<u>Recent results on forward physics</u> <u>from the CMS and CMS-TOTEM</u> <u>experiments</u>



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Introduction

- Soft inclusive measurements @ 13 TeV
 - Total (visible) inelastic cross section
 - Charged particle pseudorapidity distributions
 - Underlying Event activity in DY Test QCD in the non-perturbative region (MinBias, energy flow, UE & MPI, etc.)
- Hard diffraction
 - Diffractive dijets with proton tag
 - Jet-gap-jet events

Test Pomeron structure and pQCD evolution at low-x, BFKL vs colinear evolution

- Central exclusive production (CEP: γ - γ , γ -IP, IP-IP)
 - Light-by-light scattering
 - Exclusive ρ^0 and Upsion photoproduction
 - Exclusive dihadrons
 - Exclusive dileptons @EW scale Search for signs of saturation, exotic QCD states (e.g. glueballs), BSM physics at EW scale.

CMS and TOTEM forward detectors



Hadron Forward Calorimeter (HF) : 2.9 < $|\eta|$ < 5.2 CASTOR calorimeter: -6.6 < η < -5.2

TOTEM Roman Pots for proton tagging at \pm 220 m from IP:



Joint CMS-TOTEM runs



β^* = 90 m (developed for σ_{total} measurement)



diffractive protons: mainly in vertical RP

β^* = 0.55 m (low β^* = standard at LHC)



diffractive protons: mainly in horizontal RP

Special CMS-TOTEM runs

- High-β*optics, low-lumi, low-pileup (0.06-0.2) runs.
- Data samples: ~40/nb in 2012 @8 TeV, ~0.4/pb in 2015,
 - ~5/pb in 2018 @ 13 TeV,
- Operating since 2012:
 - 2 RP stations with silicon tracking detectors
- Acceptance: low and moderate Mx , t > 0.01 GeV²
- Physics: Low-mass resonances in CEP, diffraction with proton tag, ...

CMS-TOTEM Precision Proton Spectrometer (CT-PPS)

- Low-β* optics, high-lumi, standard LHC runs
- Data samples:
 - ~15/fb in 2016,
 - ~40/fb in 2017,
 - ~60/fb in 2018 @ 13 TeV,
- Installed and commissioned in 2016:
 - 2 RP stations for tracking detectors,
 - 1 RP station for fast timing detectors (event vertex).
- Acceptance Mx>400 GeV (CEP, 2 tagged protons).
- Physics: EW (γγ), BSM physics at EW scale, high-mass QCD, ..



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Soft inclusive measurements

Total inelastic cross section @13 TeV

Require an activity in HF or CASTOR calorimeters

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HF only: $\sigma(\xi > 10^{-6}) = 67.5 \pm 0.8 \, (\mathrm{syst}) \pm 1.6 \, (\mathrm{lumi}) \, \mathrm{mb}$

HF and CASTOR: $\sigma(\xi_{\rm X} > 10^{-7} \, {\rm or} \, \xi_{\rm Y} > 10^{-6}) = 68.6 \pm 0.5 \, ({
m syst}) \pm 1.6 \, ({
m lumi}) \, {
m mb}$

Good agreement with ATLAS measurement MinBias models for hadron-hadron scattering predict higher cross section than measured



Central dN / dn @13TeV



7

Underlying Event activity in DY @13 TeV

Underlying Event (UE) – activity not related to hard scattering:

Initial State radiation (ISR), Final State Radiation (FSR), Multi Partonic Interactions (MPI), beam remnants.

UE in inclusive Z boson production – clean signature and absence of QCD FSR Study charged particle density and Σp_{τ} activity for tracks with p_{τ} >0.5 GeV, $|\eta|$ <2



Slow rise of activity in towards and transverse region (ISR + MPI) differences at higher due to varying ISR activity At low $p_{\tau}^{\mu\mu}$ activity is dominated by MPI \rightarrow study activity for $p_{\tau}^{\mu\mu}$ <5 GeV:

Compare to data at 1.96 GeV (Tevatron) and 7 TeV (CMS) and to simulations: POWHEG + PYTHIA8 and POWHEG + HERWIG++ correctly describe the raise of activity with energy. POWHEG + PYTHIA8 describes the data witin 5%. UNIVERSALITY OF TUNES

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Hard Diffraction

- SD dijets with proton tag (jet-jet-gap)
- DD dijets with rapidity gap (jet-gap-jet)

Diffractive dijets, gap-jet-jet @8 TeV

First CMS-TOTEM measurement with tagged protons from low-pileup data.

TOTEM

CMS-PAS-FSQ-12-033 TOTEM-NOTE-2018-001

37.5 nb⁻¹ (8 TeV

03

10



Cross section as a function of ξ . Ratio of diffractive to inclusive dilets as a function of x.

CMS-PAS-FSQ-12-033 **TOTEM-NOTE-2018-001**

 $x^{\pm} = \frac{\sum_{\text{jets}} \left(E^{\text{jet}} \pm p_z^{\text{jet}} \right)}{\sqrt{s}}$

$$R = \left(\sigma_{jj}^{pX} / \Delta \xi\right) / \sigma_{jj} = 0.025 \pm 0.001 \,(\text{stat}) \pm 0.003 \,(\text{syst})$$



PYTHIA8 DG – gap survival with Dynamic Gap model based on MPI, good agreement with the data

Diffractive dijets, BFKL with jet-gap-jet @7 TeV

Jets separated by a large rapidity gap (color singlet exchange, CSE) Sensitive to BFKL dynamics, soft rescattering processes



Two leading jets: $p_1 > 40$ GeV, $|\eta| > 1.5$, $\eta_1 \eta_2 < 0$



- Excess of gap events over PYTHIA6 prediction (LO DGLAP)
- Described by HERWIG (LL-BFKL, Mueller-Tang model)

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Diffractive dijets, BFKL with jet-gap-jet @7TeV

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CSE fraction := ratio of dijets with a rapidity gap to all dijets



Comparison to Tevatron data:

A factor of ~2 suppression w.r.t. to 1.8 TeV data, larger contribution from rescattering processes



Comparison to theory:

NLL BFKL by Ekstedt, Enberg and Ingelman, 3 calculations for gap survival probability (S). Further improvements in modeling of S needed. arXiv:1703.10919 13

Similar ongoing CMS-TOTEM analysis @13 TeV, w/o and with proton tag.

Exclusive Processes



p-p runs + ultra-peripheral collisions (UPC) in p-Pb, Pb-Pb runs Pb: rich source of photons (γ flux~Z²) Light-by-light scattering in Pb-Pb @5TeV

Two back-to-back photons: E_{T} >2 GeV and $|\eta| < 2.4$. $P_{T}^{\gamma\gamma} < 1$ GeV., $m^{\gamma\gamma} > 5$ GeV

arXiv:1810.04602 submitted to PLB



Elastc $\gamma\gamma \rightarrow \gamma\gamma$ scatering

- fundamental QED/QCD process
- difficult to observe due to very small O(α^4) cross section
- sensitive to BSM physics, (loop contributions, axions,...)



Fiducial $\sigma(\gamma\gamma \rightarrow \gamma\gamma)$ cross section: 120 ± 46 (stat) ± 28 (syst) ± 4 (th) nb theory: 138 ± 14 nb 15

Nature Phys. 13 (2017) 852 ATLAS in a similar region: 13 candidates, expected background of 2.6 ± 0.7 events. Light-by-light scattering in Pb-Pb @5 TeV

CM



Most stringent limits at low masses (5-50 GeV for EM and 5-10 GeV EW)

Photoproduction of p⁰ in p-Pb @5TeV

 p_{τ} > 0.4 (0.2) GeV for leading (subleading) π, |η| < 2.0. Backgrounds: $\rho^{0}(1700) \rightarrow 4\pi$, ω production, proton dissociation.



CMS-PAS-FSQ-16-007



Pb

<u>Photoproduction of p⁰ in p-Pb @5TeV</u>

CMS-PAS-FSQ-16-007



Regge theory (soft Pomeron): $\alpha' \approx 0.25$

18

GeV⁻²

180

Photoproduction of Upsilon in p-Pb @5 TeV

arXiv:1809.11080

submitted to EPJC

Di-muon system: 0.1< p_{τ} <1 GeV and $|\eta|$ < 2.2.

Negligible DPE Xc $\rightarrow \gamma$ Y (present in LHCb pp data)

CMS pPb 32.6 nb⁻¹ (5.02 TeV) CMS Events/0.08 GeV 18 10⁴ 16 (qd) Y(nS) $\rightarrow \mu^{+}\mu^{-}$ signal ZEUS 2009 (e-p) 14 12 QED $\gamma\gamma \rightarrow u^+u^-$ continuum ZEUS 1998 (e-p) Y(1S)p H1 2000 (e-p) LHCb (p-p, 7,8 TeV) CMS (pPb, 5.02 TeV) ď 10³ 11 11.5 12 μ⁺μ mass (GeV) 10.5 85 95 10 12 CMS pPb 32.6 nb⁻¹ (5.02 TeV) fIPsat B_{γ(nS)→μ⁺μ} dσ_{γ(nS)}/dp_T² nb/(GeV)² IIM-BG IIM-LCG 10² bCGC-BG JMRT-LO JMRT-NLO Fit CMS: δ=1.08±0.42 Fit HERA+CMS+LHCb: δ=0.76±0.14 Data ² minimization fit to data 10² 10^{3} W_{yp} (GeV) Data sensitive to signs of saturation, 0.2 0.6 0.4 0.8 put new constraints on the evolution of gluon density at low x. $p_T^2 (GeV)^2$ **Exponential fit:** 19 $b = 6.0 \pm 2.1 \, (\text{stat}) \pm 0.3 \, (\text{syst}) \, \text{GeV}^{-2}$

Similar ongoing CMS analysis with pPb data @8 TeV, with ~5-fold higher statistics.



Similar CMS analysis @5 TeV and @13 TeV \rightarrow energy dependence of the cross section



CEP @13 TeV with CMS-TOTEM

CMS-DP-2017/008 Tracks in CMS + diffractive protons in TOTEM Roman Pots (acc. for $t_{1,2}$ > 0.01 GeV²) About 0.4/pb of low-pileup 2015 data (μ = 0.06-0.15), About 10x more statistics (\sim 5/pb) taken in 2018. Different proton configurations: top-top diagonal bottom-bottom Joint CMS-TOTEM β^* =90m pp 2015 data at \sqrt{s} = 13 TeV (0.4 pb⁻¹ Joint CM/S-TOTEM β^* =90m pp 2015 data at \sqrt{s} = 13 TeV (0.4 pb⁻¹) pxoteM (GeV) p^{TOTEM} (GeV) 10³ Exclusivity condition: 10³ $c_{MS} = p$ TOTEM р x,y 10^{2} **⊀**∩² Elastic pileup 10 Joint CMS-TOTEM β^* =90m pp 2015 data at \sqrt{s} = 13 TeV (0.4 pb⁻¹) -0.510 dN/d(p^{CMS}-p^{TOTEM} CMS-TOTEM Preliminary 20000 18000 16000 CMS-TOTEM Preliminary CMS-TOTEM Preliminary 14000 0.5 0.5 1.5 -0.5 n 1.5 n p_Y^{CMS} (GeV) p^{CMS} (GeV) 12000 10000 Very pure sample of exclusive events selected. 8000 **Ongoing analyses:** 6000 • Study f0/f2 resonances in the Mx<4 GeV mass range. 4000 Determine scalar (0^{++}) and tensor (2^{++}) glueball candidates and their 2000 21 decays: ππ, KK, ρρ, ... -0.2-0.10.2 0.3 -0.4-0.30 p^{CMS}-p^{TOTEM} (GeV)

Exclusive $\gamma\gamma \rightarrow l+l-$ production with CT-PPS

TOTEM

JHEP 07 (2018) 153 First CT-PPS measurement with tagged protons from high-pileup data. р Initial data taking in 2016, using existing TOTEM Si-strip tracking detectors integrated with CMS DAQ, used to establish safe Roman Pot insertions, detector operations, alignment and optics correction procedures. Initial analysis of "standard candle" process: $\gamma\gamma \rightarrow |+|$ -Only 1 proton required, to increase acceptance at lower masses. Background from real dileptons, in coincidence with random RP tracks from pileup or beam-background protons Matching required – compare ξ calculated from protons and from dileptons $\xi(\mu\mu) = \frac{1}{\sqrt{c}} \times (p_T(\mu_1)e^{\pm\eta(\mu_1)} + p_T(\mu_2)e^{\pm\eta(\mu_2)}),$ CMS+TOTEM 2016, L = 9.4 fb⁻¹, √s = 13 TeV CMS+TOTEM 2016, L = 9.4 fb⁻¹, √s = 13 TeV 0.2 0.2 ξ(l⁺l⁻) ξ(l'† CT-PPS right arm CT-PPS left arm 0.18 0.18 No acceptance for any RP No acceptance for any RP No acceptance for near RP No acceptance for near RP 0.16 0.16 — Matching l⁺l⁻ events - Matching l^+l^- events - Non-matching l^+l^- events - Non-matching l^+l^- events. 0.14 0.14 - Out of acceptance $l^+ l^-$ events $-\Box$ Out of acceptance l^+l^- events 0.12 0.12 Red: µ⁺µ⁻ Red: µ+µ-0.1 0.1 Blue: e⁺e⁻ Blue: e⁺e⁻ 0.08 0.08 0.06 0.06 0.04 0.04 0.02 0.02 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2 ξ(RP) ξ(RP) Observed: 12 μ + μ - and 8 e+e- events with matching kinematics (20 in total) Background estimate: 1.49 \pm 0.07 (stat.) \pm 0.53 (syst.) μ + μ - events 22 2.36 ± 0.09 (stat.) ± 0.47 (syst.) e+e- events Combined significance: 5.1σ

Exclusive $\gamma\gamma \rightarrow l+l-$ production with CT-PPS

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Event properties:

TOTEM

- Dilepton mass-rapidity distributions consistent with acceptance for single arm events
- No double tagged candidates, consistent with Standard Model expectations
- Mass spectrum from 110 GeV to >900 GeV

Proton-tagged $\gamma\gamma$ collisions at the EW scale!

2017-2018 data:

- Si-strip tracking replaced with 3D Si-pixel tracking
- operation with fast diamond tracking detectors
- About 100/fb of data with RP inserted so far
- High-mass/low cross section BSM, electroweak, and QCD & top physics with forward protons, such as gauge boson pair production (WW, ZZ, Zγ, γγ), searches for anomalous couplings, new resonances,...









- Soft inclusive measurements with valuable input to phenomenological QCD models. Universality of MC tunes.
- Diffractive dijets with proton tag measured for the first time at the LHC.
- Diffractive jet-gap-jet events a clear experimental indication of BFKL evolution, but compromised by soft rescattering processes.
- Rear exclusive processes measured for the first time, e.g. light-by-light scattering + limits on ALPs, dileptons @EW scale with proton tag.
- About 5/pb of CMS-TOTEM data to study exclusive production of low-mass resonances + glueballs.
- About 100/fb of CT-PPS data. Excellent prospects for high-mass/low cross section BSM, electroweak, and QCD physics with forward protons.

Thank you for your attention!