XXII International Workshop on Deep Inelastic Scattering and Related Subjects

Warsaw (Poland), April 27th- May 2nd 2014

Diffractive and Exclusive Measurements at CMS

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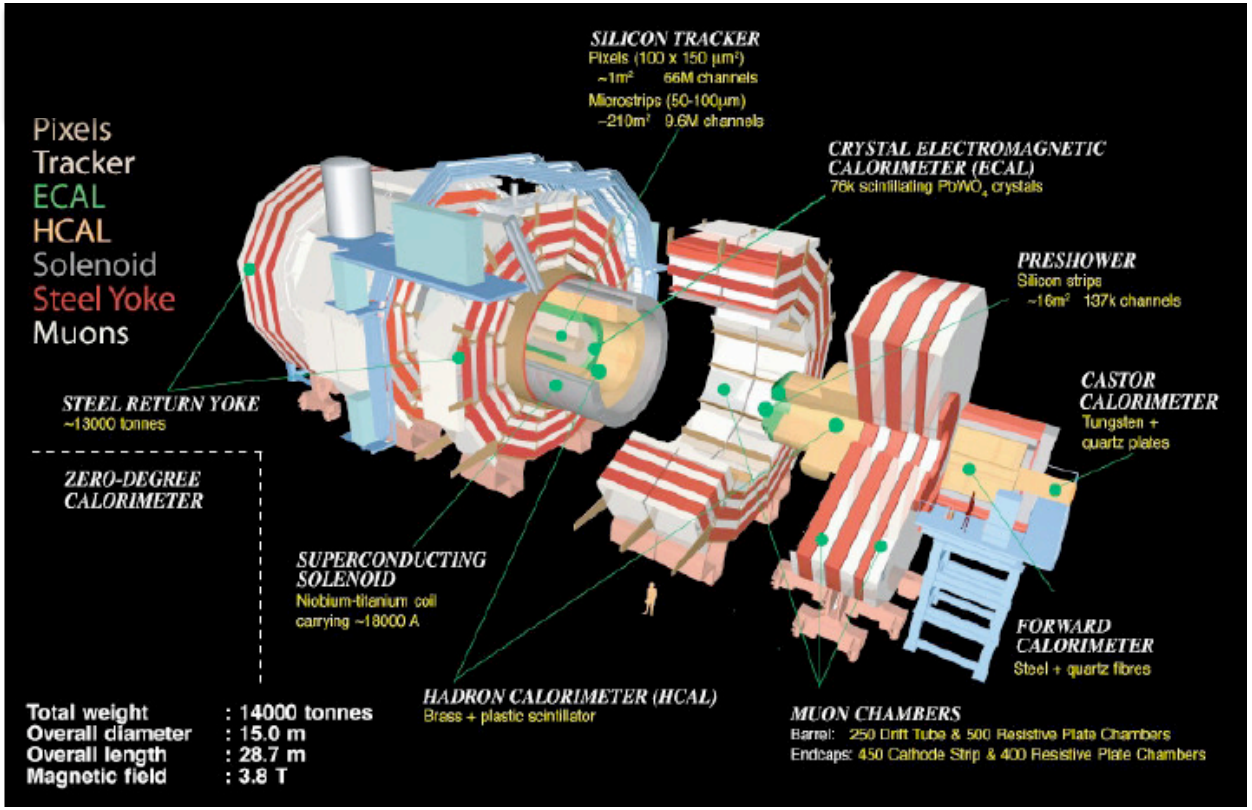
on behalf of the CMS Collaboration

Outline

- CMS detector and forward instrumentation

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

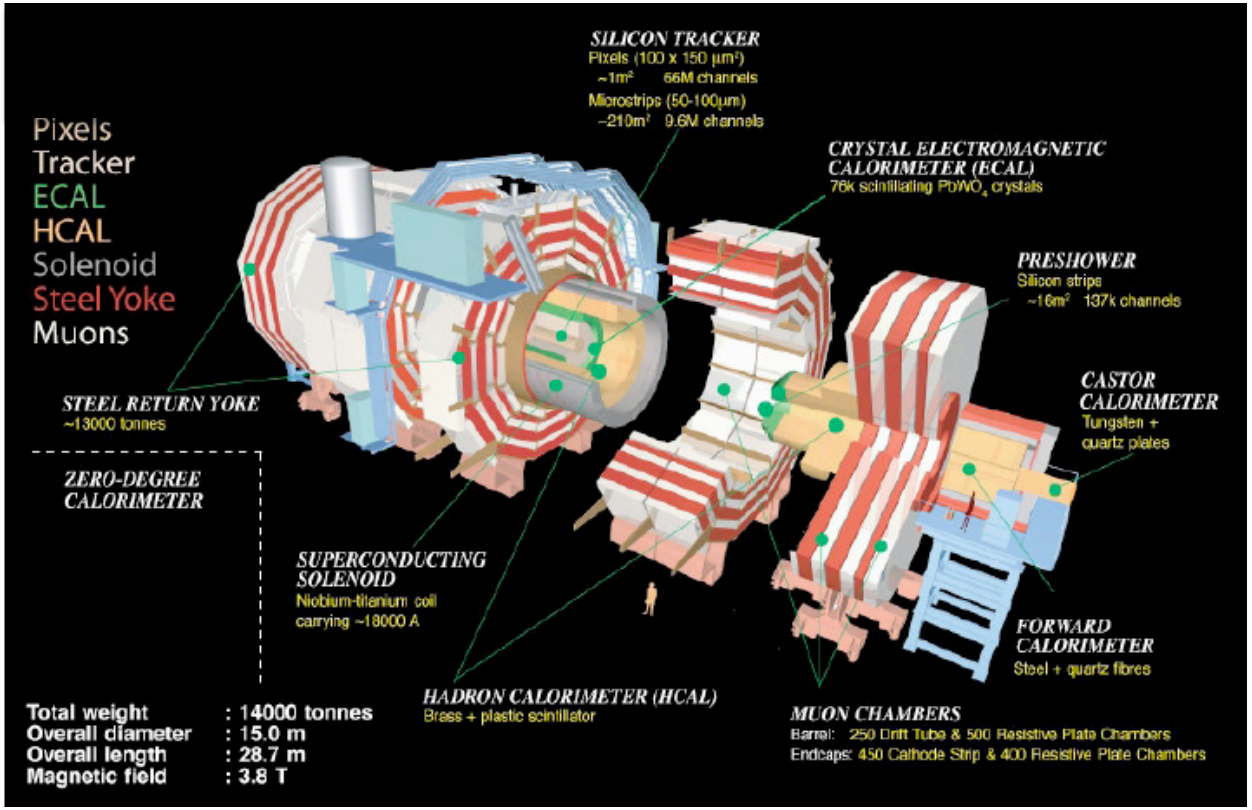
CMS detector

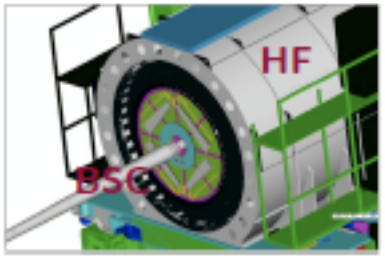


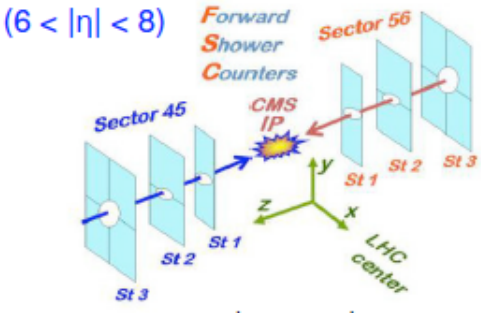
- **Tracker**: $|\eta| < 2.4$, $p_T > 100$ MeV
- **Calorimeters:** $|\eta| < 3$ (barrel and endcap)

  electromagnetic calorimeter ECAL
  hadronic calorimeter HCAL

CMS detector forward instrumentation



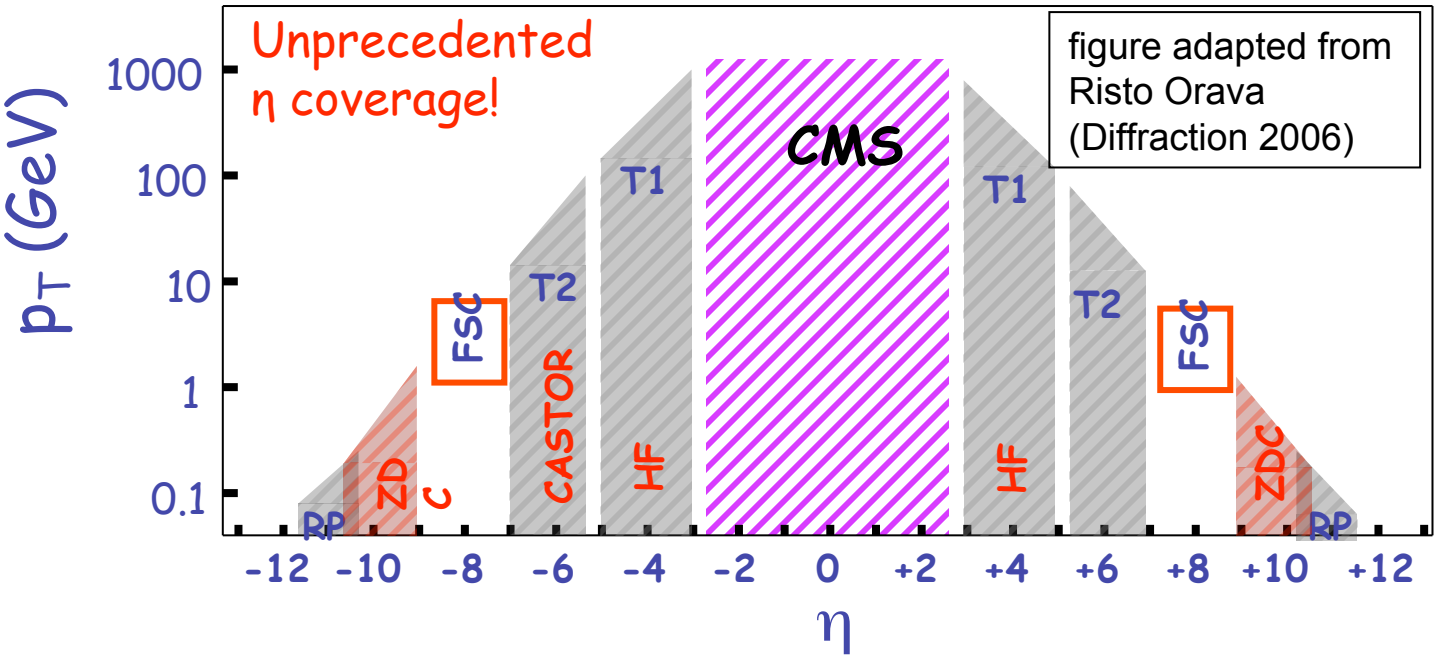




- **Hadron Forward calorimeter (HF):** 2.9 < |η| < 5.2 (10 m from IP)
- **Beam Scintillator Counters BSC :** 3.2 < |η| < 4.7 (in front of HF)
- **CASTOR calorimeter:** -6.6 < |η| < -5.2 (14.4 m from IP, one side only)
- **Forward Shower Counters FSC:** 6 < |η| < 8 (59-114 m from IP)
- **Zero Degree calorimeter:** |η| > 8.1 (140 m from IP)

+ TOTEM detector
(see previous talk)

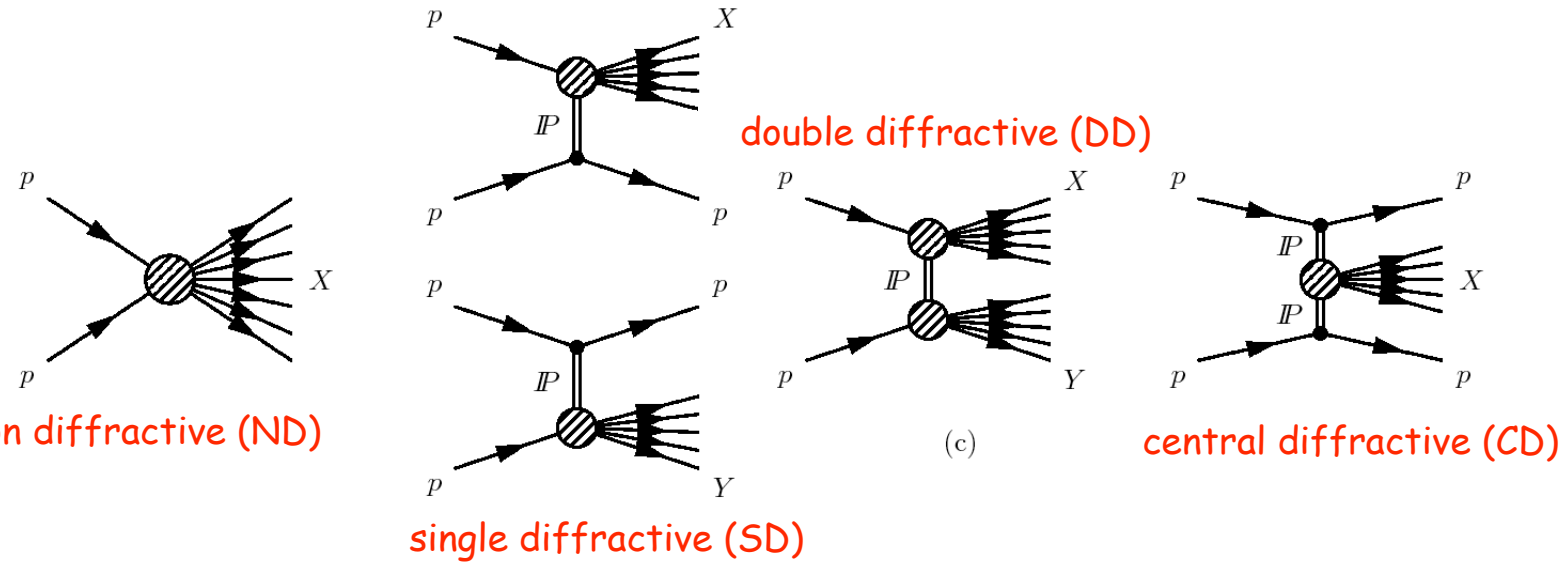
About pseudorapidity



- 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

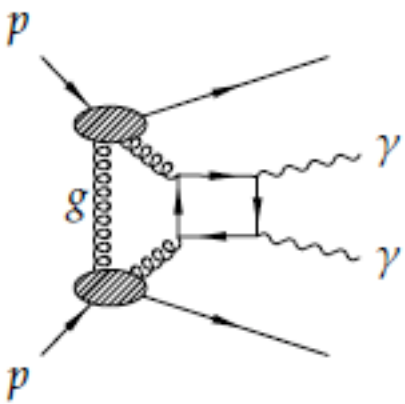
  Measure proton structure, QCD at high parton densities, discovery physics

…exclusive reactions

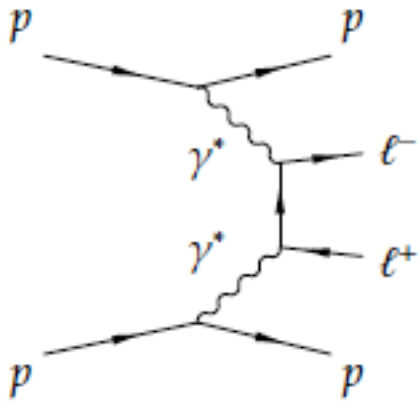
Study the reaction

$$pp \rightarrow p^{(*)}Xp^{(*)}$$

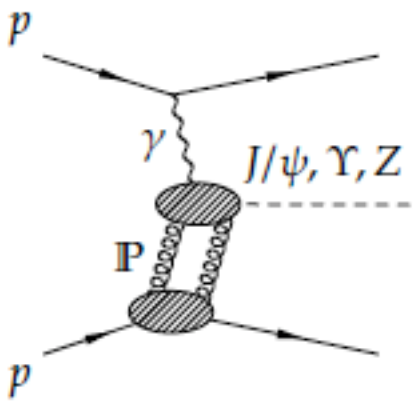
where numerous production mechanisms can contribute to produce the central system
$X = e^+e^-, \mu^+\mu^-, \gamma\gamma, W^+W^-, \ldots$



IPIP exchanges



γγ interactions

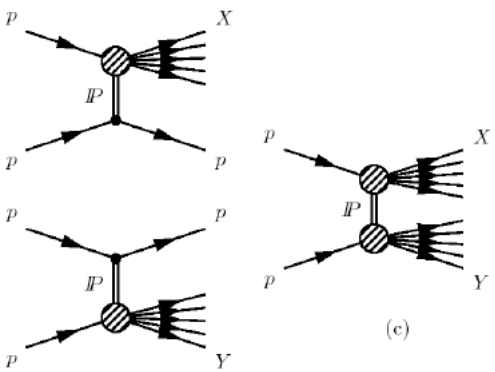


γIP fusion

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
  [CMS FSQ-12-026, TOTEM-2014-2] First CMS-TOTEM paper ever!
- Two-photon production of W^+W^- pairs
  [CMS PAS FSQ-12-010, arXiv:1305.5596]

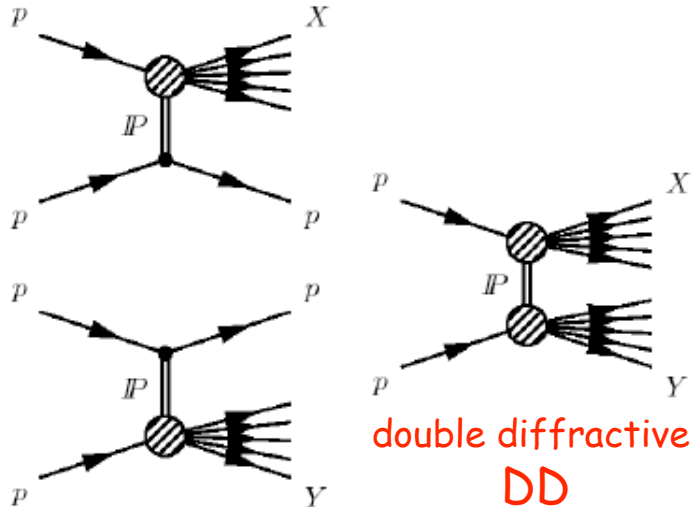
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ



Soft diffractive cross sections

Event selection

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



single diffractive
SD

double diffractive
DD

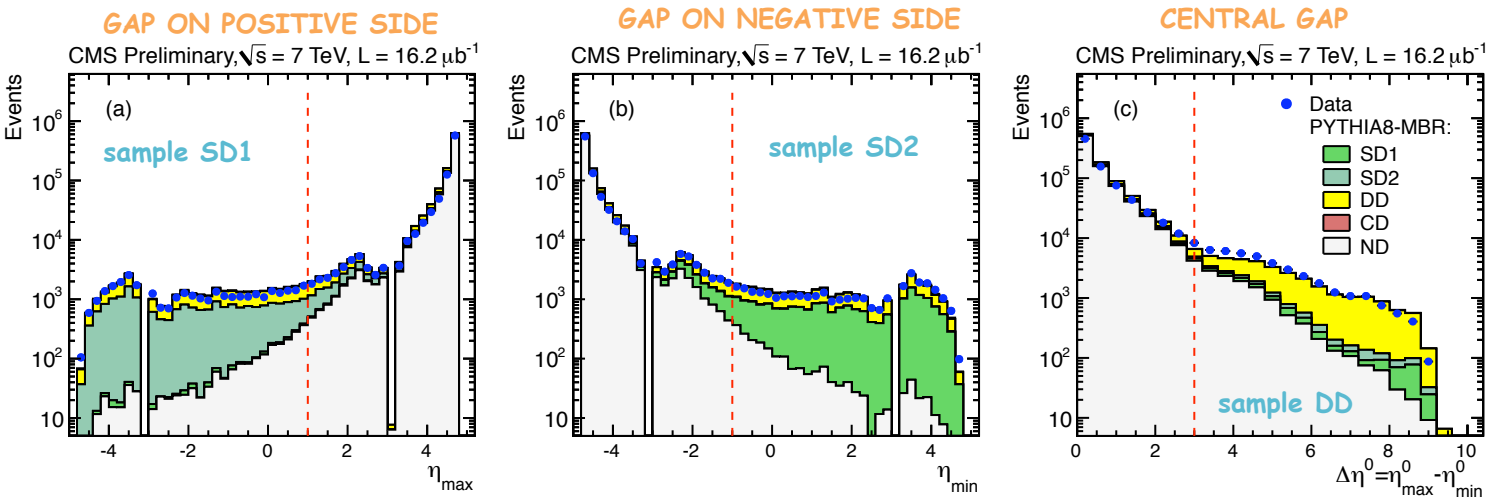
Sample
16.2 μb^{-1} low pileup (μ=0.14) data at $\sqrt{s}$ = 7 TeV

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 Rockfeller model
systematics: PYTHIA8-4C, diffraction with Schuler & Sjostrand model from PYTHIA6

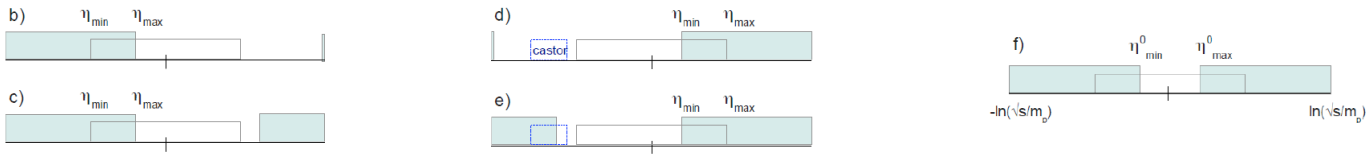
Experimental topologies

- 3 experimental topologies based on the position of the LRG



η_{max} (η_{min}): highest (lowest) η of the particle candidates in |η| < 4.7

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



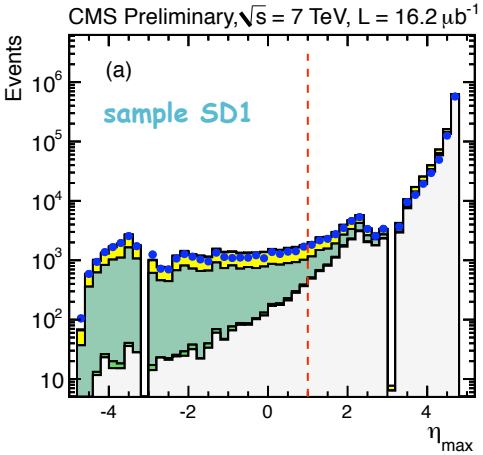
dominated by SD anb DD events

dominated by DD events

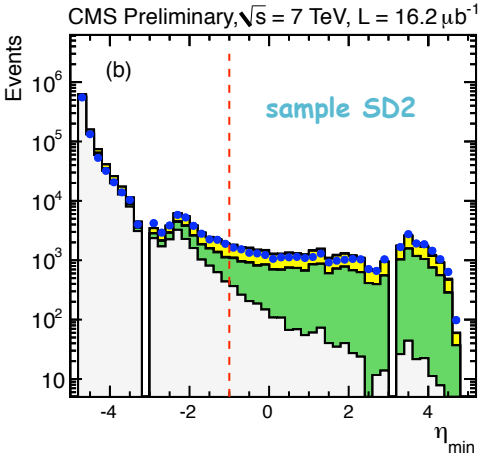
Experimental topologies

- 3 experimental topologies based on the position of the LRG

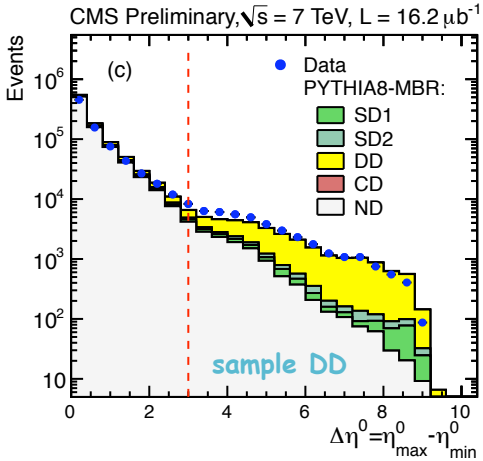
GAP ON POSITIVE SIDE



GAP ON NEGATIVE SIDE



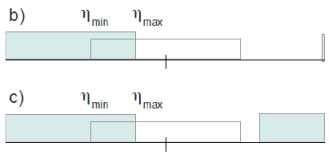
CENTRAL GAP

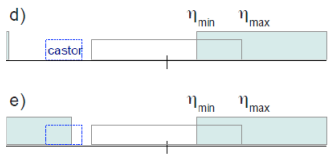


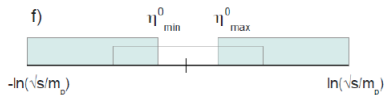
$\eta_{max} < 1$

$\eta_{min} > -1$

$\Delta\eta_0 > 3$







control sample

SD and DD cross sections

DD cross section

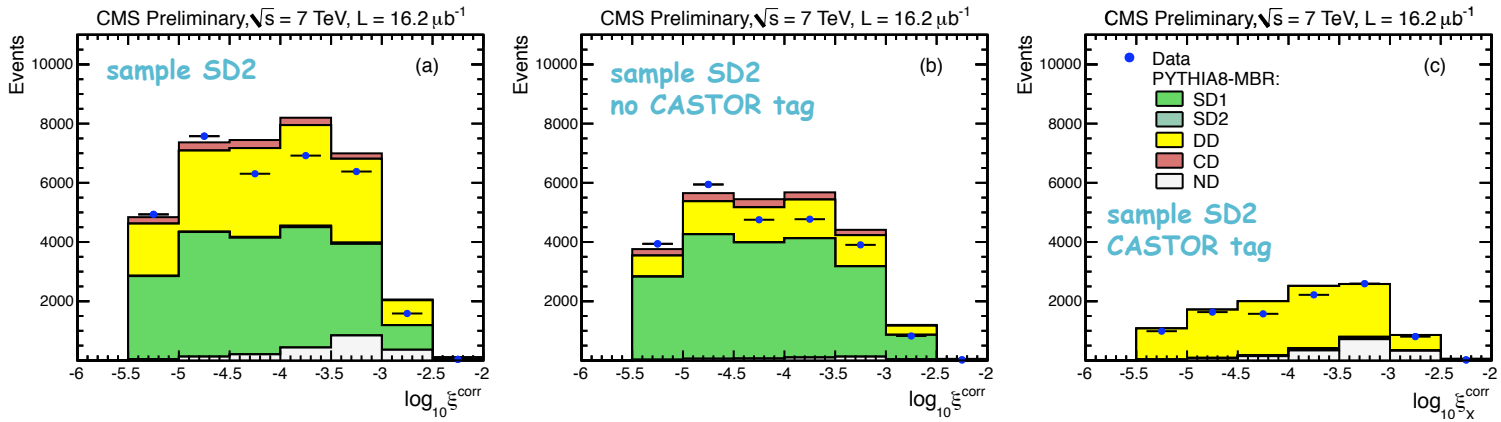
CASTOR used to tag the undetected low mass system in $-6.7 < \eta < -5.2$

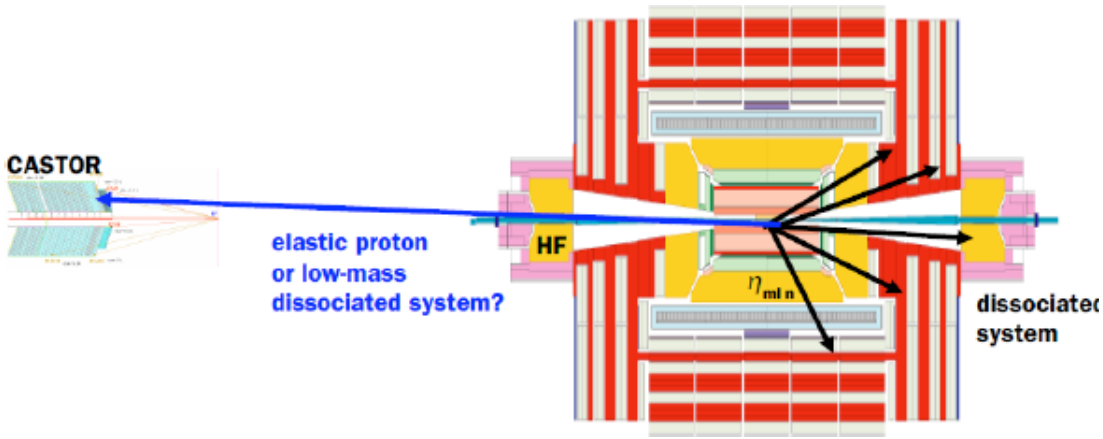
Detector level ξ distributions

$$\xi = \frac{M_X^2}{s} = \frac{\sum(E^i + p_z^i)}{\sqrt{s}}$$

proton fractional momentum loss reconstructed from particle candidates in |η| < 4.7

COMPARISON to PYTHIA8-MBR



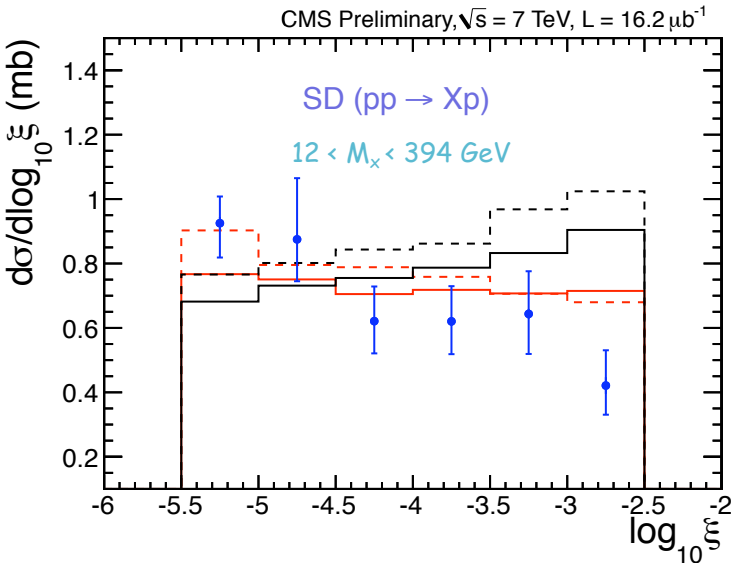


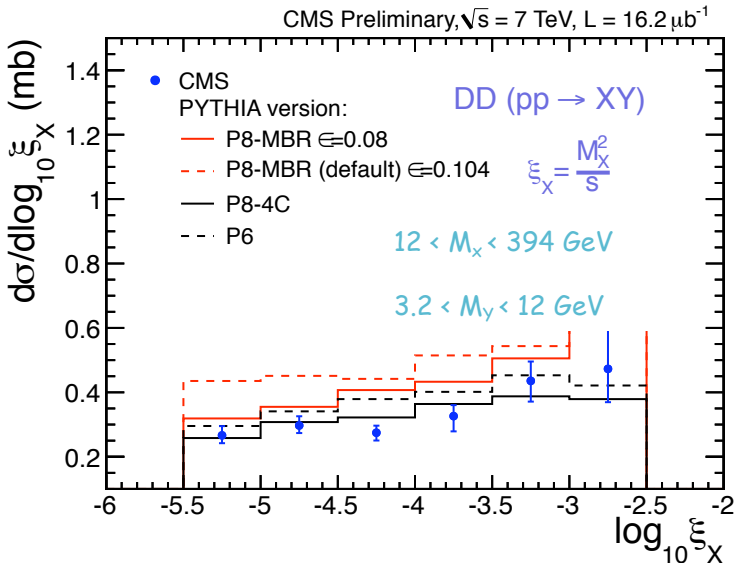
CASTOR used to tag the undetected low mass system

-6.7 < η < -5.2

3.2 < M < 12 GeV

SD and DD cross sections vs ξ





$$\frac{d\sigma^{SD}}{d\log_{10}\xi} = \frac{N^{data}_{noCASTOR} - (N_{DD} + N_{CD} + N_{ND})^{MC}}{acc \cdot \mathcal{L} \cdot (\Delta \log_{10}\xi)_{bin}}$$

$$\frac{d\sigma^{DD}}{d\log_{10}\xi_X} = \frac{N^{data}_{CASTOR} - (N_{ND} + N_{SD} + N_{CD})^{MC}}{acc \cdot \mathcal{L} \cdot (\Delta \log_{10}\xi_X)_{bin}}$$

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

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

→ Schuler&Sjostrand model cannot describe the falling behaviour of SD cross section

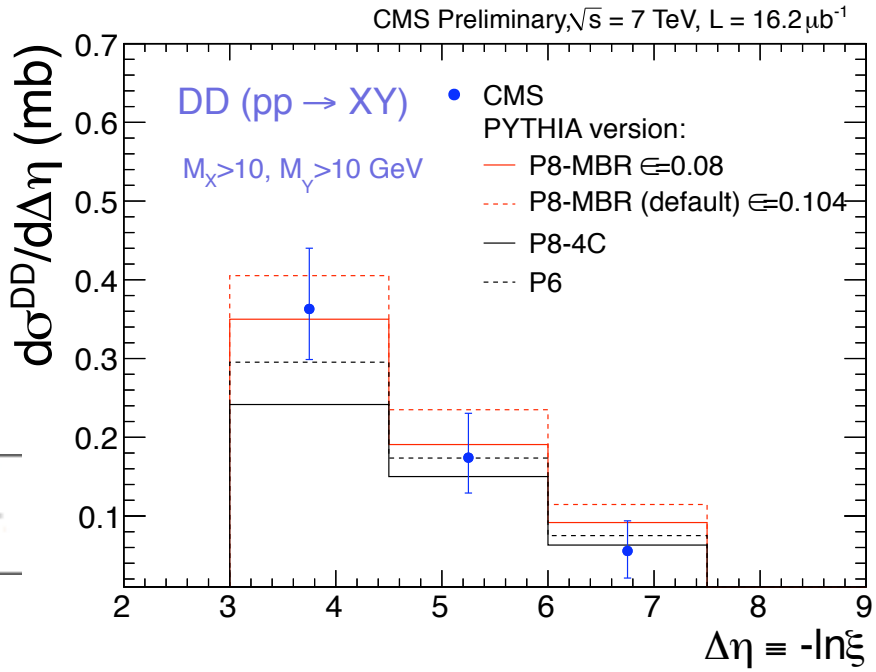
→ Single diffractive cross section integrated over -5.5 < log ξ < -2.5:

$\sigma^{SD}_{vis} = 4.27 \pm 0.04(stat.) + 0.65/-0.58(syst.)$ mb for 1.1 < log(M_X/GeV) < 2.6

DD cross section vs Δη

$\Delta\eta = -\ln \xi$ $\qquad \xi = \frac{M_X^2 \cdot M_Y^2}{s \cdot m_p^2}$

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



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

→ Agreement with data

→ Double diffractive cross section integrated over Δη>3, M_X > 10 GeV, M_Y> 10 GeV:

$$\sigma_{vis}^{DD} = 0.93 \pm 0.01(stat.) + 0.26/-0.22(syst.) \quad \text{mb}$$

Forward rapidity gap cross section

Event selection

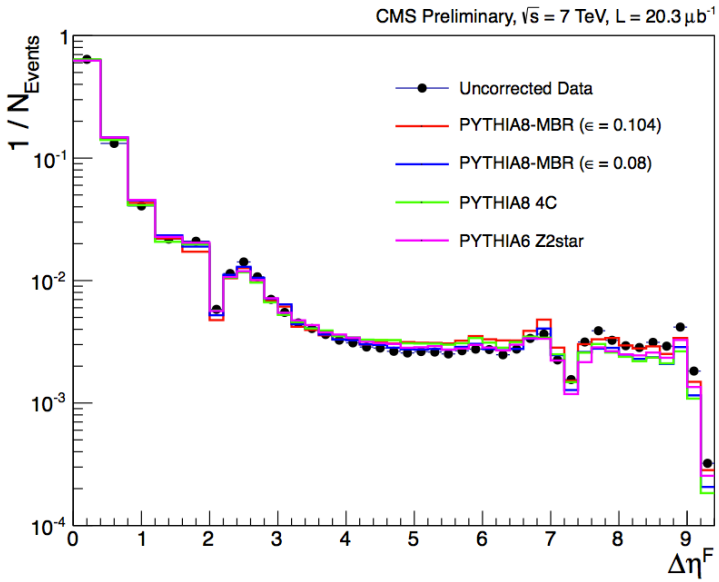
- Inclusive measurement, no separation of SD and DD

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

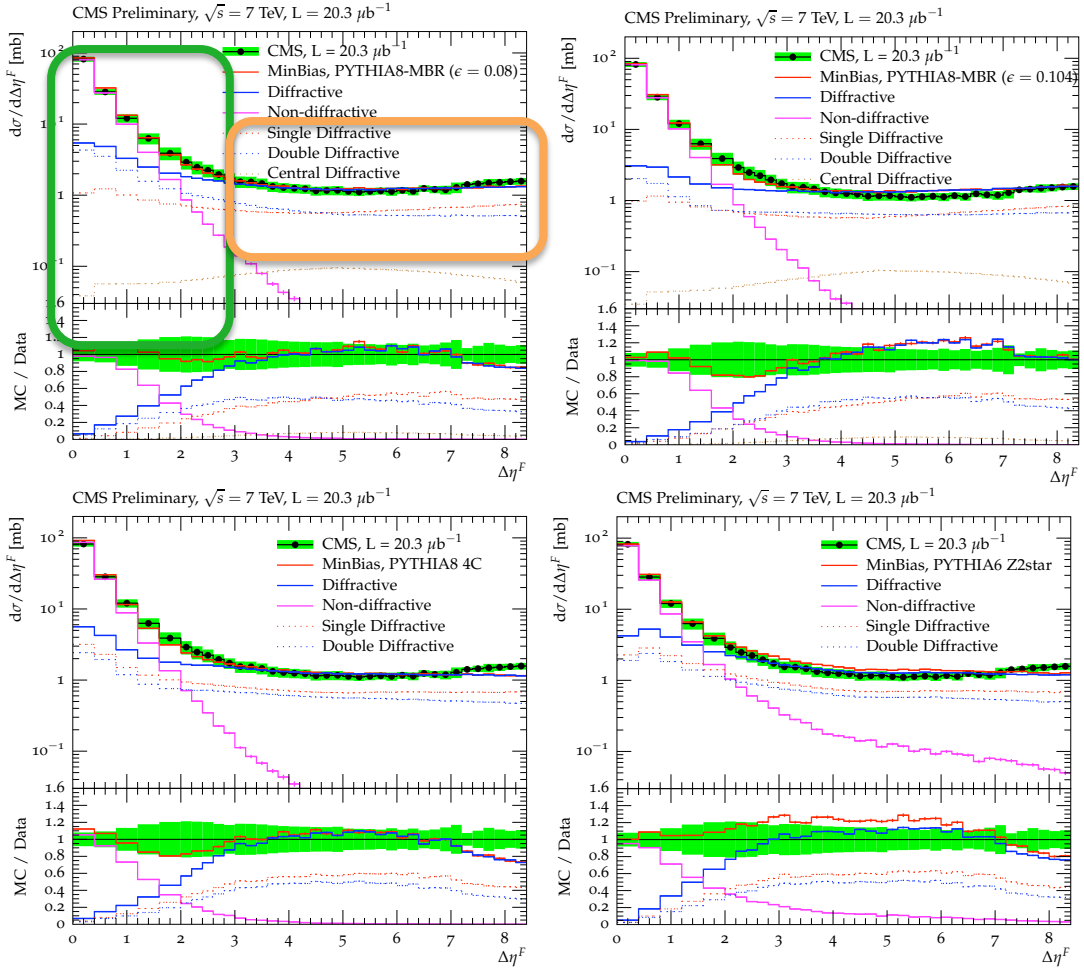
Selection
minimum bias trigger (hit in either of the BSCs)
based on Particle Flow (PF) objects
at least 2 PF in the BSC acceptance
no vertex requirement (to retain M_X < 100 GeV)

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

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



Forward rapidity gap cross section



$$\frac{d\sigma(\Delta\eta^F)}{d\Delta\eta^F} = \frac{A(\Delta\eta^F)}{\Delta\eta_{binwidth}} \frac{N(\Delta\eta^F) - N_{BG}(\Delta\eta^F)}{\varepsilon(\Delta\eta^F) \times \mathcal{L}}$$

→ **At low $\Delta\eta_F$**

Exponentially suppressed ND contribution is dominant

Sensitivity to fluctuations in soft particle hadronization

→ **At large $\Delta\eta_F$**

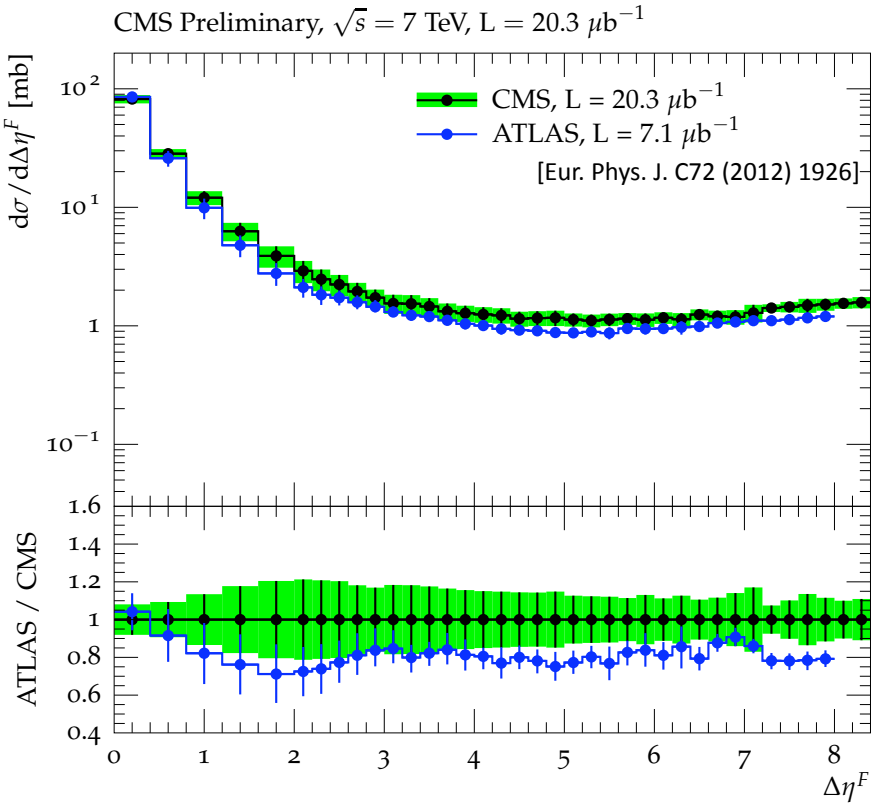
Diffractive plateau ~ 1 mb/ unit of gap size

SD ~ DD contribution

Best description of the data by PYTHIA8-MBR with smaller intercept

Forward rapidity gap cross section

COMPARISON TO ATLAS



- 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

First result
CMS+TOTEM!

Pseudorapidity distribution of charged particles

Event selection and reconstruction

Sample

- 45.4 μb^{-1} common CMS+TOTEM 2012 low pileup run at $\sqrt{s}$ =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 μb^{-1} common CMS+TOTEM 2012 low pileup run at $\sqrt{s}$ =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)
- T2 track reconstruction, key issue is primary/secondary particle separation
- standard CMS track reconstruction algorithm

CENTRAL REGION

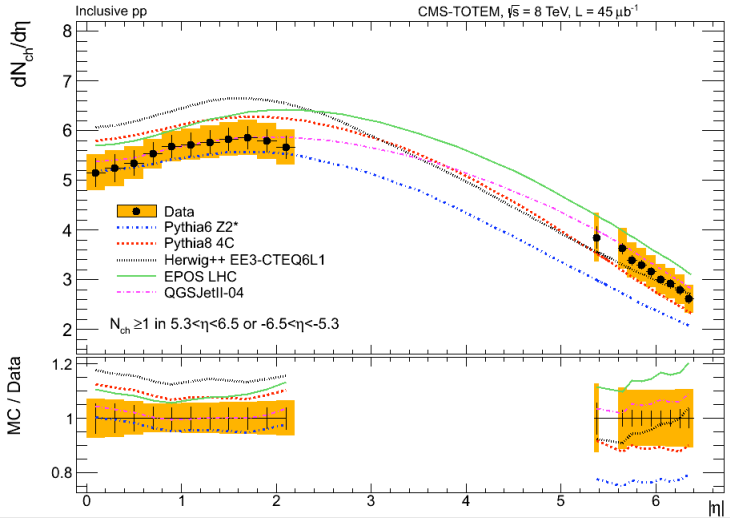
Source	Inclusive	NSD-enhanced	SD-enhanced
Event and primary track selection ($C_{sel}(\eta)$)	3–5%	4–6%	9–16%
Tracking efficiency	3.9%	3.9%	3.9%
Trigger efficiency	0.1%	0.1%	0.1%
Model dependence	1–4%	1–4%	1–4%
Correction to $p_T = 0$	0.2%	0.2%	0.2%
Statistical	0.1%	0.1%	0.1%
Total	5–7%	6–8%	10–17%

FORWARD REGION

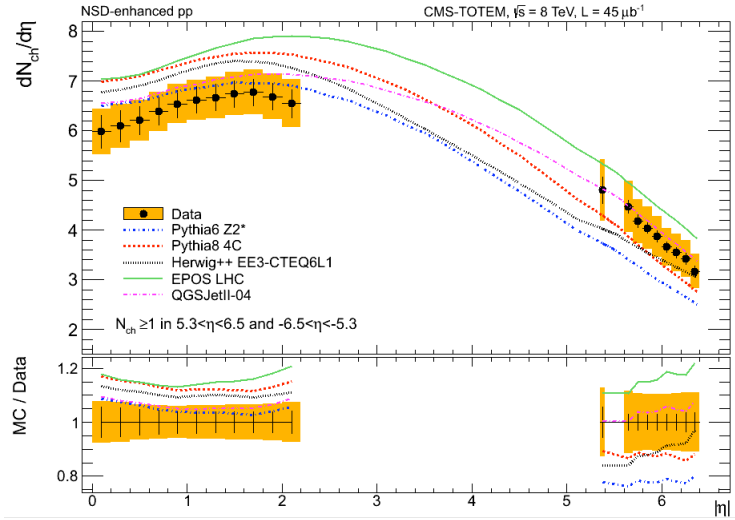
Source	Inclusive	NSD-enhanced	SD-enhanced
Tracking efficiency data-MC discrepancy	5–6%	5–6%	5–6%
Primary selection (including alignment)	4–5%	4–5%	4–5%
Non-primaries in the double-Gaussian peak	5%	5%	5%
Material effects	3–6%	3–6%	3–6%
High-multiplicity events	3%	3%	3%
Event selection	2-3%	2-3%	13-15%
Tracking efficiency dependence on energy spectrum and magnetic field	2%	2%	2%
Track quality criterion	1%	1%	1%
Correction to $p_T = 0$	0.5%	0.5%	0.5%
Trigger efficiency	0.2%	0.2%	0.2%
Statistical	0.1%	0.1%	0.1%
Total (after averaging half-arms)	10–12%	10–12%	16–18%

Central & forward $dN_{ch}/d\eta$

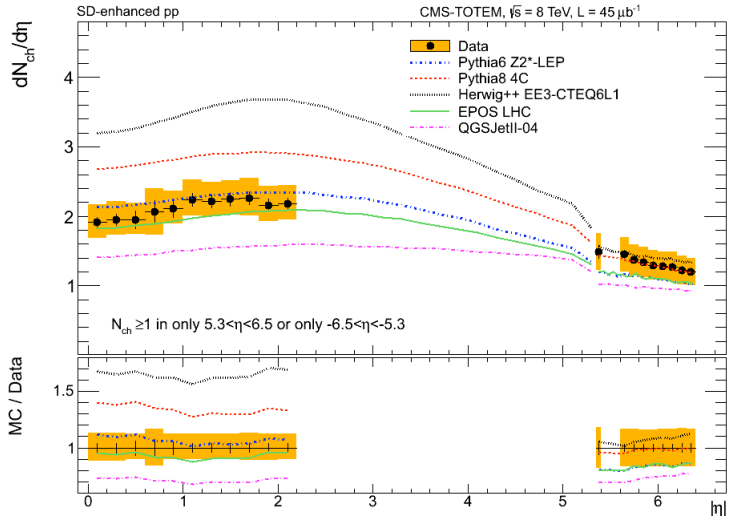
INCLUSIVE



NSD ENHANCED



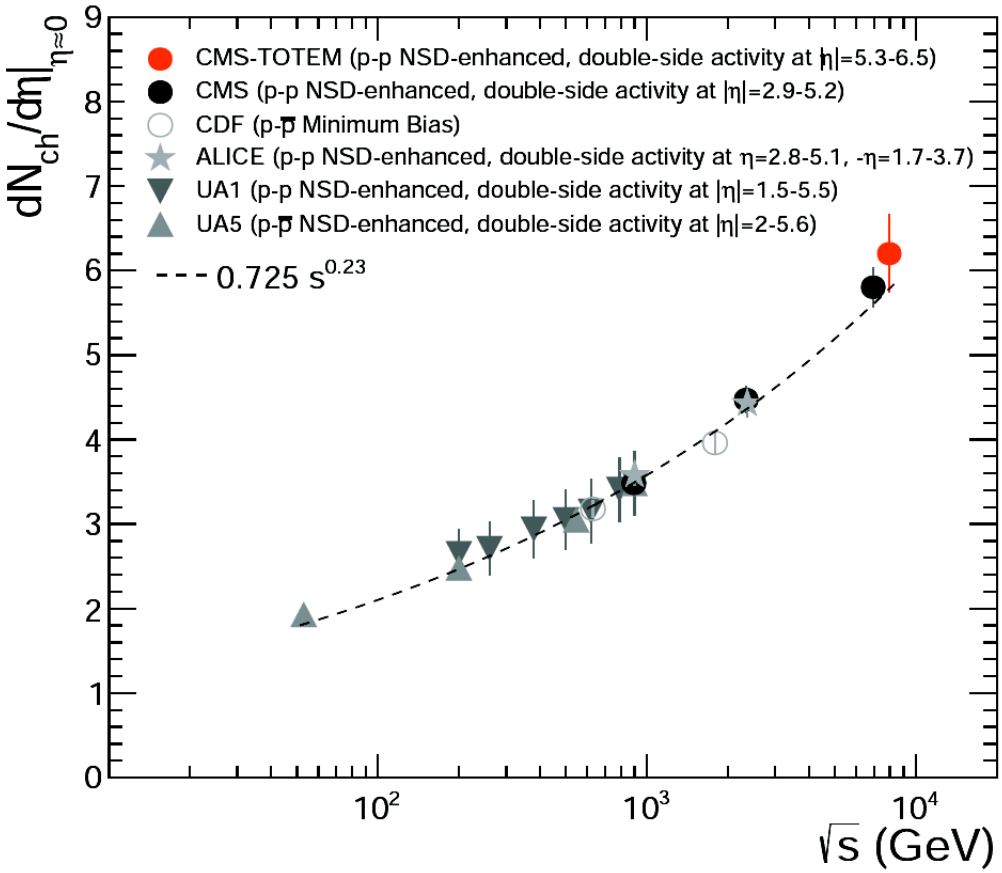
SD ENHANCED



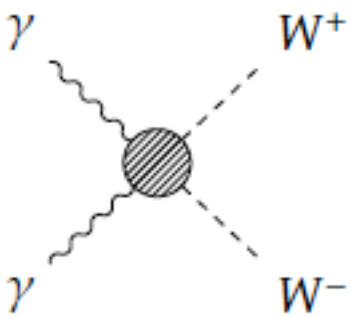
→ Multiplicity of SD events significantly smaller than NSD

→ No MC able to describe $dN_{ch}/d\eta$ of all events and samples in the whole rapidity region

Centre-of-mass energy dependence



Particle production at mid rapidities is expected to follow a power-law centre-of mass energy dependence s^{ε} → Fitting the data yield $\varepsilon=0.23\pm0.01$



Two-photon production of W pairs

Theoretical framework

GENUINE ANOMALOUS QUARTIC COUPLINGS (aQGCs)

- SM Lagrangian density contains (triple and) quartic couplings between γ and W bosons

- Effective Lagrangian with 2 additional dimension-6 terms:

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

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

  - Parameters a_0^W and a_C^W
  - Λ: scale for new physics

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

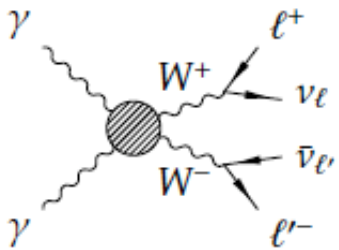
$$a_{0,C}^W \to a_{0,C}^W\left(W_{\gamma\gamma}^2\right) = a_{0,C}^W\left(1 + \frac{W_{\gamma\gamma}^2}{\Lambda_{\text{cutoff}}^2}\right)^{-2}$$

  - Λ_{cutoff}: energy cutoff scale ($\Lambda_{cutoff} \to \infty$ = no form factor)
  - $W_{\gamma\gamma}$: γγ center of mass energy

Event selection

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

- Unlike-flavor dilepton decay channel: $\gamma\gamma \to W^+W^- \to \mu^\pm e^\mp \nu\bar{\nu}$

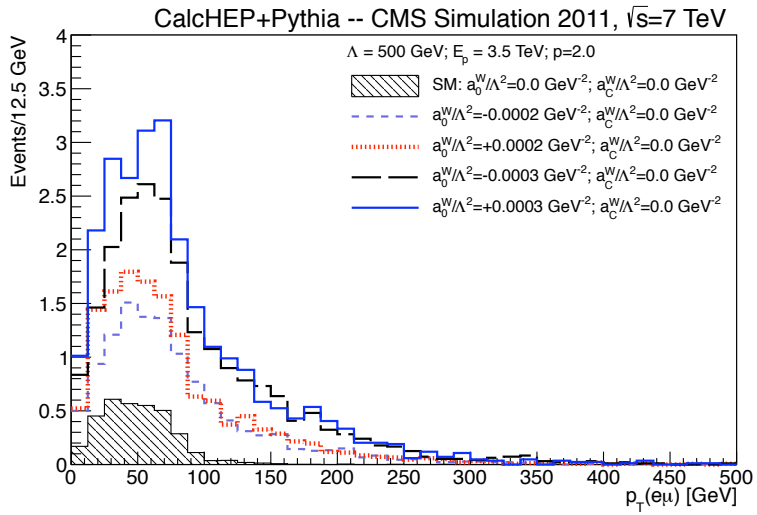


- Control sample: $pp \to p^{(*)}\mu^+\mu^- p^{(*)}$

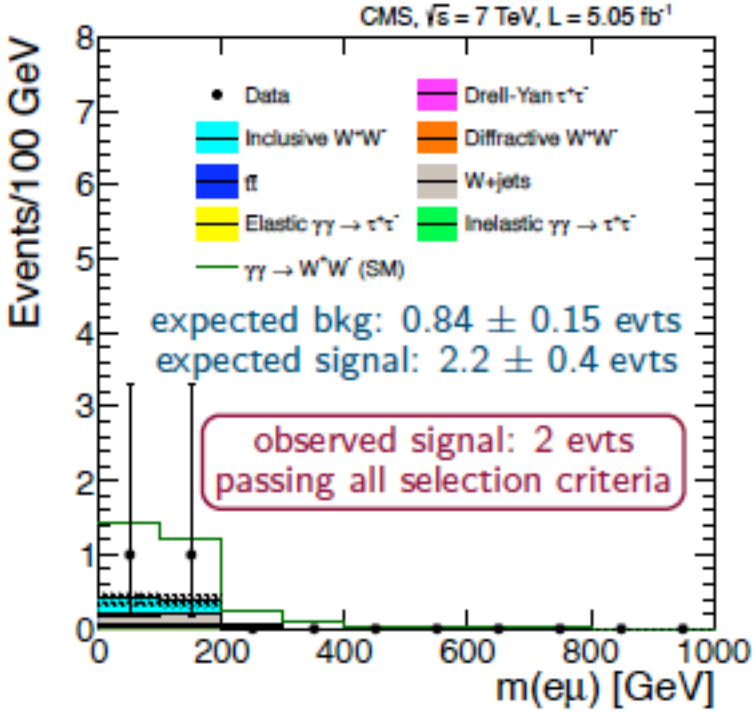
Sample
5.05 μb^{-1} 2011 data at $\sqrt{s}$ = 7 TeV

SM signal region:
$p_T(\mu^\pm e^\mp)$ > 30 GeV
no extra tracks associated to the dilepton vertex

aQGCs search:
$p_T(\mu^\pm e^\mp)$ > 100 GeV
no extra tracks associated to the dilepton vertex



SM signal $\gamma\gamma \to W^+W^- \to \mu^\pm e^\mp \nu\bar{\nu}$



$\sigma\left(pp \to p^{(*)}(\gamma\gamma \to W^+W^-)p^{(*)}\right) \times BR(W^\pm \to \mu^\pm\nu,\ e^\pm\nu) = 2.2^{+3.3}_{-2.0}$ (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 x BR at 95% C.L.:

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

		OPAL (2004)	DØ (2013)	CMS (2013)
a_0^W/Λ^2	no form factor	$\pm 2 \times 10^{-2}$	$\pm 4.3 \times 10^{-4}$	$\pm 4.0 \times 10^{-6}$
	Λ_{cutoff} = 500 GeV		$\pm 2.5 \times 10^{-3}$	$\pm 1.5 \times 10^{-4}$
a_c^W/Λ^2	no form factor	$^{+3.7}_{-5.2} \times 10^{-2}$	$\pm 1.5 \times 10^{-3}$	$\pm 1.5 \times 10^{-5}$
	Λ_{cutoff} = 500 GeV		$\pm 9.2 \times 10^{-3}$	$\pm 5.0 \times 10^{-4}$

→With Λ_{cutoff} = 500 MeV :
Up 20 times more stringent than the best Tevatron limits
Two order of magnitude improvement wrt LEP

→With Λ_{cutoff} = ∞ 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
  - $\sigma_{vis}^{SD} = 4.27 \pm 0.04(stat.) + 0.65/-0.58(syst.)$ mb for $-5.5 < \log \xi < -2.5$
  - $\sigma_{vis}^{DD} = 0.93 \pm 0.01(stat.) + 0.26/-0.22(syst.)$ 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 $p_T(\mu^{\pm}e^{\mp}) > 100$ GeV