Forward physics capabilities of CMS with the CASTOR and ZDC detectors

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on behalf of the CMS Collaboration

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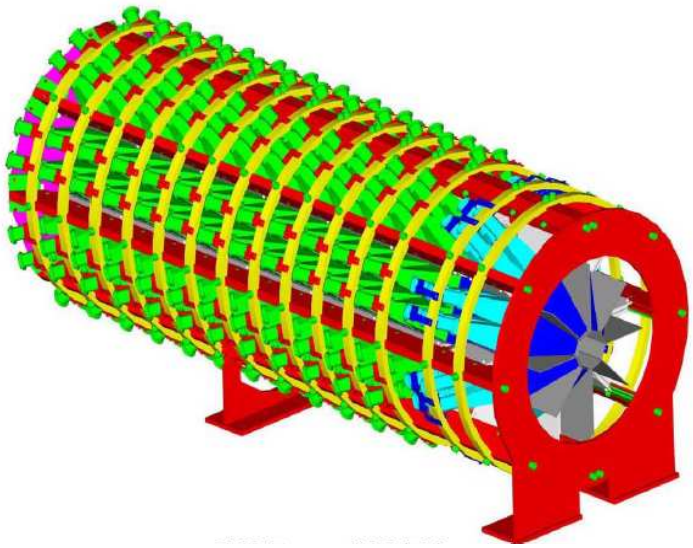
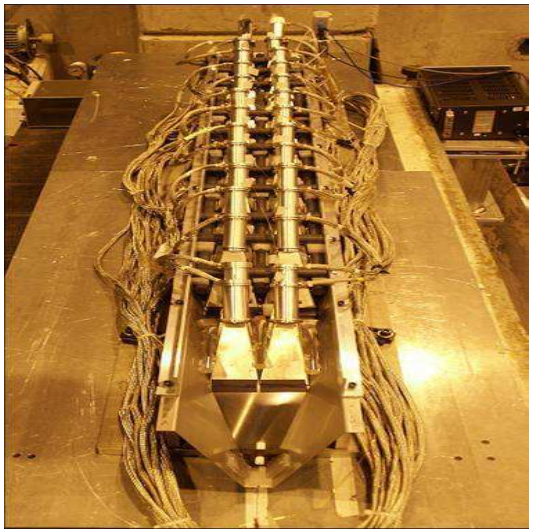
Outline

- CMS Instrumentation in the Forward region:
  - Forward Calorimeters Castor and ZDC
- Physics program:
  - Parton Shower evolution
  - Multiple Partonic Interactions
  - Diffraction
  - Constrain UHE cosmic rays models
- Processes - Signatures:
  - Multi-Jet analysis with a Forward Jet
  - Central - Forward Activity Correlation
  - Rapidity Gaps Measurement

CASTOR Calorimeter



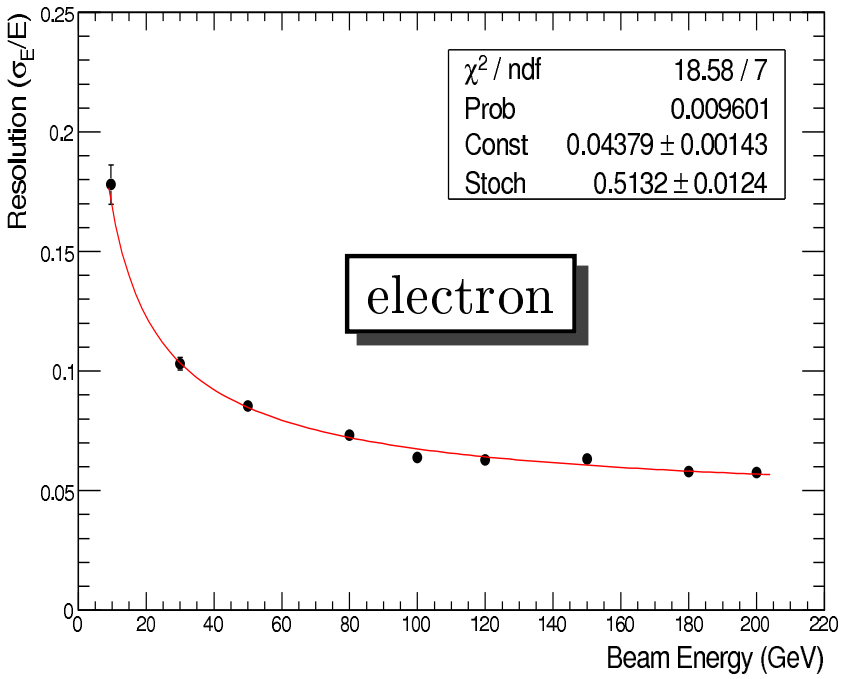


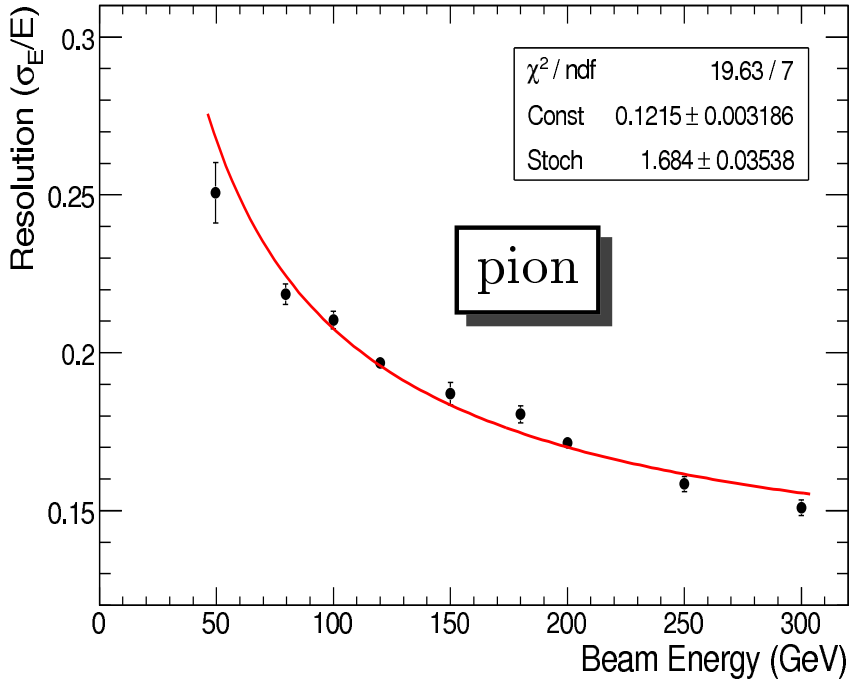
- forward region coverage $-6.6 < \eta < -5.2$
- $z = -14.37$ m
- octagonal cylinder, inner radius = 3.7 cm, outer radius = 14 cm
- Cerenkov calorimeter, signal transmitted to PMTs through aircore lightguides
- sandwich structure of W absorber plates and quartz plates as active material
- 2 electromagnetic sections = 20.12 X_0
  12 hadronic sections, total depth = 10.3 λ_I
- 16-fold segmentation in ϕ (Tower)
  14-fold segmentation in z
  no segmentation in η
- total 16 * 14 = 224 channels

- half CASTOR (with 2 octants in readout) in test beam in May 2009
- full CASTOR slightly reduced in depth to be installed in June 2009 (192 channels)

CASTOR energy resolution

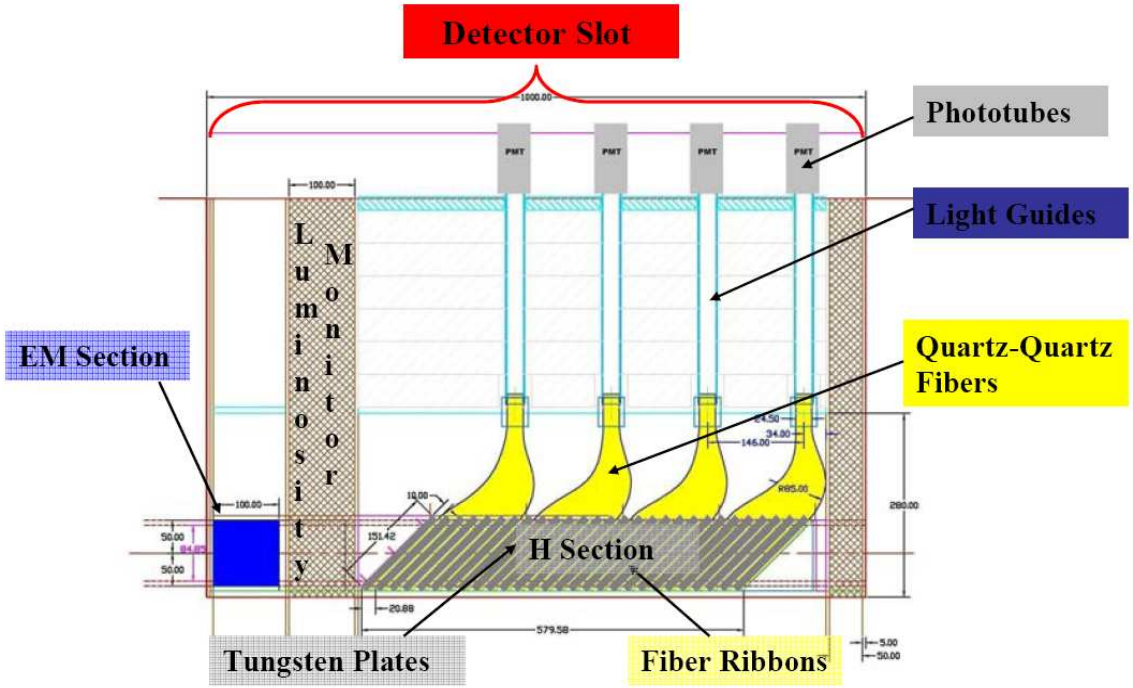
- Results from the 2007 test beam [CMS NOTE-2008/022]





- from 18 % at 10 GeV to 6 % at 200 GeV
- from 25 % at 50 GeV to 15 % at 300 GeV

Zero Degree Calorimeters (ZDCs)

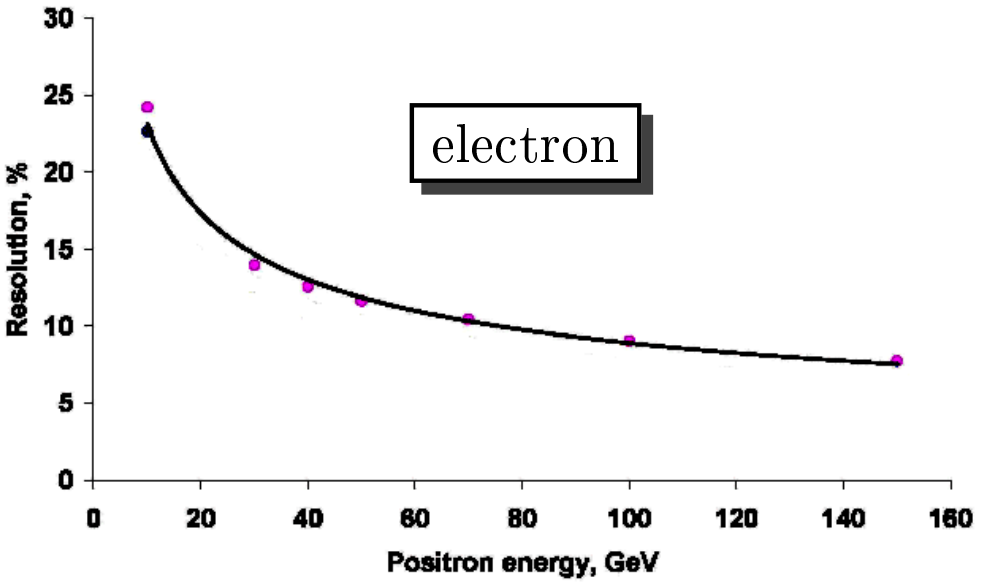


- located at 140 m from the interaction point
- Cerenkov calorimeter with a sandwich structure of W and quartz
- electromagnetic section, 19 X_0, 5-fold horizontal segmentation to measure the pseudorapidity of the forward energy deposits
- hadronic section, 5.6 λ_I, 4-fold longitudinal segmentation
- ZDC can measure neutral particles (γ, π^0, n) produced at $|\eta| > 8.1$ full acceptance for neutral energy flow at $|\eta| > 8.4$

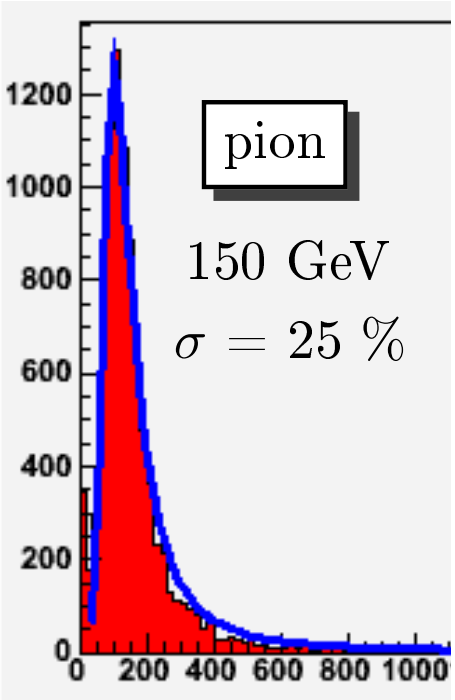
Zero Degree Calorimeter

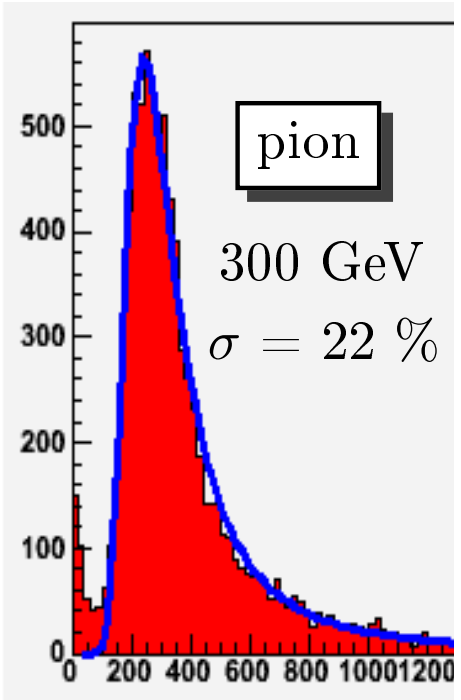
- ZDCs are integrated into CMS

ZDCs energy resolution



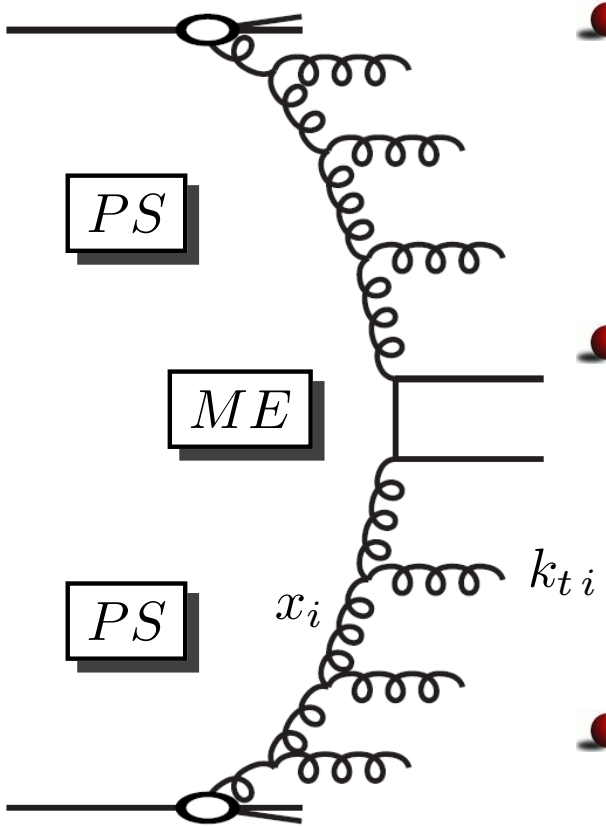
- from 25 % at 10 GeV to 7 % at 150 GeV
- agreement between TB data and simulation





- from 25 % at 150 GeV to 22 % at 300 GeV

Description of $p\,p$ collision



- Matrix Element associated to the hard scattering
  - exact QCD calculation at given fixed order
  - hard scale $Q = p_t, M$ considered subsystem
  - produced at given value of Bjorken x_b
- Parton Shower links hard scattering to proton
  - takes into account higher order contributions
  - by resumming a subset of leading diagrams at each order
  - which diagrams are leading depends on x, Q^2
- Various models for the Parton Shower evolution

DGLAP evolution

- low to high Q^2
- ordered in k_t
- $\sim \ln Q^2$
- PYTHIA

BFKL evolution

- high to low x
- ordered in x
- $\sim \ln(1/x)$

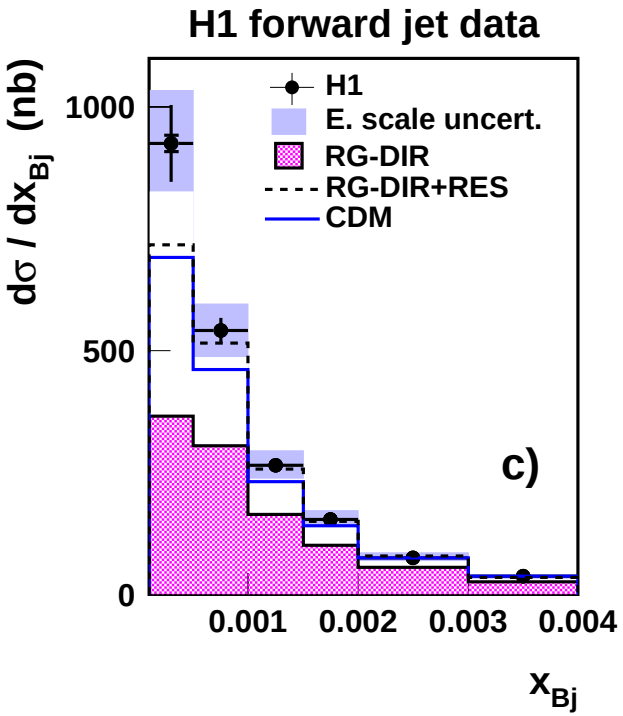
Color Dipole Model

- independent dipole radiation
- unordered in k_t
- BFKL-like scenario
- ARIADNE

Multi-Jet analysis with a Forward Jet

- Differences between various models for the Parton Shower evolution are more prominent in the forward region
  - DGLAP: ordering in k_t: softest emissions are the ones closest to the proton remnant direction
  - BFKL/CDM: no k_t ordering : forward emissions can be arbitrarily large as long as they are allowed by kinematics

  → study forward jet to distinguish between the various models
- At HERA [Eur.Phys.J.C46:27-42,2006]

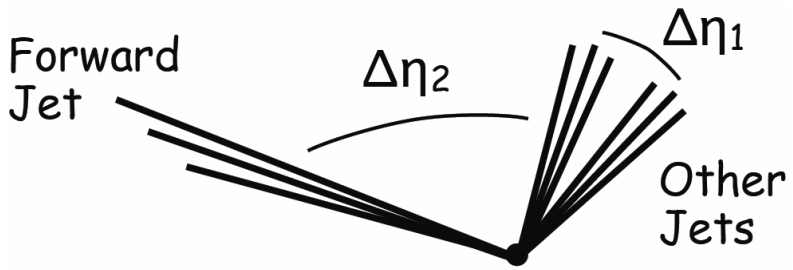


- RAPGAP: matching between LO ME and PS generated according to DGLAP
  - DIR: one DGLAP evolution chain fails to describe data
  - RES: two DGLAP evolution chains
- CDM: independent gluon radiation

→ Parton Shower dynamics beyond the DGLAP direct approximation

$\Delta\eta$ distribution in Multi Jet events

- Study events with at least 3 jets, one of them is a forward jet
  - order jets by decreasing rapidity: $\eta_{fwdjet} > \eta_{jet2} > \eta_{jet1}$
  - define rapidity separation between jets: $\Delta\eta_1 = \eta_{jet2} - \eta_{jet1}$
    $\Delta\eta_2 = \eta_{fwdjet} - \eta_{jet2}$

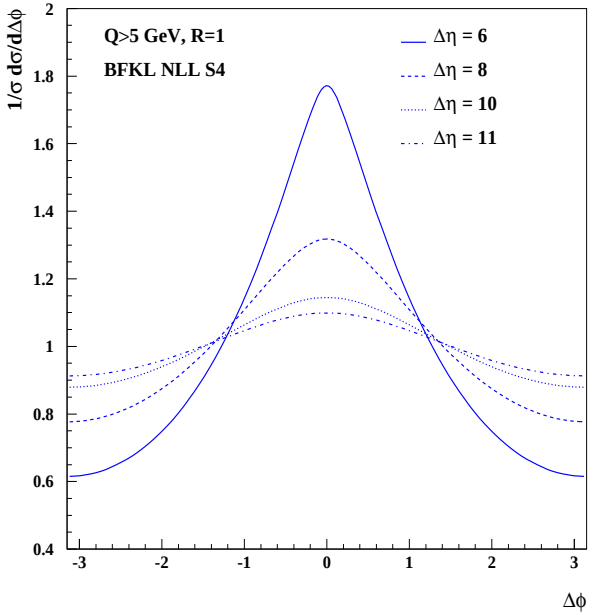


- look at $\Delta\eta$ distribution to distinguish between the various PS models
- select events with different topologies to look at breaking of k_t ordering
  - $\Delta\eta_1$ small, $\Delta\eta_2$ large $(6 < \Delta\eta_2 < 10)$: enhances the available phase-space in x for BFKL-type radiations between fwd jet and dijet
  - $\Delta\eta_1$ small, $\Delta\eta_2$ small: all 3 jets in forward region
  - $\Delta\eta_1$ large: possible BFKL evolution bewteen 2 jets of dijet system

See also Salim Cerci's talk about jet studies
in the Hadronic Forward calorimeter

Mueller-Navelet (MN) dijet event

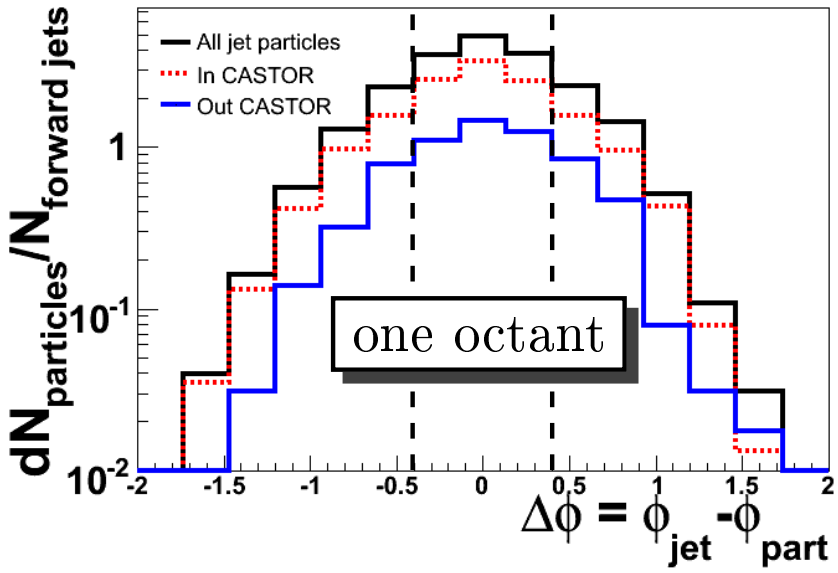
- event in which a jet is detected in each of the forward directions
- process characterized by two hard scales: p_{t1}, p_{t2} of the forward jets
  - suppress emissions ordered in k_t described by DGLAP
- MN jets separated by a large rapidity interval $\Delta\eta \sim \ln(s/p_{t1}p_{t2})$
  - open the phase-space in x and enhance BFKL-type radiations
- study azimuthal decorrelation $\Delta\phi$ between Mueller-Navelet dijet ($\Delta\phi = \phi_1 - \phi_2 - \pi$) to access parton dynamics beyond DGLAP
  - DGLAP evolution: 2 jets more balanced in p_t (at LO $\Delta\phi = 0$)
  - BFKL evolution: higher order emissions, flatter $\Delta\phi$ distribution

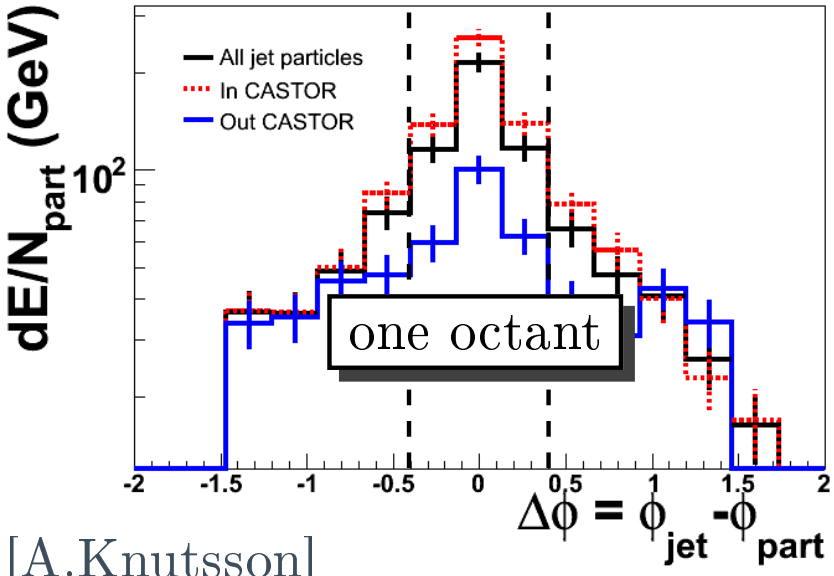


- MN dijet $\Delta\phi$ distribution in NLL BFKL for CDF kinematics, $p_{t1} = p_{t2} > 5$ GeV [C. Marquet and C. Royon, Phys. Rev. D **79** (2009) 034028]
- for increasing $\Delta\eta$, more and more BFKL-type radiations, flatter $\Delta\phi$ distribution
- One CASTOR jet and one backward jet for various $\Delta\eta$ and CASTOR jet energies

Forward Jets in CASTOR

- Which profile do we expect for a forward jet in CASTOR ?
- Generator study with PYTHIA, CTEQ6L pdf, QCD jets mode
- Study at hadron level, no detector simulation applied
- Look at particle multiplicity and particle energy distribution in fwd jet as a function of the distance in ϕ between jet axis and jet particles (CASTOR has no segmentation in η)



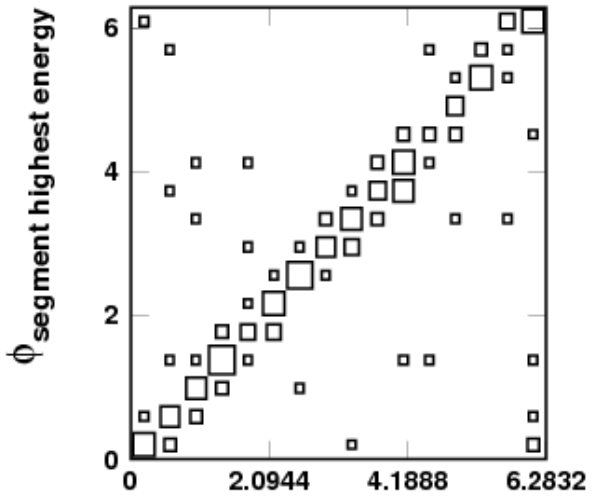


[A.Knutsson]

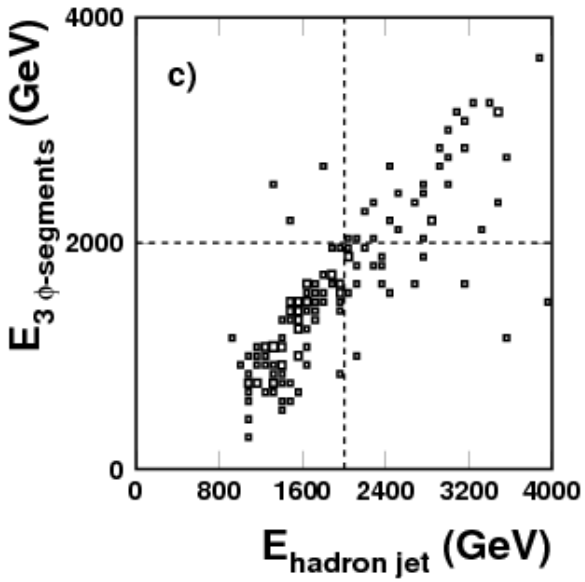
- On average $\sim$ 10 particles in the octant around jet axis
  $\sim$ 100 GeV / particle in the octant around jet axis

CASTOR Jets - Hadron Jets

- Generator level analysis of QCD jets with PYTHIA, CTEQ6L pdf
- Study at hadron level, no detector simulation applied
- CASTOR has no segmentation in η, 16-fold segmentation in ϕ (tower)
  - a CASTOR jet is identified by the most energetic tower to which the two neighboring ones are added
  - particle energy smeared according to test beam data
  - particle energy > 1 GeV to take noise into account
- Look at energy and ϕ correlation between CASTOR jet and hadron jet



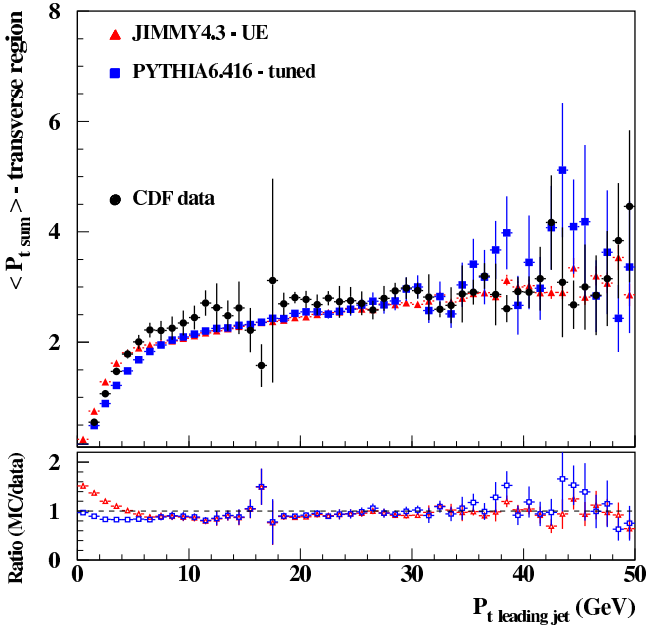
[A.Knutsson]

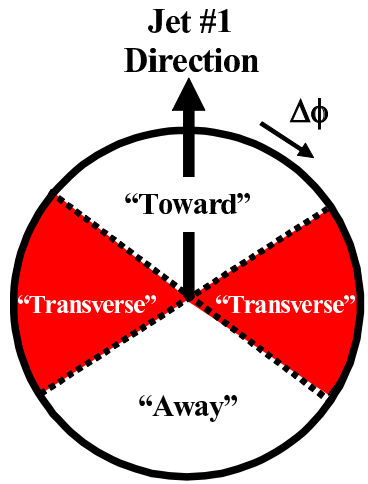


- good correlation in ϕ
- reasonable correlation in energy
- to be confirmed by full simulation

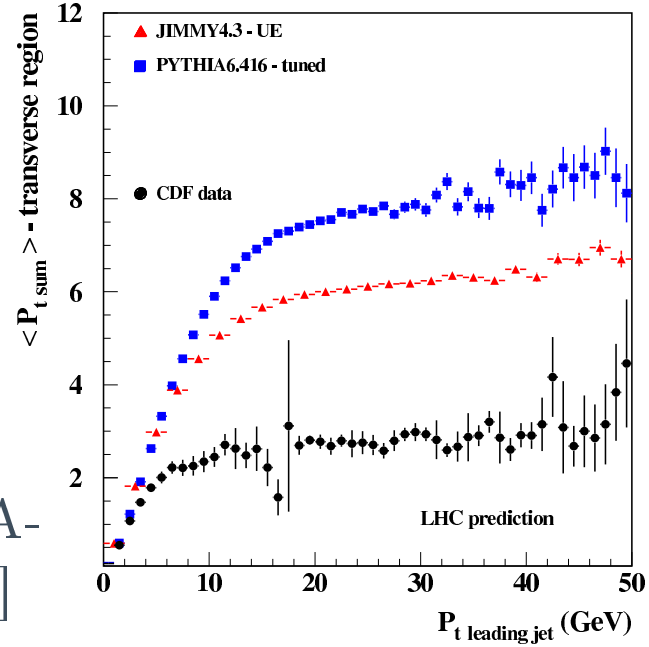
Underlying Event (UE)

- UE is defined as everything except the hard scattered components
  - Initial and Final State Radiation: gluon emissions
  - Multiple Parton Interactions: additional softer parton scattering
  - Beam-Beam Remnants: particles coming from the proton breakup
- UE is unavoidable background (jet reconstruction, isolation cut)
- Study UE in transverse region wrt leading jet ($60° < \Delta\phi < 120°$, $|\eta| < 1$)





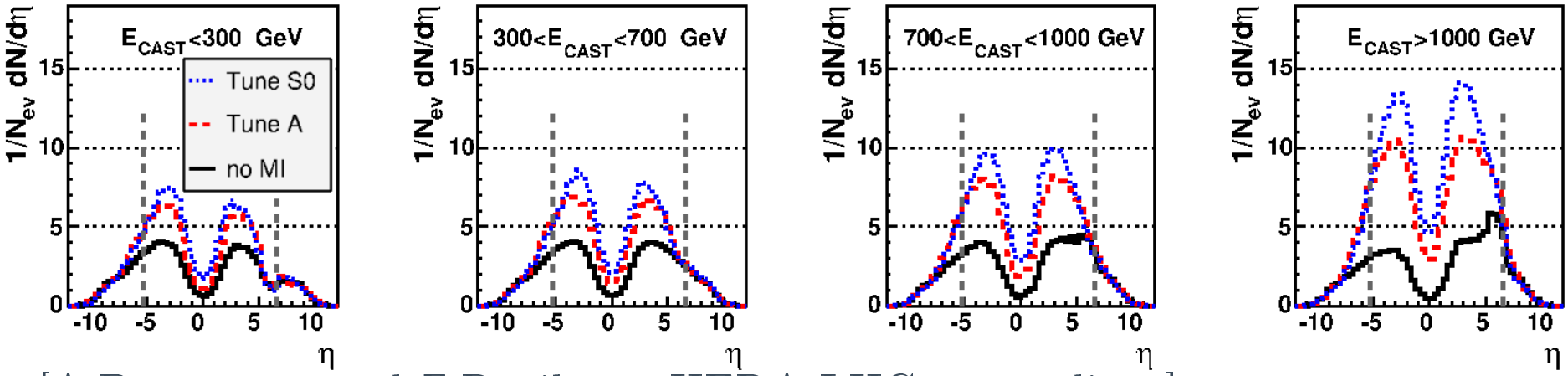
[A.Moraes, HERA-LHC proceedings]



- MPI tuned to describe Tevatron data give large difference at LHC
- MPI will need to be tuned as soon as data available

Underlying Event and CASTOR

- MPI occur between the spectator partons of the colliding protons
  - Energy flow in forward region strongly affected by MPI
  - Energy deposit in CASTOR sensitive to the various MPI models
- MPI induce correlations between activity in central and forward region
  - study by looking at the energy deposit in CASTOR
- Generator level analysis of inclusive QCD processes with PYTHIA, for several MPI tunes: Rick Field tune A, Sandhoff-Skands tune S0



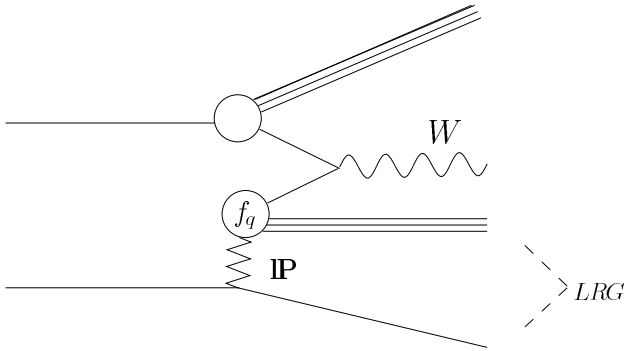
[A.Bunyatyan and Z.Rurikova, HERA-LHC proceedings]

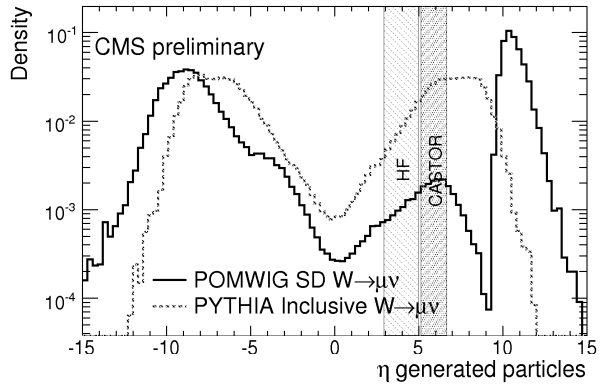
- Without MPI: no long-range correlations are observed
- With MPI: larger E_{CASTOR} ⟶ higher central particle multiplicity
- CASTOR may contribute to distinguish between various MPI tunes

More details about UE and MPI in Nick Van Remortel's talk

CASTOR as veto detector

- SD W production and SD dijet production: Large Rapidity Gap [CMS PAS DIF-07-002 and CMS PAS FWD-08-002]
- energy weighted η distribution of stable particles in SD and non-diff W:





- Tower multiplicity in CASTOR calorimeter to select diffractive signal

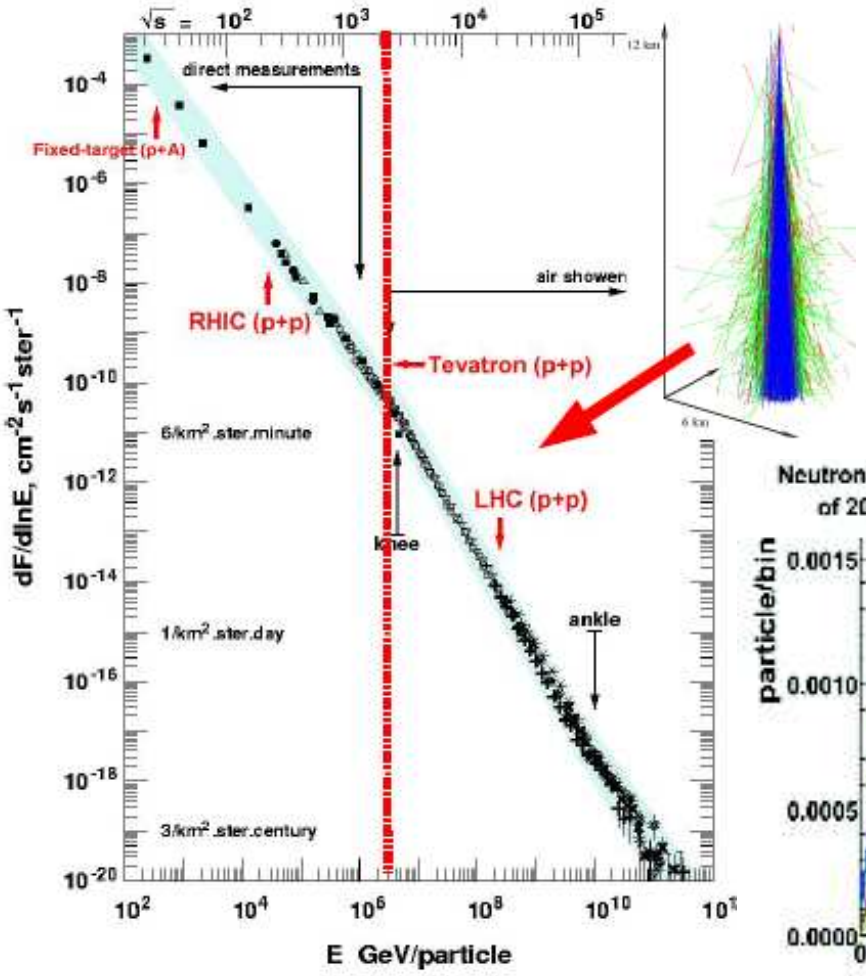
More details about this in Maria Margherita Obertino's talk

ZDC $p\,p$ Forward Physics program

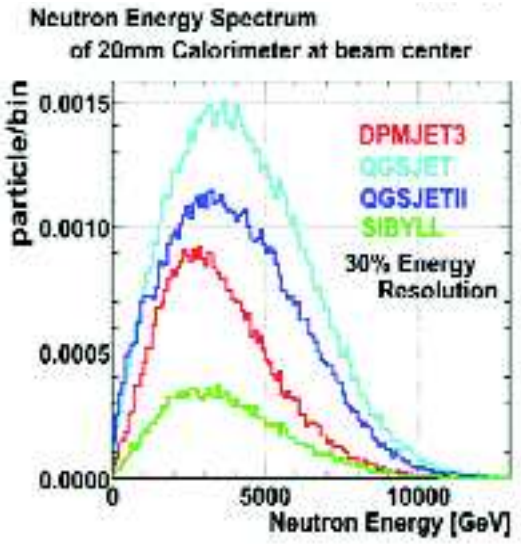
- ZDC as veto detector for diffractive events selection
  - Low energy threshold
  - Fast enough answer to go into level 1 trigger
  - Online veto for diffractive events selection
  - Also used to suppress diffractive proton dissociation background
- Correlation between neutral forward energy flow and particle multiplicity in the central region
- Measure Forward neutron production
  - Low x part of the gluon pdf
  - Constrain UHE cosmic rays models
- Luminosity Monitoring
  - from $p - p$ bremsstrahlung
  - from forward neutron production

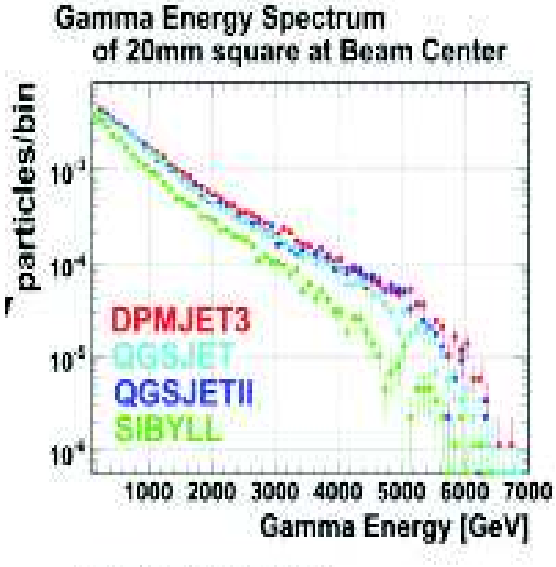
Tuning of UHE cosmic rays models

- Cosmic rays energy spectrum



- No "laboratory" data available above 100 TeV ⟶ very uncertain extrapolations to UEH
- LHC: $\sqrt{s} = 14$ TeV ⟶ $E_{lab} = 10^5$ TeV
- Tuning of Monte Carlo models for UHE cosmic rays from measurement of forward neutral particles flow





Conclusion

- Forward Cerenkov Calorimeters Castor and ZDC

- Physics program:
  - Multi-Jet analysis with a Forward Jet
    Parton Shower dynamics beyond DGLAP
  - Central - Forward Activity Correlation
    Multiple Partonic Interactions in Underlying Event
  - Veto detector for Diffractive events selection
  - Constrain UHE cosmic rays models

- Status of the detectors:
  - ZDCs are integrated into CMS
  - half CASTOR in test beam in May 2009
  - full CASTOR to be installed in June 2009

Back-up Slides

QCD at low x in $p\,p$ collision

- At low x: partons undergo long Parton Shower before they meet
  forward particles production can arise in two ways

- Collision between a low x and a high x parton
  - hard scattering system goes forward: forward production from ME
  - relation between x_{min} of low x parton and η of forward system:
    $x_{min} = \frac{Q}{\sqrt{s}} e^{-\eta}$, with $Q = p_t$ for forward jet production
    M for Drell-Yan pair production
  - at LHC: for $Q > 10$ GeV and $\eta \sim 6$: $x_{min} \geqslant 10^{-6}$
    x_{min} decreases by factor 10 every 2 units of rapidity

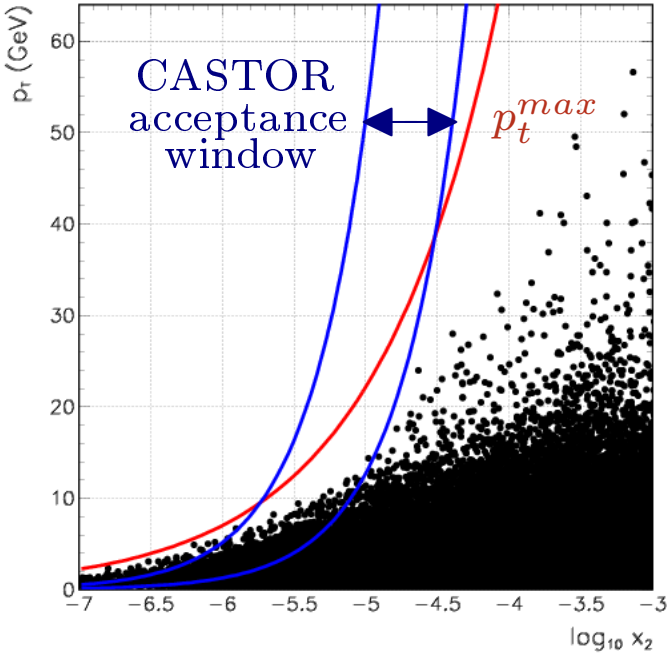
  ⟶ sensitivity to saturation in low x region

- Collision between two low x partons
  - hard scattering system produce central dijet
  - forward jet comes from QCD evolution of Parton Shower
  - evolution from high x (forward jet) to small x (central dijet)

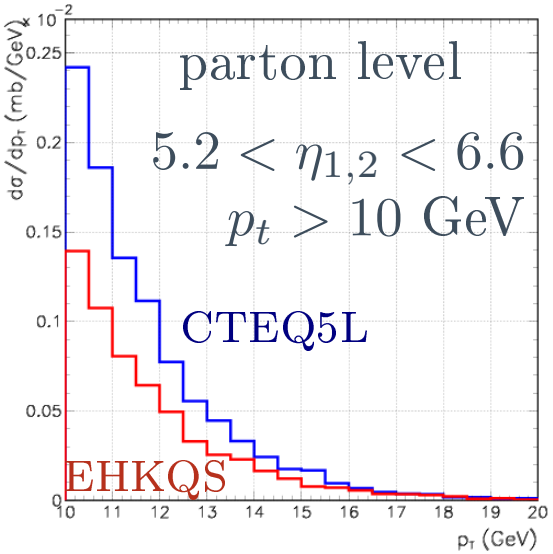
  ⟶ study BFKL dynamics, higher order contributions to PS

Forward Jets (from ME) and saturation

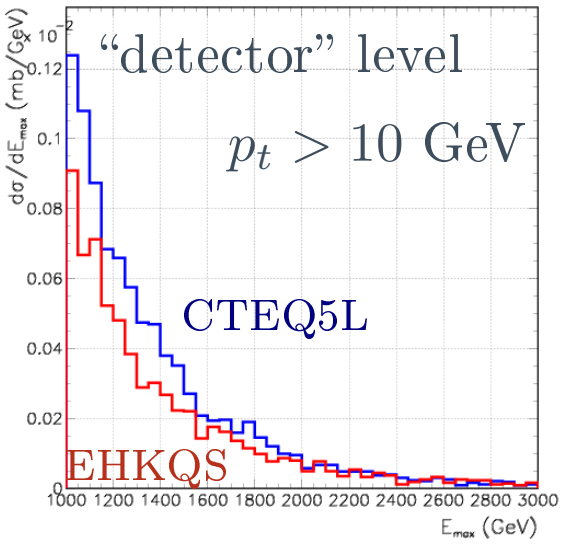
- generator study with PYTHIA, CTEQ5L pdf, QCD jets mode
- Matrix Elements are mainly $q\,g$ and $g\,g$ scatterings in the t channel
- "detector" level: stable particles in CASTOR are merged into towers
- p_t^{max} for jet in CASTOR $\sim$ 35 GeV
  x range from 10^{-6} to 10^{-5}



- sensitivity to saturation: usual CTEQ5L pdf and saturated EHKQS pdf



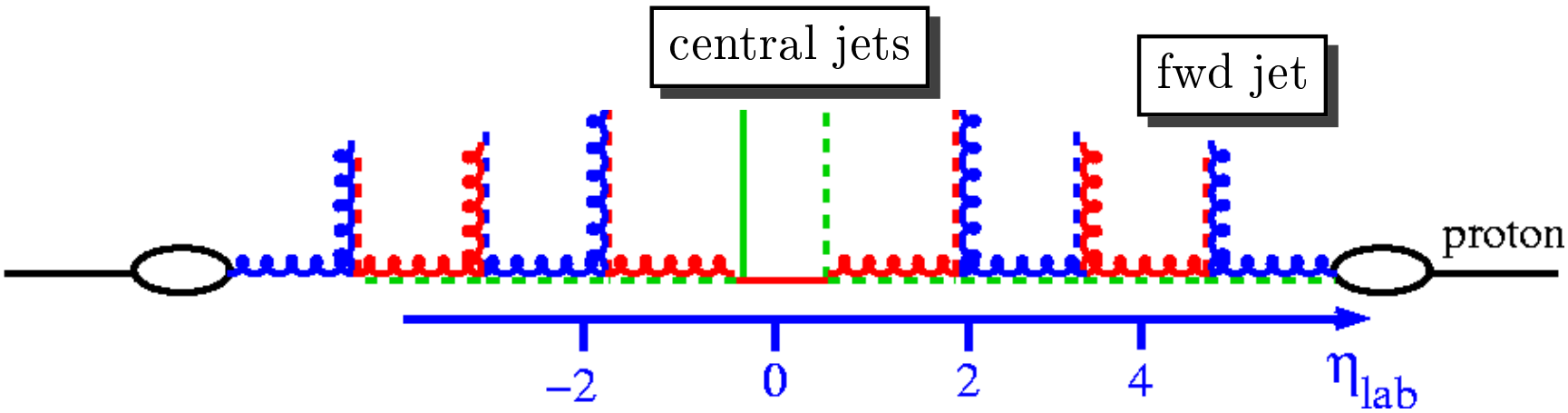
reduction less clear for high p_t jets on detector level



Forward Jets and Parton Shower

- Differences between various models for the Parton Shower Evolution are more prominent in the forward region
  - DGLAP: ordering in k_t: softest emissions closest to proton remnant
  - BFKL/CDM: no k_t ordering : forward emissions can be arbitrarily large as long as allowed by kinematics

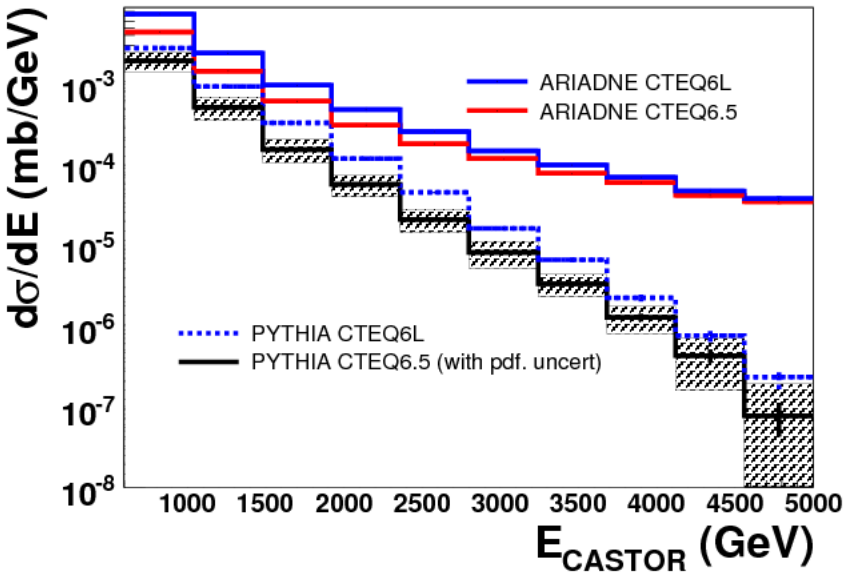
    → forward jet study to disentangle between the various models
- event selection: 1 forward jet in CASTOR ($5.2 < \eta < 6.6$)
  1 central dijet ($|\eta| < 2$, $p_t > 10$ GeV)

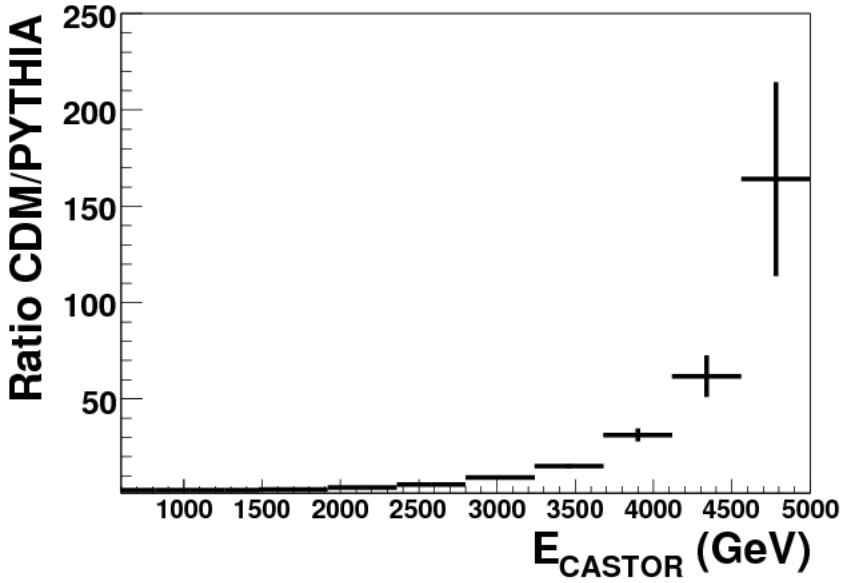


  - rapidity separation between central and forward jets: enhances the available phase-space in x for BFKL-type radiation

Forward Jets and Parton Shower

- Predictions from PYTHIA (DGLAP) are compared to predictions from ARIADNE (CDM) ($L < 1\ pb^{-1}$)
- Two different pdf sets CTEQ6L, CTEQ6.5
- Tune A parameters for the description of Multiple Partons Interactions
- Study at the CASTOR jet level (no detector simulation applied)

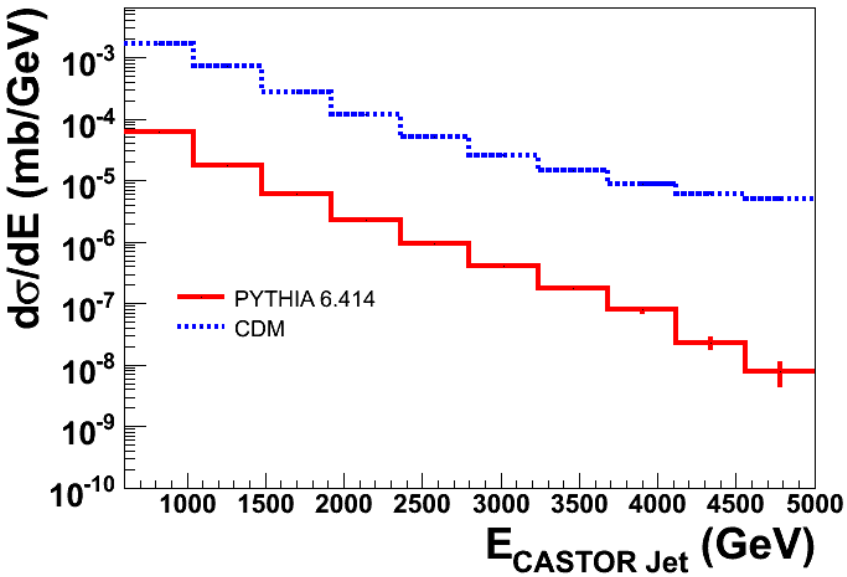


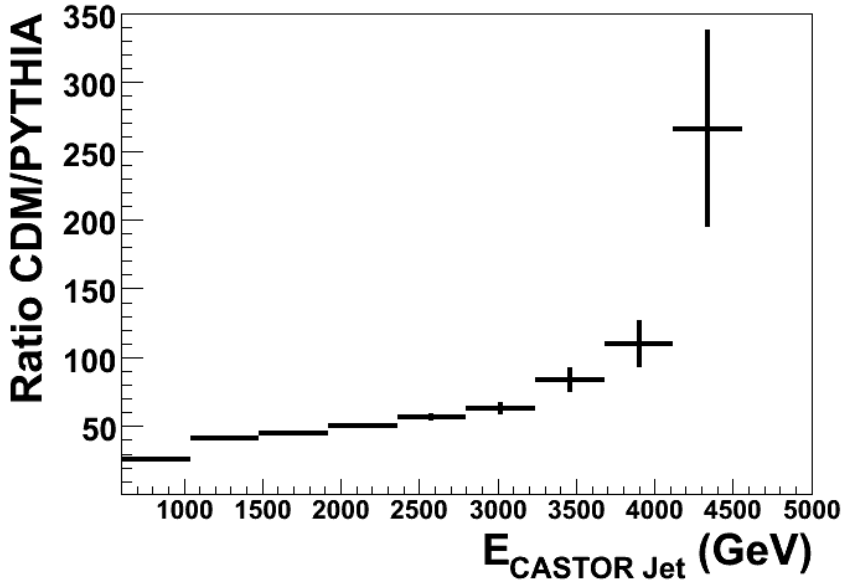


- Sensitivity to Parton Shower at high energy where difference between DGLAP and BFKL-like behaviours is bigger than pdf uncertainty: CDM gives more hard jets in CASTOR region

Forward Jets and Parton Shower

- event selection: 1 forward jet in CASTOR ($5.2 < \eta < 6.6$)
  1 central dijet ($|\eta| < 2$, $p_t > 25$ GeV)
  (CMS can not trigger on central jets as low as 10 GeV)
- PYTHIA (DGLAP) compared to ARIADNE (CDM) ($L < 1\ pb^{-1}$)
- One pdf set CTEQ6L, Multiple Partons Interactions Tune A
- Study at the CASTOR jet level (no detector simulation applied)

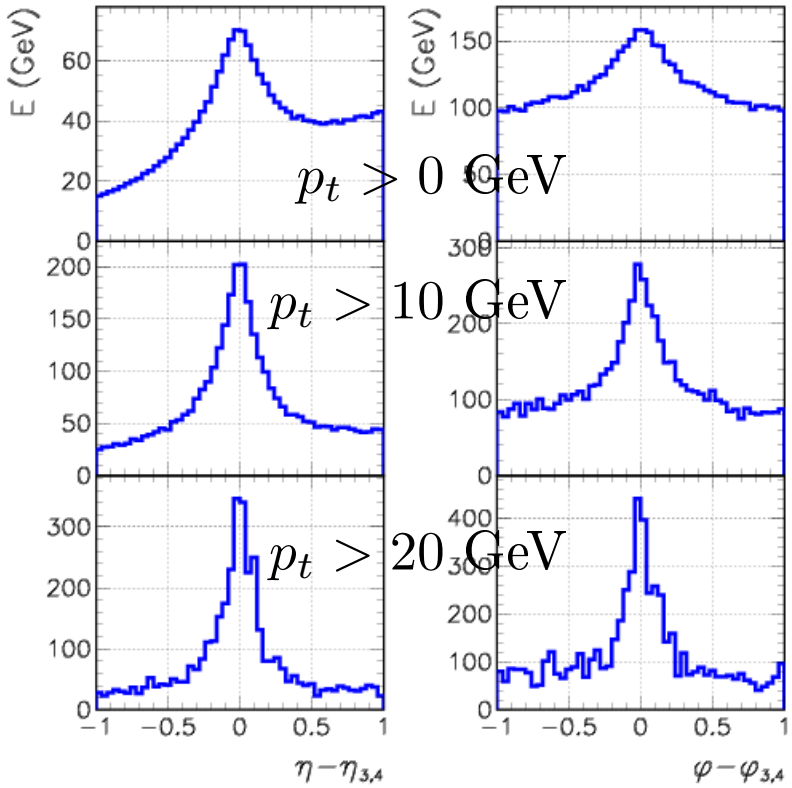


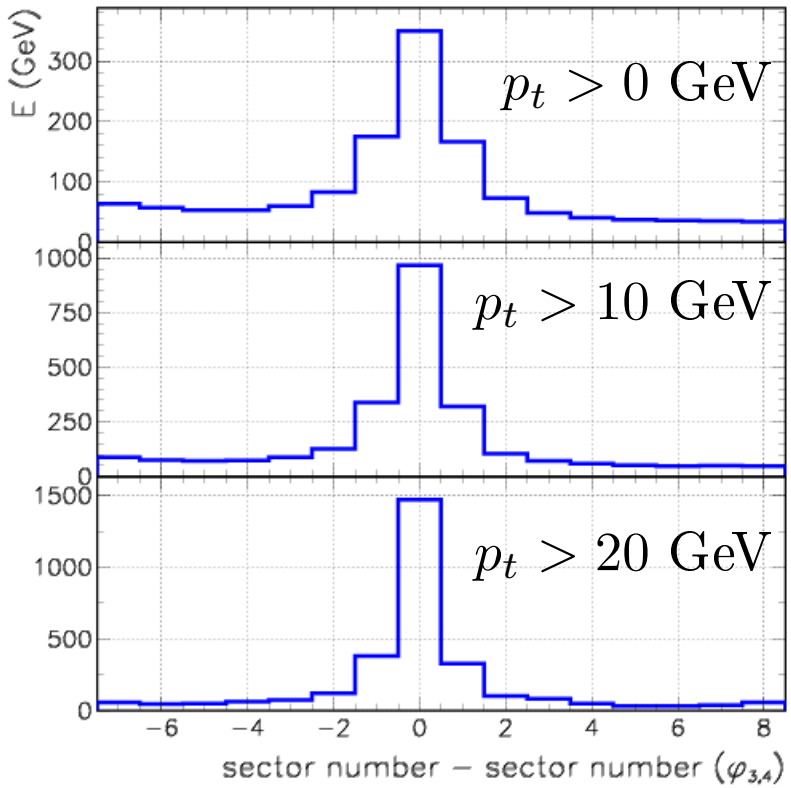


- Measurement can still disentangle between different models for Parton Shower: CDM (BFKL-like emissions) gives more hard jets in CASTOR

Jet profiles in CASTOR

- Generator level analysis of QCD jets with PYTHIA, CTEQ6L pdf
- At least one gluon from the ME required to be in CASTOR acceptance
- At hadron level: Energy distribution as a function of the distance in η and ϕ between the gluon and the particles in CASTOR
- At "detector" level: distribution as a function of the difference in ϕ sector





- jets stand out from the "pedestal energy deposit"