# Forward jets

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**on behalf of**

**CMS Collaboration**

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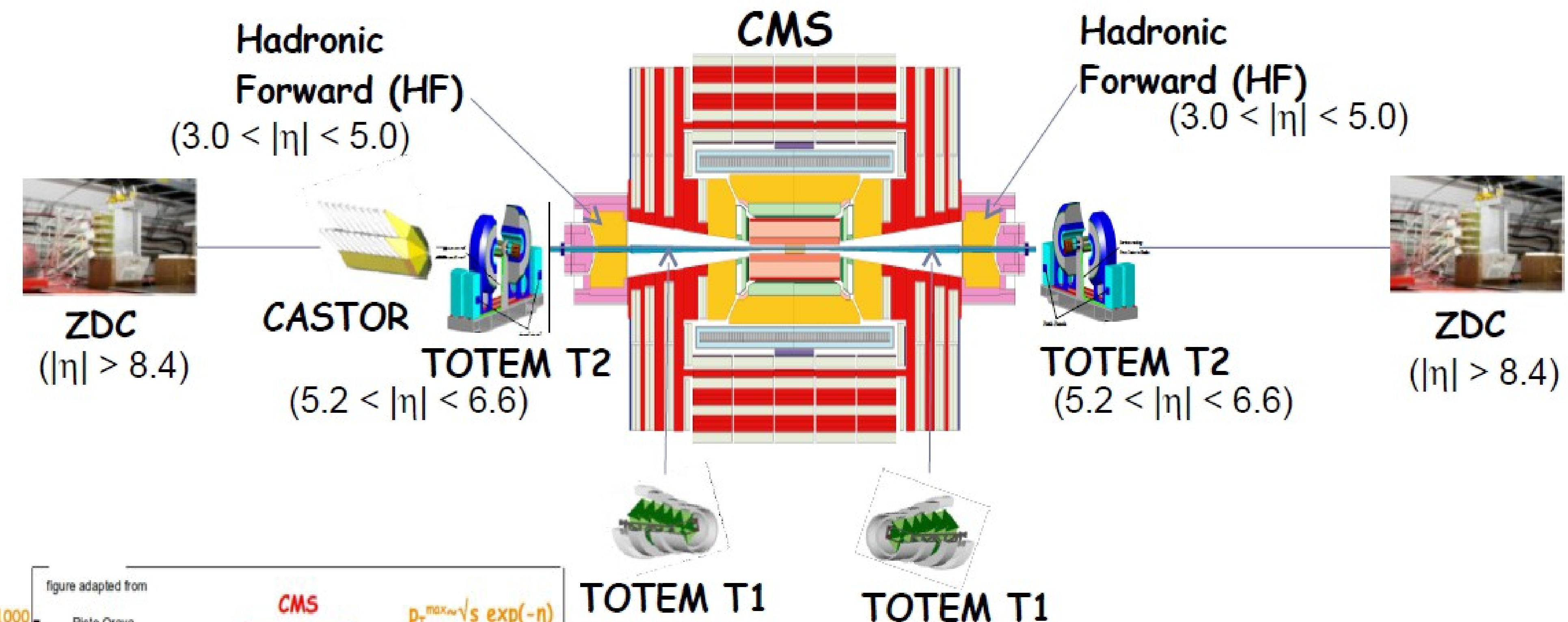
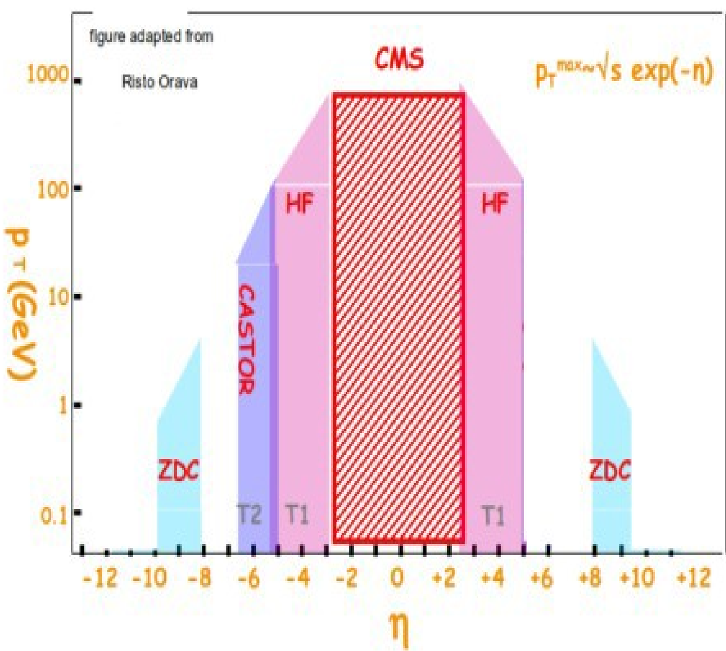
# The Outline



- Apparatus
- Forward energy flow
- Forward jets spectrum
- Correlations between jets
- Outlook and Summary

# Apparatus




- **H**adronic **F**orward calorimeters (HF)
- **C**entauro **A**nd **ST**range **O**bjects **R**esearch (CASTOR) – calorimeter
- **Z**ero **D**egree **C**alorimeter (ZDC)

\+ Totem (T1/T2) separate experiment
→ tracking detectors

# Apparatus

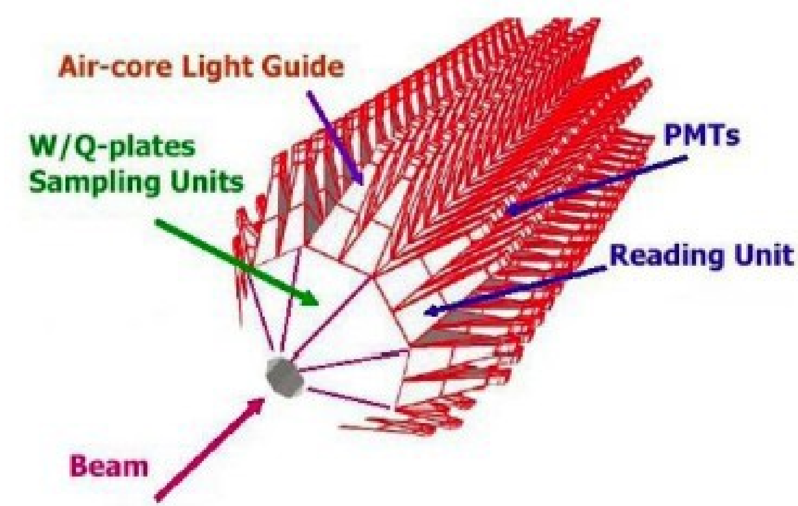



## Hadronic Forward (HF) Calorimeter

- Located at 11.2 m from IP
- Rapidity coverage: $3 < |\eta| < 5$
- 0.175x0.175 segmentation in $\eta$ and $\phi$
- Steel absorbers and embedded radiation-hard quartz fibers for fast collection of Cherenkov light

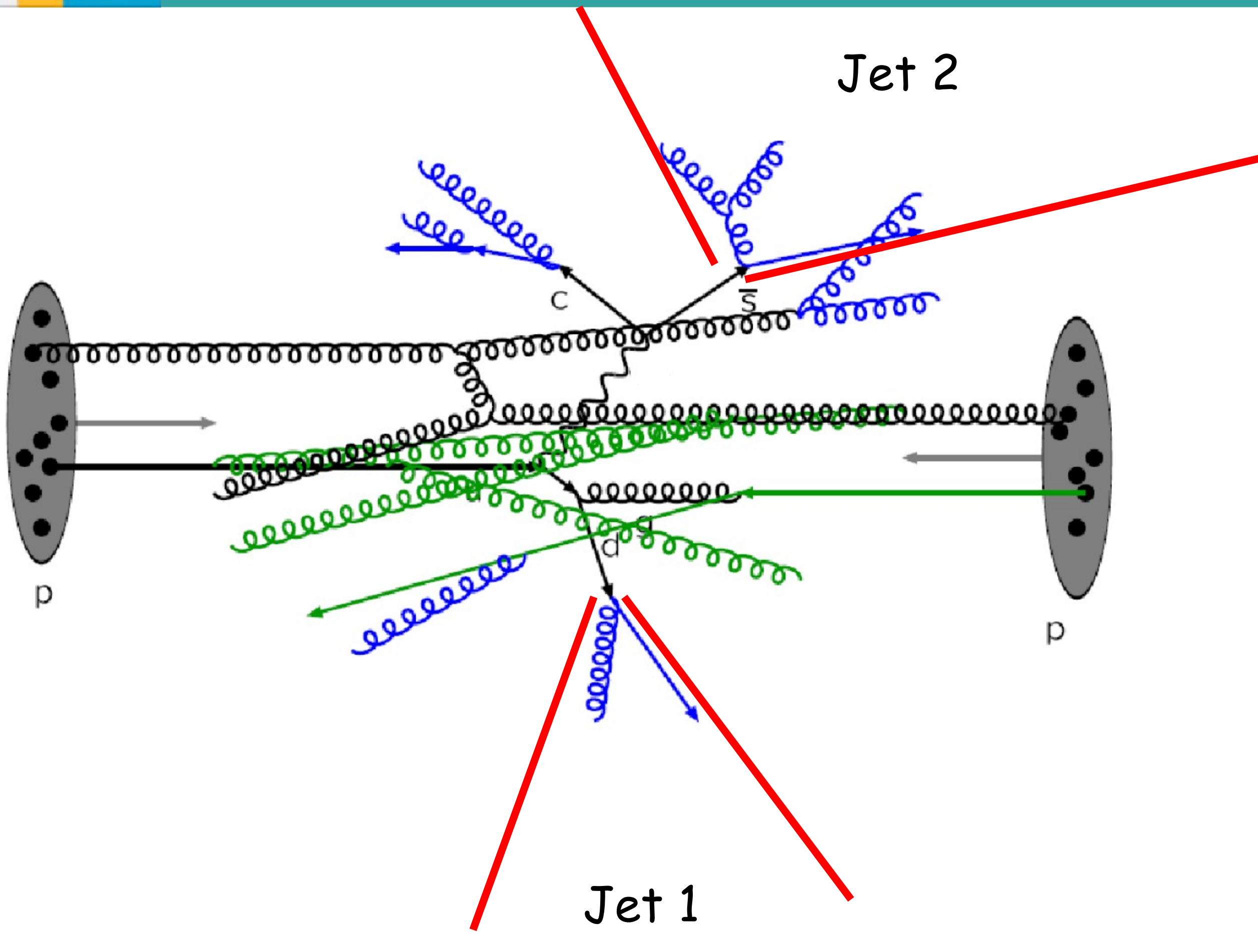
## CASTOR Calorimeter

- Located at 14.3 m from IP
- Rapidity coverage: $-6.6 < \eta < -5.2$
- Segmentation in $\phi$ (16 sectors)
- 14 modules (2EM+12HAD)
- Alternate tungsten absorbers and quartz plates

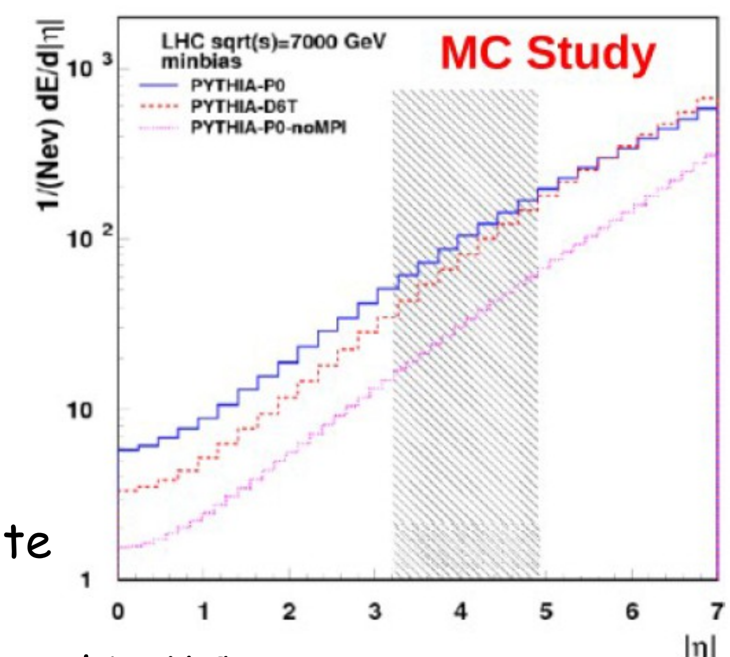


# Energy Flow






- Jets are on top of the energy deposites from Multiple Parton Interactions (MPI)
- Especially important in the forward region



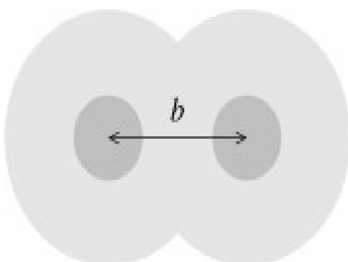

- Good understanding of energy flow (MPI) is a prerequisite for jets measurement.
- But provides also tools for tunning MPI models implemented in MC

# Energy Flow

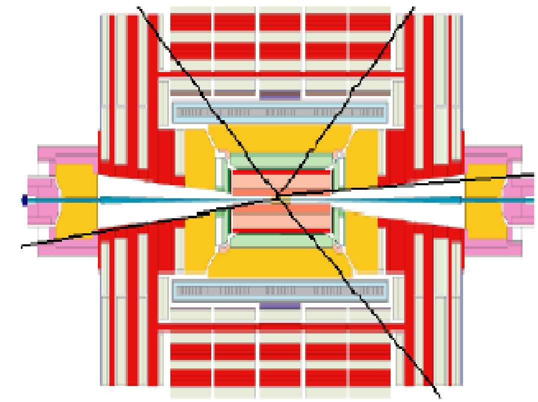


## Measurement for HF: $3.15<|\eta|<4.9$

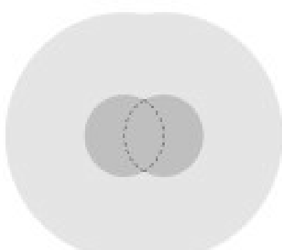
Minimum bias



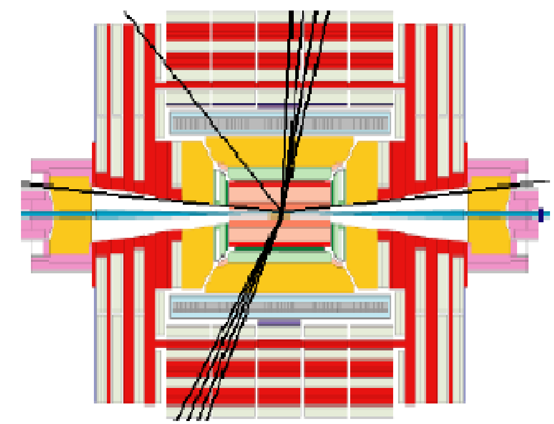

activity at both sides of IP
(coincidence between BSC) +
vertex reconstructed
(diffraction highly reduced)



Hard scale $\hat{p}_T$



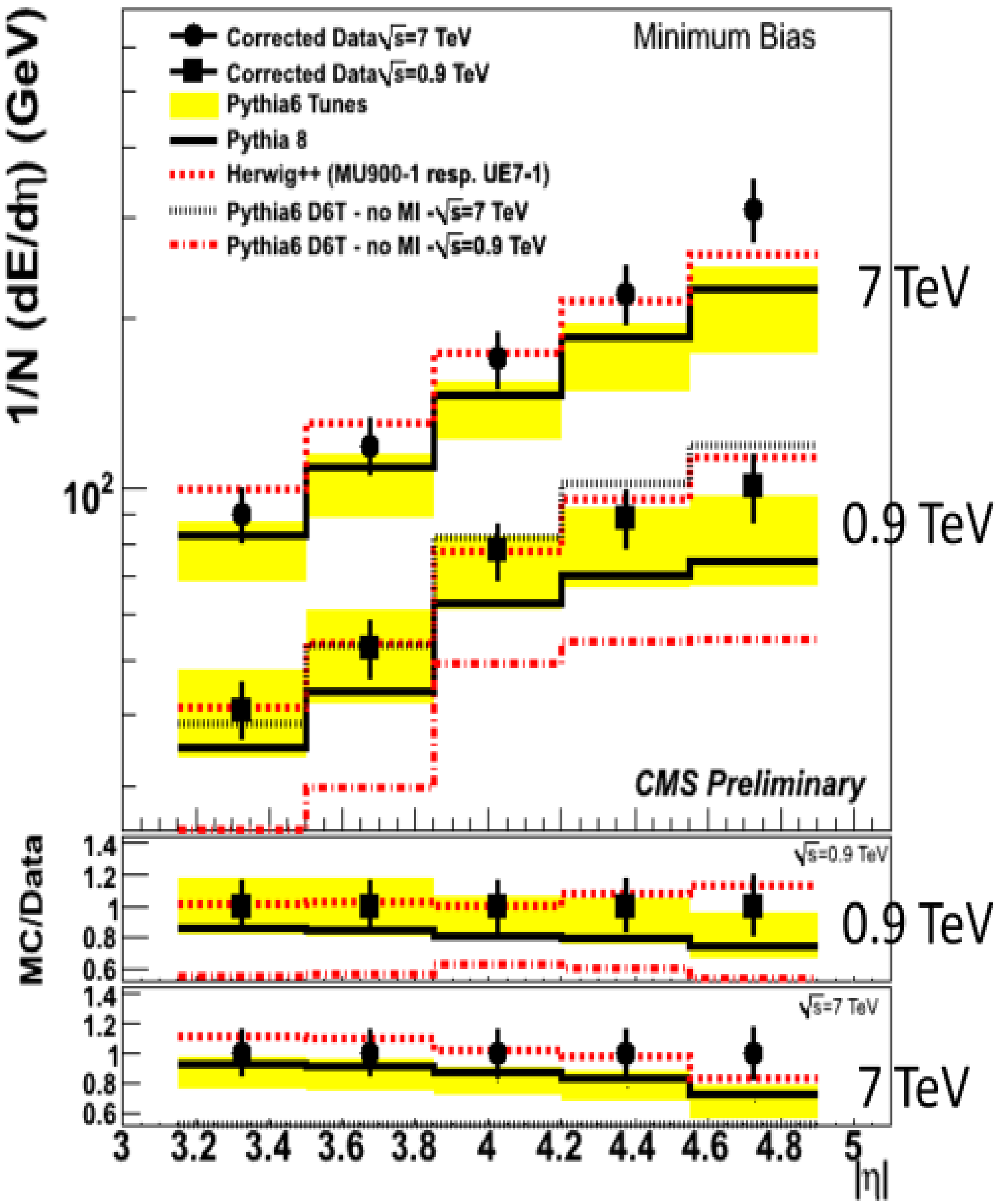
Central jets: $|\eta| < 2.5$
Back-to-back:
$|\Delta\varphi(jet_1,jet_2) - \pi| < 1$
Scale:
900 GeV → $p_T > 8$ GeV
7000 GeV → $p_T > 20$ GeV



**Expectations:**

- Energy flow should rise with energy
- Energy flow should rise from MB to di-jet sample
- Test different models (and tunes) of MPI

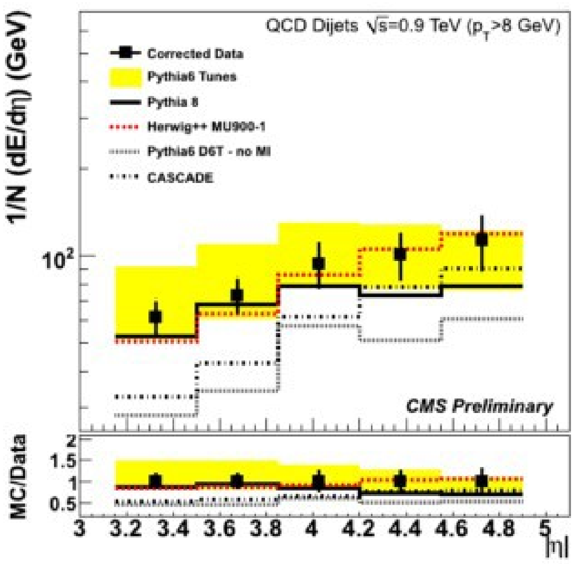
# Energy Flow

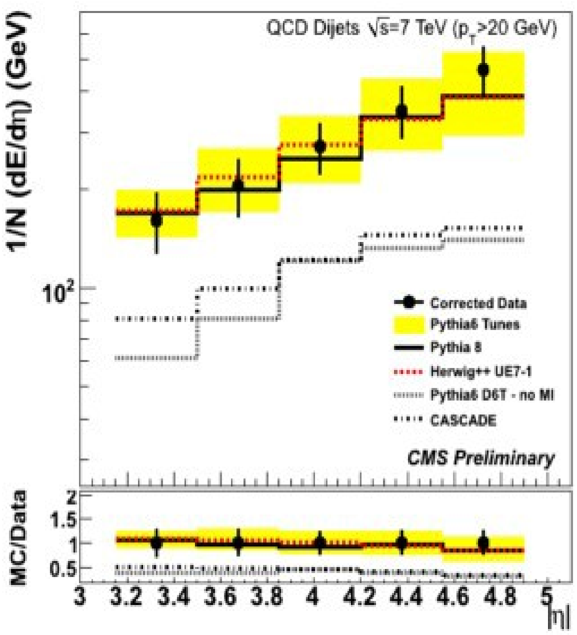



**Minimum bias sample**

- Pythia 6 band (~20%) composed from different tunes, including those tuned to LHC central region data (Z2, P11, AMBT1) → do not do well
- Pythia 8 flatter than data
- Herwig++ describes data at both cms energy with some problems at highest rapidities
- Significant contribution from MPI interactions (Pythia6 without MPI interaction ~ 40% below data)

# Energy Flow



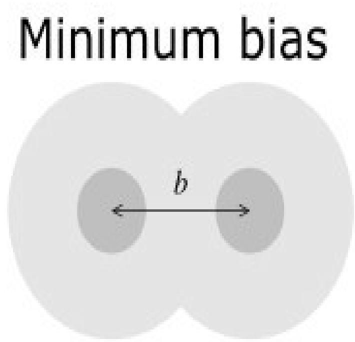




## Dijet sample

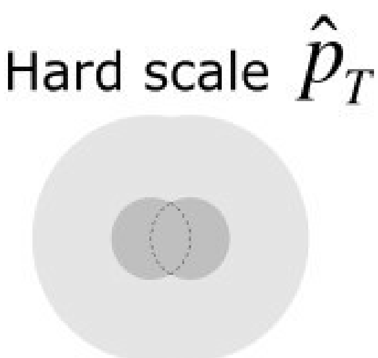
- Energy flow larger than in minimum bias sample central events are selected with scale cut
- Pythia 6 band envelopes the data
- Pythia 8 describes the data at 7 TeV
- Herwig++ (2.5) well describes data at 7 TeV
- Large contribution from MPI (switching off MPI reduces energy flow by factor of two)

# Energy Flow

## Measurement for CASTOR: $-6.6<\eta<-5.2$




Similar definition as in HF analysis + cut on minimal energy deposit in CASTOR (noise removal)

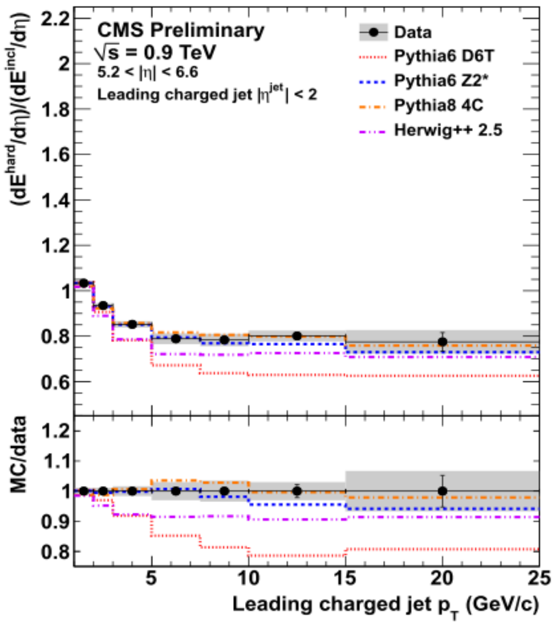


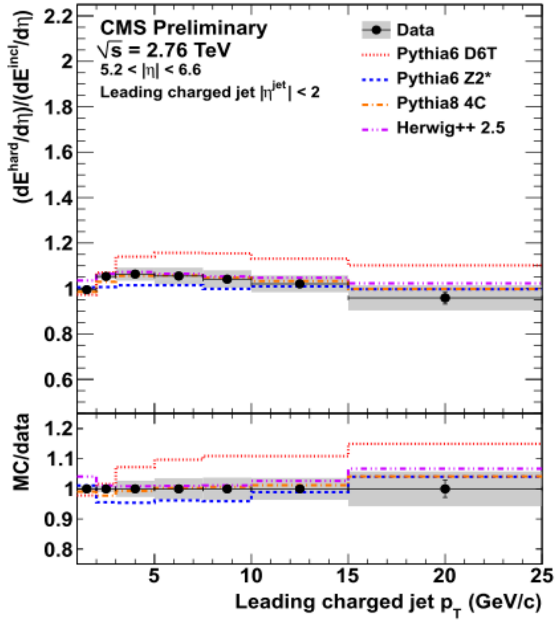

Central jet: $|\eta| < 2$
Reconstructed with a track-jet algorithm
$p_T>1$ GeV
Energy flow in CASTOR as a function of jet $p_T$

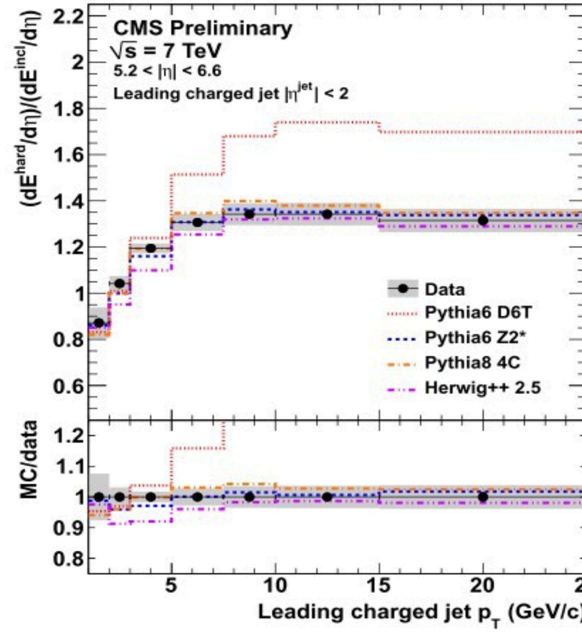
- Three energies: 0.9, 2.76 and 7 TeV
- Results quoted as ratios E(hard)/E(MB) – removal of most of the systematic effects

# Energy Flow






- 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

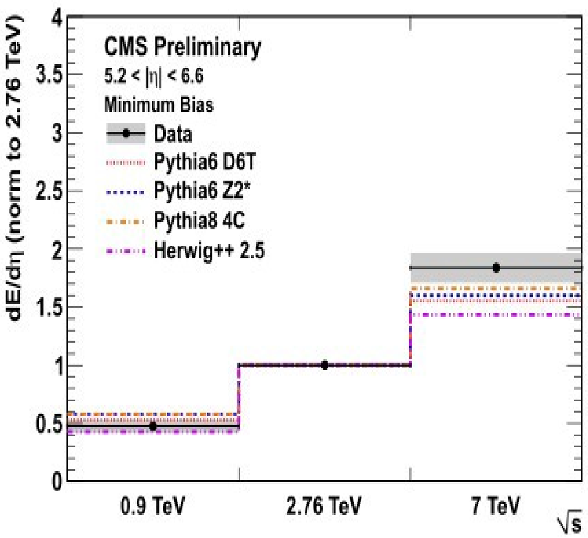
# Energy Flow

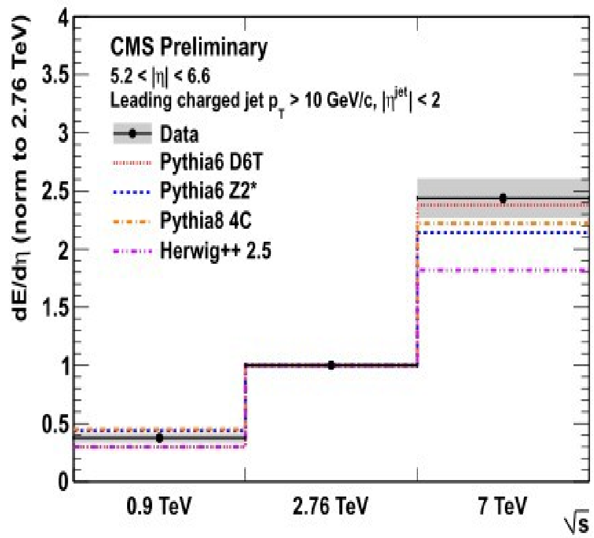


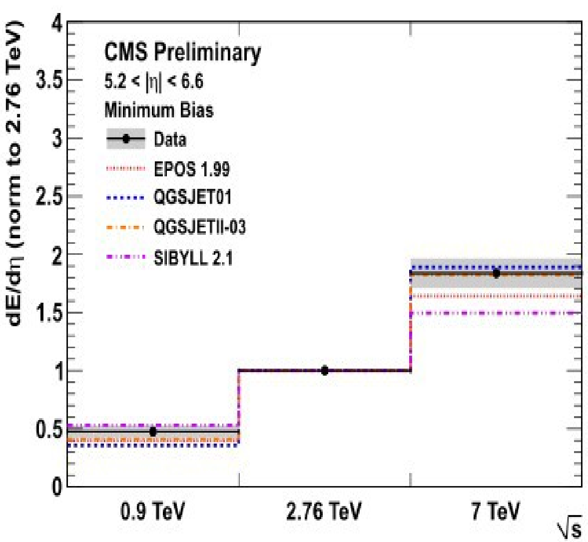
- Normalization to 2.76 TeV sample done separately for MB and dijets ($p_T$>10 GeV)

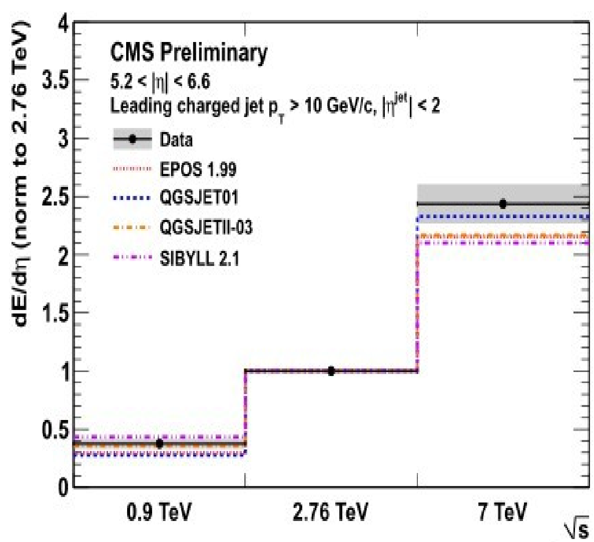
Minimum Bias

Dijet ($p_T$>10 GeV)



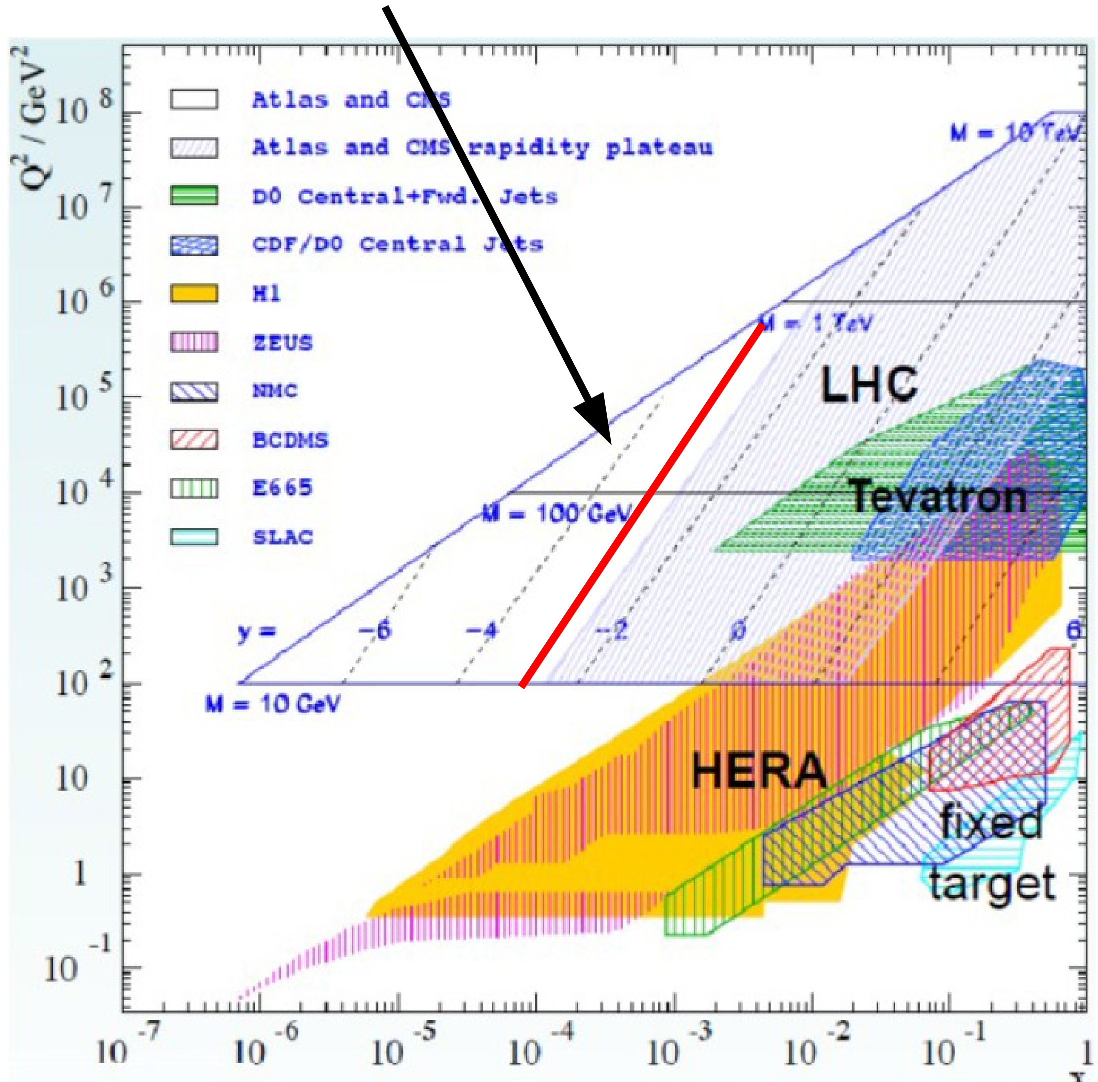




- Eflow increase faster in events with hard scale
- MB sample: PYTHIA, HERWIG do not describe the rise at 7 TeV
- MB sample: QGSJET as the only one describes it well
- Dijet sample: PYTHIA and QGSJET are the best

# Forward jets

- Forward jets in LHC
  - access to $x \sim 10^{-6}$
- Forward jets appear usually in asymmetric collisions $x_1 << x_2$

Acceptance of the forward detectors



# Forward jets



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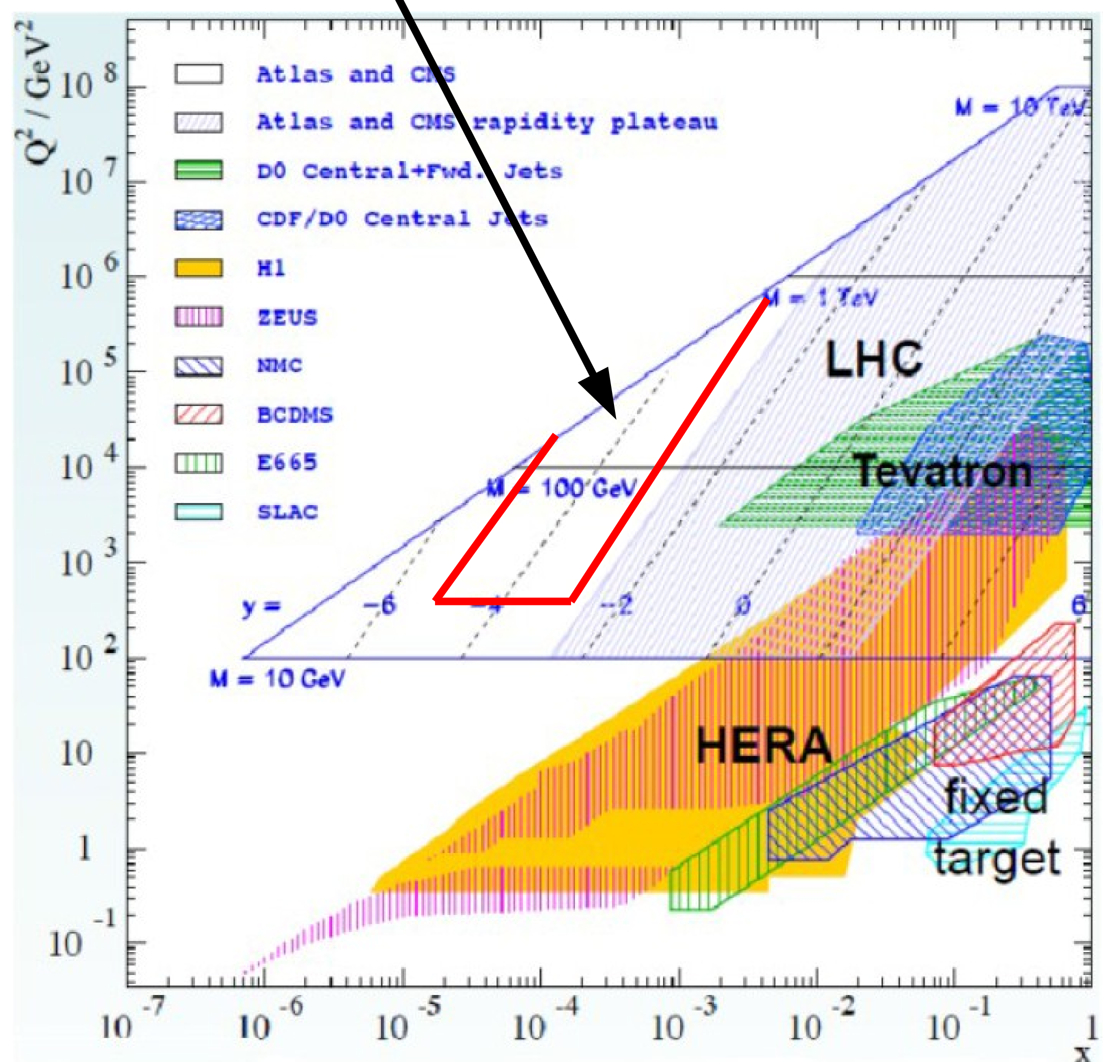
- Forward jet in HF with $p_T > 35$ GeV: $x \sim 10^{-4}$

Acceptance for forward jets (HF)



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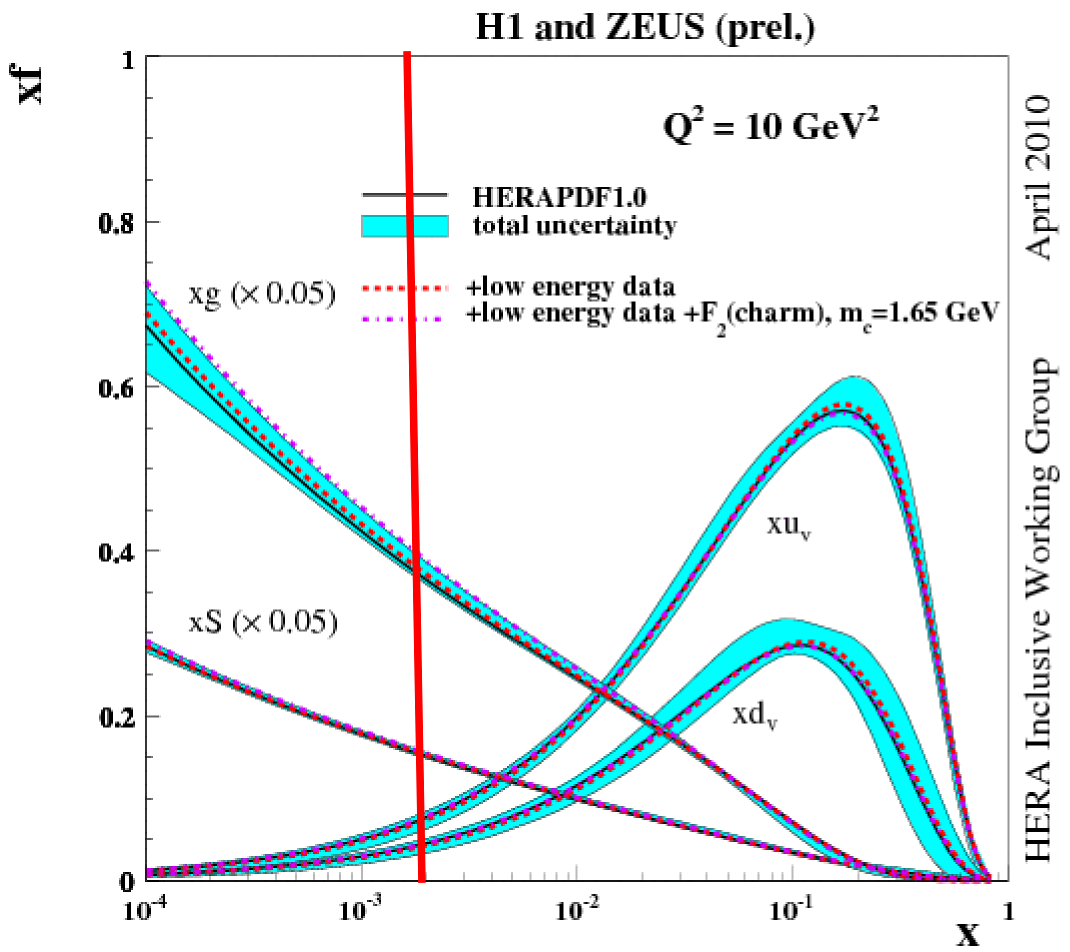
- Access to gluon densities at small x



# Forward jets



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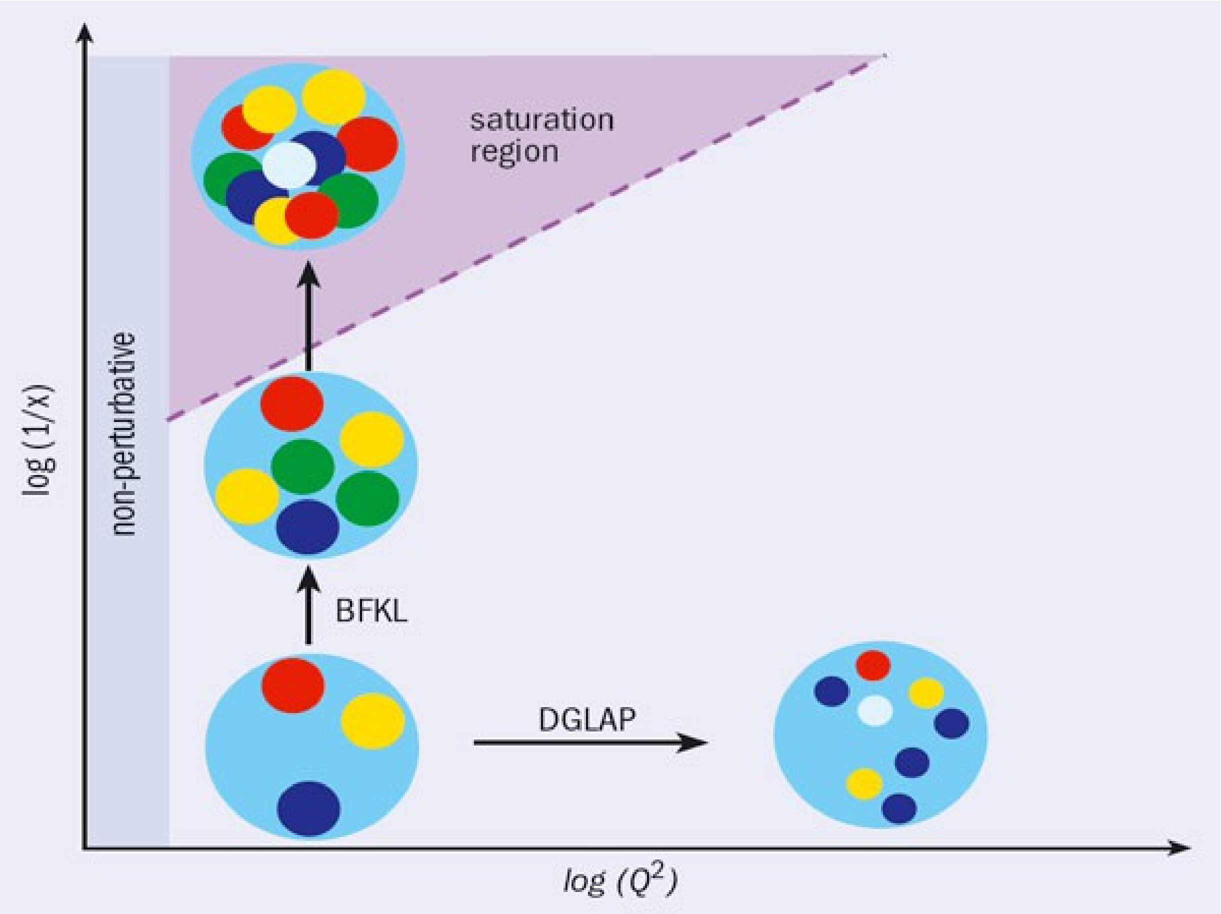
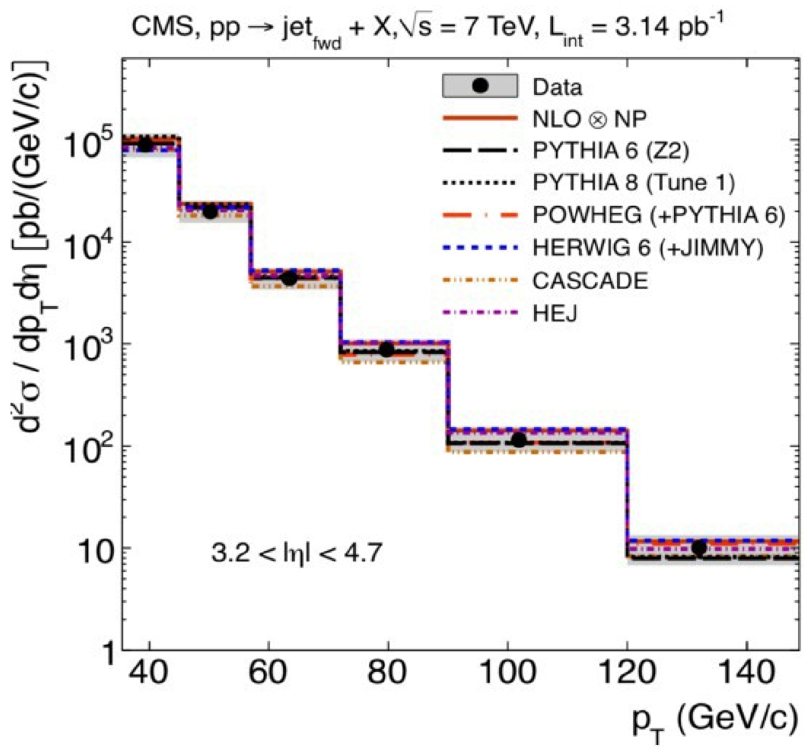
- Forward jet in HF with $p_T > 35$ GeV: $x \sim 10^{-4}$
- Access to gluon densities at small x
- BFKL vs DGLAP – correlation between jets



# Inclusive forward jets



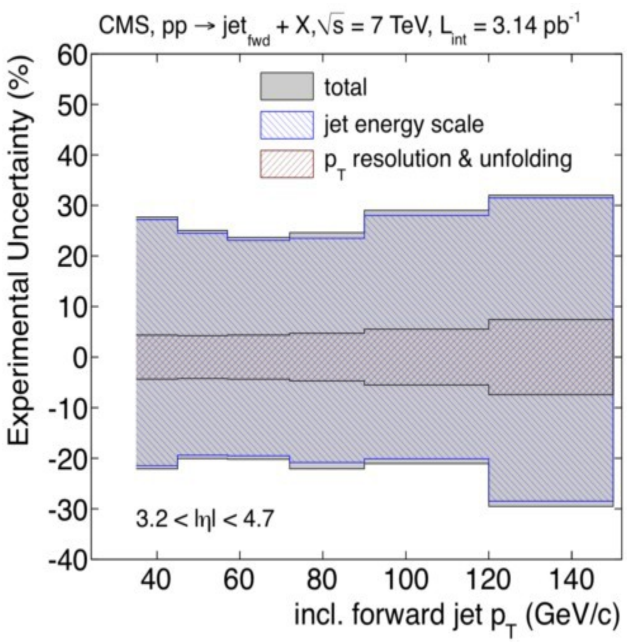
**FWD-11-002, JHEP 1206 (2012) 036**




- 3.2 < |η(jet)| < 4.7
- 3.14 $pb^{-1}$ from 7 TeV 2010 (low pile-up)
- Single jet trigger with $p_T$>15 GeV
- $p_T$ and η dependence remove using dijet and jet+photon events
- Fully corrected to the hadron level

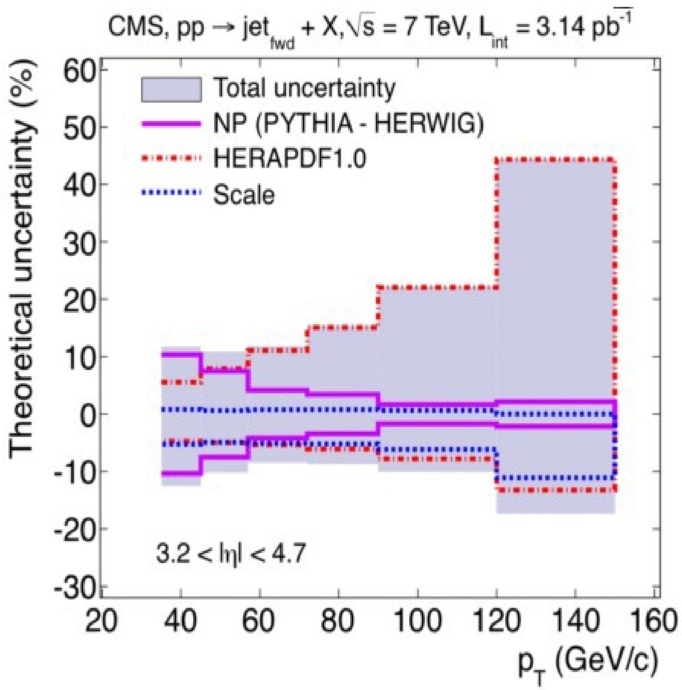
Experimental uncertainties:

- statistical unc.: small (1-10%)
- energy scale unc. ~6% → scales to 20-30% for the jets cross section
- resolution + detector->hadron corrections: 3-6%
- Luminosity uncertainty: 4%



# Inclusive forward jets



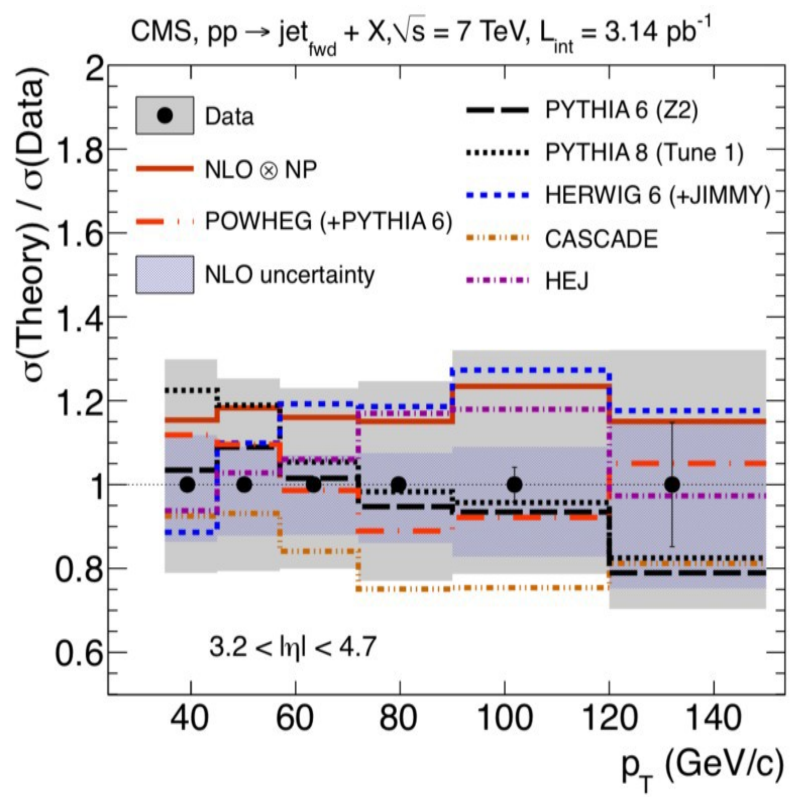



Theoretical uncertainties:

- Non perturbative effects (model difference in hadronisation corrections) – dominates at low $p_T$, 10%
- PDF uncertainties dominate at large $p_T$, up to 40%
- Scale uncertainty 5-10%

Results:

- Fixed order QCD, NLO+PS and DGLAP MC describe the data
- BFKL-type HEJ describes the data
- CCFM CASCADE seems to be below
- NLO is 20% above the central value

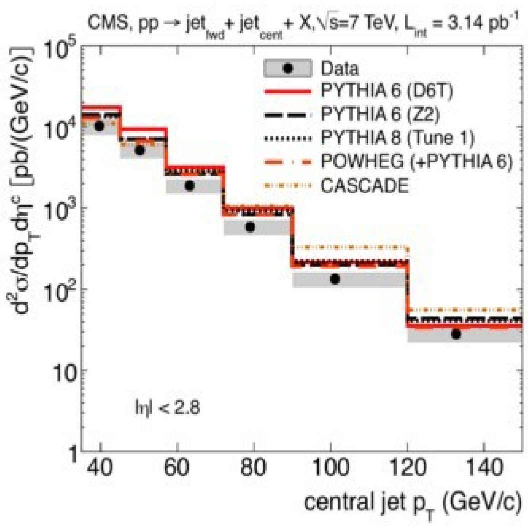


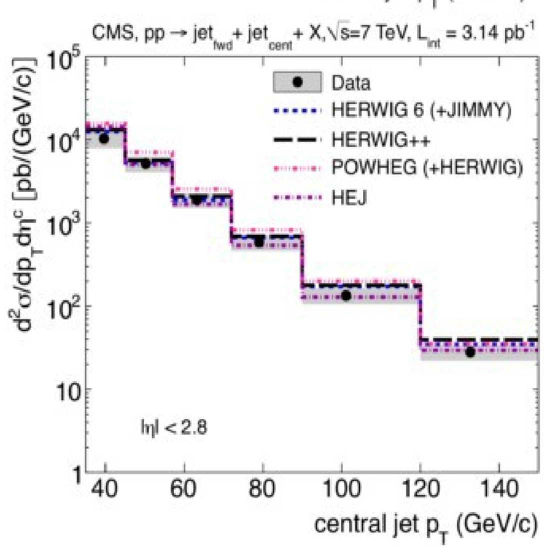
# Forward – central jets



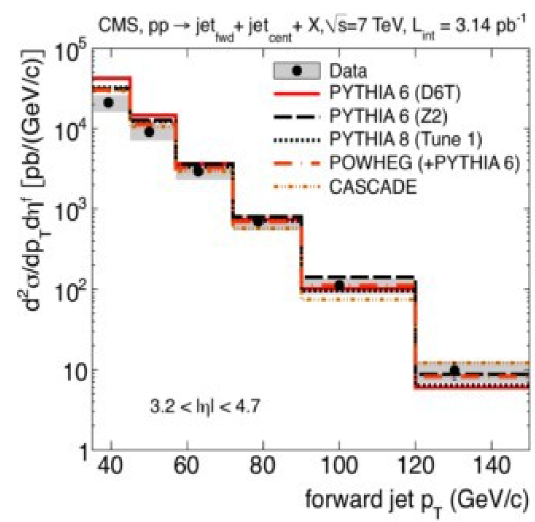
- Similar selection of events with a pair → forward + central jets
- For a central jet: $|\eta(\text{jet})| < 2.8$

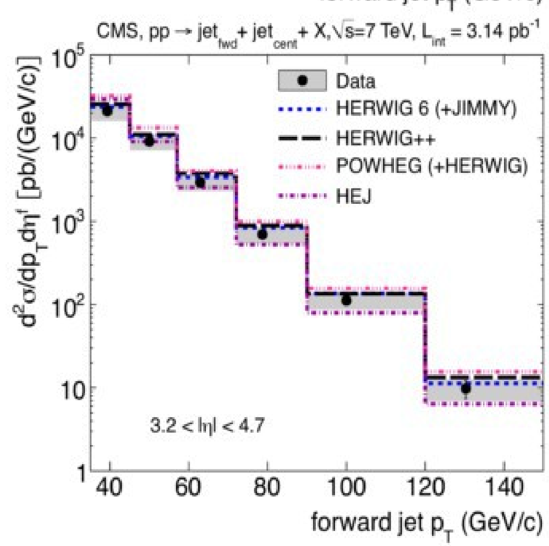
Central jet



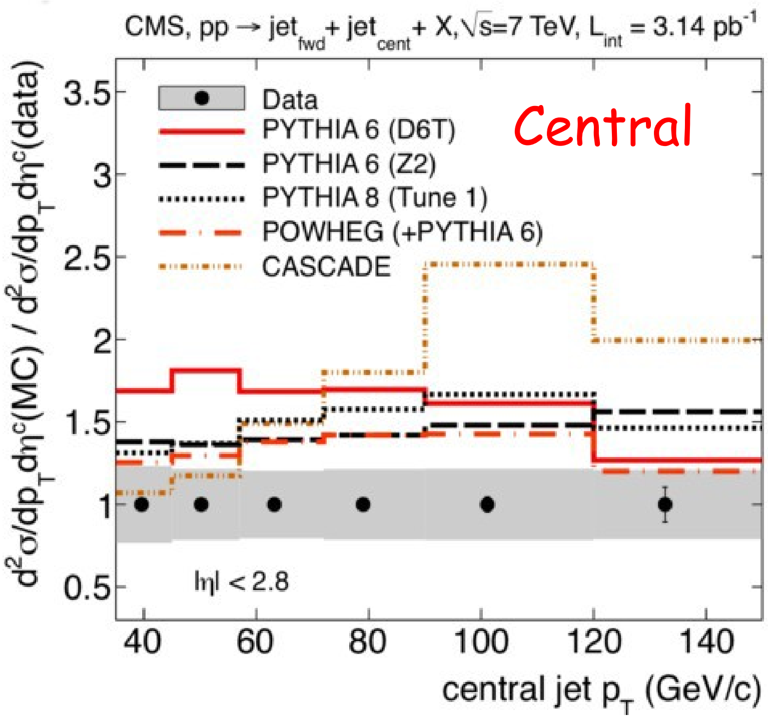

Forward jet



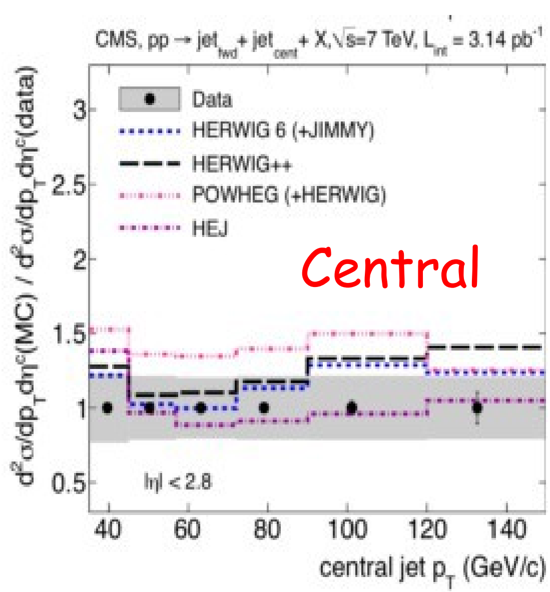
# Forward – central jets

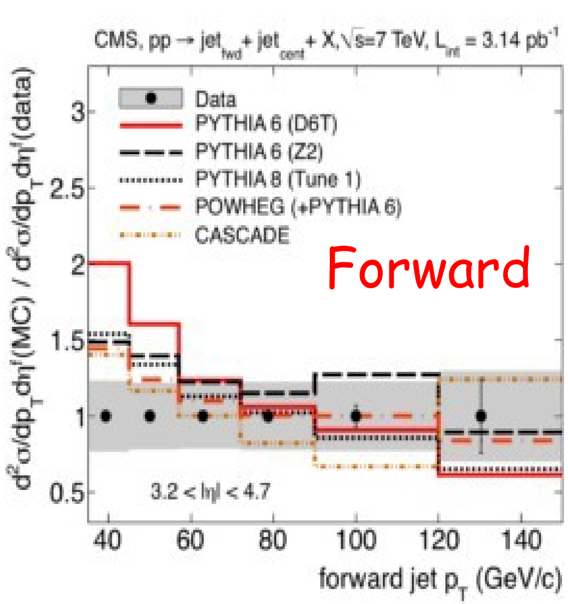


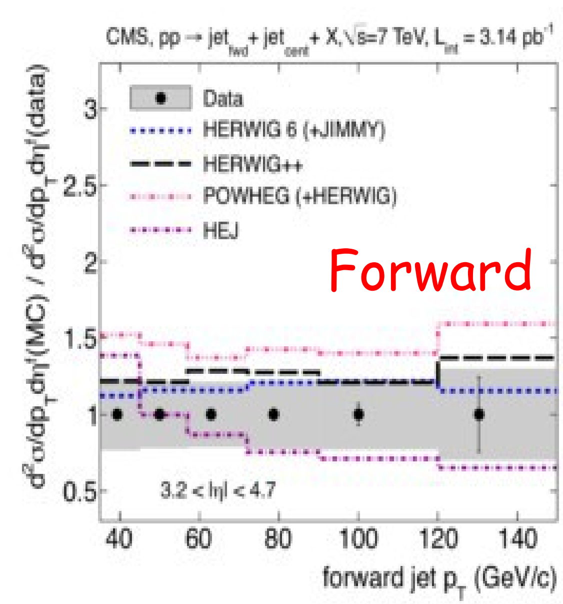



Results:

- Large discrepancies, especially for central jets
- Models overshoot the data
- HERWIG6 and HERWIG++ do the best job
- Also HEJ is OK
- CASCADE predicts different behaviour
- For forward jets most of the models predict steeper shape (more low-$p_T$ events)

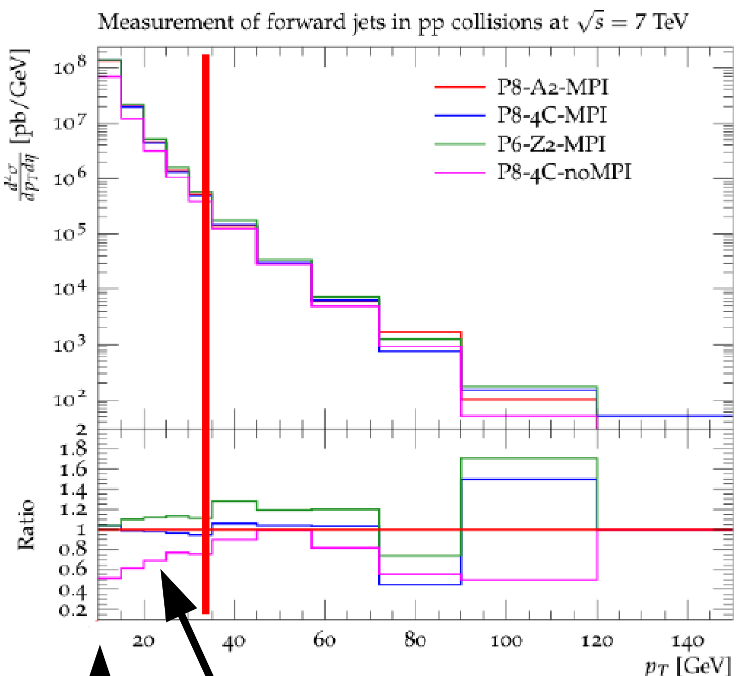


# Influence of MPI on forward jets

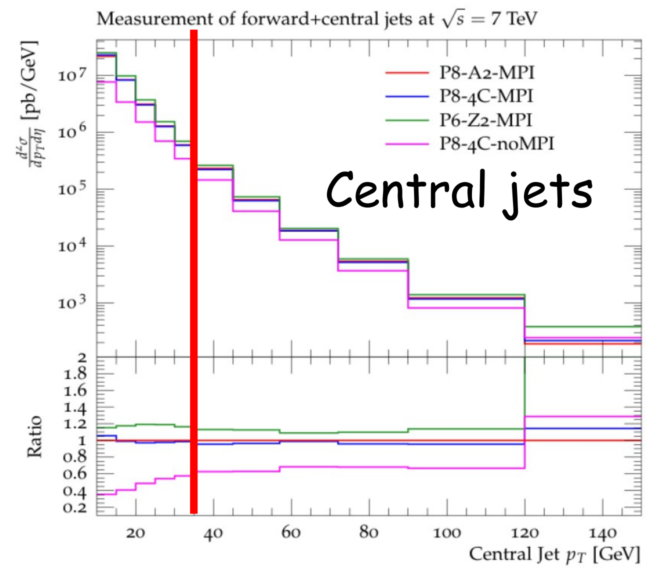
## Inclusive forward jets




10 GeV

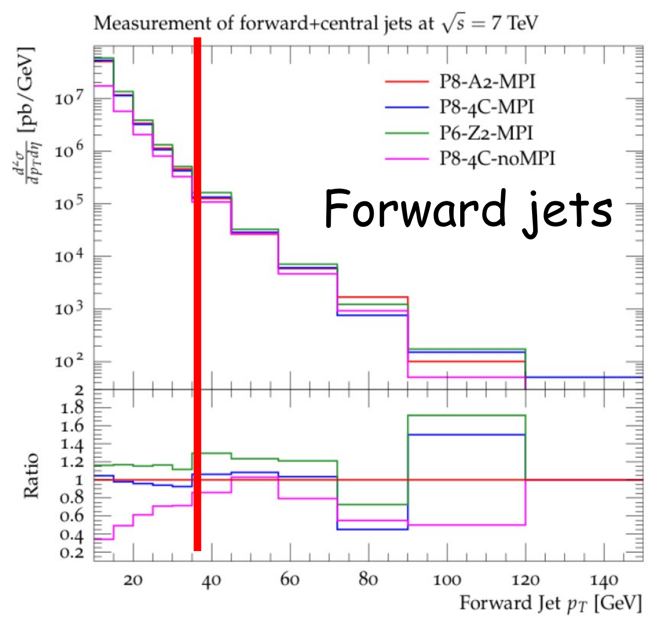
Pink line: ratio of no-MPI to MPI Pythia

Important at low $p_T$




Important at low $p_T$

But still important at moderate $p_T$



# Dijet production with large rapidity separation



FWD-10-014,
Eur.Phys.J. C72 (2012) 2216

- Three samples of dijets are defined. In all samples:
  - a pair of calorimetric jets with $p_T$ > 35 GeV and $|y|$ < 4.7

  (1) Exclusive sample: exactly two jets (defined with above requirements) are allowed for an event.

  (2) Inclusive sample: each pair of selected jets is taken

  (3) Muller-Navelet (MN) sample: a subset of inclusive sample where only most forward-backward jets are selected

- A cross section for events from the sample is calculated as a function of $|\Delta y|$ between the jets

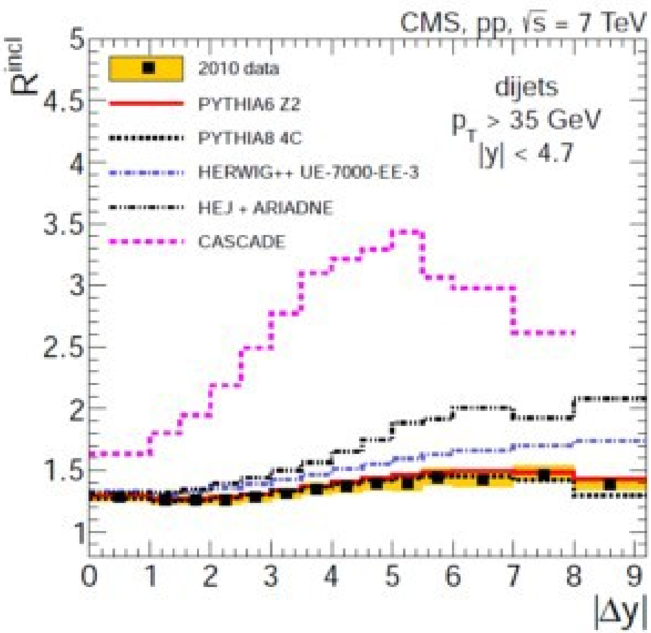
- Finally cross-section ratios:

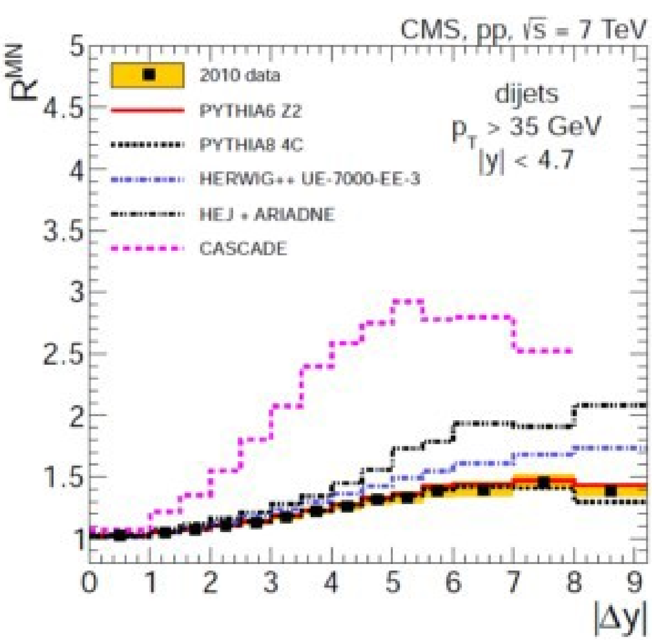
$$R_{incl} = \frac{\sigma_{incl}(\text{dijet})}{\sigma_{excl}(\text{dijet})}, \quad R_{MN} = \frac{\sigma_{MN}(\text{dijet})}{\sigma_{excl}(\text{dijet})}$$

- Probe effects beyond the collinear factorization, increasing phase space in $|\Delta y| \rightarrow$ radiation probability increases

# Dijet production with large rapidity separation






- 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 agree 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
- Keep in mind – $p_T$ > 35 GeV, what will happen at lower $p_T$ ?

# Summary



- Plenty of results based on activity and jets in forward detectors exist
  - Forward energy flow in $3 < \eta < 6.6$ → MPI, small-x physics
  - Inclusive jets → PDF, BFKL/CCFM/DGLAP
  - Correlations central-forward → BFKL/CCFM/DGLAP
  - Additional jets in an event → BFKL/CCFM/DGLAP
- Still many results to come soon
  - Angular correlations between jets
  - How low in $p_T$ can we go with our data?
  - Even more forward jets
  - Observables at different energies: 2.76/7/8 TeV (14 TeV in future)
  - Stay tuned...

But not only stay → it is time to follow with theoretical interpretations and predictions