Measurement of dijet production with a leading proton in proton-proton collisions at 8 TeV with the CMS and TOTEM detectors at the LHC

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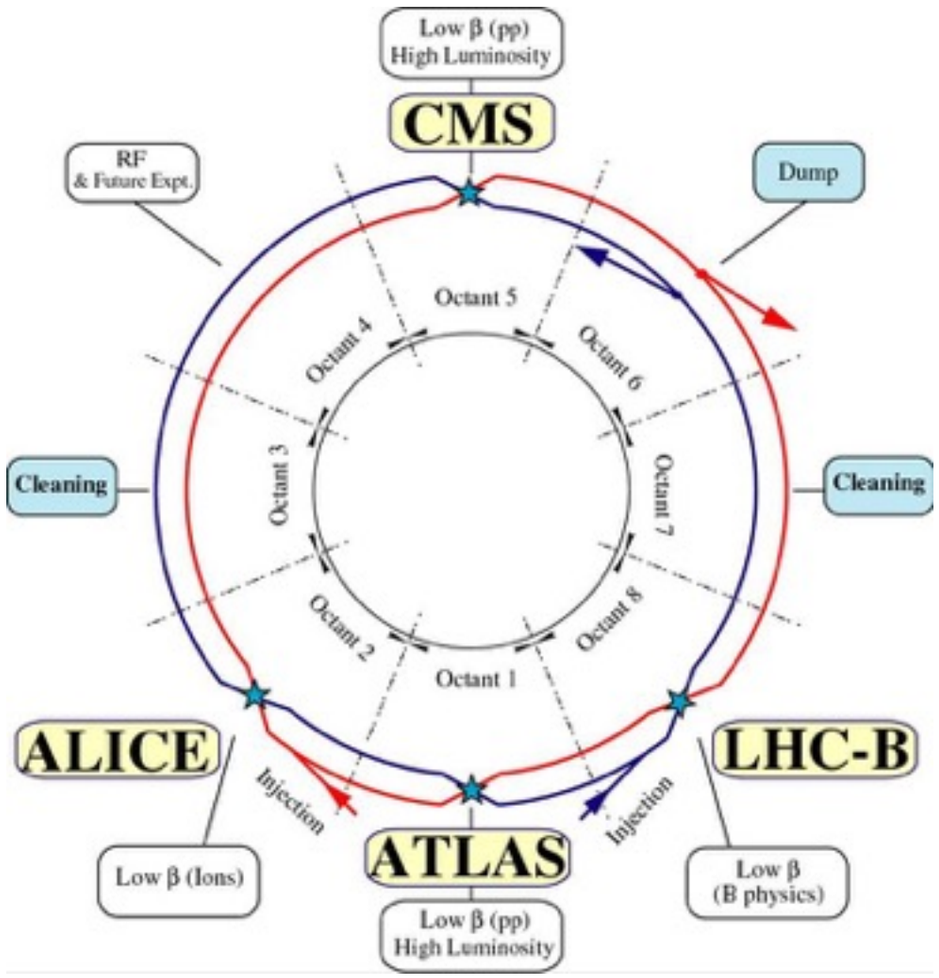
CMS-PAS-FSQ-12-033
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/FSQ-12-033/index.html

QCDDIFF2018: Workshop on QCD and Diffraction
Cracow, Poland

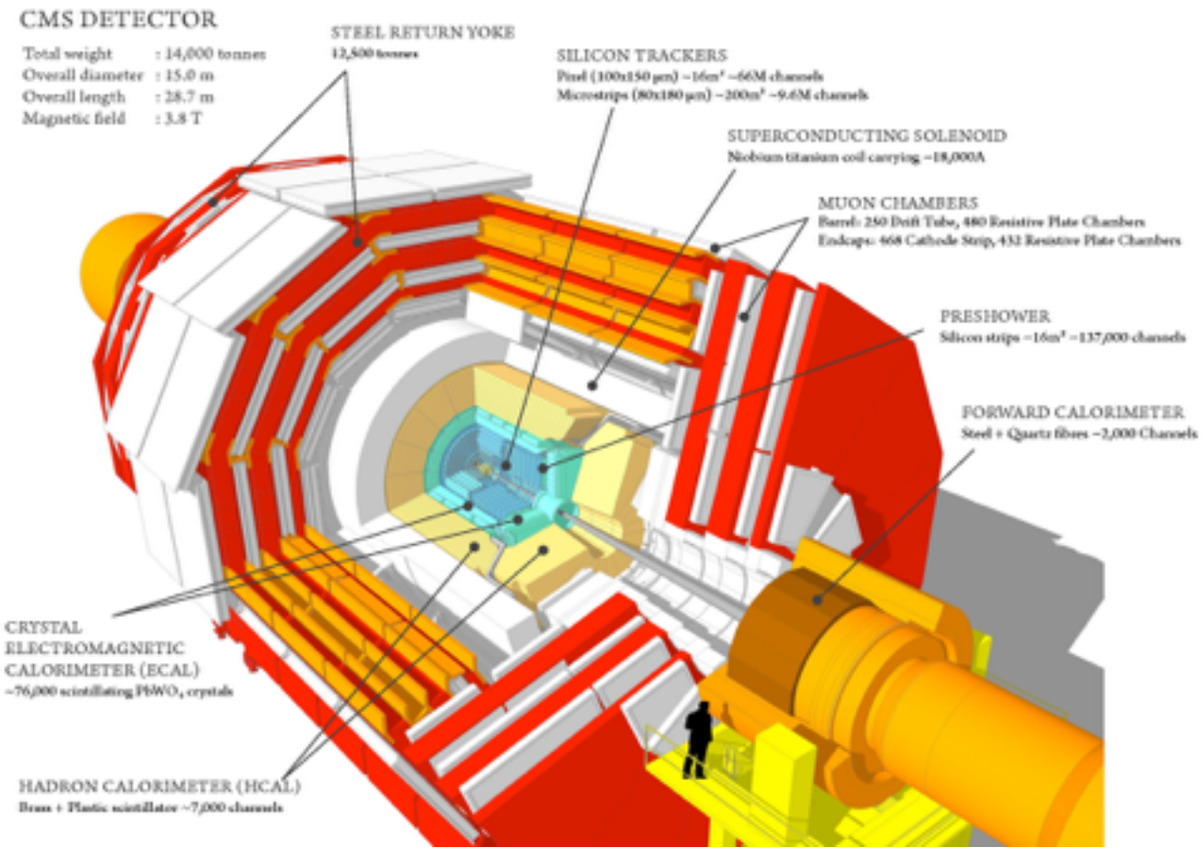
November 15, 2018

The Large Hadron Collider



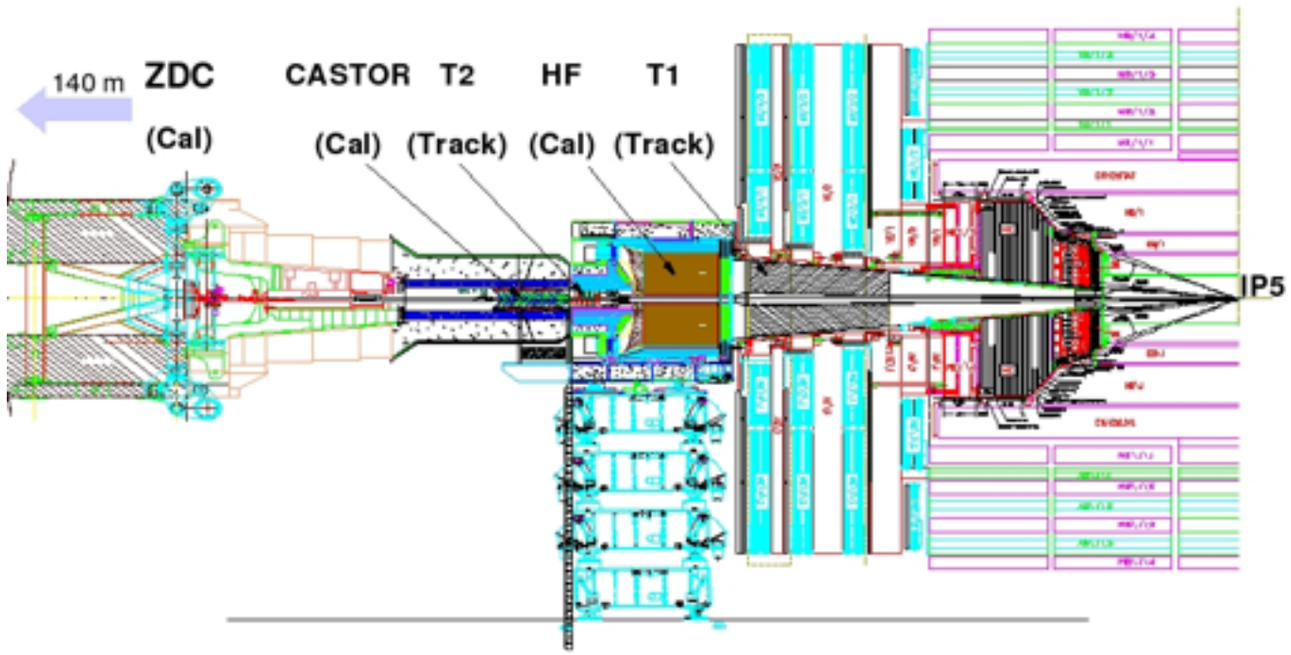
- The LHC is a two-ring superconducting accelerator and collider.
- It can produce collisions with either protons or heavy ions.
- Four detectors are located at four points of collision along the LHC beam line: CMS, ATLAS, ALICE and LHCb.
- The LHC was designed to accelerate protons to an energy of 7 TeV and collide them at $\sqrt{s}$ = 14 TeV. Currently, the LHC is operating at $\sqrt{s}$ = 13 TeV.
- In 2012, the beam energy of 4 TeV was reached. This LHC running period is used in this analysis.

Compact Muon Solenoid



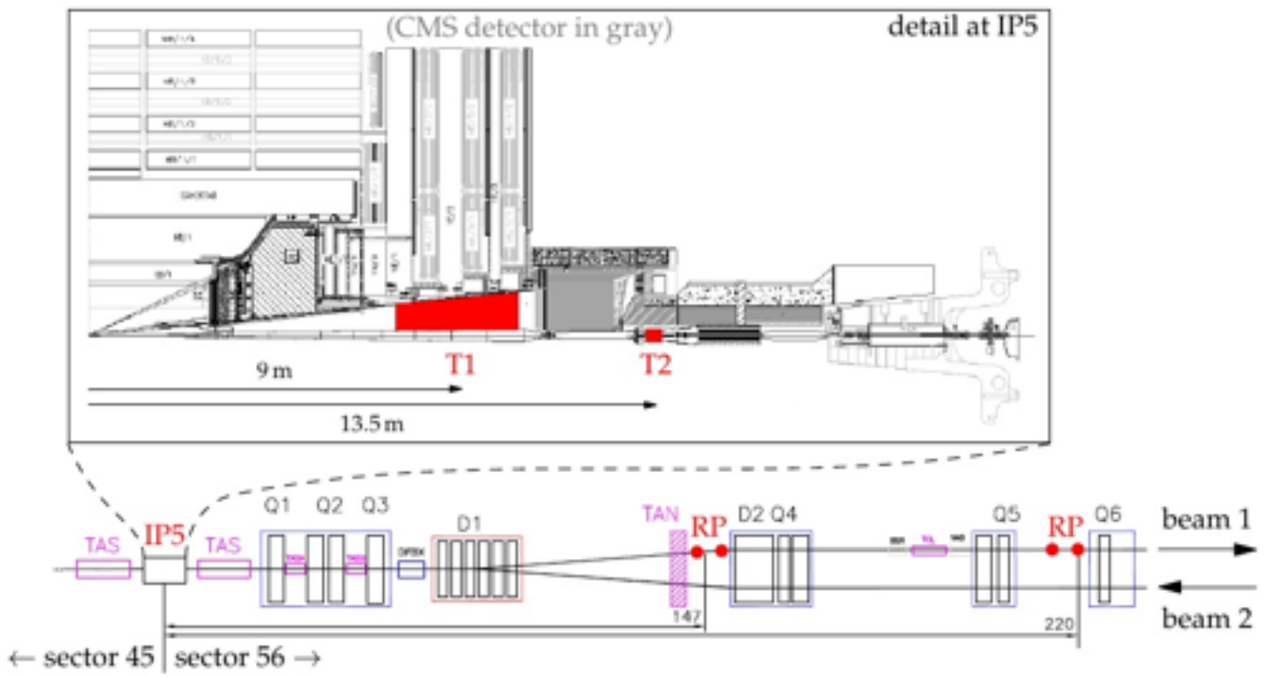
- The CMS detector is built around IP5 of the LHC.
- It was designed to be a general purpose detector .
- CMS has a cylindrical shape and its sub-detectors are:
  - silicon tracker ($|\eta| < 2.5$),
  - electromagnetic calorimeter ($|\eta| < 3.0$),
  - hadronic calorimeter ($|\eta| < 5.0$),
  - the magnet,
  - the muon system ($|\eta| < 2.4$).

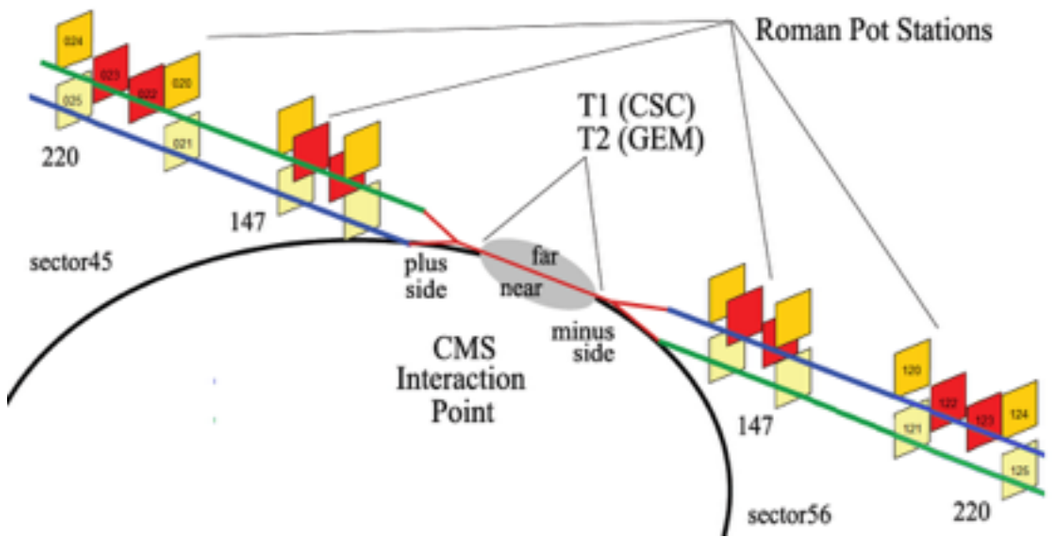
- There are several sub-detectors around the CMS interaction point with coverage beyond $|\eta| = 5$.



TOTEM experiment

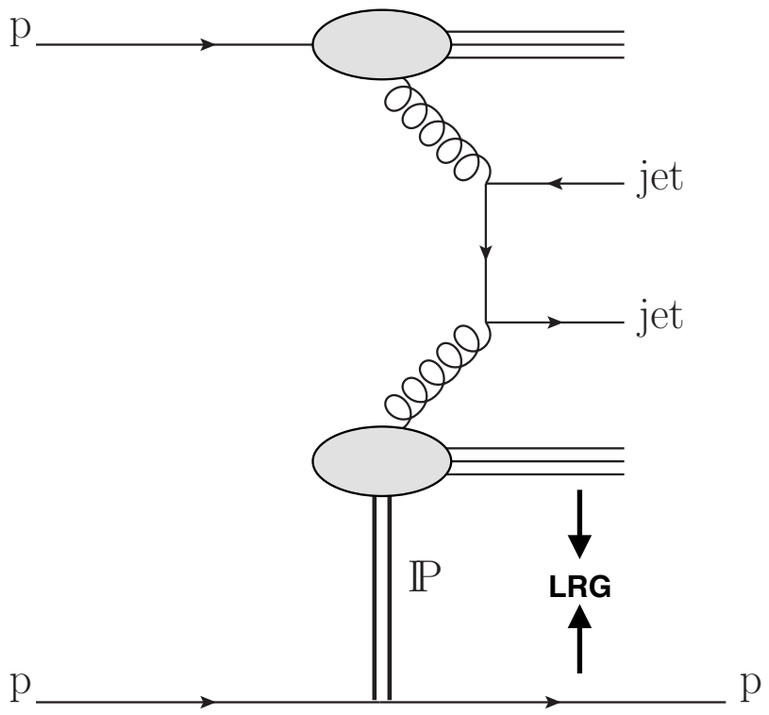
- The TOTEM experiment is composed of 3 different detectors located symmetrically on both sides of the IP5:
  - T1 and T2 detectors placed in front of the HF and CASTOR calorimeters of CMS ($3.1 < |\eta| < 6.5$) detect charged particles and are dedicated to the measurement of the inelastic rate.
  - Roman Pot (RP) stations at ~147 m and 220 m allow the measurement of the scattered proton in the kinematic region that depends on the beam optics.





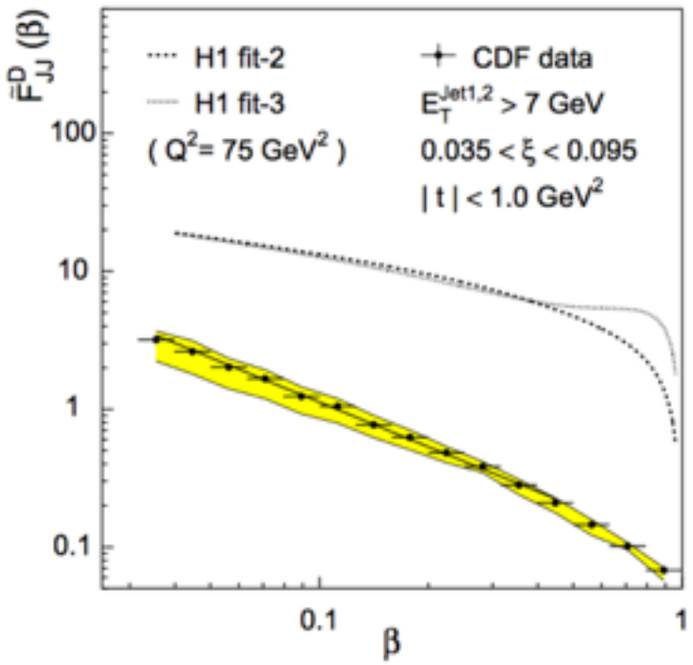
- The RP stations in the LHC sector 45 have positive z coordinates, while those in sector 56 have negative z coordinates according to the chosen coordinate system.

Single diffractive dijet production



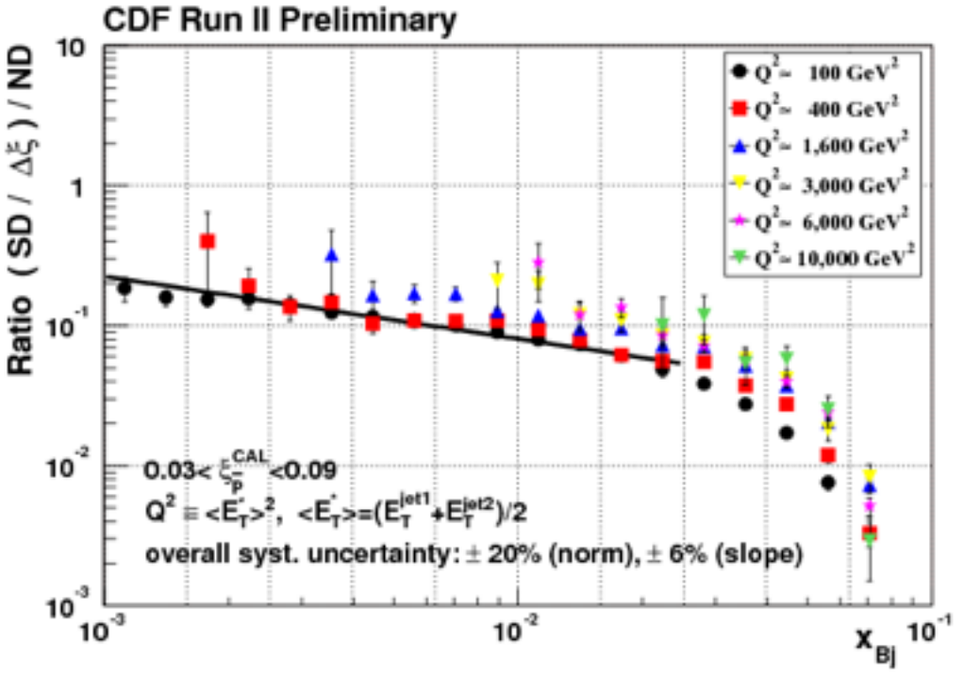
- Diffractive dijet production is characterized by the presence of a high momentum proton, with only a small energy loss and with a large rapidity gap (LRG) adjacent to the scattered proton.
- Diffractive dijet processes has been studied in pp and ep collisions at CERN, Fermilab and DESY.
- Hard diffraction can be described in terms of diffractive parton distribution functions (dPDFs).
- The dPDFs have been determined by the HERA in diffractive DIS and successfully applied to describe different hard diffractive processes in ep collisions.

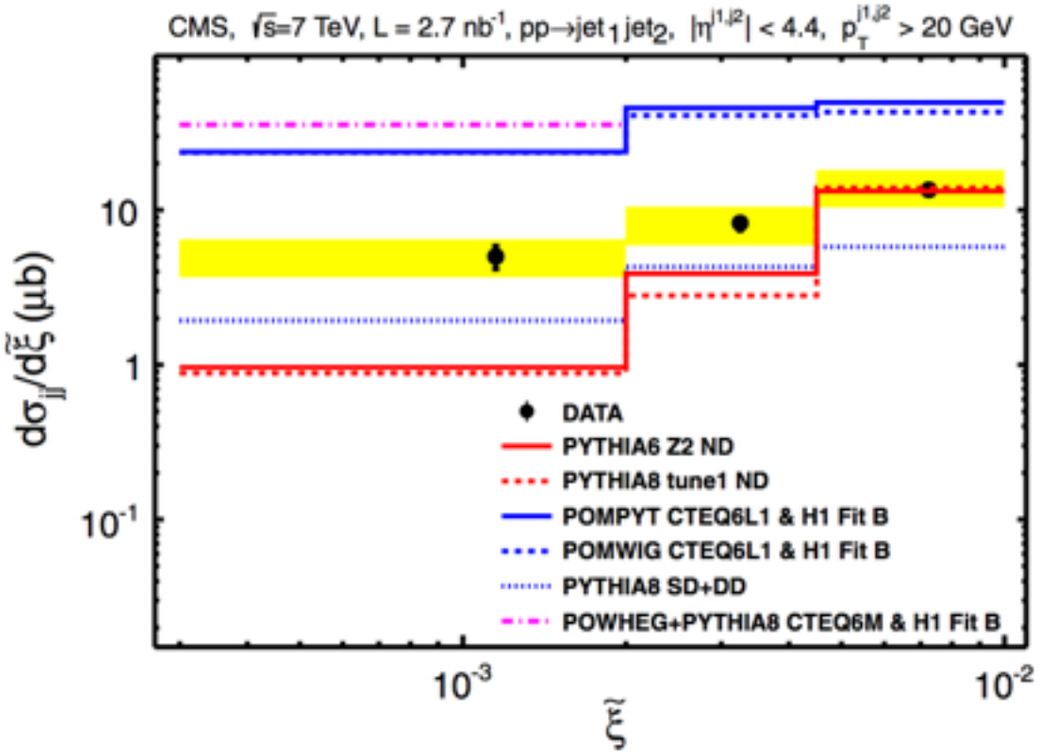
- In hadron-hadron collisions hadron diffraction is suppressed with respect to HERA predictions. The suppression factor, often called the rapidity gap survival probability, was measured to be ~10% at Tevatron energies.
- The suppression is attributed to additional soft partonic interactions which spoil the gap formed by the Pomeron exchange and also break the outgoing proton.



Single diffractive dijet production

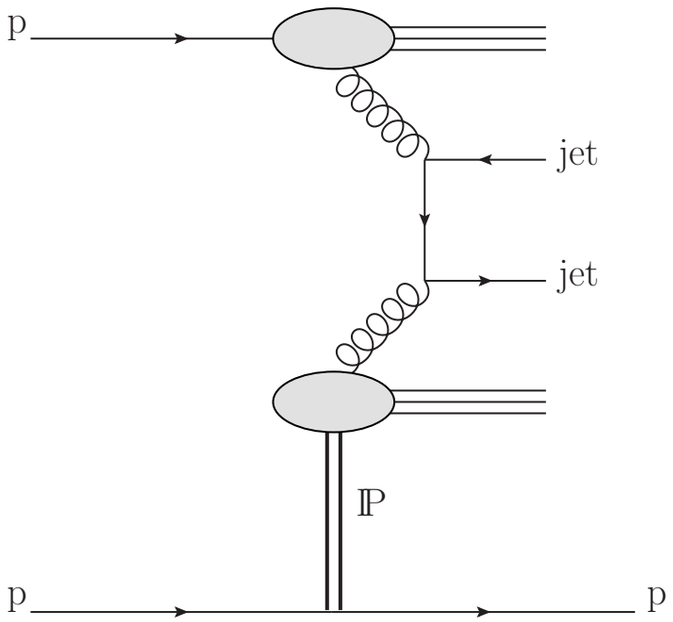
- The CDF experiment measured the ratio of single-diffractive and inclusive events.
- The ratio of single-diffractive and inclusive dijet cross sections is to leading order (LO) approximation proportional to the ratio of the corresponding structure functions.





- Previous results of hard diffraction in dijet production at CMS show the effect of factorization breaking.
- The low ξ bin shows significant contribution from diffractive dijet production, observed for the first time at the LHC .

Single diffractive dijet production



$$t = (p_i - p_f)^2 \qquad \xi = 1 - \frac{|p_f|}{|p_i|}$$

- This analysis presents the measurement of hard diffraction processes with a leading proton using the CMS and TOTEM detectors.
- The dijet system, separated from the proton by a LRG, is measured with the CMS detectors.
- As the acceptance in pseudorapidity at CMS is limited, the measurement of the scattered proton is not possible. This is however achieved with the coverage in the forward direction by the TOTEM experiment.

- It is possible to measure ξ and t using the RP system. This allows the suppression of the contribution from proton-dissociative events.
- With CMS-only information it is not possible to measure ξ or t, but it is possible to estimate ξ from the energies and longitudinal momenta of the particles measured in CMS.

$$\xi^{\pm}_{\mathrm{CMS}} = \frac{\sum(E^i \pm p^i_z)}{\sqrt{s}},$$

Single diffractive dijet production

- This analysis presents the measurements of the cross section as a function of t and ξ of single-diffractive dijet production.

- The ratio of the single-diffractive to inclusive dijet yields is presented as a function of *x*, the momentum fraction of the parton initiating the hard scattering.

- x can be estimated from the energies and longitudinal momenta of the two highest transverse momentum jets in the event, and an additional third jet if present. The latter is selected with $p_T > 20$ GeV.

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

(+/- signs correspond to the scattered proton moving towards the +/- z direction.)

Data samples

- Data collected in July 2012 during a dedicated run with low probability of pileup and ß* = 90 m optics configuration.

- The data have been collected with a common hardware-level trigger. Events are combined offline by requiring that both the CMS and TOTEM reconstructed events have the same LHC orbit and bunch numbers.

- The data correspond to an integrated luminosity of 37.5 nb^{-1} calculated by scaling the luminosity measured by CMS with the one measured by TOTEM.

Event Selection

- At trigger level, dijet events were selected by requiring at least two jets with $p_T > 20$ GeV.
- Offline, the selection required at least two jets with $p_T > 40$ GeV and $|\eta| < 4.4$.
- At least one good reconstructed primary vertex and at least one reconstructed proton track in the RP stations also were required.
- Events with protons in the RP stations in both sides are rejected if the kinematics is consistent with those from elastic scattering.
- To suppress the contribution of pileup and beam-halo events in which the proton is uncorrelated with the hadronic final state measured in CMS it is required that $\xi_{cms} - \xi_{totem} < 0$.
- Hit coordinates on the RP stations satisfy the following fiducial cuts: $0 < x < 7$ mm and $8.4 < |y| < 27$ mm.
- Kinematic cuts: $0.03 < |t| < 1.0$ GeV^2 and $0 < \xi < 0.1$.

Selection	Sector 45	Sector 56
At least 2 jets ($p_T > 40$ GeV, $\|\eta\| < 4.4$)	427689	
Elastic scattering veto	405112	
Reconstructed proton	9530	
RP and fiducial cuts	2137	3033
$0.03 < \|t\| < 1.0\,\text{GeV}^2$, $0 < \xi_{\text{TOTEM}} < 0.1$	1393	1806
$\xi_{\text{CMS}} - \xi_{\text{TOTEM}} \leq 0$	368	420

Monte Carlo simulation

- **Inclusive samples:**
  - PYTHIA6 (Tune: Z2).
  - PYTHIA8 (v. 8.153. Tunes: 4C, CUETP8M1, CUETP8S1)
  - HERWIG6
- **Diffractive samples:**
  - PYTHIA8 (v. 8.153. Tunes: 4C and CUETP8M1)
  - PYTHIA8 (v. 8.223. Tune: CUETP8M1)
  - POMWIG.

Monte Carlo simulation: Diffractive processes

- Diffractive parton distribution functions (dPDFs) from a fit to deep inelastic scattering data (H1 fit B) have been used.
- POMWIG uses an NLO dPDF fit. Both Pomeron and Reggeon exchange contributions were simulated.
- PYTHIA8 was simulated with an LO dPDF fit. Only Pomeron exchange was simulated.
- To further improve the description of the data, the generators were reweighted as a function of β, the fraction of the Pomeron momentum carried by the interacting parton.
- PYTHIA8 v.8.223 implements a model to simulate Hard Diffraction with two alternative scenarios:
  - **MPI-unchecked:** Unsuppressed (Dynamic gap suppression framework is not applied).
  - **MPI-checked:** It does not allow any further MPIs to occur between the two incoming hadrons and thereby the model introduces a dynamical rapidity gap survival probability.

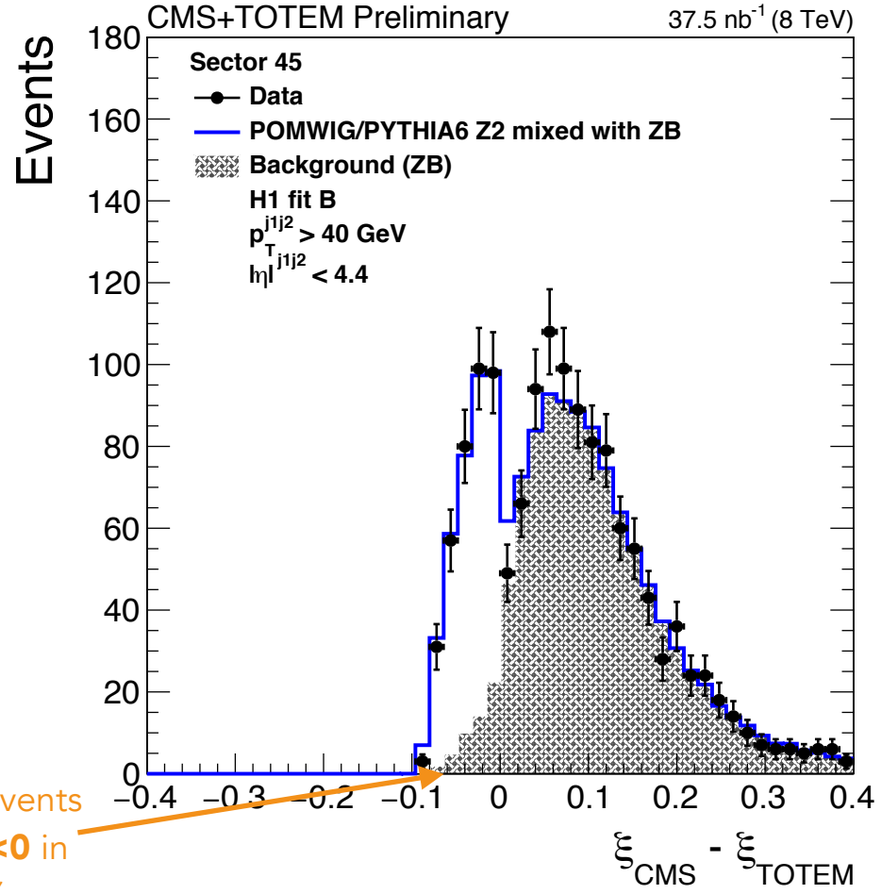
Background

- The background considered is that due to the overlap of a pp collision and additional beam-halo particles measured in the RP stations.

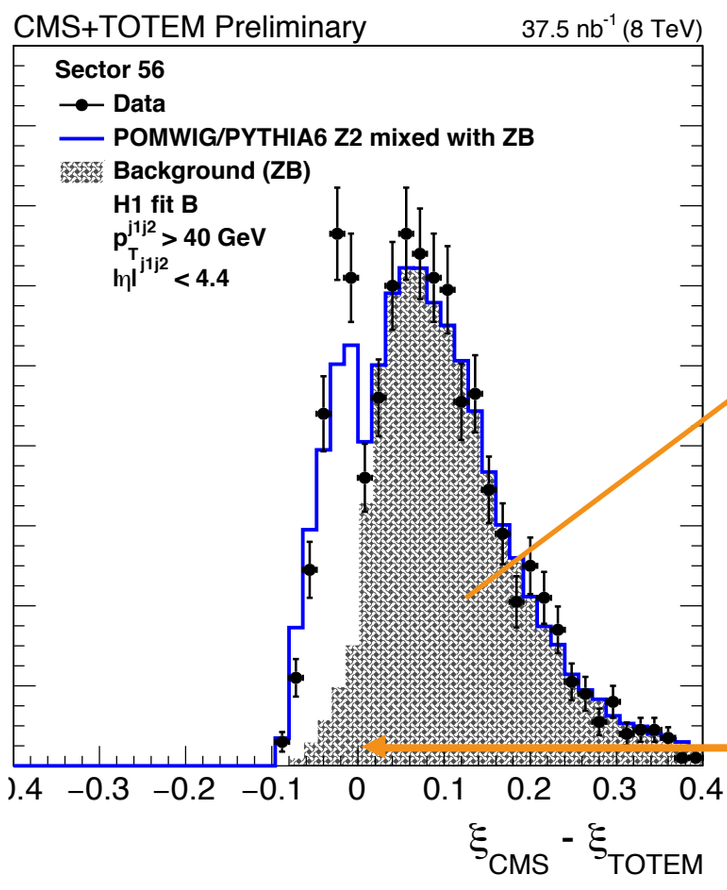
- Two methods were used to estimate it yielding consistent results.

Background: ZeroBias

- Zero bias events selected without the requirement of a vertex were mixed with the diffractive and non-diffractive MC to describe the background events.
- Each MC event was associated to an event taken randomly from the ZB sample.
- An event with a proton in the RPs is considered as signal if it originates from the MC sample or as background if it originates form the ZB sample.
- The background is estimated separately for events with a proton traversing the two top or the two bottom RPs on each side.



Background for events with $\xi_{cms} - \xi_{totem} < 0$ in sector 45 is ~14%



Kinematically forbidden region.

Background for events with $\xi_{cms} - \xi_{totem} < 0$ in sector 56 is ~16%

Results: Cross section as a function of t and ξ

$$\frac{d\sigma_{jj}}{dt} = \mathcal{U}\left\{\frac{N^i_{jj}}{\mathcal{L}A^i\Delta t^i}\right\} \qquad \frac{d\sigma_{jj}}{d\xi} = \mathcal{U}\left\{\frac{N^i_{jj}}{\mathcal{L}A^i\Delta \xi^i}\right\}$$

N^i_{jj} : number of dijet events in the *i*-th bin

$\mathcal{L}$: integrated luminosity

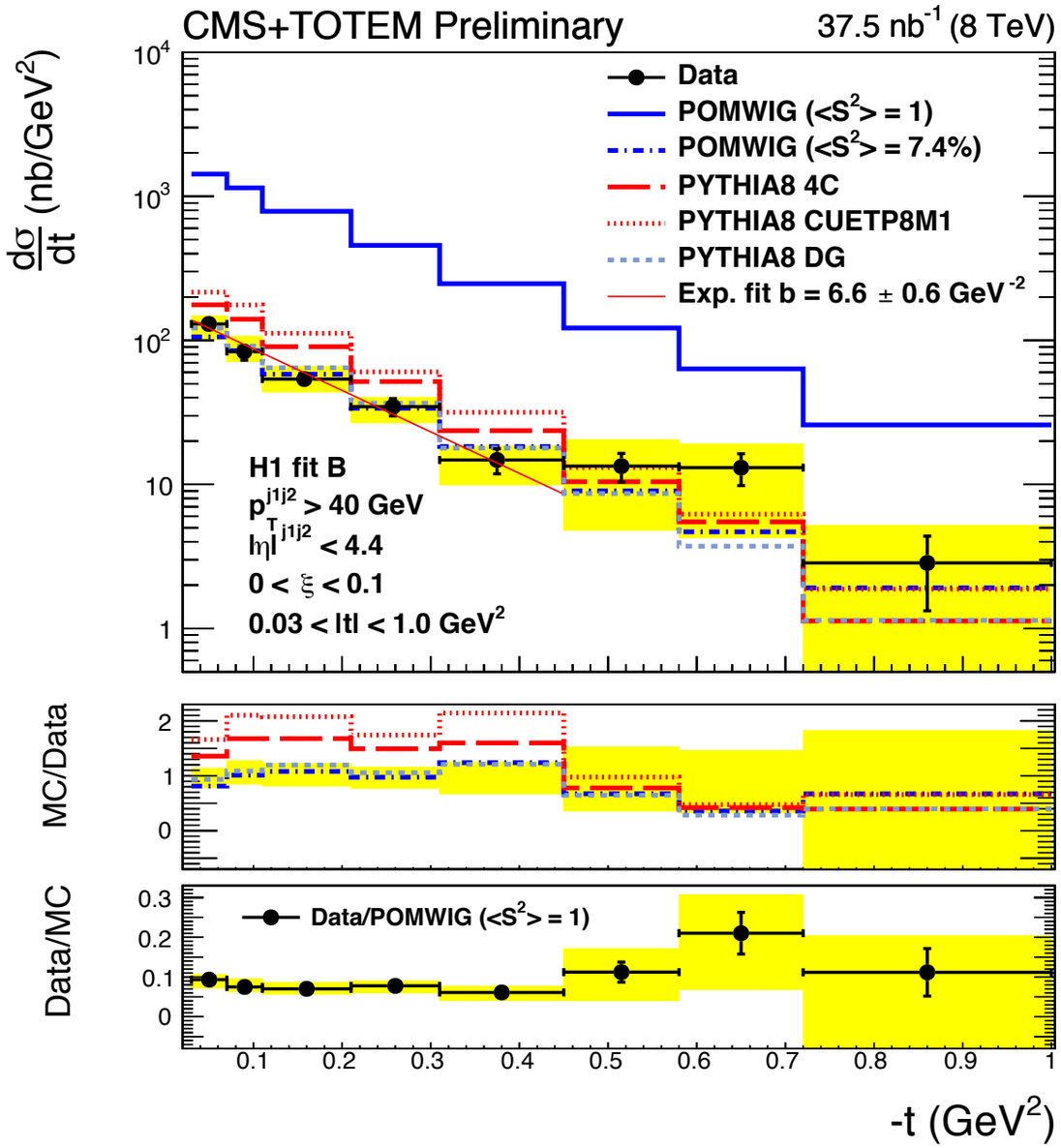
A^i : acceptance

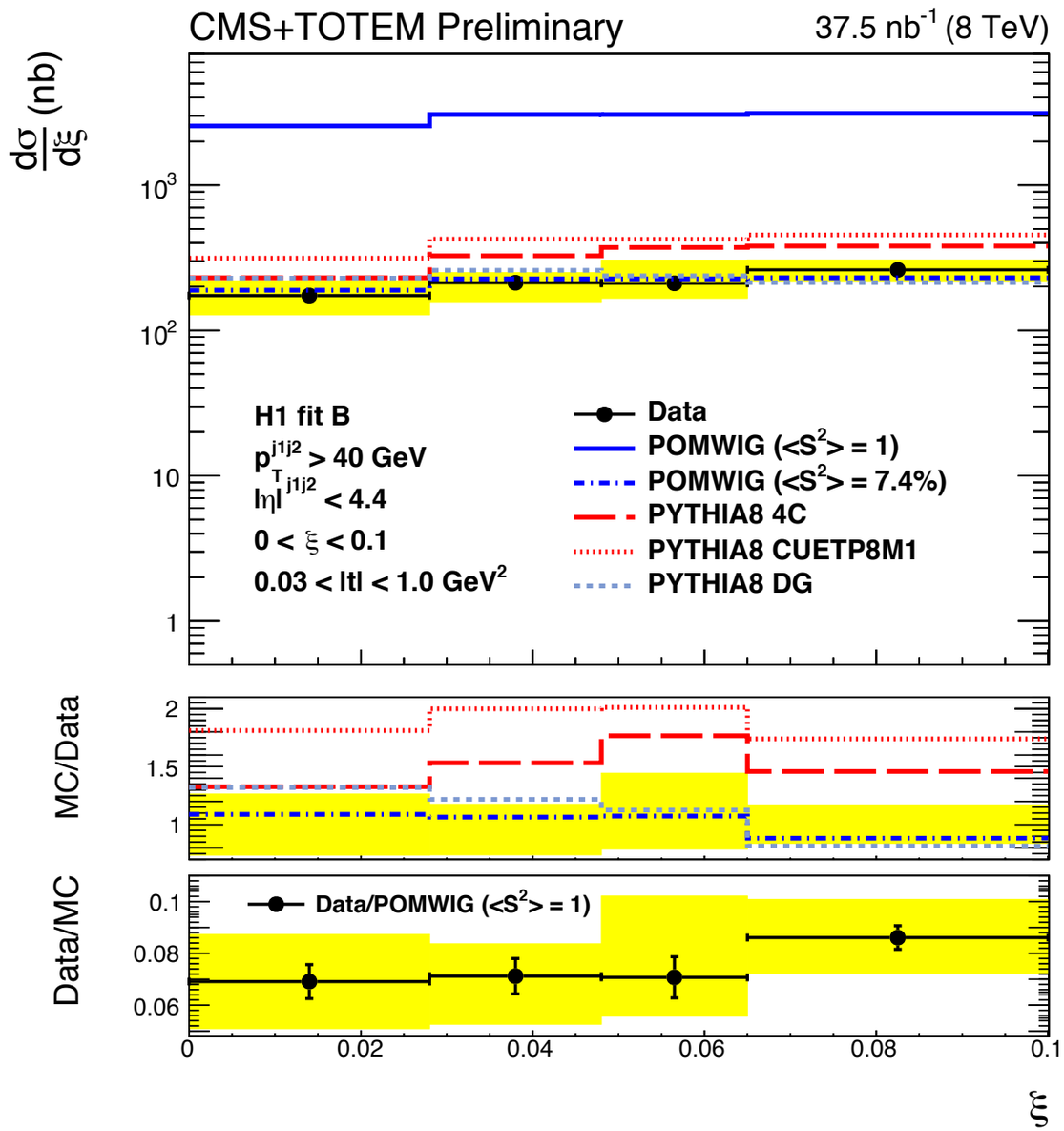
Δt^i , $\Delta \xi^i$: bin widths

$\mathcal{U}$: unfolding corrections.

Results: Cross section as a function of t and ξ

- Cross section for the two sectors averaged: σ = 21.7 ± 0.9 (stat) +3.0/-3.3 (syst) ± 0.9 (lumi) nb.
- PYTHIA8 Dynamic Gap model shows overall a good agreement with the data (σ **= 23.7 nb**).





Systematic Uncertainties: t and ξ cross sections

- Kinematic region: $p_T > 40$ GeV, $|\eta| < 4.4$, $0 < \xi < 0.1$ and $0.03 < |t| < 1.0$ GeV^2
- Cross section: $\boldsymbol{\sigma} = 21.7 \pm 0.9$ (stat).
- The jet energy scale and horizontal dispersion uncertainties are the main contributions.

Uncertainty source	$\Delta\sigma/\sigma$
Trigger efficiency	±2 %
Calorimeter energy scale	+1/-2 %
Jet energy scale and resolution	+9/-8 %
Background	±2 %
Resolution	±2 %
Horizontal dispersion	+9/-12 %
Acceptance and unfolding	±2 %
Unfolding bias	±3 %
Total	+14/-15 %

Results: Suppression factor

- The overall suppression factor can be obtained from the integrated cross section measured and the corresponding value from the MC. $\mathcal{S} = 7.4\,^{+1.0}_{-1.1}\,\%$
- The MC models used to calculate this factor is POMWIG (~294 nb) and PYTHIA8 (~280nb). The latter is used when the Dynamic Gap framework is not applied (MPI-unchecked).
- These MC models use the H1 dPDF fit.
- The H1 fit B dPDFs include the contribution from proton dissociation in ep collisions. In order to account for a different normalisation of the dPDF when a leading proton is detected ($M_Y = M_p$), the suppression factor should be corrected by the ratio $\boldsymbol{\sigma}(M_Y < 1.6)/\boldsymbol{\sigma}(M_Y = M_p) = 1.23 \pm 0.03$ (stat) $\pm$ 0.16 (syst).

$$\mathcal{S} = (9 \pm 2)\,\%$$

Results: Ratio of the single diffractive to inclusive dijet yields

$$R(x) = \frac{\sigma_{\mathrm{jj}}^{\mathrm{pX}}(x)/\Delta\xi}{\sigma_{\mathrm{jj}}(x)} = \frac{\mathcal{U}\left\{N_{\mathrm{jj}}^{\mathrm{pX}}/A_{\text{CMS-TOTEM}}\right\}/\Delta\xi}{\mathcal{U}\left\{N_{\mathrm{jj}}/A_{\mathrm{CMS}}\right\}}$$

N_{jj} : number of dijet events without the requirement of a proton selected in the RPs.

$N_{\mathrm{jj}}^{\mathrm{pX}}$: number of single diffractive dijet events with $\xi < 0.1$

A_{CMS} : acceptance for inclusive dijet events, evaluated with PYTHIA6, HERWIG6, PYTHIA8 4C, PYTHIA8 CUETP8M1 and PYTHIA8 CUETP8S1.

$A_{\text{CMS-TOTEM}}$: acceptance of CMS and TOTEM for single diffractive dijet events, evaluated with POMWIG, PYTHIA8 4C and PYTHIA8 CUETP8M1.

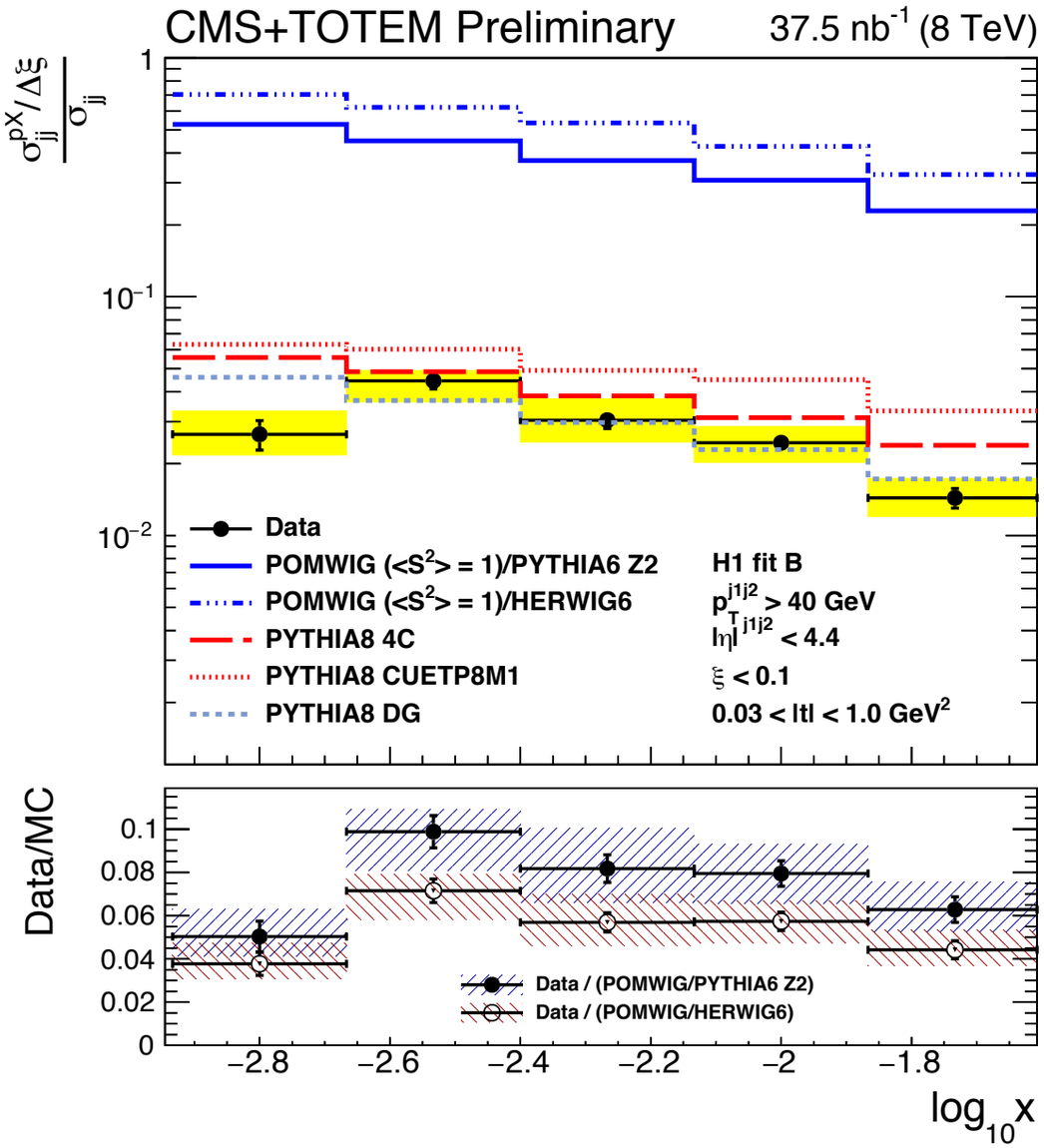
$\mathcal{U}$: unfolding corrections.

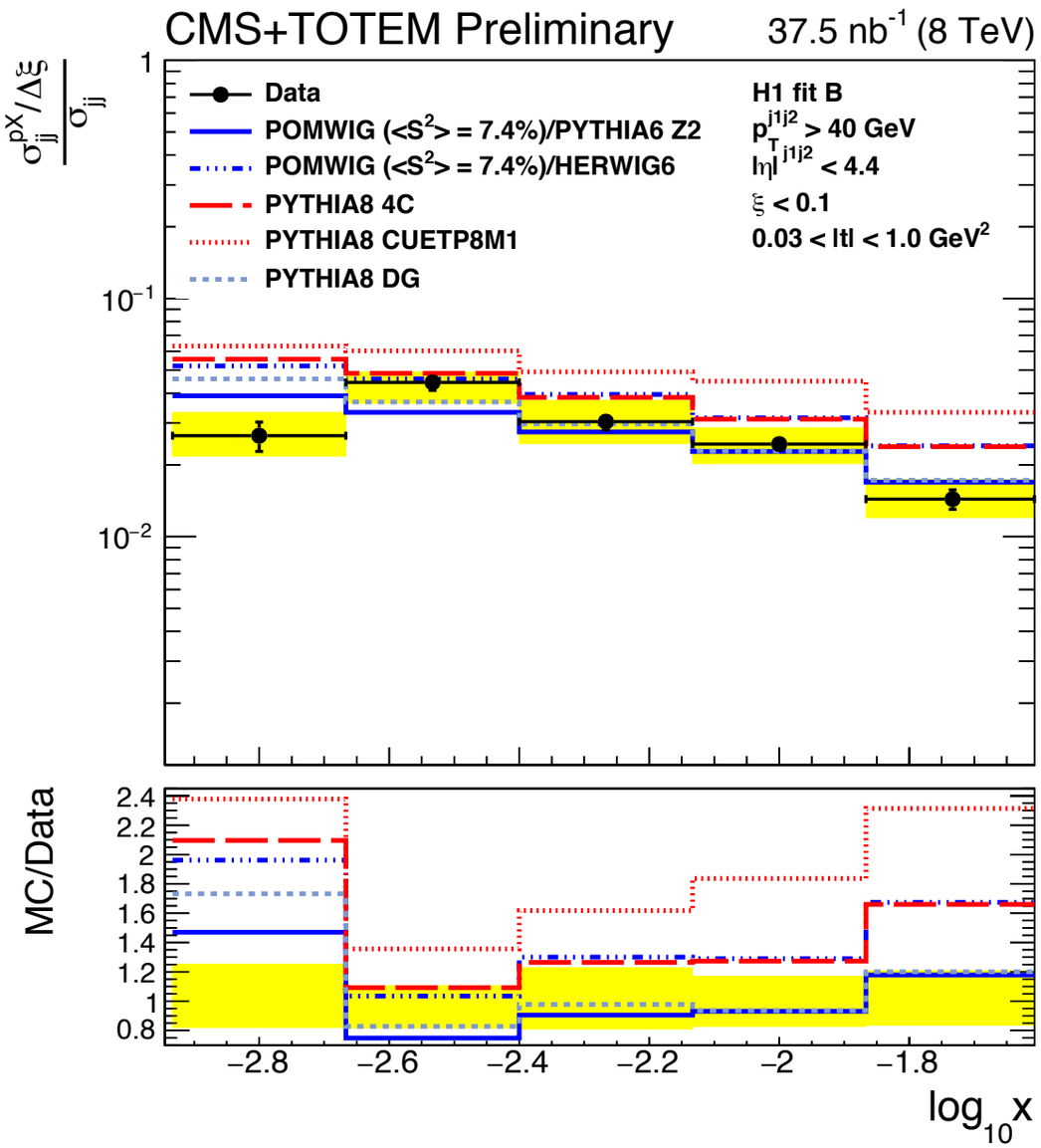
Results: Ratio of the single diffractive to inclusive dijet yields

- Ratio in the kinematic region given by $p_T > 40$ GeV, $|\eta| < 4.4$ and $-2.9 < \log_{10} x < -1.6$

  $R = 0.025 \pm 0.001\ (stat) \pm 0.003\ (syst)$.

- POMWIG is presented when no correction is applied (corresponds to prediction from dPDF) (left) and with the correction of $\langle S^2 \rangle = 7.4\%$ (right).





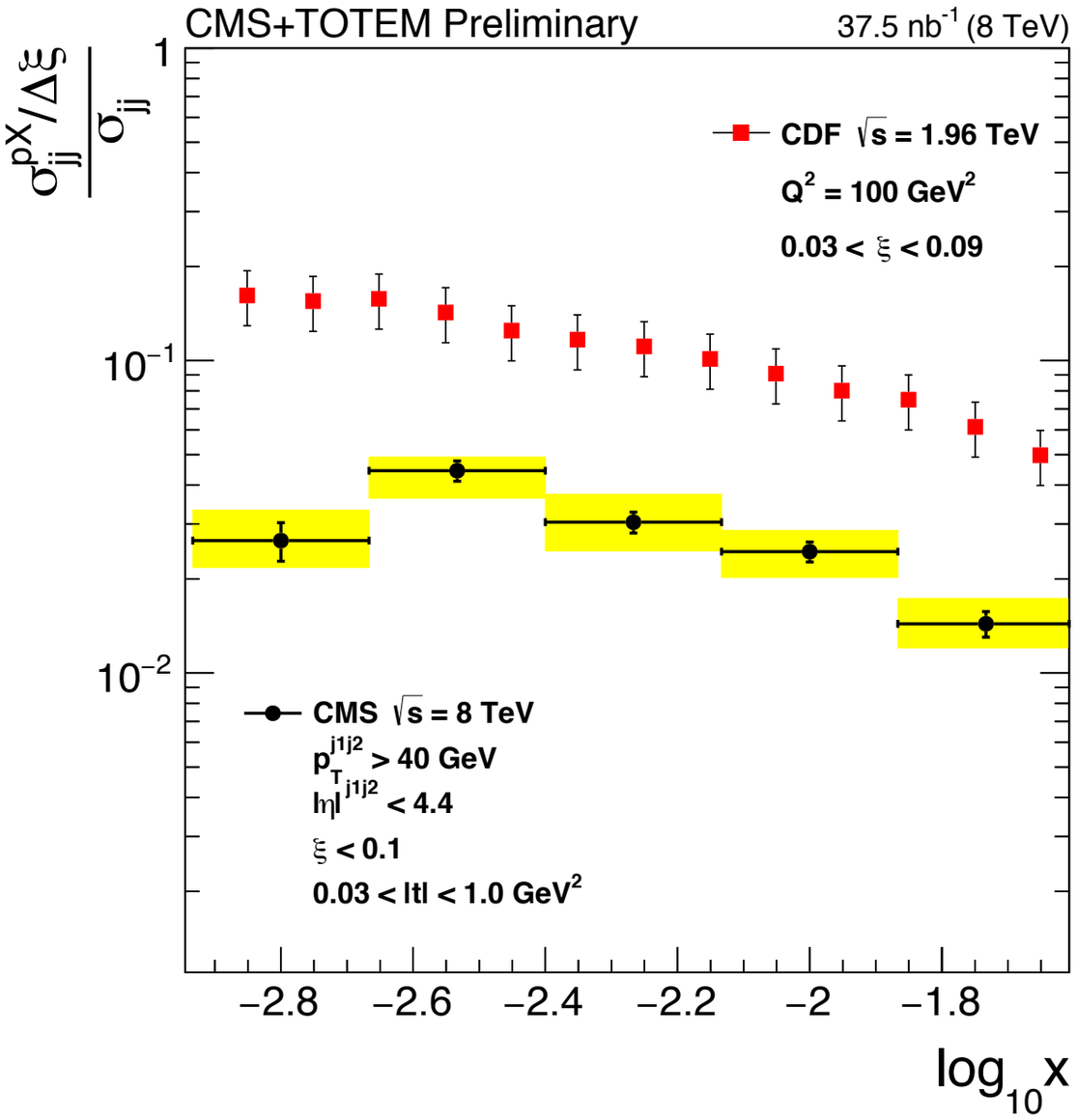
Systematic Uncertainties: Ratio

- Kinematic region: $p_T > 40$ GeV, $|\eta| < 4.4$, $0 < \xi < 0.1$, $0.03 < |t| < 1.0$ GeV^2 and $-2.9 < \log_{10} x < -1.6$
- Measured ratio: $R = 0.025 \pm 0.001$ (stat).
- The horizontal dispersion uncertainty is the main contribution.

Uncertainty source	$\Delta R/R$
Calorimeter energy scale	+1/-2 %
Jet energy scale and resolution	±2 %
Background	±1 %
Resolution	±2 %
Horizontal dispersion	+9/-11 %
Acceptance and unfolding	±2 %
Unfolding bias	±3 %
Total	+10/-13 %

Results: Ratio of the single diffractive to inclusive dijet yields

- The present data are compared with the results from CDF.
- The present data are lower than the CDF results.
- A decrease of the ratio with centre-of-mass energy has also been observed by CDF by comparing their 630 and 1800 GeV data.



Summary

- The differential cross section of single-diffractive dijet production has been measured as a function of t and ξ in the kinematic region $0 < \xi < 0.1$ and $0.03 < |t| < 1.0$ GeV^2. The two jets were measured with $p_T > 40$ GeV and $|\eta| < 4.4$.

- The ratio of single-diffractive to inclusive cross sections has been measured as a function of x in the region of $-2.9 < \log_{10} x < -1.6$. A decrease of the ratio is observed when compared to the results from CDF at lower centre-of-mass energy.

- After accounting for a constant correction, related to the rapidity gap survival probability, POMWIG shows a good agreement with the data.

- The PYTHIA8 Dynamic Gap model describes well the data overall both in shape and normalisation within the uncertainties.

- The ratio of the single-diffractive cross section and the corresponding value from either the POMWIG or PYTHIA8 Dynamic Gap predictions give an estimate of the suppression from the HERA dPDFs used in the analysis. After accounting for the correction in the dPDF normalisation due to proton dissociation, the suppression factors have been found in the range of $S = (9 \pm 2)$ %

Back Up

Monte Carlo simulation: Roman Pot acceptance (Parameterisation)

- **Proton Transport:** Parameterisation as a function of the kinematics of generator level protons, such as the vertex position, θ_x^*, θ_y^*, ξ and t.

- **Proton reconstruction inefficiency:** Inefficiency is evaluated directly from the elastic scattering data -> ~6%.

- **Reconstruction of t and ξ:** The reconstructed values can be obtained from two methods. (Difference between the two models is used as a systematic uncertainty).

1. By smearing the variables ξ and t.

$$\xi_{rec} = \xi_{gen} + \sigma_{\xi_{gen}}$$

$$t_{rec} = t_{gen} + \sigma_{t_{gen}}$$

$\sigma_{\xi_{gen}}$, $\sigma_{\mathrm{t_{gen}}}$ are quadratic functions, parametrized with values calculated from elastic and diffractive scattering data.

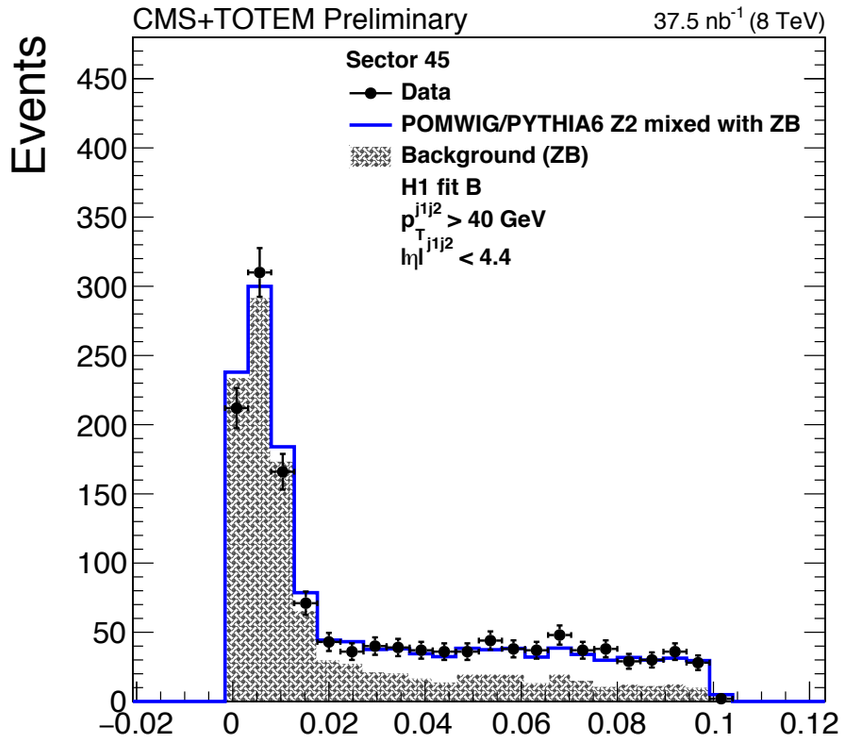
2. By smearing the scattering angles by 25.10 μrad and 2.43 μrad

$$\theta_x^* = \theta^* \cos(\phi^*) \qquad \theta_y^* = \theta^* \sin(\phi^*)$$

$$\theta' = \sqrt{\theta_x'^2 + \theta_y'^2} \qquad \phi' = \arctan\left(\frac{\theta_y'}{\theta_x'}\right)$$

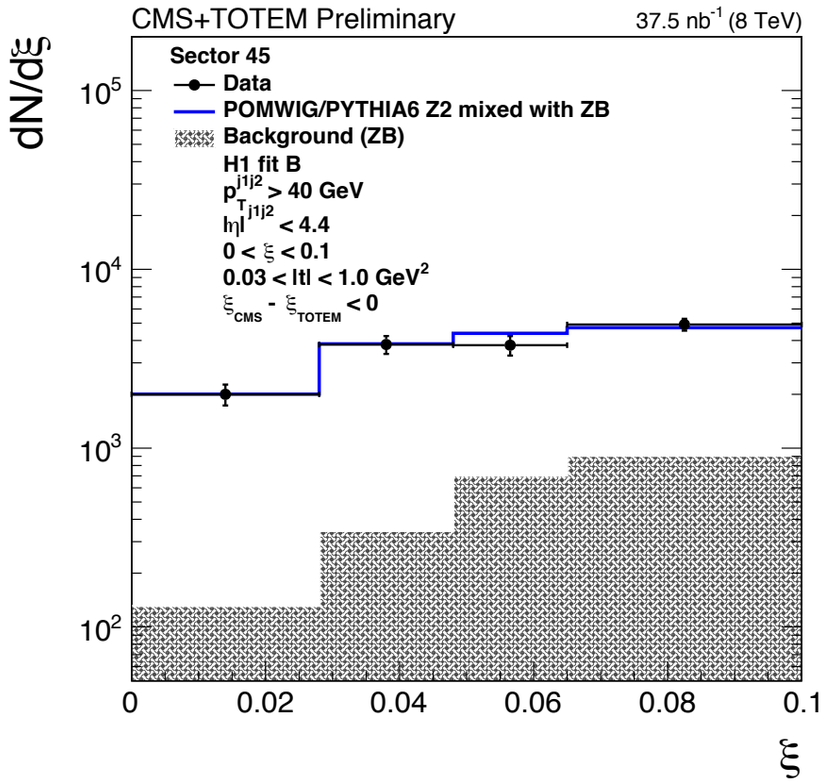
$$p_z' = \pm(1-\xi')p_i \qquad p_T' = p_z' \tan(\theta') \qquad p_x' = p_T' \cos(\phi') \qquad p_y' = p_T' \sin(\phi')$$

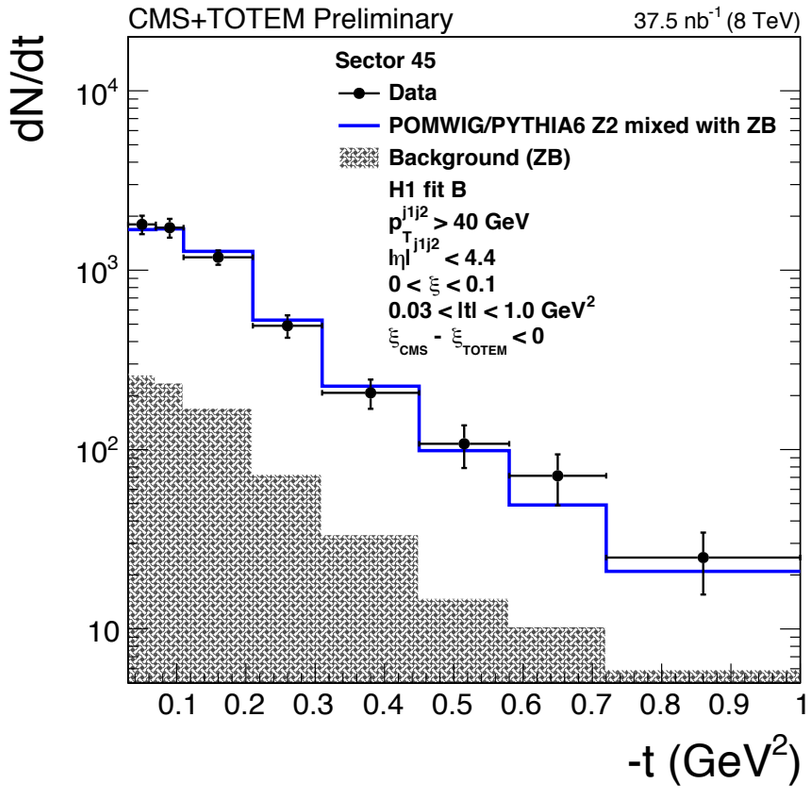
Background: ZeroBias (Sector 45)



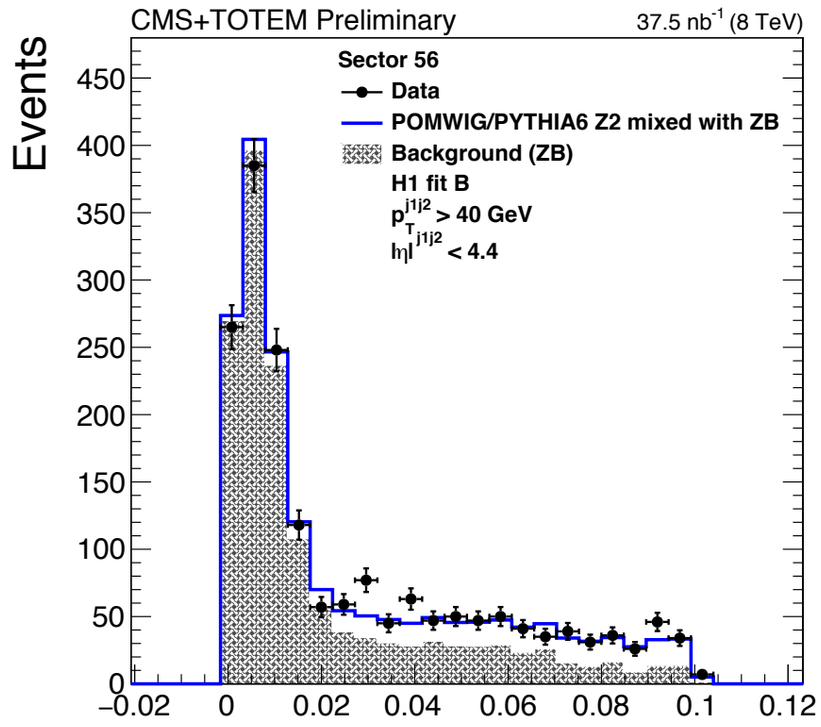
Before $\xi_{cms} - \xi_{totem} < 0$ cut.

After $\xi_{cms} - \xi_{totem} < 0$ cut.



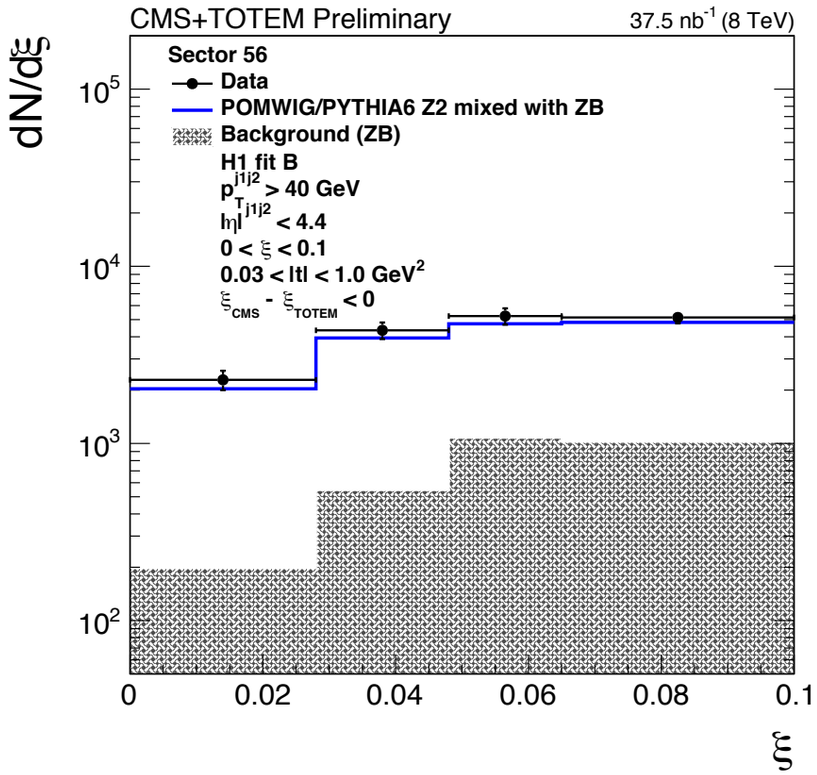


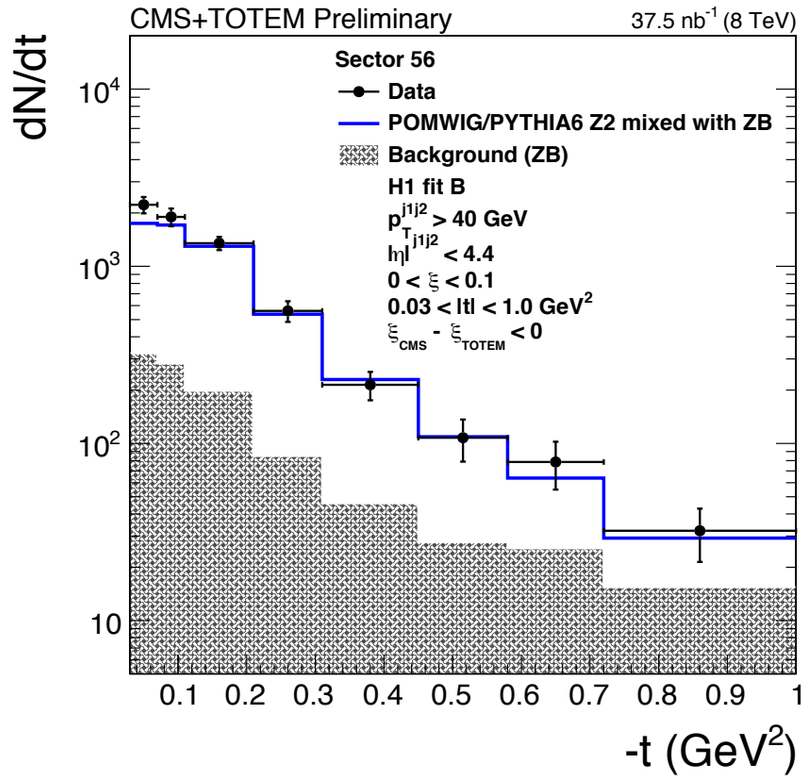
Background: ZeroBias (Sector 56)



Before $\xi_{cms} - \xi_{totem} < 0$ cut.

After $\xi_{cms} - \xi_{totem} < 0$ cut.





Systematic Uncertainties

- **Trigger Efficiency:** Variation of the fit parameters within uncertainties.
- **Calorimeter Energy Scale:** Estimated by changing the energy of the PF objects by +/- 10 %.
- **Jet Energy Scale and Resolution:** Reconstructed jet energy variation according to the JES uncertainty. JER calculated varying the scale factors applied to the MC depending on η.
- **Background:** Half of the difference between the two methods used to estimate the background.
- **RP acceptance:** Estimated modifying the vertical fiducial cut by 200 μm and by reducing the horizontal cut by 1 mm.
- **Resolution:** Half of the difference between the two smearing methods to reconstruct the variables t and ξ.
- **Horizontal dispersion:** Calculated scaling the value of ξ by +/- 10 %.
- **t-slope:** Changing the value of the exponential t-slope in the MC by that measured from the data.
- **β-reweighting:** Half of the difference in the results when removing the reweighting as a function of β.

Systematic Uncertainties

- **Acceptance and unfolding**: Calculated when the acceptance is recomputed with different MC.

- **Unfolding regularisation:** Half of the difference when the distributions are unfolded with number of iterations calculated when $\Delta\chi^2/\chi^2 = 2\%$.

- **Unfolding Bias:** MC sample unfolded with a different model.

- **Luminosity:** Uncertainty on the integrated luminosity was taken as 4%.