From exclusive production, through diffraction, to jets correlations - forward physics results from CMS

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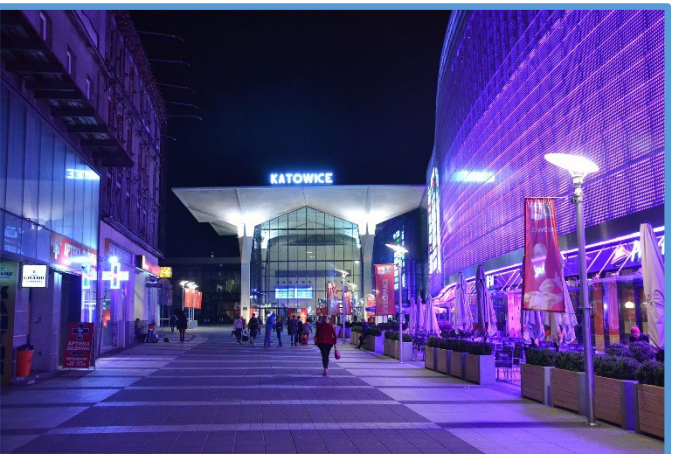
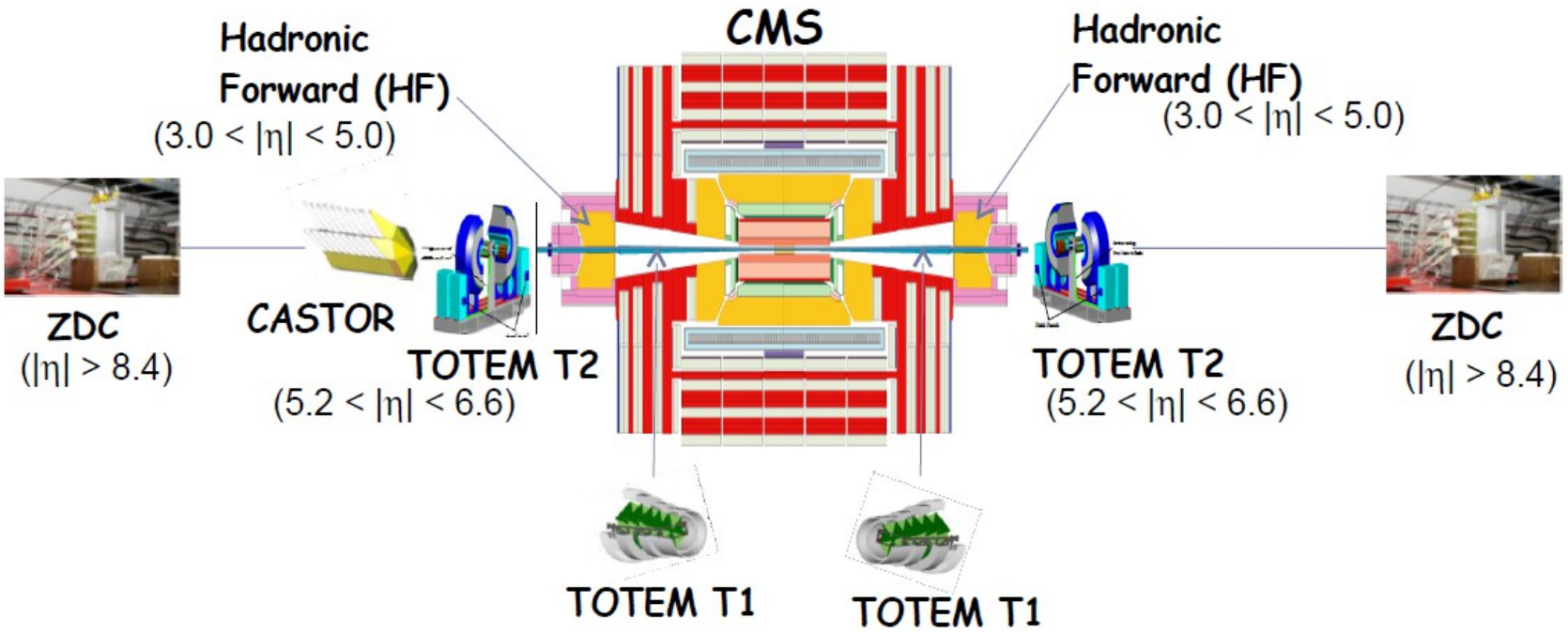


"Collider Physics"
2nd Symposium of
the Division for Physics
of Fundamental Interactions of
the Polish Physical Society
Katowice

CMS detector at forward rapidities



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

- Hadronic Forward calorimeters (HF)
- Centauro And STrange Objects Research (CASTOR) - calorimeter
- Zero Degree Calorimeter (ZDC)
- Beam Scintillator Counters BSC: $3.2 < |\eta| < 4.7$
- Forward Shower Counters FSC: $6 < |\eta| < 8$

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

Physics at forward rapidities

- Exclusive production – almost nothing also in the forward region
- Diffraction – nothing at one side (or in the center)
- Multi parton interactions – activity everywhere but the largest component forward
- Jets – pQCD in the forward region
- Correlations between jets

The data from Run1, an overview of the possibilities.

Exclusive production

Central Exclusive Production (CEP)

→ study of the reactions: $p\,p \to p^{(*)}\,X\,p^{(*)}$

→ numerous production mechanisms: $\gamma\gamma$, $\gamma|P$, $|P|P$ ...

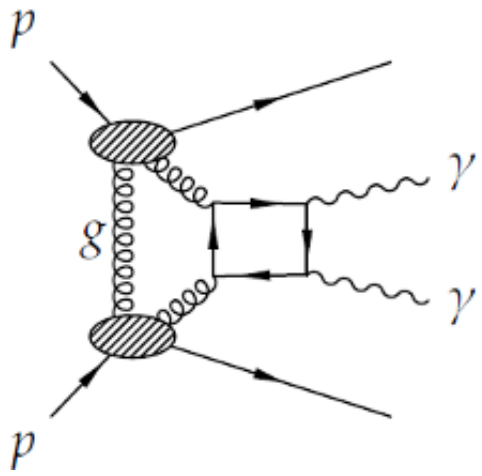
→ different central systems: e^+e^- , $\mu^+\mu^-$, $\gamma\gamma$, jj , W^+W^- , H ...

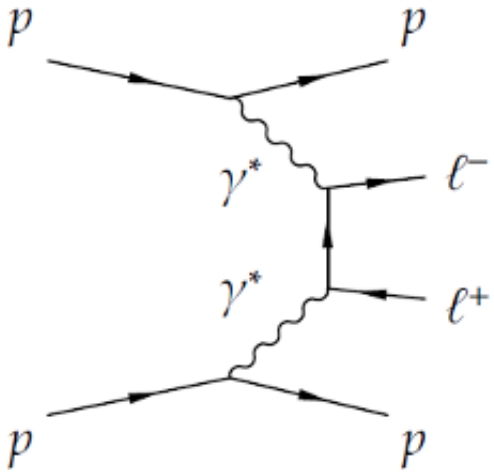
→ observables:

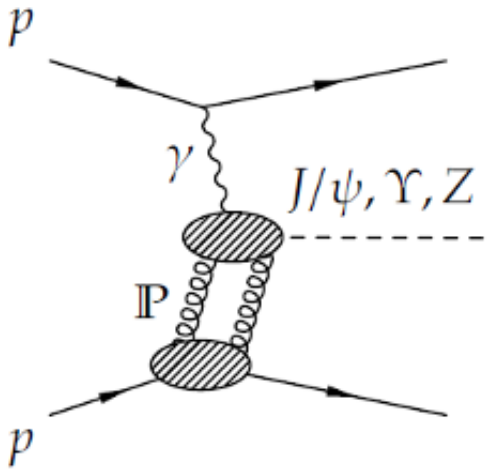
→ well defined activity in the detector corresponding to the central state

→ no additional activity

→ protons outside the acceptance

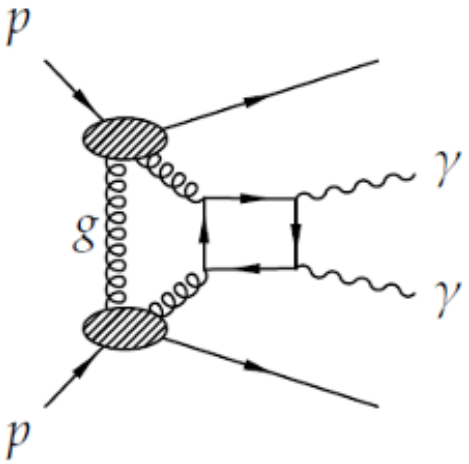






Exclusive production

JHEP 11 (2012) 080



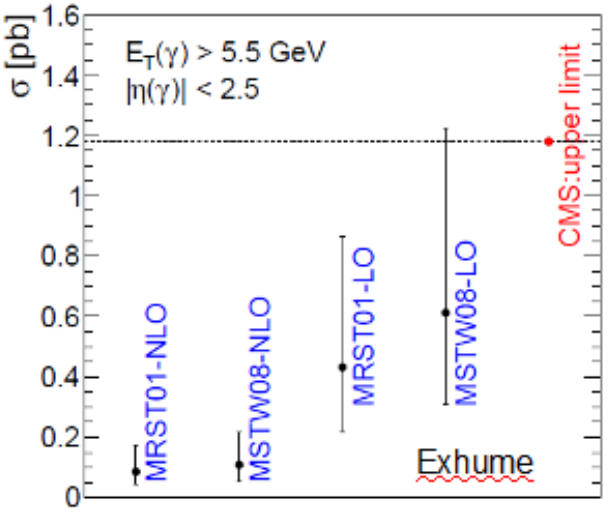
- Data: L=36 pb^{-1} , 2010 data (low pile-up)
- Selection:
  - Two isolated photons
  - E_T > 5.5 GeV
  - $|\eta|$ < 2.5
  - No additional activity within $|\eta|$ < 5.2

No candidates observed → upper limit on the cross section (95% CL):

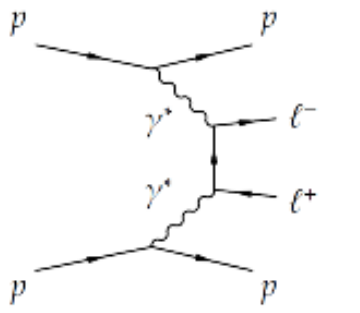
$$\sigma^{prod}\big|_{E_T(\gamma)>5.5\ \text{GeV},\ |\eta(\gamma)|<2.5} < 1.18\ \text{pb}$$

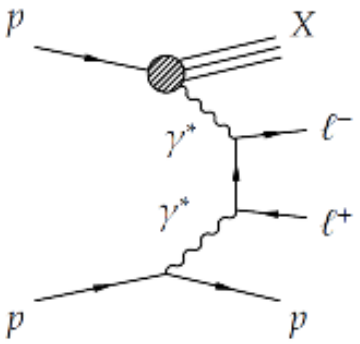
Predictions from various models:

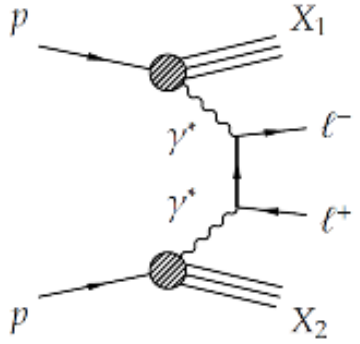
MC generator		PDFs set MRST01	PDFs set MSTW08
ExHuMe	LO	0.432	0.612
	NLO	0.086	0.109
SuperCHIC	LO		0.472
	NLO	0.103	
Harland-Lang *et al* (2012)	LO		0.180
	NLO	0.039	



Exclusive production





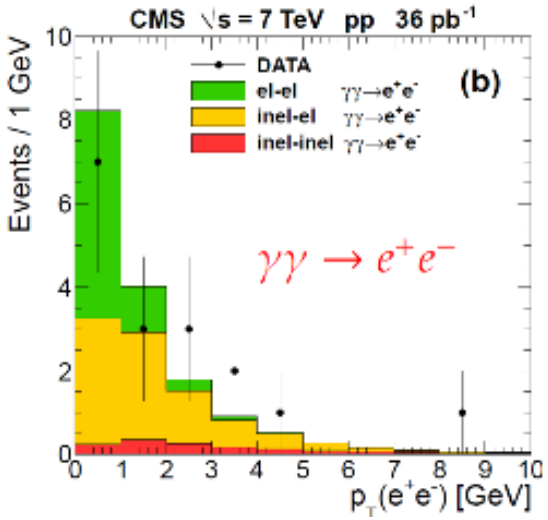


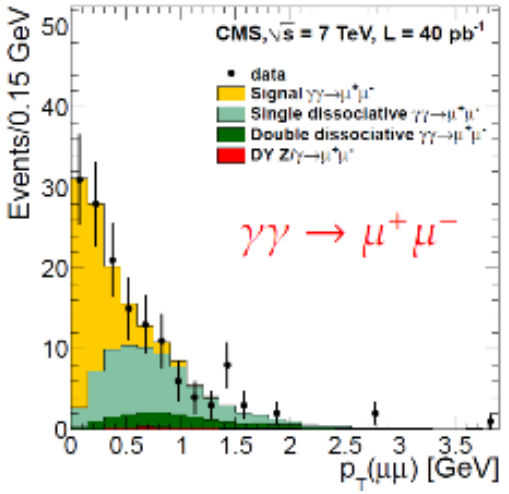
- Low pile-up
- Pure QED process

$\gamma\gamma \rightarrow e^+e^-$: JHEP 11 (2012) 080
$\gamma\gamma \rightarrow \mu^+\mu^-$: JHEP 11 (2012) 052

- Dimuon channel: $p_T(\mu) > 4$ GeV , $|\eta(\mu)| < 2.5$, $m(\mu\mu) > 11.5$ GeV
- Dielectron channel: $p_T(e) > 5.5$ GeV , $|\eta(e)| < 2.1$
- Vertex with two leptons and no additional tracks

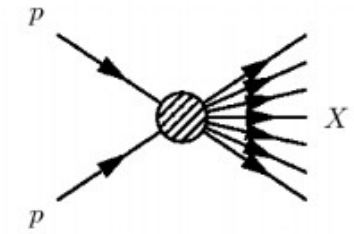
In dielectron channel: 17 candidates observed,
SM prediction: 16.3 +/- 1.3 (signal) + 0.85 +/- 0.28 (background)
In dimuon channel: $\sigma(pp \rightarrow p\mu^+\mu^- p) = 3.38^{+0.58}_{-0.55}\,(\text{stat.}) \pm 0.16\,(\text{syst.}) \pm 0.14\,(\text{lumi.})$ pb
Data/Theory ratio: $0.83^{+0.14}_{-0.13}\,(\text{stat.}) \pm 0.04\,(\text{syst.}) \pm 0.03\,(\text{lumi.})$



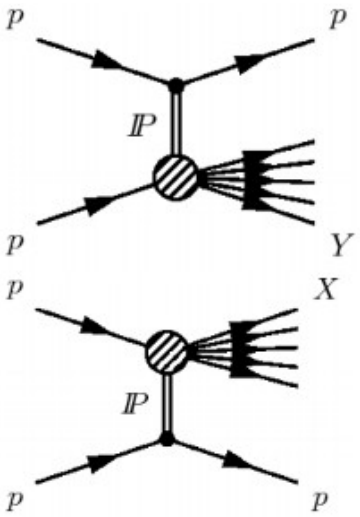


Soft diffraction

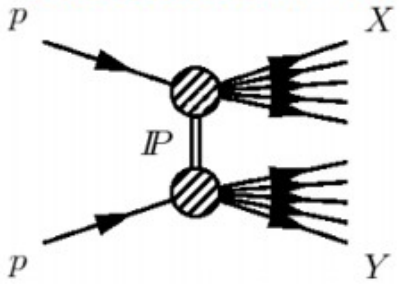
non-diffraction



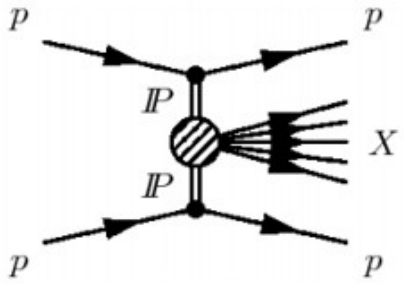
single diffractive dissociation (SD)



double diffractive dissociation (DD)



central diffraction



Phys.Rev. D92 (2015) no.1, 012003

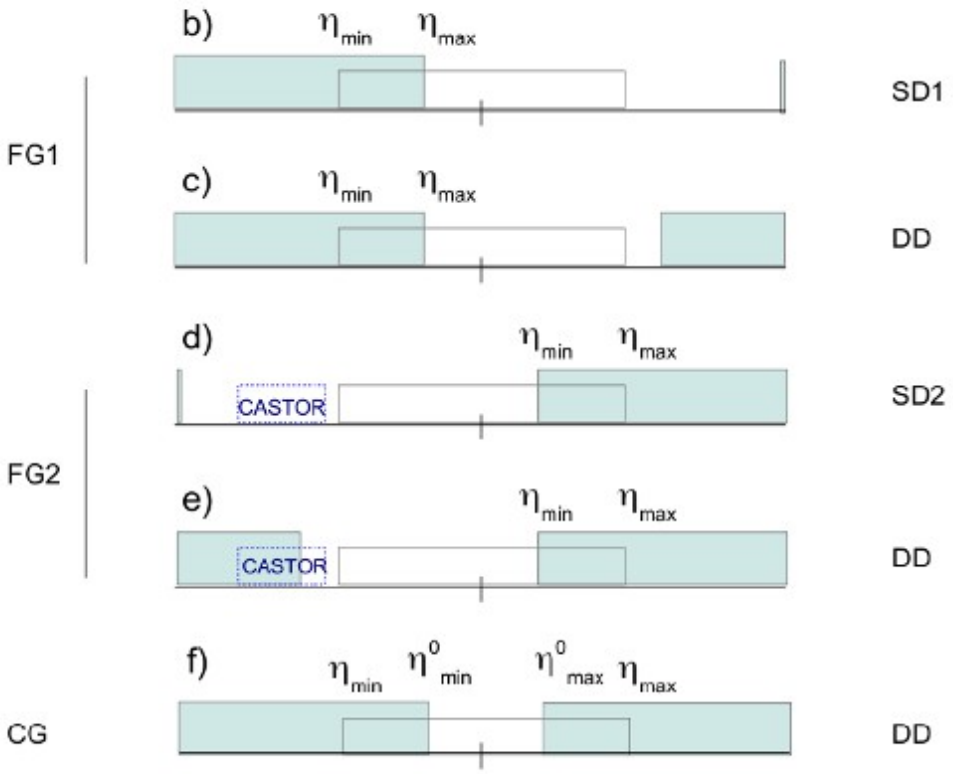
Selection:

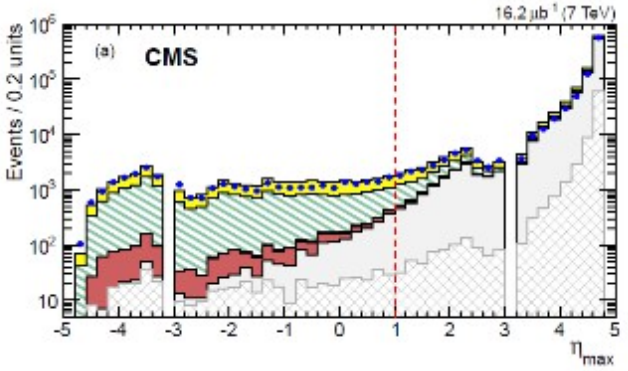
- 2010 low pile-up data
- Online: activity in either of the BSC - Minimum Bias trigger
- No vertex requirement (low diffractive masses Mx<100 GeV accepted)
- Diffractive offline selection: Large Rapidity Gaps within $|\eta|<4.7$

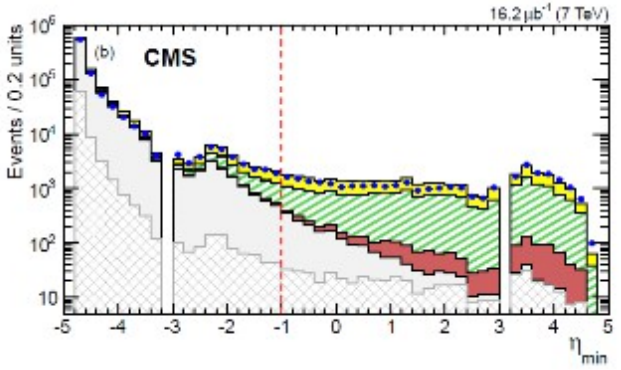
Monte Carlo for comparison:

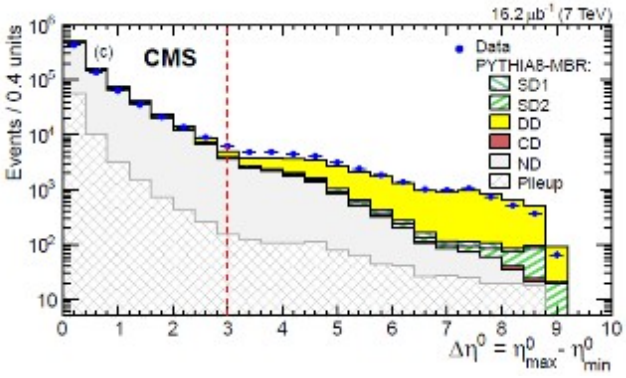
- PYTHIA8-MBR - with Minimum Bias Rockefeler model
- PYTHIA8-4C - with diffraction from Schuler&Sjostrand from PYTHIA6

Soft diffraction









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

Soft diffraction

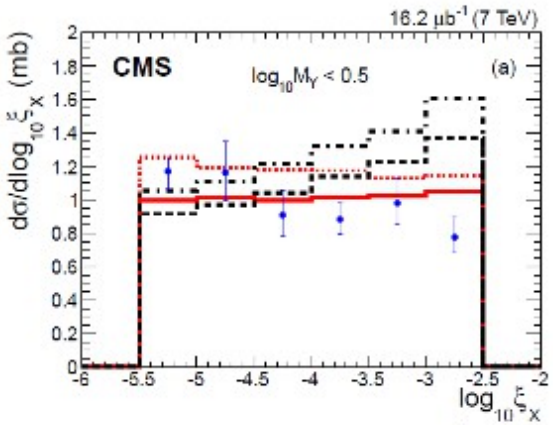
$$\xi_X = \frac{M_X^2}{s} \longrightarrow \xi_X^{rec} = \frac{\sum (E^i - p_z^i)}{\sqrt{s}}$$

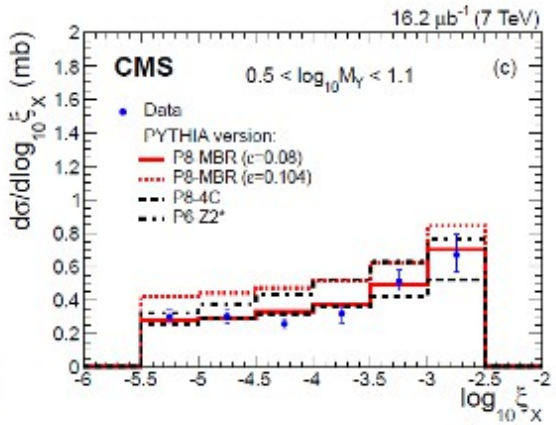
$$\Delta\eta = \eta^0_{max} - \eta^0_{min}$$

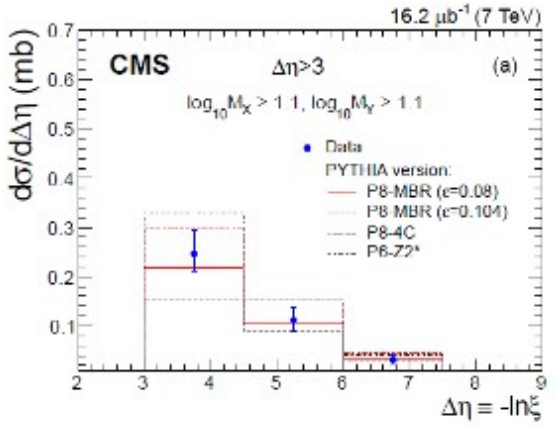
no-CASTOR tag

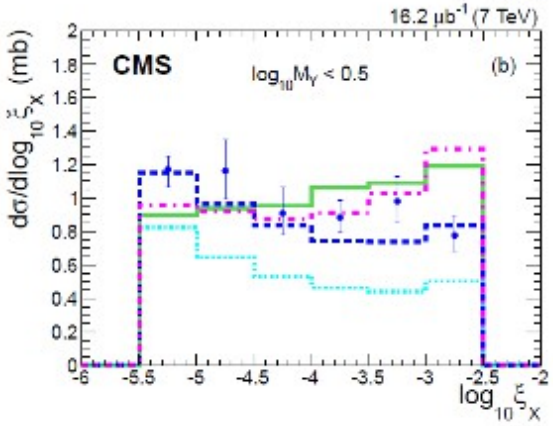
Castor tag

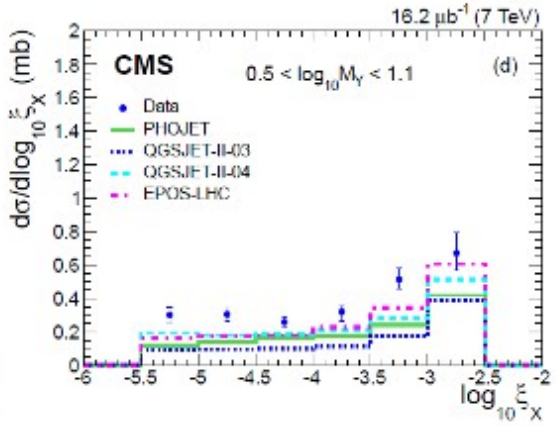
Central gap sample

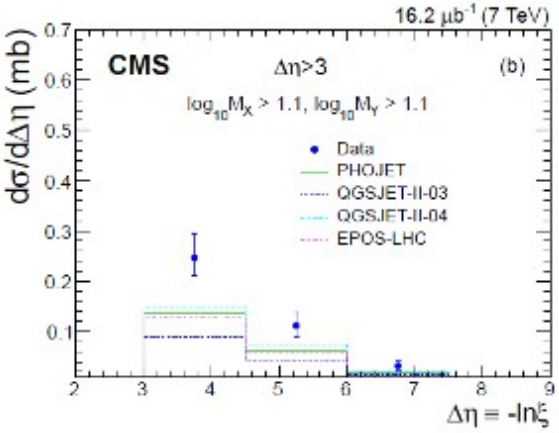










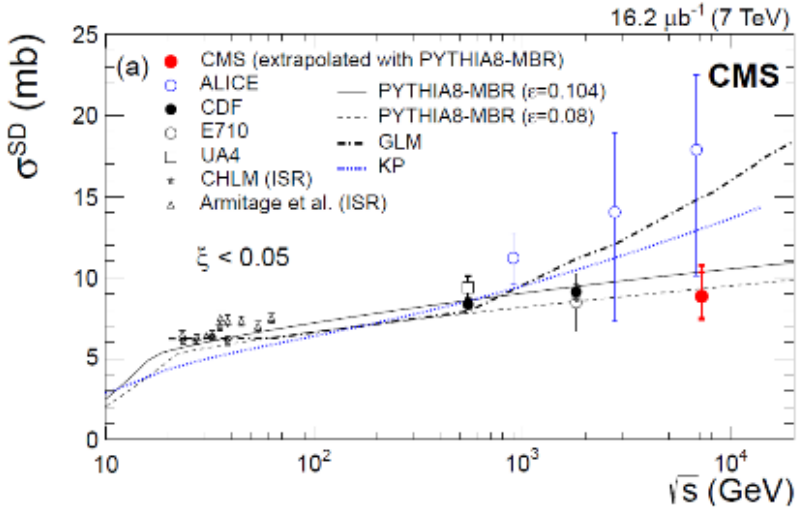


Soft diffraction

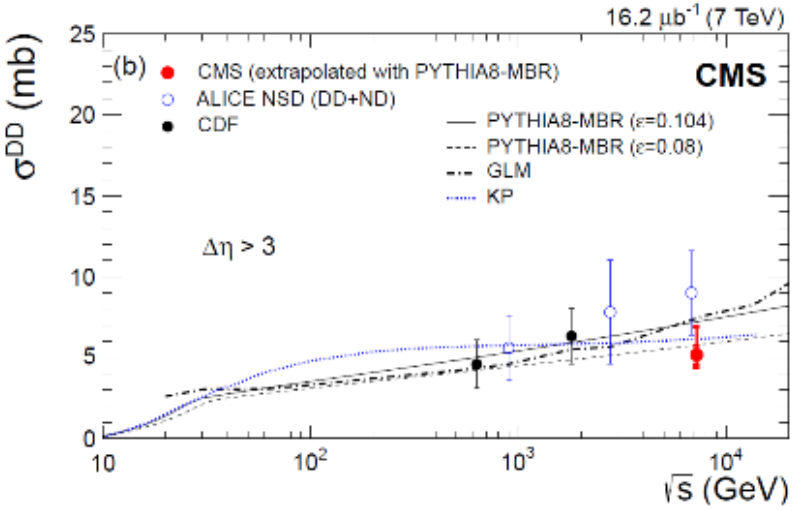
Extrapolation to the not observed region: PYTHIA 8 MBR (ε = 0.08)

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

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



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



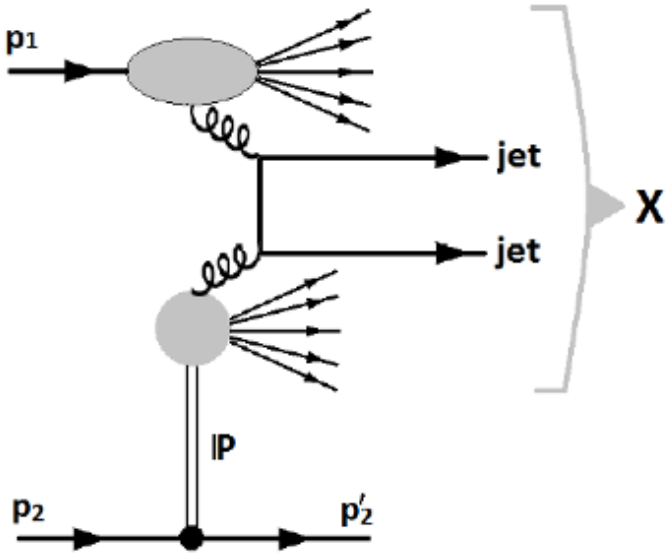
CMS results consistent with MBR and KP model predictions – DD cross section weakly rising with energy

Hard diffraction

Selection:

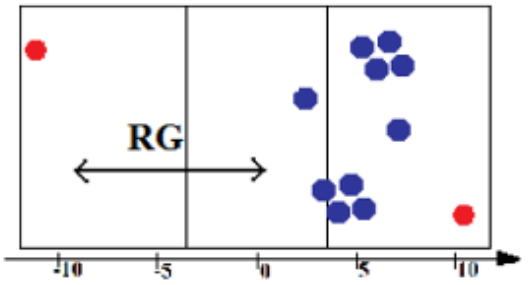
- ~2.7 nb^{-1} of low pile-up data (μ=0.09), from 2010
- Online: 6 GeV uncorrected jet p_T
  (>95% efficient for dijets with p_T>20 GeV)
- A primary vertex with |z|<24 cm
- Quality cuts imposed on jets
- Two jets with p_T>20 GeV and in |η| < 4.4

→ **277 953 events**



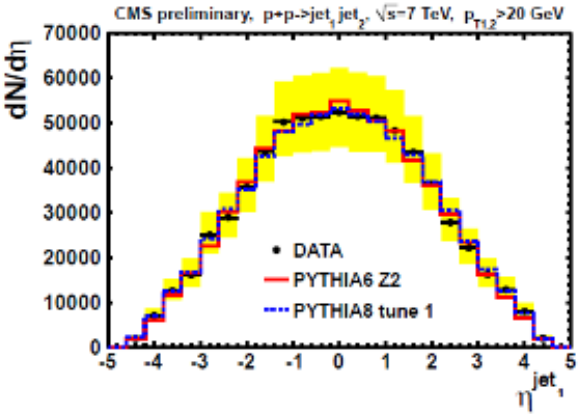
- η_{MAX} < 3 (η_{MIN} > -3), corresponding to LRG >1.9

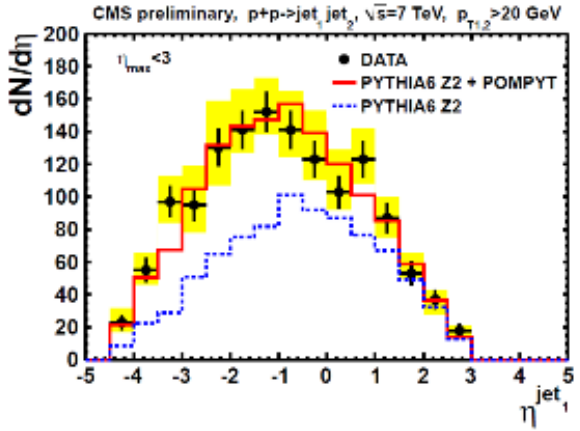
→ **442 events**

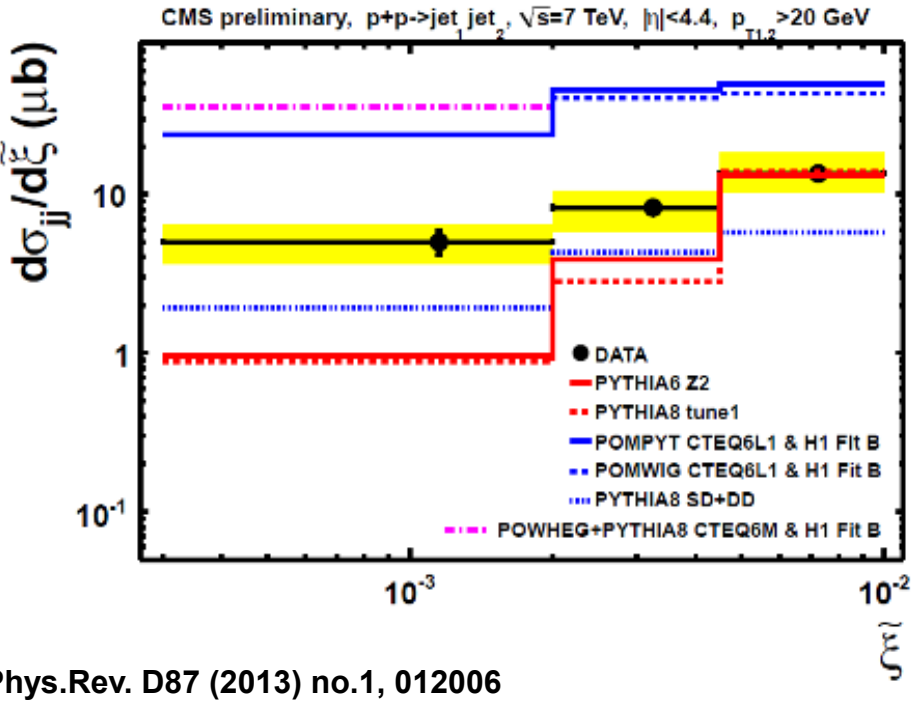


Hard diffraction

Leading jet η (before and after η_{MAX} cut)







- PYTHIA6 and PYTHIA8 without hard diffraction cannot describe the data
- POMPYT, POMWIG predicts more events than in data (factor ~5)

- Estimate of the rapidity-gap survival probability: 0.12 (from POMPYT/POMWIG)
- From POWHEG it is: 0.08

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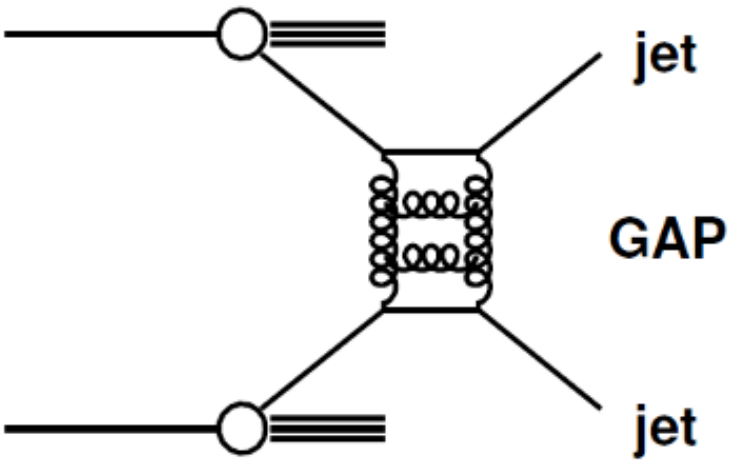
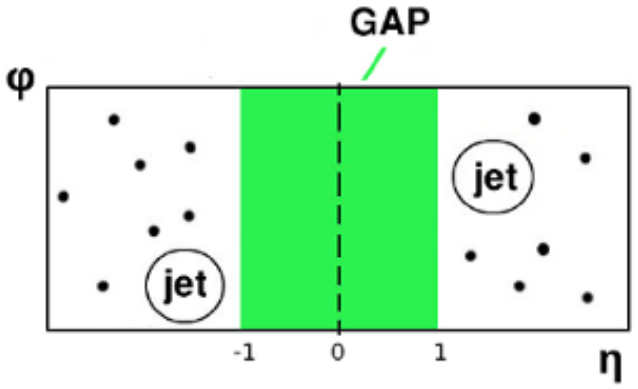
Hard diffraction



- Jets separated by a large rapidity gap
- Color singlet exchange
- Probe BFKL dynamics
- Rescattering processes – rap-gap survival

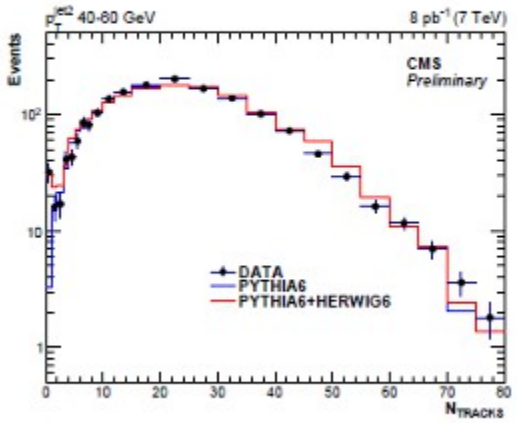
Selection:

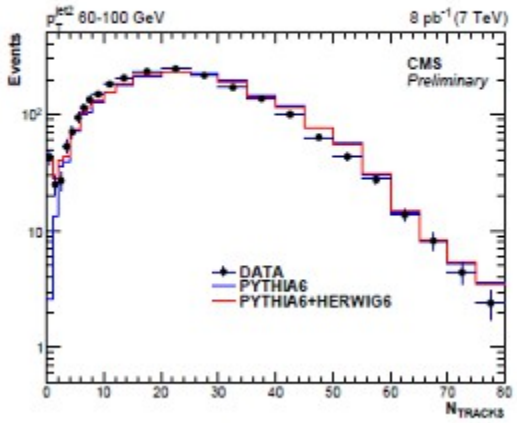
- Three samples of dijets with the lower energy jet in p_T bins:
  40-60 GeV, 60-100 GeV, 100-200 GeV
- $\eta_{jet1} \times \eta_{jet2} < 0$ (jets in different hemispheres)
- $|\eta_{jet1,2}| > 1.5$
- Number of tracks calculated in $|\eta|<1$ interval
  → tracks with $p_T > 0.2$ GeV

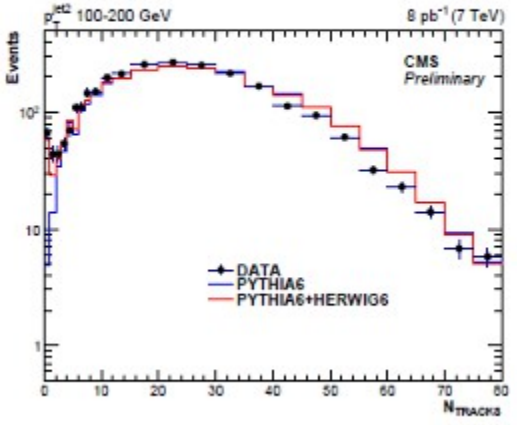


Hard diffraction

Number of tracks in the central rapidity interval

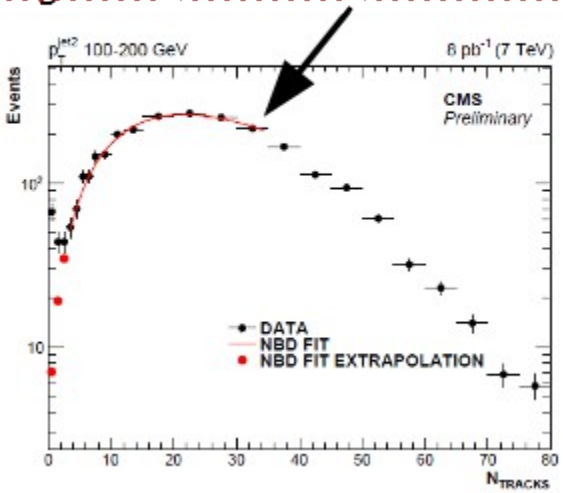


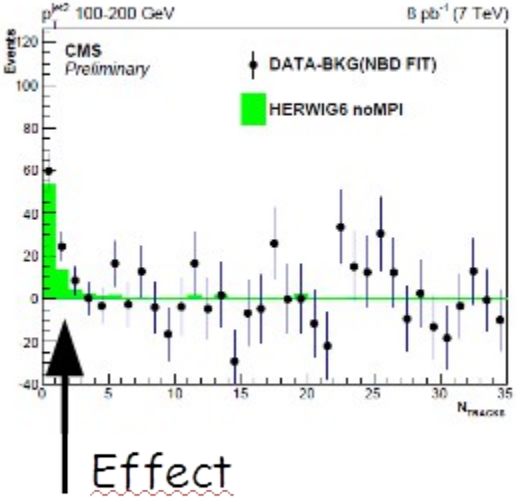




- Clear excess of gap events over PYTHIA6 predictions – first bins

Negative binomial distribution fitted

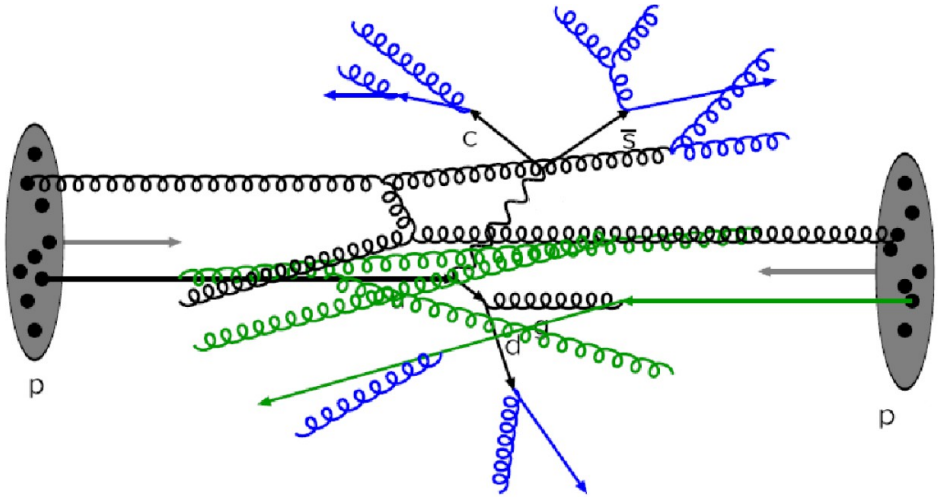




Underlying event

- Hard scattering

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

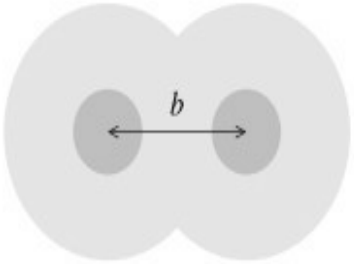


Underlying Event

Underlying event

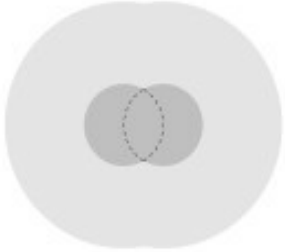
Measurement of energy density at forward rapidities for CASTOR: -6.6<η<-5.2

Minimum bias

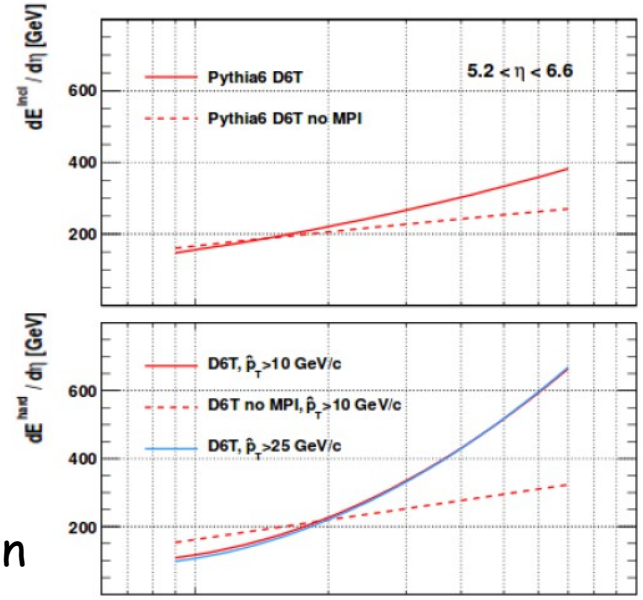


BSC trigger
Energy density not much affected by MPI

Hard scale $\hat{p}_T$

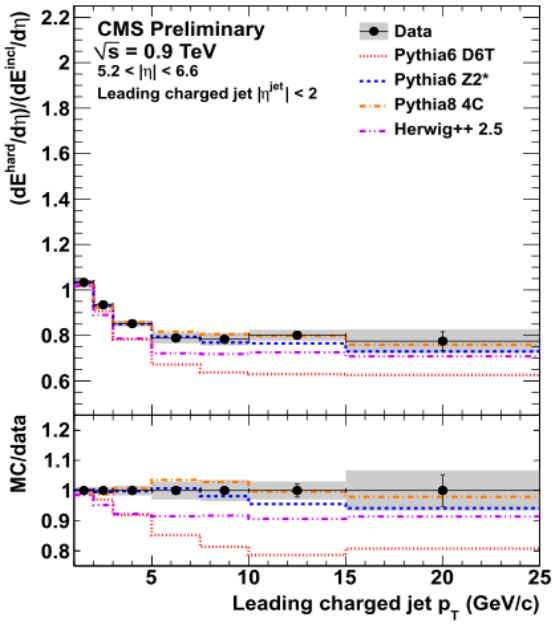


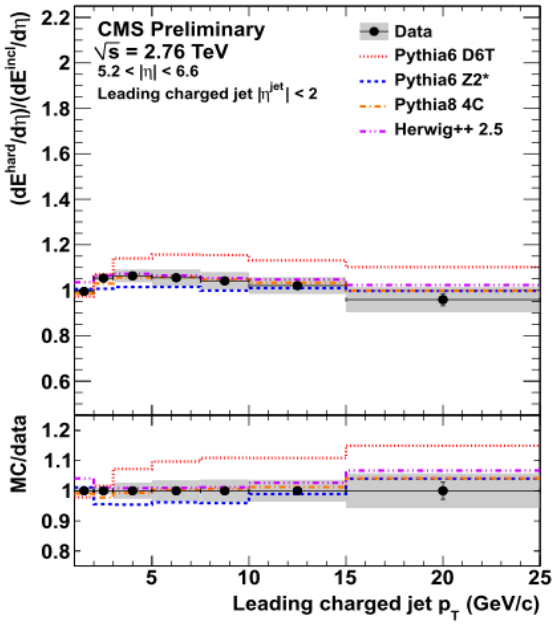
Central jet: |η| < 2
Track-jet algorithm
pT>1 GeV
Energy flow in CASTOR as a function of jet pT
Energy flow strongly affected by MPI

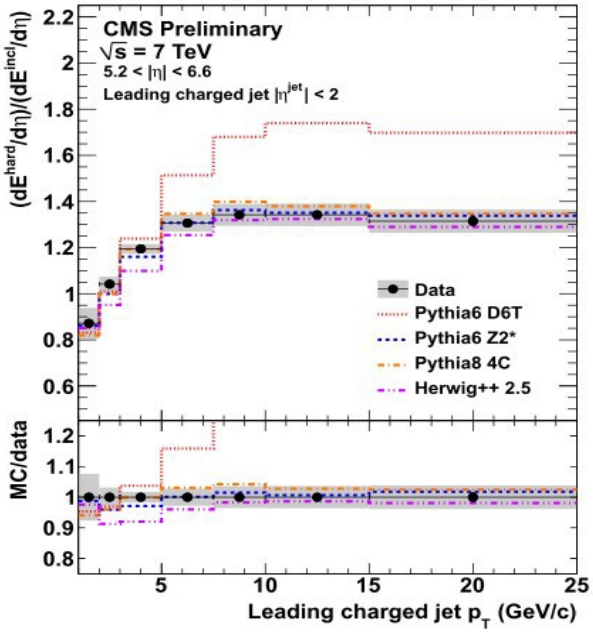


- Three energies: 0.9, 2.76 and 7 TeV
- Results quoted as ratios E(hard)/E(MB) – removal of most of the systematic effects
- Factorization of MPI contribution

Underlying event







- 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 pT
- plateau at higher pT

- 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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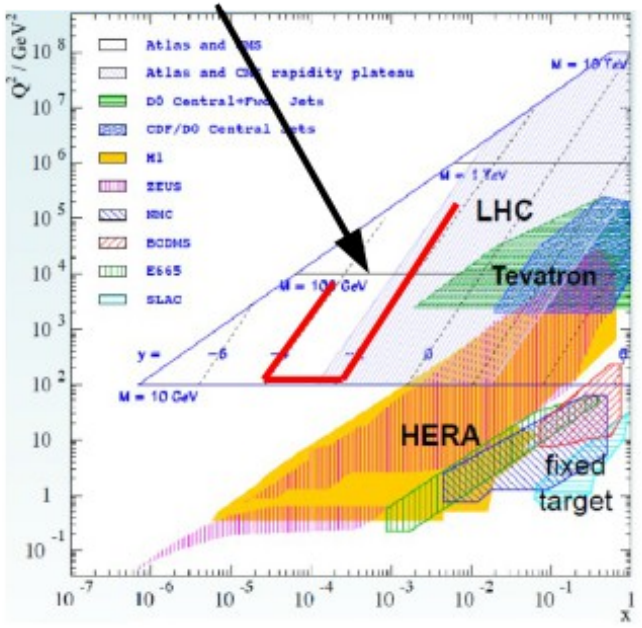
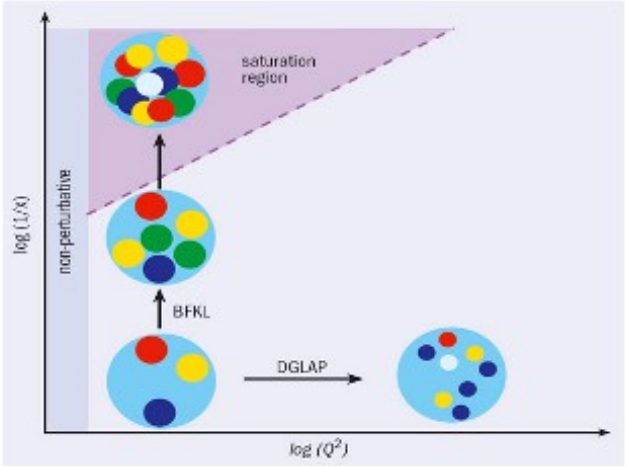
Forward jets

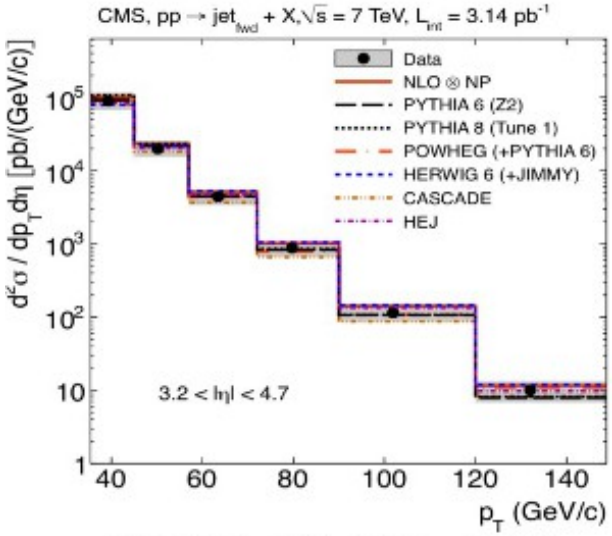
- Forward jets in LHC
  - access to $x \sim 10^{-6}$
- Forward jets appear usually in asymmetric collisions $x_1 << x_2$
- Forward jet in HF with $p_T > 35$ GeV: $x \sim 10^{-4}$
- Access to gluon densities at small x
- BFKL vs DGLAP – correlation between jets

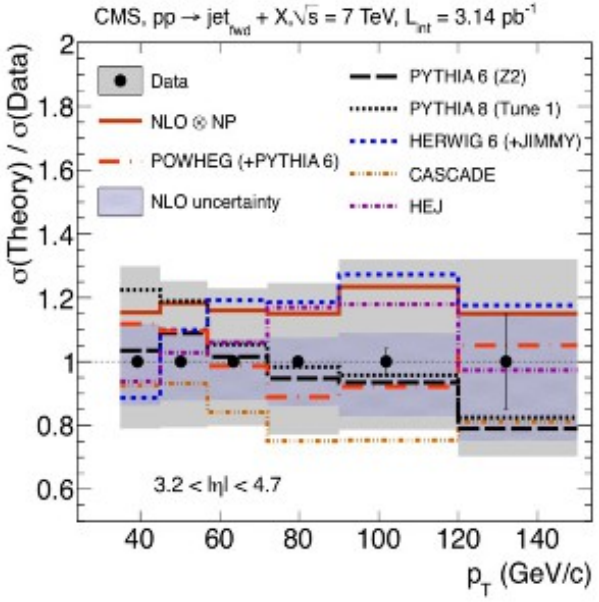
Acceptance for forward jets (HF)





Forward jets





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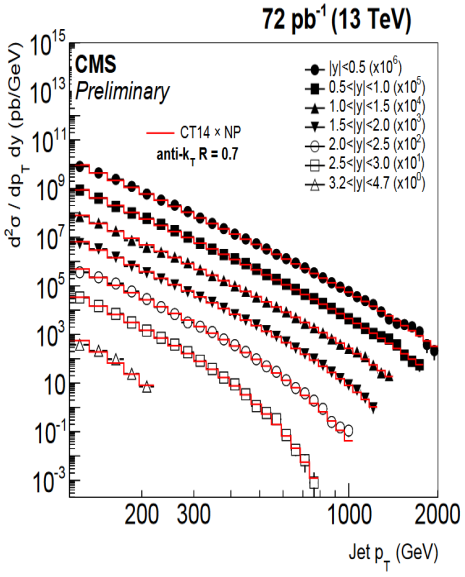
- Jets in $3.2 < |\eta(\text{jet})| < 4.7$ (HF) and $p_T > 35$ GeV
- 3.14 pb^{-1} from 7 TeV 2010 (low pile-up)
- statistical unc.: small (1-10%)
- energy scale unc. ~6% → scales to 20-30% for the jets cross section
- theoretical uncertanities (non-perturbative effects, pdf, scale)

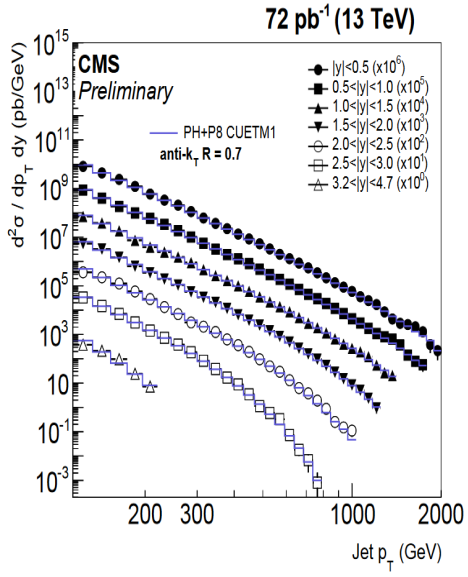
- DGLAP MC (Pythia, Herwig) describe the data
- BFKL-type HEJ describes the data
- CCFM CASCADE seems to be below
- NLO (NLOJET++) is 20% above the central value
- NLO+PS (POWHEG+Pythia6) best

Forward jets

NLOJet++



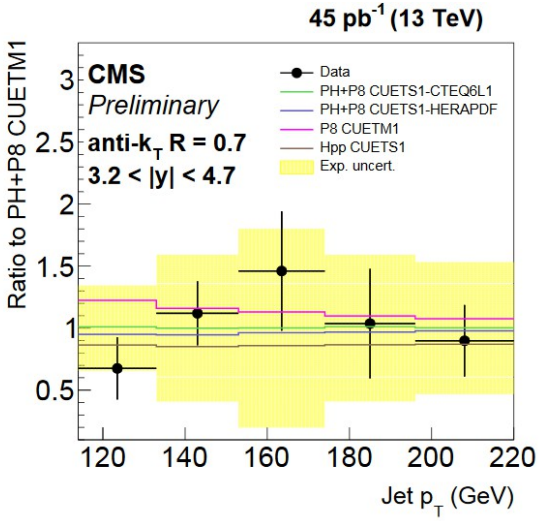
Powheg+Pythia8

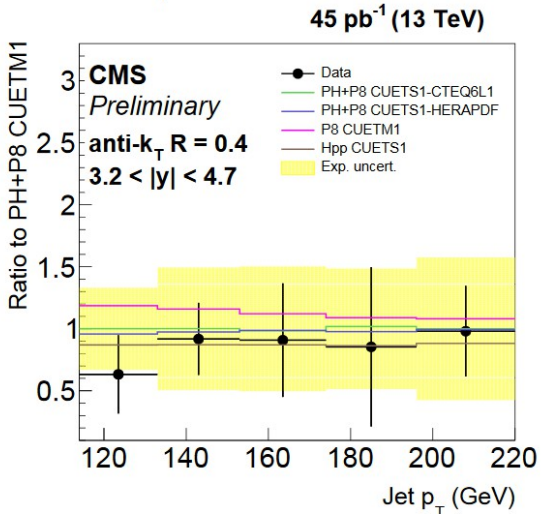


- Good agreement in the whole spectrum in pT and y

  Comparison with two different jet cone sizes: 0.4 and 0.7

- Good agreement with both sizes for Powheg+Pythia8

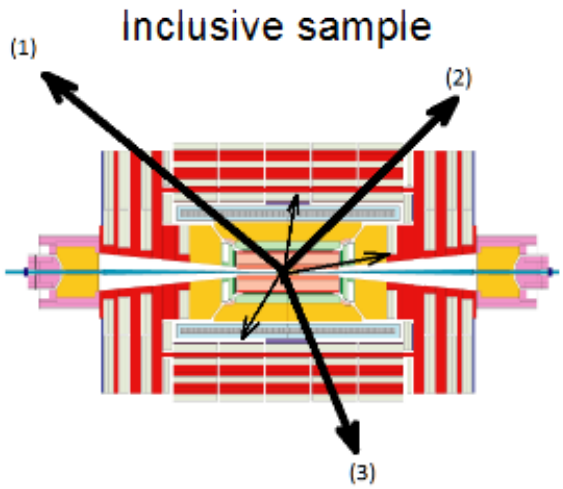




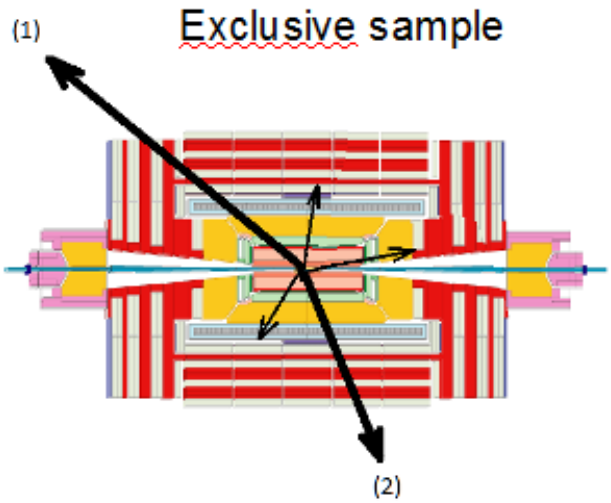
CMS-PAS-15-007

Jets correlations

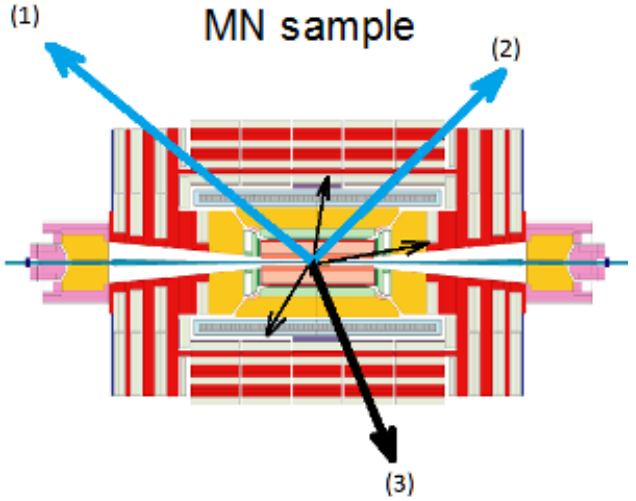
Pairs of calorimetric jets with p_T > 35 GeV and |y| < 4.7



(1)-(2) , (2)-(3) , (1)-(3)



(1)-(2)



(1)-(2)

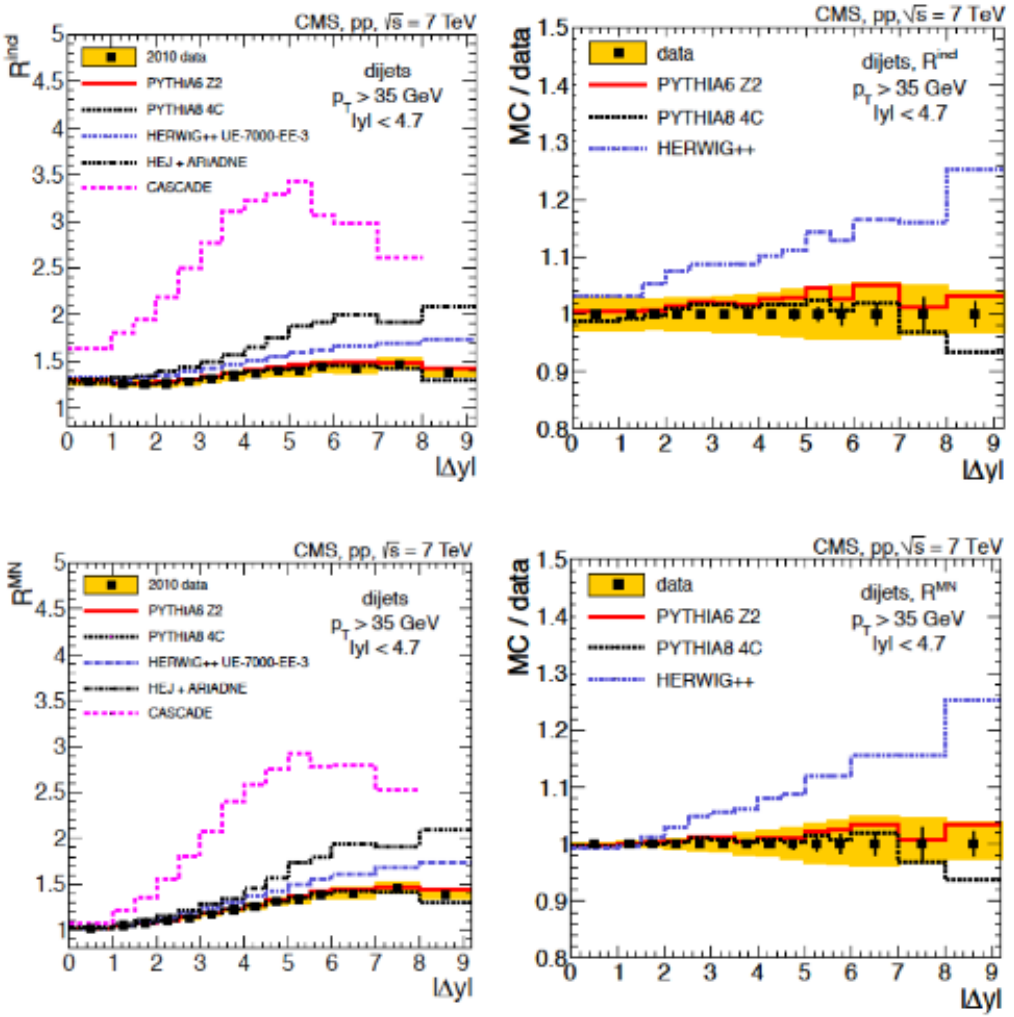
- A cross section for events from the sample is calculated as a function of |Δy| between the jets
- Finally cross-section ratios:

$$R_{incl} = \frac{\sigma_{incl}(\text{dijet})}{\sigma_{excl}(\text{dijet})}, R_{MN} = \frac{\sigma_{MN}(\text{dijet})}{\sigma_{excl}(\text{dijet})}$$

- Probe effects beyond the collinear factorization → phase space in |Δy| → radiation probability increases

Jets correlations

- σ(inclusive) = 1.2-1.4 σ(exclusive)
- R rises with |Δy| as expected
- For largest |Δy| the drop in R is observed - kinematic limit
- PYTHIA Z2 and PYTHIA8 4C agrees perfectly with the data
- HERWIG++ predicts higher R at medium and large rapidity separation
- HEJ+ARIADNE and CASCADE (BFKL-motivated generators) predict much faster rise of R



General conclusion: No visible effects beyond collinear factorization + LL parton-showers

Jets correlations

ArXiv 1601.06713 , to be published in 2016

- 41 pb^{-1} from 7 TeV 2010
- At least two jets with p_T>35 GeV and $|\eta|$<4.7
- MN pair → two jets with largest rapidity separation in the event

Observables:

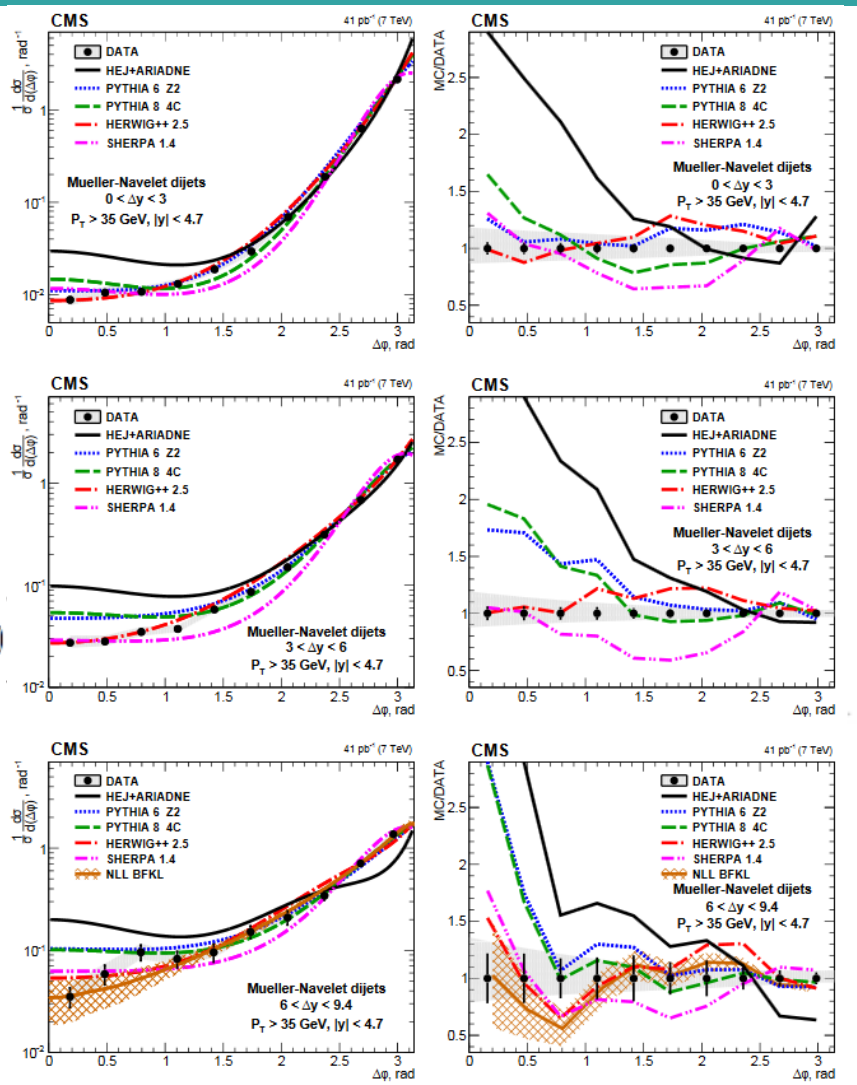
- Azimuthal separation: Δφ
- Fourier coeficcients:

$$\frac{1}{\sigma}\frac{d\sigma}{d(\Delta\phi)}(\Delta y, p_{T\min}) = \frac{1}{2\pi}\left[1 + 2\sum_{n=}^{\infty} C_n(\Delta y, p_{T\min})\cos(n(\pi - \Delta\phi))\right.$$

0 < Δy < 3
3 < Δy < 6
6 < Δy < 9.4

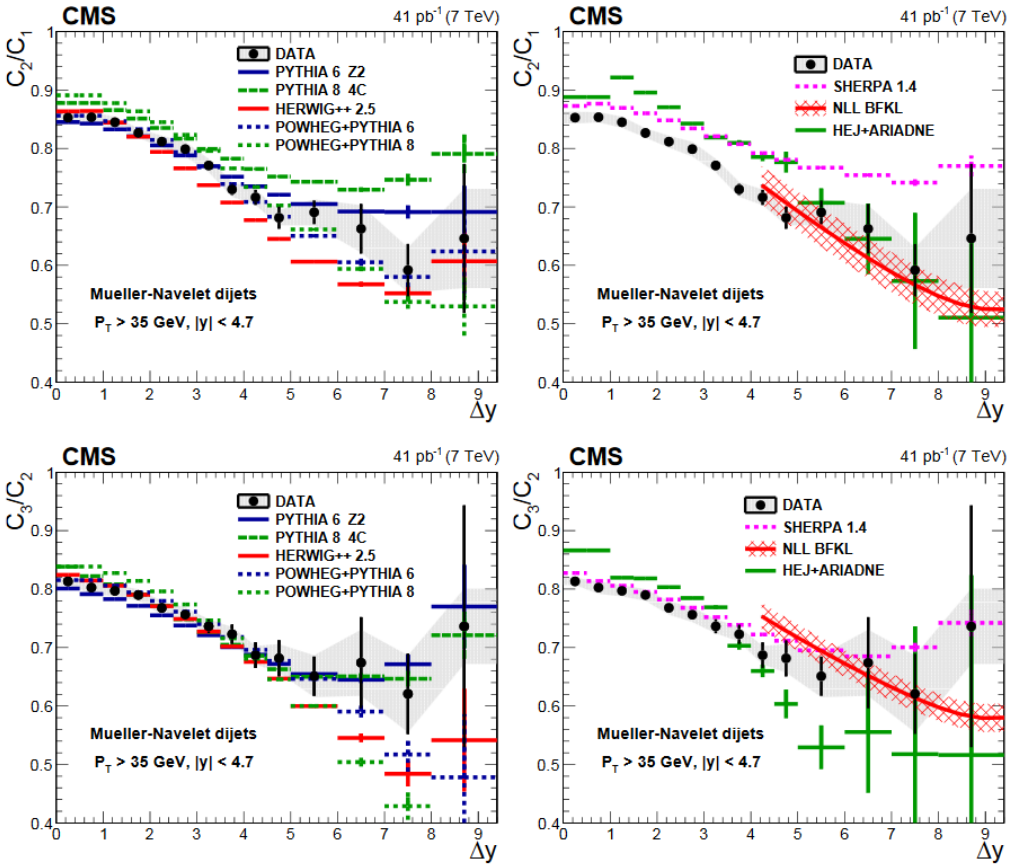
C1 = <cos(π - Δφ)>
C2 = <cos(2*(π - Δφ))>
C3 = <cos(3*(π - Δφ))>

- Ratios: C_2/C_1 and C_3/C_2



Herwig++ provides the best description in all bins

Jets correlations



- In ratios DGLAP contributions are suppresed
- Pythia/Herwig good agreement at low Δy, at large Δy discrepancies
- Sherpa/HEJ is above the data
- BFKL NLL calculation describes well the ratios, especially C_2/C_1

Conclusions

- Reach forward physics programm in CMS from RUN1
- Measurements of Standard Model (QCD and QED) physics
  - → exclusive production (di-photon, di-lepton)
  - → diffraction (soft, hard)
  - → QCD evolution (BFKL)
  - → MPI (energy flow, tracks)
- Many new measurements in regimes never probed before
  - → 7 TeV, 8 TeV
  - → forward rapidities
- Work on the phenomenology/models needed
  - → tuning of MPI models
  - → correlations
- Much more results to come - 13/14 TeV

- Forward physics - perfect testing ground for models and theories

Thank you

Invitation

Variouse faces of QCD II

When: 8-9 October (Sat-Sun)
Where: Świerk (NCBJ) – with a transport from Warsaw city center
Price: free of charge
Organizers: PTF, NCBJ, UW
Official WWW page – by the end of May

Number of speakers confirmed: B. Badełek, W. Broniowski, F. Giacosa
S. Głazek, L. Goerlich, K. Golec-Biernat, K. Kutak, M. Misiura, L. Motyka,
M. Praszałowicz, A. Sandacz, R. Staszewski, A. Szczurek, L. Szymanowski,
W. Wiślicki, S. Wycech

Slots available, please propose your talks: jakub.wagner@ncbj.gov.pl ,
grzegorz.brona@fuw.edu.pl