trigger (hit in either of the BSCs)
based on Particle Flow (PF) objects
at least 2 PF in the BSC acceptance
no vertex requirement (to retain \( M_X < 100 \) GeV)

Monte Carlo
PYTHIA8-MBR, diffraction with Minimum Bias Rockefeller model
PYTHIA8-4C, diffraction with Schuler & Sjostrand model from PYTHIA6
PYTHIA6-Z2*

Forward rapidity gap \( \Delta \eta_F = \max(4.7-\eta_{\text{max}}, 4.7+\eta_{\text{min}}) \)
largest gap between each edge of the detector and the position in \( \eta \)
of the first particle found in moving away from the edge
Forward rapidity gap cross section

At low $\Delta \eta_F$
Exponentially suppressed ND contribution is dominant
Sensitivity to fluctuations in soft particle hadronization

At large $\Delta \eta_F$
Diffractive plateau $\sim 1$ mb/unit of gap size
SD $\sim$ DD contribution
Best description of the data by PYTHIA8-MBR with smaller intercept

$$\frac{d\sigma(\Delta \eta_F)}{d\Delta \eta_F} = \frac{A(\Delta \eta_F) \ N(\Delta \eta_F) - N_{BG}(\Delta \eta_F)}{\Delta \eta_{had} \times \epsilon(\Delta \eta_F) \times \mathcal{L}}$$
Forward rapidity gap cross section

COMPARISON TO ATLAS

CMS Preliminary, $\sqrt{s} = 7$ TeV, $L = 20.3 \mu b^{-1}$

- Different hadron level definition: $|\eta| < 4.7$ (CMS) vs $|\eta| < 4.9$ (ATLAS) → up to 5% effect

- Unfolding based on different MCs: PYTHIA8-MBR (CMS) vs PYTHIA8 (ATLAS) → up to 10% effect

→ Agreement within uncertainties

→ CMS result extends ATLAS measurement by 0.4 unit of gap size
Pseudorapidity distribution of charged particles
Event selection and reconstruction

Sample
- 45.4 μb⁻¹ common CMS+TOTEM 2012 low pileup run at √s = 8 TeV, β*=90 m optics
- time synchronization of the two experiments
- events combined offline requiring same orbit and bunch numbers

Selection & track reconstruction
- minimum bias trigger provided by TOTEM T2 telescopes (> 90% of inelastic)

- 3 experimental topologies based on different selection criteria for T2 tracks
  - inclusive sample: at least one primary candidate in T2
    99% non diffractive events + diffractive events with masses > 3.6 GeV
  - sample enhanced in non single diffractive (NSD): at least one primary candidate in T2, in both z-directions
  - sample enhanced in single diffractive (SD): at least one primary candidate in T2, in only one z-direction
Event selection and reconstruction

Sample
- 45.4 \mu b^{-1} common CMS+TOTEM 2012 low pileup run at \sqrt{s} = 8 \text{ TeV} , \beta^* = 90 \text{ m} optics
- time synchronization of the two experiments
- events combined offline requiring same orbit and bunch numbers

Selection & track reconstruction
- minimum bias trigger provided by TOTEM T2 telescopes (> 90% of inelastic)
- T2 track reconstruction, key issue is primary/secondary particle separation
- standard CMS track reconstruction algorithm

<table>
<thead>
<tr>
<th>Source</th>
<th>CENTRAL REGION</th>
<th>Tracking efficiency</th>
<th>Trigger efficiency</th>
<th>Model dependence</th>
<th>Correction to p_T = 0</th>
<th>Statistical</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
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<td>Inclusive</td>
<td>NSD-enhanced</td>
<td>SD-enhanced</td>
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<td>Event and primary track selection (C_{sel}(\eta))</td>
<td>3-5%</td>
<td>4–6%</td>
<td>9–16%</td>
<td>3.9%</td>
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<td>0.1%</td>
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<tr>
<td>Total</td>
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<td>6–8%</td>
<td>10–17%</td>
<td>5–6%</td>
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FORWARD REGION

<table>
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<th>NSD-enhanced</th>
<th>SD-enhanced</th>
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<tr>
<td>Tracking efficiency data-MC discrepancy</td>
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<td>5–6%</td>
<td>5–6%</td>
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<tr>
<td>Primary selection (including alignment)</td>
<td>4–5%</td>
<td>4–5%</td>
<td>4–5%</td>
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<tr>
<td>Non-primaries in the double-Gaussian peak</td>
<td>5%</td>
<td>5%</td>
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<tr>
<td>Material effects</td>
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<td>3–6%</td>
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<tr>
<td>High-multiplicity events</td>
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<td>2%</td>
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<td>on energy spectrum and magnetic field</td>
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<td>Track quality criterion</td>
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<tr>
<td>Correction to p_T = 0</td>
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<td>Trigger efficiency</td>
<td>0.2%</td>
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<td>0.2%</td>
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<tr>
<td>Statistical</td>
<td>0.1%</td>
<td>0.1%</td>
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<tr>
<td>Total (after averaging half-arms)</td>
<td>10–12%</td>
<td>10–12%</td>
<td>16–18%</td>
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</table>
Central & forward $dN_{ch}/d\eta$

→ Multiplicity of SD events significantly smaller than NSD

→ No MC able to describe $dN_{ch}/d\eta$ of all events and samples in the whole rapidity region
Particle production at mid rapidities is expected to follow a power-law centre-of-mass energy dependence $s^\varepsilon \Rightarrow$ Fitting the data yield $\varepsilon = 0.23 \pm 0.01$
Two-photon production of $W$ pairs
Theoretical framework

GENUINE ANOMALOUS QUARTIC COUPLINGS (aQGCs)

- SM Lagrangian density contains (triple and) quartic couplings between $\gamma$ and $W$ bosons

- Effective Lagrangian with 2 additional dimension-6 terms:

\[
\mathcal{L}_6^0 = \frac{e^2 a_0^W}{8 \Lambda^2} F_{\mu\nu} F^\mu^\nu W^+W^- - \frac{e^2}{16 \cos^2 \Theta_W} \frac{a_0^Z}{\Lambda^2} F_{\mu\nu} F^\mu^\nu Z^\alpha Z_\alpha \\
\mathcal{L}_6^C = \frac{-e^2 a_C^W}{16 \Lambda^2} F_{\mu\alpha} F^{\mu\beta} (W^{+\alpha}W^{-\beta} + W^{-\alpha}W^{+\beta}) - \frac{e^2}{16 \cos^2 \Theta_W} \frac{a_C^Z}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} Z^\alpha Z_\beta
\]

- Parameters $a_0^W$ and $a_C^W$

- $\Lambda$: scale for new physics

- aQGCs make the $\gamma\gamma \rightarrow W^+W^-$ cross section increase quadratically with energy \\
  → dipole form factors introduced to preserve unitarity

\[
a_0^W \rightarrow a_0^W (W_{\gamma\gamma}^2) = a_0^W \left(1 + \frac{W_{\gamma\gamma}^2}{\Lambda_{\text{cutoff}}^2}\right)^{-2}
\]

- $\Lambda_{\text{cutoff}}$: energy cutoff scale ($\Lambda_{\text{cutoff}} \rightarrow \infty = \text{no form factor}$)

- $W_{\gamma\gamma}$: $\gamma\gamma$ center of mass energy
Event selection

- Two contributions to signal
  - elastic production: \( pp \rightarrow pW^+W^-p \)
  - proton-dissociative production: \( pp \rightarrow p^*W^+W^-p^* \),
    (one or both protons dissociate into a low-mass system that escapes detection)

- Unlike-flavor dilepton decay channel: \( \gamma\gamma \rightarrow W^+W^- \rightarrow \mu^+\mu^-\nu\bar{\nu} \)

- Control sample: \( pp \rightarrow p^*(\mu^+\mu^-p^*) \)

**Sample**
5.05 \( \mu b^{-1} \) 2011 data at \( \sqrt{s} = 7 \) TeV

**SM signal region:**
\( p_T(\mu^+\mu^-) > 30 \) GeV
no extra tracks associated to the dilepton vertex

**aQGCs search:**
\( p_T(\mu^+\mu^-) > 100 \) GeV
no extra tracks associated to the dilepton vertex
SM signal $\gamma\gamma \rightarrow W^+ W^- \rightarrow \mu^\pm e^\mp \nu \bar{\nu}$

$\sigma(pp \rightarrow p^{(*)}(\gamma\gamma \rightarrow W^+ W^-)p^{(*)}) \times BR(W^\pm \rightarrow \mu^\pm \nu, e^\pm \nu) = 2.2^{+3.3}_{-2.0}$ (stat.) fb (SM prediction 4.0 ± 0.7 fb)
Search for aQGCs

- No events observed in data, consistent with SM expectation of 0.14
- Upper limit on the cross section \( \times \) BR at 95\% C.L.:

\[
\sigma \left( pp \rightarrow p^{(*)}(\gamma \gamma \rightarrow W^+W^-)p^{(*)} \right) \times BR(W^\pm \rightarrow \mu^\pm \nu, e^\pm \nu) < 1.9 \text{ fb}
\]

<table>
<thead>
<tr>
<th>( a^W_0/\Lambda^2 )</th>
<th>( \Lambda_{\text{cut off}} = 500 \text{ GeV} )</th>
<th>( \Lambda_{\text{cut off}} = \infty \text{ MeV} )</th>
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<tr>
<td>no form factor</td>
<td>( \pm 2 \times 10^{-2} )</td>
<td>( \pm 4.3 \times 10^{-4} )</td>
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<td>( a^W_c/\Lambda^2 )</td>
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- With \( \Lambda_{\text{cut off}} = 500 \text{ MeV} \):
  - Up 20 times more stringent than the best Tevatron limits
  - Two order of magnitude improvement wrt LEP

- With \( \Lambda_{\text{cut off}} = \infty \text{ MeV} \):
  - Two order of magnitude improvement wrt Tevatron

Limits would much improve with a proton tagger (see next talk)
Summary

- Inclusive single diffractive and double diffractive cross sections at 7 TeV
  - $\sigma_{\text{vis}}^{SD} = 4.27 \pm 0.04(\text{stat.}) \pm 0.65/0.58(\text{syst.})$ mb for $-5.5 < \log \xi < -2.5$
  - $\sigma_{\text{vis}}^{DD} = 0.93 \pm 0.01(\text{stat.}) \pm 0.26/0.22(\text{syst.})$ mb for $\Delta \eta > 3$, $M_X > 10$ GeV, $M_Y > 10$ GeV

- Forward rapidity gap cross section

  CMS extends the ATLAS measurement by 0.4 unit of gap size

- Charged particle pseudorapidity distributions for $|\eta| < 2.2$ and $5.3 < |\eta| < 6.4$
  - first publication CMS+TOTEM
  - input for tuning and testing the models from central to forward pseudorapidities

- Upper limit on the $\gamma\gamma \rightarrow W^+W^-$ production cross section for $p_T(\mu^+\mu^-) > 100$ GeV