Soft QCD Results from CMS

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on behalf of the CMS collaboration

11^{th} workshop on Non-Perturbative QCD
Paris 2011, June 6-10

Outline

- Introduction
- Inclusive Particle Distributions
- Traditional Underlying Event Measurement
- Forward Energy Flow
- "The Ridge" in *pp* and *PbPb*

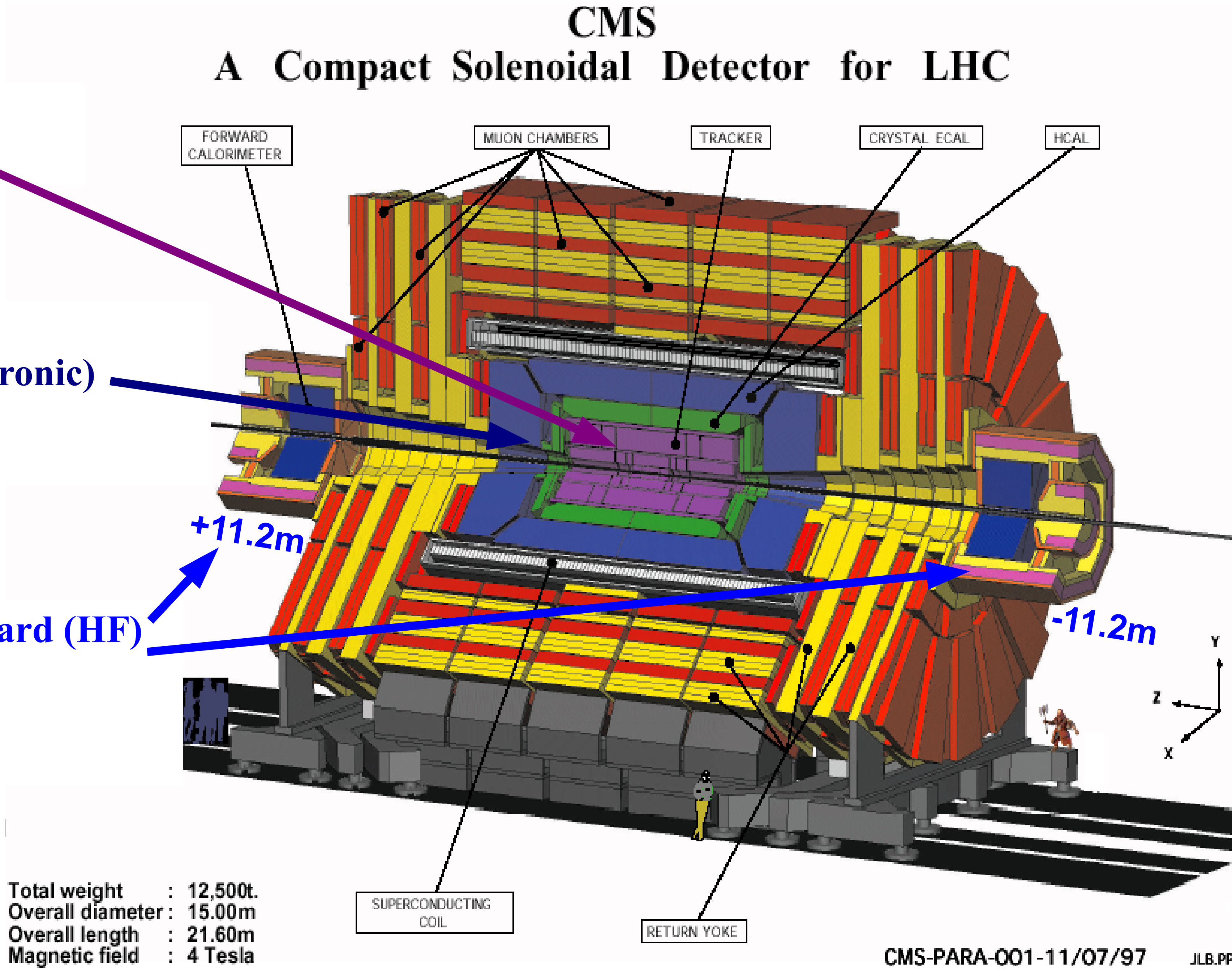
Introduction

The CMS Detector

Tracker
|η| < 2.5

Calorimeters
(EM and Hadronic)
|η| < 3.0

Hadronic Forward (HF)
Calorimeters
2.9 < |η| < 5.2

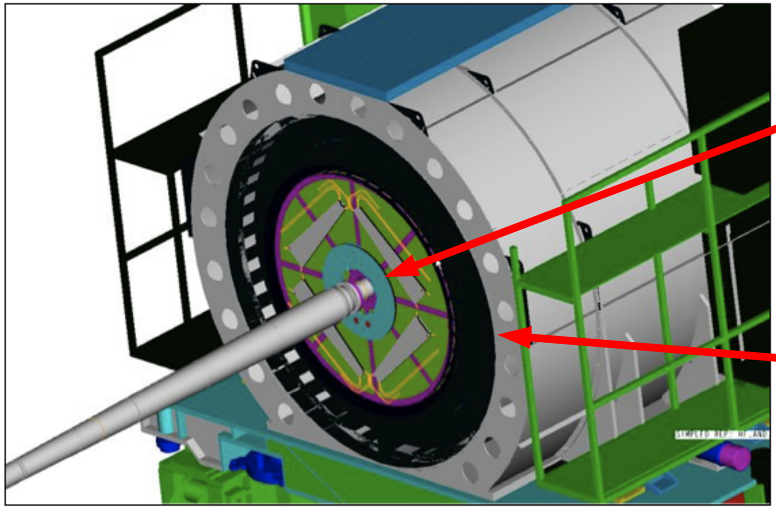


Minimum Bias Events

(Basic selection for most of the measurements in this talk.)

At CSM, the minimum bias (MB) events are triggered with

- A filled bunch passing the beam pickups (BPTX)
AND
- Any hit in the Beam Scintillator Counters (BSC)



In addition, often also **coincidence activity on both sides (BSC or HF)** is required.

→ **Non-single diffractive (NSD) events**.

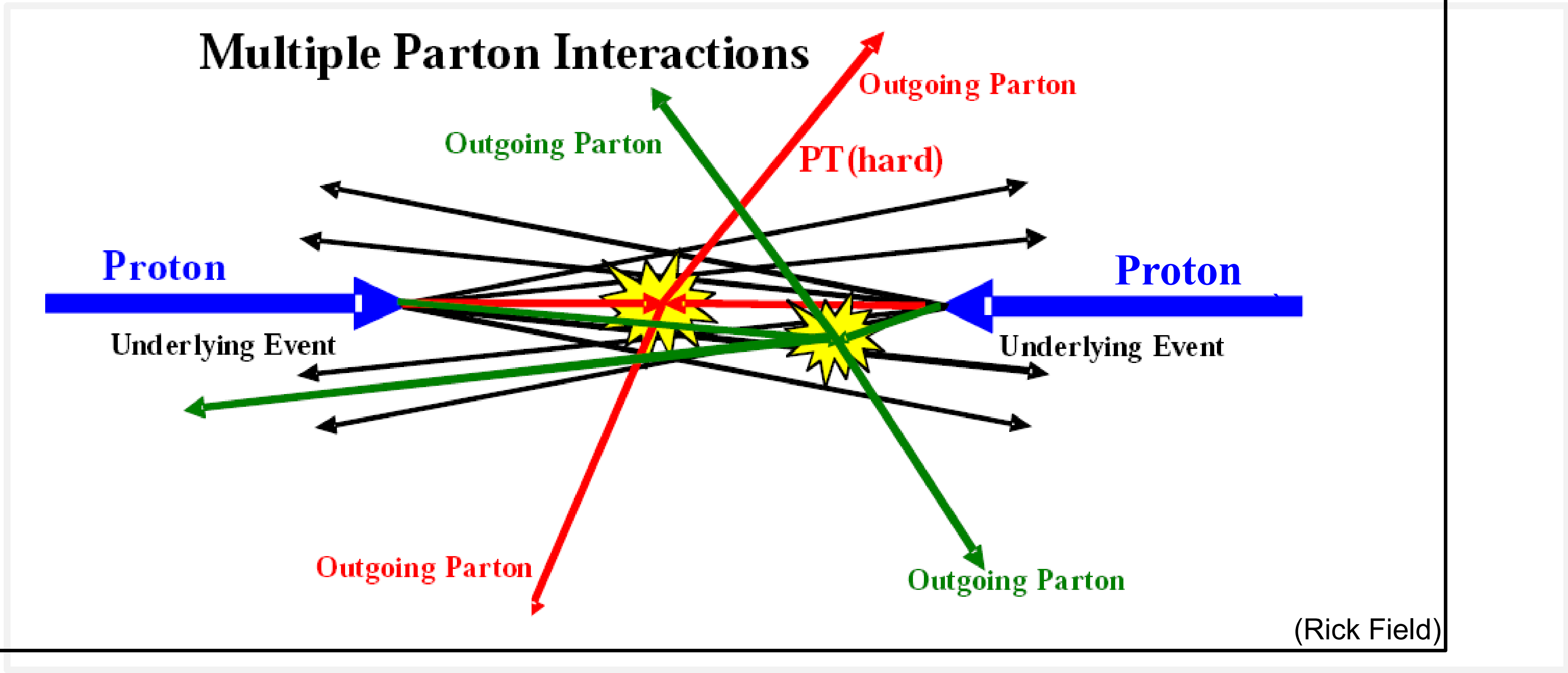
The Underlying Event (UE)

UE = everything except the studied LO process:

- Parton showers
- Multiple interactions (MI):

  Additional remnant-remnant, or parton-remnant interactions

- Not pile up (machine dependent).



(Rick Field)

MC Event Generators

- **PYTHIA 6**
  - LO ME + DGLAP parton showers.
  - Fragmentation from the Lund string model.
  - Multiparton interactions (MPI)
  - Extensively tuned to LEP and TEVATRON data. Many different tunes exists.

- **PYTHIA 8**
  - The C++ version of Pythia 6.
  - Updated MPI/UE models
  - Hard diffraction included

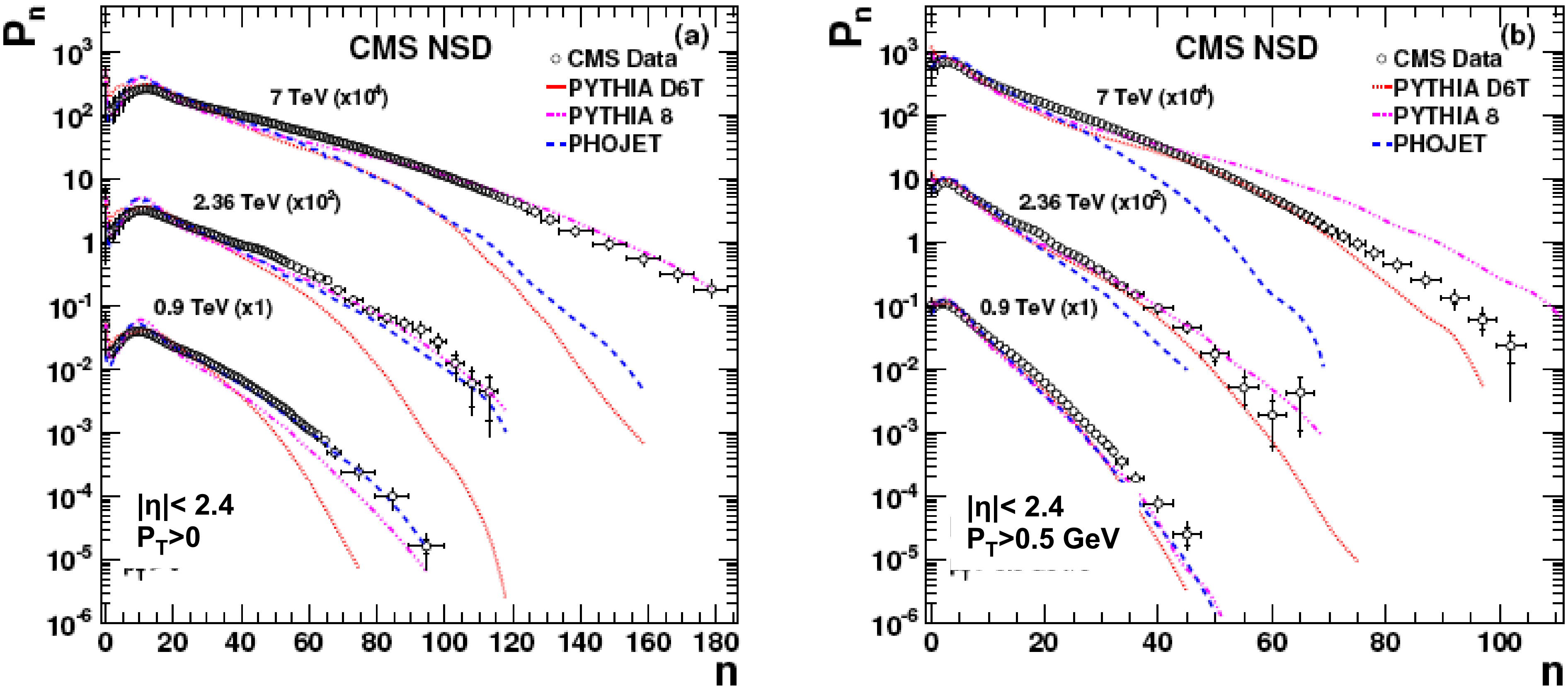
- **HERWIG++**
  - LO ME + DGLAP parton showers.
  - Cluster fragmentation.
  - Multiparton interactions.

- **CASCADE**
  - Based on the k_t factorization approach.
  - LO ME (off-shell) + CCFM based final state parton showers (no k_t ordering).
  - Unintegrated PDFs.
  - Fragmentation from the Lund string model.
  - No multiparton interactions.

Particle Spectra

Charged Particle Multiplicities

Particle multiplicities in Non Single Diffractive (NSD) events.
(P_n – probability to produce n particles.)



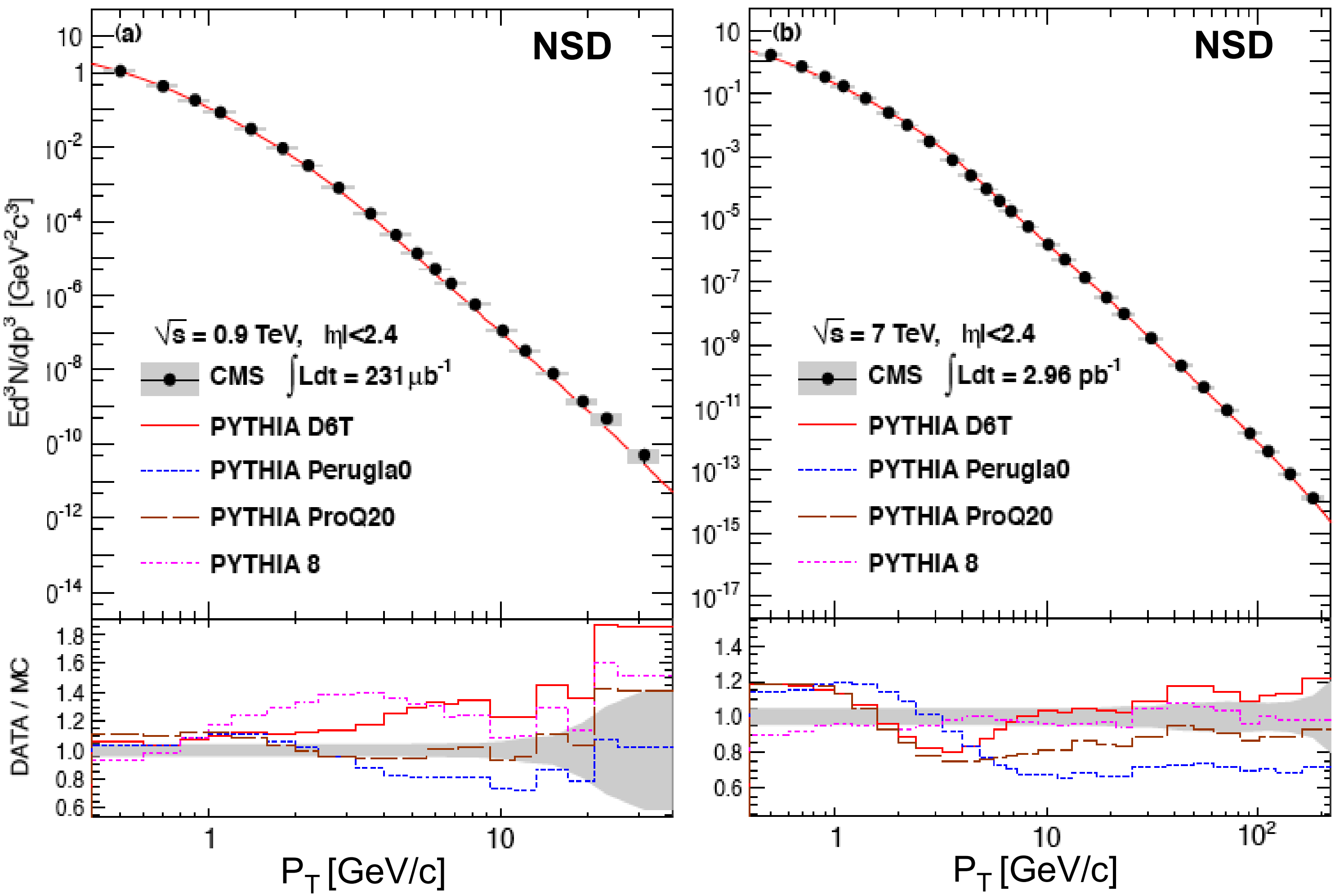
CMS-QCD-10-004, J. High Energy Phys. 01 (2011) 079

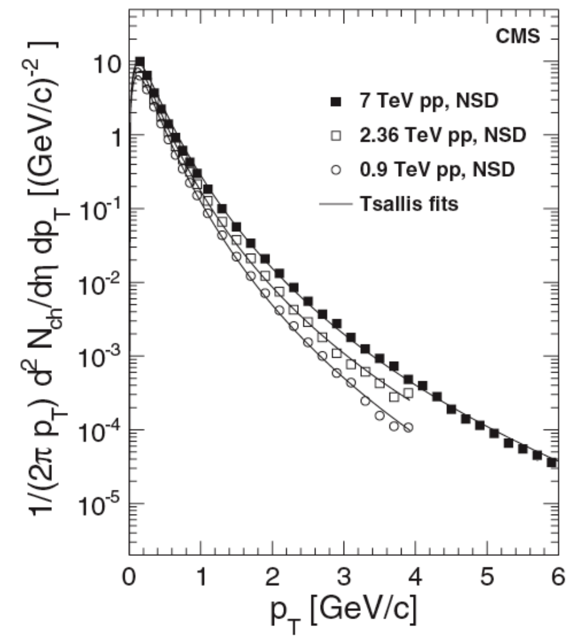
- **None of the considered MC describes the details of the data.**
- **Models that describe the data at 0.9 TeV, fails at 7 TeV.**
- **Deviation between data and MC different for p_T > 0 and p_T > 500 MeV.**

→ **Energy dependencies not understood by tested models.**

Charged Particles – P_T Distributions

CMS-QCD-10-006, Phys. Rev. Lett. 105 (2010) 022002
CMS-QCD-10-008, arXiv:1104.3547



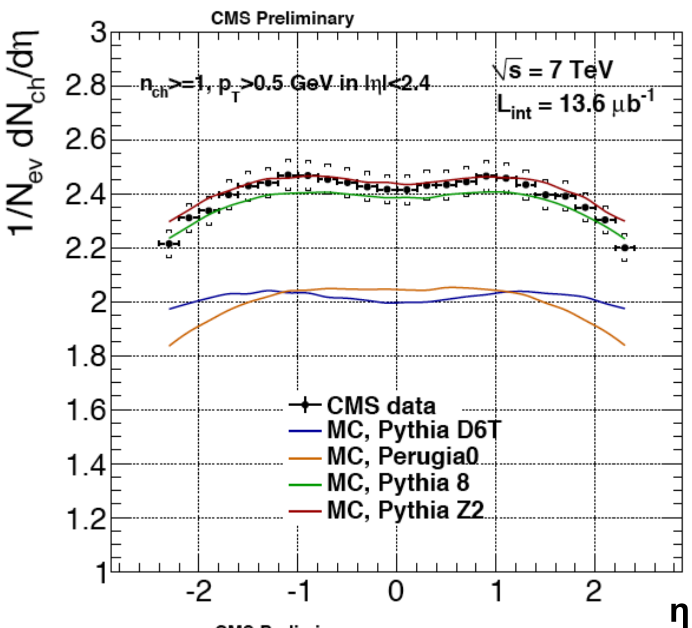


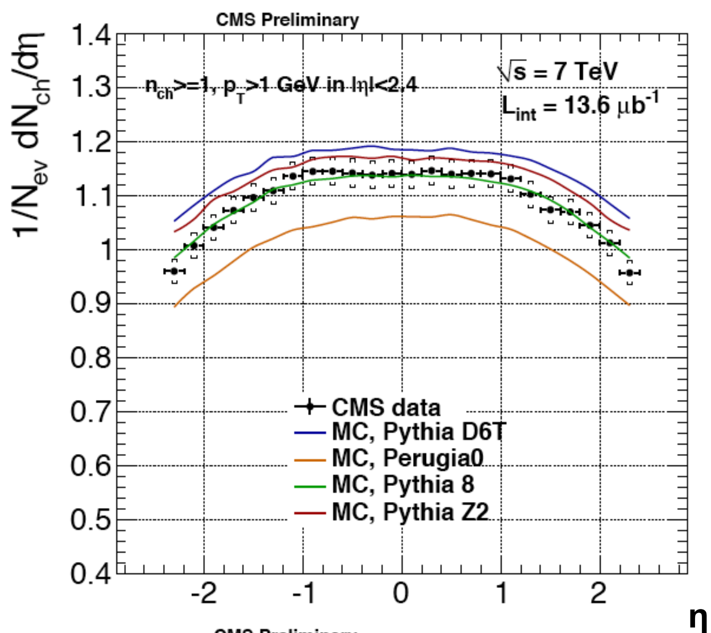
- Transverse momentum spectra **not understood** by tested MC models/tunes.
- Tested MC describes data differently at different energies.
- High sensitivity to choice of tunes.

Rapidity Distributions of Charged Particles

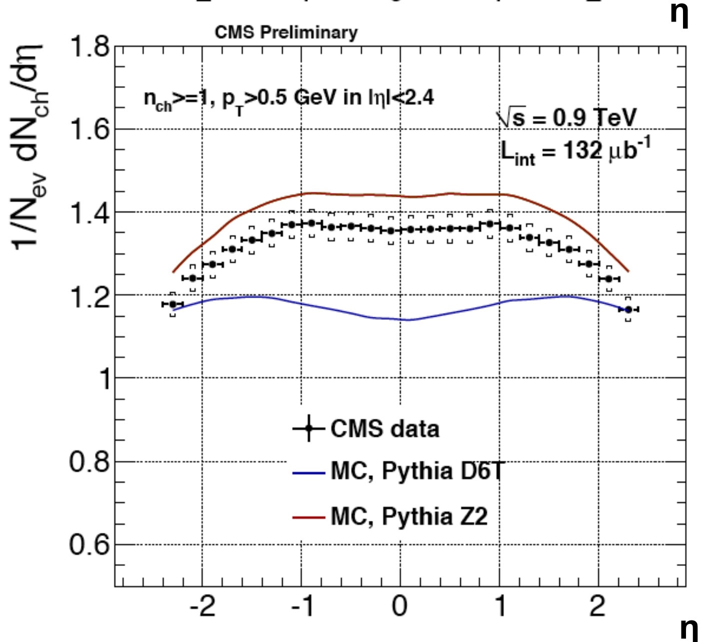
CMS-PAS-QCD-10-024

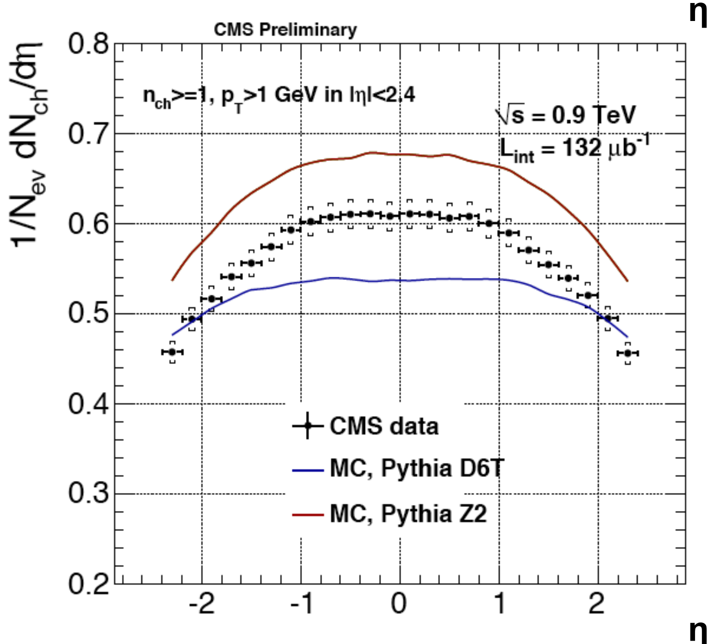
MB events (also including NSD events), with at least one charged particle with $P_T > 0.5$ GeV or $P_T > 1$ GeV.

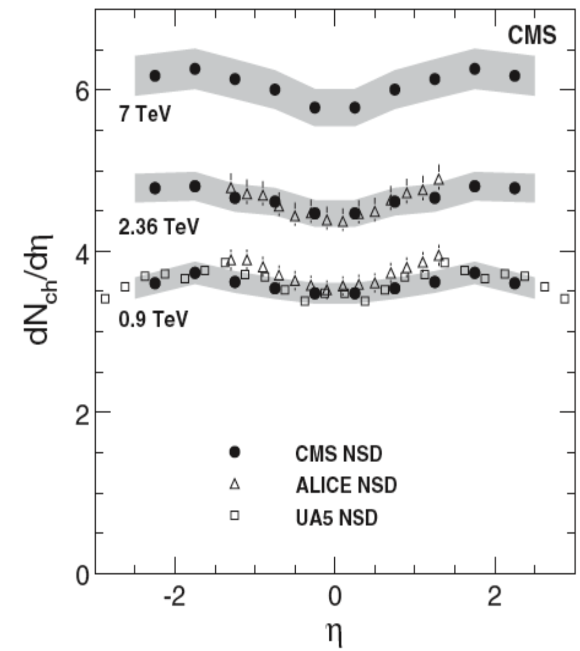




- At √s=7 TeV – nice description of data by Pythia 6 (Z2) and Pythia 8.
- At √s=7 TeV – failure by old Pythia 6 tunes
- Again, problem with energy dependence: Pythia 6 Z2 fails to describe the √s=0.9 TeV data







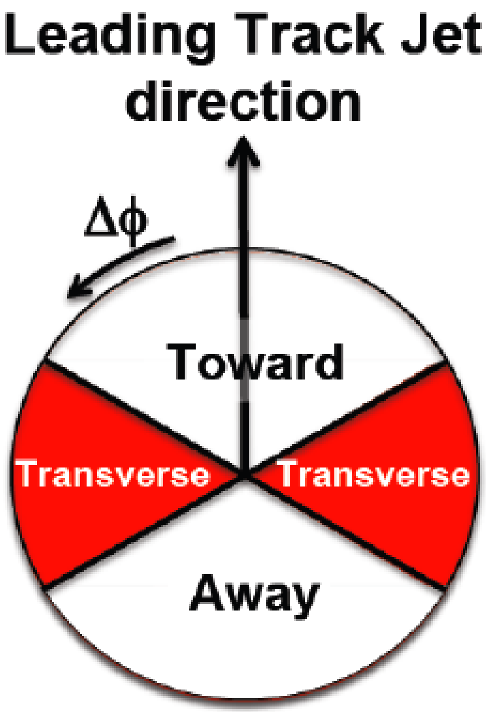
Phys. Rev. Lett. 105 (2010) 022002

Traditional UE measurement

UE measurement at $\sqrt{s}$=0.9 and 7 TeV

Traditional UE measurement (a là TEVATRON):

Measure the transverse energy flow and particle multiplicity transverse to the high p_T object(s) produced in the event.



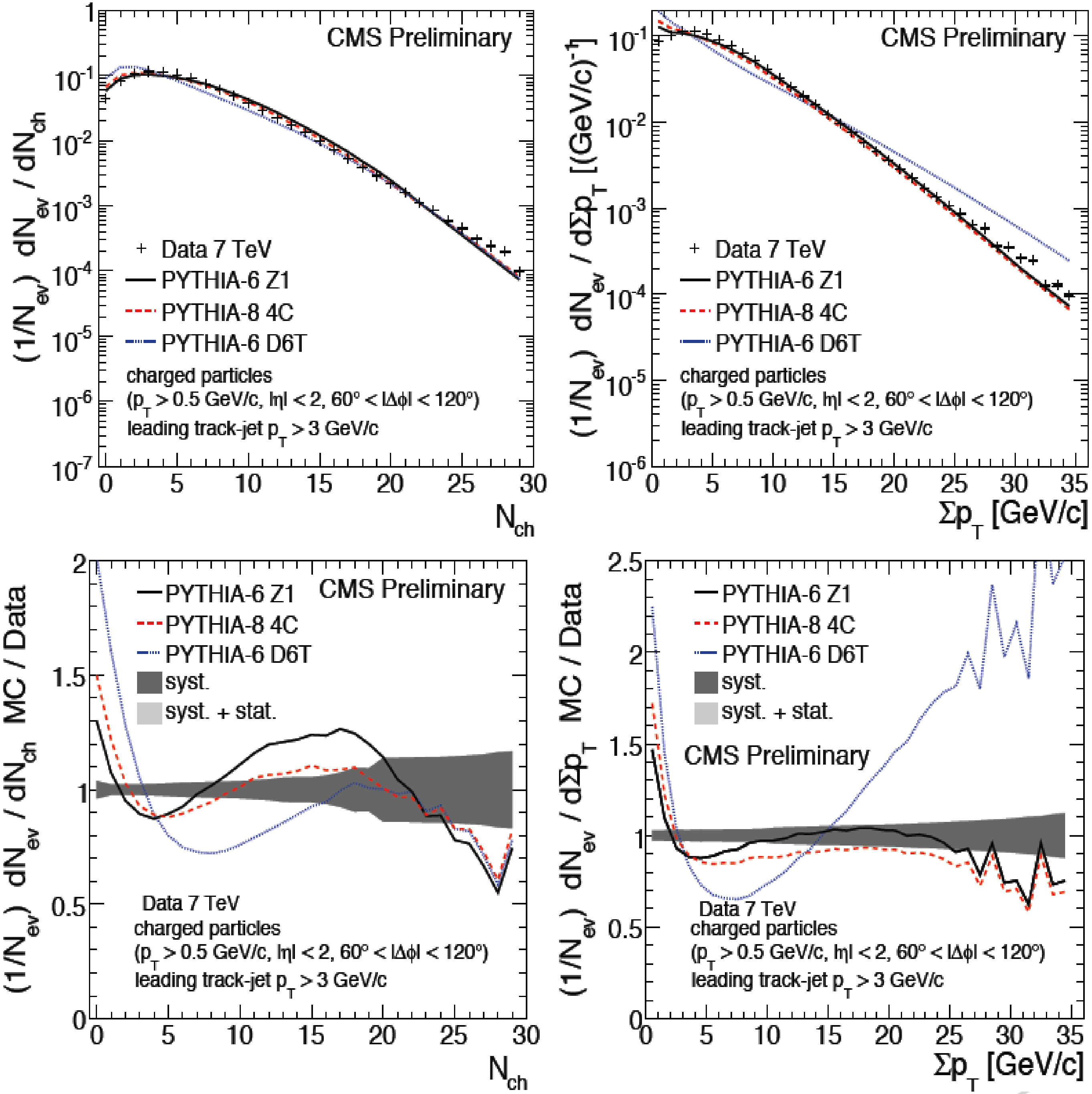
Toward (leading jet region): $|\Delta\Phi| < 60^o$
Away (back to leading jet region): $|\Delta\Phi| > 120^o$
Transverse: $60^o < \Delta\Phi < 120^o$

- **In the toward (jet) and away (back to jet) region the UE signal may be washed away by the hard activity.**
- **High activity also in away region due to momentum balance.**

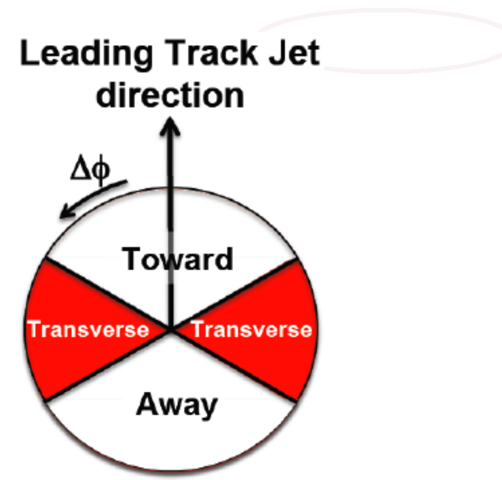
→ **Transverse regions most sensitive to MI and UE.**

CMS-QCD-10-001, Eur. Phys. J. C 70 (2010) 555-572
CMS-PAS-QCD-10-010

Transverse Particle Distributions



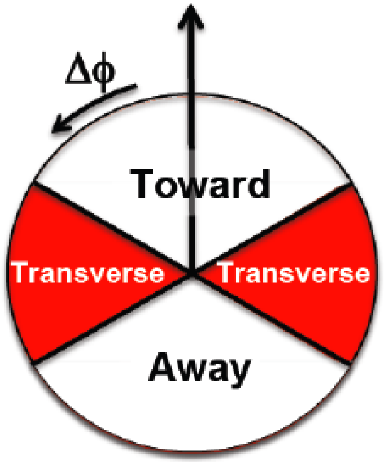
- **NSD MB events, selected as described earlier.**
- **Particle multiplicities and $\sum P_t$ of charged particles transverse to the leading track jet.**
- **Comparisons to Pythia 6 and Pythia 8.**
- **Shape not at all understood by considered MC (see ratio plots).**



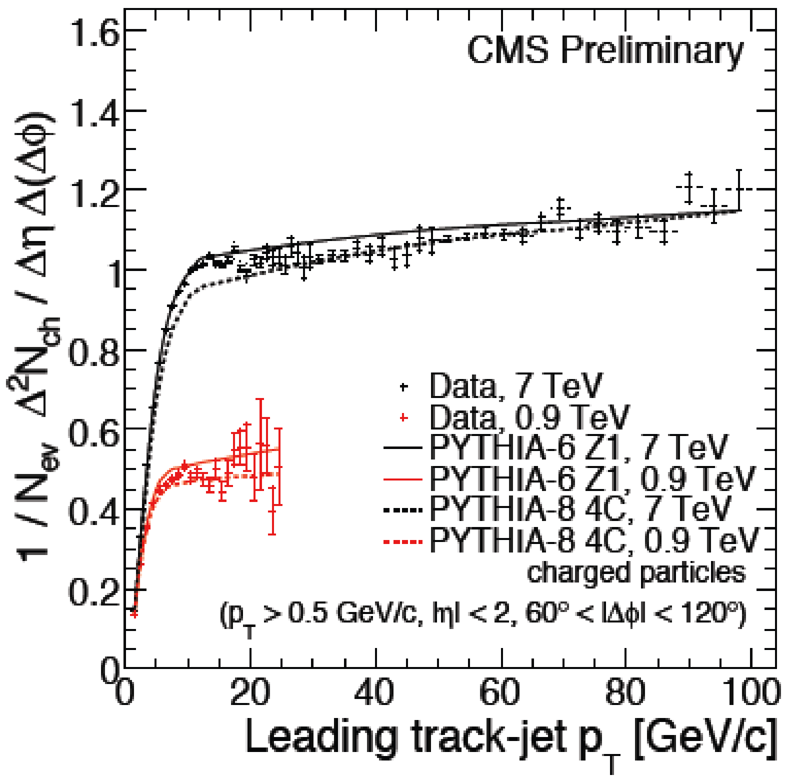
Transverse Activity as a Function of the Leading Track Jet

for √s=0.9 and 7 TeV data

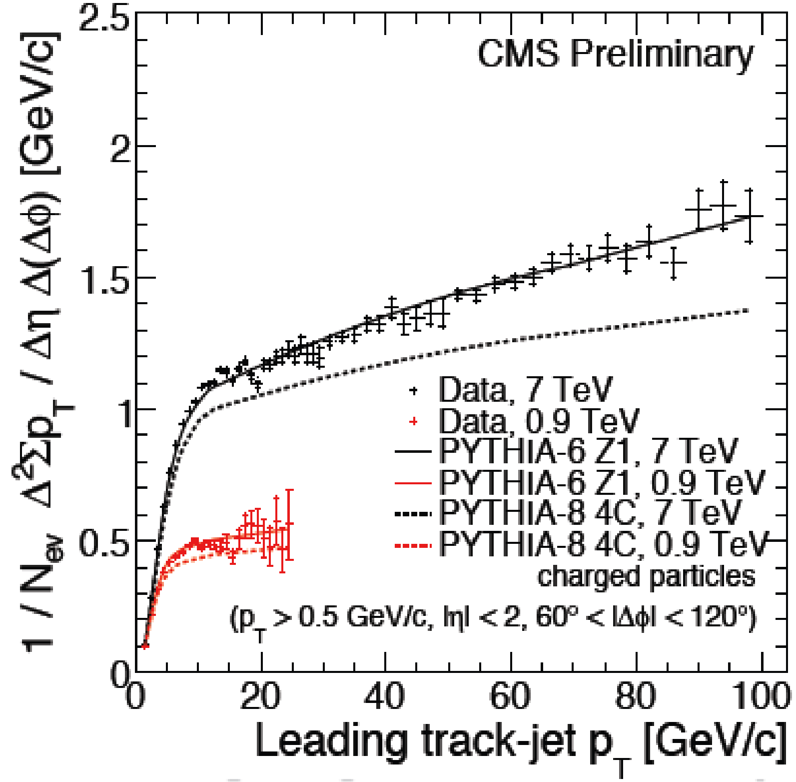
Leading Track Jet direction



Charged particle multiplicity in the transverse region



Scalar $\sum p_T$ for charged particles in the transverse region

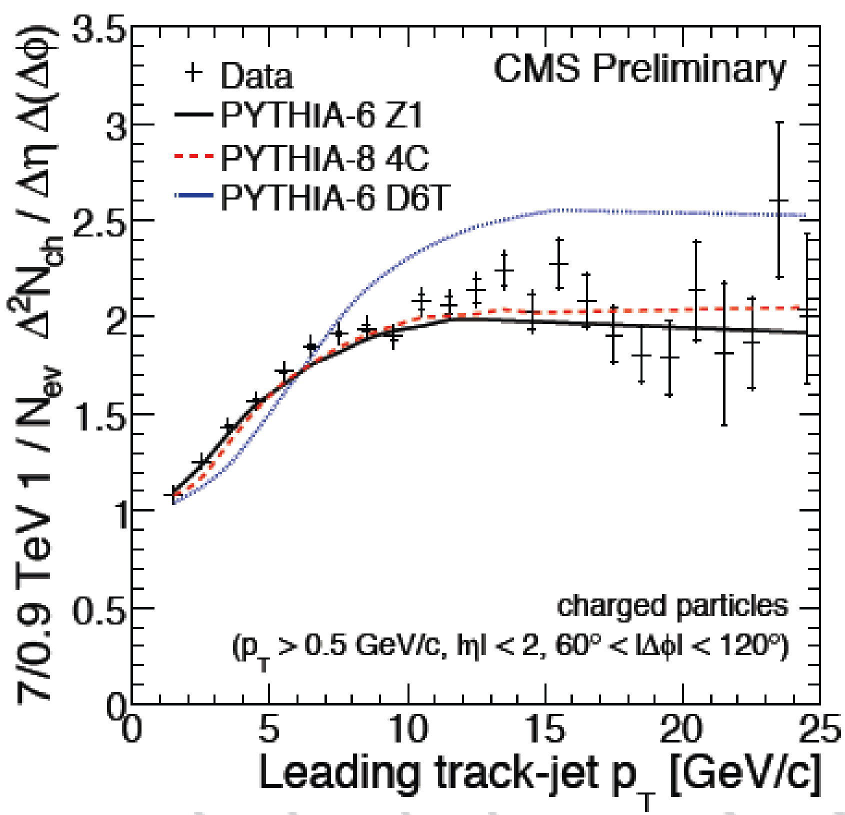


- **Nice illustration of the energy dependence in the UE:**
  - Dependence on both √s and hardness of reaction.

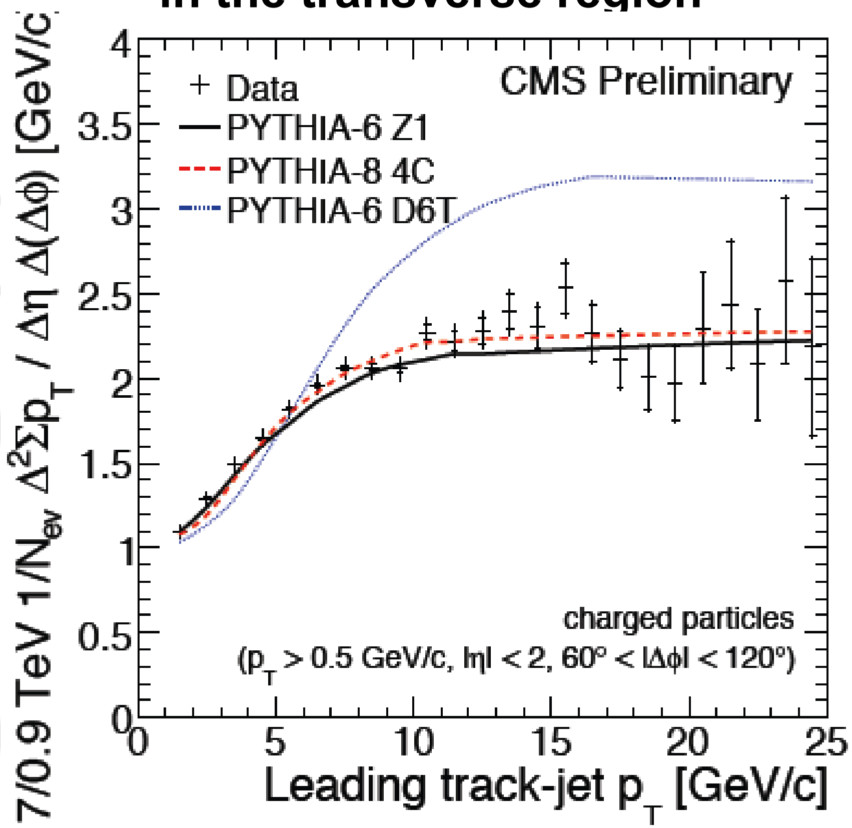
- **Significant higher UE in √s=7 TeV data compared to √s=0.9 TeV data.**

Transverse Activity as a Function of the Leading Track Jet

Ratio: √s= 7 TeV / √s= 900 GeV
Charged particle multiplicity in the transverse region



Ratio: √s= 7 TeV / √s= 900 GeV
$\sum P_t$ of charged particles in the transverse region



- **Not just a simple dependence between UE and √s:**
  The increase with center of mass energy depends on the hardness of the reaction.

- **Ratios nicely described by Pythia 6 and Pythia 8 (with good choice of tunes).**

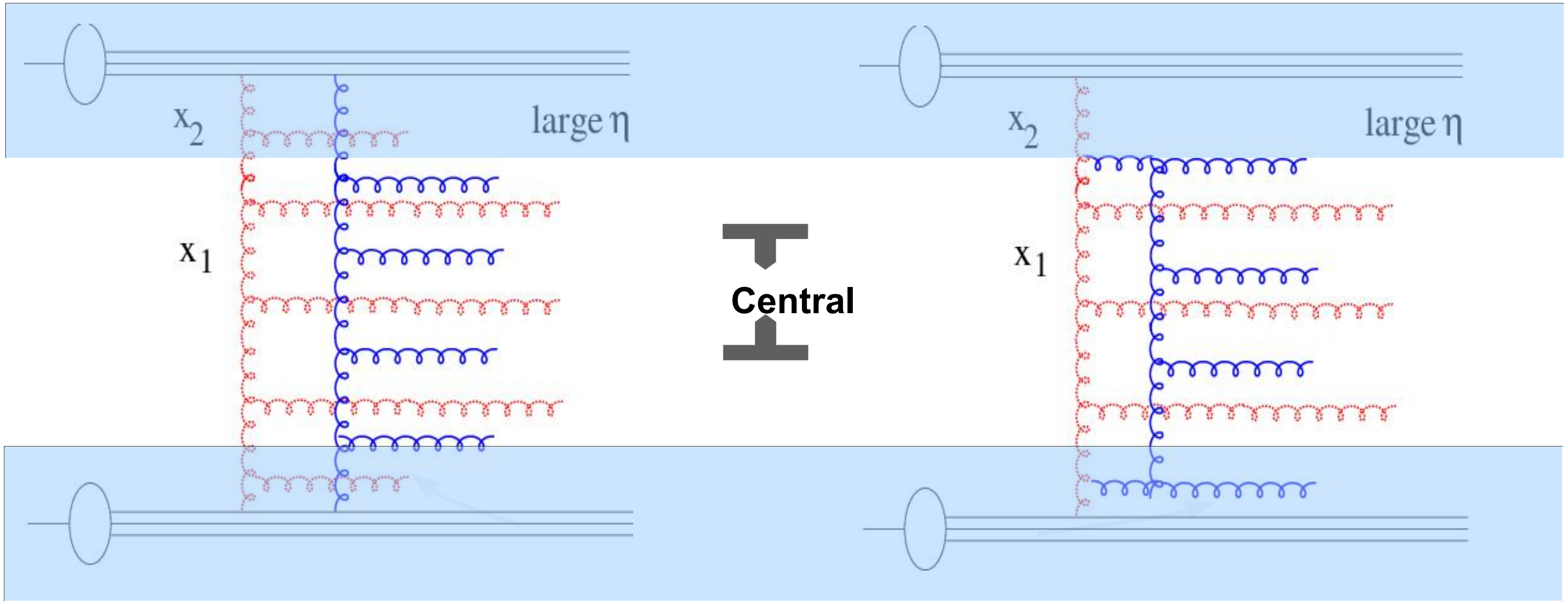
Forward Energy Flow

Forward Energy Flow

Forward region:

- Long range in rapidity between forward and central activity.
Opens up for higher order reactions. → Further sensitivity to QCD.

- Energy flow in the forward region:
Information about color (re)connections to the proton remnant?



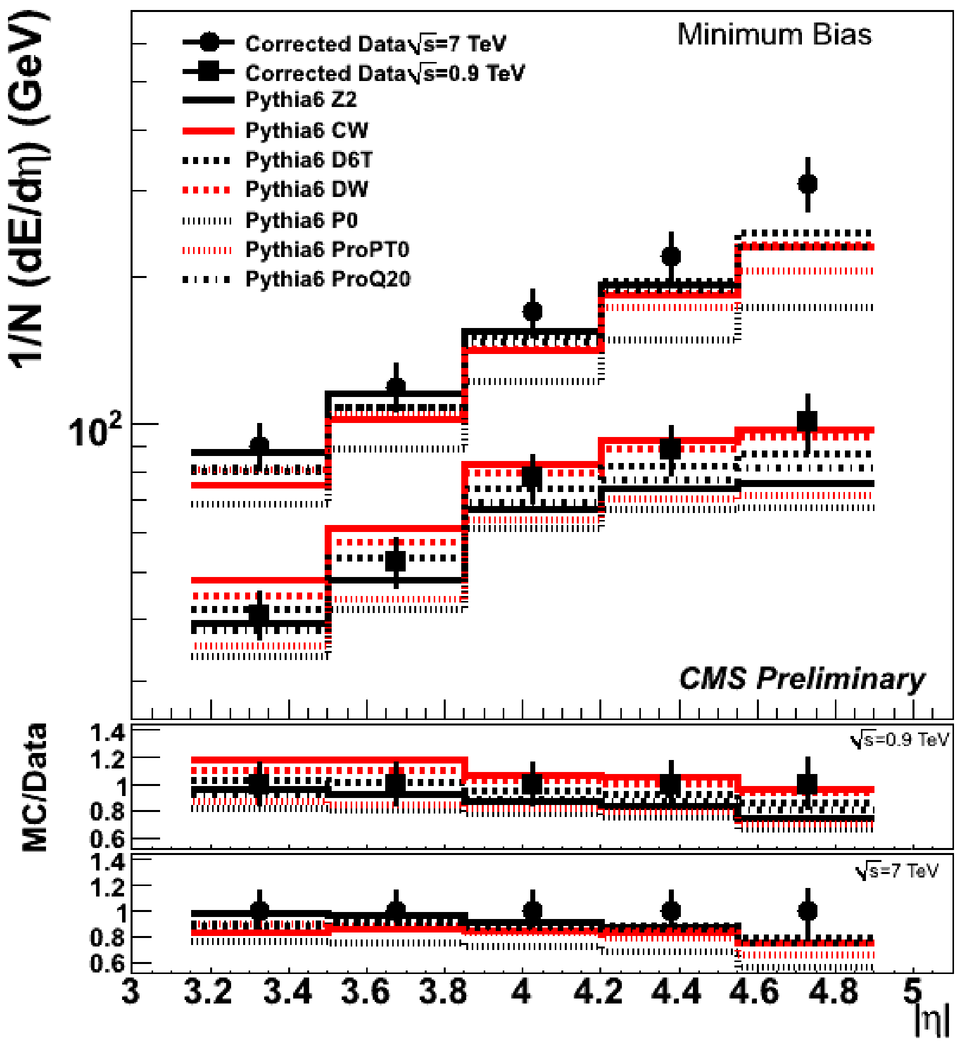
Forward energy flow

- UE unexplored in this region (3.15<|η|<4.9), in pervious collider experiments.

CMS-PAS-FWD-10-011

$$\frac{1}{N}\frac{dE}{d\eta}[GeV]$$ measured for all particles in (3.15<|η|<4.9)

MB event selection: At least one charged particle in both the forward and the backward region. (SD events suppressed)

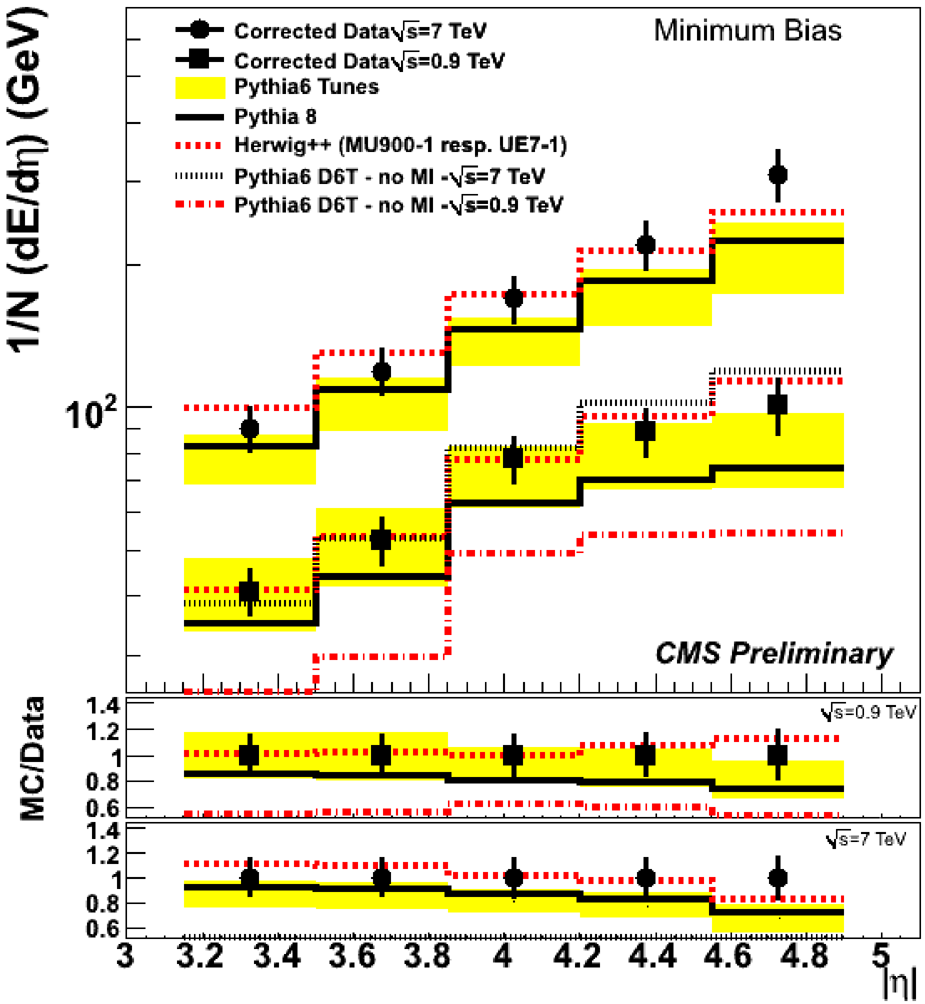


- **Strong dependence on c.o.m energy.**
- **Energy flow increase with η (closer to beam remnant)**
- **No Pythia 6 tune describe the √s = 7 TeV data at high eta.**
- **Several tunes equally good within errors.**

Forward Energy Flow in MB Events

$\frac{1}{N}\frac{dE}{d\eta}[GeV]$ **measured for all particles in (3.15<|η|<4.9)**

MB event selection: One charged particle in both the forward and the backward region. (SD events suppressed)

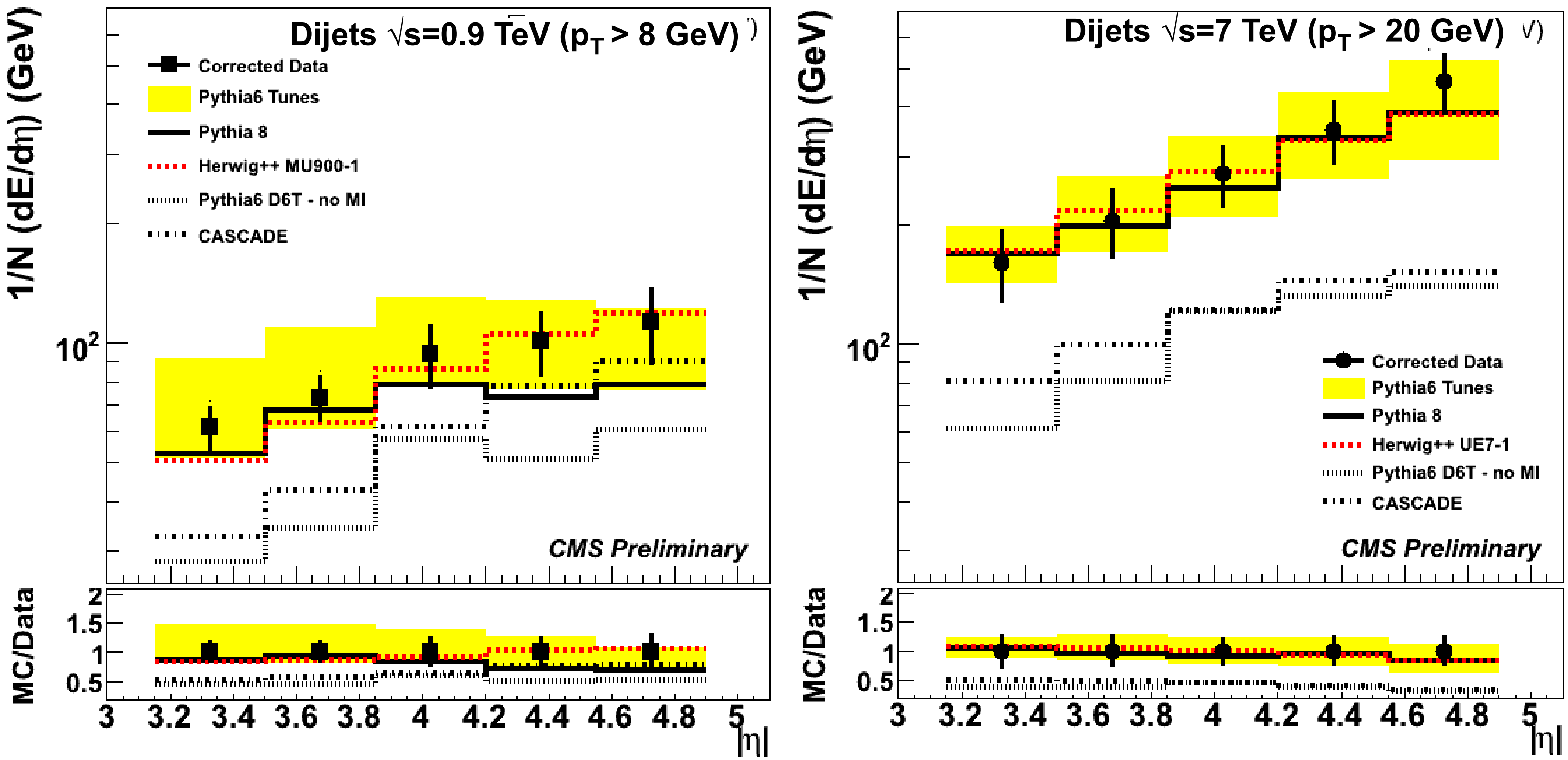


- **Pythia 6 band composed from the different Pythia 6 tunes on the last slide.**
- **Herwig++ describes the data using center-of-mass specific tunes.**
- **Pythia 8 fails at high eta**
- **Significant contribution from multiparton interactions.**

Forward Energy Flow in Dijet Events

Events with a hard sub-system. Sub-sample to the MB event sample.

Anti-kt algorithm (R=0.5)	$\sqrt{s}$=0.9 TeV	$\sqrt{s}$=7 TeV
High p_T	p_T > 8 GeV	p_T > 20 GeV
Central	$\lvert\eta\rvert < 2.5$	
Back-to-back	$\lvert\Delta\varphi_{jet1,jet2} - \pi\rvert < 1$	



- **Significantly higher forward energy flow in dijet events than in MB.**
- **Pythia 8 describes the data at $\sqrt{s}$=7 TeV.**
- **Herwig++ good, when using c.o.m. specific tunes.**
- **Large contribution from MI.**
- **Cascade (k_t-factorization based MC, no MI) – somewhat more activity than Pythia 6 w/o MI.**

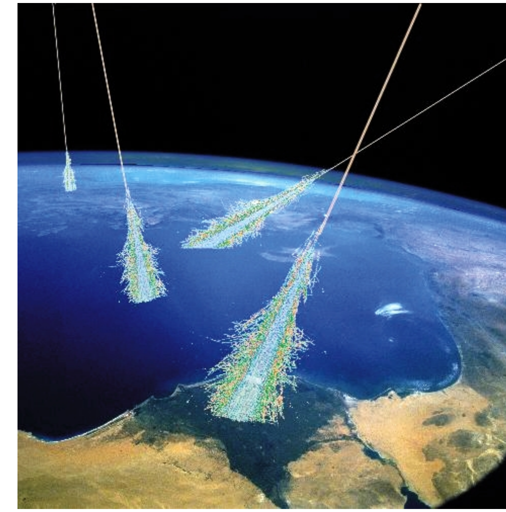
Comparison to Cosmic Ray MC

Forward energy flow overall very good description by cosmic ray MC generators.

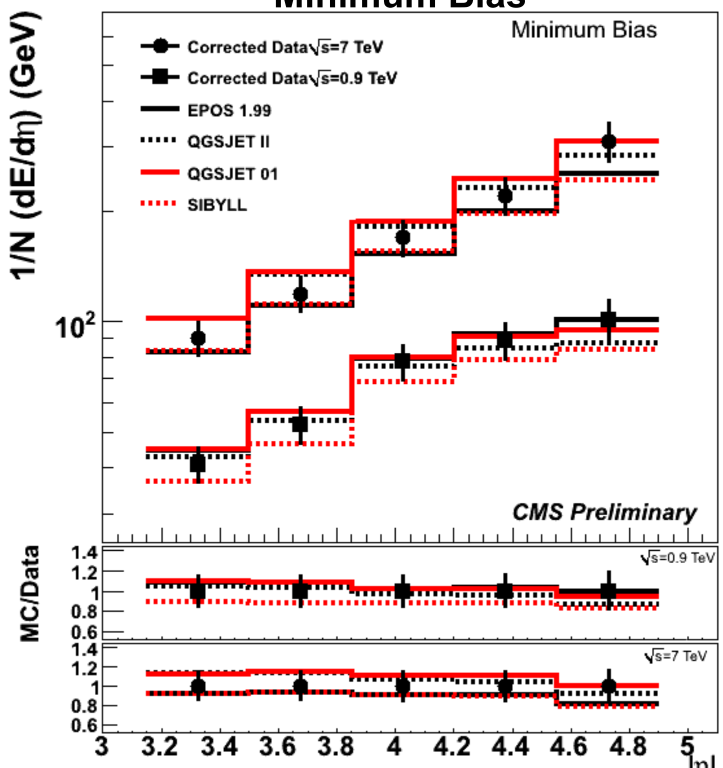
No surprise...

MC originally made for cosmic ray – of which 90% are protons – interactions with the atmosphere.

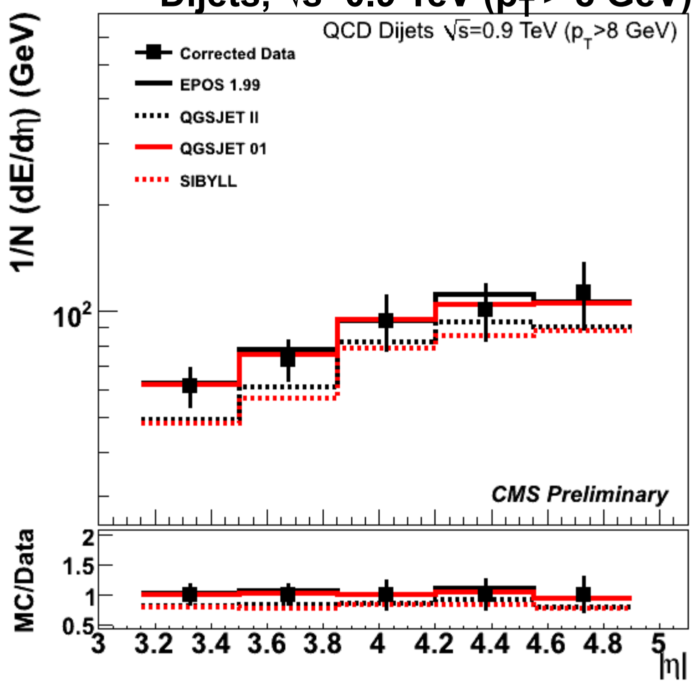
Forward particle production important in air shower models – majority of the energy carried by the forward particles.



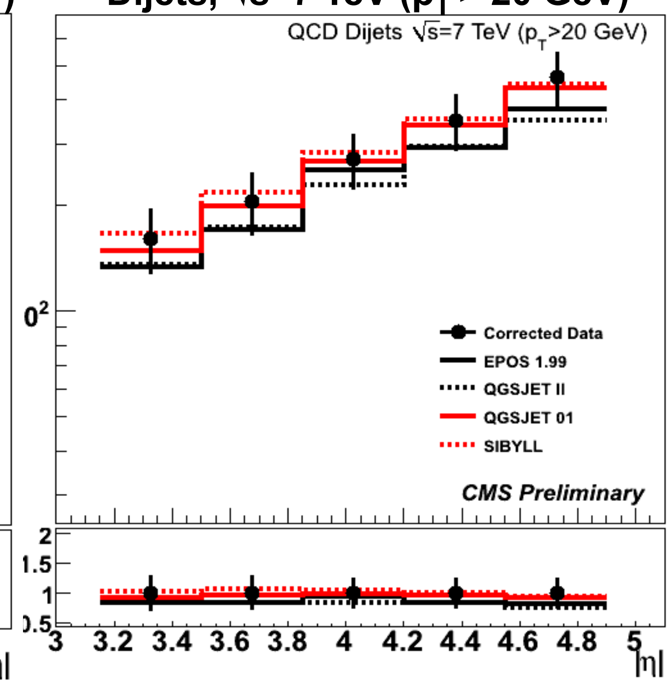
Minimum Bias



Dijets, $\sqrt{s}$=0.9 TeV (p_T > 8 GeV)

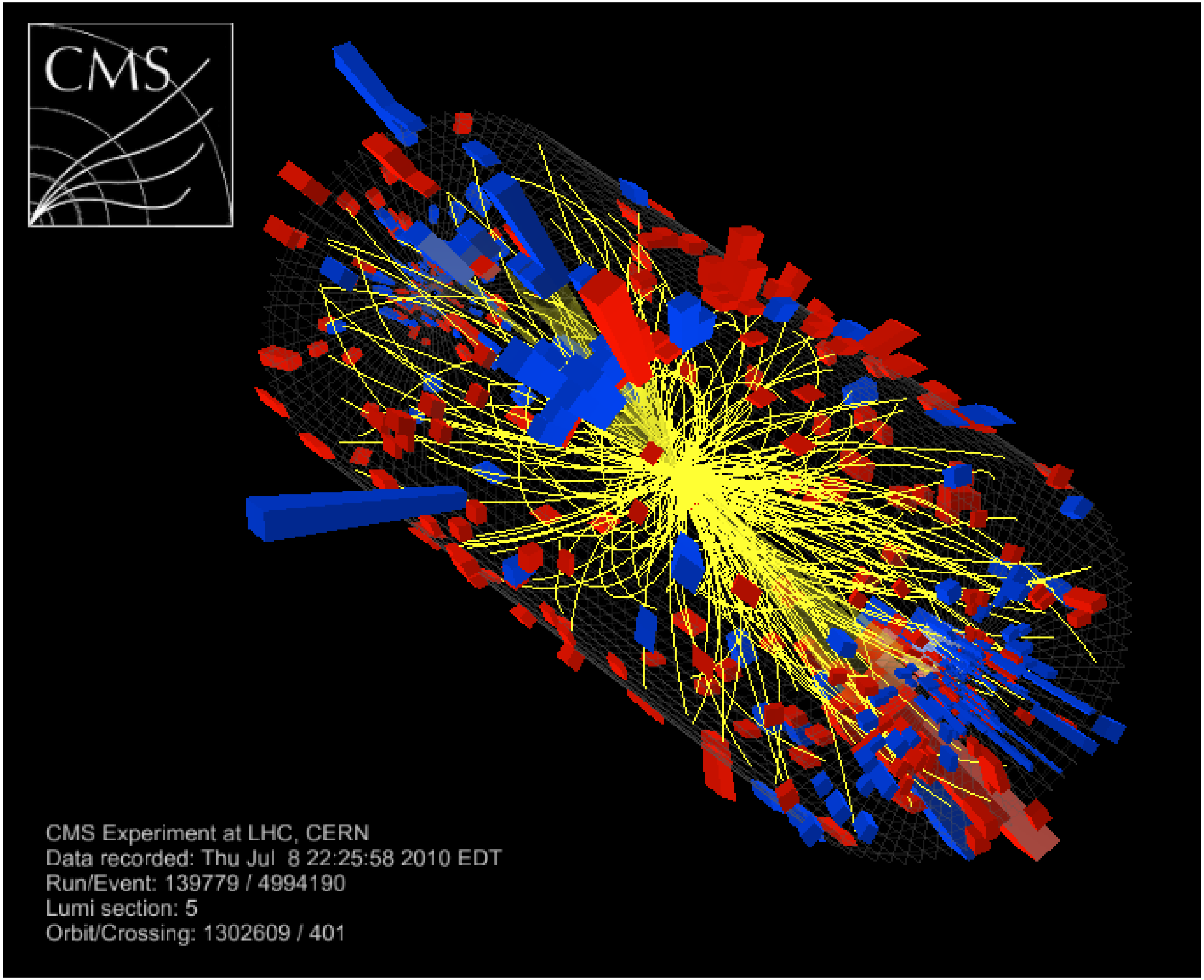


Dijets, $\sqrt{s}$=7 TeV (p_T > 20 GeV)



Particle correlations in pp and PbPb

High Multiplicity Event



Dedicated trigger for events with N_{Tracks} > 110.

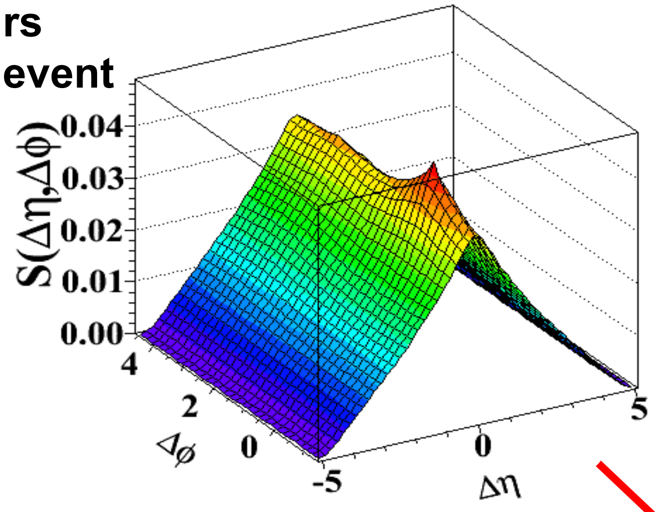
268 reconstructed particles in the tracker in a single pp collision: the highest multiplicity event in ~70 billion inelastic events. (Summer 2010, 1/pb)

Correlation Function Definition

Signal distribution:

$$S_N(\Delta\eta,\Delta\varphi) = \frac{1}{N(N-1)}\frac{d^2N^{signal}}{d\Delta\eta d\Delta\varphi}$$

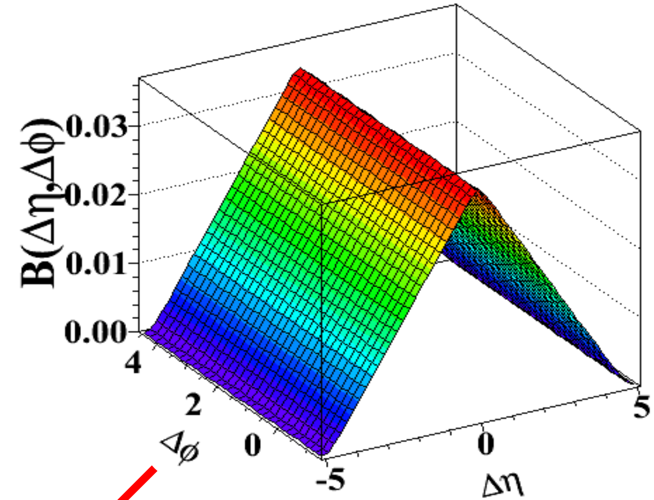
Particle pairs from same event



Background distribution:

$$B_N(\Delta\eta,\Delta\varphi) = \frac{1}{N^2}\frac{d^2N^{bkg}}{d\Delta\eta d\Delta\varphi}$$

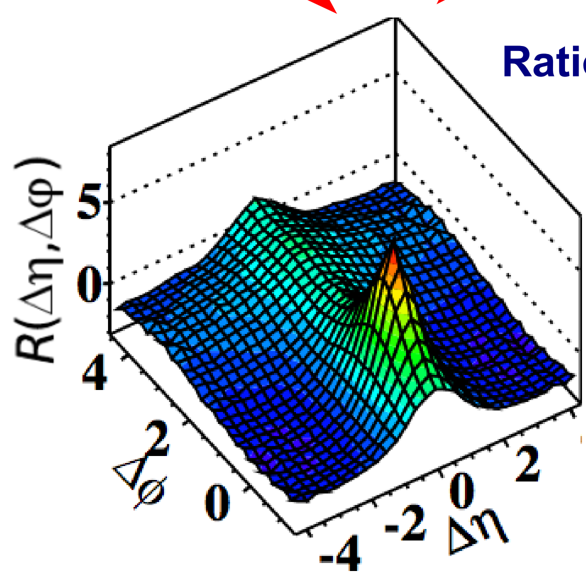
Pairs from mixed events



$$\Delta\eta = \eta_1 - \eta_2$$
$$\Delta\varphi = \varphi_1 - \varphi_2$$

Ratio – Signal/Background

$$R(\Delta\eta,\Delta\varphi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\varphi)}{B_N(\Delta\eta,\Delta\varphi)} - 1\right)\right\rangle_N$$



CMS pp 7TeV

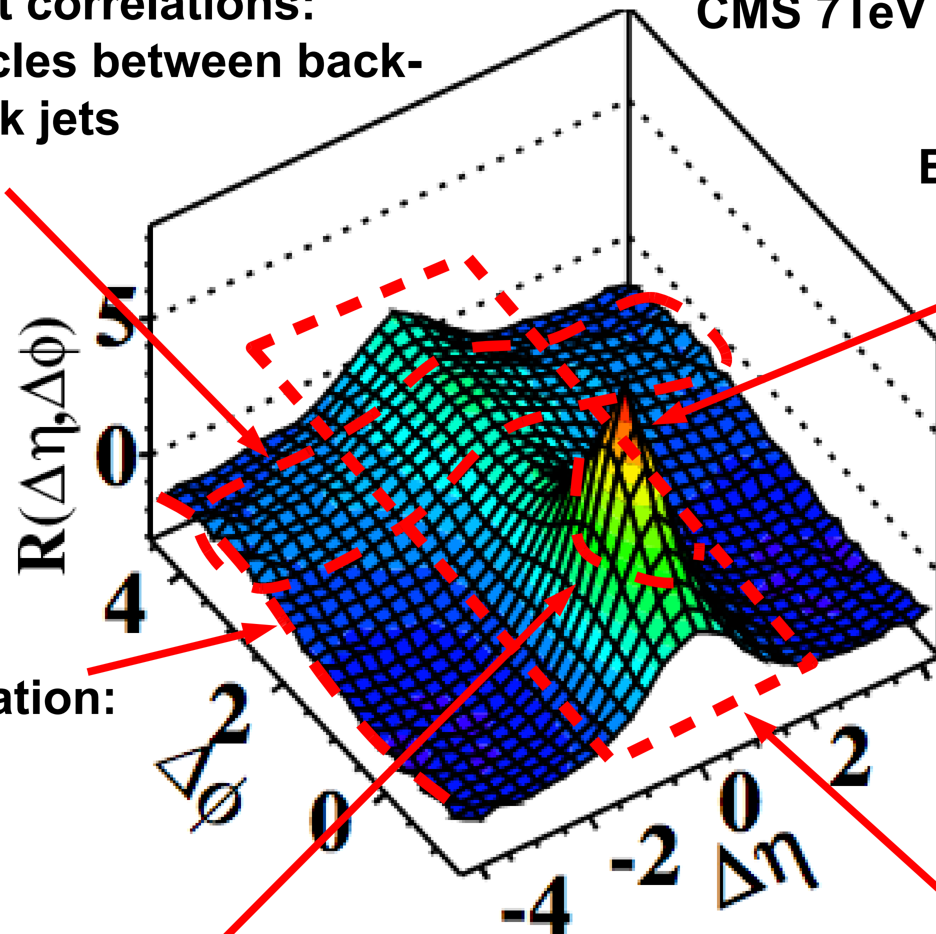
CMS-QCD-10-002,
J. High Energy Phys. 09 (2010) 091

Long and short range correlations

"Away-side" jet correlations:
Correlation of particles between back-to-back jets

CMS 7TeV pp min bias

Bose-Einstein correlations:
(Δφ,Δη) ~ (0,0)



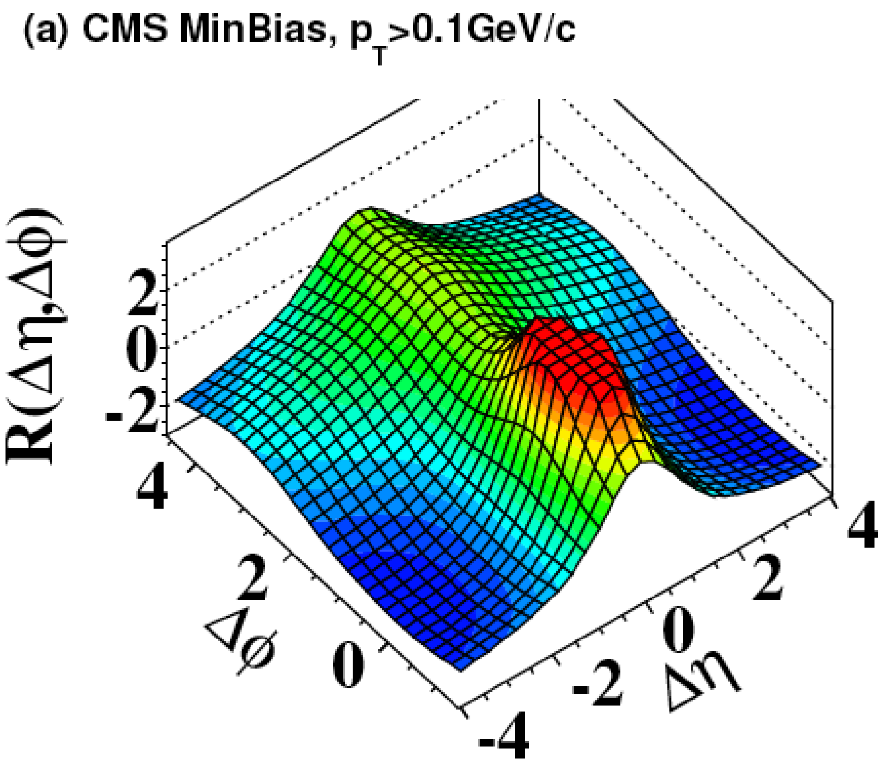
Momentum conservation:
~ cos(Δφ)

"Near-side", Δφ~ 0 jet peak:
Correlation of particles within a single jet

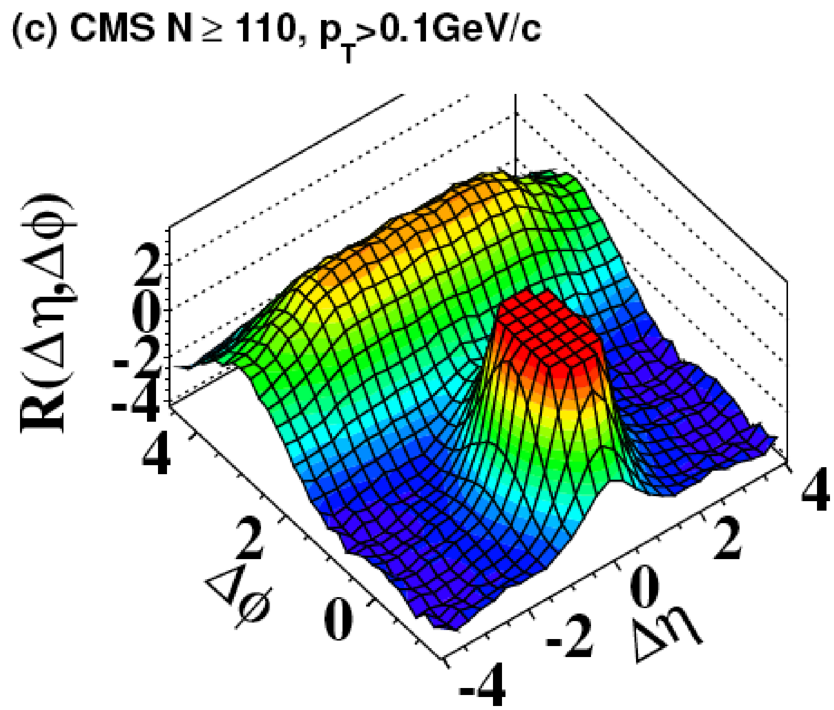
Short-range correlations (|Δη| < 2):
Resonances, string or cluster fragmentation

CMS-QCD-10-002, J. High Energy Phys. 09 (2010) 091

MinBias



High Multiplicity (N>110)

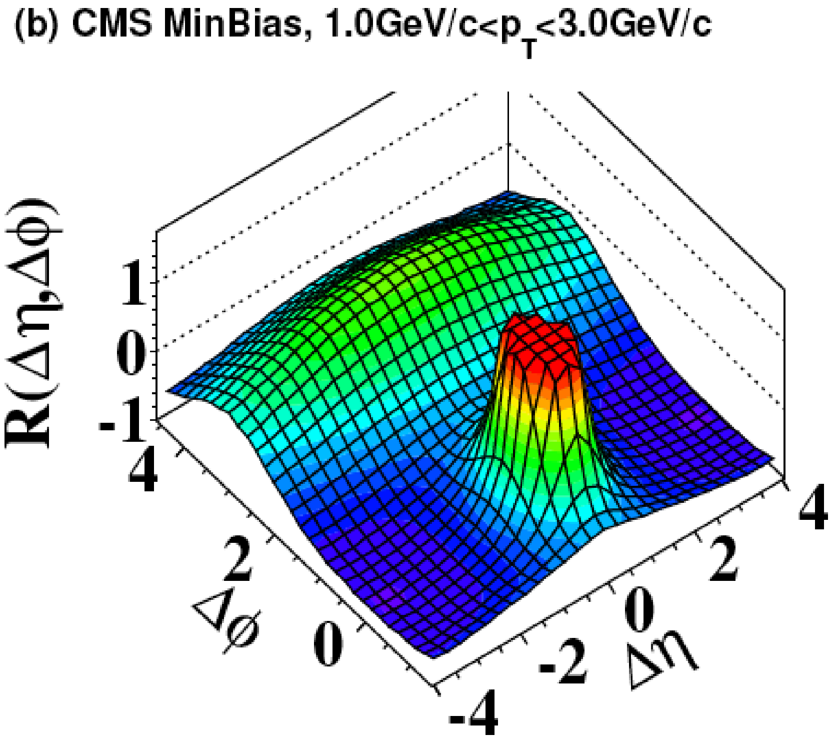


- The jet peak is cut for better visibility of the correlations.
- Jet peak correlations with away-side – stronger in the high multiplicity events. (More jet events.)
- No significant “new” structure seen in the high multiplicity events.

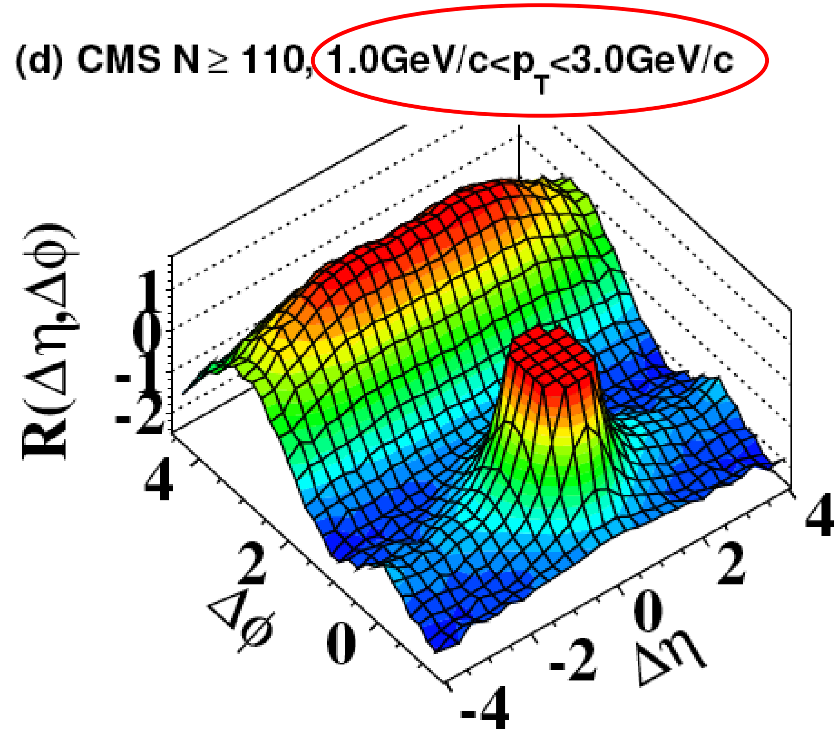
Results for Particles with 1.0 < P_T < 3 GeV

CMS-QCD-10-002, J. High Energy Phys. 09 (2010) 091

MinBias



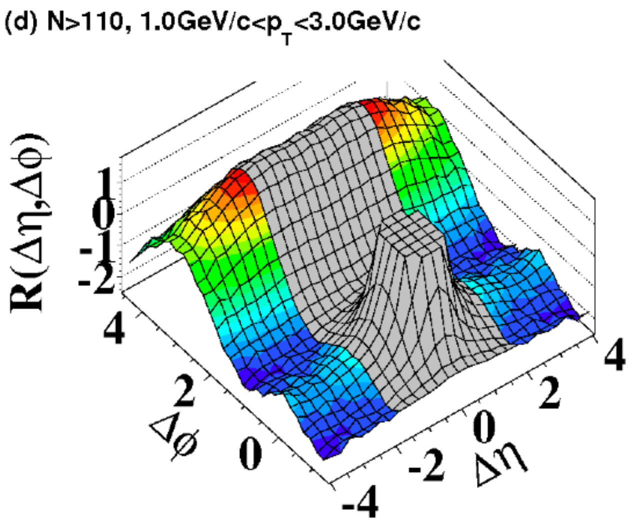
High Multiplicity (N>110)



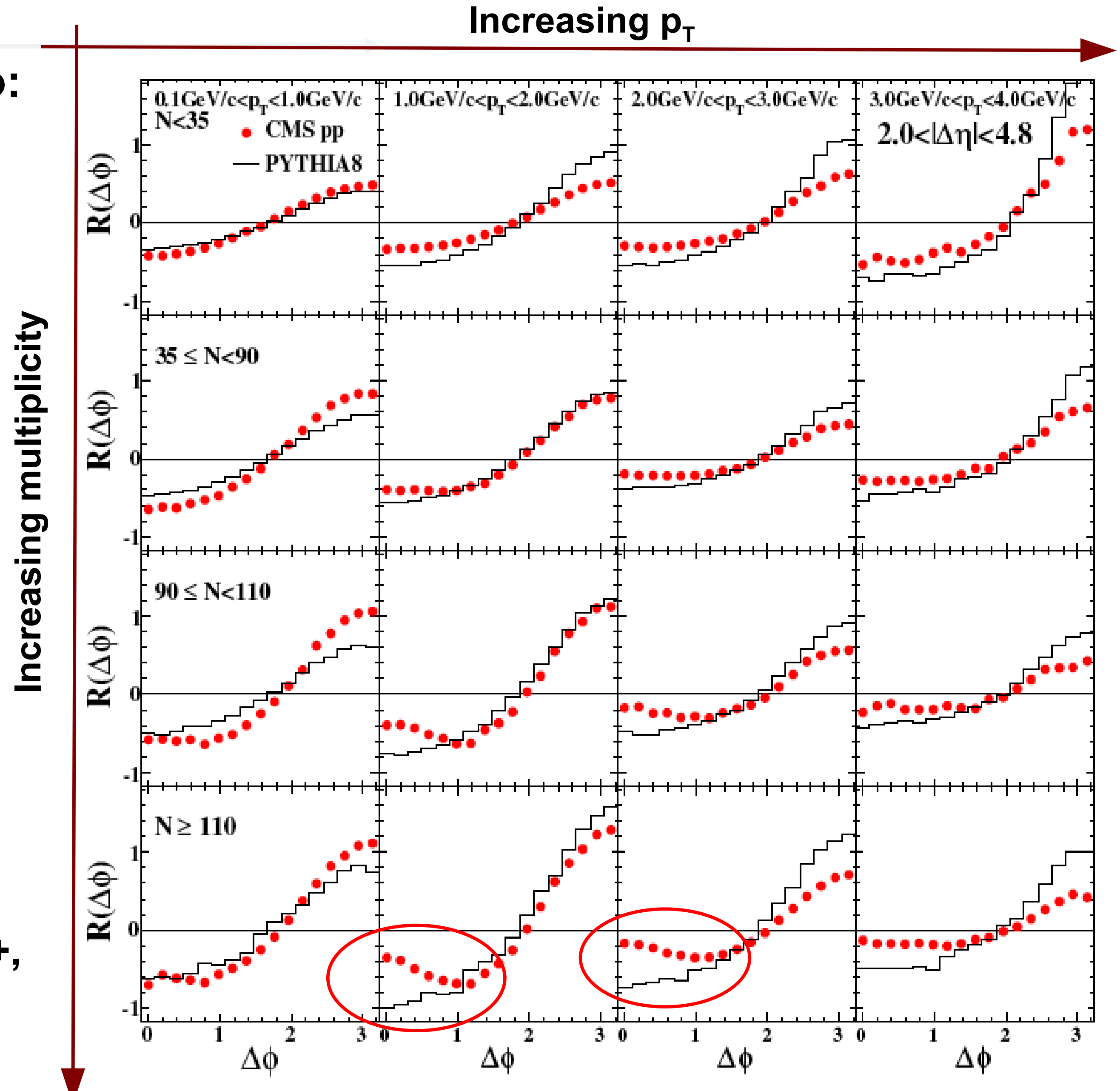
- **Limiting pt of particles to 1<p_T<3 GeV.**
  - **gives a stronger correlation between the away region and the jet region in both MB and high multiplicity events.**
  - **gives a pronounced structure at large Δη around ΔΦ=0 in the high multiplicity events.**

Differentially in bins of p_T and N

Project 2 < |Δη| < 4.8 onto Δφ:

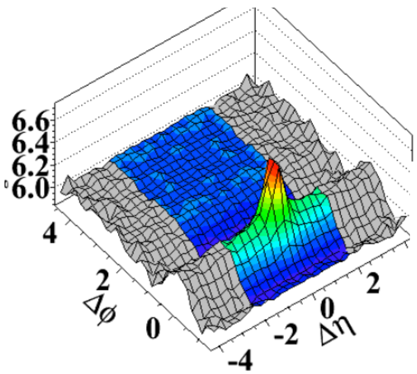


- **Ridge most pronounced for high multiplicity events and at 1 < p_T < 3 GeV.**
- **No ridge seen in Pythia 8. (Also not in Pythia6, Herwig++, and Madgraph.)**

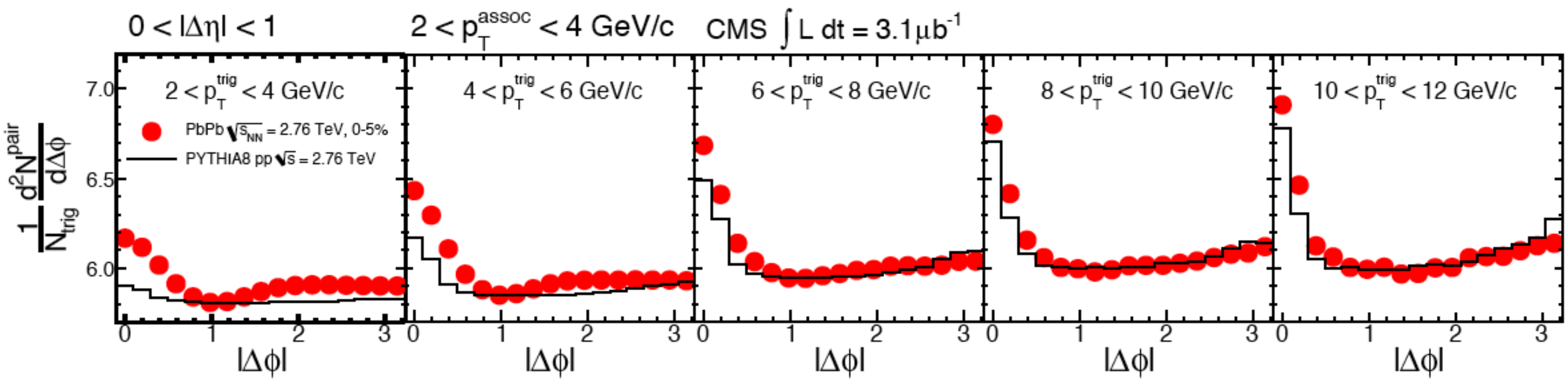


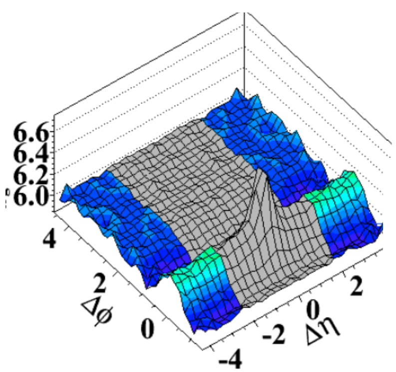
Ridge in Heavy Ion collsions.

CMS-HIN-11-001, arXiv:1105.2438

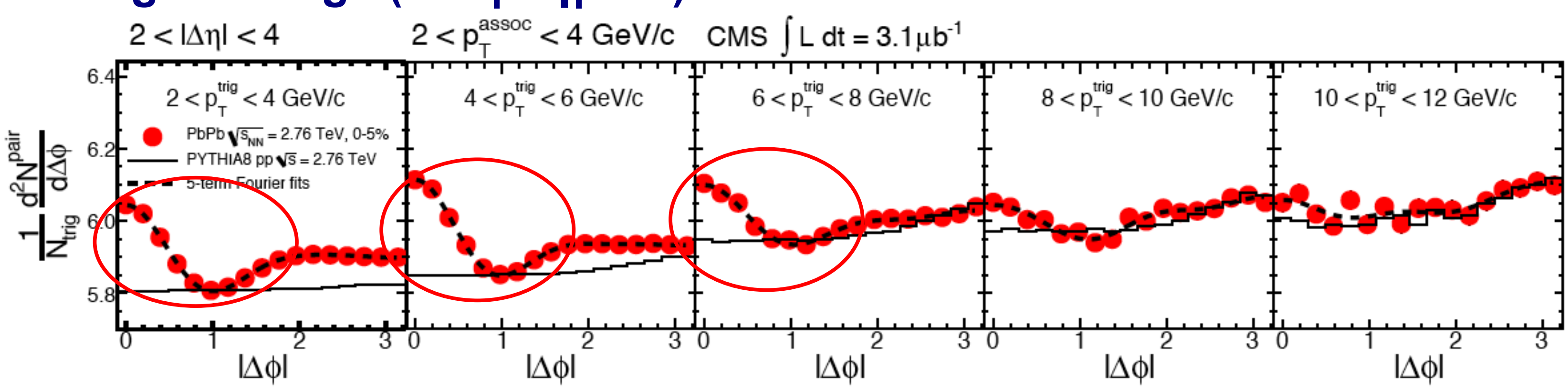


Short range (0 < |Δη| < 1)





Long eta range (2 < |Δη| < 4)



- **"The Ridge" significant in the long range correlations.**
- **At low p_T – large deviation between MC and data. (No ridge in MC.)**

Summary

- A wide range of soft QCD data presented.
  - Inclusive particle spectra.
  - Traditional UE measurement.
  - Forward energy flow.
  - The Ridge in *pp* and *PbPb*.

- Common for several of the presented measurements:
  - Measured quantities depends strongly on center-of-mass energy, and the QCD scale in the event.
  - Sensitivity to UE tunes and models.
  - Data described by MC generators, but inconsistencies:
    No single MC generator or tune describes all measurements, depending on energies and event types (e.g. MB or dijets)

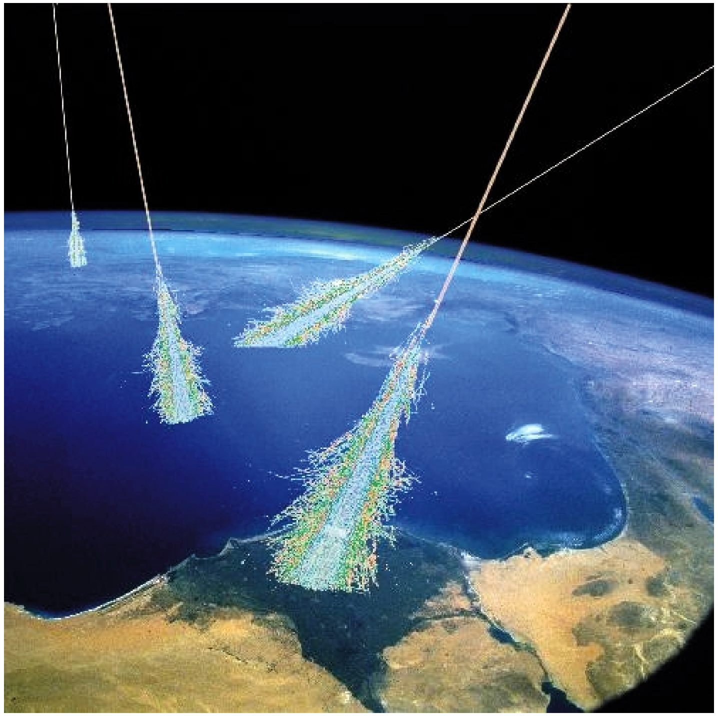
- Energy dependencies not completely understood.

- High sensitivity to models and tunes → Data usable for increased understanding.

- 2 particle correlations. "The ridge" seen in both pp and PbPb.
  Unexcpected effect in pp – first turn-up in LHC data.

BACK UPS

MC Event Generators 2/2



Cosmic Ray MC generators

- **QGSJET**
- **SIBYLL**
- **EPOS**

Originally made for cosmic ray – of which 90% are protons – interactions with the atmosphere. (Air shower models.)

Forward particle production important in air shower models – majority of the energy carried by the forward particles.

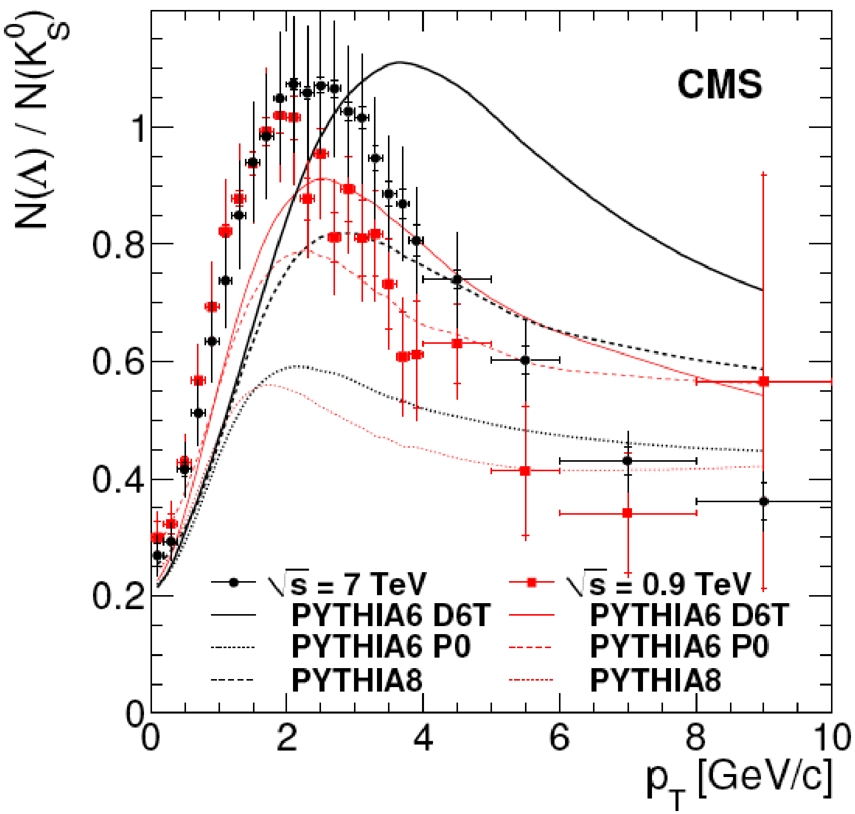
MC generators QGSJET, SIBYLL and EPOS are based on Regge theory.

Interactions described as multiple Pomeron exchanges, but include also DGLAP parton ladders.

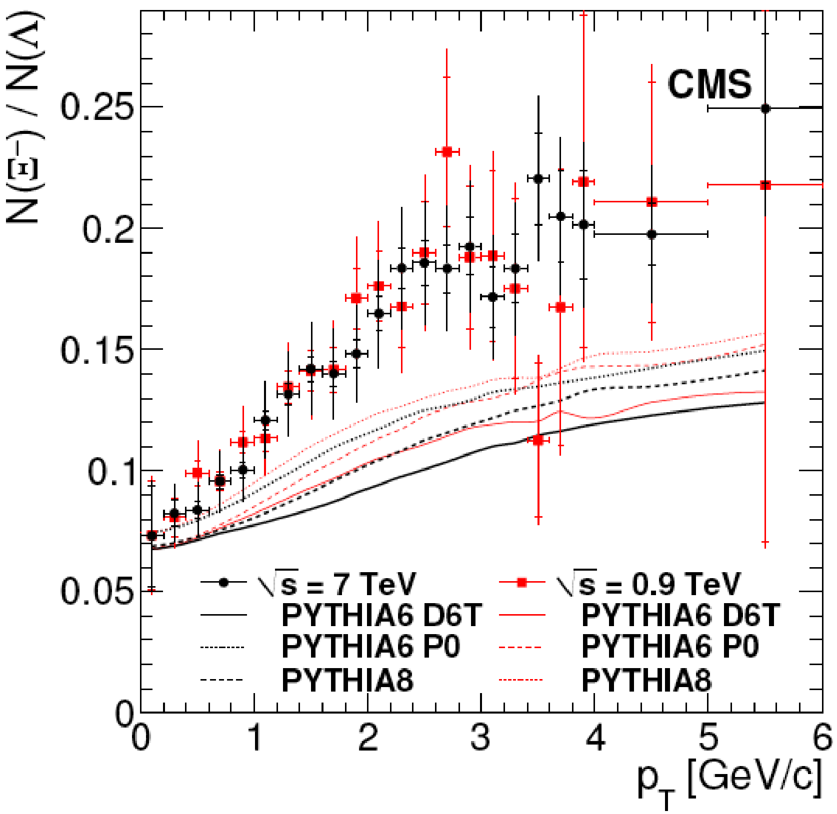
Strangeness production

Particle multiplicities in Non Single Diffractive (NSD) events.

Ratio: N(Lambda) / N(K0S)



Ratio: N(Sigma) / N(Lambda)

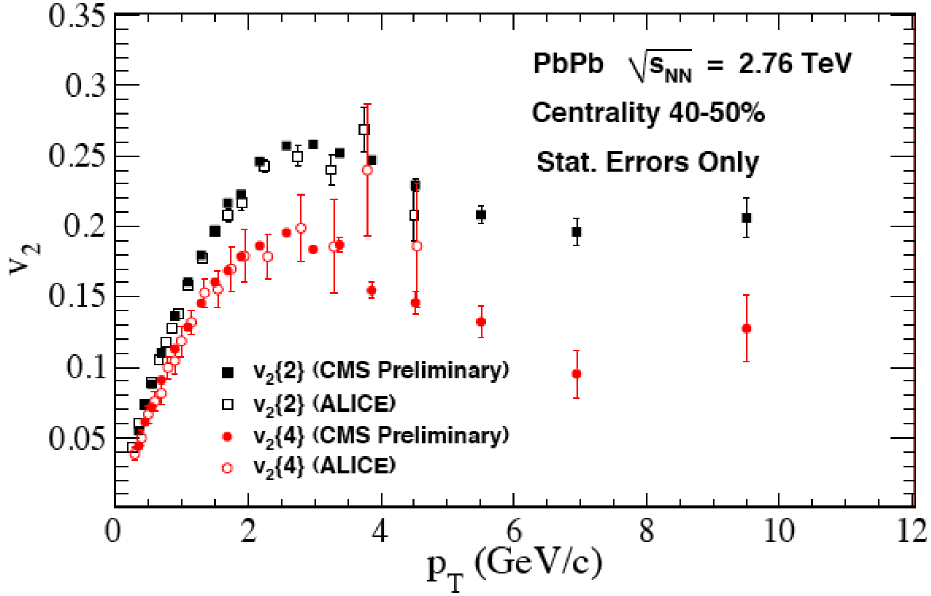


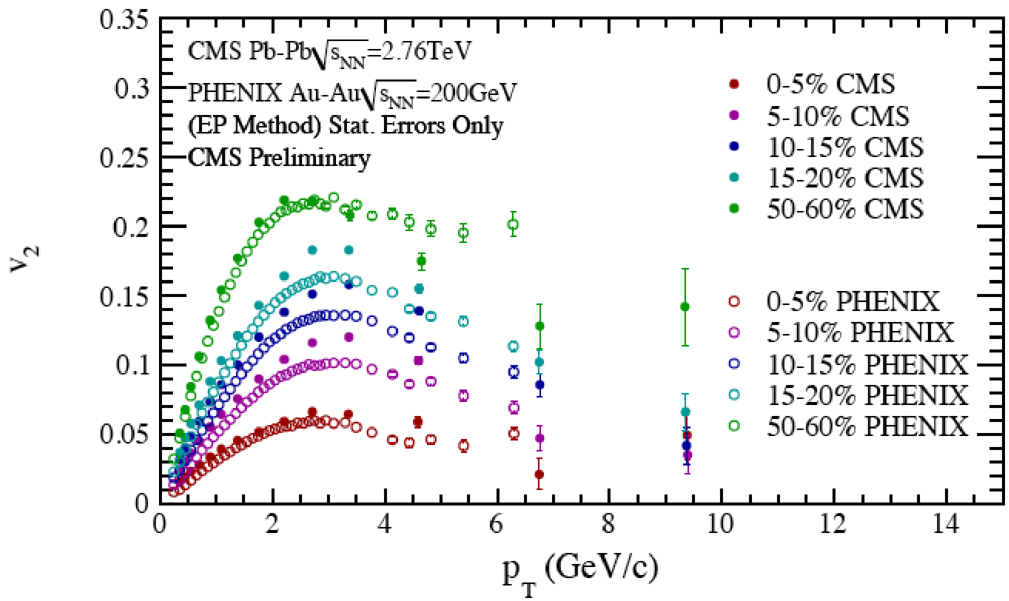
- **Strangeness production not described by considered MC**
- **Use CMS strangeness data to improve of MC parameters, see e.g. Rick Fields talk at BOOST 2011, Princeton.**

HIN-10-002

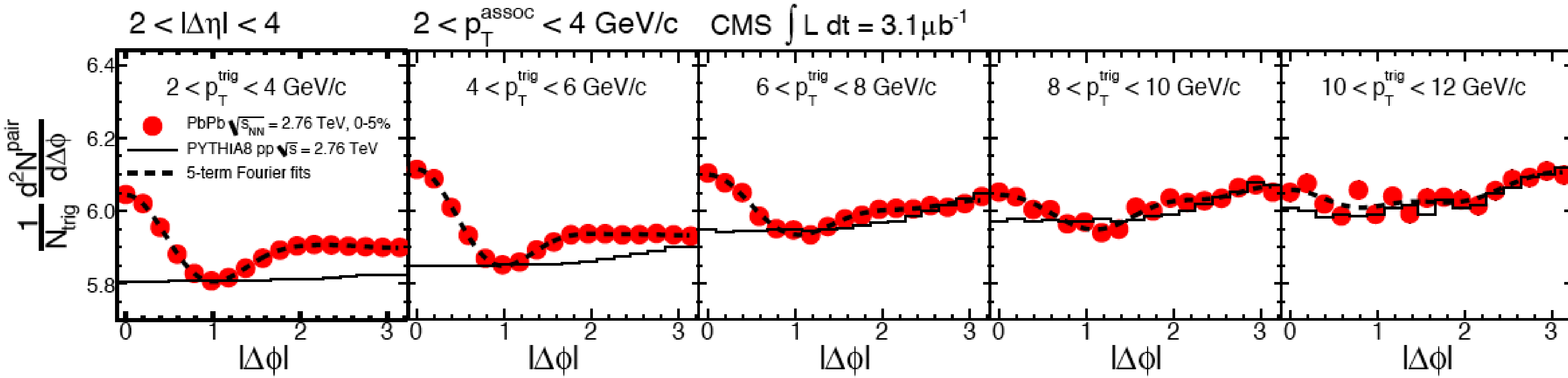
Elliptic flow.

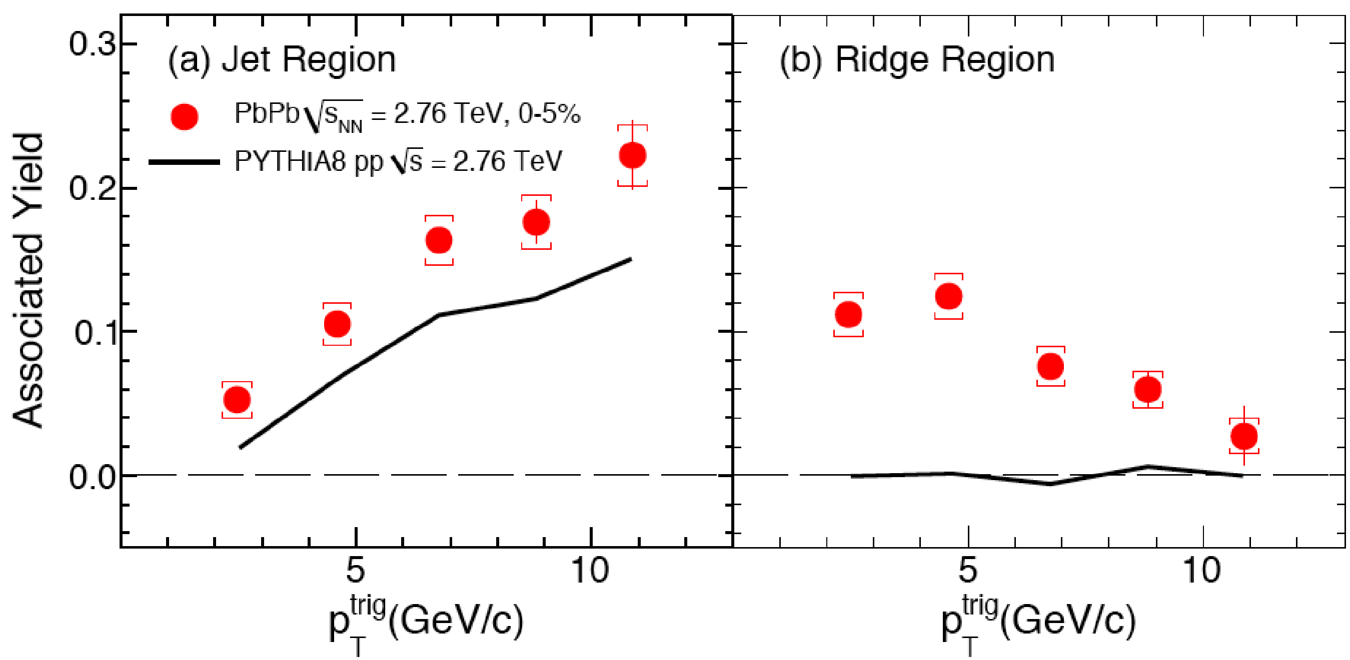
Anisotropy parameter: v2



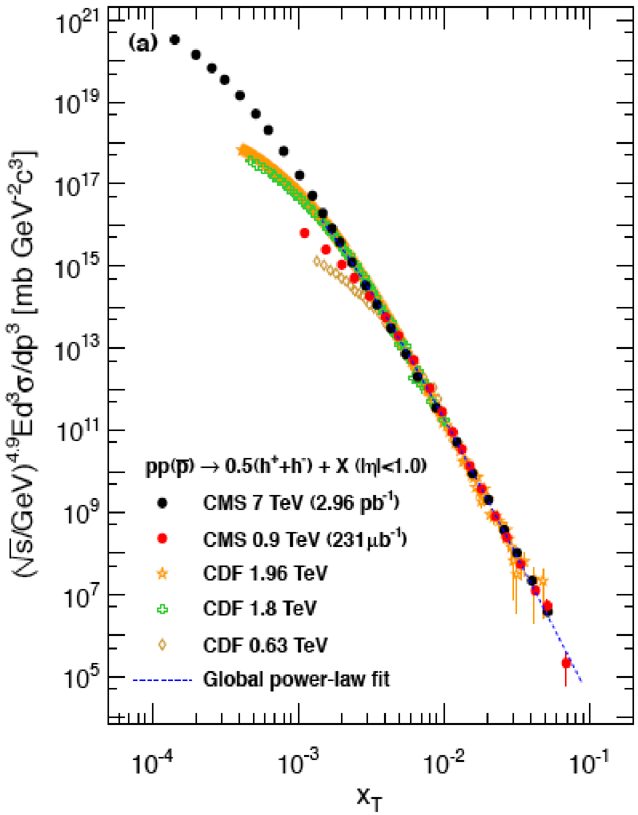


Long range


2 < |Δη| < 4
2 < p_T^assoc < 4 GeV/c
CMS ∫L dt = 3.1μb^-1
2 < p_T^trig < 4 GeV/c
4 < p_T^trig < 6 GeV/c
6 < p_T^trig < 8 GeV/c
8 < p_T^trig < 10 GeV/c
10 < p_T^trig < 12 GeV/c
PbPb √s_NN = 2.76 TeV, 0-5%
PYTHIA8 pp √s = 2.76 TeV
5-term Fourier fits
1/N_trig d²N^pair/dΔφ
|Δφ|


(a) Jet Region
(b) Ridge Region
PbPb √s_NN = 2.76 TeV, 0-5%
PYTHIA8 pp √s = 2.76 TeV
Associated Yield
p_T^trig(GeV/c)

$x_T=2p_T/\sqrt{s}$



CMS-QCD-10-008