Diffractive cross sections and hard diffraction at the LHC

A. Vilela Pereira on behalf of the ATLAS, CMS and TOTEM Collaborations

Universidade do Estado do Rio de Janeiro
Outline

Total, inelastic & diffractive cross section measurements at the LHC

Hard diffraction

High-β*/Low pile-up running with proton tagging

CT-PPS and AFP: proton spectrometers at high-luminosity
ATLAS, CMS & TOTEM @ LHC
The ATLAS detector

- Muon Detectors
- Electromagnetic Calorimeters
- Solenoid
- Forward Calorimeters
- End Cap Toroid
- Barrel Toroid
- Inner Detector
- Hadronic Calorimeters
- Shielding

Detector characteristics:
- Width: 44m
- Diameter: 22m
- Weight: 7000t

CERN AC - ATLAS V1997
Roman Pot (RP) (vertical) stations at \(~ 240\) m from ATLAS IP.

8 fiber detectors (2 x 10 layers; 0.5 mm fibers; resolution \(~ 35\) um).

Fully integrated in ATLAS DAQ.

Material taken from P.Fassnacht Forward Physics Working Group workshop - March 2016
The CMS detector
Forward detectors @ CMS

**Detector configuration during 2010 - 2011**

- **CASTOR**
  
- **Hadronic Forward (HF)**
  
- **CMS**
  
- **Hadronic Forward (HF)**
  
- **ZDC**
  
**I40m**

**(-6.6 < η < -5.2)**

**ZDC**

**(|η| > 8.1)**

**W-absorbers/quartz plates**

**12 longitudinal modules/16 azimuthal sectors**

**HF BSC**

Acceptance limited to |η| < 4.9 at analysis level

**Hadron Forward:**

@11.2m from interaction point

Rapidity coverage: 3 < |η| < 5

Steel absorbers/quartz fibers (Long+short fibers)

0.175x0.175 η/φ segmentation

**7**

ICHEP2016 - Chicago - August 3-10 2016
Forward detectors @ CMS

Analogous forward detector instrumentation, at large pseudorapidity, present as well in ATLAS, in particular:

**Forward Calorimeter (FCal):** Liquid argon sampling calorimeter \((3.1 < |\eta| < 4.9)\).

**Minimum-bias trigger scintillators (MBTS):**
In front of each endcap calorimeter. Inner and outer octagonal rings w/ 8 and 4 counters respectively \((2.07 < |\eta| < 3.86)\).

**LUCID:** Forward Cherenkov detector \((5.6 < |\eta| < 5.9)\).

Detector configuration during 2010 - 2011

**Hadron Forward:**
@11.2m from interaction point
Rapidity coverage: \(3 < |\eta| < 5\)
Steel absorbers/quartz fibers (Long+short fibers)
0.175x0.175 \(\eta/\phi\) segmentation
Acceptance limited to \(|\eta| < 4.9\) at analysis level
The TOTEM detectors

Roman Pots (RPs)
Detect outgoing protons at very small angles (elastic, diffractive and photon-induced processes).

T1: $3.1 < |\eta| < 4.7$
T2: $5.3 < |\eta| < 6.5$
Detect charged particles from collision.

Vertical RPs
Horizontal RPs
Cylindrical RPs (w/ CT-PPS)

$\sim 220$ m

Material taken from N. Minafra - Low-x 2016
Outline

Total, inelastic & diffractive cross section measurements at the LHC

Hard diffraction

High-\(\beta^*\)/Low pile-up running with proton tagging

CT-PPS and AFP: proton spectrometers at high-luminosity
The total and (in)elastic cross sections

\[ \sigma_{\text{tot}} \propto \frac{16\pi}{1 + q^2} \left. \frac{dN_{\text{el}}}{dt} \right|_0 \]

Luminosity independent:

\[ \sigma_{\text{tot}} = \frac{16\pi}{1 + q^2} \frac{dN_{\text{el}}/dt|_0}{N_{\text{el}} + N_{\text{inel}}} \]

\[ \rho \text{-independent:} \]

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

TOTEM:

- EPL 96(2011) 21002
- EPL 101(2013) 21002
- EPL 101(2013) 21004
- PRL 111 (2013) 012001

ATLAS STDM-2015-22

arXiv:1607.06605
The total and (in)elastic cross sections

More on elastic scattering:
Measurement of the total cross section from elastic scattering in pp-collisions at $\sqrt{s}=8$ TeV with the ATLAS detector, arXiv:1607.06605
Evidence for Non-Exponential Elastic Proton-Proton Differential Cross-Section at Low $|t|$ and $\sqrt{s} = 8$ TeV by TOTEM, Nucl. Phys. B 899 (2015) 527-546

ATLAS STDM-2015-22
arXiv:1607.06605

TOTEM:
EPL 96(2011) 21002
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EPL 101(2013) 21004
PRL 111 (2013) 012001
The total and (in)elastic cross sections

More on elastic scattering:

Measurement of the total cross section from elastic scattering in pp-collisions at √s=8 TeV with the ATLAS detector, arXiv:1607.06605


See talk later today on “Total, elastic and inelastic pp cross sections at the LHC” by Tomas Sykora.
The inelastic cross section at 13 TeV

Preliminary ATLAS result (instead of that from arXiv:1606.02625)

CMS Preliminary

13 TeV

CMS FSQ-15-005

Higher detector acceptance by using CASTOR

ATLAS STDM-2015-05
arXiv:1606.02625

See talk later today on “Total, elastic and inelastic pp cross sections at the LHC” by Tomas Sykora.

ATLAS (MBTS)
Pythia 8
ATLAS (ALFA)
EPOS LHC
TOTEM
QGSJET-II
ALICE
LHCb
Auger
pp (non-LHC)
p\bar{p}
The inelastic cross section at 13 TeV

Model-dependent extrapolations to $\xi < 10^{-6}$ region

ATLAS STDM-2015-05
arXiv:1606.02625

CMS FSQ-15-005

See talk later today on “Total, elastic and inelastic pp cross sections at the LHC” by Tomas Sykora.
Diffractive dissociation processes

**Single-diffractive dissociation (SD):**
\[ t = (p - p')^2 \; ; \; \xi = (M_X)^2/s \]

**Double-diffractive dissociation (DD):**

**Central-diffractive dissociation (CD):**

**Sketch of single-diffractive event:**

LRG: Large Rapidity Gap

Diffractive dissociation corresponds to a considerable fraction of the pp inelastic cross section.

Soft diffraction in general model dependent.

Defining and constraining diffractive component important ingredient in the tuning of MC generators at the LHC.
Diffractive topologies at detector level

Look at highest/lowest $\eta$ of particles reconstructed in detector ($\eta_{\text{max}}/\eta_{\text{min}}$) for forward gaps (SD/DD)

Look at closest-to-zero positive/negative $\eta$ of particles in detector ($\eta^0_{\text{max}}/\eta^0_{\text{min}}$) for central gaps (DD)

**CMS FSQ-12-005**
*Phys. Rev. D 92 (2015) 012003*

Use CASTOR to separate SD and DD contributions
Diffractive cross sections

Results compared to predictions from PYTHIA6, PYTHIA8 (Tune 4C), PYTHIA8-MBR (+ other models)

\[
\sigma_{\text{vis}}^{\text{SD}} = 4.06 \pm 0.04 \text{ (stat.)} \pm 0.69 \text{ (syst.) mb} \quad (-5.5 < \log_{10} \xi_{X,Y} < -2.5)
\]

\[
\sigma_{\text{vis}}^{\text{DD}} = 2.69 \pm 0.04 \text{ (stat.)} \pm 0.29 \text{ (syst.) mb} \quad (-5.5 < \log_{10} \xi_{X,Y} < -2.5 \ ; \ 0.5 < \log_{10} M_{Y,X} < 1.1 \ ; \ \Delta \eta > 3)
\]

**CMS FSQ-12-005**

*Phys. Rev. D 92 (2015) 012003*
**Diffractive cross sections**

\[ \sigma^{SD} (\xi < 0.05) = 8.84 \pm 0.08 \text{ (stat.)} \pm 1.49 \text{ (syst.)} \pm 1.17 \text{ (extrap.)} \text{ mb} \]

\[ \sigma^{DD} (\Delta \eta > 3) = 5.17 \pm 0.08 \text{ (stat.)} \pm 0.55 \text{ (syst.)} \pm 1.62 \text{ (extrap.)} \text{ mb} \]

**CMS FSQ-12-005**

*Phys. Rev. D 92 (2015) 012003*
Diffractive cross sections (TOTEM)

\[ \sigma^{SD} = 6.5 \pm 1.3 \text{ mb} \]

\[ (3.4 \text{ GeV} < M_{\text{diff}} < 1.1 \text{ TeV}) \]

Material taken from N. Minafra - Low-x 2016
Probing hard diffraction

Diffractive events where a hard scale is present: high-\(p_T\) jets, W/Z’s, ...

HERA/Tevatron: Breaking of QCD factorization in hadron-hadron collisions.

Smaller cross sections than expected based on diffractive PDFs (dPDFs) convolved with partonic cross sections.

Soft interactions between spectator patrons from incoming protons quantified by “rapidity gap survival probability” (<\(S^2\>)), roughly independent of the hard process.

\[
\xi = \frac{M_X^2}{s}
\]

\[
\frac{d^2\sigma}{d\xi dt} = \sum \int dx_1 dx_2 f(\xi, t) f_{IP}(x_1, \mu) f_{p}(x_2, \mu) \hat{\sigma}
\]

D PDF parameterisation: Pomeron (and Reggeon) flux \(\otimes\) pdf

Proton PDF

Implemented in “hard-diffractive” MC’s, e.g. POMPYT, POMWIG, FPMC; also PYTHIA8, HERWIG++ etc.
Probing hard diffraction

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\]

\[
|p| f(\xi, t) = e^{B t} \frac{\xi^2 \alpha_{IP}(t)}{2 \alpha_{IP}(t) - 1}
\]

dPDF parameterisation: Pomeron (and Reggeon) flux \(\otimes\) pdf

Partonic cross section

 Implemented in “hard-diffractive” MC’s, e.g. POMPYT, POMWIG, FPMC; also PYTHIA8, HERWIG++ etc.
Evidence of hard diffraction

Diffractive component is enhanced with respect to the non-diffractive (ND) in the low-$\xi$ and high $\Delta \eta^F$ (size of forward gap) region.

Information from central ATLAS apparatus (sum over all particles in event).

High ND contribution in diffractive kinematic region.

ATLAS Simulation

\[
\xi = \frac{1}{\sqrt{s}} \sum p_T \frac{x}{s} \simeq \frac{M^2}{s}
\]

ATLAS STDM-2014-04

doi:10.1016/j.physletb.2016.01.028
Evidence of hard diffraction

Requiring forward gap ($\Delta\eta^F > 2$), excess is seen at low $\xi$.

MC-based extraction of gap survival probability.

$$S^2 = 0.16 \pm 0.04 \text{ (stat.)} \pm 0.08 \text{ (syst.)}$$
Evidence of hard diffraction

Requiring forward gap ($\Delta \eta^F > 2$), excess is seen at low $\xi$. MC-based extraction of gap survival probability.

$S^2 = 0.16 \pm 0.04 \text{ (stat.)} \pm 0.08 \text{ (syst.)}$

$S^2_{\text{data/MC}} = 0.12 \pm 0.05 \text{ (LO MC)}$

$S^2_{\text{data/MC}} = 0.08 \pm 0.04 \text{ (NLO MC)}$
Production of jets separated by a large rapidity gap

Events with two jets separated by a large rapidity gap.

Color-singlet exchange; sensitive to BFKL dynamics and rapidity gap survival probability.

HERWIG6: hard color-singlet exchange (LL Mueller-Tang model) + UE.
Production of jets separated by a large rapidity gap

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HERWIG6: hard color-singlet exchange (LL Mueller-Tang model) + UE.

Extraction of color-singlet exchange fraction from first two bins of \( N_{\text{tracks}} \) distribution.

Three lower-energy jet \( p_T \) bins. Increase of fraction with jet \( p_T \).

Decrease with center-of-mass energy (comparison to Tevatron results).
Outline

Total, inelastic & diffractive cross section measurements at the LHC

Hard diffraction

High-$\beta^*$/Low pile-up running with proton tagging

CT-PPS and AFP: proton spectrometers at high-luminosity
Outlook: CMS & TOTEM extended forward detectors

July 2012: ($\beta^* = 90$ m, 8 TeV)
Common CMS-TOTEM data taking at low pile-up with around 50 nb$^{-1}$ collected.

October 2015: ($\beta^* = 90$ m, 13 TeV)
$\sim 400$ nb$^{-1}$ recorded (CMS/TOTEM) from around 700 nb$^{-1}$.
$<N_{\text{int}}/Bx>$ less than $\sim 0.10$.

TOTEM Roman Pots (RPs) to detect protons scattered from diffractive processes.

TOTEM T2 tracking stations at very forward angles

In 2012 Run also: Forward Shower Counters (FSC) covering $|\eta| \sim 6$-8.

Forward proton spectrometer associated with complete central coverage

ATLAS (ALFA) operational during high-$\beta^*$ running.
dN_{ch}/d\eta in central + forward regions

CMS-TOTEM, \sqrt{s} = 8 \text{ TeV}, L = 45 \mu\text{b}^{-1}

Inclusive pp

- Data
- Pythia6 Z2*
- Pythia8 4C
- Herwig++ EE3-CTEQ6L1
- EPOS LHC
- QGSJetII-04

SD-enhanced pp

- Data
- Pythia6 Z2*
- Pythia8 4C
- Herwig++ EE3-CTEQ6L1
- EPOS LHC
- QGSJetII-04

N_{ch} \geq 1 in 5.3<\eta<6.5 or -6.5<\eta<-5.3

MC / Data

- N_{ch} \geq 1 in only 5.3<\eta<6.5 or only -6.5<\eta<-5.3

CMS FSQ-12-026

Services routing:
From Castor to Racks
dN_{ch}/d\eta in central + forward regions

Inclusive pp

CMS-TOTEM, \sqrt{s} = 8 \text{ TeV}, L = 45 \mu \text{b}^{-1}

N_{ch} \geq 1 \text{ in } 5.3<\eta<6.5 \text{ or } -6.5<\eta<-5.3

MC / Data

Data

Pythia6 Z2*

Pythia8 4C

Herwig++ EE3-CTEQ6L1

EPOS LHC

QGSJetII-04

CMS FSQ-15-001


CMS FSQ-12-026

dN_{ch}/d\eta in central + forward regions

CMS-TOTEM, \sqrt{s} = 8 \text{ TeV}, L = 45 \mu b^{-1}

CMS-FSQ-12-026


K. Österberg

The End

CMS-FSQ-15-008

CMS-FSQ-15-008
d$N_{ch}/d\eta$ in central + forward regions

CMS Preliminary

SD selection

- data
- PYTHIA8 CUETM1
- PYTHIA8 CUETS1
- PYTHIA8 CUETM1 MBR
- PYTHIA8 4C MBR

CMS-TOTEM, $\sqrt{s} = 8$ TeV, $L = 45 \mu$b$^{-1}$

- Data
- Pythia6 Z2*
- Pythia8 4C
- Herwig++ EE3-CTEQ6L1
- EPOS LHC
- QGSJetII-04

$N_{ch} \geq 1$ in $|\eta| < 2.4$
$p_T > 0.5$ GeV

$N_{ch} \geq 1$ in only $5.3 < \eta < 6.5$ or only $-6.5 < \eta < -5.3$
Example: central dijet event candidate with two leading protons (2012 Run)

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
Outlook: The CT-PPS Project

CMS-TOTEM
Precision Proton Spectrometer

Components installed in tunnel

CT-PPS TECHNICAL DESIGN REPORT
CERN-LHCC-2014-021

CERN-LHCC-2014-021

CMS-TOTEM Precision Proton Spectrometer

TCL 4 & TCL 6 in 4-5 and 5-6
Electrical patch panel
Service lines for LV/HV/DAQ
CT-PPS specific:
- 2 * RP box with RF shield in 4/5
- 2 * RP box with RF shield in 5/6
- 1 * RP cylinder in 4/5
- 1 * RP cylinder in 5/6

ICHEP2016 - Chicago - August 3-10 2016
Forward proton detectors

Detector concept

- The CMS-Totem Precision Proton Spectrometer (CT-PPS) will allow precision proton measurement in the very forward region on both sides of CMS in standard LHC running conditions.
- Proton spectrometer uses machine magnets to bend protons.
- Two stations for tracking detectors and two stations for timing detectors installed at ~205-215 m from the IP (on both sides).

M. Gallinaro - “CMS-TOTEM Precision Proton Spectrometer” - LHCFwd - CERN, Oct. 28, 2015

New collimator TCL6 to protect magnet Q6

Timing detectors:
Measures the time-of-flight of scattered protons

Tracking detectors:
Measures the displacement of the scattered protons w.r.t. the beam

Timing detectors:
- Proton timing measurement from both sides of CMS allows to determine the primary vertex, correlate it with the central detector’s, reject pileup.
- Time resolution 10 ps → 2 mm
- Reasonable segmentation
- Radiation hard
- Minimize impact on beam

M. Gallinaro - “CMS-TOTEM Precision Proton Spectrometer” - LHCFwd - CERN, Oct. 28, 2015

$\sigma_{z_{vtx}} = \frac{c}{2} \sqrt{2\sigma^2_{\Delta t}} \quad \sigma_{\Delta t} = 10 \text{ ps} \approx 2 \text{ mm}$

$\sigma_{\Delta t} = 30 \text{ ps} \approx 6 \text{ mm}$

“3D” pixel sensors with columnar electrodes

$\sigma_y \sim 2 \text{ mm}$
Forward proton detectors

ATLAS: AFP (ATLAS Forward Proton)
Similar strategy concerning RPs and sensors.
First arm under commissioning (2016/2017).
Later installation of second arm and time-of-flight detectors.

Tracking detectors:
Measures the displacement of the scattered protons w.r.t. the beam

Material taken from M. Trzebinski - LHC Forward Physics WG - March 2016
ICHEP2016 - Chicago - August 3-10 2016
Forward proton detectors

ATLAS: AFP (ATLAS Forward Proton)
Similar strategy concerning RPs and sensors.
First arm under commissioning (2016/2017).
Later installation of second arm and time-of-flight detectors.

CT-PPS status:
First phase of operation during 2016 using TOTEM silicon strip detectors.
Several fb⁻¹ of data already collected.
Diamond (high resolution time-of-flight) detectors installed in cylindrical RP and under commissioning.

Tracking detectors:
Measures the displacement of the scattered protons w.r.t. the beam

“3D” pixel sensors with columnar electrodes

Material taken from M. Trzebinski - LHC Forward Physics WG - March 2016
Summary & Outlook

Detailed measurements of total and (in)elastic cross sections across LHC centre-of-mass energies.

Direct measurements of diffractive cross sections (fiducial and extrapolated).

Hard-diffractive processes observed at the LHC (CMS and ATLAS) from LRG method. Rapidity gap survival probability MC-based extraction.

Study of BFKL dynamics from observation of dijets with a large rapidity gap.

ATLAS RP system and common CMS-TOTEM data taking during special low pile-up and high-β* Runs at 8 and 13 TeV: studies of diffractive processes with full proton kinematics.

ATLAS AFP and CT-PPS will enhance the physics reach at the LHC.

Operation of Roman Pots at high luminosity. Timing detectors with high precision. Tracking detectors with 3D pixel sensors.

Sensitivity to anomalous gauge couplings and search for new resonances.
Extra slides
Charged hadron pseudorapidity density in inelastic pp collisions at 13 TeV;
Central value: $5.49 \pm 0.01$ (stat.) $\pm 0.17$ (syst.);
First LHC paper at 13 TeV.

CMS FSQ-15-001
Diffractive cross sections

CMS FSQ-12-005

*Phys. Rev. D 92 (2015) 012003*
Forward pseudorapidity gap cross section from backward/forward edge of detector (up to HF only).

Hadron level definition directly related to that at detector level.
Diffractive dijet candidate
Dijet production

Distributions are obtained as a function of $\xi^+$ and $\xi^-$, and averaged.

A combination of PYTHIA6 (Tune Z2) and POMPYT is used to describe the data, where their relative contributions are obtained from a fit to the $\xi$ distribution.

Note that different MC tunes would imply considerable variations in relative yields.

Suppression of events with high $\xi$ values after $\eta_{\text{max}} < 3$ (or $\eta_{\text{min}} > -3$) selection, while low-$\xi$ region is mostly unaffected.

Results in three $\xi$ bins: (0.0003,0.002); (0.002,0.0045); (0.0045,0.01)
Dijet cross section

\[
d\sigma_{jj} \over d\tilde{\xi} = \frac{N_{jj}^i}{L \cdot \epsilon \cdot A^i \cdot \Delta\tilde{\xi}^i}
\]

\[
A_{MC}^i = \frac{N^i(\tilde{\xi}_{Rec})}{N^i(\tilde{\xi}_{Gen})}
\]

Excess of events in low-\(\xi\) region with respect to non-diffractive MC’s PYTHIA6 and PYTHIA8

POMPYT and POMWIG (LO) diffractive MC’s as well as the NLO calculation from POWHEG, using diffractive PDFs, are a factor \(\sim 5\) above the data in lowest \(\xi\) bin

PYTHIA8 diffractive cross sections are considerably lower due to different pomeron flux parametrisation

Normalisation discrepancies can be interpreted as estimates (after subtracting proton dissociation) of rapidity gap survival probability:

\[
S^2_{data/MC}^{(*)} = 0.12 \pm 0.05 \ (LO \ MC)
\]

\[
S^2_{data/MC}^{(*)} = 0.08 \pm 0.04 \ (NLO \ MC)
\]

\( (*) \) MC based subtraction of proton dissociation
Forward gap selection in HF (3 < |η| < 4.9)
Signed η_{lepton} distribution (η_{lepton} < 0 when e,μ opposite to the pseudorapidity gap)

Flat for non-diffractive, asymmetric for diffractive events
Evidence of diffractive W production in the data
Fit for PYTHIA (ND) + POMPYT (SD):
\[ f_{SD} = 50.0 \pm 9.3\text{(stat.)} \pm 5.2\text{(syst.)} \% \]
“Central Exclusive” production

Exclusive channel through exchange of color singlet, lowest order given by gluon-gluon fusion, plus screening low-$Q^2$ gluon

Protons remain intact as in QED process, or dissociate in a low mass system, and are separated from the central system ($\gamma\gamma$, $H$, etc.) by rapidity gaps

Main theoretical uncertainties common among different final states. Higher cross section channels, such as $\gamma\gamma$ or dijets, can test predictions for central exclusive production of new states.
CMS-TOTEM central dijet events

Forward Shower Counters

59 - 114 m

TOTEM Roman Pots

220 m

TOTEM T2

Forward Shower Counters

P

P

P

P
CMS-TOTEM detectors

TOTEM RPs (220m)

TOTEM RPs
(220m)

Vertical Roman Pot
Horizontal Roman Pot

4 meters

Services routing:
From Castor to Racks
Patch Panels

TOTEM T2
(In trigger only)

K. Österberg
Recorded data (2015 high-\(\beta^*\))

CMS overall recorded \(\sim 0.7 \text{ pb}^{-1}\)

TOTEM overall recorded \(\sim 0.4 \text{ pb}^{-1}\)

\(<N_{\text{int}}/Bx>\) less than \(\sim 0.10\)

ATLAS (ALFA) operational during high-\(\beta^*\) running.
Detector acceptance vs $\beta^*$

$\beta^* = 0.55 \text{ m} \ (\text{low } \beta^* = \text{standard at LHC})$

$\beta^* = 90 \text{ m} \ (\text{special development for RP runs})$

M. Deile, 2015
CMS + TOTEM triggers: Summary

In CMS: RP + T2 veto (L1) + Track (HLT)

NEW in 2015:
- 3 RP Units/arm!
- Improved acceptance

- CMS: RP + T2 veto (L1) + Track (HLT)

RomanPots Double Arm & T2 Veto + at least 1 track in CMS-Tracker

**CMS HLT rate ~ 1.5-2 kHz**

Right topology for low mass central diffraction, glueballs searches

In Totem very high statistics of elastic scattering!

**Totem Rate ~ 45 Khz**

**CMS HLT rate ~ 5 Khz**

Right topology for high mass central diffraction, missing mass searches

Elastic scattering “background” is excluded

**Totem Rate ~ 5 Khz**

**CMS HLT rate ~ 5 Khz**

**CMS only: Jets, Double Muons (L1)**

**CMS HLT up to ~ 10 kHz**
CMS-TOTEM common data taking:
Low mass states + 2 protons

“L1 TOTEM 0”
TOTEM collects all RP triggered events
CMS selects only subset after HLT
Event synchronization offline
TOTEM Rate ~ 45 kHz
CMS Rate ~ 1.5 - 2 kHz
Physics performance: Central Exclusive Production

Central Exclusive Production as main Physics motivation:

i) photon-photon fusion

ii) gluon-gluon fusion in colour-singlet, $J^{PC} = 0^{++}$, state

High-$p_T$ system X detected by the CMS detectors at central pseudorapidity with high-energy, very low angle scattered protons detected by CT-PPS;

The two outgoing protons must balance perfectly the system X momentum, hence creating strong kinematical constraints;

Its mass $M_X$ is obtained from the momentum loss of the two protons, allowing to study invisible final states with difficult reconstruction in CMS;

The Physics potential includes the study of gauge boson production by photon-photon fusion and anomalous $\gamma\gamma WW$, $\gamma\gamma ZZ$ and $\gamma\gamma\gamma\gamma$ couplings, search for new BSM resonances and the study of QCD in a new domain.

Full simulation studies carried out for two benchmark channels: Exclusive WW production and Exclusive dijet production.
Anomalous quartic couplings

Effective Lagrangian with quartic anomalous operators $\gamma\gamma WW$ and $\gamma\gamma ZZ$:

$$\mathcal{L}_6^0 = -\frac{e^2}{8} \frac{a_0^W}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} W^+ W^- \frac{e^2}{16 \cos^2 \theta_W} \frac{a_0^Z}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} Z^\alpha Z_\alpha$$

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

Ansatz coupling form factors introduced to avoid violating unitarity at high energies:

$$a \rightarrow \frac{a}{(1 + W_{\gamma\gamma}^2/\Lambda^2)^n}$$

E. Chapon, C. Royon, O. Kepka (2009)