Workshop on
Results and prospects of forward physics at the LHC

CMS results on hard exclusive and diffractive processes

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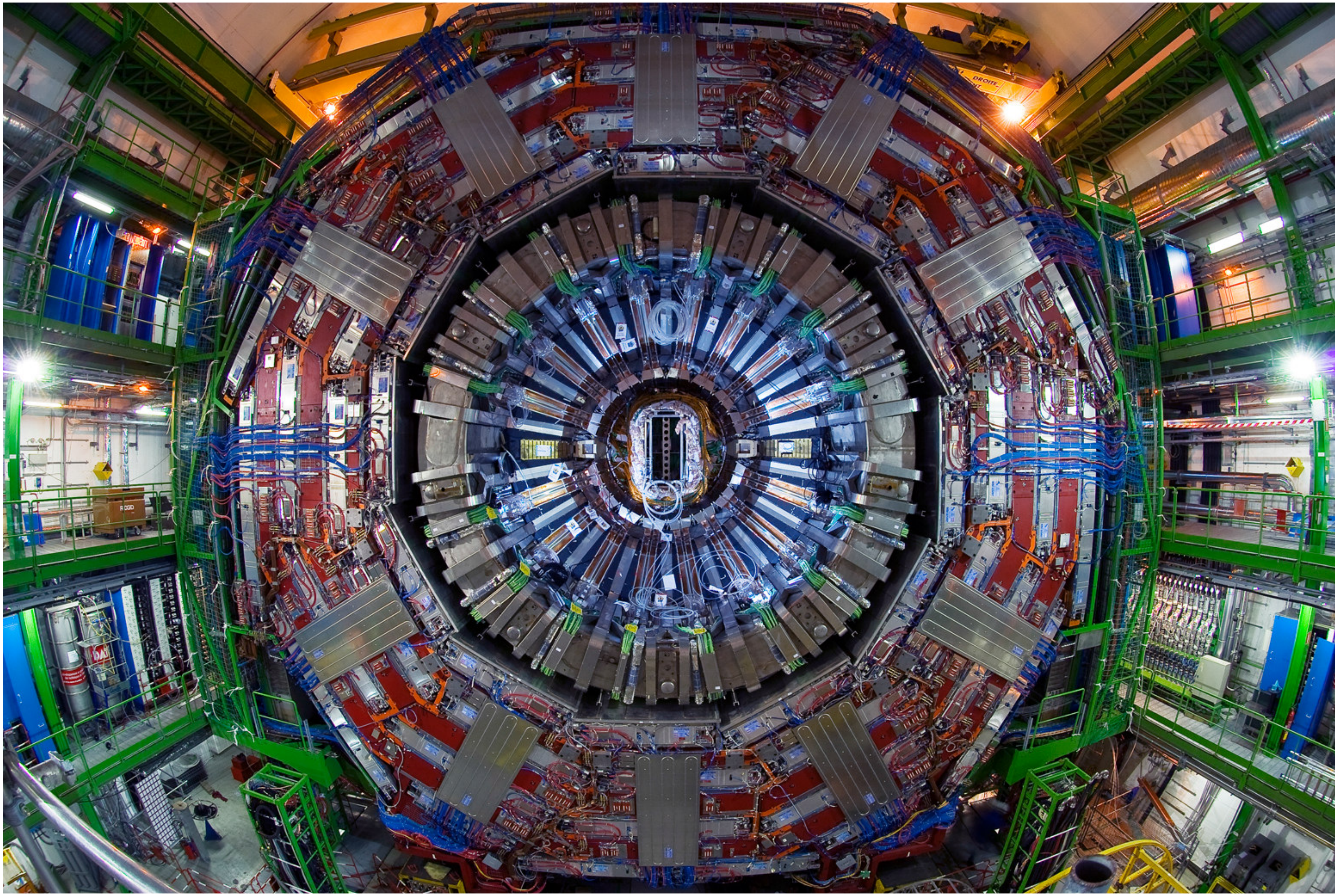
On behalf of the CMS Collaboration

Outline

- **CMS detector and forward instrumentation**
- **Evidence for hard diffraction:**
  - diffractive dijet production
  - W/Z events with (pseudo-)rapidity gaps
- **Central exclusive production:**
  - exclusive $\gamma\gamma$ production
  - exclusive e^+e^-, $\mu^+\mu^-$, WW production

CMS detector

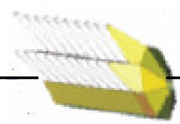


Forward instrumentation

±140 m

ZDC

(|η| > 8.1)



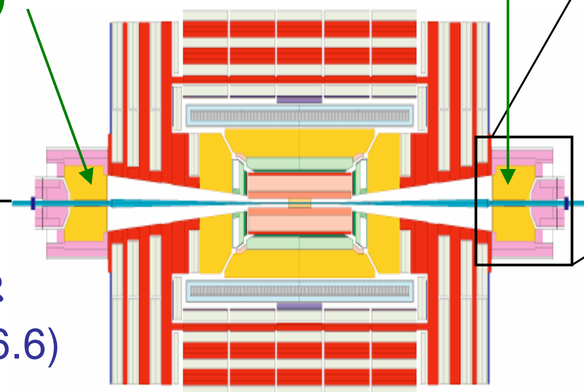
CASTOR

(5.3 < |η| < 6.6)

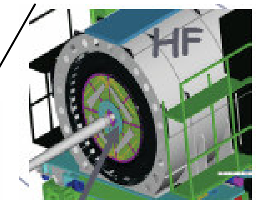
Hadronic Forward (HF)

(2.9 < |η| < 5.2)

CMS



HF



Beam Scintillator Counters (BSC)

(3.23<|η|<4.65)

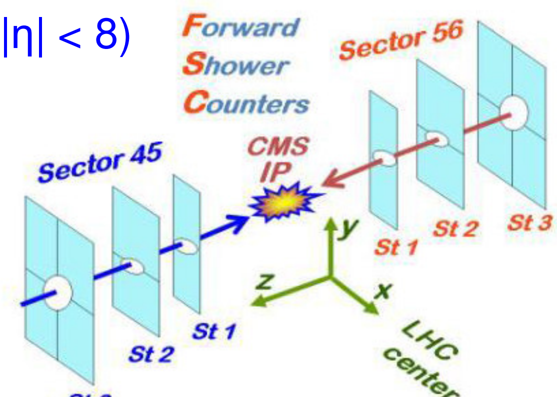
±175 m

BPTX (Beam pick-up timing)

CASTOR & ZDC not used in results presented in this talk

Forward Shower Counters (FSC)

(6 < |η| < 8)



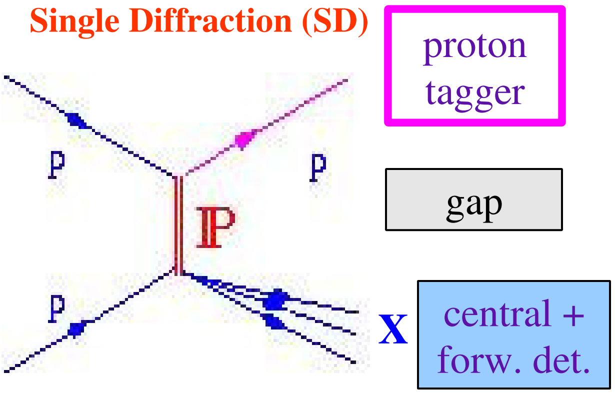
± (59 -114) m

Hadronic Forward:

- @11.2 m from the IP
- rapidity coverage: 2.9<|η|<5.2
- steel absorbers and embedded radiation-hard quartz fibers for fast collection of Cherenkov light
- acceptance limited to 3<|η|<4.9 at analysis level

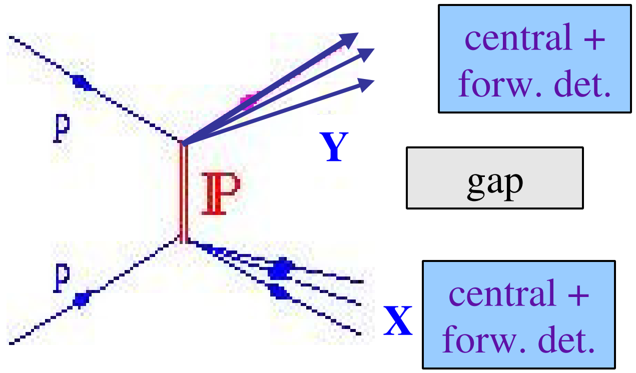
Diffraction at LHC

Single Diffraction (SD)

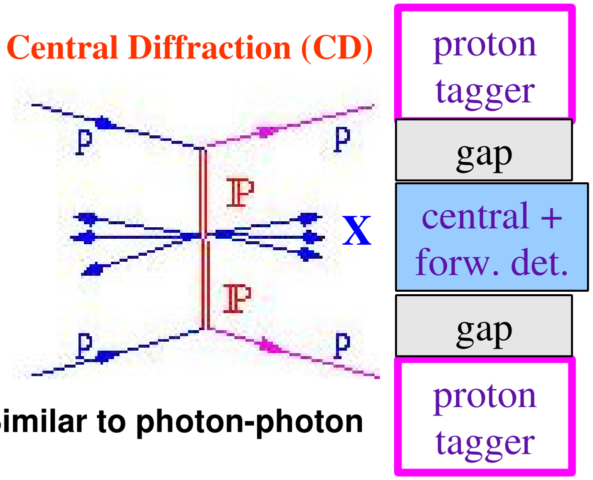


Similar to photon-proton

Double Diffraction (DD)



Central Diffraction (CD)



Similar to photon-photon

Absence of colour flow between the proton(s) and the system X implies **large gap(s) in the rapidity distribution of the hadronic final state**:
→ require **absence of signal in the forward detectors** (if no pile-up!)
(otherwise, proton taggers are required → not yet there)

- Inclusive diffraction represents a **large fraction of σ_{tot}** !
  (dominated by SD events pp → Xp)

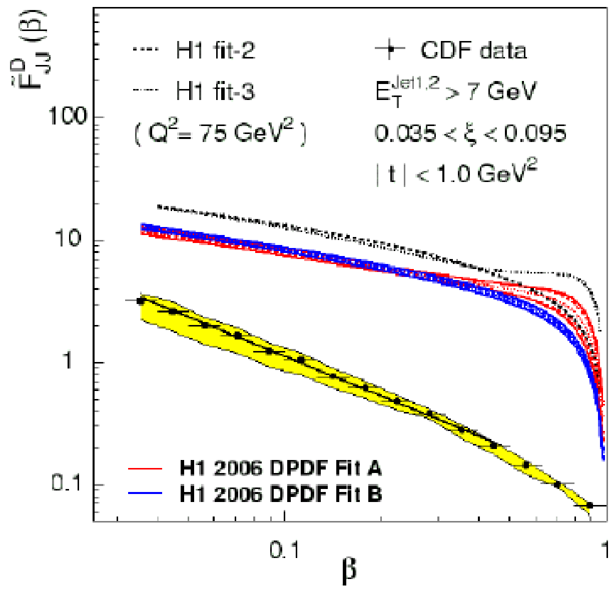
Seen at UA8, HERA, Tevatron, **and now at LHC!**

- **Diffraction also occurs in the presence of a hard scale: jets, W, Z, heavy quarks, …**
  → tool to study (perturbative) QCD and the structure of the proton

- In pp interactions, rescattering between spectators breaks factorization
  → need to measure **rapidity gap survival probability** !

Factorization breaking and gap survival probability

CDF, PRL 84 (2000) 5043 + P.Newman/H1



Diffractive dijet measurement in ppbar by CDF

Comparison with NLO predictions with **HERA DPDFs as input**:

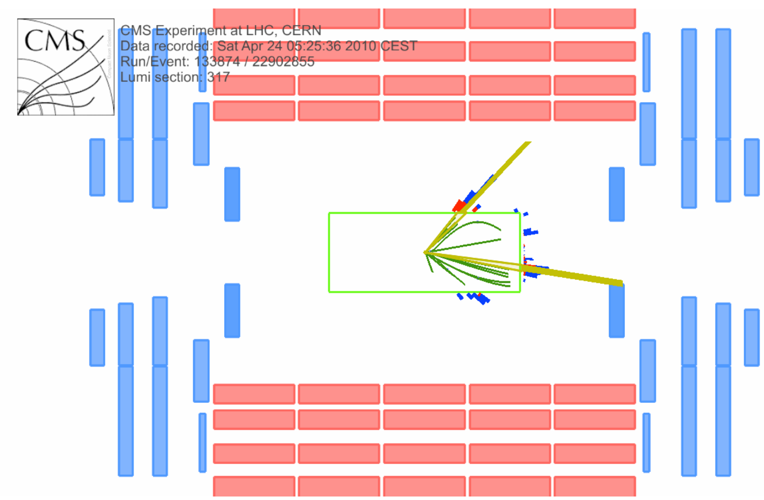
Significant **overestimation** (~ factor 10) of the data by NLO calculations and **different shape**

Factorisation not expected to hold for diffractive hadron-hadron collisions

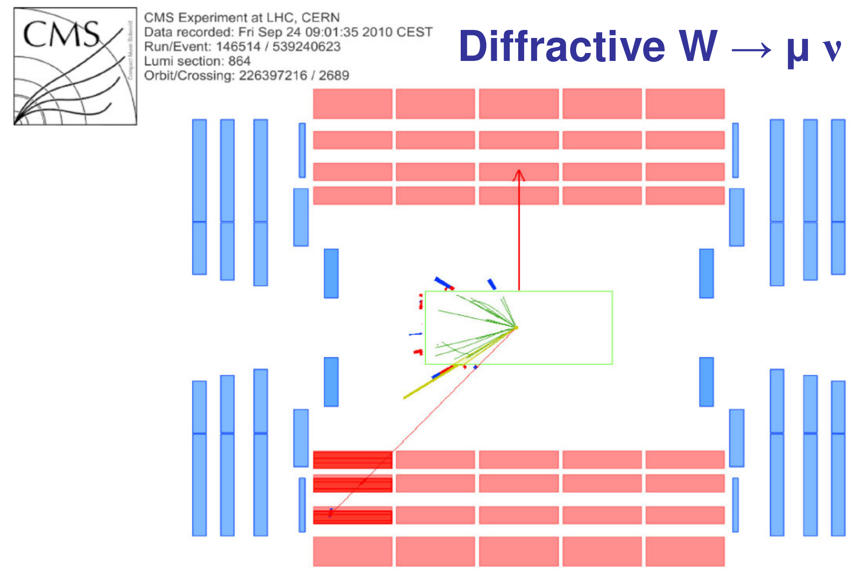
- Violation of factorisation is understood in terms of (soft) rescattering between spectator partons, in initial and final states, suppressing the large rapidity gap: suppression ⟷ '**rapidity gap survival probability**'
- Models including rescattering corrections via multi-pomeron exchanges are able to describe the suppression observed [**KKMR, EPJ C21 (2001) 521**]
- **Rapidity gap survival probability essential for LHC!**

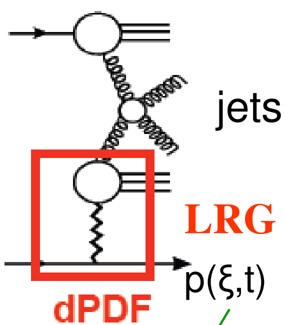
Evidence for hard diffraction

Diffractive dijet candidate



Diffractive W → μ ν





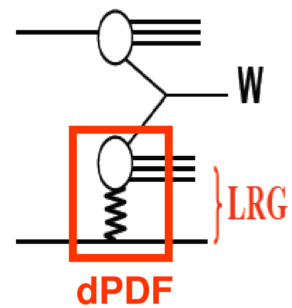
Assuming QCD and Regge factorizations:

$$\frac{d\sigma}{d\xi dt} = \sum \int dx_1 dx_2 d\hat{t} \underbrace{f(\xi,t) f_{\mathbb{P}}(x_1,\mu)}_{\text{dPDF: pomeron flux} \otimes \text{pdf}} \overbrace{f_p(x_2,\mu)}^{\text{proton PDF}} \underbrace{\frac{d\hat{\sigma}(\hat{s},\hat{t})}{d\hat{t}}}_{\text{partonic cross section}}$$

proton PDF

dPDF: pomeron flux ⊗ pdf

partonic cross section



$\xi = (M_X)^2/s$

fractional momentum loss of the scattered proton

Implemented in "hard-diffractive" MCs:
POMPYT, POMWIG, PYTHIA8, …

Diffractive dijet production: event selection & ξ reconstruction

PRD 87 (2013) 012006

Sample: 2.7 nb^{-1} of 2010 data at 7 TeV, taken at low instantaneous luminosity
→ **average number of pile-up interactions per event is 0.09**

Event selection:

- good quality primary vertex
- beam related background and noise rejection
- at least **2 jets with p_T > 20 GeV** and **axes within |η| < 4.4**
- **η_{max} < 3 (η_{min} > - 3)** to enhance **the diffractive contribution**

$\eta_{max/min}$ = pseudorapidity of the most forward/backward particle-flow object in the calorimeter
→ **this selection corresponds to a gap Δη ~ 1.9 in the HF calorimeter acceptance**

ξ reconstruction:

$$\xi \longrightarrow \tilde{\xi}^{\pm} = \frac{\sum \left(E^i \pm p_z^i\right)}{\sqrt{s}} \simeq \frac{M_X^2}{s}$$

for SD events at low ξ

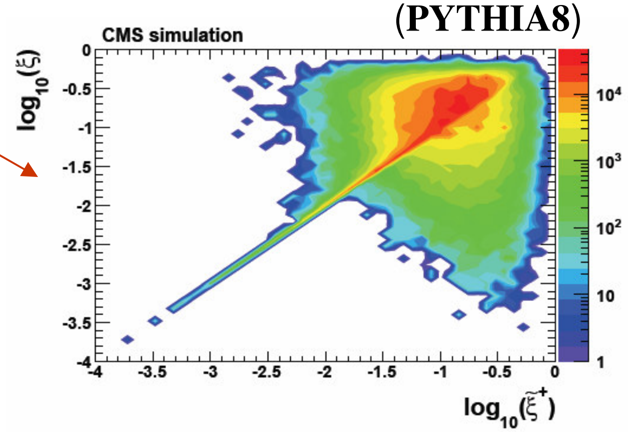
sum over all particle-flow objects above threshold

$$\begin{cases} \tilde{\xi}^{+} & \rightarrow \eta < +4.9 \\ \tilde{\xi}^{-} & \rightarrow \eta > -4.9 \end{cases}$$

$$\tilde{\xi}^{\pm}_{rec} = C\tilde{\xi}^{\pm}$$

C = 1.45±0.04

(PYTHIA8)



ξ distribution

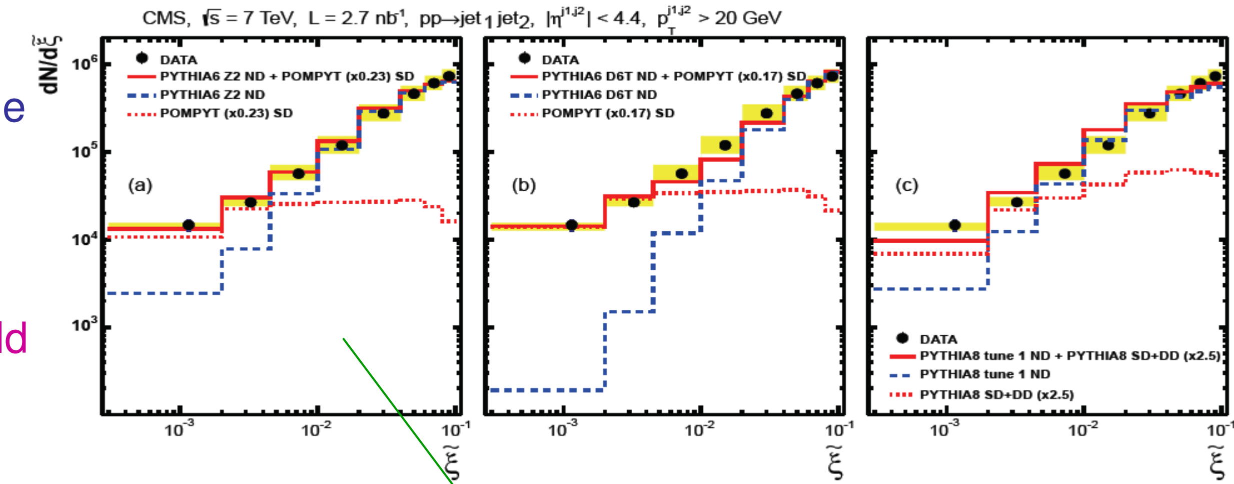
PRD 87 (2013) 012006

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

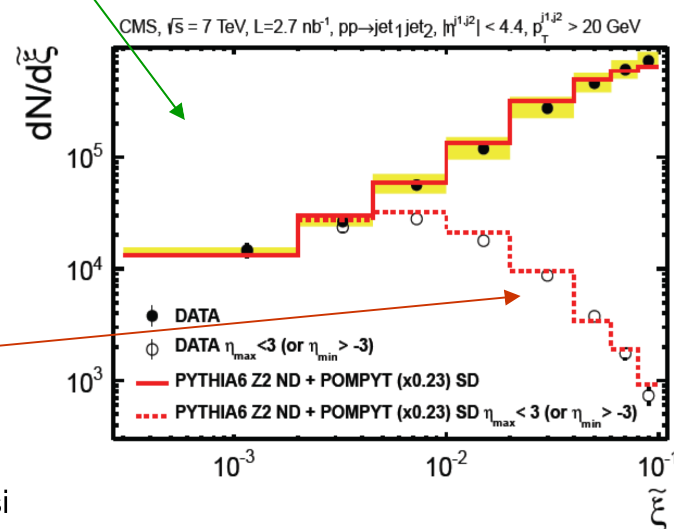
Data are fitted to different MC combinations ND+SD to obtain the **relative contributions of diffractive and non-diffractive components**

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

Before $\eta_{max/min}$ cut



After $\eta_{max/min}$ cut



Energy scale uncertainties

A combination of **PYTHIA6 ND (Tune Z2)** and **POMPYT SD (scaled by 0.23!)** results in the best description of the data

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

→ **extract dijet cross section in first 3 bins**

Dijet cross section

Three ξ bins: (0.0003,0.002); (0.002,0.0045); (0.0045,0.01)

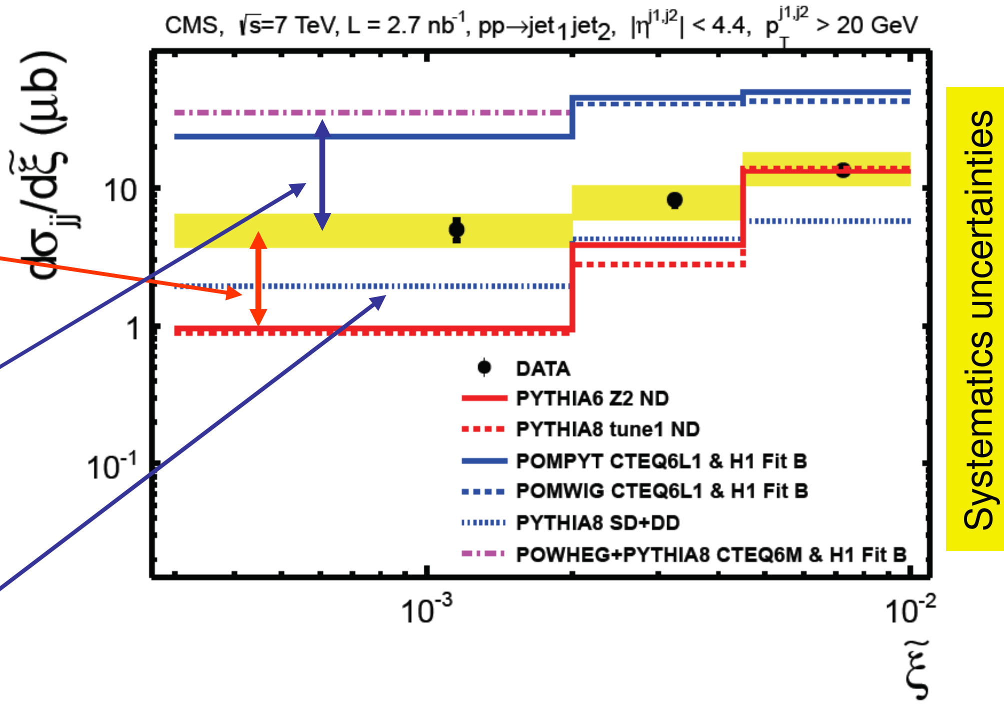
PRD 87 (2013) 012006

Data corrected for pile-up

Excess of events at low ξ
w.r.t. non-diffractive MCs :
→ **evidence for hard diffraction**

POMPYT and POMWIG (LO) diffractive MC's as well as the **NLO calculation from POWHEG**, all using H1 fit B dPDFs, are a **factor ~5 above the data in lowest ξ bin**

PYTHIA8 diffractive cross section is considerably **lower due to different pomeron flux parametrisation**



In the first bin dominated by diffraction:

$\sigma_{meas} / \sigma_{MC} = 0.21 \pm 0.07$ **(LO MC)**

$\sigma_{meas} / \sigma_{MC} = 0.14 \pm 0.05$ **(NLO MC)**

which can be considered as **upper limits of the rapidity gap survival probability** (cross section also includes DD)

Assuming 41% of proton dissociation in data, the **rapidity gap survival probability** can be estimated:

$S^2 = 0.12 \pm 0.05$ **(LO)**

$S^2 = 0.08 \pm 0.04$ **(NLO)**

[Size similar to that measured at Tevatron but different ξ range!]

W/Z events with an η gap

EPJ C72 (2012) 1839

Sample: 36 pb^{-1} of 2010 data at 7 TeV, taken with increasing instantaneous luminosities
→ sample divided in 3 periods with different pile-up conditions
PU contribution studied with zero-bias data samples and well reproduced by luminosity-dependent MC simulations

Event selection:

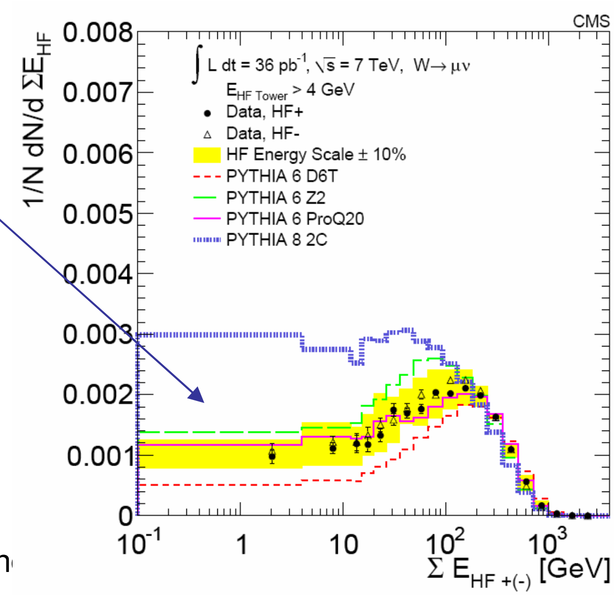
- good quality primary vertex; **events with more than one vertex are rejected to limit PU**
- beam related background and noise rejection
- identification of W and Z events (independent of instantaneous luminosity and BG < 1%):

W → lν : one isolated lepton within |η| < 1.4 and p_T > 25 GeV ; missing E_T > 30 GeV

Z → ll : two isolated leptons with opposite charge and p_T > 25 GeV; a least one within |η| < 1.4; invariant mass 60 < M_{ll} < 120 GeV

- **energy deposition in either HF+ or HF- less than 4 GeV to select LRG events (Δη > 1.9)**

→ diffractive component in W/Z data set



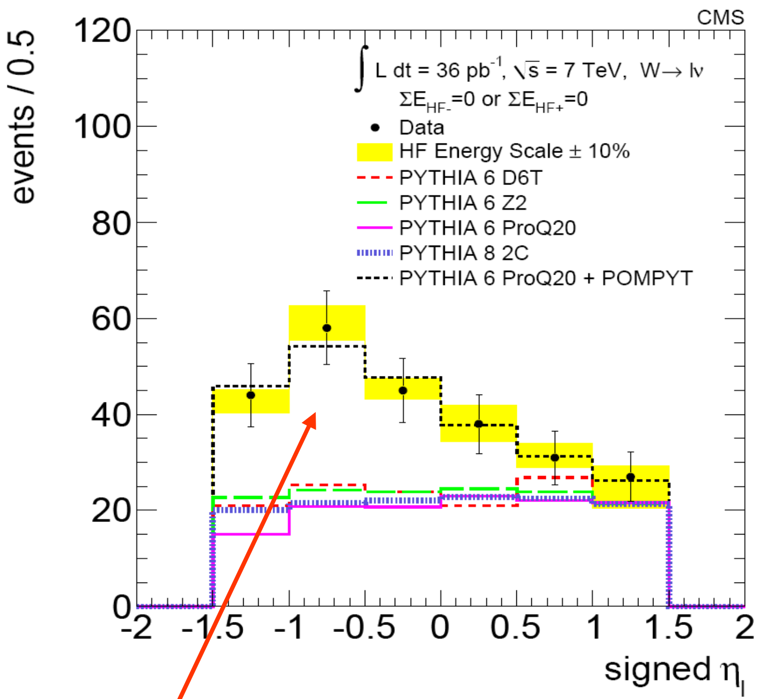
Fraction of W/Z events with a forward gap over HF:

W→lν: 1.46 ± 0.09(stat.) ± 0.38(syst.) %

Z→ll: 1.57 ± 0.25(stat.) ± 0.42(syst.) %

W→lν events with an η gap

EPJ C72 (2012) 1839



Signed lepton η distribution in **events with a LRG**:

η_l < 0: lepton and gap are in **opposite hemispheres**

η_l > 0: lepton and gap are in **the same hemisphere**

Large asymmetry observed:

diffractively produced W/Z are boosted in the direction opposite to the gap, as simulated by POMPYT

dPDFs peak at smaller x than the proton PDFs →
bosons are boosted in the direction of the parton with larger x, which is typically the direction of the dissociated proton, opposite to the gap

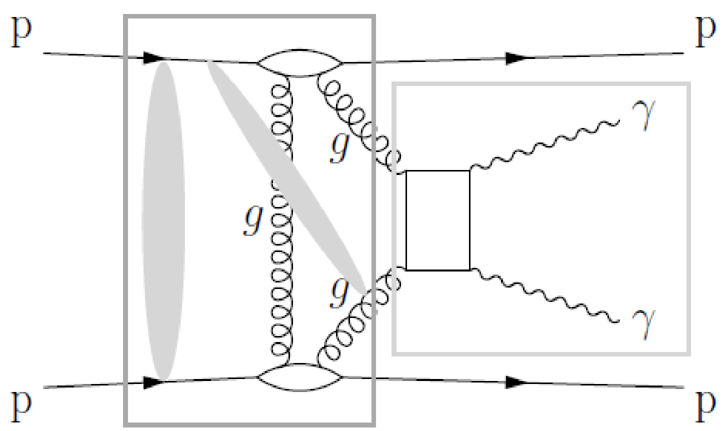
Evidence for diffractive W production in the data

From a fit with PYTHIA ND and POMPYT SD:

fraction of W diffractive events in LRG sample

f_{SD} = 50.0 ± 9.3(stat.) ± 5.2(syst.)%

Central exclusive production

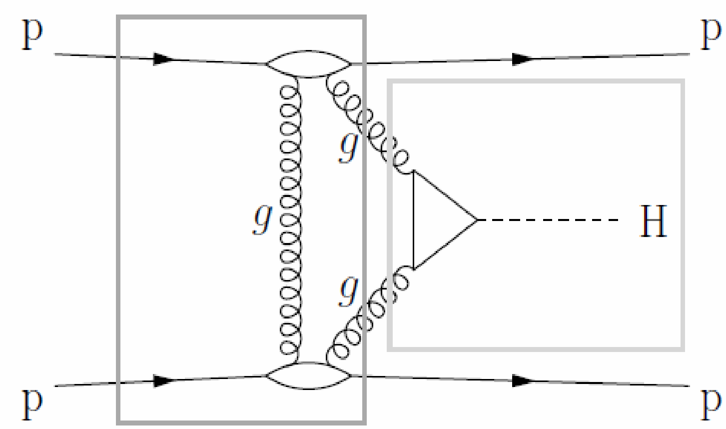


Exclusive γγ events are produced via **double pomeron exchange** or, in partonic terms, as $gg \rightarrow \gamma\gamma$ via a quark loop, plus an additional 'screening' gluon. Contributions from $q\bar{q} \rightarrow \gamma\gamma$ and $\gamma\gamma \rightarrow \gamma\gamma$ are estimated less than 1% of $gg \rightarrow \gamma\gamma$

Semi-exclusive production if one or both protons dissociate into a low mass state

Exclusive γγ production is closely related to exclusive Higgs boson production

Since main theoretical uncertainties are common among different states, exclusive γγ production provides an excellent test of the theoretical predictions for Higgs central exclusive production



Exclusive $\gamma\gamma$ production

JHEP 11 (2012) 080

Sample: 36 pb^{-1} of 2010 data at 7 TeV, using only data with low pile-up contamination

Event selection:

- exactly **2 photons** with **E_T > 5.5 GeV** and **$|\eta|$ < 2.5,** balanced in E_T and back-to-back in ϕ
- cosmic-ray rejection
- **exclusivity** selection: no other particle in the region **$|\eta|$ < 5.2**

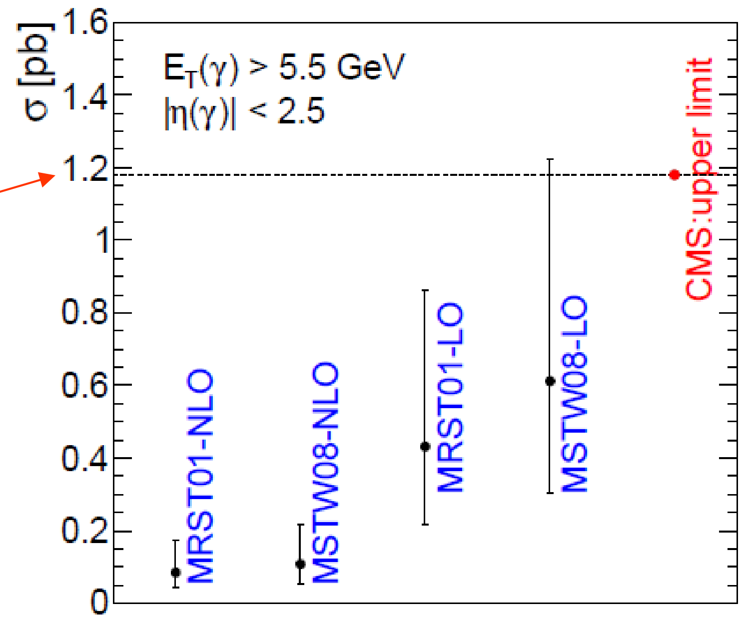
No candidate events observed with an expected background of 1.79 ± 0.40

95% CL upper limit:

σ (E_T > 5.5 GeV, $|\eta|$ < 2.5) < 1.18 pb

on the **sum of exclusive and semi-exclusive** production

Compared to **theoretical predictions for exclusive production only** (semi-exclusive production estimated of similar magnitude)
Difference between LO and NLO mainly due to low-x gluon density



obtained with the **ExHuME** MC, implementing the **KMR model**

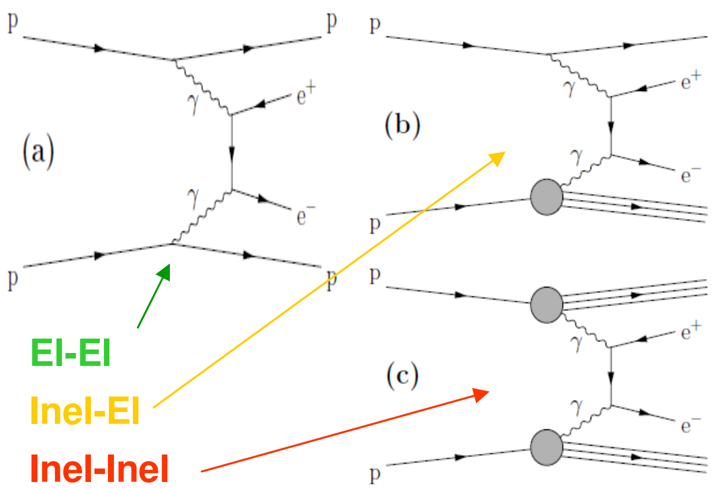
Exclusive $\gamma\gamma \rightarrow e^+e^-$ production

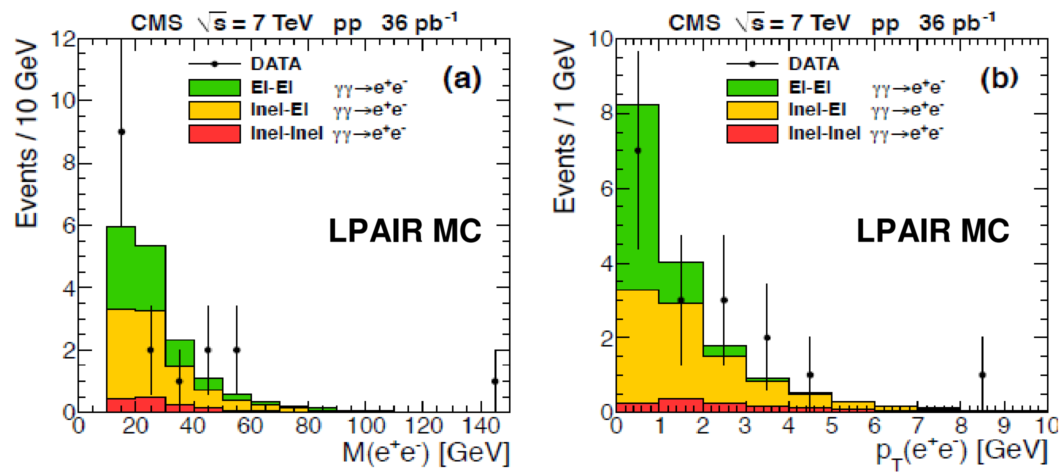
JHEP 11 (2012) 080

Sample: 36 pb^{-1} of 2010 data at 7 TeV, using only data with low pile-up contamination
same sample used for exclusive $\gamma\gamma$ event search

Event selection: very similar to the one applied for exclusive $\gamma\gamma$ analysis

- exactly **2 electrons** of opposite charge, each with **E_T > 5.5 GeV** and **$|\eta|$ < 2.5,** balanced in E_T and back-to-back in ϕ
- cosmic-ray rejection & **exclusivity** selection: no other particle in the region **$|\eta|$ < 5.2**





17 exclusive or semi-exclusive event candidates observed, with an expected background of 0.85 ± 0.28, **consistent with the QED-based prediction by LPAIR** of 16.3 ± 1.3 events, providing a validation of the selection procedure for the $\gamma\gamma$ exclusive production search

Exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ production

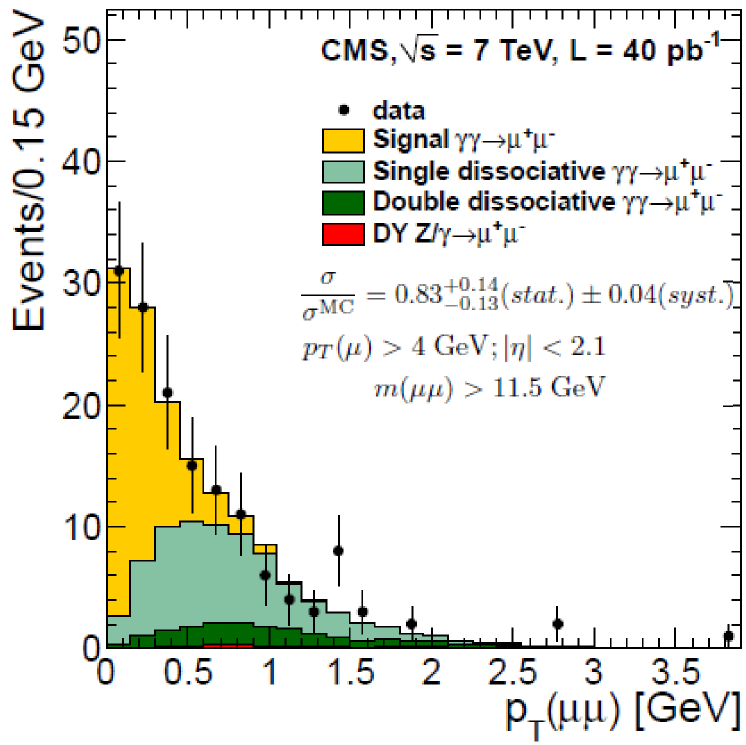
JHEP 01 (2012) 052

Sample: 40 pb^{-1} of 2010 data at 7 TeV, with any pileup conditions

Event selection:

- exactly **2 muons** of opposite charge, with **p_T > 4 GeV** and **$|\eta|$ < 2.1**
- **exclusivity** selection: **primary vertex** with exactly 2 muons and no other track within 2 mm
- cosmic-ray rejection
- **$m(\mu\mu)$ > 11.5 GeV** to reject Y photoproduction

Signal extracted with a binned maximun likeliwood fit to the $p_T(\mu\mu)$ distribution



Cross section for **exclusive μμ production** in the selected kinematic region:

$$\sigma(pp \rightarrow p\mu^+\mu^-p) = 3.38^{+0.58}_{-0.55}\,(\text{stat.}) \pm 0.16\,(\text{syst.}) \pm 0.14\,(\text{lumi.})\ \text{pb}$$

consistent with the predicted value

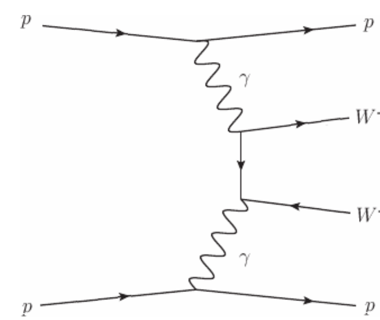
Exclusive $\gamma\gamma \to W^+W^-$ production

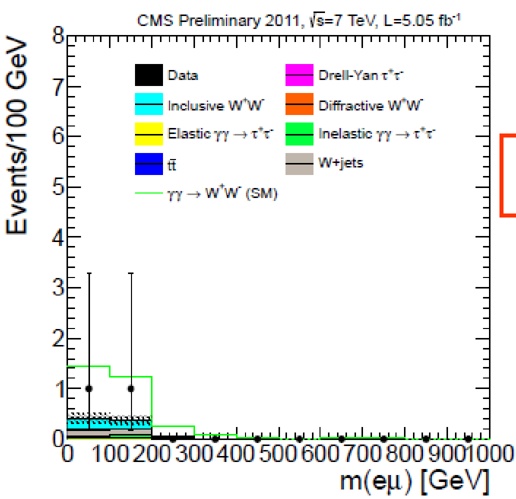
CMS PAS FSQ-12-010

Sample: 5.05 fb^{-1} of 2011 data at 7 TeV

Event selection:

- to limit the background, **only consider the decay channel μe**, using μμ as control sample
- exclusivity : μe vertex with no associated charged tracks
- dilepton trasverse momentum **p_T > 30 GeV** for SM signal region
- **p_T > 100 GeV** to study deviations from SM and look for the anomalous quartic gauge couplings



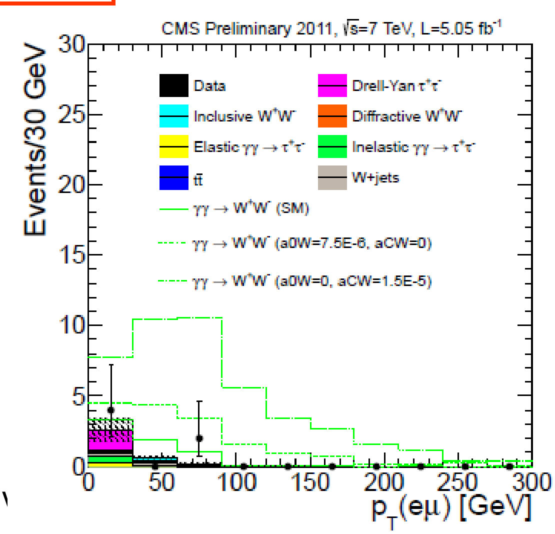


2 events observed in the SM signal region with 2.2 ± 0.5 expected and 0.84 ± 0.13(stat.) background

$$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}) = 2.1^{+3.1}_{-1.9}\ \text{fb}$$

In the AQGC research region p_T > 100 GeV no events are observed in the data, consistent with SM of 0.14

Limits set to anomalous quartic coupling parameters.



Summary

First measurements of hard diffraction at LHC:

- **the dijet cross section was measured**. Comparing the measured cross section to diffractive MC predictions based on dPDFs from HERA, an **estimate of the gap survival probability** was obtained

- **W/Z events with a pseudorapidity gap ($\Delta\eta > 1.9$) were observed**. For most of these events, the charged leptons from W/Z decays are found in the hemisphere opposite to the gap, **consistent with diffractive W/Z production**

Central exclusive production:

- **no exclusive or semi-exclusive $\gamma\gamma$ events were observed** and an upper limit to the production cross section was set

- **exclusive and semi-exclusive e^+e^-, $\mu^+\mu^-$, WW events were measured in agreement with the expectations**, providing a valid check to the selection procedure of other exclusive processes

Outlook

Analysis of CMS+TOTEM data

- July 2012 – **first pp common data taking @ $\sqrt{s}$ = 8 TeV**
  ~11h, 43 nb^{-1} collected (~25 M events)
  special optics β^{*}=90m, with ~100 bunches
  bi-directional exchange of triggers
  various triggers for Soft and Hard DPE
- Past weeks – **pPb common data taking**
- These days – **new pp common data taking @ $\sqrt{s}$ = 2.76 TeV**

Lots of potential studies and measurements ahead !

Backup slides

Dijet cross section

PRD 87 (2013) 012006

Table 3: Differential cross section for inclusive dijet production as a function of $\tilde{\xi}$ for jets with $p_T^{j1,j2} > 20\,\text{GeV}$ and jet-axes in the pseudorapidity range $|\eta^{j1,j2}| < 4.4$.

$\tilde{\xi}$ bin	$d\sigma_{jj}/d\tilde{\xi}$ (μb)
$0.0003 < \tilde{\xi} < 0.002$	$5.0 \pm 0.9(\text{stat.})^{+1.5}_{-1.3}(\text{syst.})$
$0.002 < \tilde{\xi} < 0.0045$	$8.2 \pm 0.9(\text{stat.})^{+2.2}_{-2.4}(\text{syst.})$
$0.0045 < \tilde{\xi} < 0.01$	$13.5 \pm 0.9(\text{stat.})^{+4.5}_{-3.1}(\text{syst.})$

Uncertainty source	$0.0003 < \tilde{\xi} < 0.002$	$0.002 < \tilde{\xi} < 0.0045$	$0.0045 < \tilde{\xi} < 0.01$
1. Jet energy scale	$(+26; -19)\%$	$(+21; -20)\%$	$(+28; -16)\%$
2. Jet energy resolution	$(+6; -4)\%$	$(+4; -3)\%$	$(+3; -2)\%$
3. PF energy, p_T threshold, C	$(+7; -15)\%$	$(+14; -8)\%$	$(+12; -11)\%$
4. MC model uncertainty	$(+5; -3)\%$	$(+2; -14)\%$	$(+3; -1)\%$
5. One-vertex selection	$(+6; -0)\%$	$(+0; -1)\%$	$(+1; -0)\%$
6. Jet objects (Calorimeter, PF)	$(+0; -4)\%$	$(+0; -4)\%$	$(+2; -4)\%$
7. $\tilde{\xi}^+$, $\tilde{\xi}^-$ difference	$\pm 8\%$	$\pm 8\%$	$\pm 11\%$
8. Trigger efficiency	$\pm 3\%$	$\pm 3\%$	$\pm 3\%$
9. Luminosity	$\pm 4\%$	$\pm 4\%$	$\pm 4\%$
Total error	$(+30; -26)\%$	$(+27; -29)\%$	$(+33; -23)\%$

Exclusive $\gamma\gamma$ and e^+e^- production

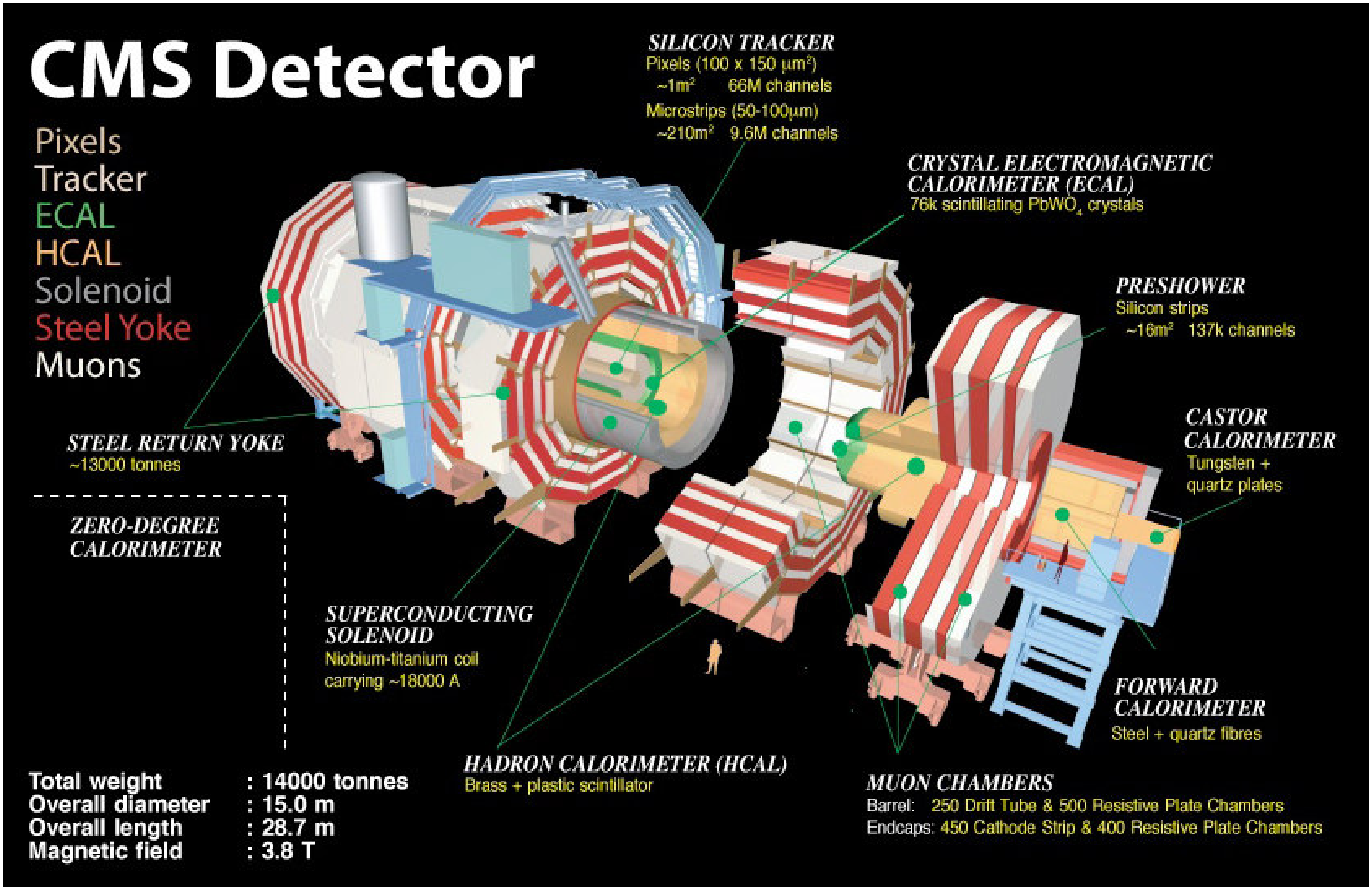
JHEP 11 (2012) 080

Table 1: Number of diphoton and dielectron candidates remaining after each selection step.

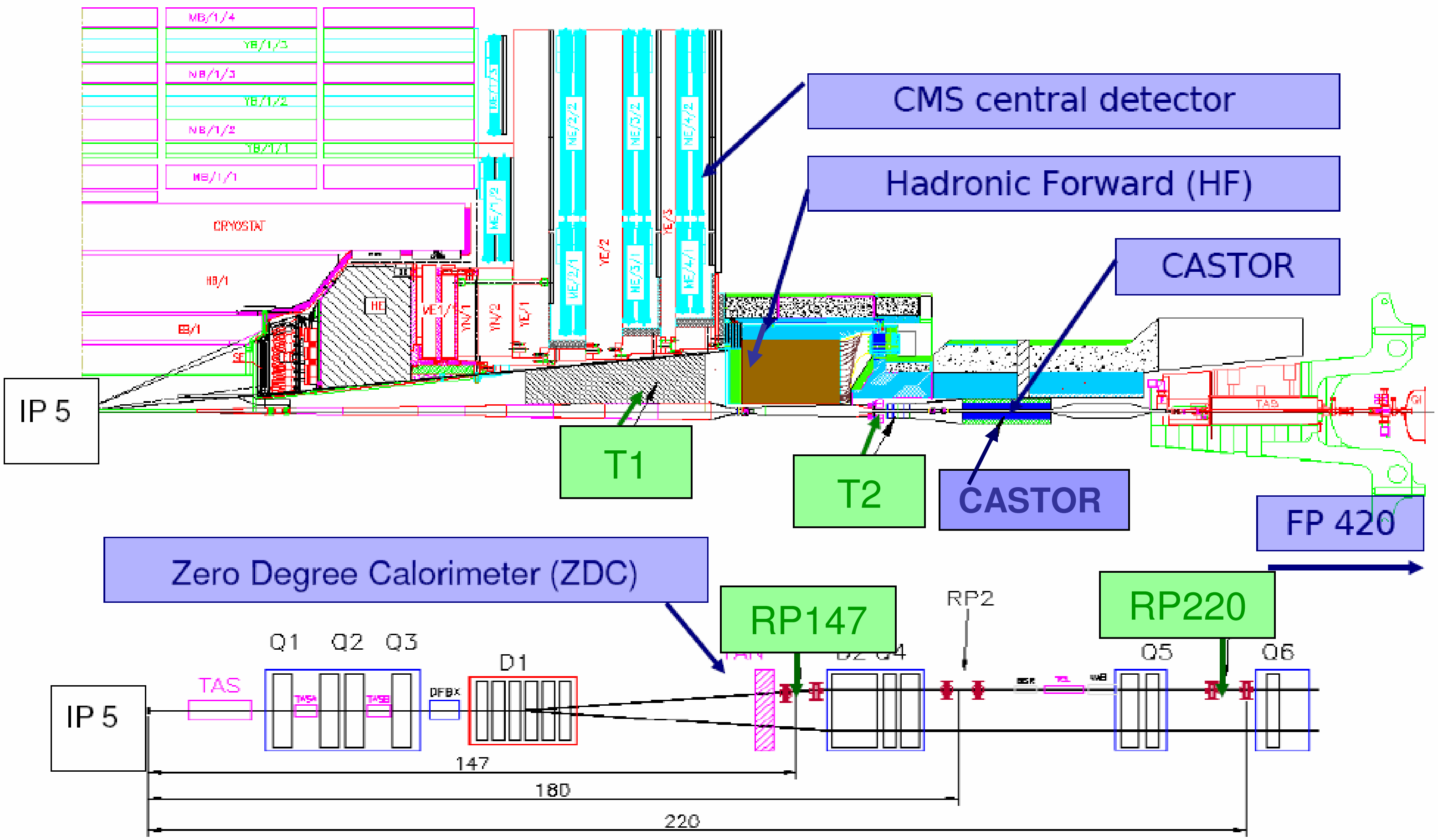
Diphoton analysis		Dielectron analysis	
Selection criterion	Events remaining	Selection criterion	Events remaining
Trigger	3 023 496	Trigger	3 023 496
Photon reconstruction	1 683 526	Electron reconstruction	132 271
Photon identification	40 692	Electron identification	1 668
Cosmic-ray rejection	34 234	Cosmic-ray rejection	1 321
Exclusivity requirement	0	Exclusivity requirement	17

Table 4: Background event yields expected for both the diphoton and the dielectron analyses. The quoted uncertainties are statistical.

Diphoton analysis		Dielectron analysis	
Background	Events	Background	Events
Non-exclusive	1.68 ± 0.40	Non-exclusive	0.80 ± 0.28
Exclusive e^+e^-	0.11 ± 0.03	Exclusive $\Upsilon(1S,2S,3S) \to e^+e^-$	Negligible
Cosmic ray	Negligible	Cosmic ray	0.05 ± 0.01
Exclusive $\pi^0\pi^0$ and $\eta\eta$	Negligible	Exclusive $\pi^+\pi^-$	Negligible
Total	1.79 ± 0.40	Total	0.85 ± 0.28


CMS Detector
Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² 66M channels
Microstrips (50-100μm)
~210m² 9.6M channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
76k scintillating PbWO4 crystals
PRESHOWER
Silicon strips
~16m² 137k channels
CASTOR CALORIMETER
Tungsten + quartz plates
STEEL RETURN YOKE
~13000 tonnes
ZERO-DEGREE CALORIMETER
SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A
FORWARD CALORIMETER
Steel + quartz fibres
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
MUON CHAMBERS
Barrel: 250 Drift Tube & 500 Resistive Plate Chambers
Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

Forward detectors at IP5



CMS: blue

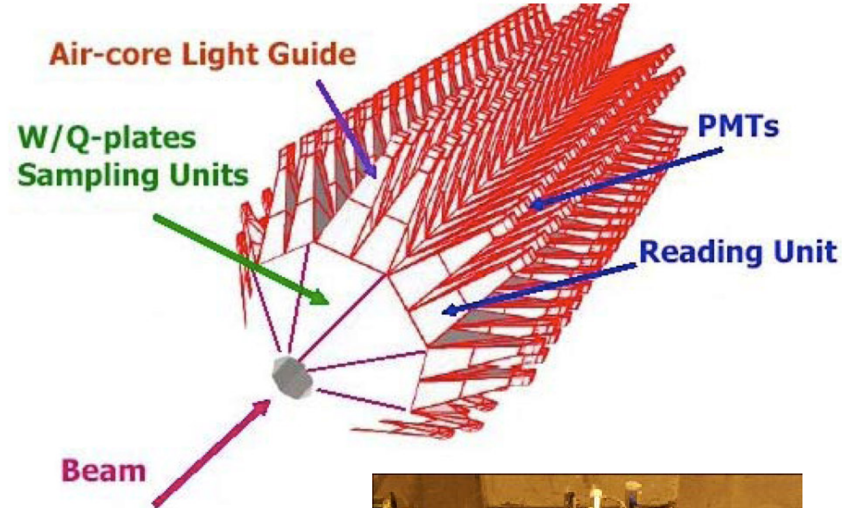
TOTEM: green

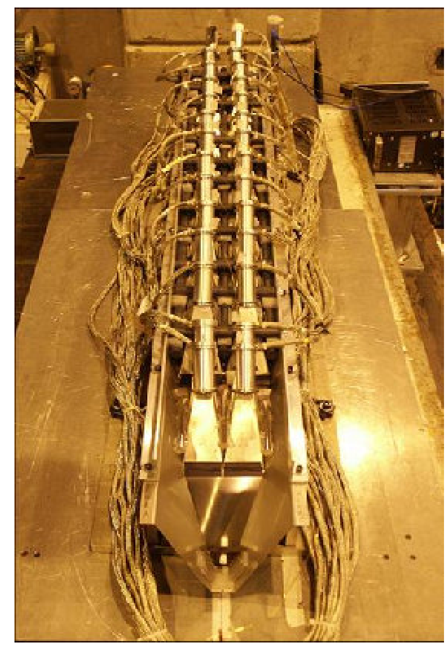
Hadron Forward calorimeter

- @11.2 m from the interaction point
- rapidity coverage: $2.9 < |\eta| < 5.2$
- steel absorbers and embedded radiation-hard quartz fibers for fast collection of Cherenkov light
- long (1.65 m) and short (1.43 m) fibers are placed alternately and run parallel to the beam axis along the absorbers

The CASTOR calorimeter

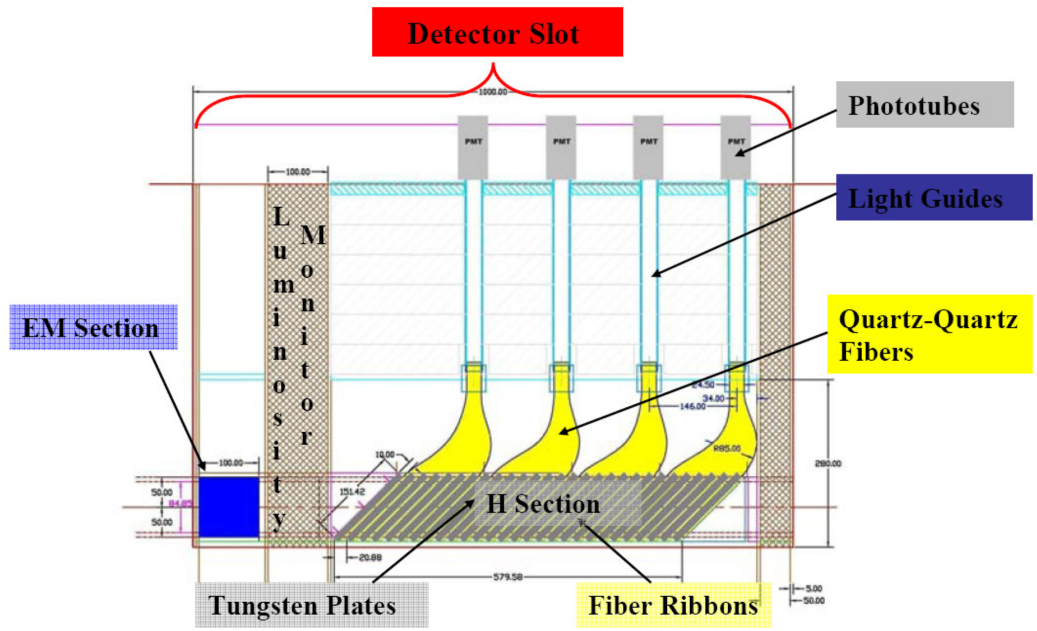
- rapidity coverage: $5.3 < |\eta| < 6.6$
  → enhances the hermiticity of CMS
- 14.37 m from the interaction point
- octogonal cylinder with inner radius 3.7 cm, outer radius 14 cm and total depth 10.5 λ_I
- signal collection through Cherenkov photons transmitted to PMTs through aircore lightguides
- W absorber & quartz plates sandwich, with 45° inclination with respect to the beam axis
- electromagnetic and hadronic sections
- 16 seg. in φ, 14 seg. in z
  no segmentation in η

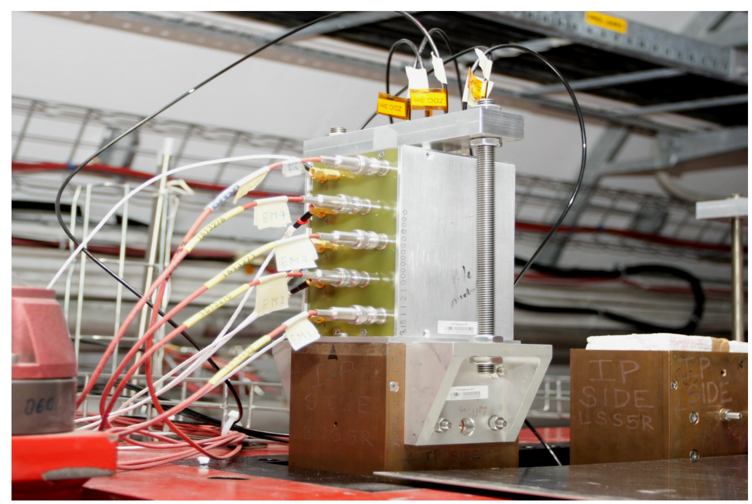




The Zero Degree Calorimeter

- 140 m from interaction point in TAN absorber
- Tungsten/quartz Cherenkov calorimeter with separate e.m.(19 X_0) and had.(5.6 λ_I) sections
- em: 5-fold horizontal seg. had: 4-fold seg. in *z*
- Acceptance for neutrals (γ, π^0, n) from $|\eta| > 8.1$ (100% for $\eta > 8.4$)

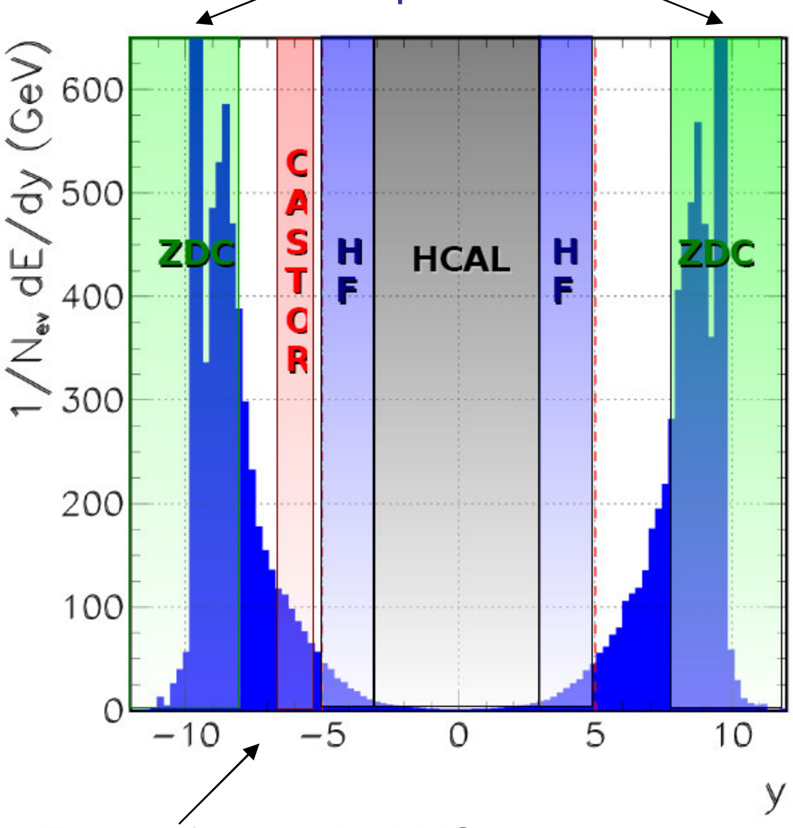




Rapidity coverage at CMS

Largest calorimetric rapidity coverage ever!

Elastic and diffractive protons



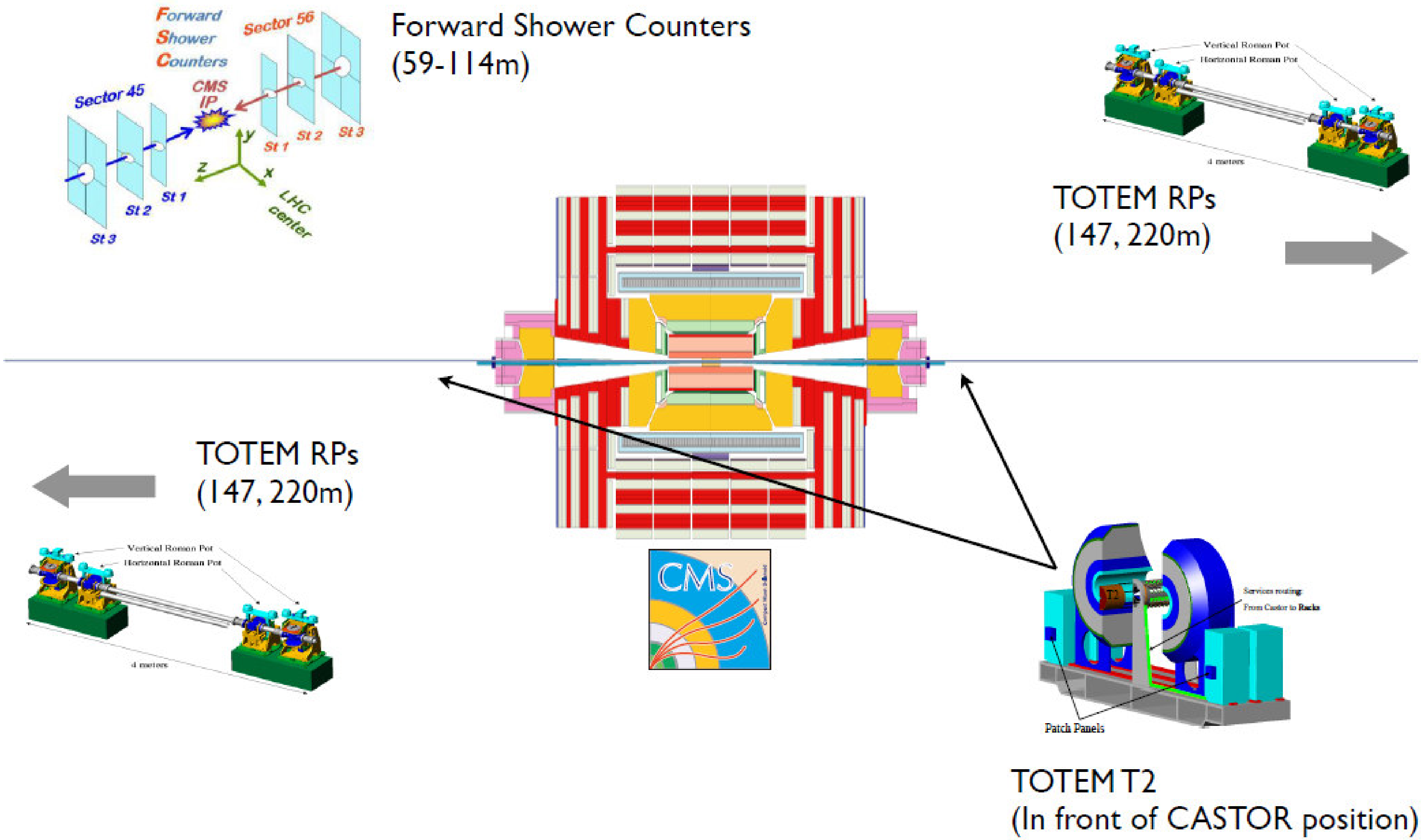
Energy flow at the LHC

- Most energy is deposited between $8 < |y| < 9$
- Main CMS calorimeters: $|y| < 5$

Maximal rapidity at the LHC:

$$y_{max} = \ln \frac{\sqrt{s}}{m} \approx 11.5$$

CMS+TOTEM detectors



CMS+TOTEM

TOTEM+CMS joint data taking:

- 2-arm proton reconstruction, $\xi_{1,2}=\Delta p_1,2/p_{1,2}$
- Prediction of mass to be seen in CMS from reconstructed protons:

  $M^2 = s\cdot\xi_1\xi_2$
- Initial vs. final state comparison: M_{TOTEM} =? M_{CMS}
- Prediction of central particle flow topology from leading protons (rapidity gaps) : $\Delta\eta_{1,2} = -\ln\xi_{1,2}$
- Large η-coverage:

  CMS: $-5.5<\eta<5.5$

  T1: $3.1 < |\eta| < 4.7$

  T2: $5.3 < |\eta| < 6.5$

  FSC: $6 < |\eta| < 8$