Recent CMS and CMS-TOTEM results on diffraction and exclusive production

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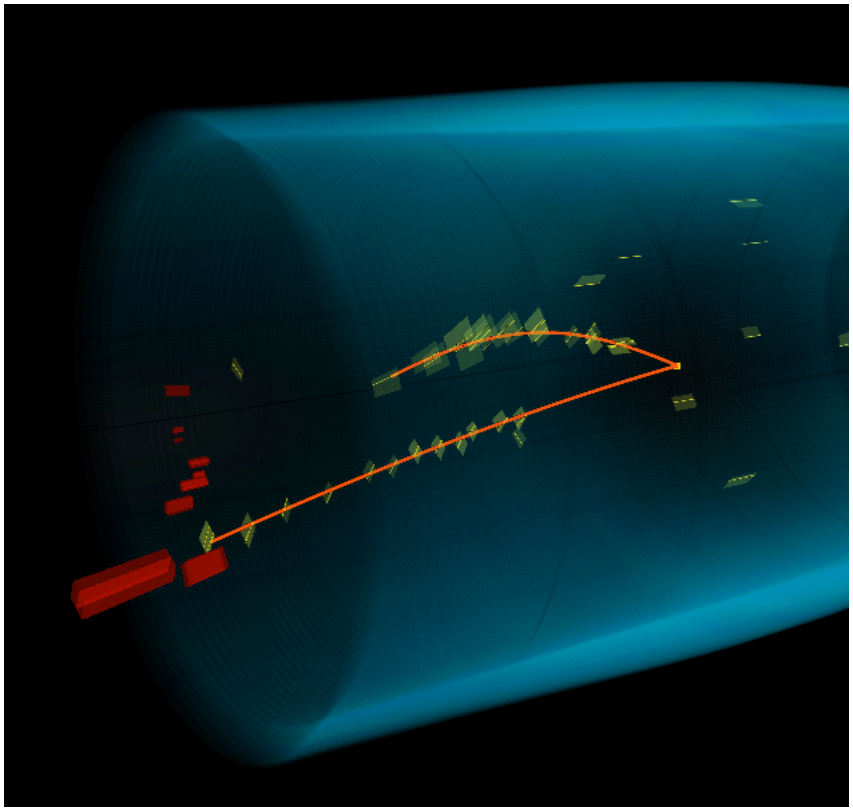
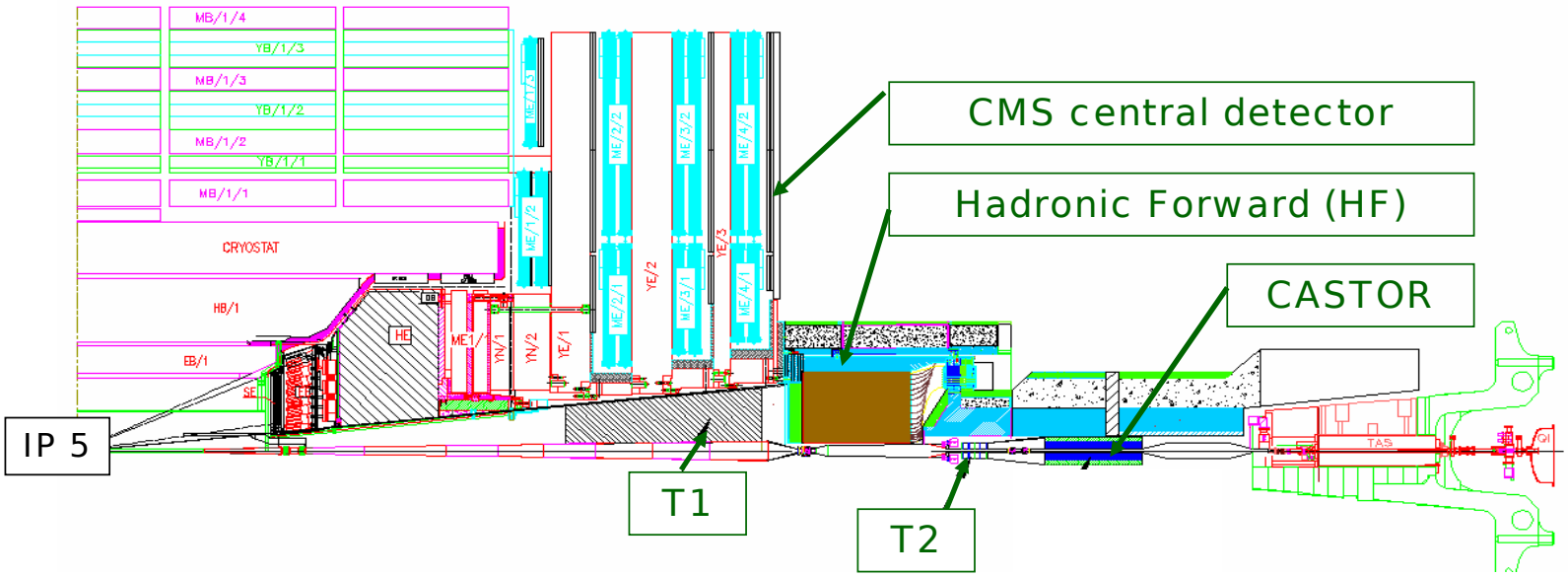
Introduction

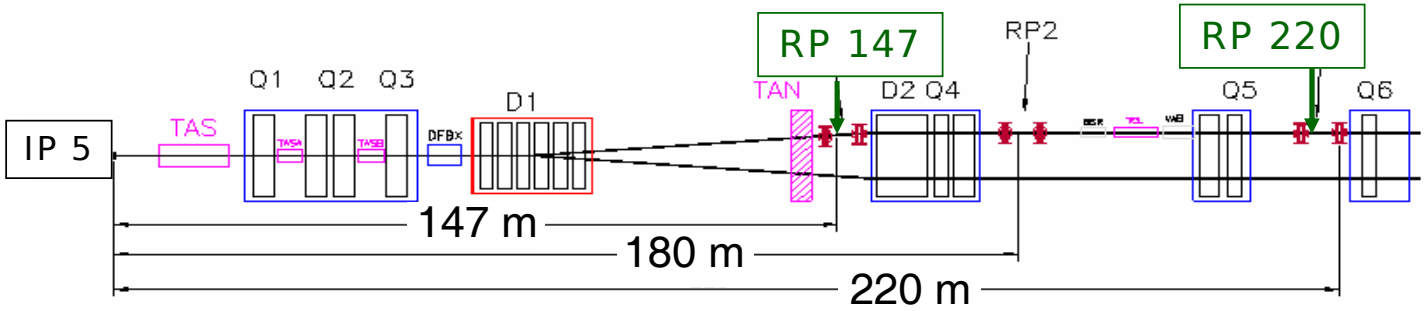
Many important questions in diffraction and exclusive physics!



- Pomeron structure
- Soft survival effects
- BFKL dynamics
- Low mass resonances
- Glueballs

The Forward Detectors of CMS experiment





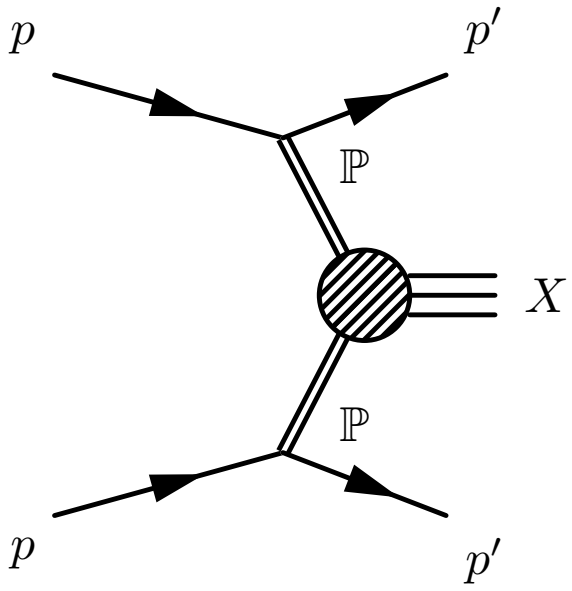
Outline

- **NEW:** Exclusive dipion production at 5.02 and 13 TeV
  CMS-PAS-FSQ-16-006
- Diffractive dijets with proton tagging at 8 TeV
  CMS-PAS-FSQ-12-033
- Dijets with a large rapidity gap between jets at 7 TeV
  Eur. Phys. J. C **78**, no. 3, 242 (2018)
- Inelastic cross section at 13 TeV
  JHEP **1807**, 161 (2018)

Exclusive dipion production at 5.02 and 13 TeV

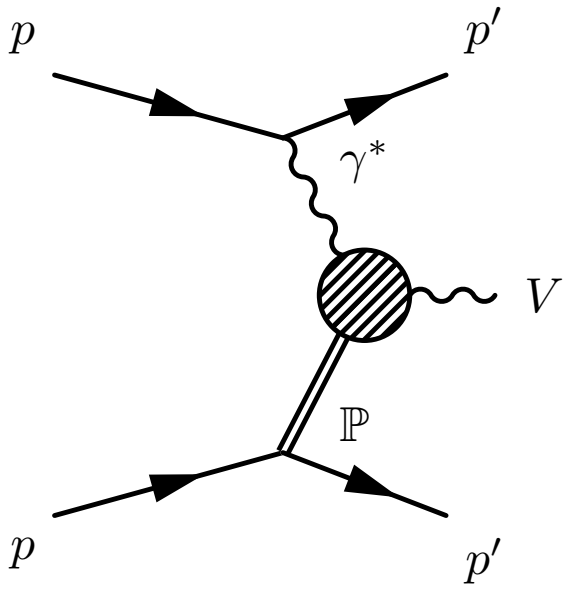
Motivation

- Restricted quantum numbers.
- Filter certain low mass resonances.
- Gluon-rich environment in DPE $\rightarrow$ glueball search.



Double pomeron exchange (DPE)

$I^G(J^{PC}) = 0^+(J^{++})$, J is even



Vector meson photoproduction

$I(J^{PC}) = 0, 1(1^{--})$

Dataset, trigger, event selections

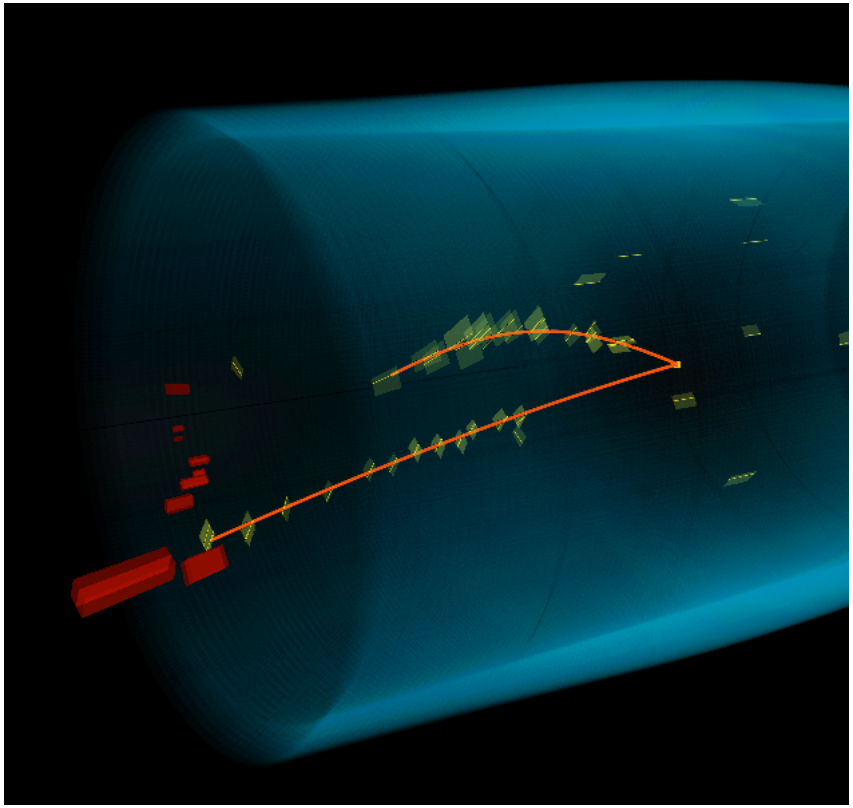
Dataset: low-pileup data in 2015 at

- $\sqrt{s} = 5.02$ TeV, 522 μb^{-1}
- $\sqrt{s} = 13$ TeV, 258 μb^{-1}

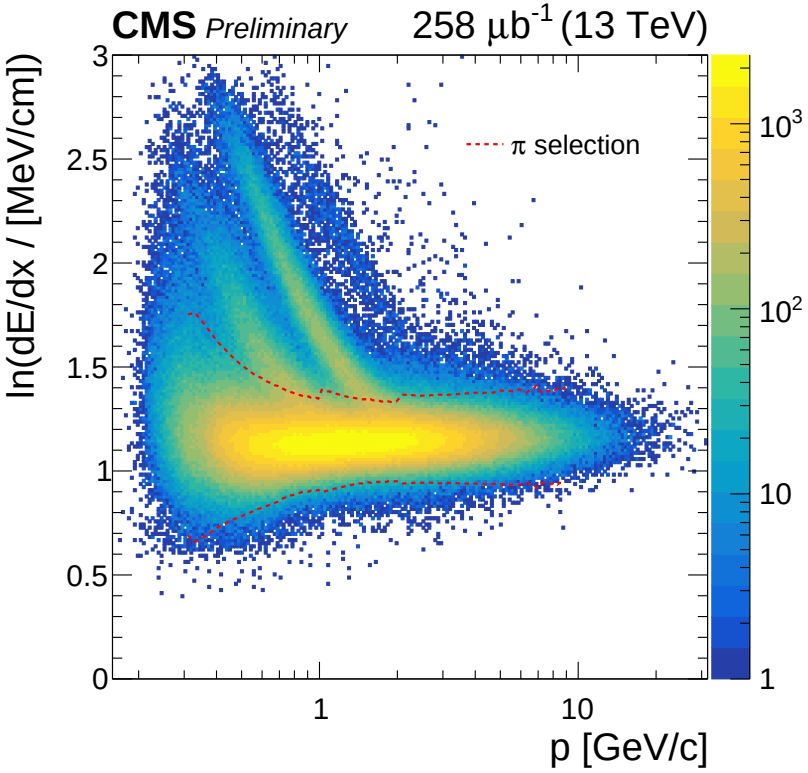
Trigger: random bunch-crossings (zero bias events)

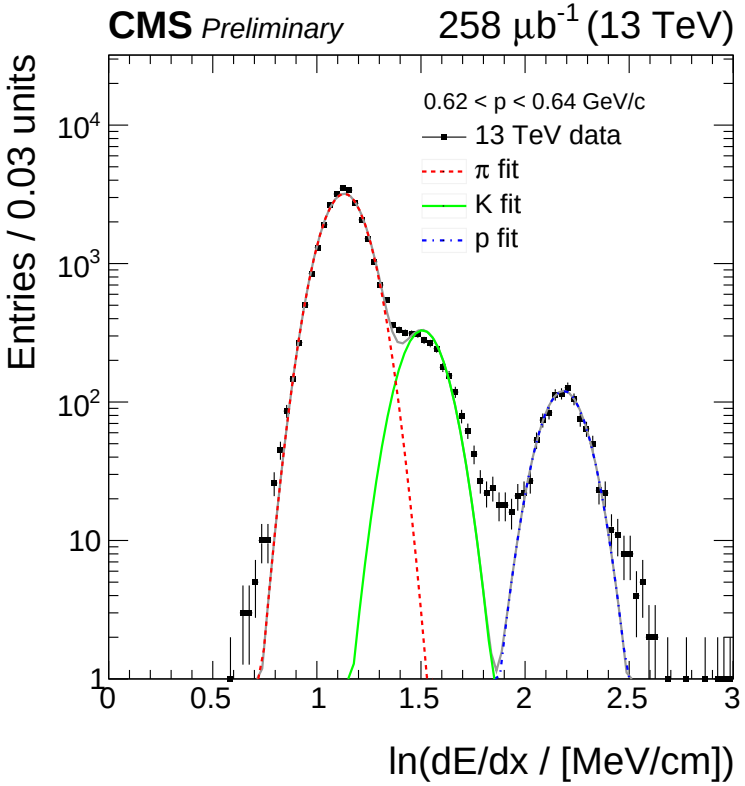
Event selection:

- Two tracks, passing high purity criteria.
- Single interaction vertex.
- No activity in calorimeters, except 3σ cone around track hits.
- π identification via dE/dx
- $p_T(\pi) > 0.2$ GeV, $|\eta(\pi)| < 2.4$.



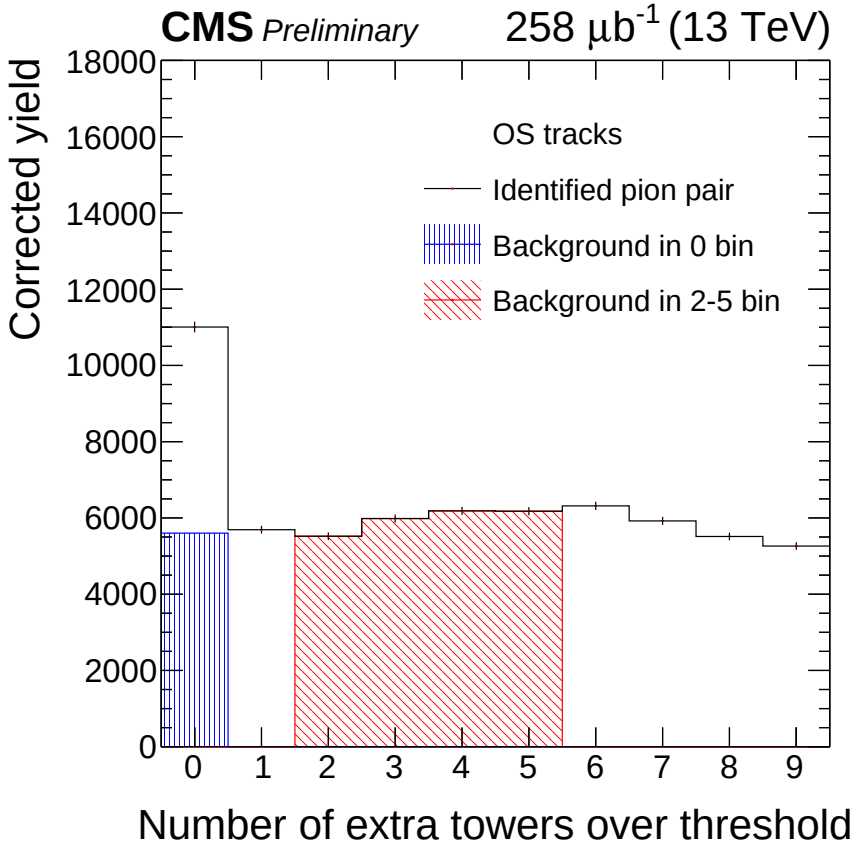
Particle identification





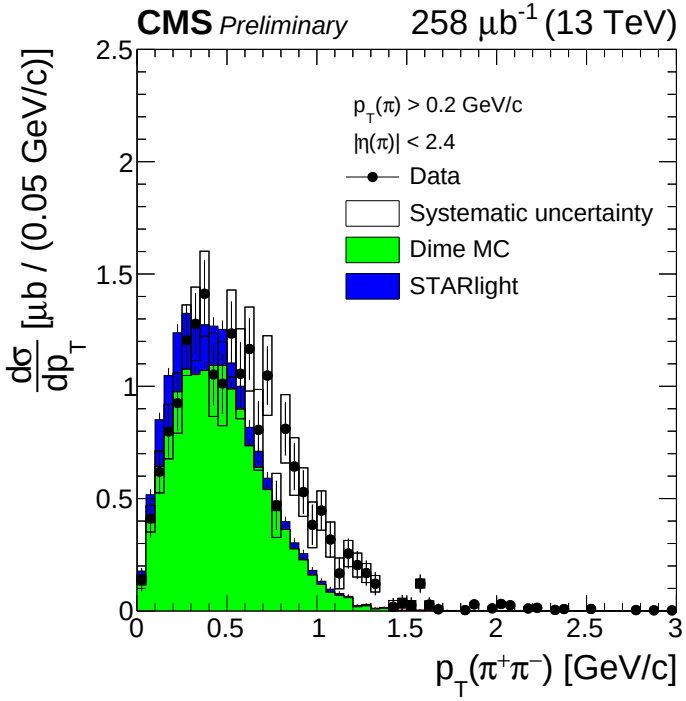
- Separate π and K candidates
- p-slices fitted with Gaussians
- High π identification efficiency $\rightarrow$ large K contamination, treated in the analysis

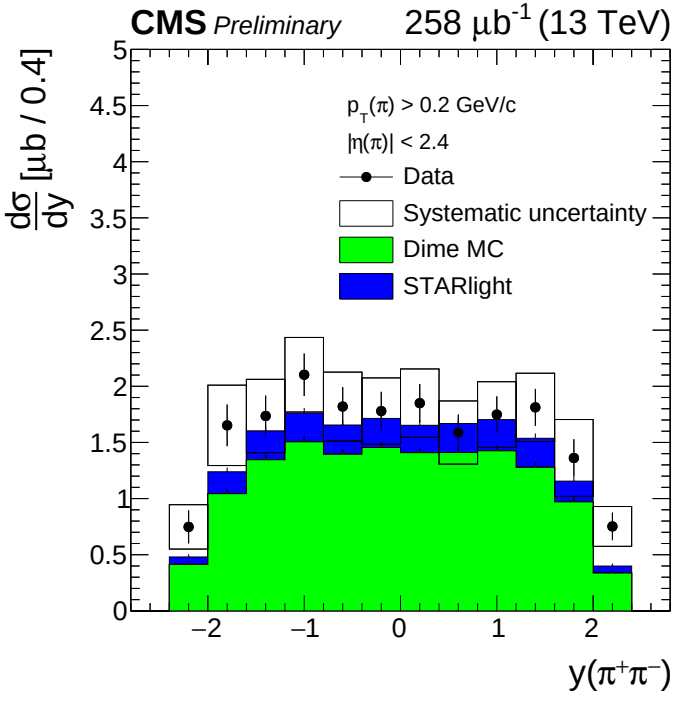
Multihadron background estimation



- Using a sample with extra calorimeter hits
- Background distribution from events with 2 – 5 extra calorimeter hits
- Normalization based on same sign distribution
- Systematic uncertainties from varying control region

Results



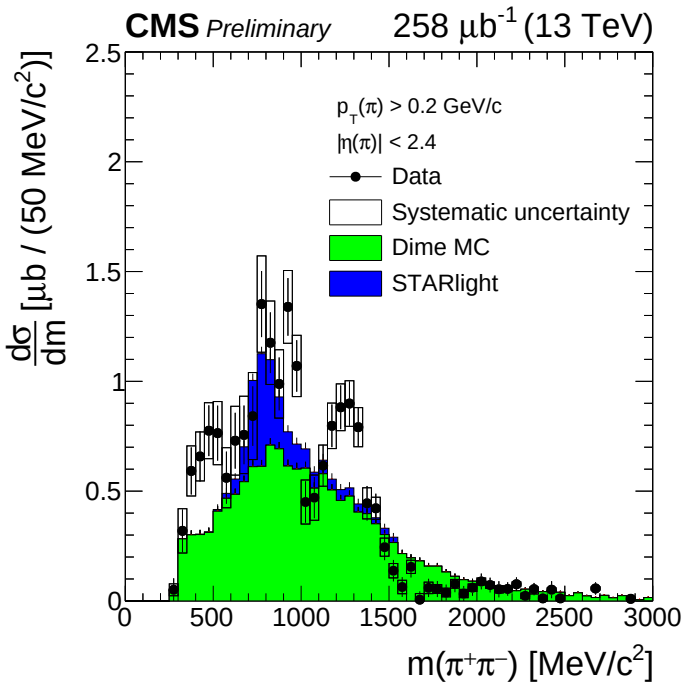


- STARLIGHT: exclusive $\rho(770)$ photoproduction.
- DIME MC: DPE continuum contribution.
- No simulation describes certain low mass resonances (f_0 and f_2).
- Total exclusive $\pi^+\pi^-$ cross section in $p_T(\pi) > 0.2$ GeV, $|\eta| < 2.4$:

$$\sigma(\sqrt{s} = 5.02\text{ TeV}) = 19.6 \pm 0.4\,(\text{stat.}) \pm 3.3\,(\text{syst.}) \pm 0.01\,(\text{lumi.})\ \mu\text{b}$$

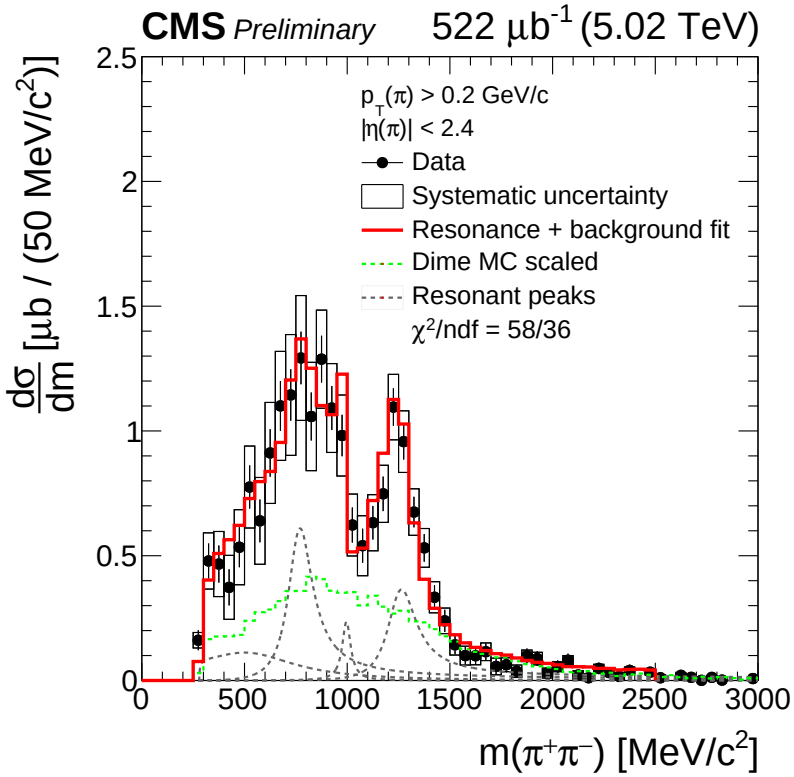
$$\sigma(\sqrt{s} = 13\text{ TeV}) = 19.0 \pm 0.6\,(\text{stat.}) \pm 3.2\,(\text{syst.}) \pm 0.01\,(\text{lumi.})\ \mu\text{b}$$

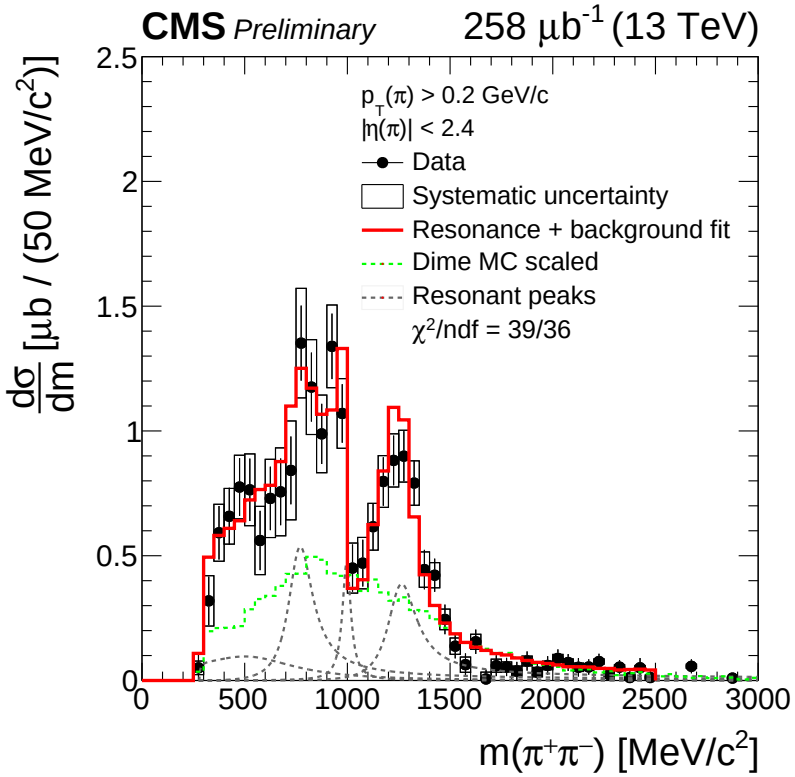
Results – invariant mass distribution



- Enhancement in $\rho(770)$ region
- Sharp drop at around 1 GeV
  - Indication of $f_0(980)$ resonance
  - Interference between resonance and continuum
- Significant peak at $f_2(1270)$
- Dime MC overestimates 1500 MeV region

Results – mass fits





- Fits with interfering Breit-Wigners
- Convolution with Gaussian to model resolution
- Resonance yields extracted

Results – resonance yields

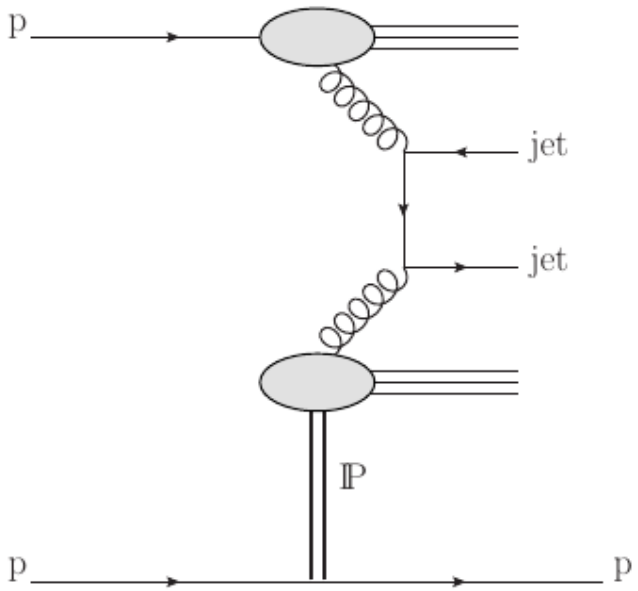
Resonance	$\sigma_{pp\to p'p'X\to p'p'\pi^+\pi^-}$ [μb]
	$\sqrt{s} = 5.02$ TeV
$f_0(500)$	1.7 ± 0.7 (stat.) ± 0.2 (syst.) ± 0.04 (lumi.)
$\rho^0(770)$	3.2 ± 0.7 (stat.) ± 0.3 (syst.) ± 0.1 (lumi.)
$f_0(980)$	0.3 ± 0.1 (stat.) ± 0.03 (syst.) ± 0.01 (lumi.)
$f_2(1270)$	1.9 ± 0.5 (stat.) ± 0.2 (syst.) ± 0.04 (lumi.)
	$\sqrt{s} = 13$ TeV
$f_0(500)$	1.4 ± 0.5 (stat.) ± 0.2 (syst.) ± 0.03 (lumi.)
$\rho^0(770)$	2.8 ± 0.8 (stat.) ± 0.3 (syst.) ± 0.1 (lumi.)
$f_0(980)$	0.6 ± 0.2 (stat.) ± 0.1 (syst.) ± 0.01 (lumi.)
$f_2(1270)$	2.0 ± 0.7 (stat.) ± 0.2 (syst.) ± 0.05 (lumi.)

STARlight results for $\rho^0(770)$:

- 5.02 TeV: 2.3 μb
- 13 TeV: 3.0 μb

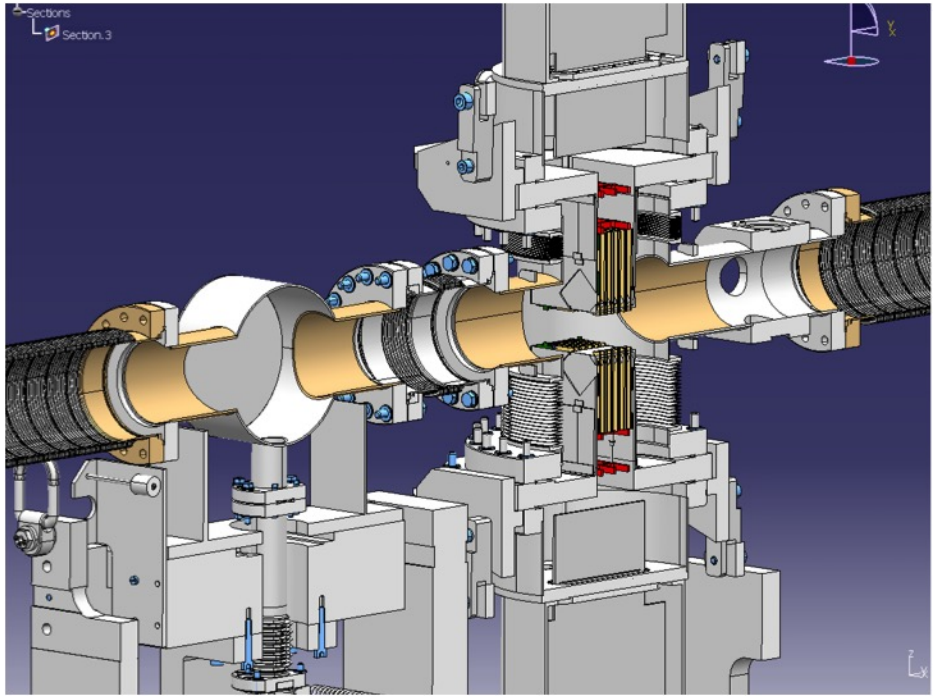
Diffractive dijets with proton tagging at 8 TeV

Motivation



- Single diffraction
- Rapidity gap around proton
- Factorization theorem: Convolution of diffractive PDFs and + pQCD
- Spoiled by soft rescattering

TOTEM Roman Pots



- Small tracking detectors, detect beam protons
- 147 m and 220 m from IP
- 4-momumten transfer squared:

$$t = (p_f - p_i)^2$$

- Fractional momentum loss:

$$\xi_{\text{TOTEM}} = 1 - \left| \frac{\mathbf{p}_f}{\mathbf{p}_i} \right|$$

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

Dataset, trigger, event selection

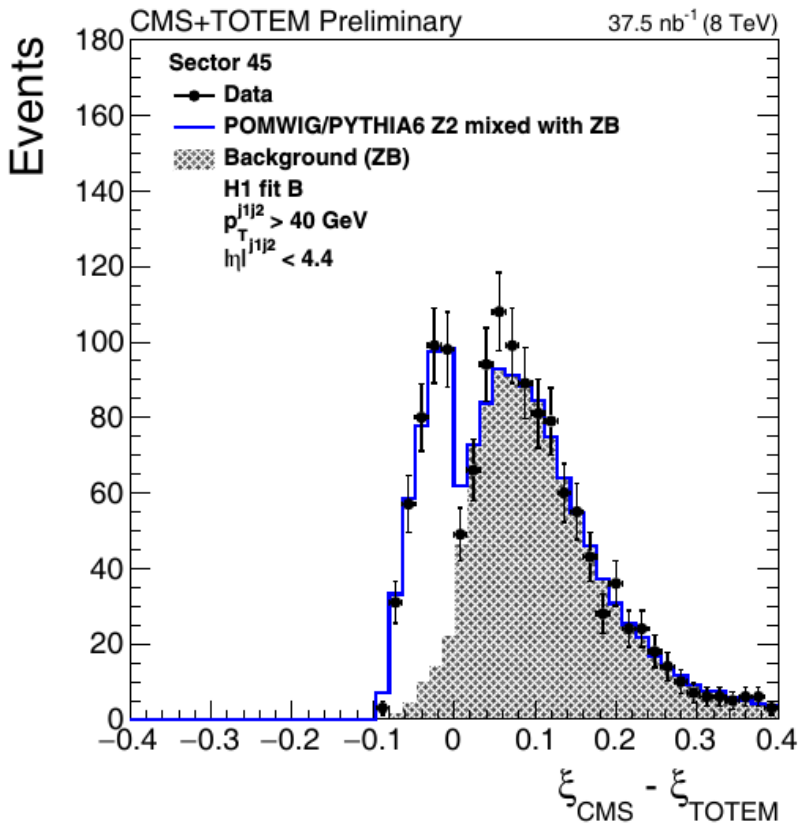
Dataset: low pileup pp at $\sqrt{s} = 8$ TeV, special beam optics: $\beta^* = 90$ m, 37.5 nb^{-1}

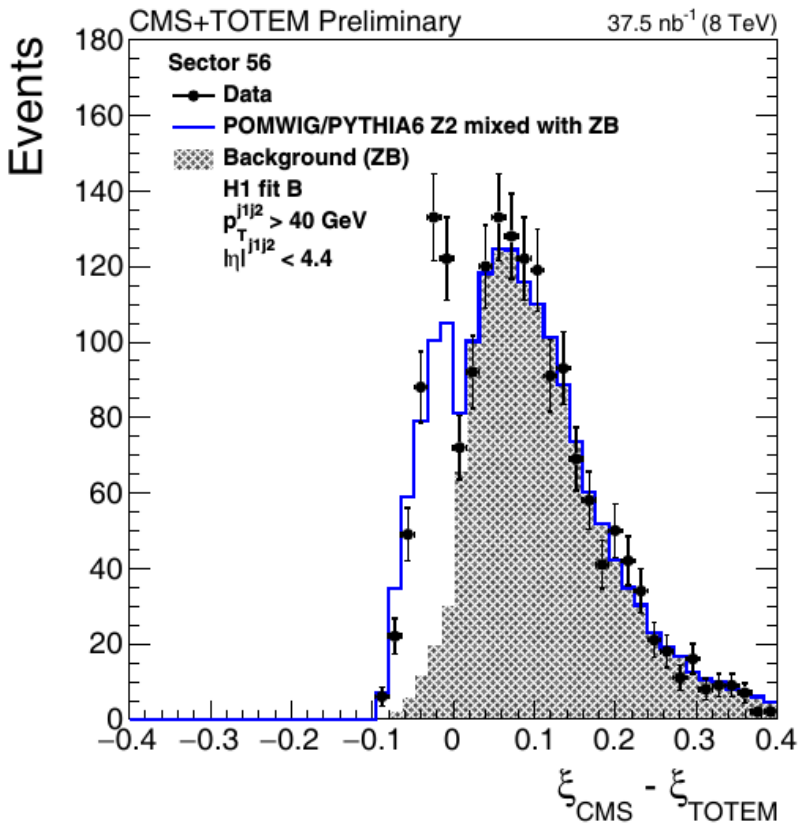
Trigger: dijets with $p_T > 20$ GeV

Event selections:

- At least two jets with $p_T > 40$ GeV and $|\eta| < 4.4$
- At least one reconstructed primary vertex
- At least one proton in RP
  - $0 < x_{RP} < 7$ mm and $8.4 < |y_{RP}| < 27$ mm
- Rejecting elastic events
- Kinematic cuts:
  - $0.03 < |t| < 1.0$ GeV^2 and $0 < \xi_{TOTEM} < 0.1$

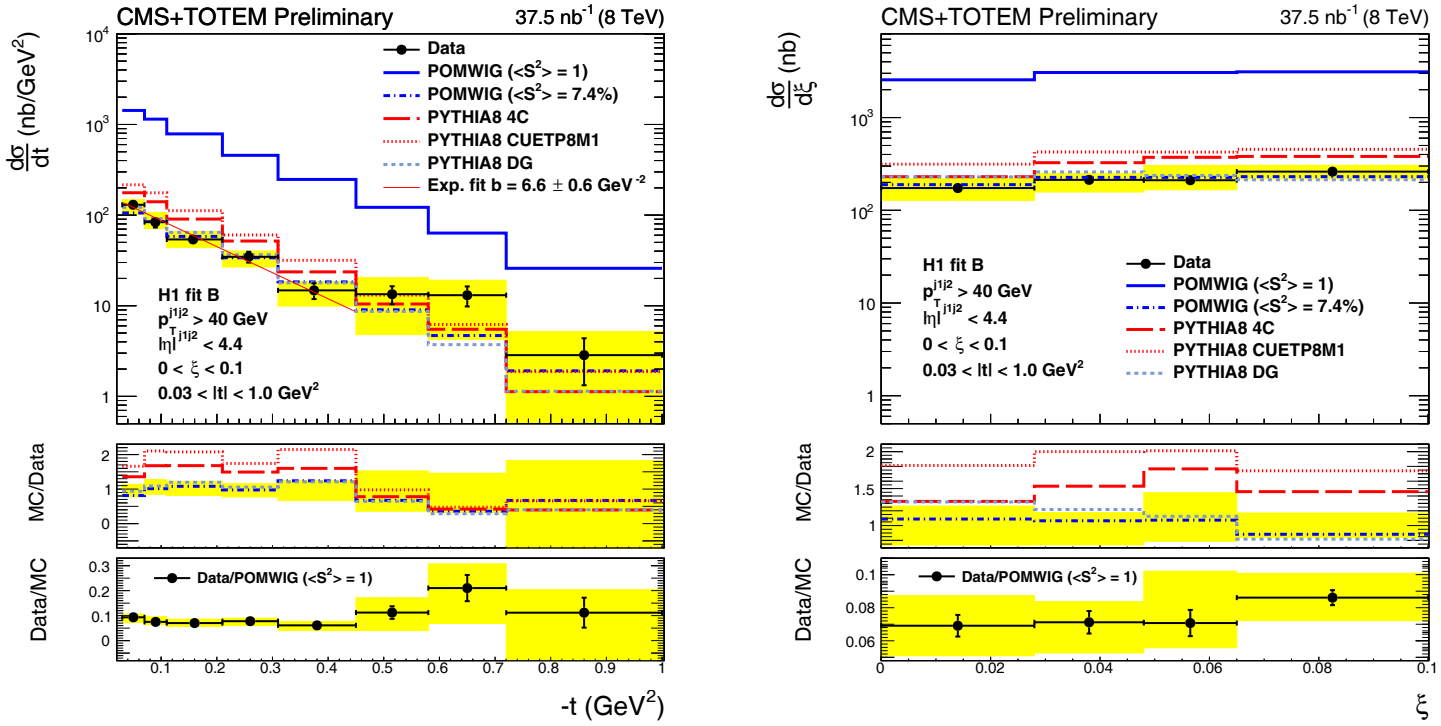
Background to diffractive dijets





- Background distribution from zero bias events
- To suppress background: $\xi_{\text{CMS}} - \xi_{\text{TOTEM}} \leq 0$

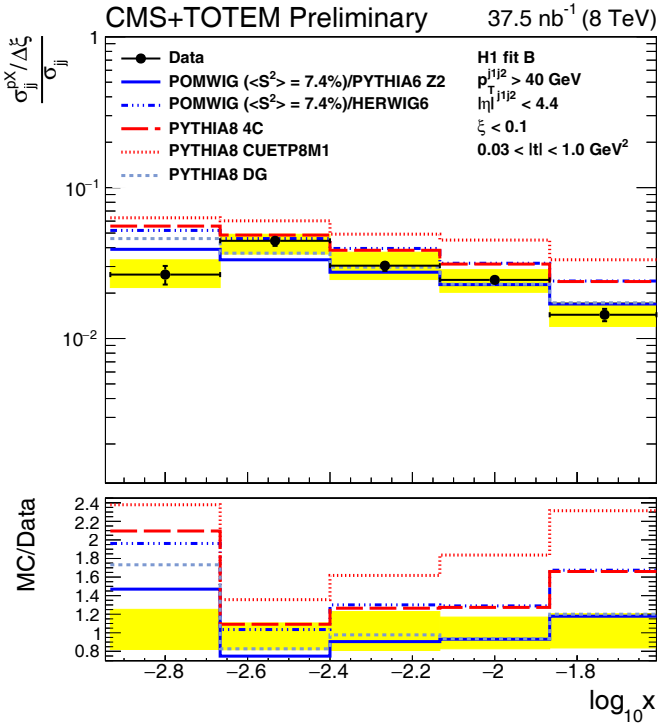
Results

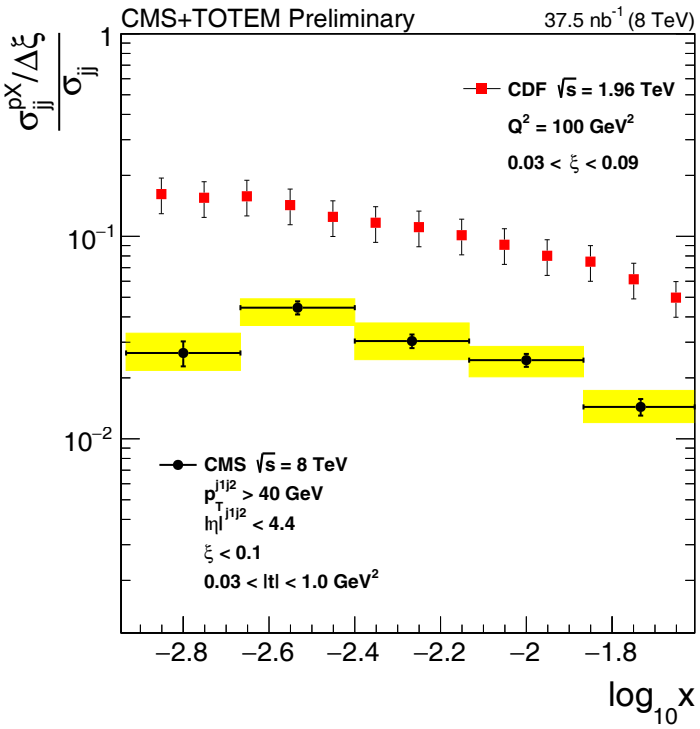


- Unfolded with iterative d'Agostini method
- Pythia 8 DG and Pomwig gives good description
- Pythia 8 4C and CUETP8M1 predicts higher contribution
- Cross section in the kinematic region:

$$\sigma_{jj}^{pX} = 21.7 \pm 0.9\ (\text{stat})^{+3.0}_{-3.3}\ (\text{syst}) \pm 0.9\ (\text{lumi})\ \text{nb}$$

Results

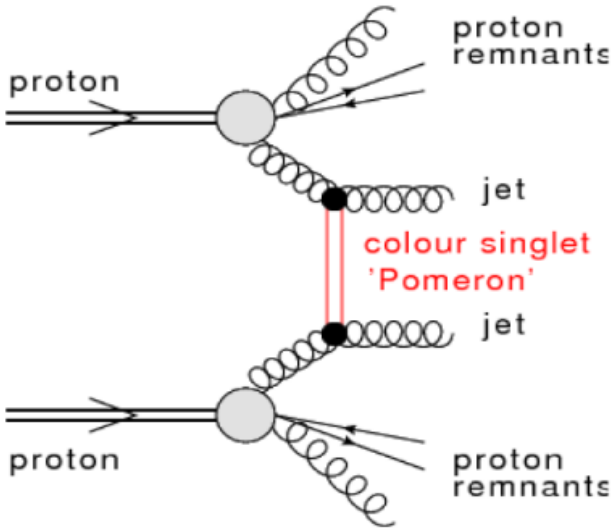




- Ratio of SD dijet versus inclusive dijet cross section
- Generally large deviation at low-x
- Pomwig and Pythia 8 DG gives better description
- Cross section decreased compared to CDF – feature already seen in CDF

Dijets with a large rapidity gap between jets at 7 TeV

Motivation



- Two jets with large p_T
- pQCD, described by DGLAP equations
- Large rapidity gap between jets:
  - BFKL equations give better description
- Color singlet exchange (CSE)

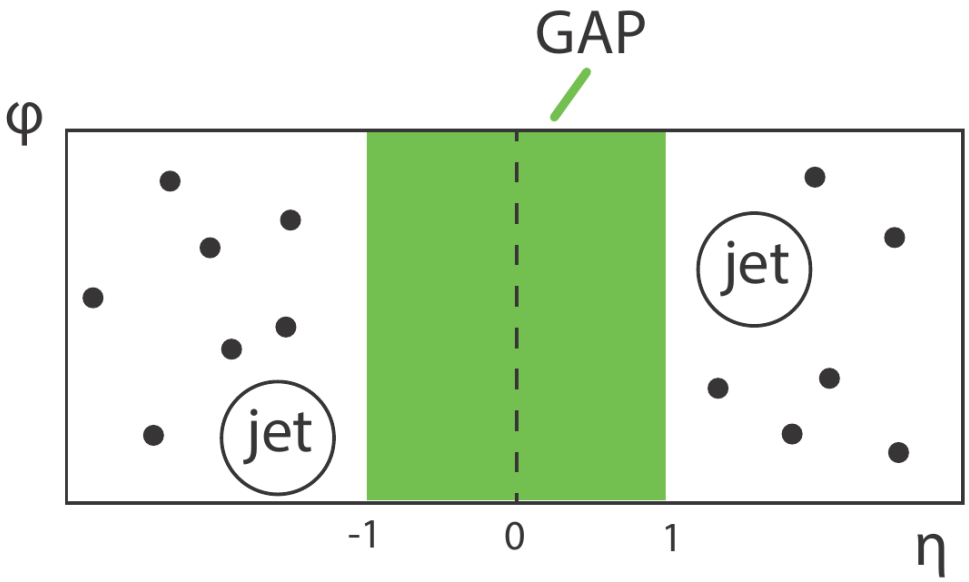
$\Rightarrow$ Described by pomeron

Dataset, trigger

Dataset: low pileup data at $\sqrt{s} = 7$ TeV (2010), 8 pb^{-1}

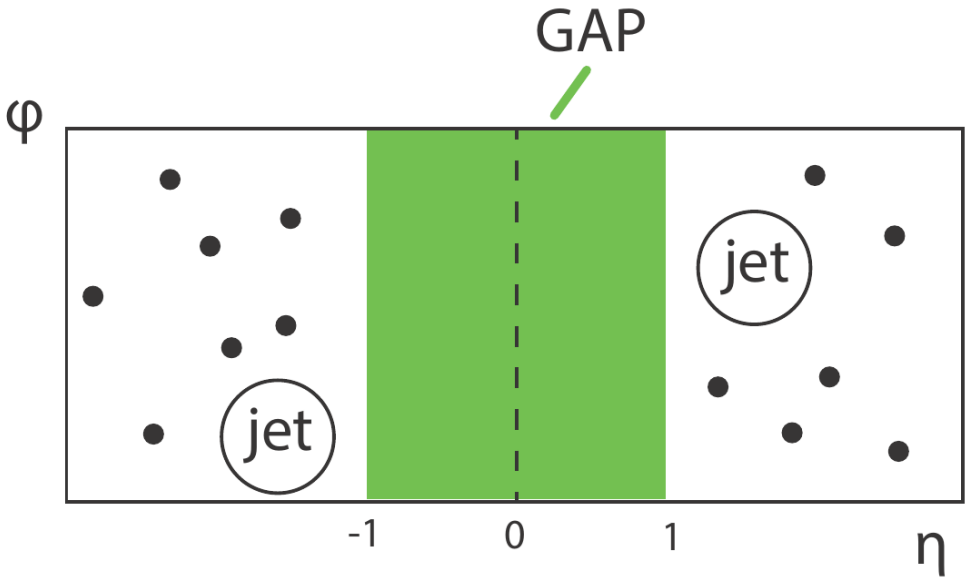
Trigger:

- Dijet with $p_T > 15$ and 30 GeV
- Single jet with $p_T > 70$ GeV

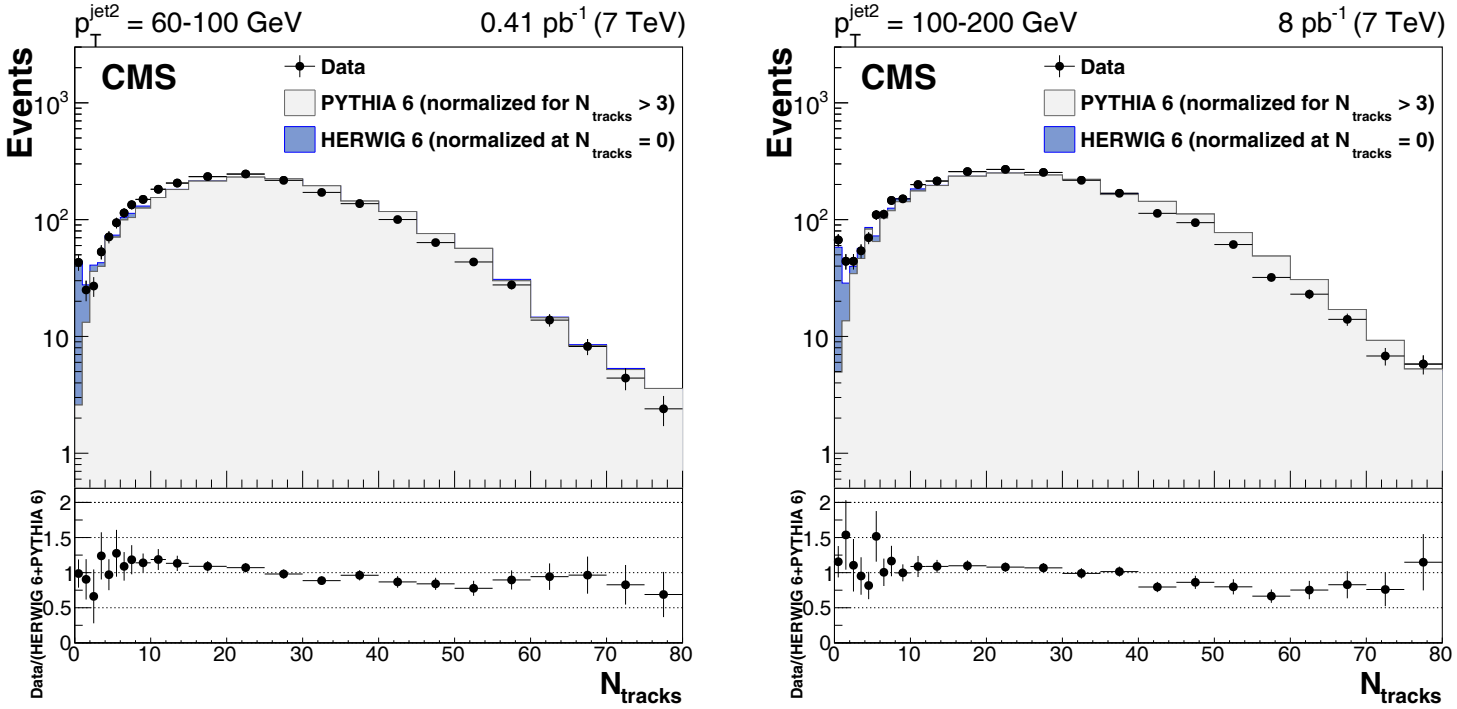


Event selections

- At least two jets
- Maximum one vertex with $|z| < 24$ cm
- Rejecting beam-scraping events
- Two leading jets in $1.5 < |\eta^{\text{jet}}| < 4.7$
- Leading jets with opposite η sign

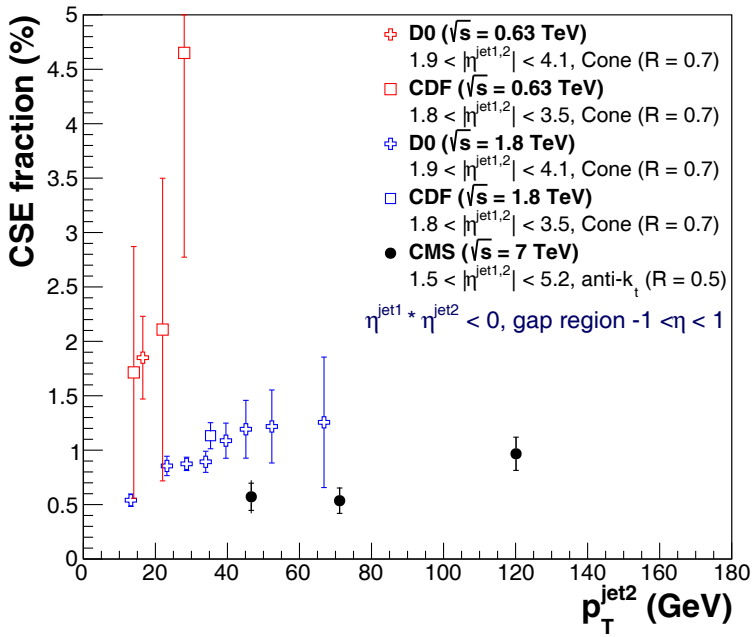


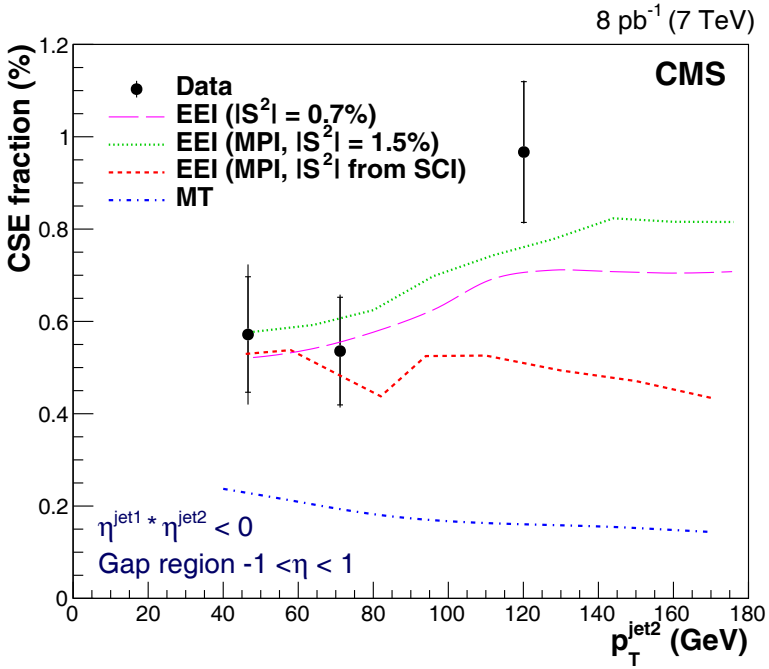
Track multiplicity in rapidity gap



- Pythia 6 with Z2*: LO DGLAP, non-CSE
- Herwig 6: LL BFKL, only CSE
- CSE fraction is measured
- Two methods to estimate non-CSE:
  - NBD fit on N_{track} distribution
  - Using same side jets

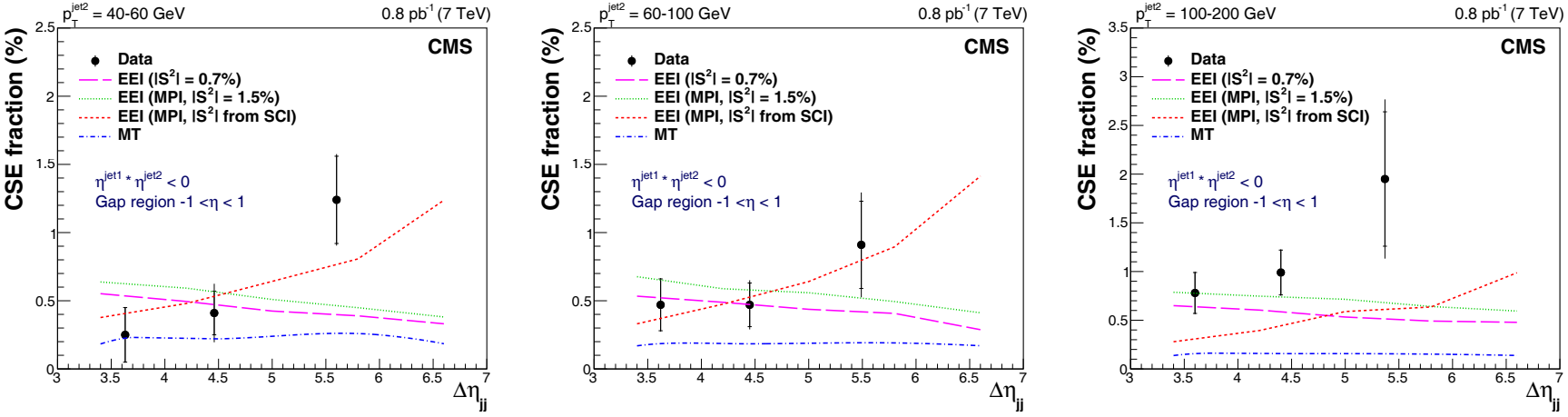
Results





- Factor of 2 decrease compared to $\sqrt{s} = 1.8$ TeV
  - Expected from Tevatron scaling
  - Stronger contribution from rescattering
- Mueller and Tang (MT) LL model does not reproduce the rise with $p_{T,\mathrm{jet2}}$ and underestimates the fraction of CSE events
- Ekstedt, Enberg and Ingelman (EII) NLL model gives better agreement

Results



- In three $p_T^{jet,2}$ bins
- MT model does not reproduce the rise with $\Delta\eta_{jj}$ and underestimates the fraction of CSE events
- EEI model with MPI and soft color interaction reproduces rise $\Delta\eta_{jj}$
- Other EEI settings provide decreasing trend

Inelastic cross section at 13 TeV

Motivation

- σ_{inel}: fundamental observable in high-energy particle, nuclear and cosmic ray physics
- Input for phenomenological hadronic interaction models
- Used in tuning of MC generators
- Crucial ingredient for Glauber models
- Important in estimation of pileup

Dataset, trigger, event selection

Dataset: low pileup datasets at $\sqrt{s} = 13$ TeV in 2015, with magnets on: 40.8 μb^{-1}, with magnets off: 28.0 μb^{-1}

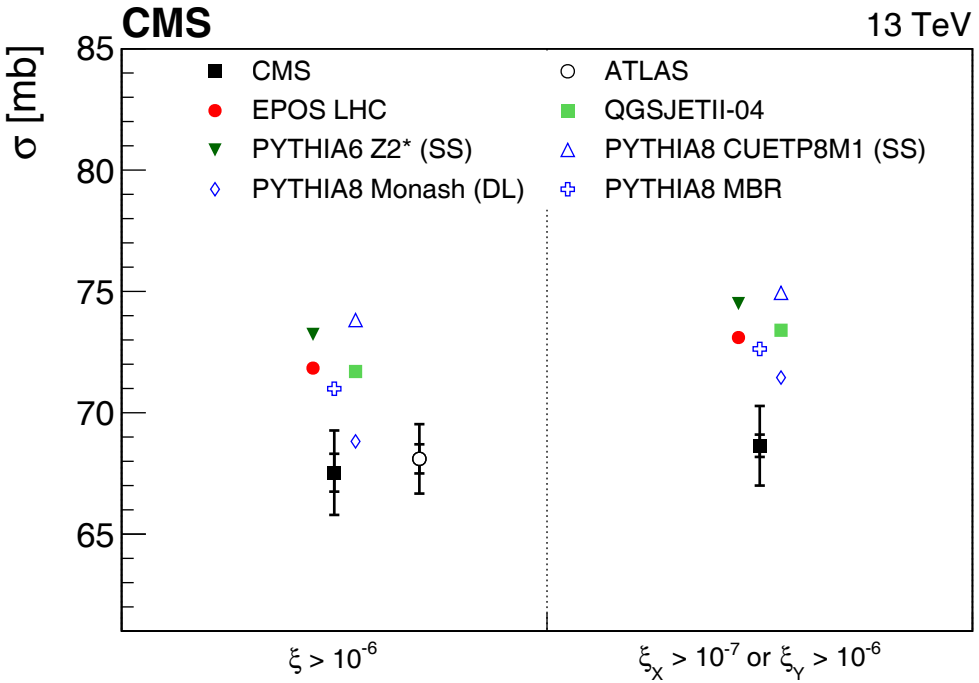
Trigger: random bunch crossings (zero bias)
+ single/no bunch triggers for calorimeter noise study

Event selection:

- Energy deposit larger than 5 GeV in HF
- OR larger than 5 GeV in CASTOR (only in $B = 0$ T)
- At stable particle level:
  - $\xi > 10^{-6}$ (HF only)
  - $\xi_X > 10^{-6}$, $\xi_Y > 10^{-7}$ (HF+CASTOR)

$$\xi_{X,Y} = \frac{M^2_{X,Y}}{s} \qquad \xi = \max(\xi_X, \xi_Y)$$

Results



- Pileup correction applied bunch-by-bunch
- Correction for detector effects based on MC samples
- Fully corrected inelastic cross section:

$$\sigma(\xi > 10^{-6}) = 67.5 \pm 0.8\ \text{(syst)} \pm 1.6\ \text{(lumi) mb}$$

$$\sigma(\xi_X > 10^{-6}\ \text{or}\ \xi_Y > 10^{-7}) = 68.6 \pm 0.5\ \text{(syst)} \pm 1.6\ \text{(lumi) mb}$$

Summary

NEW: Exclusive dipion production at 5.02 and 13 TeV

- $f_0(500)$, $\rho(770)$, $f_0(980)$ and $f_2(1270)$ resonances observed
- Total and resonant cross sections measured

Diffractive dijets with proton tagging at 8 TeV:

- Joint measurement of CMS and TOTEM
- Test of survival probability in different MC
- Scaling with $\sqrt{s}$ as expected from CDF

Dijets with a large rapidity gap between jets at 7 TeV:

- BFKL dynamics tested
- Scaling with $\sqrt{s}$ as expected from CDF

Inelastic cross section at 13 TeV:

- Cross sections in fiducial regions:

$$\sigma(\xi > 10^{-6}) = 67.5 \pm 0.8 \text{ (syst)} \pm 1.6 \text{ (lumi) mb}$$
$$\sigma(\xi_X > 10^{-6} \text{ or } \xi_Y > 10^{-7}) = 68.6 \pm 0.5 \text{ (syst)} \pm 1.6 \text{ (lumi) mb}$$

- Results consistent with ATLAS result

Thank you for your attention!