Forward and Diffractive results from CMS and ATLAS

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(on behalf of the CMS and ATLAS collaborations)

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Outline

- CMS and ATLAS detectors
- Physics Motivation
- Measurement from ATLAS and CMS
  - Forward Energy Flow in Minimum Bias and Dijet Events
  - Forward Energy Flow, Central Track Multiplicities in W or Z Events
  - Forward Jet Production
  - Dijet Production with a veto on additional central jet activity
  - Inclusive to Exclusive Dijet Cross Section as a function of $|\Delta y|$?
  - Observation of Diffraction
  - Measurement of Rapidity Gap Cross Sections
- Conclusion
CMS and ATLAS detectors

**HF calorimeter:**
- 11.2 m from IP
- $2.9 < |\eta| < 5.2$
- Cerenkov calorimeter
- steel absorber and embedded quartz fibers
- possible to distinguish showers generated by $e/\gamma$ from showers generated by hadrons
- 13 rings in $\eta$

**FCAL calorimeter:**
- $3.1 < |\eta| < 4.9$
- LAr/Cu modules
- LAr/W modules
- to measure both electromagnetic and hadronic energy
Physics Motivation

• Forward region probes small $x$ content of the proton where
  • parton densities might become very large
  • probability for more than one partonic interaction/event should increase
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→ Measurement of the forward Energy Flow sensitive to
  • parton radiation at large $\eta$
  • description of the Multi Parton Interaction (MPI)
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  • description of the Multi Parton Interaction (MPI)

• Forward production means large asymmetry between $x$ carried by struck partons:
  $x_2 \ll x_1$ in order to boost the final system in the forward direction
Physics Motivation

• Forward region probes **small x content** of the proton where
  • parton densities might become **very large**
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  • description of the Multi Parton Interaction (MPI)

• Forward production means **large asymmetry between x** carried by struck partons:
  $x_2 << x_1$ in order to boost the final system in the forward direction

→ **Forward Jet Production** sensitive to
  • Underlying **hard QCD scattering** at parton level
  • Parton radiation and parton distribution function (pdf)

in the **low x** region where
  • Parton densities need to be **further constrained**
  • Deviation from DGLAP dynamics are expected
Physics Motivation

- **Simultaneous Production of a central and a forward jet** sensitive to
  - Multiple Parton Interaction (MPI)
  - Different types of QCD evolution for parton radiation dynamics
    - DGLAP: resummation of the leading logs in $Q^2$
    - BFKL: resummation of the leading logs in $1/x$
    - CCFM: resummation of the leading logs in both $Q^2$ and $1/x$
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• Dijet Production with a veto on additional central jet activity enables to study
  • QCD radiation effects in particular event topology
    • Mueller-Navelet and Mueller-Tang Dijet
    • Wide angle soft gluon radiation
  • In a phase-space region where DGLAP evolution should be inadequate
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• **Observation of Diffraction and Rapidity Gap Cross Sections Measurement**
  • Constrain diffractive fractions of the total inelastic cross section
  • Constrain diffractive models in MC generators PYTHIA and PHOJET
Physics Motivation

- **Simultaneous Production of a central and a forward jet** sensitive to
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    - Wide angle gluon radiation
  - In a phase-space region where **DGLAP evolution** should be **inadequate**
- **Observation of Diffraction and Rapidity Gap Cross Sections Measurement**
  - Constrain **diffractive fractions** of the total inelastic cross section
  - Constrain **diffractive models** in MC generators PYTHIA and PHOJET
- **Ratio of inclusive to exclusive dijet production cross section** = \( f(|\Delta y|) \)
  - Sensitive to effects beyond collinear factorization (BFKL dynamics)
Forward Energy Flow

(CMS PAS FWD-10-011)
Forward Energy Flow

- Forward energy flow $1/N \frac{dE}{d\eta}$ measured in the region $3.15 < |\eta| < 4.9$ (HF), at 2 center-of-mass energies 900 GeV and 7 TeV, for 2 different event classes:

  Minimum Bias Events

  Events with a hard scale: central dijet system

  - at least 2 jets with $|\eta| < 2.5$
  - $p_t > 8$ GeV at 900 GeV
  - $p_t > 20$ GeV at 7 TeV

- MB trigger: beams and charged particles in $3.9 < |\eta| < 4.4$ on both sides of detector

- Offline selection: good primary vertex, beam-induced background rejection

- Data corrected to hadron level (Pythia6): stable final state particles (ν and μ excl.), w/o energy cut, in the range $3.15 < |\eta| < 4.9$ + at least one particle in $3.9 < |\eta| < 4.4$ on both sides (to mimic MB trigger used at detector level and minimise the correction)

- Largest Systematics Uncertainties

<table>
<thead>
<tr>
<th>MB sample</th>
<th>Dijet sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF energy scale</td>
<td>10 %</td>
</tr>
<tr>
<td>HF simulation</td>
<td>3-9 %</td>
</tr>
<tr>
<td>Model dependence</td>
<td>1-3 %</td>
</tr>
<tr>
<td>→ Total</td>
<td>11-14 %</td>
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</tbody>
</table>
Rise of Energy Flow with $\eta$, corresponding to a flat $E_t$ flow
Increase in $E_t$ flow with $\sqrt{s}$ similar to increase in charged particle multiplicity
Different Pythia 6 tunes shown as band → large spread – Pythia 8 within this band
Herwig++ describes data rather well
Pythia6 w/o MPI undershoots data by 40 %
Predictions from generators used in cosmic ray physics work pretty well
Flatter $\eta$ dependence wrt Energy Flow in MB, corresponding to a decreasing $E_t$ flow
Increase of $E_t$ flow with $\sqrt{s} \rightarrow E_t$ flow much larger than at HERA
Bands from different **Pythia 6 tunes** cover data – **Pythia 8** within this band

**Herwig++** describes data rather well

**Pythia6 w/o MPI** undershoots data

**Cascade** shows a faster increase at 900 GeV – misses normalization at 7 TeV
Predictions from generators used in cosmic ray physics work pretty well.
Forward Energy Flow, Central Track Multiplicities and Large Rapidity Gaps in W and Z Boson Events at 7 TeV pp Collisions

(CMS PAS FWD-10-008)
Forward Energy Flow with W or Z

• Previous: MPI models investigated with MB data and final states with high $p_t$ jets

• W or Z are colorless: clear separation of hard interaction and Underlying Event
  - Observables: central track multiplicity in $|\eta| < 2.5$
    - 2 track $p_t$ thresholds: $p_t > 0.5$ GeV (1 GeV)
    (tracks from W(Z) decays are excluded)
  - forward energy flow in $3.15 < |\eta| < 4.9$ (HF)
    correlations among these 2 observables

• W selection: one isolated $e$ or $\mu$, $p_t > 25$ GeV, $|\eta| < 1.4$
  - missing $E_t > 30$ GeV, $M_{l\nu} > 60$ GeV

• Z selection: two isolated $e$ or $\mu$, opposite charge, $p_t > 25$ GeV
  - at least one has $|\eta| < 1.4$, $60 < M(ll) < 120$ GeV

• PU rejection: only single vertex events are selected
  - matching of vertex to charged lepton track(s)

• Observables are not corrected for detector effects: direct comparison with MC
  (no correction for soft PU which do not have reco vertex (well modeled by MC))

• Systematics Uncertainty: HF energy scale uncertainty: 10 %
Central Track Multiplicity & Fwd Energy Flow

Tune Z2 provides good description of data
Tune ProQ20 significantly underestimates the high multiplicity tail

→ none of the tunes provides simultaneously a satisfactory description
Correlations Track Multiplicity & Energy Flow

- W → μν distributions for different energies in HF-
  - central track multiplicity
    - 20 < E HF - < 100 GeV (a)
    - 200 < E HF - < 400 GeV (b)
  - Energy in HF +
    - E HF - > 500 GeV (c)

- Energy in HF + & HF - strongly correlated

→ strong correlation in data and simulation

but none of the tunes provides satisfactory description at all energies

→ energy in HF + & HF - strongly correlated

(c) Pythia 8 good (not in inclusive case)
**W boson events with a LRG**

- **Large Rapidity Gap:** no energy deposit in HF tower above 4 GeV (+ or - side)
- **Signed charged lepton $\eta$:** sign is positive when lepton and gap in the same hemisphere, negative otherwise
- **Diffractive W production:** W boosted in the direction opposite to the gap (dpdf tends to lower $x$ values than pdf) → asymmetry expected
- **Data fitted to POMPYT (Diffractive component) and PYTHIA 6 (ND component) with relative fraction as free parameter**

According to POMPYT: $50 \pm 9.3$ (stat) $\pm 5.2$ (syst) % LRG W events can be attributed to diffractive production
Jets production in the forward region

CMS PAS FWD-10-003
CMS PAS FWD-10-006
ATLAS-CONF-2011-047
Jets production in the forward region

- Measurement of inclusive forward jet cross section at 7 TeV (CMS PAS FWD-10-003)

  \[ L = 3.14 \text{ pb}^{-1}, \text{ anti-}k_t \text{ jet algorithm (R = 0.5)} \]
  \[ 3.2 < |\eta| < 4.7 - 35 < p_t < 150 \text{ GeV} \]

- Measurement of the cross section for simultaneous production of a central and a forward jet at 7 TeV (CMS PAS FWD-10-006)

  \[ L = 3.14 \text{ pb}^{-1}, \text{ anti-}k_t \text{ jet algorithm (R = 0.5)} \]
  central region \( |\eta| < 2.8 \) - forward region \( 3.2 < |\eta| < 4.7 \)
  at least one jet in central and forward region
  \( p_t > 35 \text{ GeV} \)

- Measurement of inclusive jet and dijet cross sections at 7 TeV using the ATLAS detector (ATLAS-CONF-2011-047)

  \[ L = 37 \text{ pb}^{-1}, \text{ anti-}k_t \text{ jet algorithm (R = 0.4 and R = 0.6)} \]
  \( 2.8 < |y| < 4.4 \) for forward jets
  \( 20 < p_t < 300 \text{ GeV} \) for forward jets

- All measurements corrected to hadron level
Inclusive forward jets

Inclusive forward jet cross section at 7 TeV

Experimental uncertainty: 25-30%
• dominated by JES uncertainty
  (steeply falling $p_T$ spectrum)

Theoretical uncertainty: 10-15%
• uncertainty on non-pert correction
• pdf uncertainty
• scale uncertainty

Within the current uncertainties, all pQCD predictions reproduce the measurement
LO + PS: Pythia 6, Pythia 8, Herwig
NLO + PS: Powheg + Pythia 6
Fixed order NLO * Non Perturb. correction
CCFM: CASCADE (different slope)
Main Systematic uncertainties:
- Jet Energy Scale uncertainty
- Model dependence correction factor

At $p_t = 20$ GeV, $3.6 < |y| < 4.4$:
- JES uncertainty $+80\%$ -$50\%$
- Correction factor $20\%$
Inclusive forward jets

Data compared to NLO predictions using different PDF sets

Data and predictions normalized to prediction using CTEQ 6.6

NNPDF, HERAPDF and particularly MSTW 2008 agree better with data than CTEQ 6.6
Inclusive forward jets

Data compared to Powheg NLO predictions interfaced to Pythia 6 and Herwig (PS & hadronization)

Data and predictions normalized to NLO prediction (MSTW 2008)

Difference between parton shower implementations?
Forward and central jets

Associated forward jet – central jet cross sections at 7 TeV

Systematic uncertainties are similar to the inclusive forward jet case
Total systematic uncertainty $\sim 30\%$ dominated by JES uncertainty $\sim 25\%$
Forward and central jets

Associated forward jet – central jet cross sections at 7 TeV

All Pythia tunes overestimate jet spectrum (disagreement larger at low pt)
Herwig gives better description
Powheg NLO + Parton Shower (Pythia or Herwig): does not reduce disagreement
CASCADE does not reproduce jet spectrum
HEJ gives good description (suited for 2 jets separated by large rapidity interval)
Measurement of dijet production with a veto on additional central jet activity at 7 TeV using the ATLAS detector

ATLAS-CONF-2011-038
Dijet production with a veto on third jet

- anti-\(k_t\) algorithm (\(R = 0.6\)), \(p_t > 20\) GeV, \(|y| < 4.4\)
- Quantify amount of radiation in \(\Delta y\) bounded by the dijet?
  
  \[\text{measurement of the gap fraction:}\]
  
  fraction of events with no additional jet with \(p_t > Q_0\) in \(\Delta y\) bounded by the dijet system
  
  \(Q_0 = \text{veto scale}\)

- Probe different QCD radiation phenomena by playing with \(\Delta y\) and dijet average \(p_t\)

  \(Q_0 << \text{dijet average } p_t\):
  
  wide-angle soft gluon radiation
  
  \(\Delta y >>\): open phase space for BFKL dynamics

  Mueller-Navelet Dijet
  
  \(\Delta y \gg\): define dijet system: 2 jets most separated in \(y\)

  Mueller-Tang Dijet

- \(Q_0 << \text{dijet average } p_t\) and \(\Delta y \gg\):

  Color Singlet BFKL ladder: Mueller-Tang Dijet
Gap fraction

Gap fraction as a function of $\Delta y$ for various dijet average $p_\text{t}$ slices

- Dijet defined as the 2 leading $p_\text{t}$ jets
- HEJ describes data well at low dijet average $p_\text{t}$
  - HEJ predicts too large gap fraction at large dijet average $p_\text{t}$
    - HEJ suited to describe emissions of similar $p_\text{t}$
    - fails when dijet average $p_\text{t} >> Q_0$
- Powheg + Pythia: best description when all phase space considered
- At larger $\Delta y$, Powheg + Pythia deviates from data
  - full QCD calculation becomes more needed as $\Delta y$ increases
  - NLO + PS approximation becomes unsufficient
Gap fraction

Gap fraction as a function of $\Delta y$ for various dijet average $p_t$ slices

- Dijet defined as the 2 jets most separated in $y$ (larger $p_t$ imbalance)

- HEJ does not describe data well at low dijet average $p_t$
  $\rightarrow$ resummation of soft emissions important

- Powheg, HEJ: gap fraction too small at large $\Delta y$
Measurement of inclusive to exclusive dijet production ratio at large rapidity intervals at 7 TeV

CMS PAS FWD-10-014
Inclusive to exclusive Dijet production

• Ratio of inclusive to exclusive dijet production = f (|Δy|)
  • $p_t > 35$ GeV, $|y| < 4.7$
  • exclusive case: only 2 jets with $p_t > 35$ GeV are allowed
  • inclusive case: each pair of jets with $p_t > 35$ GeV is taken into account

• Ratio corrected for detector effects (Pythia 6 Z2)

• Main systematic uncertainty: model dependence of correction factor: 1-8%
  • from difference between Herwig 6 + Jimmy and Pythia 6 Z2
  • increases with $Δy$
Inclusive to exclusive Dijet production

- Ratio increases with $|\Delta y|$ (phase space for additional hard radiation increases)
- Ratio decreases at highest $|\Delta y|$ (kinematic limitation for inclusive dijet prod)
- Pythia 6 Z2 (with & w/o MPI), Pythia 6 D6T agree well (MPI effect negligible)
- Herwig++: too high ratio at medium $|\Delta y|$  
- Herwig 6 + Jimmy: above data for $|\Delta y| > 2$
Observation of diffraction at 7 TeV
CMS PAS FWD-10-007
Observation of Diffraction at 7 TeV

• Diffractive event selection:

MB trigger: beams and charged particles in $3.9 < |\eta| < 4.4$ on either sides of detector
offline selection: good primary vertex, beam-induced background rejection
4 GeV threshold in HF, 3 GeV in other calorimeters

• Peak in $\xi$ distribution

$\Sigma (E \pm P_z)$ related to the momentum loss of the scattered proton (runs over all calorimeter energy deposits)
proton fractional momentum loss: $\xi \approx \Sigma (E \pm P_z) / \sqrt{s}$
diffractive peak expected at low values of this variable ($\sigma \sim 1 / \xi$)

• uncorrected data compared to Pythia 6 D6T, Pythia 8 and Phojet
main systematic uncertainty due to $\pm10\%$ energy scale variation
Pythia 6 D6T describes better the non-diffractive part of the spectrum

Events below 5 GeV are mainly diffractive
Rapidity Gap Cross Sections
at 7 TeV
ATLAS-CONF-2011-059
Gap Finding Algorithm

• Detector divided into rings in $\eta$

• Ring contains activity if
  - at least one calorimeter cell above threshold ($|\eta| < 4.9$)
  - at least one good track with $p_t > 200$ MeV ($|\eta| < 2.5$)

• Two different rapidity gap definitions in the analysis:
  - **Floating gap**: largest consecutive run of empty rings, parametrized by its size $\Delta\eta$ and nearer edge to the acceptance limit $\eta_{\text{start}}$
    - data and Monte Carlo divided into a 2-dim array ($|\eta_{\text{start}}|, \Delta\eta$)
    - optimize fraction of diffractive dissociation in Monte Carlo
  - **Forward gap**: largest consecutive run of empty rings, starting at the edge of the acceptance ($|\eta| = 4.9$) and of size $\Delta\eta^F$
    - rapidity gap cross section \[ \frac{d\sigma(\Delta\eta^F)}{d\Delta\eta^F} \]
Rapidity Gap Cross Section

• Cross Section corrected to hadron level:

\[
\frac{d\sigma(\Delta\eta^F)}{d\Delta\eta^F} = \frac{A(\Delta\eta^F)}{\Delta\eta_{\text{ring}}} \frac{N(\Delta\eta^F) - N_{\text{BG}}(\Delta\eta^F)}{\varepsilon(\Delta\eta^F) \times \mathcal{L}}
\]

• \(\varepsilon(\Delta\eta F)\) = product of trigger and offline selection efficiency

• \(A(\Delta\eta F)\) = correction factor for bin migration (from detector to hadron level)
Rapidity Gap Cross Section

- **Pythia 8** gives better description at low $\Delta \eta^F$, Phojet at high $\Delta \eta^F$
- Evidence for diffraction at high $\Delta \eta^F$
  - exponential decrease of ND component
  - plateau from SD and DD component
- **Diffractive cross section ~ 1 mb per unit of $\Delta \eta^F$ at high $\Delta \eta^F$**
- Dominant systematic uncertainties
  - Model dependence ~ 10 – 15%
  - Energy scale ~ 5 – 30 % (increase linearly with $\Delta \eta^F$ in the region with only calorimeter coverage)
Rapidity Gap Cross Section

- Zoom on the cross section at high $\Delta\eta^F$
- Phojet normalisation better than the one from Pythia 8
- Pythia 8 overestimates DD contribution
Conclusion

• ATLAS and CMS have interesting forward and diffractive physics results

• Forward energy flow
  • strongly affected by MPI - help to constrain MPI
  • correlation with central track multiplicity gives further constraint

• Forward Jet Production gives low-\(x\) information about
  • parton radiation dynamics - pdfs
  • simultaneous fwd and central production increases sensitivity
  • constraint limited by uncertainty from Jet Energy Scale

• Dijet Production with a veto on central jet activity
  • powerful tool to study in details QCD radiation effects
  • full QCD calculation needed to describe jets separated by large \(\Delta y\)

• Rapidity Gap cross section
  • Pythia 8 better at low \(\Delta \eta^F\) (ND dominated) - Phojet better at high \(\Delta \eta^F\) (SD and DD)
  • Diffractive cross section \(\sim 1\) mb per unit of \(\Delta \eta^F\) at high \(\Delta \eta^F\)

• Ratio of inclusive to exclusive dijet production cross section \(= f(|\Delta y|)\)
  • Pythia 6 Z2 and D6T agree well with the measurement (MPI effect negligible)
  • Herwig++ - Herwig 6 + Jimmy above the data
Back Up
PYTHIA MPI tunes

• Perturbative 2-to-2 partonic cross-section is regularized in PYTHIA by the introduction of a cutoff $p_{T0}$:

$$\sigma \propto \frac{1}{(p_T^2 + p_{T0}^2)^2}$$

• $p_{T0}$ governs the description of the amount of MPI: larger MPI activity for smaller values of $p_{T0}$

• $p_{T0}(\sqrt{s}) = p_{T0}(\sqrt{s_0}) (\sqrt{s}/\sqrt{s_0})^\epsilon$

<table>
<thead>
<tr>
<th></th>
<th>$p_{T0}(\sqrt{s_0})$</th>
<th>$\sqrt{s_0}$</th>
<th>$\epsilon$</th>
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<tbody>
<tr>
<td>D6T</td>
<td>1.84</td>
<td>1.96</td>
<td>0.16</td>
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<td>PROQ20</td>
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<td>P0</td>
<td>2.0</td>
<td>1.8</td>
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<tr>
<td>DW</td>
<td>1.9</td>
<td>1.8</td>
<td>0.25</td>
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CMS Detector

**HF calorimeter:**
- 11.2 m from IP
- $2.9 < |\eta| < 5.2$
- Cerenkov calorimeter
- steel absorber and embedded quartz fibers
- possible to distinguish showers generated by $e/\gamma$ from showers generated by hadrons
- 13 rings in $\eta$

Superconducting solenoid, 6m internal diameter, magnetic field 3.8 T
Within field volume: silicon pixel and strip tracker
   electromagnetic (ECAL) and hadronic (HCAL) calorimeter
Outside field volume: muon chambers embedded in iron return yoke
ATLAS Detector

Tracking detector surrounded by solenoid magnet, magnetic field 2 T
Within field volume: Silicon pixel, silicon microstrip and transition radiation tracking detectors
Outside field volume: electromagnetic and hadronic calorimeters, muon chambers

FCAL calorimeter:
- $3.1 < |\eta| < 4.9$
- LAr/Cu modules
- LAr/W modules
- to measure both electromagnetic and hadronic energy
Monte Carlo and Theoretical Predictions

- **Pythia6**: reference (base line) generator used for
  - correction of the data from detector to hadron level
  - estimation of the Non-Perturbative (NP) correction for fixed order calculation
  - LO $2 \to 2$ Matrix Element
  - $p_t$ ordered parton shower
  - Lund string model for hadronization
  - only contains soft diffraction contribution

- **Pythia8**: includes hard diffractive final states (HERA diffractive pdf)

- **Herwig (linked with Jimmy) and Herwig++**:  
  - LO $2 \to 2$ Matrix Element
  - angular ordered parton shower
  - cluster hadronization model

- **Underlying Event** is modelled in Pythia and Herwig by Multiple Parton Interaction
Monte Carlo and Theoretical Predictions

- **ALPGEN**: parton-level multiparton event generator
  - LO Matrix Element with up to 6 partons in the final state
  - interfaced to Pythia or Herwig (parton showering, hadronisation, MPI)

- **HEJ**: parton-level event generator
  - all order description of wide angle emissions of similar $p_t$ (BFKL-inspired limit)
  - suited for events with at least 2 jets separated by a large rapidity interval

- **POWHEG**: framework to implement a NLO parton shower event generator
  - full NLO QCD $2 \rightarrow 2$ partonic scattering
  - interfaced to Pythia or Herwig (parton showering, hadronisation, MPI)

- **PHOJET**: event generator implementing the two-component Dual Parton Model
  - combines Regge Theory with pQCD predictions
  - to describe both soft and hard diffraction
Monte Carlo and Theoretical Predictions

- **POMPYT**: hadron level event generator for diffractive hard scattering processes
- **CASCADE**: hadron level event generator
  - CCFM evolution equation for the initial state cascade
  - Off-shell Matrix Element
  - Unintegrated pdf
- **NLOJet++**
  - NLO parton level cross section
  - to which corrections are applied for Non-Perturbative effects
    - NP corrections determined with Parton Shower event generator
    - ratio of generator predictions with and w/o hadronization and UE
Gap fraction as a function of dijet average $p_t$ for various $\Delta y$ slices

- Dijet defined as the 2 leading $p_t$ jets
- HEJ describes data well at low dijet average $p_t$
- HEJ predicts too large gap fraction at large dijet average $p_t$
- Powheg + Pythia: good at low $\Delta y$
- At larger $\Delta y$, good in shape only
Observation of Diffraction at 7 TeV

• Large Rapidity Gap (LRG)

Diffractive events characterized by the absence of forward hadronic activity in HF due to the presence of a Large Rapidity Gap

→ Diffractive peak expected at low energy deposition and low tower multiplicity in HF
Observation of Diffraction at 7 TeV

- Comparison with different Pythia 6 tunes

Pythia 6 D6T, DW, CW reproduce the data best
Enriched Diffractive Sample

- Require low activity (Large Rapidity Gap) on one side of the detector (HF+ or HF-) → enhance the diffractive component
- Look at properties of diffractive system X on the other side to test MC description ($\xi = \frac{M_X^2}{s}$)
- PHOJET and Pythia 8 give a better description of the diffractive system

\[ E(HF+) < 8 \text{ GeV} \]
Enriched Diffractive Sample

- Comparison with different Pythia 6 tunes

→ None of them reproduces the diffractive component

\[ E(\text{HF}^+) < 8 \text{ GeV} \]
Calorimeter energy deposit

- Energy Significance $E / \sigma$ noise in data (MB and random trigger) well modeled by MC over many orders of magnitude

- Electromagnetic, hadronic end-cap and forward calorimeter

- Selection based on energy significance per cell and at least one cell above significance threshold

- Significance threshold derived separately for each ring by requiring that the probability of finding at least one noisy cell in a ring is constant

  $\rightarrow \ 4.8 < \text{significance threshold} < 5.8$