Measurements of Forward Energy Flow and Forward Jet Production with CMS

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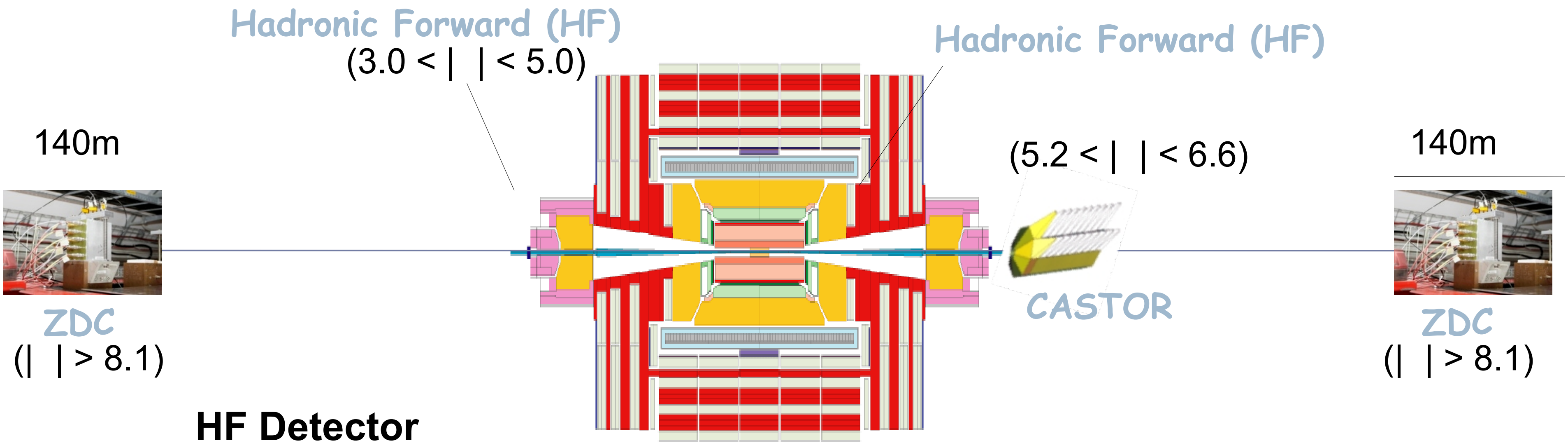
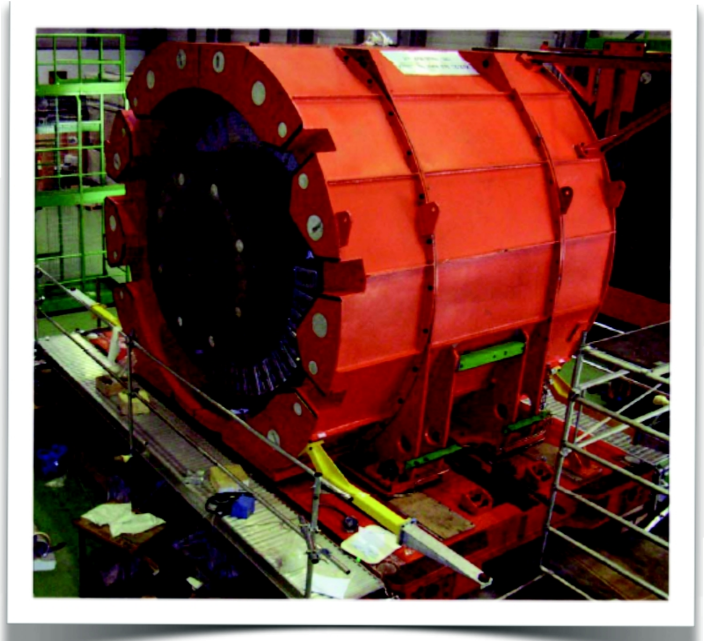
Outline

- Forward Energy Flow
  - Minimum bias, dijet events, W/Z- bosons
- Forward Jets
  - Inclusive forward jets
  - Central + forward jets
- Conclusions

CMS: Forward Detectors



HF Detector



- @11.2 m from interaction point
- Rapidity coverage: **3 < |η| < 5**
- Steel absorbers/quartz fibers

(Long+short fibers)

- 0.175x0.175 η/φ segmentation

Forward Energy Flow

Energy Flow: Motivation

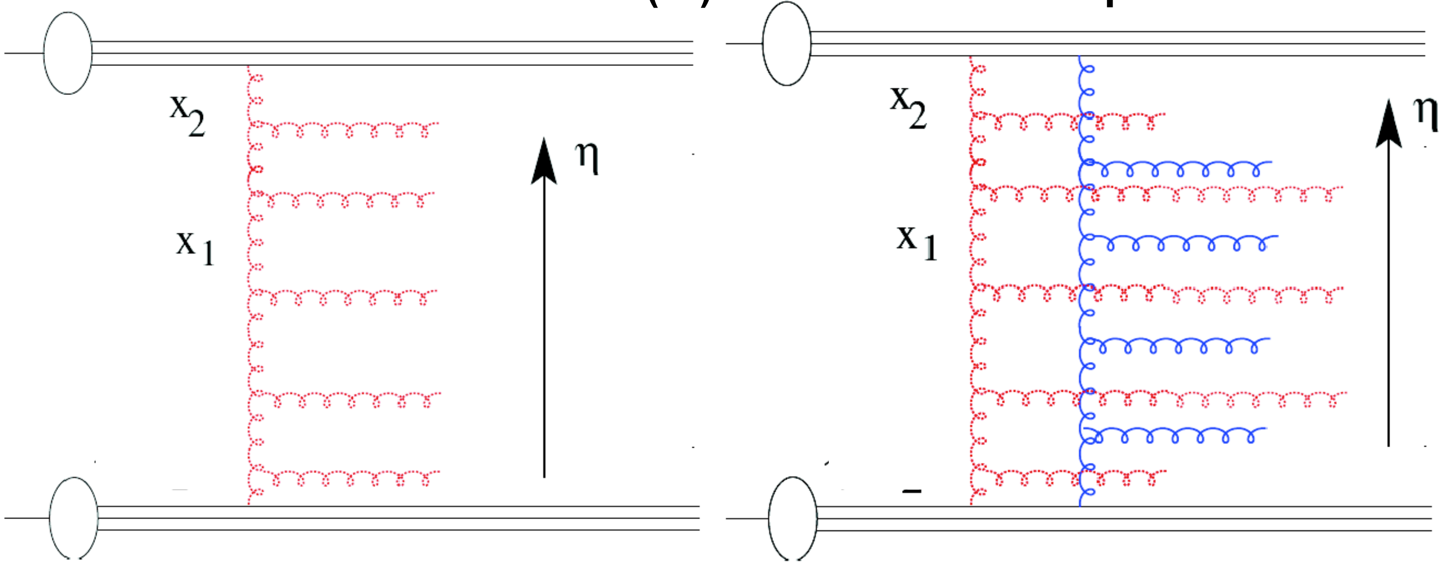
CMS PAS FWD-10-011

- **High energy collisions - large parton densities important:**
  - High probability for multiparton interactions.
  - Low x physics.
  - Possible saturation effects.

    → High sensitivity to QCD.
- **Forward region:**
  - Long range in rapidity between forward and central activity.
    - Opens up for higher order reactions.

      → Further sensitivity to QCD.
  - Energy flow in the forward region:

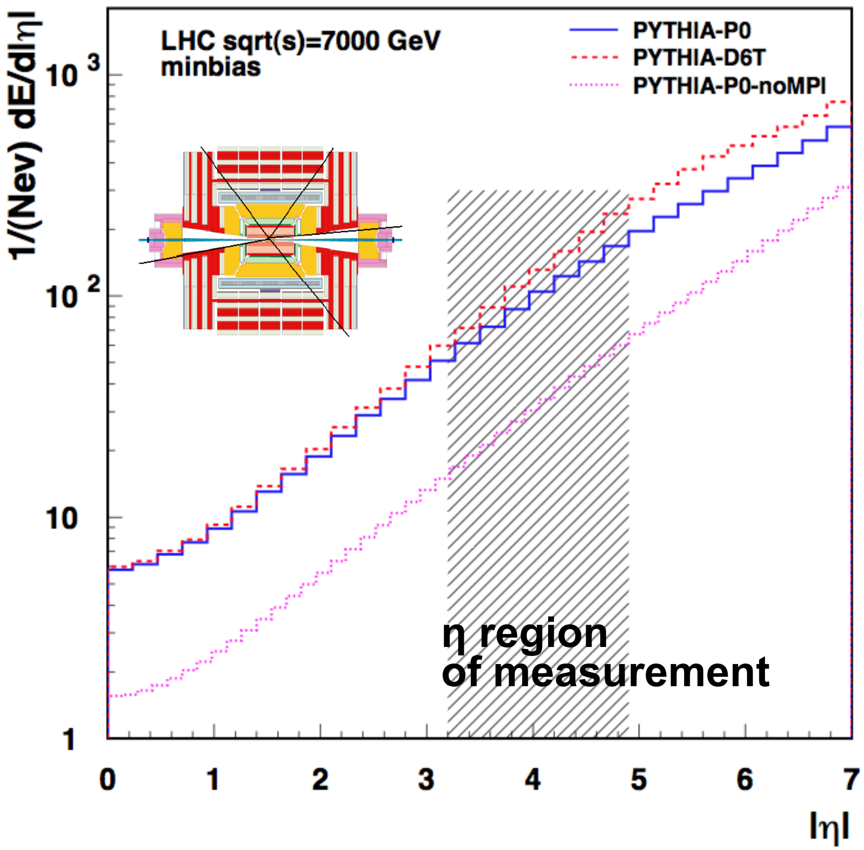
    Information about color (re)connections to the proton remnant.

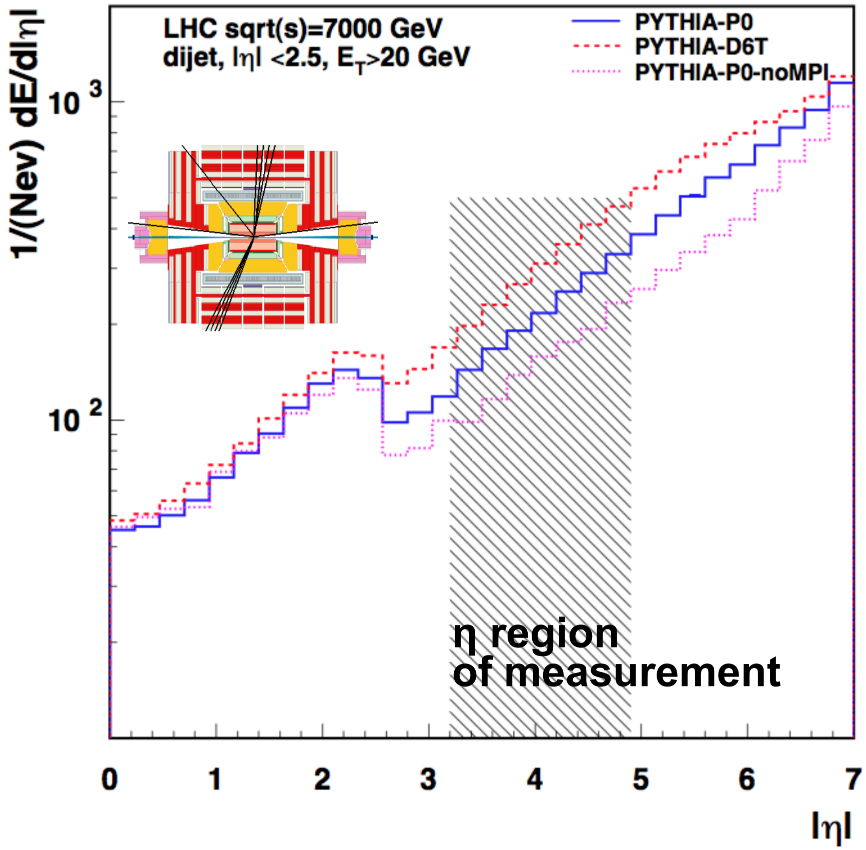


Energy Flow: Predictions

MC studies of Energy flow for **Minimum Bias** and **Dijet events**.

- Tunes made to UE measurements in the central region.
- Use the forward region to explore the underlying event.
- Discriminate between models.
- Possibility to use data to improve MC models and tunes.





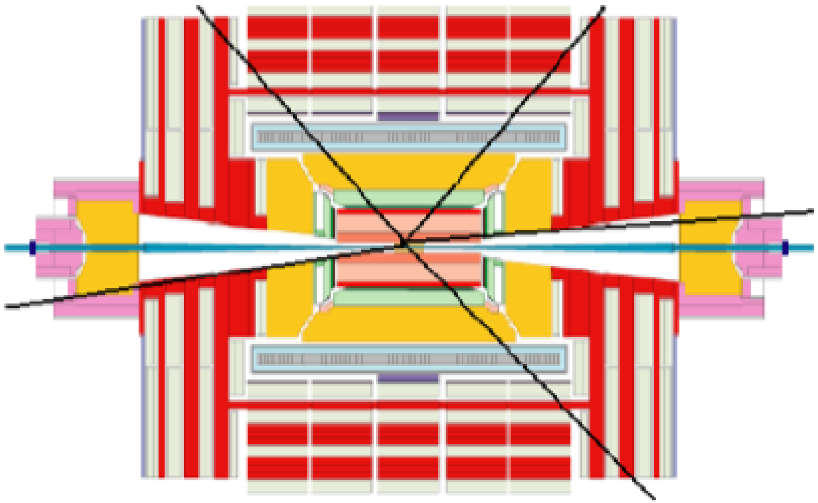
Analysis Strategy

- Energy flow as a function of rapidity in the forward region: **3.15 < |η| < 4.9**

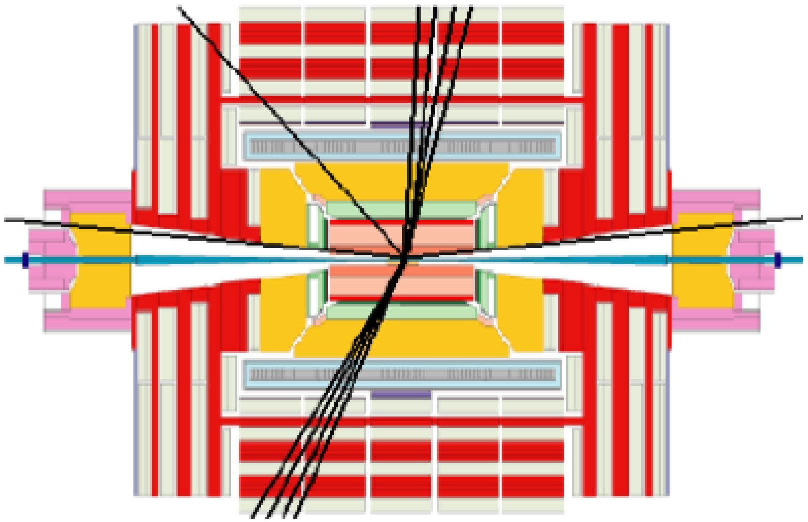
$$\frac{1}{N_{events}} \frac{dE}{d\eta} [\text{GeV}]$$

- Data: 2010, $\mathscr{L}$ **(√*s=0.9 TeV*) = 239 μb^{-1}**, $\mathscr{L}$ **(√*s=7 TeV*) = 206 μb^{-1}**

Minimum Bias events
(zero or few partonic interactions)



Events with a hard central dijet system
(one or more high p_T partonic interactions)



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Minimum Bias events
(zero or few partonic interactions)

Event Selection

- Events are selected with a **Non-Single-Diffractive trigger** which requires MB activity in coincidence in both the forward and the backward region.
- Technical cuts such as good vertex selection and rejection of background events.

Events with a hard central dijet system
(one or more high p_T partonic interactions)

Event Selection

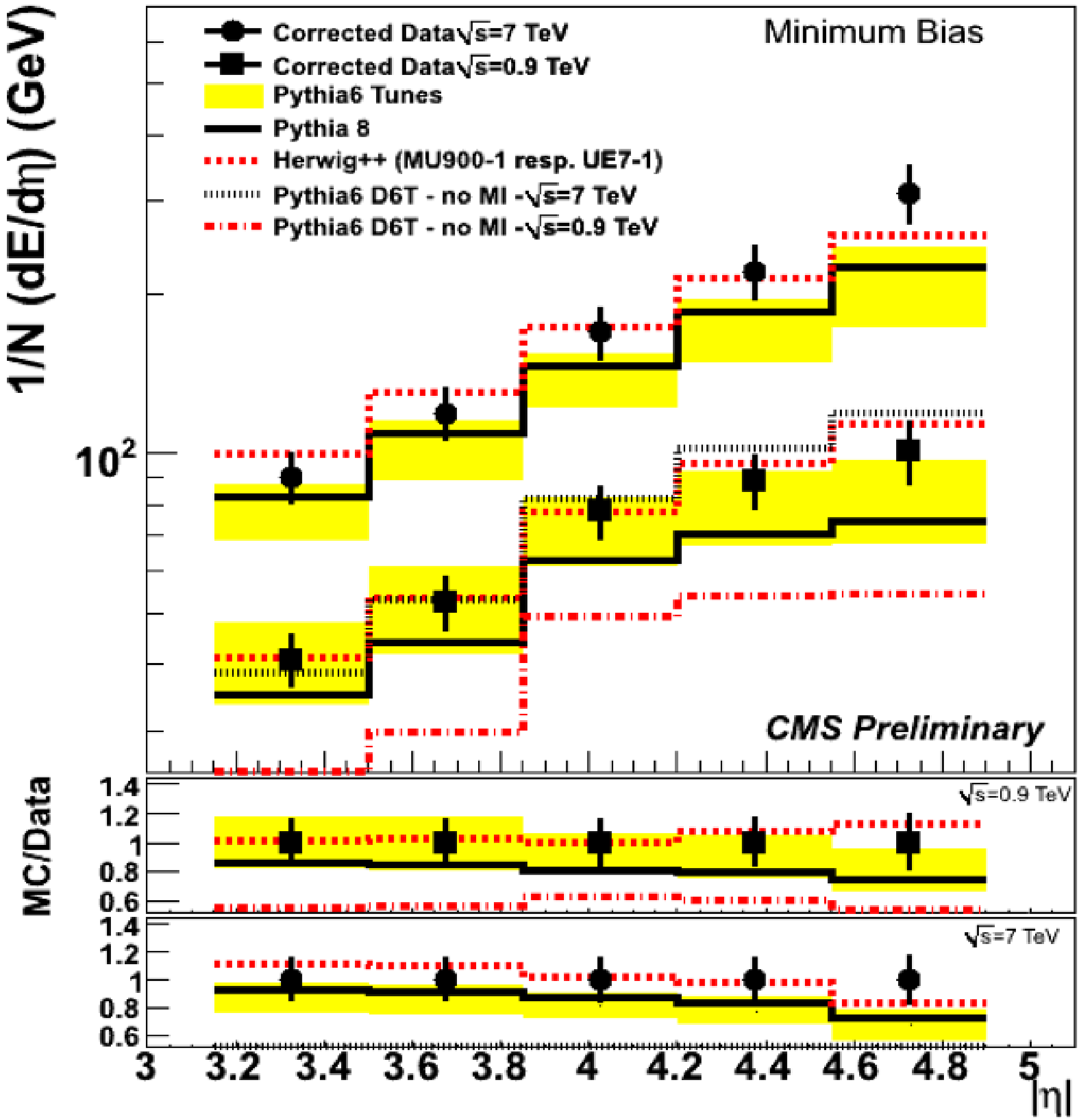
Subsample of the MB events

- Jets are defined with the Anti-k_T algorithm with R = 0.5.
- Select events in which the **leading and the sub-leading jet** fulfills:

	√*s=0.9 TeV*	√*s=7 TeV*
High p_T	p_T > 8 GeV	p_T > 20 GeV
Central	$\lvert\eta\rvert < 2.5$	
Back-to-back	$\lvert\Delta\varphi_{jet1,jet2} - \pi\rvert < 1$	

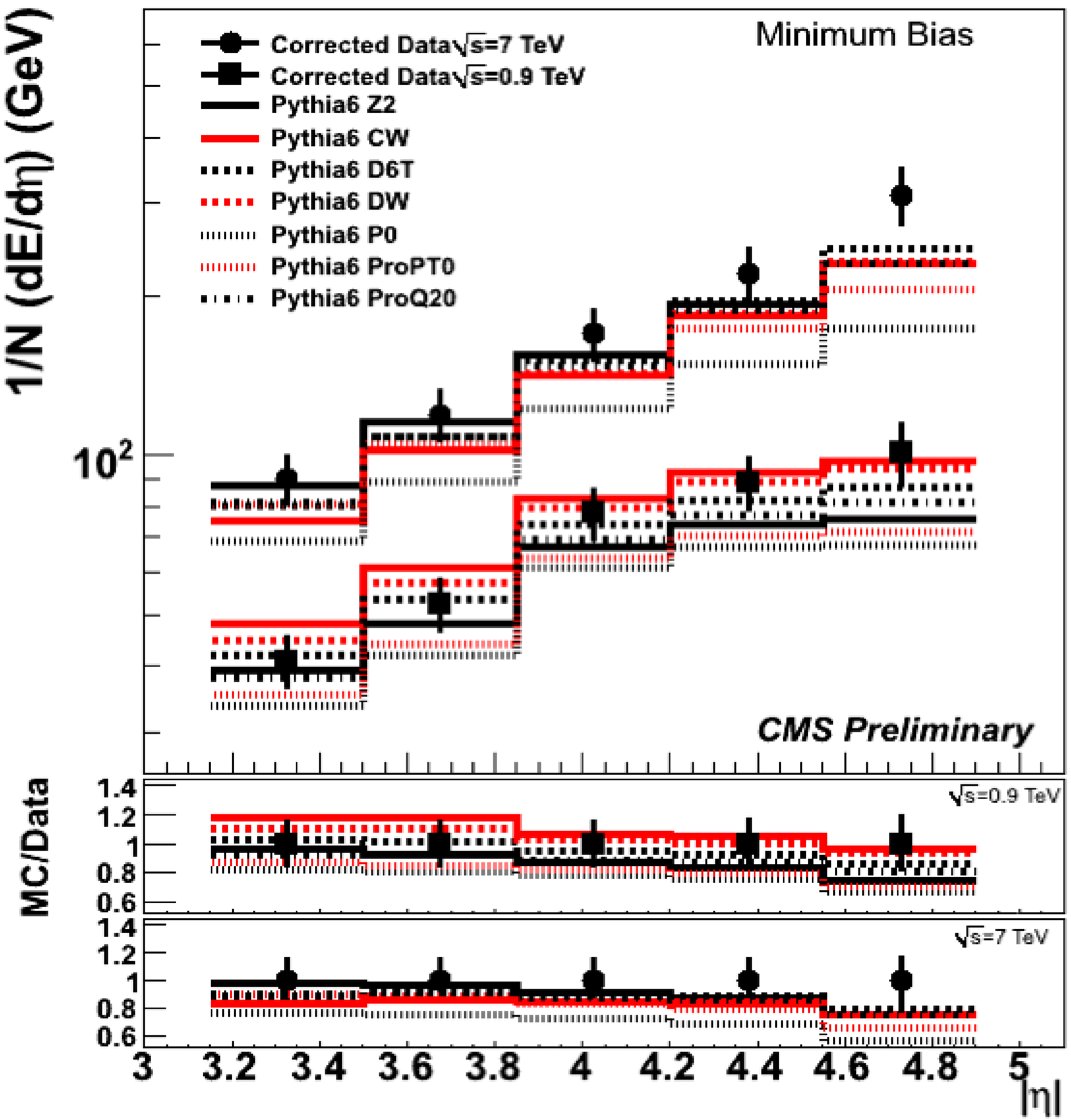
- The measured energy flow has been corrected to hadron level.

Results: MinBias



Comparison to different MCs

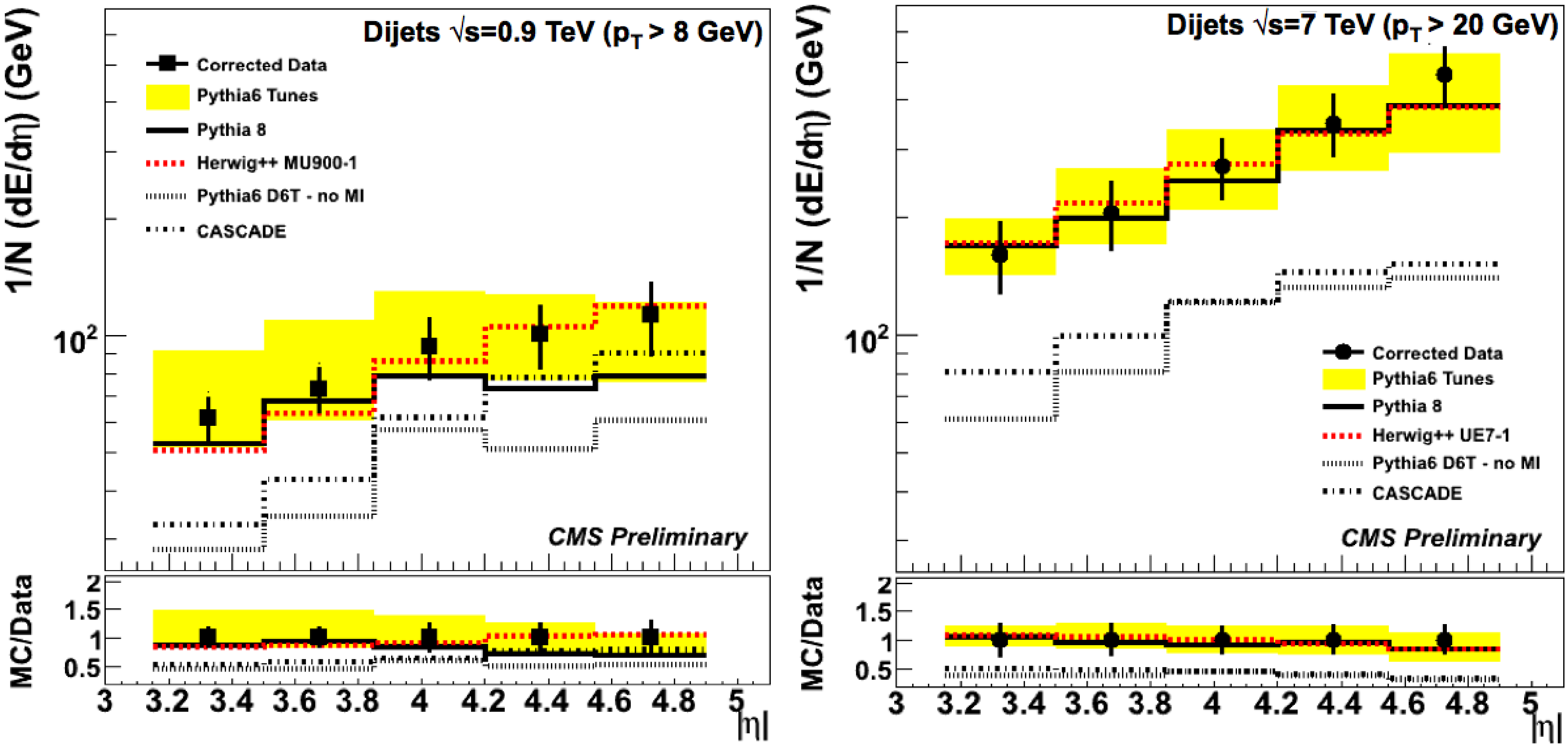
- Error bars: systematic uncertainties (dominated by energy scale)
- Measurement is corrected to hadron level.
- Average energy **increases** strongly with η: from **30** to **90 GeV @ 0.9 TeV**
  from **80** to **300 GeV @ 7 TeV**
- **Models without MPI** predict too little energy.
- **Models with MPI** bring prediction closer to the measurement, but a large spread is available.
- Only Herwig describes the data using center-of-mass specific tunes.
- Yellow band represents Pythia tunes



Comparison to different Pythia 6 tunes

- None of the tunes describes data well
- Large sensitivity to underlying event tunes.
- All tunes were tuned to central underlying event measurements.

Results: Dijet Events

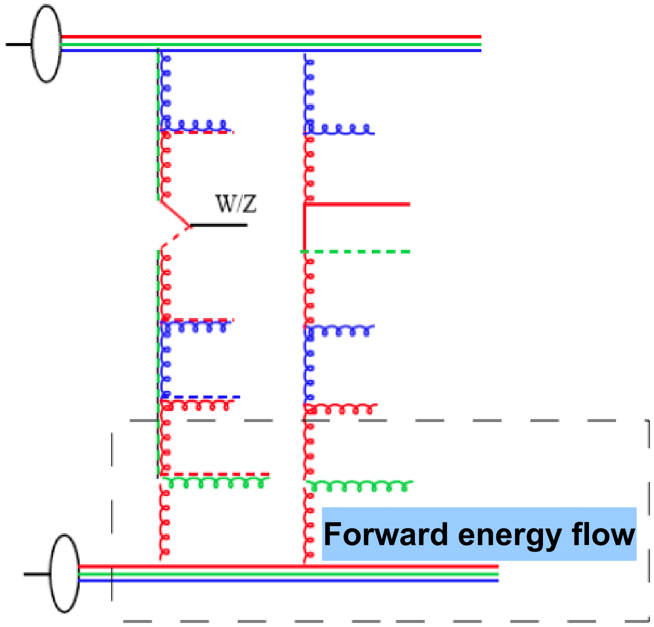


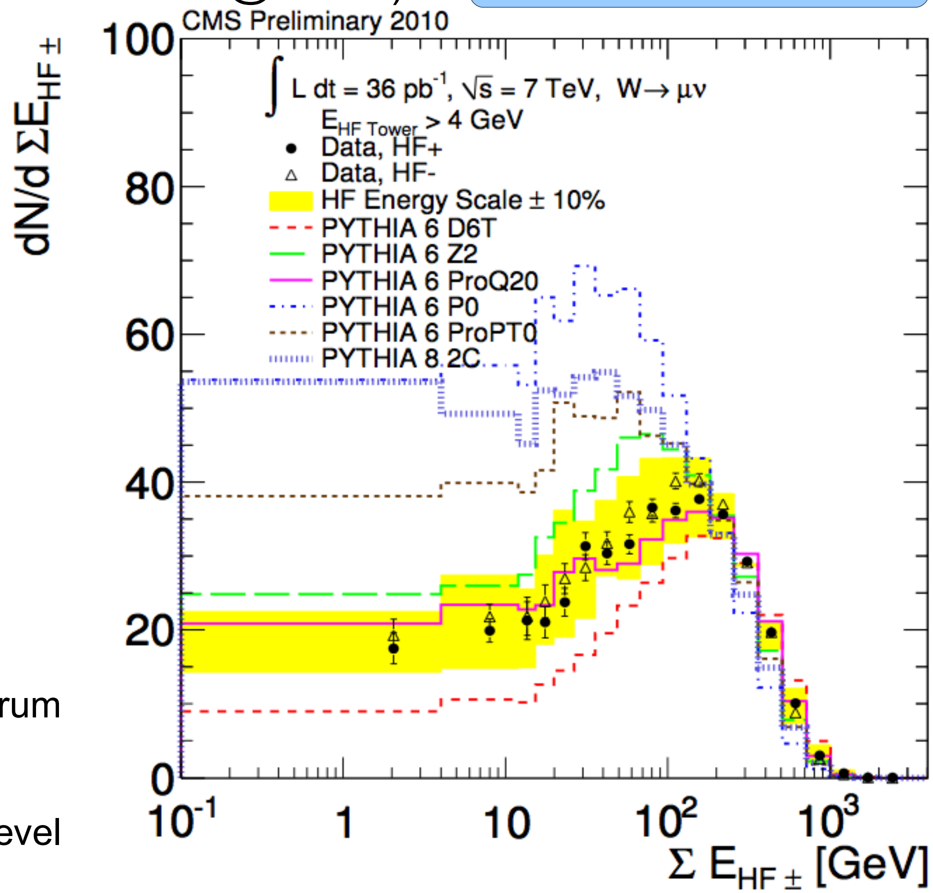
- Average energy increases from **60 to 100 GeV @ 0.9 TeV, from 180 to 500 GeV @ 7 TeV**
- A **large increasement** compared to minimum bias, due to a hard scale in the process.
- **Models w/o MPI again** predict too little energy flow.
- **CASCADE** with different parton showers is larger than **PYTHIA w/o PS** but not enough.
- **Need MPI** to bring prediction closer to data.
- All tunes does a reasonable job.

Forward Energy Flow in W/Z Events

- Another example of energy flow with a hard process: now instead of jets, **W/Z (decay into *eν* & μν)** events used (in 2010 data @ 7 TeV)

CMS PAS FWD-10-008





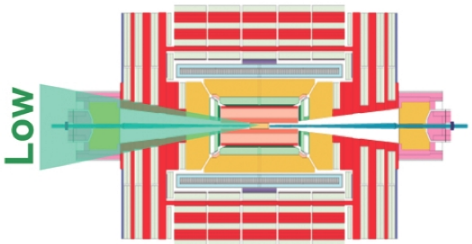
- Energy spectrum (uncorrected): looking @ spectrum instead of average but integrated over $3 < |\eta| < 4.9$.
- Observe on average 100-200 GeV on detector level (uncorrected) similar to dijet case.
- Here integrate over η , before it was taken per unit of η
- ProQ20 tune provides the best description of the HF energy distribution as seen in energy flow study.

- Energy scale uncertainty is 10%
- Different models give very different predictions
- Shape of the distribution is very model dependent

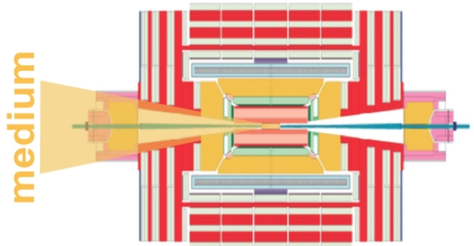
Correlation Studies

- To study differences and correlation of energy flow and track multiplicities in more detail, split in 3 HF energy ranges:

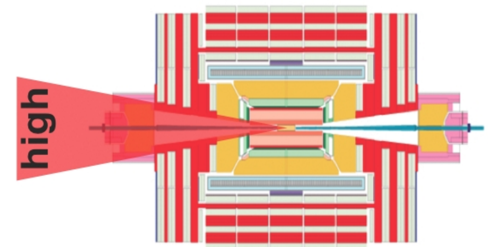
Low: 20 – 100 GeV
(region of largest discrepancy)



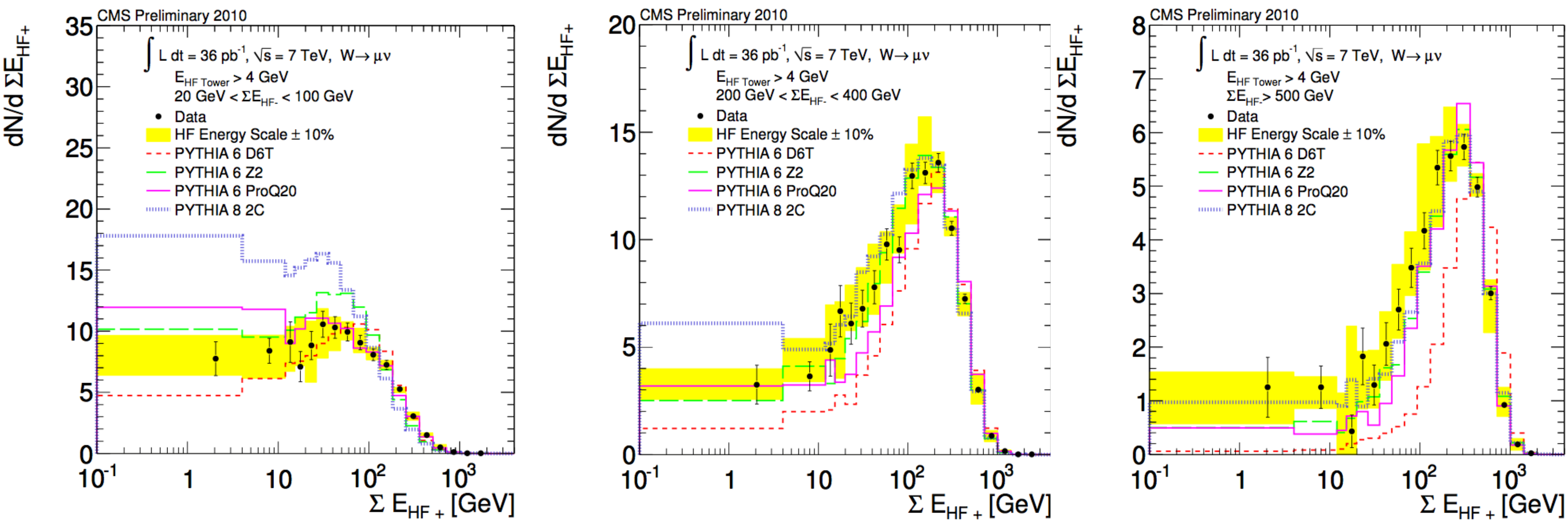
Medium: 200 – 400 GeV
(peak region)



High: > 500 GeV
(high energy region)



Categorize event with HF− energy deposit "Look" at opposite side (i.e. HF+) deposit



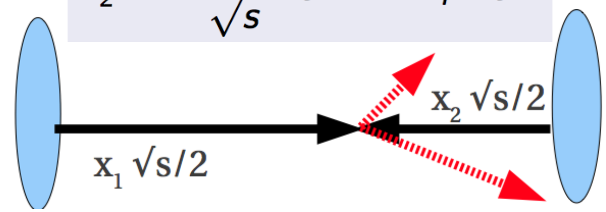
- No PYTHIA tune is able to describe FWD energy flow and central track multiplicity simultaneously.

Forward Jets

Motivation

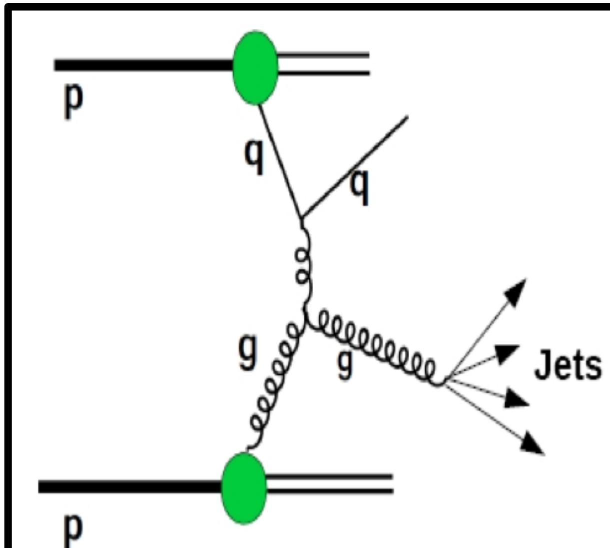
- Forward jets allow to probe the low-x domain (10^{-5}) region sensitive to non-linear QCD effects
- Test theory in a previously **unexplored kinematic** regime
- Parton dynamics: deviations beyond DGLAP (p_T ordered emission) evolution (BFKL (x ordered emission), CCFM)
- First step to understand Higss production via vector boson fusion

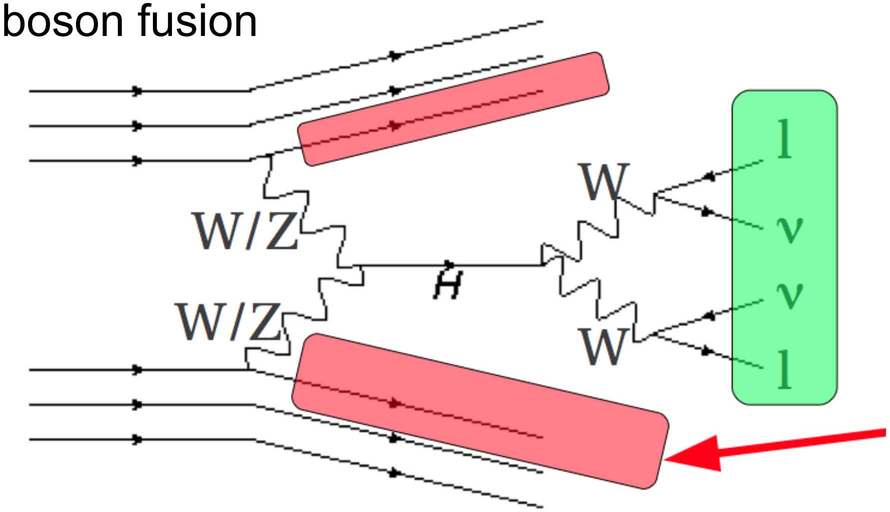
$$x_2^{min} \approx \frac{p_T}{\sqrt{s}} \cdot e^{-y} = x_T \cdot e^{-y}$$



Jets in high region

$$\mathbf{x = x_{parton} / x_{proton}}$$



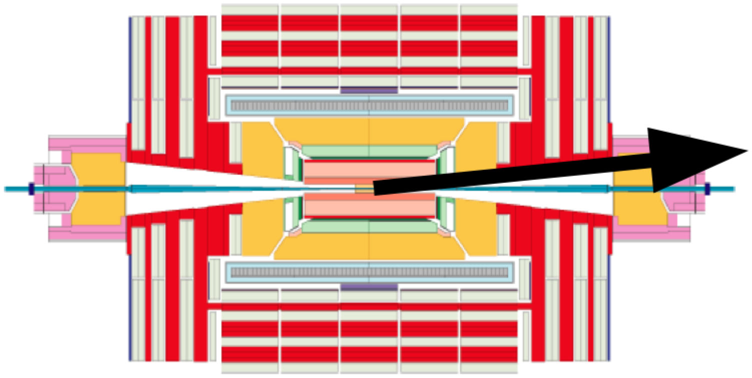


Forward-Backward Jets

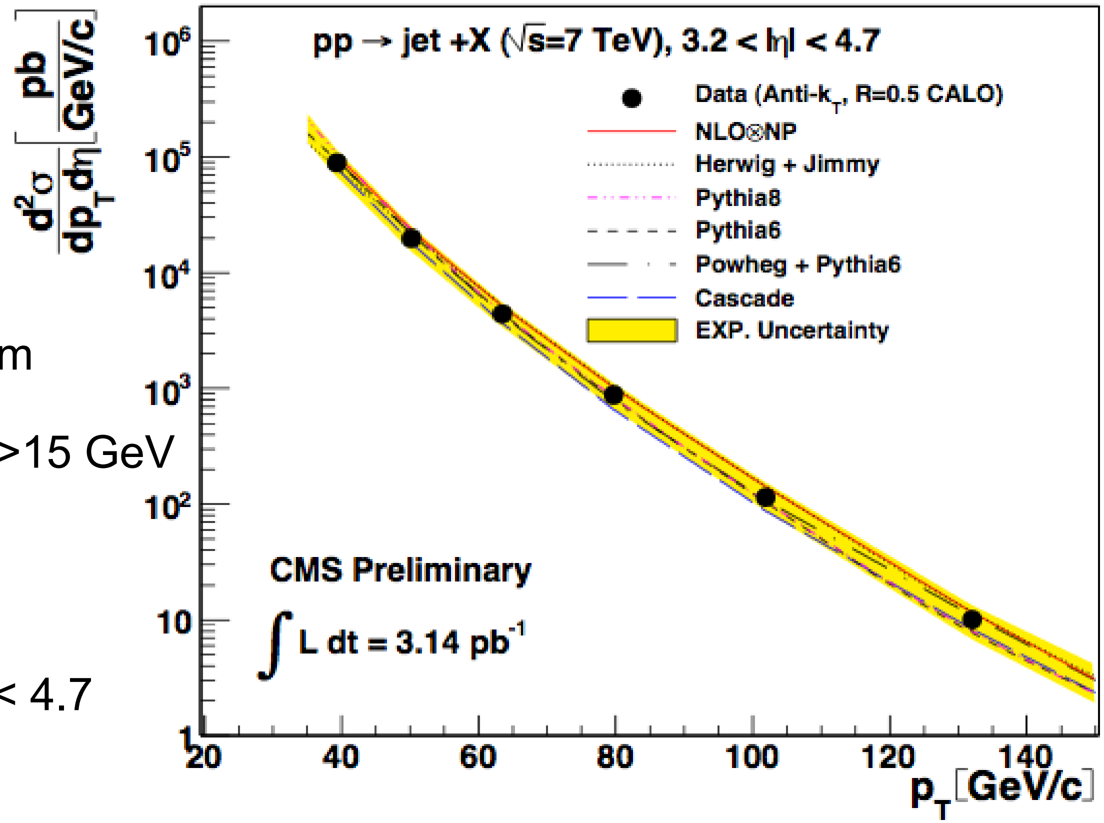
Inclusive Forward Jet Cross Section

pp →jet + X

CMS PAS FWD-10-003



Inclusive fwd. jet x-section, fully corrected & unfolded



- Anti-k_T (R=0.5) jet clustering algorithm
- Single jet trigger with uncorrected p_T>15 GeV
- Jet identification criteria
- Good primary vertex
- Fiducial acceptance in HF: $3.2 < |\eta| < 4.7$

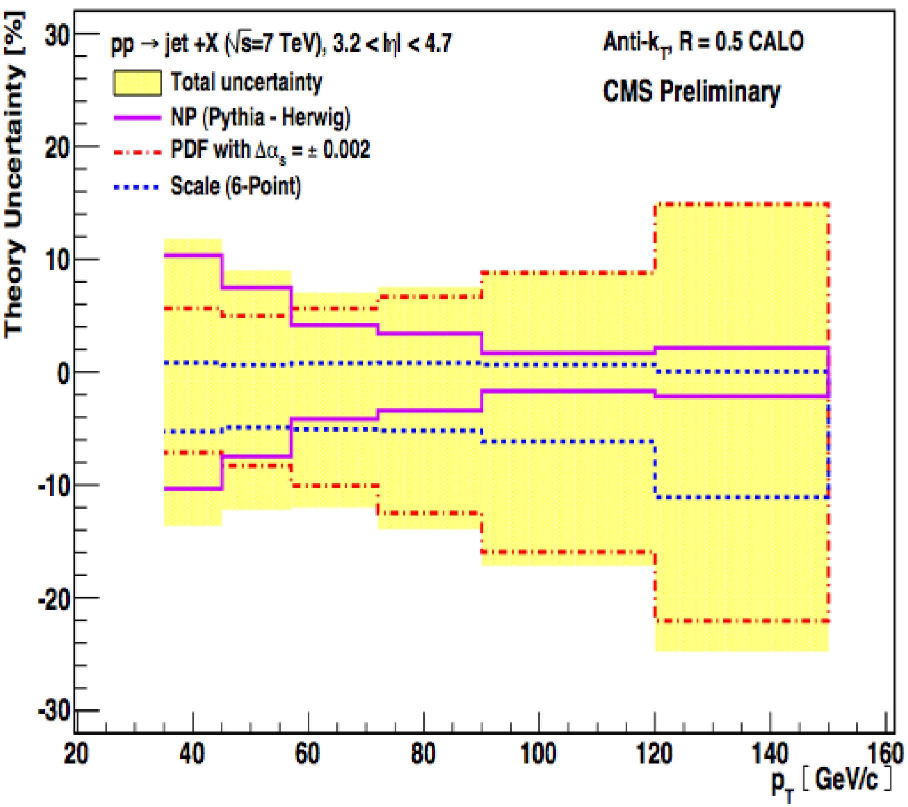
Systematic Uncertainties

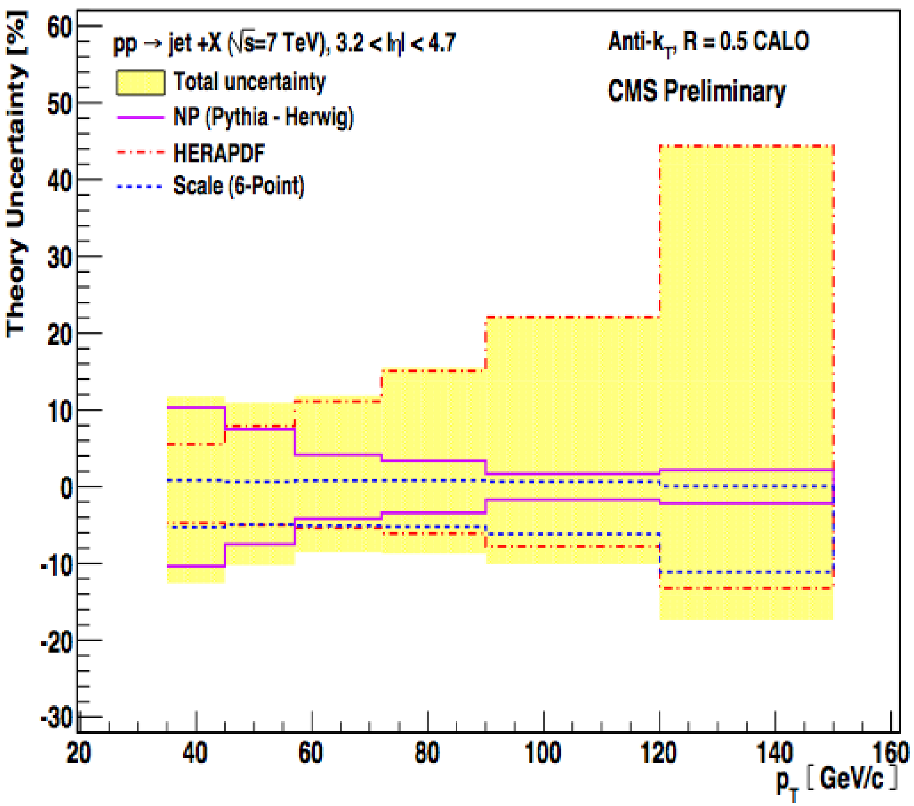
Theoretical Uncertainties

- Hadronization and UE (Pythia & Herwig)
- PDF uncertainty
- Renormalization & factorization scales

→ Maximum envelope ~10%

- Same NP & scale uncert. with the PDF envelope obtained using the HERAPDF parton densities as a cross check.
- HERAPDF set accounts for the experimental, model & parametrisation uncertainties of the HERA data fit.





Systematic Uncertainties

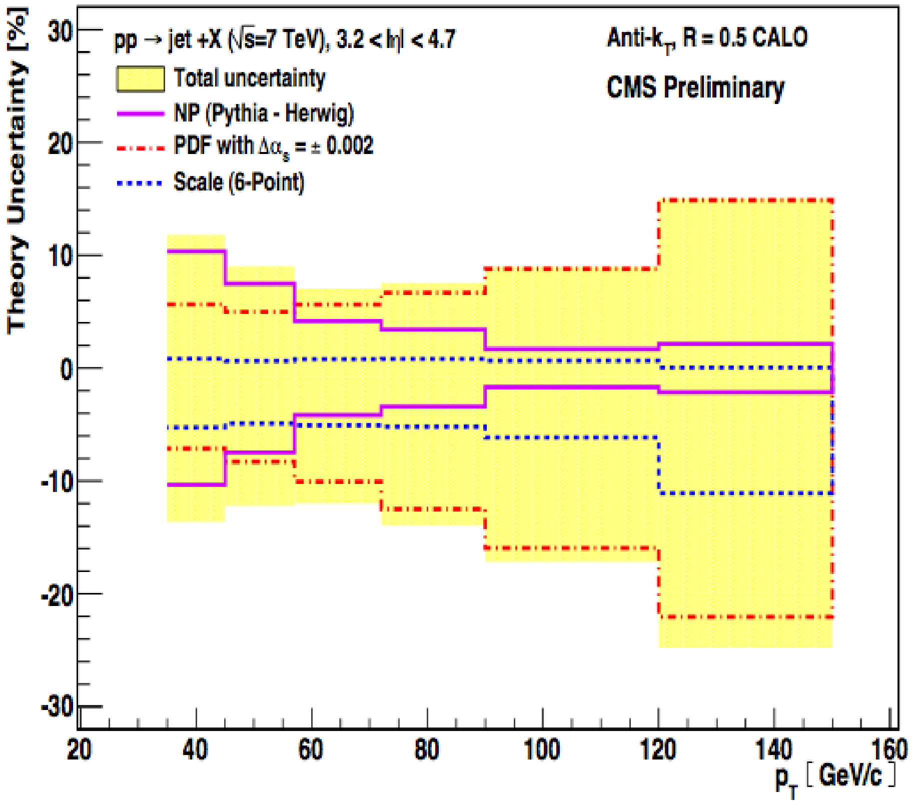
Theoretical Uncertainties

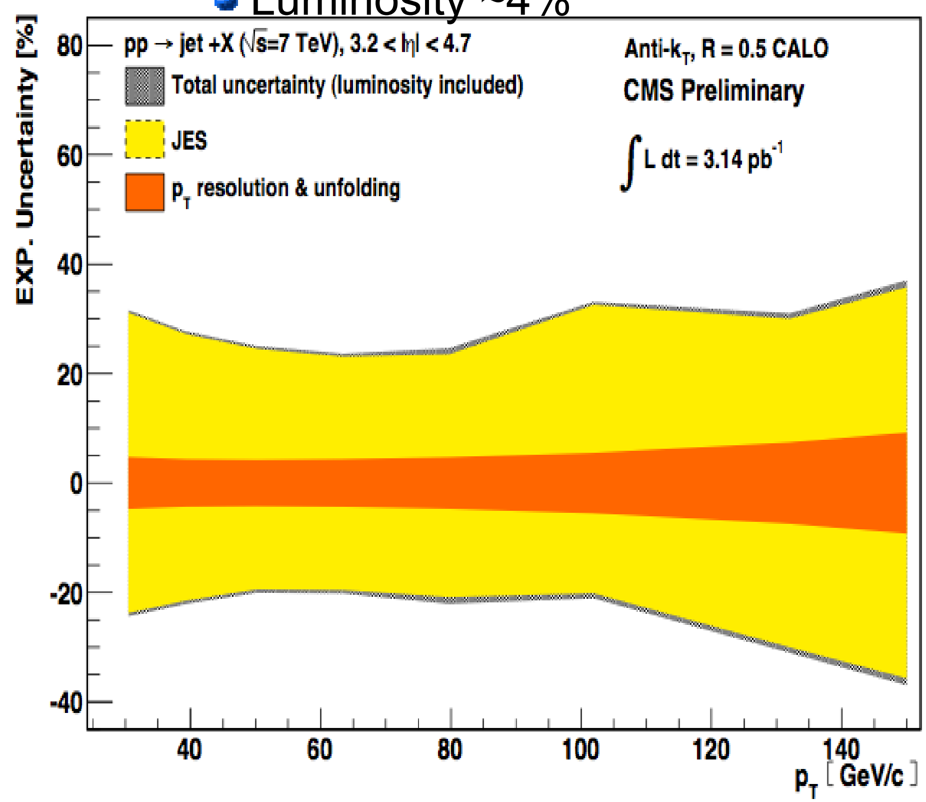
- Hadronization and UE (Pythia & Herwig)
- PDF uncertainty
- Renormalization & factorization scales

→ Maximum envelope ~10%

Experimental Uncertainties

- Jet energy scale ~30%
- p_T resolution ~6%
- Model dependence ~3%
- Luminosity ~4%

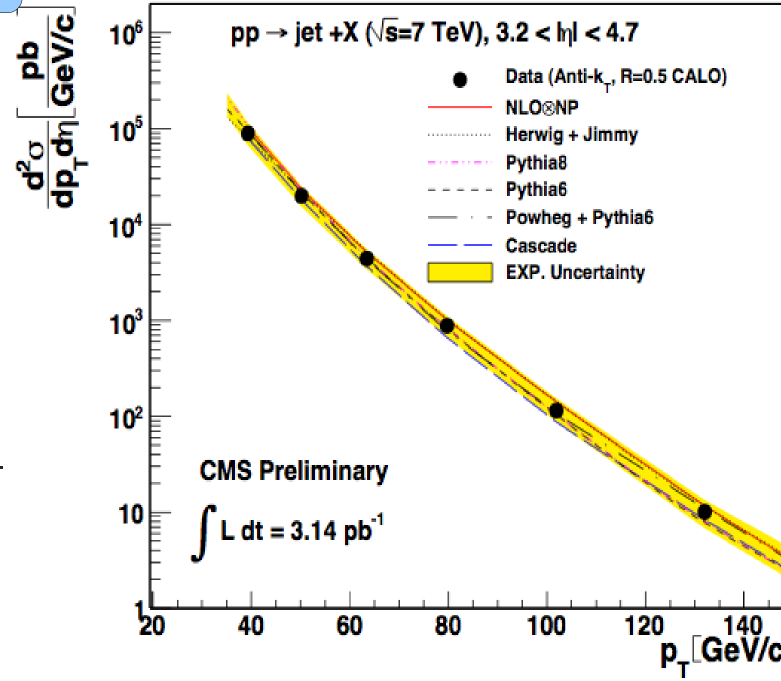


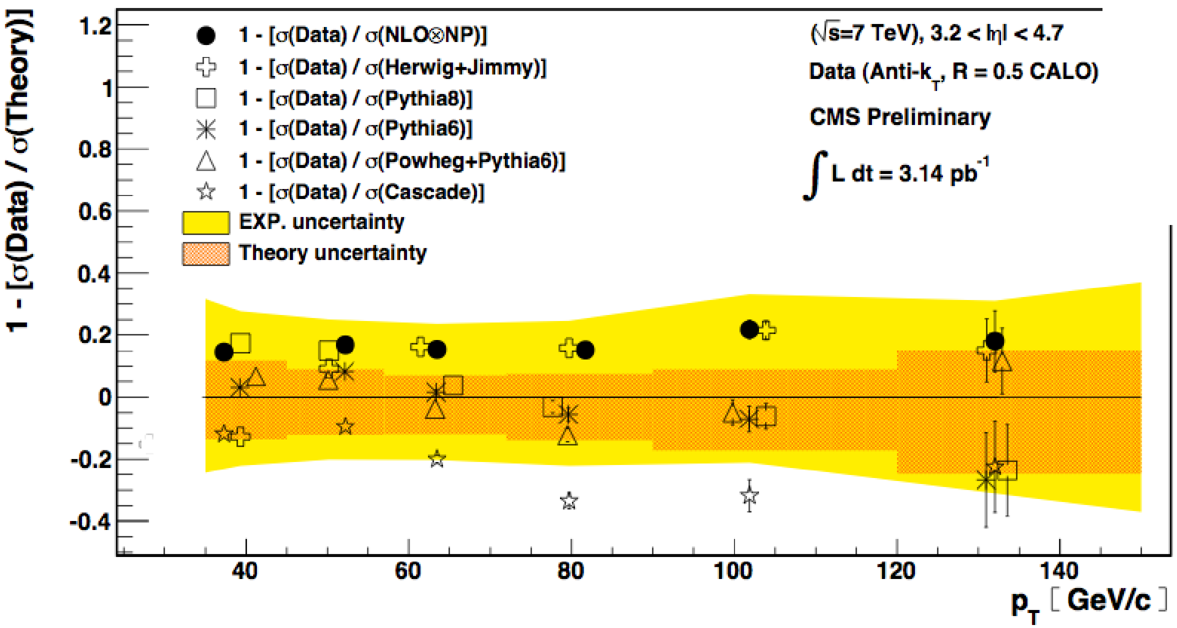


Results

Comparison to various hadron-level theoretical predictions

- NLO – DGLAP: works fine
- MC calculations with parton shower & hadronisation, also describe the shape & normalization
- NLO + parton shower also works fine.
- CCFM calculation (CASCADE) uses a completely different approach describes the spectrum & shape.



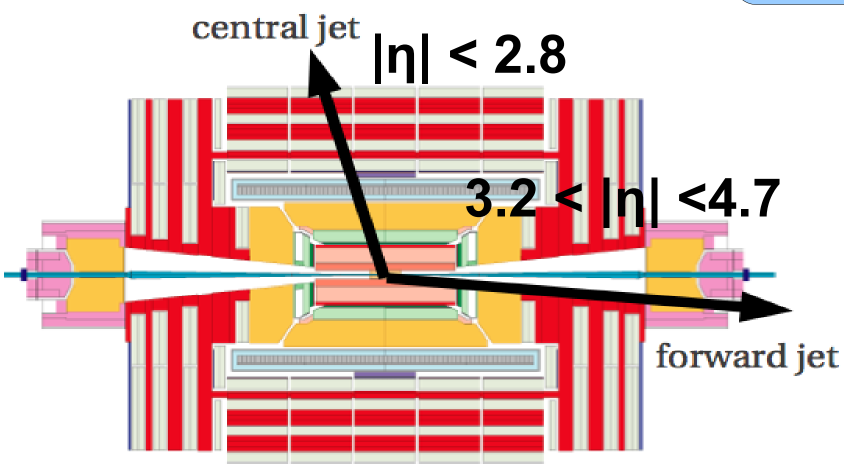


- With the inclusive measurement we have a **benchmark** for comparison with theory
- But it is too inclusive with the present uncertainties in order to see the differences.

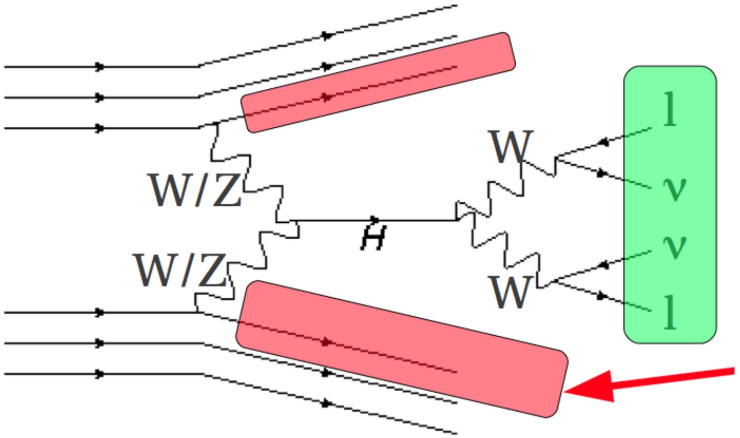
Simultaneous Production of Fwd.+Central Jets

CMS PAS FWD-10-006

More differential measurement: 1 event characterized by the presence of two jets: **1 central + 1 forward**



- Gain information on MPI & multi-jet production
- Allow to study different types of parton radiation dynamics (DGLAP, BFKL or CCFM)
- Understanding the dynamics of fwd. jet production: essential for the control of the backgrounds in searches of the Higgs boson produced via VBF mechanism.
- VBF cross section, is fundamental to understand the EWSB mechanism



Data corrected to hadron level

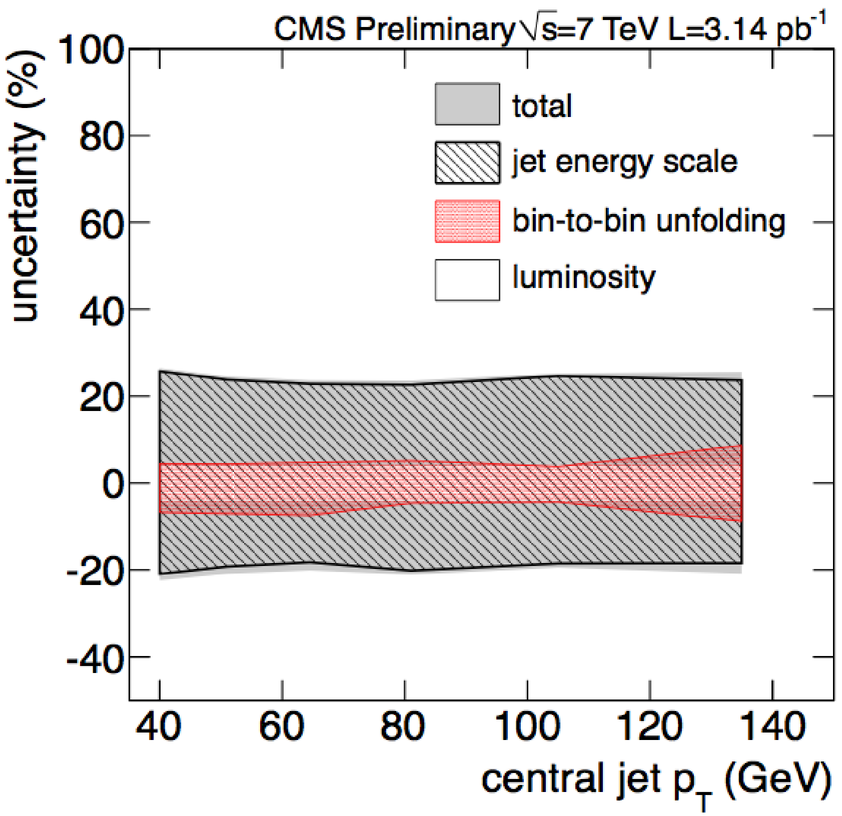
$$\frac{d\sigma}{dp_T^{central}\,d\eta^{central}\,dp_T^{forward}\,d\eta^{forward}}$$

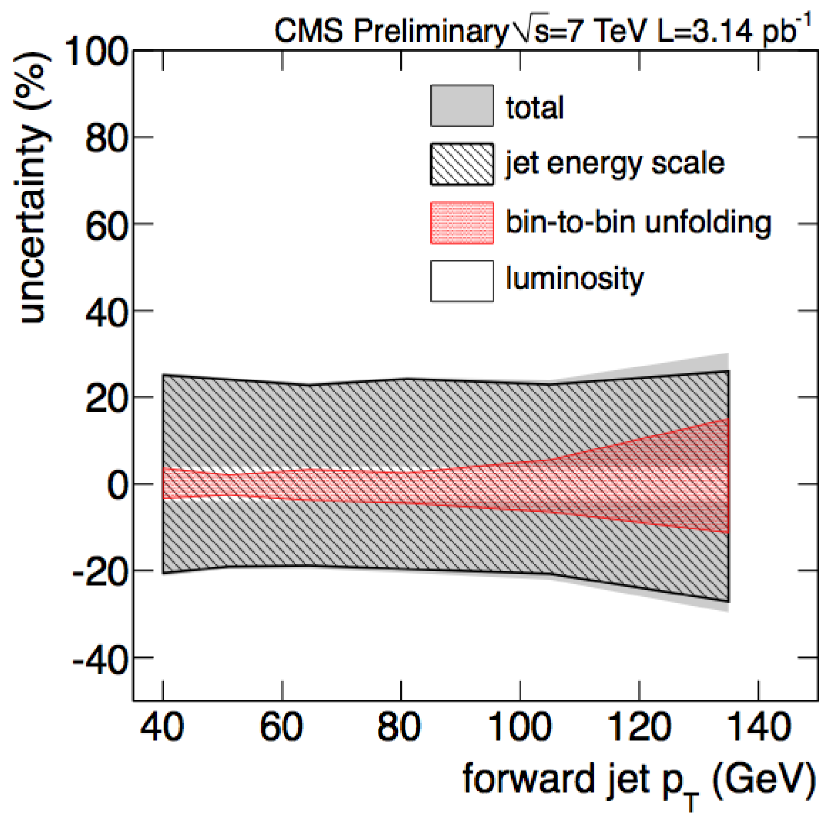
$$\frac{d\sigma}{dp_T^{central}\,d\eta^{central}}$$

$$\frac{d\sigma}{dp_T^{forward}\,d\eta^{forward}}$$

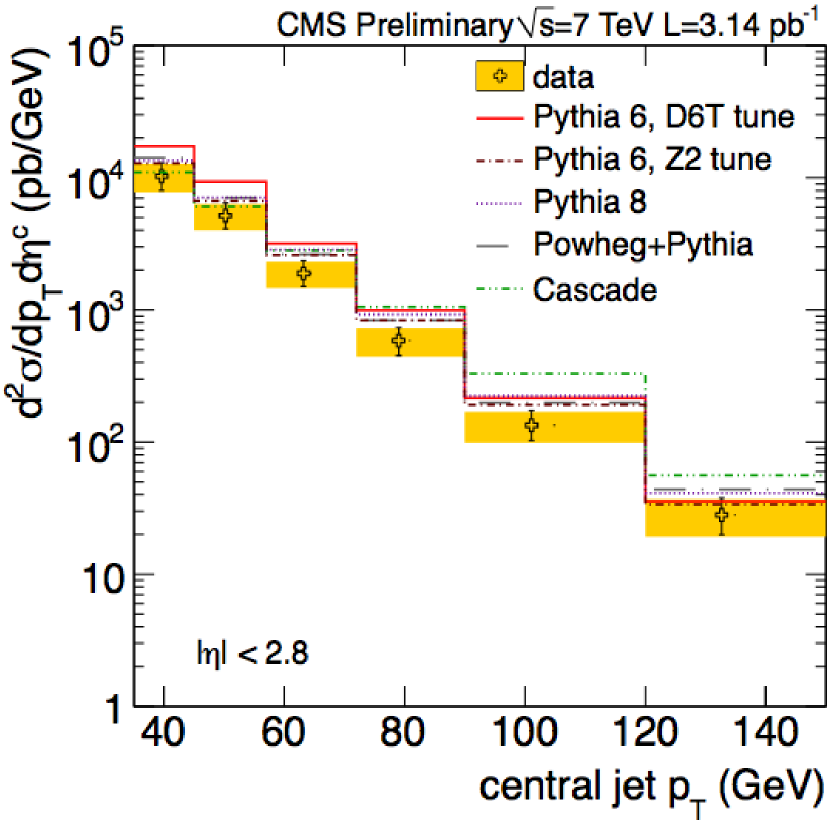
Systematics: Experimental Uncertainties

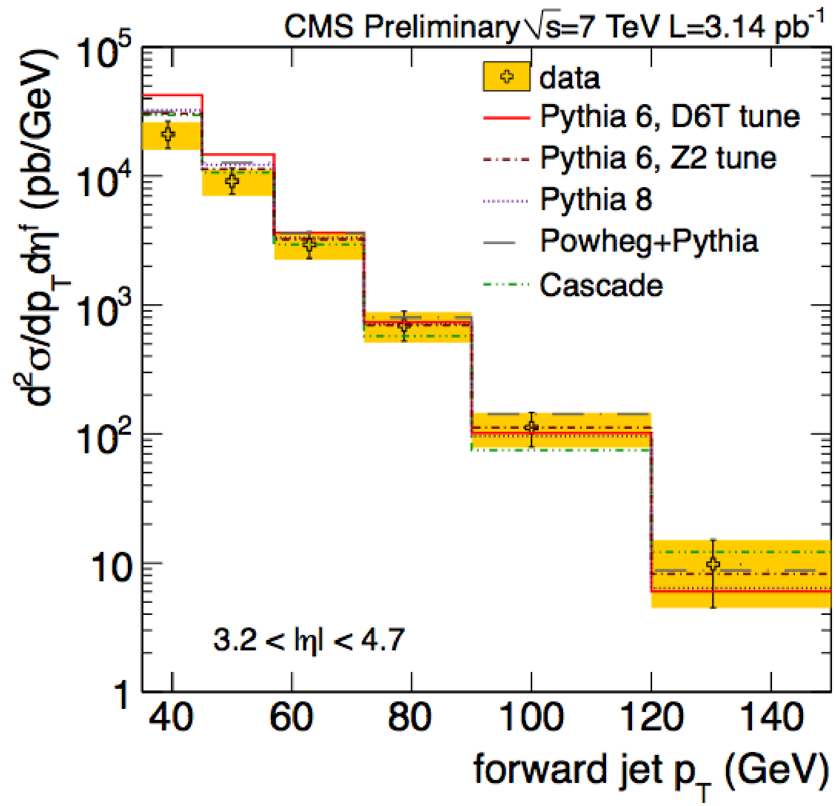
Absolute jet energy scale	~25%
p_T resolution and unfolding method	< 5%
Luminosity	~4%





Forward - Central Jets: Results

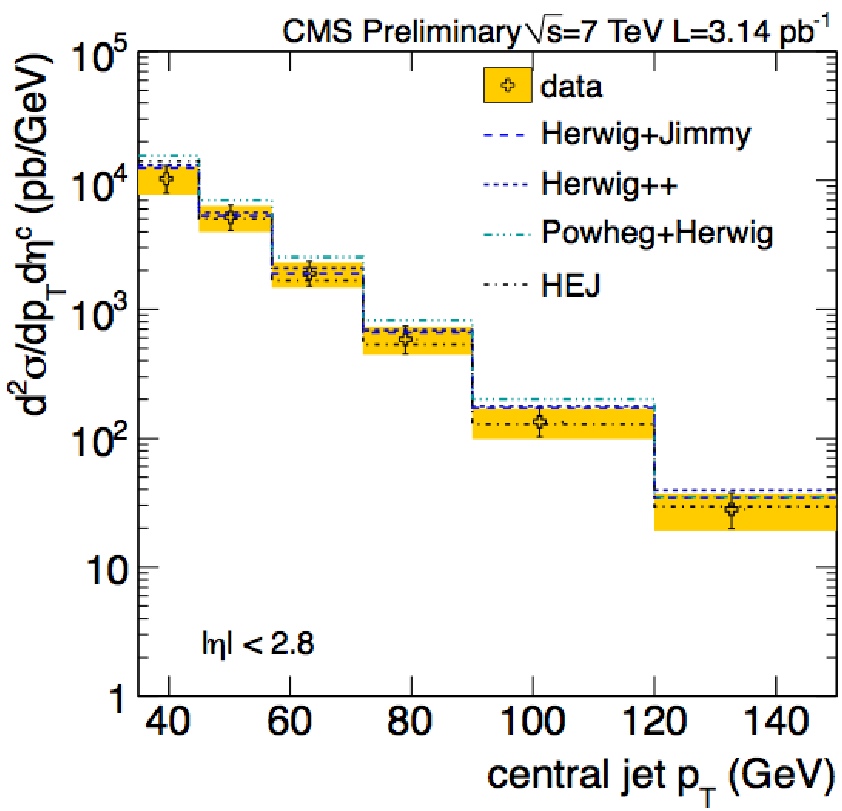


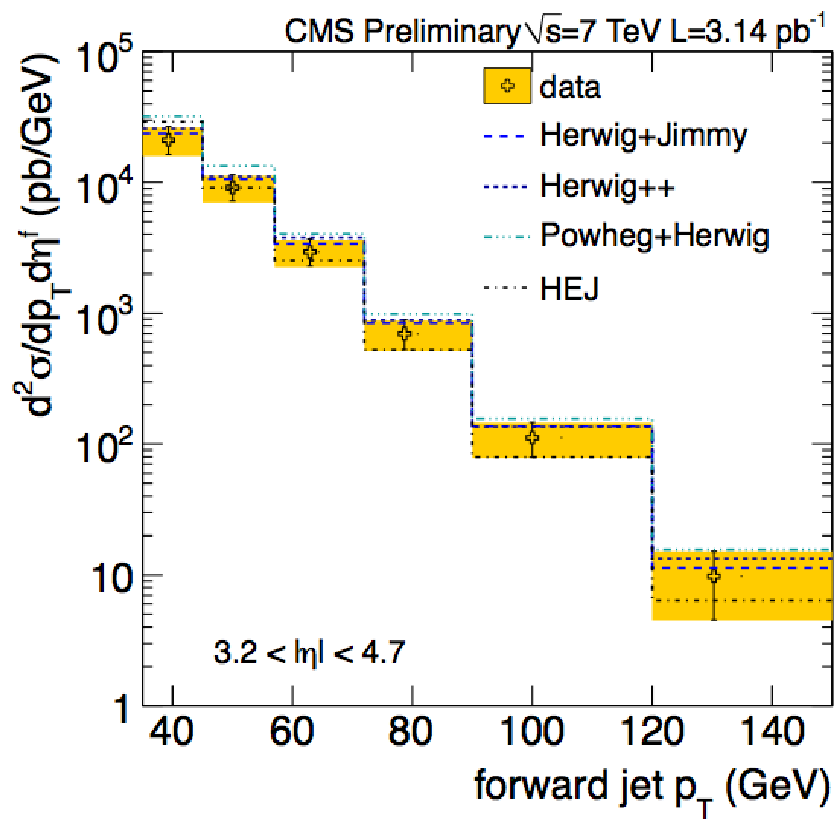


- Fwd. p_T spectrum falls more (over 3 orders of magnitude) compared to central p_T.
    - This behaviour is reproduced by theory predictions.
- None of the predictions can describe the full spectrum.
- Including NLO contributions (Powheg) to both parton showers increases data/theory disagreement

Forward - Central Jets: Results

Comparison to various hadron level theoretical predictions





- Herwig reproduces better shape and absolute normalization
- Herwig without NLO is not so reliable as Powheg
- HEJ with multijet topologies in good agreement

Conclusions

Energy Flow

- Measured in the forward region $3.15 < |\eta| < 4.9$, @$\sqrt{s}$ = 0.9 and 7 TeV
  - Energy in forward region is significant from 50 - 300 GeV as seen in energy flow.
  - Strong dependence seen on c.m.e.: energy rises with c.m.e. & η
  - MPI is needed to describe the energy flow
    - Models without MPI cannot account for the energy flow
  - The significant energy seen for dijet and W/Z events
    - Correlations between charged particles and fwd. energy flow is non trivial.

Forward Jets

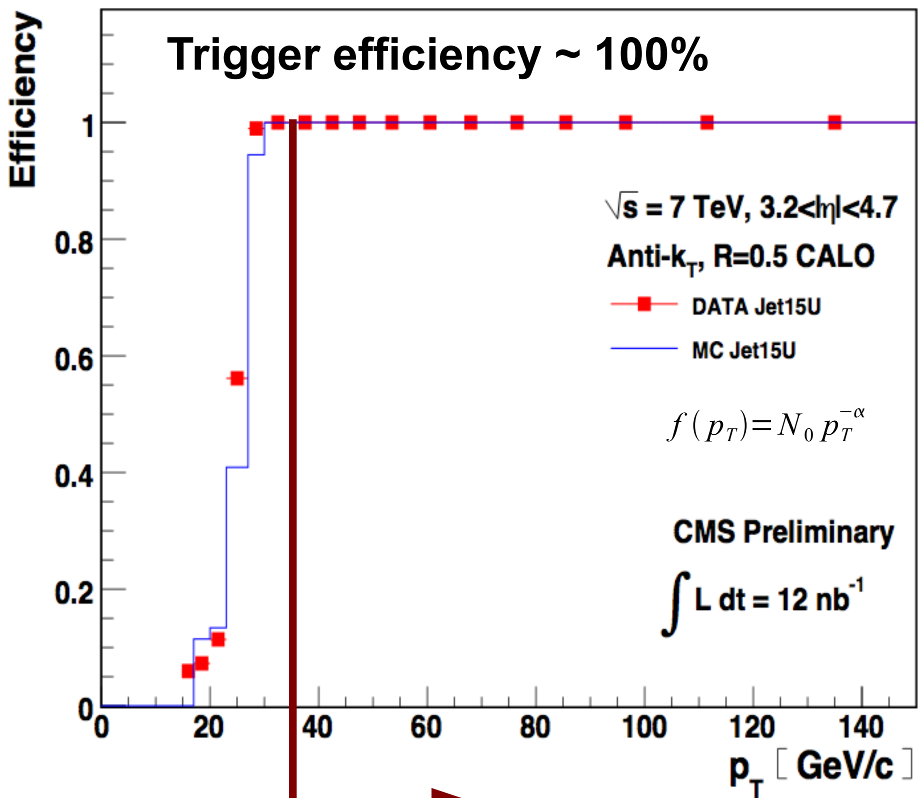
- Going from energy flow to fwd. jets, the reasonable description of inclusive jet spectra is seen.
  - However, asking for a central jet in addition, the cross section shows interesting behaviour: fwd. jet spectra fall steeper than central jet spectra
- Description of both fwd.& central jets is non trivial and not all models which describe well the inclusive fwd. jet describe the fwd. - central jets.
- The measurements can be used for tuning the MPI parameters (energy flow), whereas the jet xsection measurements tell about the perturbative behavior of parton radiation, and can be compared with BFKL/CCFM and DGLAP like calculations (even to NLO)

Backup

Analysis Strategy

Hadron level cross section of forward jets

$$\frac{d^2\sigma}{dp_T d\eta} = \frac{C_{unfold}}{\mathcal{L}} \cdot \frac{N_{jets}}{\Delta p_T \cdot \Delta \eta}$$



p_T > 35 GeV

- **C_{unfold}** : bin-by-bin correction factor from detector to hadron level (trigger eff., event clean-up, jet-ID cuts & JER)

MC bin-by-bin unfolding

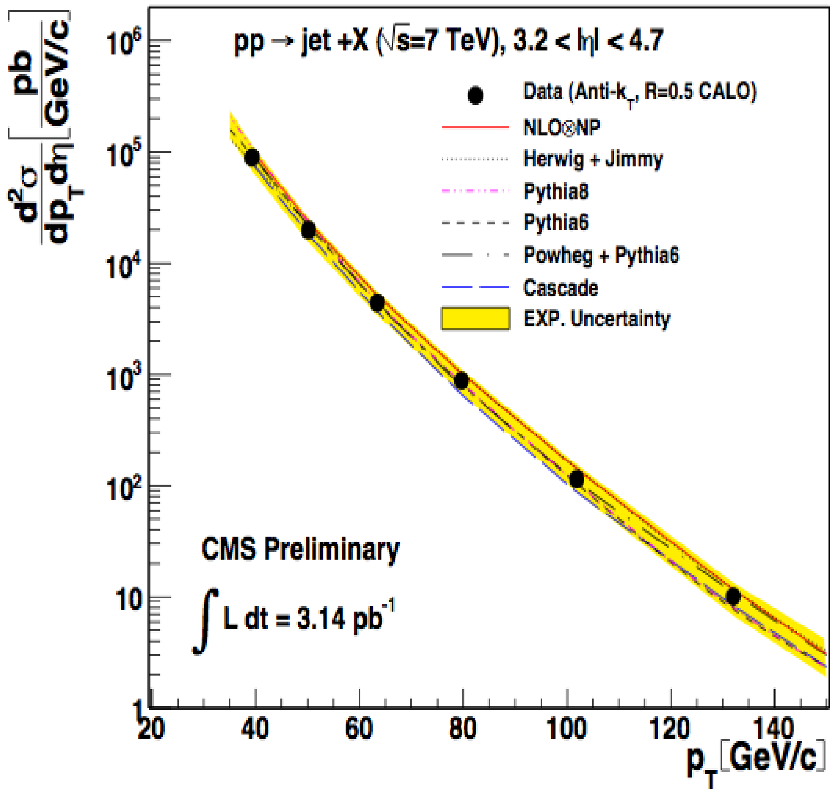
$$C_{unfold} = \frac{N^{MC}(\ E_{had}^{MC} \in bin\ i)}{N^{MC}(\ E_{det}^{MC} \in bin\ i)}$$

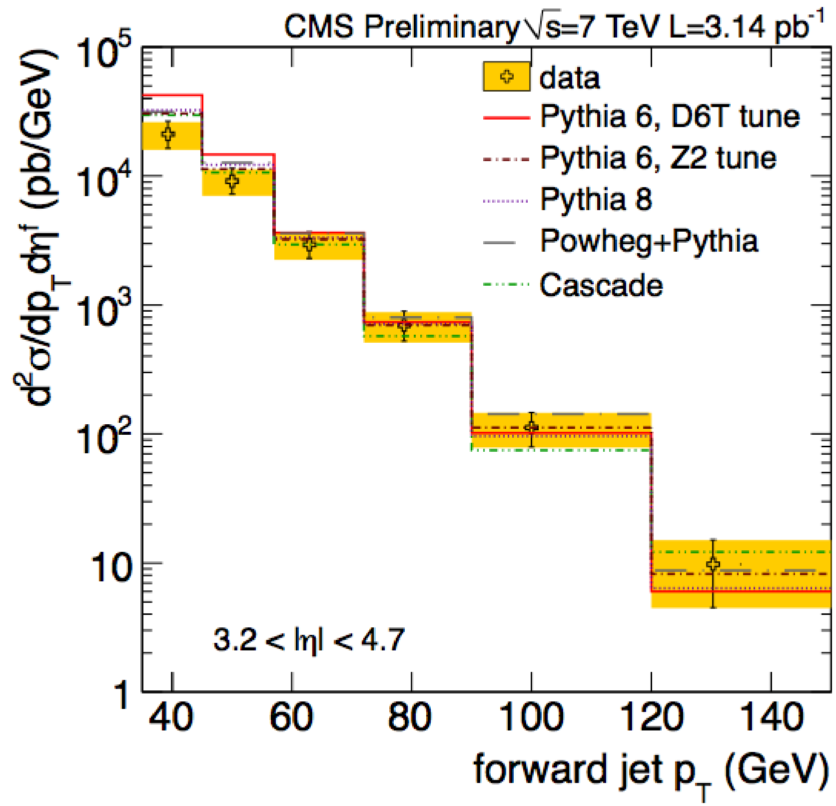
Ansatz bin-by-bin method

- Convolution of hadron level distribution with a gaussian smearing that simulated JER and fit to data

$$f(p_T) = N_0 \cdot p_T^{-\alpha} \cdot \left(1 - \frac{2\cosh(y_{min})\, p_T}{\sqrt{s}}\right)^{\beta} e^{(-\gamma/p_T)}$$

Forward - Central Jets: Results





- Comparison of fwd. -central jets with the Inclusive fwd. jets

Energy Flow: Uncertainties

- **Energy scale uncertainty:** 10%
- **Model dependent systematic uncertainties**

Estimated by using different models for the bin-by-bin corrections

Energy flow in Minimum Bias events: 3 – 10%

Energy flow in dijet events: 7 – 20%

- **Uncertainties from**
  - **Position of primary vertex**
  - **Channel-by-channel miscalibration**
  - **HF noise cut**
  - **Hits in the PMT read-out part**
  - **Corrections for geometric uncertainties**

Background (beam gas, pileup) add up to < 5%.

- **Total systematic uncertainty**
  - ***Energy flow in Minimum Bias events: 11 – 14%***
  - ***Energy flow in dijet events: 13 – 22%***
- **Statistical uncertainty: < 0.1%**

Event Selection

- LHC collision data sets with pp interactions @ 0.9 and 7 TeV.
- @ least 1 reconstructed primary vertex (PV) to reject non-IP collision events.
- Position of PV: required to be consistent with the beam spot centre to within 15 cm in z direction and have at least three tracks associated with it.
- Remove the beam induced background events producing an anamalous large number of pixel hits (require > 10 tracks and 25% purity)

$$E_{FLOW}(dijet) = \frac{1}{N_{dijet}} \frac{\Delta E}{\Delta \eta}(dijet)$$

$$E_{FLOW}(minbias) = \frac{1}{N_{minbias}} \frac{\Delta E}{\Delta \eta}(minbias)$$

- **Minimum Bias Sample:** All events trigger with MB trigger activity on both sides of IP + vertex reconstructed.

- **Dijet Sample** **:** Jets are reconstructed by means of the anti-kT jet algorithm (with R=0.5)

  $p_T > 8$ GeV for 0.9 TeV
  $p_T > 20$ GeV for 7 TeV

Monte Carlo: Tunes

		D6T (108)	DW (103)	Pro-Q20 (129)	P0 (320)
pdfs		CTEQ6L	CTEQ5L	CTEQ5L	CTEQ5L
p_{t0}	PARP(82)	1.84 GeV	1.9 GeV	1.9 GeV	2.0 GeV
E_0	PARP(89)	1.96 TeV	1.8 TeV	1.8 TeV	1.8 TeV
ϵ	PARP(90)	0.16	0.25	0.22	0.26
fragmentation	standard	standard	standard	professor LEP tune	professor LEP tune
Q^2_{max} factor (ISR)	PARP(67)	2.5	2.5	2.65	1.0
Q^2_{max} factor (FSR)	PARP(71)	4.0	4.0	4.0	2.0

- LEP data revisited better fragmentation tunes.
- More Tevatron data included better underlying-event tunes.
- LEP + Tevatron tunes combined: new generation of tunes.
- Tunes available for BOTH new and old MPI models + Systematic HARD / SOFT / CR / PDF variations (incl LO)

- Different pdfs, cuts for ISR and FSR, fragmentation model
  - "Hard Interaction"+ **p_T- ordered** ISR+FSR
- MPI create kinks on existing strings, rather than new strings
  - p_T-ordered MPI