XXIV International Workshop on Deep Inelastic Scattering and Related Subjects

DESY (Hamburg), April 11th- 15th 2016

Soft and hard diffraction at CMS

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on behalf of the CMS Collaboration

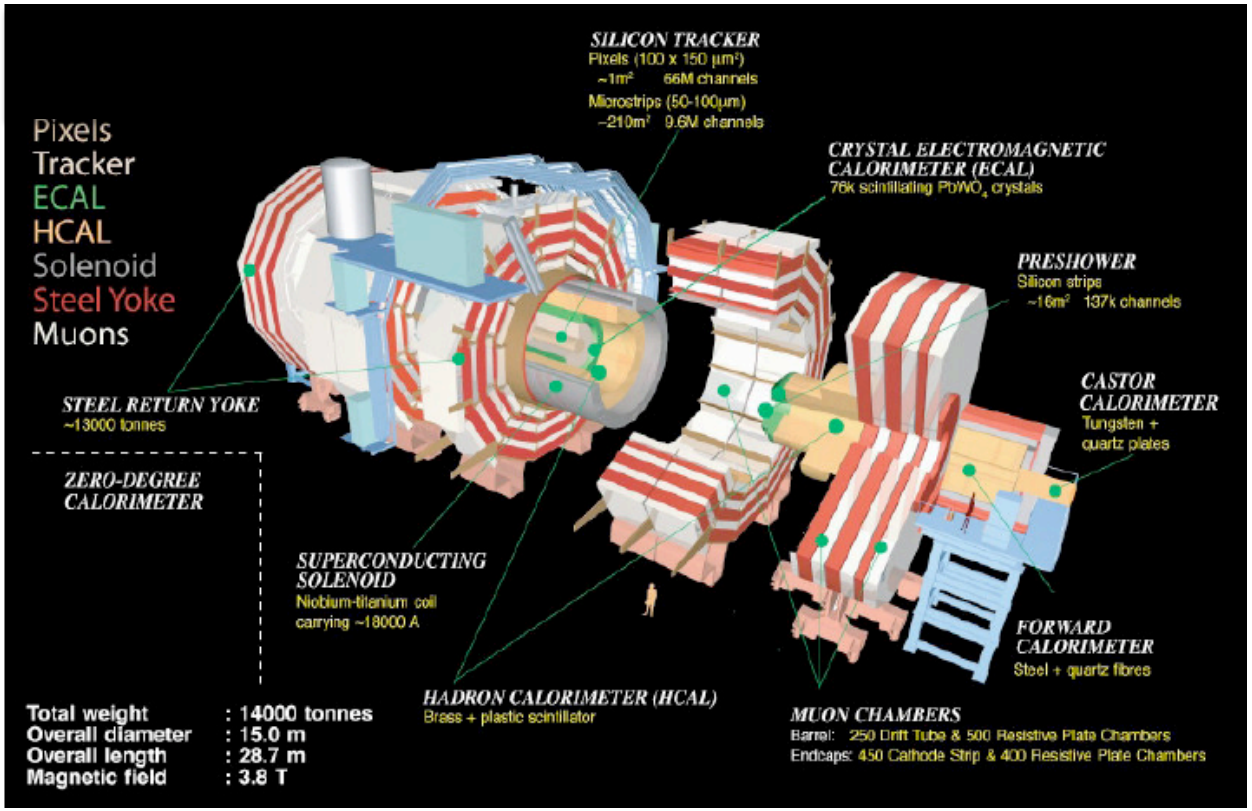
Outline

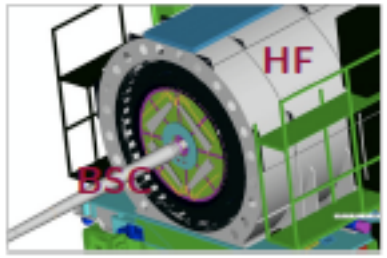
- CMS detector and forward instrumentation
- Introduction
- Single and double diffractive cross sections at $\sqrt{s}$ = 7 TeV
  [PRD 92 (2015) 012003]
- Forward rapidity gap cross section at $\sqrt{s}$ = 7 TeV
  [PRD 92 (2015) 012003]
- Jet-gap-jet
  [CMS PAS FSQ-12-001]

First observation at the LHC!

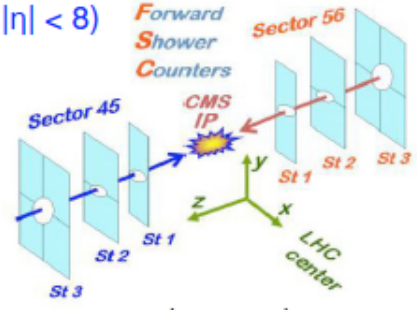
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

CMS detector forward instrumentation





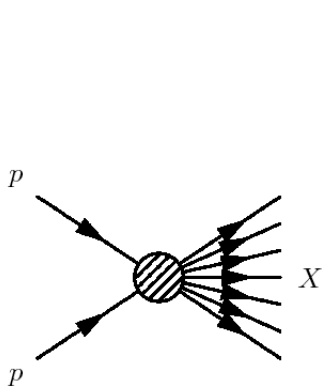
(6 < |η| < 8)



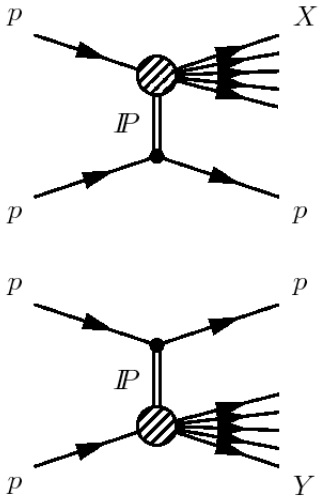
- **Hadron Forward calorimeter (HF):** 2.9 < |η| < 5.2 (10 m from IP)
- **Beam Scintillator Counters BSC :** 3.2 < |η| < 4.7 (in front of HF)
- **CASTOR calorimeter:** -6.6 < |η| < -5.2 (14.4 m from IP, one side only)
- **Forward Shower Counters FSC:** 6 < |η| < 8 (59-114 m from IP)
- **Zero Degree calorimeter:** |η| > 8.1 (140 m from IP)

+ TOTEM detector
(see Sercan's talk)

About diffractive and…

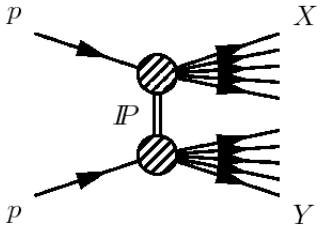


Non Diffractive (ND)

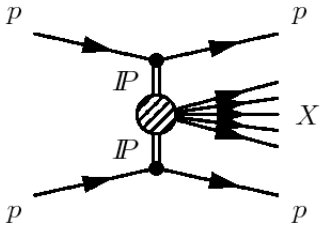


Single Diffractive (SD)

Double Diffractive (DD)



(c)



Double Pomeron Exchange (DPE)

- Energy of scattered protons ≈ beam energy (within a few %) → **protons in the final state**

  Pomeron exchange (IP), **Large Rapidity Gap (LRG)**

- **If X = anything:**
  - Measure fundamental quantities of soft QCD
  - Contributes significantly to pile-up, underlying event (SD ~ 15 mb, DD ~ 10 mb)

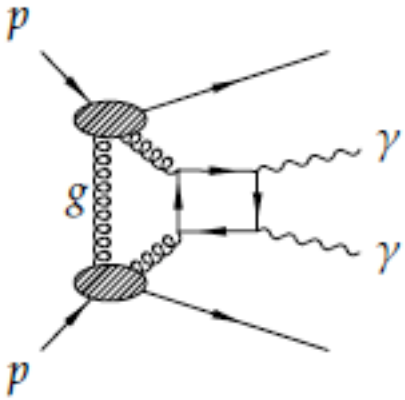
- **If X includes jets, W's, Z's:**
  - **Hard processes, calculable in perturbative QCD**
  - **Measure proton structure, QCD at high parton densities, discovery physics**

…exclusive reactions

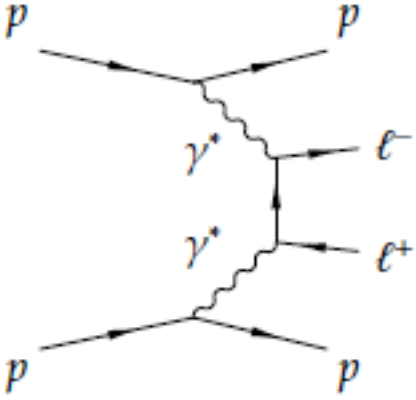
Study the reaction

$$pp \rightarrow p^{(*)}Xp^{(*)}$$

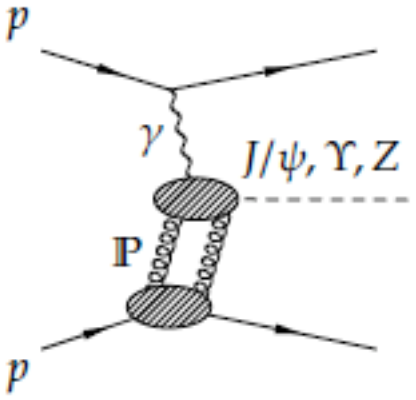
where numerous production mechanisms can contribute to produce the central system
X = e^+e^-, $\mu^+\mu^-$, $\gamma\gamma$, W^+W^-, …



IPIP exchanges



γγ interactions



γIP fusion

R. Chudasama's, M. Khazad, D. Takaki

Challenge to tag the LRG with CMS

- The rapidity gap(s) maybe **very forward and outside CMS acceptance**
- **Pileup** events destroy the gap(s)
- The **gap(s) survival probability** is low

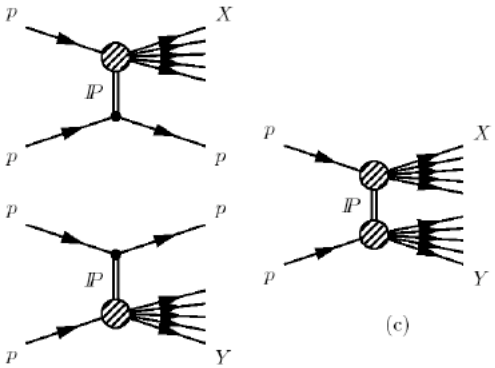
→ LRG not always/really usable → proton tracking (and timing) detectors

☐ Already installed
- TOTEM Roman Pot (RP) stations
  N.B.: joint TOTEM-CMS data

S. Sen

☐ > 2016
- CT-PPS (CMS-TOTEM)

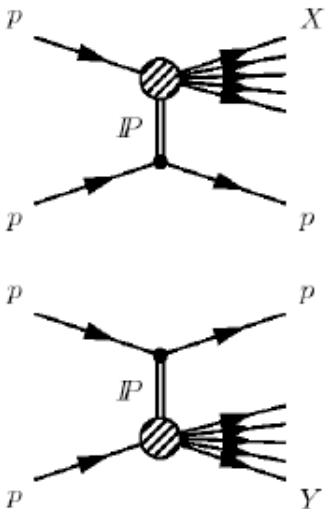
Exclusive analyses based on vertexing still possible in a pileup environment



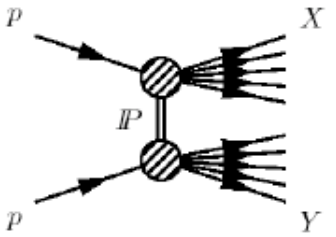
Soft diffractive cross sections

Event selection

- Based on Large Rapidity Gap (LRG) tagging
- Kinematics defined by M_X and M_Y
  (hadronic systems with largest separation in rapidity)
- Single and double diffractive contributions
  separated with CASTOR tag (-6.6 < |η| < -5.2)



single diffractive
SD



double diffractive
DD

Sample
16.2 μb^{-1} low pileup (μ=0.14) data at $\sqrt{s}$ = 7 TeV

Selection
minimum bias trigger
no vertex requirement (to retain M_X < 100 GeV)

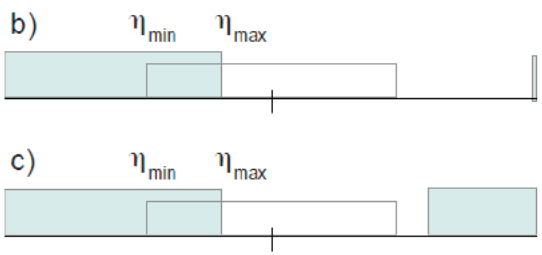
LRG cut based on Particle Flow (PF) objects

Monte Carlo
acceptance+background: PYTHIA8-MBR, diffraction with Minimum Bias Rockfeller model
systematics: PYTHIA8-4C, diffraction with Schuler & Sjostrand model from PYTHIA6

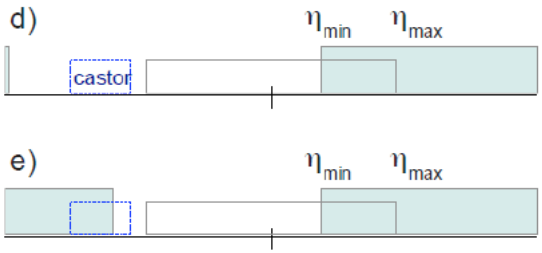
Experimental topologies

- 3 experimental topologies based on the position of the LRG

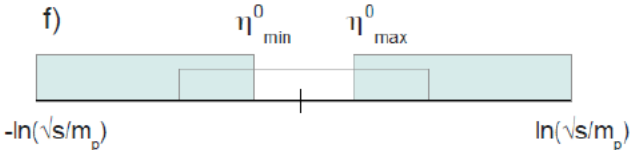
GAP ON POSITIVE SIDE



GAP ON NEGATIVE SIDE



CENTRAL GAP



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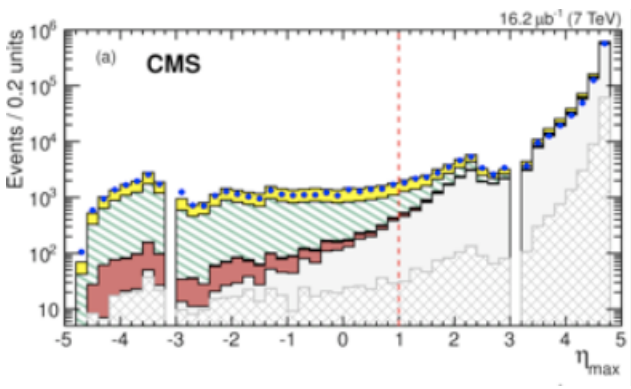

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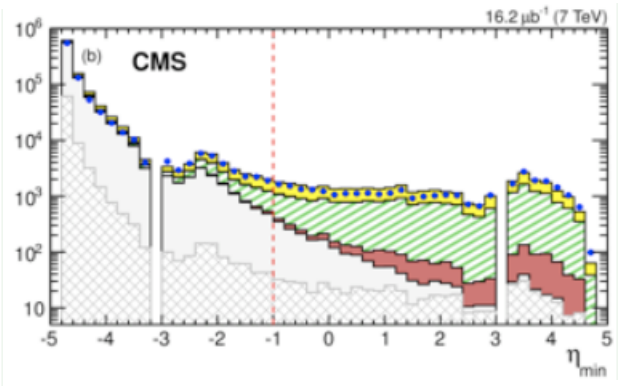

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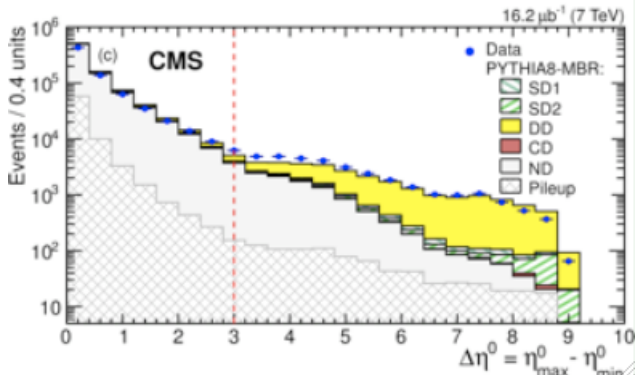
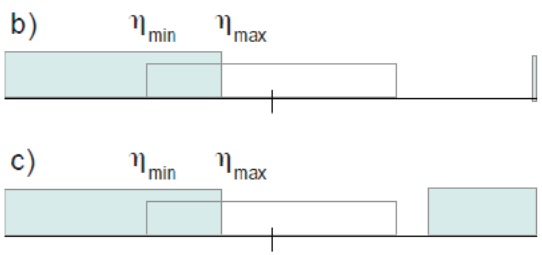
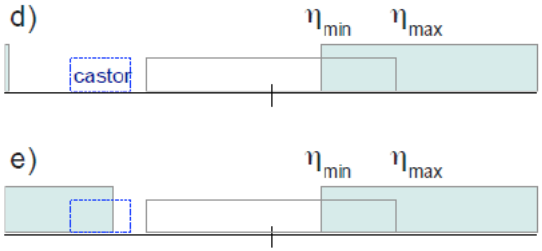
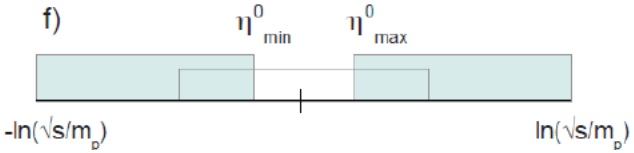


η_{max} (η_{min}): highest (lowest) η of the particle candidates in $|\eta| < 4.7$

$\Delta\eta^0$: difference between the closest-to zero positive (η^0_{max}) and negative (η^0_{min}) η of the particle candidates in $|\eta| < 4.7$







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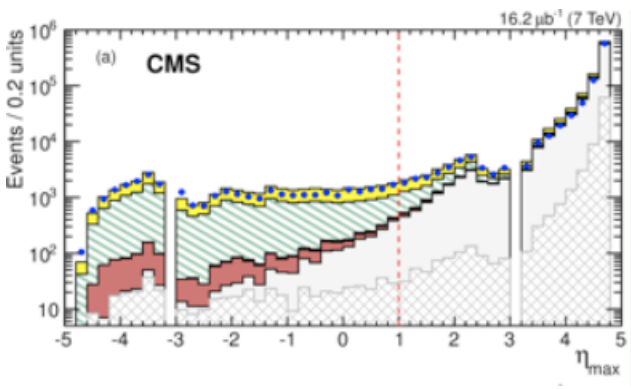

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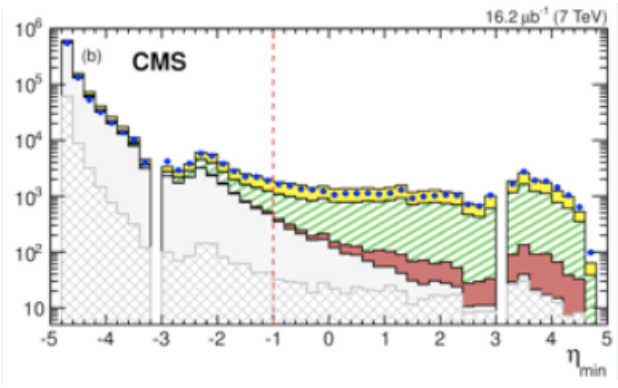

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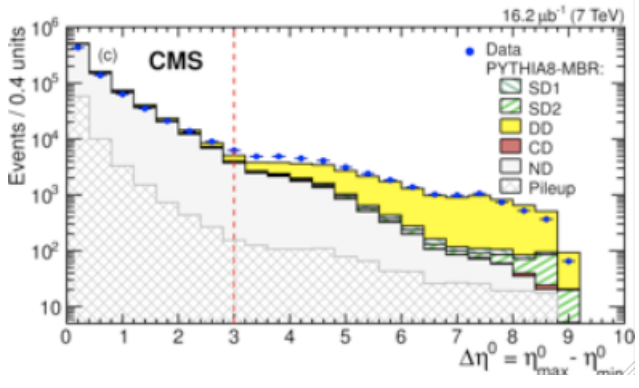

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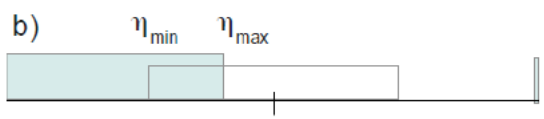
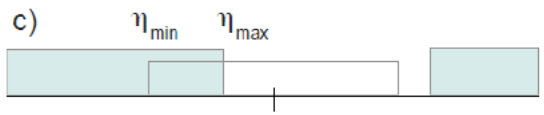
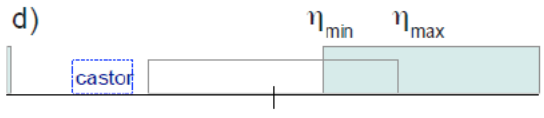
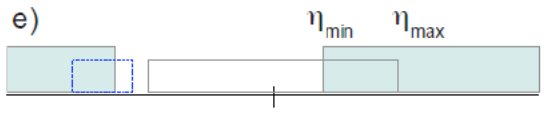
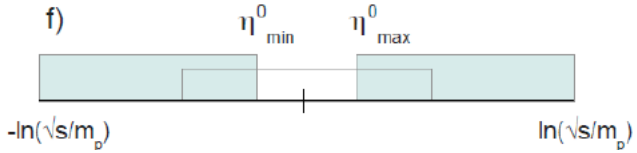








dominated by SD and DD events



dominated by DD events

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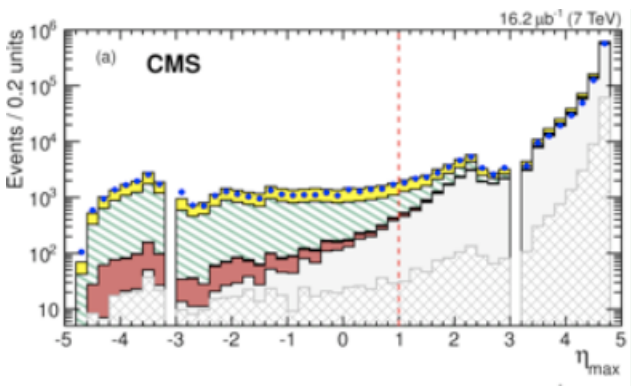
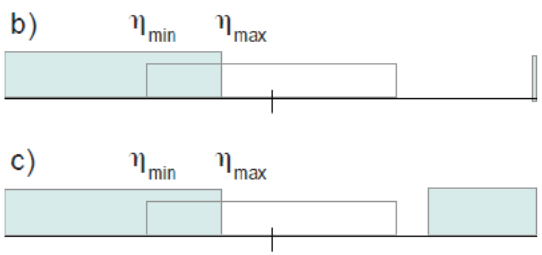
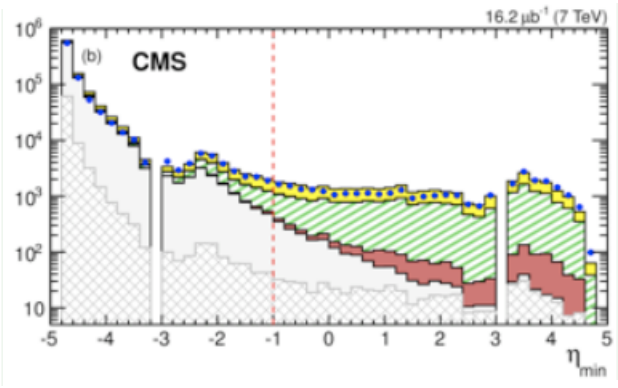


$\eta_{max} < 1$

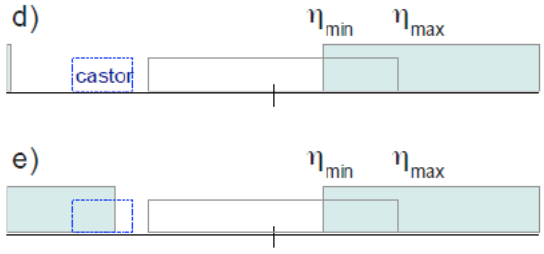


control sample

GAP ON NEGATIVE SIDE



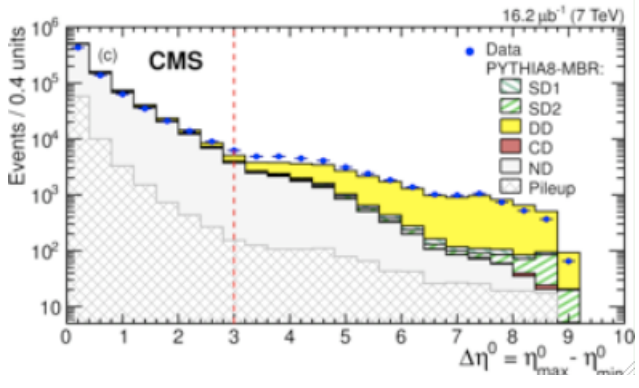
$\eta_{min} > -1$



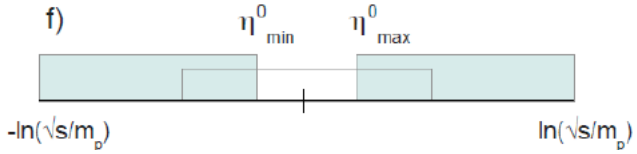
SD and DD cross sections

CASTOR used to tag the undetected low mass system in $-6.6 < \eta < -5.2$

CENTRAL GAP



$\Delta\eta_0 > 3$



DD cross section

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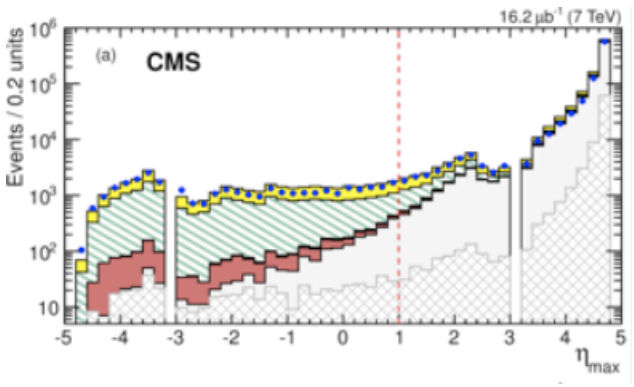
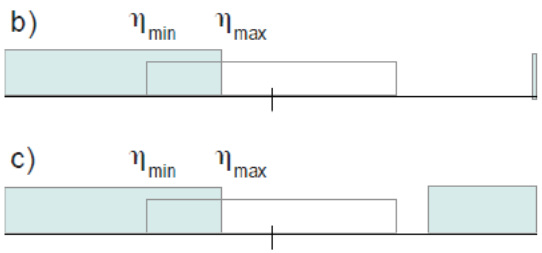


η_{max} <1



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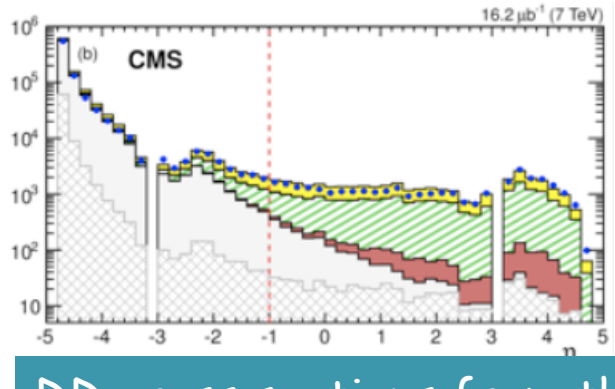

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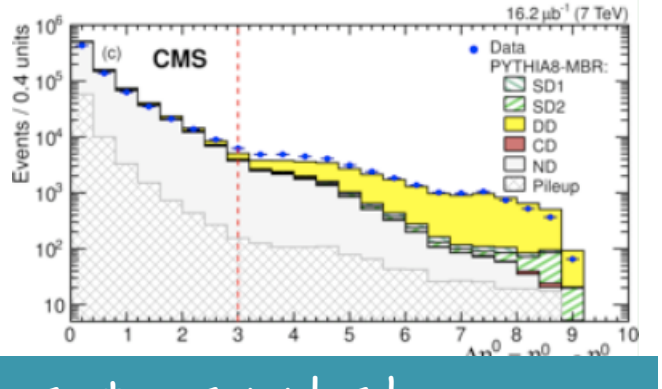
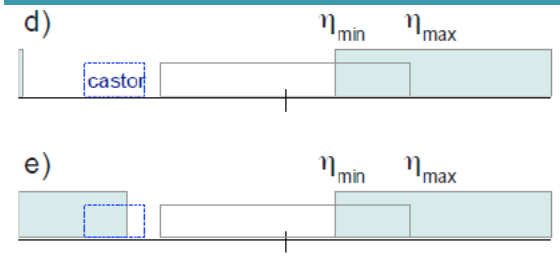


DD cross sections from these two samples have different (M_X,M_Y) coverages:

$1.1 < \log_{10} M_x < 2.5$ $\quad$ $\log_{10} M_x > 1.1$

$0.5 < \log_{10} M_y < 1.1$ $\quad$ $\log_{10} M_y > 1.1$



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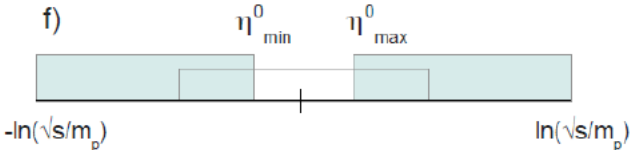

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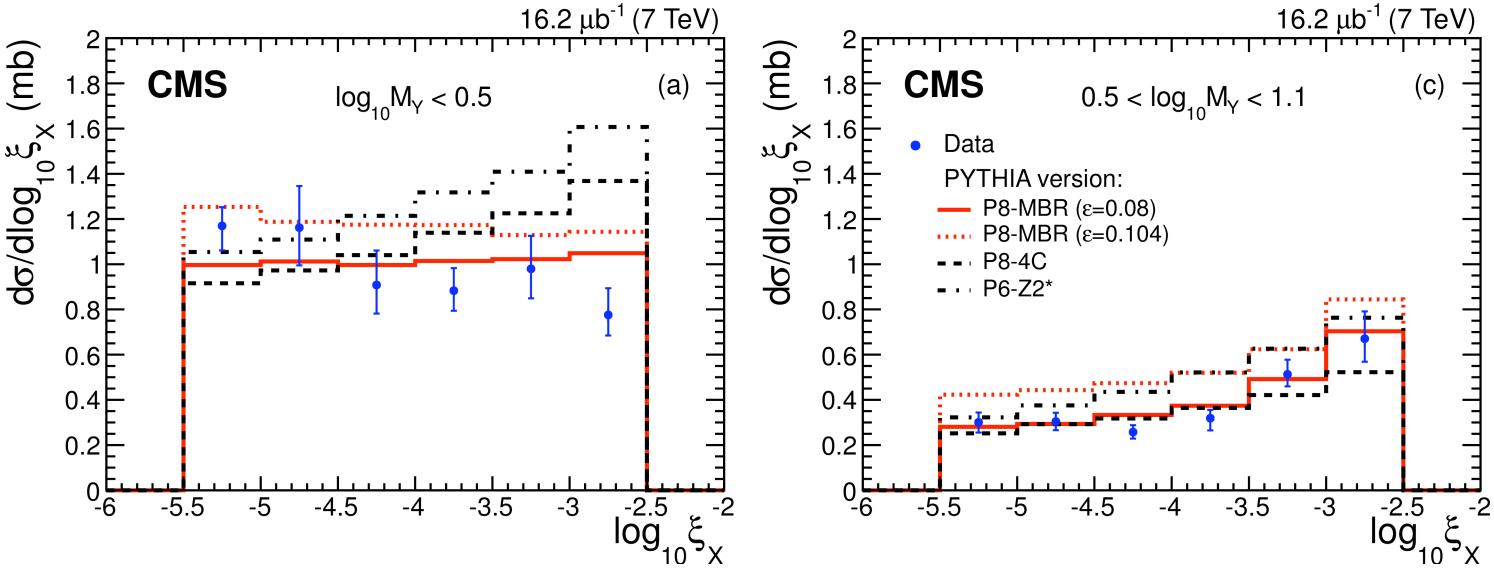
SD and DD cross sections vs ξ

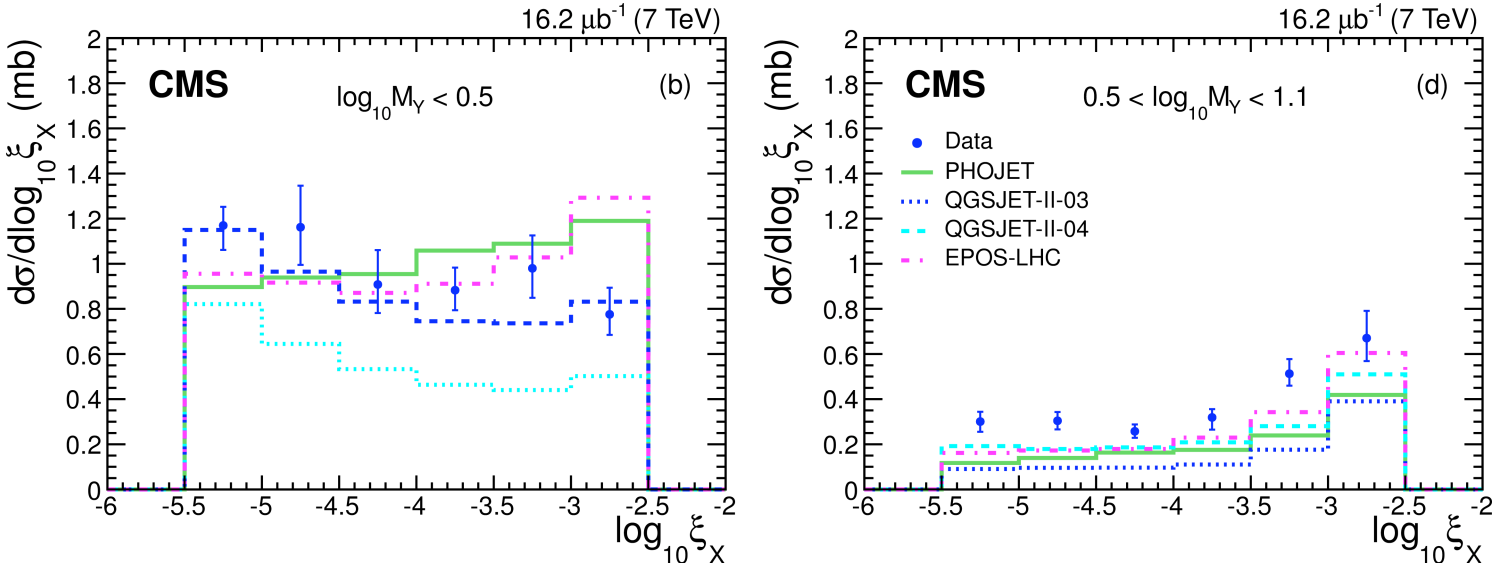


$$\frac{d\sigma}{d\log_{10}\xi_X} = \frac{N^{evt}}{\mathcal{L}(\Delta\log_{10}\xi_X)_{bin}}$$

with ξ = $\frac{M_X^2}{s} = \frac{\sum(E^i + p_z^i)}{\sqrt{s}}$ proton fractional momentum loss reconstructed from particle candidates in |η| < 4.7

- MBR model for 2 values of the Pomeron intercept α_{IP} (0) (1.08 e 1.104)
- Same implementation of Schuler & Sjostrand model in PYTHIA8-4C and PYTHIA6

SD and DD cross sections vs ξ



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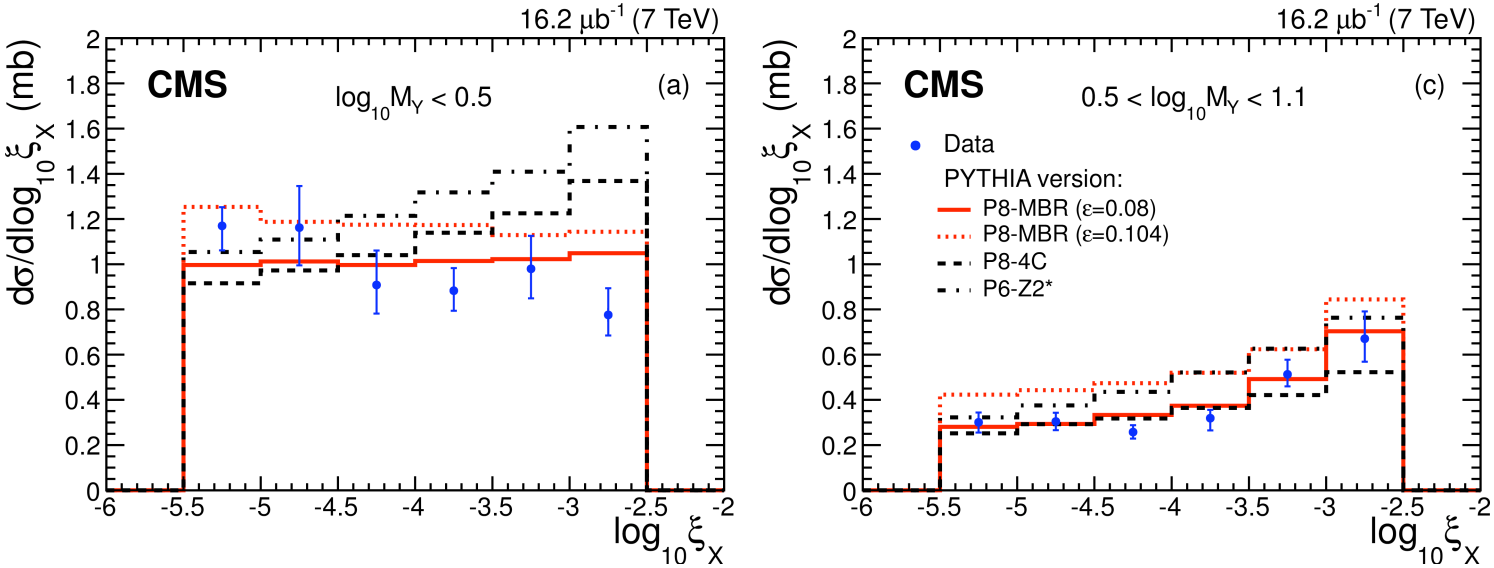

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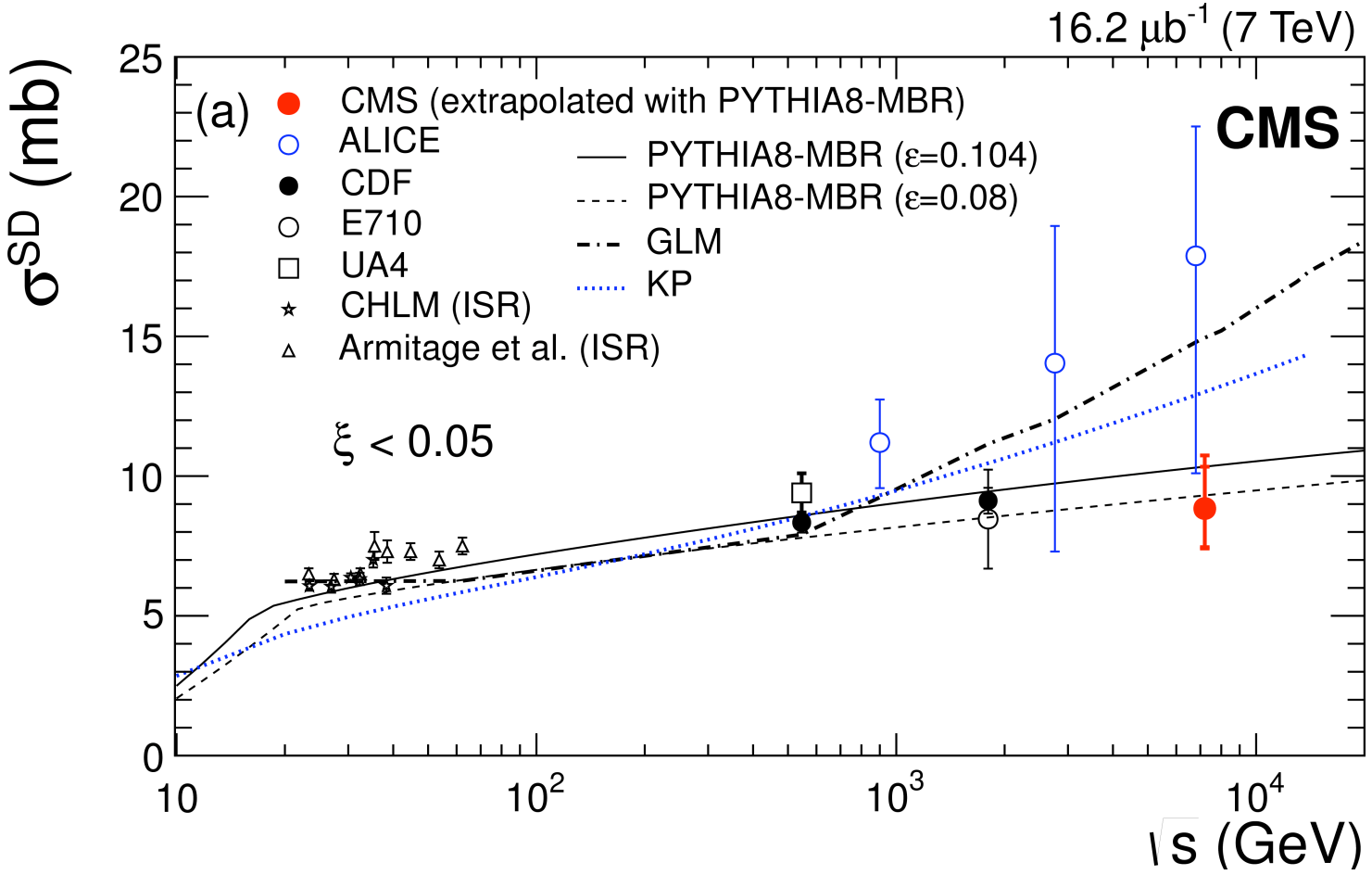
- Same implementation of Schuler & Sjostrand model in PYTHIA8-4C and PYTHIA6

Cross section integrated over -5.5 < log ξ < -2.5, then background-corrected to obtain

$$\sigma_{vis}^{SD} = 4.06 \pm 0.04(stat.) + 0.69/-0.63(syst.) \text{ mb}$$

Extrapolation to ξ < 0.05 with PYTHIA8-MBR →

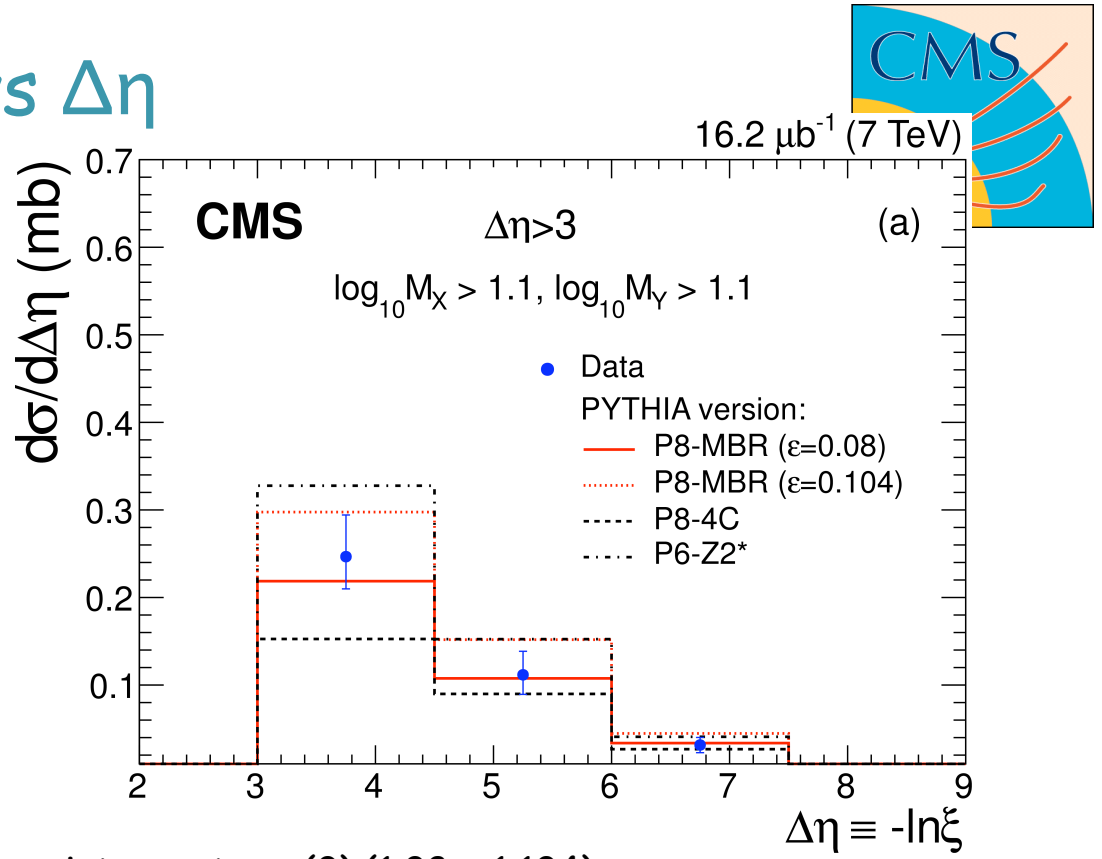
SD cross section



DD cross section vs Δη

$\Delta\eta = -\ln \xi$ $\quad \xi = \frac{M_X^2 \cdot M_Y^2}{s \cdot m_p^2}$

$$\frac{d\sigma}{d\Delta\eta} = \frac{N^{evt}}{\mathcal{L}(\Delta\eta)_{bin}}$$



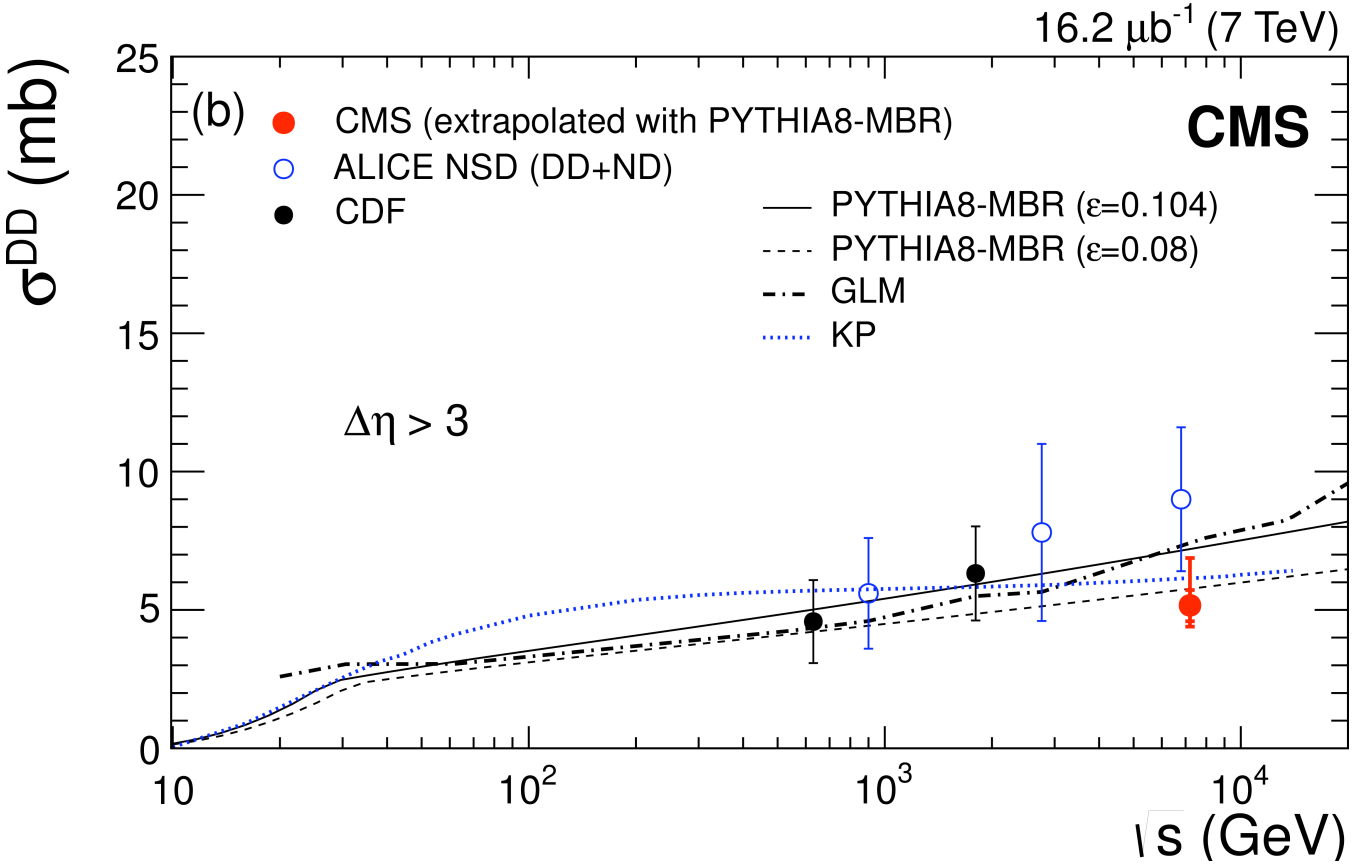
- MBR model for 2 values of the Pomeron intercept α_{IP} (0) (1.08 e 1.104)
- Same implementation of Schuler & Sjostrand model in PYTHIA8-4C and PYTHIA6

Cross section integrated over -5.5 < log ξ < -2.5, then background-corrected and summed between the forward and central gap samples to obtain

$$\sigma_{vis}^{DD} = 2.69 \pm 0.04(stat.) + 0.29/-0.30(syst.) \text{ mb}$$

Extrapolation to Δη>3 with PYTHIA8-MBR →

DD cross section



Forward rapidity gap cross section

Event selection

- Inclusive measurement, no separation of SD and DD

Sample

16.2 μb^{-1} low pileup (μ=0.14) data at $\sqrt{s}$ = 7 TeV

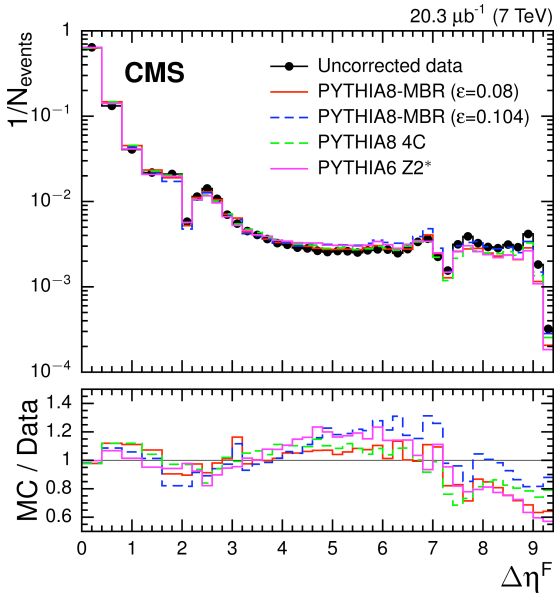
Selection

minimum bias trigger (hit in either of the BSCs)
based on Particle Flow (PF) objects
at least 2 PF in the BSC acceptance
no vertex requirement (to retain M_X < 100 GeV)

Monte Carlo

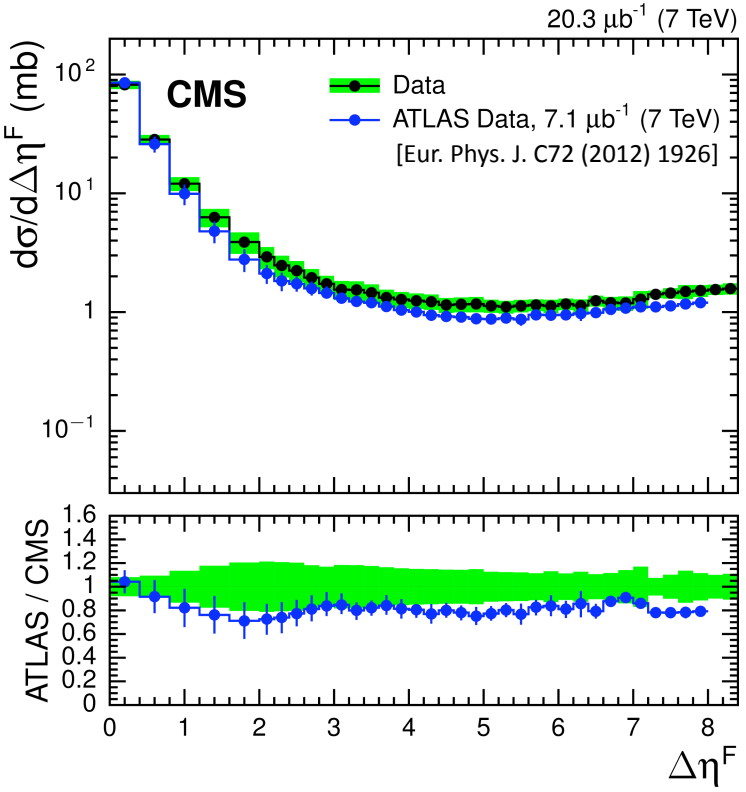
PYTHIA8-MBR, diffraction with Minimum Bias Rockfeller model
PYTHIA8-4C, diffraction with Schuler & Sjostrand model from PYTHIA6
PYTHIA6-Z2*

Forward rapidity gap $\Delta\eta_F = \max(4.7-\eta_{max}, 4.7+\eta_{min})$
largest gap between each edge of the detector and the position in η of the first partice found in moving away from the edge



Forward rapidity gap cross section

COMPARISON TO ATLAS



$$\frac{d\sigma}{d\Delta\eta^F} = \frac{N^{evt}}{T_e \mathcal{L}(\Delta\eta^F)_{bin}}$$

- Different hadron level definition:
  $|\eta| < 4.7$ (CMS) vs $|\eta| < 4.9$ (ATLAS)
  → up to 5% effect

- Unfolding based on different MCs:
  PYTHIA8-MBR (CMS) vs PYTHIA8 (ATLAS)
  → up to 10% effect

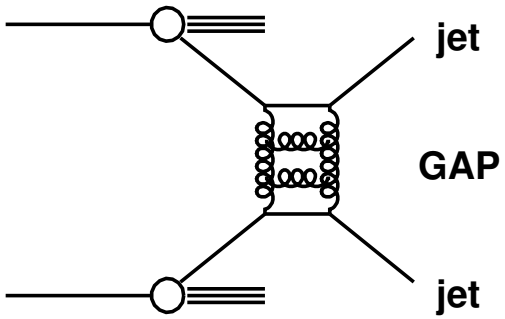
→ Agreement within uncertainties

→ CMS result extends ATLAS measurement by 0.4 unit of gap size

Rapidity gap between jets

Motivation

[CMS PAS FSQ-12-001]



Gap → **color singlet exchange (CSE) between incoming partons**

Four-momentum transfer much larger than in standard diffractive processes → can be understood in BFKL-inspired QCD approach to parton-parton scattering

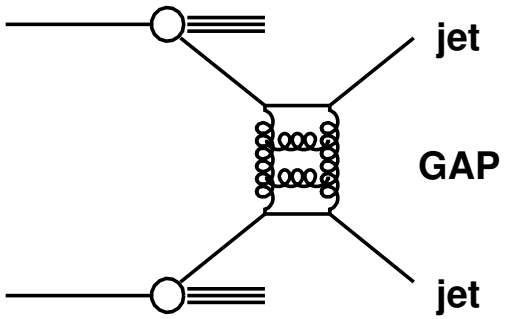
- Disentangling BFKL-DGLAP
- Gap survival probability

First observed by D0 and CDF and later at HERA

This is first observation at the LHC!

Event selection

[CMS PAS FSQ-12-001]



Sample

10 pb^{-1} low pileup data at $\sqrt{s}$ = 7 TeV

Selection

0 or 1 vertex

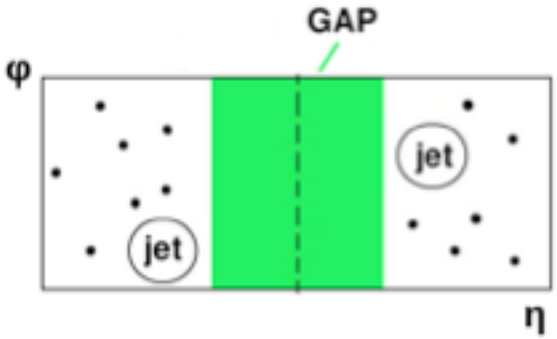
$|\eta^{jet1}| > 1.5$, $|\eta^{jet2}| > 1.5$

two leading jets in opposite hemispheres ('OS sample')

Monte Carlo

CSE: - HERWIG color singlet, LL BFKL Mueller-Tang (MT) model reweighted to describe jet p_T spectrum
- JIMMY package for MPI

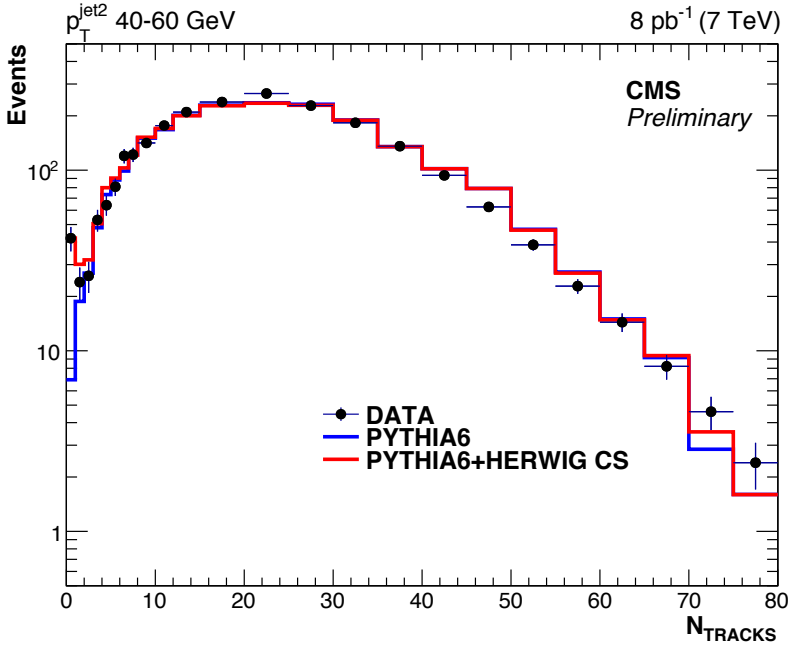
inclusive dijets: PYTHIA6 Z2*



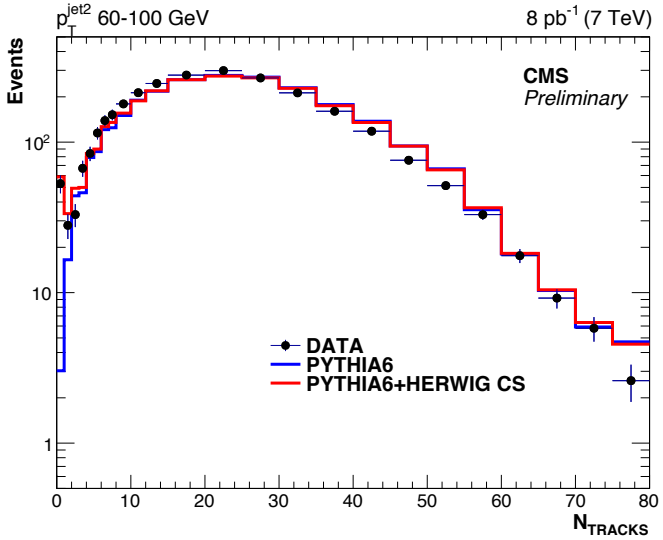
Charged multiplicity distribution in the **gap region** between the leading jets used to discriminate between CSE and not-CSE events

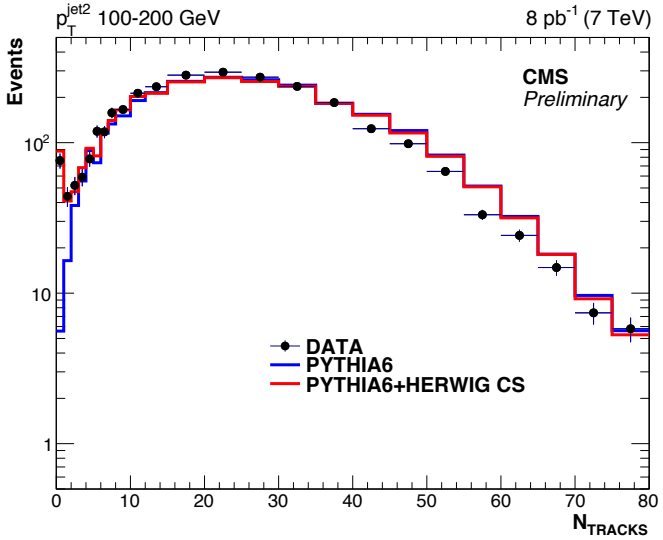
Charged multiplicity |η| < 1 window

[CMS PAS FSQ-12-001]



- Excess of events in the lowest track multiplicity bins not described by PYTHIA 6
- Addition of **HERWIG color singlet → reasonable agreement**



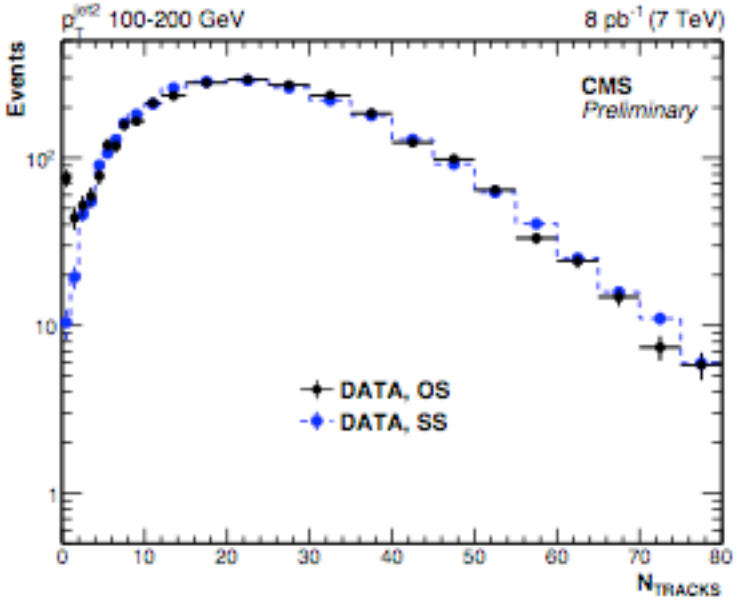


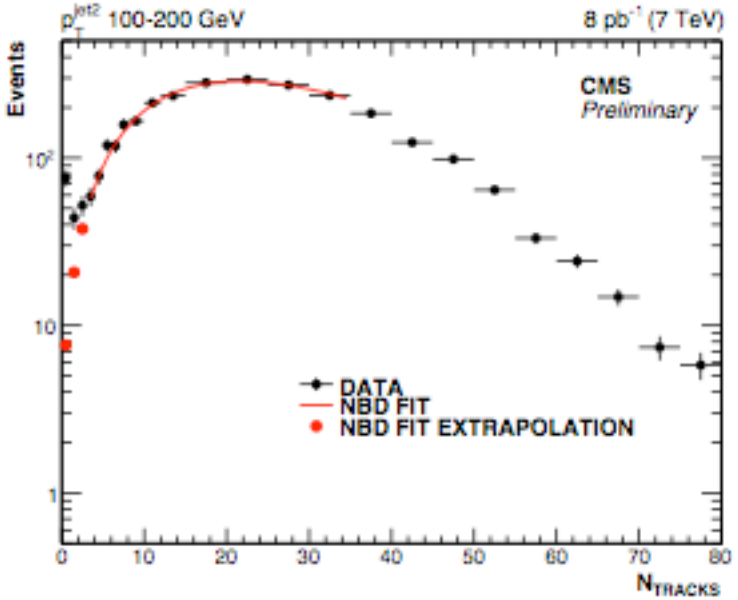
[CMS PAS FSQ-12-001]

Signal definition

Signal is gap fraction, f_{CSE}= $N_{events\ with\ gap}/N_{all\ dijet\ events}$

- **Count events exceeding QCD (PYTHIA) background at low multiplicites**
- Several approaches to background estimation tested
  - Data driven: sample with two leading jets in same hemisphere ('SS sample')
  - Negative Binomial Distribution (NBD) fit to the multiplicity tail extrapolated to low N_{TRACKS}



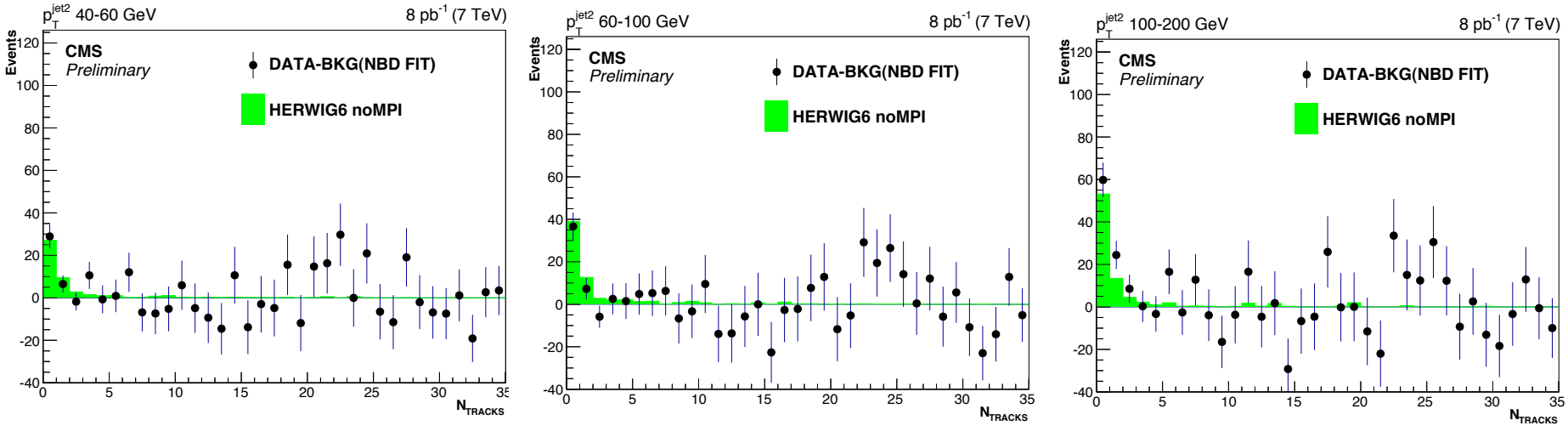


→ **Use NBD fit as baseline, SS as systematics**

Signal definition

[CMS PAS FSQ-12-001]

- Compare data after background subtraction to HERWIG noMPI

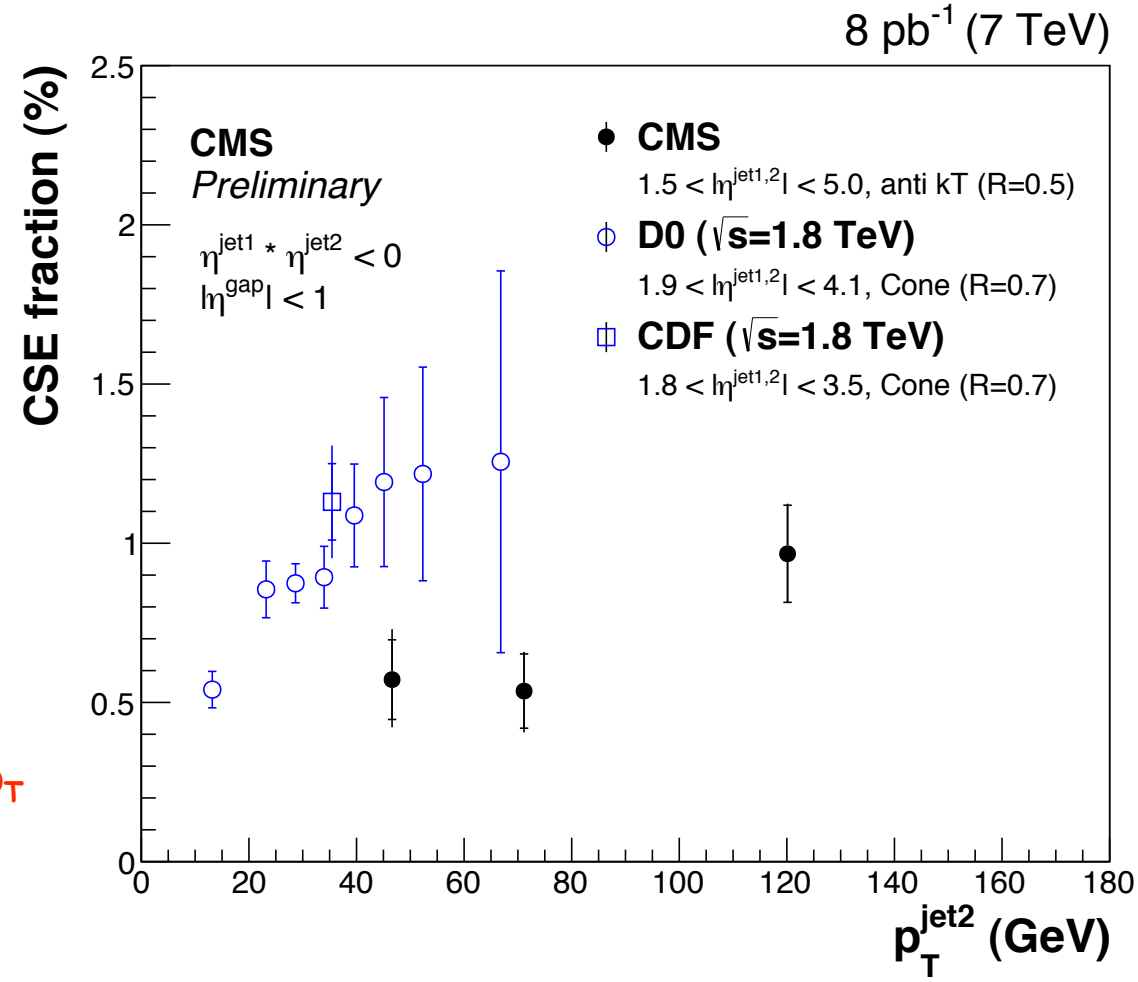


→ **Excess described by HERWIG noMPI**

→ **Bins with N_{TRACKS} = 0,1,2 included in the signal definition**

Results: gap fraction vs p_T

[CMS PAS FSQ-12-001]

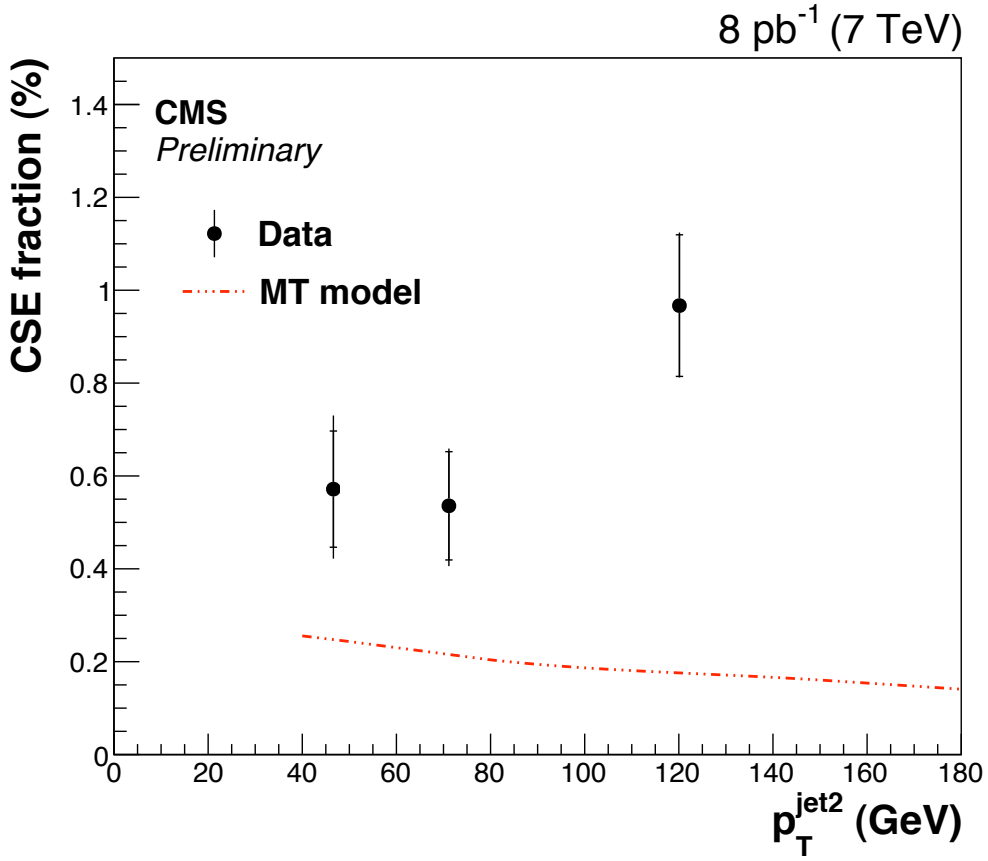


→ **Modest increase with p_T**

→ **Suppression by a factor of about 2 observed wrt CDF and D0 results**
in agreement with earlier observation by CDF and D0 (gap fraction decreases when √s increases from 0.63 to 1.8 TeV)

Results: gap fraction vs p_T

[CMS PAS FSQ-12-001]



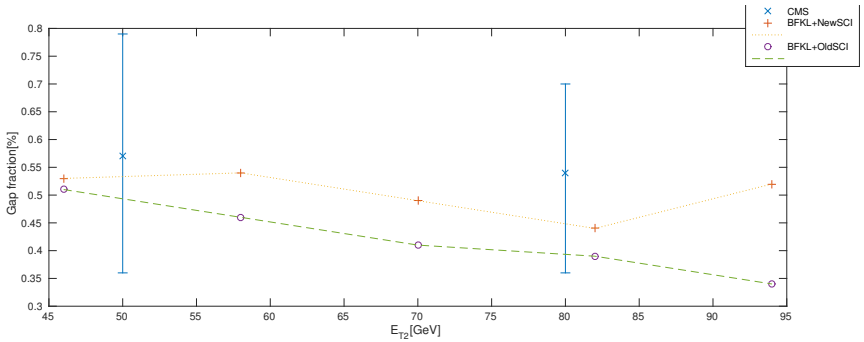
→ The MT (no simulation of MPI) does not reproduce the rise with p_T and underestimates the CSE fraction

[CMS PAS FSQ-12-001]

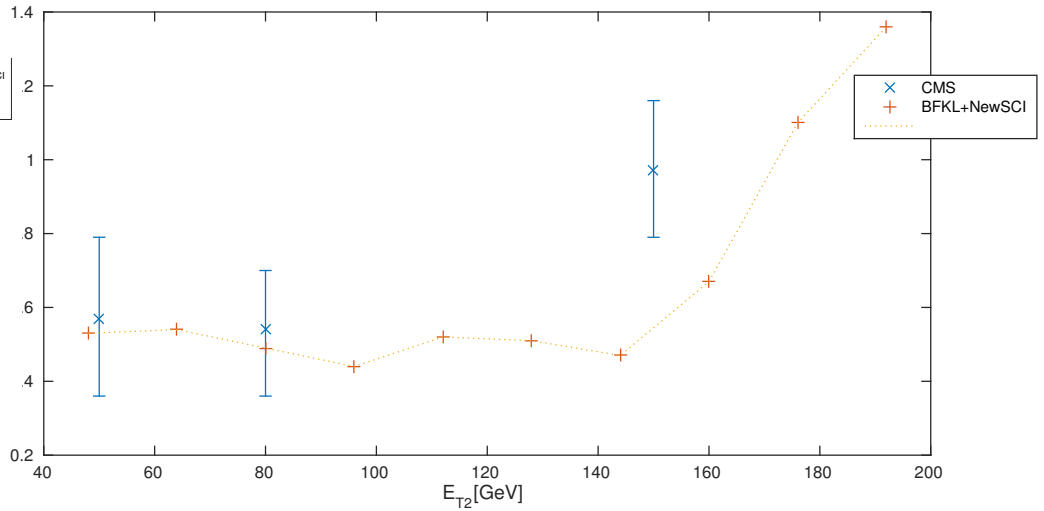
Results: gap fraction vs p_T

Modified soft color interaction (SCI) model by A. Ekstedt, R. Enberg, G. Ingelman and L. Motyka [private communication]

Original model with BFKL equation solved at NLL [PLB 524 (2002) 273]



(a) $100 > E_{T2} > 40\text{GeV}$

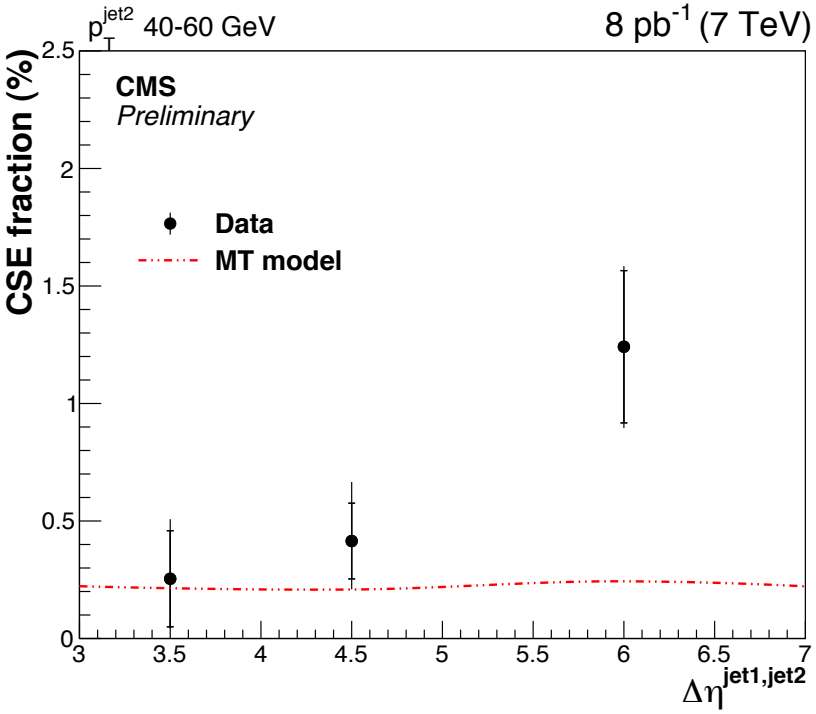


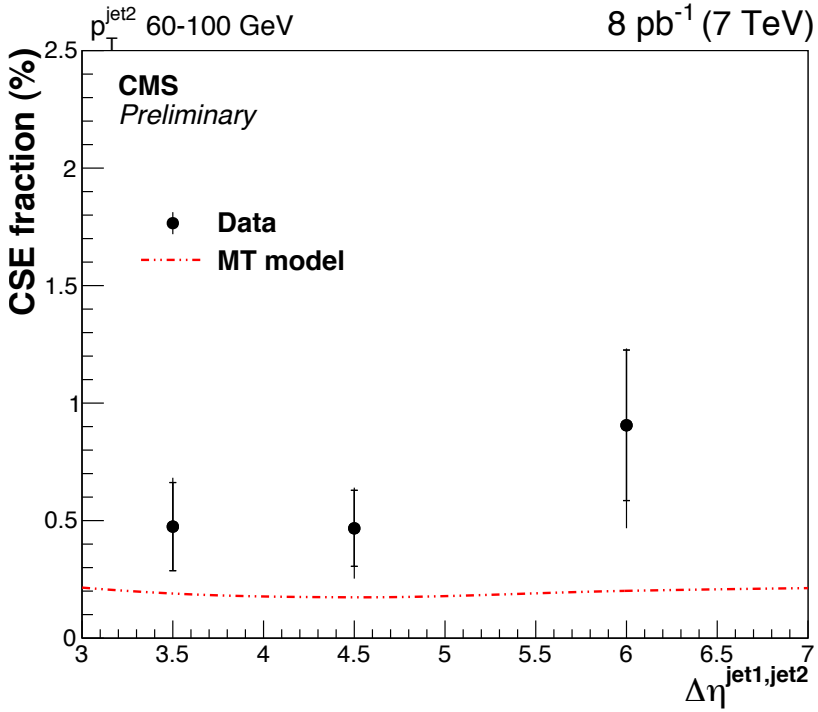
→ For large p_T the old SCI destroys too many gaps

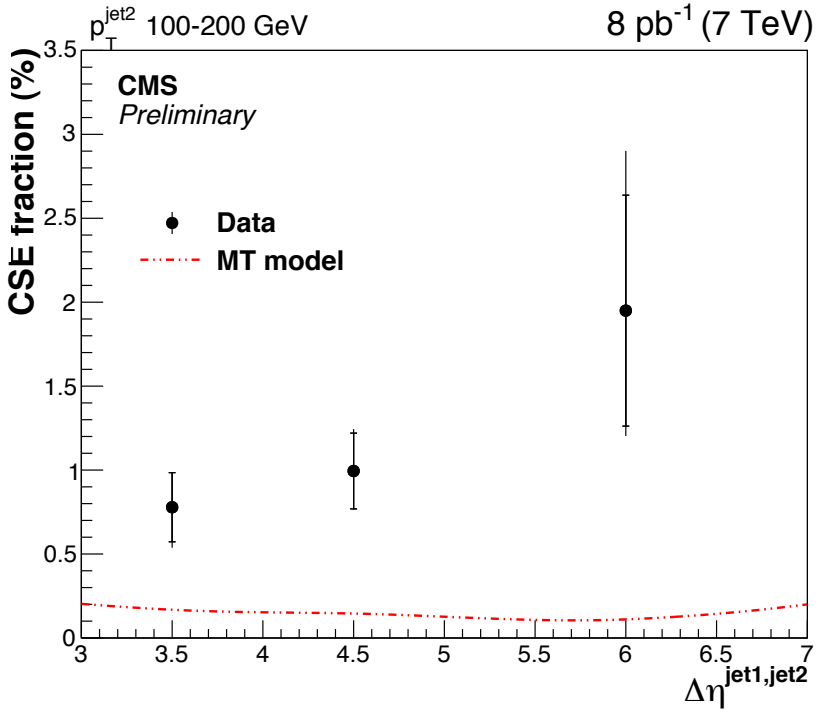
→ Relatively good description by the modified SCI

[CMS PAS FSQ-12-001]

Results: gap fraction vs $\Delta\eta^{jet1,jet2}$







→ Increase with Δη, though large errors

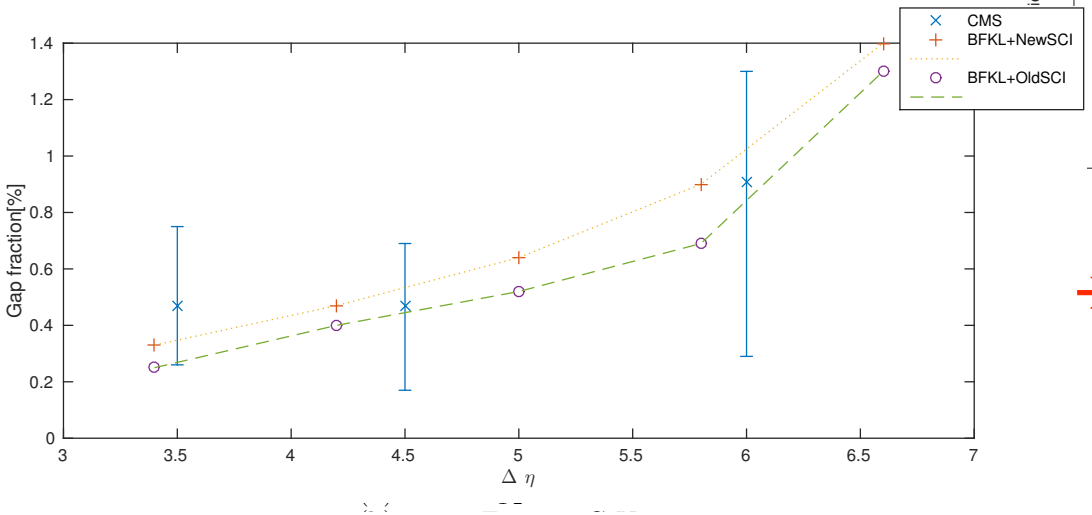
→ The MT model (no simulation of MPI) does not reproduce the rise with p_T and underestimates the CSE fraction

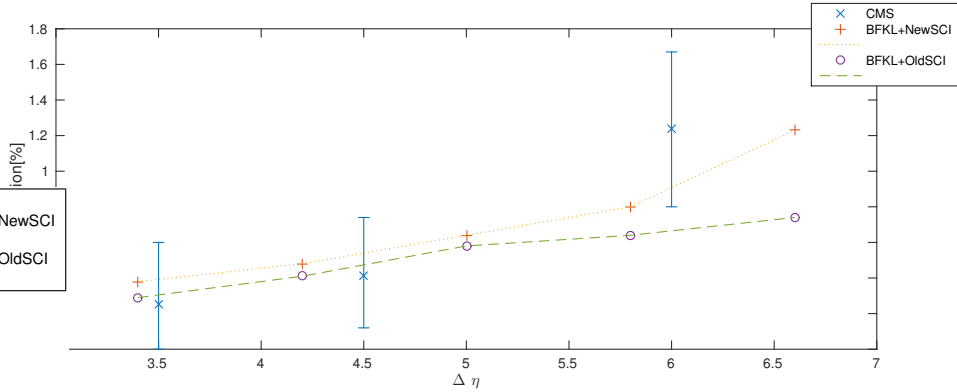
Results: gap fraction vs $\Delta\eta^{jet1,jet2}$

[CMS PAS FSQ-12-001]

Modified soft color interaction (SCI) model by A. Ekstedt, R. Enberg, G. Ingelman and L. Motyka [private communication]

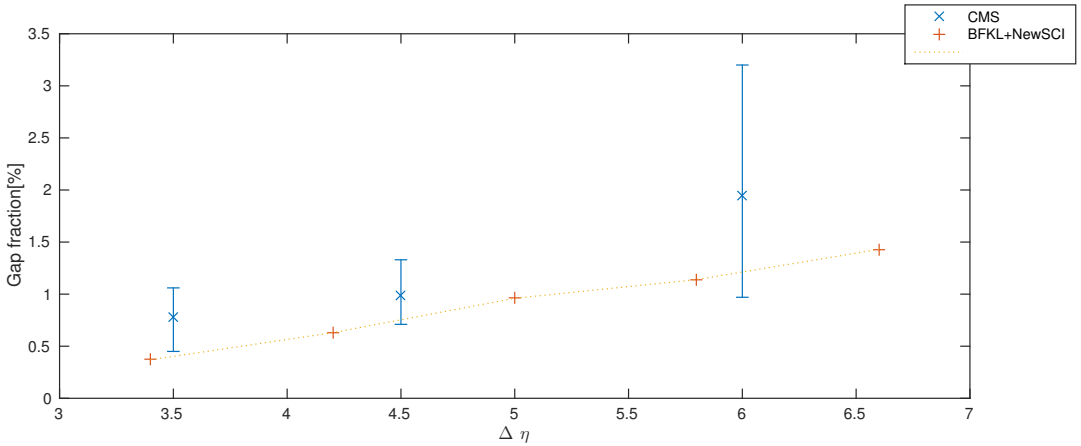
Original model with BFKL equation solved at NLL [PLB 524 (2002) 273]





(a) $60 > E_{T2} > 40\text{GeV}$

→ **Fair description by both old and modified SCI**



(c) $200 > E_{T2} > 100\text{GeV}$

Summary

- First LHC measurement of jet-gap-jet events

- Inclusive single diffractive and double diffractive cross sections at 7 TeV

- Forward rapidity gap cross section

  CMS extends the ATLAS measurement by 0.4 unit of gap size

CMS diffraction with run I data

- A few measurements with **Run I** data based on LRG tagging
  - Dijet production [PRD 87 (2013) 012006]
  - W/Z events with a pseudorapidity gap [EPJ C72 (2012) 1839]
  - Jet-gap-jet analyses [CMS PAS FSQ-12-001]

- **CMS-TOTEM** common 2012/2015 data with **proton tag** under analysis

S. Sen

Looking foward to proton tagging with TOTEM/CT-PPS in Run II!

See Yellow Report for Forward Physics [CERN/LHCC 2013-021]

BACKUP

CMS diffraction with run I data

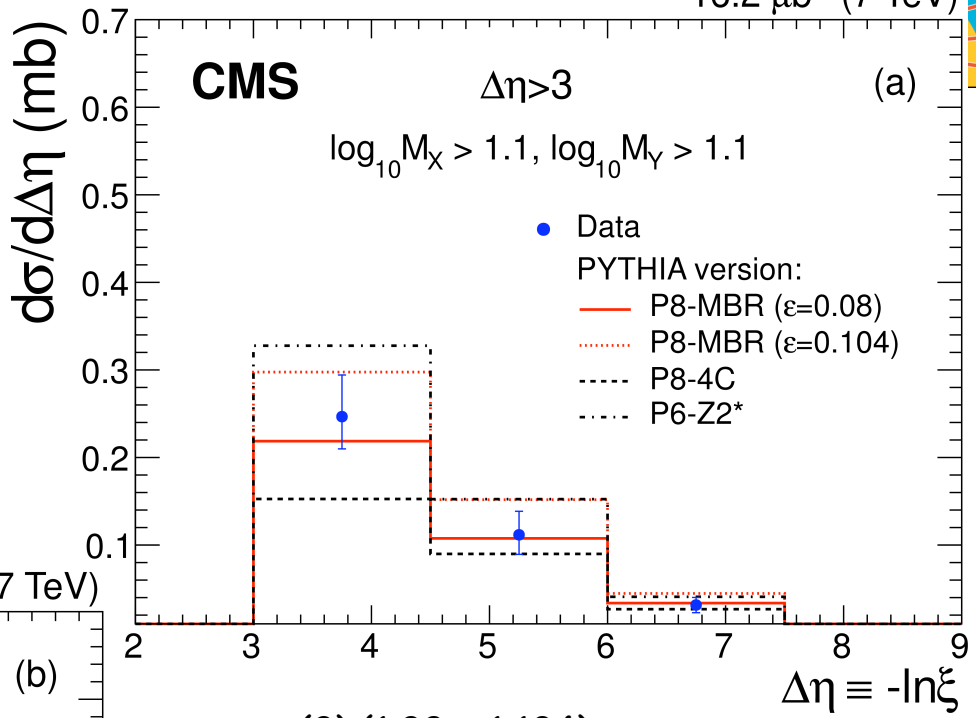
- A few measurements with **Run I** data based on LRG tagging
  - Dijet production
    - CMS [PRD 87 (2013) 012006]
    - ATLAS [PLB 754 (2016) 214]
  - W/Z events with a pseudorapidity gap observed by CMS
    [EPJ C72 (2012) 1839]
  - Jet-gap-jet analyses
    - ATLAS [EPJ C72 (2012) 1926, EPJ C74 (2014) 3117]
    - **New**: CMS [CMS PAS FSQ-12-001]
- **CMS-TOTEM common 2012/2015 data with proton tag under analysis**

See S. Sen's talk

DD cross section vs Δη

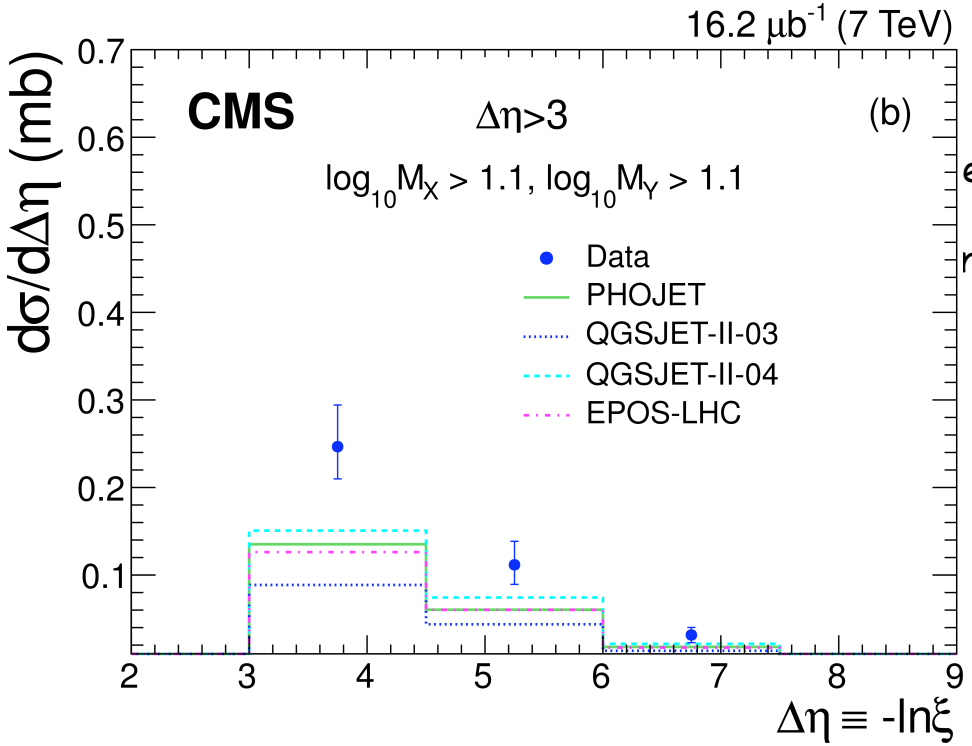
$\Delta\eta = -\ln \xi$ $\quad \xi = \frac{M_X^2 \cdot M_Y^2}{s \cdot m_p^2}$

$$\frac{d\sigma}{d\Delta\eta} = \frac{N^{evt}}{\mathcal{L}(\Delta\eta)_{bin}}$$



ercept α_{IP} (0) (1.08 e 1.104)

nd model in PYTHIA8-4C and PYTHIA6

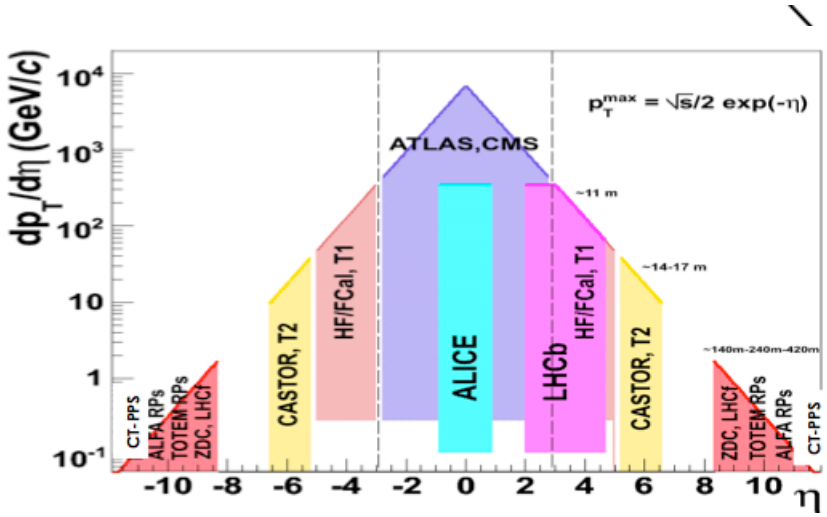


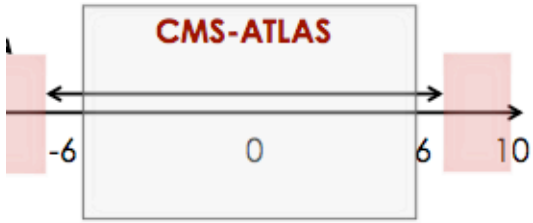
Where is the rapidity gap at LHC ?

- Total room for particle production @LHC: $\Delta\eta \approx \ln(s/m_p^2) \approx 20$
- Rapidity range effectively populated by particles: $\Delta\eta \approx \ln(m_X^2/m_p^2)$

  Depends on M_X, e.g. with M_X= 500 GeV: $\Delta\eta \approx 12$

→ The resulting gap size depends on the process, e.g. in central diffraction, assuming two symmetric gaps, each will have a size of $\Delta\eta \approx \frac{1}{2}(20-12) \approx 4$
i.e. **very forward, often outside CMS-ATLAS acceptance**





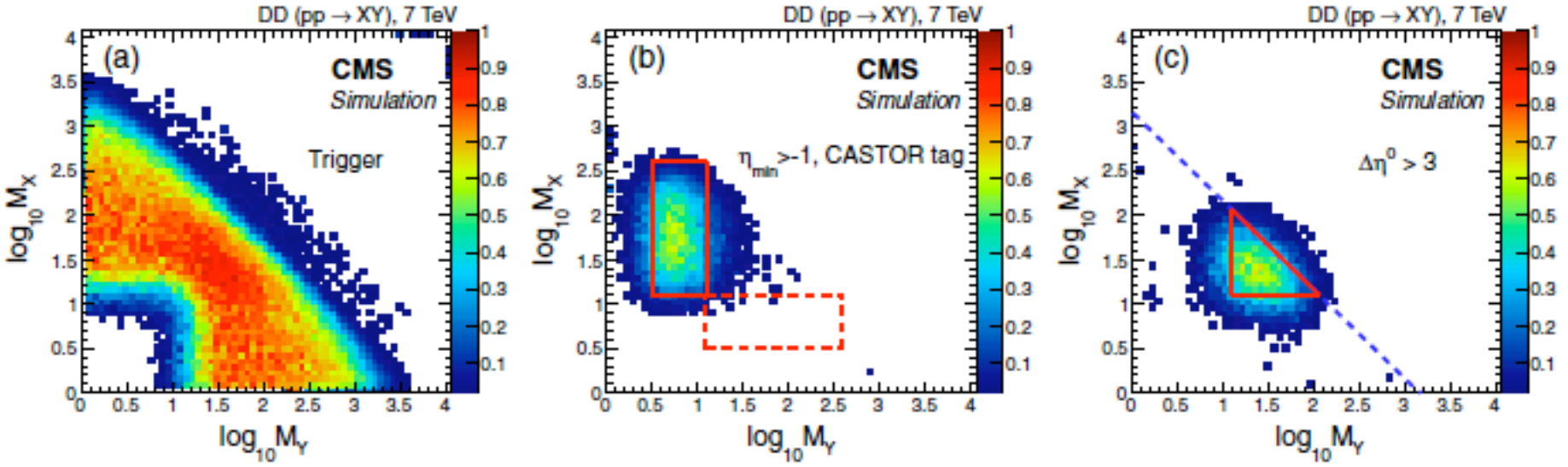


FIG. 6 (color online). Simulated (PYTHIA 8 MBR) event selection efficiency in the M_X vs. M_Y plane for true DD events after (a) the trigger selection, and (b) the FG2 selection with a CASTOR tag or (c) the CG selection (Fig. 3). The regions delimited by the solid (red) lines in (b) and (c) are those of the cross section measurements; the dashed (red) box in (b) corresponds to the enlarged region for which the cross section is given (Sec. IX), assuming the same dependence on M_X and M_Y; the dashed (blue) line in (c) marks the region of $\Delta\eta > 3$.

Detector level ξ distributions

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

proton fractional momentum loss reconstructed from particle candidates in |η| < 4.7

COMPARISON to PYTHIA8-MBR

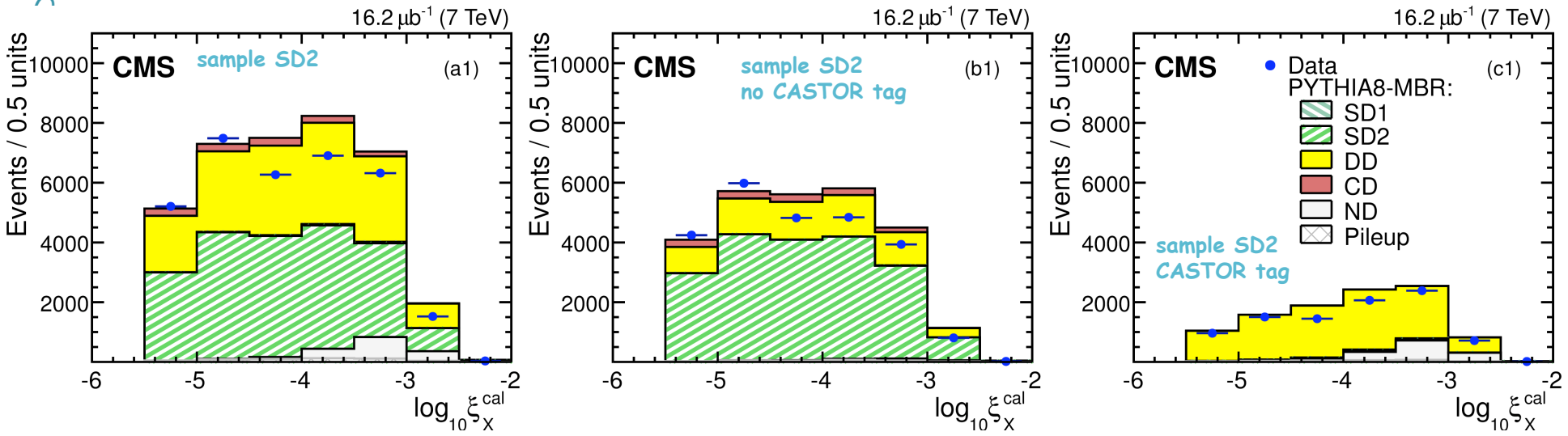
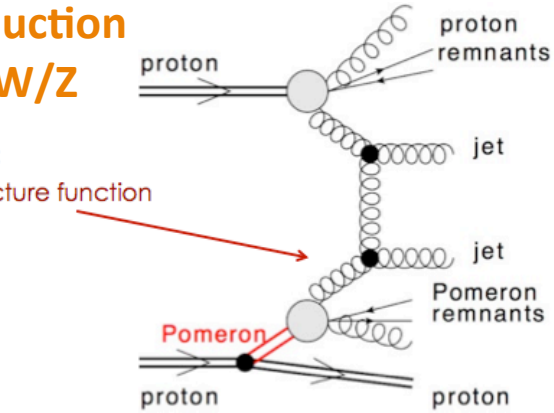


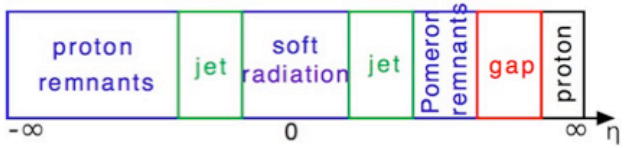
FIG. 8 (color online). Detector-level distributions of the reconstructed and calibrated ξ_X for (a) the entire FG2 sample, and the FG2 subsamples with (b) no CASTOR tag, and (c) a CASTOR tag (statistical errors only). The data are compared to the predictions of the PYTHIA 8 MBR (top three plots) and PYTHIA 8 4C (bottom three plots) simulations, which are normalized to the integrated luminosity of the data sample. The contribution of each of the generated processes is shown separately.

Topologies of gap events in (hard) diffraction

SD production of jets, W/Z

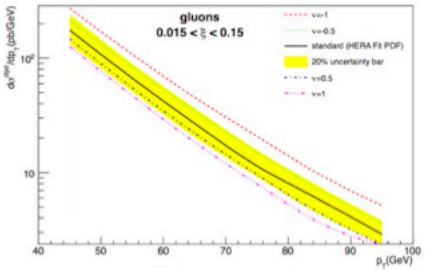


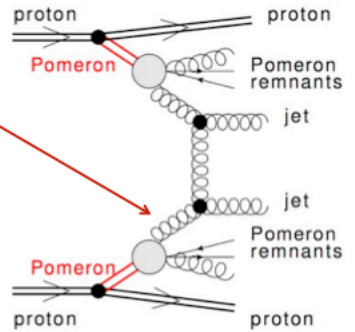
Main Goal:
Gluon structure function

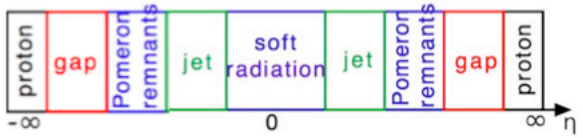


DPE

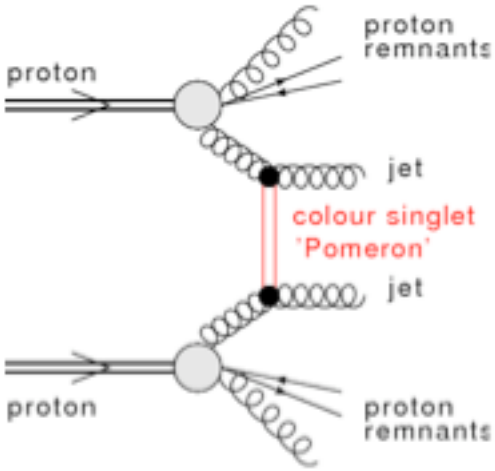
Main Goal:
Gluon structure function





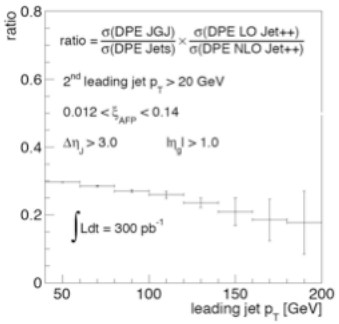


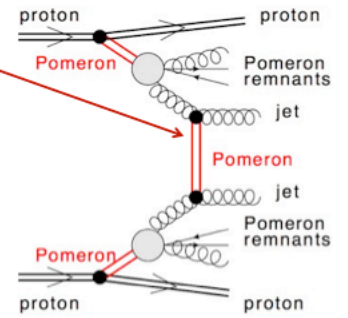
jet-gap-jet

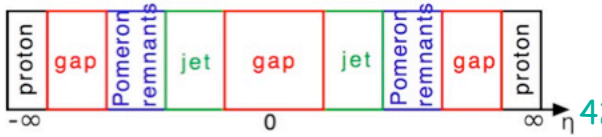


DPE with jet-gap-jet

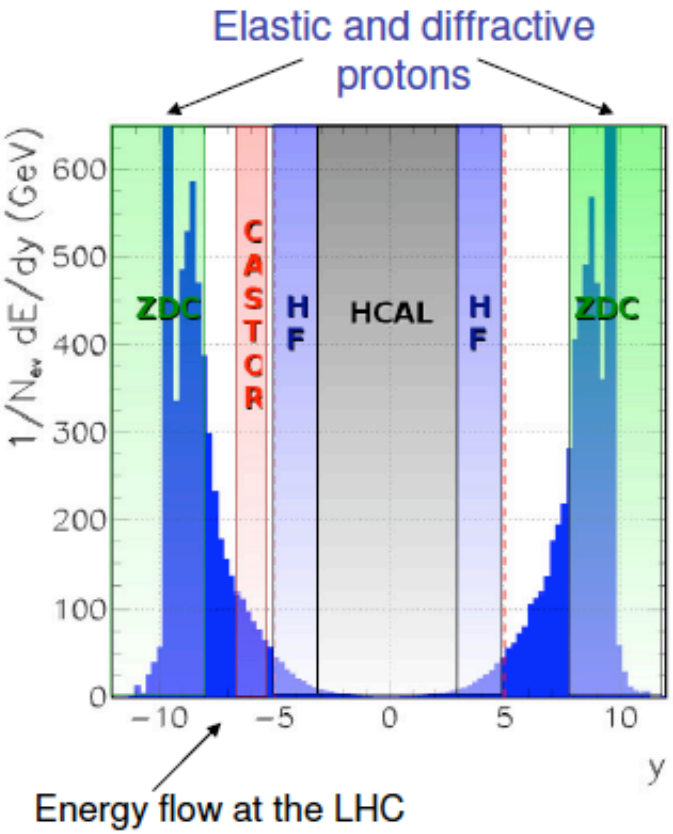
Main Goal: BFKL evolution between the hard scale set by the two jets







Largest calorimetric rapidity coverage ever!



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

Maximal rapidity at the LHC:

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