DIFFRACTION 2012

CMS results on soft and hard diffraction

Ada Solano
Univ. of Torino and INFN

On behalf of the CMS Collaboration

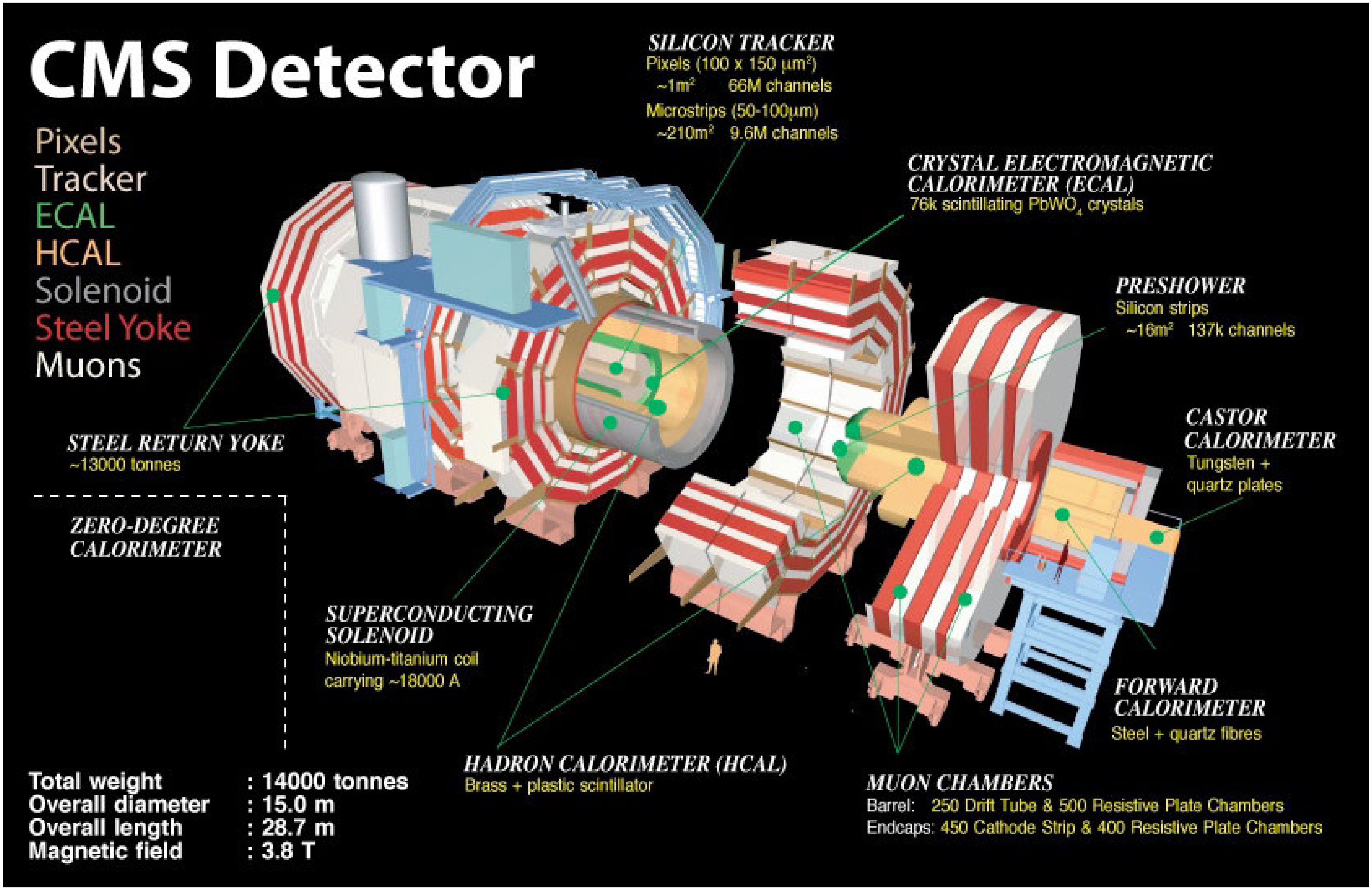
Outline

- **CMS detector and forward instrumentation**
- **Observation of inclusive (soft) diffraction**
- **Evidence for hard diffraction:**

  - diffractive dijet production

  - W/Z events with (pseudo-)rapidity gaps

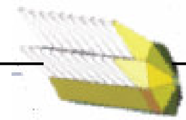
CMS detector



Forward instrumentation

±140 m

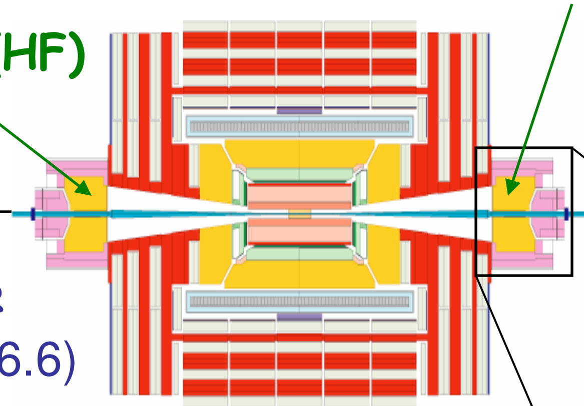
ZDC
(|η| > 8.1)



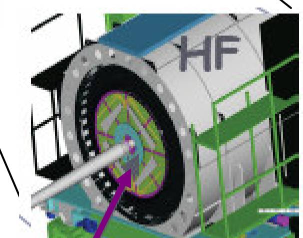
CASTOR
(5.3 < |η| < 6.6)

Hadronic Forward (HF)

CMS



Hadronic Forward (HF)
(2.9 < |η| < 5.2)



±175 m

BPTX (Beam pick-up timing)

CASTOR & ZDC not used in results presented in this talk

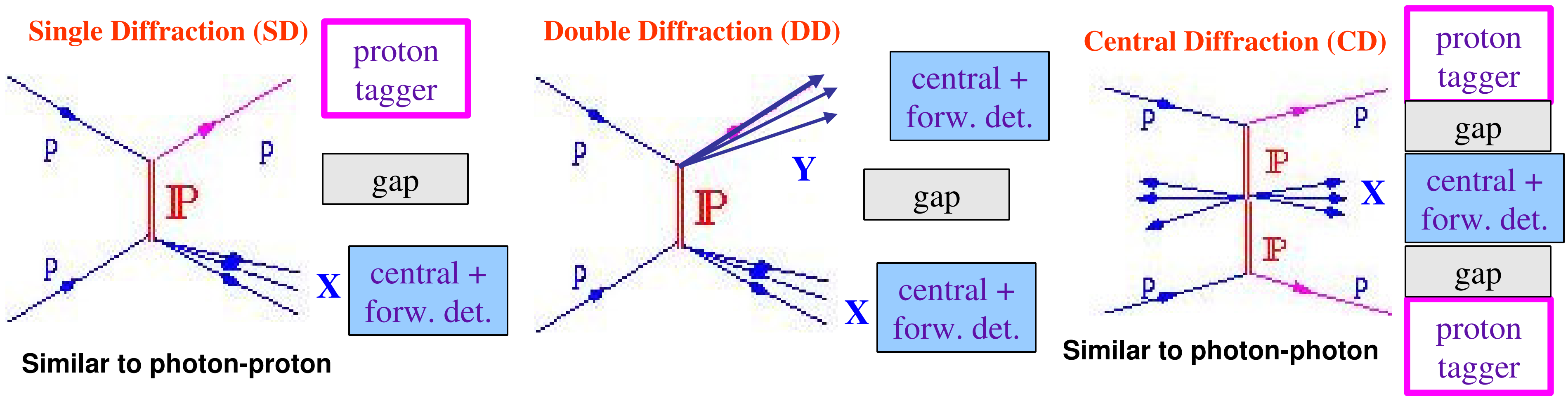
Hadronic Forward:

- @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

Beam Scintillator Counters (BSC):

- @10.86 m from the IP
- rapidity coverage: 3.23<|η|<4.65
- set of 16 scintillator tiles with a time resolution of 3 ns

Diffraction at LHC



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)

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

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

Inclusive diffraction: Event selection & acceptance

CMS PAS FWD-10-007

Sample: 20 μb^{-1} of 2010 data at 7 TeV, taken at low instantaneous luminosity
→ **probability of additional interactions per bunch crossing < 0.5%**

Event selection:

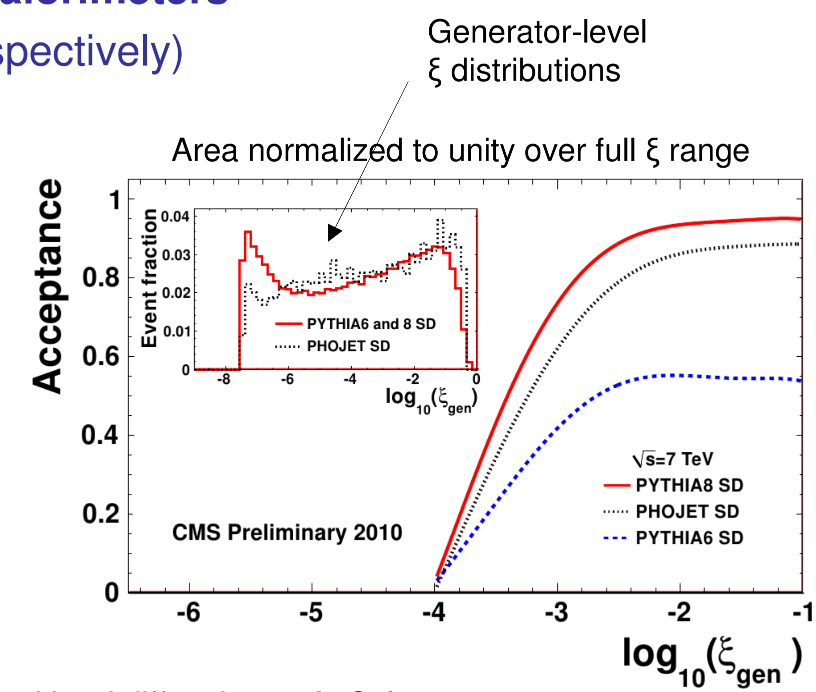
- BSC OR && both BPTX signals
- well centered primary vertex with good quality
- beam halo rejection (BSC)
- **filtering of events with characteristic noise in calorimeters** (1.5, 2 and 4 GeV for barrel, endcaps and HFs, respectively)

Acceptance for SD events, after all selection cuts:

ξ is the fractional momentum loss of the scattered proton: **$\xi = (M_X)^2/s$**

PYTHIA and **PHOJET** have a substantially different modelling of diffraction → different efficiency

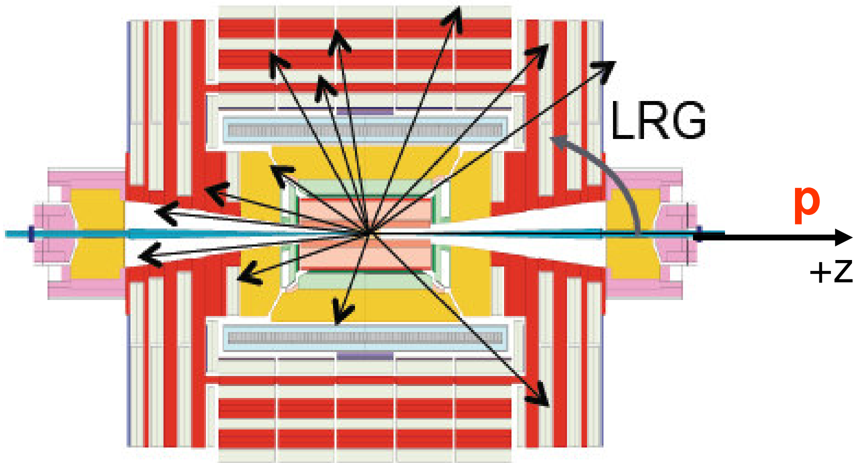
The acceptance for low-ξ events is small since **at low M_X the system X may escape undetected**



Observation of diffraction

CMS PAS FWD-10-007

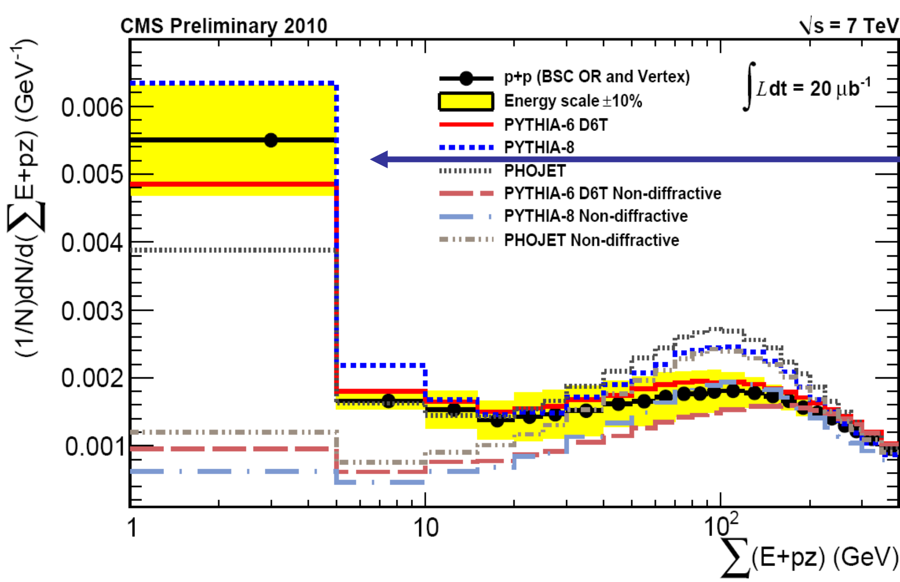
Sketch of SD event pp → Xp



$\Sigma(E\pm p_z)$ runs over all calorimeter towers, including HF, and is related to the momentum loss of the scattered proton **p**:

$\Sigma(E\pm p_z) \approx 2E_{IPomeron}$

[+(-) if p moves in +z(-z) direction]



Diffractive events are expected to peak at small values of $\Sigma(E\pm p_z)$ since the diffractive cross section is proportional to $1/\xi$

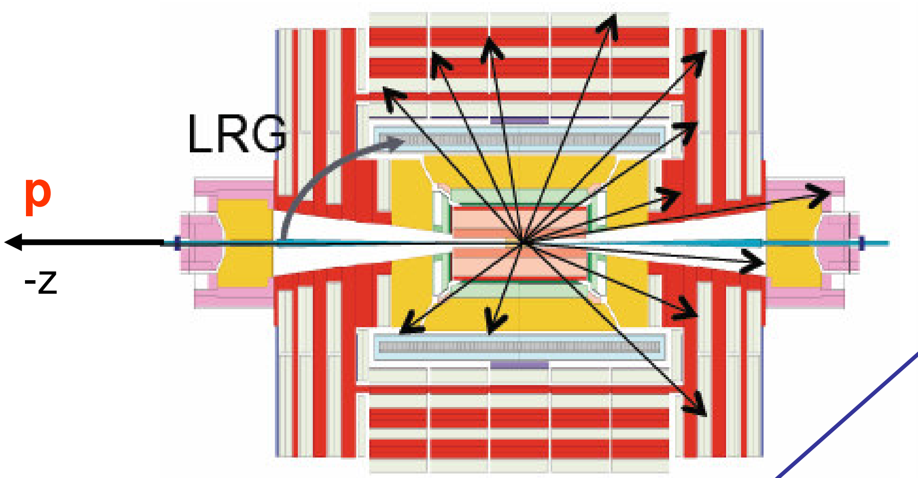
Main systematic uncertainty due to ±10% energy scale variation

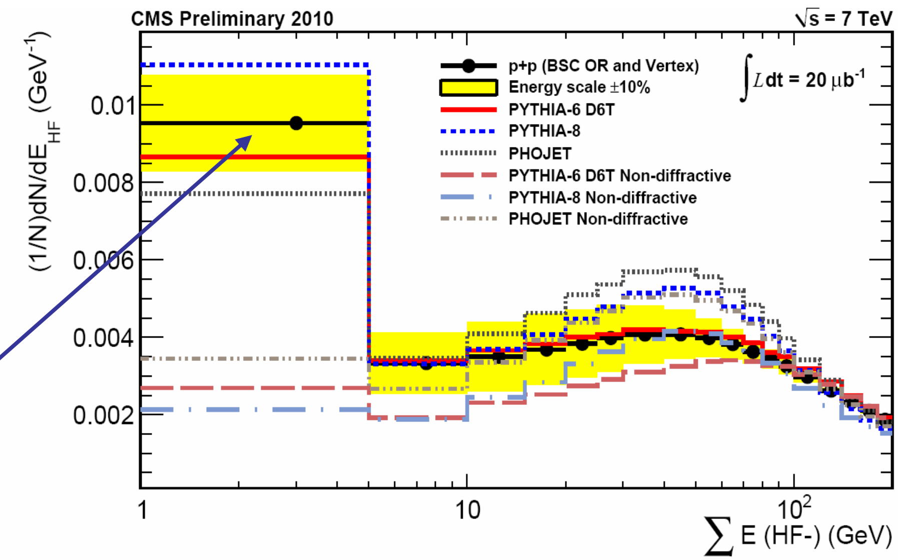
NB: uncorrected plot

Observation of diffraction

CMS PAS FWD-10-007

Sketch of SD event pp → X**p** (opposite side)

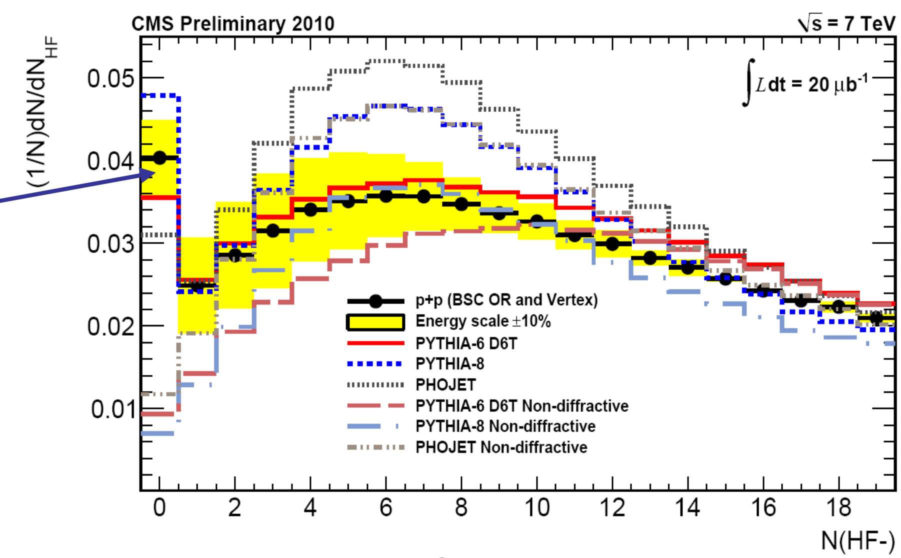




Evidence for a diffractive contribution also looking at the **absence of forward activity in HF**:
- zero-energy bin in HF
- zero towers above threshold in HF

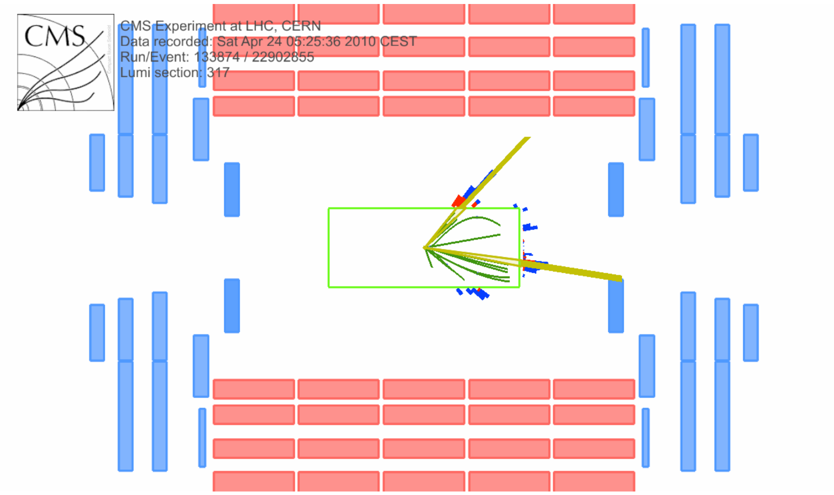
→ presence of a LRG extending over HF

NB: uncorrected plots

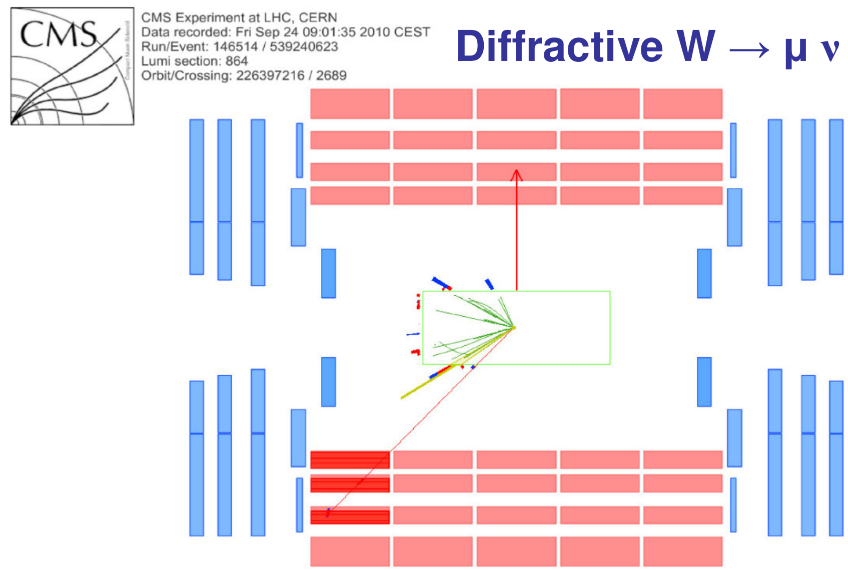


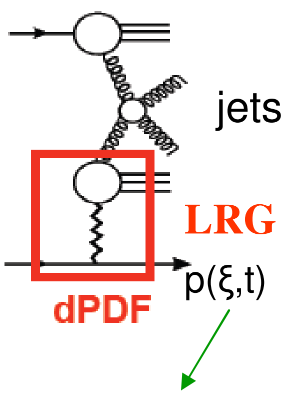
Evidence for hard diffraction

Diffractive dijet candidate



Diffractive W → μ ν





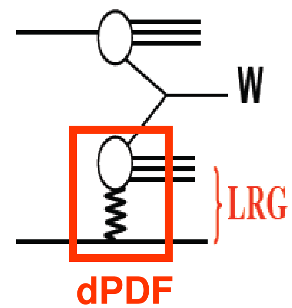
Assuming QCD and Regge factorizations:

proton PDF

$$\frac{d\sigma}{d\xi dt} = \sum \int dx_1 dx_2 d\hat{t}\, \boxed{f(\xi,t) f_{\mathbb{P}}(x_1,\mu)}\, \boxed{f_p(x_2,\mu)}\, \boxed{\frac{d\hat{\sigma}(\hat{s},\hat{t})}{d\hat{t}}}$$

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

arXiv:1209.1805v1 [hep-ex]
submitted to PRD

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 $|\eta| < 4.4$**
- **$\eta_{max} < 3$ ($\eta_{min} > -3$)** 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:

for SD events at low ξ

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

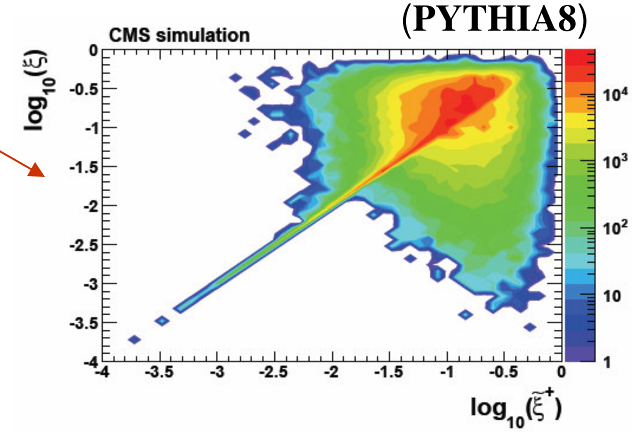
sum over all particle-flow objects above threshold

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

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

$$\boxed{C = 1.45 \pm 0.04}$$

(PYTHIA8)



ξ distribution

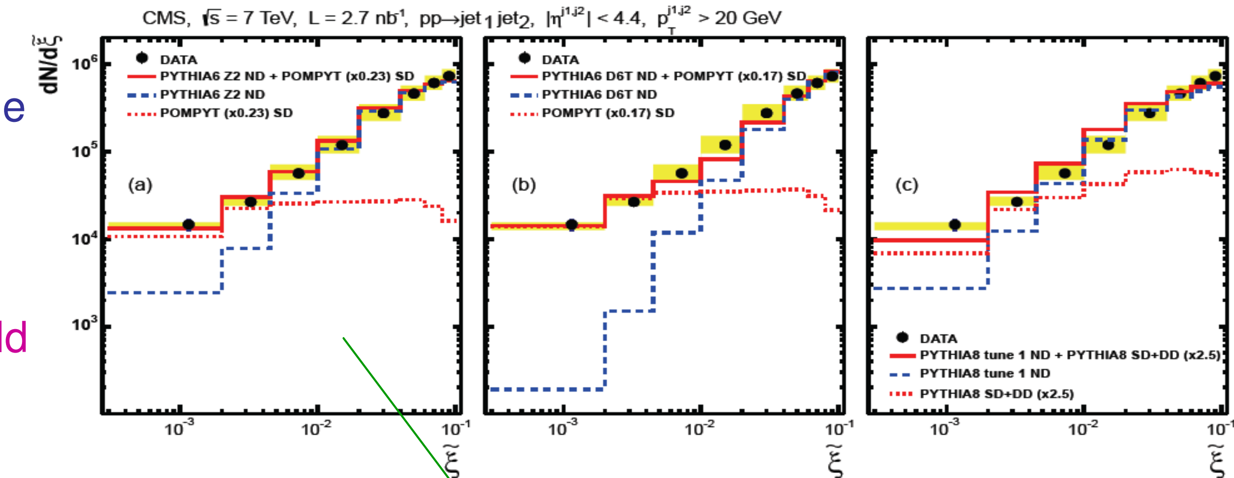
arXiv:1209.1805v1 [hep-ex]
submitted to PRD

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

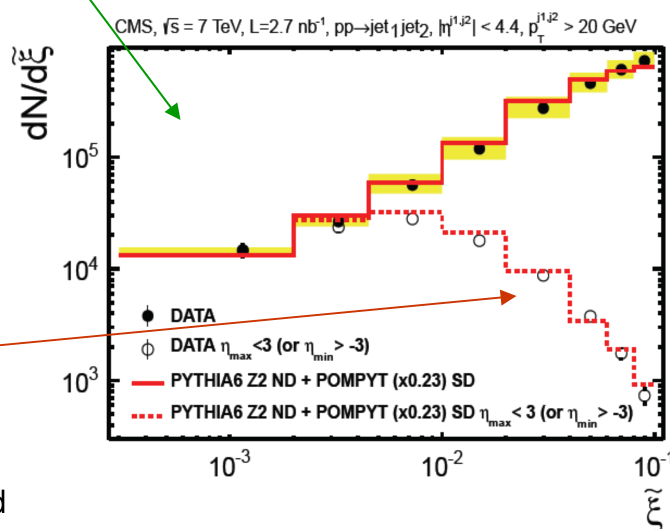
Data are fitted to different MC combinations ND+SD to obtain the **relative contributions of diffractive and non-diffractive components**

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

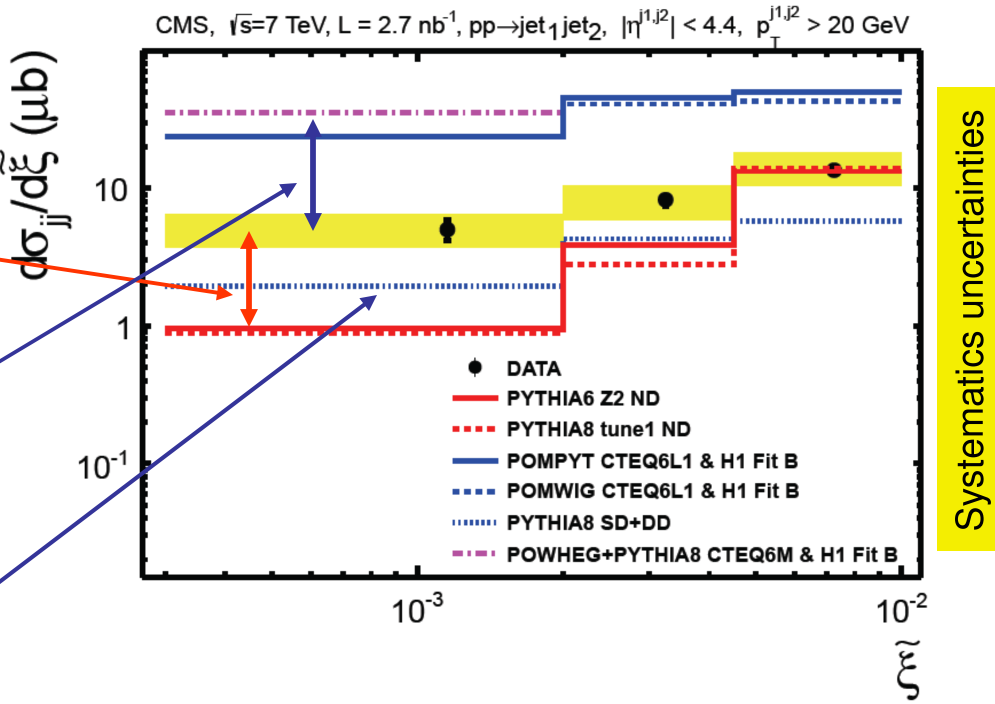
Suppression of events with high-ξ values after $\eta_{max} < 3$ (or $\eta_{min} > -3$) selection, while low-ξ region is mostly unaffected
→ **extract dijet cross section in first 3 bins**

Dijet cross section

Three ξ bins: (0.0003,0.002); (0.002,0.0045); (0.0045,0.01)
Data corrected for pile-up

arXiv:1209.1805v1 [hep-ex]
submitted to PRD

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

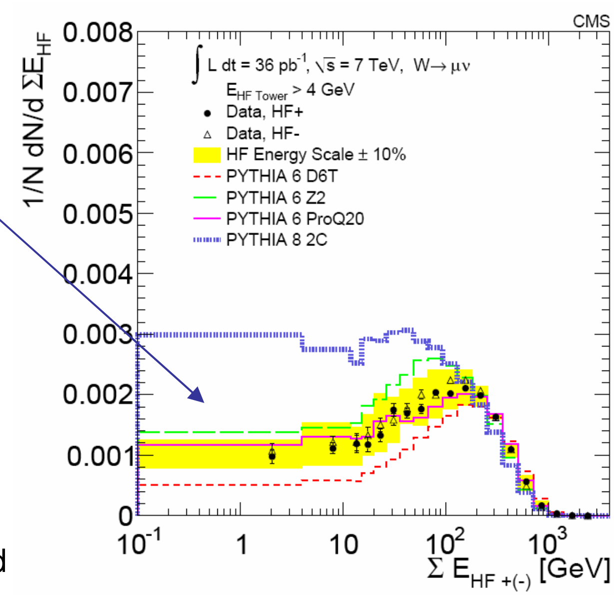
Event selection:

- good quality primary vertex; **events with more then 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



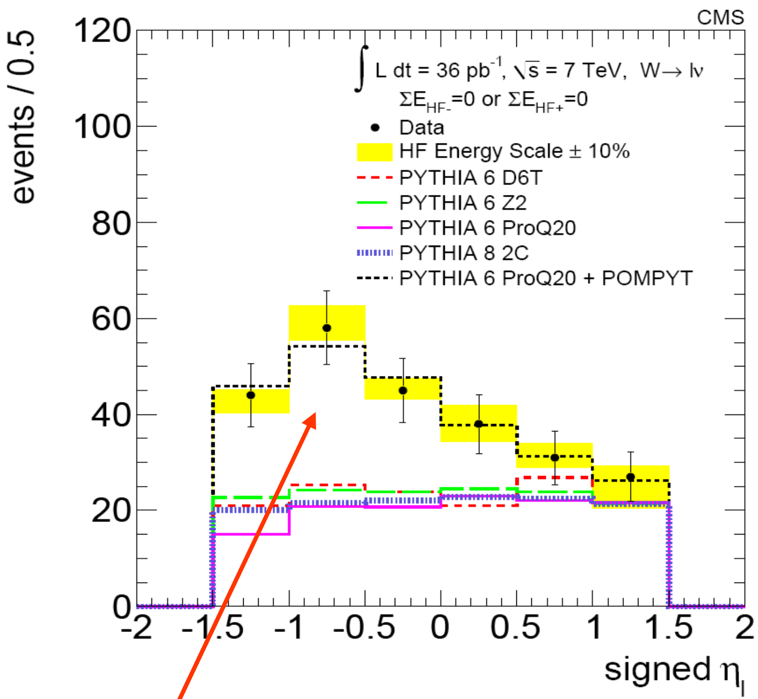
Fraction of W/Z events with a forward gap over HF:

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

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

W/Z events with an η gap

EPJ C72 (2012) 1839



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

$\eta_l < 0$: lepton and gap are in **opposite hemispheres**

$\eta_l > 0$: 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

$$f_{SD} = 50.0 \pm 9.3(\text{stat.}) \pm 5.2(\text{syst.})\%$$

Summary

- **Evidence for the observation of Single Diffraction at 7 TeV :**
  - single-diffractive events appear as a peak at small value of $E \pm p_z$, reflecting the 1/ξ behaviour of the diffractive cross section
  - single-diffractive events also appear as a peak in the zero-bin of the energy and multiplicity distributions of the forward calorimeter HF, reflecting the presence of a LRG over HF

- **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**

Backup slides

Dijet cross section

arXiv:1209.1805v1 [hep-ex]
submitted to PRD

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 $|\eta^{j1,j2}| < 4.4$.

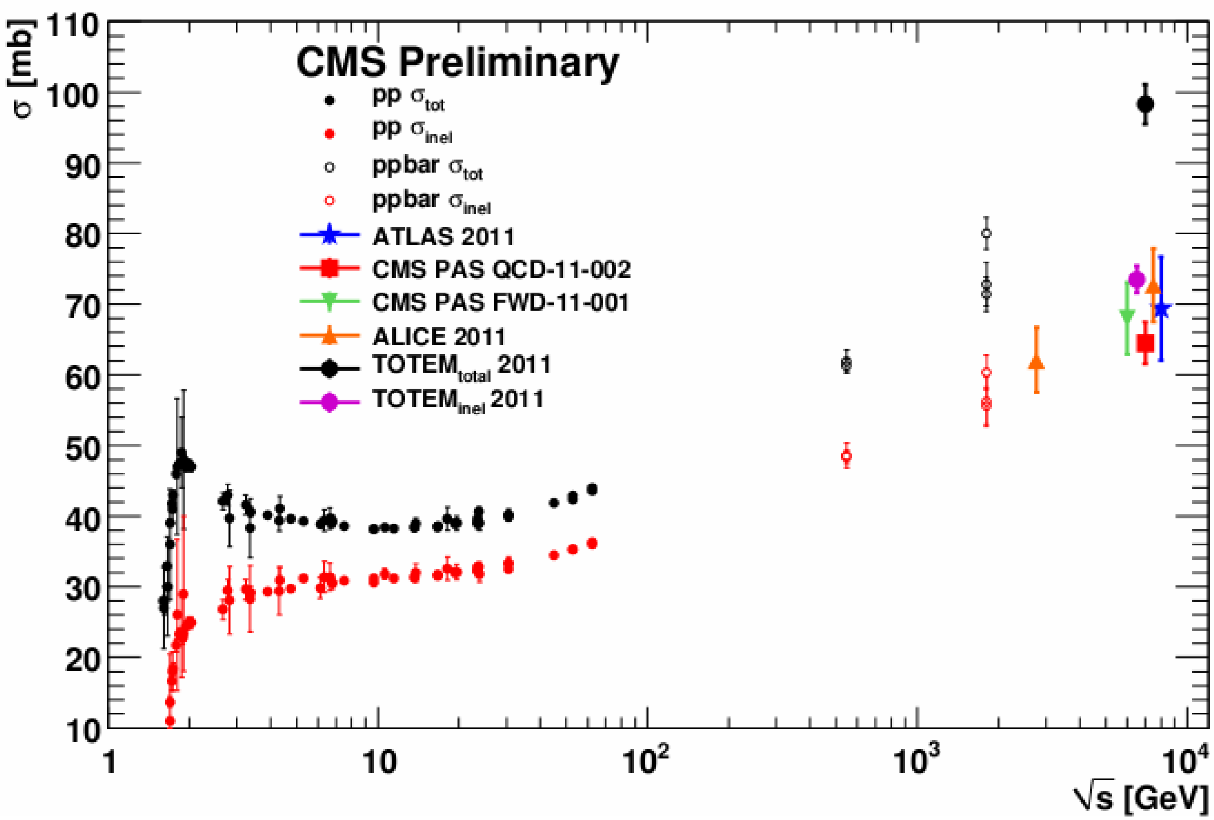
$\tilde{\xi}$ bin	$d\sigma_{jj}/d\tilde{\xi}$ (μb)
$0.0003 < \tilde{\xi} < 0.002$	$5.0 \pm 0.9(\text{stat.})^{+1.5}_{-1.3}(\text{syst.})$
$0.002 < \tilde{\xi} < 0.0045$	$8.2 \pm 0.9(\text{stat.})^{+2.2}_{-2.4}(\text{syst.})$
$0.0045 < \tilde{\xi} < 0.01$	$13.5 \pm 0.9(\text{stat.})^{+4.5}_{-3.1}(\text{syst.})$

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	$(+30; -26)\%$	$(+27; -29)\%$	$(+33; -23)\%$

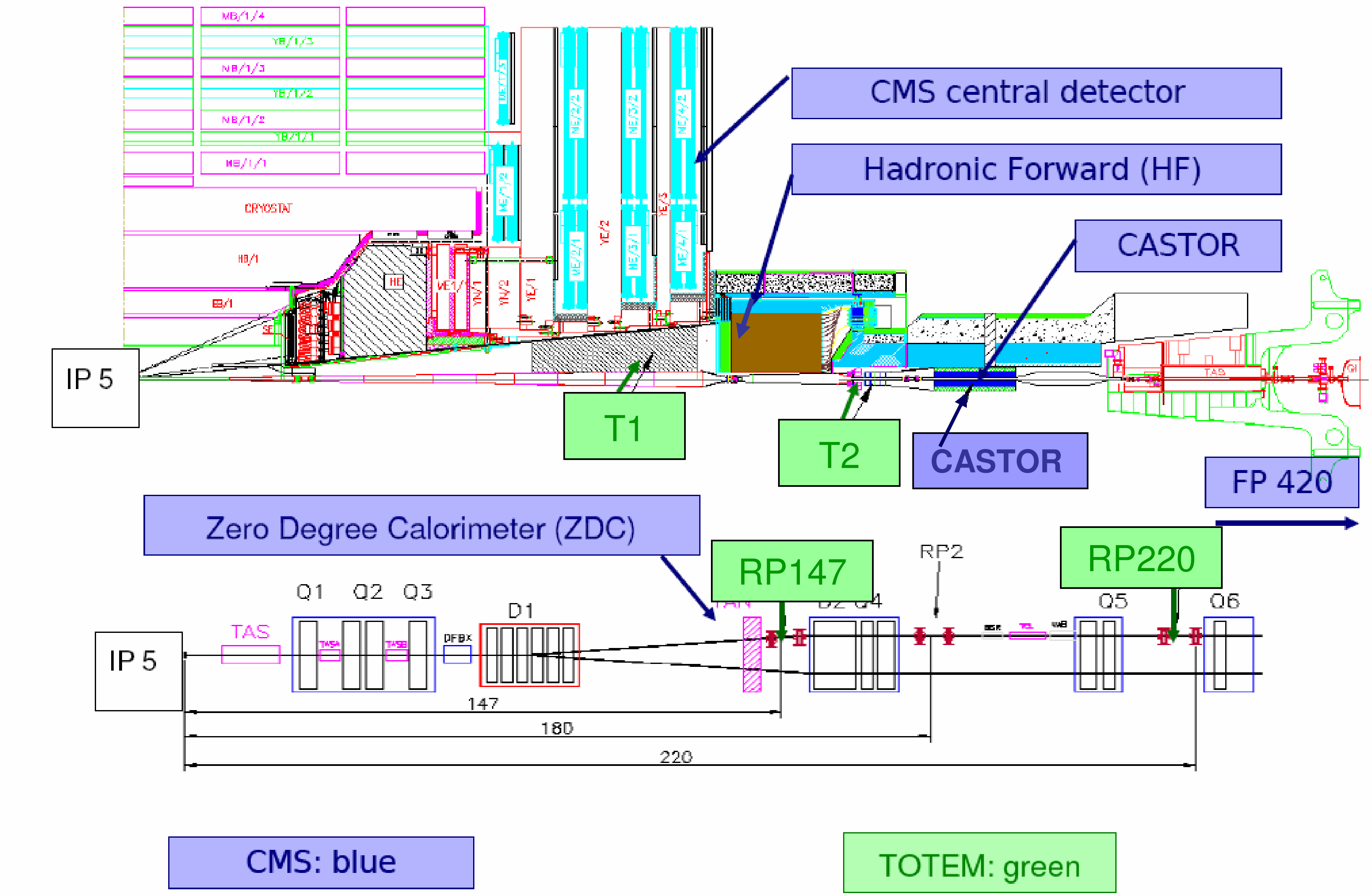
σ_{inel}

CMS PAS QCD-11-002

Total inelastic pp and ppbar cross section values



Forward detectors at IP5

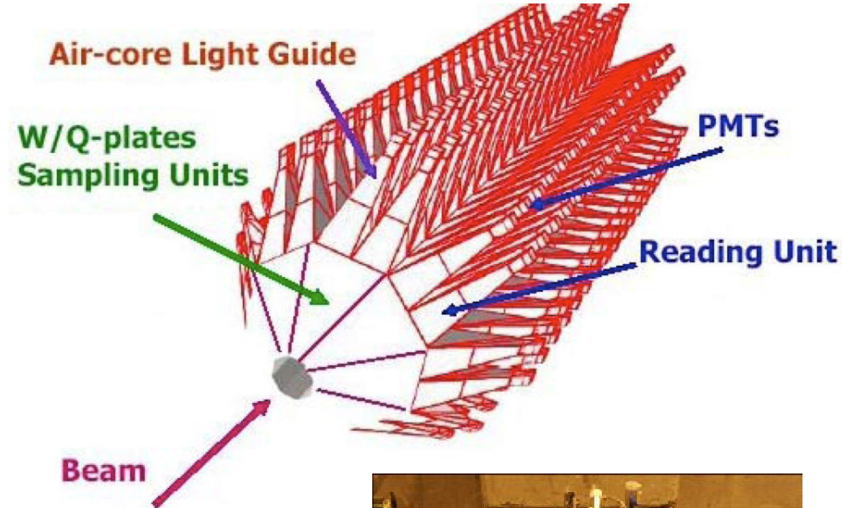


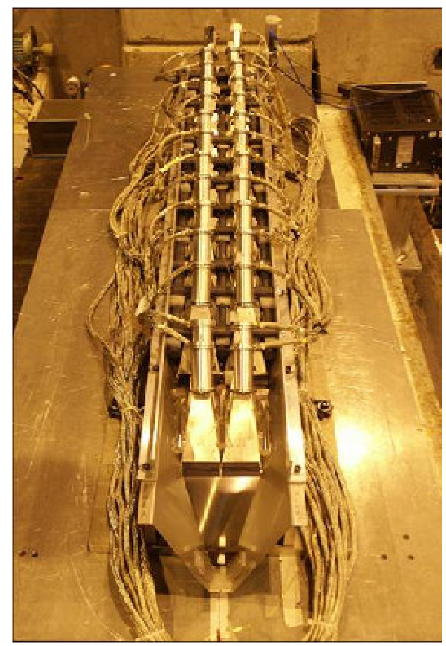
Hadron Forward calorimeter

- @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

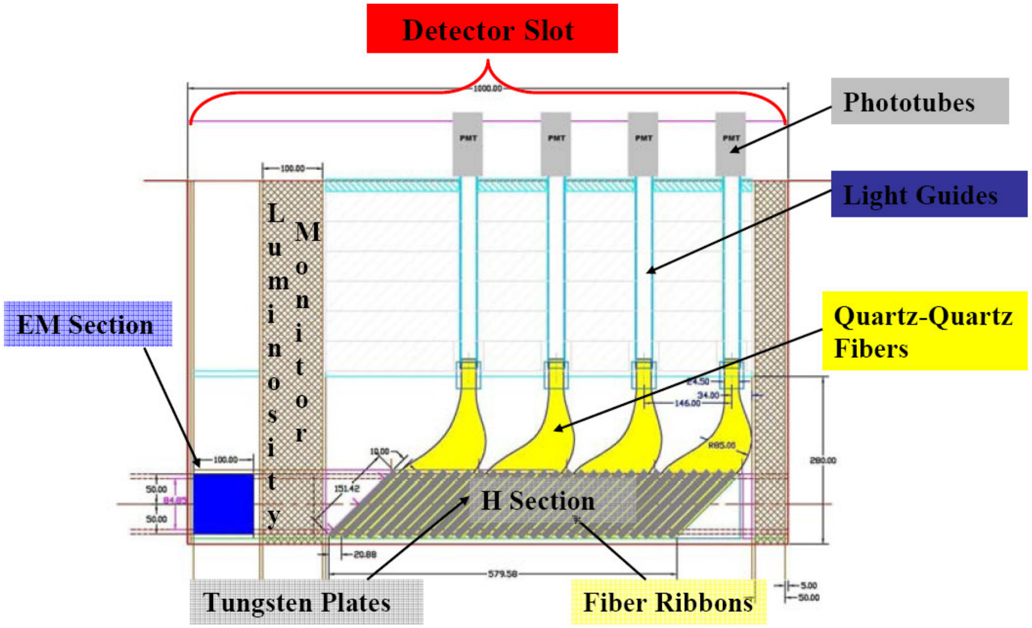
- rapidity coverage: $5.3 < |\eta| < 6.6$
  → enhances the hermiticity of CMS
- 14.37 m from the interaction point
- octogonal cylinder with inner radius 3.7 cm, outer radius 14 cm and total depth 10.5 λ_I
- signal collection through Cherenkov photons transmitted to PMTs through aircore lightguides
- 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

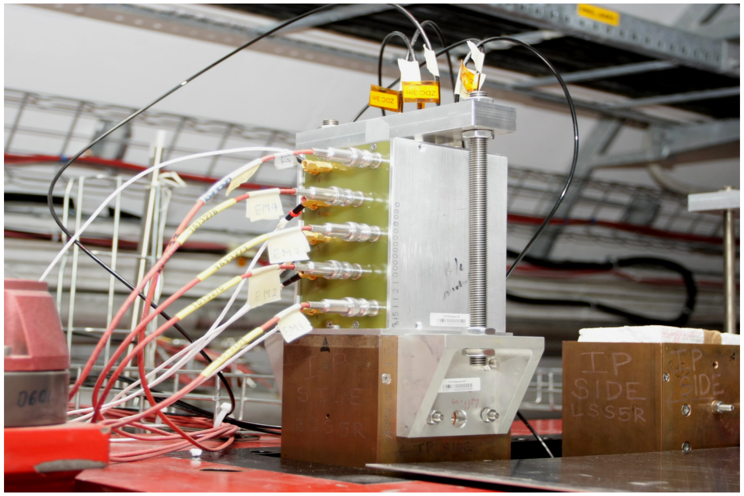




The Zero Degree Calorimeter

- 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 $\eta > 8.4$)

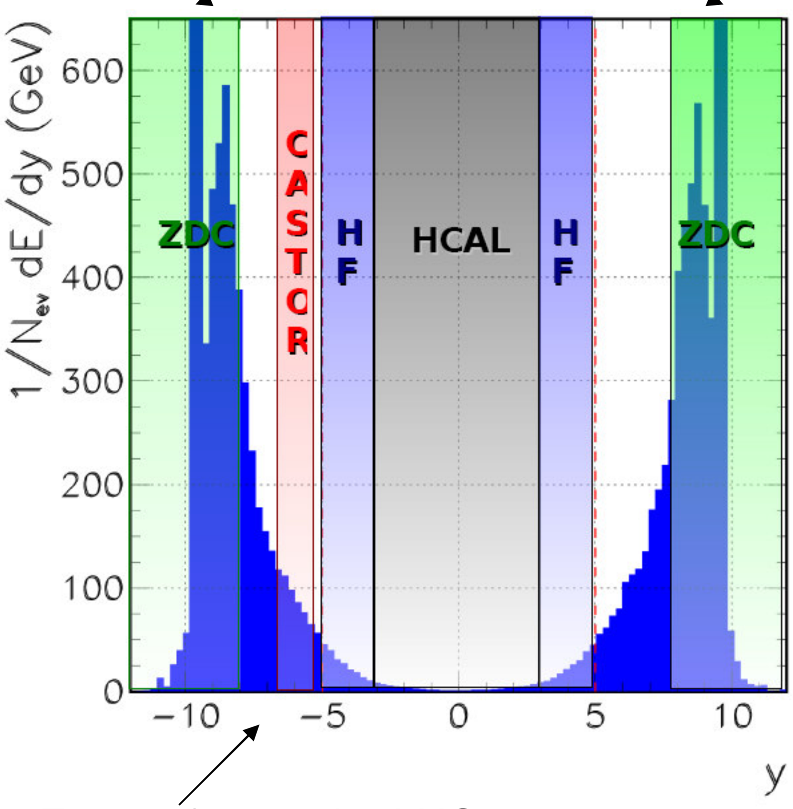




Rapidity coverage at CMS

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 (+ HPS)

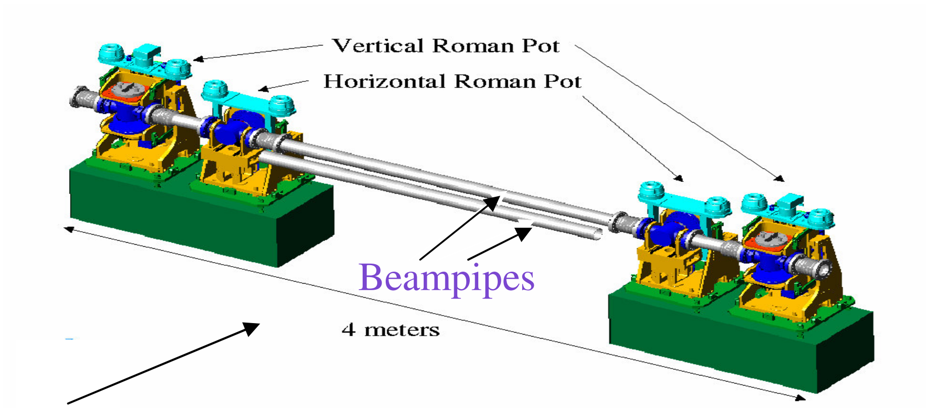
TOTEM:

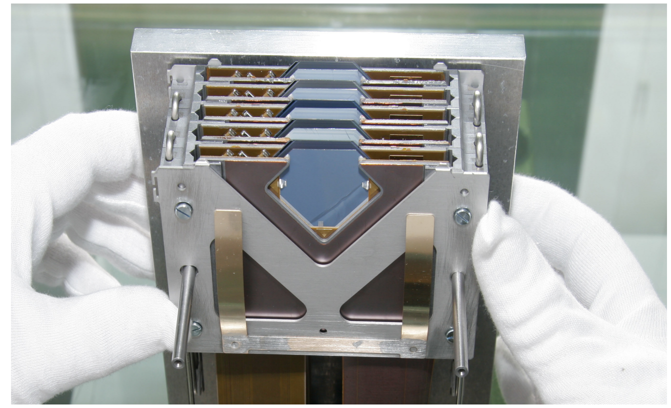
- An approved experiment at LHC for measuring σ_{tot} & $\sigma_{elastic}$, at same IP as CMS
- Expression of wish of CMS + TOTEM to carry out a joint physics program, with joint CMS+TOTEM data taking given to LHCC:
  "Prospects for diffraction and forward physics at the LHC"
  CERN LHCC 2006-039 G124, CMS note 2007-02, TOTEM note 06-5
- Collaboration started for common data taking and for writing a proposal for a joint upgrade in the forward region.

FP420 → HPS

- **FP420:** ATLAS+CMS R&D project to study the feasibility of installing high precision silicon tracking and fast timing detectors close to the beams at 420 m from the IPs:
  "The FP420 R&D Project: Higgs and New Physics with forward protons at the LHC"
  (arXiv:0806:0302 [hep-ex])
- Evolved in **HPS** (presently **HPS240**), a CMS proposal under review to become an official CMS project for the upgrade of the forward region

Proton taggers around IP5

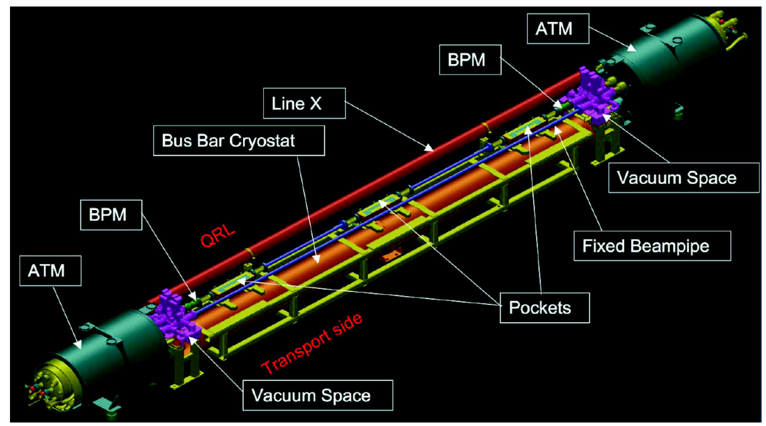




TOTEM uses Roman pot technique to approach the beam with their Si detectors

HPS420, because of location in cryogenic region of LHC, will use a movable beampipe

Extremely radiation hard novel technology:
3D silicon detectors
Cherenkov timing detectors with $\sigma_t \sim 10$ ps
to filter out events with protons from pile-up



ξ = fractional momentum loss of the incident proton

Acceptance:

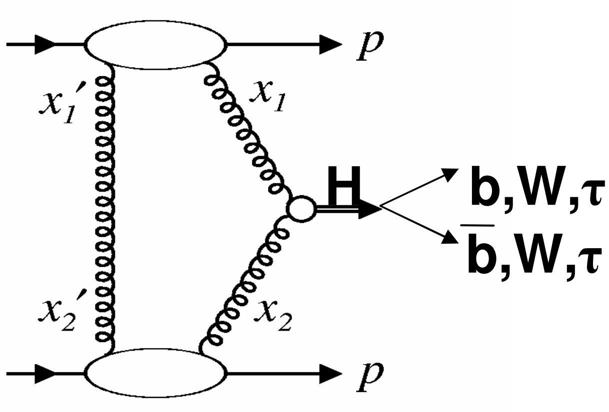
At nominal LHC beam optics (β^* = 0.5 m): **$0.02 < \xi < 0.2$** with **TOTEM**

$0.002 < \xi < 0.02$ with **HPS420**

Physics potential of forward p tagging

For many physics processes, tagging the outgoing scattered proton(s) will be the only mean of detection at high luminosity due to pile-up

- **Central exclusive production pp → pXp**: possible Higgs discovery channel in certain region in MSSM !



Selection rules: central system is $J^{PC} = 0^{++}$ (to good approx)

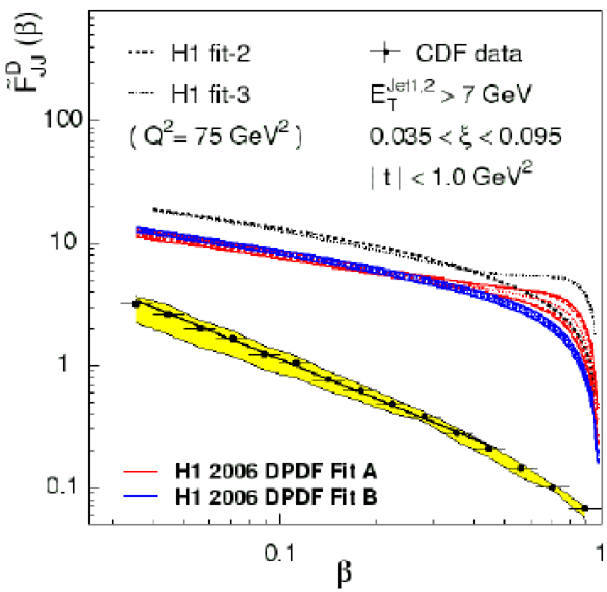
Excellent mass resolution (~GeV) from the protons, independent of decay products of the central system

For light (~120 GeV) Higgs:
Proton tagging improves S/B for SM Higgs dramatically
CEP may be the discovery channel in certain regions in MSSM

CP quantum numbers and CP violation in Higgs sector directly measurable from azimuthal asymmetry of the protons

- **QCD program on hard diffraction at high luminosities**: dPDFs, GPDs, S^2, …
- **γγ processes**: similar to diffraction but smaller |t| and higher central system energies
  → HPS420 indispensable for precision measurements at high lumi: anomalous gauge boson couplings, SUSY slepton and chargino, …

Factorization breaking at Tevatron 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!**