Review of CMS and TOTEM results on Multi Parton Interactions, soft QCD and diffraction.

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on behalf of

CMS Collaboration

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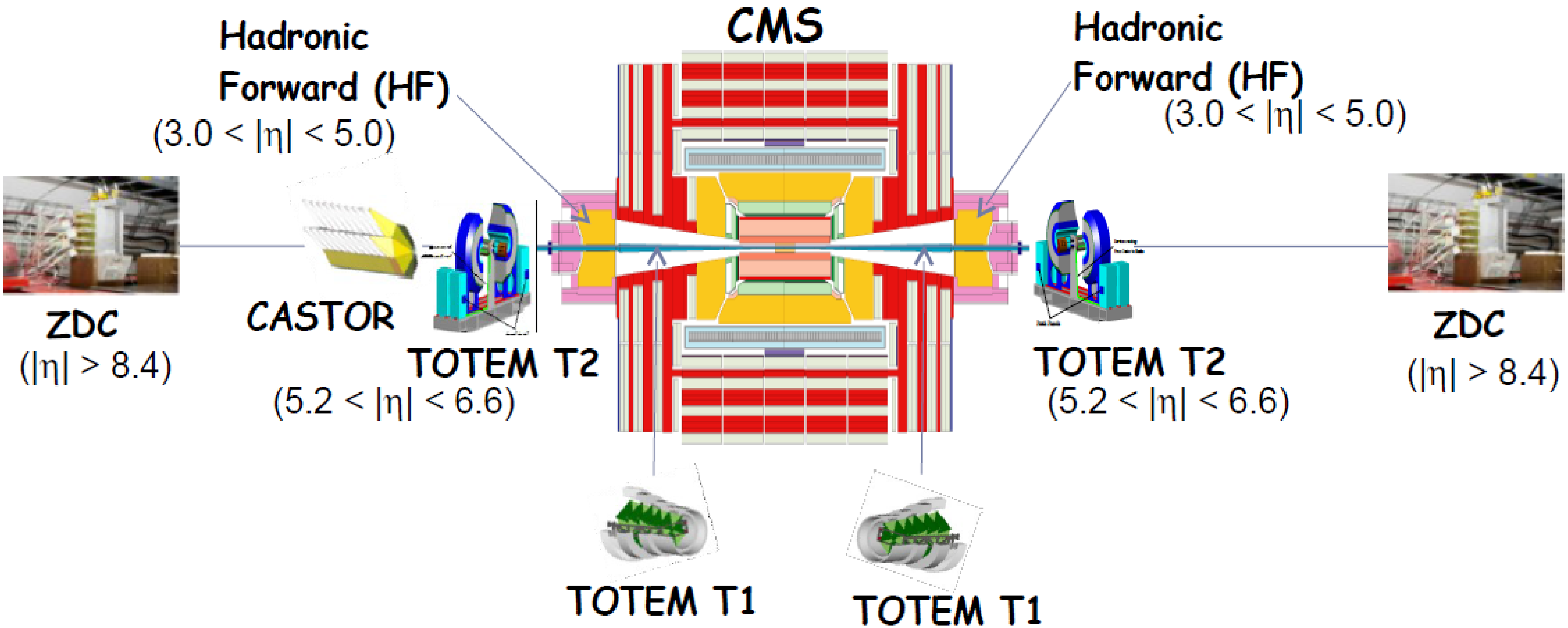
Outline

- CMS detector at forward rapidities
- Underlying event with leading tracks (PAS FSQ-12-020)
- Underlying event with leading track jets (PAS FSQ-12-025)
- Charged particles distributions (Eur. Phys. J. C (2014) 74:3053)
- Soft diffraction results (PAS FSQ-12-005)
- TOTEM results on double diffractive disoc. (PRL 111 (2013) 262001)
- Summary

CMS at Forward Rapidities



- Tracker $|\eta|<2.4$, $p_T > 100$ MeV
- Electromagnetic calorimeter ECAL
- Hadronic Calorimeter HCAL
- Muon chambers

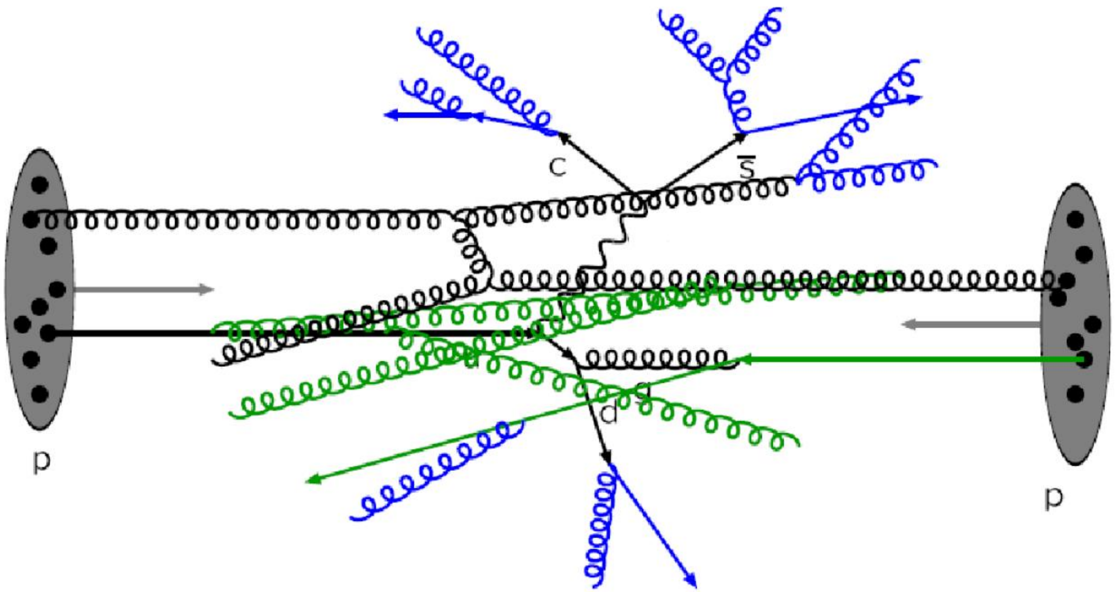
- **H**adronic **F**orward calorimeters (HF) $3<|\eta|<5$
- Very Forward Calorimeter (CASTOR) $5.2<|\eta|<6.6$
- **Z**ero **D**egree **C**alorimeter (ZDC)
- **B**eam **S**cintillator **C**ounters BSC: $3.2<|\eta|<4.7$
- **F**orward **S**hower **C**ounters FSC: $6<|\eta|<8$

+ Totem (T1/T2 tracking detectors and RP roman pots) separate experiment

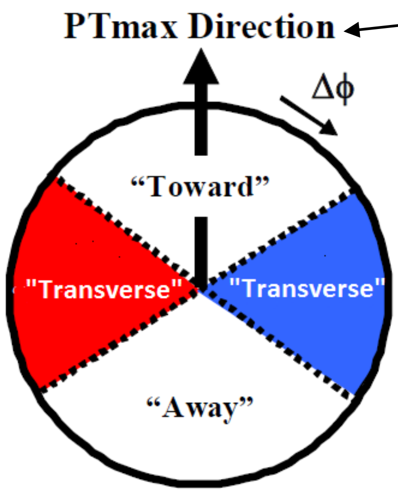
Underlying Event Activity

- Hard scattering

- Initial and final state radiation
- Multiple Parton Interaction (MPI)
- Beam-beam remnants



→ Underlying Event



Leading object in an event (track, jet)

- Toward: |Δϕ| < 60°
- Away: |Δϕ| > 120°
- Transverse: 60° < |Δϕ| < 120° – UE activity measured

Underlying Event with Leading Track or Track Jet

Data samples:

- Low pile-up runs
- For leading tracks: 0.9 TeV, 7 TeV
- For leading track jets: 2.76 TeV (0.9 TeV and 7 TeV: JHEP 1109 (2011) 109)
- Minimum Bias trigger (BSC) + + jet triggers (tresholds 20, 40 GeV)

Vertex requirements:

- Only one vertex within 10 cm around the interaction point

Leading tracks selection:

- p_T>0.5 GeV and $|\eta|$<0.8

Leading track jet selection:

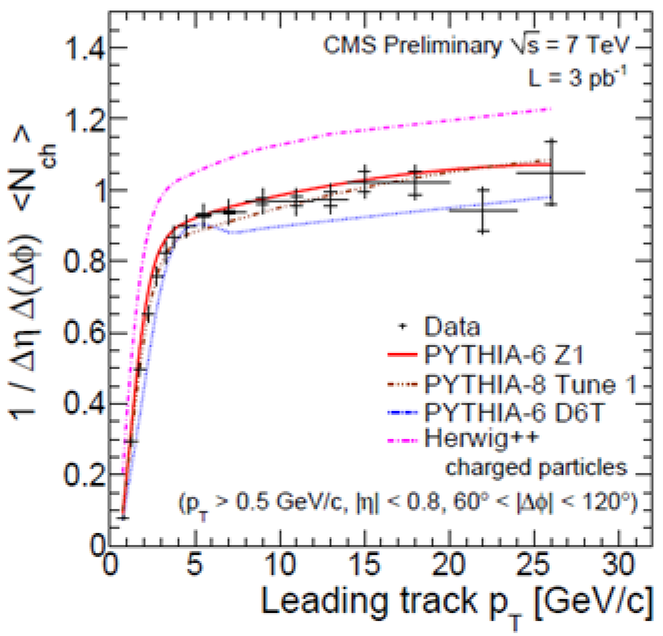
- Leading track jet with p_T>1 GeV, $|\eta|$<2.0, clustered with SISCone 0.5
- Tracks used: p_T>0.5 GeV, $|\eta|$<2.5

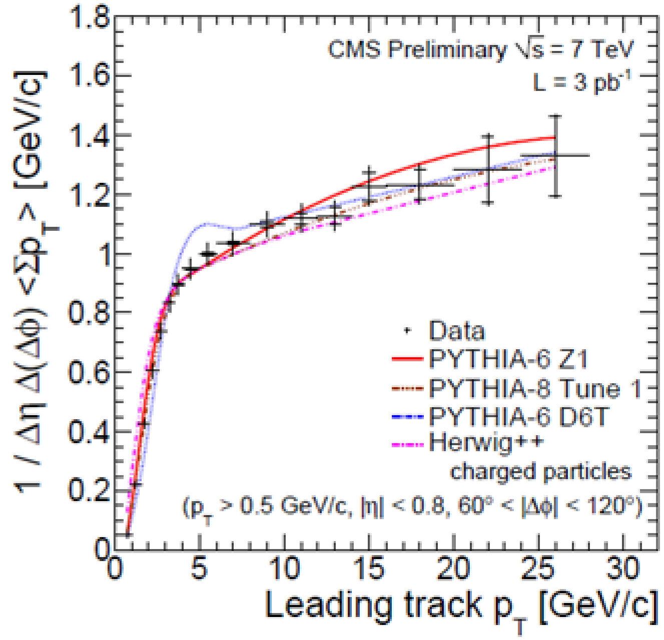
Observables:

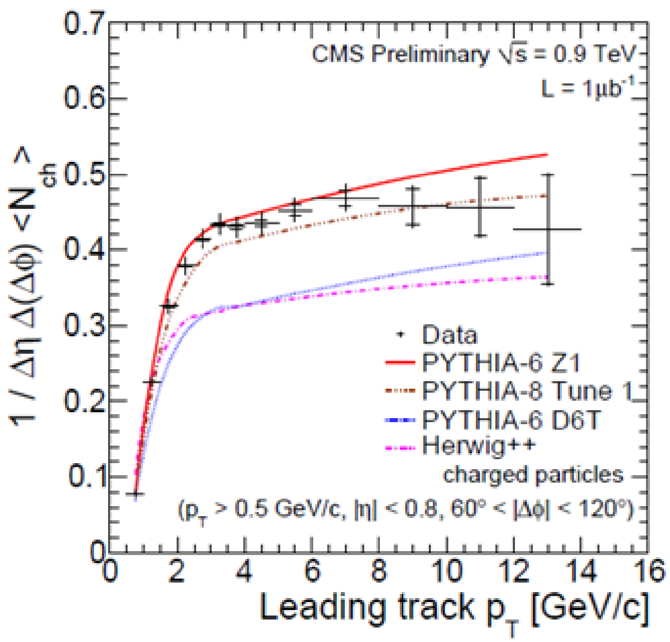
- The charge density: N_{ch}
- The transverse momentum density: $\sum p_T$

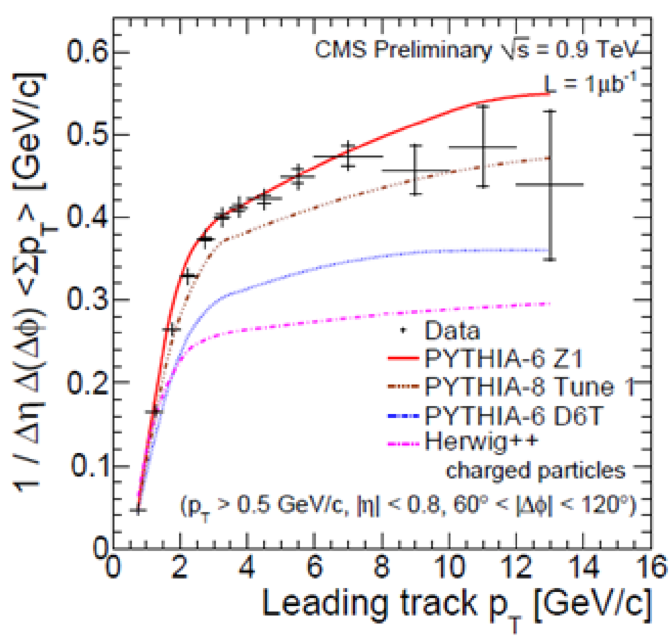
} As a function of the leading object p_T

Underlying Event with Leading Track



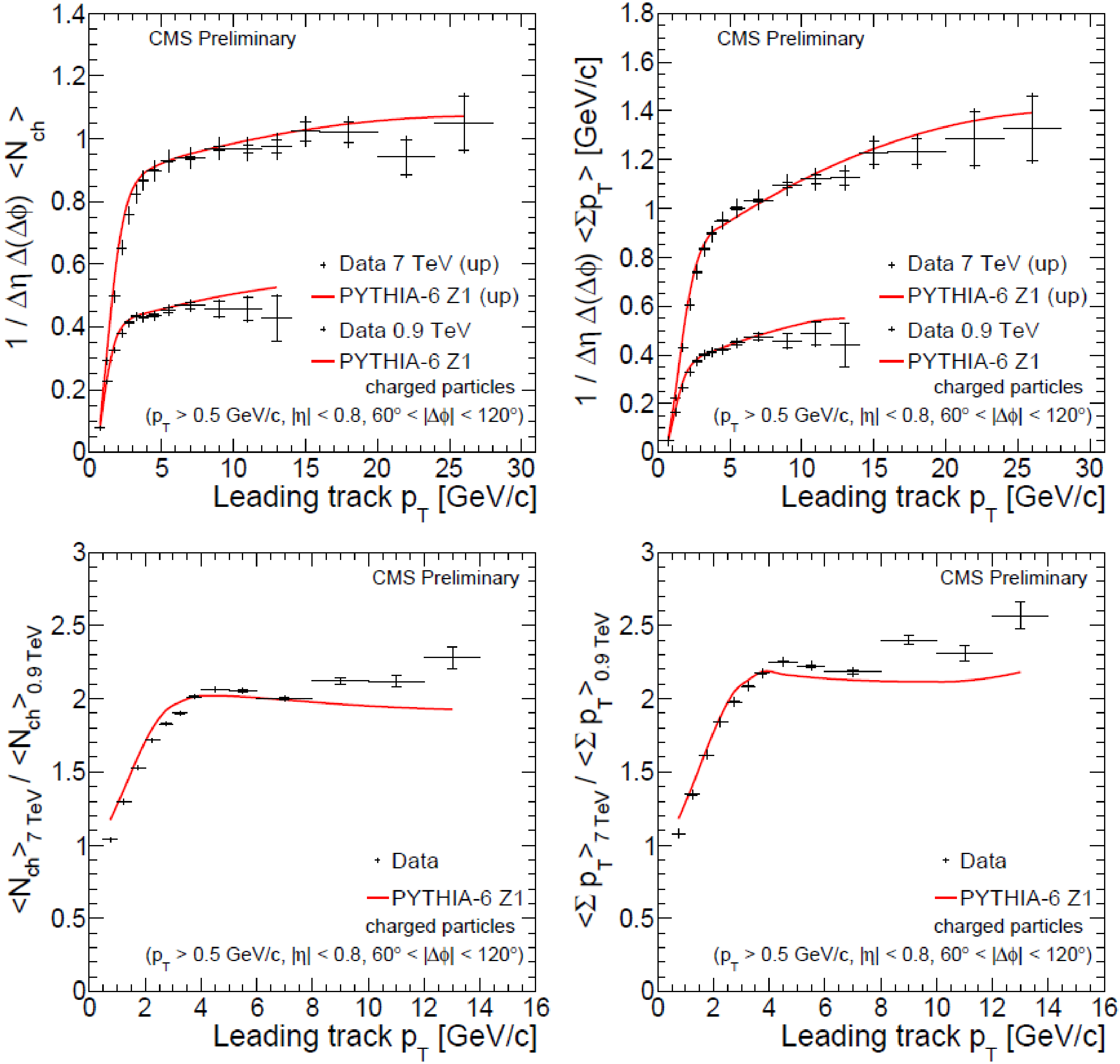






- Rapid raise for p_T<5 GeV → increase of MPI corresponding to more central collisions
- Plateau region, slow increase of the UE activity due to radiative contributions, energy scale, harder fragmentation
- PYTHIA6-Z1 and PYTHIA8-T1 are in agreement with the data
- HERWIG++ predicts softer spectrum
- HERWIG++ , PYTHIA6-D6T predict much less activity

Underlying Event with Leading Track



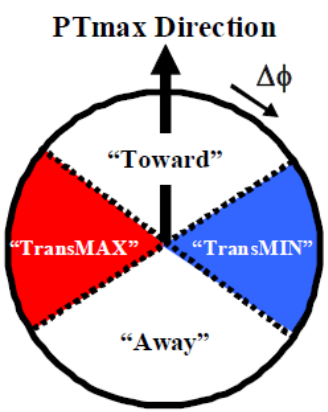
- PYTHIA-Z1 selected for comparison – best description in both observables at both energies
- Increse 2-2.5 between the energies at the plateau region

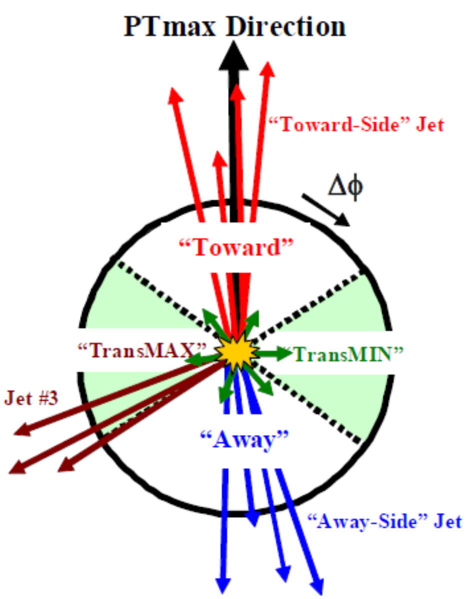
Underlying Event with Leading Track Jet

Leading object in an event – a charged particle jet

- Measurement up to higher p_T scales
- Decrease sensitivity to the hadronization and shower effects

- Jet clustering – based only on the information from tracker → acess to lower p_T

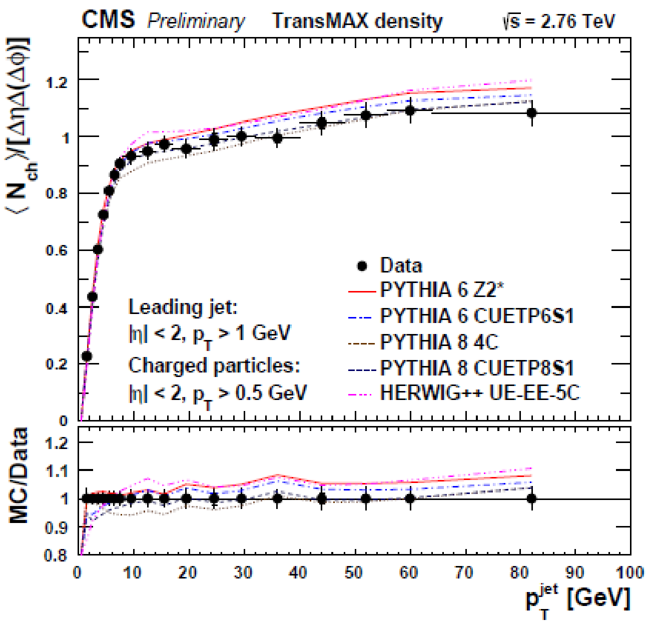


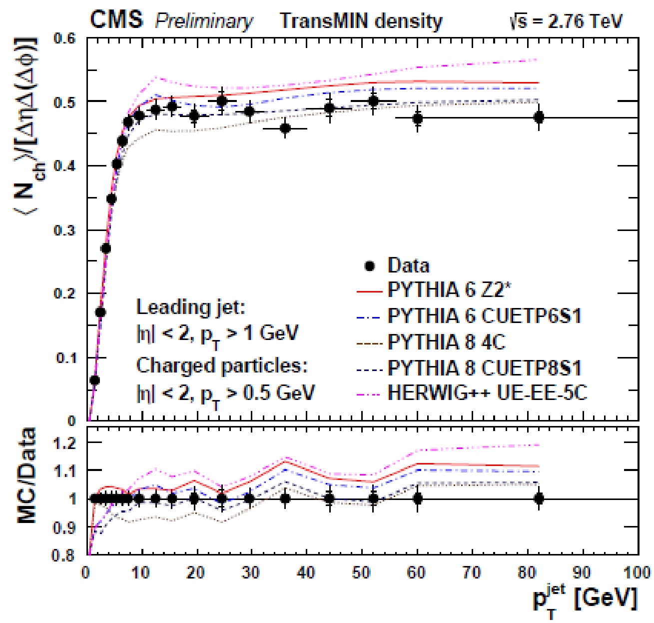


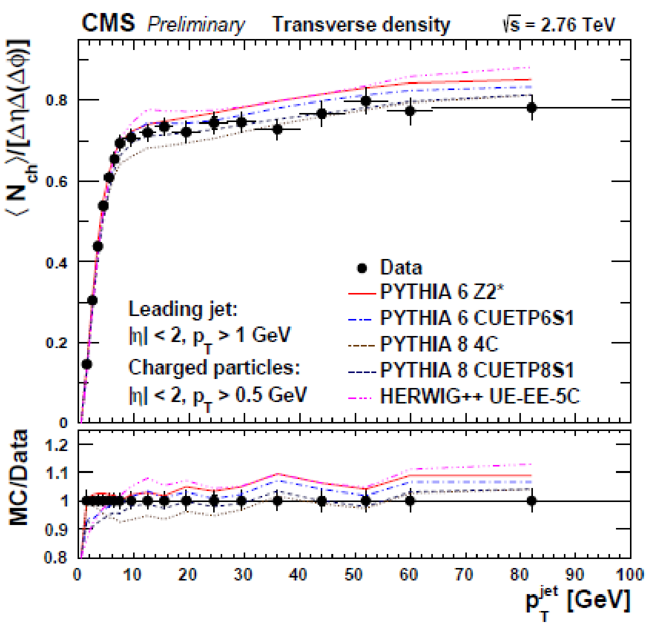
Transverse region divided:

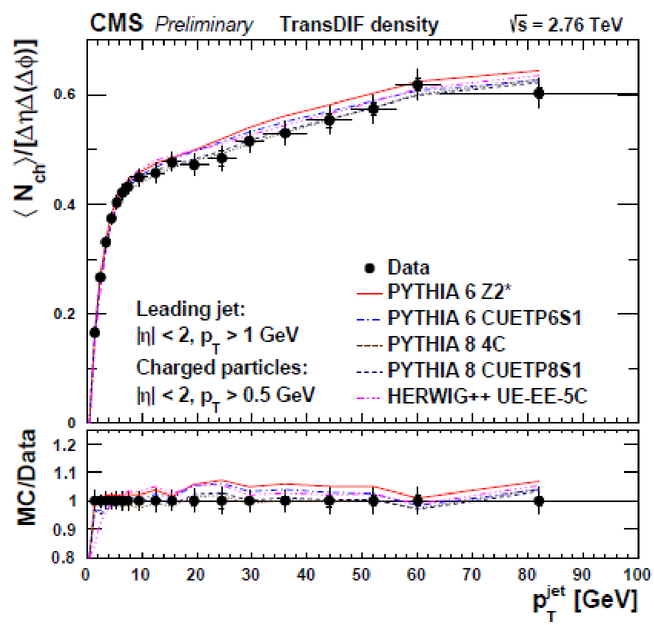
- TransMIN – lower activity, sensitive to MPI + beam-beam remnants
- TransMAX – higher activity, sensitive to MPI + beam-beam remnants + initial and final radiation
- TransDIF = TransMAX – TransMIN, sensitive to initial and final radiation

Underlying Event with Leading Track Jet

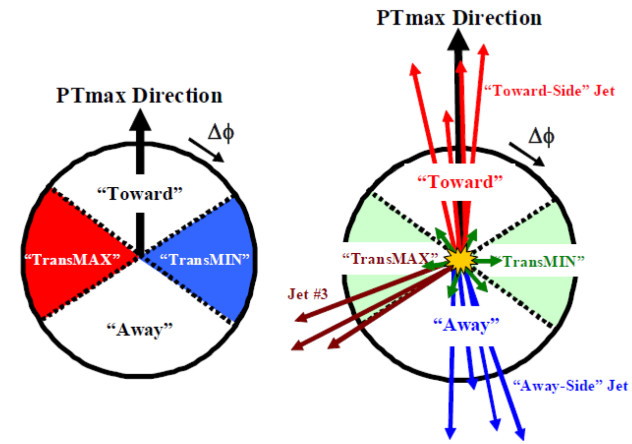




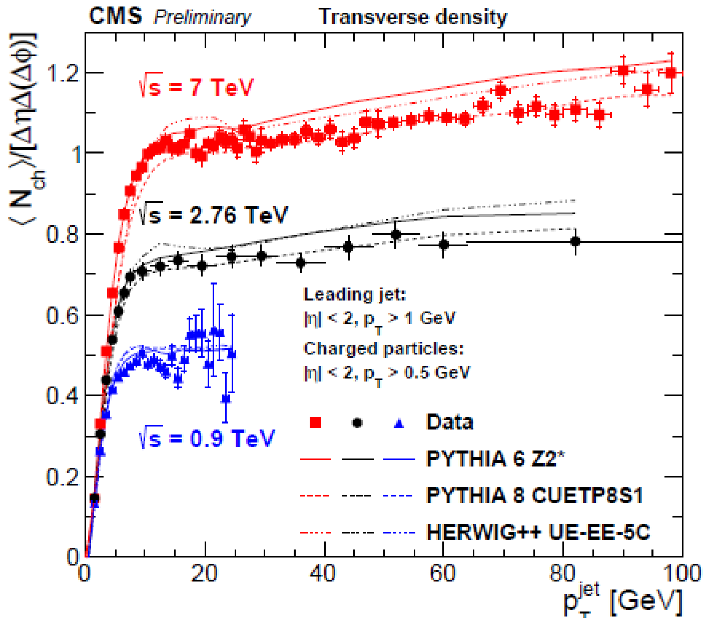


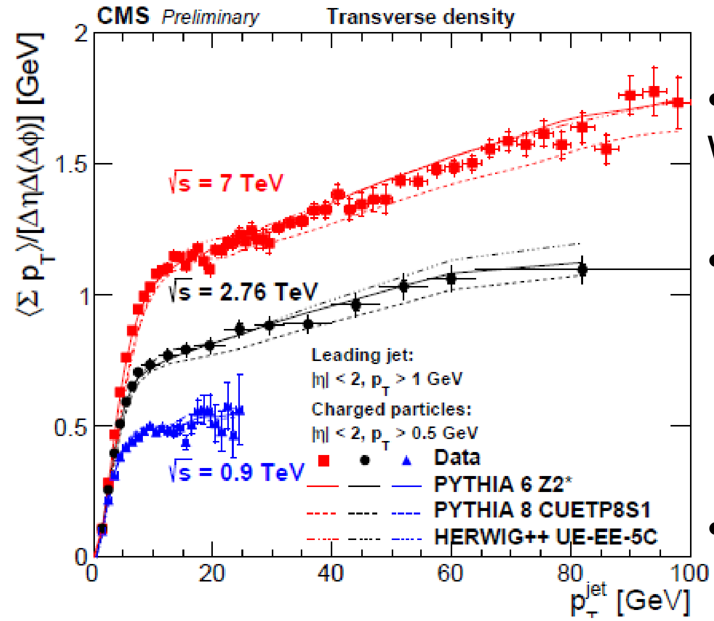


- In TransMAX slow rise at large p_T – increase of initial and final state radiation
- In TransMIN a plateau at large p_T visible - MPI and beam-beam remnant almost independent on the hard scale once the most central events selected
- The difference from initial and final state radiation - TransDIF

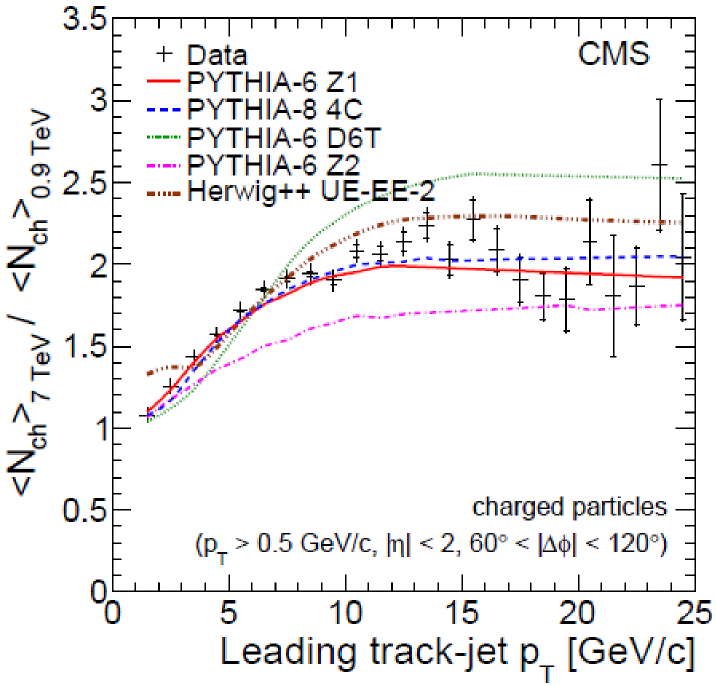


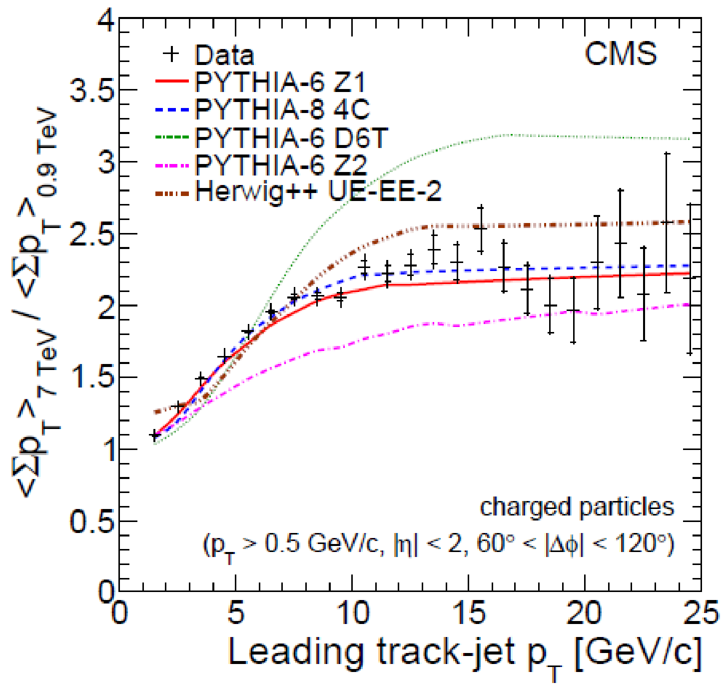
Underlying Event with Leading Track Jet





- Transverse density rises with energy
- The best description is obtained with new tunes, eg. PYTHIA8 CEUTP8S1 or PYTHIA6 Z2*
- Older tunes give much less accurate desription





Charged particles distribution

Data sample:

- 8 TeV 2012 data, 17,4 nb^{-1} , β*=90 m
- Trigger provided by TOTEM T2 telescopes: charged track pT>40 MeV in 5.3<|η|<6.5
- Data corrected to the stable particle level with Z2* PYTHIA6 tune
- Inclusive sample: track in at least one T2
- Non-single diffractive sample (NSD-enhanced): tracks in both T2s

Vertex requirements:

- Only one vertex within 15 cm around the interaction point

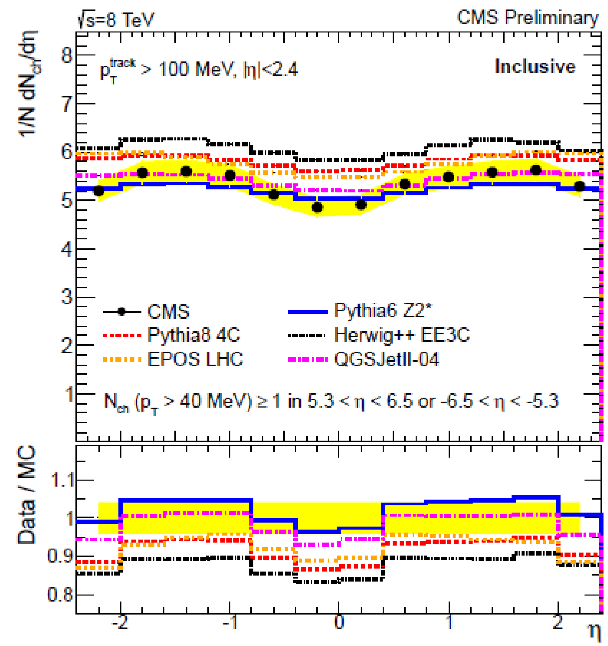
Tracks selection:

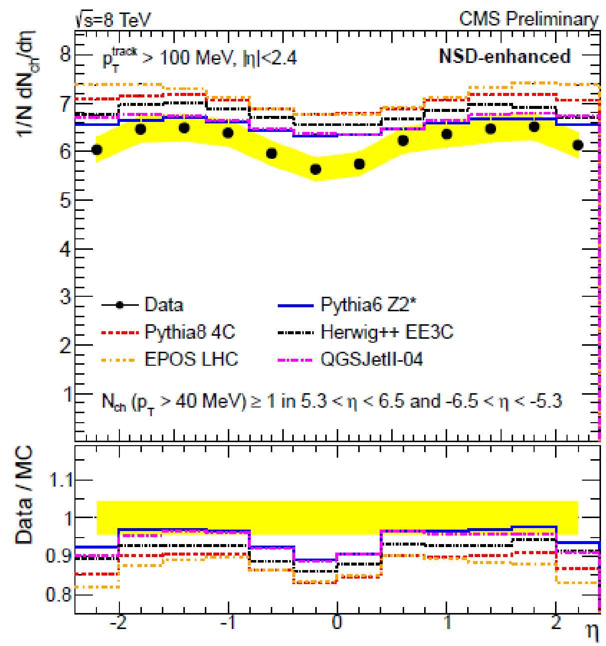
- p_T>0.1 GeV and p_T>1 GeV
- |η|<2.4
- Cut on the impact parameters – removal of the secondary tracks

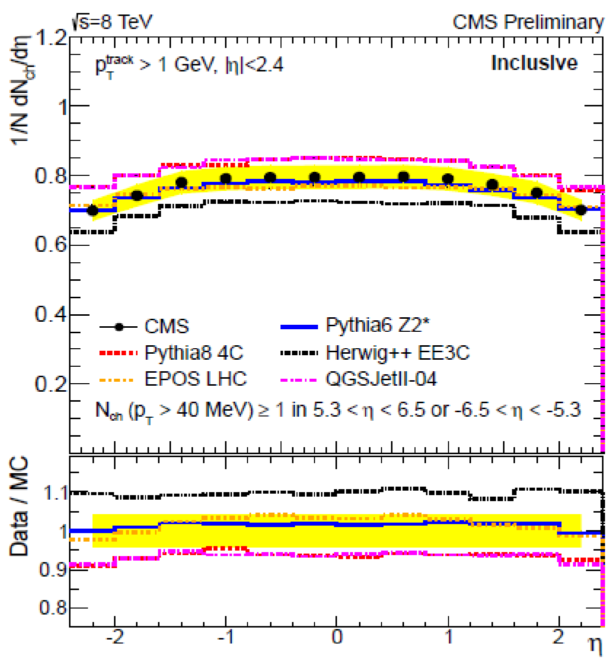
Observables:

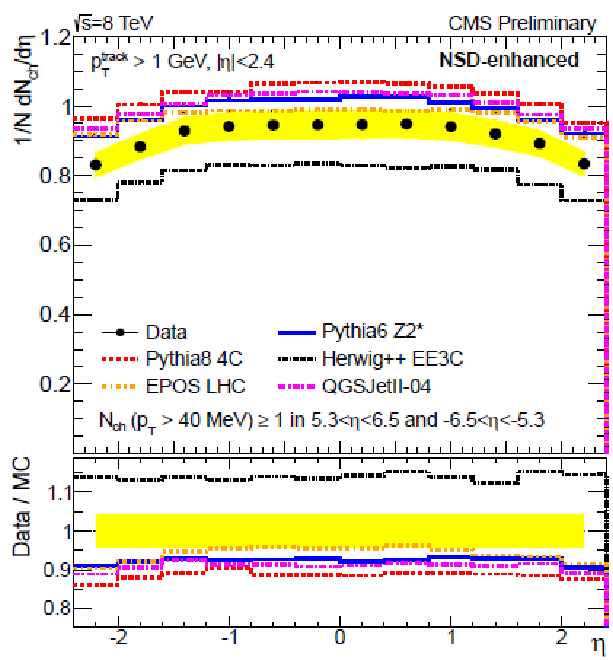
- Charged particle pseudorapidity distribution: $dN_{ch}/d\eta$
- Leading-track transverse momentum distribution: $dN_{ch}/dp_{T,leading}$ (additional cut p_T>0.4 GeV)

Charged particles distribution



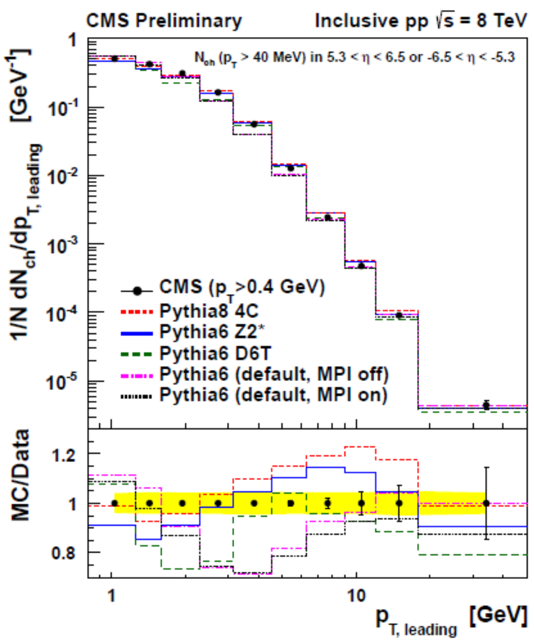


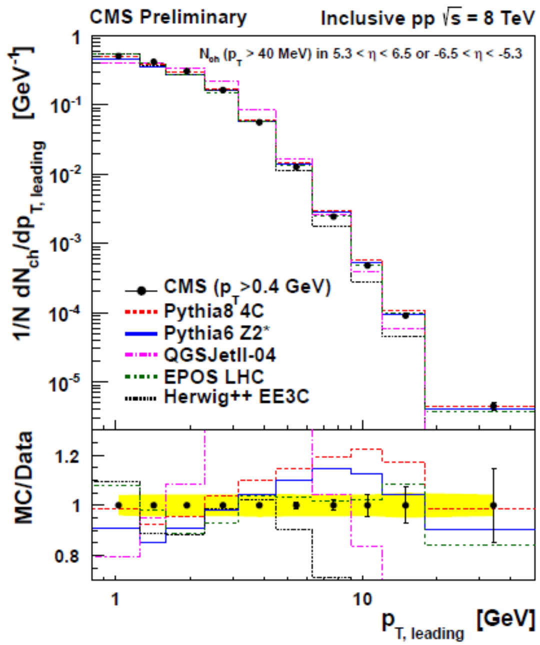




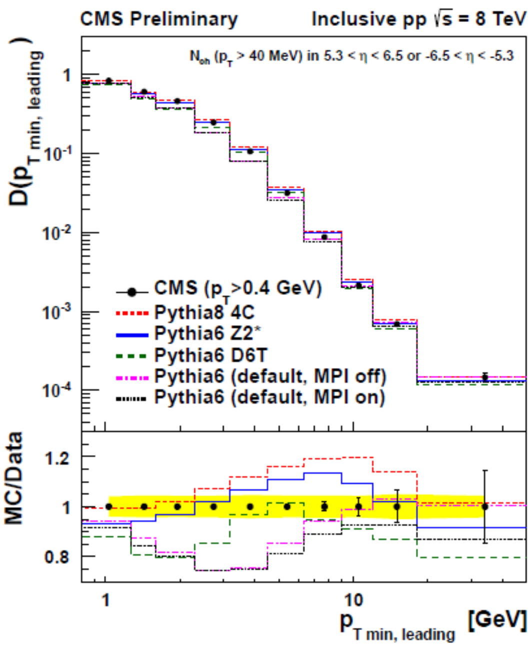
- The average multiplicity for inclusive sample for p_T>0.1 GeV is 5.4 +/- 0.2, for p_T>1 GeV is 0.78 +/- 0.03
- The average multiplicity for NSD-enhanced sample for p_T>0.1 GeV is 6.2 +/- 0.3, for p_T>1 GeV is 0.93 +/- 0.04
- PYTHIA6 Z2* describes the data in inclusive sample best
- In NSD-enhanced sample for p_T>0.1 GeV all models overshoot the data, for p_T>1 GeV all models except for HERWIG++ overshoot the data

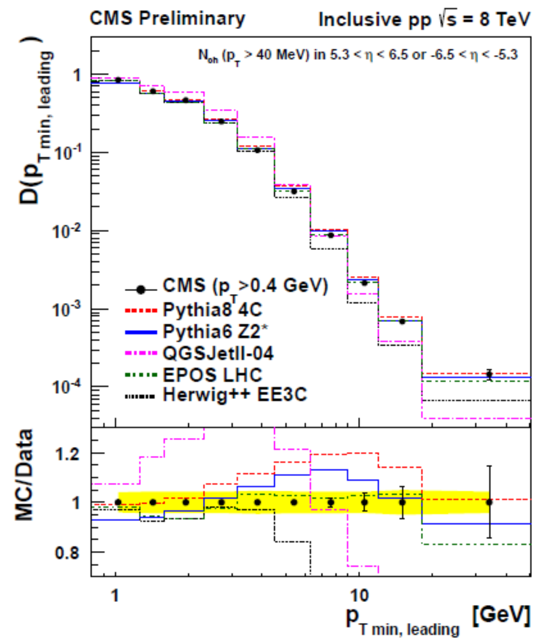
Charged particles distribution





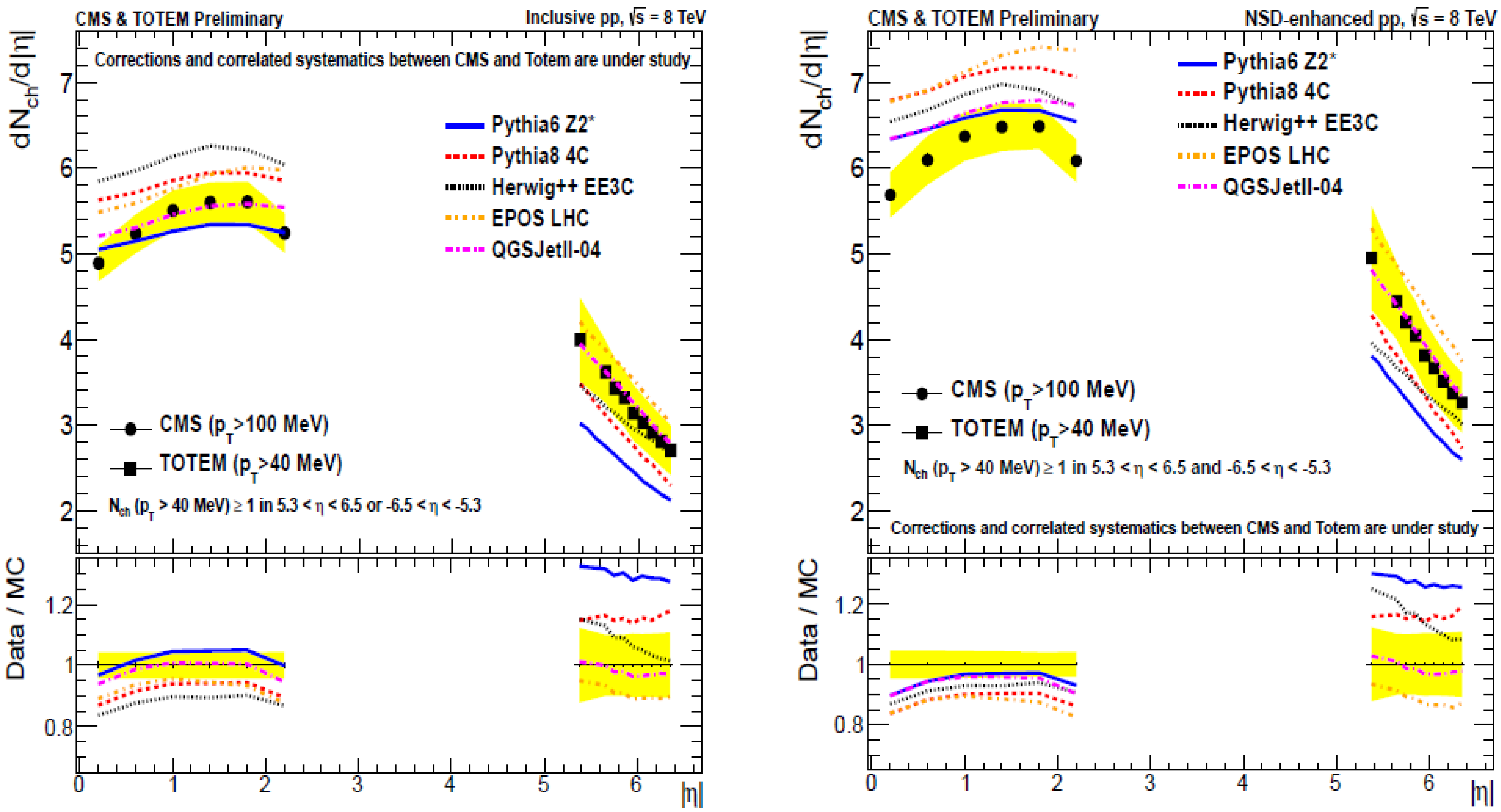
- The shape of the distributions is not well described by any of the models
- Effect of MPI has a small impact
- EPOS LHC seems to describe the data best





- $D(p_{\mathrm{T,min}}) = \frac{1}{N_{\mathrm{events}}} \sum_{p_{\mathrm{T,leading}} > p_{\mathrm{T,min}}} \Delta p_{\mathrm{T,\,leading}} \left(\frac{dN_{\mathrm{ch}}}{dp_{\mathrm{T,leading}}} \right)$
- The same conclusions holds

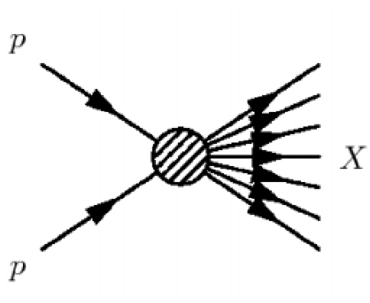
Charged particles distribution



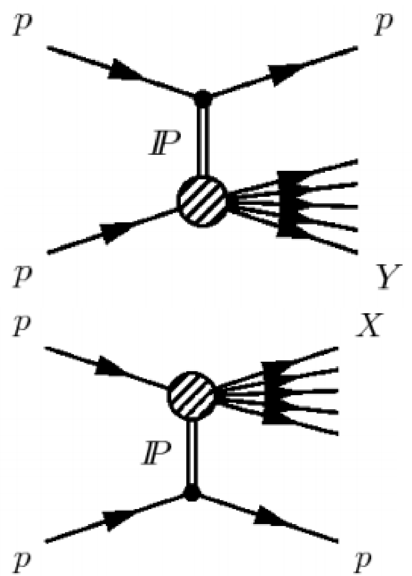
At central detector p_T>100 MeV cut, while in TOTEM p_T>40 MeV cut

Soft Diffraction

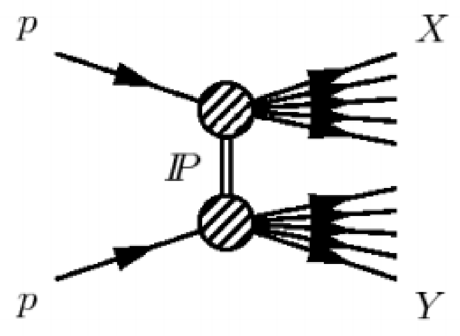
non-diffraction



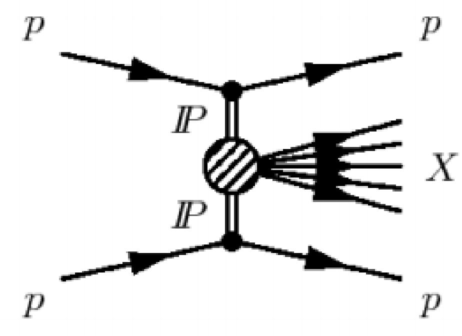
single diffractive dissociation (SD)



double diffractive dissociation (DD)



central diffraction

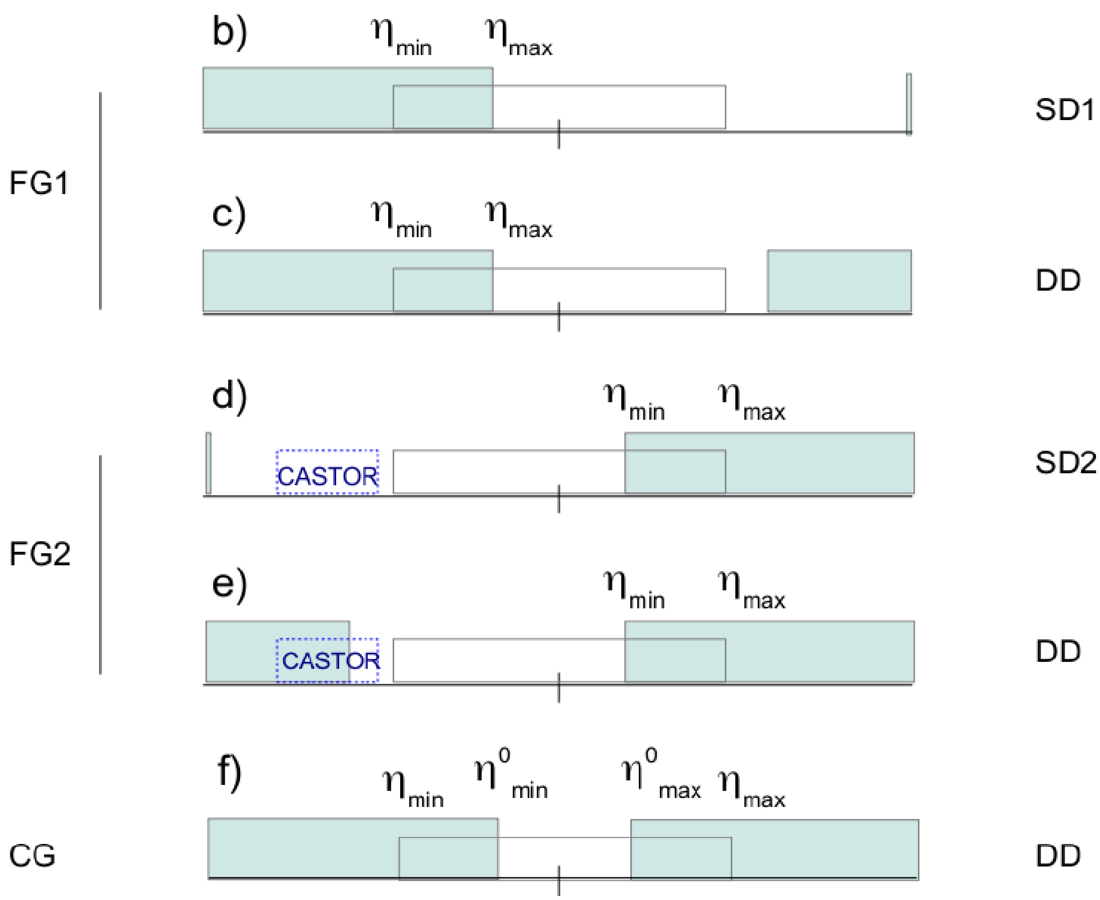


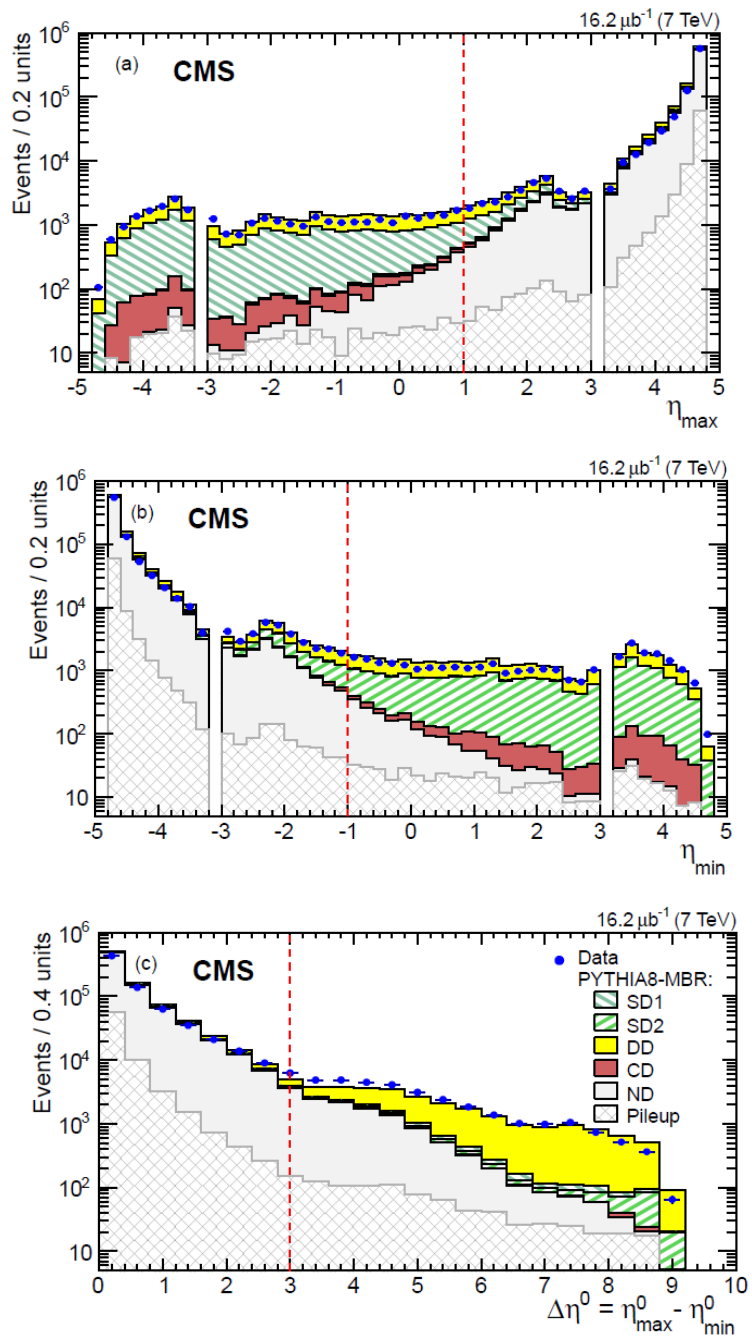
send to PRD,
arXiv:1503.08689
CMS-PAS-FSQ-12-005

Selection:

- ~20 μb^{-1} of low pile-up data (μ=0.14), from 2010
- Online: activity in either of the BSC – Minimum Bias trigger
- No vertex requirement (low diffractive masses 12<Mx<100 GeV accepted)
- Diffractive offline selection: Large Rapidity Gaps within |η|<4.7

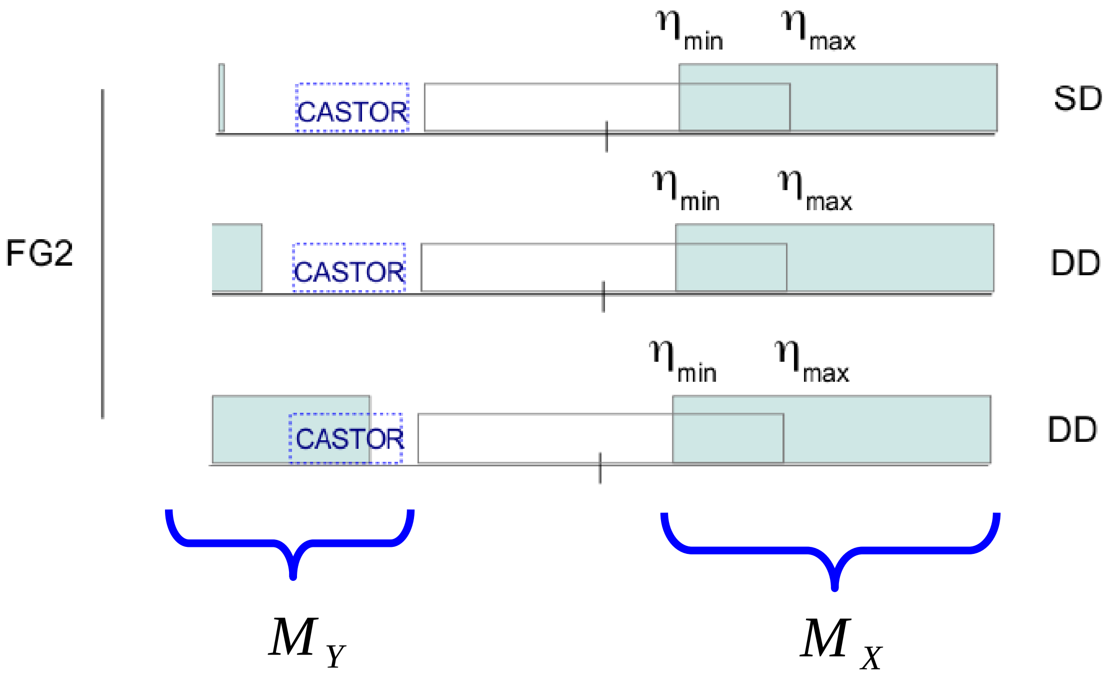
Diffractive event topologies





- η_{max} (η_{min}) highest (lowest) η of the particle candidate with $|\eta|<4.7$
- $\Delta\eta = \eta^0_{max} - \eta^0_{min}$

Forward gap



$\log_{10} M_Y < 0.5$

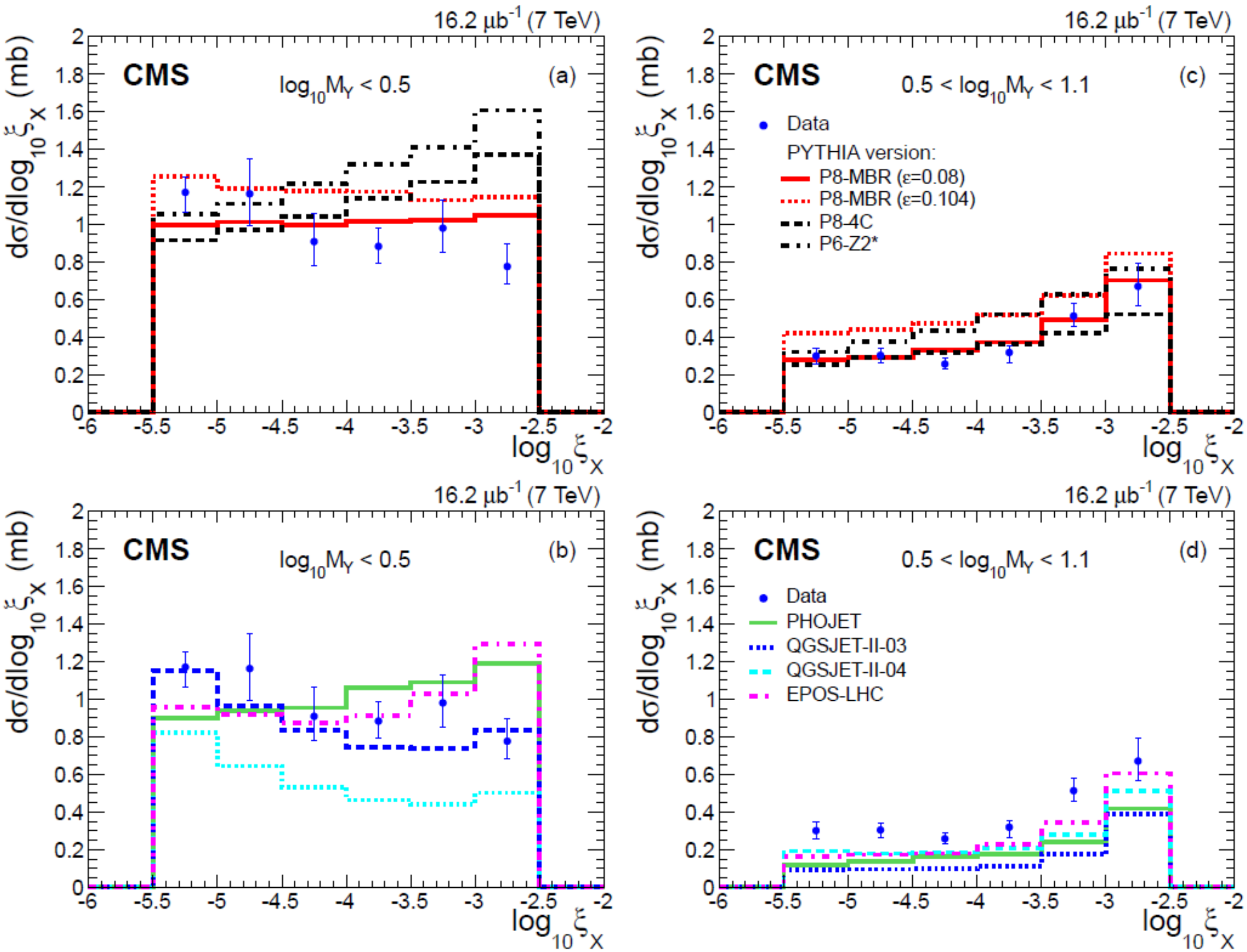
$0.5 < \log_{10} M_Y < 1.1$

M_X, M_Y in GeV

- Variable ξ defined as: $$\xi_X = \frac{M_X^2}{s}$$
- Reconstructed: $$\xi_X^{rec} = \frac{\sum (E^i - p_z^i)}{\sqrt{s}}$$
- And corrected for undetected particles: (PYTHIA 8 MBR) $$\log_{10} \xi_X^{cal} = \log_{10} \xi_X^{rec} + C(\xi_X^{rec})$$

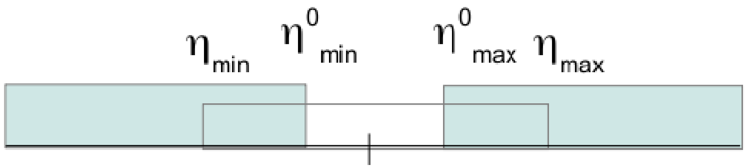
Forward gap

no-CASTOR tag — Castor tag



- Data with tag favor ε = 0.08
- PYTHIA8-4C and PYTHIA6-2Z* higher than data in no-CASTOR tag
- PYTHIA8-4C and PYTHIA6-2Z* predicts raising behavior in no-CASTOR tag
- PHOJET, QGSJET, EPOS cannot describe data in tag sample

Central gap

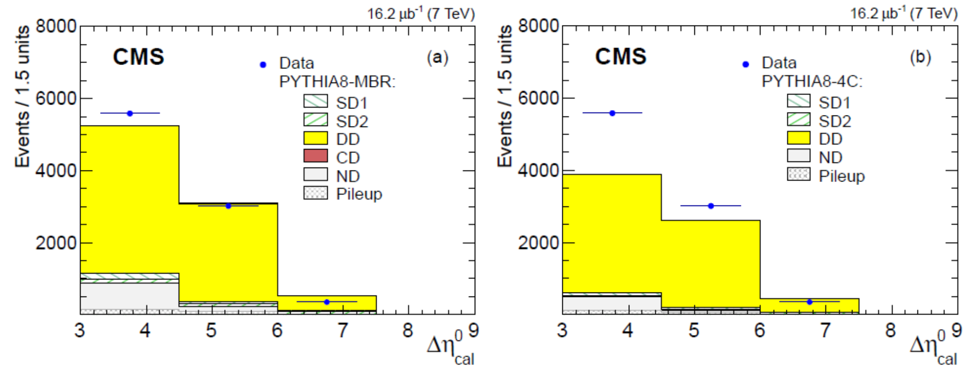
CG  DD

Range: $\log_{10} M_X > 1.1$

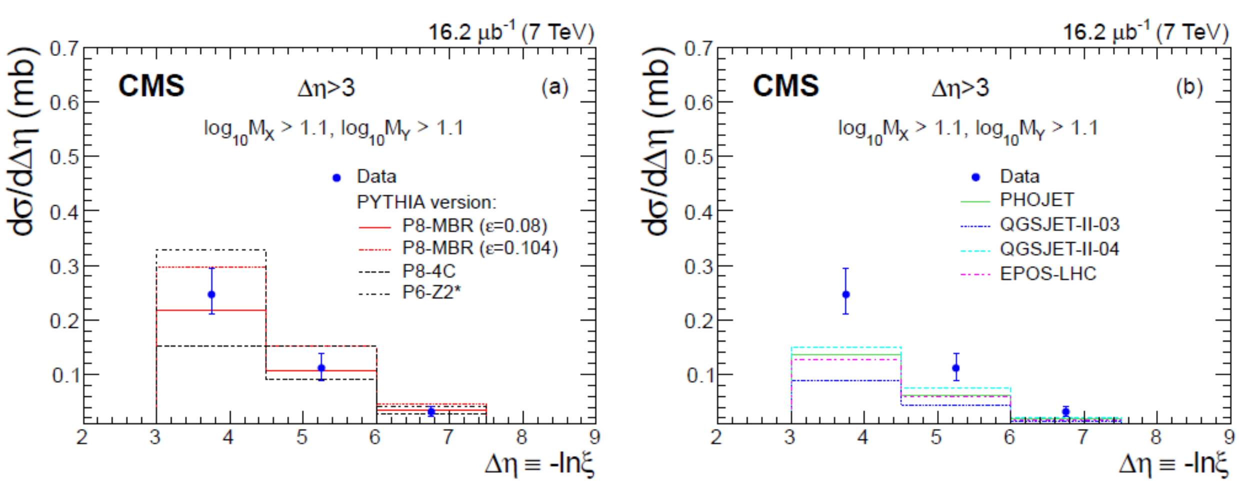
$\log_{10} M_Y > 1.1$

$$\Delta\eta = \eta^0_{max} - \eta^0_{min}$$

- Reconstructed: $\Delta\eta_{rec}$
- And corrected for detector effects: $\Delta\eta_{cal} = \Delta\eta_{rec} - C$



- Unfolding (response matrix from PYTHIA MBR)



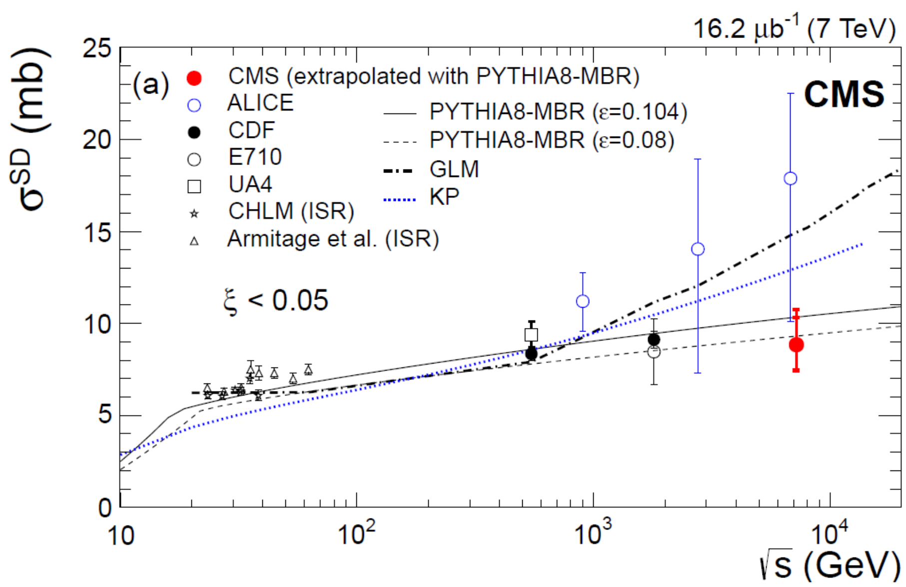
- P8-MBR describes the data
- P8-4C underestimates
- P6-Z2* overestimates
- PHOJET, QGSJET, EPOS underestimates

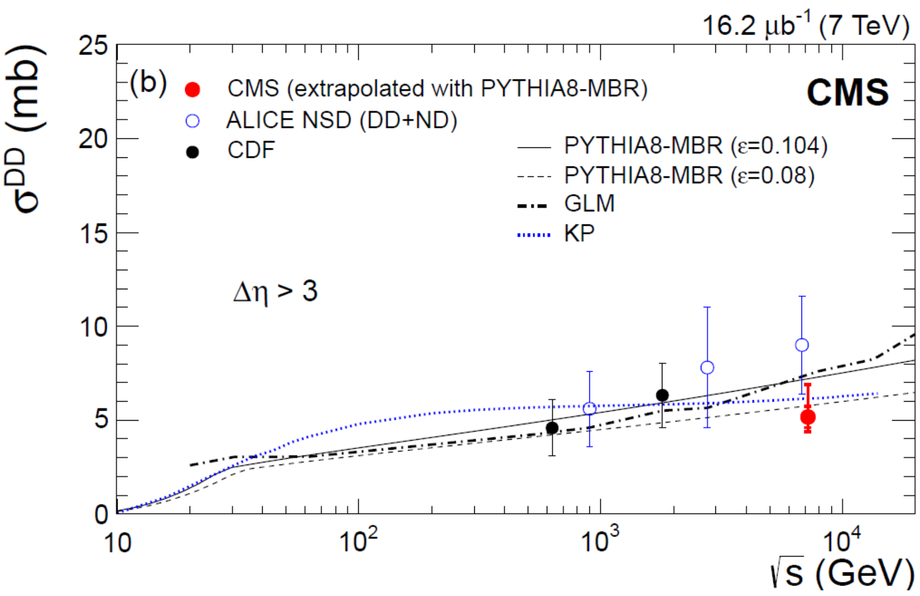
Cross section

Extrapolation to the not observed region: PYTHIA 8 MBR (ε = 0.08)

$$\sigma^{SD} = 8.84 \pm 0.08(stat)^{+1.49}_{-1.38}(syst)^{+1.17}_{-0.37}(extr)\, mb \qquad \xi_{X(Y)} < 0.05$$

$$\sigma^{DD} = 5.17 \pm 0.08(stat)^{+0.55}_{-0.57}(syst)^{+1.62}_{-0.51}(extr)\, mb \qquad \Delta\eta > 3$$

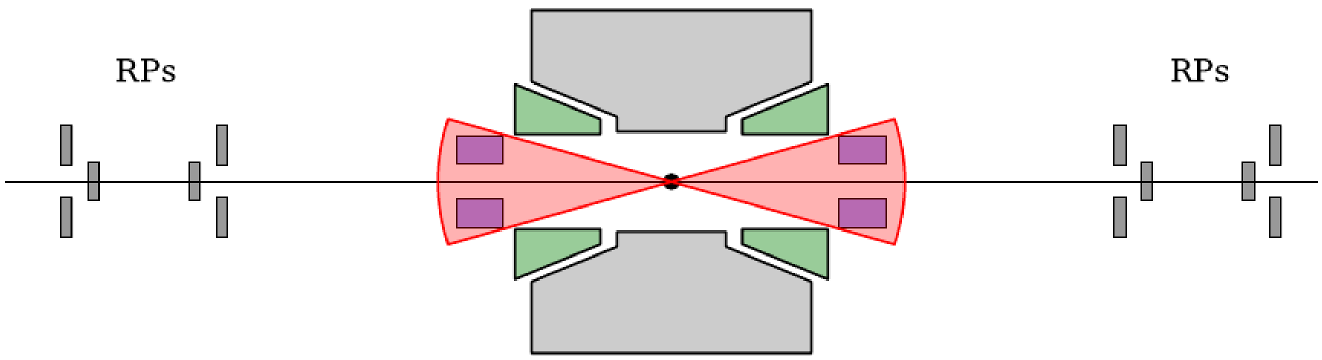




CMS results consistent with MBR predictions – SD cross section weakly rising with energy

CMS results consistent with MBR and KP model predictions – DD cross section weakly rising with energy

Double diffraction with TOTEM



- Tracks in both T2: $5.3 < |\eta| < 6.5$
- Veto on tracks in T1: $3.1 < |\eta| < 4.7$

- Corrected to: $4.7 < |\eta| < 6.5$ → **3.4 GeV < M < 8 GeV**

Total cross section:

$$\sigma_{DD(4.7<|\eta_{min}|<6.5)} = 116 \pm 25\ \mu b$$

Pythia 8 $\sigma_{DD(4.7<|\eta_{min}|<6.5)} = 159\ \mu b$

Phojet $\sigma_{DD(4.7<|\eta_{min}|<6.5)} = 101\ \mu b$

Summary

- A large set of observables sensitive to UE and MPI available
- Models can be tuned to describe the observables
- CMS is ready for 13/14 TeV data taking
- CMS performed measurement of diffractive dissociation cross section in pp
- Extrapolation of the SD and DD to the regions $\xi < 0.05$ and $\Delta\eta > 3$ gave:

$$\sigma^{SD} = 8.84 \pm 0.08(stat)^{+1.49}_{-1.38}(syst)^{+1.17}_{-0.37}(extr)\,mb$$

$$\sigma^{DD} = 5.17 \pm 0.08(stat)^{+0.55}_{-0.57}(syst)^{+1.62}_{-0.51}(extr)\,mb$$

- PYTHIA8-MBR describes the data in all the measured regions
- TOTEM published DD results, more results on SD, CD to come

Spares

Underlying Event with Leading Track

Leading object in an event – a track with the highest p_T

Data samples:

- 2010 low pile-up
- 0.9 TeV → 1 μb^{-1} , negligible pile-up
- 7 TeV → 3 pb^{-1} , 1.05 collisions per event
- Minimum Bias trigger (BSC)

Vertex requirements:

- Only one vertex within 10 cm around the interaction point

Tracks selection:

- p_T>0.5 GeV and $|\eta|$<0.8
- Quality filters used – only high purity tracks retained
- Cut on the impact parameters – removal of the secondary tracks

Observables:

- The charge density: N_{ch}
- The transverse momentum density: $\sum p_T$

As a function of the leading track p_T

Underlying Event with Leading Track Jet

Leading object in an event – a charged particle jet

Data samples:

- New results: 2.76 TeV, 2011, 0.3 nb^{-1} , negligible pile-up
- For comparison: 0.9 TeV and 7 TeV → **JHEP 1109 (2011) 109**
- Minimum Bias trigger (BSC) + jet triggers (tresholds 20, 40 GeV)

Vertex requirements:

- Only one vertex within 10 cm around the interaction point

Tracks selection:

- p_T>0.5 GeV and $|\eta|<2.0$
- Quality filters used – only high purity tracks retained
- Cut on the impact parameters – removal of the secondary tracks

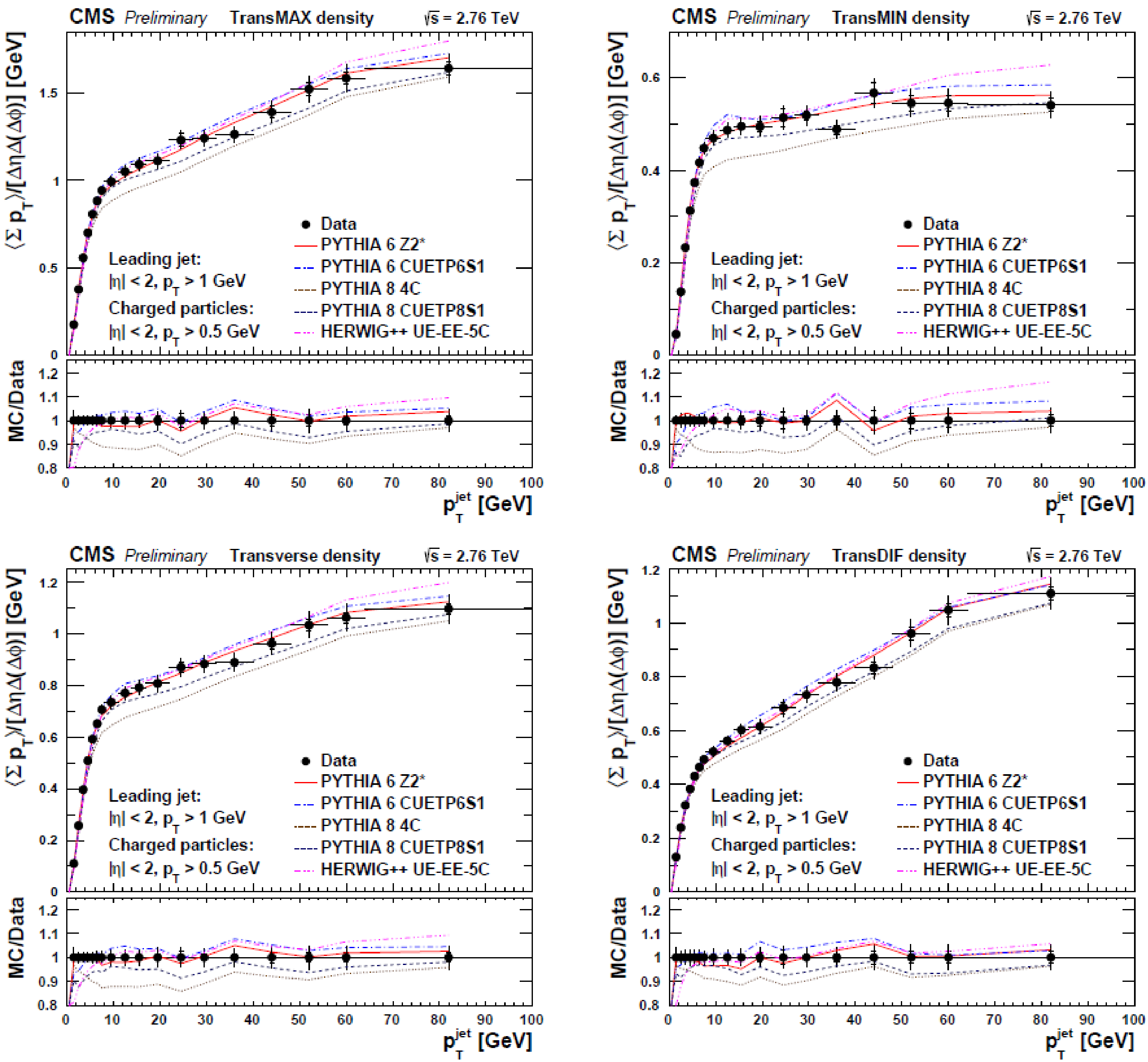
Jet requirements:

- Leading track jet with pT>1 GeV, $|\eta|<2.0$, clustered with SISCone 0.5
- Tracks used: pT>0.5 GeV, $|\eta|<2.5$

Observables:

- The same as in leading track analysis

Underlying Event with Leading Jet



- The same trend
- In TransMAX much faster rise at large p_T
  - average momentum of particles rises
- Best description: PYTHIA6 with Z2*
- All models and tuned predicts similar behaviour
- MPI and beam-beam remnant almost independent on the hard scale once the most central events selected p_T>8 GeV
- Initial and final state radiation increase with p_T

Cross section

Integrated cross section measured for 3 samples:

- FG2, no-CASTOR tag $-5.5 < \log_{10}\xi_X < -2.5$ $\log_{10} M_Y < 0.5$
- FG2, CASTOR tag $-5.5 < \log_{10}\xi_X < -2.5$ $0.5 < \log_{10} M_Y < 1.1$
- CG $\Delta\eta > 3$ $\log_{10} M_X > 1.1$ $\log_{10} M_Y > 1.1$

Cross section	$\sigma_{\text{no-CASTOR}}$(mb) SD dominated	σ_{CASTOR} (mb) DD dominated	σ_{CG} (mb) DD dominated
Data	$2.99 \pm 0.02^{+0.32}_{-0.29}$	$1.18 \pm 0.02 \pm 0.13$	$0.58 \pm 0.01^{+0.13}_{-0.11}$
PYTHIA 8 MBR	3.05	1.24	0.54
PYTHIA 8 4C	3.31	1.10	0.40
PYTHIA 6 Z2*	3.86	1.52	0.78
PHOJET	3.06	0.63	0.32
QGSJET-II 03	2.63	0.48	0.22
QGSJET-II 04	1.70	0.78	0.37
EPOS	2.99	0.85	0.31

Cross section

From no-CASTOR tag sample, visible SD cross section:

- Substraction of DD component → from PYTHIA 8 MBR

$$\sigma^{SDvis} = 4.06 \pm 0.04 (stat)^{+0.69}_{-0.63} (syst)\, mb \qquad -5.5 < \log_{10} \xi_X < -2.5$$

From CASTOR tag sample, visible DD cross section:

$$\sigma^{DDvis}_{CASTOR} = 1.06 \pm 0.02 (stat) \pm 0.12 (syst)\, mb \qquad -5.5 < \log_{10} \xi_X < -2.5$$

$$0.5 < \log_{10} M_Y < 1.1$$

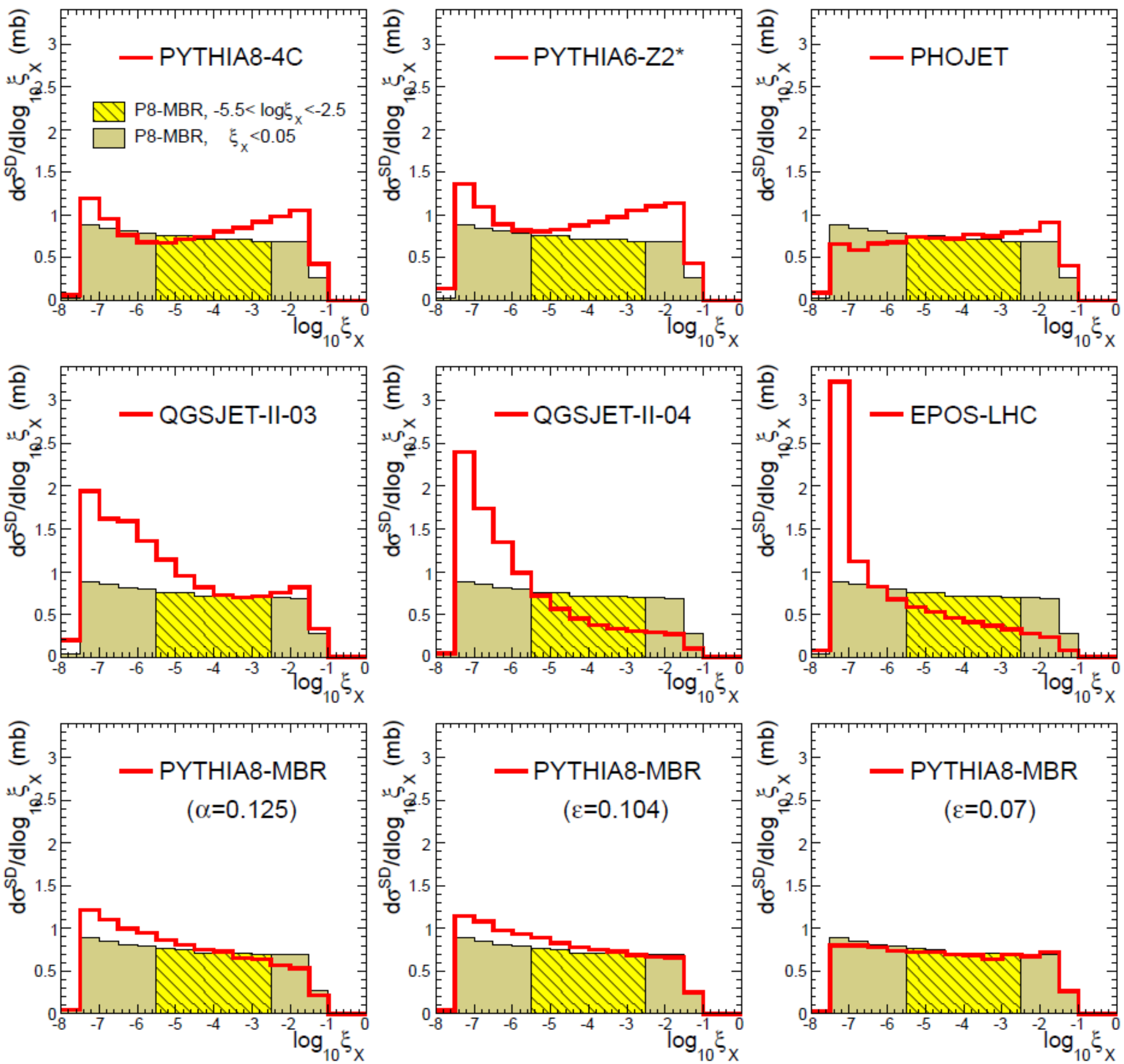
From CG sample, visible DD cross section:

$$\sigma^{DDvis}_{CG} = 0.56 \pm 0.01 (stat)^{+0.15}_{-0.13} (syst)\, mb \qquad \Delta\eta > 3$$

$$\log_{10} M_X > 1.1$$

$$\log_{10} M_Y > 1.1$$

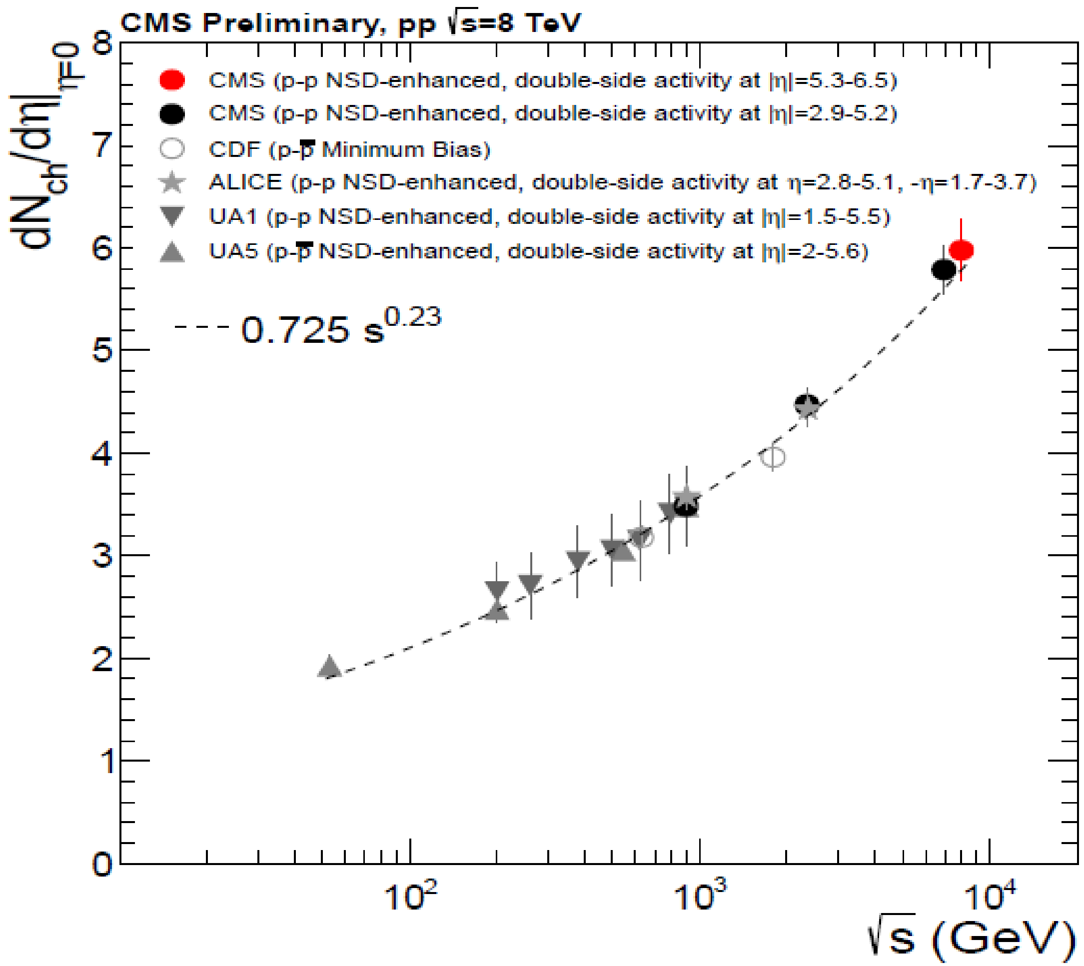
Extrapolation



i	MC model	f^{SD}	f^{SD}_{MBR}
1	PYTHIA 8 MBR ($\varepsilon = 0.08$)	2.18 (1.00)	2.18 (1.00)
2	PYTHIA 8 4C	2.32 (1.06)	2.51 (1.15)
3	PYTHIA 6 Z2*	2.29 (1.06)	2.89 (1.34)
4	PHOJET	2.06 (0.95)	2.18 (1.00)
5	QGSJET-II 03	2.72 (1.25)	3.19 (1.46)
6	QGSJET-II 04	3.62 (1.66)	2.30 (1.06)
7	EPOS	3.44 (1.58)	2.15 (0.99)
8	PYTHIA 8 MBR ($\alpha' = 0.125$)	2.27 (1.04)	2.34 (1.07)
9	PYTHIA 8 MBR ($\varepsilon = 0.104$)	2.23 (1.03)	2.42 (1.11)
10	PYTHIA 8 MBR ($\varepsilon = 0.07$)	2.16 (0.99)	2.09 (0.96)

i	MC model	f^{DD}	f^{DD}_{MBR}
1	PYTHIA 8 MBR ($\varepsilon = 0.08$)	1.92 (1.00)	1.92 (1.00)
2	PYTHIA 8 4C	2.52 (1.32)	1.86 (0.97)
3	PYTHIA 6 Z2*	2.39 (1.25)	2.15 (1.13)
4	PHOJET	1.80 (0.94)	0.60 (0.31)
5	QGSJET-II 03	—	—
6	QGSJET-II 04	2.04 (1.07)	0.94 (0.49)
7	EPOS	4.73 (2.47)	1.93 (1.01)
8	PYTHIA 8 MBR ($\alpha' = 0.125$)	1.97 (1.03)	2.32 (1.21)
9	PYTHIA 8 MBR ($\varepsilon = 0.104$)	2.00 (1.04)	2.37 (1.24)
10	PYTHIA 8 MBR ($\varepsilon = 0.07$)	1.88 (0.98)	1.73 (0.90)

Charged particles distribution



- Comparison for NSD sample
- Previouse CMS results extrapolated to p_T=0 GeV.
- Extrapolation factor ~5%
- The same used for 8 TeV
- $dN_{ch}/d\eta\,|_{\eta=0} \sim s^{\varepsilon}$, $\varepsilon \approx 0.23$

MC Models

Monte Carlo:

- PYTHIA8-4C
  - diffraction generated according to Schuler&Sjostrand model from PYTHIA6
  - SD and DD cross sections scaled down by 10% and 12%

- PYTHIA8-MBR (Minimum Bias Rockefeler model)
  - diffraction generated based on renormalized Regge theory model
  - developed for CDF
  - linear parametrization of the Pomeron trajectory $\alpha(t) = 1 + \varepsilon + \alpha' t$
  - $\alpha' = 0.25\ \text{GeV}^{-2}$, $\varepsilon = 0.08$ or 0.104
  - DD cross section scaled down by 15%

- PYTHIA6-Z2*

- PHOJET

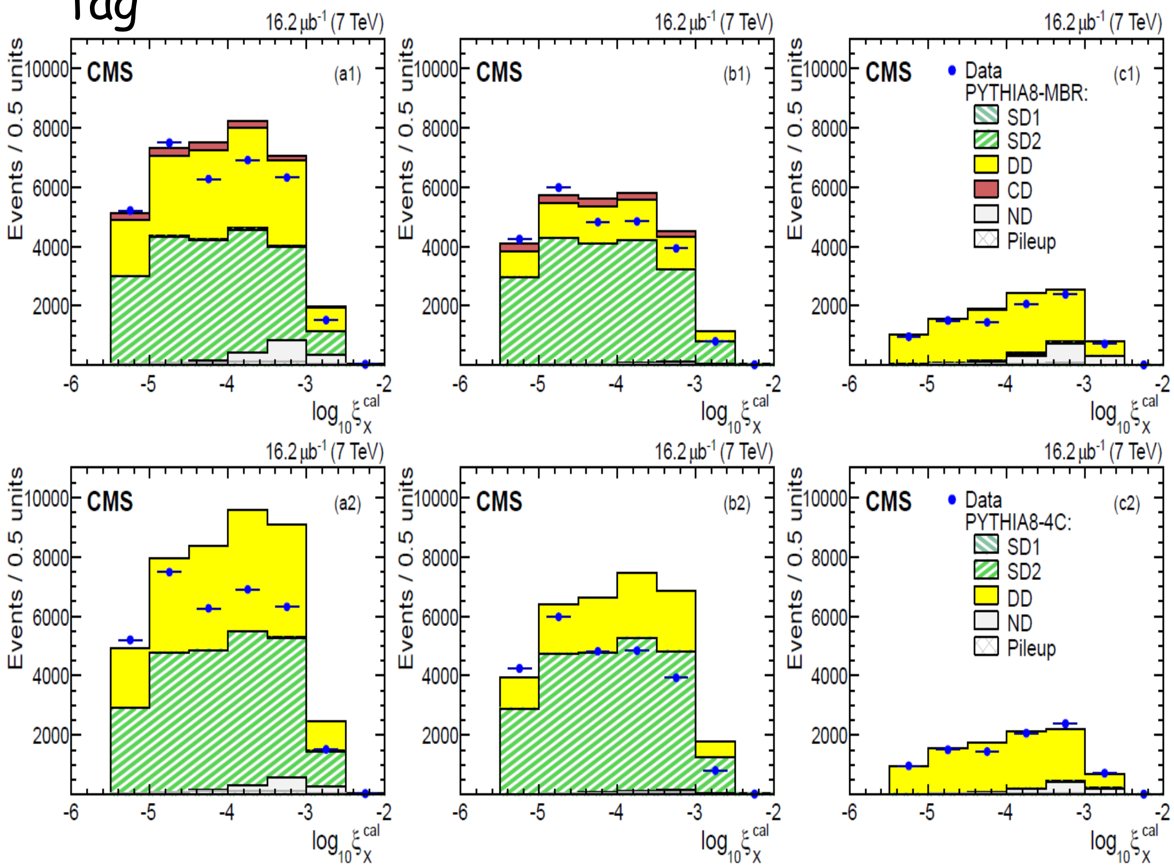
- QGSJET-II
- EPOS

} cosmic rays MC

Forward gap

Detector level distributions

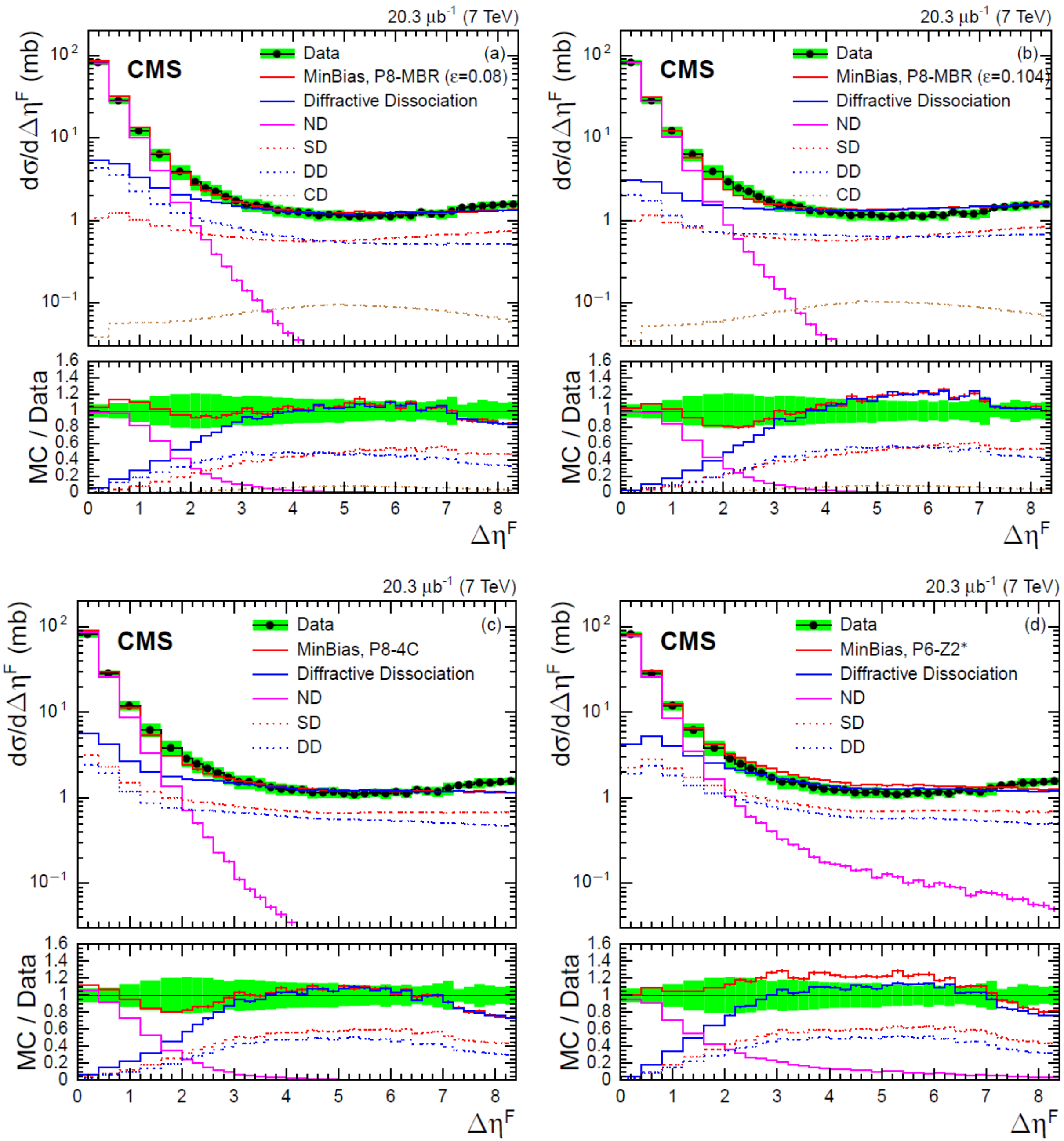
full sample tag   no-CASTOR tag   CASTOR



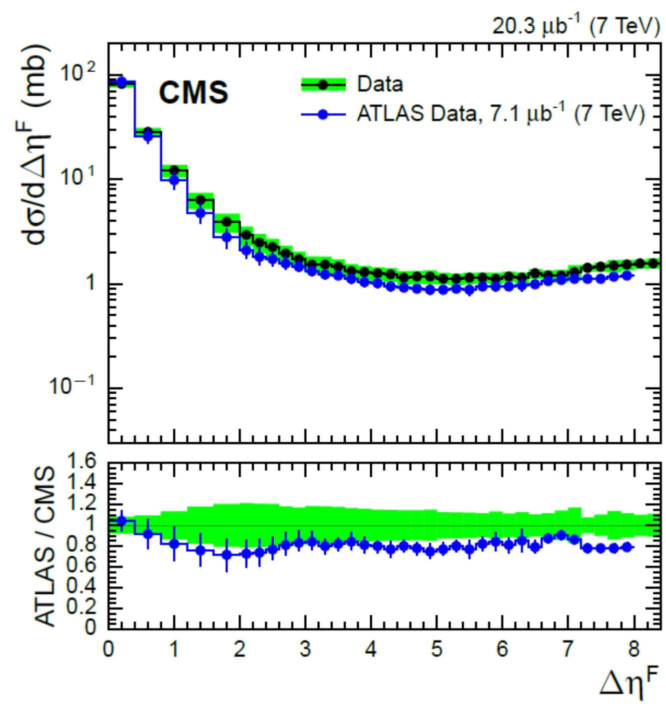
Cross section measured in bins of ξ_X

- Data unfolded (acceptance and migration corrections)
- PYTHIA 8 MBR
- Corrections for pile-up

Pseudorapidity gap cross section



- Exponential falling non-diffractive contribution
- Diffractive plateau at $\Delta\eta_F > 3$
- mixture of SD and DD events
- Best described: PYTHIA8+MBR with 0.08 intercept.

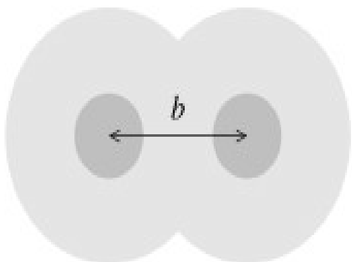


Differences in acceptance

Underlying Event at Forward Rapidities

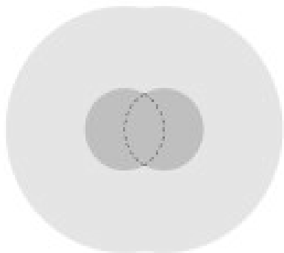
Measurement of energy density at forward rapidities with CASTOR: $-6.6<\eta<-5.2$

Minimum bias

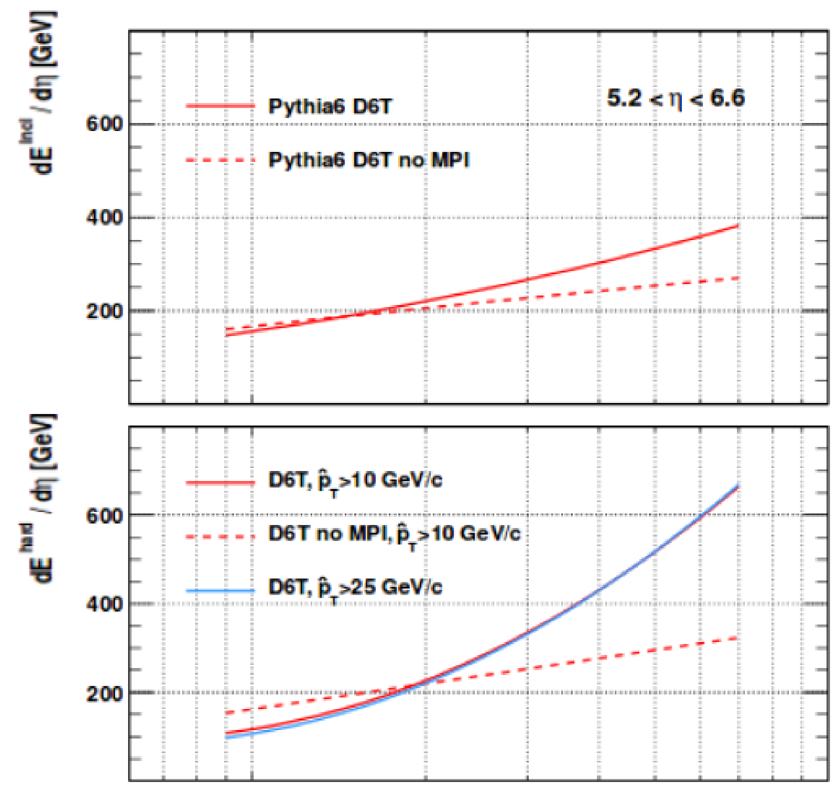


BSC trigger
Energy density not much affected by MPI

Hard scale $\hat{p}_T$

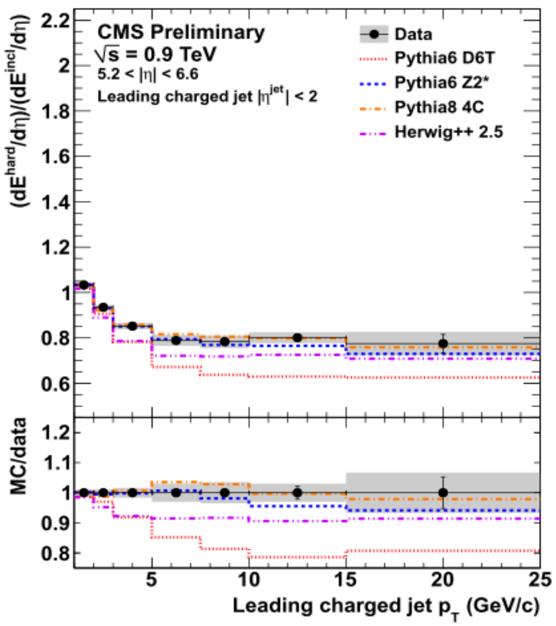


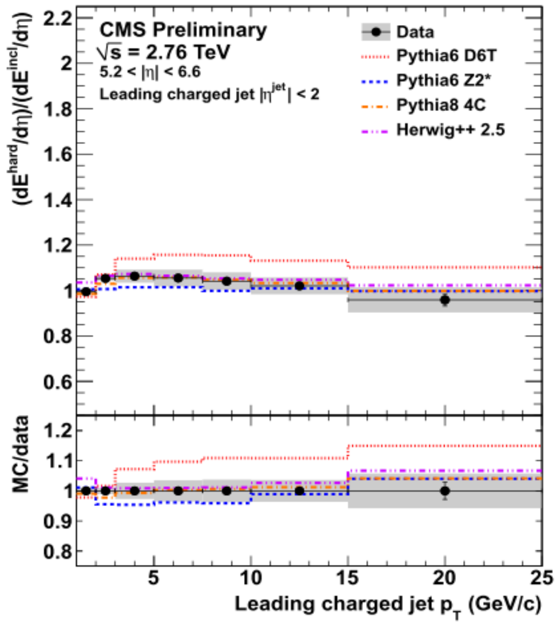
Central jet: $|\eta| < 2$
Track-jet algorithm
$p_T>1$ GeV
Energy flow in CASTOR as a function of jet p_T
Energy flow strongly affected by MPI

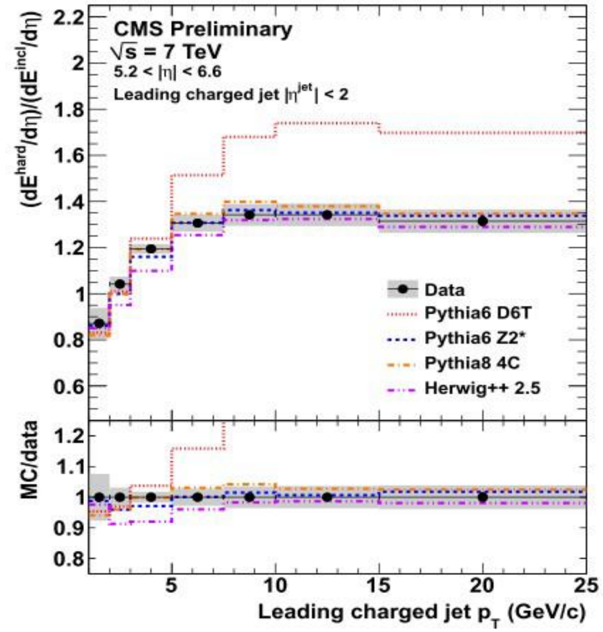


- Three energies: 0.9, 2.76 and 7 TeV
- Results quoted as ratios E(hard)/E(MB) – removal of most of the systematic effects
- Factorization of MPI contribution

Underlying Event at Forward Rapidities







- E(MB)>E(hard scale)
- Increase in central activity depletes proton remnant

- E(MB)≈E(hard scale)

- E(MB)<E(hard scale)
- Fast rise of forward activity at small p_T
- plateau at higher p_T

- Good description by the PYTHIA LHC tunes: Z2*, 4C
- Pre-LHC tunes fail: D6T
- Herwig++ 2.5 describe the data well

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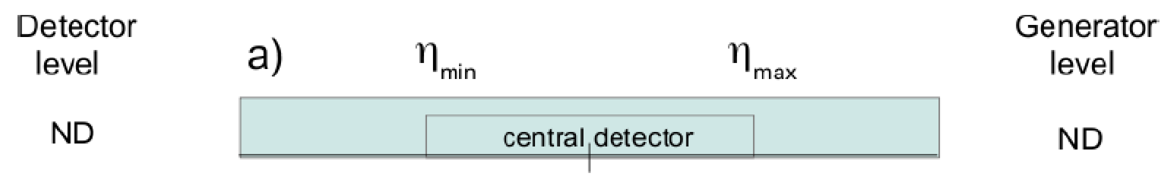
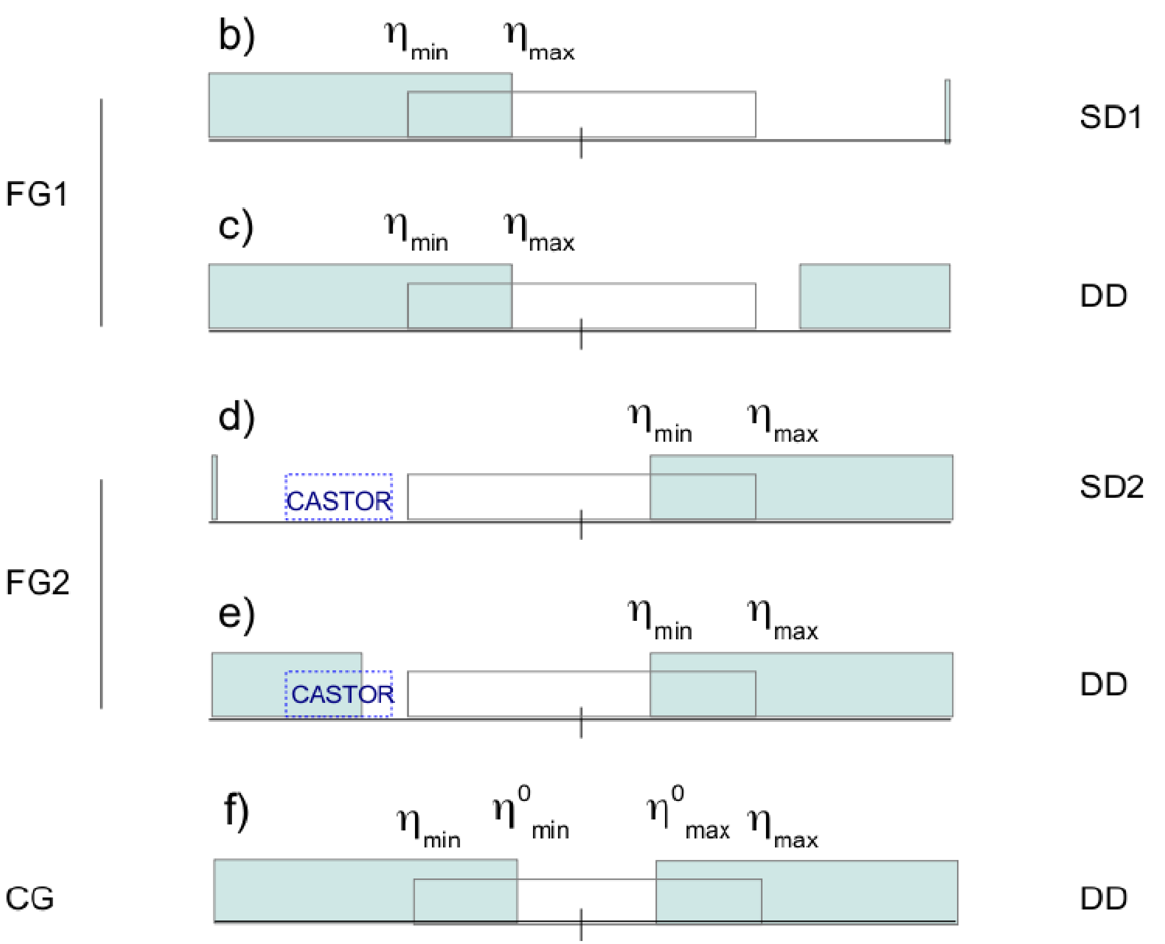
Diffractive event topologies



Three experimental topologies based on the position of the LRG without CASTOR information



SD1 - gap on positive side

DD – but without detection of particles at "+" side

SD2 - gap on negative side

DD – but without detection of particles at "-" side at central detector

DD - gap in the center