Forward physics results from CMS

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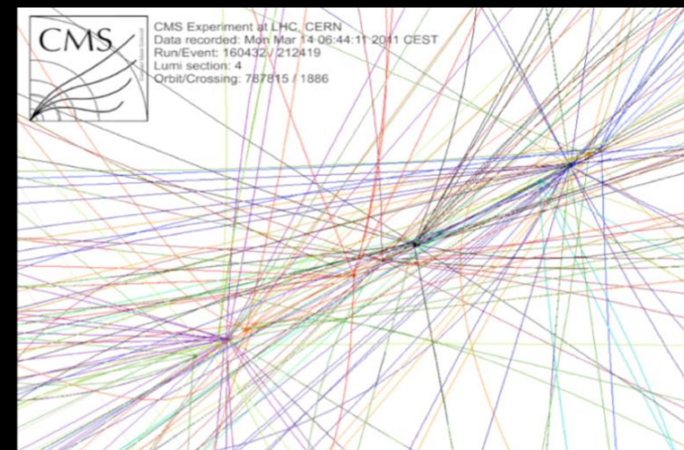
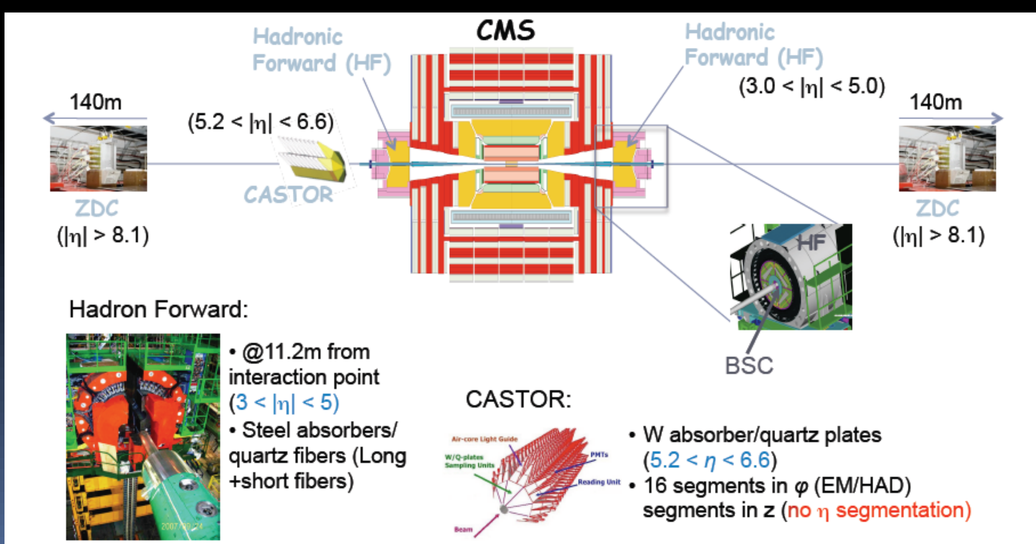
for the CMS collaboration

The setting:CMS@LHC

- High energy and high luminosity
  - Allows high statistics precision measurements, and sensitivity to "rare" processes (hard diffraction, exclusive production)
  - But high luminosity comes with high "pileup" – average 2-4 extra interactions/crossing in 2010, 5-8 in 2011
  - Low pileup needed for some analysis





- Good detector coverage
  - Tracking to $|\eta| < 2.4$
  - Hadronic calorimeter (HF) to $|\eta| < 5$
  - Forward calorimeters (cover $-6.6 < \eta < -5.2$ (CASTOR) and $|\eta| > 8.1$ (ZDC)

Overview

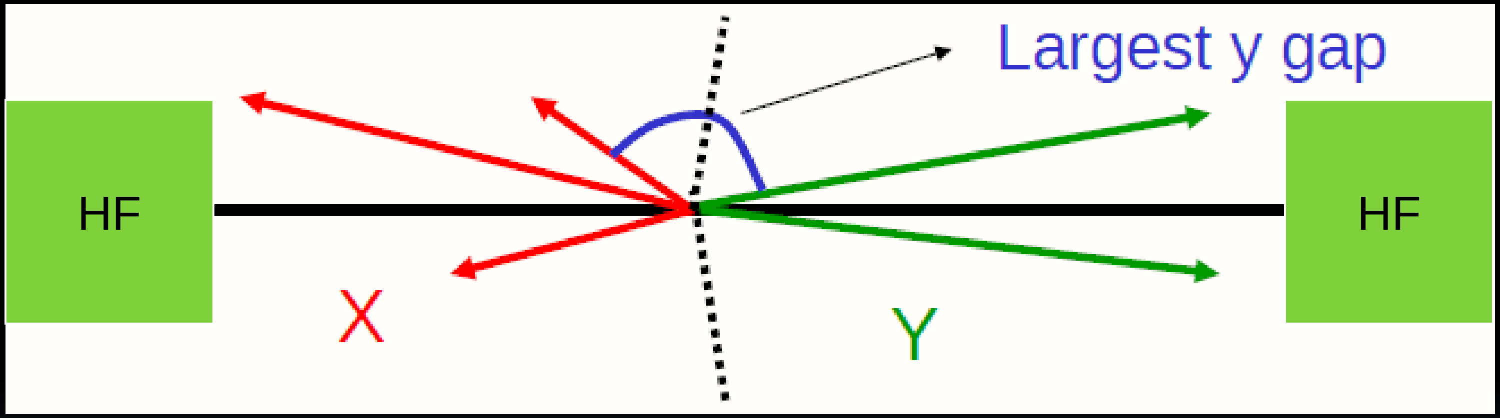
- Cross section Measurement using HF
- Studying the Underlying Event with different strategies
  - Drell-Yan events
  - Using very forward hadronic activity
- Dijet production ratio at large Δy
- Many other interesting results not covered here
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

Measurement of the inelastic cross-section using HF calorimeter

CMS PAS QCD 11-002

Event Selection

- Single sided event selection is used: either HF has at least one hit above 5 GeV total energy
- Counted number of events in the data (after subtracting background): N_{inel}



- $\xi = M_X^2/s$ where M_X is the invariant mass of the system
- In case of single diffractive events, ξ is the fractional momentum loss of the scattered proton
- Events with small ξ can escape detection

Inelastic cross section with $\xi > 5\times10^{-6}$

- f_ξ: fraction of visible events that are low mass (contamination)
- ε_ξ: fraction of high mass events that are visible (efficiency)

$$\sigma_{\rm inel}(\xi > 5\times10^{-6}) = \frac{N_{\rm inel}(1-f_\xi)F_{\rm pileup}}{\mathcal{L}\epsilon_\xi}$$

Pile-up correction

Luminosity

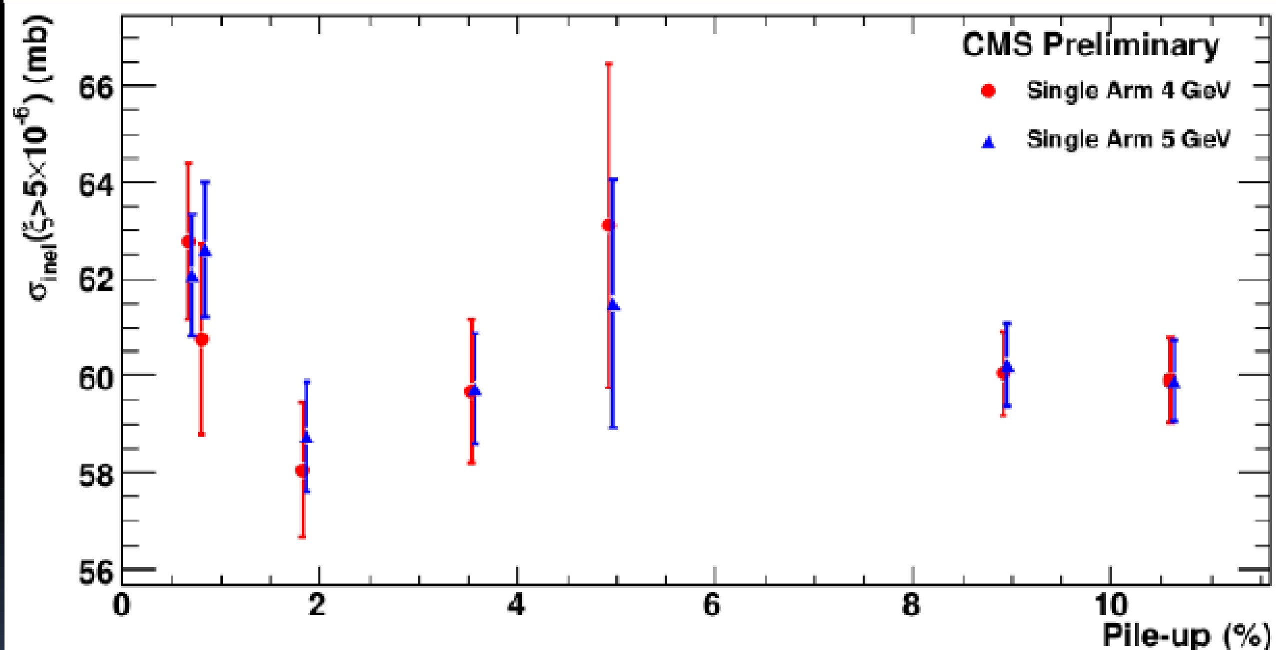
- Systematic:

-Noisy tower exclusion

-Run-by-run luminosity variations

-HF energy threshold

-Model dependence measurement



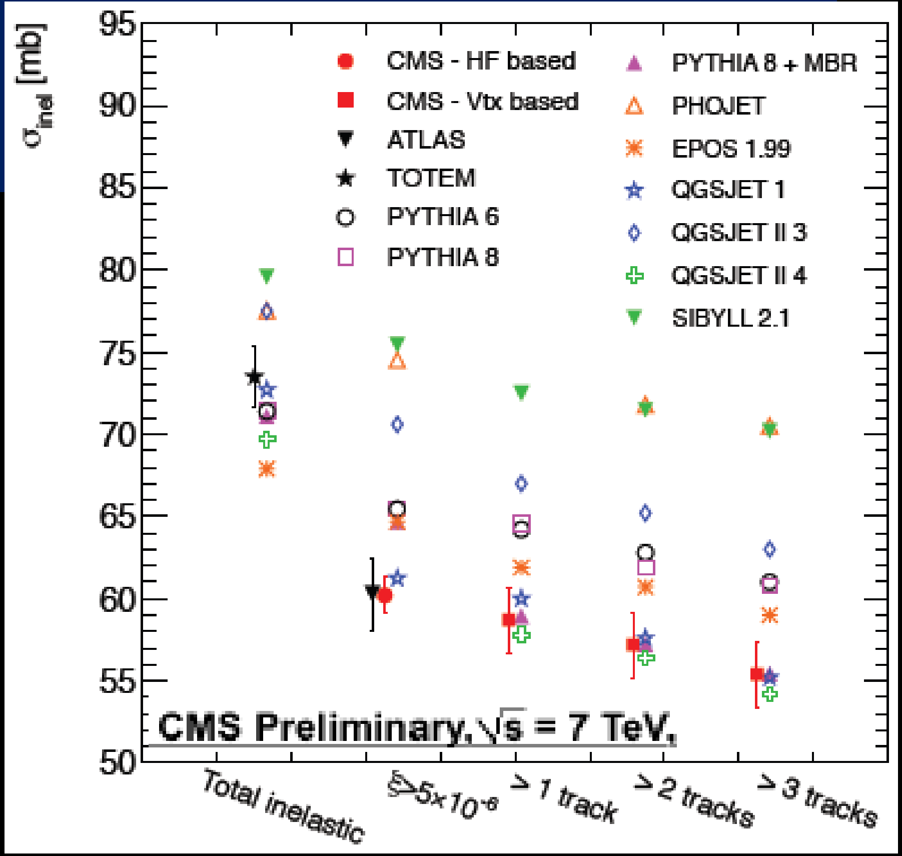
- Average the σ values obtained under various (low) pileup conditions

→ χ^2/ndof = 1.2 with the 5 GeV selection

$$\sigma_{\rm inel}(\xi > 5\times10^{-6}) = 60.2 \pm 0.2({\rm stat.}) \pm 1.1({\rm syst.}) \pm 2.4({\rm lumi.})\ {\rm mb}$$

Results

- PYTHIA8+MBR and QGSJET reproduce globally the data.
- Other models under (over-) predict low (high-) mass diffraction

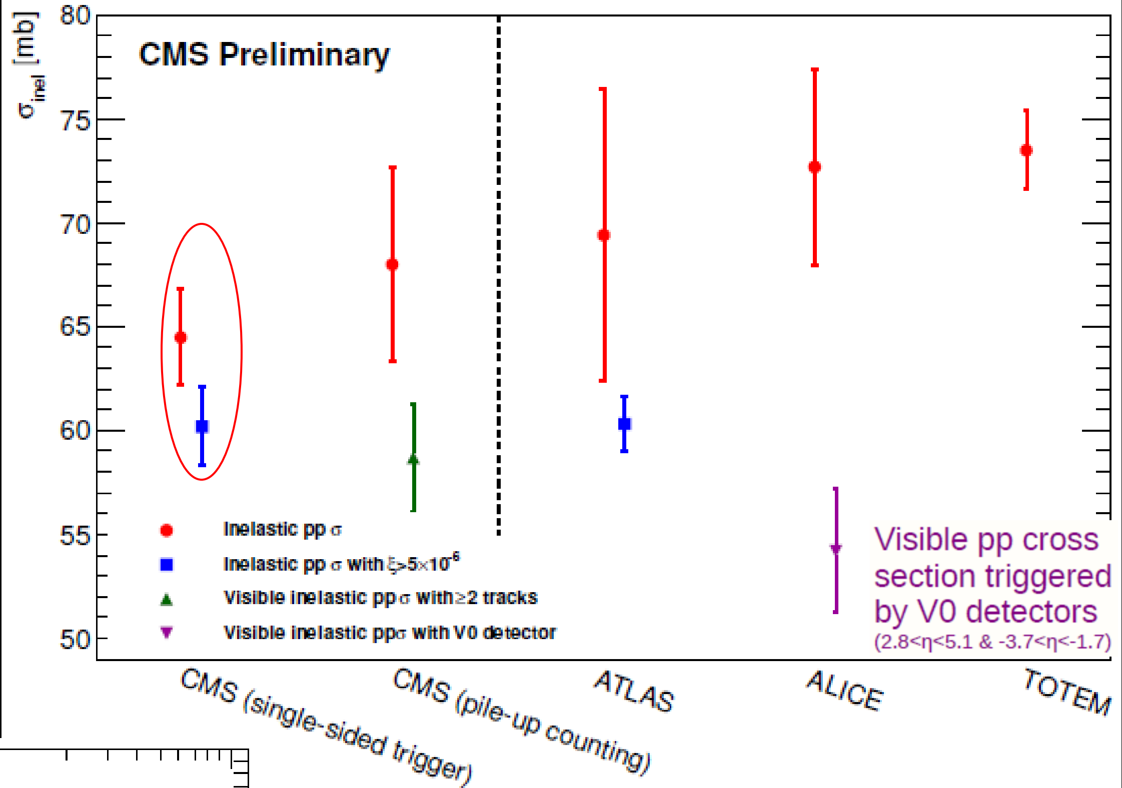


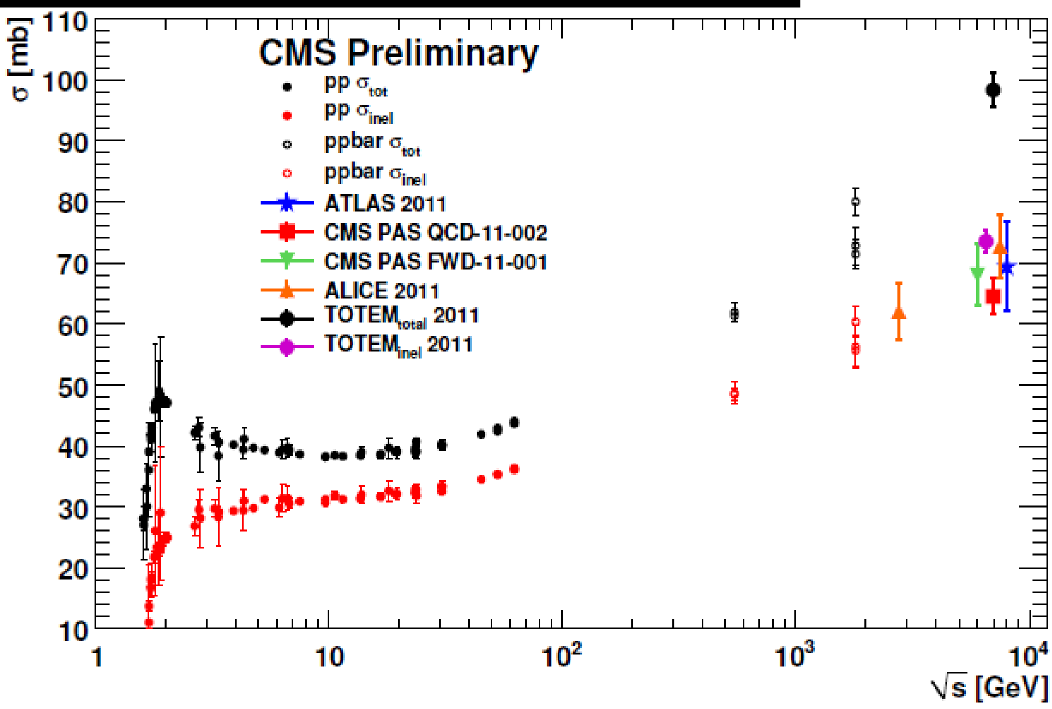
CMS PAS FWD-11-001

$$\sigma_{inel}(>1\text{track}) = [58.7 \pm 2.0(\text{syst}) \pm 2.4(\text{lum})]\ \text{mb}$$

$$\sigma_{inel}(\xi > 5\times10^{-6}) = 60.2 \pm 0.2(\text{stat.}) \pm 1.1(\text{syst.}) \pm 2.4(\text{lumi.})\ \text{mb}$$

Comparison with other measurements





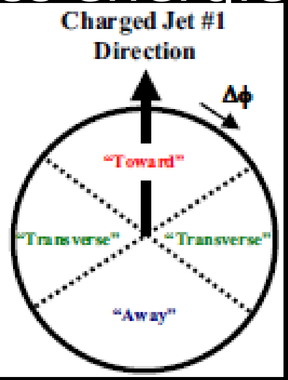
Study of the underlying event

CMS QCD 11-012

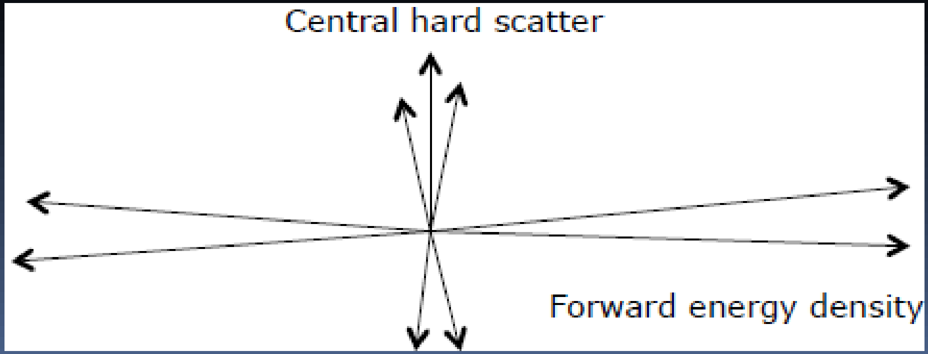
CMS PAS FWD 11-003

Measuring the UE

- Study the UE as a function of the hard scale of the event, and at different centre-of-mass energies
- CMS did several approaches:
  - at central rapidities



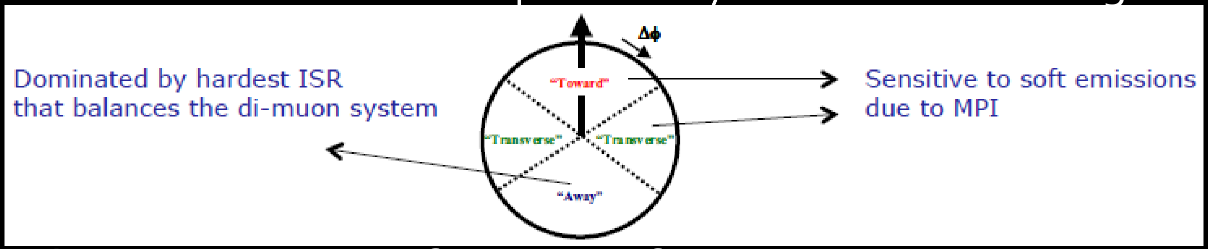
    - Hard scatter & UE in same η range
    - divide ϕ phase space to separate the UE from the hard scatter
    - look at particle densities, energies in the transverse region
    - As function of the hard scatter p_T scale
    - leading jets [DOI: 10.1007/JHEP 09(2011)109]; **Drell-Yan**
  - **at forward rapidity**
    - UE observables separated with
    - large Δη from hard scatter
    - No division of ϕ phase space
    - Possible to study UE ϕ structure



UE activity in Drell-Yan

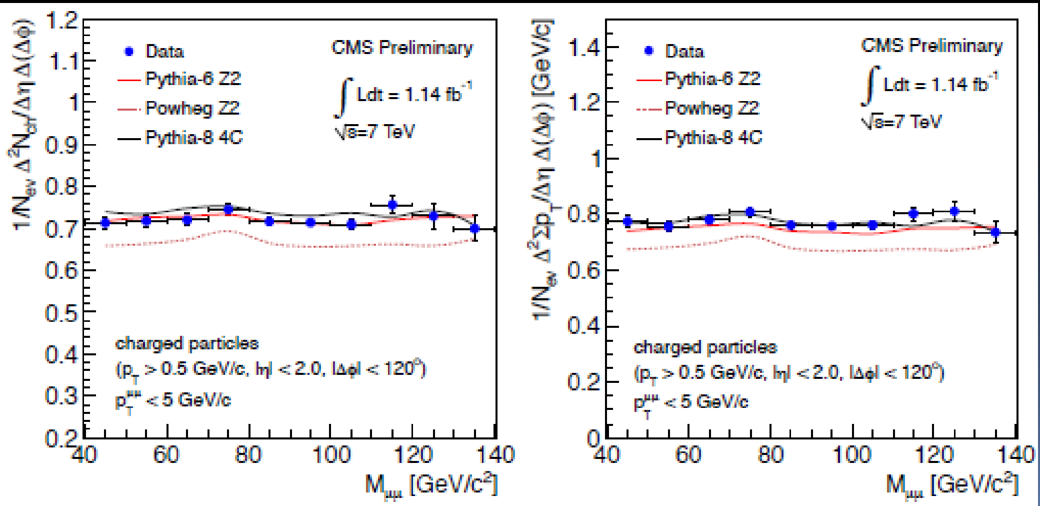
CMS QCD 11-012

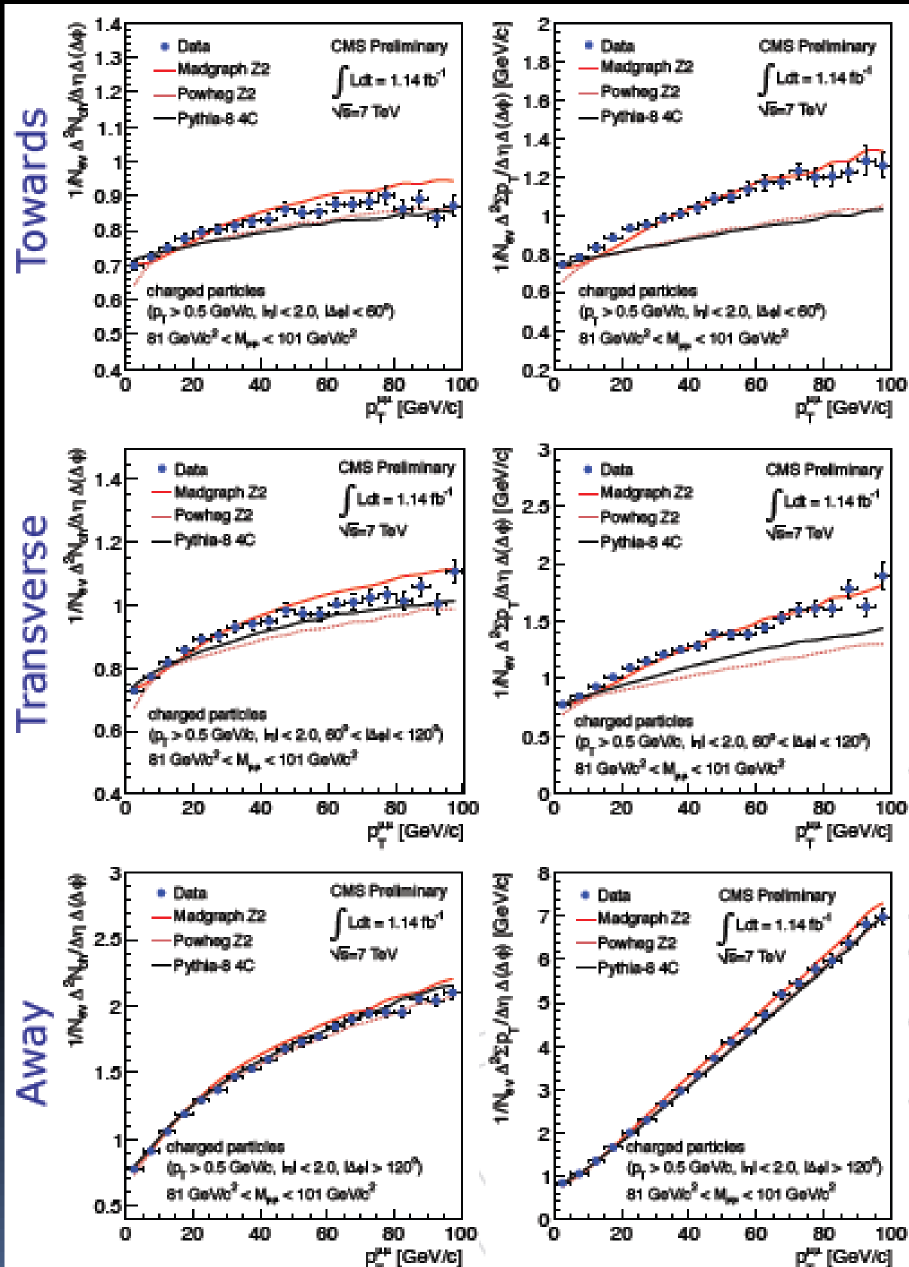
- Complementary approach to existing measurements
  - Drell-Yan: experimentally clean, theory well understood
  - absence of QCD FSR & low probability of brehmsstrahlung from muons



- Study the UE activity as function of
  - the di-muon p_T: minimize background, study dependence in narrow mass window ; energy scale sufficiently large to saturate MPI →**probes ISR spectrum**
  - the di-muon mass: - look at wide $M_{\mu\mu}$ range for di-muon p_T < 5 GeV/c →**verify MPI saturation**

- Drell-Yan event selection:
  - exactly 2 opposite charge isolated p_T > 20 GeV/c, |η| < 2.4 from vertex well centered around the beam-spot
  - charged particles for UE: central high purity tracks from primary vertex p_T > 0.5 GeV/c, |η| < 2, $\sigma(p_T)/p_T$ < 5%





Dependence of UE activity vs di-muon p_T for 81 GeV/c2 < $M_{\mu\mu}$ < 101 GeV/c2

At this energy scale → MPI saturated
→p_T dependence sensitive to ISR

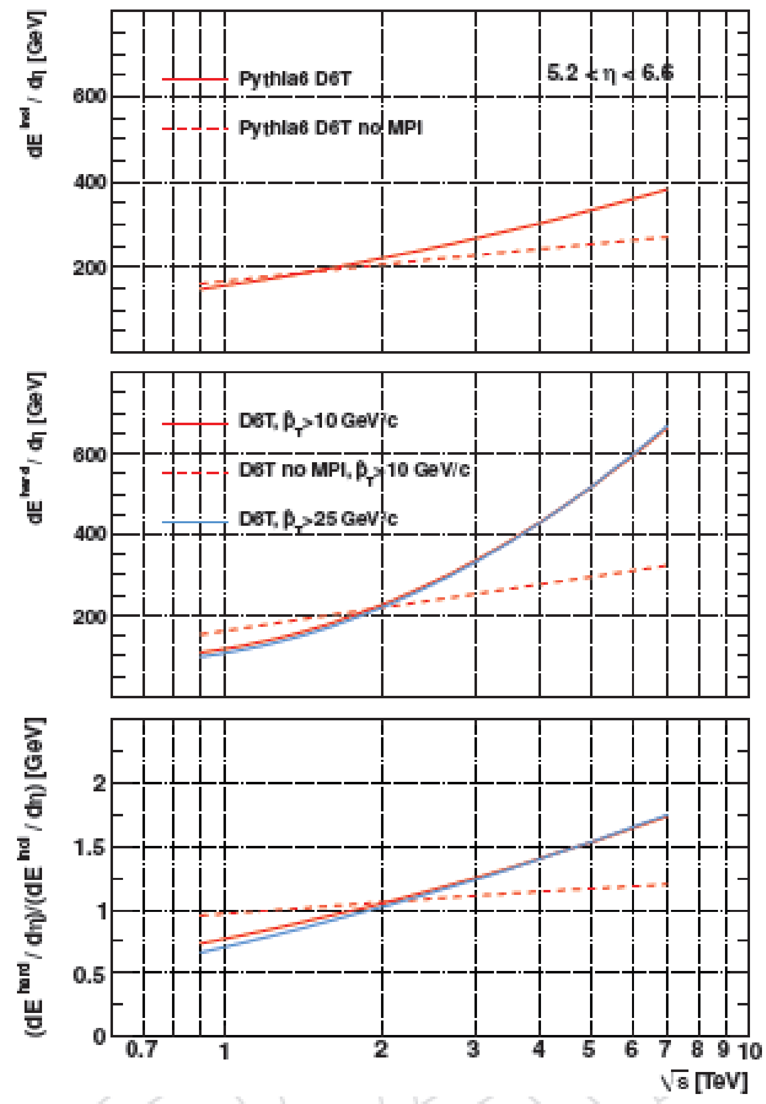
Towards & transverse region:
→slow growth in particle & energy density with increasing di-muon p_T
→Madgraph with tune Z2 describes the data well
→Powheg Z2 & Pythia8 4C fail to describe the data (but agree at low p_T)

Away region:
mostly sensitive to spectrum of hardest emission
→equally well described by all tunes & generators

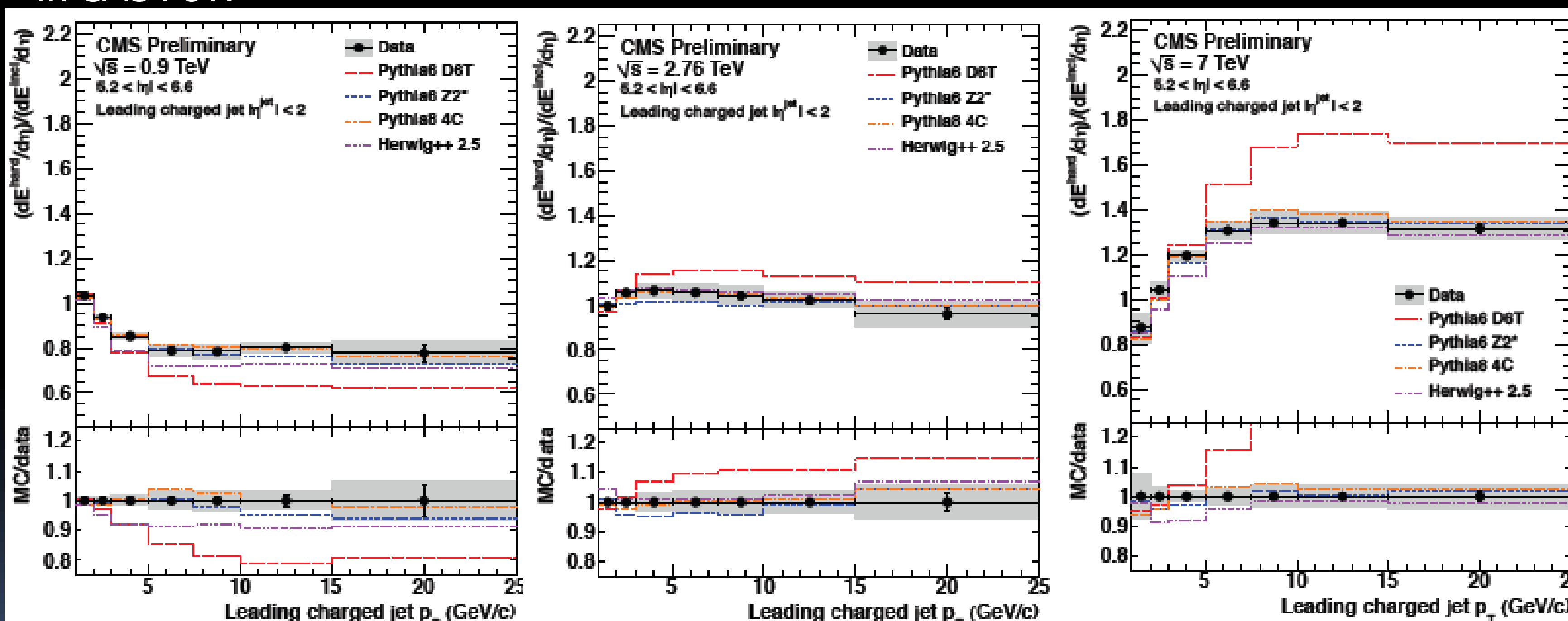
UE at Forward Rapidity

CMS PAS FWD 11-003

- Measure the Underlying Event (UE) activity by comparing energy density in CASTOR ($-6.6 < \eta < -5.2$) for minimum bias events w.r.t. events with a hard scale
- Minimum bias (inclusive events)
  - energy density not much affected by MPI
- Hard scale
  - energy flow strongly affected by MPI
  - use the central leading track-jet with $p_T > 1$ GeV/c and $|\eta| < 2$
- Use ratio of energy densities
  - independent of calibration
  - minimizes systematic uncertainties
- Study the ratio as function of Hard scale
- Study Energy Flow as function of $\sqrt{s}$

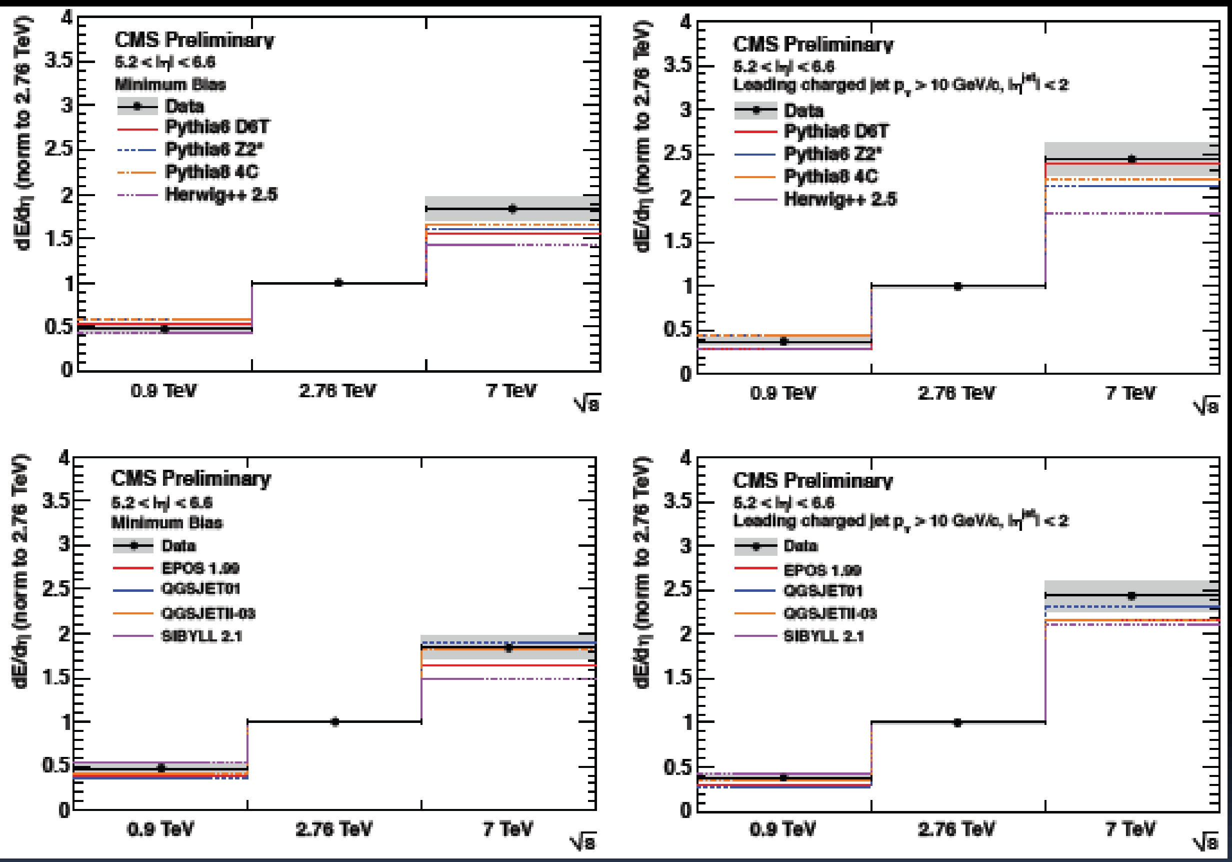


- Hard-to-inclusive ratio vs leading track-jet p_T at $\sqrt{s}$ = 0.9, 2.76, 7 TeV
- At 0.9 TeV: ratio below 1
  - production of central hard jets accompanied with higher UE activity depletes energy of the proton remnant which fragments in CASTOR
- At 7 TeV well known UE behaviour:
  - fast increase at low p_T followed by a
  - plateau above p_T=8 GeV/c
- At 2.76 TeV the increase of the ratio is much reduced



- Pythia tunes fitted to LHC (Z2*, 4C) & Herwig 2.5 describe data well
- Older tune Pythia6 D6T fails to describe the results

- Normalized energy density vs √s:
  - normalized to 2.76 TeV (minimize systematic uncertainties)
  - for both inclusive and hard scale events (leading track-jet, p_T > 10 GeV/c, |η| < 2)



Energy density increases much faster in events with a hard scale

Inclusive events:
→None of the Pythia & Herwig models can describe the relative increase at 7 TeV
→QGSJET describes data, other tunes underestimate

Hard scale:
→Pythia6 D6T & QGSJET01 close to the data,
other tunes underestimate the increase

- Increase of the UE activity with centre-of-mass energy very challenging

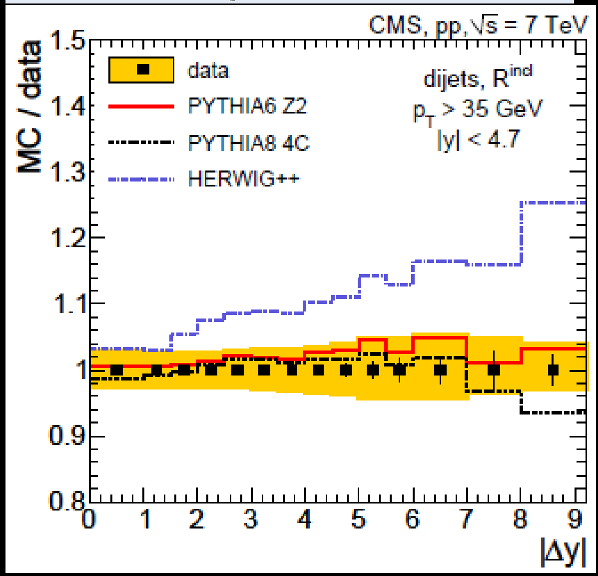
Ratio of inclusive/exclusive dijets

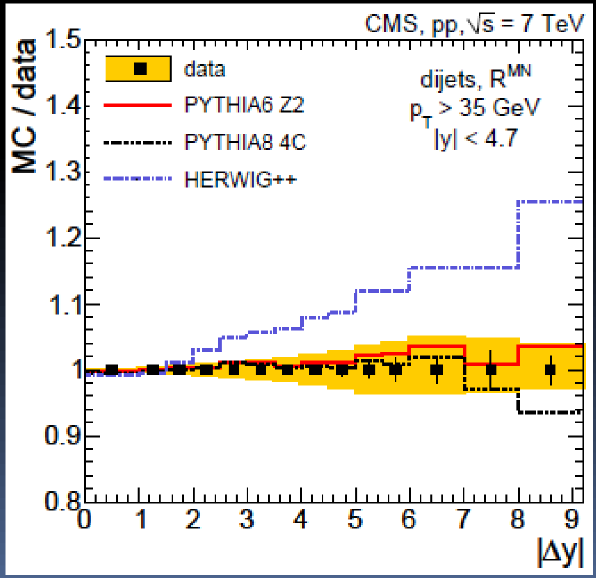
- Motivation: Pin down effects beyond collinear factorization, BFKL evolution, etc.
- Measurement of the ratios as a function of the separation $|\Delta y|$ for calorimeter jets with

  $p_T > 35$ GeV and $|\eta| < 4.7$
- exclusive: only two selected jets allowed per event.
- inclusive: each pair of selected jets considered.
- Mueller-Navelet (MN): Subset of inclusive with most fwd and most bw jet
- Selection: single-jet trigger above 15 GeV for moderate $\Delta\eta$ (33 nb^{-1}) dedicated fwd-bw jet-pair trigger for large $\Delta\eta$ (5 pb^{-1}).
- Bin-by-bin correction for detector effects from HERWIG++ (tune 23) and PYTHIA6 (Z2) (default PYTHIA, HERWIG for uncertainty).
- Small corrections, but largest uncertainty

  1.3 - 5.6%.

$$R = \frac{\sigma_{dijet}(\text{inclusive or MN})}{\sigma_{dijet}(\text{exclusive})}$$

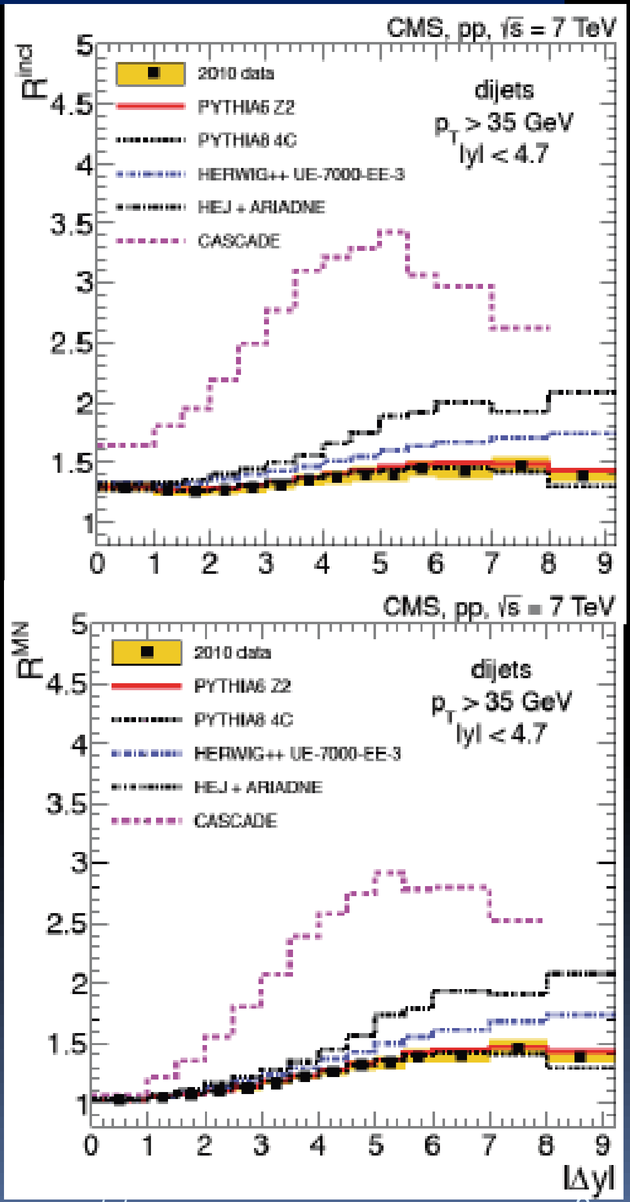




Results

- σ_{incl} 1.0-1.4 times larger than σ_{excl}.
- Expected rise of R with Δy (phase space for hard parton radiation).
- Decrease at highest Δy: kinematics.
- At largest |Δy| R_{incl} ~ R_{MN} as expected

- PYTHIA6 (Z2) with and without MPI and PYTHIA8 (4C) agree well with data. Small MPI effect.
- HERWIG++ 2.51 (tune UE-7000-EE-3) too high at medium/large separation.
- CASCADE and HEJ+ARIADNE do not describe the data.



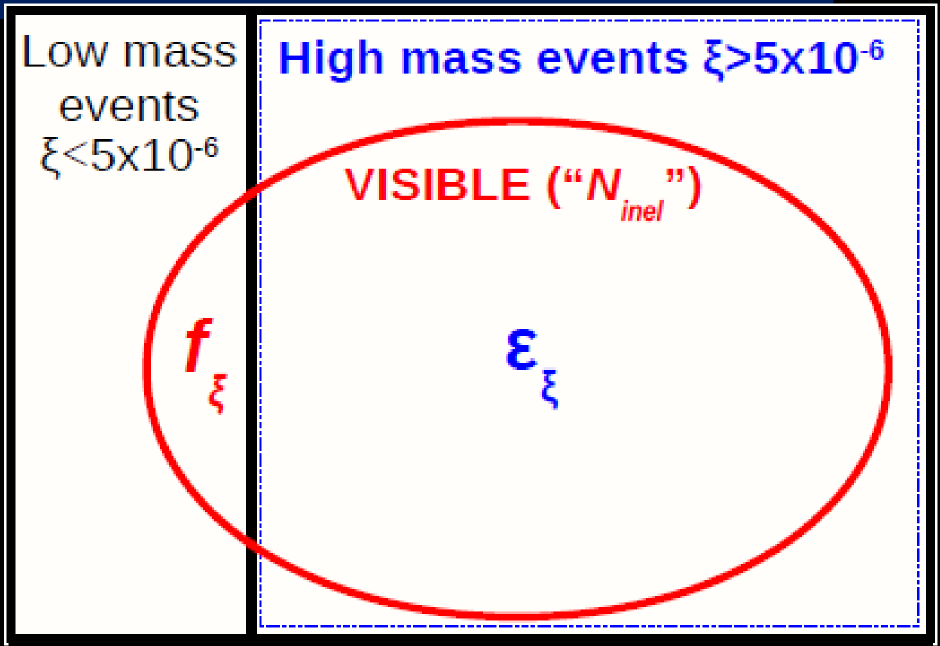
Conclusions

- Inelastic cross-section
  - New measurement based on single sided trigger
  - Compares well with ATLAS and σ_{inel} from pileup vertex counting
  - QGSJET and PYTHIA8-MBR reproduce globally the data. Other models under (over-) predict low (high-) mass diffraction
- Underlying Event
  - Models tuned to LHC data can describe many aspects
  - Evolution of central & forward energy densities as function of the hard scale
  - Notable discrepancies
    - UE activity in the towards & transverse regions in Drell-Yan at high p_T
    - relative increase of forward energy density in inclusive and hard scale events
- Ratio of inclusive to exclusive dijet as function of rapidity separation
  - Good description by PYTHIA6/8; HERWIG with difficulties
  - Small sensitivity to MPI simulation.
- CMS results provide new constraints for non-perturbative and semi-hard QCD dynamics on MCs

Extra

Cross section calculation

- f_ξ: fraction of visible events that are low mass (contamination)
- ε_ξ: fraction of high mass events that are visible (efficiency)



$$\sigma_{\rm inel}(\xi > 5\times10^{-6}) = \frac{N_{\rm inel}(1-f_\xi)F_{\rm pileup}}{\mathcal{L}\epsilon_\xi}$$

Pile-up correction

Luminosity

Luminosity and Pile-up

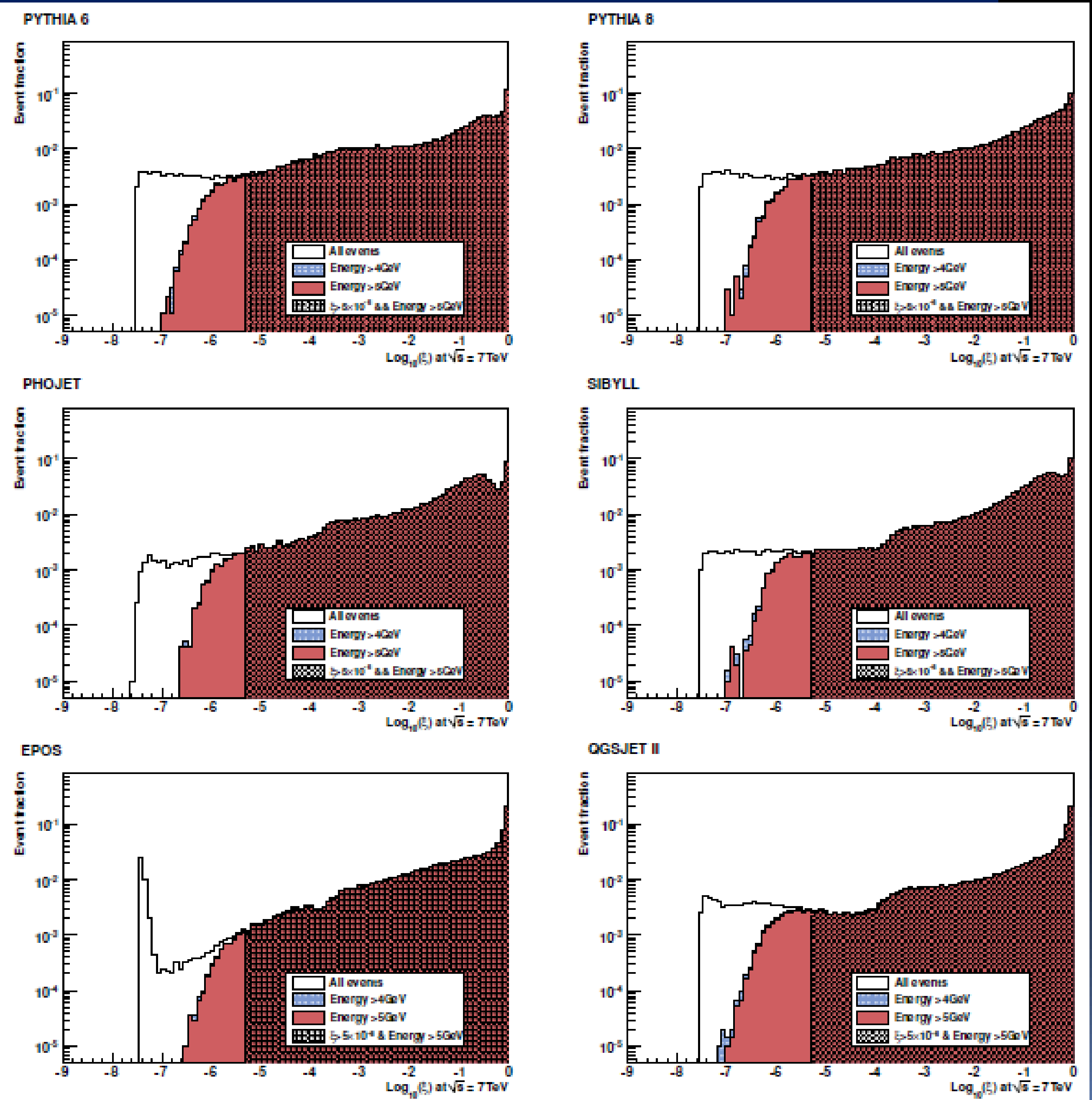
- The integrated luminosity (L) is based on the Van der Meer scans
- The uncertainty of the luminosity is 4%: dominates the systematic uncertainties of this analysis
- Number of collisions per bunch crossing follows Poisson - Average λ *(pile-up)*

$$F_{\text{pileup}} = \frac{\Sigma_{i=1}^{\infty} i P(i,\lambda)}{\Sigma_{i=1}^{\infty}(1-(1-\epsilon_{\text{inel}})^i)P(i,\lambda)} \cdot \epsilon_{\text{inel}} = \frac{\epsilon_{\text{inel}}\lambda}{\Sigma_{i=1}^{\infty}(1-(1-\epsilon_{\text{inel}})^i)P(i,\lambda)} = 1 + \frac{1}{2}\lambda\epsilon_{\text{inel}} + \frac{1}{12}\lambda^2\epsilon_{\text{inel}}^2 + \mathcal{O}(\lambda^3)$$

- Correction factor – accounts for multiple collisions being counted as one.

Extrapolation to Inelastic pp - Models

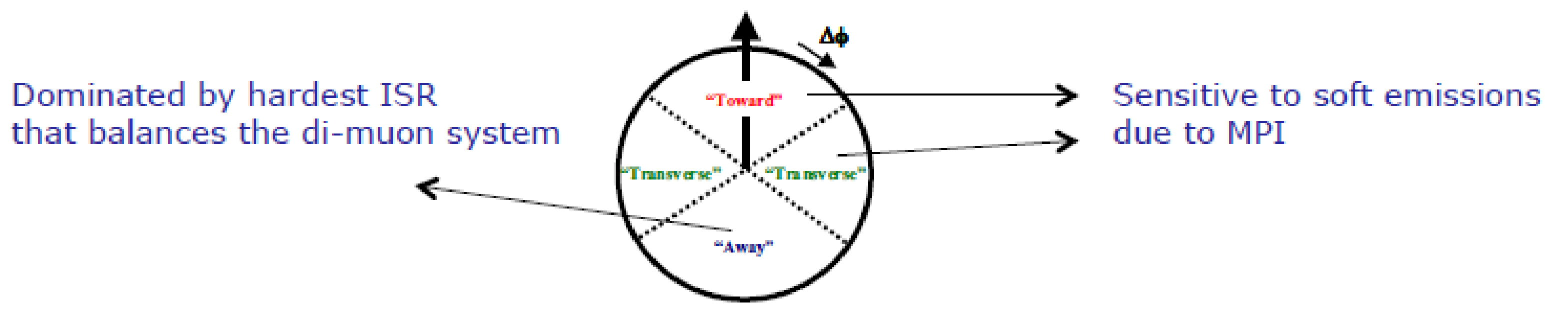
- PYTHIA 6 D6T
- PYTHIA 8
- PHOJET
- SYBILL 2.1
- EPOS 1.99
- QGSET-II 4
- Generator level



UE activity in Drell-Yan

CMS QCD 11-012

- Complementary approach to existing measurements
  - Drell-Yan: experimentally clean, theory well understood
  - absence of QCD FSR & low probability of brehmsstrahlung from muons
- Measure particle & energy densities in central region:
  - average number & p_T sum of the charged particles
  - central charged particles: $p_T > 0.5$ GeV/c, $|\eta| < 2$ (muons from DY excluded)



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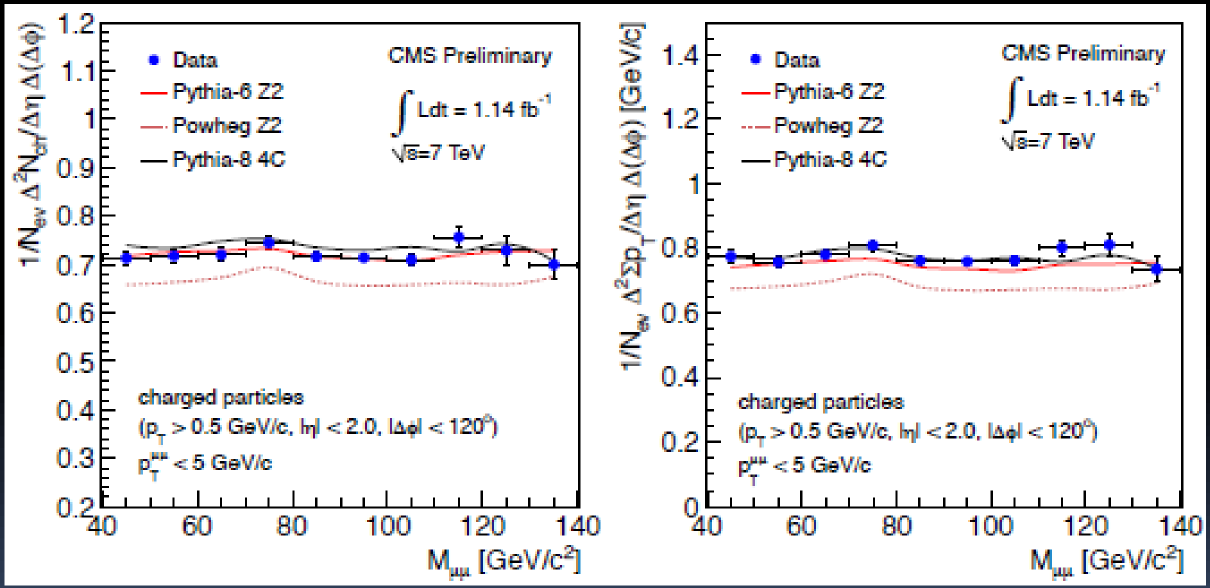
  - the di-muon mass: - look at wide $M_{\mu\mu}$ range for di-muon $p_T < 5$ GeV/c → **verify MPI saturation**

- Drell-Yan event selection:
  - exactly 2 opposite charge isolated muons with $p_T > 20$ GeV/c, $|\eta| < 2.4$ from vertex well centered around the beam-spot
  - charged particles for UE: central high purity tracks from primary vertex $p_T > 0.5$ GeV/c, $|\eta| < 2$, $\sigma(p_T)/p_T < 5\%$
- Study energy scale dependence of MPI as function of $M_{\mu\mu}$:
  - limit ISR: di-muon $p_T < 5$ GeV/c



Look at towards & transverse region: $\Delta\varphi < 120°$

Pythia6 Z2 & Pythia8 4C describe the densities well

Powheg Z2 underestimates by 10-15%

- no dependence on $M_{\mu\mu}$ → saturated MPI

LHC as a small x machine

- LHC can access lowest x values
  - for central W/Z production at

7 TeV: $x \sim 0.01$

14 TeV: $x \sim 0.005$

  - at forward rapidities ($\eta \sim 5$):

7 TeV $x \sim 6 \cdot 10^{-5}$

14 TeV $x \sim 3 \cdot 10^{-5}$

  - for central jets with p_t > 20 GeV

7 TeV : $x \sim 0.006$

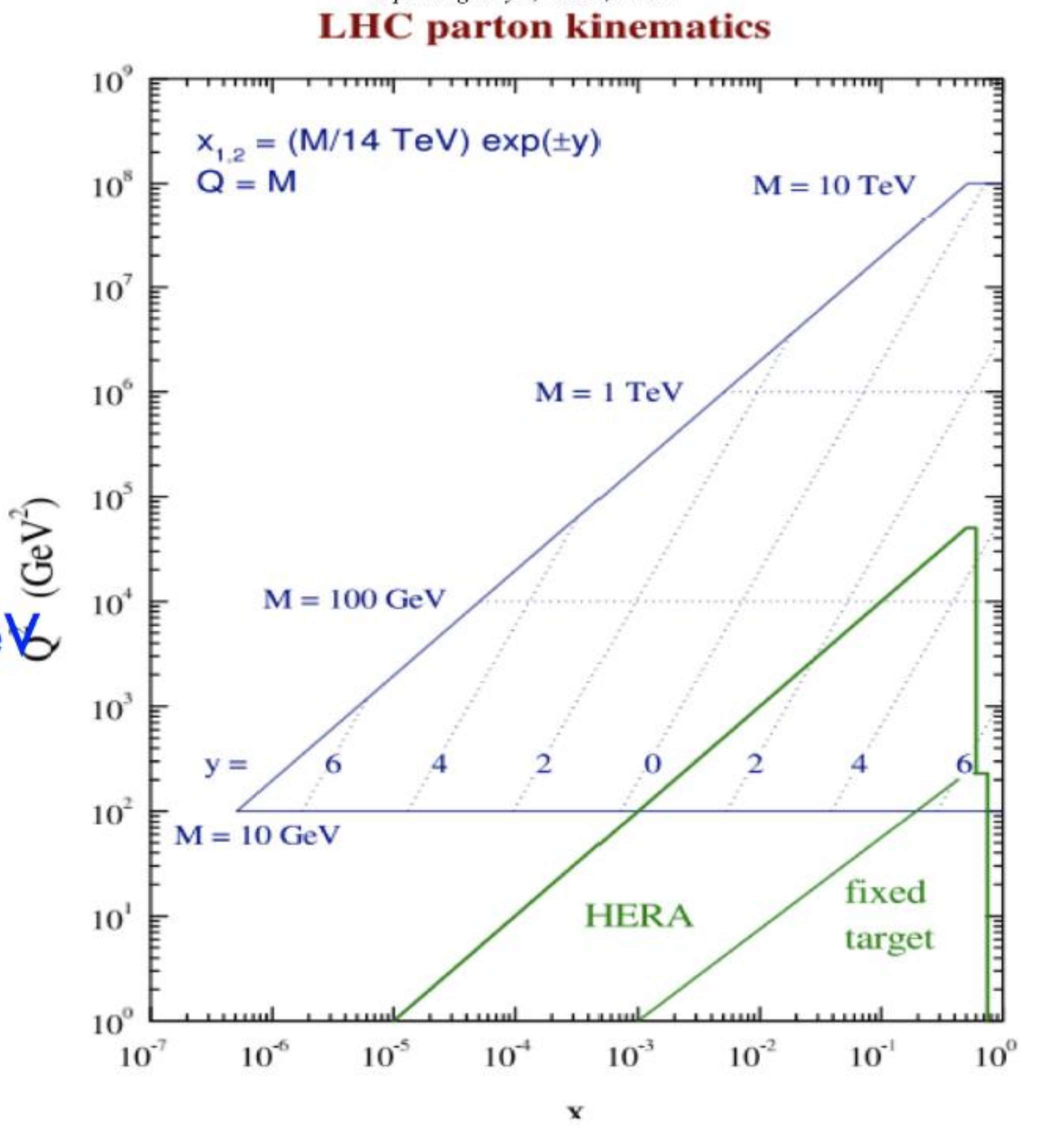
14 TeV : $x \sim 0.003$

  - at forward rapidities ($\eta \sim 5$):

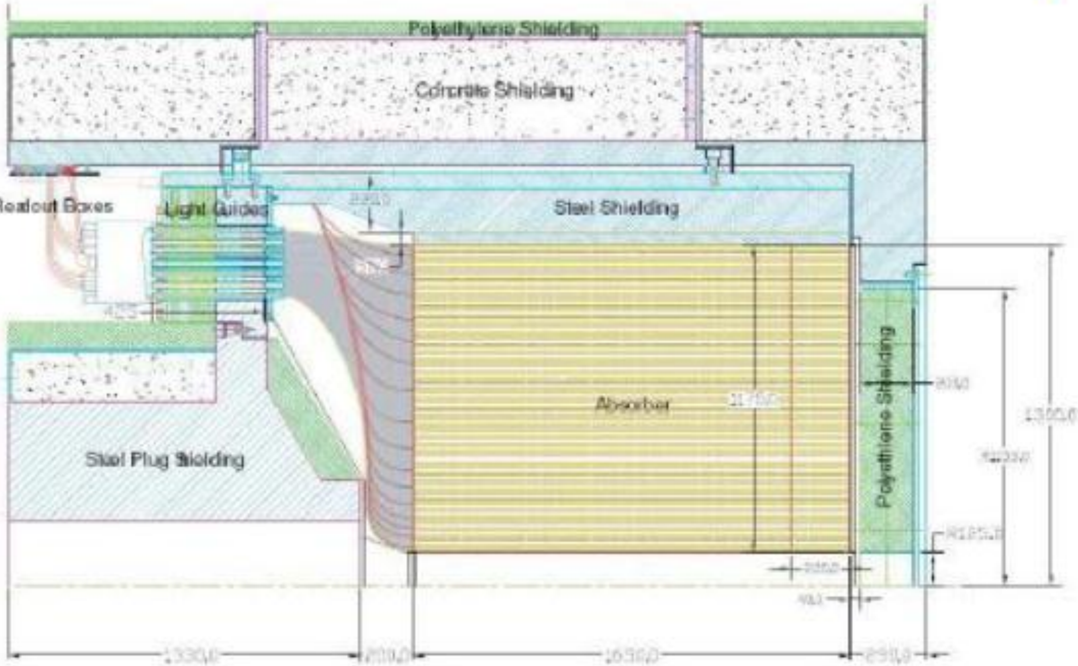
7 TeV: $x \sim 4 \cdot 10^{-5}$

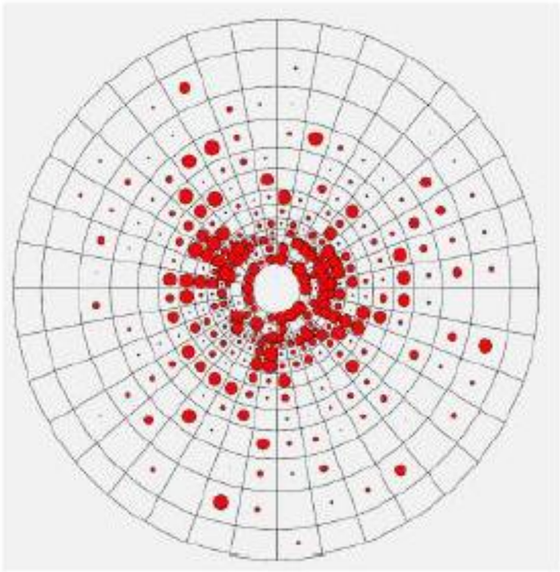
14 TeV: $x \sim 2 \cdot 10^{-5}$

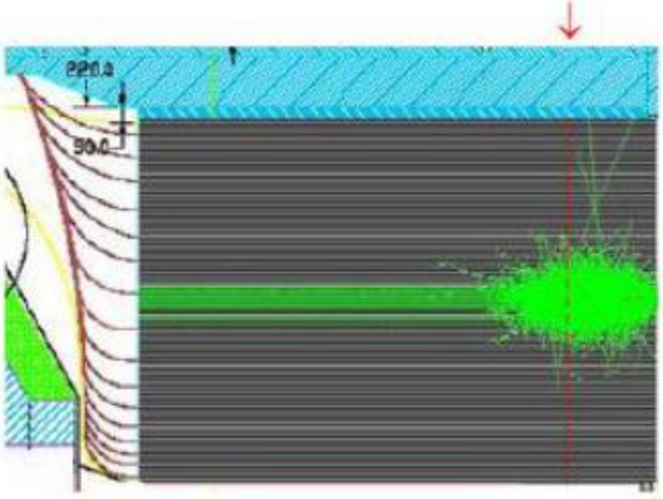
J. M. Campbell, J. W. Huston, and W. J. Stirling.
Hard Interactions of Quarks and Gluons: A Primer for LHC Physics.
Rept. Prog. Phys., 70:89, 2007.



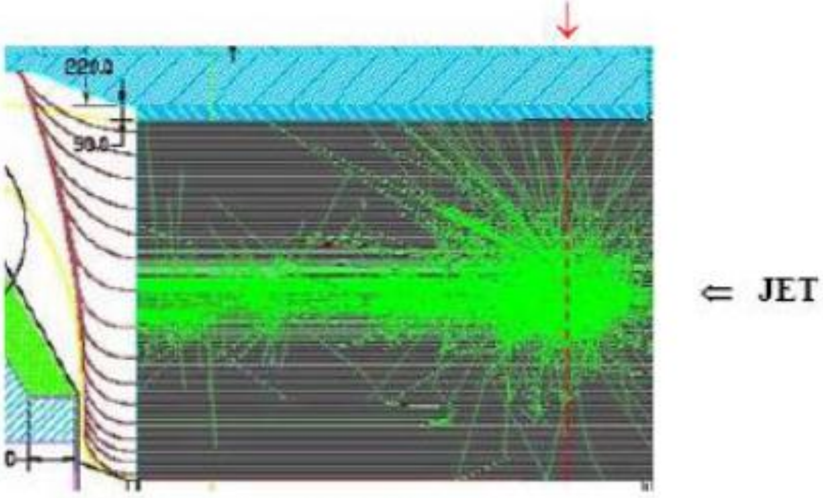
HF structure and properties



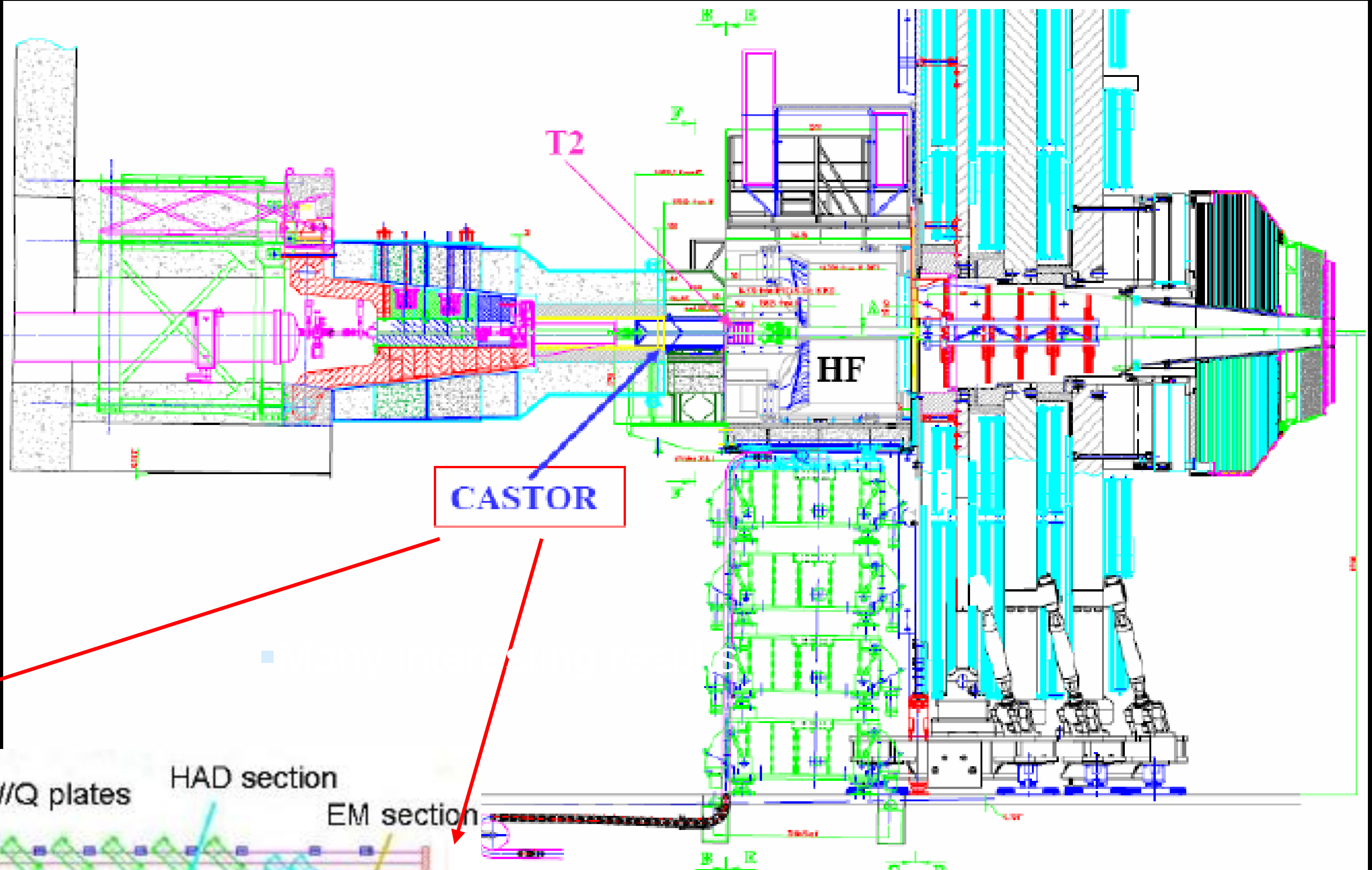


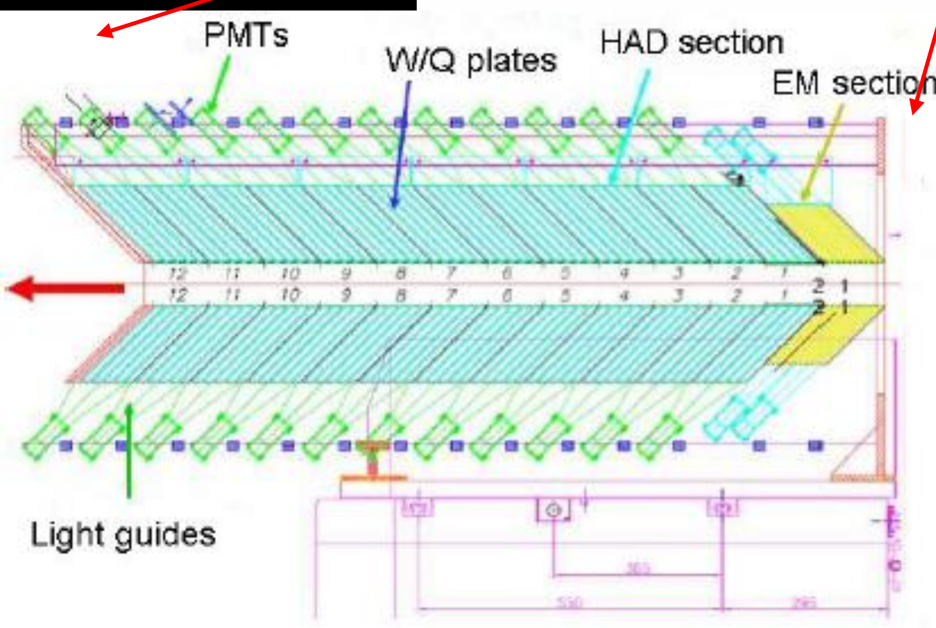


100 GeV electron shower



100 GeV proton shower


T2
HF
CASTOR


PMTs
W/Q plates
HAD section
EM section
Light guides