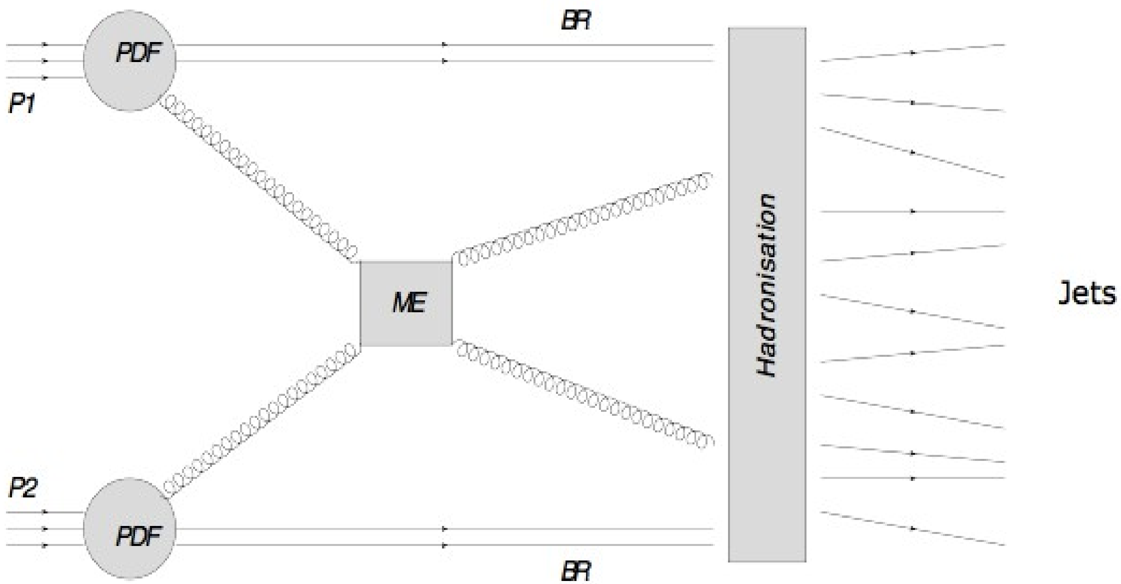
Recent results on Underlying Event and Double Parton Scattering with the CMS detector

R. Arcidiacono
on behalf of the CMS collaboration

Universita' del Piemonte Orientale, INFN Torino

Underlying Event in p-p collisions

The underlying event (UE) is everything else around the hard scattering (ME)



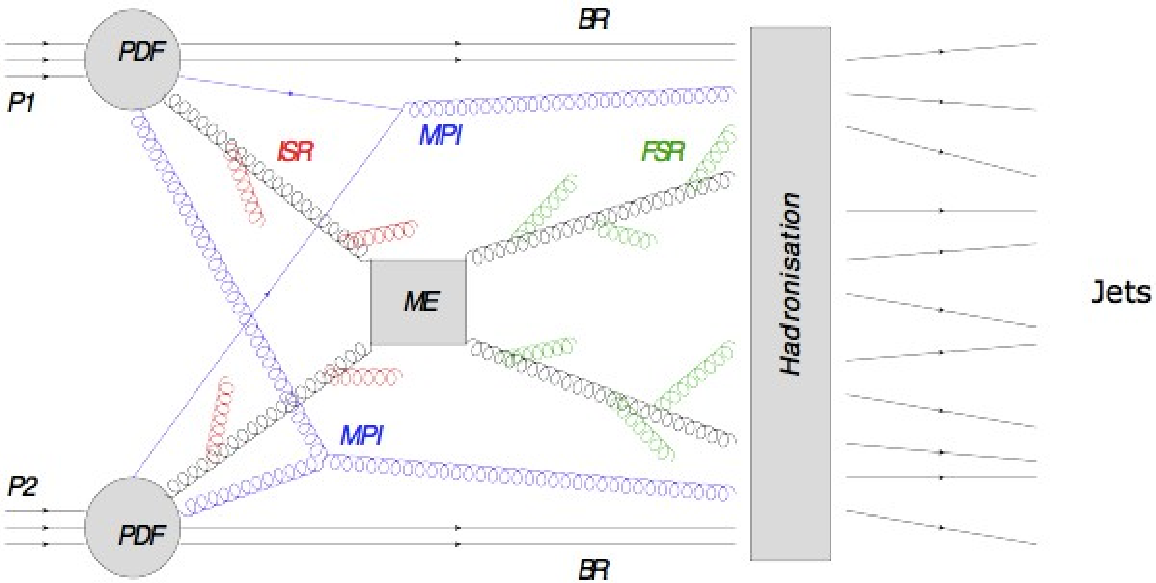
→ Initial (ISR) and final (FSR) state radiations

→ Multiple Parton Interactions (MPI). If higher-p_T interactions → Double Parton Scattering

→ Beam remnants (BR): what remains in the hadrons that did not participate in other scatterings

Underlying Event in p-p collisions

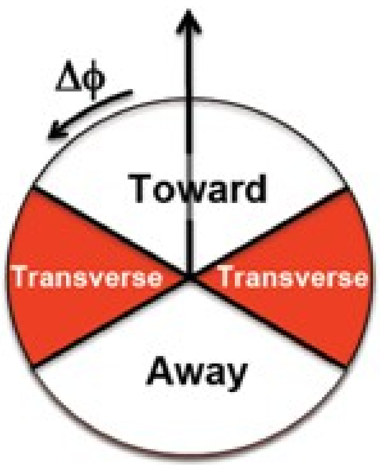
The underlying event (UE) is everything else around the hard scattering (ME)



Understanding the UE is crucial for better modelling of Monte Carlo programs used in precision measurements of the SM and in searches for new physics at high energy

The study of UE is sensitive to the interplay of perturbative methods (hard process) and phenomenological models of the soft interactions (MPI, IFR, FSR)

Underlying Event observables



UE activity is typically studied in the transverse region in pp collisions as a function of the hard scale of the event, and at different centre-of-mass energies ($\sqrt{s}$)

Clusters of tracks, or clusters of calorimeter cells with largest p_t are called leading object → expected to reflect the direction of the parton in the hard scattering. **Transverse region is expected to be sensitive to underlying event**

Measurements at central rapidities:

- Look at particle production in hadronic events: minimum bias, events containing a leading track-jet or a leading track
  - Charged Particle density and Energy density in the transverse region

- Use of Drell-Yan di-muon final state, with $m_{\mu\mu}$ close to Z → good separation of primary hard scatter from the rest, very low background. No QCD FSR

Hadron production in Minimum Bias

Eur. Phys. J. C72 (2012) 2164

UE composition studied via the analysis of absolute yields and p_T spectra of identified hadrons, at different centre-of-mass energy, in minimum bias events.

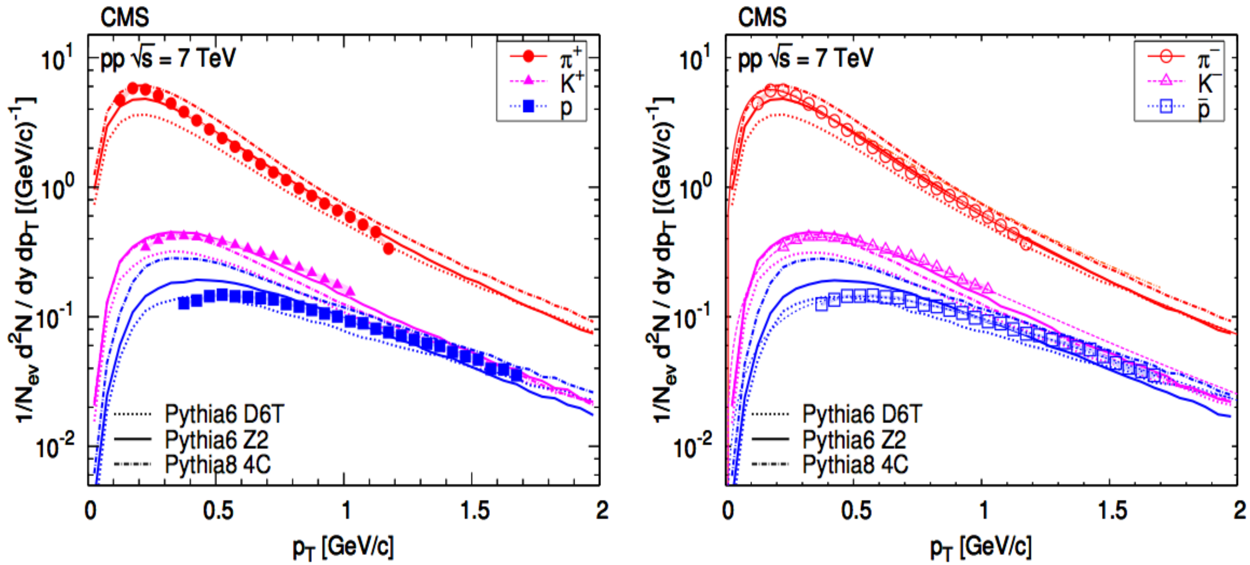
→ Charged hadrons: pions, kaons, protons in p_T range 0.1-2 GeV/c

→ Identified via dE/dx in the silicon layer of the tracker

Low PU data at 0.9, 7 and 2.76 TeV data (2011)

Transverse momentum distribution for pions, kaons, protons

Tunes D6T and 4C tend to be systematically below or above the spectra, whereas Z2 is generally closer to the measurements



CMS results consistent with existing results at low √s. Spectra also measured differentially in bins of particle multiplicity, to further constrain hadron production models.

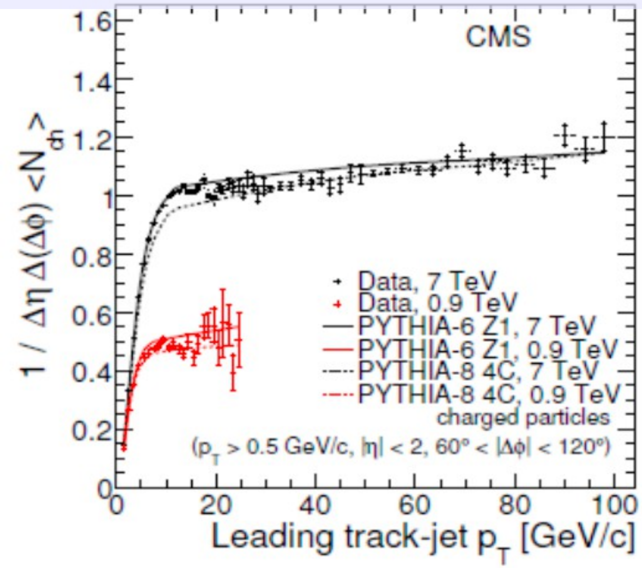
UE in events with tracks/track-jets

Charged Particle density

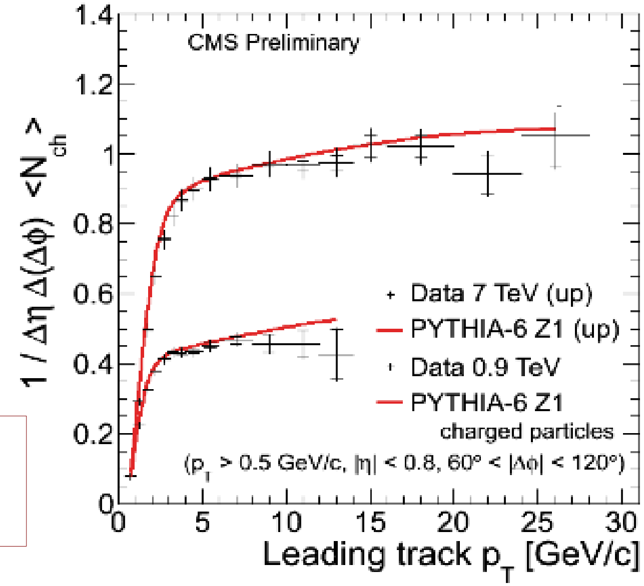
Average number of charged particle per unit pseudo-rapidity and azimuthal separation Δφ between particle and leading object

- The hard scale of the event is defined by the hardest object
- UE activity with leading jet (track) shows a sharp increase up to p_T = 10 GeV/c (5 GeV/c) → more MPI activity, more central collisions. FSR, ISR rise dominates at higher p_T.
- Strong increase of UE activity from 0.9 to 7 TeV
- Particle production saturates (MPI saturation)

UE activity: Σ charged in |η| < 2 , p_T > 0.5 GeV/c



Eur. Phys. J. C 70 (2010) 555
JHEP 09 (2011) 109



CMS PAS FSQ-12-020

Strangeness in UE activity with leading jets

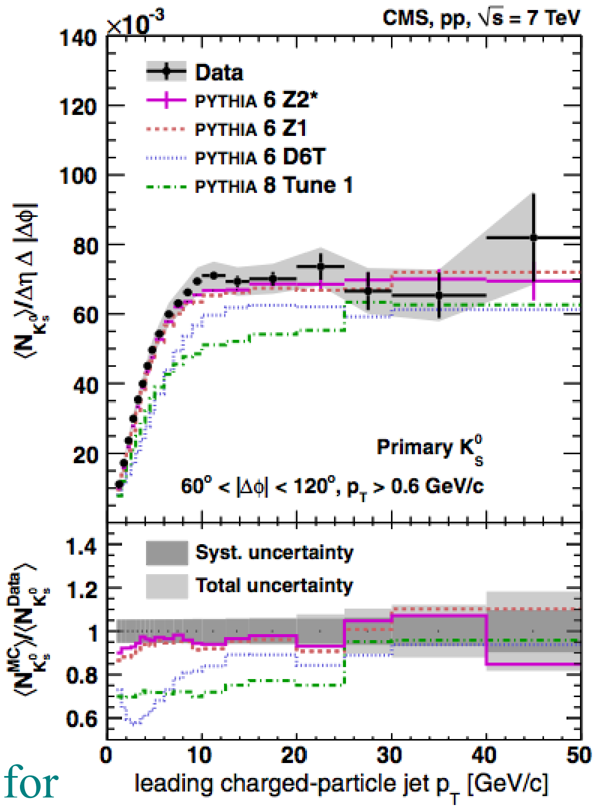
Phys. Rev. D 88, 052001 (2013)

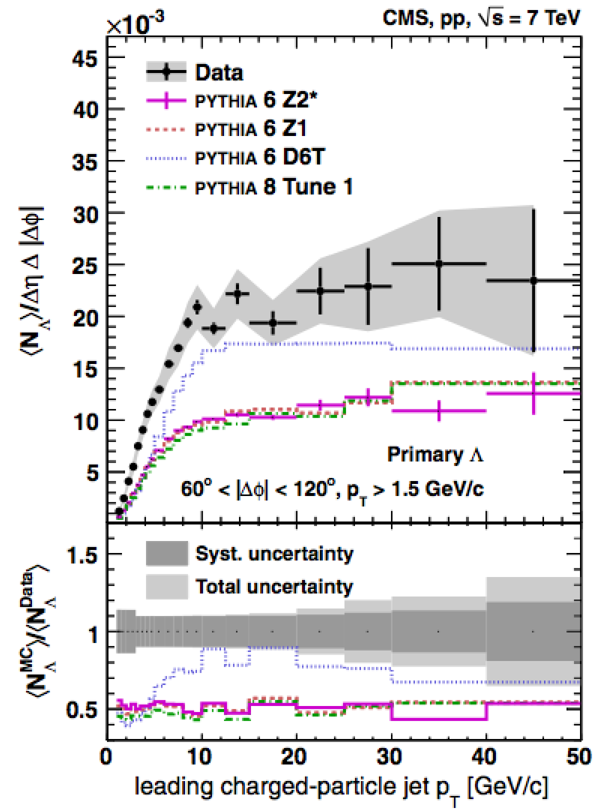
Neutral Strange Particle density in transverse region

Average number of K^0s (Λ, Λbar) particle per unit pseudo-rapidity and azimuthal separation $\Delta\varphi$ between particle and leading jet

Particle and energy density studied as a function of leading jet p_T

Steep rise followed by "saturation" region ($p_T > 10$ GeV/c) observed





Very similar to what observed for charged particles → consistent with picture of MPI activity correlated to centrality of the collision

Pythia simulations underestimate K^0s by 10-30% and Λ mesons by 50%

UE activity: K^0s (Λ, Λbar) in $|\eta| < 2$, $p_T > 0.6$ (1.5) GeV/c

Underlying Event in DY

Eur. Phys. J. C 72 (2012) 2080

UE Measurements in Drell-Yan:

UE vs $M_{\mu\mu}$ ($p_T^{\mu\mu} < 5$ GeV/c): MPI saturated above $M_{\mu\mu} = 40$ GeV/c^2.

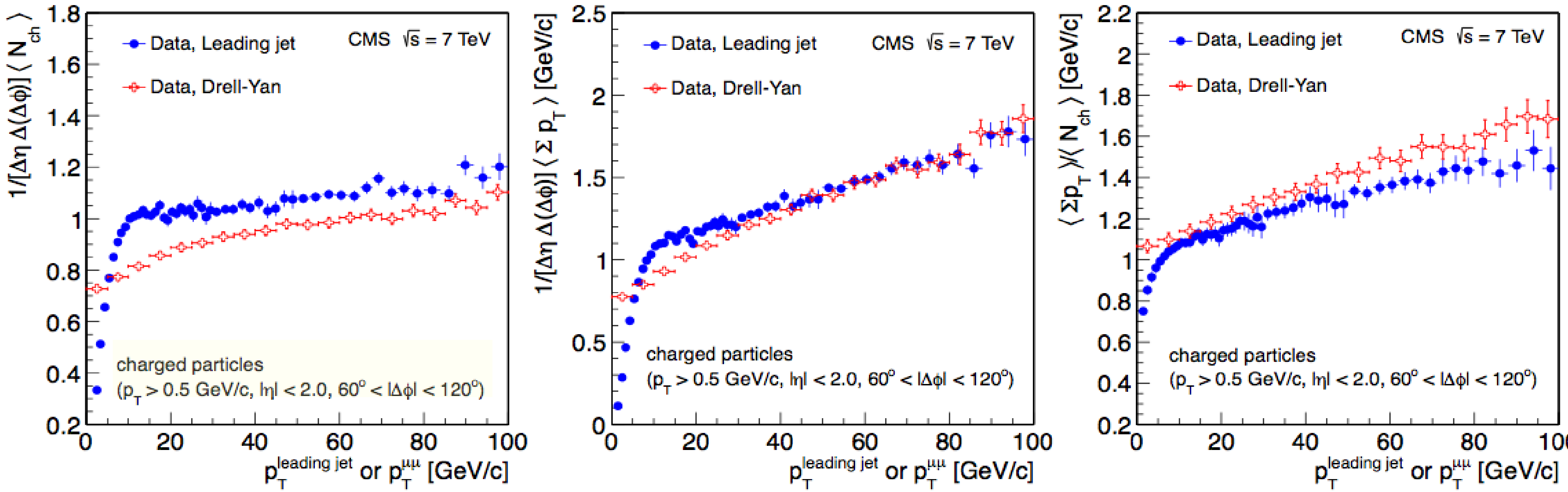
UE vs $p_T^{\mu\mu}$ ($81 < M_{\mu\mu} < 101$ GeV/c^2): Radiative increase of activity with $p_T^{\mu\mu}$.

→ Particle and energy densities compared to UE in hadronic Jets events

UE activity versus energy scale well described by tunes derived from hadronic events (PYTHIA6 and MADGRAPH with Z2), illustrating the universality of MPIs in different processes

2011 data, 2.2 fb^{-1}

particle density | energy density | ratio of energy and particle densities



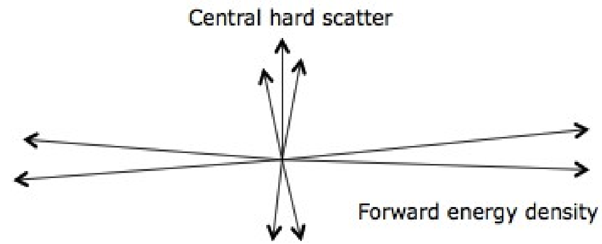
UE in forward region

Novel measurement at forward rapidities:

• measure energy density at angles very close to the proton beams

• UE observables separated by large $\Delta\eta$ from hard scatter, no division of φ phase space

Energy reaching CASTOR calorimeter, on the −z side of CMS. CASTOR: Quartz plates embedded in tungsten absorbers, providing a fast collection of the Cerenkov light.



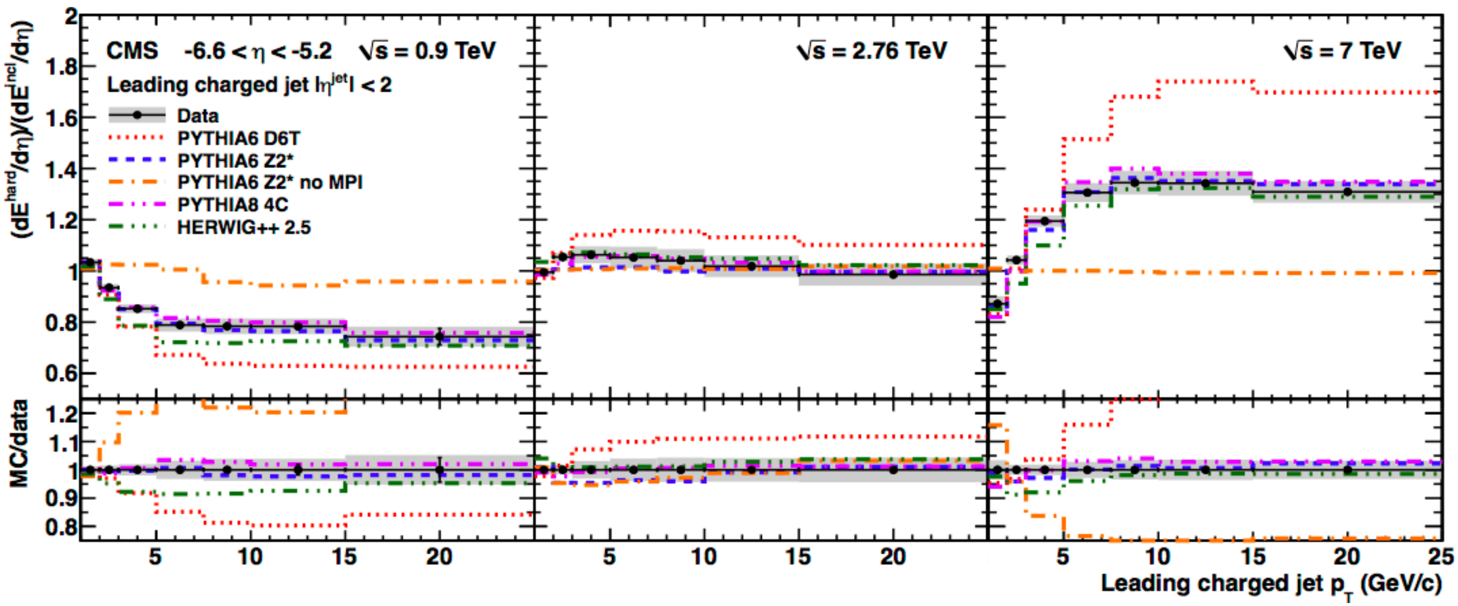
Recent measurement done using the energy flow in CASTOR ($-6.6 < \eta < -5.2$)

Complementary to measurements done at central rapidity!

UE in forward region

J. High Energy Phys. 04 (2013) 072

Hard-to-inclusive forward energy ratio (dE/dη deposited in CASTOR): ratio of activity in events with a central track-jet |η| < 2 to inclusive events

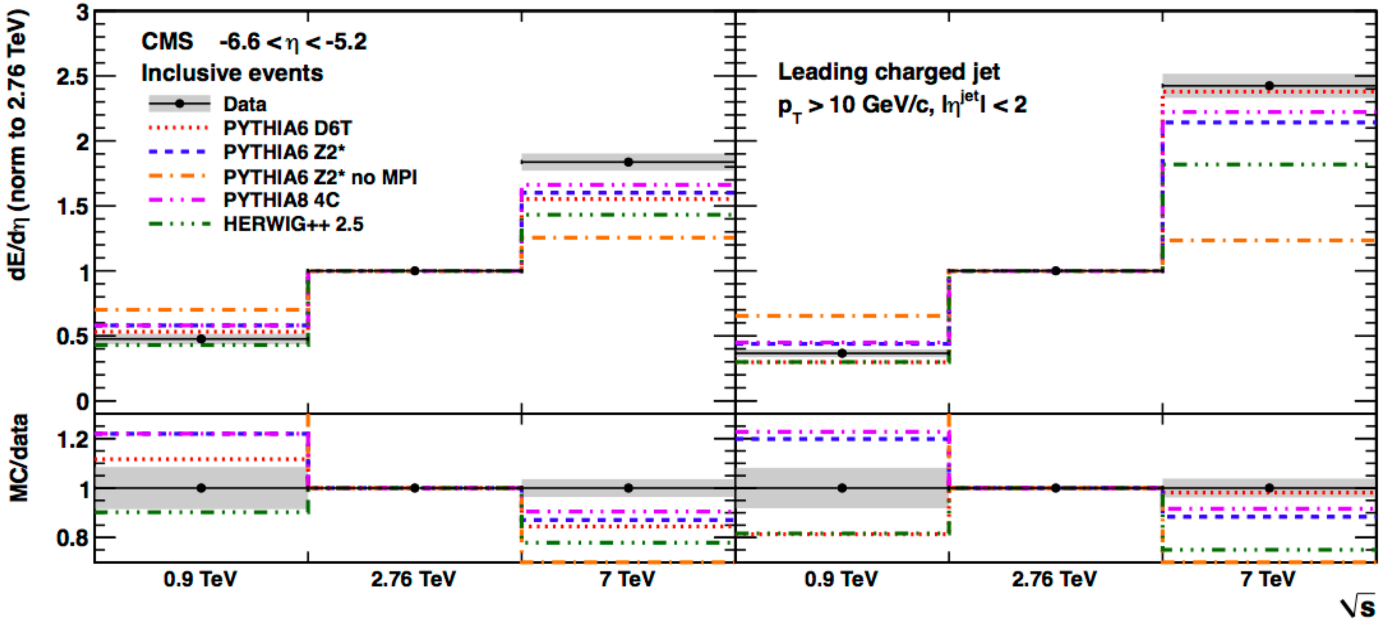


At 7 TeV, typical behavior characterized by a rapid change of the energy density at small charged particle jet p_T, followed by a plateau above 10 GeV/c.

At $\sqrt{s}$ = 7 TeV the relative energy density increases with jet p_T, while at $\sqrt{s}$ = 0.9 TeV, the energy density decreases with increasing jet p_T (central hard jets production depletes the energy of the proton remnant, which fragments within CASTOR acceptance)

UE in forward region

Energy density / energy density @ 2.76 TeV



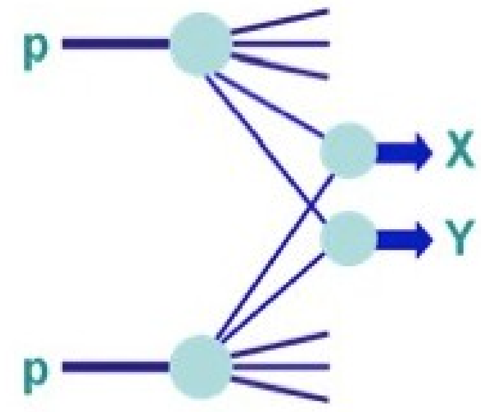
None of the PYTHIA or HERWIG++ models describe the increase with √s seen in data. For inclusive events they differ very little and all underestimate the increase from 2.76 to 7 TeV.

For events with central charged particle jets, the tunes vary widely. The description of the underlying event for this category of events is expected to differ.

Double Parton Scattering

MPI from soft to hard → Double Parton Scattering
Phenomenological description
The cross section for double-parton interactions is

$$\sigma_{XY} = m \cdot \frac{\sigma_X \cdot \sigma_Y}{\sigma_{eff}}$$



with m = ½. If X=Y , m= 1

σ_{eff}

Measure the overlap between hadrons and amount of DPS.
Process independent, scale independent, √s independent → to be tested experimentally

$\sigma_{eff} \approx 10 \div 15$ mb from CDF & D0 3jet+γ , confirmed by ATLAS W+jets
LHCb reports large discrepancies (up to a factor 3) on σ_{eff} when comparing numbers from double J/ψ, J/ψ + open/double open charm productions

CMS strategy for DPS

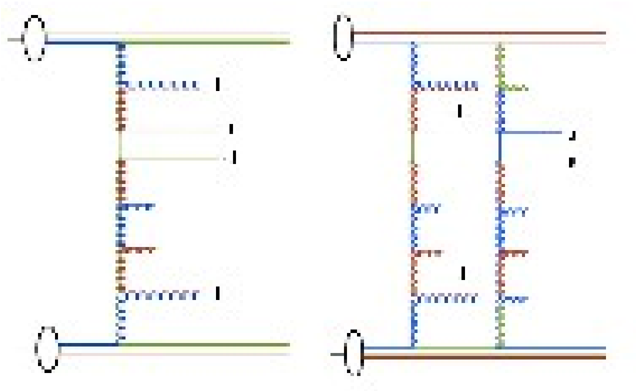
STEP1: Corrected distributions of DPS-sensitive variables
STEP2: Unambiguous definition of signal and background templates
STEP3: **Extraction of the DPS fraction** and study of the process dependence

A wide set of DPS-sensitive particle level observables is already public for the W+2jets+X channel
All the observables are reported in absolute scale and normalized to unit area, along with the computation of the systematic uncertainties

DPS in 4-jets events

CMS PAS FSQ-12-013

A 4-jet final state may arise from:
two additional jets produced via Parton Shower (PS) or in a 2nd hard scattering



pp collisions @ 7 TeV low pile-up conditions in 2010 data (36 pb^{-1})

Selection $|\eta|$ (jets) < 2.5
Hard pair of jets: $p_T > 50$ GeV/c

Soft pair of jets: $p_T > 20$ GeV/c

DPS observables: angular correlation variables between two jets (hard-jet and soft-jet pair)

$$\Delta^{rel}_{hard} p_T = \frac{|\vec{p}_T^{\,hard_1} + \vec{p}_T^{\,hard_2}|}{|p_T^{hard_1}| + |p_T^{hard_2}|}$$

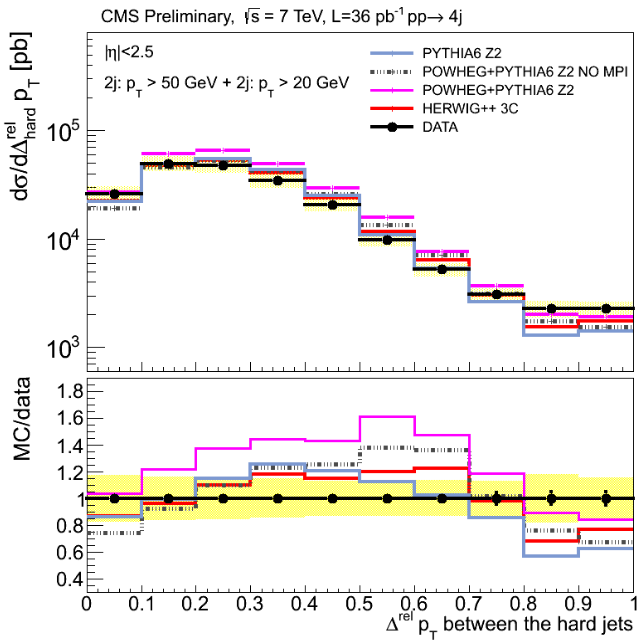
$$\Delta\eta_{hard} = \eta_{hard_1} - \eta_{hard_2}$$

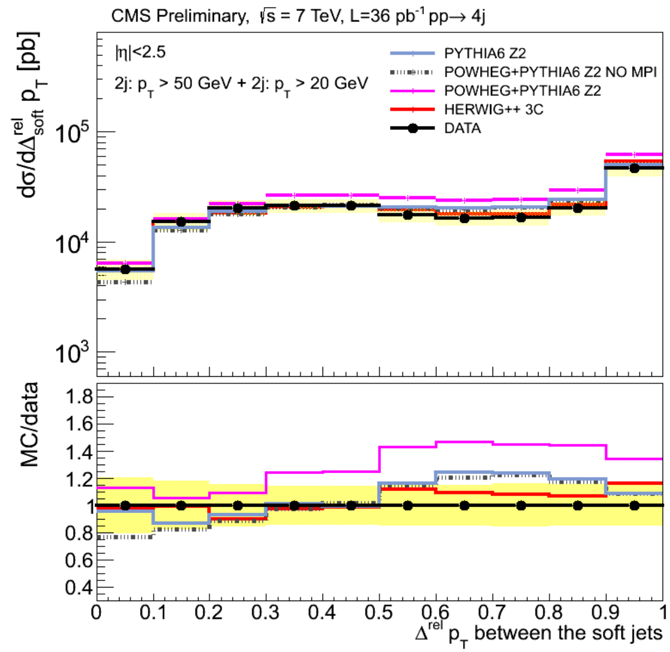
$$\Delta\phi_{hard} = \phi_{hard_1} - \phi_{hard_2}$$

Useful baseline for studies to investigate contributions from DPS

DPS in 4-jets events

Final state cross-section, σ(4 jets) = 201 ± 3 (stat.) ± 34 (syst.) nb





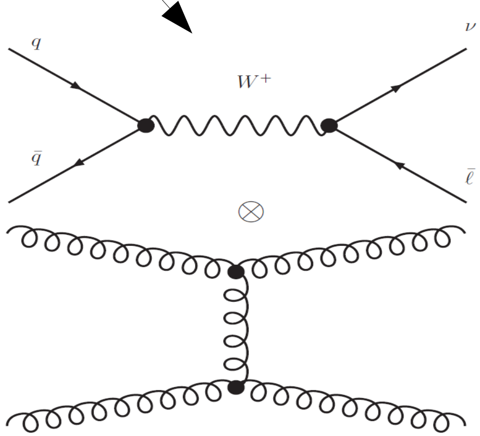
- POWHEG interfaced with Pythia6 overshoots the data by 30-40 %. (263.83 nb)
- There is an improvement if MPI is switched off. (213.54 nb)
- HERWIG++ (212.23 nb) and Pythia6 with Z2* tune(216.72 nb) describes the data very well.

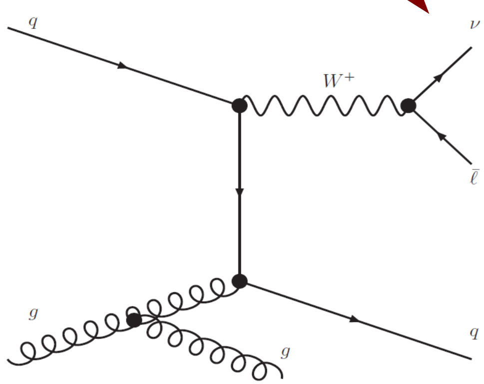
DPS in W+ 2jets

CMS PAS FSQ-12-028

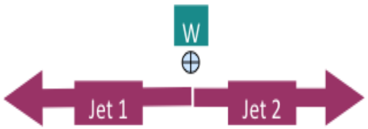
Signal: W from first hard parton-parton interaction, at least two jets from second one [W → μ ν channel]

Background: W + jets from single interaction (SPS)

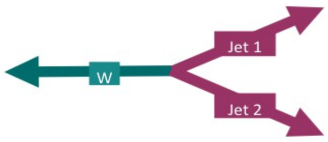




Momentum in transverse plane of the 2 jets balanced



Momentum in transverse plane of W+di-jet system overall balanced



DPS in W+ 2jets

Selection (@ detector AND particle level) :

- W $p_T(\mu) > 35$ GeV, $|\eta| < 2.1$, MET > 30 GeV , Transverse Mass(W) > 50
- Jets $p_T > 20$ GeV, $|\eta|<2$
- 2 categories based on number of jets selected: exactly two (exclusive meas.) or at least two jets (inclusive meas.)

From detector to particle level with unfolding using a Bayesian method

Observables to discriminate between SPS and DPS:

Azimuthal separation between the 2 jets (in transverse plane)

$$\Delta\varphi(j1,j2)=|\varphi(j1)-\varphi(j2)|$$

Not sensitive!

Relative transverse momentum balance between the 2 jets

$$\Delta^{rel}_{p_T}(j1,j2)=\left(\frac{\vec{p}_T(j1)+\vec{p}_T(j2)}{|p_T(j1)|+|p_T(j2)|}\right)$$

Angle between W and di-jet system in transverse plane

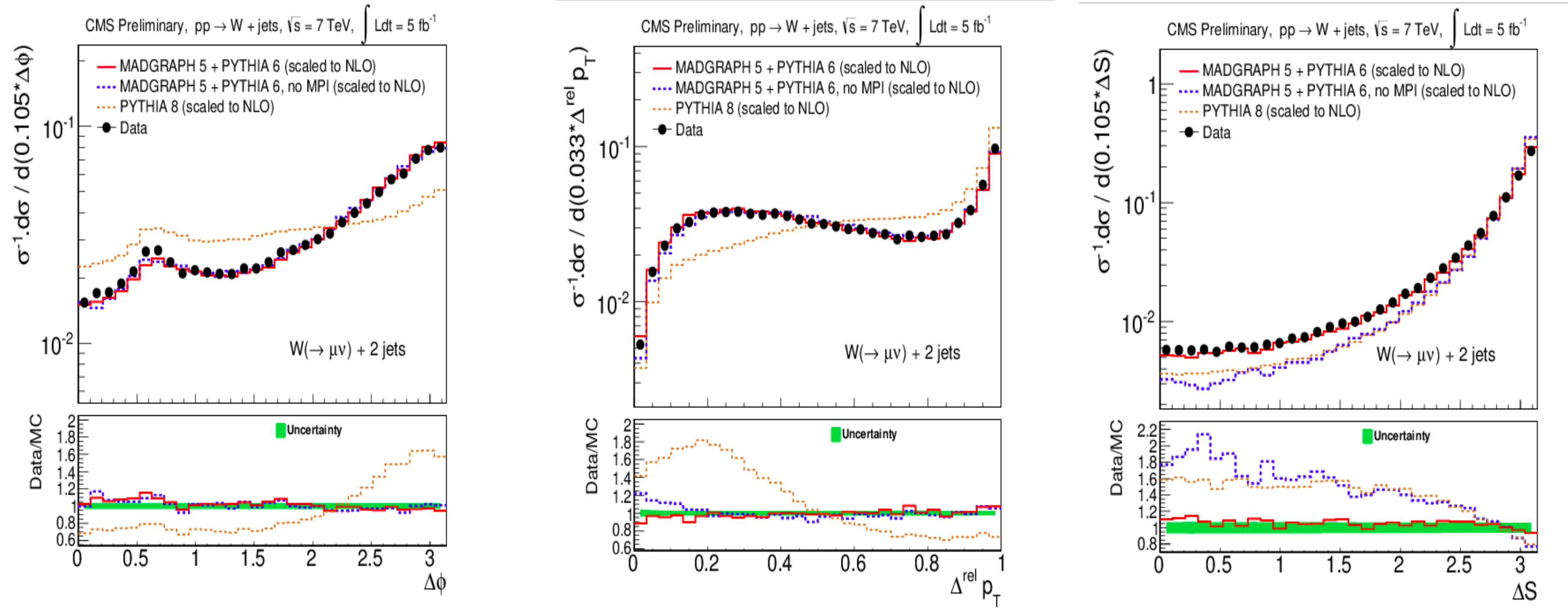
$$\Delta S=\arccos\left(\frac{\vec{p}_T(\mu,MET)\circ\vec{p}_T(dijet)}{|p_T(\mu,MET)|.|p_T(dijet)|}\right)$$

DPS in W+ 2jets

Differential cross sections and area normalized distribution corrected to particle level

$\sigma = 60.6 \pm 8.7$ pb.

exclusive 2-jets category



MADGRAPH with MPI provides a very good description of the data.

High-order diagrams with MG fill the phase space that PYTHIA8 assigns to MPI.

The ΔS observable is the only one capable to clearly distinguish MPI on vs MPI off

MC without MPI underestimate the integrated cross section by 19% (18%) for inclusive 2 jets (exclusive 2 jets) events

Summary

LHC experiments have a rich MPI research program.
CMS studied in detail minimum bias as well as Underlying Event activities at LHC energies.

At high scale of interaction, MPI gets saturated. Measurements are reasonably well described by recent tunes derived from UE activities in fully hadronic final states.
Current emphasis of the LHC experiments in MPI studies is on understanding of double parton scatterings (DPS)

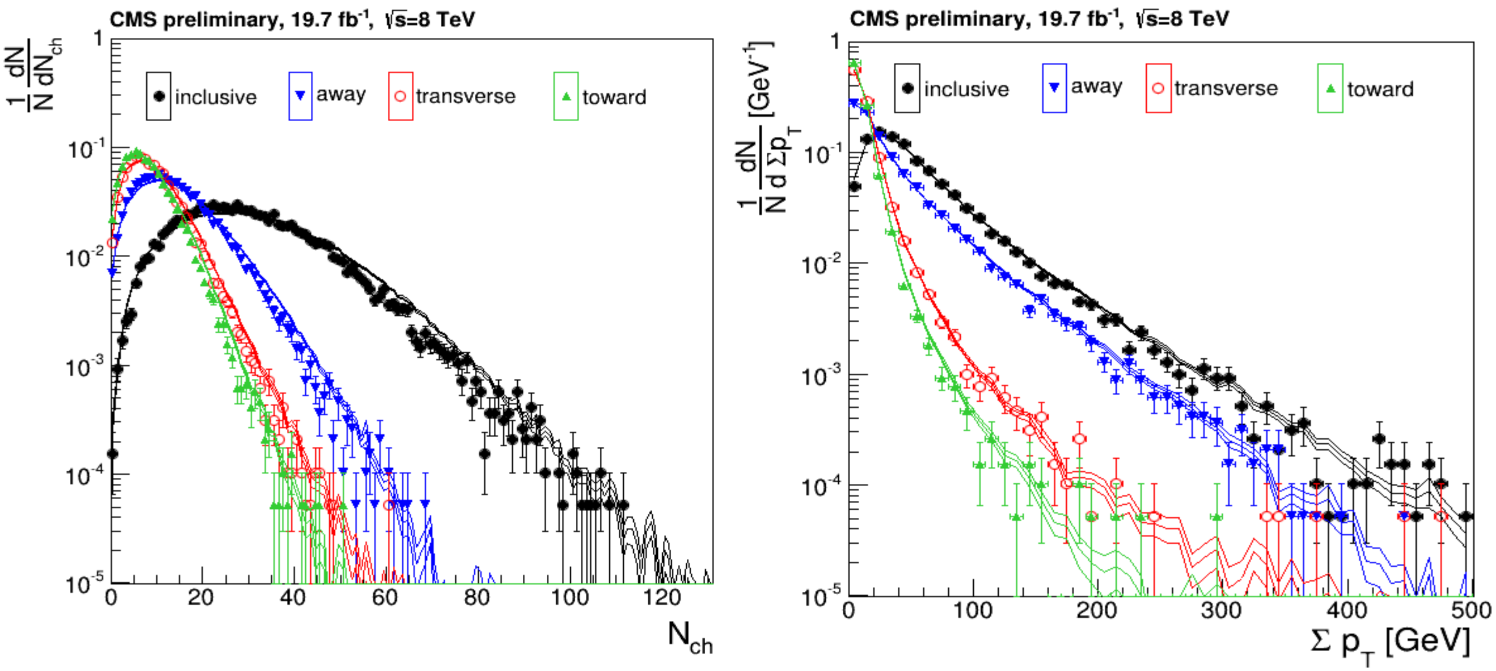
LHC provides unique opportunities to study a **wide range of QCD phenomena**.
It has so far provided data at 4 centre-of-mass energies, **great occasion** for **model building** and **MC tuning**.
We look forward to the new data at 13(14) TeV!

For a complete overview of public results please visit
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

Backup slides

UE activity in top pair events

CMS PAS TOP-13-007



NEW: approved 2 days ago

Exploratory studies of UE activity using ttbar candidate events.
→ Good agreement with MADGRAPH plus the PYTHIA 6 Tune Z2* simulation

2012 data $\sqrt{s}$ = 8 TeV, 19.7 fb^{-1}

Underlying Event in DY

UE Measurements in Drell-Yan:

Eur. Phys. J. C 72 (2012) 2080

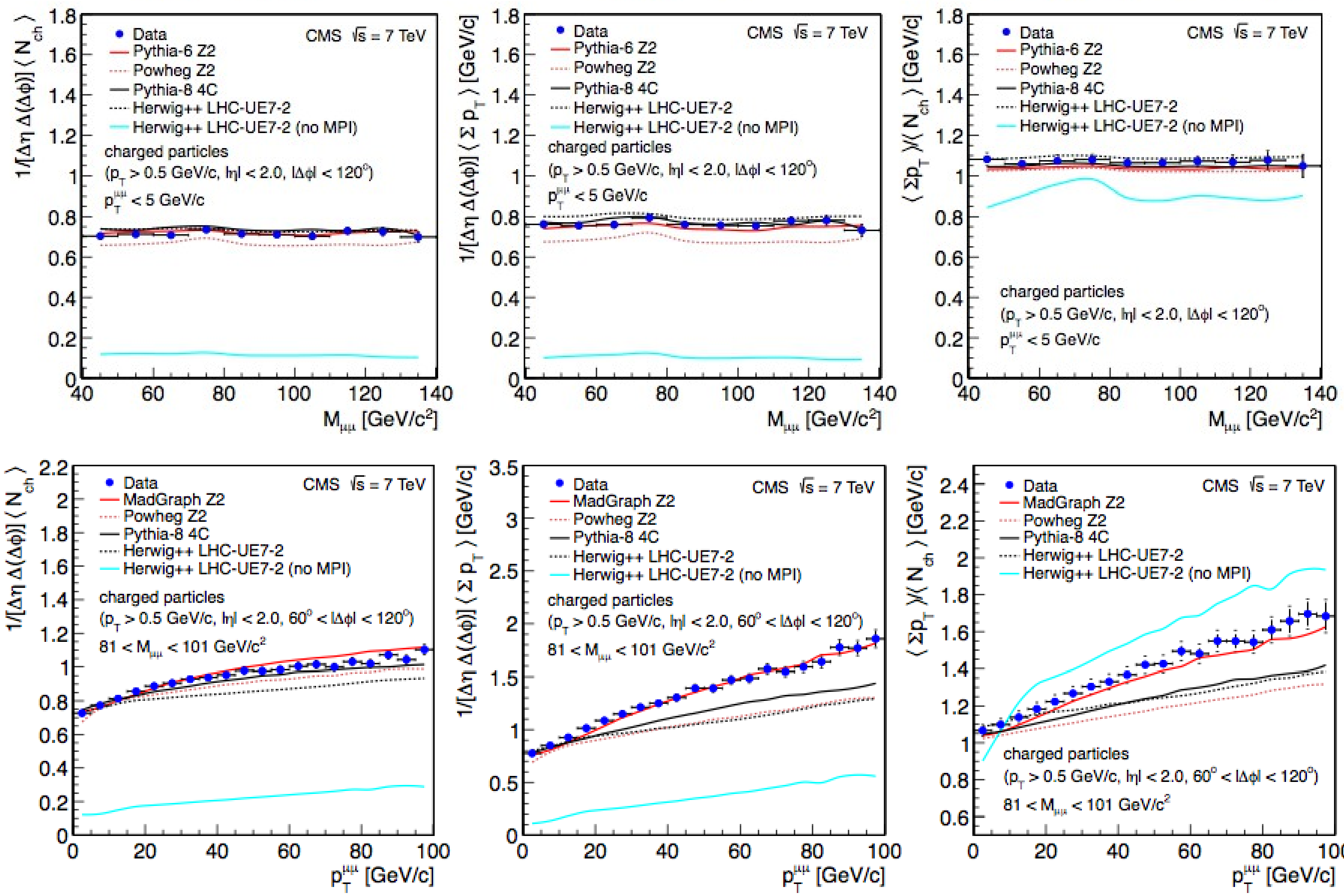
UE vs $M_{\mu\mu}$ ($p_T^{\mu\mu} < 5$ GeV/c): MPI saturated above $M_{\mu\mu} = 40$ GeV/c^2.

UE vs $p_T^{\mu\mu}$ ($81 < M_{\mu\mu} < 101$ GeV/c^2): Radiative increase of activity with p_T di lepton.

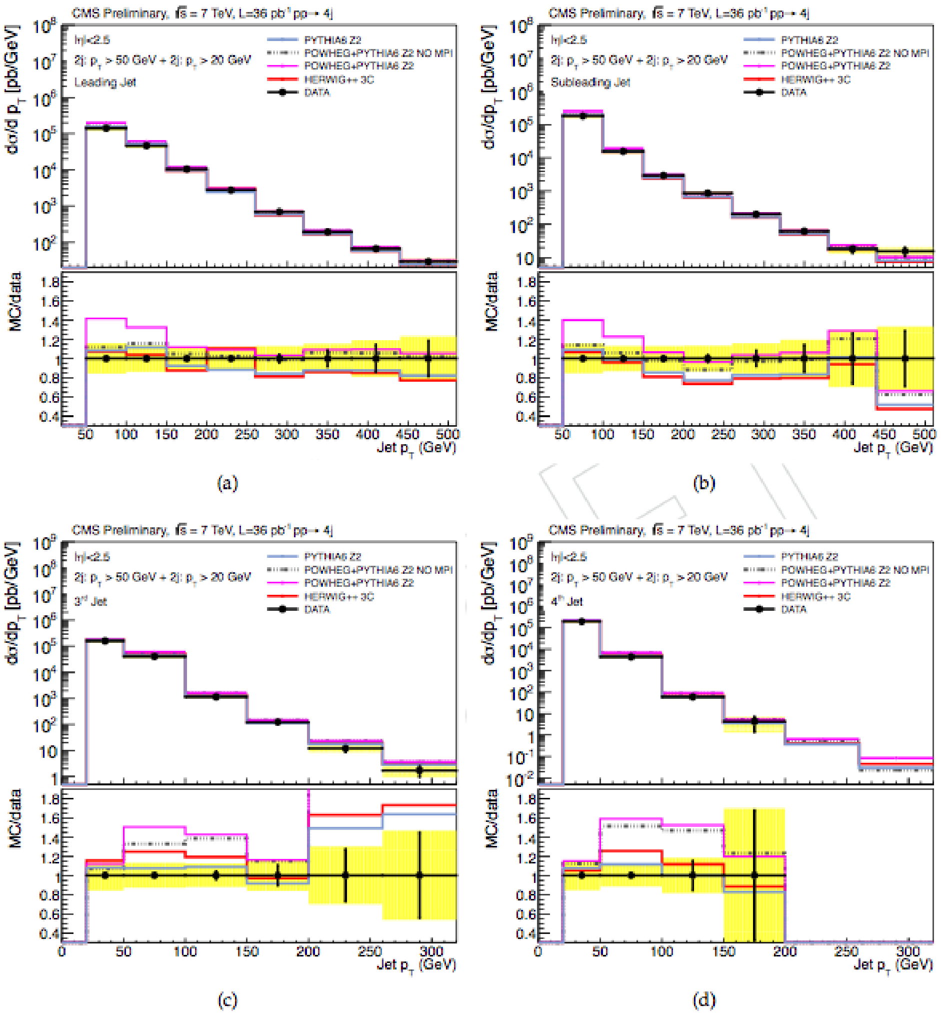
particle density

energy density

ratio of energy and particle densities

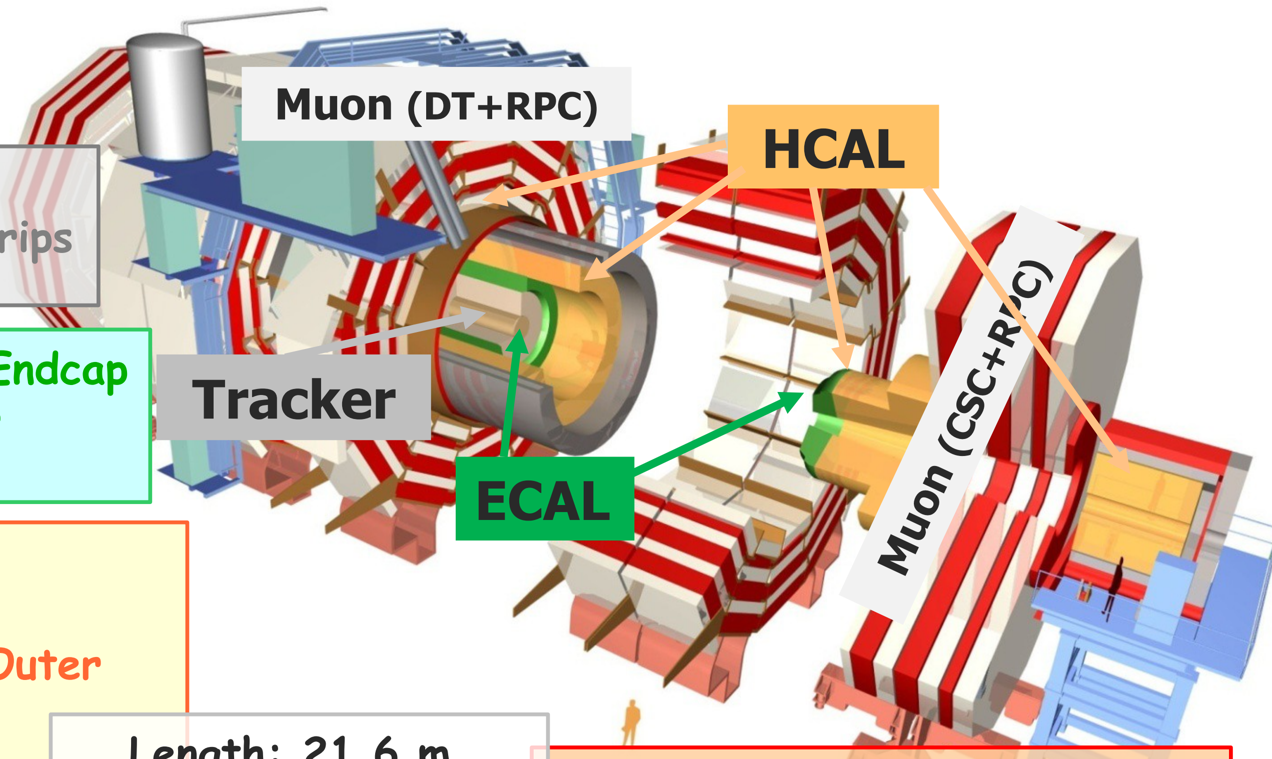


DPS via 4 jets



Cross section as a function of the jet transverse momenta pT (from top to bottom and from left to right leading, subleading, third and forth jet) compared to theoretical predictions of PYTHIA 6, HERWIG ++ and POWHEG. POWHEG is shown with and without contributions from MPI. The lower panel shows the ratio of theory prediction to data

CMS Detector



Tracker
66M Si pixels & 10M Si strips

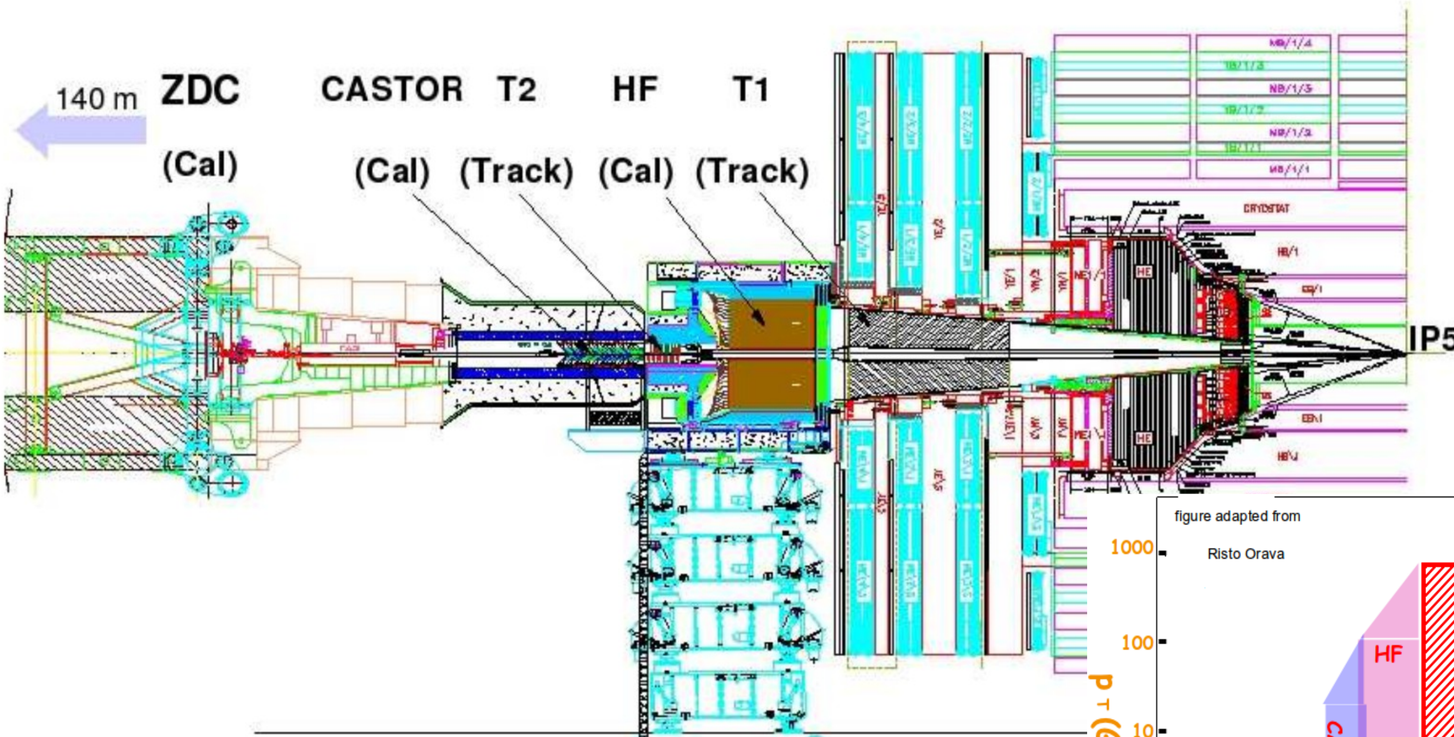
EM Calorimeter: Barrel & Endcap
PbWO4 crystal calorimeter

Hadronic calorimeter:
Brass & scintillator
Barrel, Endcap, Forward, Outer

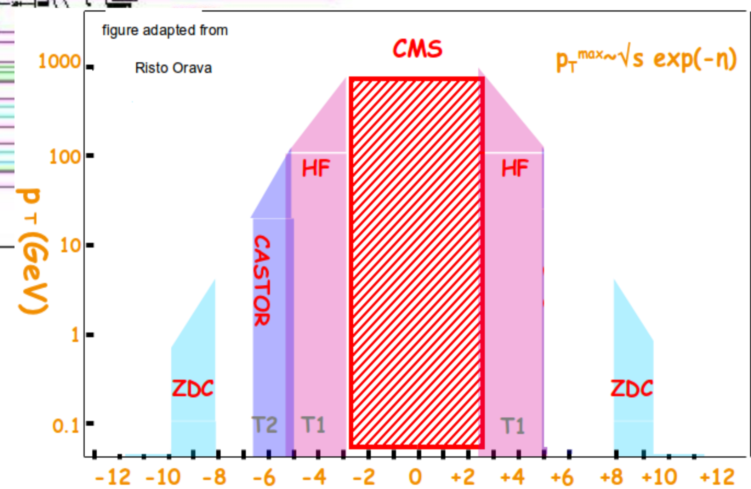
Length: 21.6 m
Diameter: 15 m
Weight:12500 tons

Muon chambers:
Barrel: Drift Tubes - Endcap: Cathode Strip Chambers -
Both interleaved with Resistive Plate Chambers

Forward Detectors



Cherenkov/quartz calorimetry in the forward region.
HadronForward (HF): Long and short quartz fibers alternated, embedded in iron absorbers.



eta coverage of CMS detector