Forward jets and energy flow with CMS at LHC

Magdalena Malek

University of Illinois at Chicago - CERN

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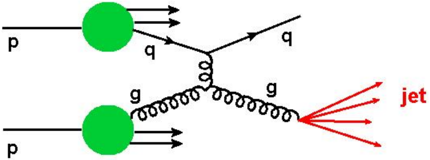
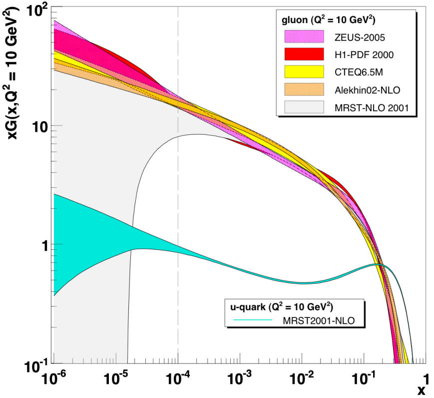
Outline

- Introduction
- Detector performances
- Ongoing analysis
  - Forward jets
  - Mueller-Navelet dijets
  - Energy flow
- Summary

Introduction

- **Low-x gluon** density in the proton is poorly known ($x = p_{parton}/p_{hadron}$)
- Forward jet production in **CMS calorimeters**:
  - HF: $x \sim 10^{-4}$
  - CASTOR: $x \sim 10^{-5}$
- **Forward** jet cross-sections **constrain low-x gluon** PDFs





$$d\sigma(pp \to \text{jet}) = \text{PDF}(x_1, Q^2) \otimes \text{PDF}(x_2, Q^2) \otimes d\sigma(qg \to \text{jet})$$

Motivation: forward jets

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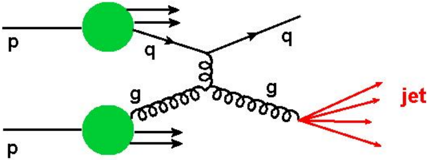

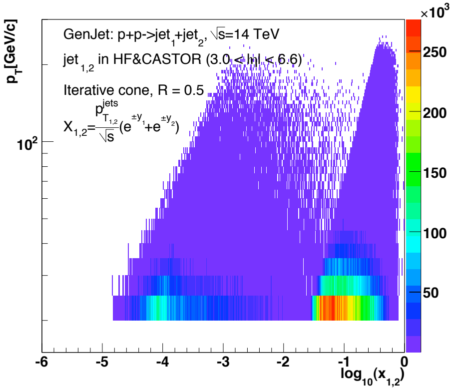

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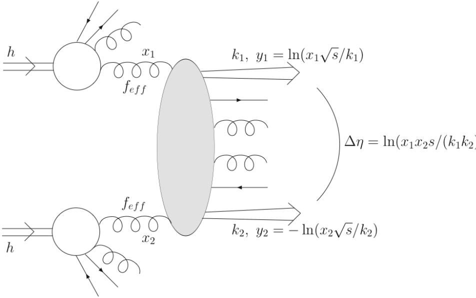
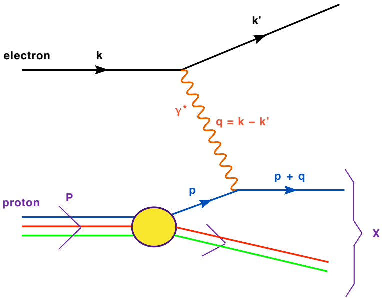
- **Mueller-Navelet dijets** with large η separation very sensitive to **low-x QCD** evolution (testing ground for BFKL)
  - **BFKL**: extra radiation between the 2 jets will **smear out** back-to-back topology
  - enhanced radiation partially compensated by gluon saturation ?
- **Increased azimuthal decorrelation** with increasing $\Delta\eta$ (w.r.t. DGLAP collinear-factorization)



- Probing parton distribution with **DIS**:
  $\hookrightarrow$ x: momentum **fraction** carried by parton
  $\hookrightarrow$ $Q^2 = -q^2$: **resolving** power



- **QPM**
  - static object composed of 3 valence quarks
  - no interaction between constituents
- **QCD** improved QPM
  - dynamic object with a very complicated structure
  - contains fluctuations smaller than its own size
- **CGC**
  - large lifetime of soft gluons
  - probe becomes more and more crowded
  - partons start overlapping and they recombine
  - non-linear evolution

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

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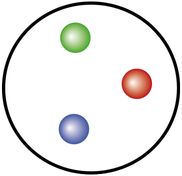

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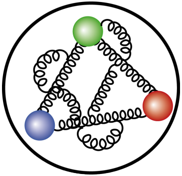

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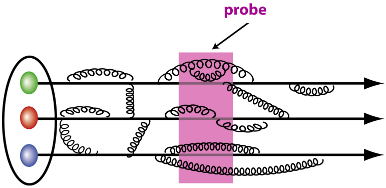

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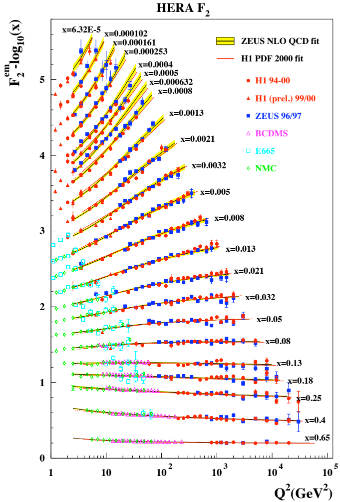

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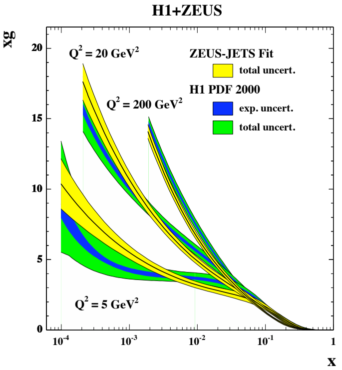


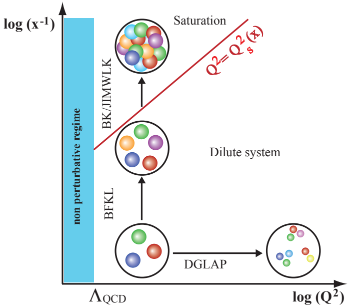
- **increasing Q^2** (Q^2 > Q$_s^2$): DGLAP ⇒ evolution towards the **dilute** system
- **decreasing x (Q^2** < Q$_s^2$): BFKL ⇒ evolution towards the **high density** system
- linear evolution equation doesn't work at low-x:
  - non-linear g+g fusion
  - unitarity violation

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** $Q_s^2 \sim \frac{\alpha_s xG(x,Q_s^2)}{\pi R^2}$

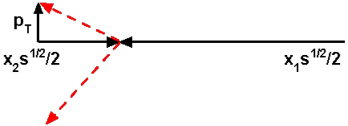
CGC

- effective field theory for high energy limit
- gluons overlap for momenta $\sim Q_s$
- non-linear JIMWLK evolution equation



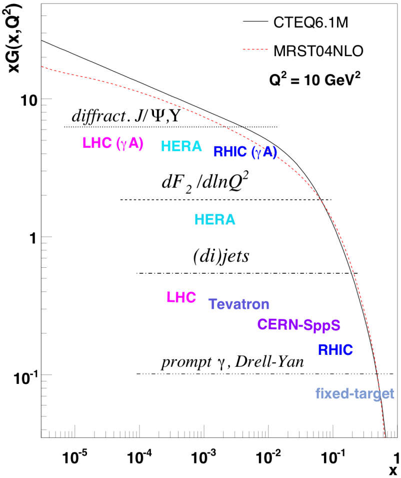
- **low-x = forward** rapidity in 2→2 process:

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



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

- Processes:
  - Drell-Yan: $p(p_1)+p(p_2) \to l\bar{l}+X$
  - prompt-γ: $p(p_1)+p(p_2) \to jet+\gamma+X$
  - di(jets): $p(p_1)+p(p_2) \to jet_1+jet_2+X$
  - heavy Q: $p(p_1)+p(p_2) \to Q+\bar{Q}+X$
  - diffractive $Q\bar{Q}$ (γp, γA)

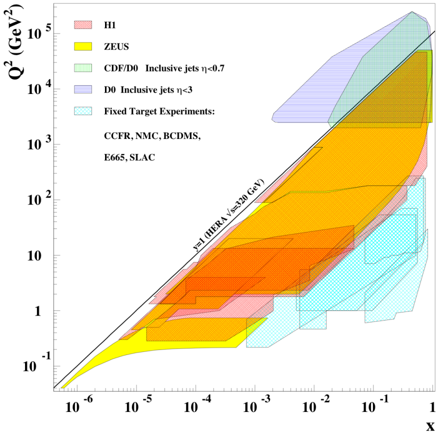


- most of our current knowledge comes from F_2 scaling violation:

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

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

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



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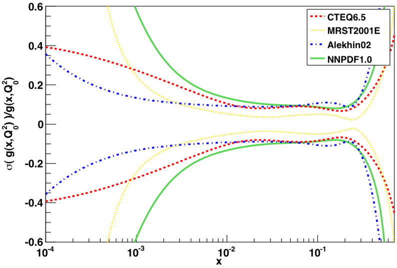
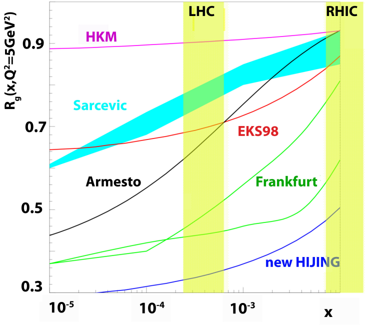


- current data from nuclear **F$_2$** and nuclear **Drell-Yan** (eA)
- **DGLAP analysis**: linear evolution + nuclear shadowing
  - shadowing: low-x gluon fusion
  - shadowing factor for PDFs:

$$R_g^A(x,Q^2) = \frac{f_g^A(x,Q^2)}{f_g(x,Q^2)}$$

- most data in **non perturbative** range (Q^2 <1-2 GeV^2): large uncertainties
- nuclear $xG(x,Q^2)$ **unknown** for x <10^{-2}
- **LHC**: Pb+Pb at 5.5 & p+Pb at 8.8 TeV:
  - x 30-45 times lower than Au+Au, d+Au at RHIC
  - saturation momentum Q$_s$ ~3 GeV
  - very large perturbative cross section



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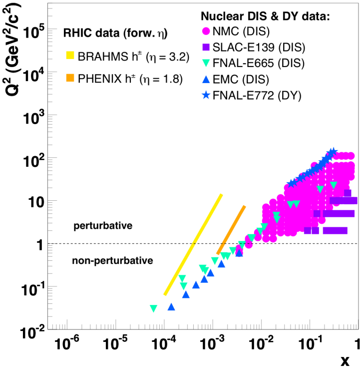

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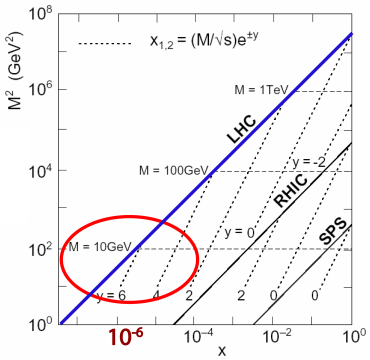
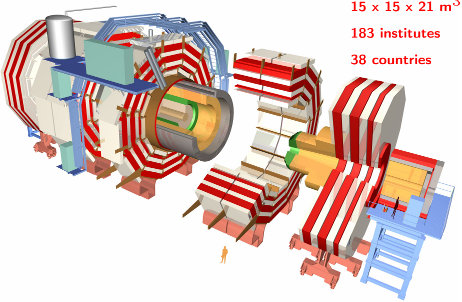


CMS: dedicated to explore physics at the **TeV scale**

- **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 ($|\eta| <2.5$)
  - **calorimeters** (electromagnetic: $|\eta| <3$, hadronic: $|\eta| <5$)
  - **muon** system ($|\eta| <2.4$)
  - few **forwards** detectors (CASTOR: -6.6$< \eta <$-5.2 and ZDC: $|\eta| >8.3$)

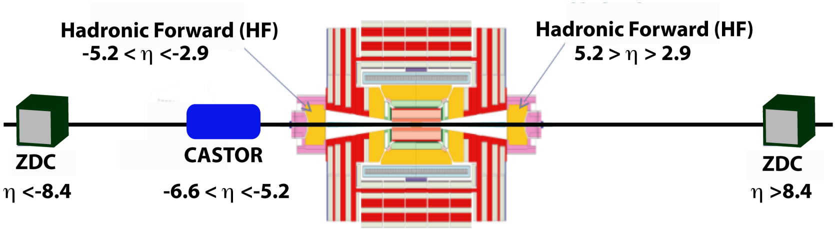


$\sim$ 2000 members

15 x 15 x 21 m^3

183 institutes

38 countries



- 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: 0.175×0.175
- 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 $\Rightarrow$ unprecedented calorimetric coverage in pseudo-rapidity

About jet analysis procedure

- jets with CMS:
  - **Calorimeter jets**: reconstructed using energy deposits in the electromagnetic and hadronic calorimeter cells, combined into calorimeter towers as inputs. A calorimeter tower consists of one or more hadron calorimeter (HCAL) cells and the geometrically corresponding electromagnetic calorimeter (ECAL) crystals
  - **Jet-Plus-Tracks jets**: allow to correct the energy and the direction of a calorimeter jet. It exploits the excellent performance of the CMS tracking detectors to improve the p_T response and resolution of calorimeter jets (tracking coverage extends up to $|\eta| \sim 2.4$)
  - **Particle Flow jets**: algorithm reconstruct, identify and calibrate each individual particle in the event by combining the information from all CMS sub-detector systems. PF particles are reconstructed as a combination of charged particle tracks and clusters in the electromagnetic and hadronic calorimeters, as well as signals in either of the two CMS pre-shower detectors and the muon system. As a result of the PF reconstruction, the inputs to the jet clustering are almost fully calibrated and the resulting higher level objects (jets) require small a posteriori energy corrections
- in our analysis:
  - full **generation-simulation-reconstruction** analysis in CMS
  - in **forward region** only calorimeter jets available
  - $\mathbf{p}_T$ range: 20–200 GeV/c
  - **3** jets algorithms used

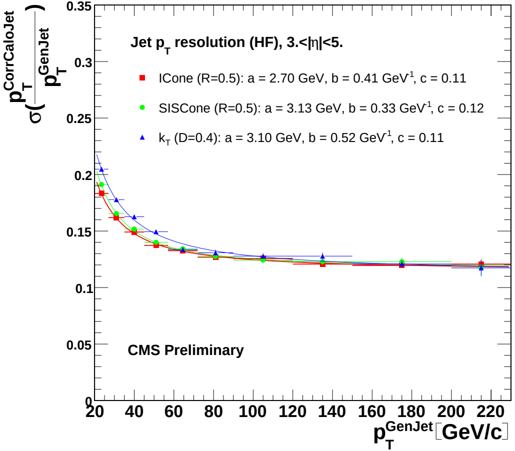
Detector performances for the forward jets

SIM-RECO studies: HF ($3 < |\eta| < 5$) p_T resolution ($\sqrt{s}$=14 TeV)

- **matching** variable: distance between SIM and RECO objects

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} \; < \; 0.2$$

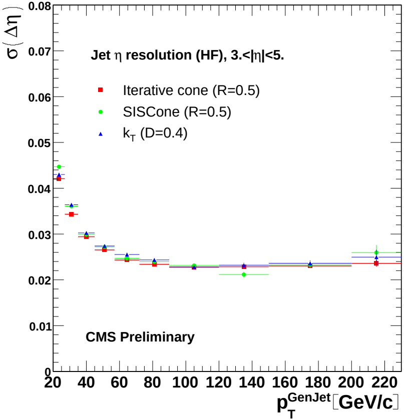
- the mean and the width of the Gaussian fits of the **jet energy response** $p_T^{CorrCaloJet}/p_T^{GenJet}$
  - $\sim$ 20% for $p_T \sim 20$ GeV
  - $\sim$ 12% for $p_T > 100$ GeV
  - ICone$\sim$SISCone$\sim$Fastk_T



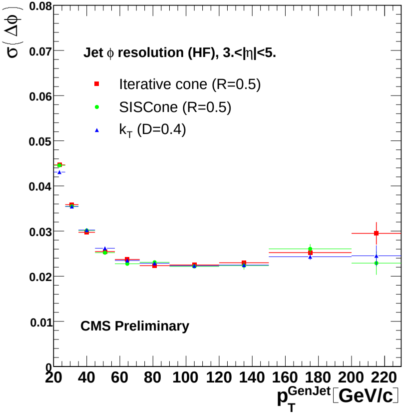
- anti–k_T gives comparable results: **official CMS** algorithm for the jet reconstruction

SIM-RECO studies: HF ($3 < |\eta| < 5$) position resolution ($\sqrt{s}$=14 TeV)

- η resolution



- ϕ resolution



- $\sim$0.04 for $p_T \sim 20$ GeV
- $\sim$0.02 for $p_T > 100$ GeV
- ICone$\sim$SISCone$\sim$Fastk$_T$

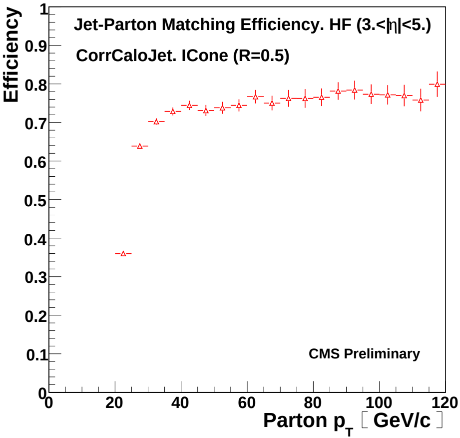
- $\sim$0.045 rads for $p_T \sim 20$ GeV
- $\sim$0.025 rads for $p_T > 100$ GeV
- ICone$\sim$SISCone$\sim$Fastk$_T$

SIM-RECO studies: jet-parton matching efficiency ($\sqrt{s}$=14 TeV)

- How much do we **believe** in the reconstructed jets?

- are they issued from hard **parton-parton** scatterings?
- or **clusters** from underlying events, noise, beam-remnants activity ?

- each outgoing parton is matched to the closest jet (SIM and RECO) which minimizes ΔR
- if the closest jet is not within $\Delta R =$ 0.2 the outgoing parton is discarded
  - low efficiency for p$_T$ <30 GeV
  - efficiency saturation for p$_T$ ~40 GeV

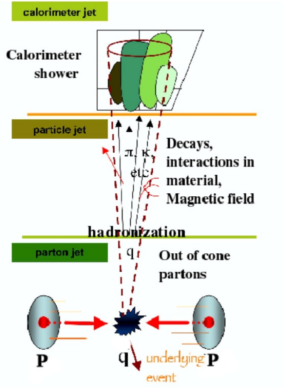


- the forward jet studies are **restricted** to the p$_T$ >35 GeV

Jet Energy Corrections

Required → **Optional** →

Reconstructed jet → Offset → Relative η → Absolute p_T → EMF → Flavor → UE → Parton → Calibrated jet

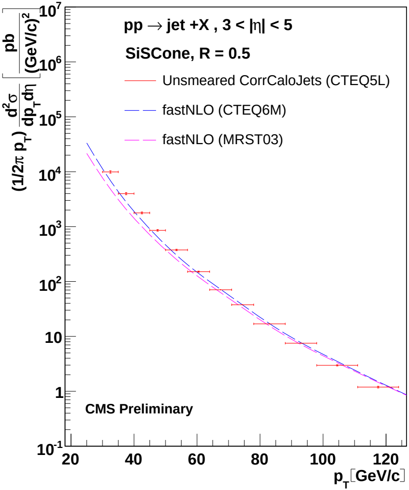


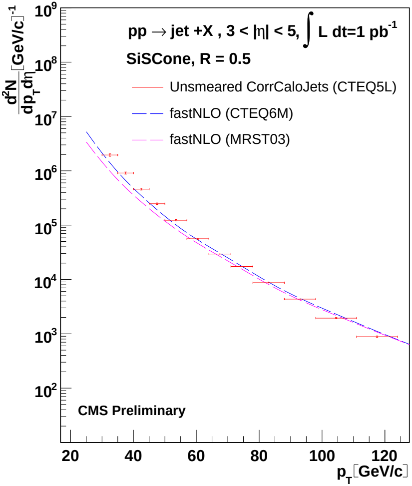
- **Why** do we need to **calibrate** jets?
  - the calorimeter response in **non-linear in p_T** and **non-uniform** across the detector
  - the jet energy scale is **the most important** uncertainty related to jets
- **Why** a **multi-step** approach?
  - each sub-correction corrects for a different effect
  - each sub-correction can be separately studied and optimized
  - easier to develop data driven methods
  - systematic uncertainties are easier to estimate
  - the approach has been used by both D0 and CDF with success

1. **default** correction
   - L1 Offset
     - removes from each jet the energy due to noise and pile-up. It will be measured from data with non zero-suppressed data
   - L2 Relative
     - removes the pseudorapidity dependance of the jet response
     - 1 pb^{-1} of the data should be enough to derive this correction
   - L3 Absolute
     - removes the p_T dependance of the jet response
2. **optional** correction
   - electromagnetic fraction, flavor, parton correction
   - can't be generalized to the default version: strongly dependent on the analysis to perform
3. **status**
   - the derivation of JEC is a complicated, multi-step procedure. Through the studies of the last 3 years, we believe we can reach reasonable JES uncertainty ($< 10\%$) with 10-50 pb^{-1} @ 7TeV
   - JEC will be provided from "day 0" (mc truth) and will be replaced with data-driven ones, as soon as they become available

Single inclusive forward jet spectrum

- invariant cross sections in HF
- for integrated luminosity of 1 pb^{-1}

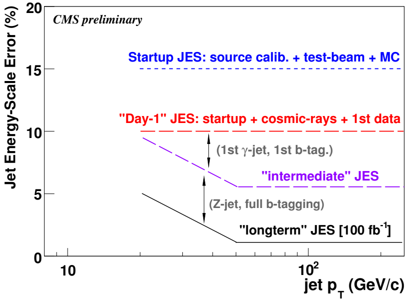


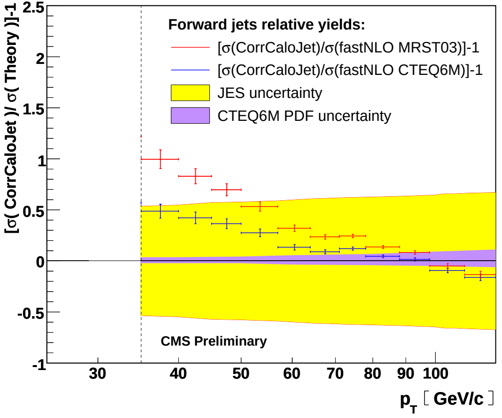


- for p_T <60 GeV sensitivity for the PDF
- large forward jet statistics will allow us to test different PDFs

Single inclusive forward jet spectrum ($\sqrt{s}$=14 TeV)

- "Day–1": p_T–constant 10% calibration error
- "intermediate": 10% (5%) error for low p_T (above 50 GeV)

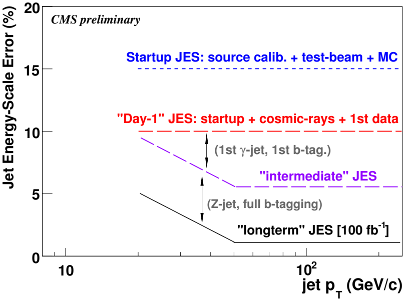


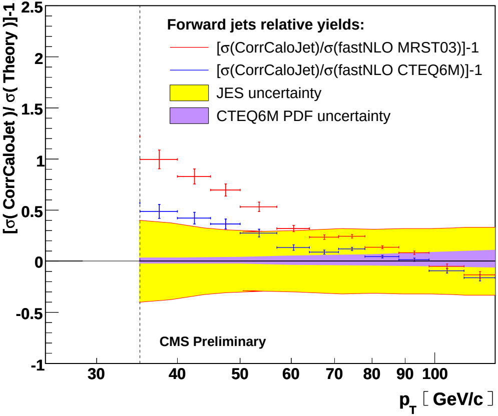


- PDF studies ⇒ only if JES uncertainty $<$ 5%

Single inclusive forward jet spectrum ($\sqrt{s}$=14 TeV)

- "Day–1": p_T–constant 10% calibration error
- "intermediate": 10% (5%) error for low p_T (above 50 GeV)

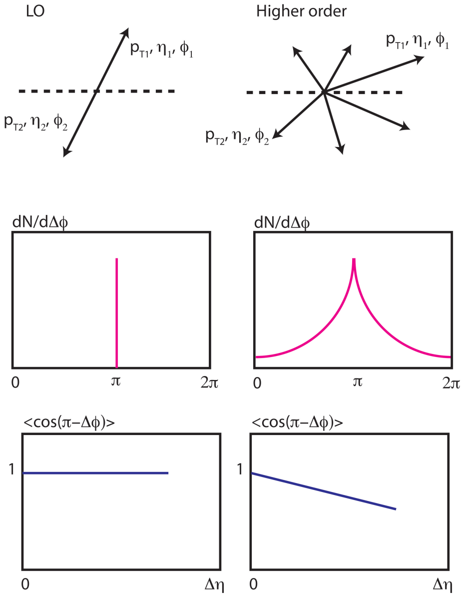




- PDF studies ⇒ only if JES uncertainty $< 5\%$

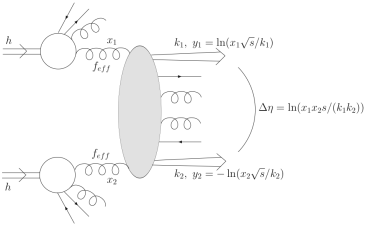
Mueller-Navelet dijets

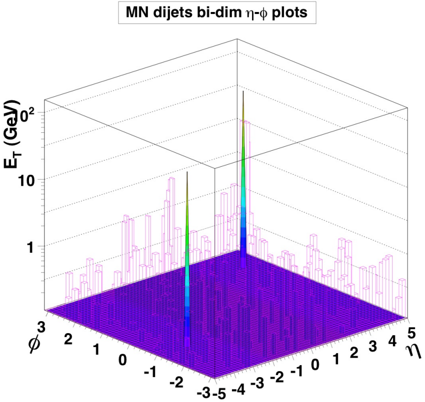
Mueller-Navelet dijets experimentally



Mueller-Navelet dijets: kinematic cuts

- $3 < |\eta_{1,2}| < 5$: 2 forward jets
- $\eta_1 \cdot \eta_2 < 0$: jets in opposite HF
- $|\eta_1|$ - $|\eta_2| < 0.5$: almost back-to-back
- E$_{T(1,2)} > 20$ GeV
- $|E_{T,1} \;-\; E_{T,2}| < 5$ GeV

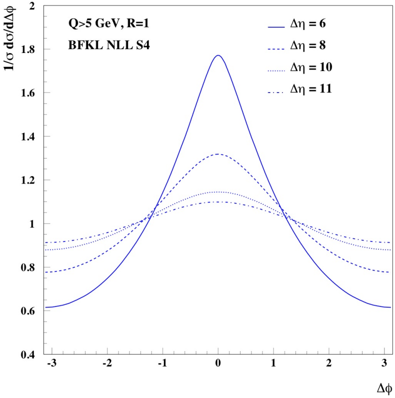




- MN–like dijet event
- + underlying event activity

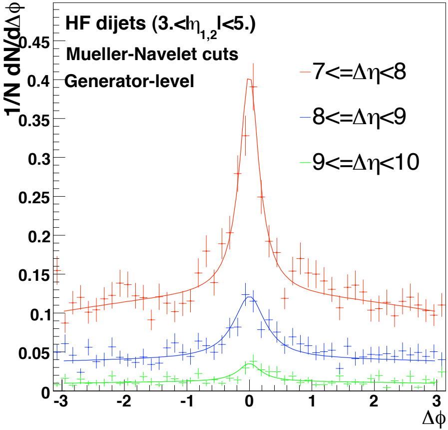
Mueller-Navelet dijets: simulation vs data

BFKL calculations



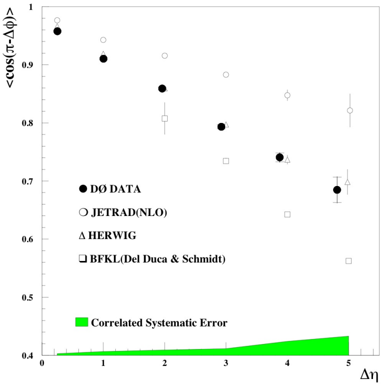
- extra radiation enhances azimuthal (back-to-back) decorrelation
- decorrelatin increases with increasing jet rapidity separation

PYTHIA–GENJET

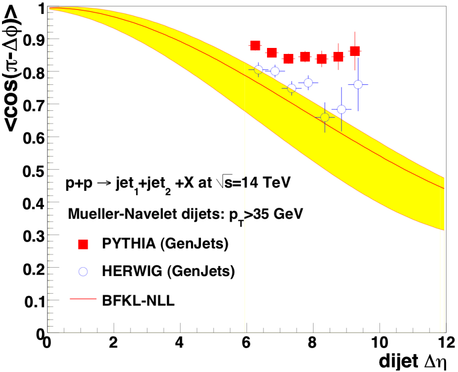


- Small azimuthal decorrelation with increasing $\Delta\eta$
- baseline of the minimal decorrelation expected in non-BFKL scenario

- D0 data: $p-\overline{p}$ at $\sqrt{s}$=1.8 TeV

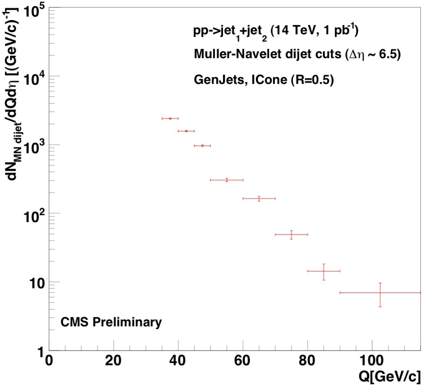


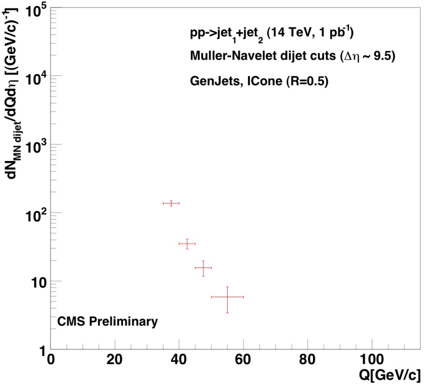
- PYTHIA/HERWIG vs BFKL



- HERWIG more decorrelation (∼15%) than PYTHIA but ∼20% less than BFKL analytical estimates

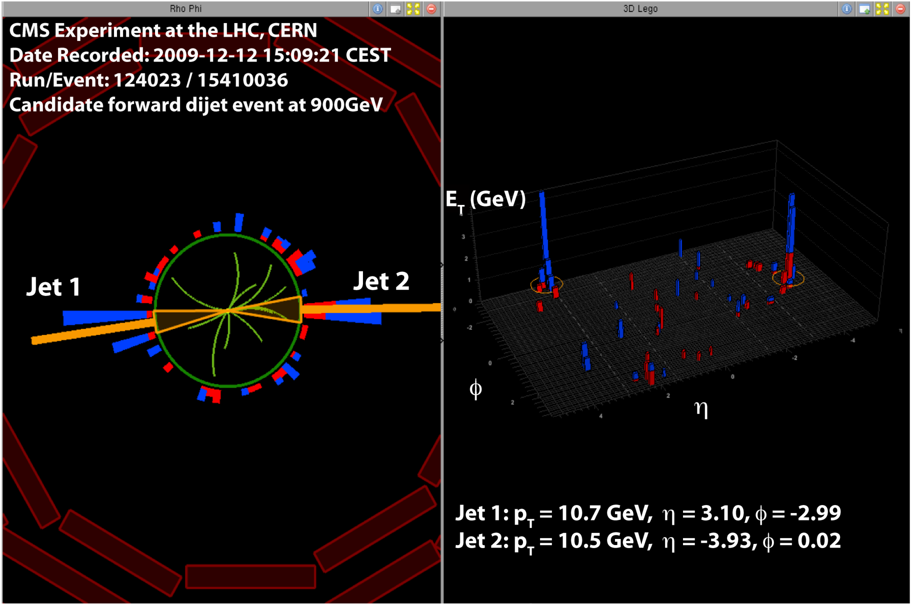
- Statistics: ∼5000(200) Mueller-Navelet-type dijets separated by $\Delta\eta \sim 6$ (9)





- enough statistics for detailed studies of $\Delta\eta$ evolution for HF: yields, ϕ decorrelation

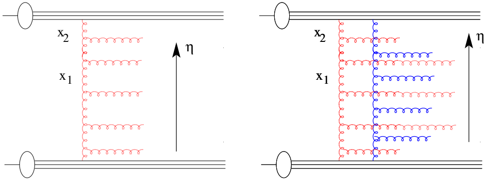
First Mueller-Navelet dijets candidate in 900 GeV data



Energy flow

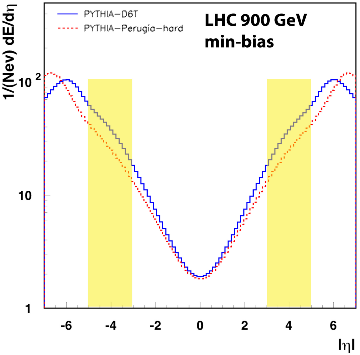
Forward energy flow: Motivation

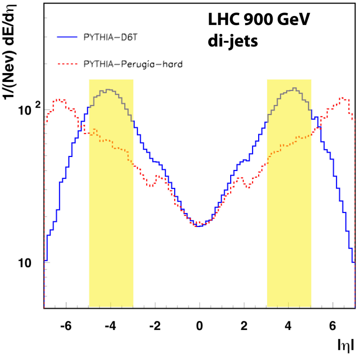
- improve the understanding of the **parton radiation** in the initial state
- study the **multiparton interactions**
- implemented in Monte Carlo event generators: need **parameters** to be adjusted to describe the measurements
- the extrapolation to larger energies is **very uncertain**
- it probes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



The energy dependance of multiple parton interactions is not well known yet !

- comparison of two different tunes: Pythia-D6T (CTEQ6L1) and Pythia-Perugia (CTEQ5L)
- energy flow in **central** region at low $\sqrt{s}$ does **not** change much with tunes
- significant difference observed in the **large pseudorapidity** region ($|\eta| > 2$)





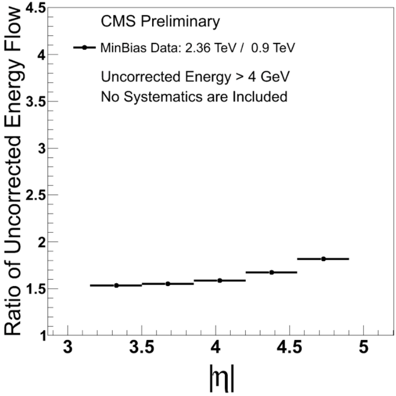
Energy flow in the forward region ⇒ has never been measured at a hadron collider

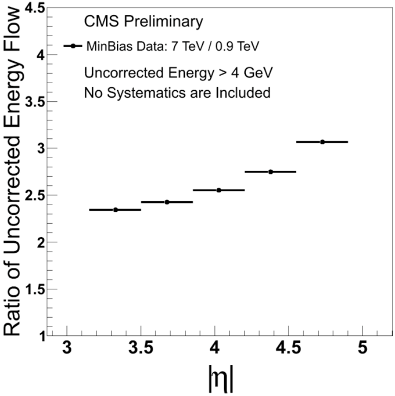
- **Event** selection
  - min-bias trigger
    - Beam Pick-up Timing for the eXperiments (BPTX): provide the information on the bunch structure and timing of the incoming beam with the precision better than 0.2 ns
    - Beam Scintillator Counters (BSC): provide hit and coincidence rates
    - rejection of beam halo events
  - rejection of non-IP events: require at least 10 tracks with 25% of the tracks to be high purity
  - at least one primary vertex reconstructed with number of tracks > 3 with $|z| < 15$ cm (distance to the CMS IP) and impact parameter $d_0 \leq 2$ cm
- **Energy flow** ratio definition

$$R_{Eflow}^{\sqrt{s_1},\sqrt{s_2}} = \frac{\frac{1}{N_{\sqrt{s_1}}}\frac{\Delta E_{\sqrt{s_1}}}{\Delta\eta}}{\frac{1}{N_{\sqrt{s_2}}}\frac{\Delta E_{\sqrt{s_2}}}{\Delta\eta}}$$

where
$\sqrt{s_1} = 2.36$ or 7 TeV
$\sqrt{s_2} = 0.9$ TeV
$N_{\sqrt{s}}$: number of selected minimum bias events for given energy
$\Delta E_{\sqrt{s}}$: energy deposited in a region in $\Delta\eta$ for a given energy (integrated over azimuthal angle)

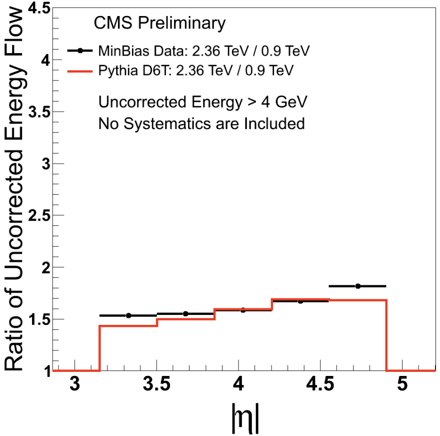
- results on the **detector level**, **no systematics** uncertainties included

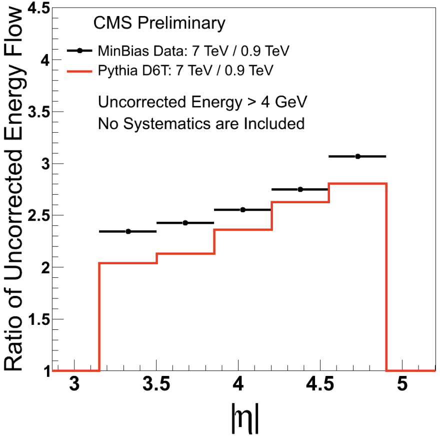




- **more energy** deposited when increasing energy
- **more energy** deposited in the **large** η region
- conclusion on the quality of the description **can't** be made without the systematics uncertainties

- results on the **detector level**, **no systematics** uncertainties included





- **more energy** deposited when increasing energy
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- conclusion on the quality of the description **can't** be made without the systematics uncertainties

Summary & Outlook

1. Physics motivation
   - low-x gluon PDFs
   - non-DGLAP (BFKL, saturation) QCD evolution
2. Jet reconstruction performances in CMS Hadron Forward calorimeter
   - very similar performances of ICone, SISCone & FastKt algorithms
   - very good response of the detector
3. Preliminary results
   - Forward jets single spectrum
     - Large stats. ($\sim$ 1M jets, 1pb^{-1}) but large systematic error ($>$30%) from JES
     - Sensitivity to PDFs differences (p_T $\sim$ 35–60 GeV/c) if JES controlled below 5%.
   - MN dijets
     - statistics: $\sim$ 5000 (200) dijets separated by $\Delta\eta$ $\sim$6 (9)
     - enhanced BFKL decorrelation should be identifiable in the data