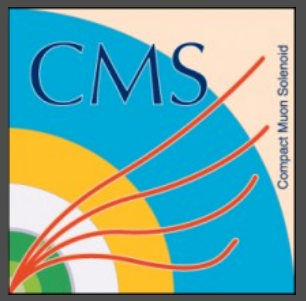


Measurements of diffraction in p-p collisions in CMS

Robert Ciesielski *on behalf of the CMS collaboration*

(The Rockefeller University)

DIS2013, XXI International Workshop on Deep-Inelastic Scattering and Related Subjects, 22-26 April 2013, Marseille, France

Outline

- **Measurement of soft diffractive SD and DD cross sections and forward rapidity gap cross section at 7 TeV**

  CMS PAS FSQ-12-005

  NEW!

- **Evidence for hard diffractive di-jet prodiction at 7 TeV**

  CMS-FWD-10-004, PRD 87 (2013) 012006

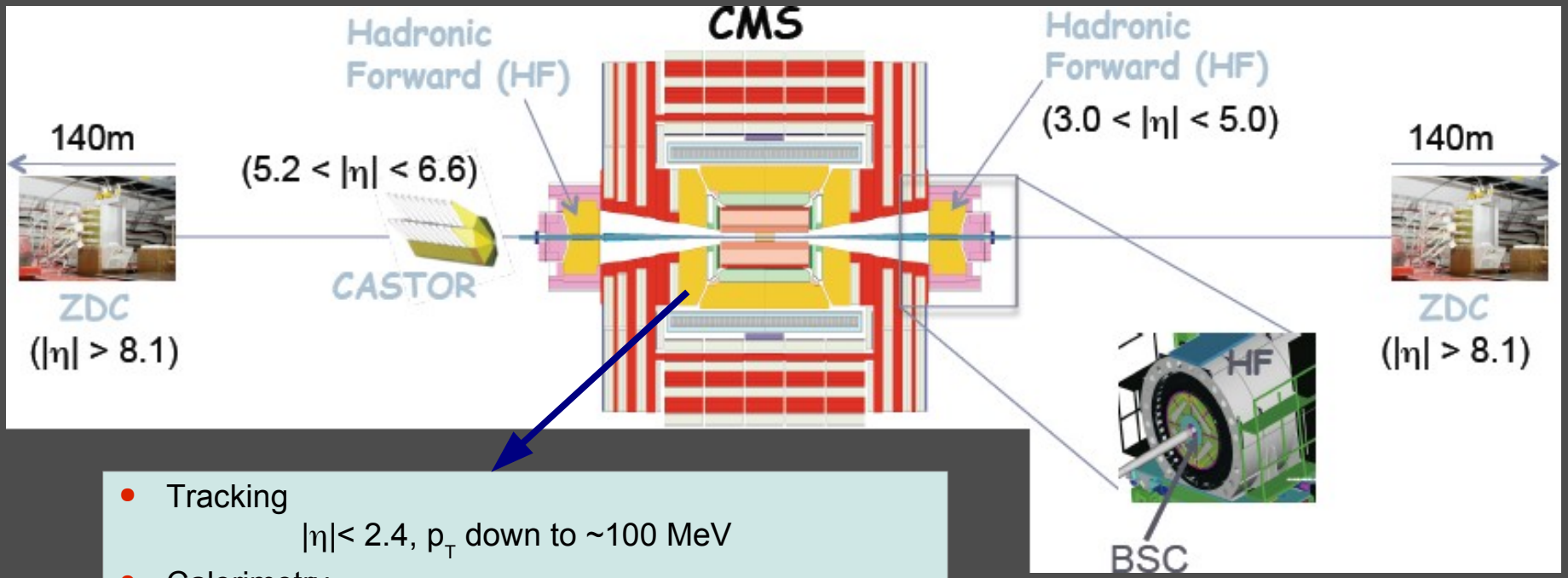
  arXiv:1209.1805

- **CMS+TOTEM event displays of high-pT jets with two leading protons at 8 TeV**

  CMS-DP-2013-004,CMS-DP-2013-006

  NEW!

CMS detector



- Tracking
  $|\eta| < 2.4$, p_T down to ~100 MeV
- Calorimetry
  Electromagnetic calorimeter $|\eta| < 3.0$
  - Hadronic calorimeter (HB,HE,HF) $|\eta| < 5.0$

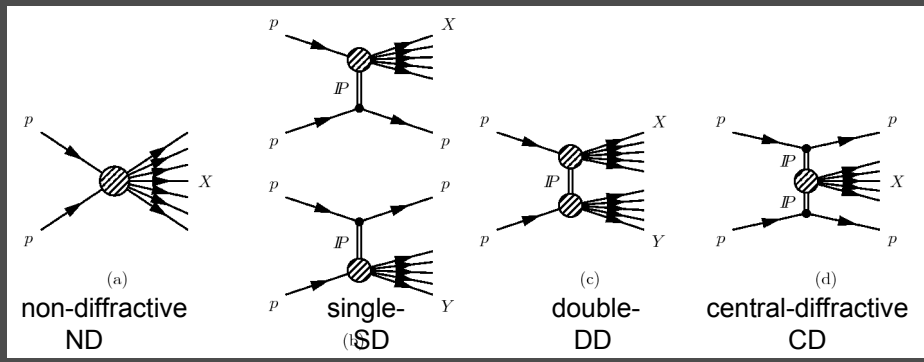
- Forward detectors:
  - HF, hadron forward calorimeter (10m from IP) $3 < |\eta| < 5$
  - BSC, beam scintillator counters (in front of HF) $3.2 < |\eta| < 4.7$
  - CASTOR calorimeter (one side only) $-6.6 < \eta < -5.2$
  - FSC (Forward Shower Counters) $6 < |\eta| < 8$
  - ZDC (zero degree calorimeter) $|\eta| > 8.1$

Soft diffractive cross sections

First CMS measurement of inclusive diffractive cross sections.

Using Large Rapidity Gap (LRG) signatures.

SD and DD separated with CASTOR ($-6.6 < \eta < -5.2$).



- Low-PU 2010 data at $\sqrt{s}$= 7 TeV.
- Minimum-Bias trigger (hit in either of BSCs).
- Based on Particle Flow objects (tracking+calorimetry).
- At least 2 PF objects in the BSC acceptance.
- No vertex requirement (to retain M_X<100 GeV).

Minimum-Bias sample in the central CMS detector ($-4.7<\eta<4.7$).

MC simulations:

- **PYTHIA8-4C**: diffraction with Schuler&Sjostrand model from PYTHIA6. Tune 4C - additional scaling of SD and DD downwards by 10% and 12%.
- **PYTHIA8-MBR (*)**: diffraction with MBR model. Pomeron intercept ε=0.08 and additional scaling of DD downwards by 15%.

CMS PAS FSQ-12-005

* MBR (Minimum-Bias Rockefeller) – implemented in Pythia8.165. Regge-based model with renormalized flux, developed for and successfully tested at CDF. Hadronization model tuned to describe diffractive masses at lower energies. More details in Dino's talk on Tuesday and in 'Recent developments on diffraction in Pythia8' talk at MPI2012@CERN.

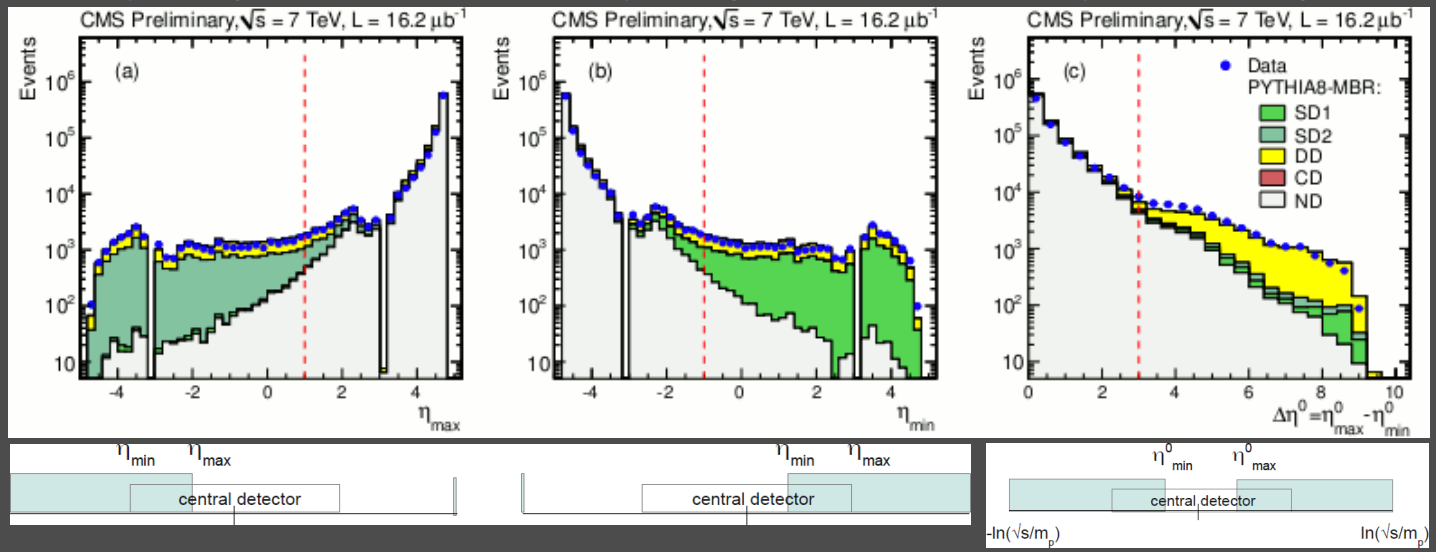
Soft diffractive cross sections

Experimental topologies of diffractive events with LRG

SD1 type – gap on +side

SD2 type – gap on -side

DD type – cental gap



$\eta_{max}(\eta_{min})$ - highest (lowest) η of the particle reconstructed in the cental detector.

$\eta^0_{max}(\eta^0_{min})$ - closest-to-zero positive (negative) η of the particle in the central detector. $\Delta\eta^0 = \eta^0_{max} - \eta^0_{min}$.

All types - measure forward-rapidity-gap cross section (and compare to ATLAS)

No separation of SD and low-mass DD events.

SD2 type, η_{min}>-1 selection + CASTOR (to separate SD/DD events) - measure SD and DD cross sections

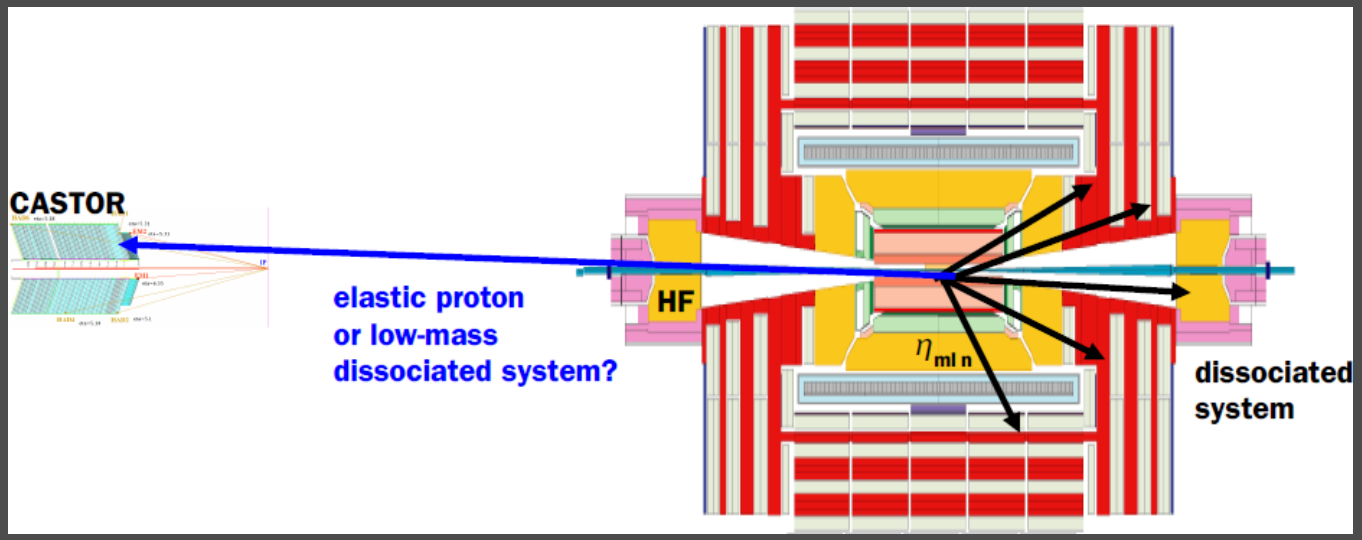
CASTOR only on -side.

DD type, $\Delta\eta^0$ >3 selection - measure DD cross section

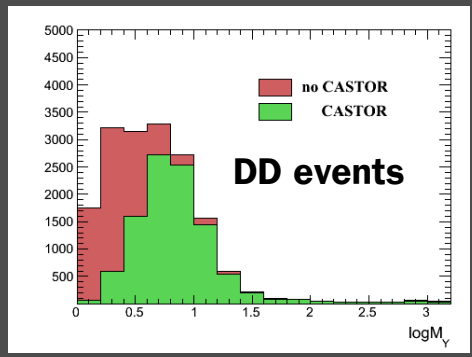
Soft diffractive cross sections

Separation of SD/DD events with CASTOR

SD2-type + η_{min}>-1 selection - SD events and DD events with low-mass hadronic system escaping detection in the central detector
→ CASTOR tag to select the sample enhanced in DD events and calculate SD and DD cross sections.



CASTOR calorimeter – layers of tungsten absorber and quartz plates.
12 longitudinal modules and 16 azimuthal sectors.
Sensitivity: $0.5 < \log_{10}(M_Y/\mathrm{GeV}) < 1.1$ $(3.2<M_Y<12$ GeV).

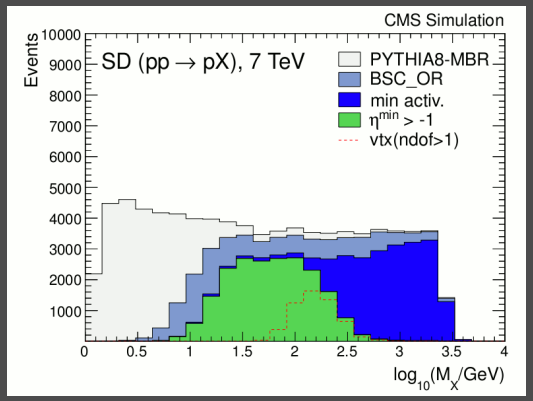


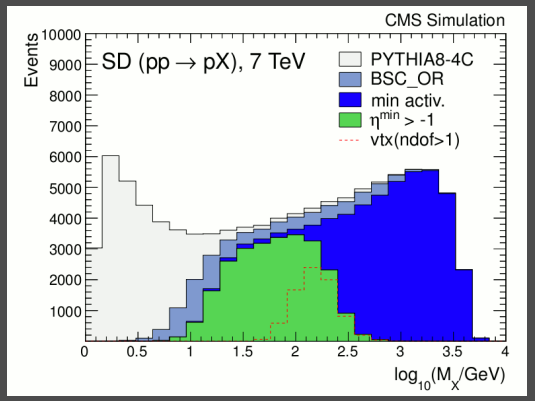
CASTOR tag – signal above threshold (1.48 GeV) in at least one of 16 sectors (summed over the first 5 modules).

Soft diffractive cross sections

Kinematic phase space (diffractive-mass range) after all selections.

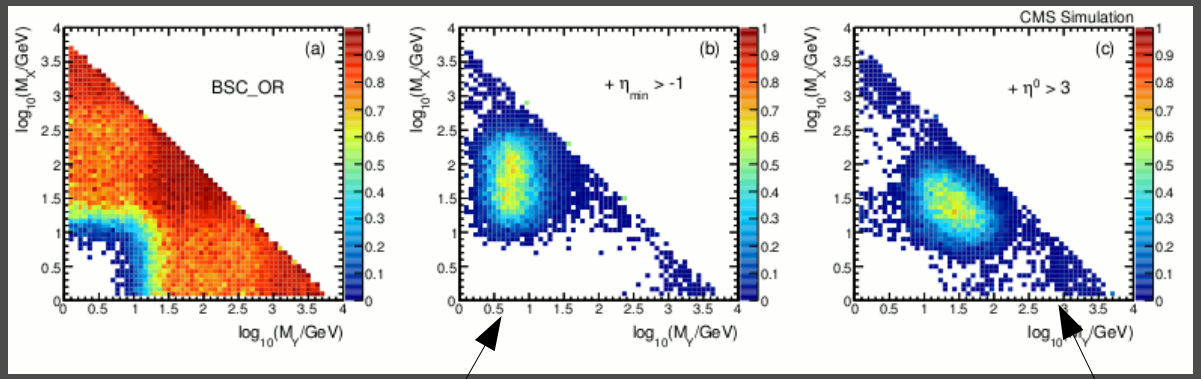
Generator level SD process →





SD2-type events with the η_{min}>-1 selection (forward gap) and no CASTOR tag:

$12 < M_X < 394$ GeV



← Generator level DD process

SD2-type events with the η_{min}> -1 selection (forward gap) and a CASTOR tag: $12 < M_X < 394$ GeV, $3.2 < M_Y < 12$ GeV

DD-type events with the $\Delta\eta^0 > 3$ selection (central gap): $\Delta\eta > 3$, $M_X > 10$ GeV, $M_Y > 10$ GeV

Two complementary measurements of DD.

CMS PAS FSQ-12-005

Soft diffractive cross sections

Detector-level distribution of fractional proton momentum loss, ζ.
CASTOR tag performance.

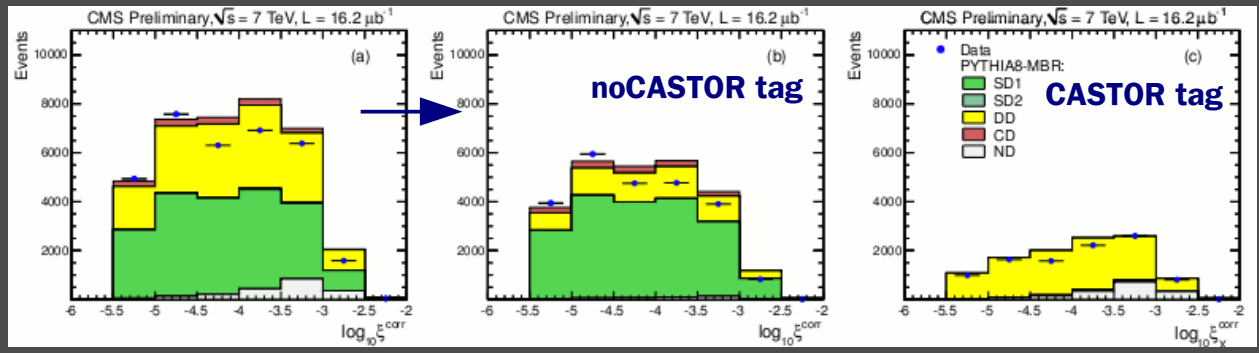
SD2 with an $\eta_{min} > -1$ selection.

SD and DD cross sections measured as a function of ζ.

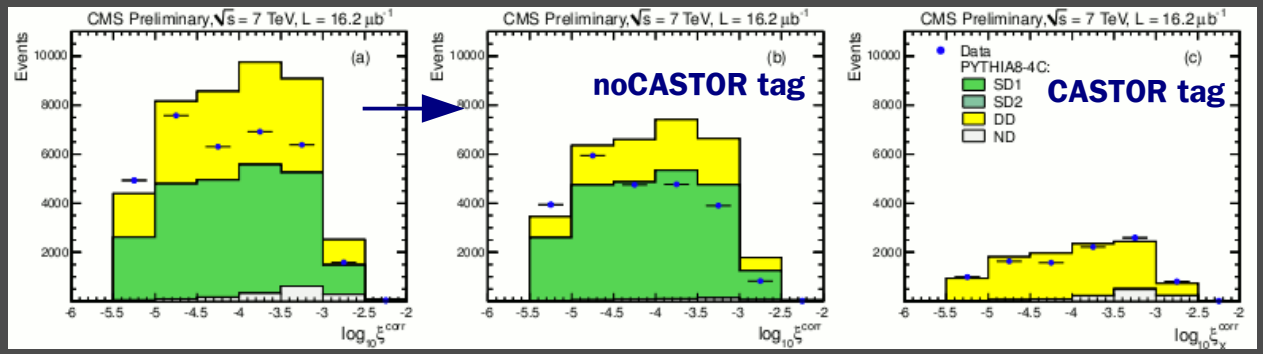
$$\xi = \frac{\sum(E^i + p_z^i)}{\sqrt{s}} \sim \frac{M_X^2}{s}$$

ζ reconstructed from PF objects, corrected for particles lost in the beam hole or below PF thresholds (MC-based ζ-dependent correction).

PYTHIA8-MBR



PYTHIA8-4C



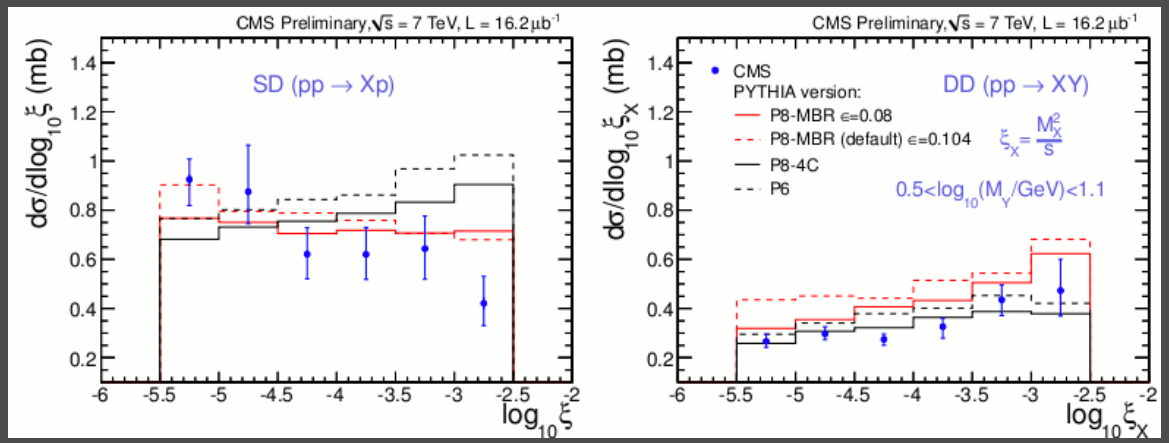
The DD contribution to the no-CASTOR tag sample reduced to ~20% (dominant background).
DD simulation validated with the CASTOR tag sample.

PYTHIA8-MBR gives a better description of the data and is used to extract cross section.
PYTHIA8-4C used for systematic checks (hadronization, diffraction model).

CMS PAS FSQ-12-005

Soft diffractive cross sections

SD and DD cross sections (bin-by-bin correction)



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

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

MC-based background subtraction (see previous slide).
acc – acceptance (pileup correction included, ~7%).
Hadron level – generated masses.

Error bars dominated by systematic uncertainties (HF energy scale and hadronization+diffraction model uncertainties dominate).

Results compared to predictions of theoretical models used in PYTHIA8-MBR, PYTHIA8-4C and PYTHIA6:

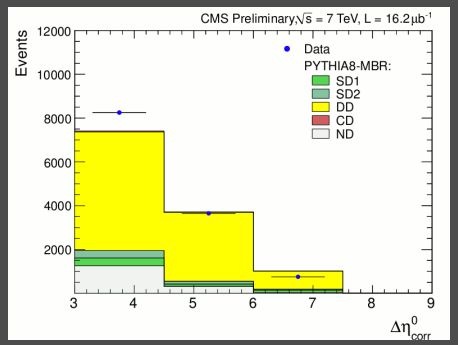
- PYTHIA8 MBR shown for two values of the Pomeron trajectory (α(t) = 1+ε+α't), ε=0.08 and ε=0.104. Both describe the measured SD cross section well. The DD data favour the smaller value of ε.
- The Schuler&Sjostrand model used in PYTHIA8-4C and PYTHIA6 describes the DD cross section, but fails to describe the falling behavior of the SD data.

The SD cross section integrated over $-5.5 < \log_{10}\xi < -2.5$:
Multiplied by 2 to account for both pp → pX and pp → Xp processes.

$$\sigma^{SD}_{vis} = 4.27 \pm 0.04\ (stat.)\ ^{+0.65}_{-0.58}\ (syst.)\ mb$$

$12 < M_X < 394$ GeV

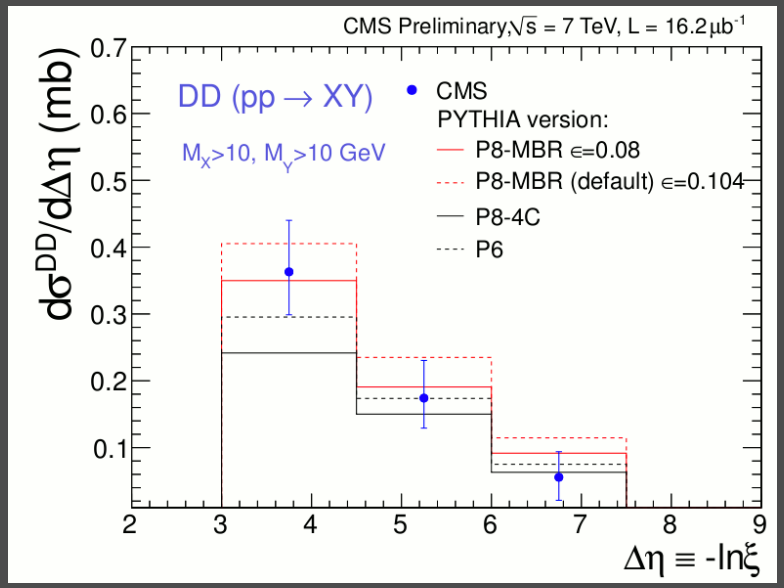
Soft diffractive cross sections



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

MC-based background subtraction, ND dominant.
acc – acceptance (pileup correction included, extrapolation from $\Delta\eta^0 > 3$ to $\Delta\eta > 3$) .
Hadron level – generated masses, $\Delta\eta = -\log(M_X^2 M_Y^2/ss_0)$.

DD cross section with central LRG (bin-by-bin correction)



Error bars dominated by systematic uncertainties (HF energy scale, and hadronization+diffraction model uncertainties dominate).

Results compared to predictions of theoretical models used in PYTHIA8-MBR, PYTHIA8-4C and PYTHIA6. The predictions are in agreements with the data.

The DD cross section integrated in the region $\Delta\eta > 3$, M_X>10 GeV, M_Y>10 GeV:

$$\sigma^{DD}_{vis} = 0.93 \pm 0.01\ (stat.)\ ^{+0.26}_{-0.22}\ (syst.)\ mb$$

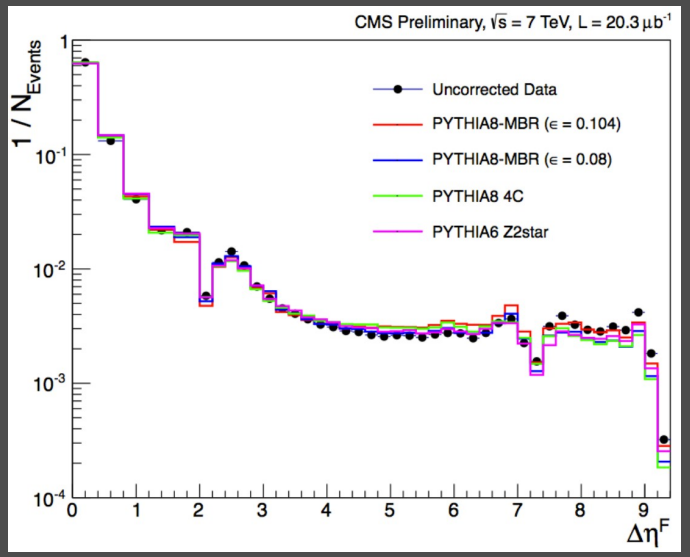
Forward rapidity gap cross section

Forward rapidity gap defined as $\Delta\eta^F = \mathrm{Max}(4.7-\eta_{max}, 4.7+\eta_{min})$.

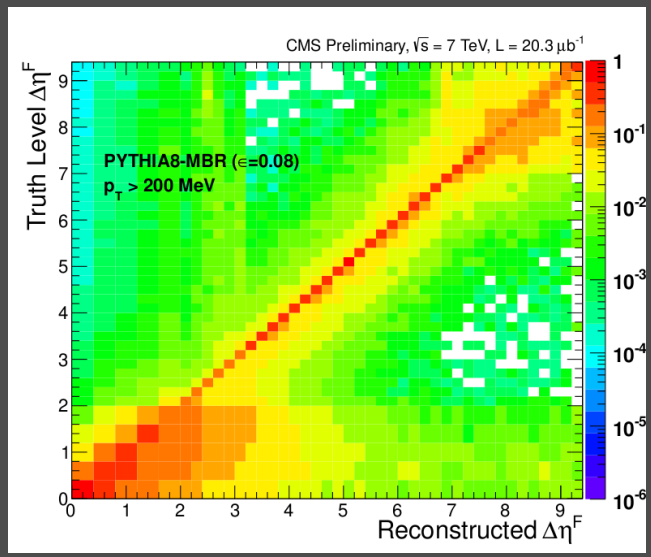
$$\frac{d\sigma(\Delta\eta^F)}{d\Delta\eta^F} = \frac{A(\Delta\eta^F)}{\Delta\eta_{binwidth}} \frac{N(\Delta\eta^F) - N_{BG}(\Delta\eta^F)}{\varepsilon(\Delta\eta^F) \times \mathcal{L}}$$

N – number of Minimum-Bias events.
N_{BG} – number of background events (beam-gas, estimated from unpaired bunches, < 1%).
A – correction factor for the migrations between bins.
ε - trigger efficiency,

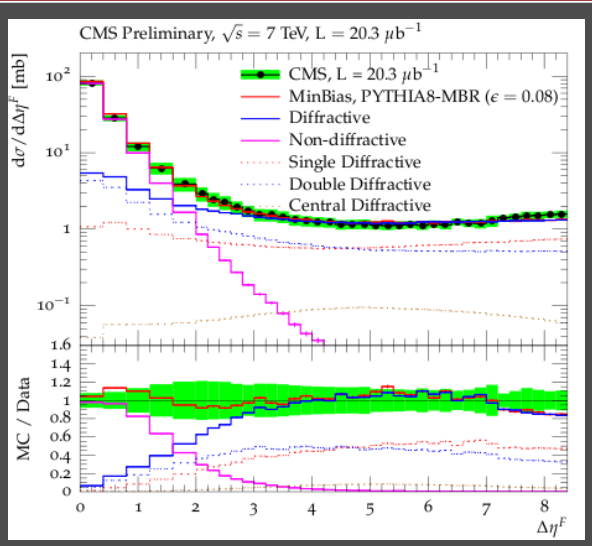
Bayesian unfolding.
Hadron level: stable FS particles with p_T>200 MeV, |η|<4.7.
Migration matrix from PYTHIA8-MBR.
Cross section limited to $\Delta\eta^F$<8.4 (small trigger efficiency uncertainty) Different run than for SD/DD cross sections.

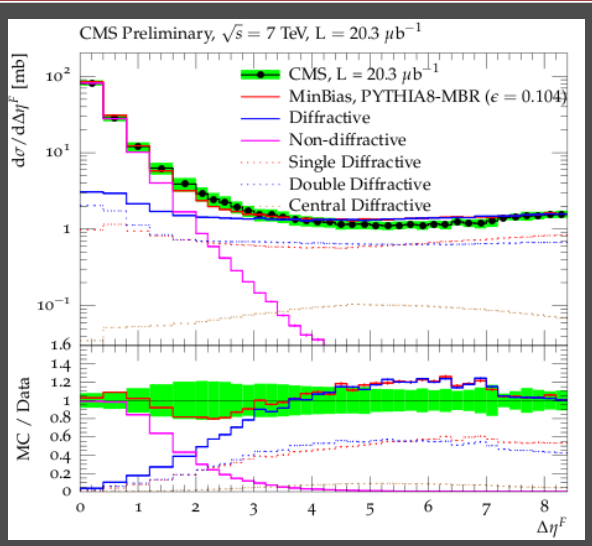


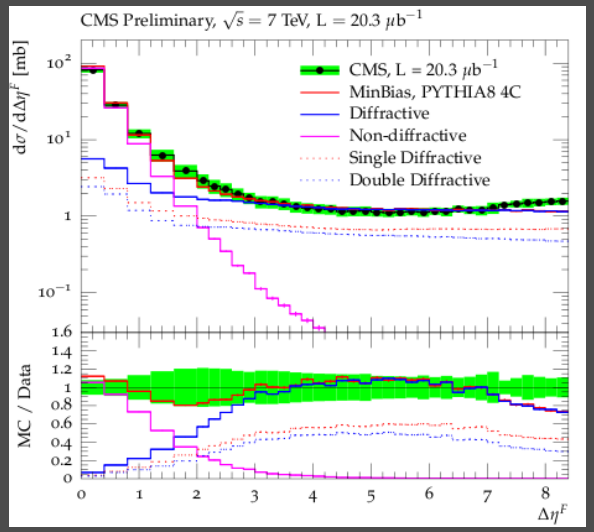
Detector-level $\Delta\eta^F$ distribution.

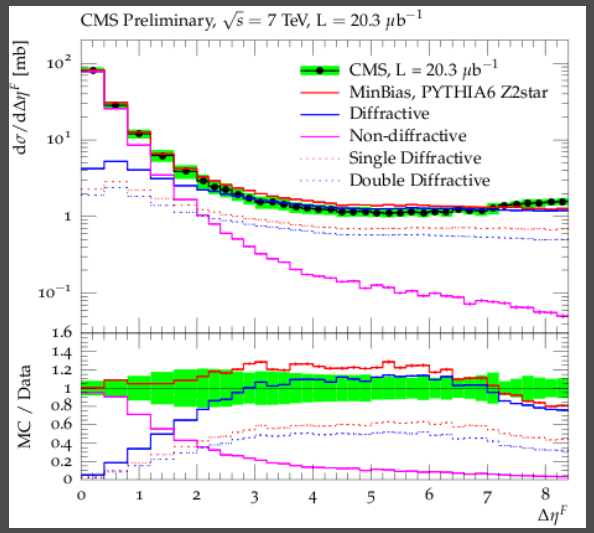


Forward-rapidity gap cross section









Hadron-level comparison of the forward rapidity gap cross section to predictions of PYTHIA8-MBR (ε=0.08 and ε=0.104), PYTHIA8-4C and PYTHIA6-Z2* simulations.

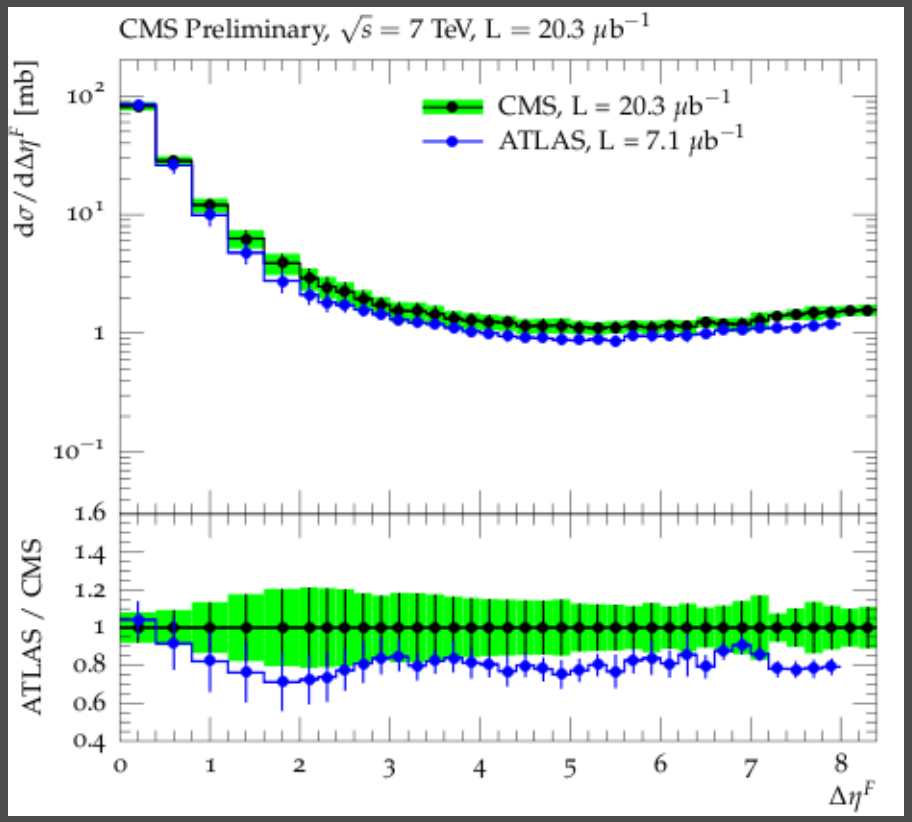
Exponentially falling ND contribution dominant for $\Delta\eta^F$<3, above this value cross section weakly changing with $\Delta\eta^F$:

Sensitivity to model dependence.
PYTHIA8-MBR (ε=0.08) – best description within uncertainties.

CMS PAS FSQ-12-005

Forward-rapidity gap cross section

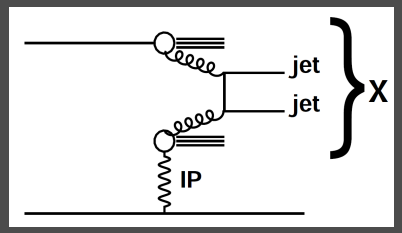
Comparison to the ATLAS measurement (EPJ C72 (2012) 1926).



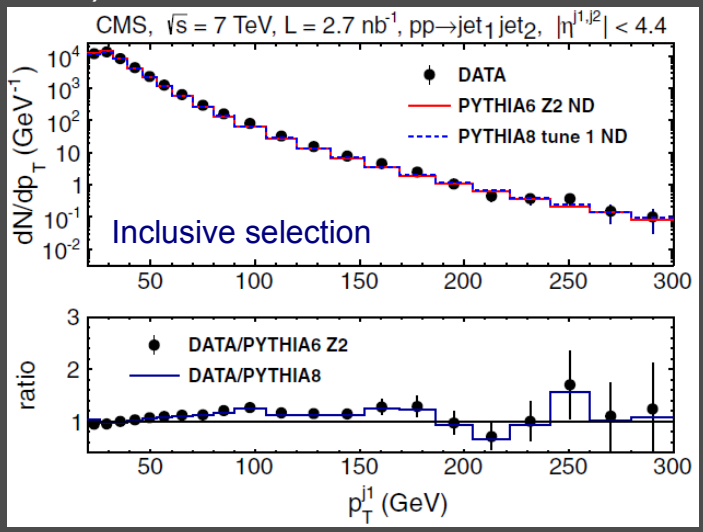
Different hadron level definition: |η|<4.7 (CMS) vs |η|<4.9 (ATLAS) – up to 5% effect.
Different MC sample used for unfolding – ~10% effect.
Agreement with ATLAS within uncertainties.
CMS extends the ATLAS measurement by 0.4 unit of gap size.

CMS PAS FSQ-12-005

Diffractive dijets



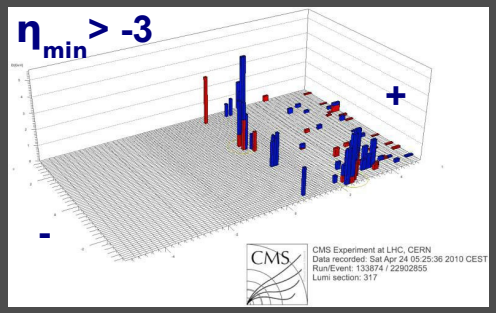
Measure hard diffractive process and compare to pQCD-based theory predictions (gap-survival probability at 7 TeV).



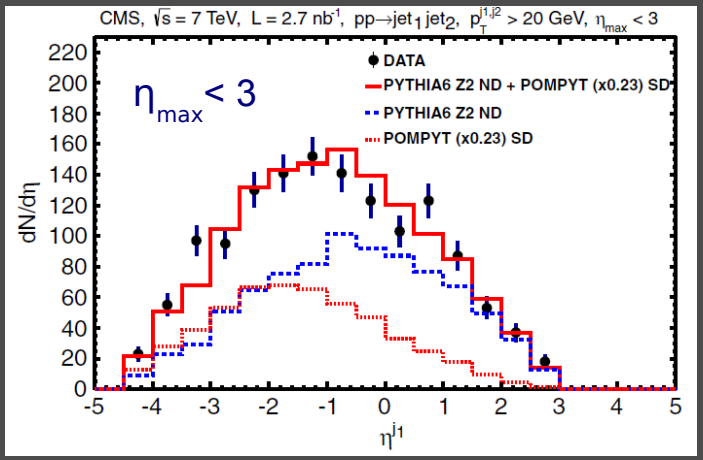
- Analysis based on 2010 data (2.7 nb^{-1}) with negligible PileUp
- Single- jet trigger, anti-kt 0.5, vertex.
- At least 2 jets with p_T>20 GeV and $|\eta|$<4.4
- Based on Particle Flow objects (tracking+calorimetry)

Large Rapidity Gap (LRG): require most forward (or backward) PF object in the event to satisfy $\eta_{max} < 3$ (or $\eta_{min} > -3$).

Corresponds to no individual energy deposit above 4 GeV in HF+ (or HF-). Rapidity gap of 1.9 units in the central CMS detector.



LRG data described by a combination of diffractive (POMPYT) and non-diffractive (PYTHIA6 Z2) samples.
relative fraction from the fit to the data



CMS-FWD-10-004, PRD 87 (2013) 012006

Di-jet cross section

Inclusive di-jet cross section extracted in 3 bins of $\tilde{\xi}$.

$$\frac{d\sigma_{jj}}{d\tilde{\xi}} = \frac{N^i_{jj}}{L \cdot \epsilon \cdot A^i \cdot \Delta\tilde{\xi}^i}$$

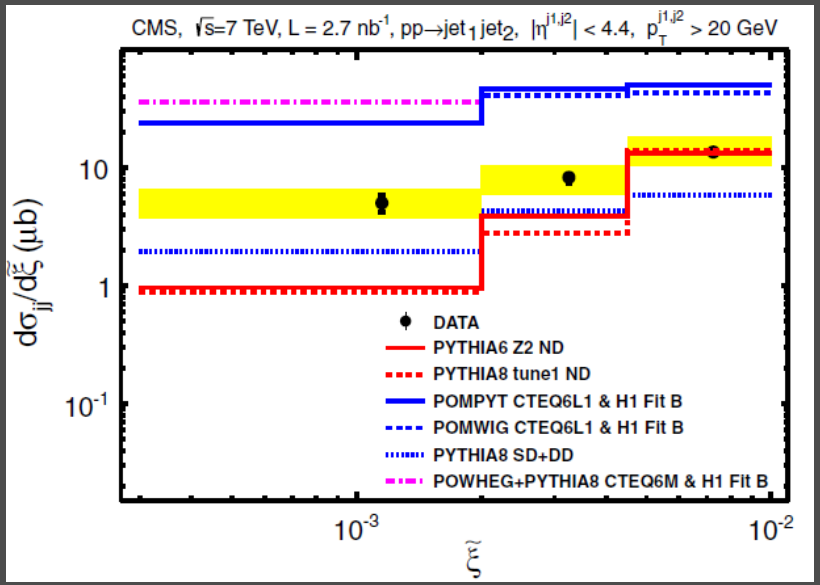
For single-diffractive events $\tilde{\xi}$ approximates proton fractional momentum loss.

$$\tilde{\xi}^{\pm} = \frac{\sum (E^i \pm p^i_z)}{\sqrt{s}} \simeq \frac{M^2_X}{s}$$

$\tilde{\xi}$ reconstructed from PF objects.
$\tilde{\xi}$+ ($\tilde{\xi}$-) corresponds to the gap on positive (negative) side.

Excess of events in low-$\tilde{\xi}$ region wrt non-diffractive PYTHIA6 and PYTHIA8 MC.

POMPYT and POMWIG (LO) diffractive MCs and NLO calculations from POMWEG, using diffractive PDFs, are a factor ~5 above the data in the lowest-$\tilde{\xi}$ bin.



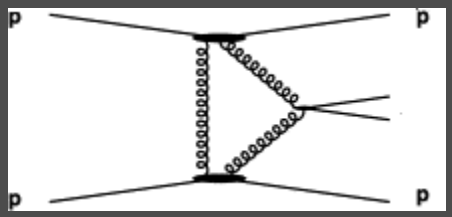
Low-$\tilde{\xi}$ region predominantly diffractive

Data/MC suppression factor is: 0.21 ±0.07 (LO MC)
0.14 ±0.05 (NLO MC).
After proton-dissociation correction, the ratio can be interpreted in terms of rapidity-gap survival probability of 0.12 ±0.05 (LO MC) and 0.08 ±0.04 (NLO MC).

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

CMS-FWD-10-004, PRD 87 (2013) 012006

CMS+TOTEM events with high-pT jets and two leading protons



Low-PU 90m β* runs with common TOTEM-CMS trigger.

Separate data taking with bidirectional exchange of trigger information
(TOTEM RP and T2 triggers to CMS, CMS combined di-jet and lepton/gamma trigger to TOTEM).

Offline event synchronisation with orbit & bunch number matching.

Data sample recorded with 'L1_DoubleJet20' trigger (CMS).

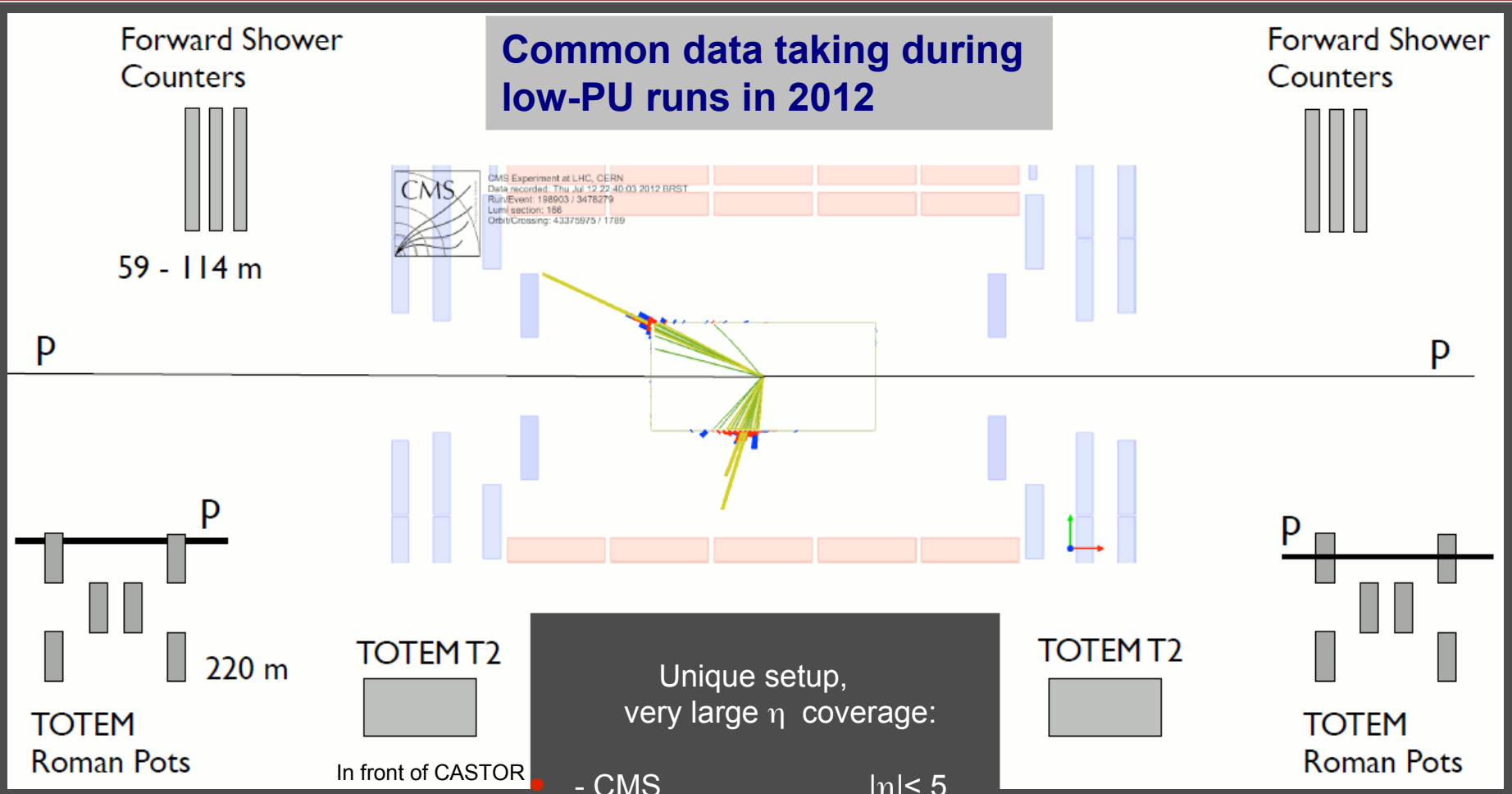
Event selection required at least two jets with p_T>20 GeV (anti-k_T, R=0.5 jets)

Forward Shower Counters (FSC) empty, 6<|η|<8.

Reconstructed proton tracks (TOTEM Roman Pots) on both sides of IP (non-elastic)

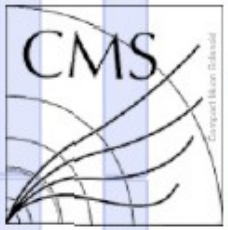
CMS-DP-2013-004,CMS-DP-2013-006

CMS+TOTEM detectors

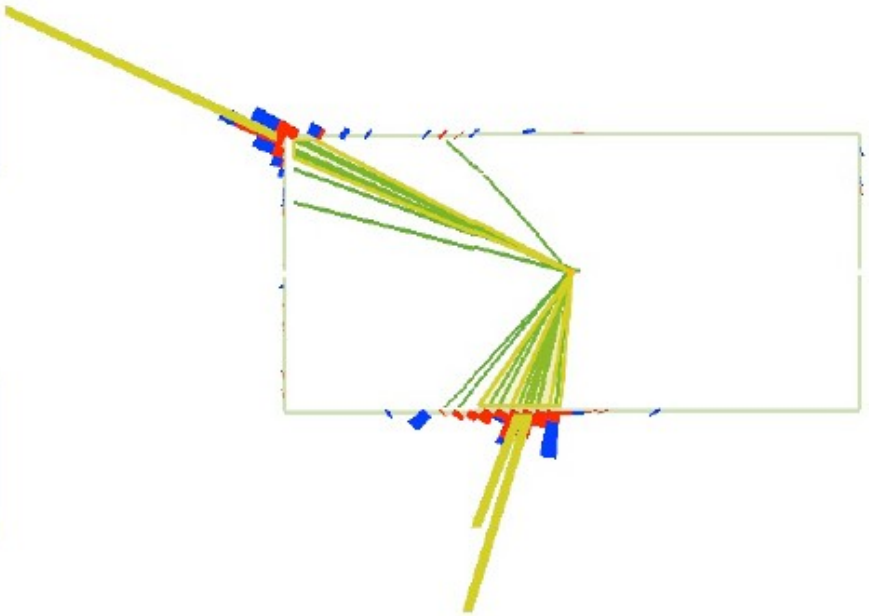


CMS-DP-2013-004,CMS-DP-2013-006

Run 198903 Event 3478279

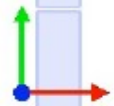


CMS Experiment at LHC, CERN
Data recorded: Thu Jul 12 22:40:03 2012 BRST
Run/Event: 198903 / 3478279
Lumi section: 166
Orbit/Crossing: 43375975 / 1789



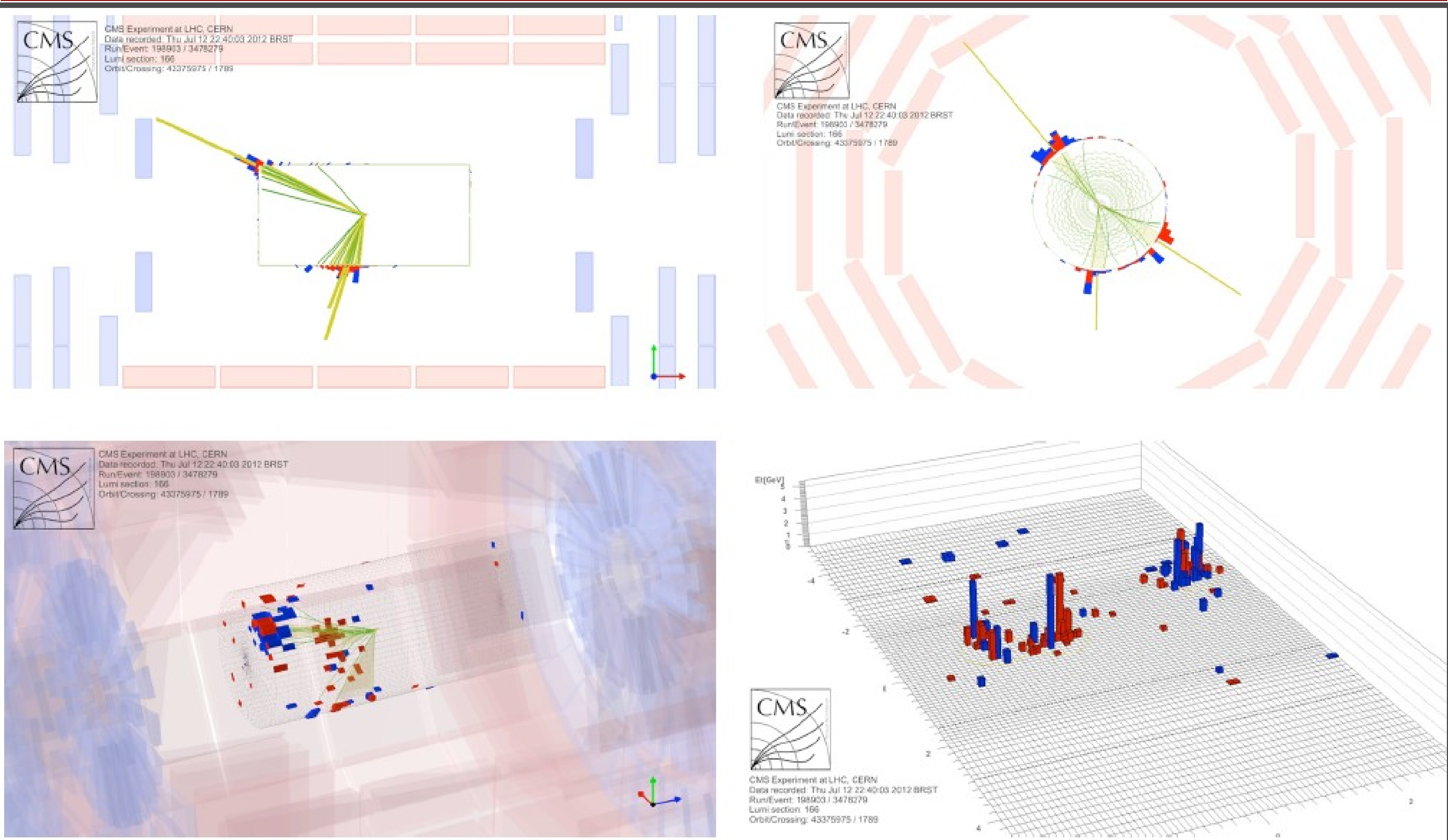
Leading three jets E_T = 65, 45, 27 GeV
proton $\Delta p/p$ = -0.01 (z+)
proton $\Delta p/p$ = -0.1 (z-)
M(pp, TOTEM) = 244 GeV
M(CMS) = 219 GeV
$\Sigma\, p_T$ (CMS) = 3.4 GeV
FSC empty in both sides

ECAL/HCAL E_T > 200 MeV
Track p_T > 1 GeV

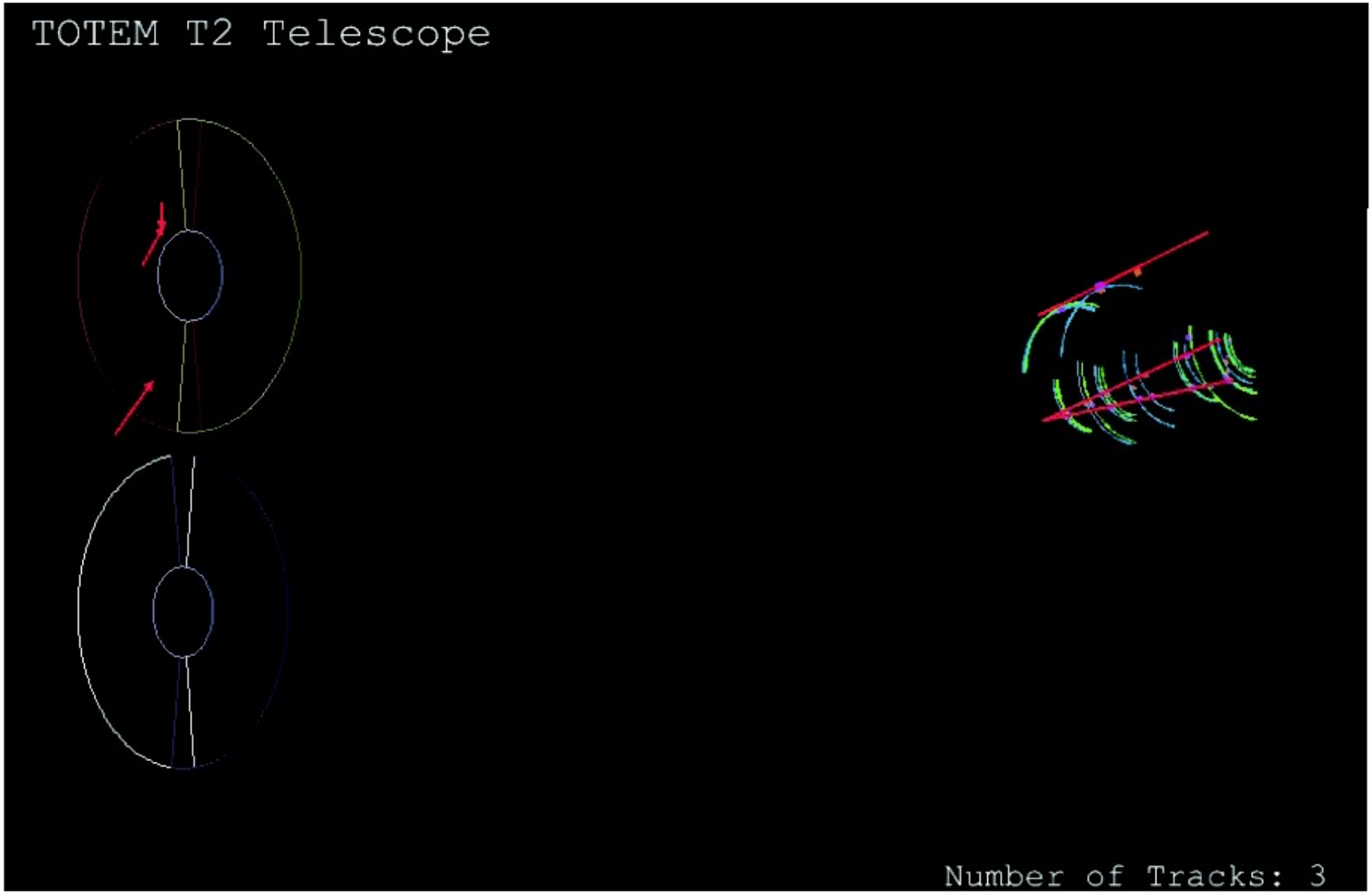


Clean dijet event in otherwise empty detector.

Run 198903 Event 3478279

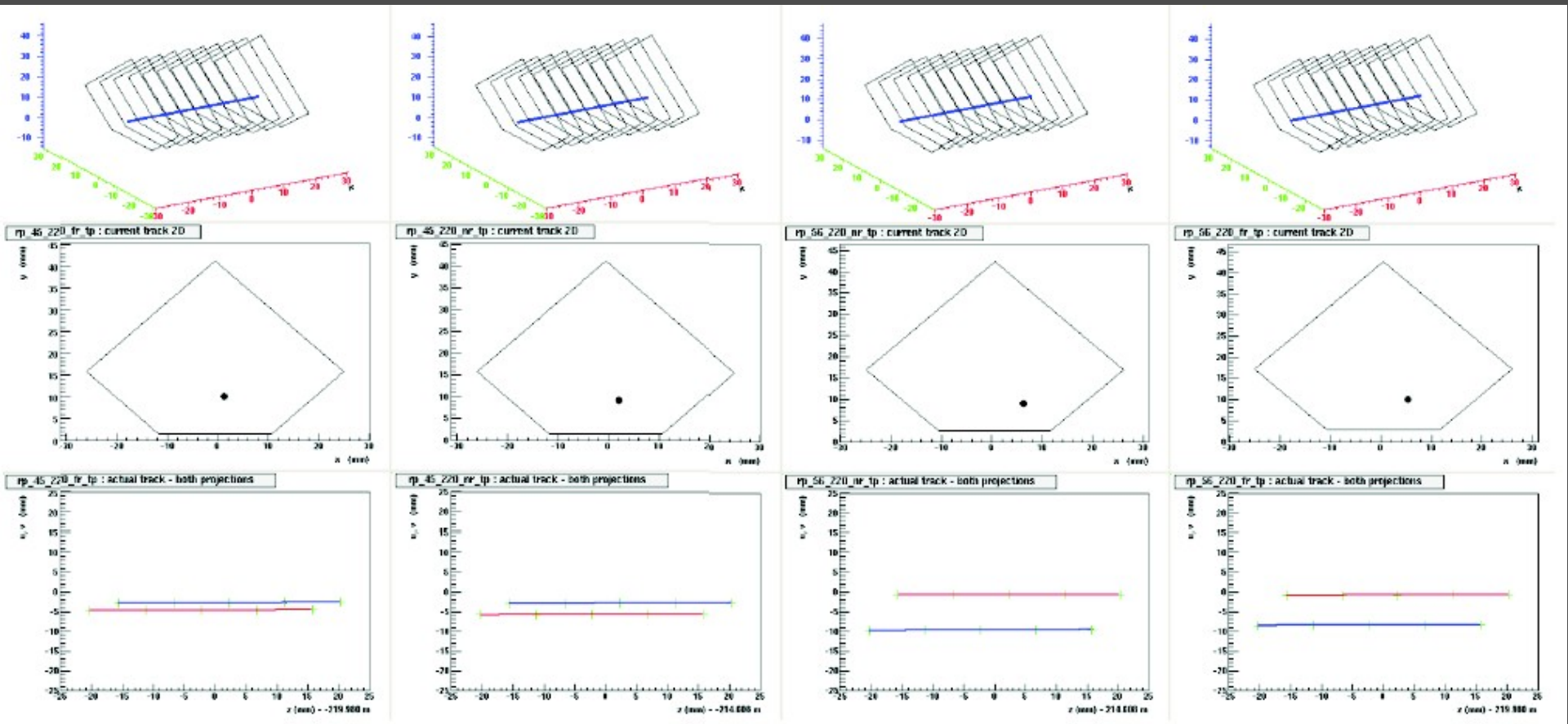


Run 198903 Event 3478279



CMS-DP-2013-004,CMS-DP-2013-006

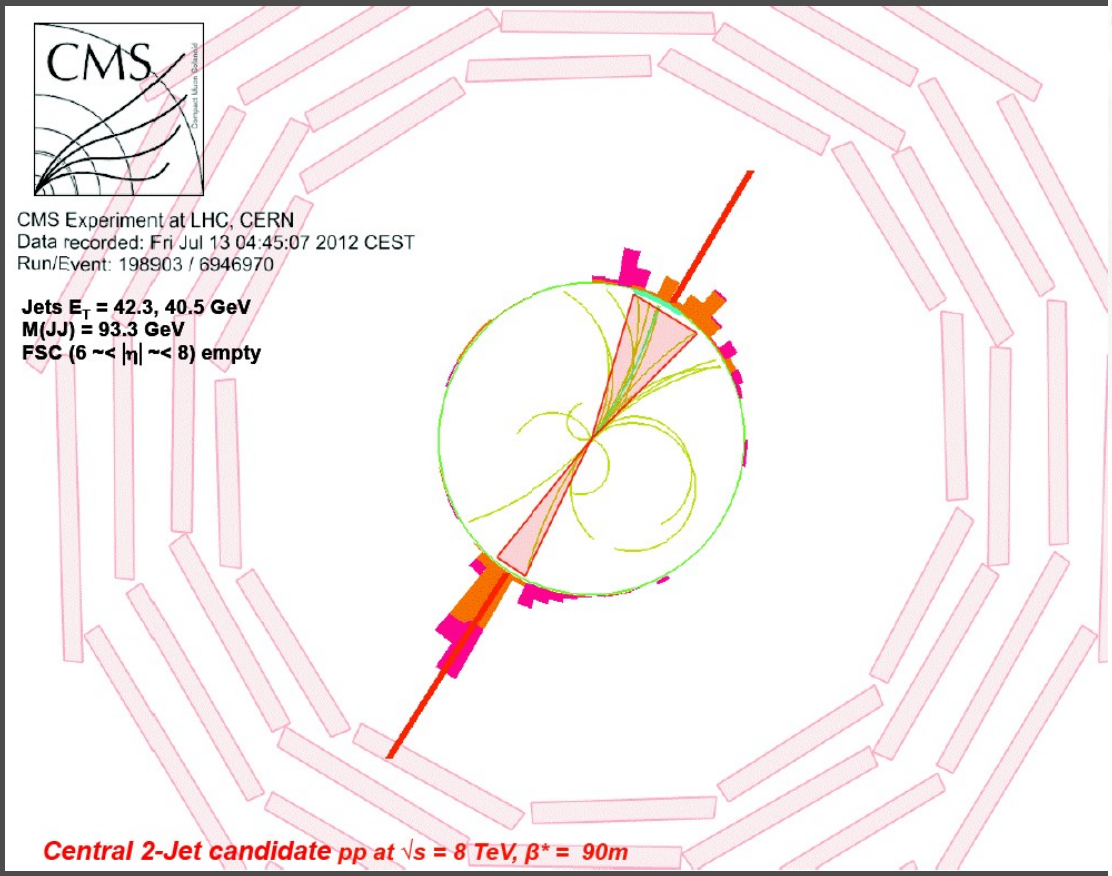
Run 198903 Event 3478279

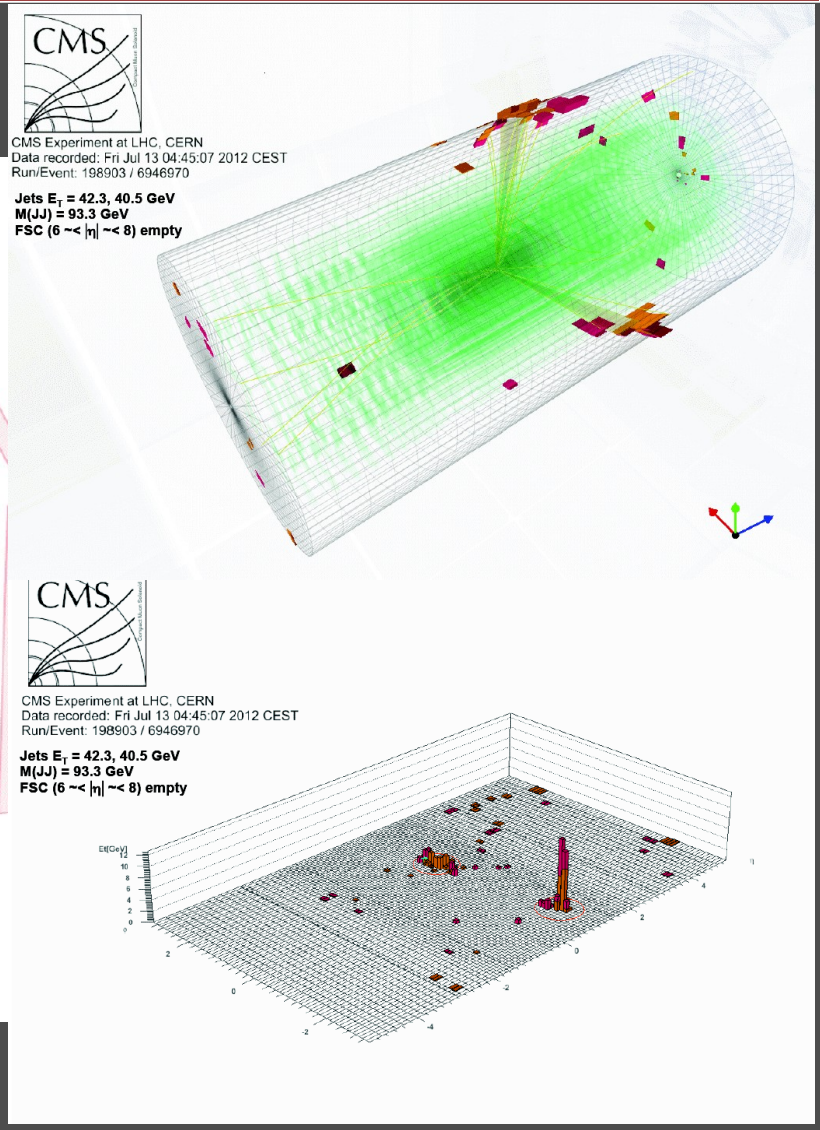


TOTEM Event 15322

CMS-DP-2013-004,CMS-DP-2013-006

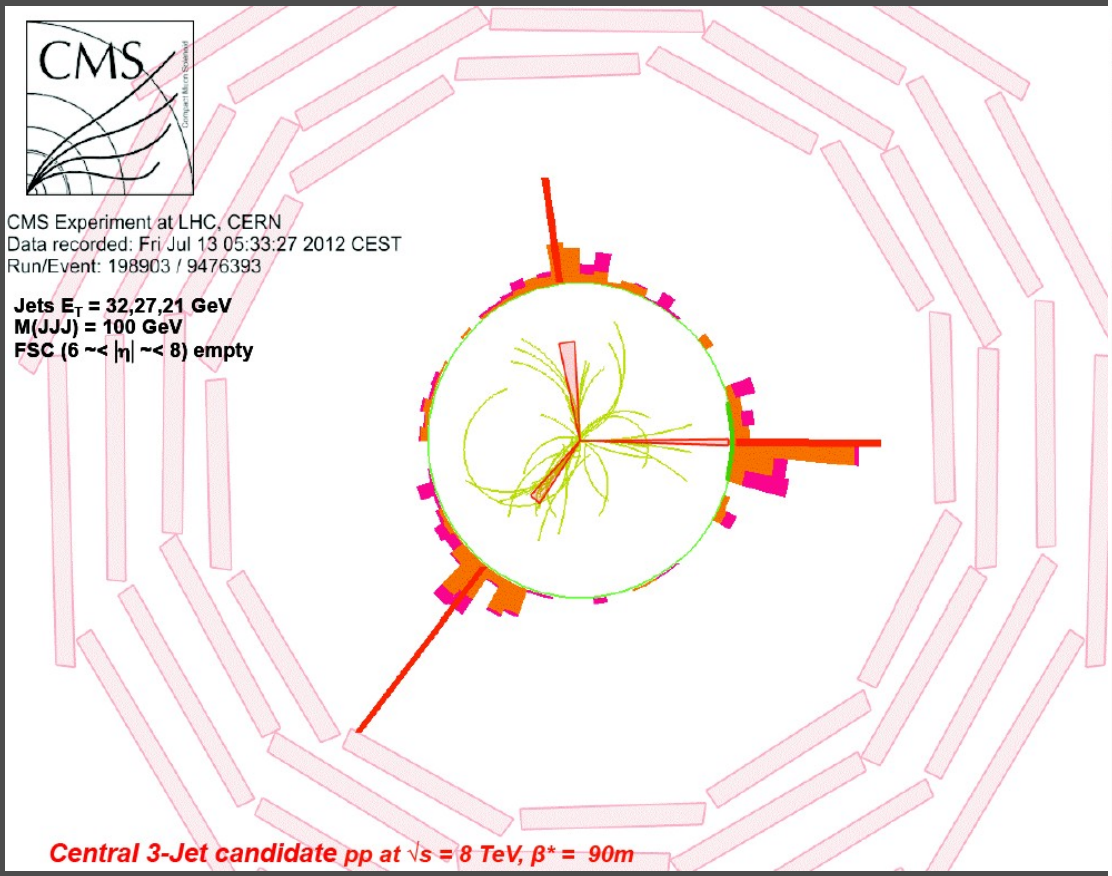
Run 198903 Event 6946970

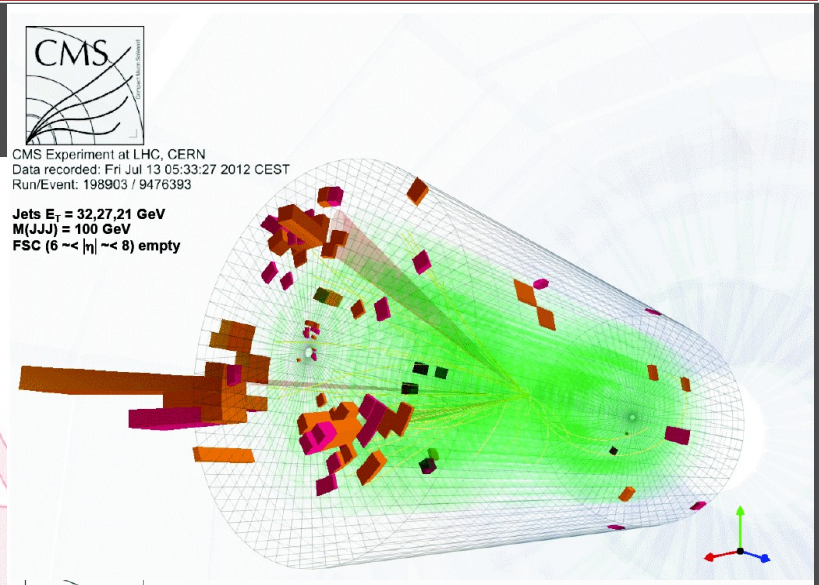


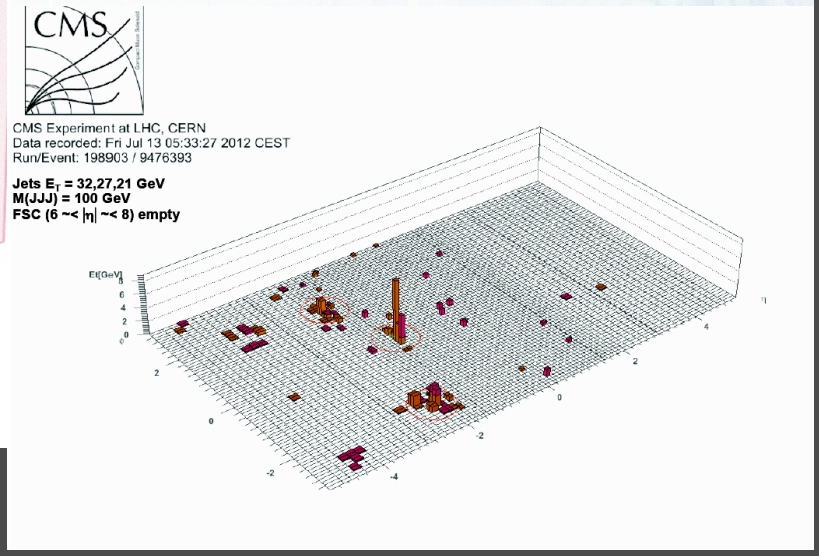


Clean dijet event in otherwise empty detector.
Forward protons in RPs.

Run 198903 Event 9476393







Clean "Mercedes" event in otherwise empty detector.
Forward protons in RPs.

Summary

- Inclusive SD and DD diffractive cross sections measured at 7 TeV:
  - $\sigma^{SD}_{vis} = 4.27 \pm 0.04\ (stat.)\ ^{+0.65}_{-0.58}\ (syst.)$ mb for $-5.5 < \log_{10}\xi < -2.5$
  - $\sigma^{DD}_{vis} = 0.93 \pm 0.01\ (stat.)\ ^{+0.26}_{-0.22}\ (syst.)$ mb for $\Delta\eta > 3$, $M_X > 10$ GeV, $M_Y > 10$ GeV
  - Forward rapidity gap cross section compared to ATLAS measurement. CMS extends the ATLAS measurement by 0.4 unit of gap size.
- Inclusive di-jet cross section measured as a function of ζ (fractional proton momentum loss, SD) at 7 TeV:
  - Excess of events over non-difractive MC predictions at lower ζ.
  - Gap-survival probability of 0.08-0.12 (LO/NLO MC) measured for $0.0003 < \zeta < 0.002$.
- CMS+TOTEM high-p_T jet event displays with two protons detected in the TOTEM RP.

Ongoing CMS+TOTEM analyses: dN/dη with CMS tracker + T2, SD di-jets with proton, soft semi-hard CD, etc.

New results on the way. Check the latest CMS results at:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ