Measurements of forward energy flow and forward jet production with CMS

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on behalf of the **CMS** Collaboration

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Outline

Introductory matter

↪ Why study the forward region?
↪ Low-x physics experimentally
↪ CMS experiment

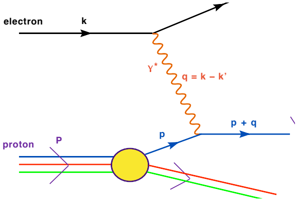
CMS results

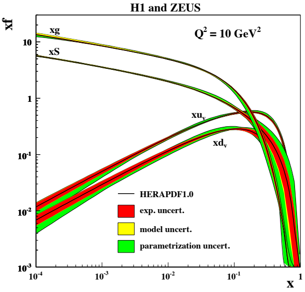
↪ forward jets (CMS PAS FWD 10-003)
↪ central-forward jets (CMS PAS FWD 10-006)
↪ inclusive and exclusive dijet ratio (CMS PAS FWD 10-014)
↪ forward energy flow (CMS PAS FWD 10-002, CMS FWD 10-011)

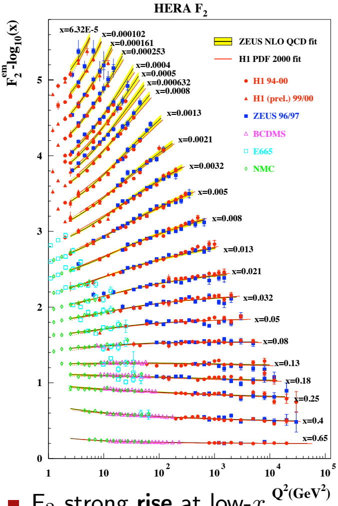
Summary/conclusions

Probing parton distribution with DIS: HERA results

- $x = x_{parton}/x_{hadron}$: momentum **fraction** carried by parton
- $Q^2 = -q^2$: **resolving** power of the exchanged boson







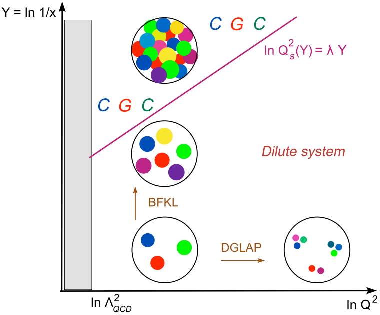
- F_2 strong **rise** at low-x
- $\frac{\partial \ln F_2}{\partial \ln Q^2} \sim$ **gluons**

Why study the forward region? Parton (x, Q^2) evolution

- **increasing** Q^2 ($Q^2 > Q_s^2$): DGLAP $\Rightarrow$ evolution towards the **dilute** system
- **decreasing** x ($Q^2 < Q_s^2$): BFKL $\Rightarrow$ evolution towards the **high density** system
- linear evolution equation **doesn't work** at low-x: non-linear g+g fusion, unitarity violation

- Saturation criterion
  - number of partons per unit area $\rho \sim \frac{xG(x,Q^2)}{\pi R^2}$
  - recombination cross-section $\sigma_{gg\to g} \sim \frac{\alpha_s}{Q^2}$
  - recombination if $\rho\sigma_{gg\to g} \geq 1$ ($Q^2 \leq Q_s^2$)
  - **saturation scale** $Q_s^2 \sim \frac{\alpha_s xG(x,Q_s^2)}{\pi R^2}$

- **CGC** (Color Glass Condensate)
  - effective field theory for high energy limit
  - gluons overlap for momenta $\sim Q_s$
  - non-linear JIMWLK evolution equation



Low-x proton PDF experimentally

- most of our current knowledge comes from **F**$_2$ studies:

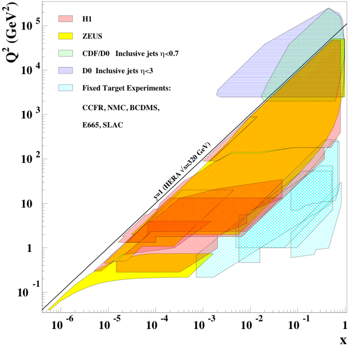
$$\frac{\partial F_2(x,Q^2)}{\partial \ln(Q^2)} \propto \alpha_s(Q^2) x g(x,Q^2)$$

- large **uncertainties** for $x < 10^{-2}$ at moderate Q^2 (<5 GeV^2)
- **low**-x = **forward** rapidity

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

every 2 units of y: x_2^{min} **decreases** by ∼10

- **LHC**: p+p at 14 TeV
  - high $\sqrt{s} \Rightarrow$ very small x
    for y <5, M<10 GeV: x ∼10^{-6}-10^{-7}
    (70 times lower than p+p at RHIC)
  - saturation momentum Q$_s$ ∼2 GeV
  - very large perturbative cross section



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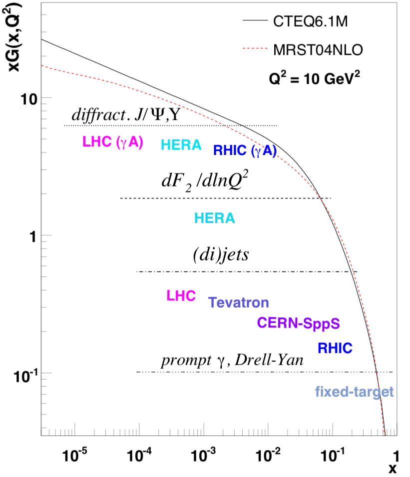


CMS experiment

CMS: dedicated to explore physics at the **TeV scale**

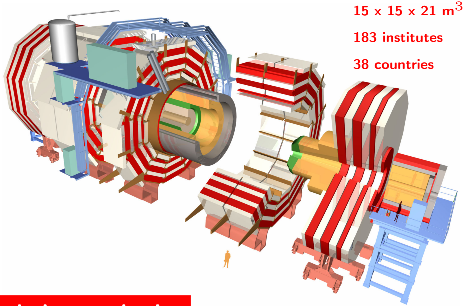
- **prime** goals: mechanism of electroweak symmetry breaking and provide evidence of physics beyond SM
- also **SM** measurements : QCD, B-physics, diffraction, top quark, and electroweak physics topics such as the W and Z boson
- Detector:
  - inner **tracking** system for $|\eta| < 2.5$
  - **calorimeters**
    - electromagnetic for $|\eta| < 3$
    - hadronic for $|\eta| < 5$
  - **muon** system for $|\eta| < 2.4$
  - few **forwards** detectors
    - CASTOR for $-6.6 < \eta < -5.2$
    - ZDC for $|\eta| > 8.4$
  - **magnet**: B=3.8 T

$\sim$ 2000 members

15 x 15 x 21 m^3

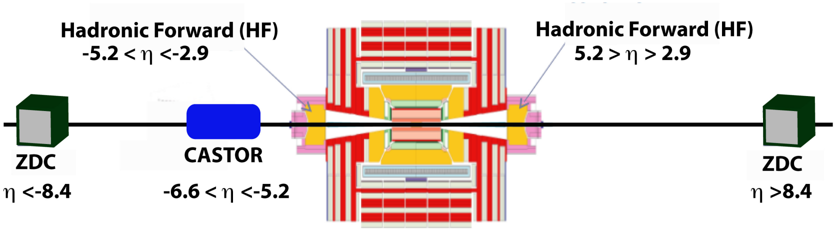
183 institutes

38 countries



Ideally suited to study low-x physics

Going forward with CMS



- **HF**
  - rapidity coverage: **2.9** $< |\eta| <$ **5.2**
  - at 11.2 m from IP
  - steel absorbers and embedded radiation -hard quartz fibers for fast collection of Cherenkov light
  - segmentation in η et ϕ: 0.175 $\times$ 0.175
- **CASTOR**
  - rapidity coverage: **-6.6** $< \eta <$ **-5.2**
  - at 14.3 m from IP
  - alternate tungsten absorbers and quartz plates
  - segmentation in ϕ: 16 sectors
  - 14 modules (2EM+12HAD)
- **ZDC**
  - rapidity coverage: $|\eta| >$ **8.4**
  - at 140 m from IP
  - tungsten/quartz Cherenkov calorimeter with separated EM and HAD sections
  - detection of neutrals (γ, π^0, n)

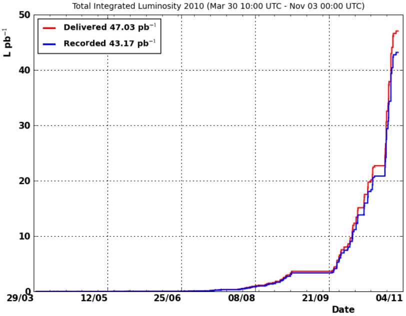
CMS has unprecedented calorimetric coverage in pseudo-rapidity

Basic events selection for p+p collisions

- only runs with **stable beam** and **fully operating detector** are used
- **removing** events which **timing** was **not consistent** with the LHC bunch crossing
- **removing beam halo** events
- **rejection** of **non-collision events**: require at least 10 tracks with 25% of the tracks to be high purity
- **primary vertex** reconstructed from at least 5 tracks with $|z| < 24$ cm

- + **additional** criteria relevant for **each** discussed analysis

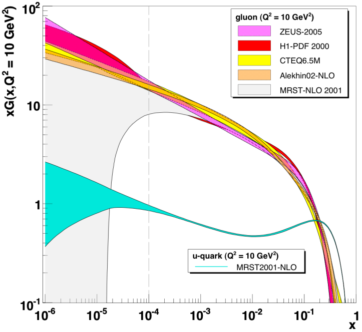
- total integrated luminosity vs time



- **excellent** LHC performances at 2010

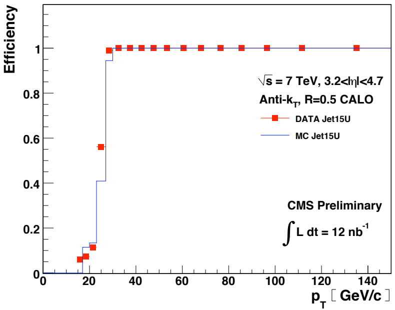
Forward jets: motivation and jet selection criteria

- **low-x gluon** density in the proton is poorly known ($x = \mathrm{p}_{parton}/\mathrm{p}_{hadron}$)



- **constrain low-x gluon** PDFs via $d\sigma = PDF(x_1, Q^2) \otimes PDF(x_2, Q^2) \otimes d\sigma(qg \rightarrow jet)$
- forward jet production in **CMS calorimeters**: for HF: $x \sim 10^{-4}$

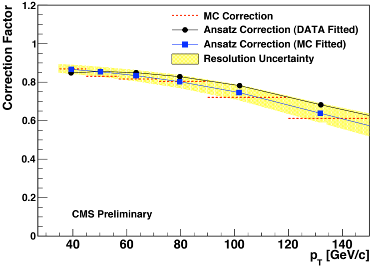
- events firing the single-jet trigger with uncorrected jet $p_T > 15$ GeV/c
- jets **corrected** for detector response



- efficiency of 100% for $p_T > 30$ GeV/c
- used in analysis are jets with:
  35 GeV $< p_T <$ 120 GeV
  $3.2 < |\eta| < 4.7$

Forward jets: correction factors and cross section

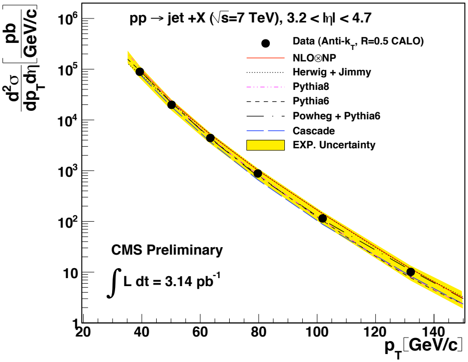
- MC bin-by-bin vs Ansatz bin-by-bin



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

- N_{jets}: nb of jets counted in a bin
- $\mathcal{L}$: integrated luminosity
- ε: efficiency of trigger, event clean-up and jet-ID cuts
- C_{corr}: correction factor to the hadron level
- Δp_T and $\Delta\eta$: p_T and η bin sizes

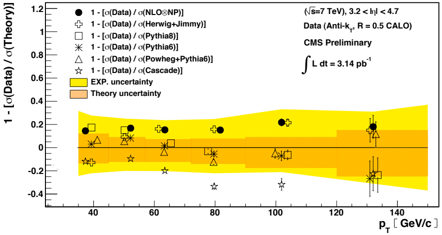
- corrected cross section



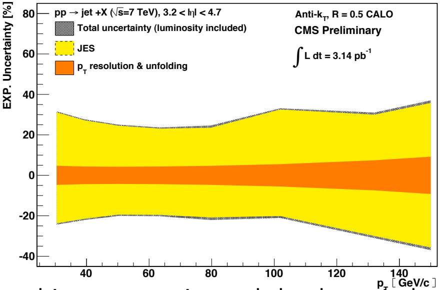
- within the current experimental and theoretical uncertainties, the various generators **reproduce** globally well the measured spectrum

Forward jets: systematic errors and comparison to theory

- data vs theory



- systematic uncertainties



- fractional difference between the experimental jet cross section and the theoretical predictions. The predictions **agree reasonably** with the measurements within the theoretical and experimental uncertainties. CASCADE appears to have a more "concave" spectral shape than the data in the intermediate p_T region
- systematic uncertainties of $\sim \pm 25\%$ **dominated** by the absolute jet energy scale. **Reduction** of uncertainties is needed in order to **extract** more precise conclusions
- **first** test of perturbative QCD calculations in the forward region at the highest energies ever, as well as a first cross-check for QCD background estimates of other scattering processes, such as vector boson fusion, characterized by forward/backward jet production

Central-forward jets: motivation and jet selection

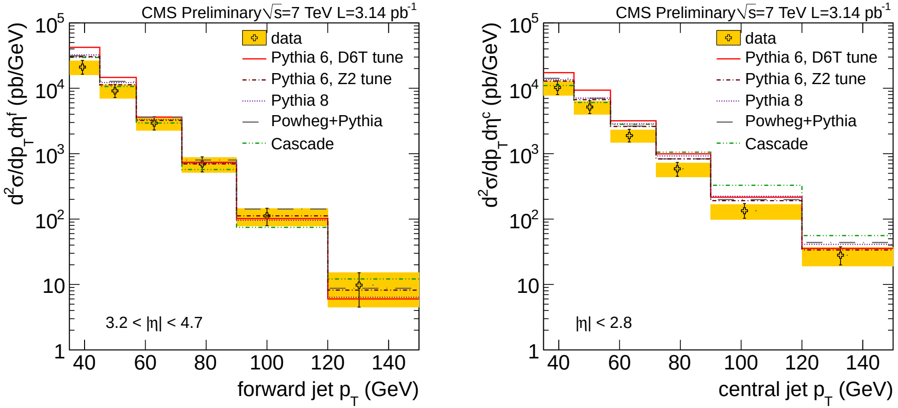
Measurement of **simulataneous** production of **forward** and **central** jets

- **multi-parton** interaction
- **multi-jet** production
- **parton** radiation
- understanding the dynamics of forward jet production is essential in controlling the **backgrounds** in Higgs searches via vector-boson fusion

- **central** / **forward** region: $|\eta| < 2.8$ / $3.2 < |\eta| < 4.7$
- jet $p_T > 35$ GeV
- trigger **efficiency** of 100%

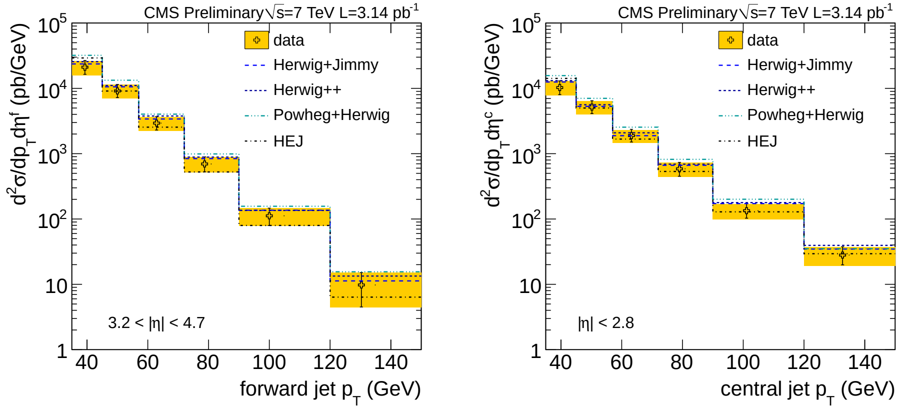
- **correction** for detector effects using MC-driven bin-by-bin unfolding
- **systematic uncertainty** 30% with **dominant** source from jet energy scale uncertainty (25%)

Central-forward jets: results (1)



- Pythia 6 (D6T): Q^2-ordered showering; Pythia 6 (Z2); Pythia 8: p_T-ordered showering, Powheg + Pythia: NLO matched with HERWIG; CASCADE: CCFM approach (parton evolution in Q^2 and in x)
- all **Pythia** tunes **overestimate** the jet spectra
- large **disagreement** for central jet spectrum and lowest p_T bins at forward region
- **Powheg + Pythia**: **describe** well data in central region
- **CASCADE**: problem with normalization for forward jets and shape for central

Central-forward jets: results (2)



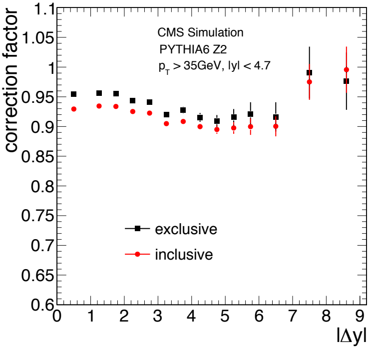
- **HERWIG**: angular ordering of soft gluon radiation; **HEJ**: all-order summation of the perturbative terms dominating the production of well-separated multiple jets at hadron colliders
- **Herwig+Jimmy** and **Herwig++**: **describe** data within the uncertainty
- HEJ (at parton level): problem with shape for forward

Incl/Excl dijets: motivation and jet selection

- ratio of **inclusive** to **exclusive** dijet production $R = \frac{\sigma_{incl}}{\sigma_{excl}}$ as a function of the absolute distance in rapidity $|\Delta y|$

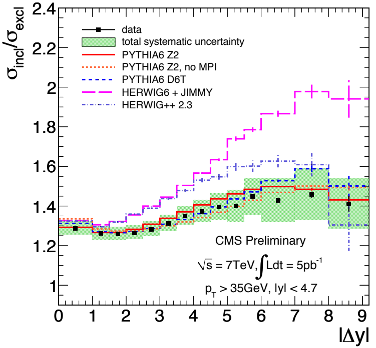
- search for **BFKL** effects in the dijets
- **inclusive jet** production described by NLO pQCD
- **dijet** production well described for moderate values of $|\Delta y|$

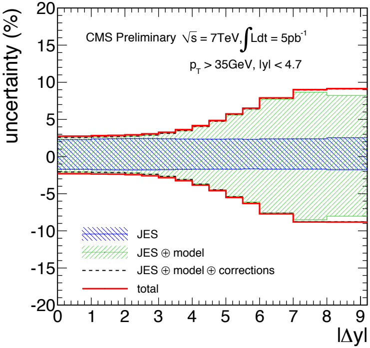
- **inclusive sample**: all pairwise combinations of jets with p_T threshold
- **exclusive sample**: events with only two jets above p_T threshold
- jets with $p_T > 35$ GeV and $|y| < 4.7$, range of rapidity separation $|\Delta y| <9.2$
- trigger efficiency (single jet and forward-backward jet) is 100% for $p_T > 35$ GeV



- bin-by-bin correction method
- ratio of the distributions at stable particle level to the detector level

Incl/Excl dijets: results and uncertainties





- σ_{incl} is 1.2–1.5 times larger than σ_{excl}
- $\frac{\sigma_{incl}}{\sigma_{excl}}$ **rises** with **increasing** $|\Delta y|$: phase space opens up for hard parton radiation
- **decreases** at highest $|y|$: kinematic limitations of the production of third jet
- PYTHIA6 **agree** with data
- HERWIG predicts **larger** $\frac{\sigma_{incl}}{\sigma_{excl}}$
- test **sensitivity** to **underlying** event tuning

- finite **resolution** in p_T and y: $< 1\%$
- **jet calibration**: $< 3\%$
- errors on **corrections**: $< 3\%$
- **model dependence** of the correction factors: $< 8\%$
- **total** uncertainty: $< 9\%$

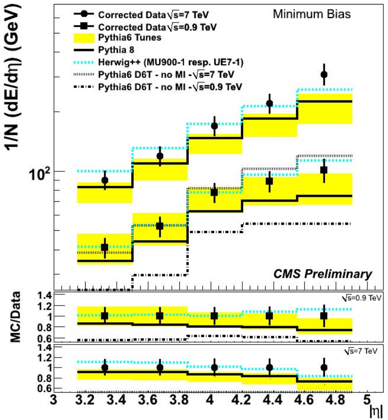
Forward energy flow: motivation

- improve the understanding of the **parton radiation** in the initial state
- study the **multiparton interactions**, probes **underlying event** in a new way
- Monte Carlo: need **parameters** to be adjusted to describe the measurements
- the extrapolation to larger energies is **very uncertain**

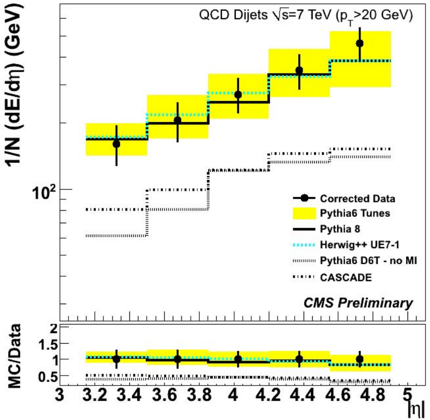
Energy flow in the forward region has never been measured at a hadron collider

Forward energy flow: results

- **Minimum Bias** sample



- **QCD** sample (with a dijet system at central part, $E_{T,jet} >$20 GeV)



- **correction factors** to hadron level of the order of 1.5–2.0
- points: the corrected data, yellow bands: obtained by taking the max and min of the variations of the different Pythia 6 tunes
- **systematic uncertainty** 11-14% and 13-22% for the minimum bias and dijet analyses

Forward energy flow: comments

- the energy flow in the forward region is measured for the **first time** in hadron-hadron collisions for **minimum bias** events and events having a **hard scale** defined by a dijet system in the central region
- the **forward** energy flow is significantly **higher** in the dijet measurement compared to the minimum bias measurement
- the **increase** in energy flow in the forward region with increasing centre of mass energy is significant and is reproduced by the Monte Carlo for minimum bias and dijet events
- it is shown that **multiple interactions** are **needed** in order to describe the data. The MC predictions **without multiple interactions** (Pythia 6 run without multiple interactions and CASCADE) significantly **undershoot** the data
- **none** of the MC simulations **can describe all energy flow measurements**, and in general the MC generators produce a somewhat too flat energy flow distribution for the minimum bias data. Though, if considering the spread of the Pythia 6 tunes as a model uncertainty, Pythia 6 describes all data. The large spread of the Pythia 6 tunes illustrates that the forward data can be used as a complementary to other UE measurements in order to improve the MC generators. The presented data can be used to further constrain **underlying event** parameters and can be included in future MC tuning

Summary

- general
  - non-linear QCD evolution must be taken into account in the high energy limit
  - first signs of non linear QCD dynamics in HERA and RHIC
  - CMS detector is working extremely well and taking a high quality data
- inclusive forward jets
  - all predictions describe the measurement within the systematic uncertainty
  - systematic uncertainty need to be decreased in order to have more precise comparison with theory
- central-forward jets
  - first measurement of simultaneous forward and central jet production
  - wide spread of Monte Carlo generators predictions
  - data are described (within the uncertainty) by HERWIG
- inclusive and exclusive dijet ratio as a function of rapidity separation
  - inclusive dijet production cross section is larger than exclusive one
  - sensitivity to underlying event tunes seems to be small compared to experimental uncertainty
  - measurement is described, within the experimental uncertainty, by PYTHIA
  - HERWIG predicts higher ratio for all rapidity domain
- forward energy flow
  - none of the MC generator can describe all types of the energy flow measurements
  - importance of the multiple interactions is demonstrated