Soft QCD Results from CMS

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for the CMS collaboration

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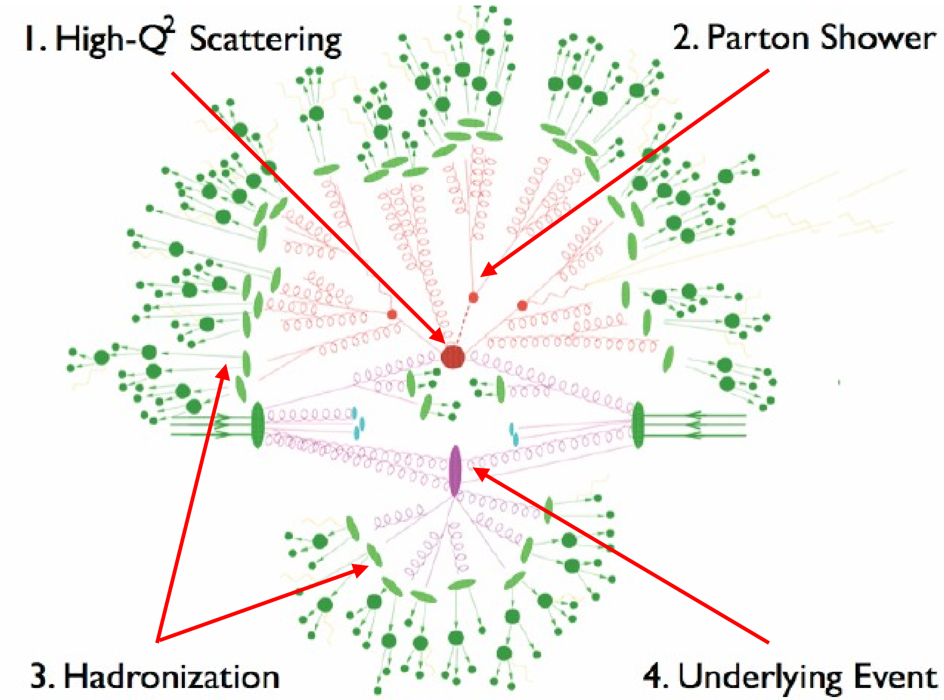
Outline

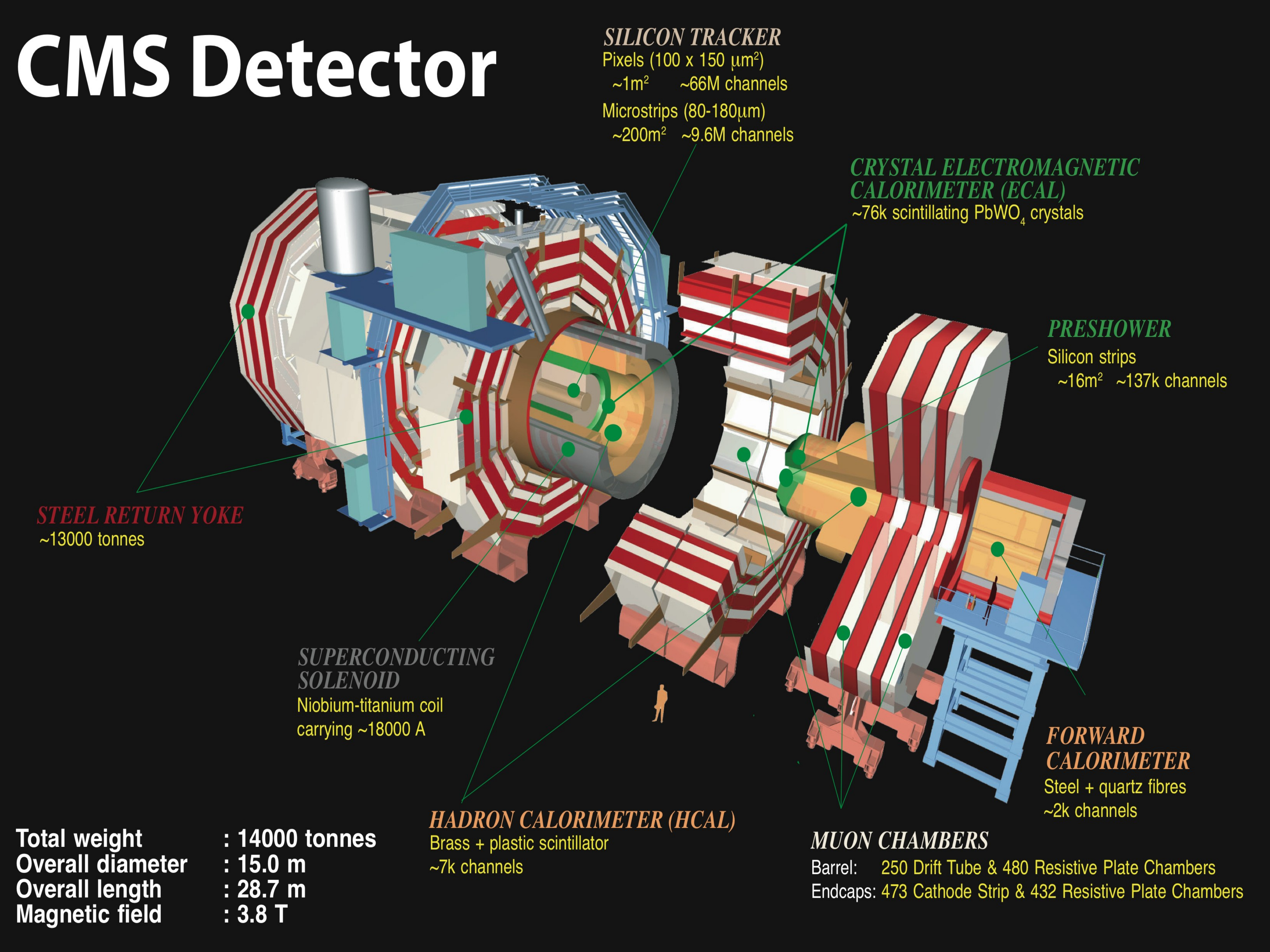
- Introduction
- Properties of Minimum Bias Events
  - Transverse momentum spectra and event-by-event multiplicity distributions of charged particles
  - Strangeness production and strange hadron spectra
- Particle Correlations
  - Short-range and long-range angular correlations in pp events at 0.9 and 7 TeV
  - Bose-Einstein Correlations measured at 0.9 and 7 TeV
- Underlying Events Measurements and MC Tunes
- Summary

Soft interactions at LHC

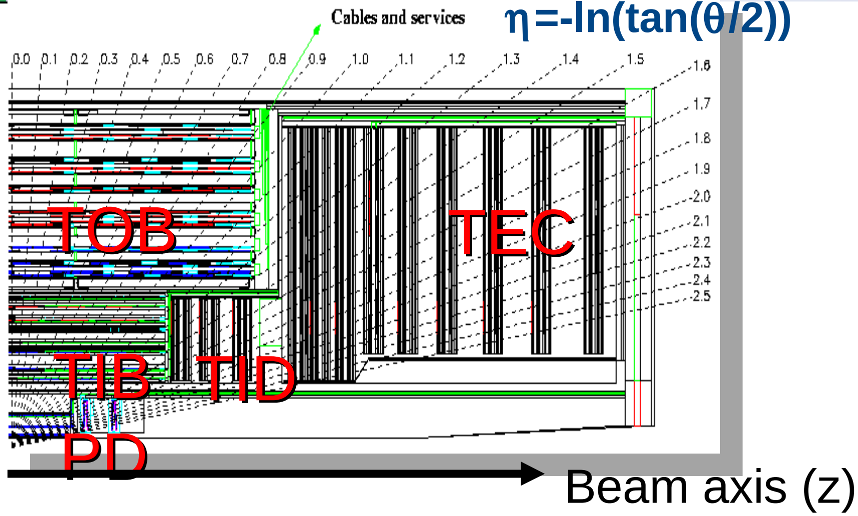
- **Collisions at LHC**
  - the majority of the pp collisions are soft, without hard parton scattering
  - no "perturbative" predictions, need to model them phenomenologically
  - Usually rely on Monte-Carlo (MC) description
- **Early LHC data provide a unique chance to deepen the knowledge on soft QCD**
  - PS, UE and hadronization models were tuned on previous data. Different models diverge at high energy predictions
- **Will provide reference for high energy pp collisions and heavy ion physics**



Understanding of soft QCD contributions is crucial for new physics searches and precision measurements of Standard Model processes

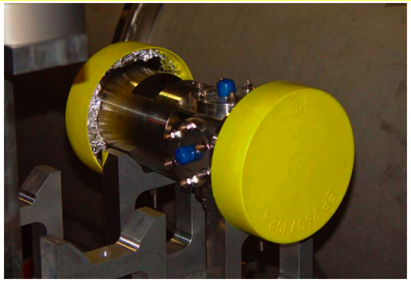

CMS Detector
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating PbWO₄ crystals
PRESHOWER
Silicon strips
~16m² ~137k channels
STEEL RETURN YOKE
~13000 tonnes
SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A
FORWARD CALORIMETER
Steel + quartz fibres
~2k channels
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels
MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 473 Cathode Strip & 432 Resistive Plate Chambers
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

Key detector components for soft QCD measurements



Beam Pickup Timing for experiments (BPTX)

z = ±175 m, time resolution 0.2 ns

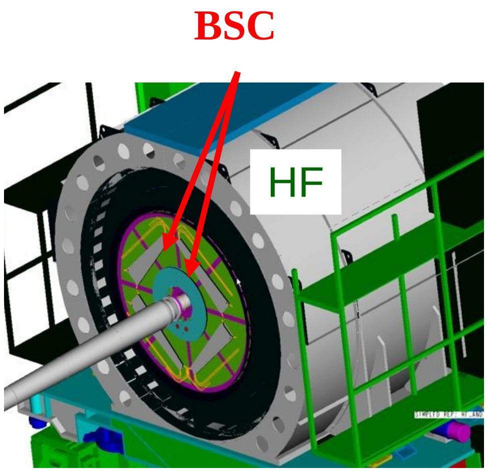


Silicon Tracker System:

- Strips: 9.3M channels; Pixels: 66M channels. > 98% operational
- Extremely high granularity and resolution
- Coverage over |η| < 2.5

Beam Scintillator Counters (BSC)

z = ±10.86 m, 3.23 < |η| < 4.65, time resolution: 3ns

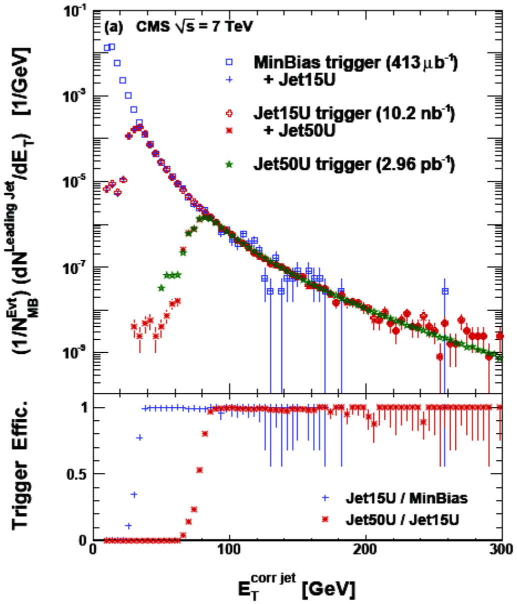


– Pixels
- » 3 barrel layers (r = 4, 7, 11 cm)
- » 2 × 2 endcap disks
- » ~ 1 m^2 Si sensor

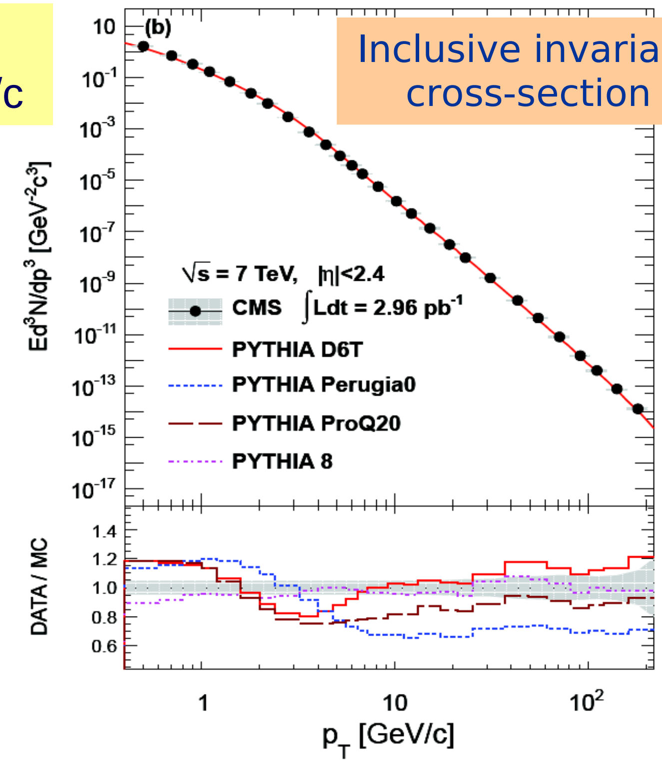
- Strips
- » 10 barrel layers
- » 9 + 3 × 2 endcap disks
- » 200 m^2 Si sensor

Transverse momentum spectra

MinBias p_T reach extended by jet triggers to ~100 GeV/c

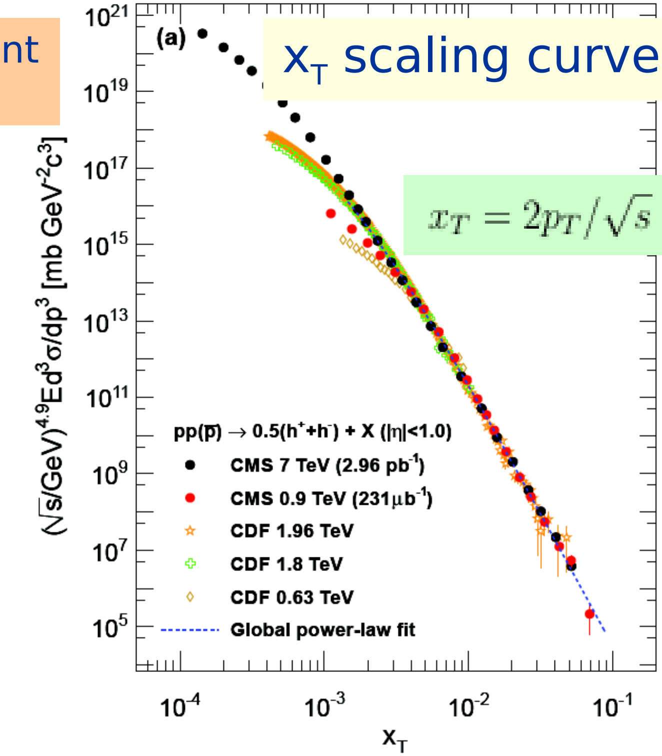


Inclusive invariant cross-section



x_T scaling curve

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



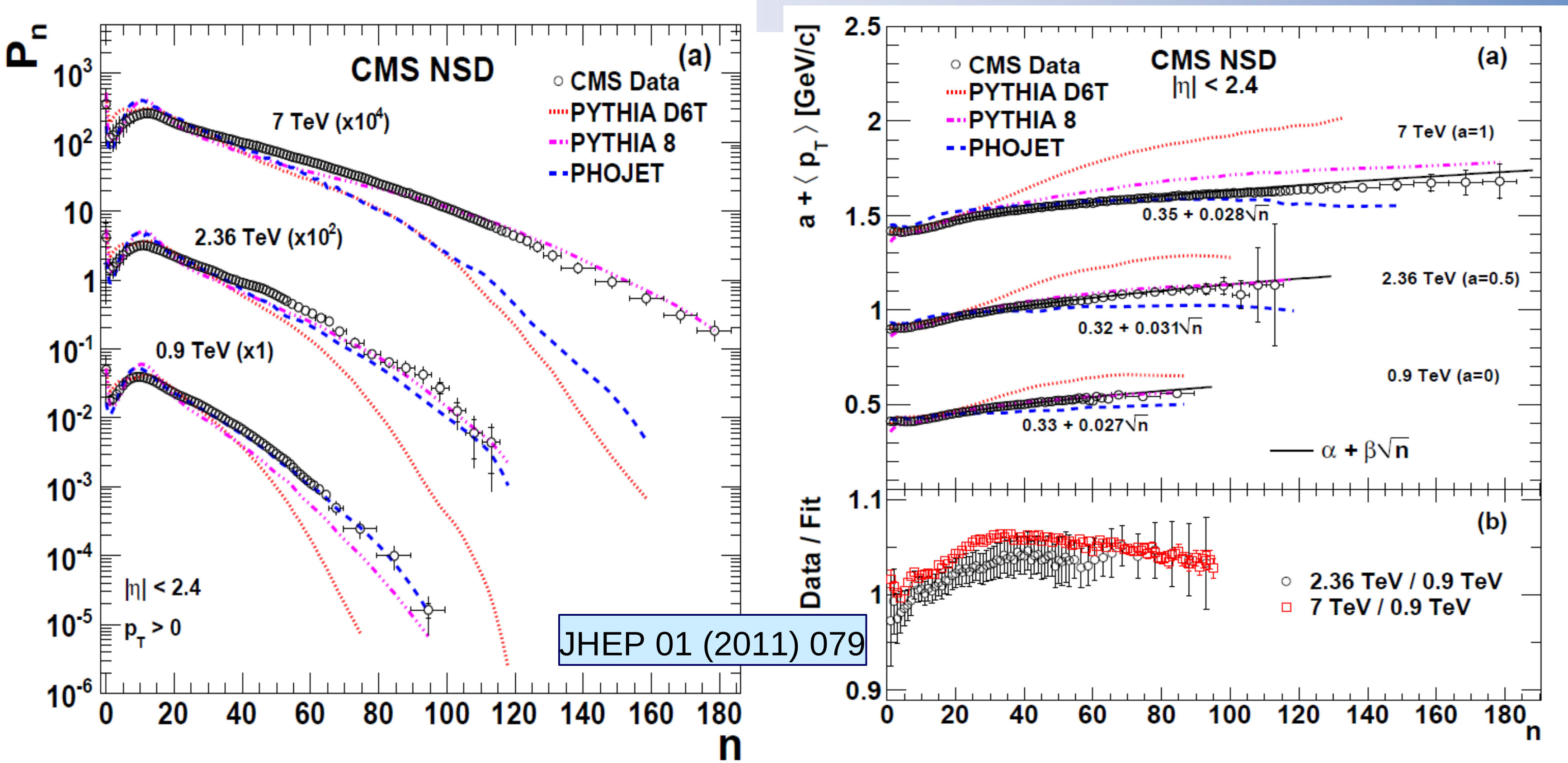
$$E\frac{d^3\sigma}{dp^3} = F(x_T)/p_T^{n(x_T,\sqrt{s})} = F'(x_T)/\sqrt{s}^{n(x_T,\sqrt{s})}$$

CMS QCD-10-008
arXiv:1104.3547

- Results at 7 TeV most compatible with PYTHIA 8 while PYTHIA 6 is worse
- Empirical $x_T = 2\ p_T\ /\ \sqrt{s}$ unifies the differential cross sections from a wide range of collision energies onto a common curve at high x_T

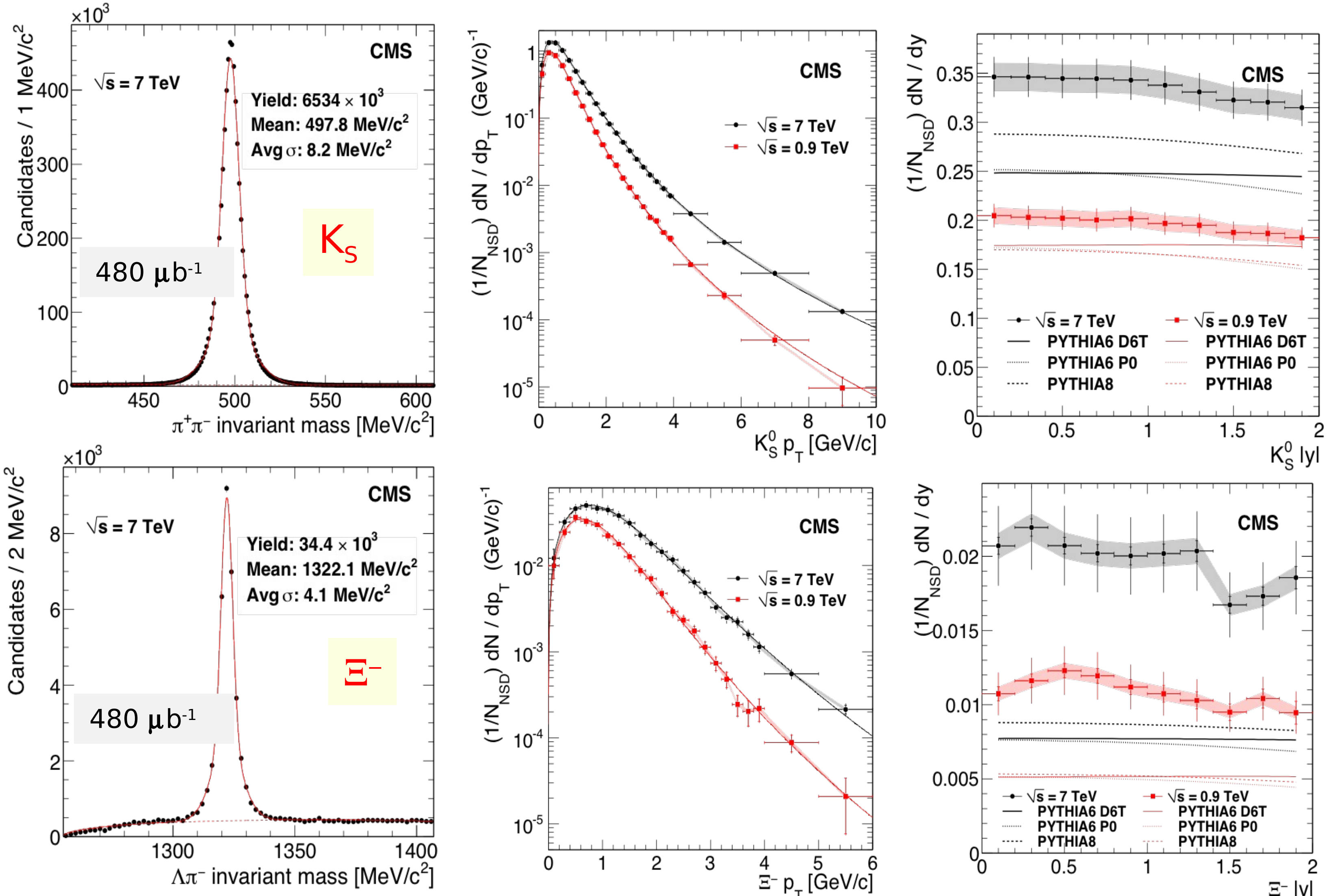
  → Interpolated (x_T and p_T scaling) data provides a reference for PbPb studies of nuclear modification factors at LHC for $\sqrt{s_{NN}}$=2.76 TeV

Charged particle multiplicities



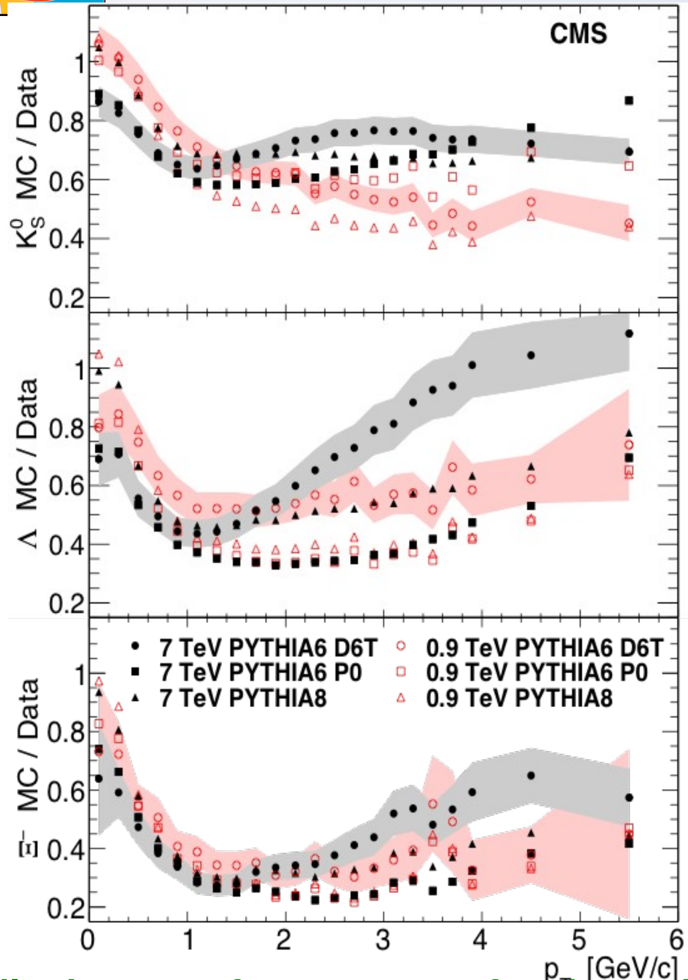
- Large multiplicity tail observed at 7 TeV (cf. $dN/d\eta$)
- $\langle p_T \rangle$ vs n scale with energy
- No Monte Carlo is able to describe all multiplicities at all energies (but PYTHIA 8 better)
- Most MC/tunes can not describe simultaneously the multiplicity and the pT dependence (PYTHIA 8 better)

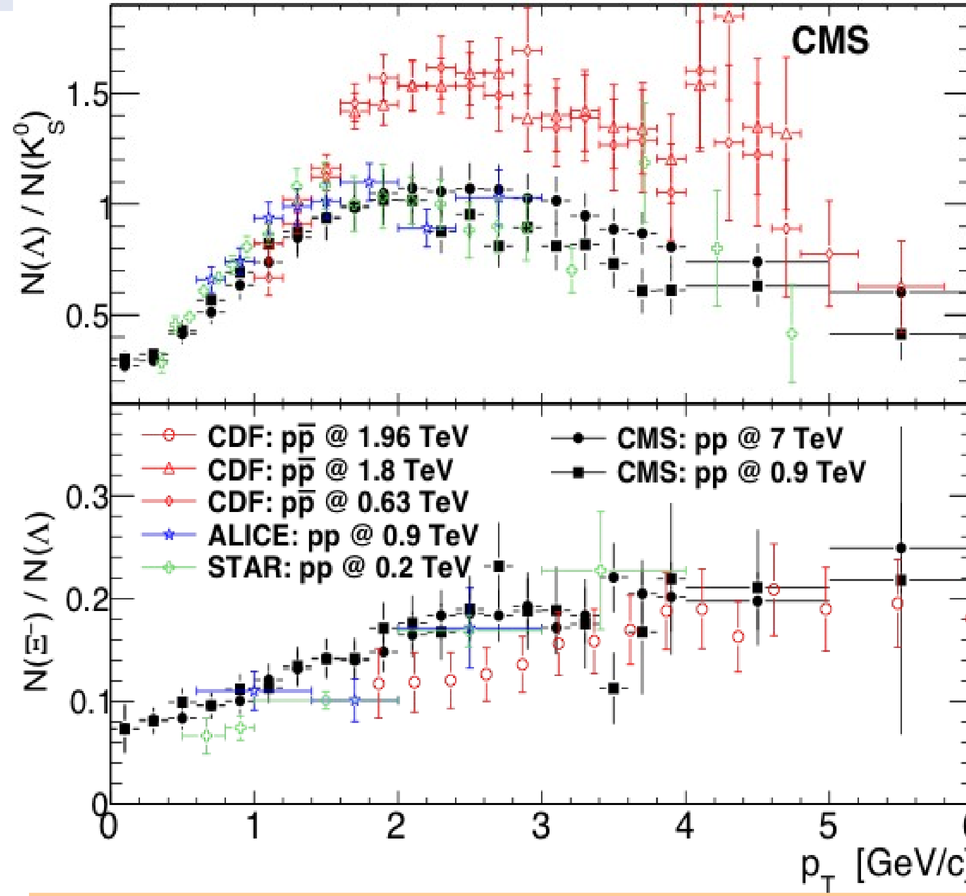
Strangeness production (K_s, Λ, Ξ)



JHEP 05(2011) 064

Strangeness production(II)





N stays approximately constant for both centre-of-mass energies.

Similar increase for strange as for charged particle with energy

→ PYTHIA fails again to match this increase !

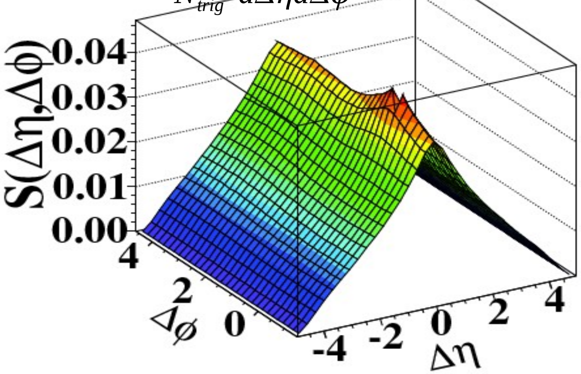
Discrepancy larger for Ξ^- at both energy and up to factor 3 at 7 TeV.

JHEP 05(2011) 064

Two-particle correlation in Δη and Δϕ

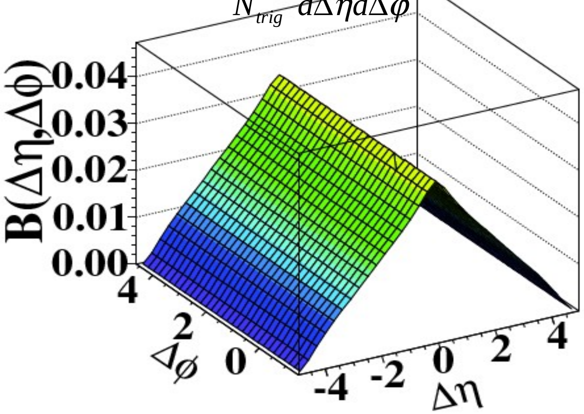
Signal distribution
= Correlated and uncorrelated pairs
from same event

$$S(\Delta\eta,\Delta\varphi)=\frac{1}{N_{trig}}\frac{d^2N^{same}}{d\Delta\eta d\Delta\varphi}$$



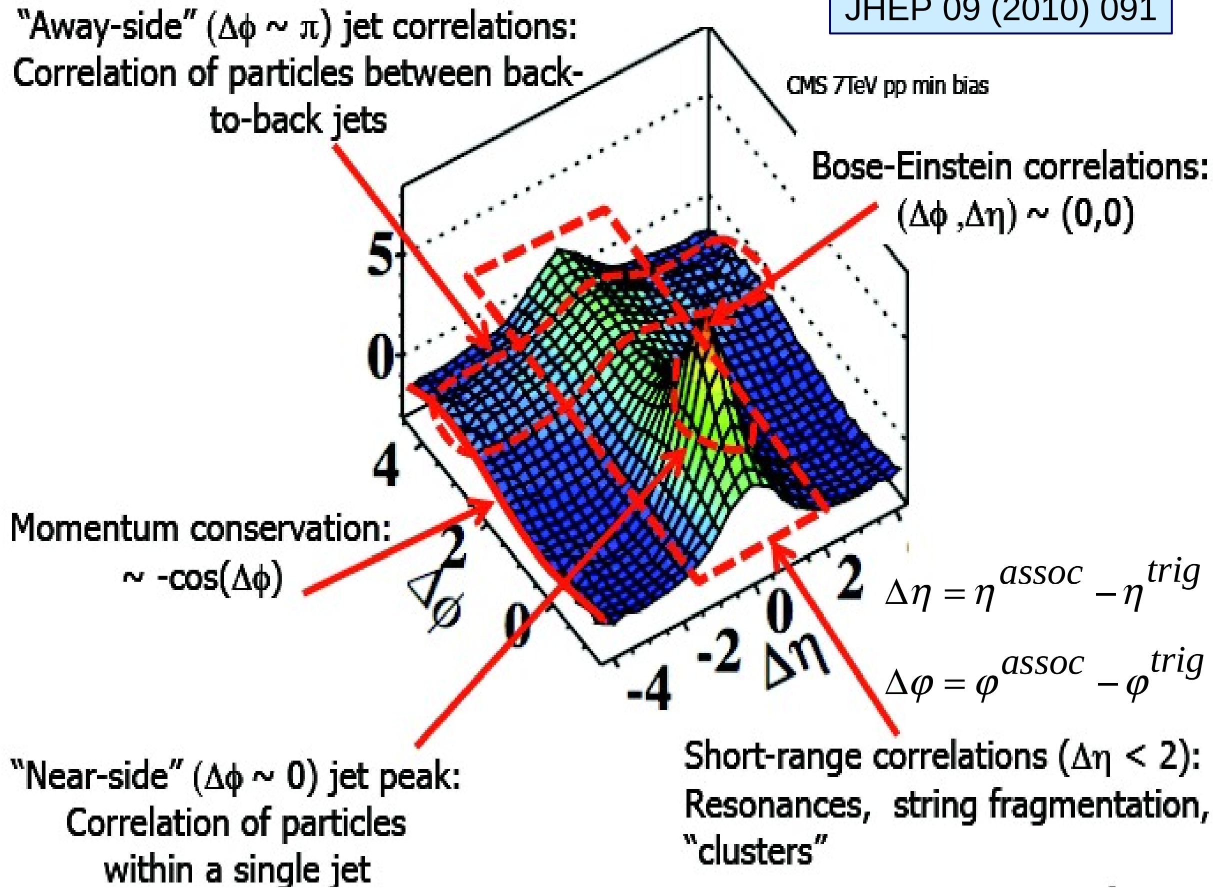
Background distribution
= Uncorrelated pairs
from mixing 2 events

$$B(\Delta\eta,\Delta\varphi)=\frac{1}{N_{trig}}\frac{d^2N^{mix}}{d\Delta\eta d\Delta\varphi}$$



MinBias, p_T > 0.1 GeV/c), 7 TeV

JHEP 09 (2010) 091



$$\Delta\eta=\eta^{assoc}-\eta^{trig}$$

$$\Delta\varphi=\varphi^{assoc}-\varphi^{trig}$$

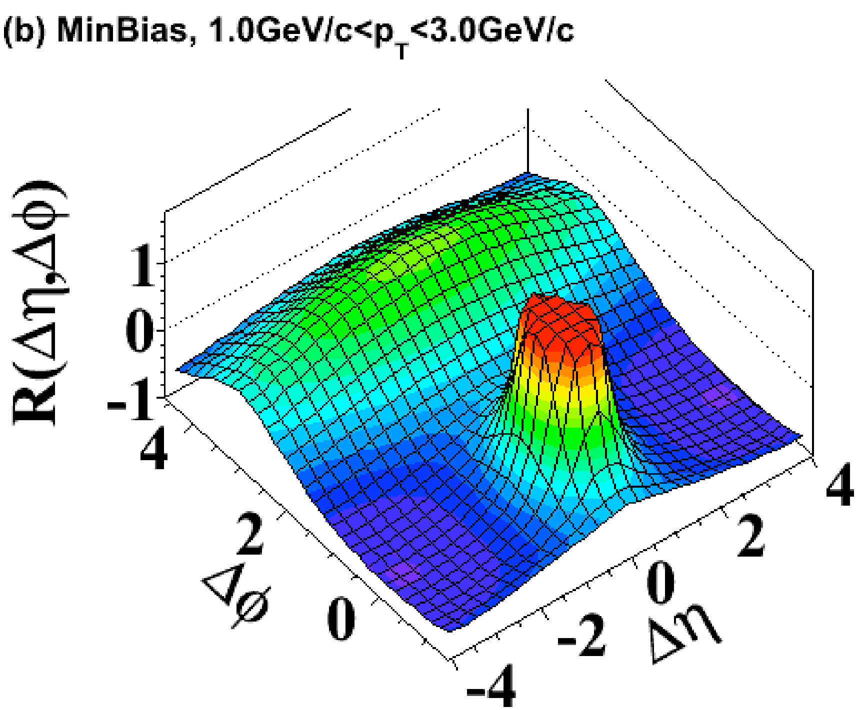
$$R(\Delta\eta,\Delta\phi)=\left\langle\left(\langle N\rangle-1\right)\left(\frac{S_N(\Delta\eta,\Delta\phi)}{B_N(\Delta\eta,\Delta\phi)}-1\right)\right\rangle_{bins}$$

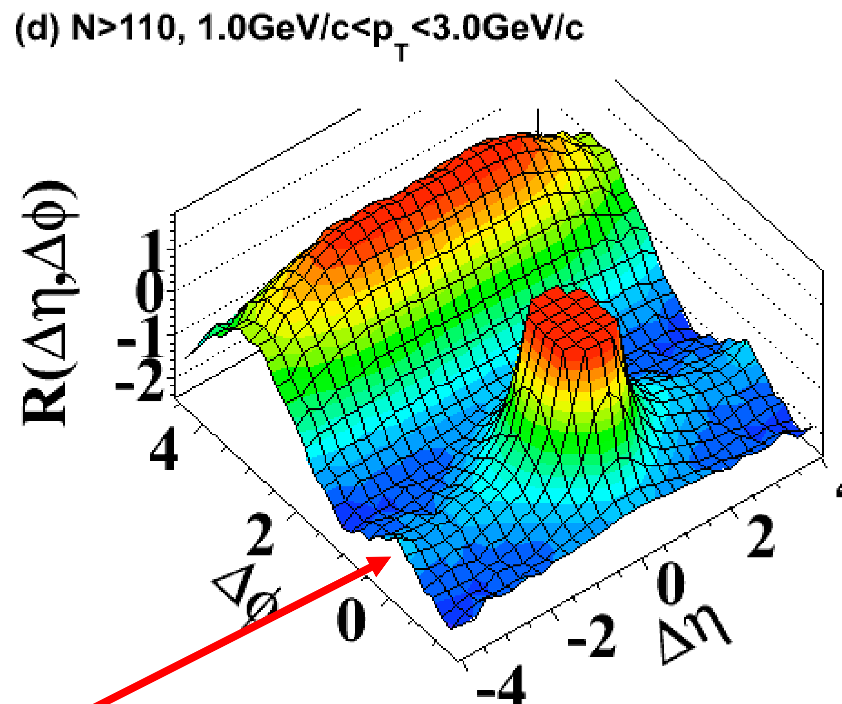
High multiplicity results at √s = 7 TeV

JHEP 09 (2010) 091

Intermediate pT : $1 < p_T < 3$ GeV/c

MinBias | **High Multiplicity: N>110**





→ **Near-Side angular correlations at high multiplicity at intermediate p_T**

… not from short range correlations (resonances, near-side jet peaks, away side correlations of particles between back-to-back jets or Bose-Einstein correlations)

… not reproduced in PYTHIA 8 (and PYTHIA 6, HERWIG++, madgraph)

The first surprise in LHC data, new testing ground for high density QCD physics!

Bose-Einstein correlations(I)

When wave-function of identical bosons overlaps, Bose-Einstein statistic changes their dynamics

→ Production probability enhancement for identical light boson with similar momenta.

→ BEC measurements give information about size, shape and space-time development of emitting source

PRL 105 (2010) 032001
JHEP 05 (2011) 029

Observable: $$R = \frac{P(p_1, p_2)}{P(p_1)P(p_2)}$$

$P(p_1,p_2)$: Joint probability of emission of a pair of bosons

$P(p_1), P(p_2)$: Individual probability of emission

→ Need to define a reference sample of non interfering boson pairs !

$$\rightarrow R(Q) = \frac{dN/dQ}{dN/dQ_{ref}}$$

Assuming particle are mostly pions

$$Q = \sqrt{-\left(p_1 - p_2\right)^2} = \sqrt{M_{inv}^2 - 4m_\pi^2}$$

Parametrization: $$R(Q) = C[1 + \lambda\Omega(Qr)](1 + \delta Q)$$

$\Omega(Qr)$: Fourier transform of emission region of effective size r

λ : BEC strength

δ : Long distance correlations

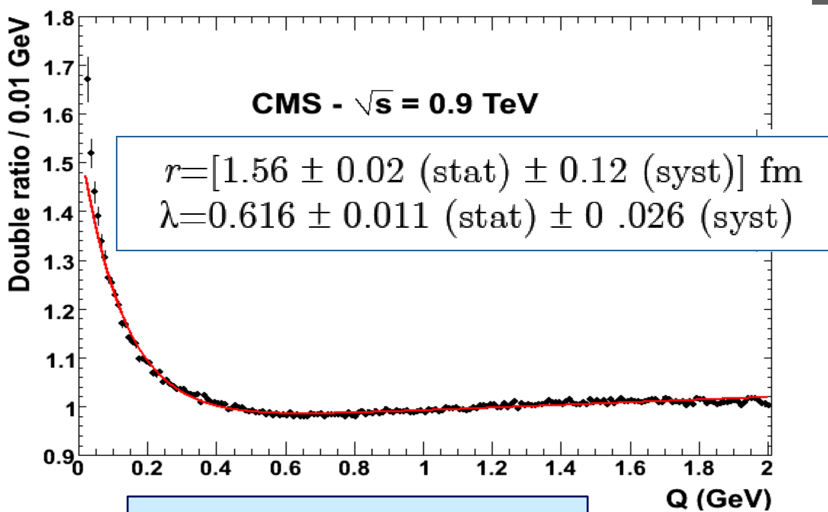
Bose-Einstein correlations(II)

Pairs of same-sign charged particles with 0.02 GeV < Q < 2 GeV are studied.

Double ratio defined to reduce biases

$$\mathcal{R}(Q) = \frac{R(Q)}{R_{MC}(Q)} = \frac{\left(\dfrac{dN_{signal}/dQ}{dN_{ref}/dQ}\right)}{\left(\dfrac{dN_{MC,\,like}/dQ}{dN_{MC,\,ref}/dQ}\right)}$$

$$\Omega(Qr) = e^{-Qr}$$



r=[1.56 ± 0.02 (stat) ± 0.12 (syst)] fm
λ=0.616 ± 0.011 (stat) ± 0 .026 (syst)

→ **BEC effective emission region grows with √s while strength is similar**

PRL 105 (2010) 032001
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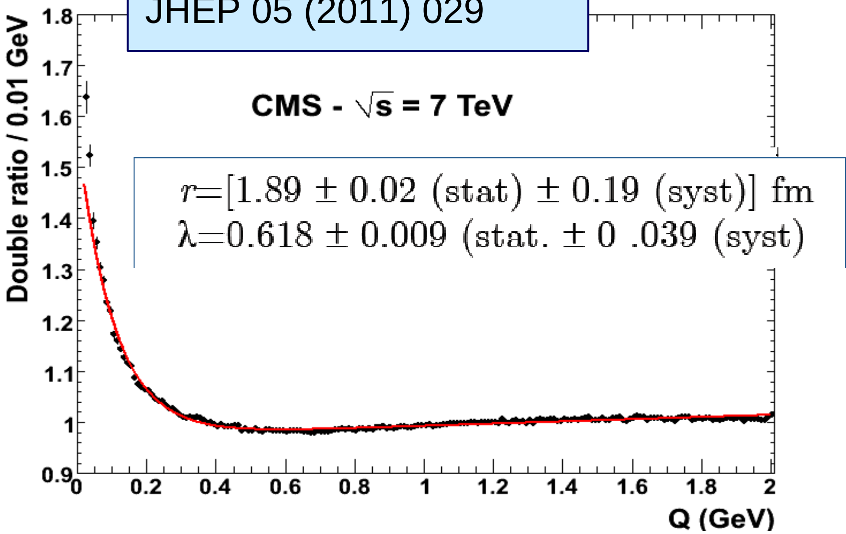
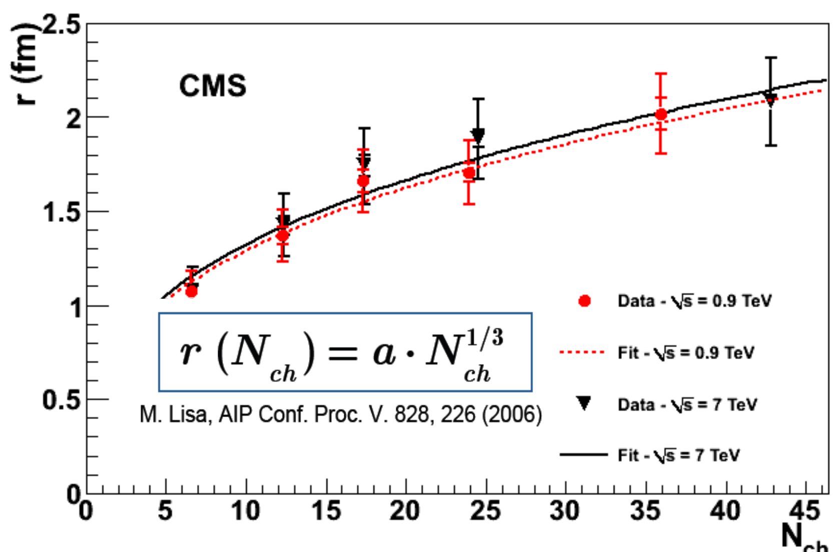


r=[1.89 ± 0.02 (stat) ± 0.19 (syst)] fm
λ=0.618 ± 0.009 (stat. ± 0 .039 (syst)



$$r\,(N_{ch}) = a \cdot N_{ch}^{1/3}$$

M. Lisa, AIP Conf. Proc. V. 828, 226 (2006)

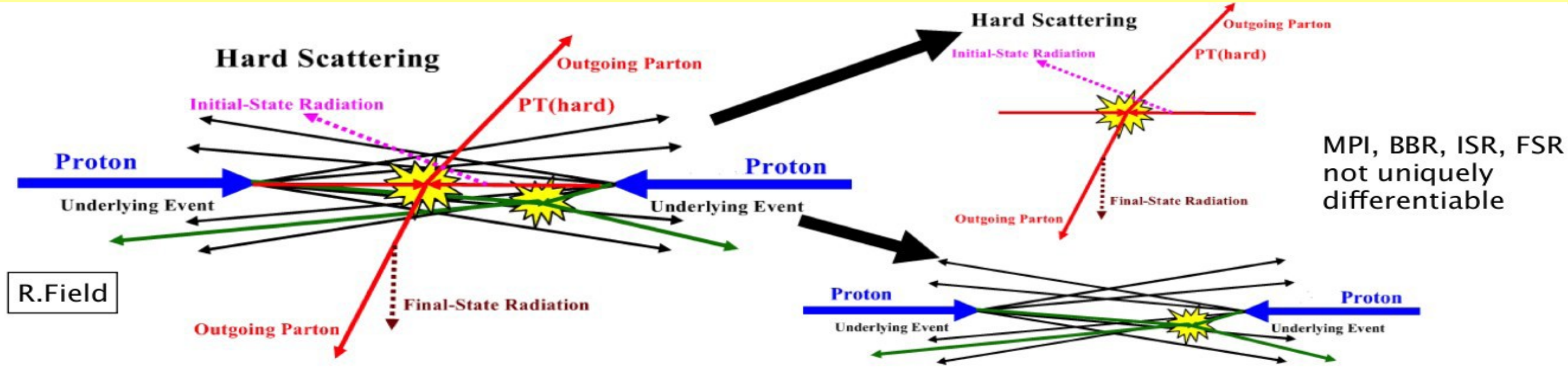
→ **BEC effective emission region grows with N as observed by previous experiments**

→ **This accounts for the grow with √s (cf. dN/dη)**

The Underlying Event

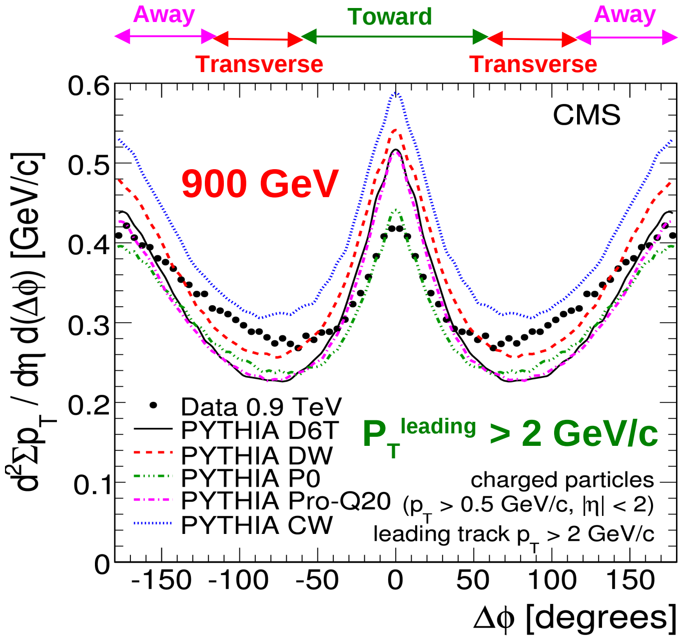
The "underlying event" is everything except the outgoing hard scattered partons

UE = beam-beam remnants + initial and final-state radiation + multiple interactions



→ UE is what we need to correct for before comparison with hard scattering predictions

→ Need to "tune" soft interactions MC model(s) to UE: previous and LHC data



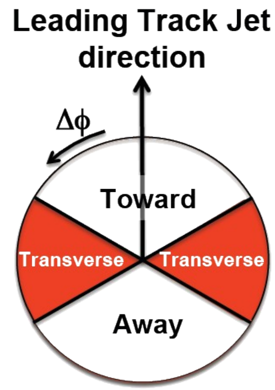
UE Observables

Activity in transverse region:

$d^2N_{ch}/d\eta d\phi$

$d^2\Sigma p_T/d\eta d\phi$

for leading track/jet topologies

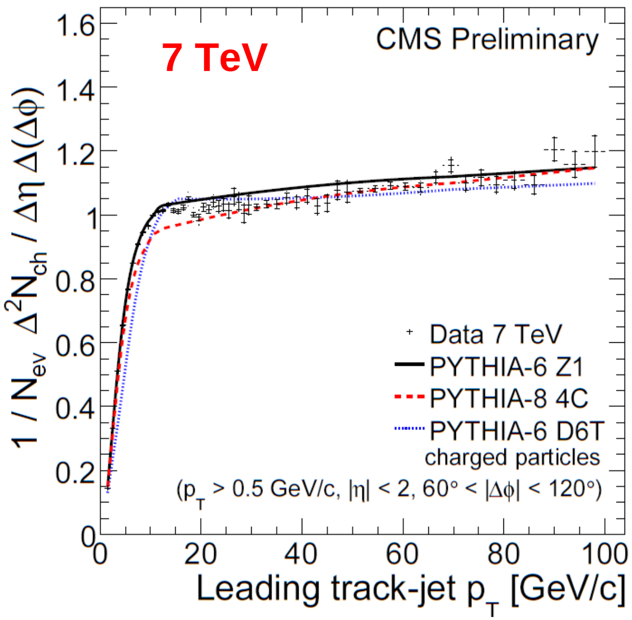


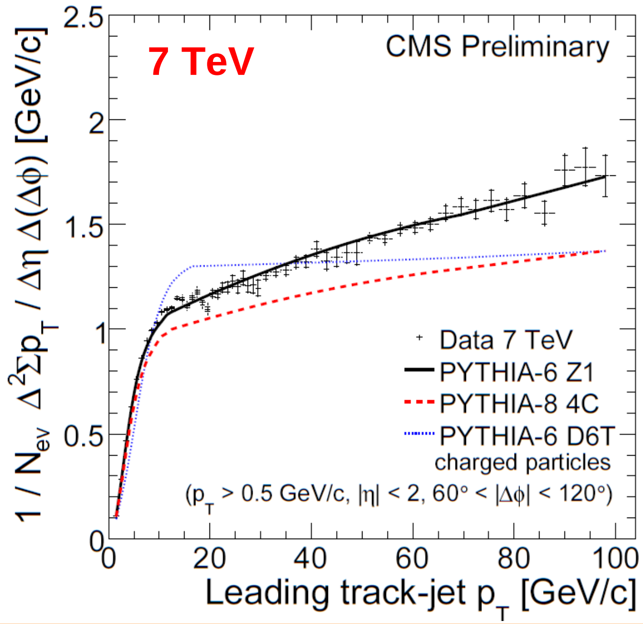
EPJ C70 (2010) 555

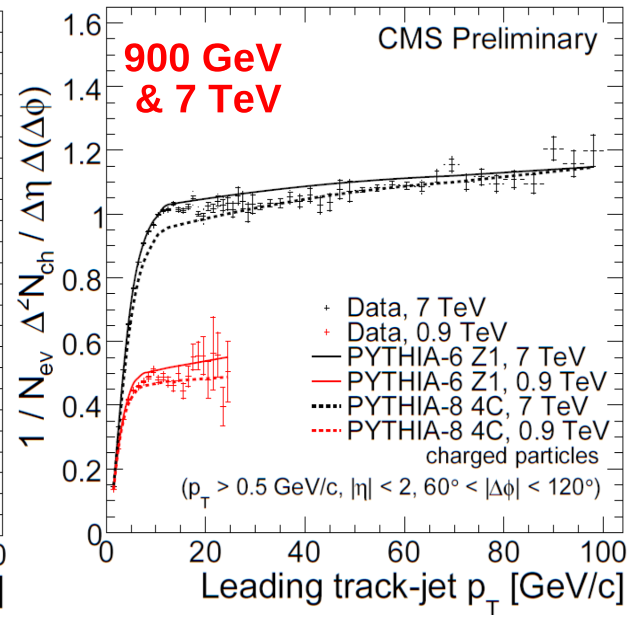
Transverse region: charge and Σp_T density

Measurement of $dN_{ch} / d\eta d(\Delta\phi)$ and $d^2\Sigma p_T / d\eta d(\Delta\phi)$ in transverse region as a function of leading track-jet PT
→ Measure activity outside jet(s) → Underlying Event

CMS QCD-10-010







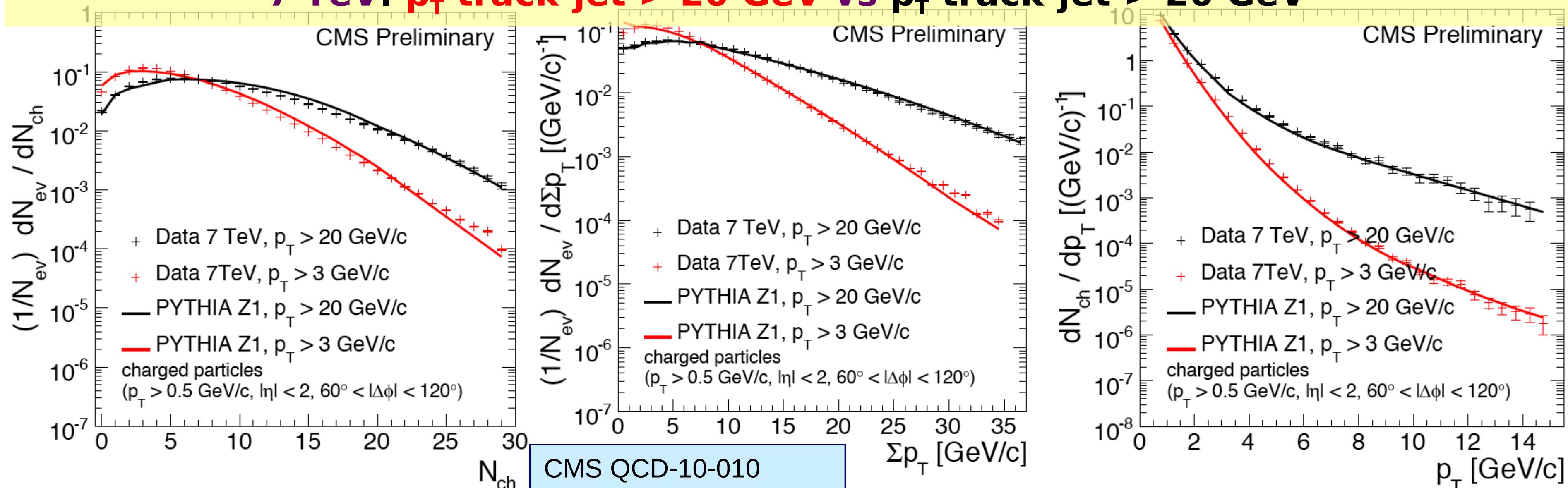
Strong growth of underlying event activity with $\sqrt{s}$. PYTHIA Z1 describes the distributions and the $\sqrt{s}$ dependence well.

Fast rise for P_T < 8 GeV/c (4 GeV/c), attributed mainly to the **increase of MPI activity**, followed by a **Plateau-like region** with ≈ constant average number of selected particles and a slow increase of ΣP_T, in a **saturation regime**.

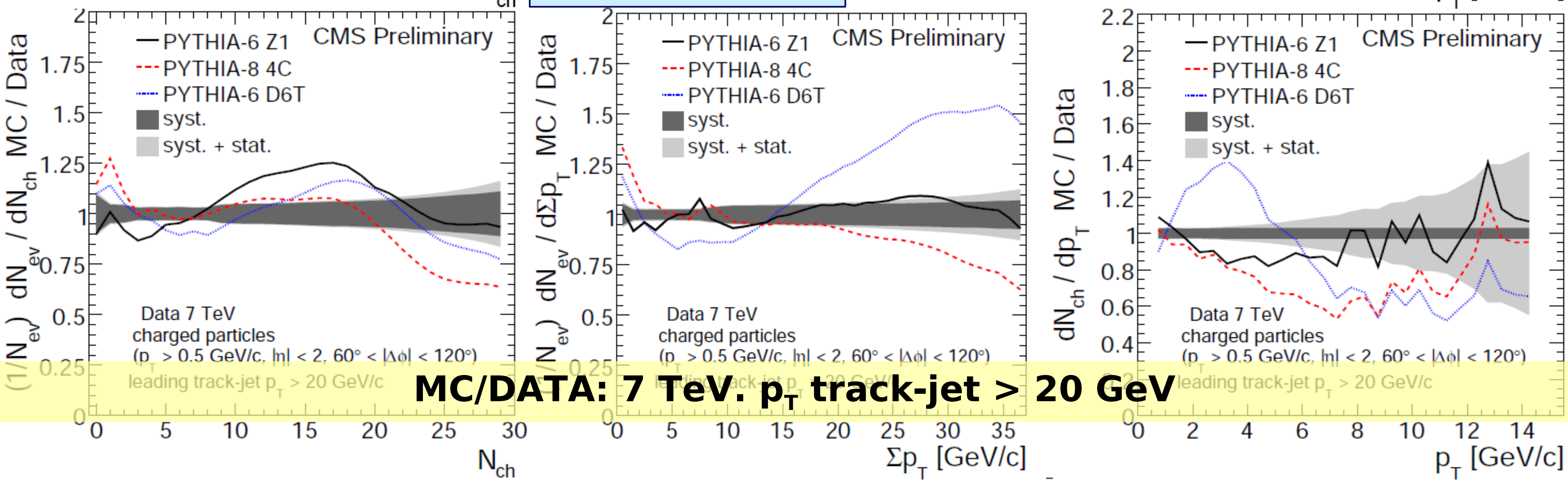
→ Increase of activity by a factor ~2 in data with $\sqrt{s}$ is more or less reproduced by PYTHIA 6 and PYTHIA 8

N_{ch}, Σp_T and p_T in the transverse region

7 TeV. p_T track-jet > 20 GeV vs p_T track-jet > 20 GeV



CMS QCD-10-010



MC/DATA: 7 TeV. p_T track-jet > 20 GeV

Summary

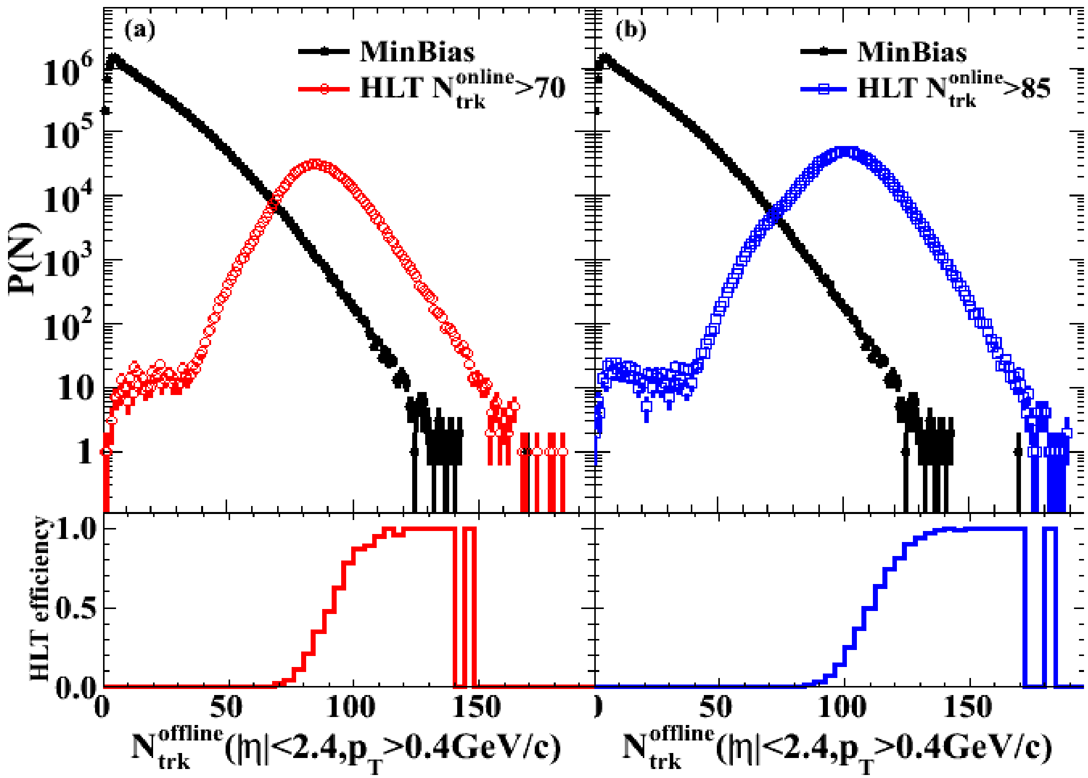
- **Various low pT QCD analyses with Minimum Bias events have been performed with CMS**
  - **transverse momentum spectra and event-by-event multiplicity distributions of charged particles have been measured and compared to different Monte Calo models.**
  - **Strange particle production in good agreement with empirical extrapolation from lower energies.**
- **Two particle correlation function has been measured at 0.9, 2.36 and 7 TeV.**
  - **A very novel feature has been observed of long range, near side two particle correlation. Not reproduced by any MC model.**
- **The BEC effect has been observed and quantified at 0.9 and 7 TeV.**
  - **The exponential parametrization has been shown better fit the data**
  - **Various parameter dependences have been investigated.**
- **For the first time UEs have been analyzed at 7 TeV.**
  - **Many MC tunings have been compared to the data. None of them being in good agreement with data. New MPI model seem to help.**

Backup slides

Trigger on High Multiplicity pp

JHEP 1009:091, 2010

Total integrated luminosity: 980nb^{-1}



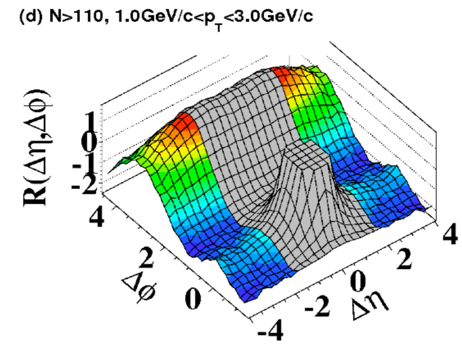
Two HLT thresholds:

- N^{online} > 70
- N^{online} > 85

N^{online} > 85 trigger un-prescaled for full 980nb^{-1} data set

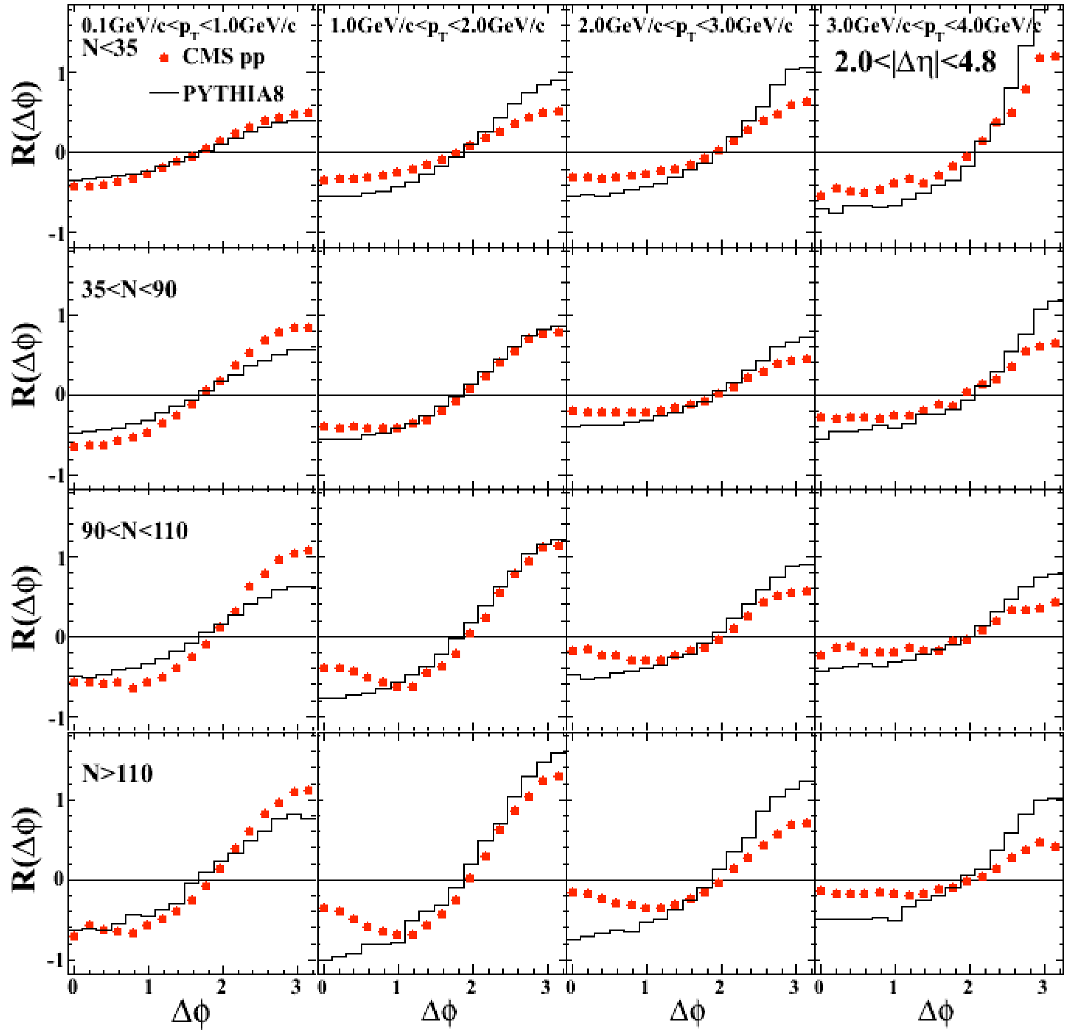
~350K top multiplicity events (N>110) out of 50 billion collisions

Multiplicity and p_T dependences



p_T range

Multiplicity



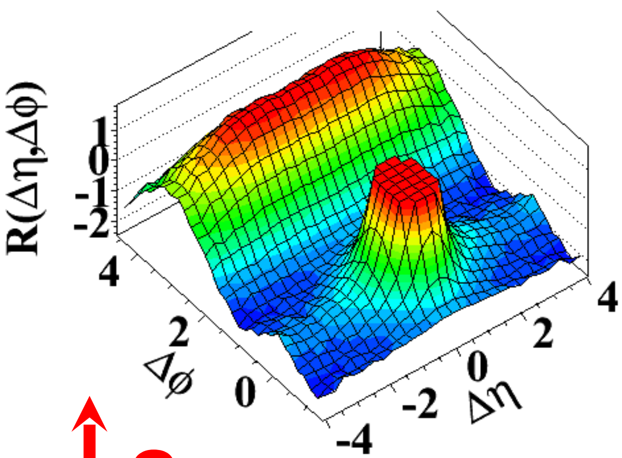
→ **Study dependence on p_T and multiplicity for $2 < |\Delta\eta| < 4.8$ for $R(\Delta\phi)$:**

"Ridge" maximal for high multiplicity and intermediate p_T : $1 < p_T < 3$ eV/c

"Ridge" not reproduced by PYTHIA 8

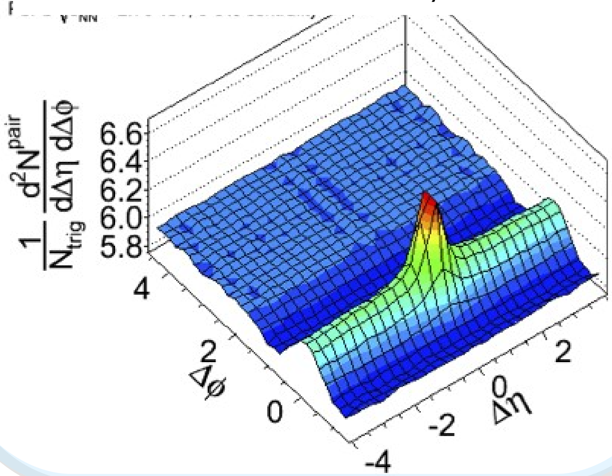
Ridge in high multiplicity pp

CMS pp 7 TeV, N ≥ 110



?

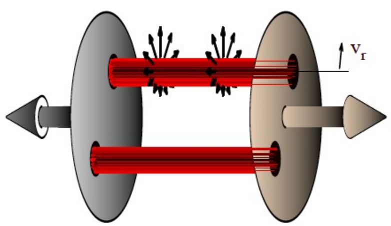
CMS PbPb 2.76 TeV, 0-5%

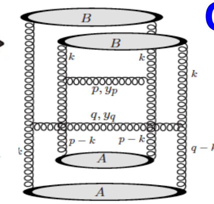


Interpretations:

Multi-jet correlations
Jet-Jet color connections
Jet-proton remnant color connections — **Jet**

Glasma tube

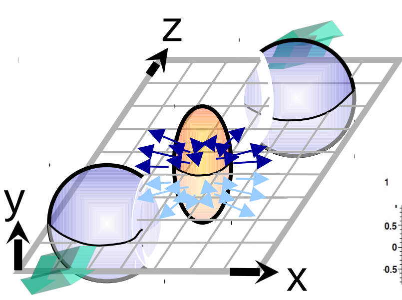




— **Color Glass Condensate**

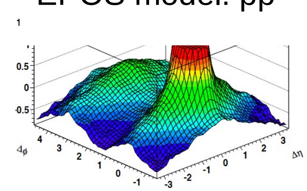
Phys. Lett. B697:21-25, 2011

Hydrodynamic flow



— **Quark Gluon Plasma**

EPOS model: pp



⋮

K. Werner, WWND2011