Karlsruhe Institute of Technology

CMS: forward jet production and energy flow

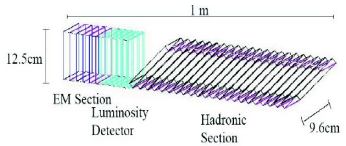
Igor Katkov

On behalf of the CMS Collaboration

Results and prospects of forward physics at the LHC: Implications for the study of diffraction, cosmic ray interactions, and more

11-12 February 2013 *CERN*

ZDC (|η| > 8.1)



[+ FSC]

Rotating

Collar

HF (3 < |η| < 5)

TOTEM/ T1

CASTOR (-6.6< η< -5.2)

T2

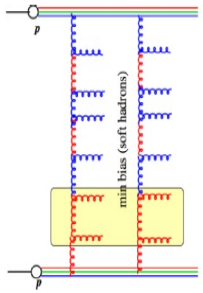
- Cherenkov/quartz calorimetry in the CMS forward region (HF @ 11.2m / CASTOR @ 14.4m / ZDC @ 140m) ↔ space, magnetic field, radiation

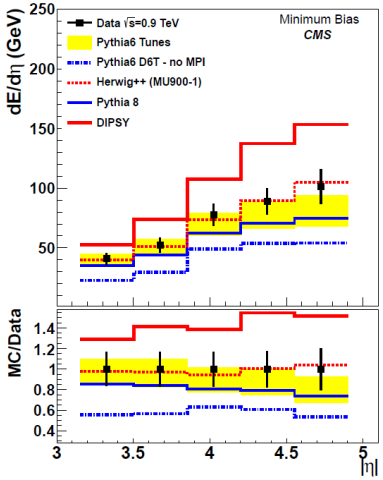
Measurement of energy flow at large pseudorapidities in pp collisions at $\sqrt{s}$ = 0.9 and 7 TeV

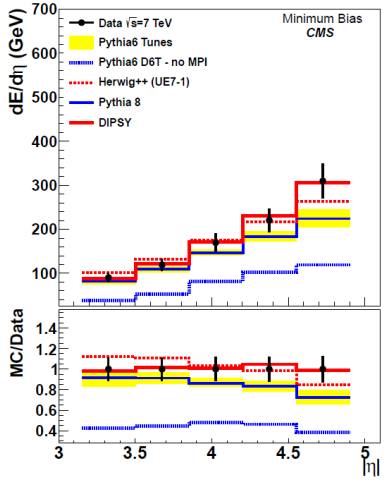
[J. High Energy Phys. 11 (2011) 148,
Erratum-ibid. J. High Energy Phys. 02 (2012) 055]

http://cds.cern.ch/record/1386739

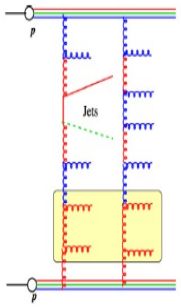
Forward energy flow

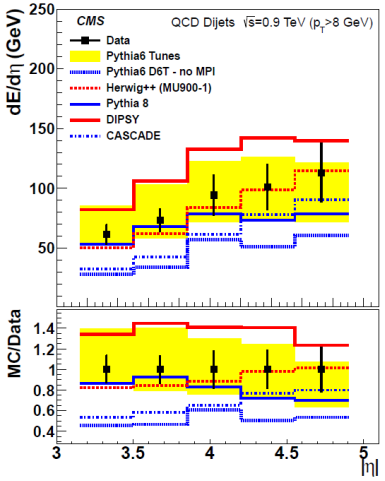


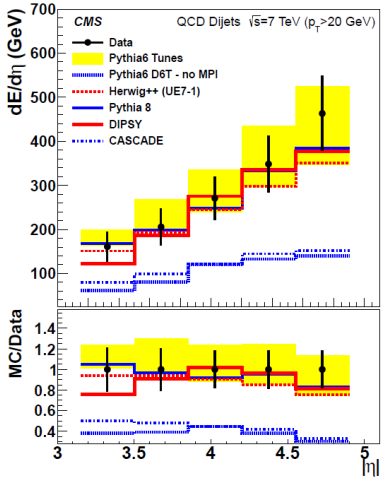


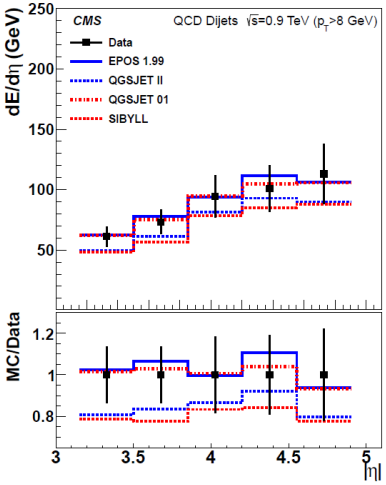


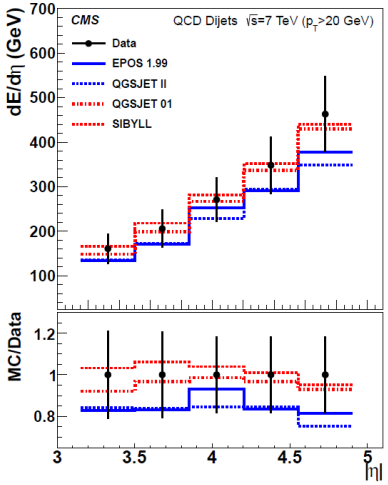
- Strong rise of energy flow with energy
- Energy flow enhnced for dijets
- Models fail w/o MPI
- Data best described by cosmic ray hadronic models









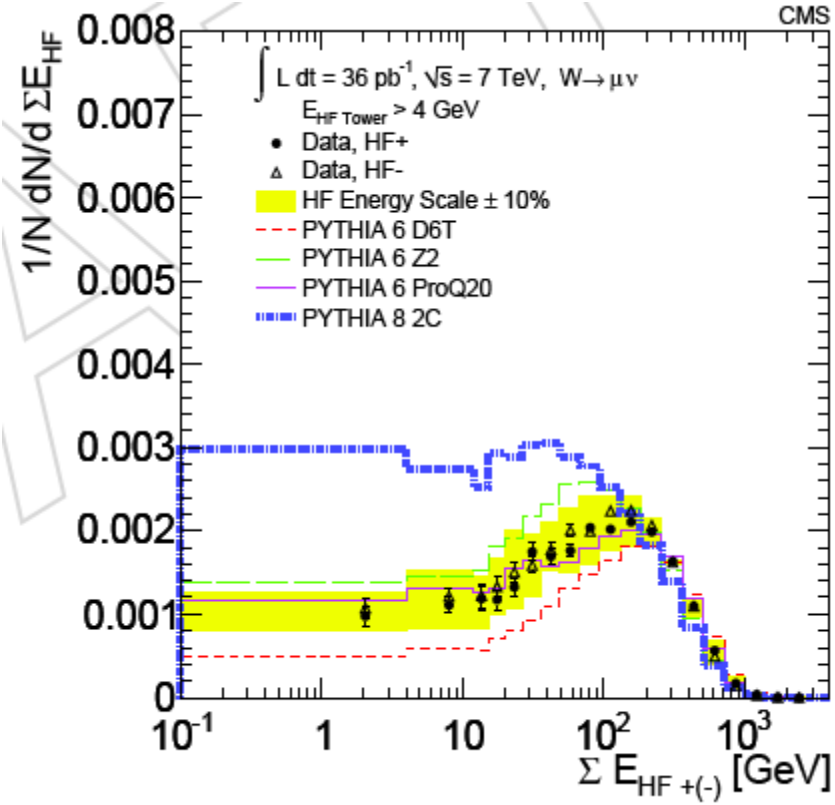


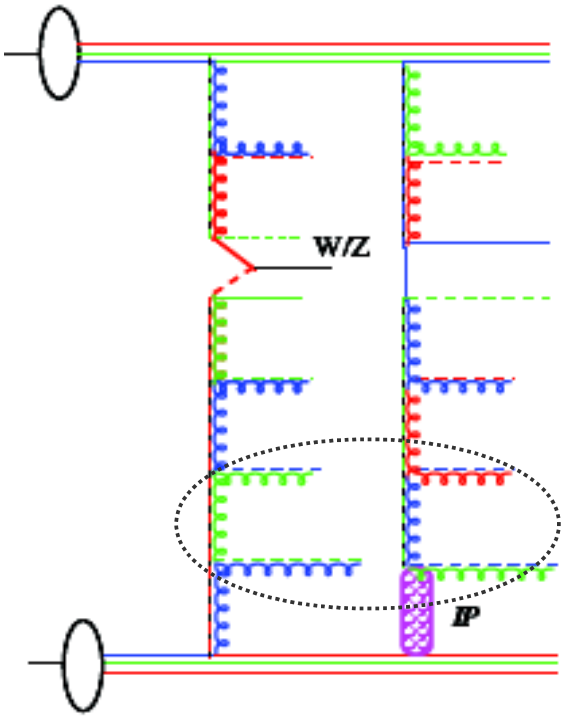
Forward Energy Flow, Central Charged-Particle Multiplicities, and Pseudorapidity Gaps in W and Z Boson Events from pp Collisions at 7 TeV

[Eur.Phys.J. C72 (2012) 1839]

http://cds.cern.ch/record/1386705

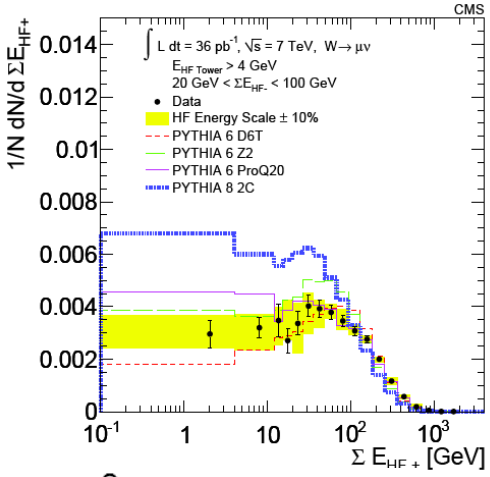
Forward energy flow with W/Z production

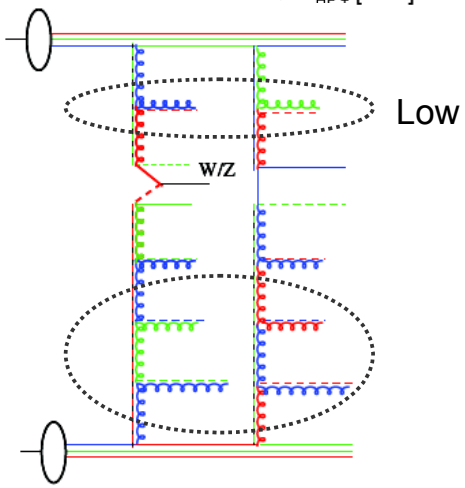




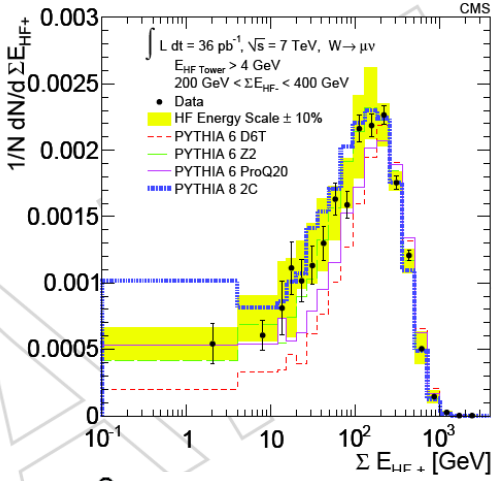
- Explore underlying event / MPI / diffraction

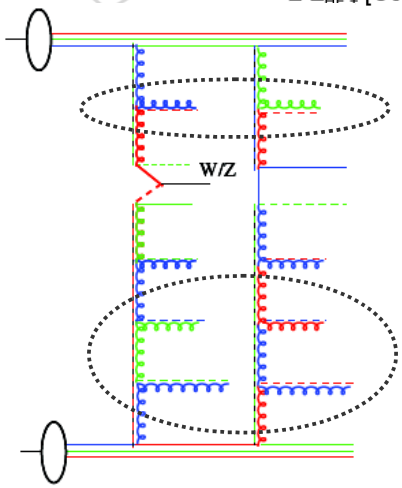
Forward energy flow with W/Z production



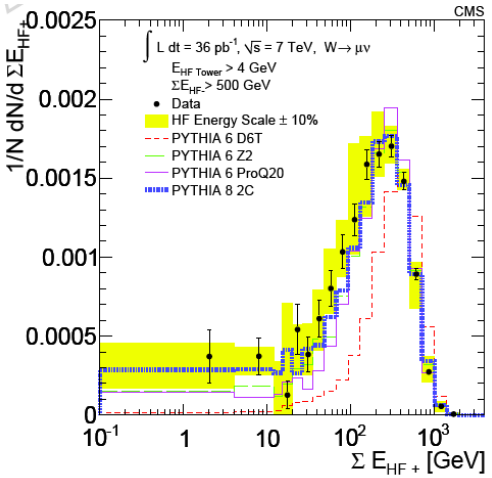


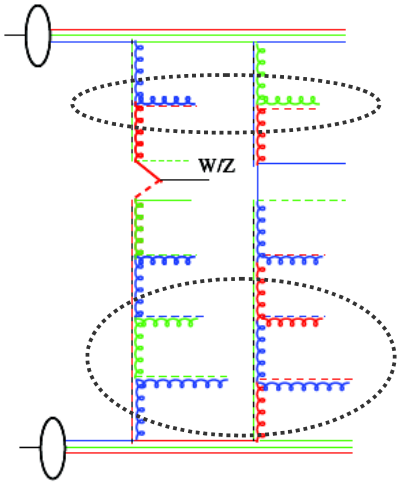
Low





Medium





High

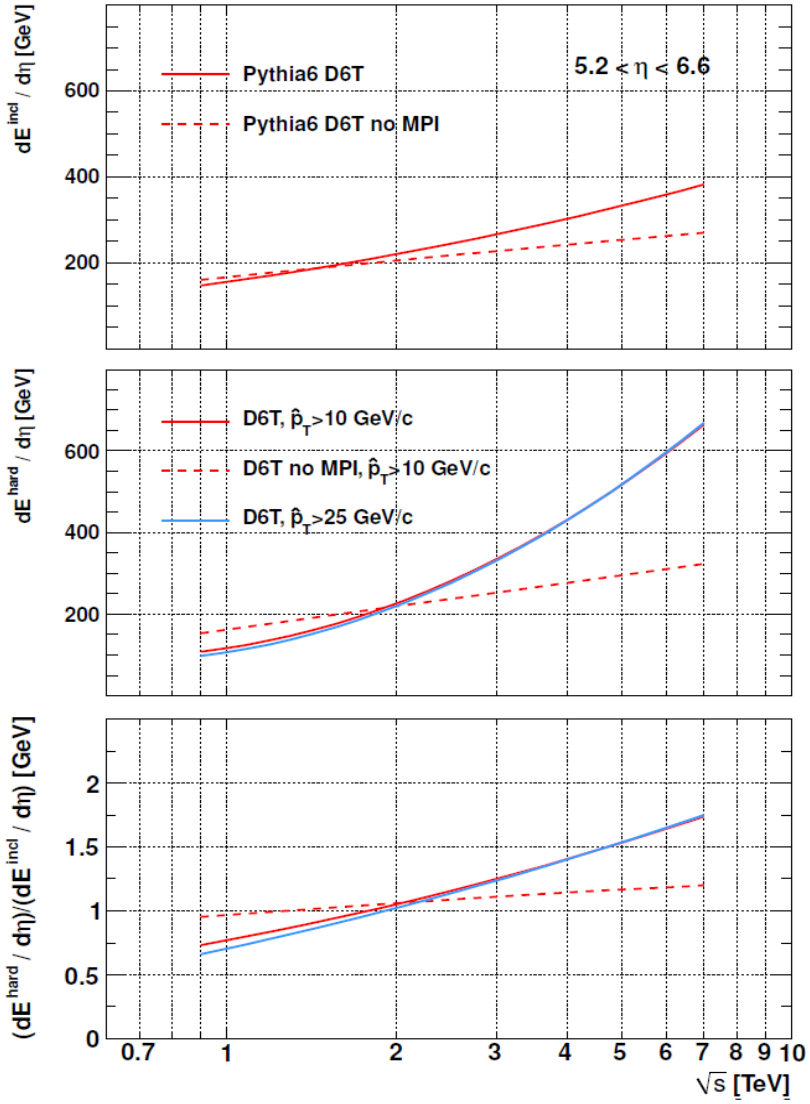
- Forward/backward strongly correlated; not well modeled

Study of the Underlying Event at Forward Rapidity in Proton-Proton Collisions at 0.9, 2.76 and 7 TeV

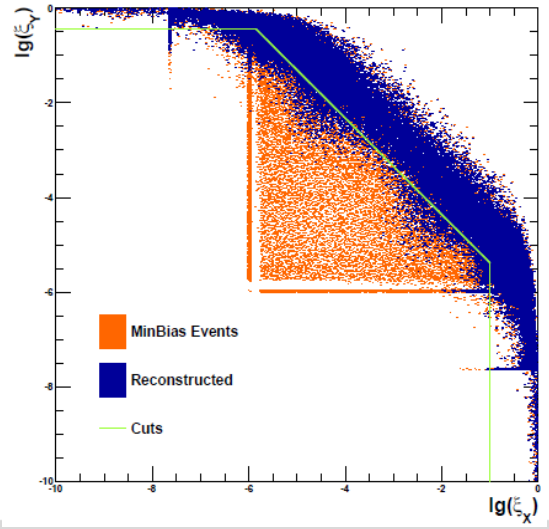
[CMS PAS FWD 11-003]

http://cdsweb.cern.ch/record/1434458

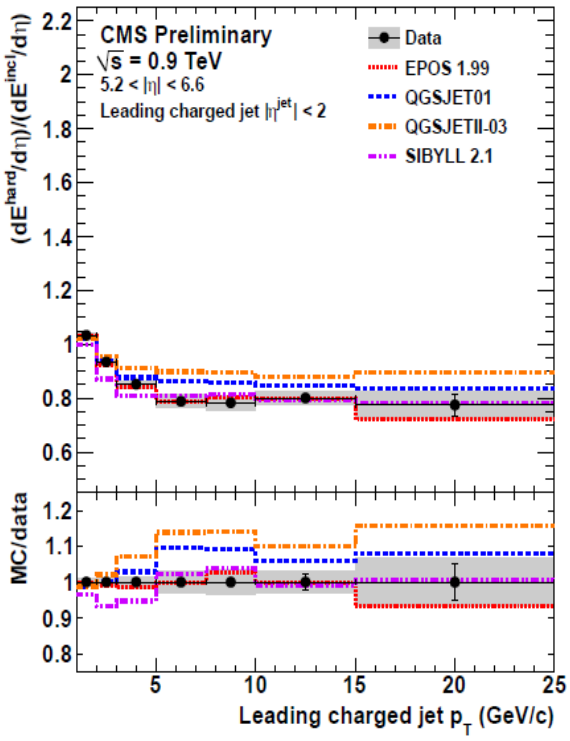
Energy flow → hard-to-inclusive ratio

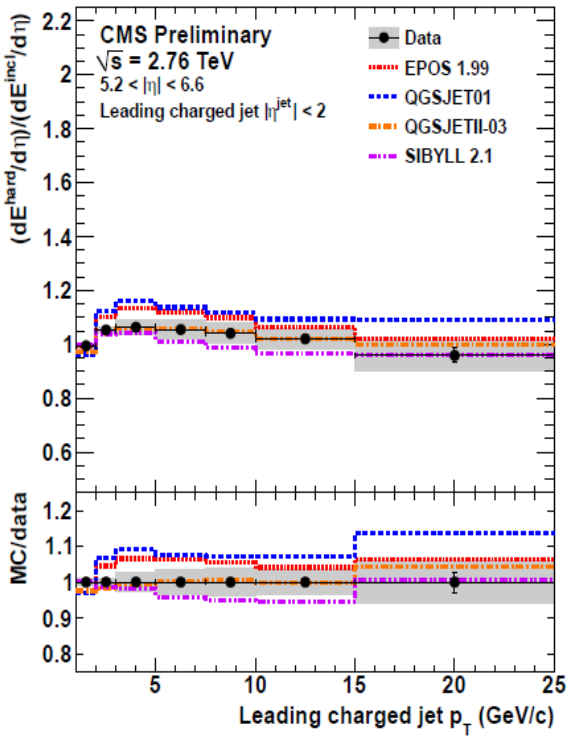


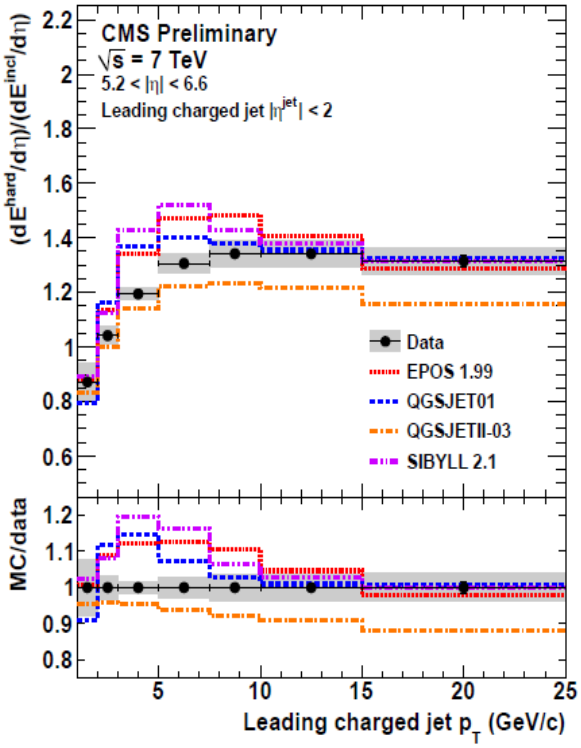
- Minimum bias / inclusive events selected suppressing diffraction
- Events with hard scale → central leading charged jet with p_T > 1 GeV/c and |η| < 2
- Ratio → reduced systematics, dominated by simulation of CASTOR geometry
- Minimization of hadron level correction factors → ξ_X, ξ_Y



Hard-to-inclusive ratio vs p_T and energy

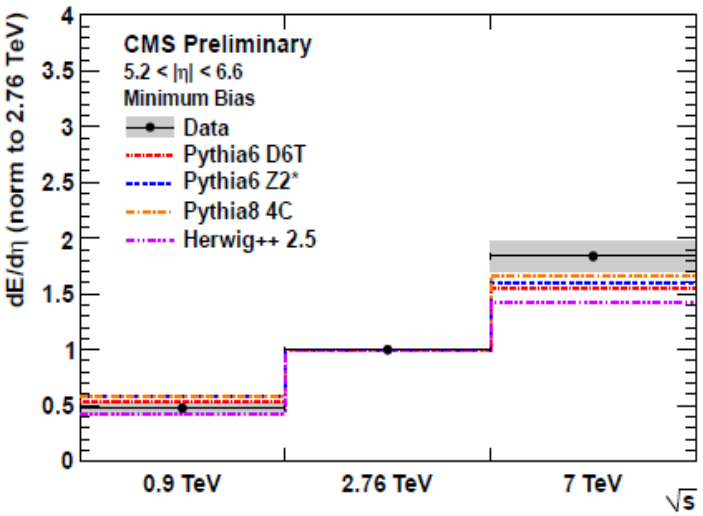


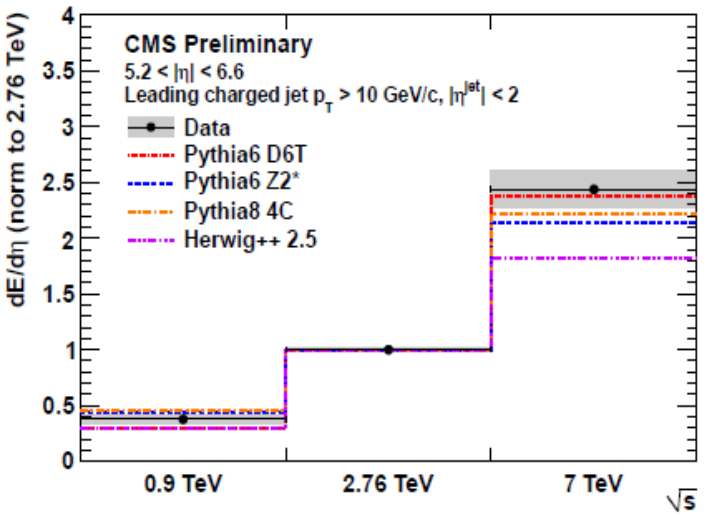


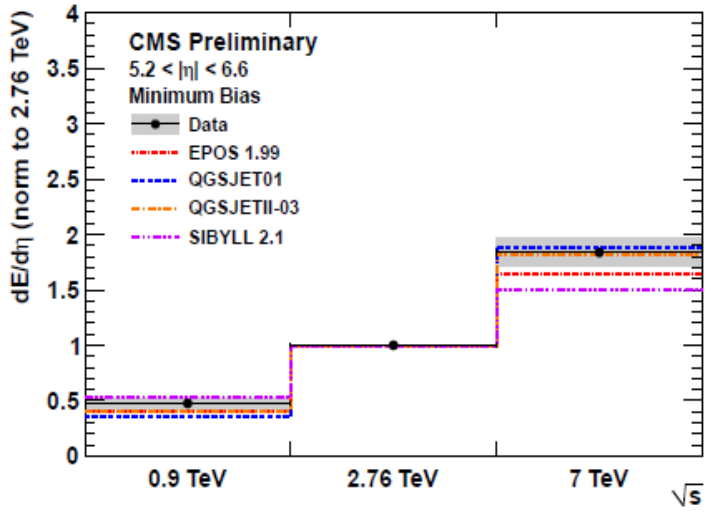


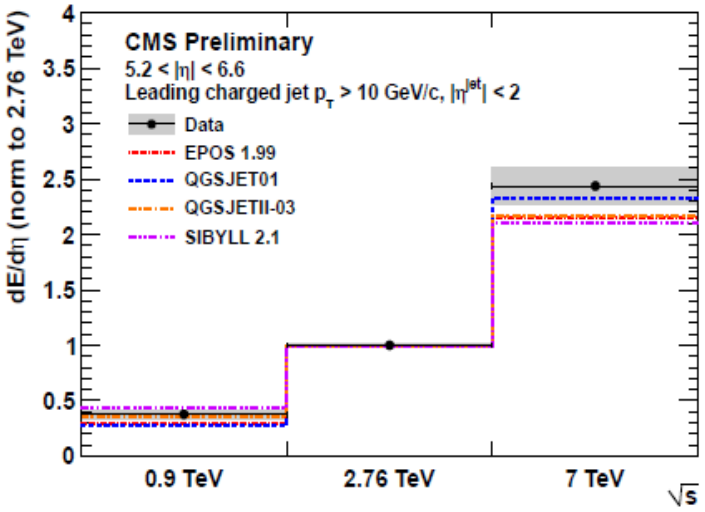
- √ s = 0.9 TeV → jet + UE activity = depletion of remnant seen in CASTOR
- √ s = 7 TeV → fast increase of MPI activity at low p_T; saturation at high p_T
- Cosmic ray models → no tuning; bracketing data; spread increases with energy

Normalized energy density (inclusive/hard scale) vs energy









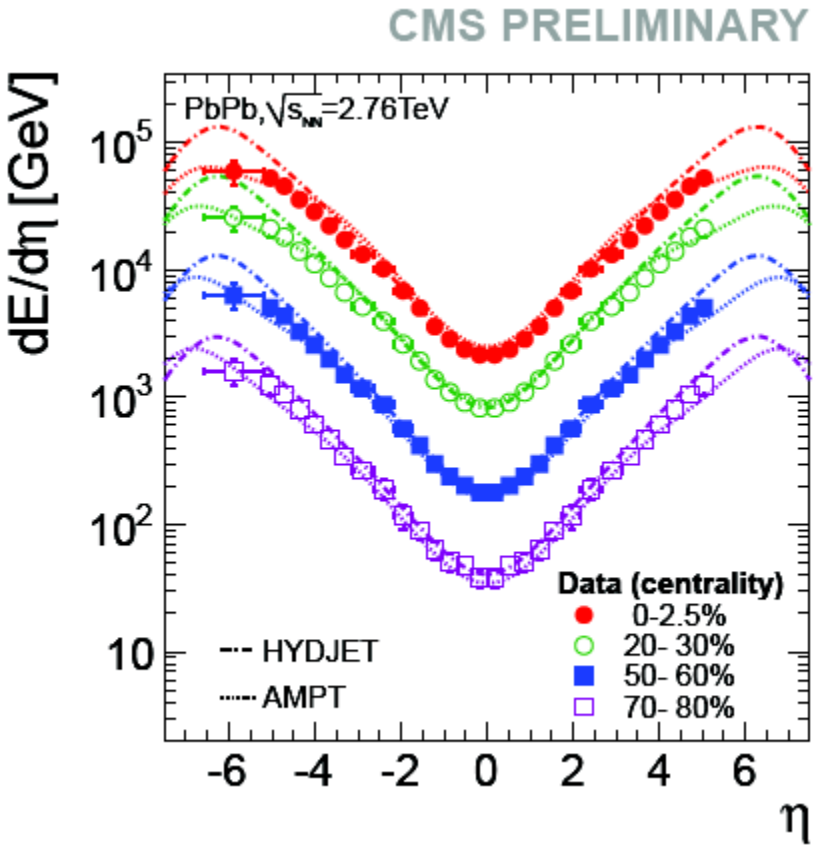
- Cosmic ray models vs Pythia / Herwig

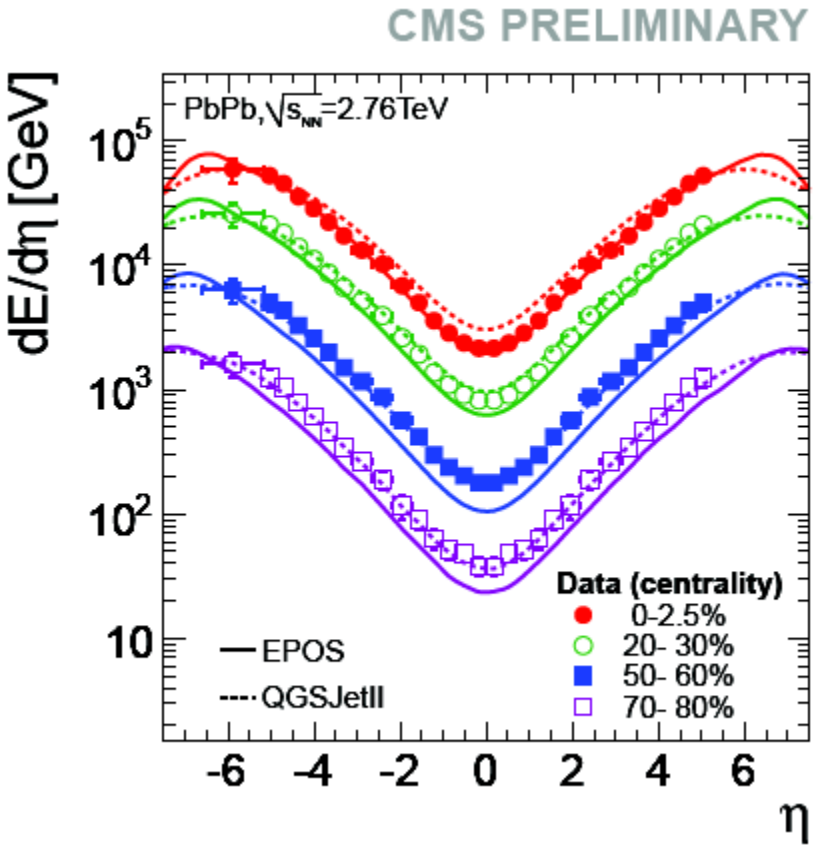
Measurement of the pseudorapidity and centrality dependence of the very forward energy density in PbPb collisions at $\sqrt{s}$=2.76 ATeV

[CMS PAS HIN 12-006]

http://cds.cern.ch/record/1472732

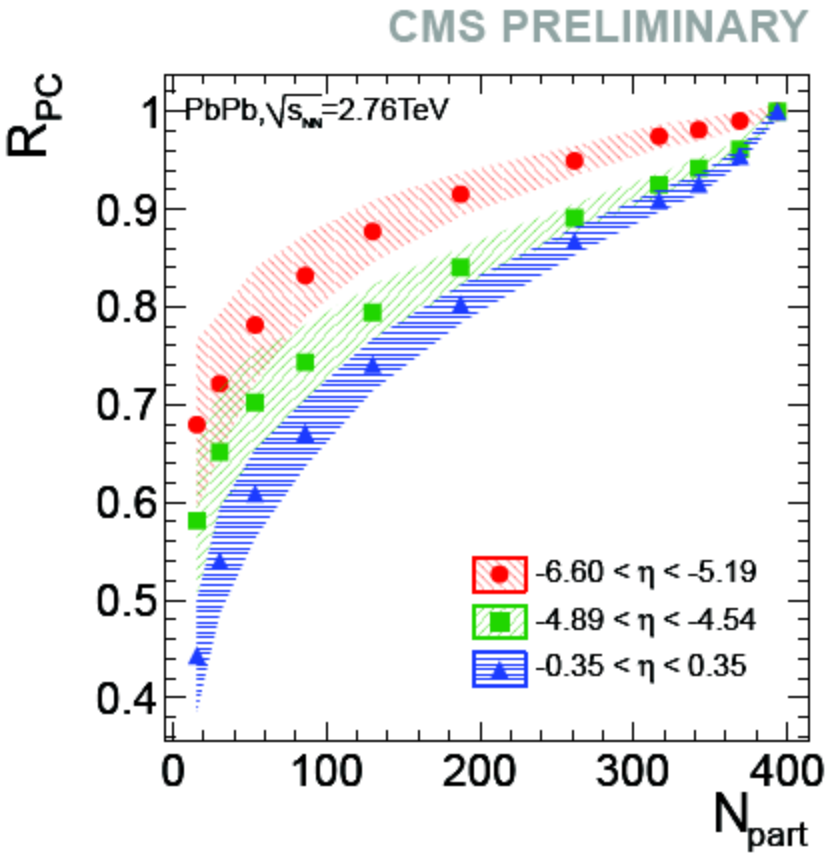
Energy density dE/dη (η, N_{part}) = < E > / Δη

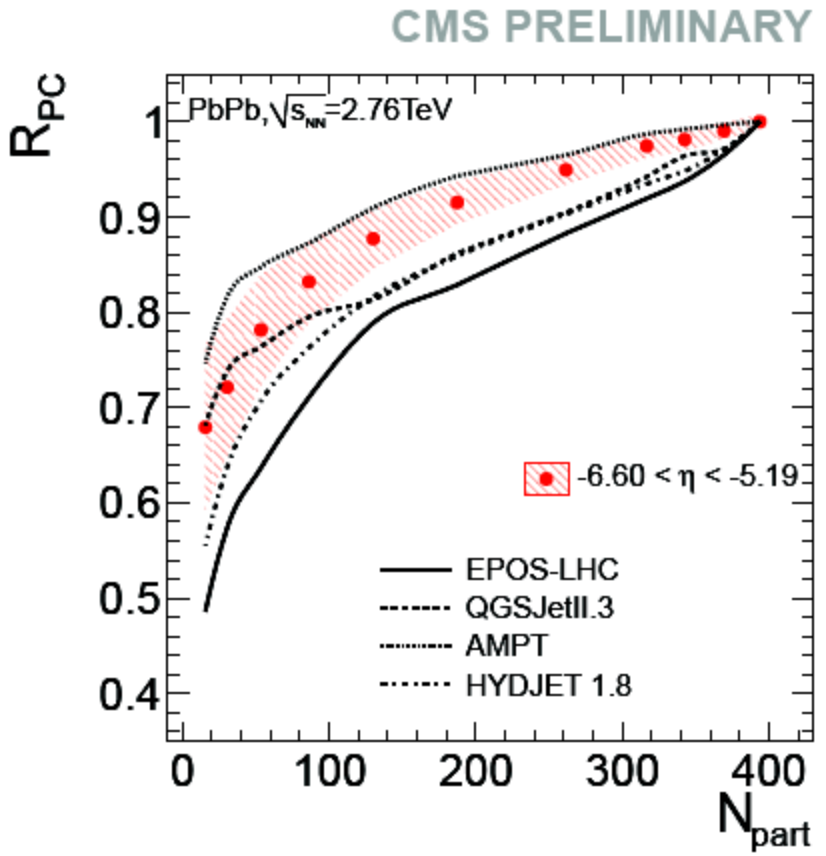




- Data vs models: rapidity and centrality dependence at the same time
- HYDJET: central rapidity; EPOS: central events; QGSJET: peripheral events

Energy density ratio peripheral vs central → $R_{PC} = \frac{\langle E \rangle(\eta, N_{part})}{\langle E \rangle(\eta, N_{part}^{max})} \cdot \frac{N_{part}^{max}}{N_{part}}$

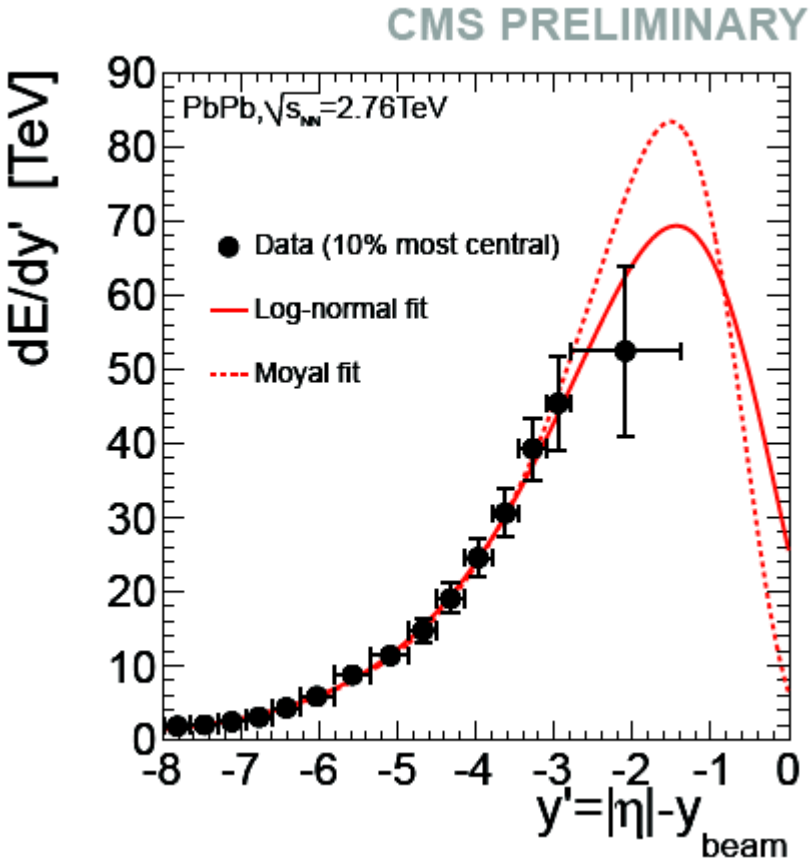


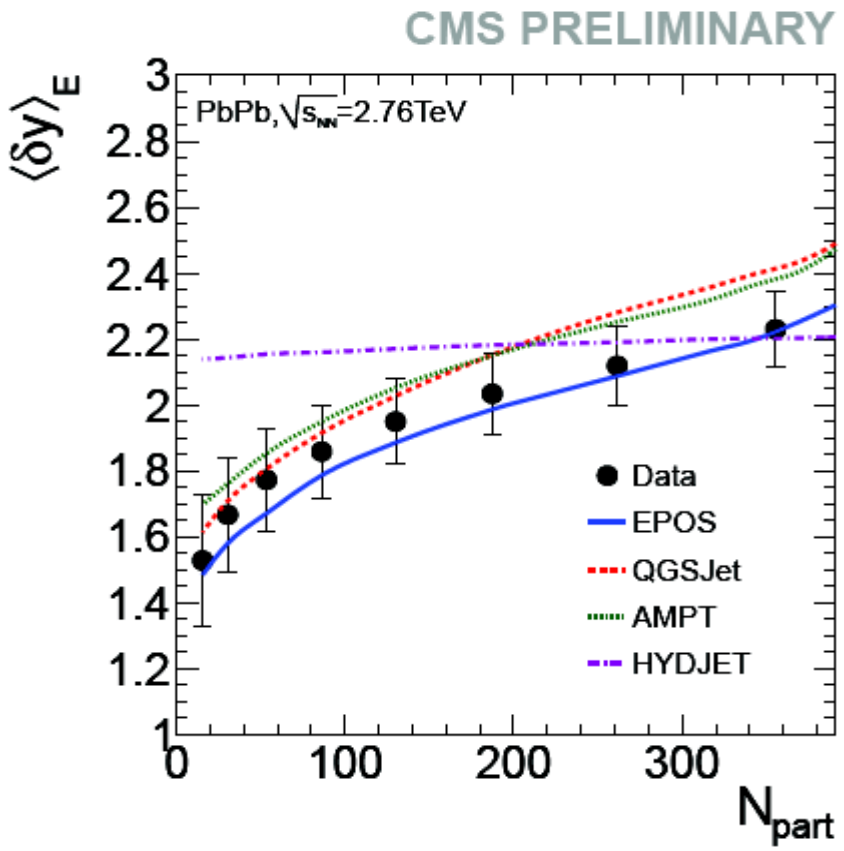


- Centrality dependence flattens out when using more forward detectors; η → x

Average energy-weighted (relative) pseudorapidity

$$\langle \delta y \rangle_{\mathrm{E}} = \frac{2}{E_{\mathrm{N}} N_{\mathrm{part}}} \int_{\infty}^{-y_{\mathrm{beam}}} y' \frac{\mathrm{d}E}{\mathrm{d}y'} \mathrm{d}y', \quad y' = |\eta| - y_{\mathrm{beam}}$$





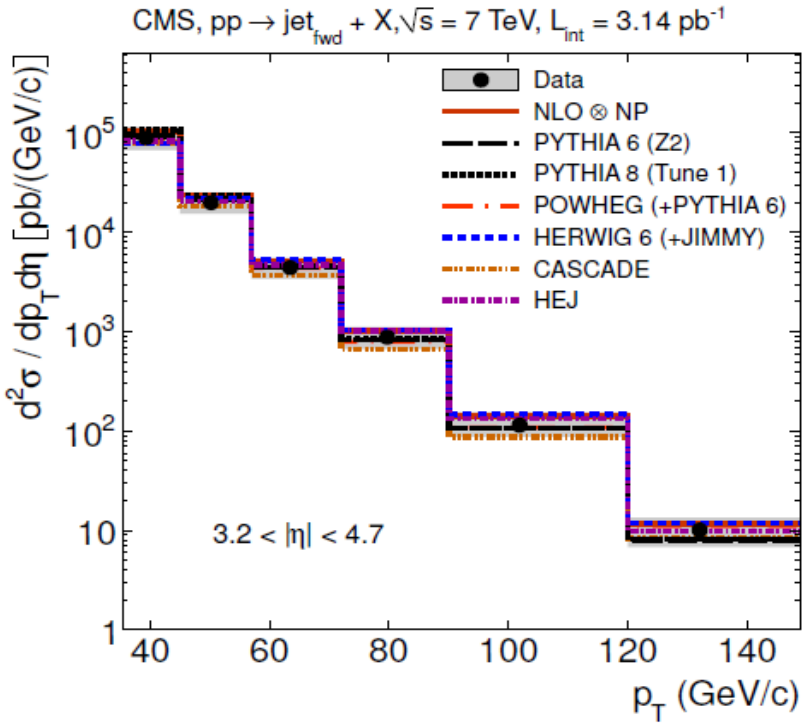
- CASTOR close to y_{beam} : beam fragmentation region

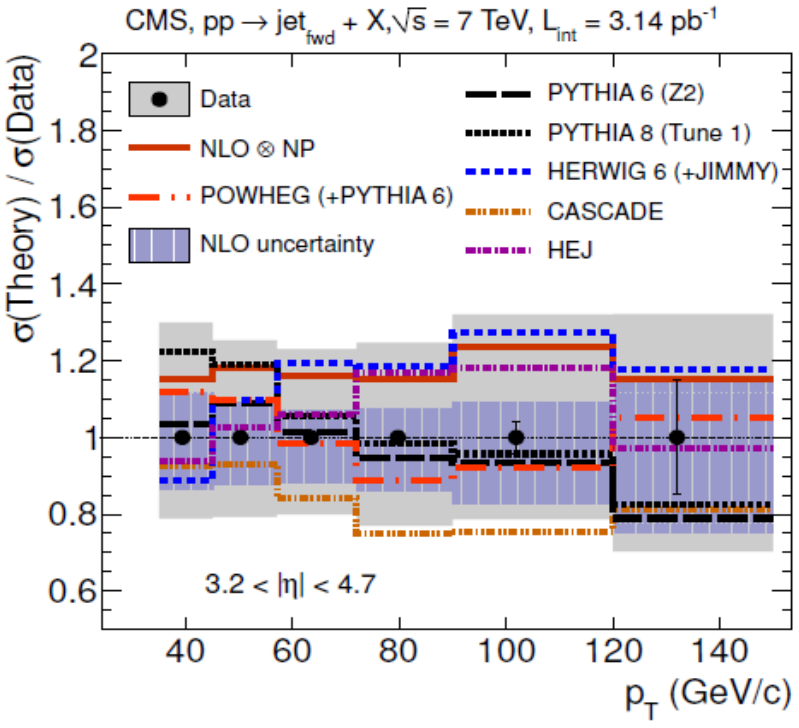
Measurement of the inclusive production cross sections for forward jets and for dijet events with one forward and one central jet in pp collisions at $\sqrt{s}$ = 7 TeV

[J. High Energy Phys. 06 (2012) 036]

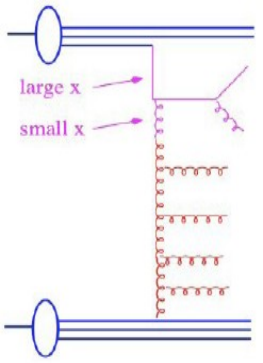
http://cds.cern.ch/record/1421692

Inclusive forward jets

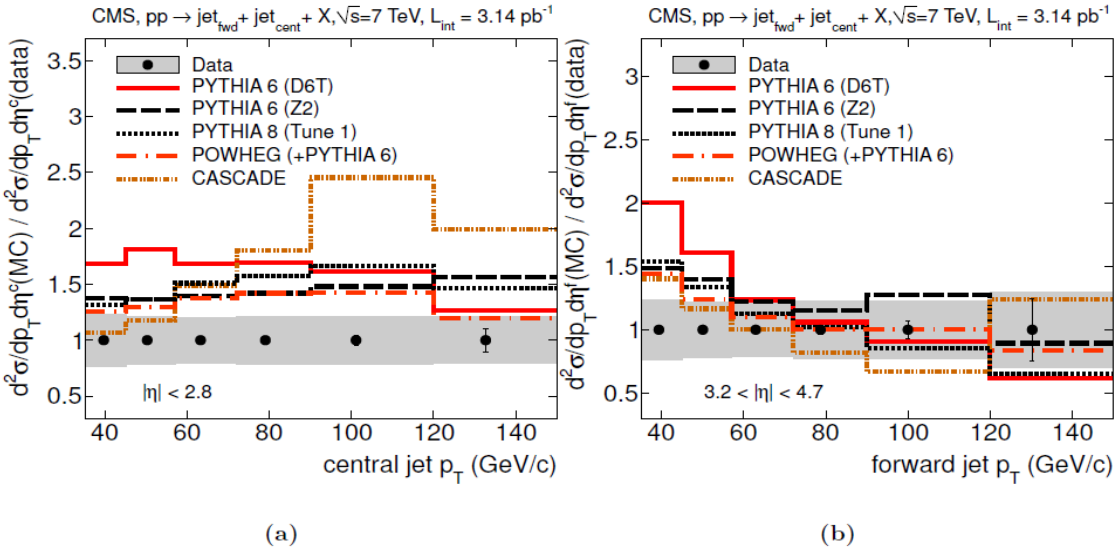


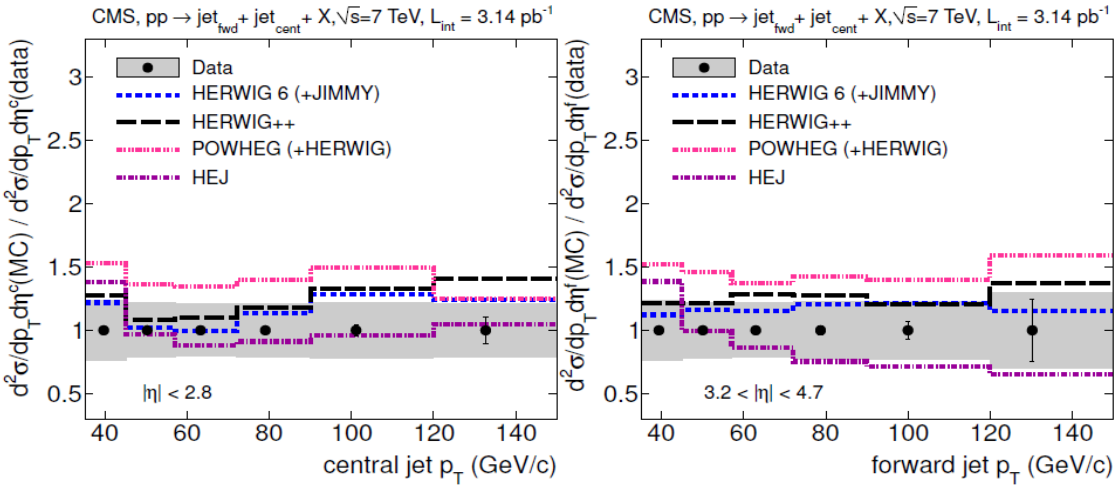


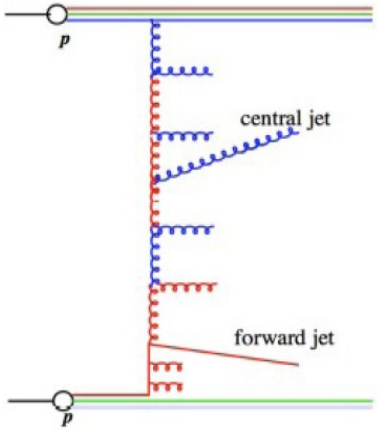
- In reasonable agreement with predictions within large JES uncertainties



Forward-central jets







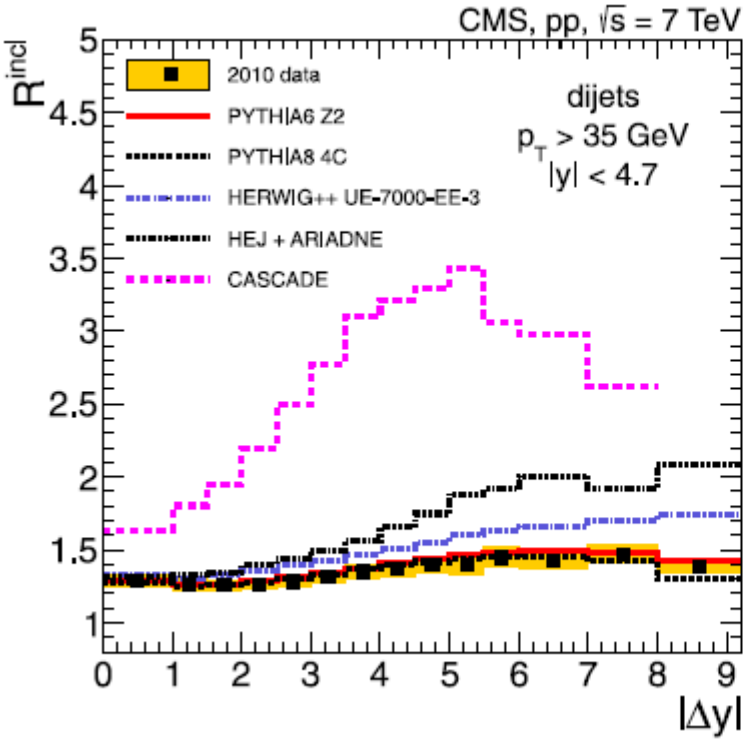
- Any effects beyond DGLAP?
- Wide spread in predictions
- Correlations pose a challenge for description

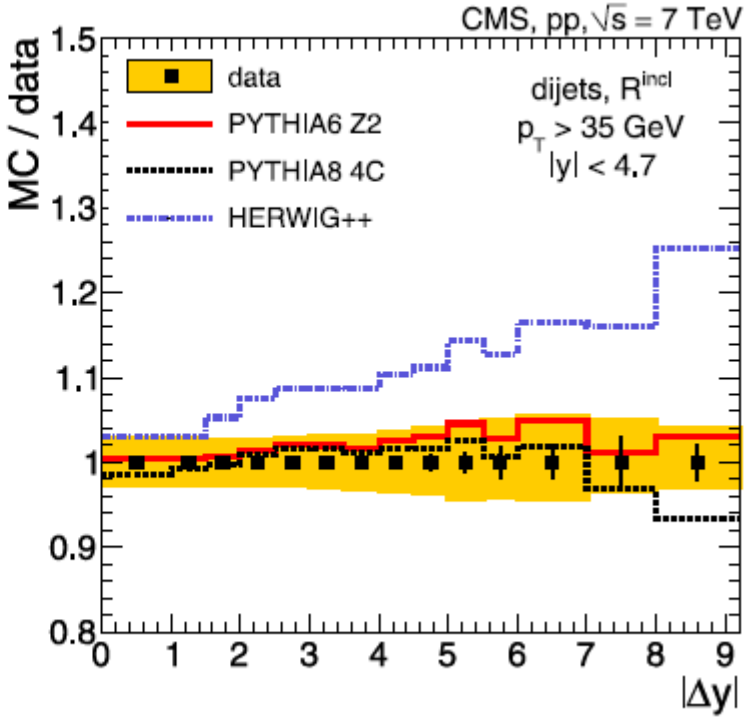
Ratios of dijet production cross sections as a function of the absolute difference in rapidity between jets in proton-proton collisions at $\sqrt{s}$ = 7 TeV

[Eur. Phys. J. C 72 (2012) 2216]

http://cds.cern.ch/record/1437010

Inclusive to exclusive di-jet ratio





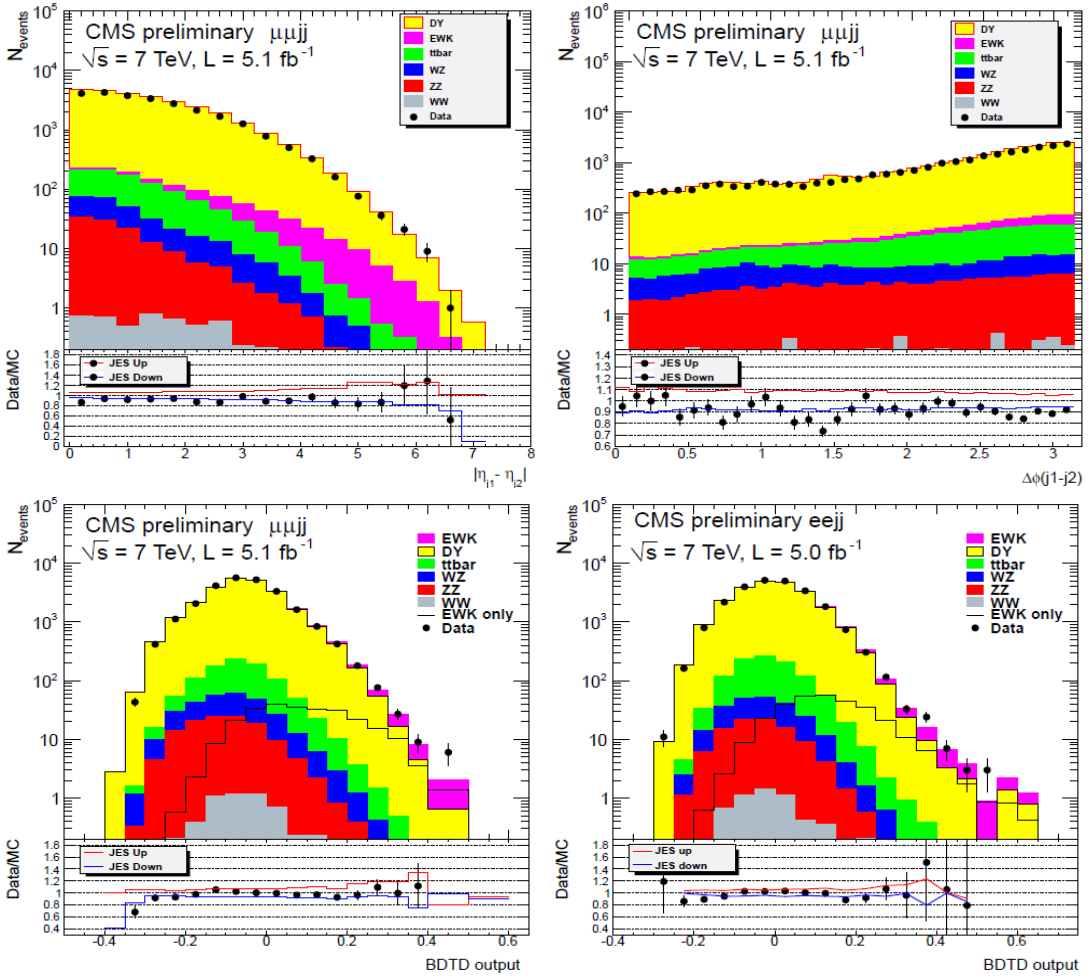
- Large rapidity separation to probe effects beyond DGLAP
- Rise of $R = \sigma_{incl} / \sigma_{excl}$ with Δy as phase space for parton emission opens
- In agreement with PYTHIA6 predictions within uncertainties

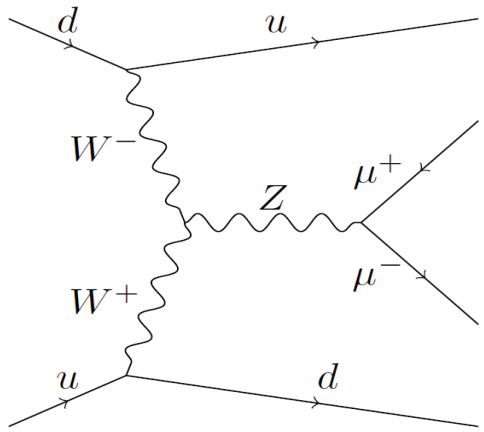
Measurement of the electroweak production cross section of the Z boson with two forward-backward jets in pp collisions at 7 TeV

[CMS PAS FSQ 12-019]

http://cds.cern.ch/record/1493475

Vector-Boson-Fusion Z production (with forward jets)





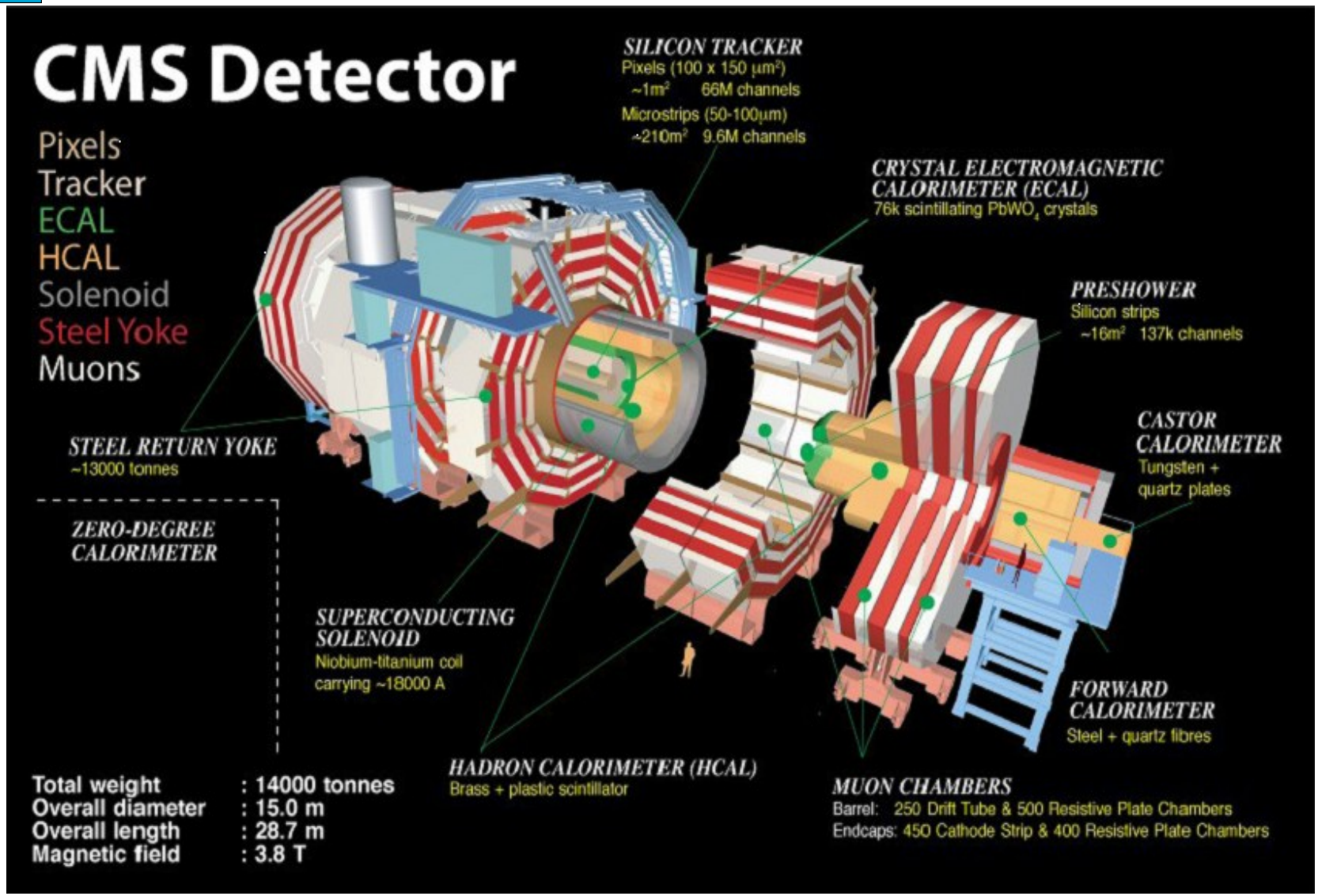
$$m_{\ell\ell} > 50\,\text{GeV},$$
$$p_T^j > 25\,\text{GeV},\ |\eta^j| < 4.0$$
$$m_{jj} > 120\ \text{GeV}$$

- EWK x-section extracted σ_{meas} = 154 ± 24 (stat) ± 46 (exp.syst) ± 27 (th.syst) ± 3 (lumi) fb
  [vs σ_{theory} = 166 fb (VBFNLO)]
- Explored CMS capabilities for VBF Higgs production measurements

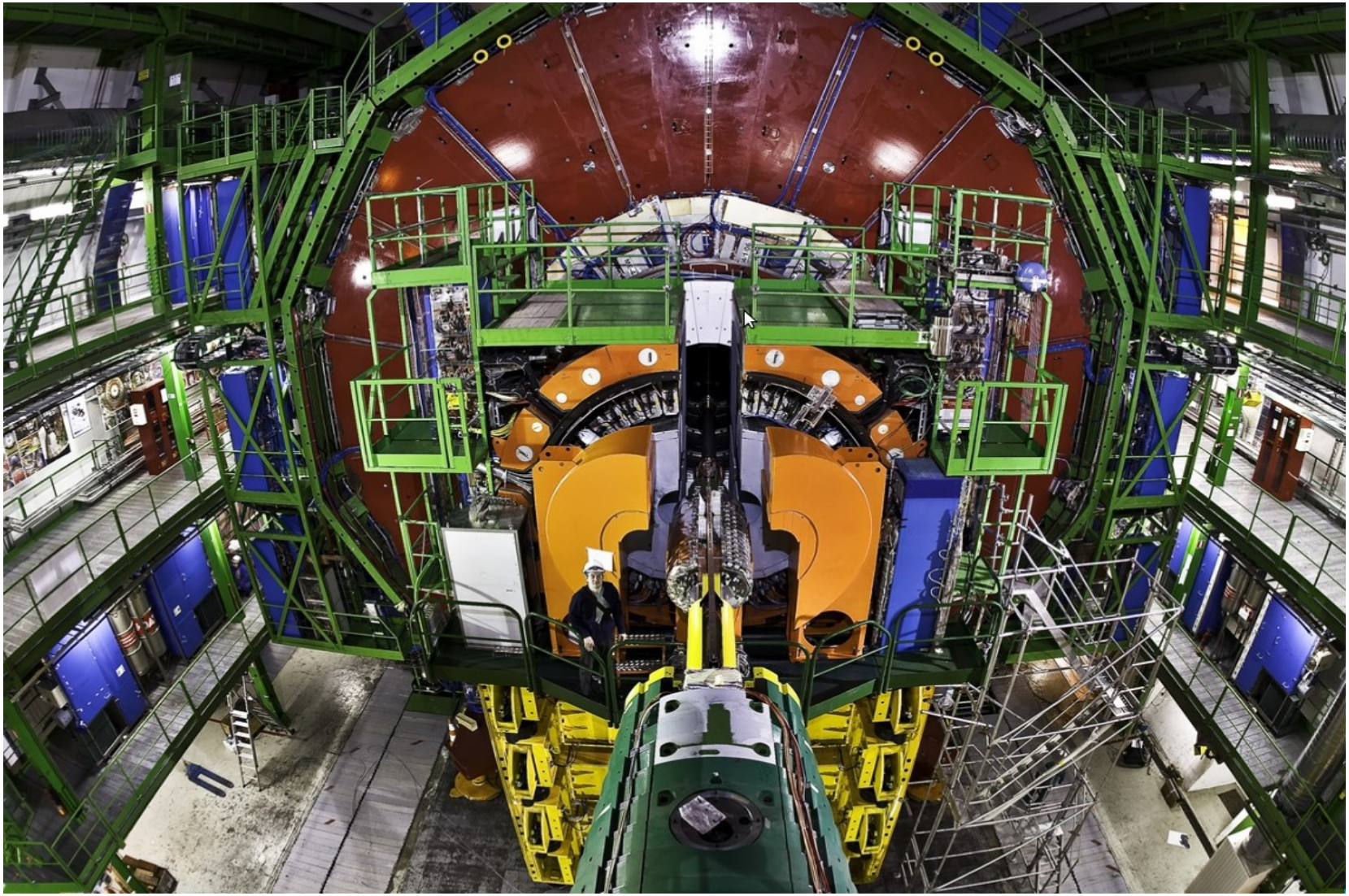
Summary and outlook

- First results employing full potential of CMS calorimetry coverage at highest collision energies
- Rich collection of results in pp (and PbPb) collisions, including evolution with energy
- Standard collider physics generators do a reasonable job for inclusive measurements; correlations in several cases pose a challenge.
- Cosmic ray hadronic models in many cases provide nice description (w/o tuning)
- Still waiting for a smoking gun / signs of the New
  - Azimuthal de-correlations in Mueller-Navelet di-jets, forward-central jet correlations, analyses of 8 TeV, pPb, CMS-TOTEM data...

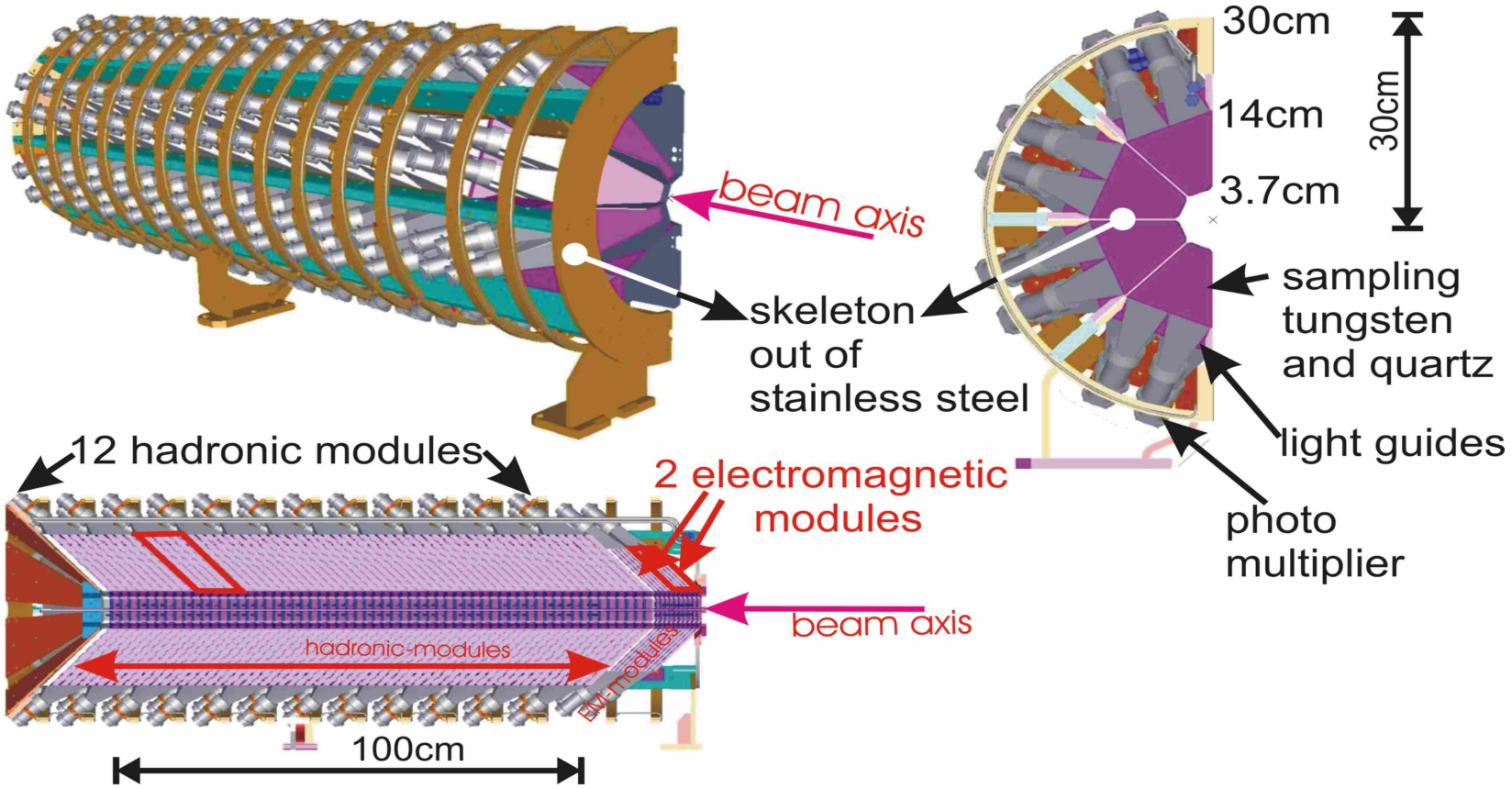
BACKUP


CMS Detector
Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² 66M channels
Microstrips (50-100μm)
~210m² 9.6M channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
76k scintillating PbWO4 crystals
PRESHOWER
Silicon strips
~16m² 137k channels
CASTOR CALORIMETER
Tungsten + quartz plates
STEEL RETURN YOKE
~13000 tonnes
ZERO-DEGREE CALORIMETER
SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A
FORWARD CALORIMETER
Steel + quartz fibres
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
MUON CHAMBERS
Barrel: 250 Drift Tube & 500 Resistive Plate Chambers
Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

CMS forward region

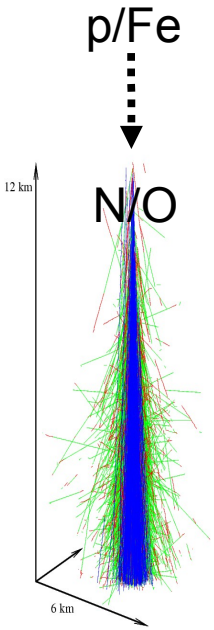


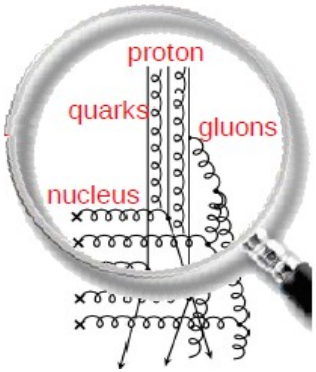
CASTOR Calorimeter design



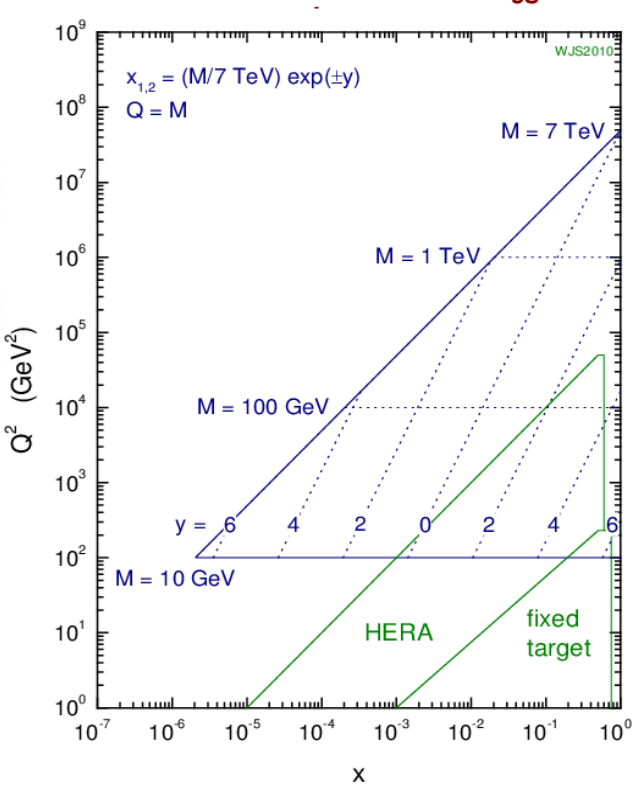
- 16 azimuthal sectors (semi-octants/towers) mechanically organised in two half calorimeters; EM part (2 modules) + HAD part (12 modules); EM = 0.7λ = $20X_0$; HAD = 12 ∗ 0.7 = 9.24λ ; overall depth = 10λ

Low-x QCD

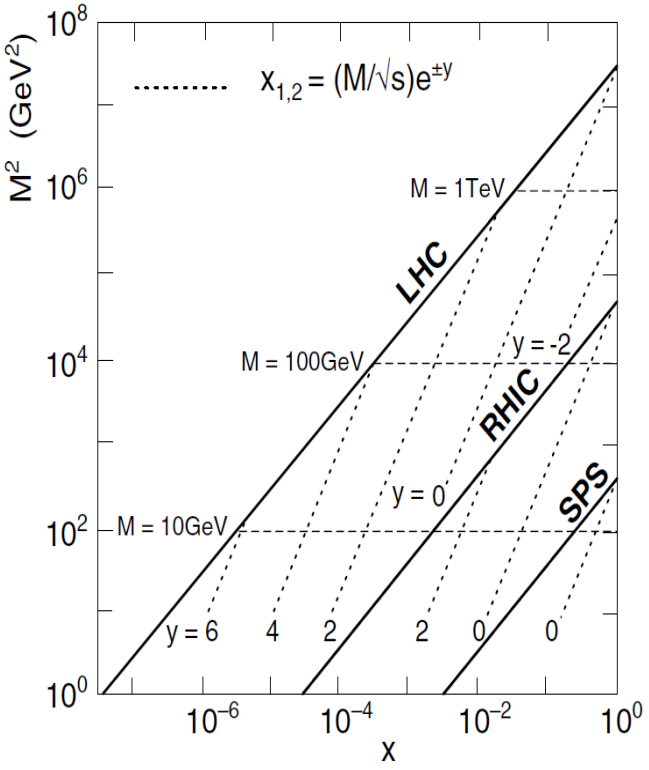




pp parton kinematics @ 7 TeV



PbPb parton kinematics @ 5.5 TeV



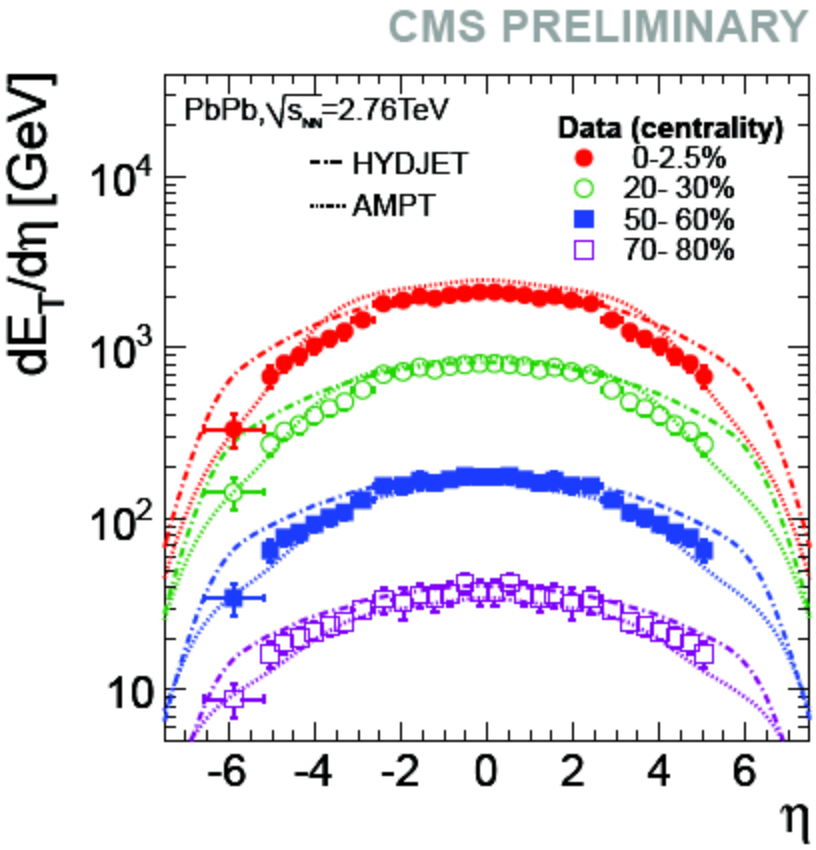
- Understanding QCD at new energy frontier: jets, particle and energy flow in pp, PbPb at √ against MC models

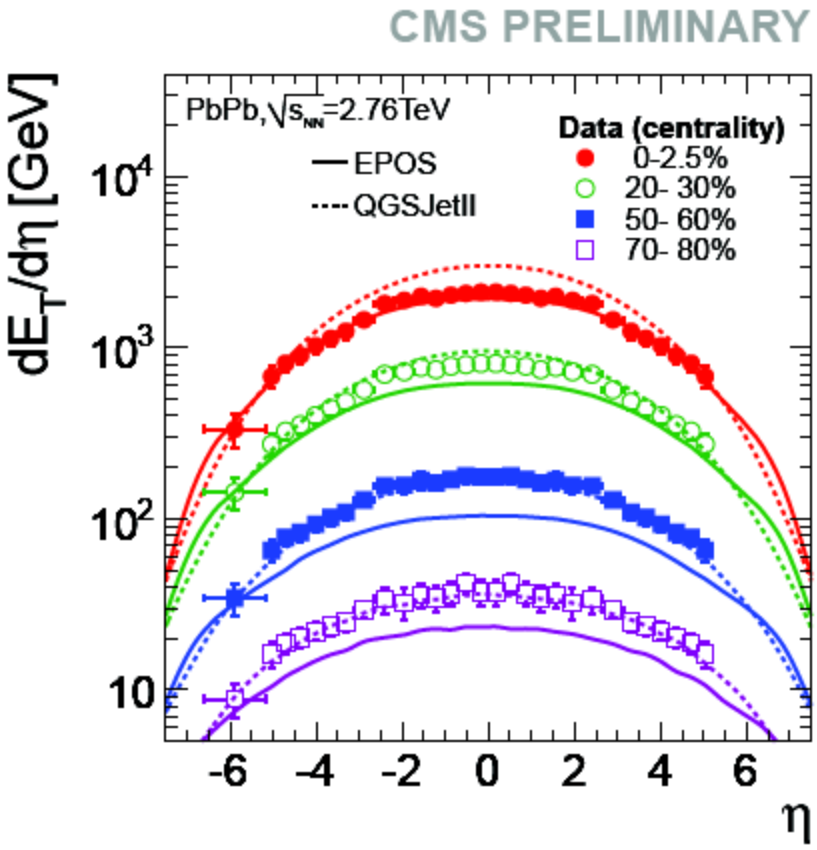
www.hep.phy.cam.ac.uk/~wjs
Nucl. Phys. A (2005) 447
David d'Enterria

Energy flow in PbPb collisions at 2.76 TeV

- Absolute energy measurement with CASTOR (region of beam fragmentation) → conservative estimate of uncertainty = 22% (cross-calibration procedure, simulation, geometry)
- Minimum bias events at nominal magnetic field
- Hadron level → all particles above lifetime threshold excluding muons / neutrinos
- Correction factors ~1.7: using only front calorimeter part (3.2 λ_I vs 10 λ_I)

Density of transverse energy, $E_T(\eta, N_{part}) = E / \cosh(\eta)$





Monte Carlo models / tunes

- Partonic cross section regularised via cut-off

$$1/\hat{p}_T^4 \rightarrow 1/(\hat{p}_T^2 + \hat{p}_{T_0}^2)^2, \quad \hat{p}_{T_0}(\sqrt{s}) = \hat{p}_{T_0}(\sqrt{s_0}) \cdot (\sqrt{s}/\sqrt{s_0})^{\epsilon}$$

- More MPI activity is predicted for smaller values of pt0
- Considered mainly PYTHIA-6 tunes consistent with UE measurements by CDF which favour pt0 = 2.0 GeV for √s0 = 1.8 TeV
- Tunes DW, P0, Pro-Q20: ε = 0.25 in agreement with CDF data at √s = 630 GeV and 1.8 TeV (DW pt0 = 1.90 GeV)
- Tune D6T: ε = 0.16 motivated by the measurements of charged particle multiplicities by UA5 at SppS collider (pt0 = 1.84 GeV)
- Tunes P0, Pro-Q20 use LEP results to describe hadron fragmentation at high *z*
- Tune P0 and PYTHIA-8: new PYTHIA MPI model interleaved with parton showering
- PYTHIA-6 includes only soft diffraction, while PYTHIA-8 includes simulation of hard diffraction
- PHOJET: alternative event generator, differs in underlying dynamical model for particle production, based on the dual-parton model with multi-Pomeron exchanges

Monte Carlo models

- CASCADE: CCFM evolution with off-shell matrix elements
- JIMMY generator for multiple interactions, close integration with HERWIG
- POWHEG: interface NLO calculations to shower Monte Carlo programs
- High Energy Jets (HEJ) generator for multi-jet processes with focus on (non-collinear) radiative corrections
- Cosmic ray models:

Older models:

Glauber based, different mostly in remnants+diffraction, for example:
QGSJet01 *(Kalmykov, Ostapchenko)*
SIBYLL *(Engel, Gaisser, Lipari, Stanev)*

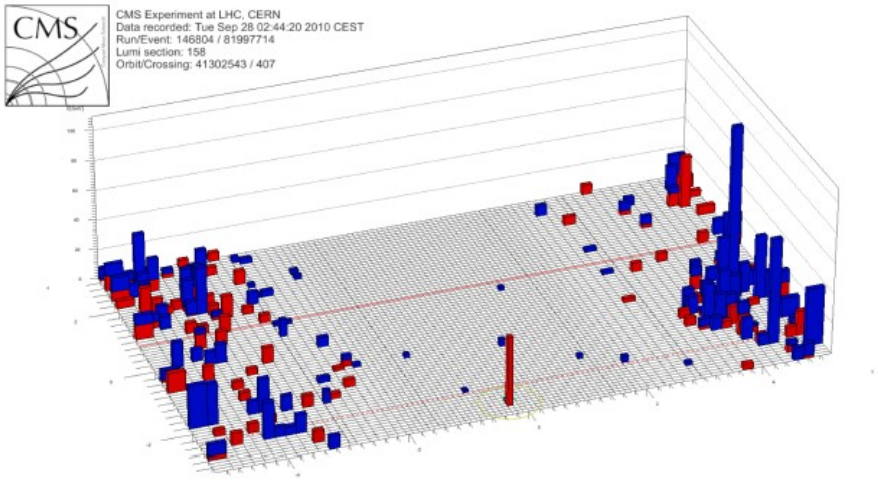
Recent models:

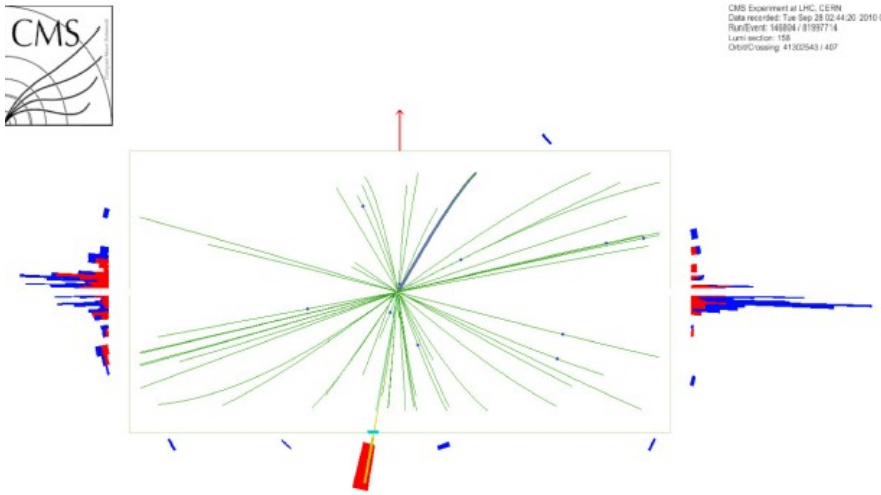
QGSJetII *(Ostapchenko)*
Theory++, Optimized for cosmic rays

EPOS *(Werner, Pierog)*
Phenomenology++
Optimized for LHC, RHIC (and cosmic rays)

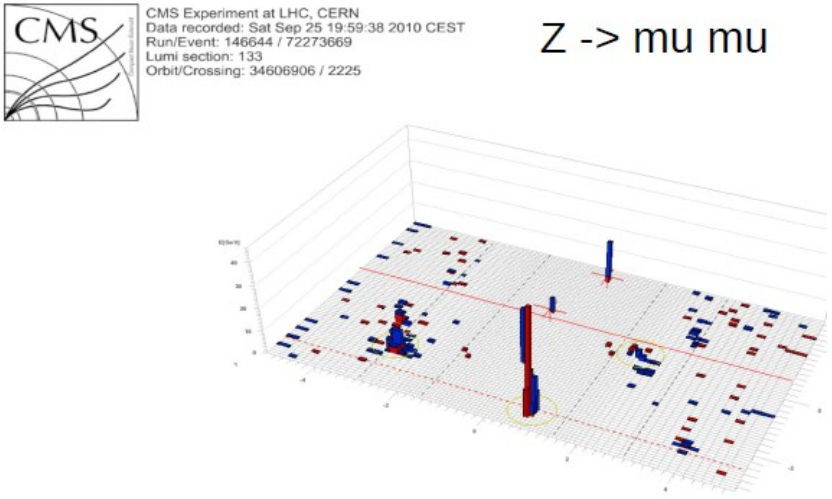
W/Z events w/o rapidity gap

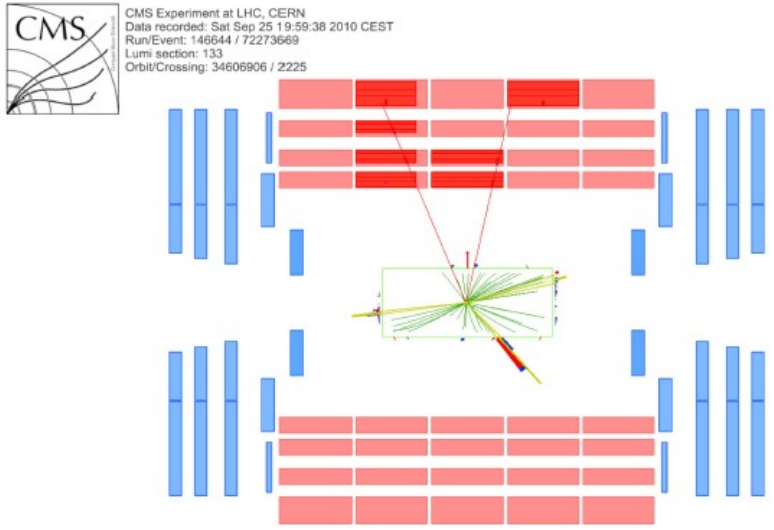
W -> e nu





Z -> mu mu





11-12 February 2013
ForwardPhysicsLHC = results and prospects of forward physics
at the LHC: implications for diffraction, cosmic rays, and more