Forward and Diffractive results from CMS and ATLAS

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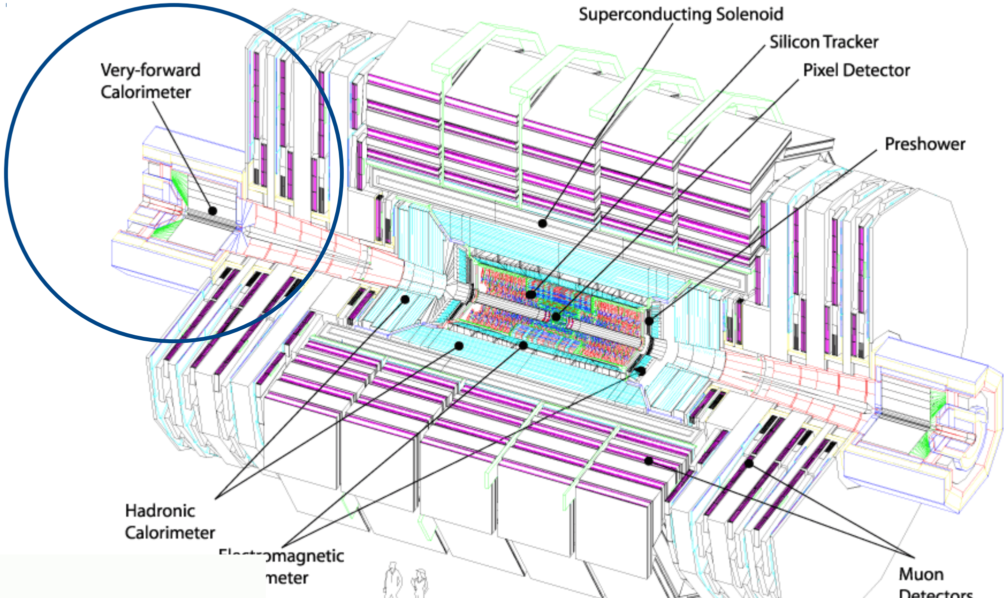
Outline

- **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**

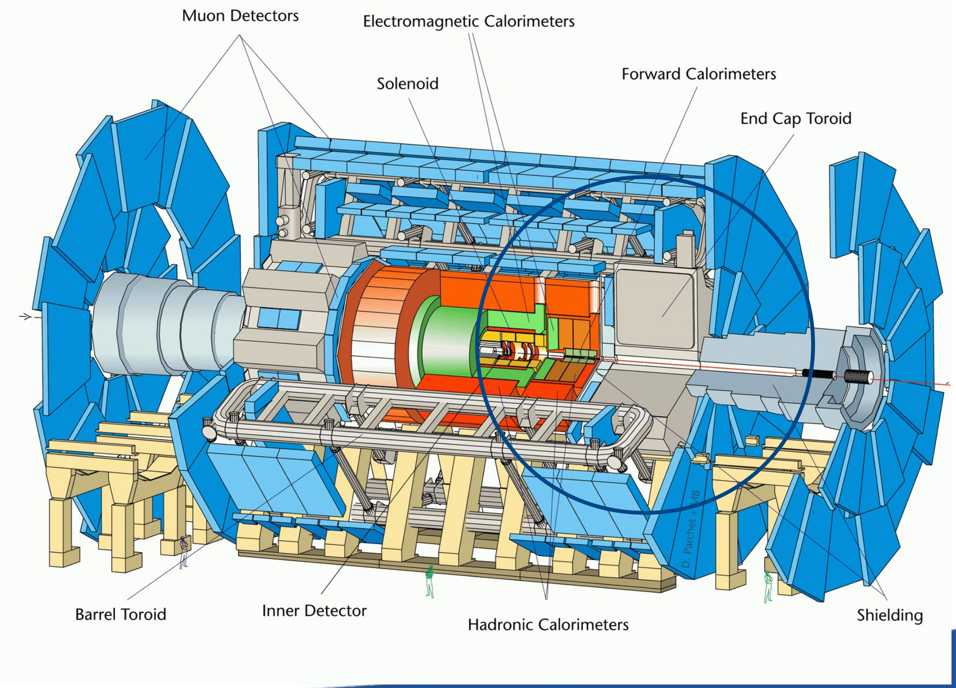
CMS and ATLAS detectors

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/γ from showers generated by hadrons
- 13 rings in η



Compact Muon Solenoid



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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→ **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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  - 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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  - Constrain diffractive models in MC generators PYTHIA and PHOJET

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  - Constrain diffractive fractions of the total inelastic cross section
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- **Ratio of inclusive to exclusive dijet production cross section = f(|Δy|)**
  - Sensitive to effects beyond collinear factorization (BFKL dynamics)

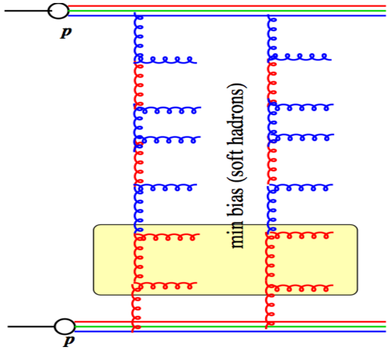
Forward Energy Flow

(CMS PAS FWD-10-011)

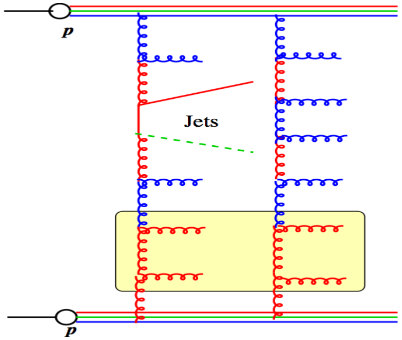
Forward Energy Flow

- Forward energy flow *1/N dE/dη* 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

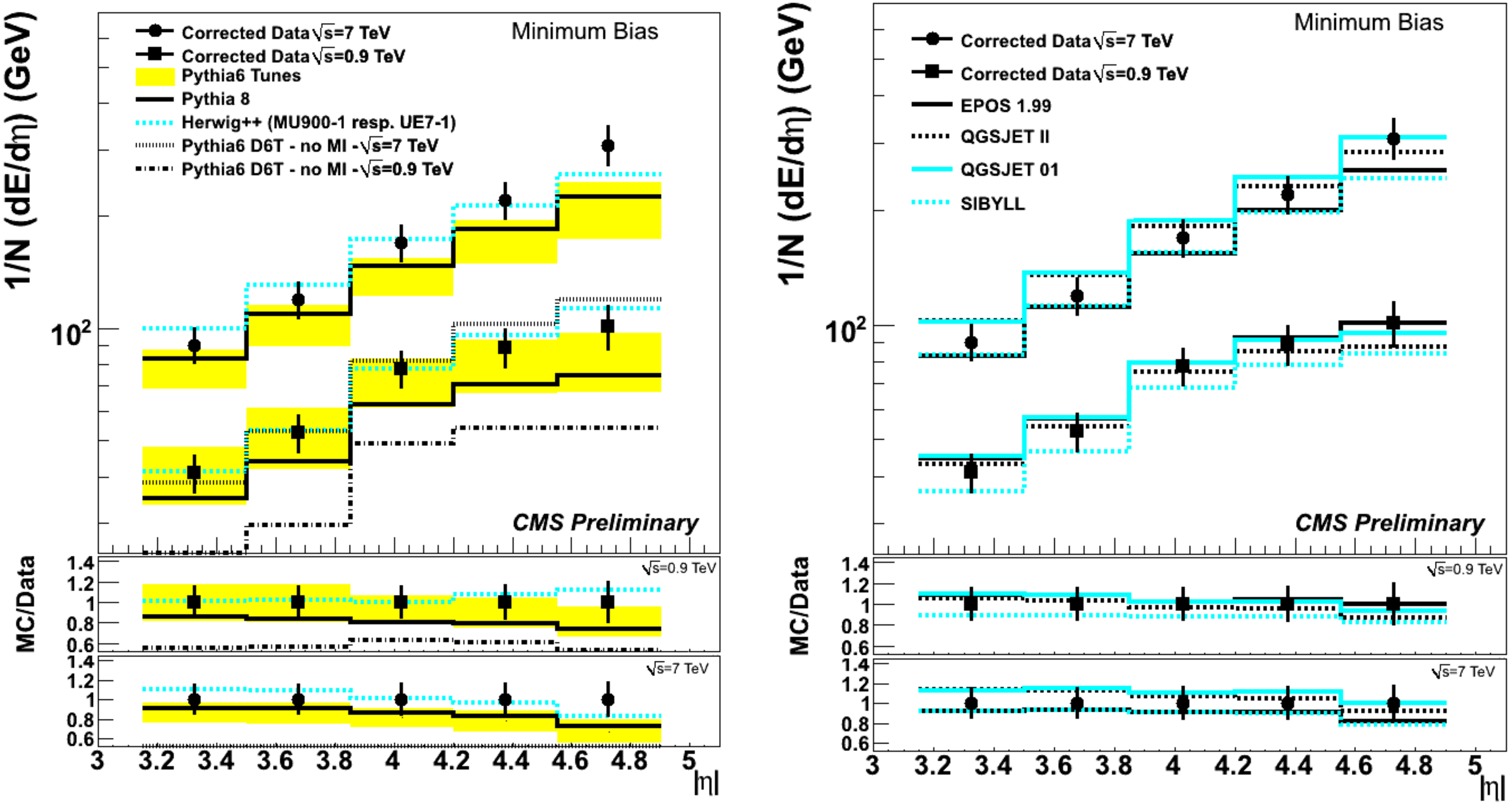
- MB trigger: beams and charged particles in $3.9 < |\eta| < 4.4$ on both sides of detector offline selection: good primary vertex, beam-induced background rejection

- Data corrected to hadron level (Pythia6): stable final state particles (υ 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

	MB sample	Dijet sample
HF energy scale	10 %	10 %
HF simulation	3-9 %	6-18 %
Model dependence	1-3 %	4-17 %
→ Total	11-14 %	13-22 %

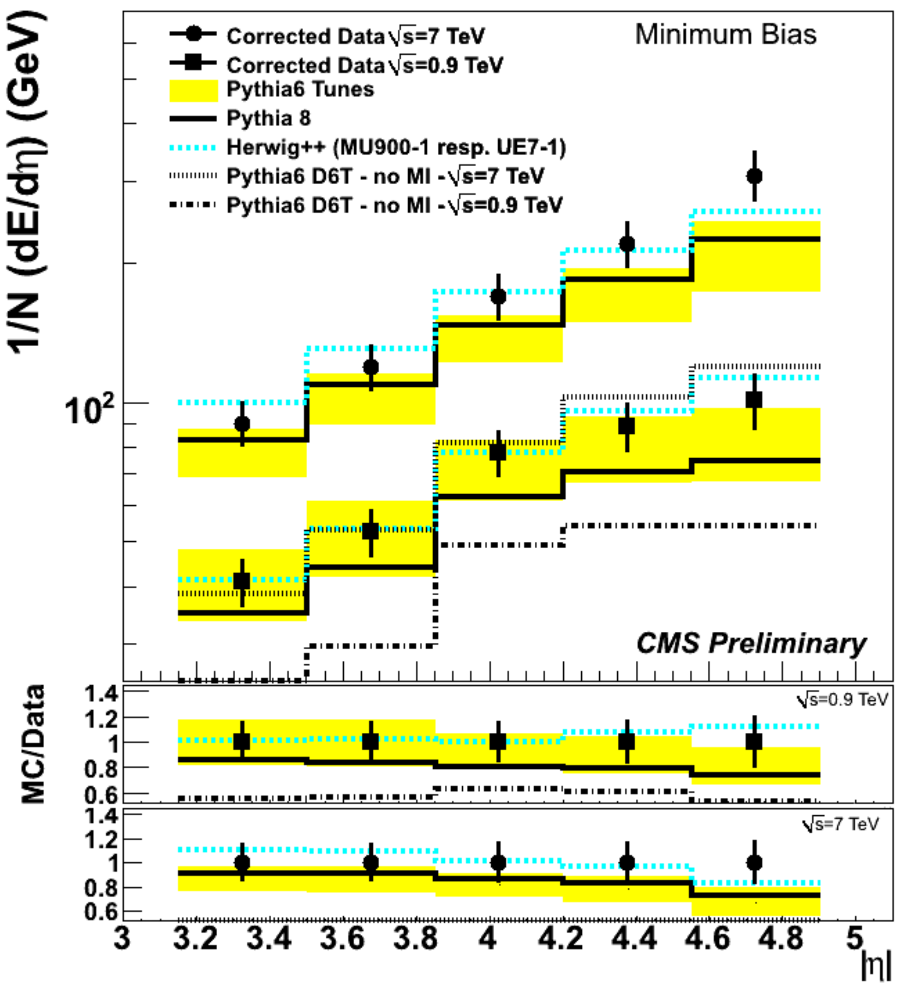
Forward Energy Flow Minimum Bias

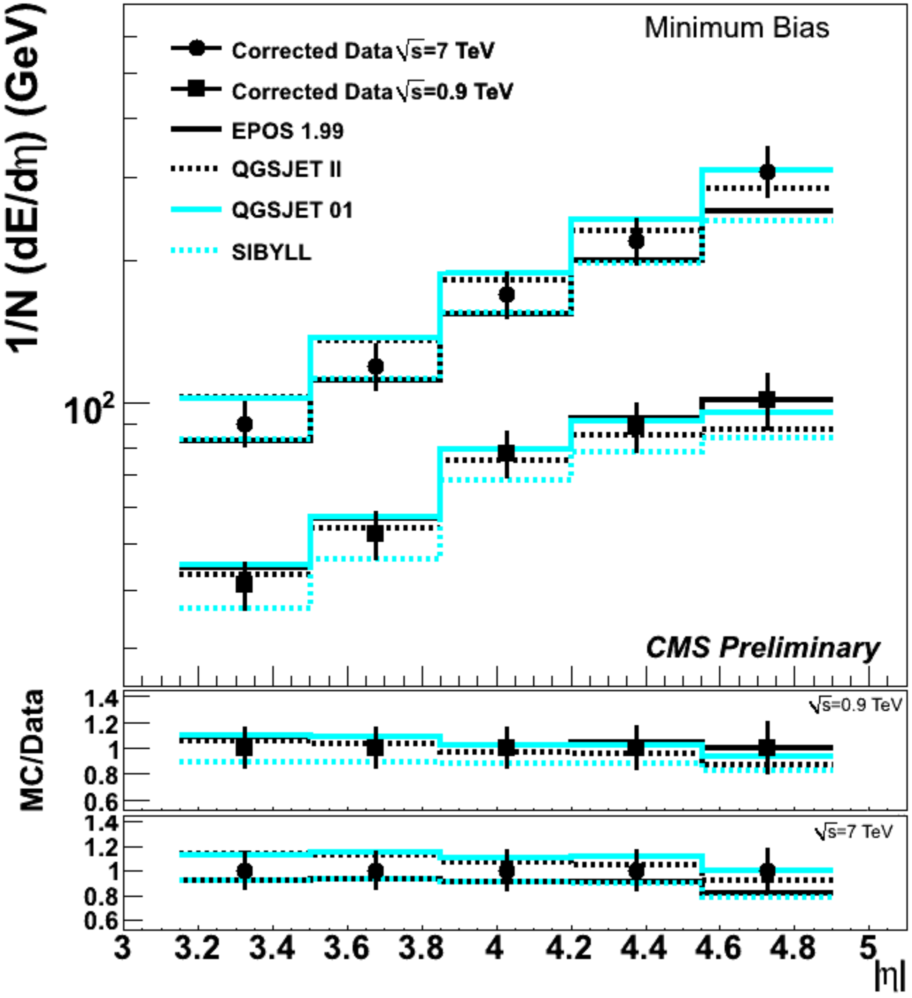


Rise of Energy Flow with η, corresponding to a flat E_t flow

Increase in E_t flow with √*s* similar to increase in charged particle multiplicity

Forward Energy Flow Minimum Bias





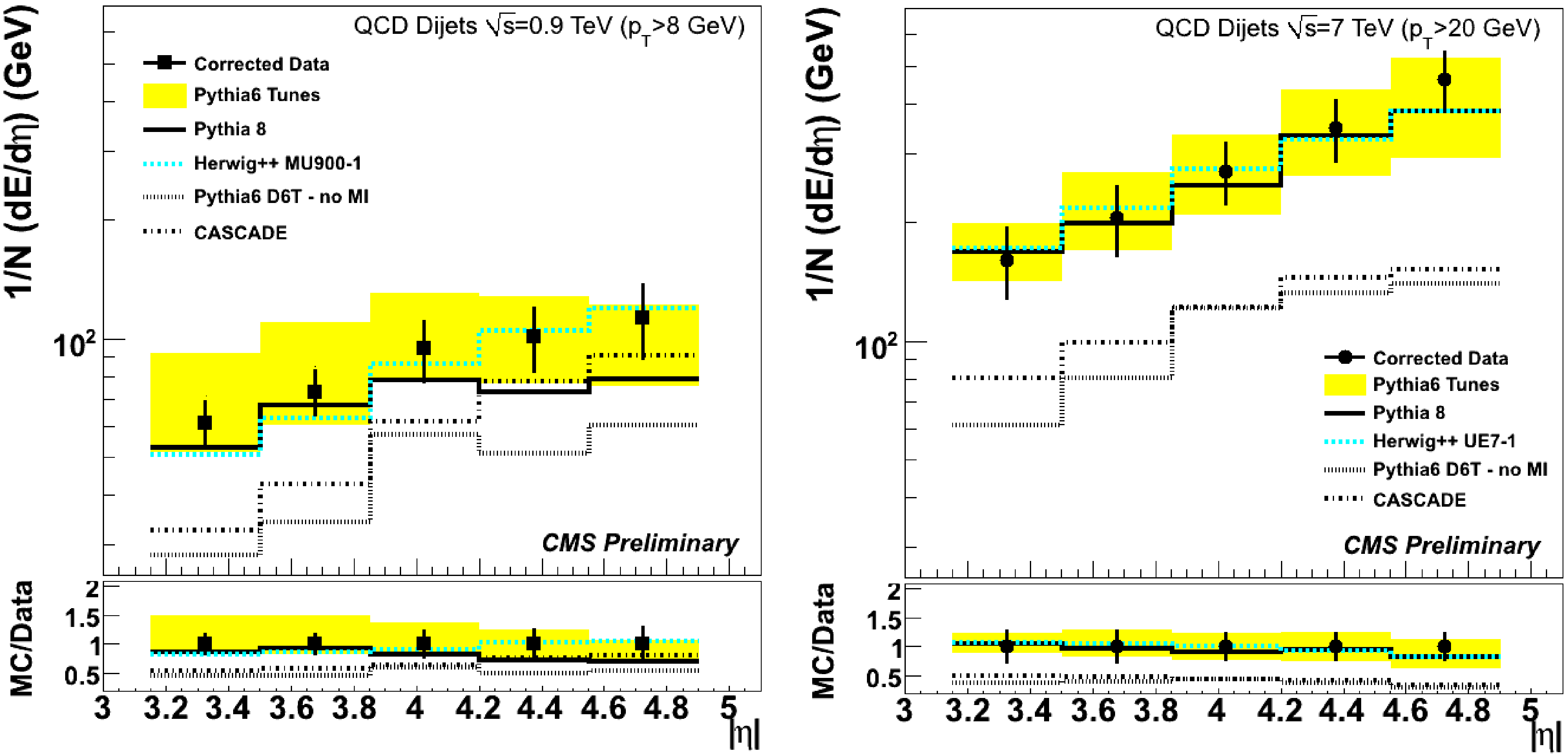
Different Pythia 6 tunes shown as band → large spread – Pythia 8 within this band

Herwig++ describes data rather well

Pythia6 w/o MPI undershoots data by 40 %

Predictions from generators used in cosmic ray physics work pretty well

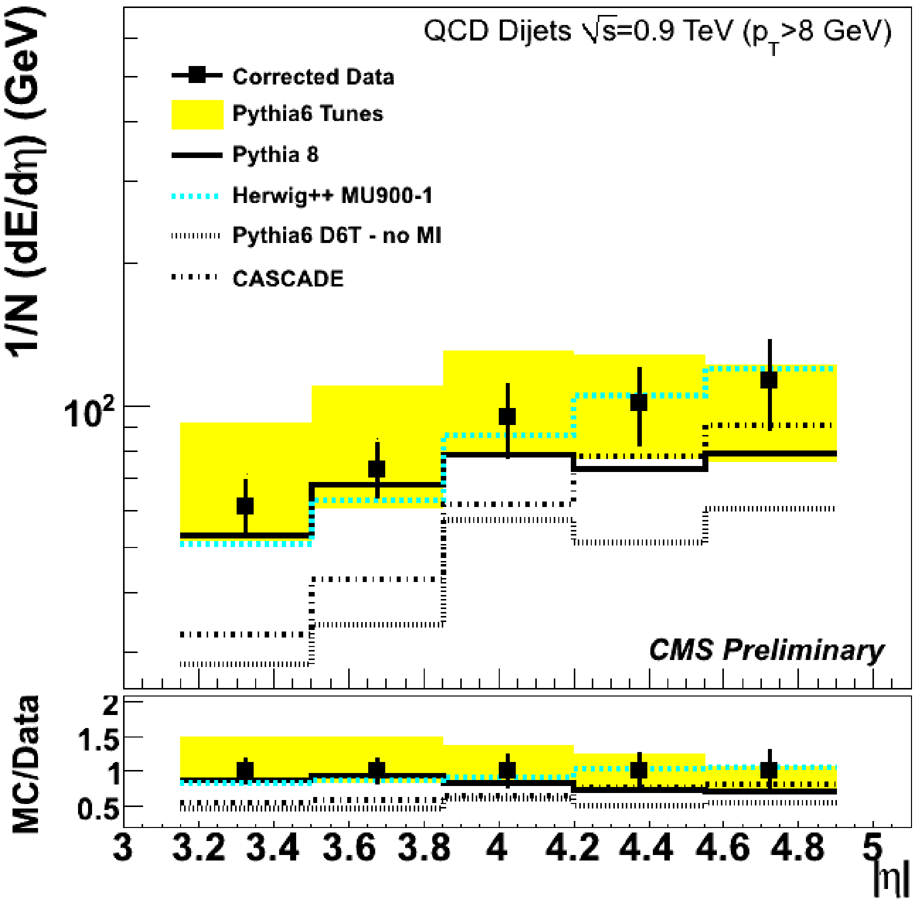
Forward Energy Flow Dijet

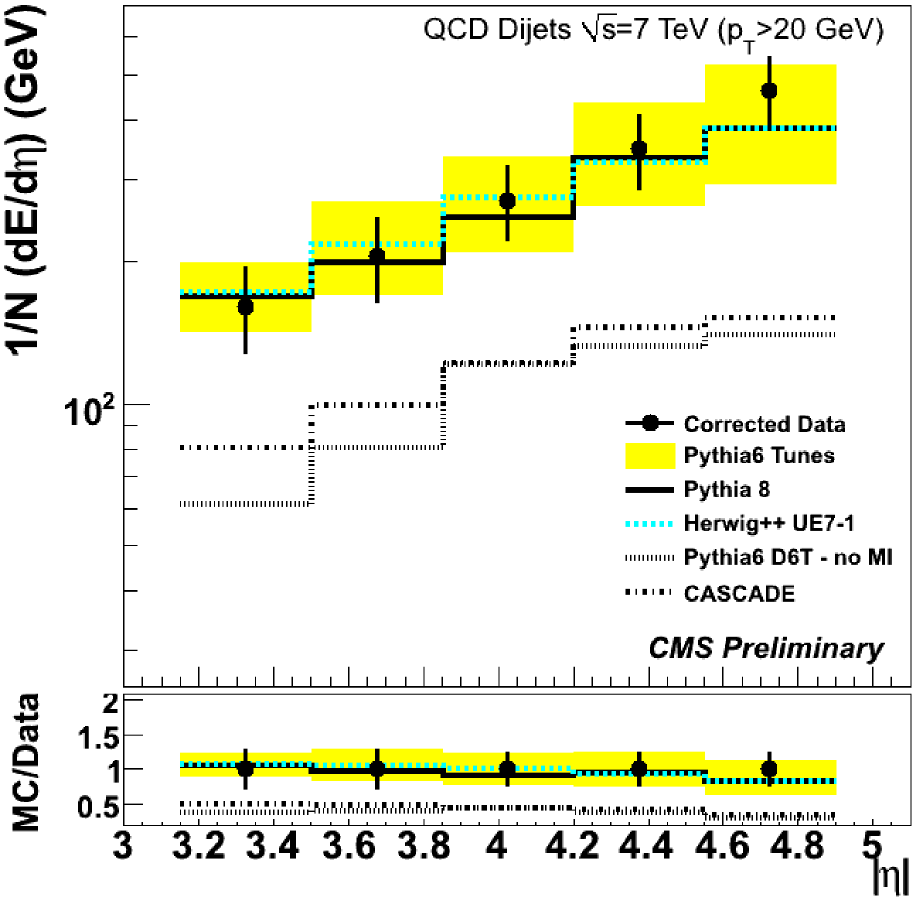


Flatter η dependence wrt Energy Flow in MB, corresponding to a decreasing E_t flow

Increase of E_t flow with $\sqrt{s}$ → E_t flow much larger than at HERA

Forward Energy Flow Dijet





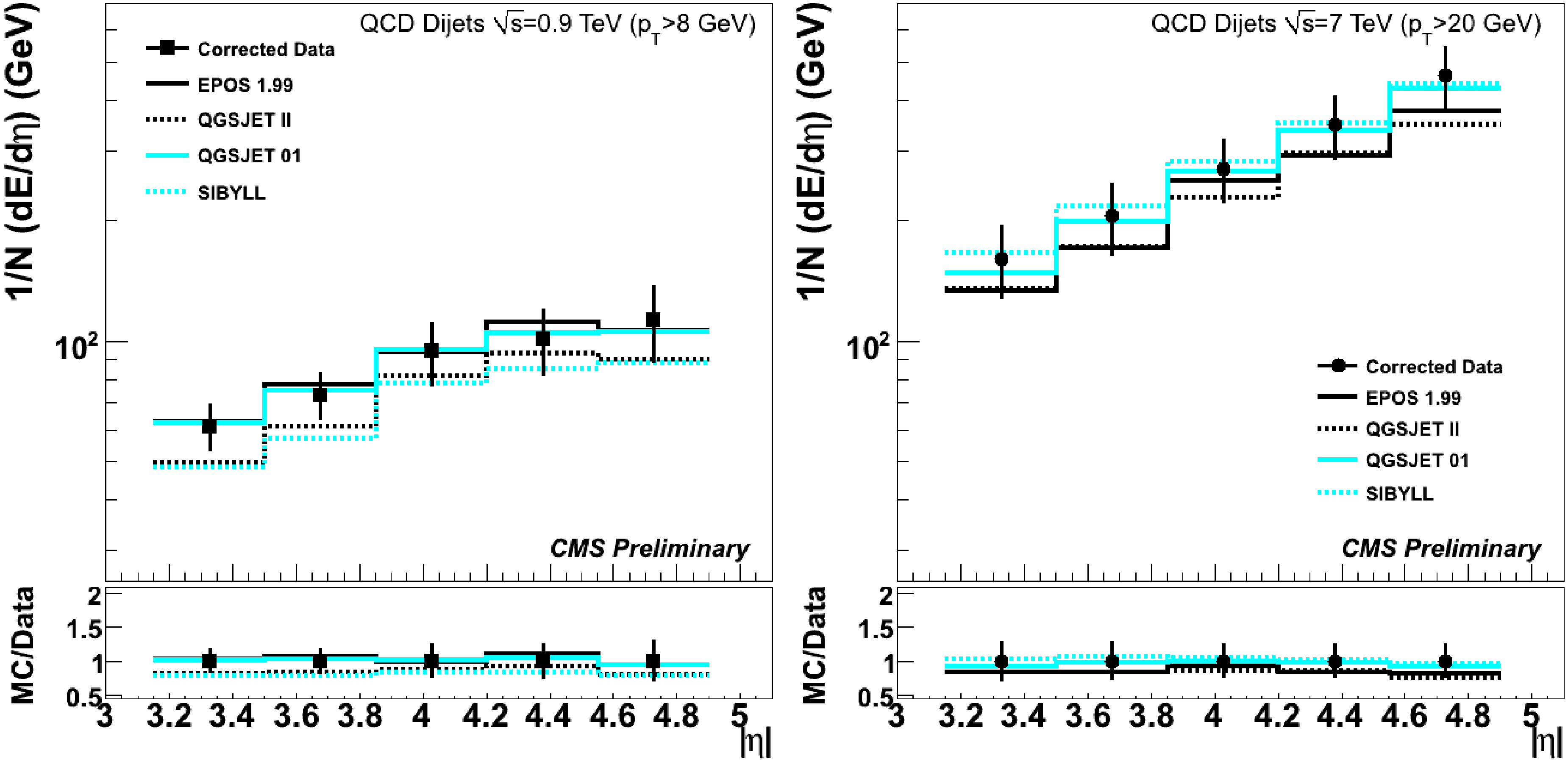
Bands from different Pythia 6 tunes cover data – Pythia 8 within this band

Herwig++ describes data rather well

Pythia6 w/o MPI undershoots data

Cascade shows a faster increase at 900 GeV – misses normalization at 7 TeV

Forward Energy Flow Dijet



Predictions from generators used in cosmic ray physics work pretty well

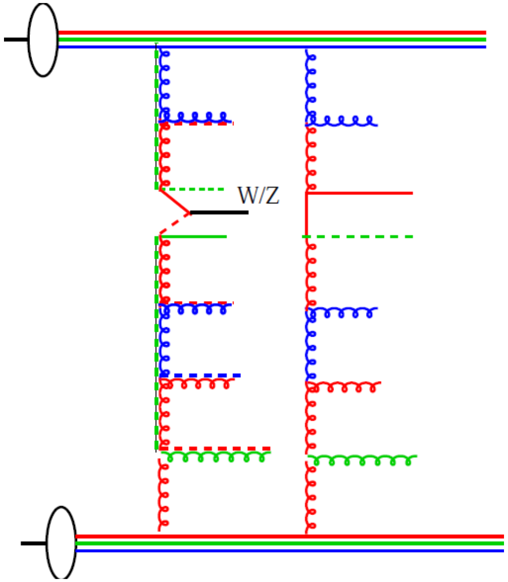
Forward Energy Flow, Central Track Multiplicities and Large Rapidity Gaps in W and Z Boson Events at 7 TeV pp Collisions

(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

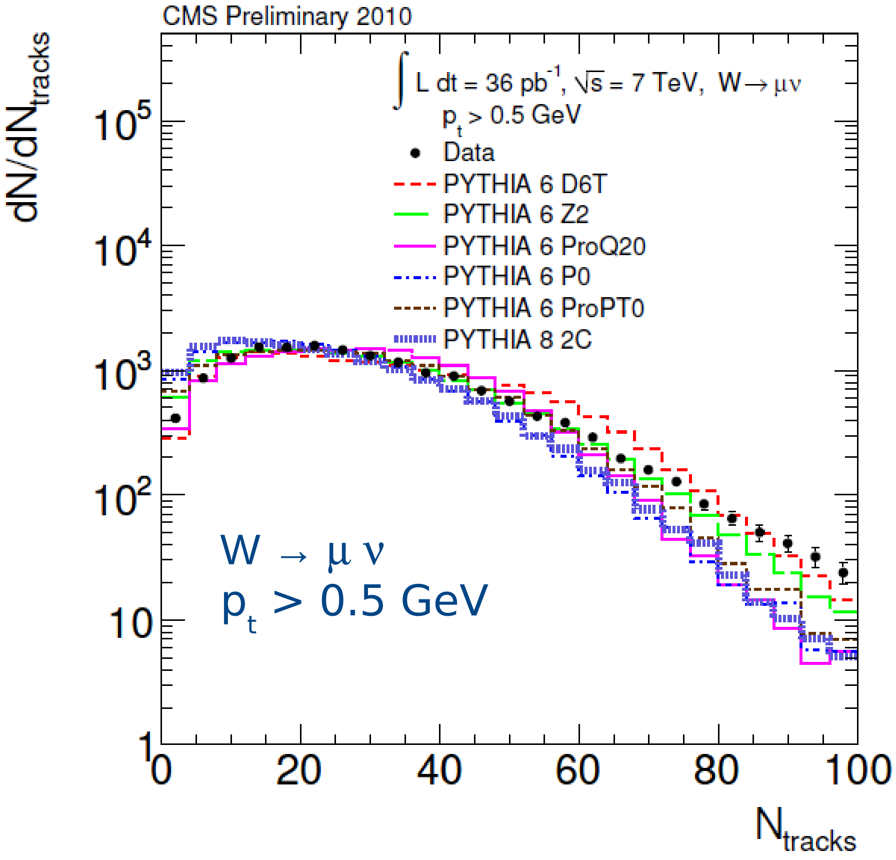


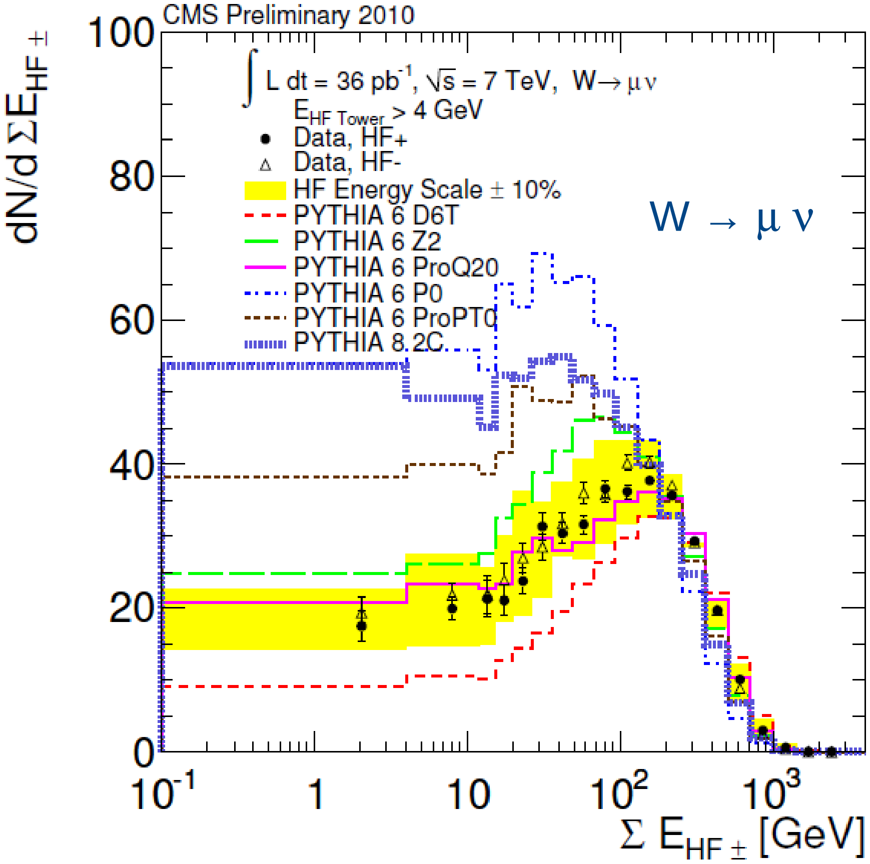
- Observables: central track multiplicity in $|\eta| < 2.5$
  2 track p_t thresholds: $p_t > 0.5$ GeV (1 GeV)
  (tracks from W(Z) decays are excluded)
  forward energy flow in $3.15 < |\eta| < 4.9$ (HF)
  correlations among these 2 observables
- W selection: one isolated e or μ, $p_t > 25$ GeV, $|\eta| < 1.4$
  missing $E_t > 30$ GeV, $M_t(l\upsilon) > 60$ GeV
- Z selection: two isolated e or μ, 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



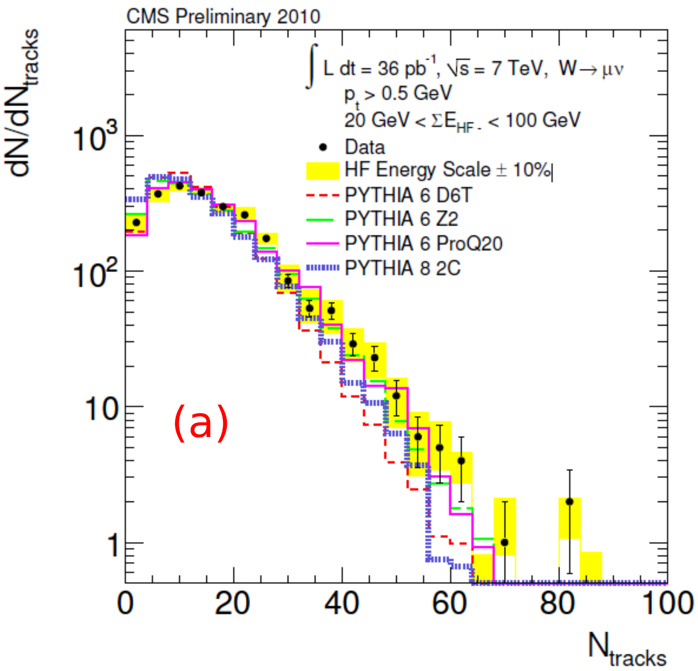


Tune Z2 provides good description of data
Tune ProQ20 significantly underestimates the high multiplicity tail

Tune Z2 predicts too small average energy
Tune ProQ20 gives very good description

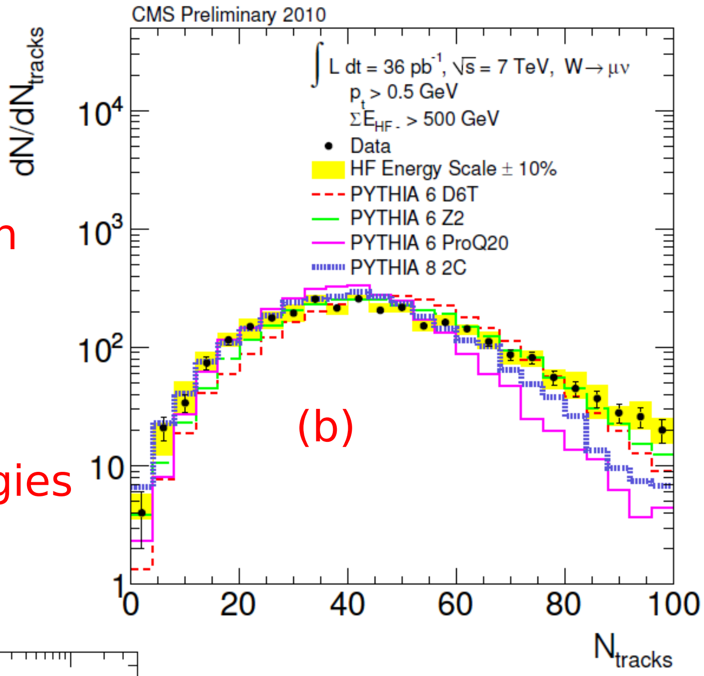
→ none of the tunes provides simultaneously a satisfactory description

Correlations Track Multiplicity & Energy Flow

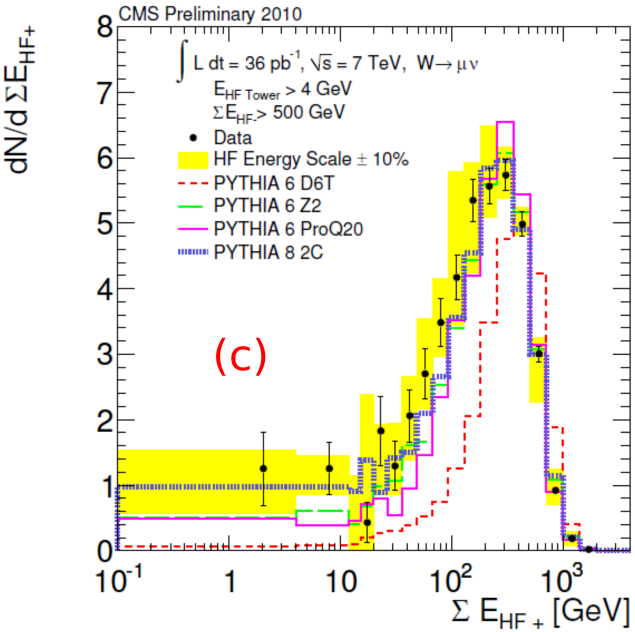


→ strong correlation
in data and simulation

but none of the tunes
provides satisfactory
description at all energies



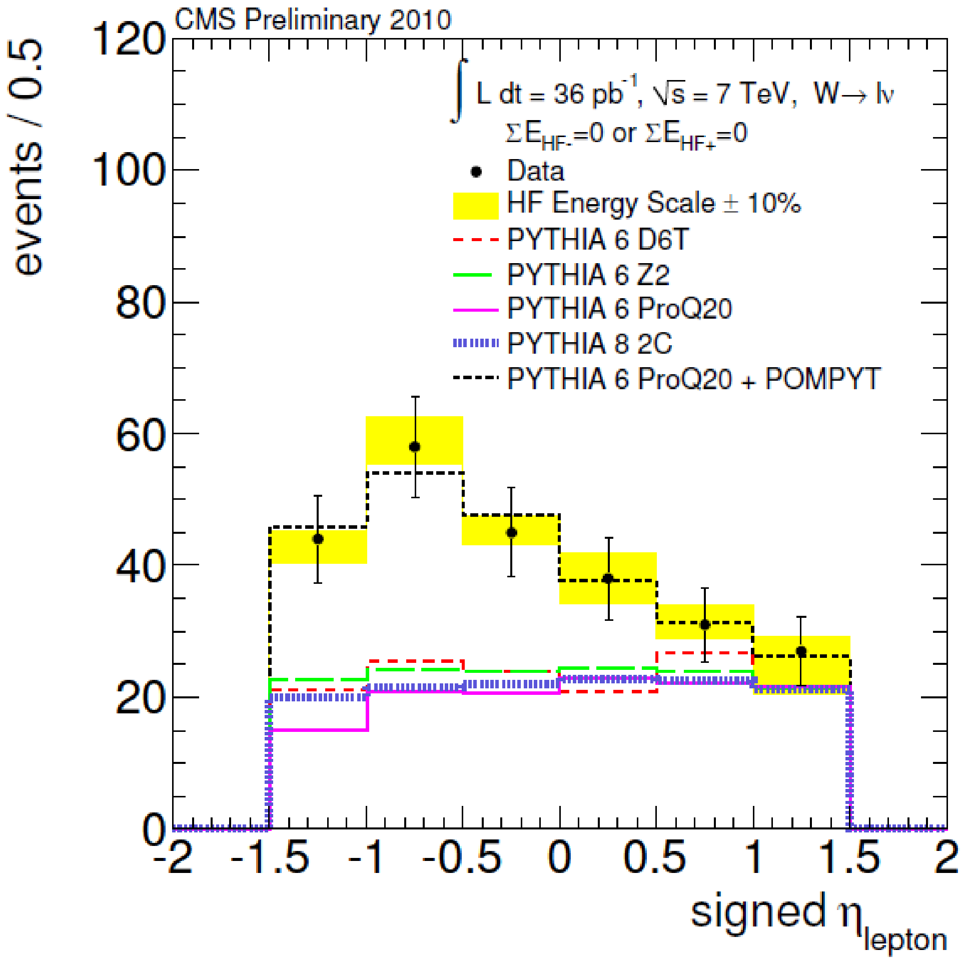
- $W \to \mu\,\nu$ distributions
  for different energies in HF-
- central track multiplicity
  20 < E HF - < 100 GeV (a)
  200 < E HF - < 400 GeV (b)
- Energy in HF +
  E HF - > 500 GeV (c)



→ energy in HF + & HF -
strongly correlated

(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 η:
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 ± 9.3 (stat) ± 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 pb^{-1}, anti-k_t jet algorithm (R = 0.5)

  3.2 < $|\eta|$ < 4.7 – 35 < p_t < 150 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 pb^{-1}, anti-k_t jet algorithm (R = 0.5)

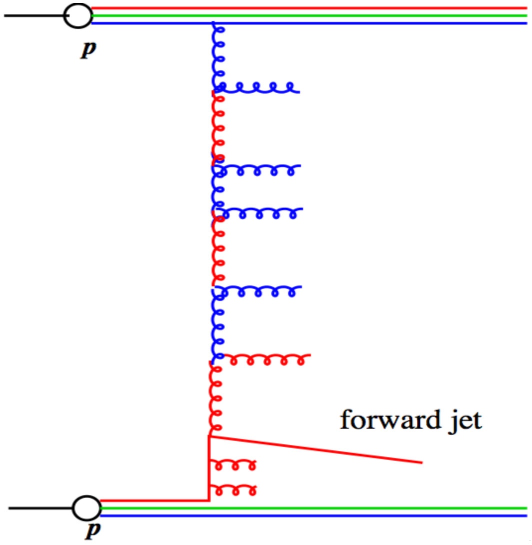
  central region $|\eta|$ < 2.8 – forward region 3.2 < $|\eta|$ < 4.7
  at least one jet in central and forward region
  p_t > 35 GeV

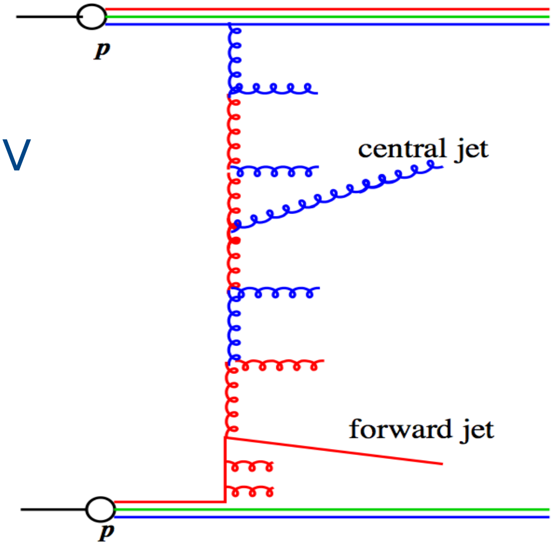
- Measurement of inclusive jet and dijet cross sections at 7 TeV using the ATLAS detector (ATLAS-CONF-2011-047)

  L = 37 pb^{-1}, anti-k_t jet algorithm (R = 0.4 and R = 0.6)

  2.8 < $|y|$ < 4.4 for forward jets
  20 < p_t < 300 GeV for forward jets

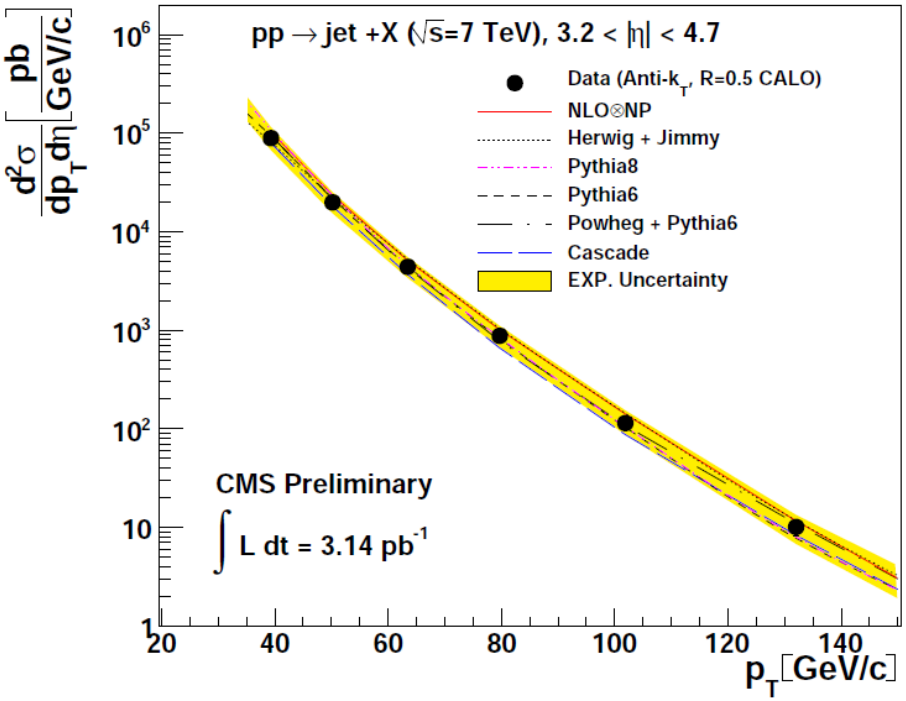
- All measurements corrected to hadron level

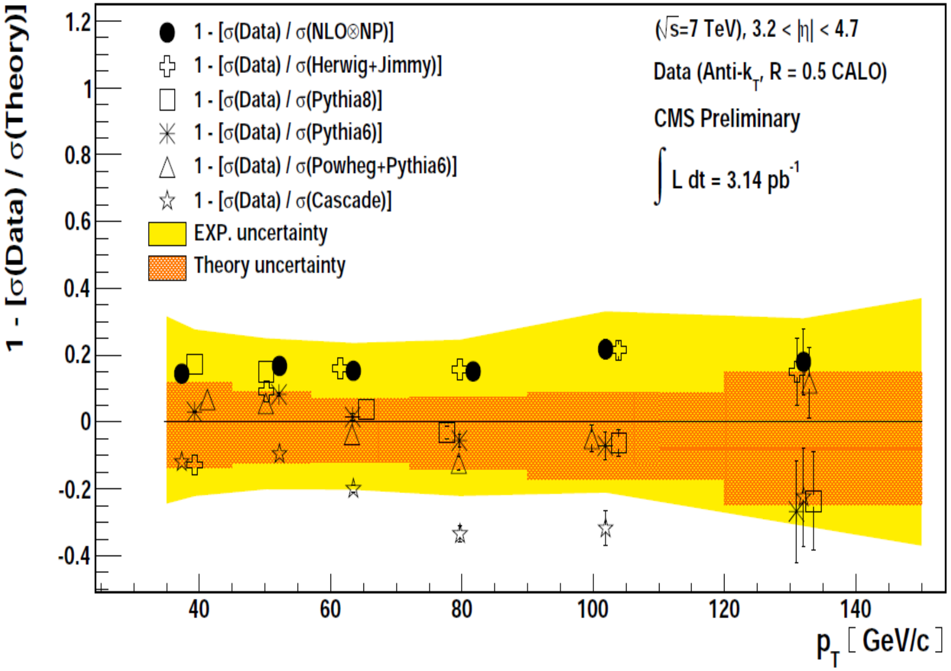




Inclusive forward jets

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

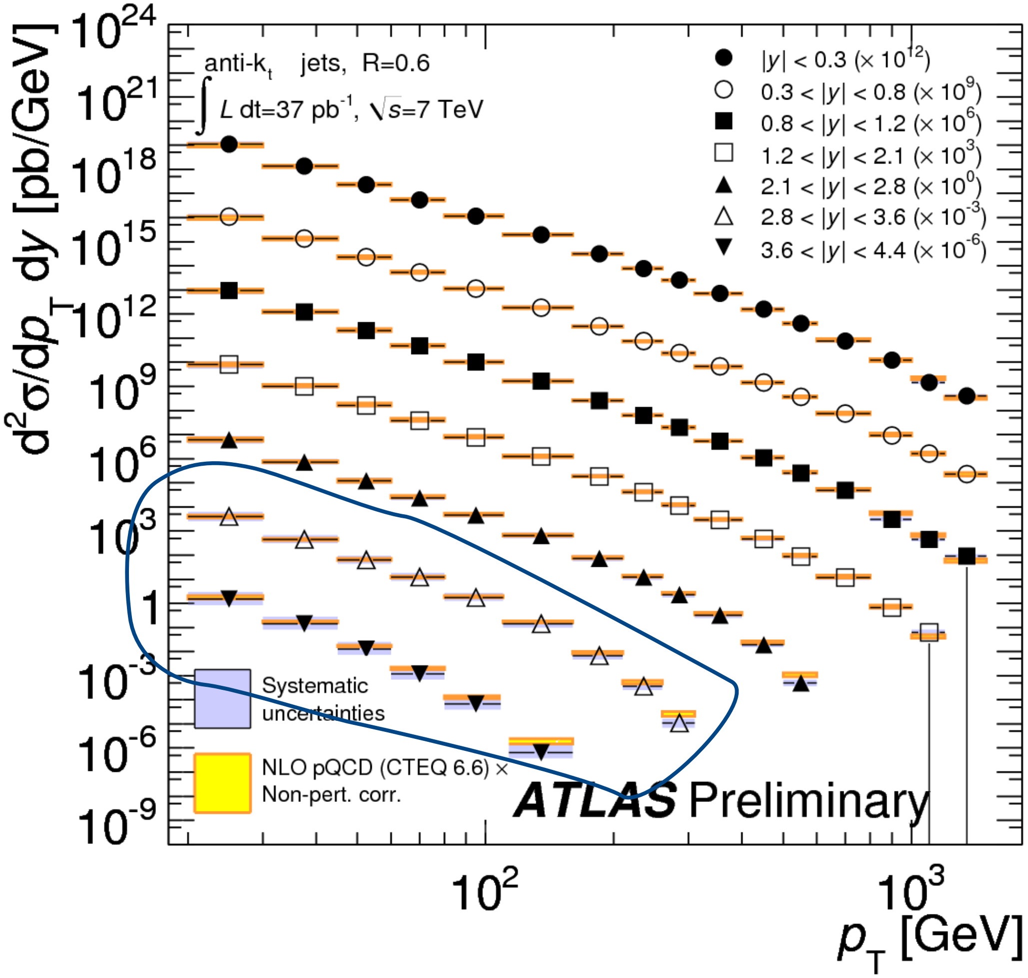
LO + PS: Pythia 6, Pythia 8, Herwig

NLO + PS: Powheg + Pythia 6

Fixed order NLO * Non Perturb. correction

CCFM: CASCADE (different slope)

Inclusive forward jets



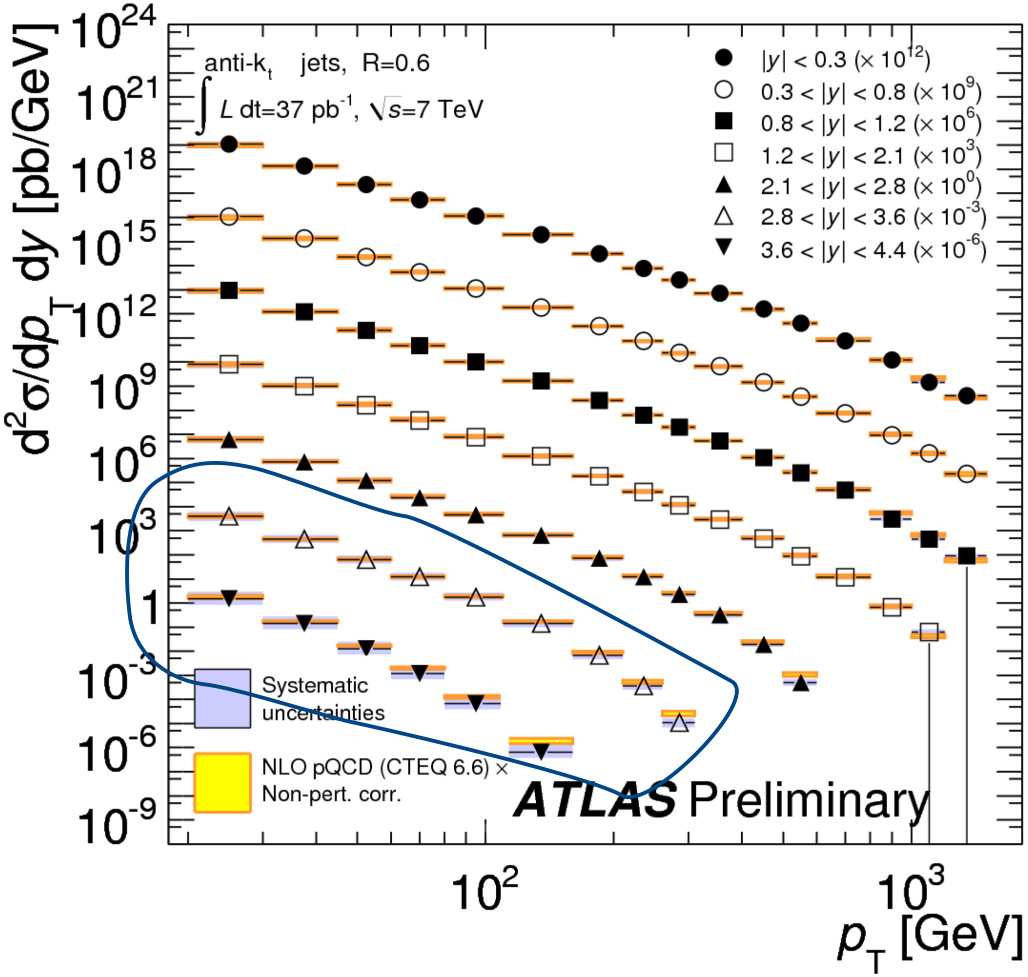
Main Systematic uncertainties:

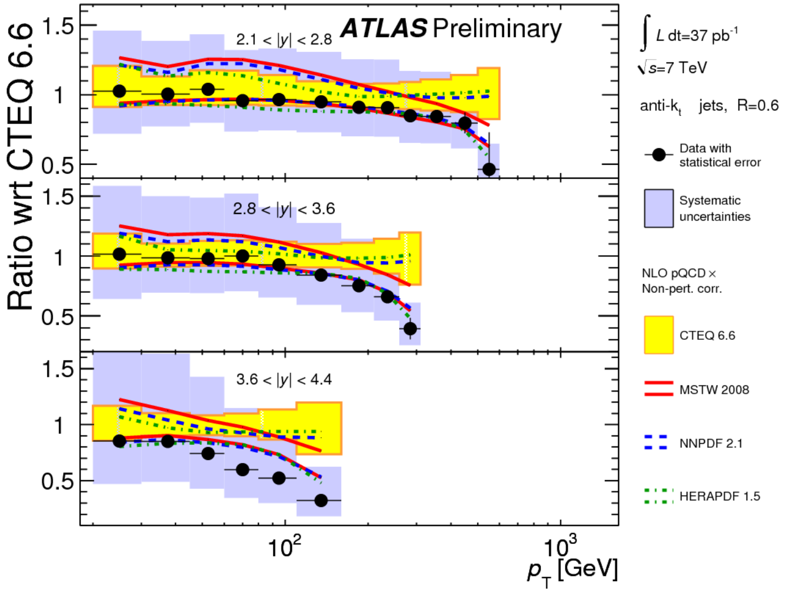
- Jet Energy Scale uncertainty
- Model dependence correction factor

At p_t = 20 GeV, $3.6 < |y| < 4.4$:

- JES uncertainty +80% -50%
- Correction factor 20%

Inclusive forward jets



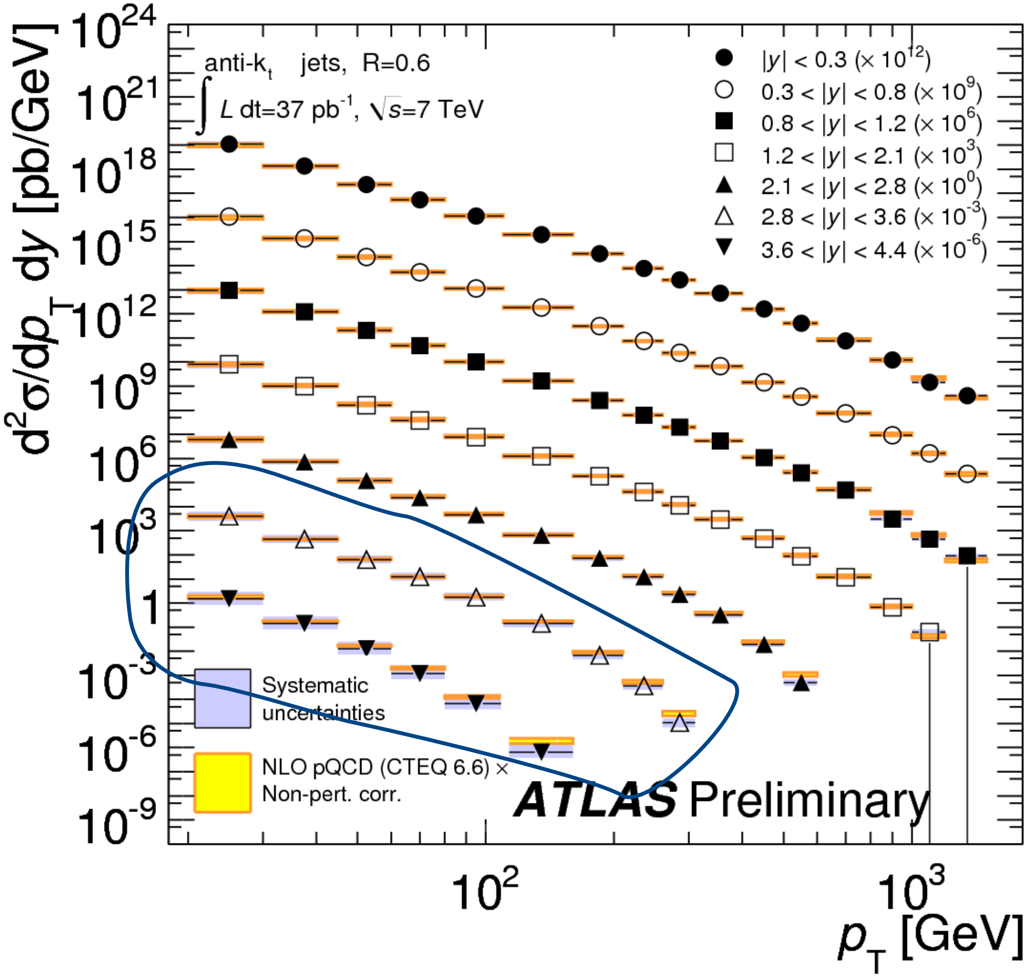


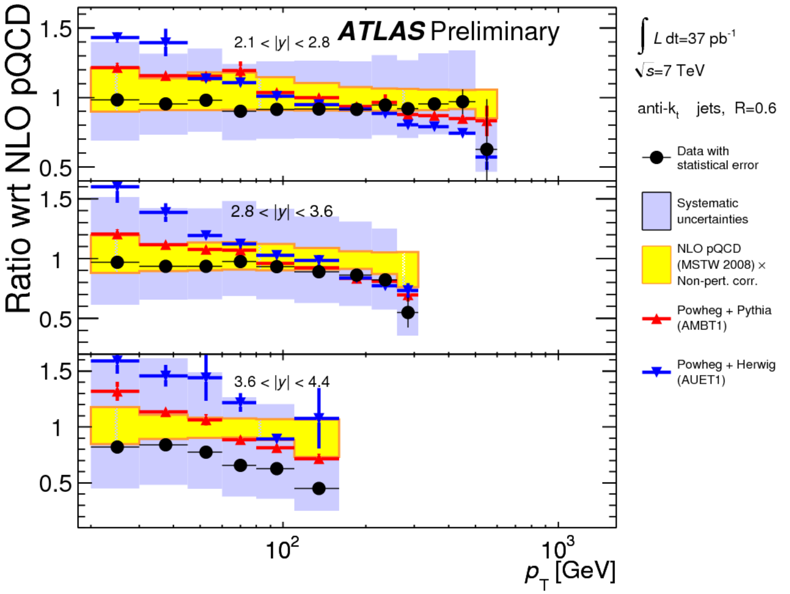
Data compared to NLO predictions using different pdf sets

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





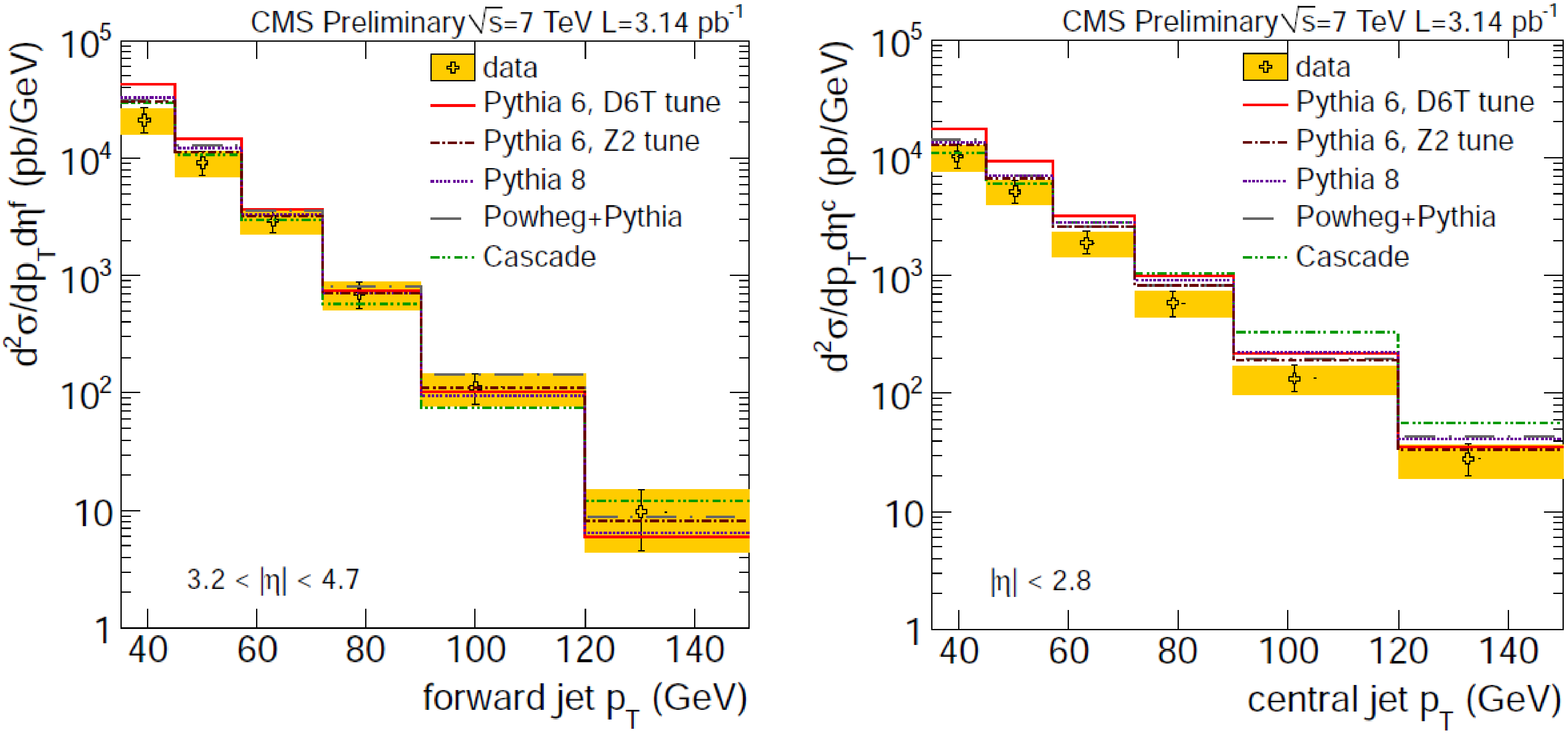
Data compared to Powheg NLO predictions interfaced to Pythia 6 and Herwig (PS & hadronization)

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

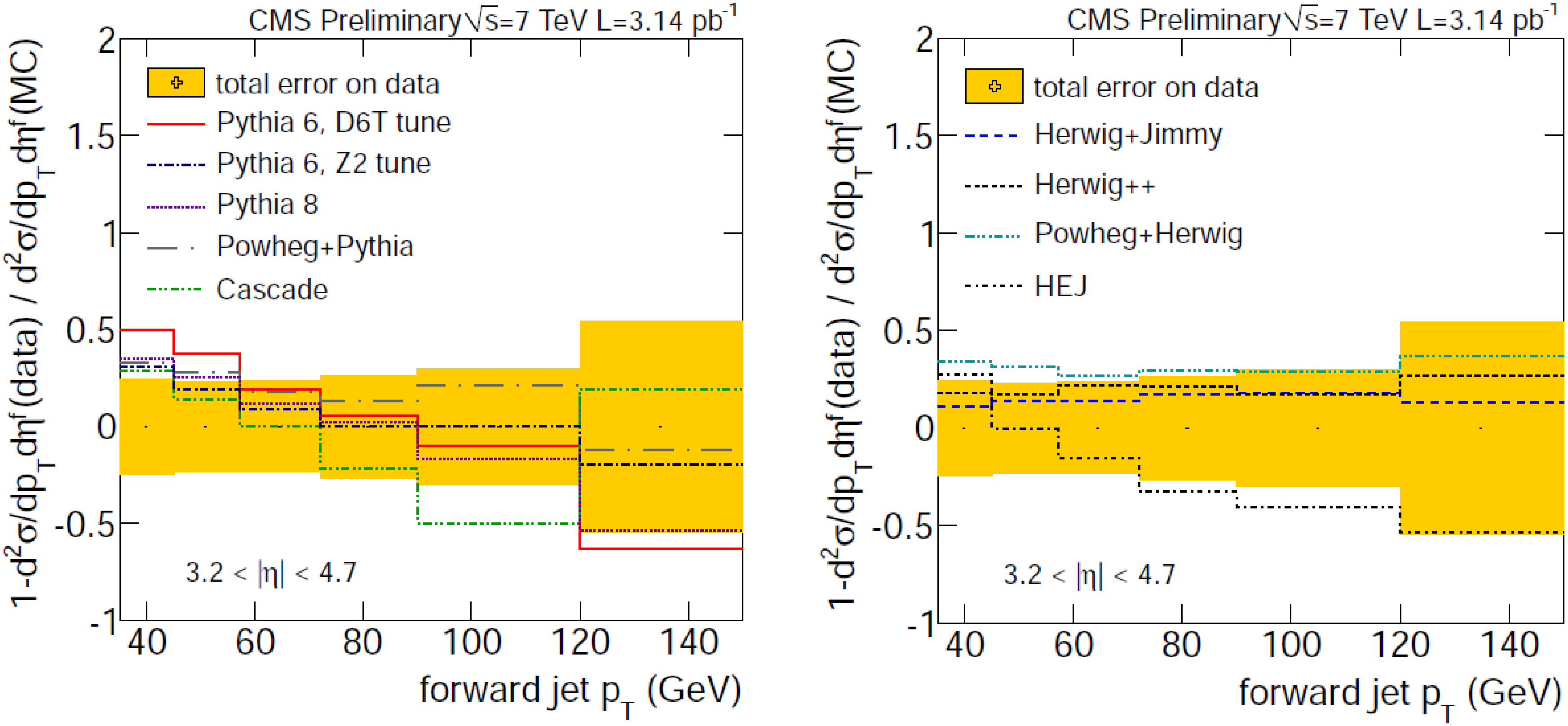


Systematic uncertainties are similar to the inclusive forward jet case

Total systematic uncertainty ~ 30% dominated by JES uncertainty ~ 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

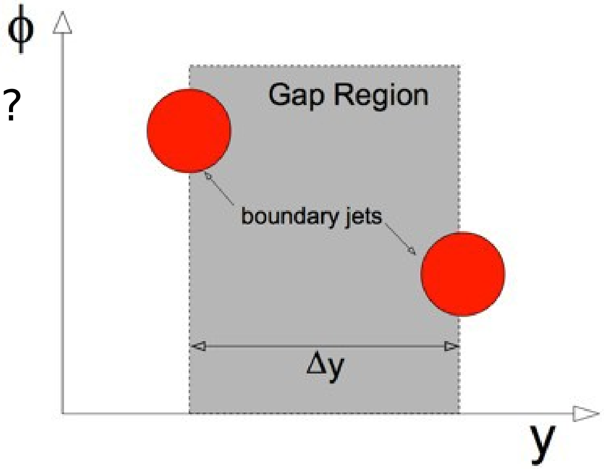
ATLAS-CONF-2011-038

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 Δy bounded by the dijet?

→ measurement of the gap fraction:
fraction of events with no additional jet
with $p_t > Q_0$ in Δy bounded by the dijet system

→ Q_0 = veto scale

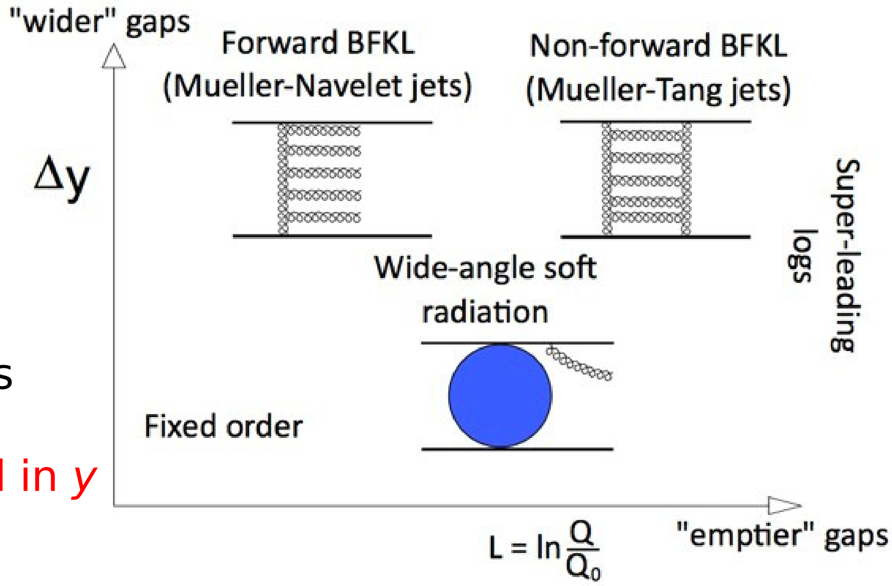


- Probe different QCD radiation phenomena by playing with Δy and dijet average p_t

- $Q_0 <<$ dijet average p_t :
wide-angle soft gluon radiation
→ define dijet system: 2 p_t leading jets

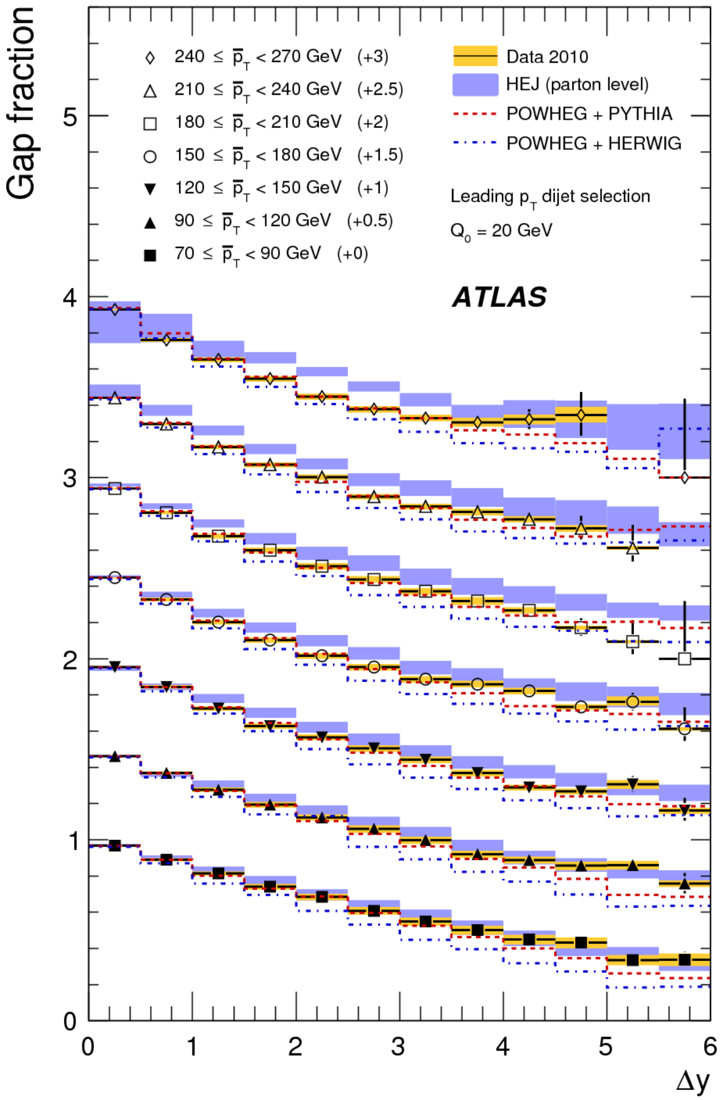
- $\Delta y >>$: open phase space for BFKL dynamics
Mueller-Navelet Dijet
→ define dijet system: 2 jets most separated in y

- $Q_0 <<$ dijet average p_t and $\Delta y >>$:
Color Singlet BFKL ladder: Mueller-Tang Dijet



Gap fraction

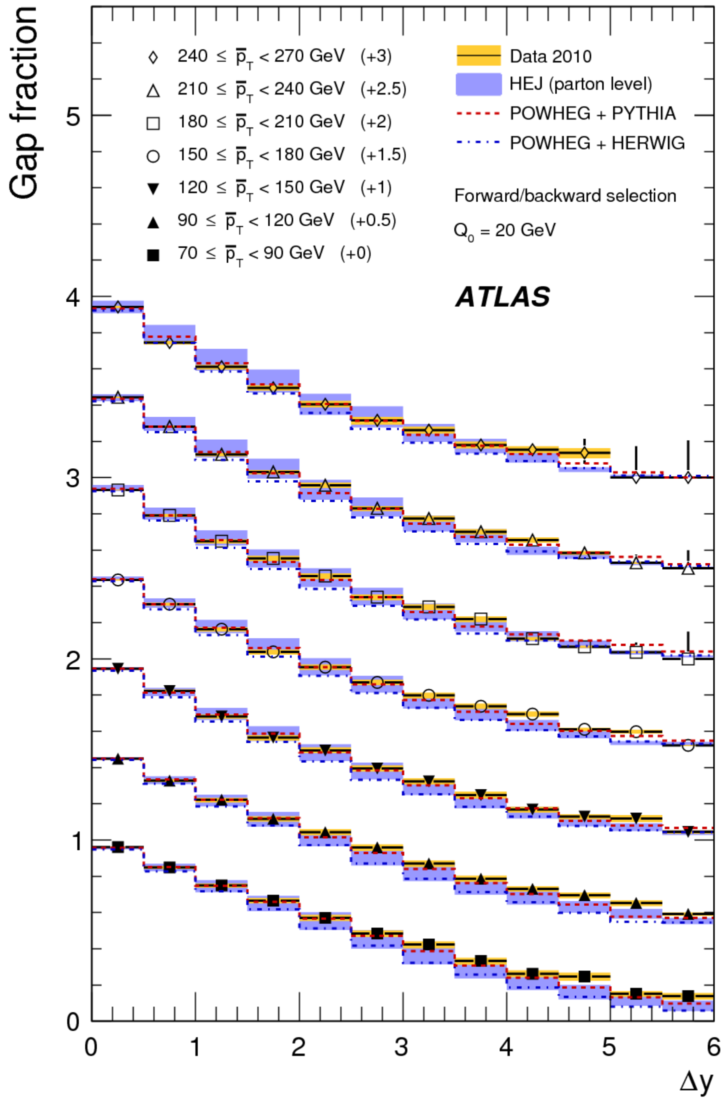
Gap fraction as a function of Δy for various dijet average p_t slices



- 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
  → HEJ suited to describe emissions of similar p_t
  → fails when dijet average $p_t >> Q_0$
- Powheg + Pythia: best description when all phase space considered
- At larger Δy, Powheg + Pythia deviates from data
  → full QCD calculation becomes more needed as Δy increases
  → NLO + PS approximation becomes unsufficient

Gap fraction

Gap fraction as a function of Δy 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
  → resummation of soft emissions important

- Powheg, HEJ: gap fraction too small at large Δy

Measurement of inclusive to exclusive dijet production ratio at large rapidity intervals at 7 TeV

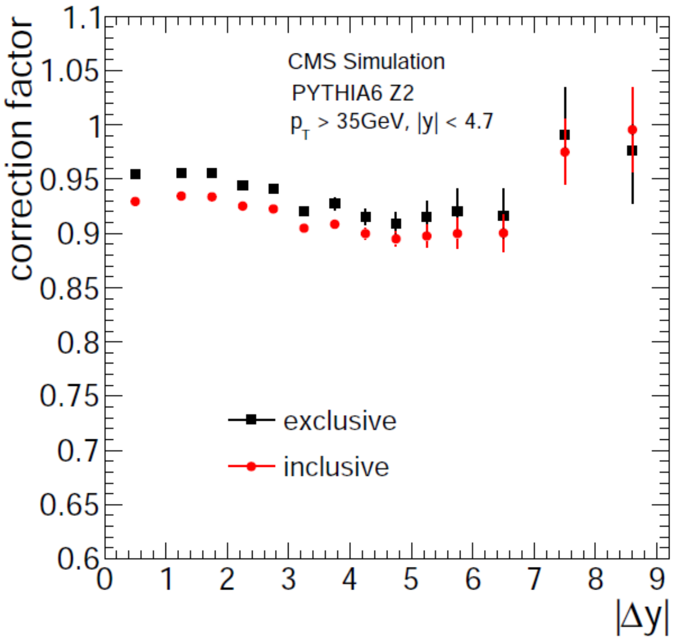
CMS PAS FWD-10-014

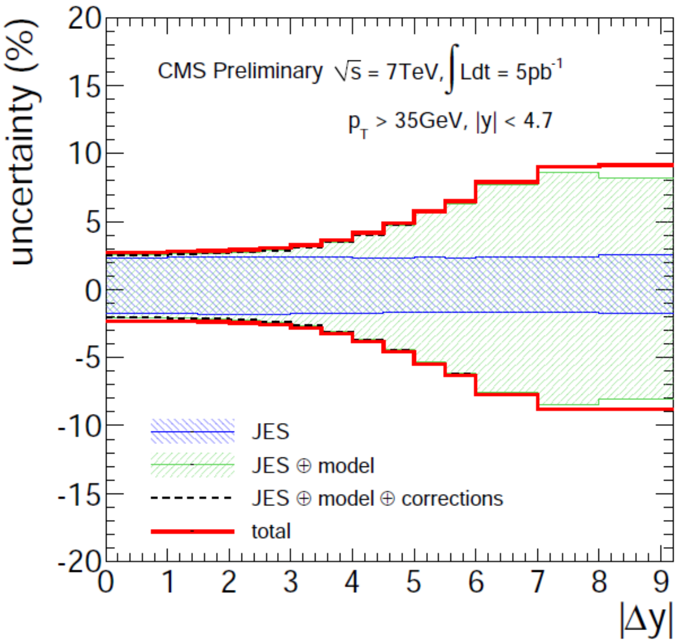
Inclusive to exclusive Dijet production

- 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

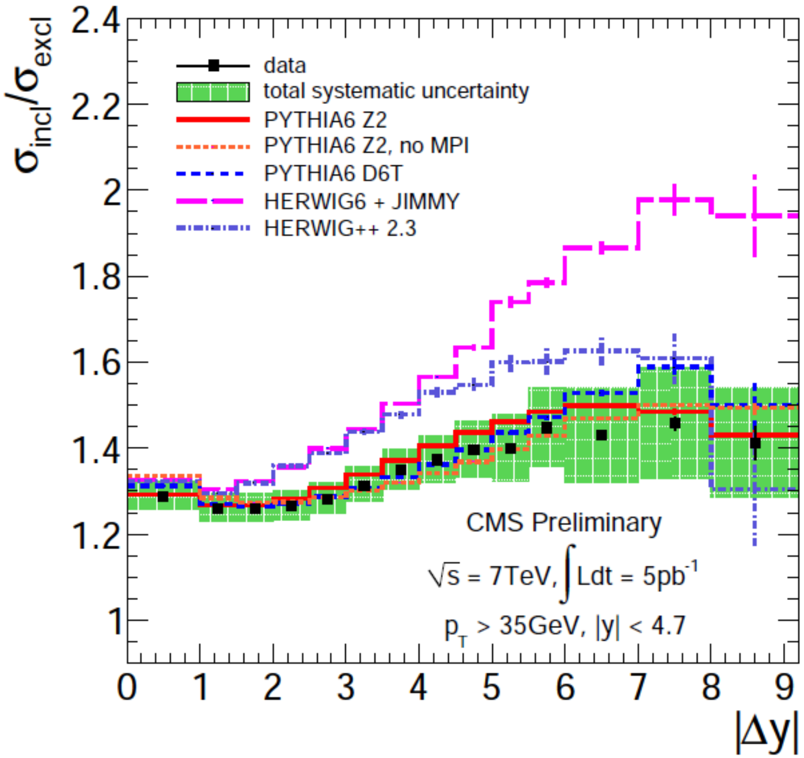
- Ratio corrected for detector effects (Pythia 6 Z2)

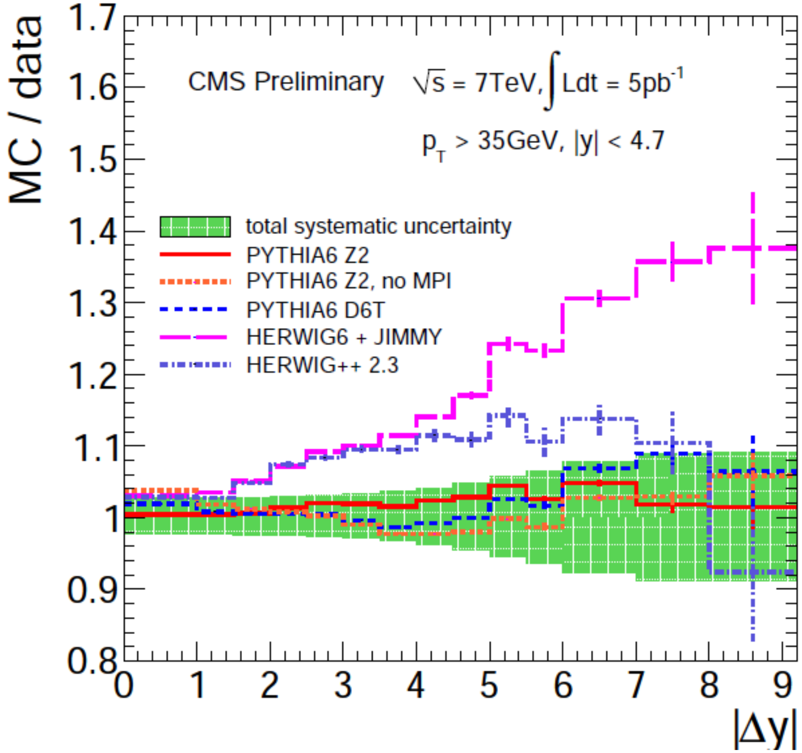
- Main systematic uncertainty: model dependence of correction factor: 1-8%
  - from difference between Herwig 6 + Jimmy and Pythia 6 Z2
  - increases with Δy





Inclusive to exclusive Dijet production





- Ratio increases with |Δ*y*| (phase space for additional hard radiation increases)
- Ratio decreases at highest |Δ*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 |Δ*y*|
- Herwig 6 + Jimmy: above data for |Δ*y*| > 2

Observation of diffraction at 7 TeV

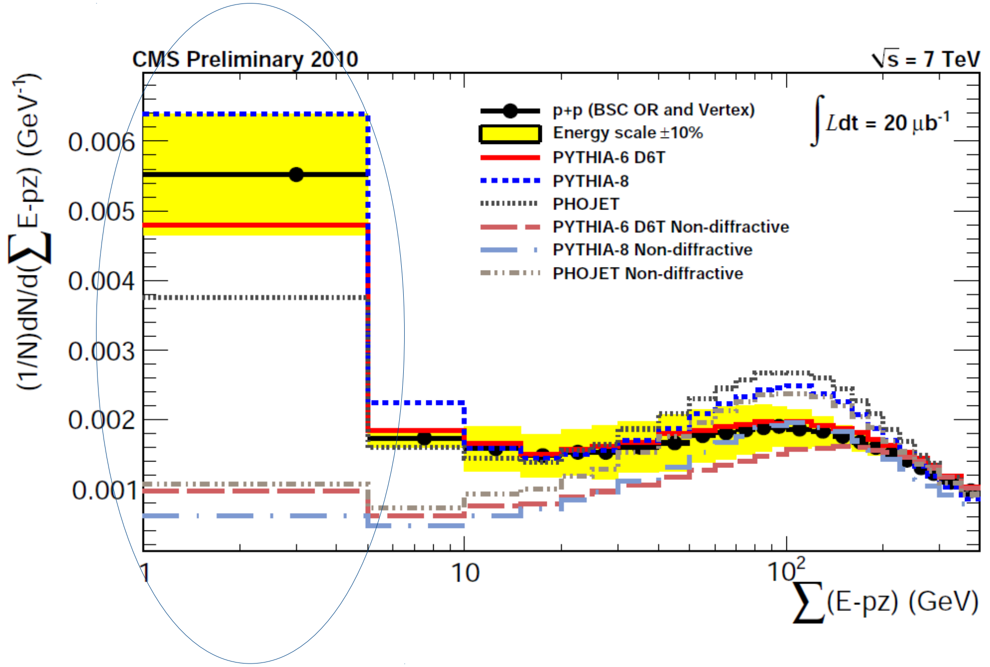
CMS PAS FWD-10-007

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 ξ distribution



Events below 5 GeV are mainly diffractive

- Σ (E ± Pz) related to the momentum loss of the scattered proton (runs over all calorimeter energy deposits)
- proton fractional momentum loss: $\xi \approx \Sigma\ (E \pm Pz)\ /\ \sqrt{s}$
- 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 ±10% energy scale variation
- Pythia 6 D6T describes better the non-diffractive part of the spectrum

Rapidity Gap Cross Sections at 7 TeV

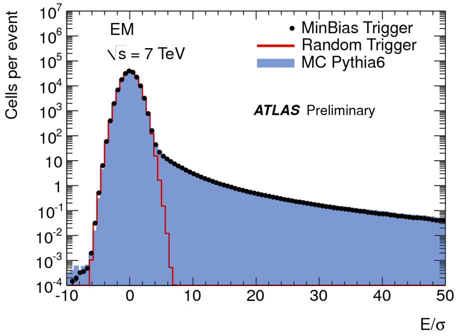
ATLAS-CONF-2011-059

Gap Finding Algorithm

- Detector divided into rings in η

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

threshold on energy significance derived separately for each ring by requiring that probability of finding at least one noisy cell in a ring is constant



- Two different rapidity gap definitions in the analysis:
    - Floating gap: largest consecutive run of empty rings, parametrized by its size Δη and nearer edge to the acceptance limit ηstart

      → data and Monte Carlo divided into a 2-dim array (|ηstart|, Δη)

      → optimize fraction of diffractive dissociation in Monte Carlo

    - Forward gap: largest consecutive run of empty rings, starting at the edge of the acceptance (|η| = 4.9) and of size $\Delta\eta^F$

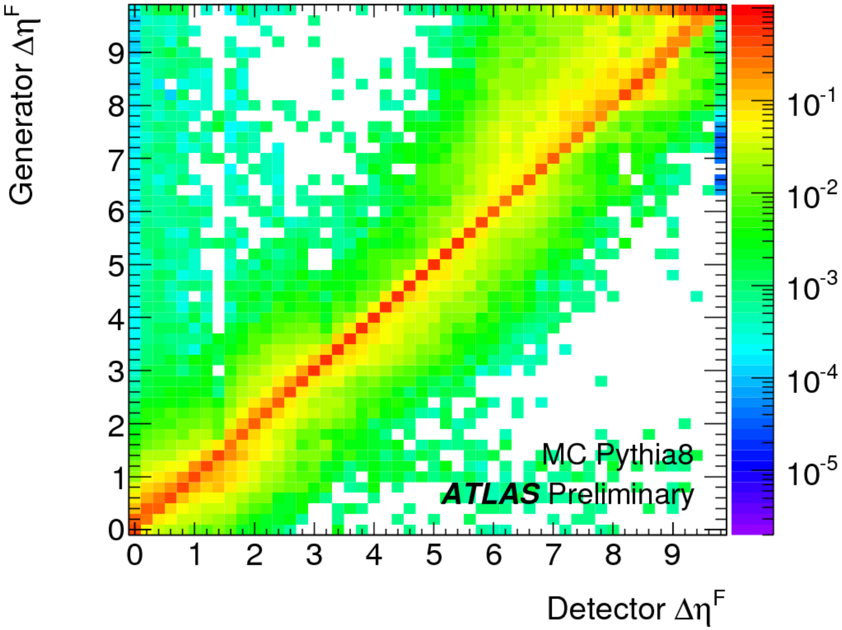
      → rapidity gap cross section $\frac{\mathrm{d}\sigma(\Delta\eta^F)}{\mathrm{d}\Delta\eta^F}$

Rapidity Gap Cross Section

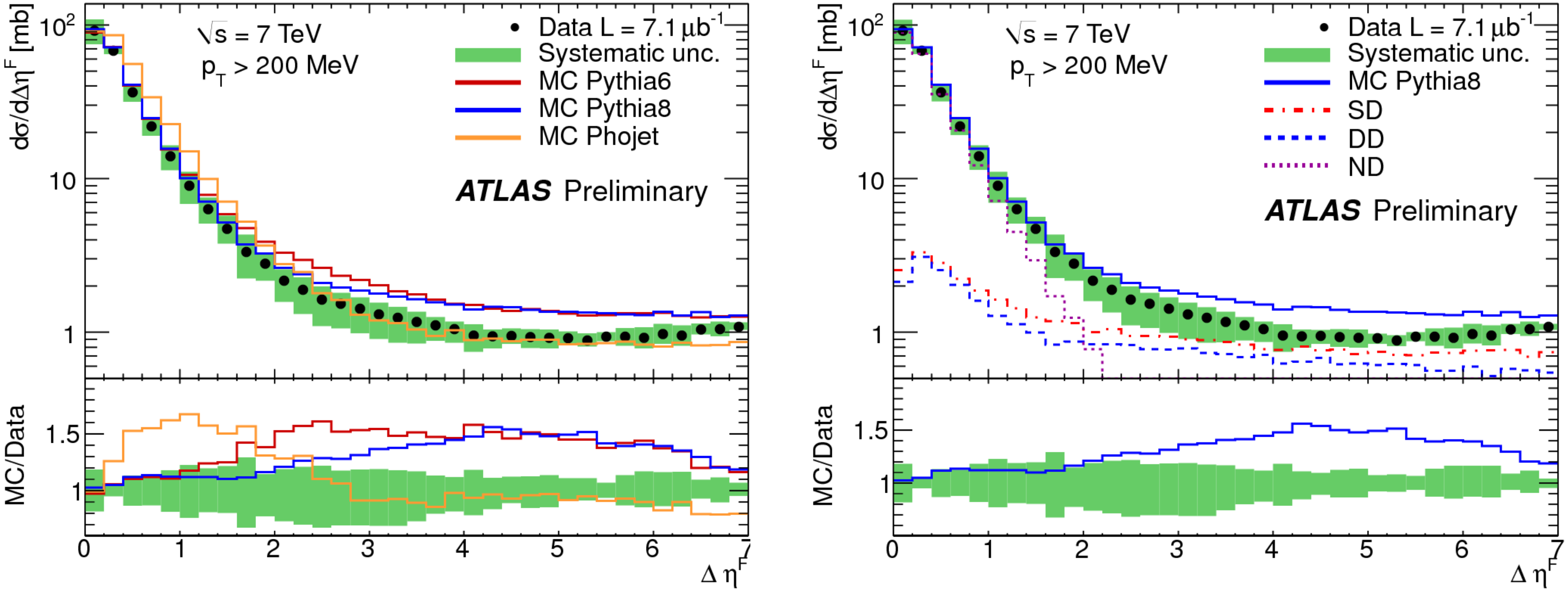
- Cross Section corrected to hadron level:

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

  - $\varepsilon(\Delta\eta F)$ = product of trigger and offline selection efficiency
  - $A(\Delta\eta F)$ = correction factor for bin migration (from detector to hadron level)

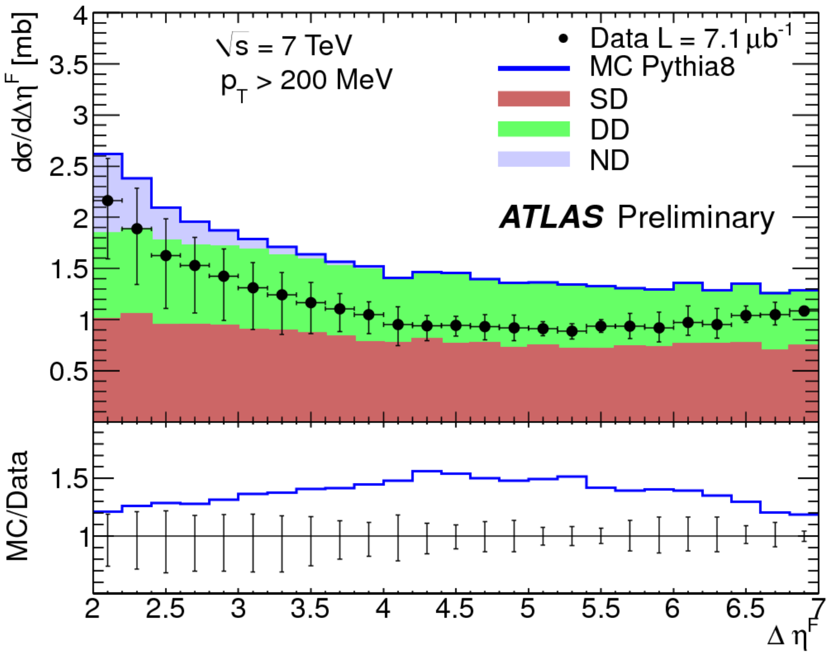


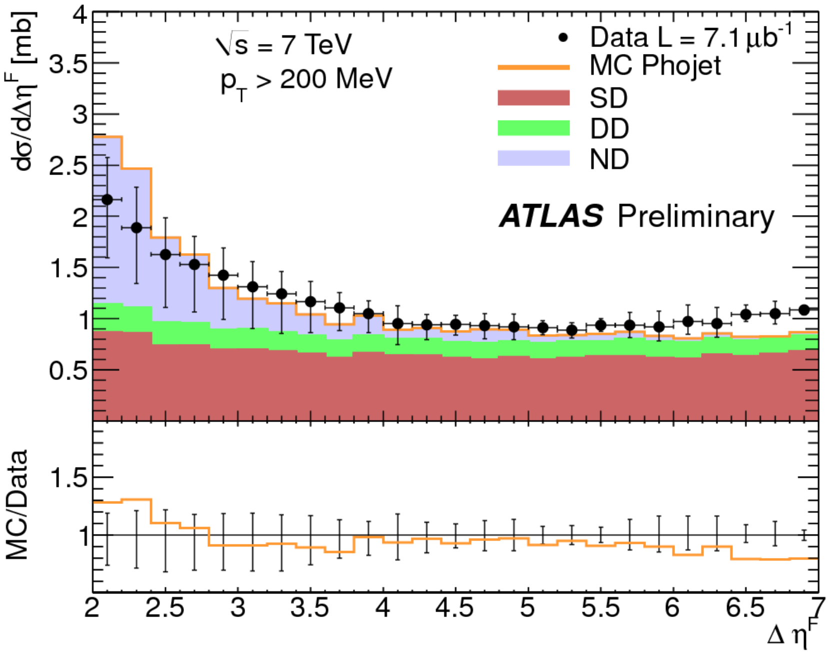
Rapidity Gap Cross Section



- 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 Δy

- 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 ~ 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}:

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

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

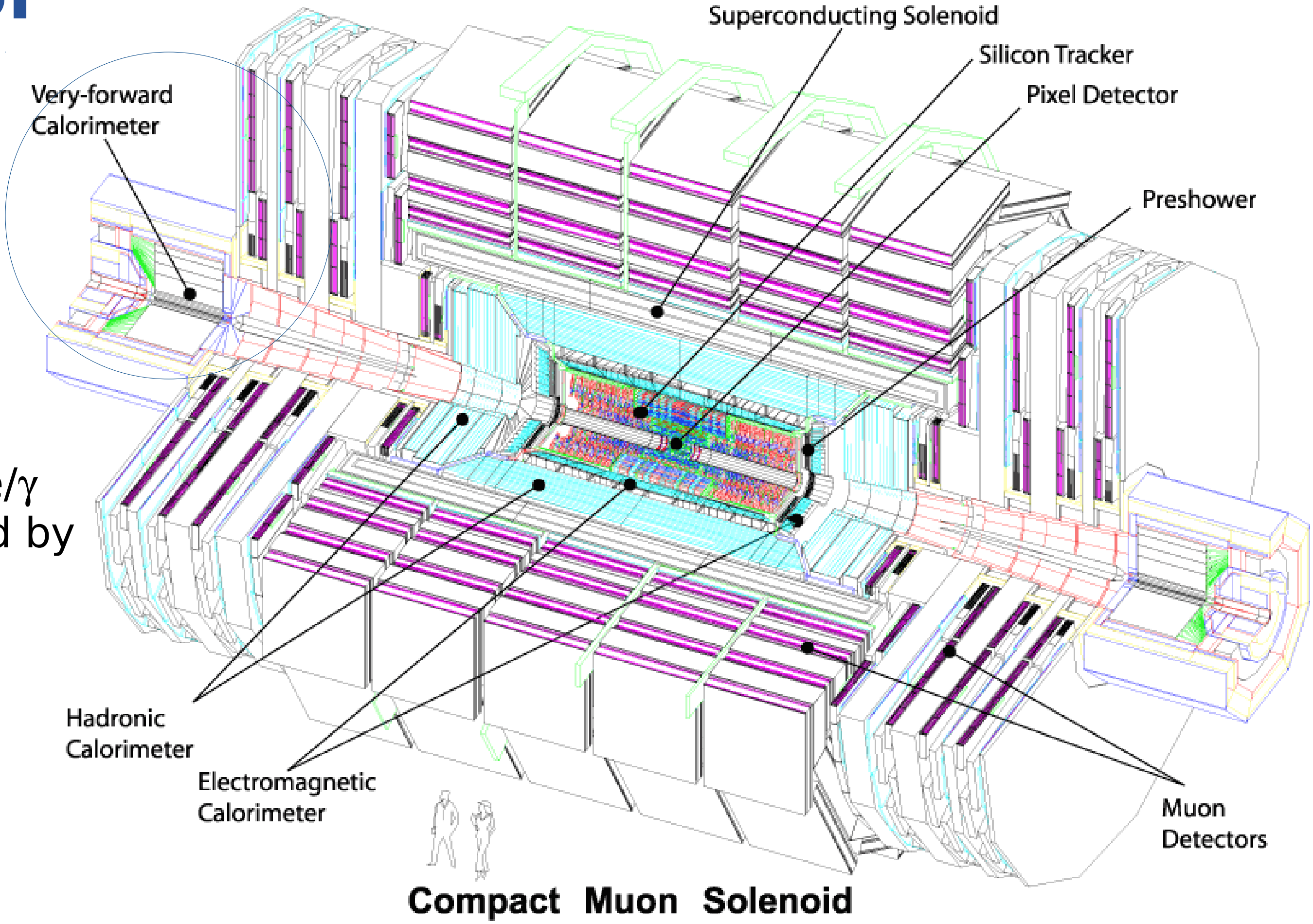
- $p_{T0}(\sqrt{s}) = p_{T0}(\sqrt{s_0})\ (\sqrt{s}/\sqrt{s_0})^{\varepsilon}$

	$p_{T0}(\sqrt{s_0})$	$\sqrt{s_0}$	ε
D6T	1.84	1.96	0.16
PROQ20	1.9	1.8	0.22
P0	2.0	1.8	0.26
DW	1.9	1.8	0.25

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/γ from showers generated by hadrons
- 13 rings in η



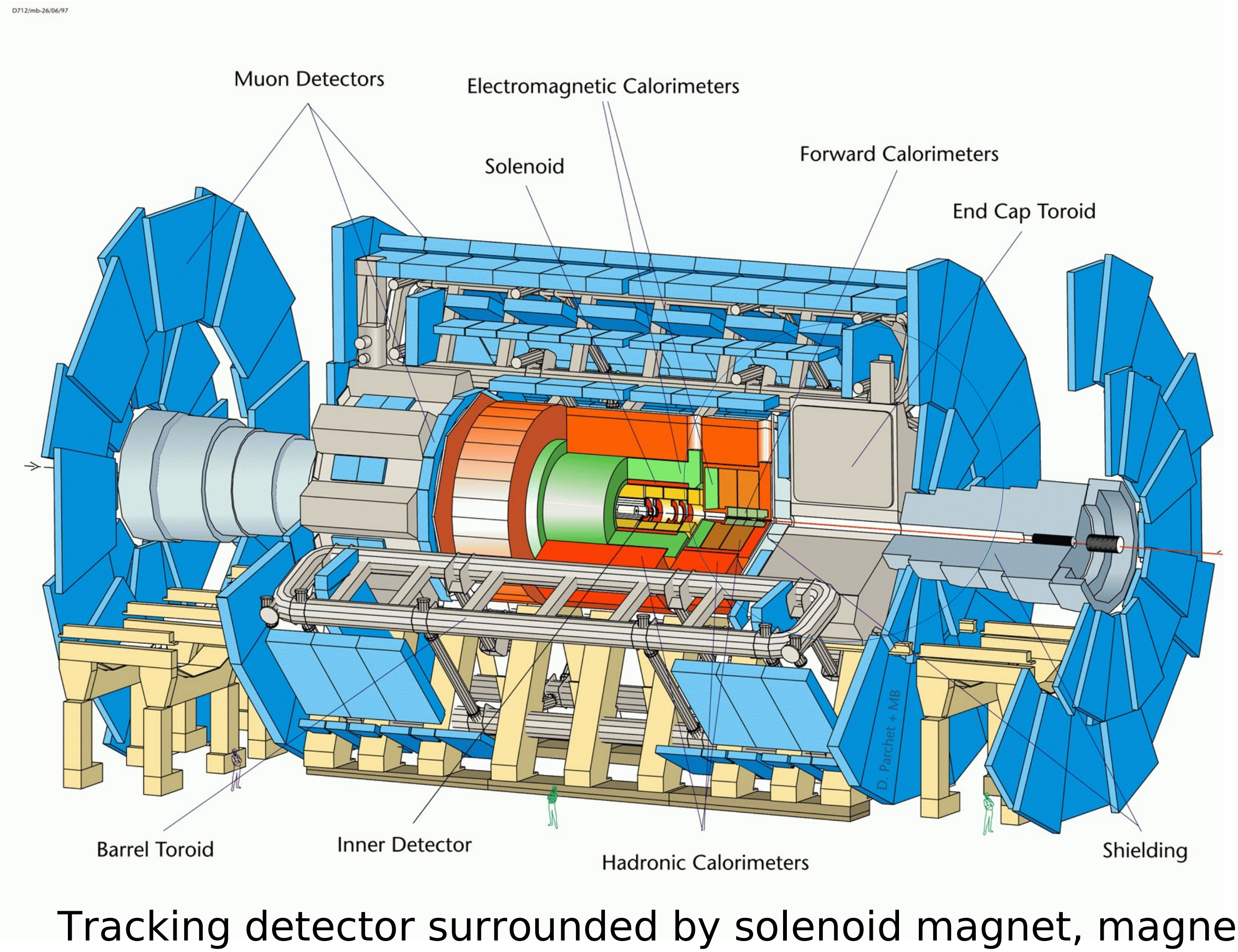
Superconducting solenoid, 6m internal diameter, magnetic field 3.8 T

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



FCAL calorimeter:

- 3.1 < |η| < 4.9
- LAr/Cu modules
- LAr/W modules
- to measure both elm and hadronic energy

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

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 → 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 → 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

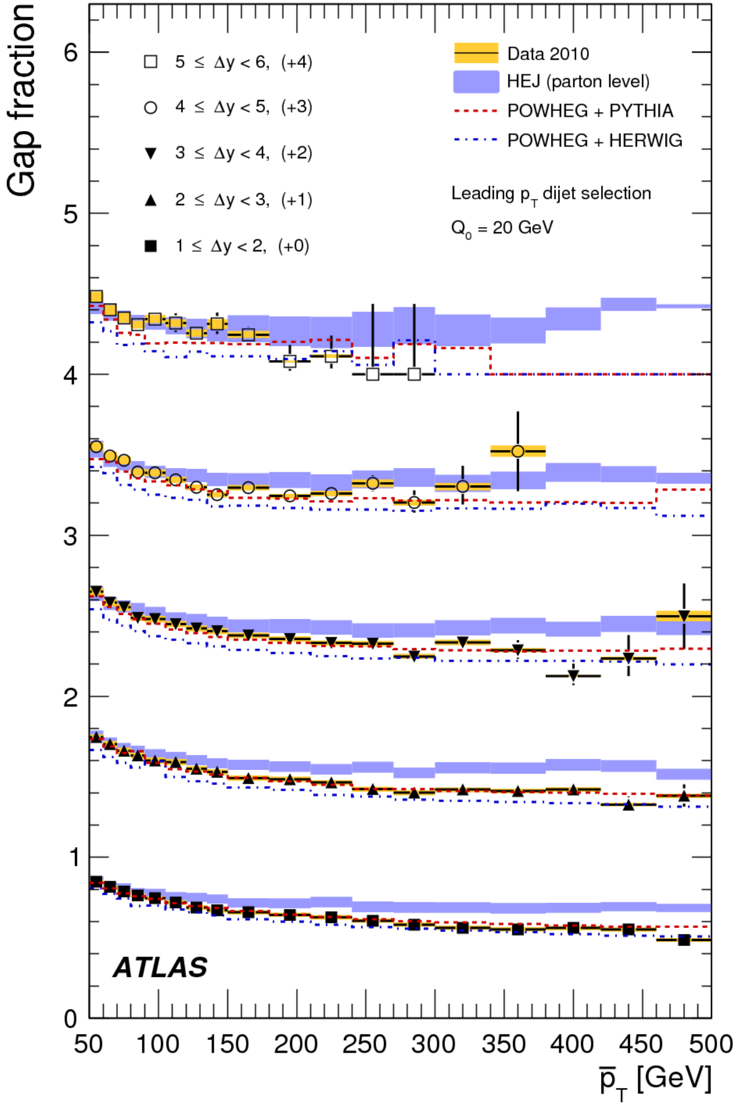
- **ALPGEN:** parton-level multiparton event generator
  - LO Matrix Element with up to 6 partons in the final state
  - interfaced to Pythia or Herwig (parton showering, hadronisation, MPI)
- **HEJ:** parton-level event generator
  - all order description of wide angle emissions of similar p_t (BFKL-inspired 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 → 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

Gap fraction as a function of dijet average p_t for various Δy 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

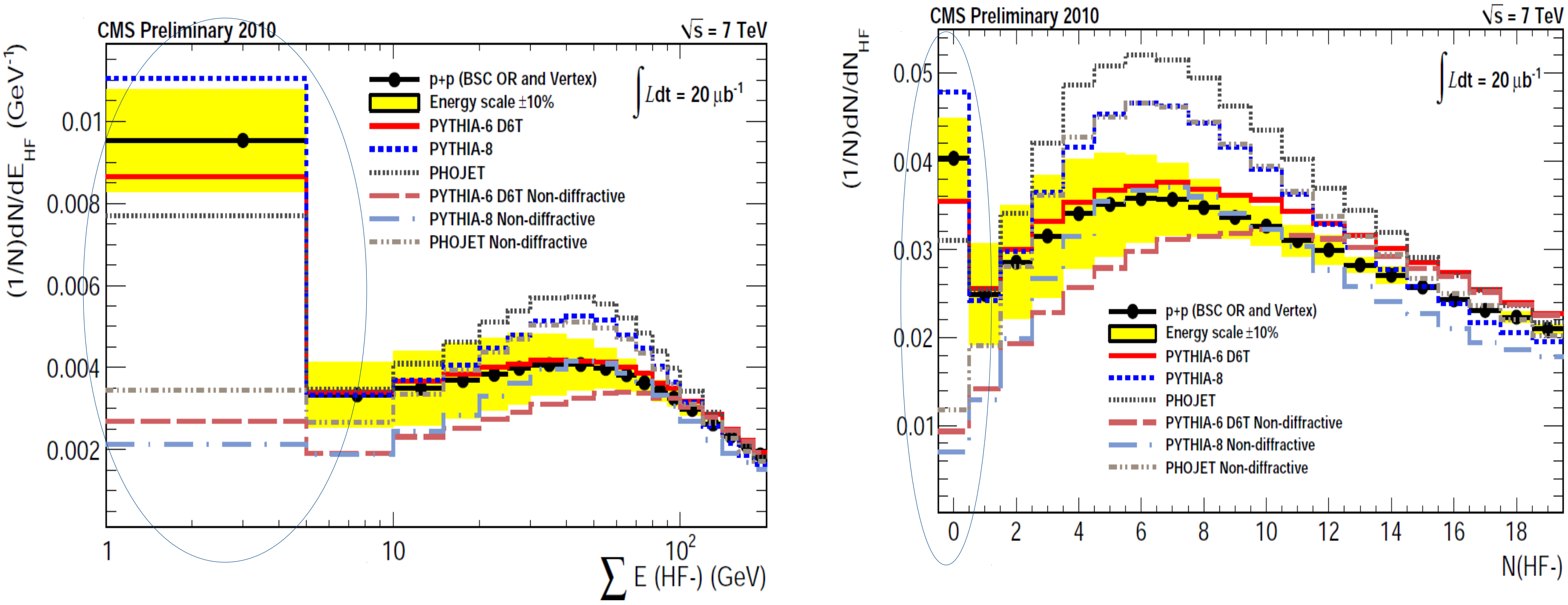
- Powheg + Pythia: good at low Δy
- At larger Δy, good in shape only

Observation of Diffraction at 7 TeV

- Large Rapidity Gap (LRG)

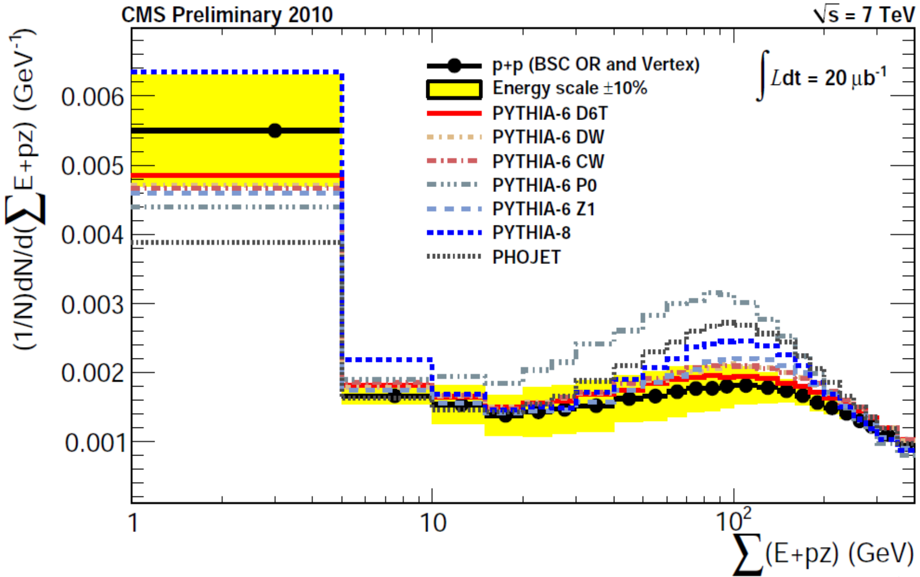
Diffractive events characterized by the absence of forward hadronic activity in HF due to the presence of a Large Rapidity Gap

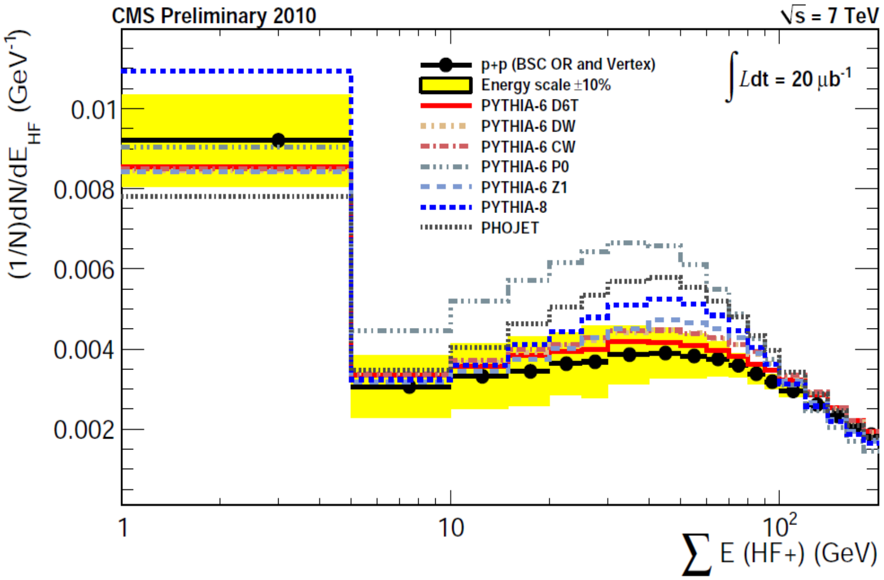
→ Diffractive peak expected at low energy deposition and low tower multiplicity in HF

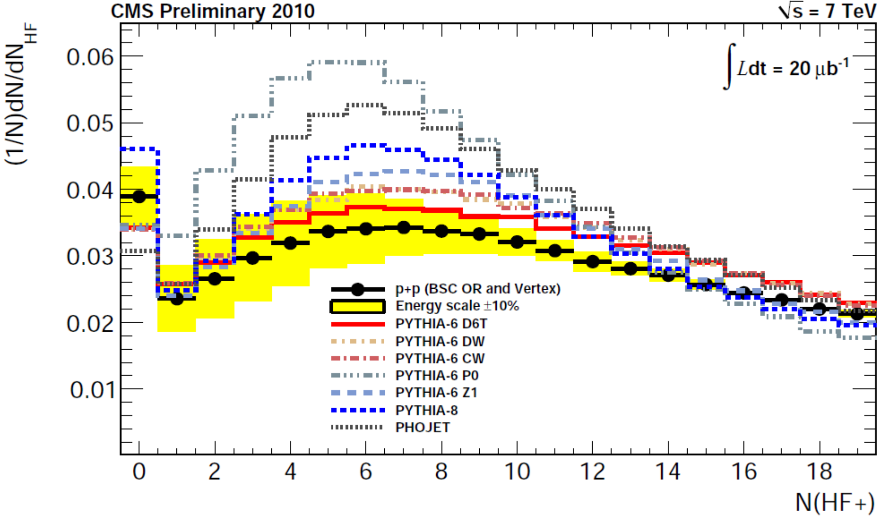


Observation of Diffraction at 7 TeV

- Comparison with different Pythia 6 tunes





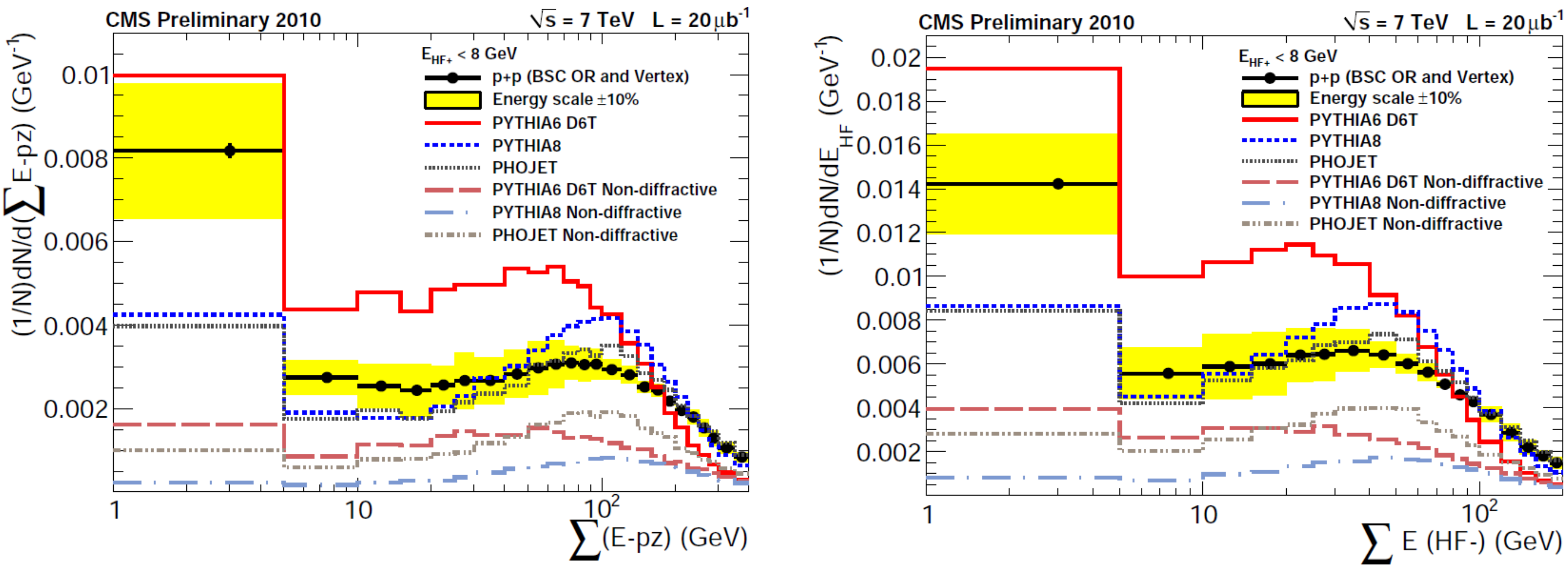


Pythia 6 D6T, DW, CW
reproduce the data best

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 ($\xi = M_X^2 / s$)
- PHOJET and Pythia 8 give a better description of the diffractive system

E(HF+) < 8 GeV

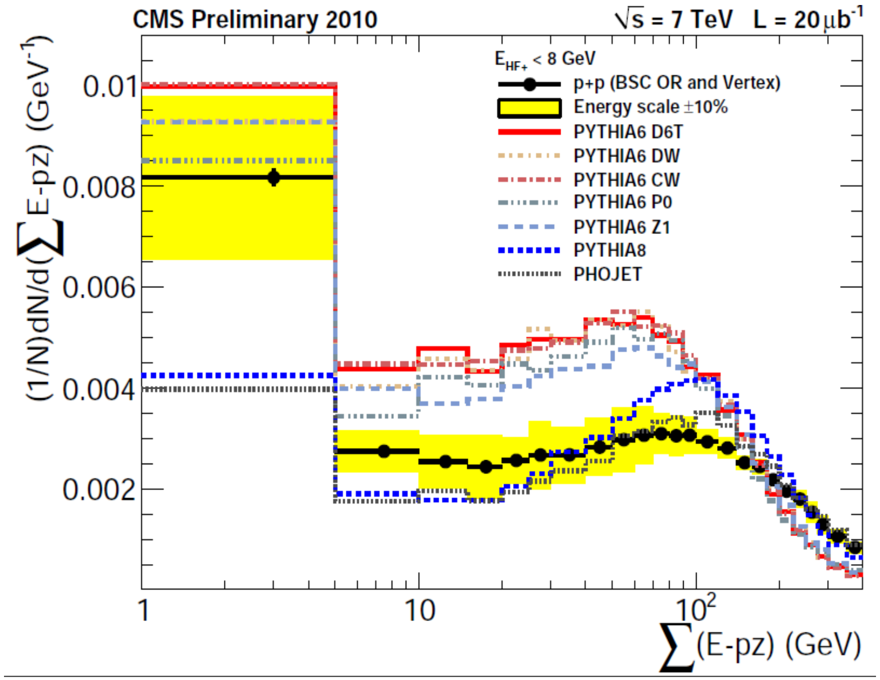


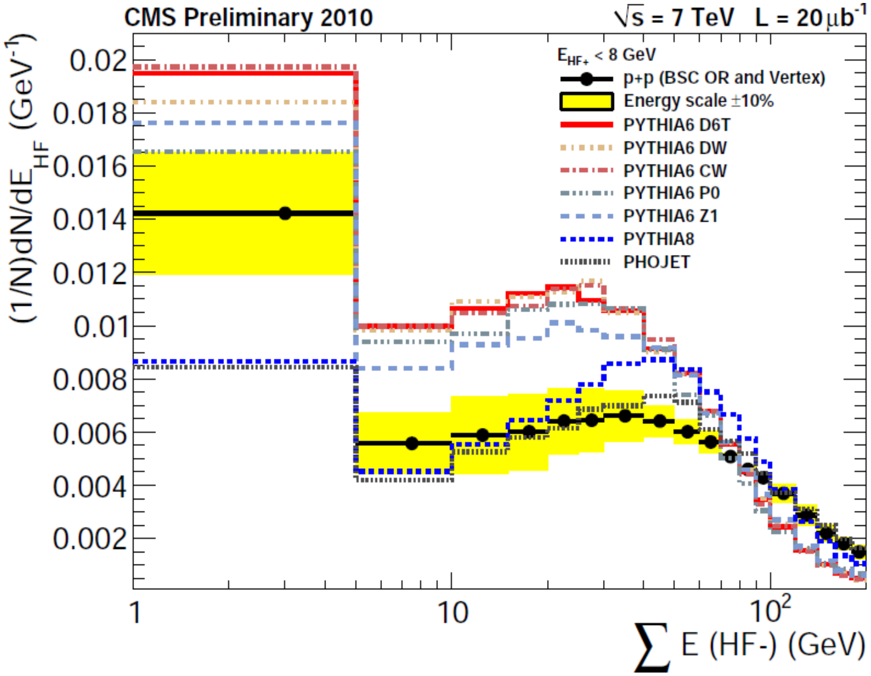
Enriched Diffractive Sample

- Comparison with different Pythia 6 tunes

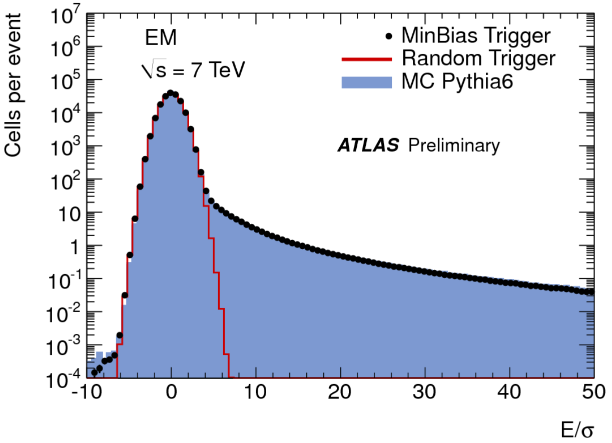
→ None of them reproduces the diffractive component

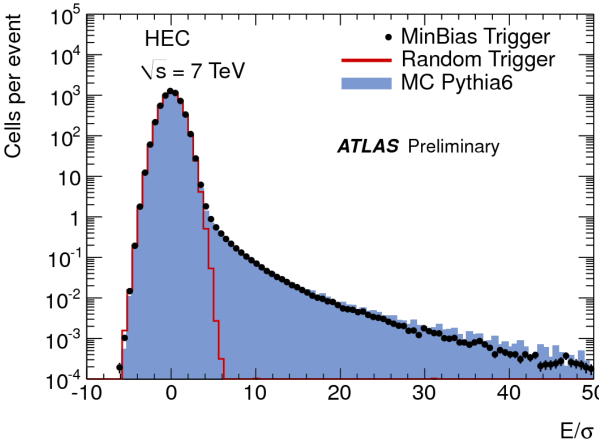
E(HF+) < 8 GeV

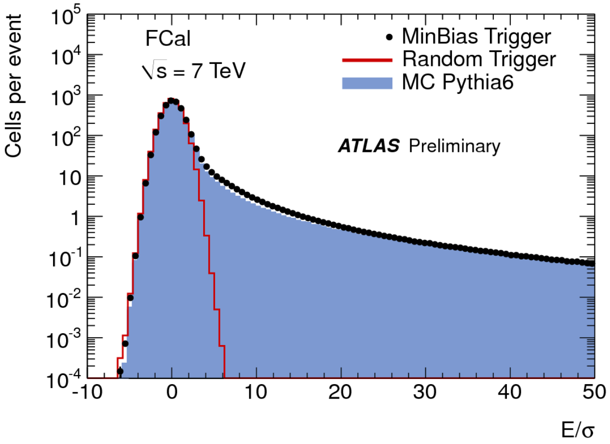




Calorimeter energy deposit







- Energy Significance E / σ 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

→ $4.8 <$ significance threshold < 5.8