Jets, diffraction & CASTOR

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QCD at LHC: forward physics and UPC collisions of heavy ions

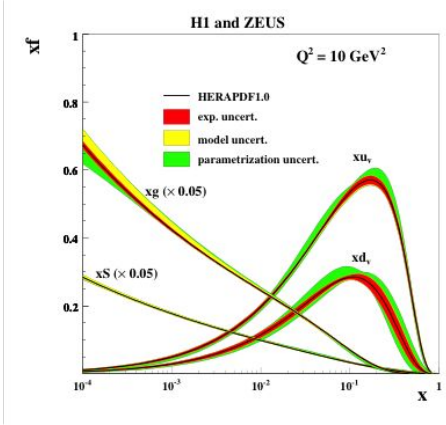
26/9/16 - 30/09/16

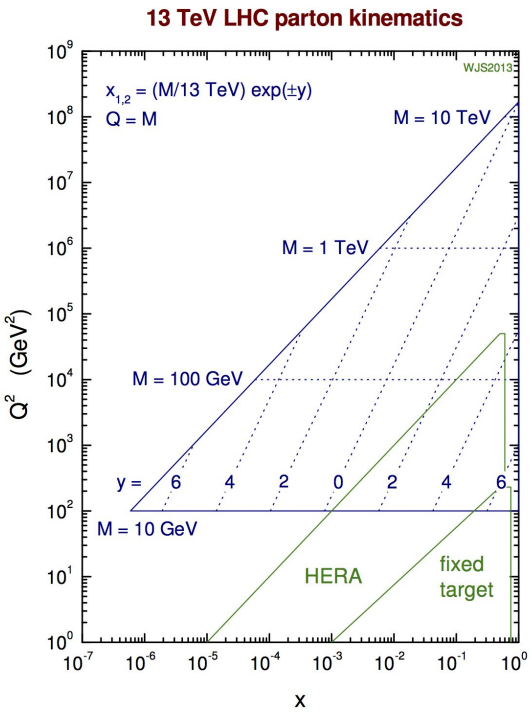
QCD at the LHC

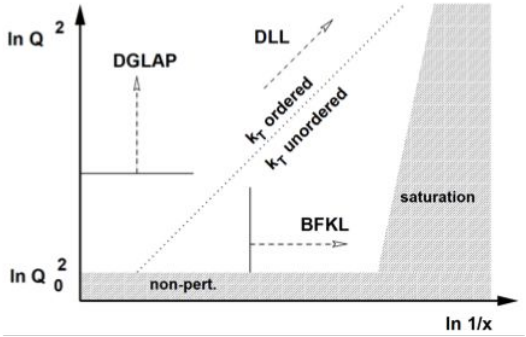
- What will happen in these new kinematic regions?
  How far do collinear approximations stay valid?

- Gluons dominate low-x region:
  saturation effects?

- What is the role of MPI in all this?







- k_T dependent, unintegrated pdf's?
- Will DGLAP break down?
- Study forward and/or low-p_T jets in pp and pA data at different centre-of-mass energies

Low p_T jets widely separated in rapidity

- First measurement of azimuthal decorrelation of most-forward and backward jets (Mueller–Navelet dijets) in pp collisions at 7 TeV with CMS

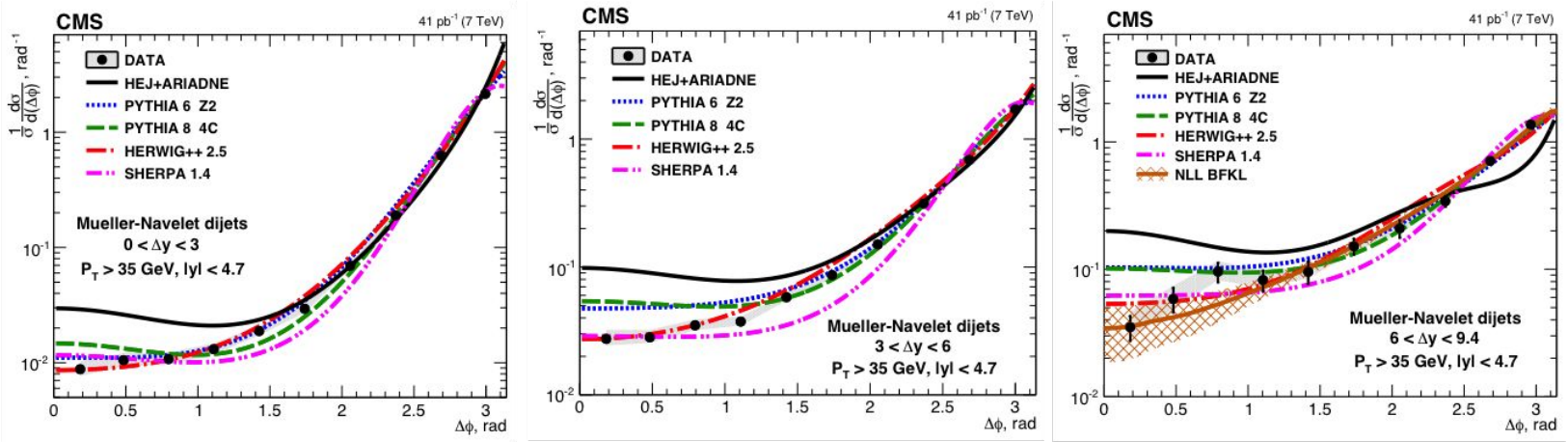
- Probe rapidity separations up to $\Delta y = 9.4$ with low-p_T jets: anti-k_T R=0.5, $p_T > 35$ GeV, $|y| < 4.7$
  Probe very forward low-p_T phase space of QCD ⇒ measure (new?) low-x parton dynamics

- Observables include:
  - $\Delta\phi$ distributions $$\frac{1}{\sigma}\frac{d\sigma}{d(\Delta\phi)}(\Delta y, p_{\mathrm{Tmin}}) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} C_n(\Delta y, p_{\mathrm{Tmin}})\ \cos(n(\pi - \Delta\phi))\right].$$
  - moments of average cosines of $\Delta\phi$: $C_n(\Delta y, p_{\mathrm{Tmin}}) = \langle\cos(n(\pi - \Delta\phi))\rangle$ for n = 1, 2, 3

  - ratios of these average cosines, as a function of Δy between MN jets.
    ⇒ suppression of DGLAP contributions in ratios, more sensitive to BFKL effects
    ⇒ reduce uncertainties of factorisation and renormalisation scales JHEP 08 (2016) 139

Low p_T jets widely separated in rapidity

- Azimuthal decorrelation angle in different bins of rapidity separation:



- DGLAP-based HERWIG++ 2.5, with leading-log (LL) parton showers and colour-coherence effects shows best performance; PYTHIA 6 Z2, PYTHIA8 4C, SHERPA 1.4 less accurate
- HEJ: LL BFKL with ARIADNE (PS + hadr.): stronger decorrelation than in data.
- BFKL calculation at NLL accuracy: describes data for large Δy

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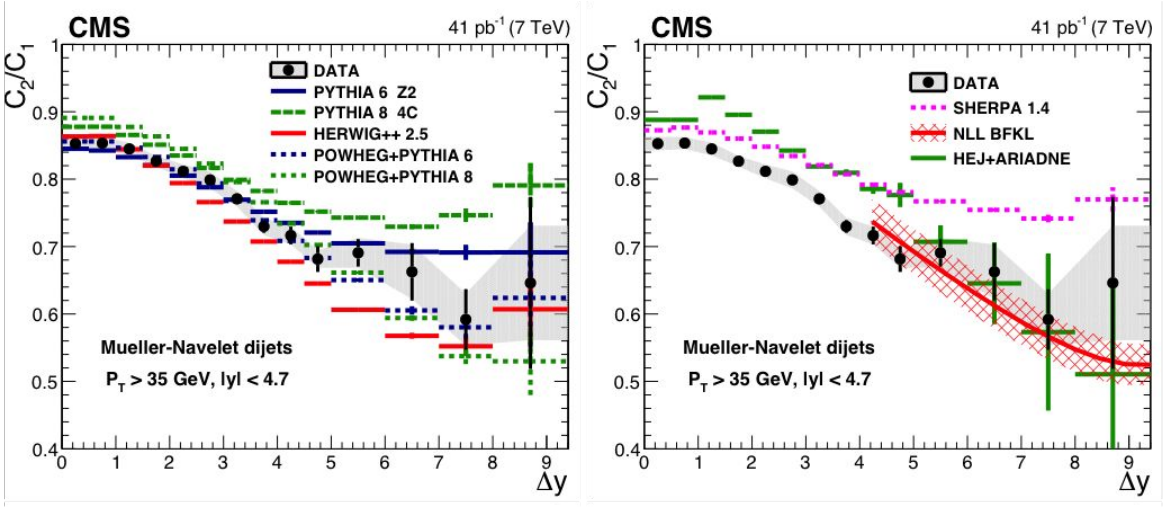
Low p_T jets widely separated in rapidity

- Ratios of average cosines, as a function of Δy between MN jets:



DGLAP-based MC generators less accurate at large Δy

POWHEG (NLO ME + PYTHIA) does not improve agreement

- BFKL calculation at NLL accuracy: good agreement for Δy > 4
  ⇒ current kinematical domain lies in transition between regions described by DGLAP and BFKL approaches

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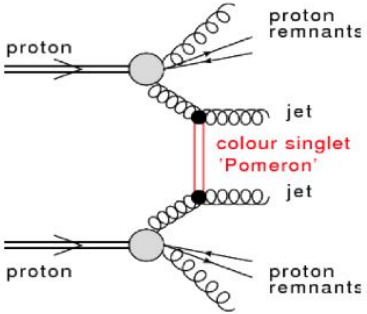
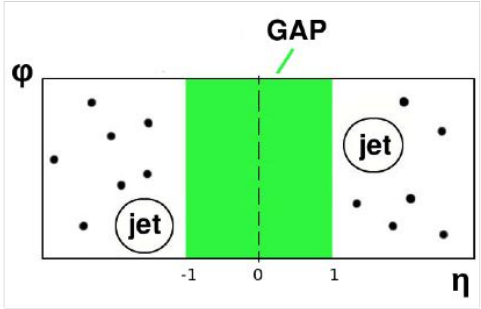
Dijet production with a large rapidity gap

- Dijet production with a large rapidity gap between the jets: CMS-PAS-FSQ-12-002



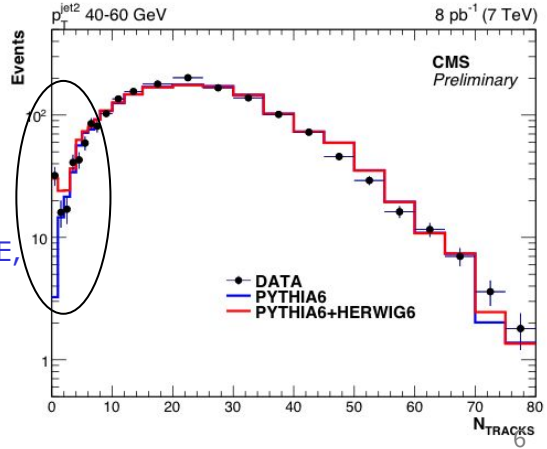


2 jets, $p_T > 40$ GeV, $1.5 < |\eta| < 4.5$, opposite hemispheres

Rapidity gap: fixed window inside $|\eta| < 1$

⇒ diffractive process with large four-momentum squared transfer
⇒ parton scattering through hard colour singlet exchange (CSE)
⇒ study of these events may allow to disentangle BFKL dynamics from DGLAP evolution

Contribution from CSE, described by Müller-Tang model in Herwig6 (LL BFKL)

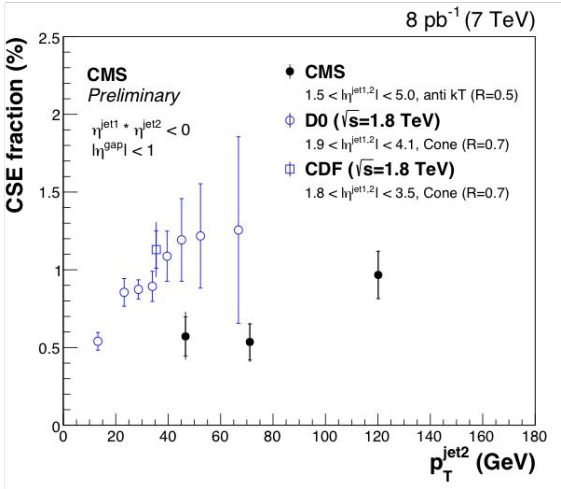


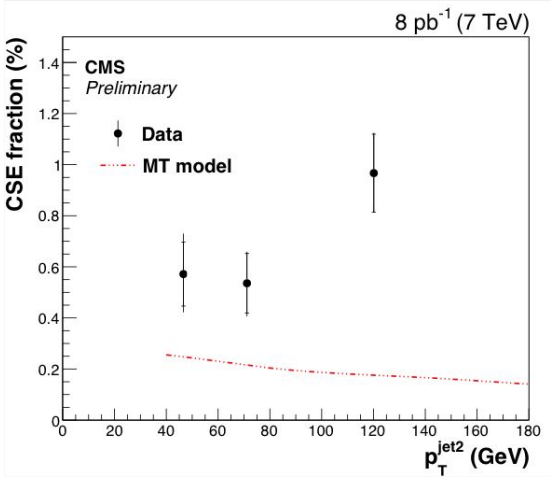
- Extract fraction of CSE events as function of $p_{T,jet2}$ (3 bins) and $\Delta\eta$ between two leading jets

Dijet production with a large rapidity gap

CMS-PAS-FSQ-12-002

- Modest increase with $p_{T,jet2}$:





p_T^{jet2} range (GeV)	f_{CSE} (%)
40-60	$0.57 \pm 0.13^{+0.09}_{-0.08}$
60-100	$0.54 \pm 0.12^{+0.04}_{-0.06}$
100-200	$0.97 \pm 0.15^{+0.04}_{-0.03}$

Mueller & Tang model does not reproduce rise with $p_{T,jet2}$ underestimates fraction of CSE

- Suppression of the gap fraction with increasing $\sqrt{s}$:

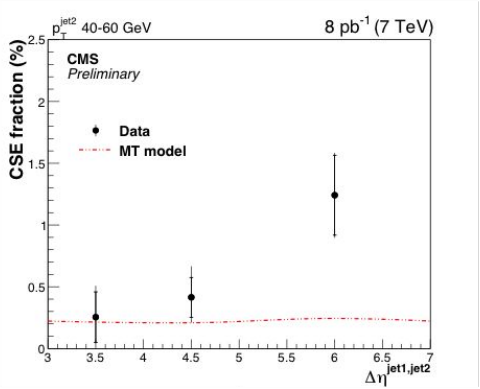
  ⇒ for $40 < p_{T,jet2} < 60$ GeV the value at 7 TeV is factor ~2 lower than at $\sqrt{s}$ = 1.8 TeV

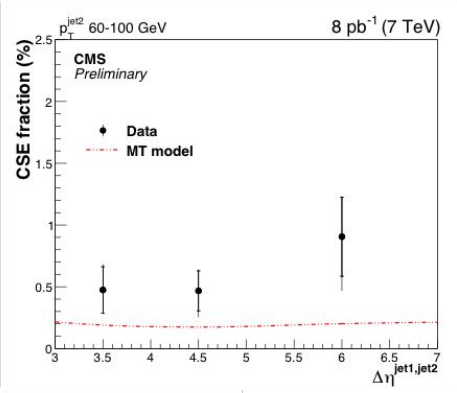
  ⇒ stronger contributions from rescattering processes

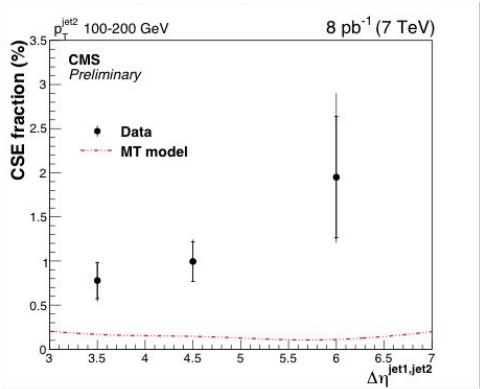
Dijet production with a large rapidity gap

- The fraction of CSE events increases with Δη:

CMS-PAS-FSQ-12-002





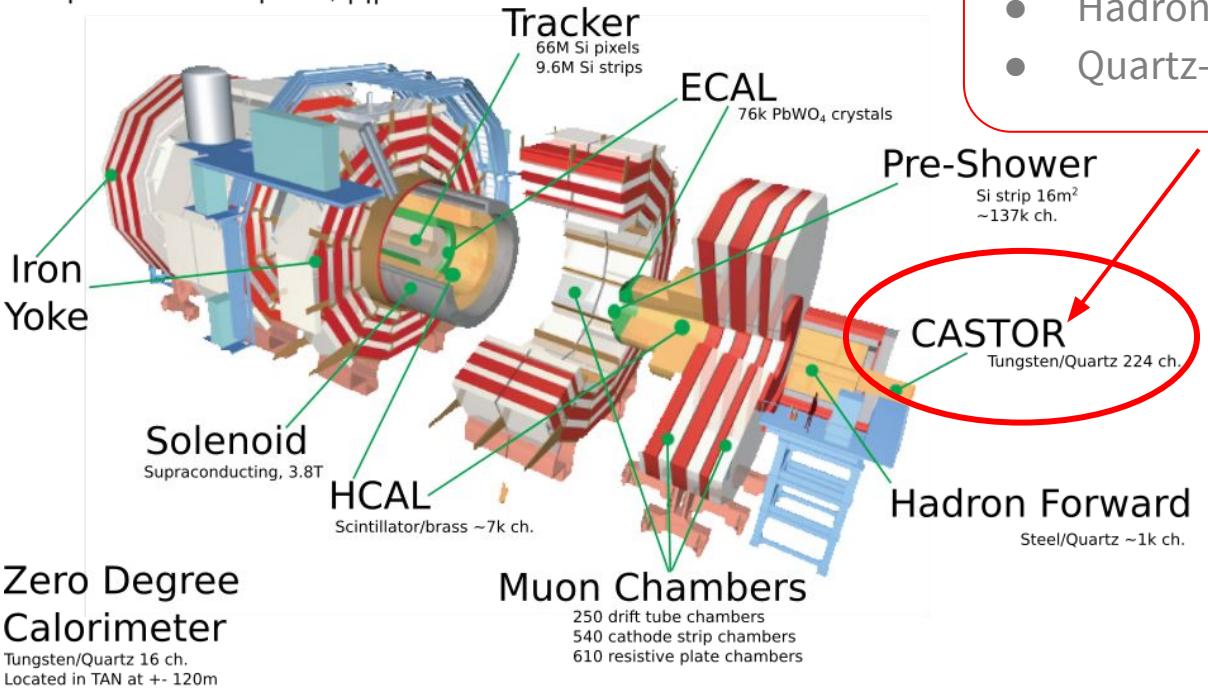


Mueller and Tang model does not reproduce the rise with Δη and underestimates the fraction of CSE events

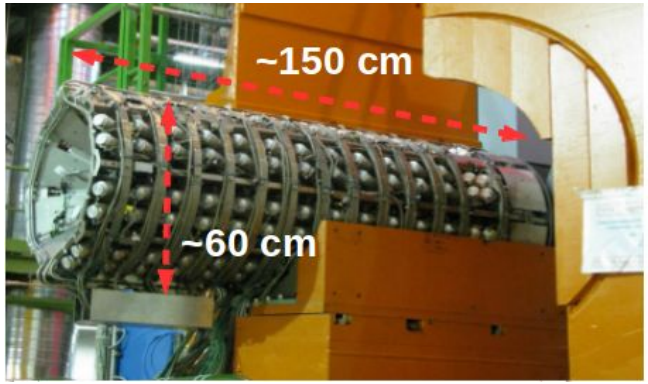
	f_{CSE} (%)		
$\Delta\eta_{jj}$ range	40-60 GeV	60-100 GeV	100-200 GeV
3-4	$0.25 \pm 0.20^{+0.15}_{-0.05}$	$0.47 \pm 0.19^{+0.09}_{-0.02}$	$0.78 \pm 0.21^{+0.07}_{-0.12}$
4-5	$0.41 \pm 0.16^{+0.19}_{-0.13}$	$0.47 \pm 0.16^{+0.06}_{-0.14}$	$0.99 \pm 0.23^{+0.11}_{-0.05}$
5-7	$1.24 \pm 0.32^{+0.11}_{-0.12}$	$0.91 \pm 0.32^{+0.07}_{-0.30}$	$1.95 \pm 0.69^{+0.66}_{-0.29}$

Very forward calorimeter CASTOR in CMS

Total weight: 14000t
Overall diameter: 15m
Acceptance: -6.6<η<5.2, |η|>8.2

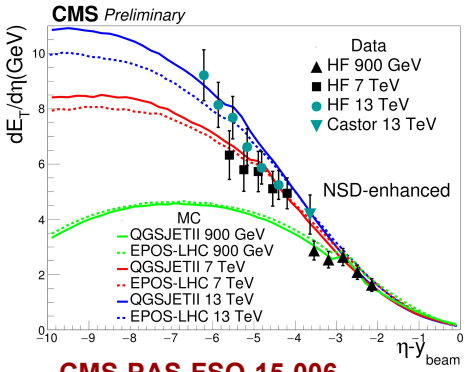


- Acceptance: $-6.6 < \eta < -5.2$
- E.M. section: 20 X_0, 32 channels
- Hadronic section: 10 λ_I, 192 channels
- Quartz-Cherenkov calorimeter



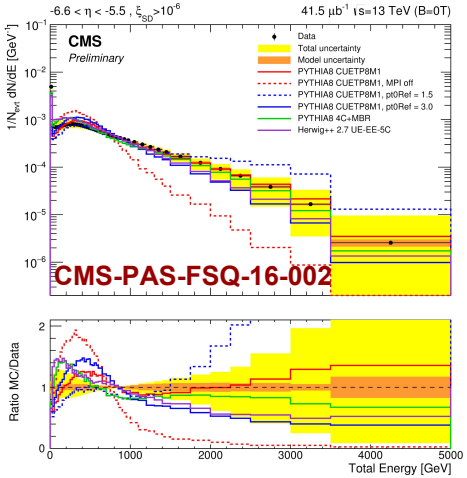
The CMS experiment at the CERN LHC , JINST 3 (2008) S08004

Very forward energy and jets at 13 TeV



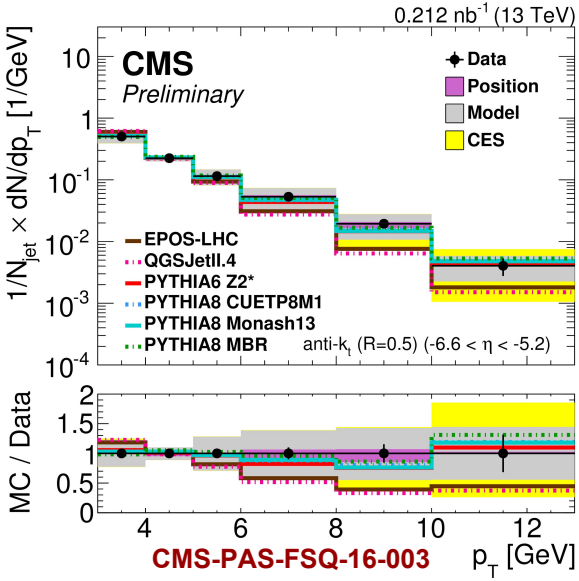
CMS-PAS-FSQ-15-006

- The average energy density as a function of distance to the beam rapidity (limiting fragmentation)
- The shape of the energy distribution in the very forward direction (hadronic, electromagnetic and total)
- The jet production cross section



CMS-PAS-FSQ-16-002

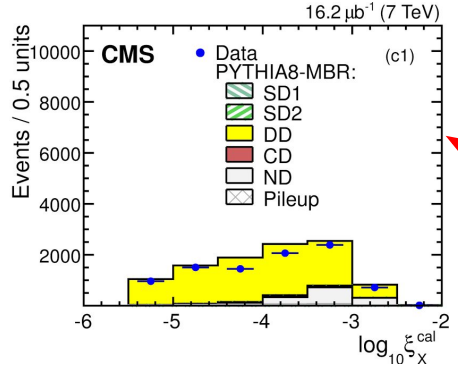
- Very sensitive to MPI, model differences.
- Important for cosmic ray air shower description.
- Diffraction and BFKL related analyses are expected.

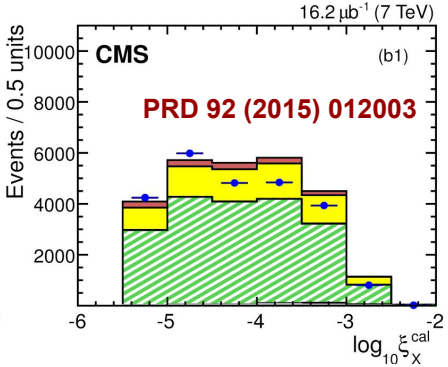


CMS-PAS-FSQ-16-003

Maximize CMS acceptance with CASTOR

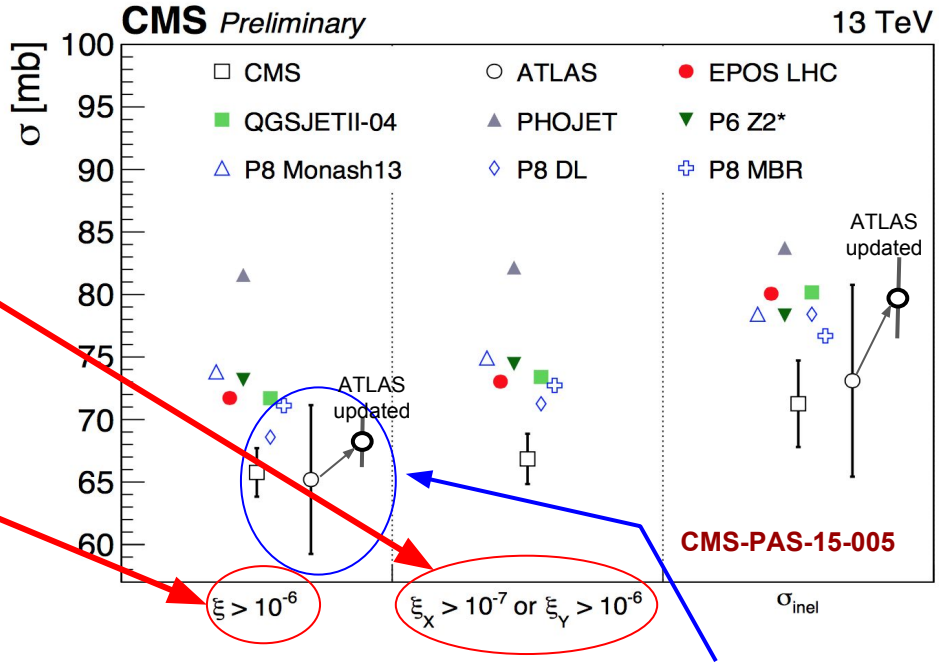
Inelastic (13 TeV) and
soft-diffractive (7 TeV) cross sections





with CASTOR

without CASTOR

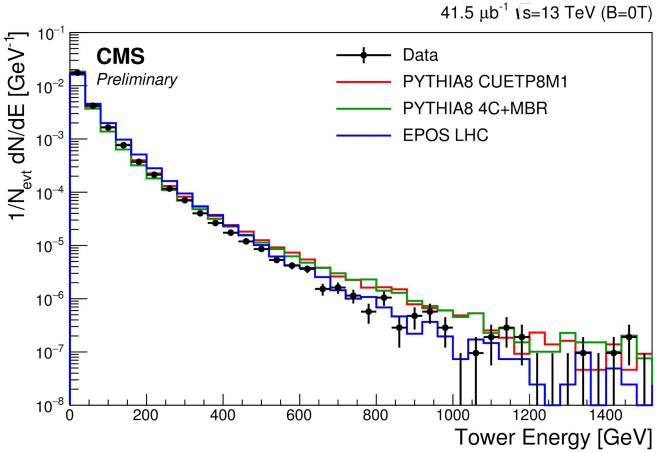


Fiducial cross section at $\xi > 10^{-6}$
ATLAS and CMS agree

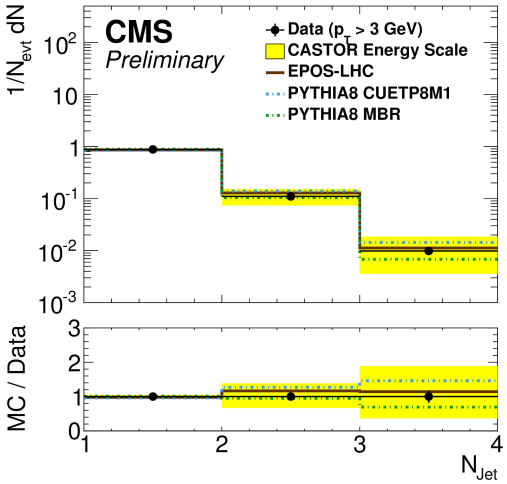
CASTOR performance during LHC Run2

- CASTOR was installed in June 2015 (during B = 0 T) and in November 2015 for HI PbPb run
- Very successful data taking, calibration & good description of data by detector-level Monte Carlo
- Several public results already shown at conferences. Papers in preparation.
- Looking forward to 2016 HI run. Still lacking 13 TeV data with B = 3.8 T...

CASTOR dN/dE



CASTOR jet multiplicity



CASTOR performance during LHC Run2

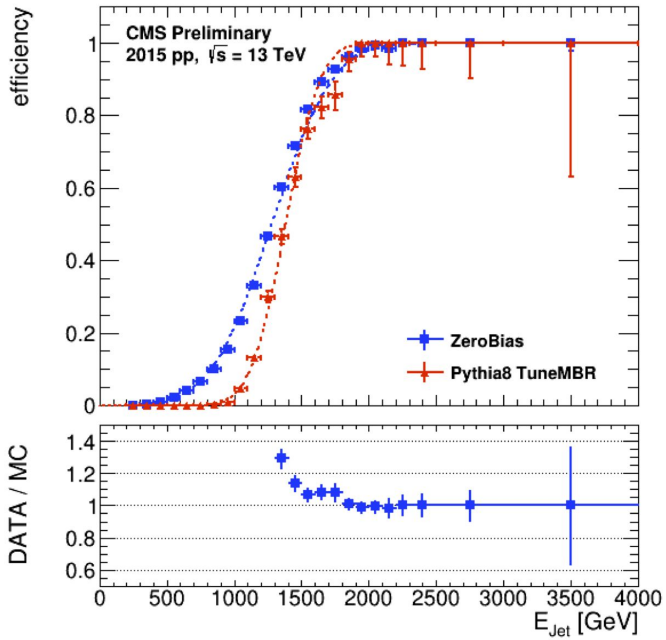
- During LHC Run2 CASTOR successfully deployed a high energy jet trigger
- This trigger will be deployed during the 8 TeV proton-ion run

- A particularly advantageous observable:
  jet spectra in CASTOR in pA/Ap

- Taking ratios between measurements
  ⇒ cancel certain systematic errors

- A similar study is ongoing at 5 TeV pA and pp data

CASTOR jet trigger efficiency in data & MC



Summary

- CMS has studied the new kinematic regions of QCD extensively at the LHC:
  - with Run1 and Run2 data at different centre-of-mass energies until 13 TeV
  - using forward and/or low-p_T jet final states to probe low-x region

- At 7 TeV the current kinematical domain lies in transition between regions described by DGLAP and BFKL approaches
- First observation of colour singlet exchange events at LHC!
  CSE fraction suppressed at 7 TeV wrt lower energies: consistent with Tevatron data

- The very forward CASTOR calorimeter demonstrated a good performance during LHC Run2 and contributed to several forward energy flow/jet measurements at 13 TeV
  ⇒ provides unique opportunity to probe low-x parton dynamics
  and saturation effects in pp and pA data