Soft QCD Results from CMS

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(On Behalf of the CMS Collaboration)

QCD@LHC 2011

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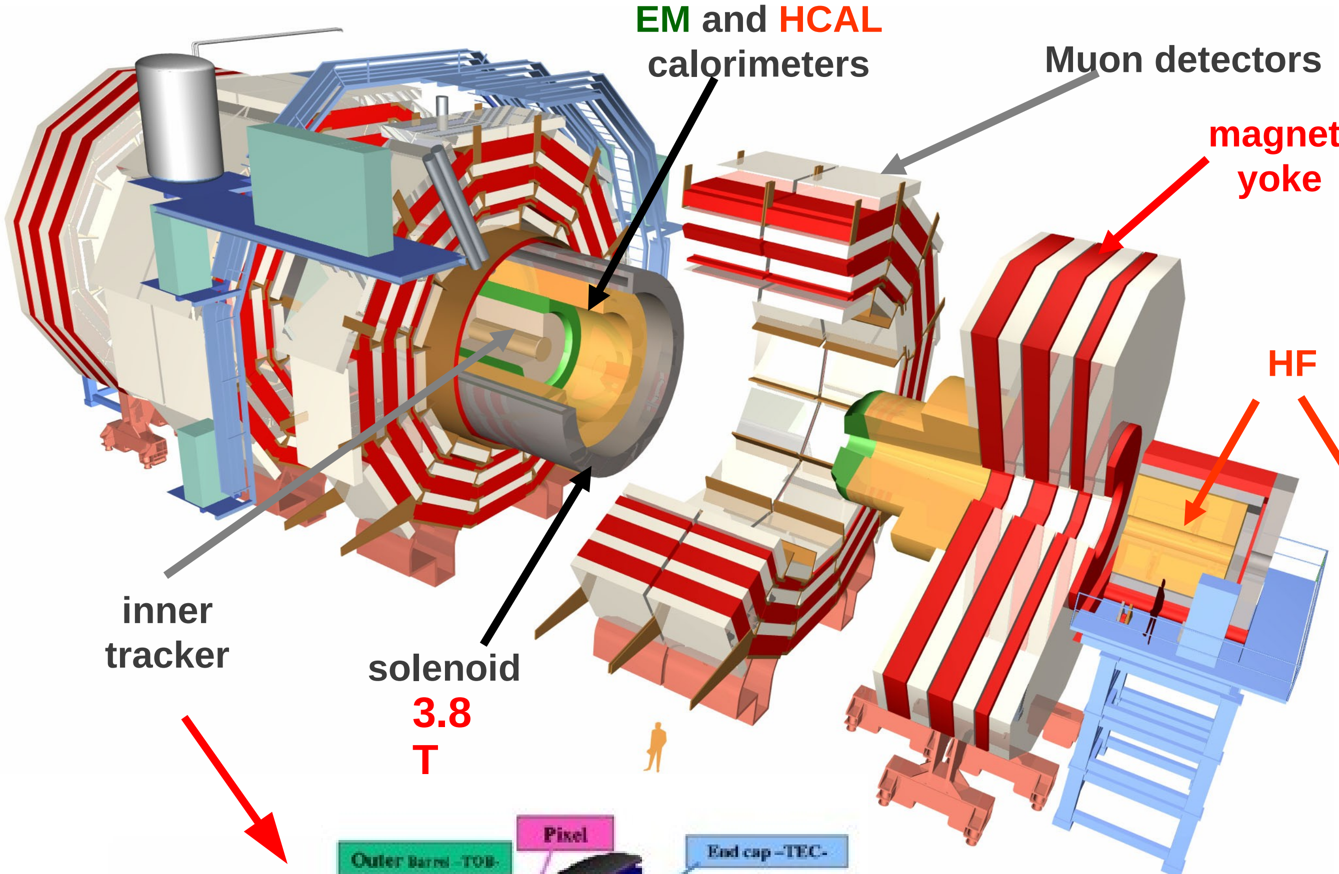
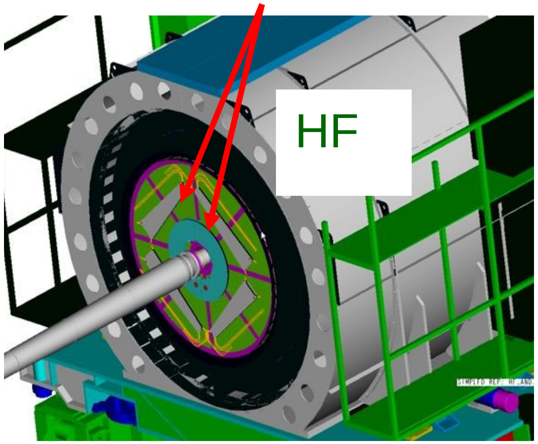
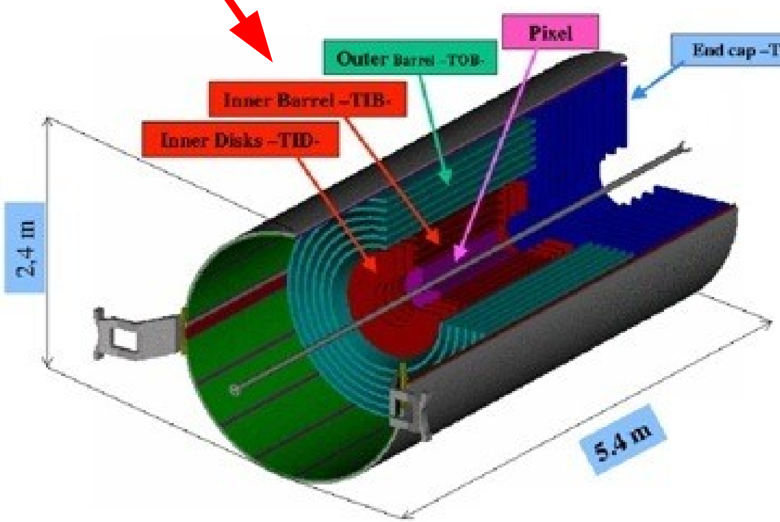
The CMS Detector



Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

Inclusive Trigger: Scintillators around Beam Pipe (BSC)





CMS η coverage:

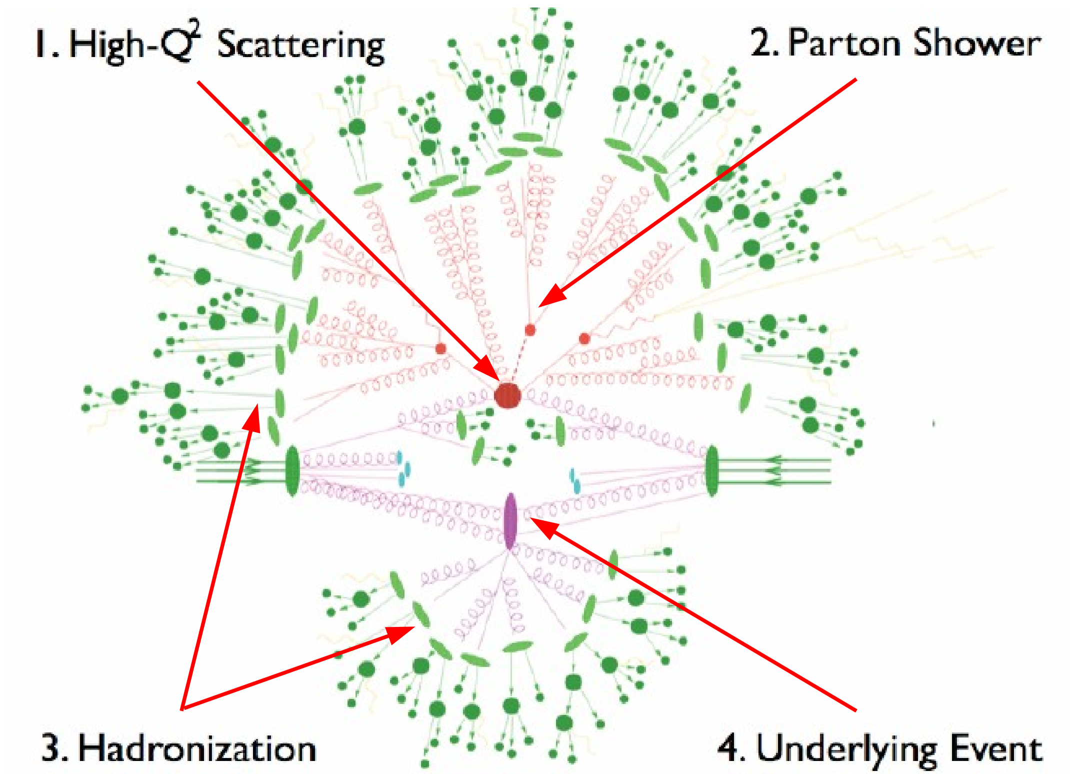
Tracker (Pixel + Strip)	$\lvert\eta\rvert < 2.4$
Calorimeters (EM+HCAL)	$\lvert\eta\rvert < 3.0$
HF Calorimeter	$3 < \lvert\eta\rvert < 5$
Muon Detectors	$\lvert\eta\rvert < 2.4$

The majority of the pp collisions are soft

→ no hard parton scattering → no "perturbative" predictions

→ need to model them phenomenologically

→ Use Monte-Carlo (MC) description to correct data:



- PS, UE and hadronization models tuned on previous (low energy) data
- Different models available diverging at high energy prior to LHC

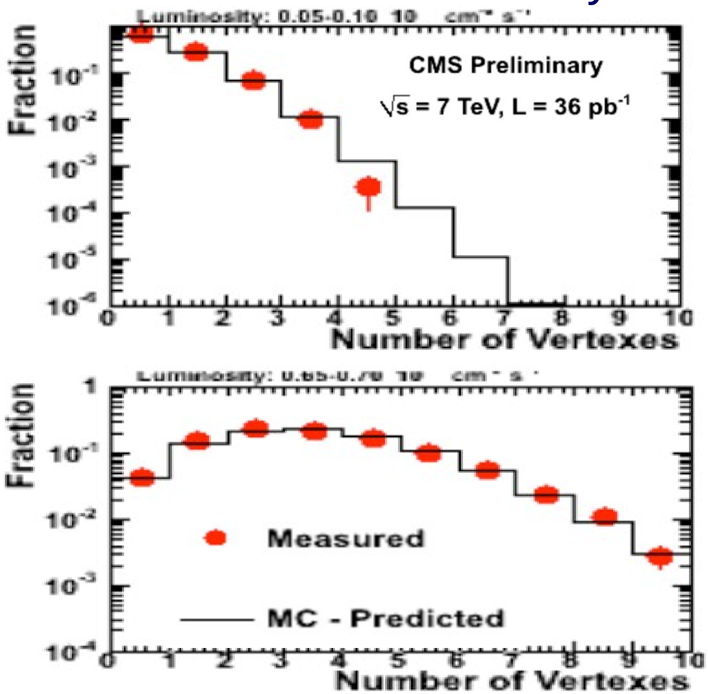
→ Early LHC data give us a unique chance to fill gaps in our knowledge on soft QCD

→ Reference for high energy pp collisions and heavy ions run

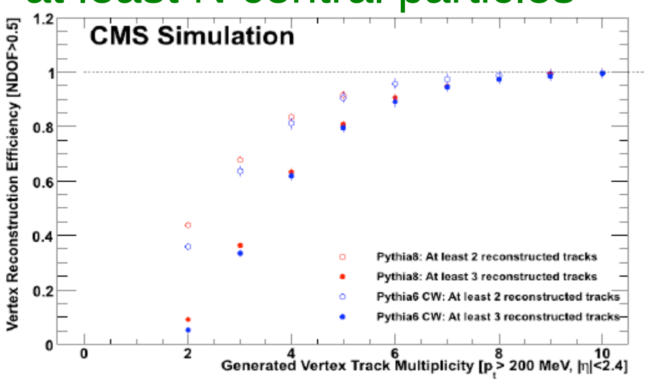
Inelastic Cross-section at $\sqrt{s}$ = 7 TeV

σ_{inel} : Method

1) Count vertex multiplicity in bins of instantaneous luminosity



2) Correct for vertex efficiency for at least N central particles

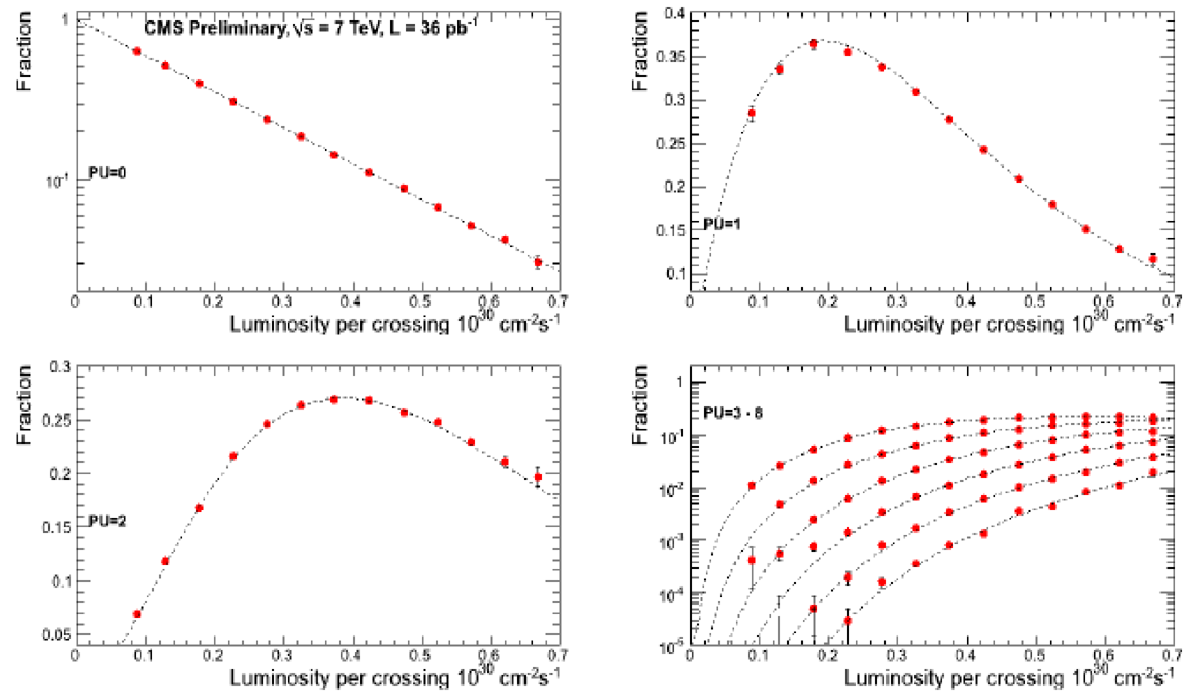


3) Assume pile-up (vs) luminosity follow Poisson law to extract σ visible

$$P(n) = \frac{(L \cdot \sigma)^n}{n!} e^{-L \cdot \sigma}$$

n: number of inelastic proton-proton (pp) interactions in a given bunch crossing

L is the bunch crossing luminosity σ the total inelastic pp cross section



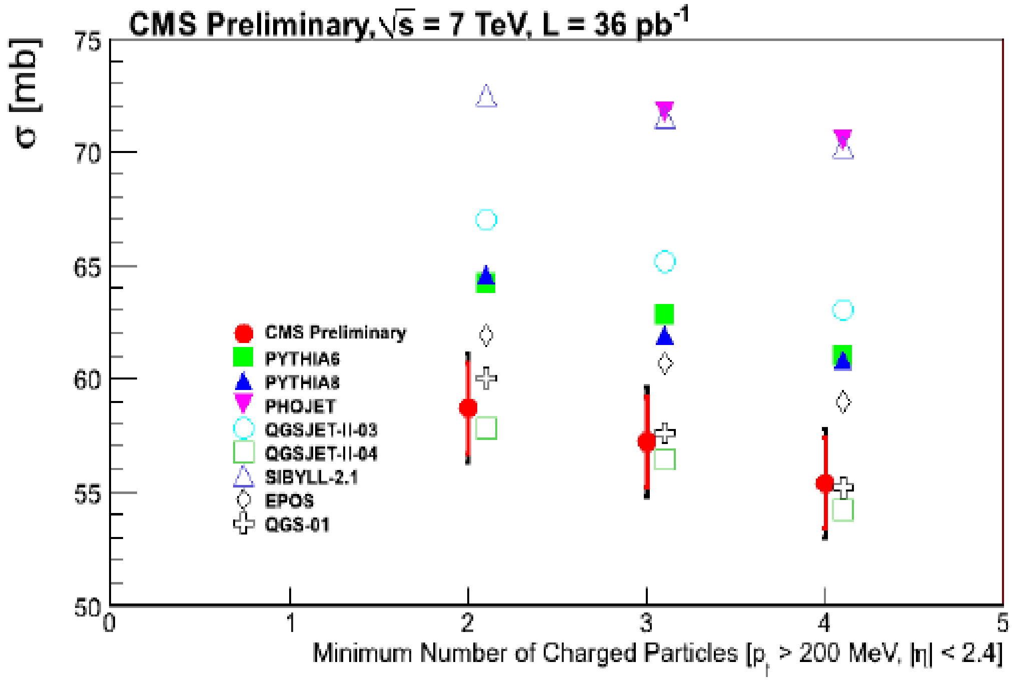
4) Extrapolate to total σ_{inel} with several MC

→ Systematic error of the extrapolation from differences among MC

σ_{inel} : Results

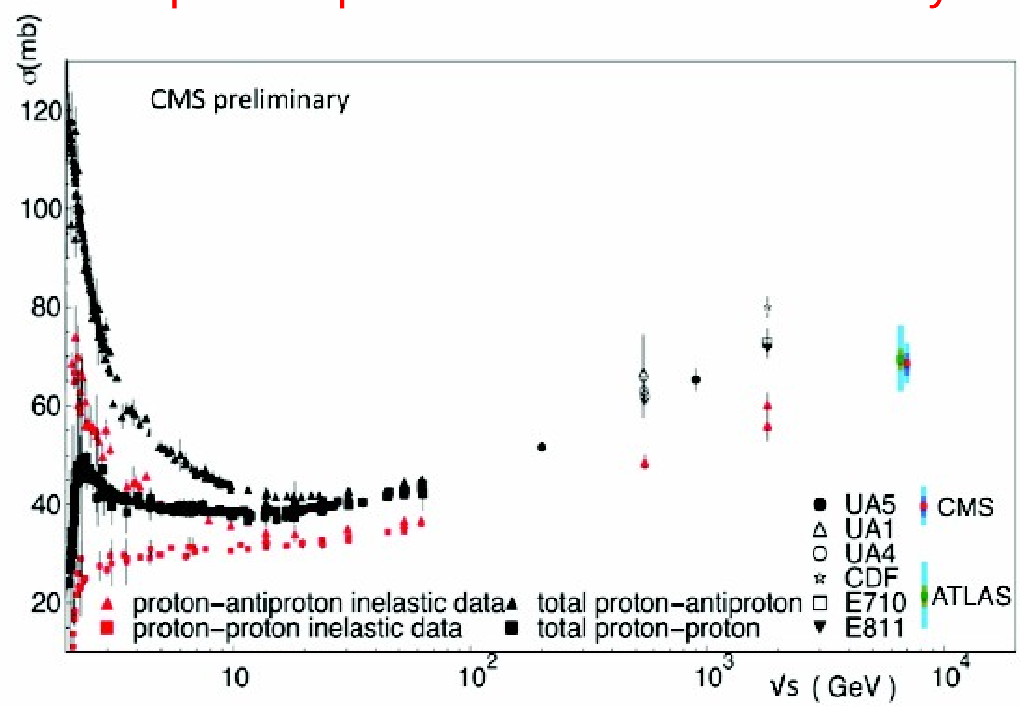
Visible Inelastic Cross-section

At least N(=2,3,4) charged particles with pT>200 MeV in |η|<2.4



Total Inelastic Cross-section

Extrapolation based on models to full phase space → extra 6% uncertainty



- PHOJET and SIBYLL largely overestimates data
- PYTHIA 6&8, EPOS and QGSJET-II-03 too high
- QGSJET-II-04 and QGS-01 in agreement

- CMS & ATLAS in good agreement
- σ_{inel} follow log increase of lower energy results

$$\sigma_{inel}(pp) = 68 \pm\ 2.0\ (\mathrm{Syst}) \pm\ 2.4\ (\mathrm{Lum})\ \pm\ 4(\mathrm{Ext.})\ \mathrm{mb}$$

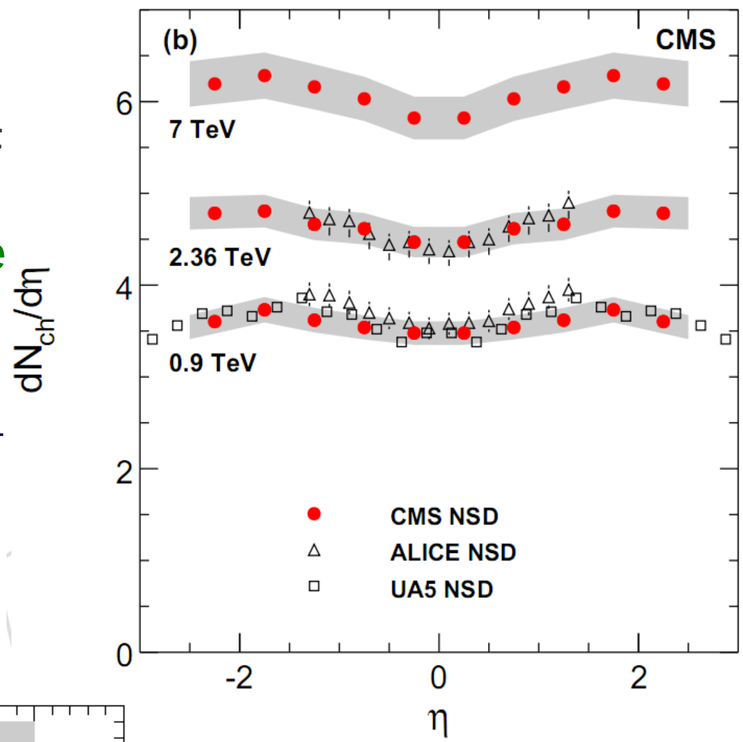
Particle Spectra

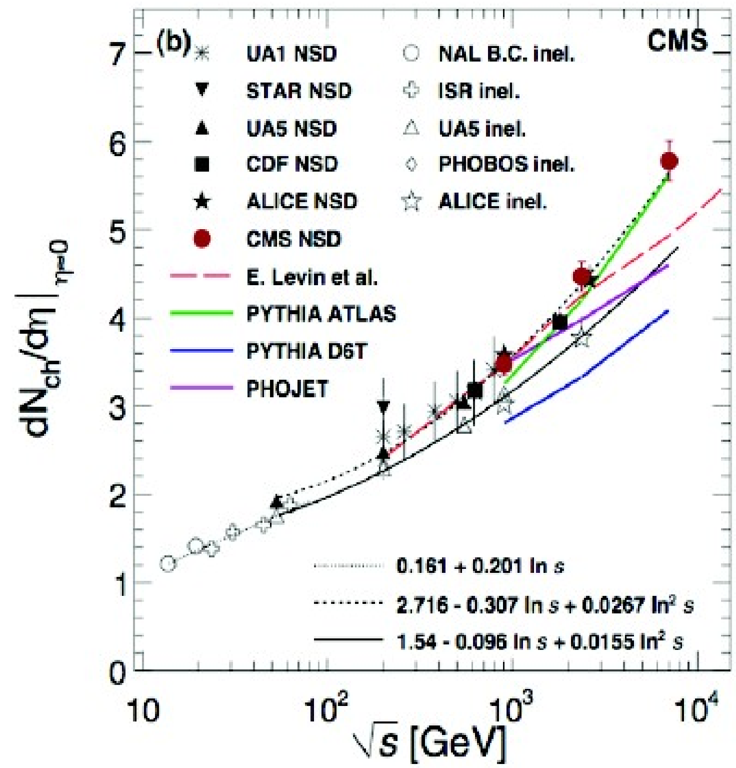
JHEP 02 (2010) 041
PRL 105 (2010) 022002

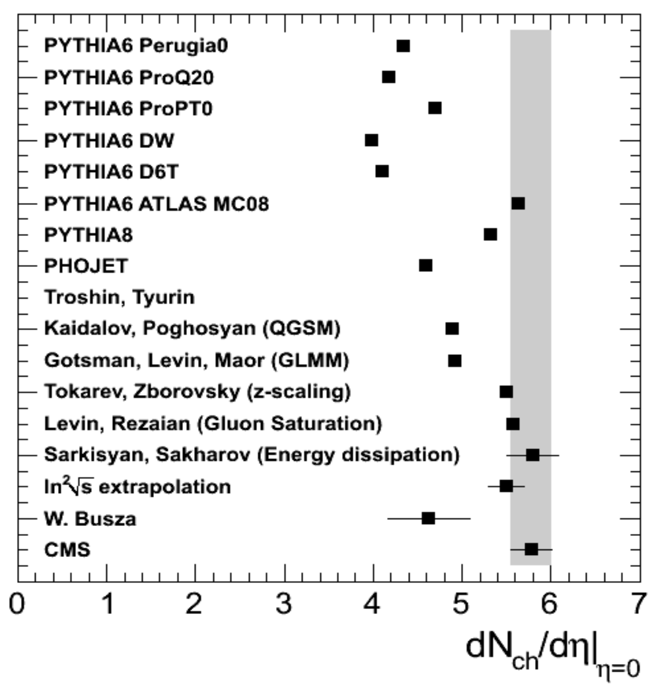
Single Charged Particle Spectra: dN/dη

<u>Event Selection:</u>
- MinBias trigger (BSC)
- At least 3 GeV in both HF
- primary vertex
  - → Corrected to non single diffraction (NSD)

<u>Charged Particle Selection:</u>
- $|\eta| < 2.5$
- corrected to $p_T > 0$ GeV/c
- 3 different methods





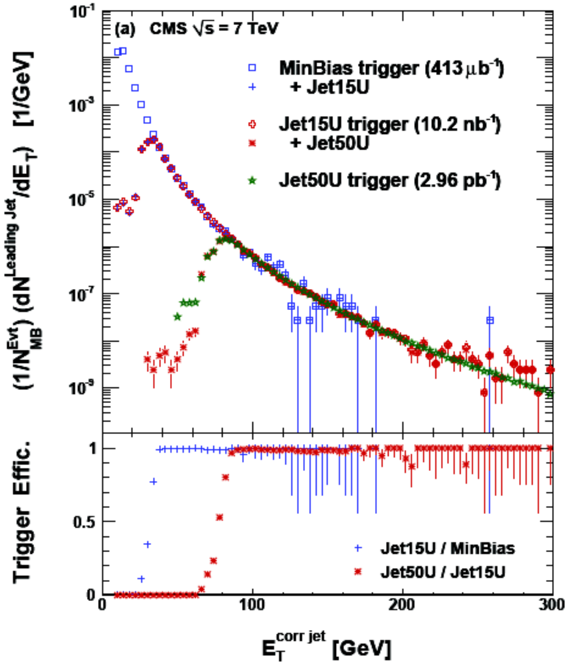


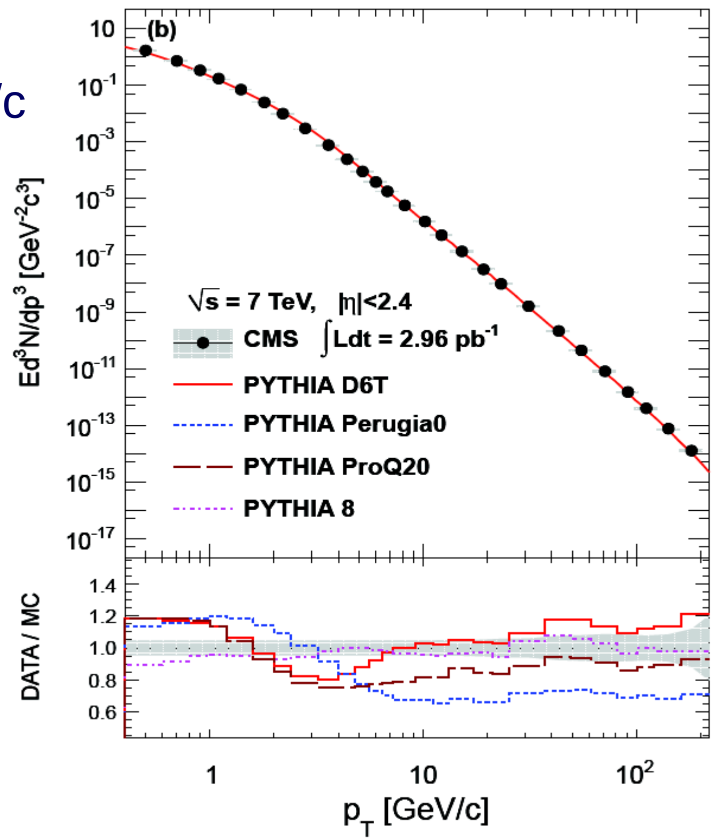
CMS measurements in agreement with other experiments.

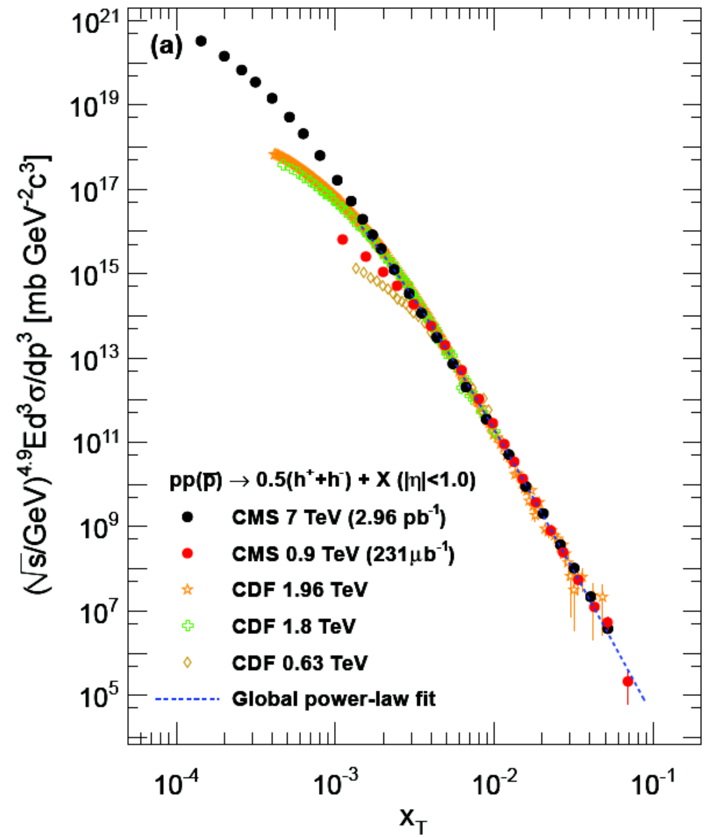
However densities are higher than most models and pre-LHC MC at high energy.
→ MC tuning effort on LHC data ongoing (see http://lpcc.web.cern.ch/LPCC/)

Single Charged Particle Spectra: dN/dp_T

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





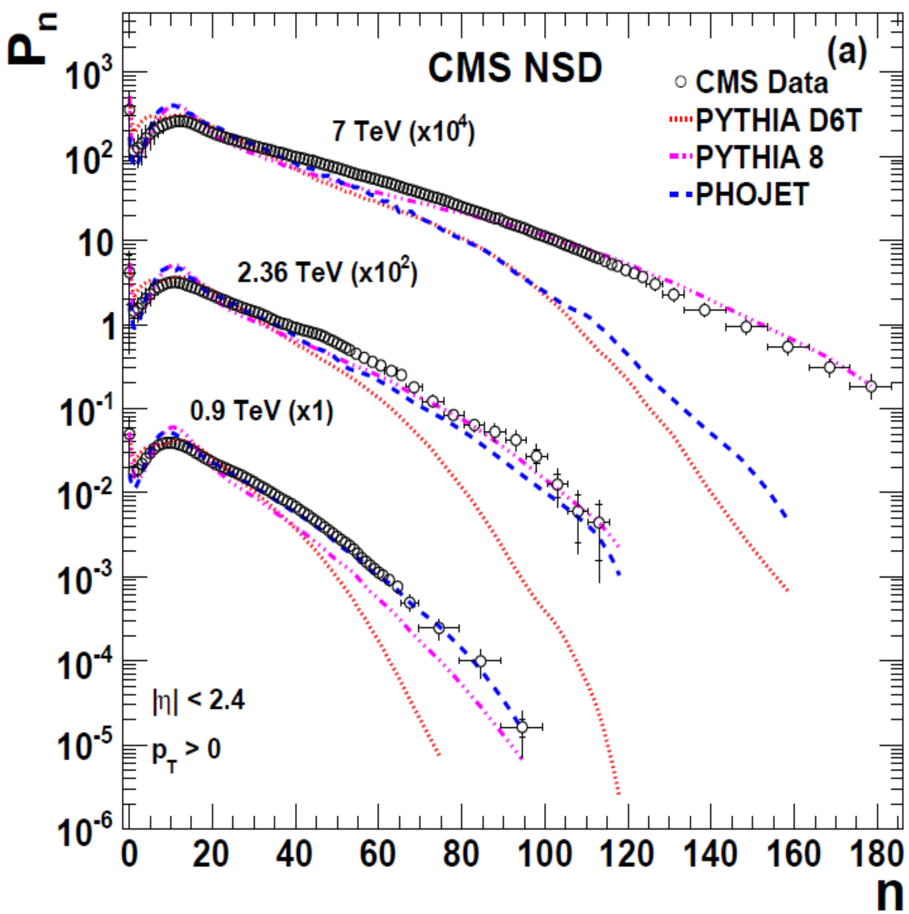


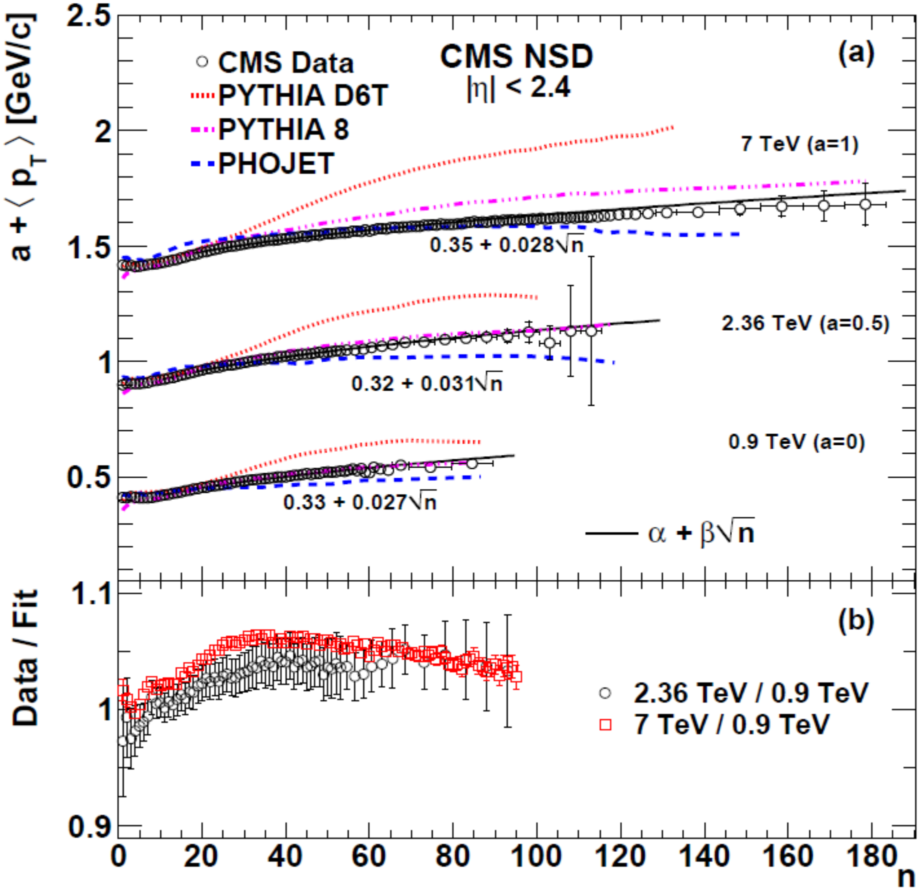
$$E\frac{d^3\sigma}{dp^3} = F(x_T)/p_T^{n(x_T,\sqrt{s})} = F'(x_T)/\sqrt{s}^{n(x_T,\sqrt{s})}$$

- 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

JHEP 01 (2011) 079

Charged Particle Multiplicities

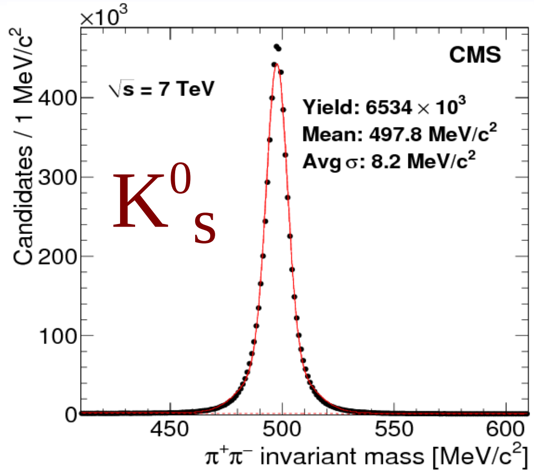


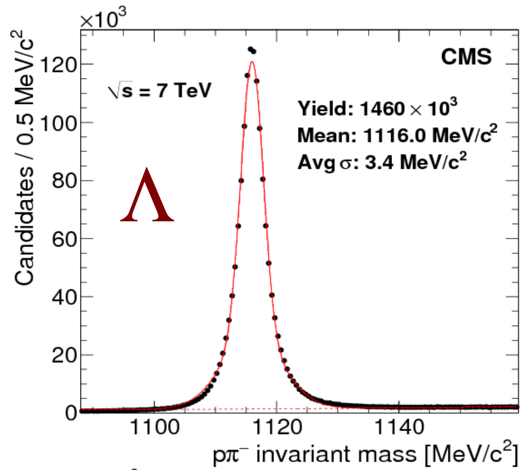


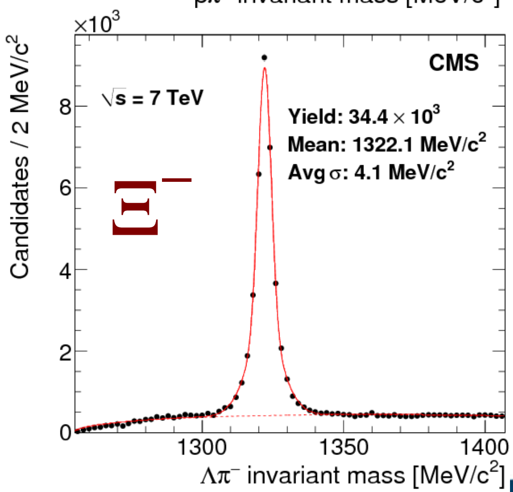
- Large multiplicity tail observed at 7 TeV (cf. dN/dη)
- $<p_T>$ vs n scale with energy
- No Monte Carlo is able to describe all multiplicities at all energies (but PYTHIA 8 better)
- Most MC/tunes can not describe simultaneously the multiplicity and the p_T dependence (again PYTHIA 8 better)

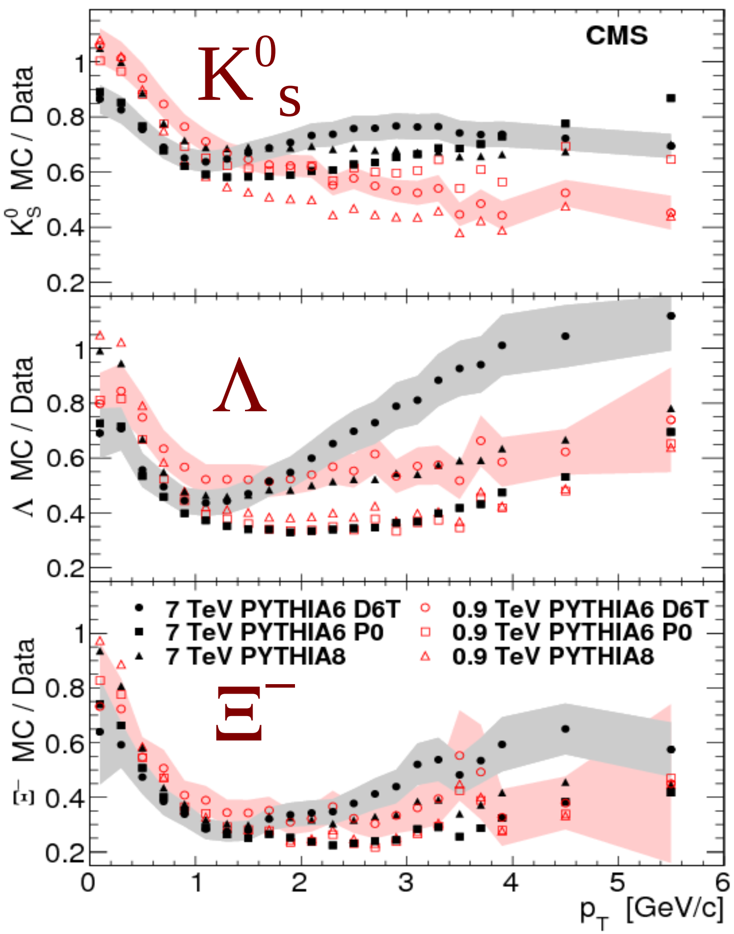
Strange Particle Production: K^0_S, Λ , Ξ^-

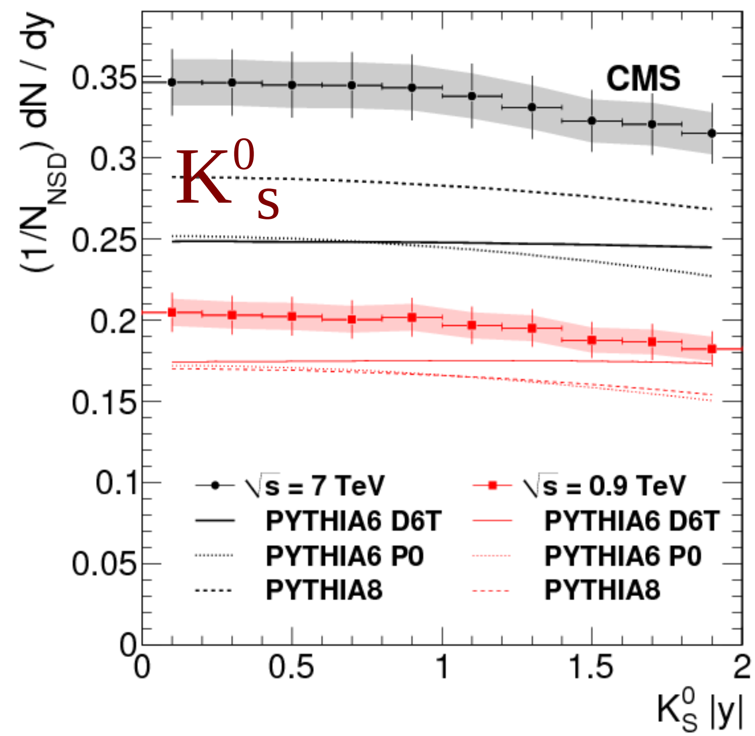
CMS Paper QCD-10-007











Similar increase for strange as for charged particle with energy → Pre-LHC PYTHIA tunes fail again to match this increase !

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

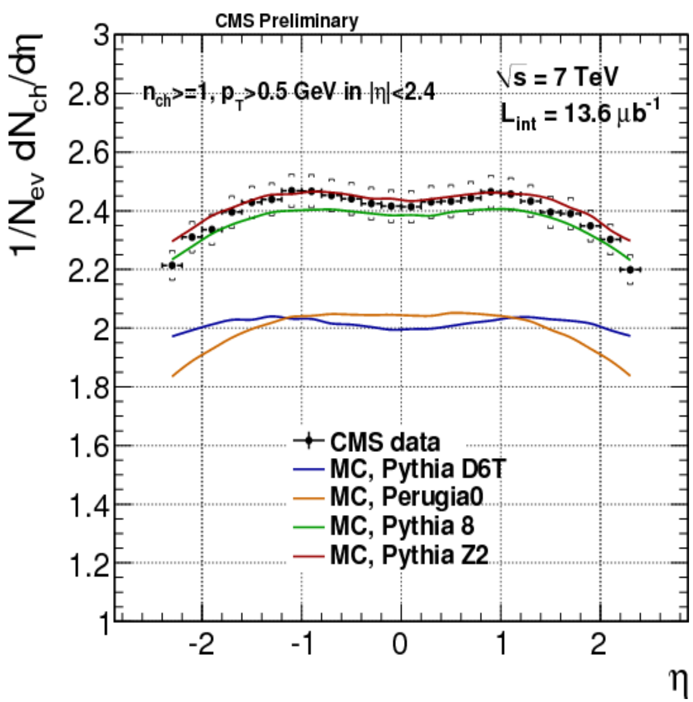
dN/dη with with at least one central charged particle

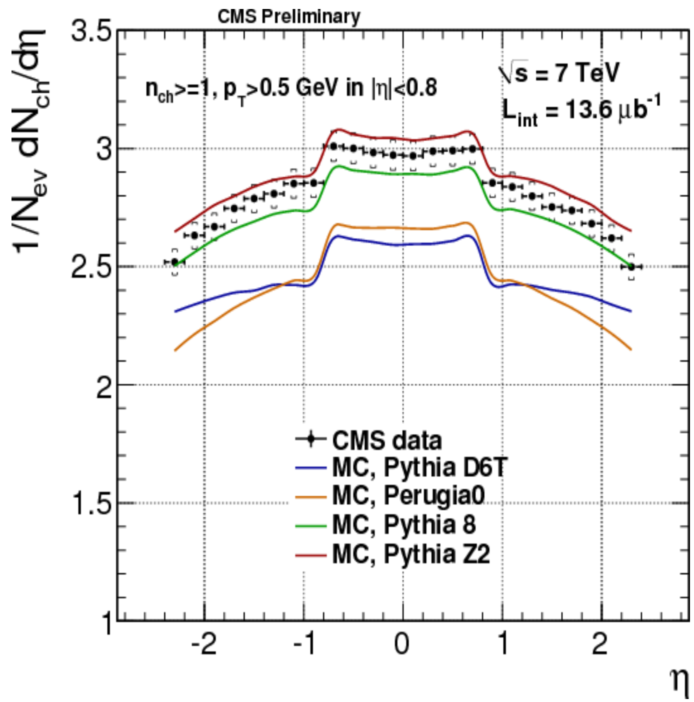
CMS PAS QCD-10-024

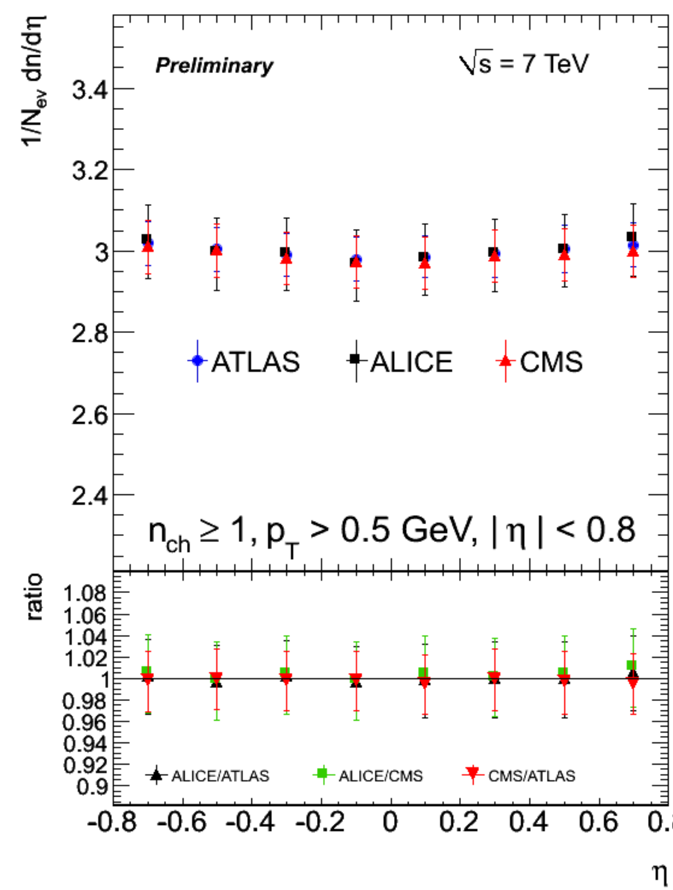
Request from MBUEWG:

* Avoid NSD definition based on MC process flags
  → "Unbiased" input for MC tuning / model comparison
* Allow direct comparison between LHC experiments

Good agreement among LHC experiments







- **PYTHIA 6 pre-LHC tunes (Perugia0, D6T) predict too low dN/dη compared to data.**
- **PYTHIA 6 Z2 tune (based on CMS UE results) and PYTHIA 8 Tune1 are close to the data.**
- **Results at 0.9 TeV also available**

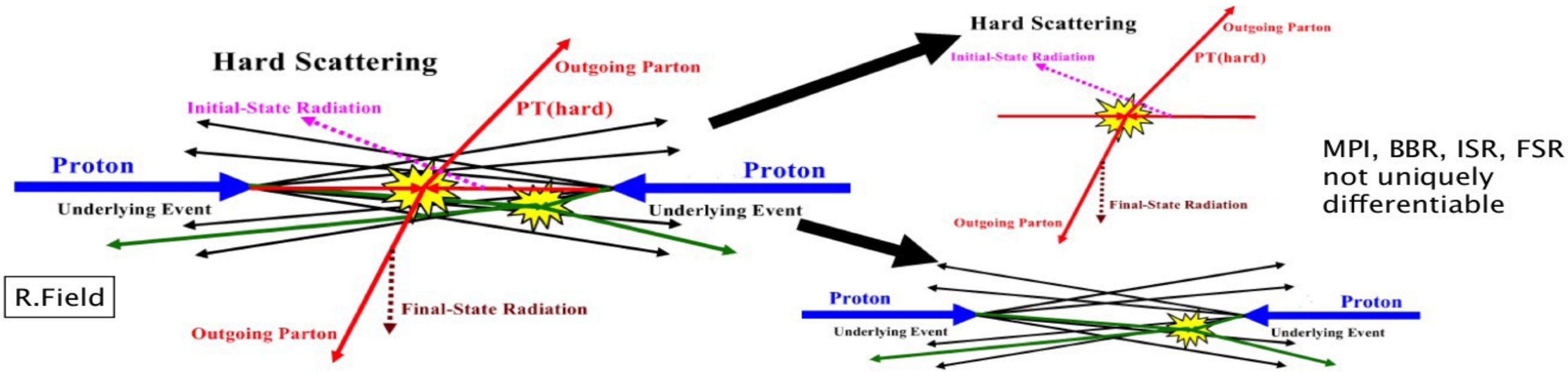
Underlying Event

EPJ C70 (2010) 555
CMS Paper QCD-10-010

The Underlying Event

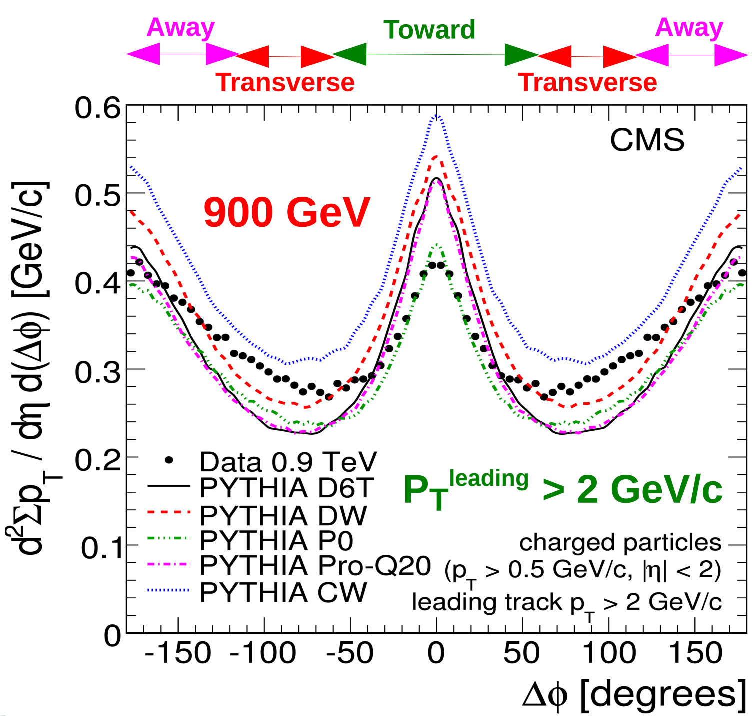
The "underlying event" is everything except the outgoing hard scattered partons

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



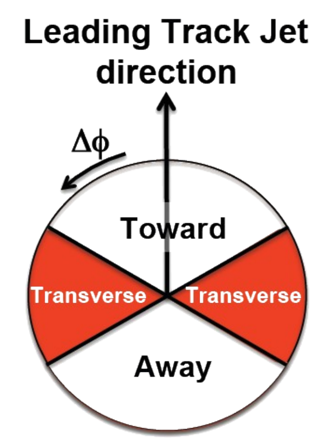
UE Observables

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



UE Data Selection: 900 GeV and 7 TeV

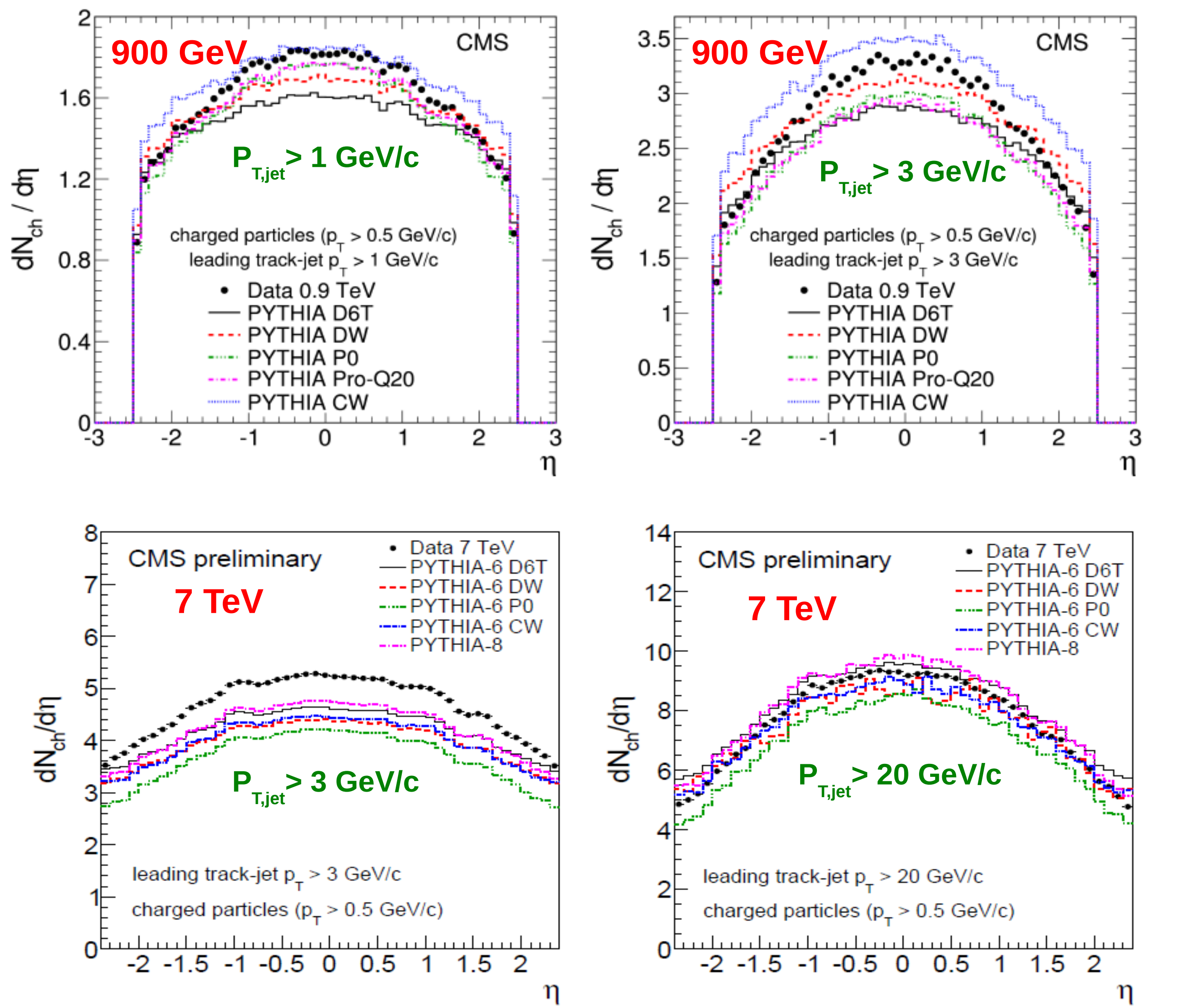
MinBias Trigger selection:
- One hit in each BSC + beam halo veto
- Beam pickups (BPTX): Bunch crossing

Event selection:
- Only one vertex
- Vertex within ±15cm of beam spot in z
- At least 3 tracks pointing to the vertex

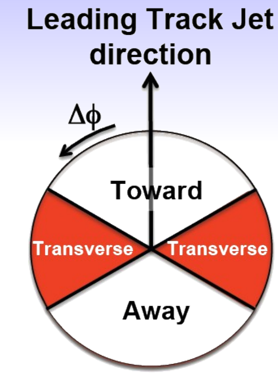
Track selection:
- $|\eta| < 2$ && $p_T > 0.5$ GeV/c
- Primary tracks (vertex associated):
  d0(vtx)/σd0<5 && dz(vtx)/σdz<5
- Background rejection: pT/σpT<5
  + extra track quality selection

Jets selection:
- SISCone (R=0.5) + Tracks Jets
- Only jets with p_T>1 GeV/c

Charged Particles (P_T>0.5 GeV/c) Pseudorapidity Density:

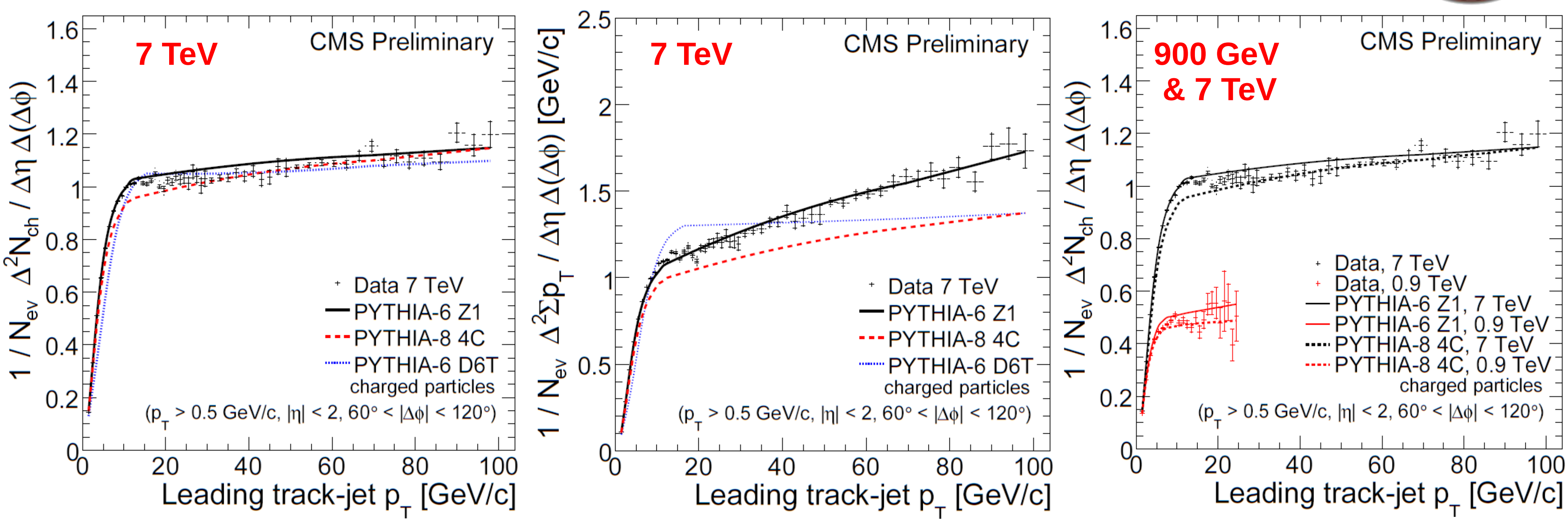


UE transverse region: charge and Σp_T density



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

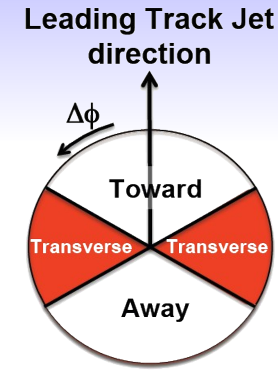
→ Measure activity outside jet(s) → Underlying Event



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**.

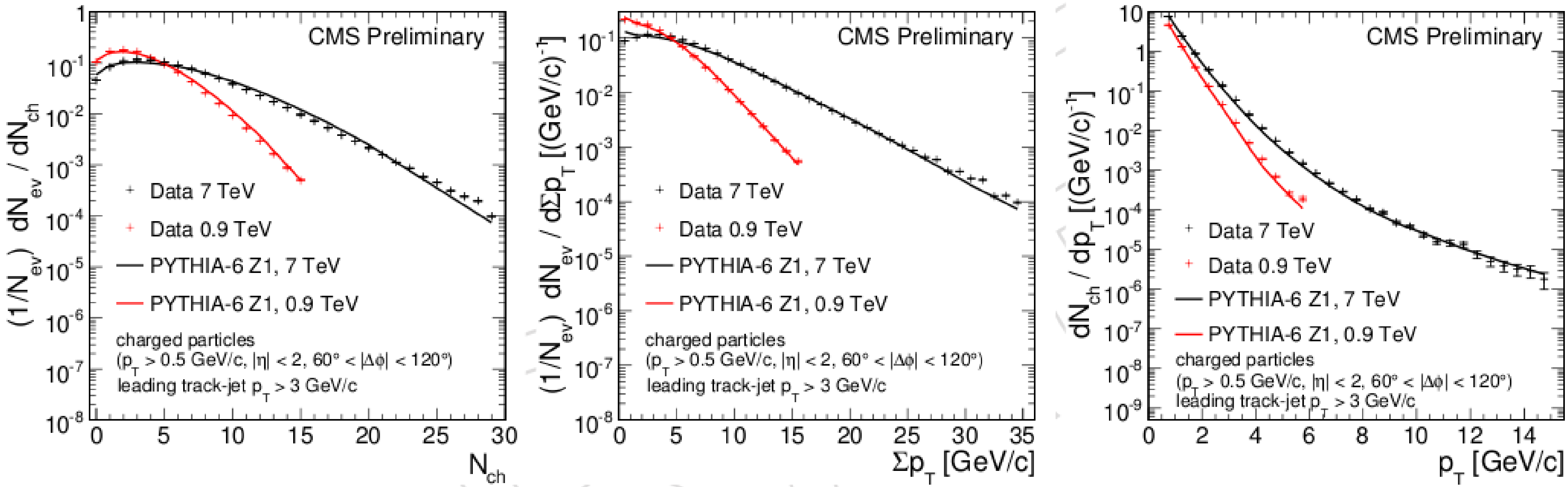
- → **Old D6T PYTHIA 6 tune reach plateau regime later than data (and is lower)**
- → **New Z2 PYTHIA 6 tune "fitted" on CMS data describes the data**
- → **New 4C PYTHIA 8 tune undershoot data at large P_T (and reach plateau late as well)**
- → **Increase of activity by a factor ~2 in data with $\sqrt{s}$ is more or less reproduced by PYTHIA 6 and PYTHIA 8**

UE transverse region: charged particles multiplicity



Measurement of charged particles multiplicity, ΣP_T and P_T dependences in transverse region

→ Measure activity outside jet(s) → Underlying Event



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New UE Approach: Jet Area/Median

Ratio of jet transverse momentum and area covered by this jet in η–φ plane

JHEP04(2010)065; M. Cacciari, G. Salam, S. Sapeta.

Jet area estimated from clustering together with overlaid grid of extremely soft ghost particle:

$$A_j = \frac{N_j^{\text{ghosts}}}{\rho^{\text{ghosts}}} = \frac{N_j^{\text{ghosts}}}{N_{\text{tot}}^{\text{ghosts}}} A_{\text{tot}}$$

Where N_j^{ghosts} : # ghosts clustered in jet

ρ^{ghosts} : ghosts density

→ Estimate background activity as:

$$\rho = \underset{j \in \text{jets}}{\text{median}} \left[\left\{ \frac{p_{\text{T}j}}{A_j} \right\} \right]$$

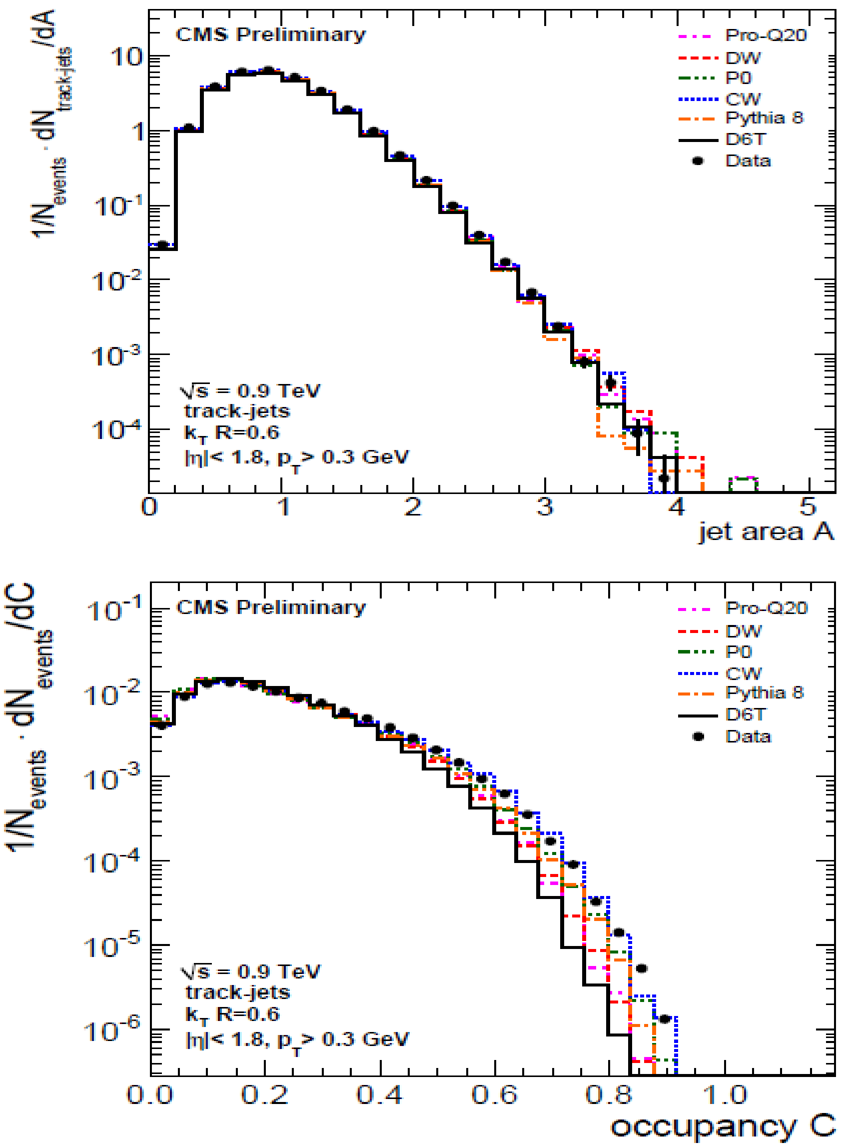
For low occupancy (900 GeV data), η–φ plane is dominated by ghosts

→ Correct ρ by event occupancy C:

$$\rho' = \underset{j \in \text{physical jets}}{\text{median}} \left[\left\{ \frac{p_{\text{T}j}}{A_j} \right\} \right] \cdot C$$

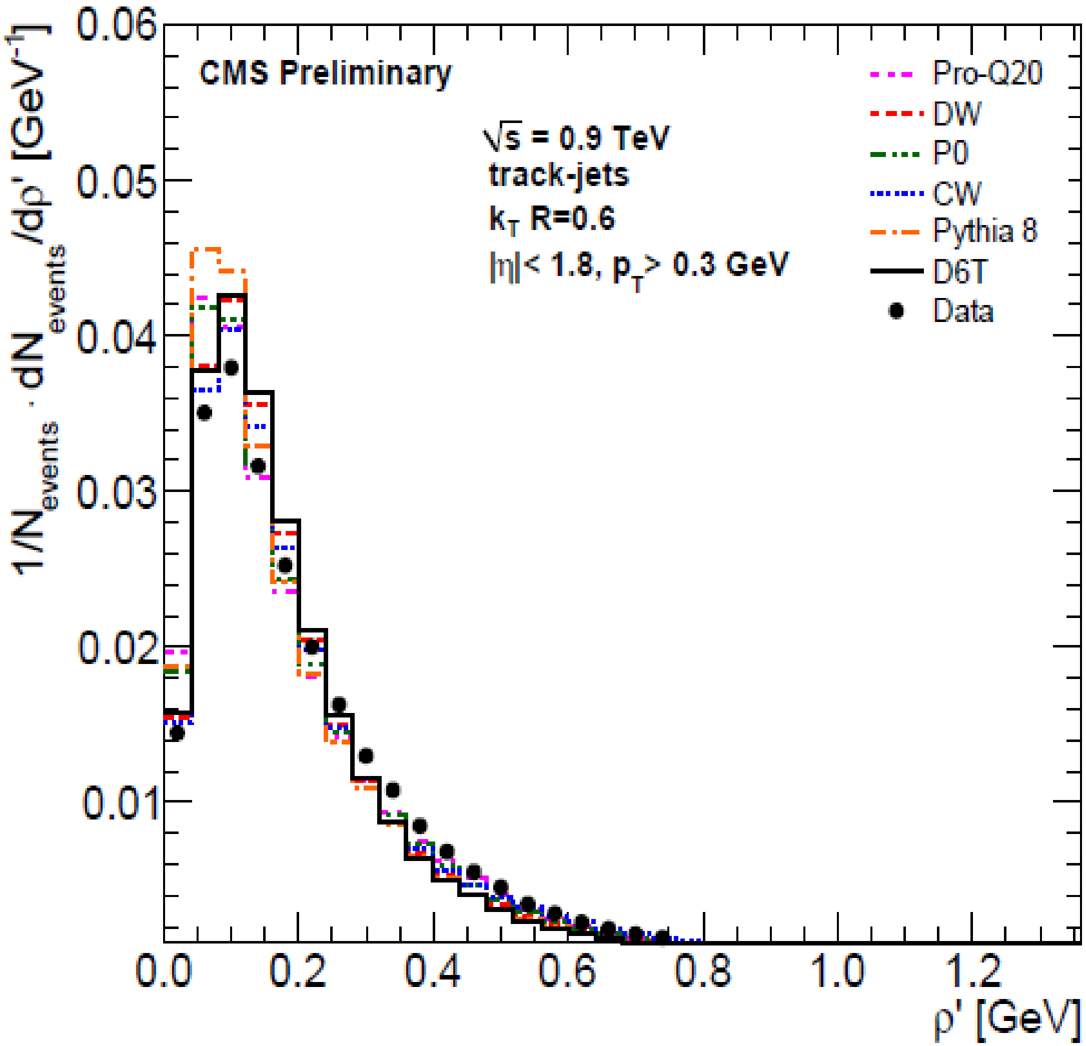
Where C = ratio jet covered area / total area:

$$C = \frac{\sum_{j \in \text{physical jets}} A_j}{A_{\text{tot}}}$$

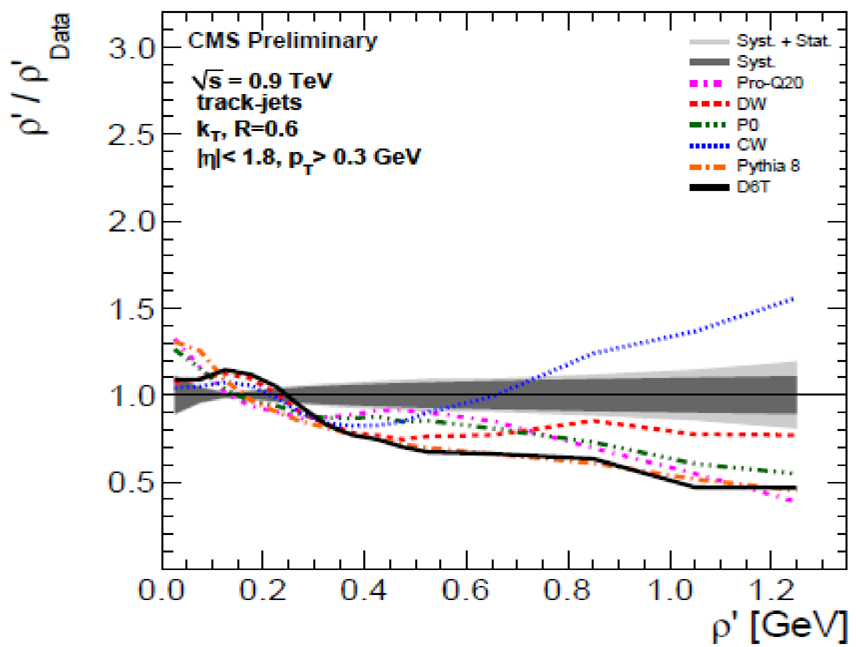


Jet / Median Area: Results at 900 GeV

Data: 900 Gev + similar selection as standard UE event and track selection



Clear sensitivity to the differences between the MC Tunes:

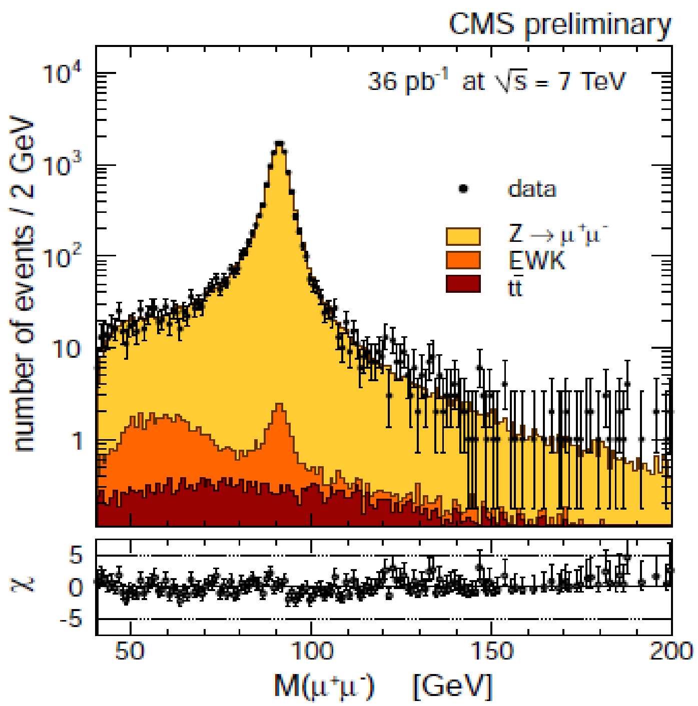


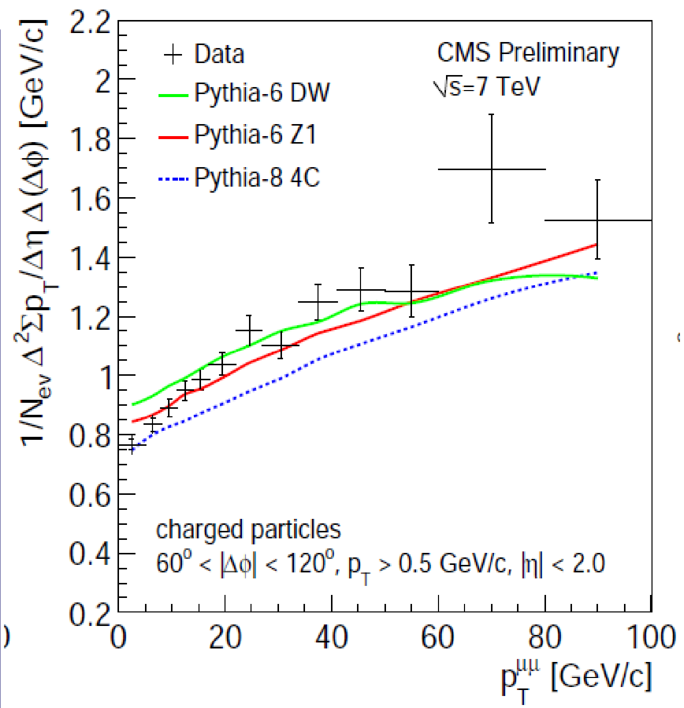
→ **Similar sensitivity as standard UE approach on different MC tunes**

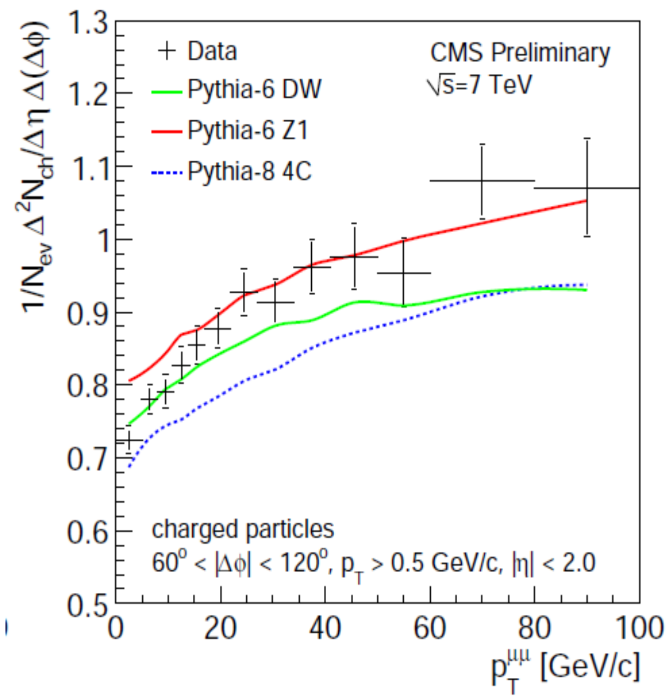
Underlying Event in Drell-Yan

CMS PAS QCD-10-040

Study of the UE in the transverse region to DY events in the μμ channel







Data selection:

- 2 well reconstructed and isolated m associated to the same vertex
- $p_{T\mu}$ > 20 GeV, $|\eta_\mu|$ < 2.4
- 60 < $M_{\mu\mu}$ < 120 GeV
- Track selection as for UE with leading jet

Both Σp_T and ans $<N_{ch}>$ increase with $p_T(\mu\mu)$ due to Increase of ISR ($M_{\mu\mu}$ already provides hard scale)

→ Respecting to UE with leading jets the MPI increase is already saturated (plateau region)

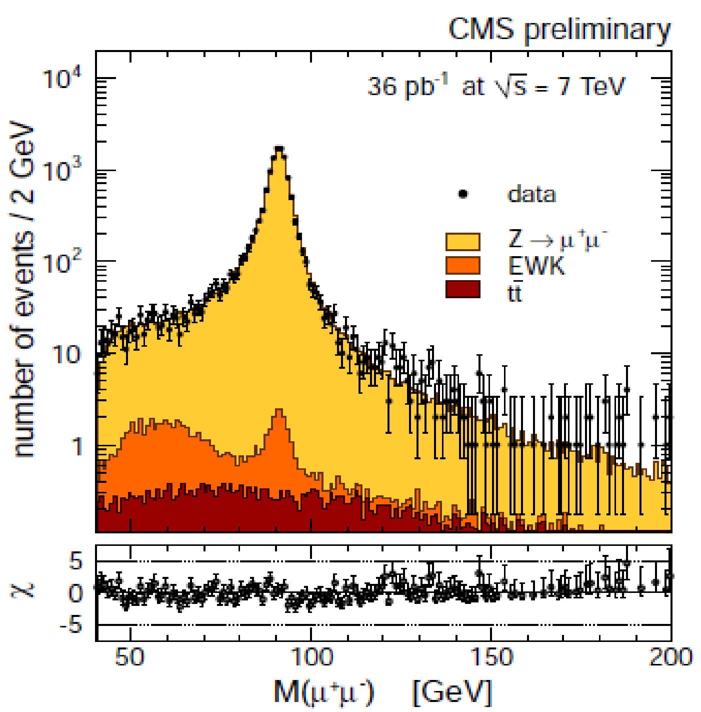
PYTHIA 6 Z1 tune provides best overall data description but too high for <Nch> at low $p_T(\mu\mu)$

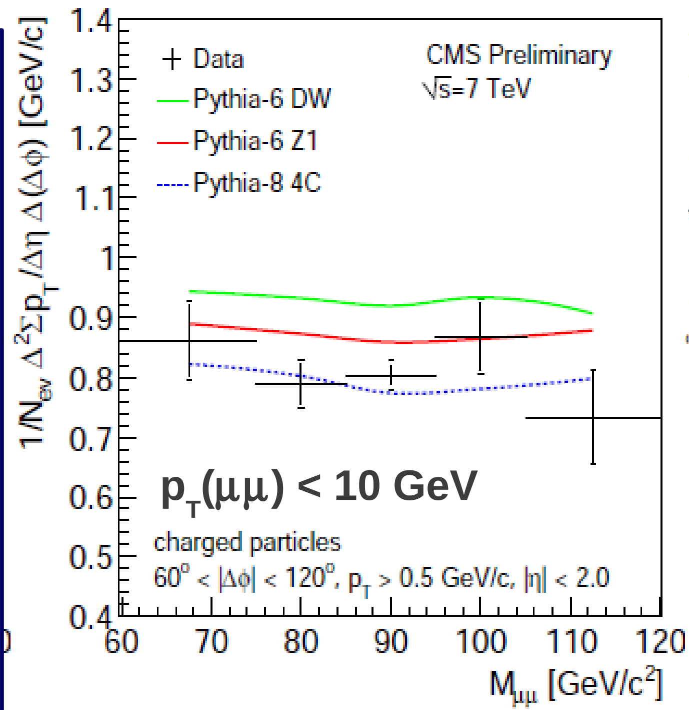
PYTHIA 8 4C tune globally too low

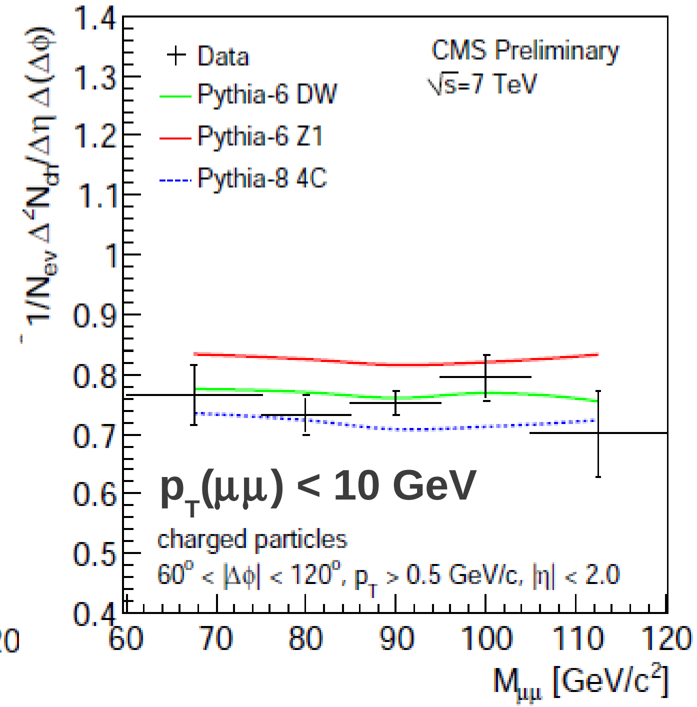
PYTHIA 6 DW tune does not reproduce the shape

Underlying Event in Drell-Yan

Study of the UE in the transverse region to DY events in the $\mu\mu$ channel







Data selection:

- 2 well reconstructed and isolated m associated to the same vertex
- $p_{T\mu}$ > 20 GeV, $|\eta_\mu|$ < 2.4
- 60 < $M_{\mu\mu}$ < 120 GeV
- Track selection as for UE with leading jet

Both Σp_T and ans $<N_{ch}>$ flat with $M_{\mu\mu}$ for $p_T(\mu\mu)$ < 10 GeV

→ **Respecting to UE with leading jets the MPI increase is already saturated (plateau region)**

	Σp_T	$<N_{ch}>$
PYTHIA 6 Z1 tune	ok	bit too high
PYTHIA 8 4C tune	ok	ok
PYTHIA 6 DW tune	bit too high	ok

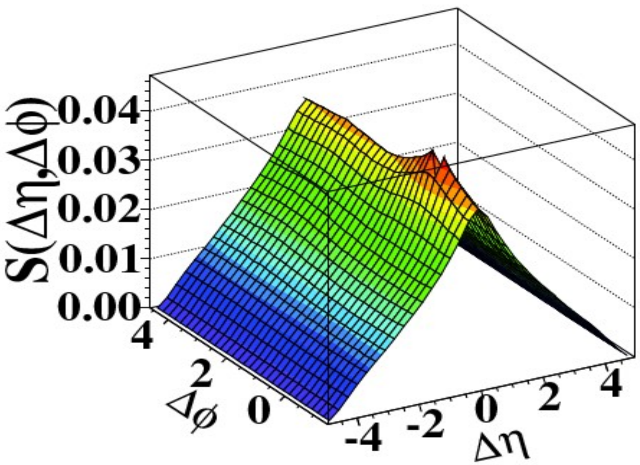
Correlations

See C. Buttlar talk (Tuesday)

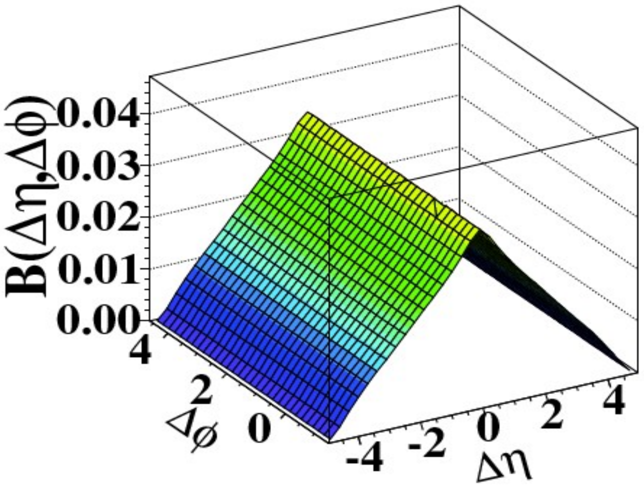
JHEP 09 (2010) 091

Two-particles correlation in Δη and Δϕ

Signal distribution
= Correlated and uncorrelated pairs
from same event



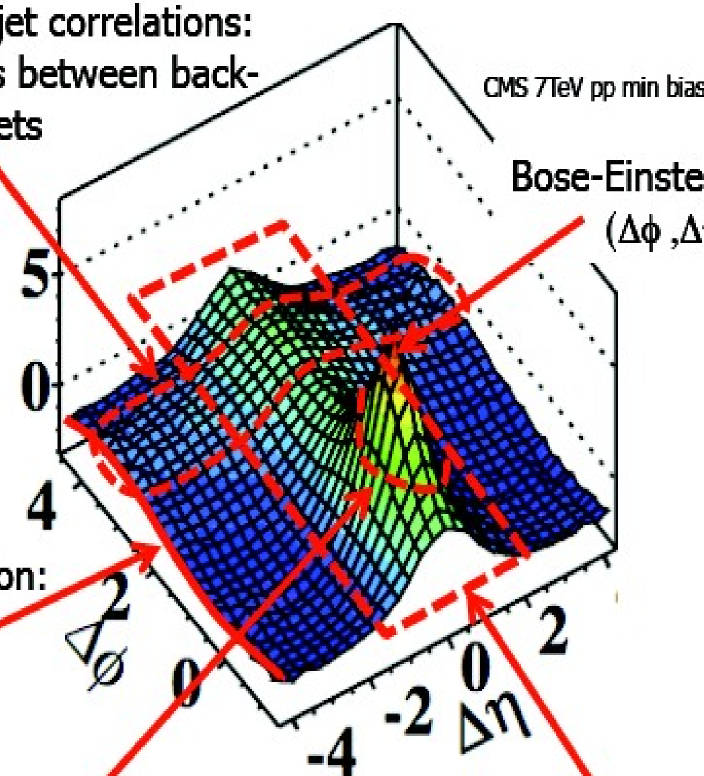
Background distribution
= Uncorrelated pairs
from mixing 2 events



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

"Away-side" (Δϕ ~ π) jet correlations:
Correlation of particles between back-to-back jets

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



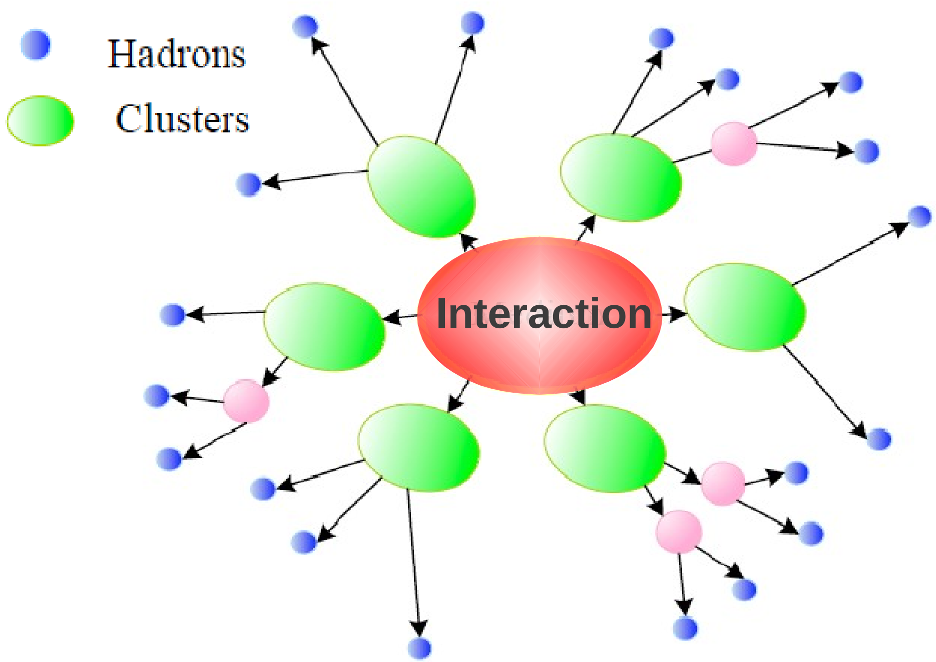
Momentum conservation:
~ -cos(Δϕ)

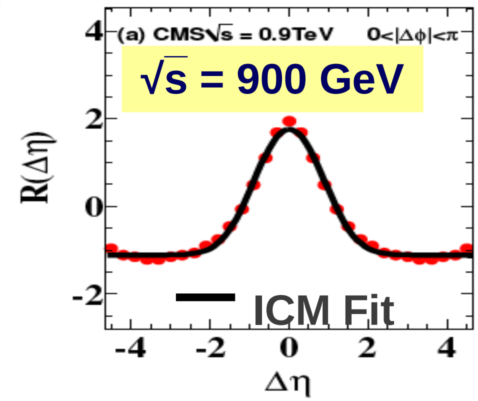
"Near-side" (Δϕ ~ 0) jet peak:
Correlation of particles within a single jet

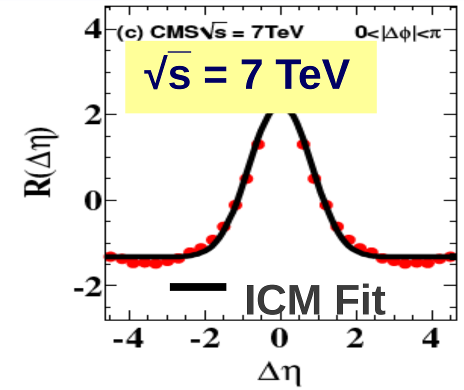
Short-range correlations (Δη < 2):
Resonances, string fragmentation, "clusters"

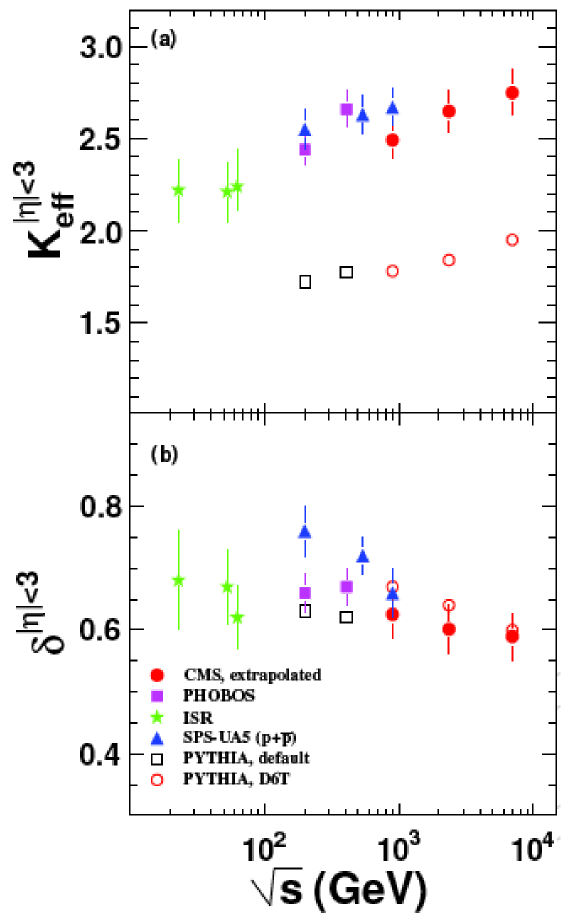
$$R(\Delta\eta,\Delta\phi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\phi)}{B_N(\Delta\eta,\Delta\phi)} - 1\right)\right\rangle_N$$

MinBias Results: Independent Cluster Model









- K_{eff} increase with $\sqrt{s}$
  (more jets at high $\sqrt{s}$?)
- δ constant with $\sqrt{s}$
  (isotropic cluster decay)
- CMS results follow trend from lower $\sqrt{s}$ data

- PYTHIA (D6T) shows similar energy dependencies for K_{eff} and δ as data

- PYTHIA (D6T) predicts too low K_{eff}

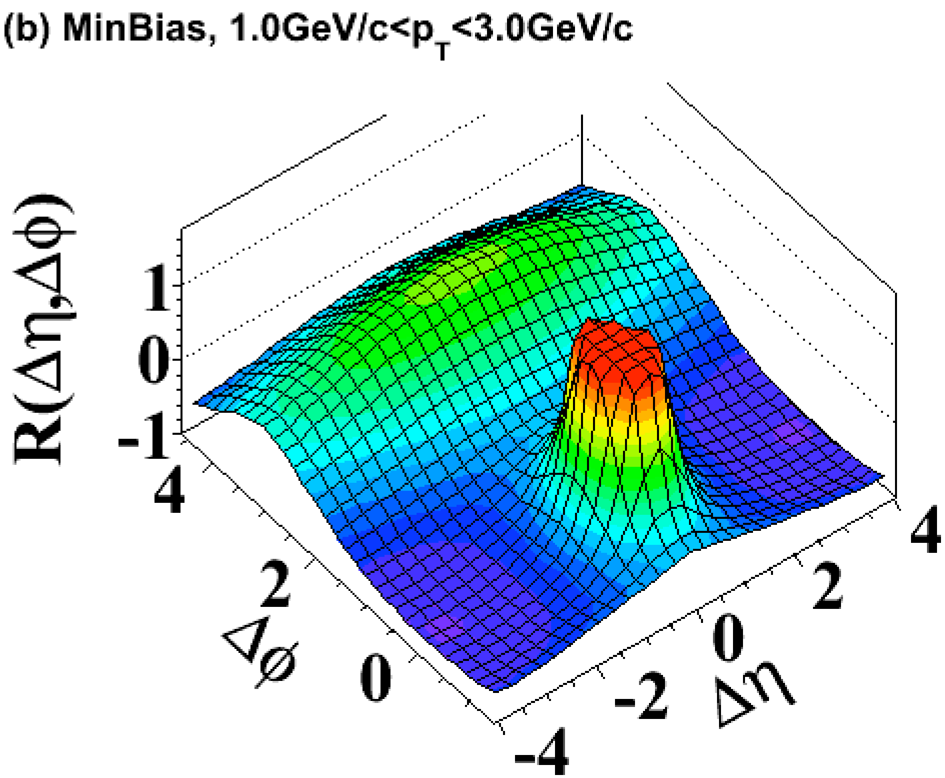
Independent Cluster Model (ICM)

- **Clusters are produced independently**
- **Each cluster decay isotropically into hadrons in its own c.m.s.**
- **Short range correlations in $\Delta\eta$ can be characterized by 2 parameters:**
  - **cluster size K → # correlated particles**
  - **cluster width δ → $\Delta\eta$ correlation size**

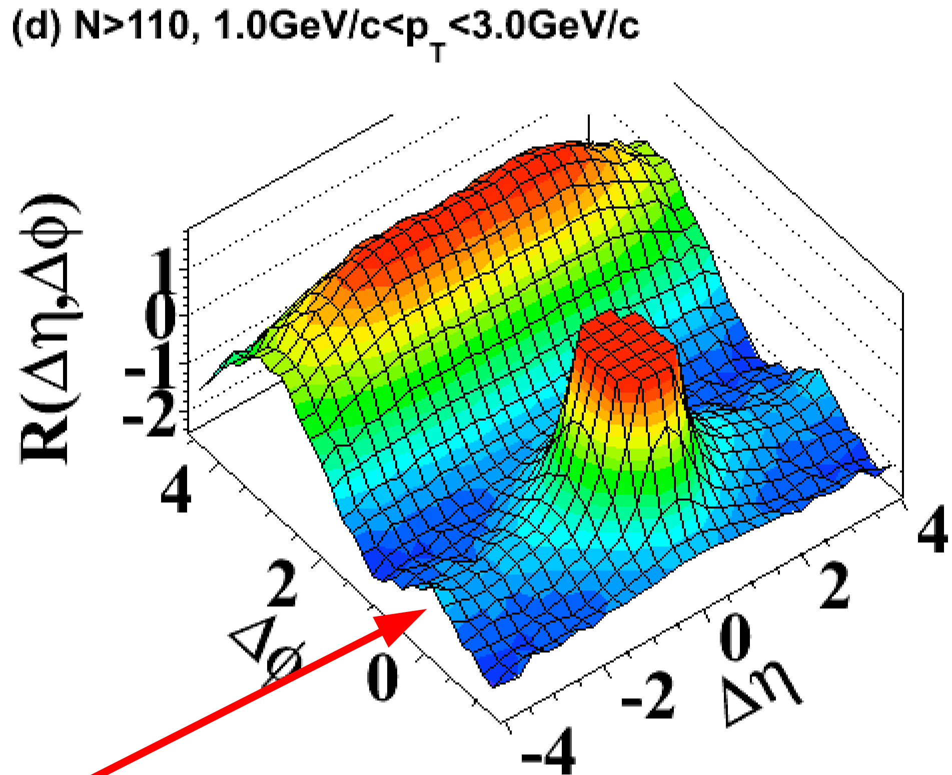
High Multiplicity Results at $\sqrt{s}$ = 7 TeV

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

MinBias



High Multiplicity: N>110

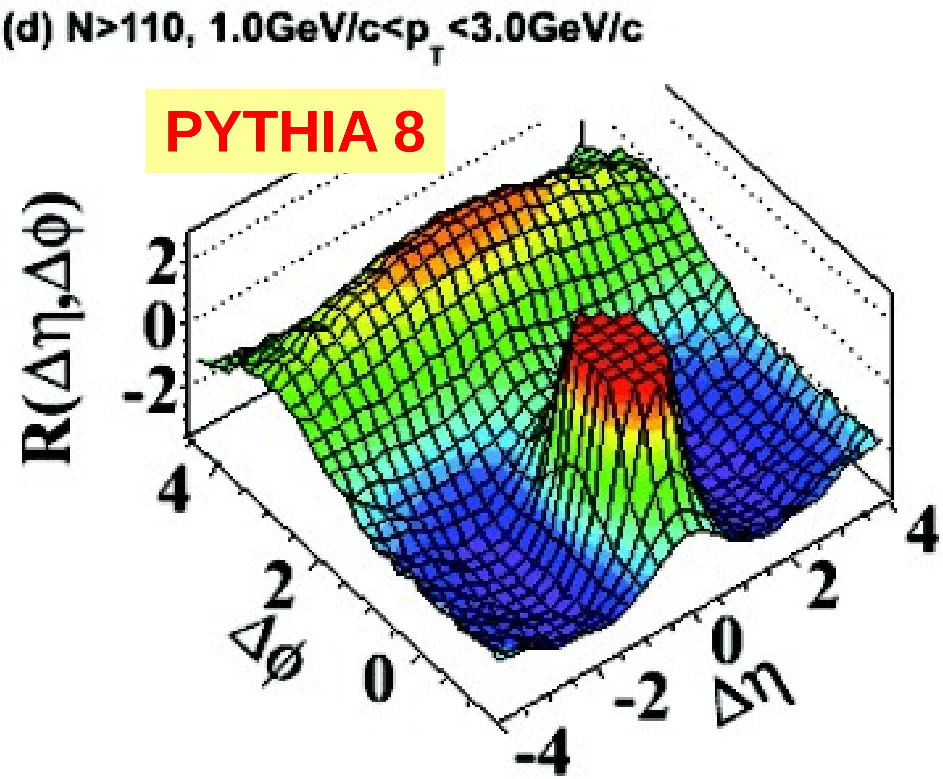


→ **Observation of a Long-Range, Near-Side angular correlations at high multiplicity in pp events at intermediate p_T (Ridge at $\Delta\phi \sim 0$)**

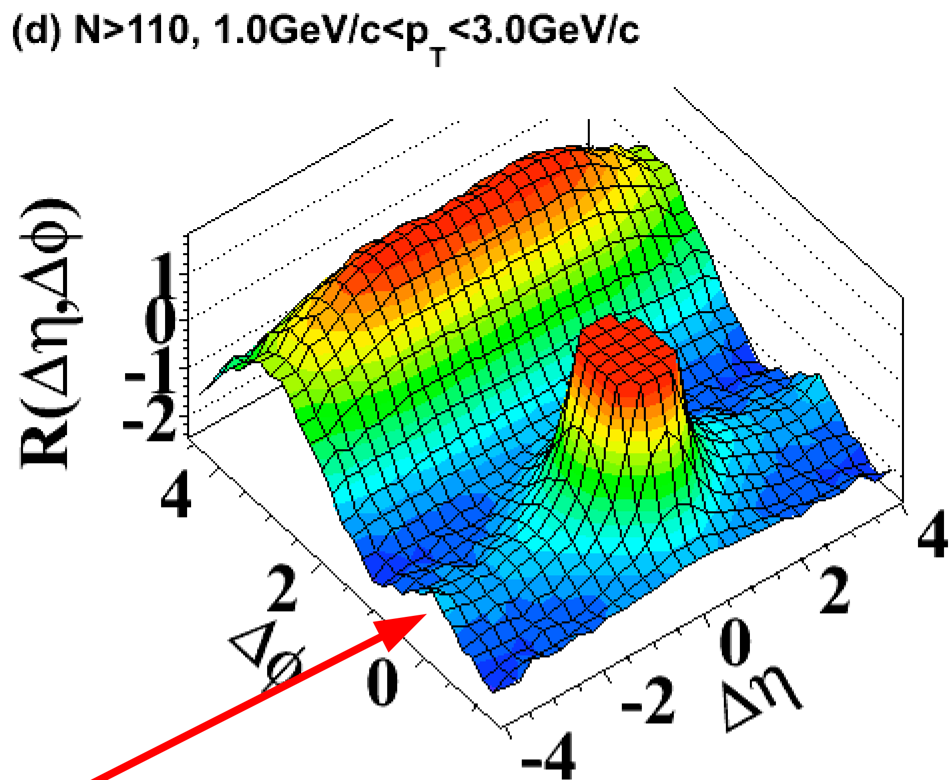
High Multiplicity Results at $\sqrt{s}$ = 7 TeV

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

High Multiplicity: N>110



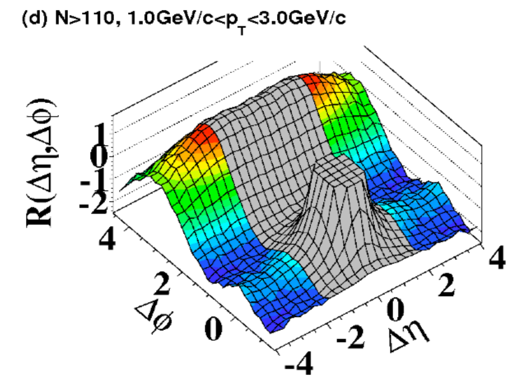
High Multiplicity: N>110



→ **Observation of a Long-Range, Near-Side angular correlations at high multiplicity in pp events at intermediate p_T (Ridge at $\Delta\phi \sim 0$)**

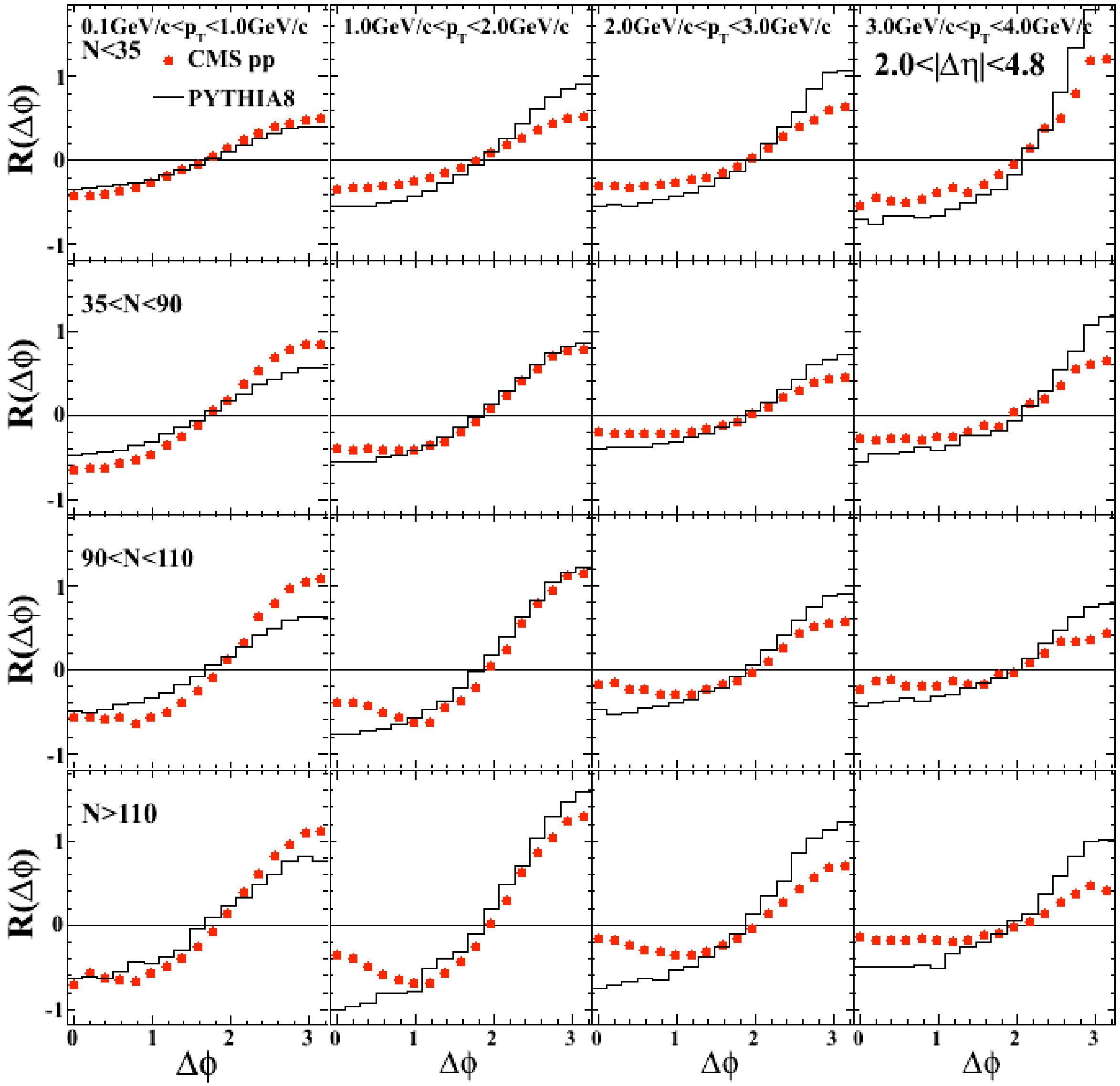
… not reproduced in PYTHIA 8 (and PYTHIA 6, HERWIG++, madgraph)

Multiplicity and p_T dependences



p_T range

Multiplicity



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

$$R(\Delta\phi) = \left\langle (N-1)\left(\frac{\int_2^{4.8} S_N(\Delta\eta,\Delta\phi)\, d\Delta\eta}{\int_2^{4.8} B_N(\Delta\eta,\Delta\phi)\, d\Delta\eta} - 1 \right) \right\rangle_N$$

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

“Ridge” not reproduced by PYTHIA 8

Bose-Einstein Correlations

PRL 105 (2010) 032001

CMS Paper QCD-10-023

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**

→ First observation in pion-production from $p\bar{p}$ annihilations – Phys. Rev. 120 (1960) 300

→ Many experimental resutls: e^+e^- @ PETRA, SLAC, LEP / $p\bar{p}$ @ SPS / ep @ HERA / fix target: NaXX, NOMAD, ...

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 is:

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

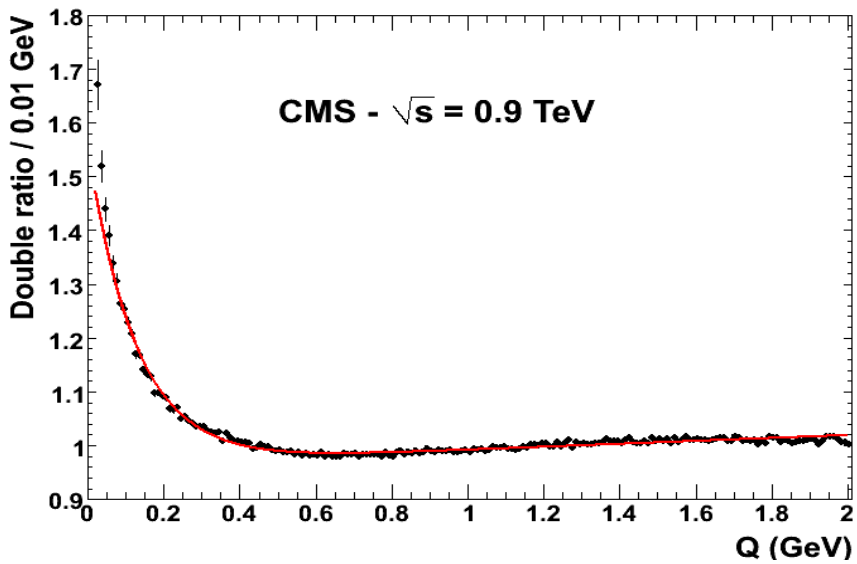
Parametrization: $$R(Q) = C[1 + \lambda\Omega(Qr)](1 + \delta Q)$$

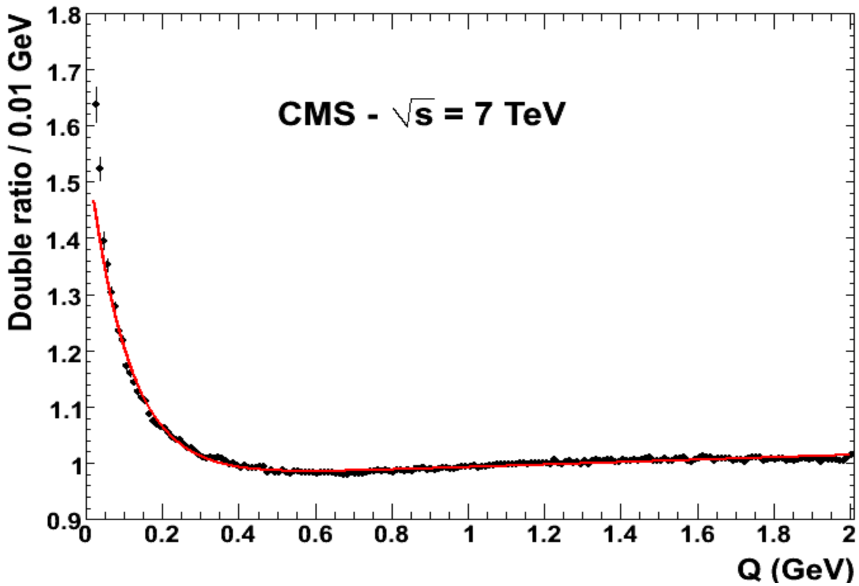
$\Omega(Qr)$: Fourier transform of emission region of effective size r

λ : BEC strength

δ : Long distance correlations

Bose-Einstein Correlations

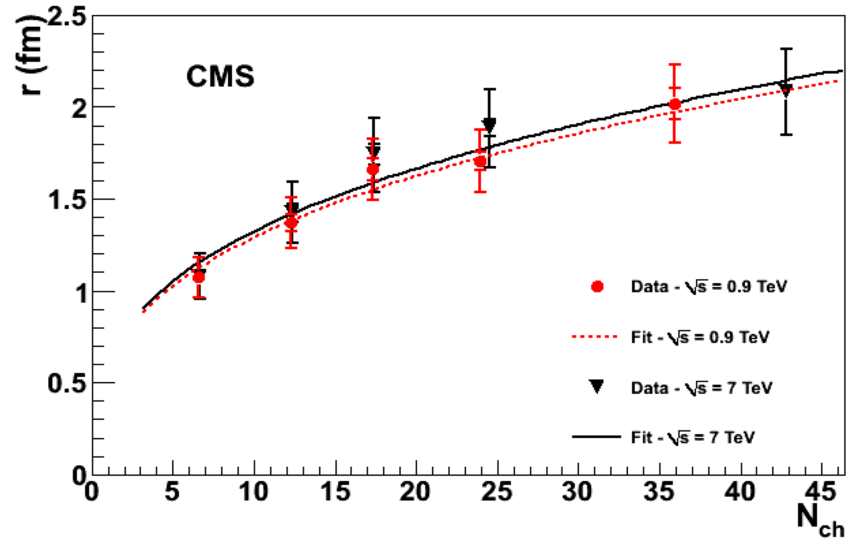




→ **Fit with $\Omega(Qr) = exp(-Qr)$:**

$\sqrt{s}$	0.9 TeV	7 TeV
r (fm)	1.56 ± 0.02 ± 0.15	1.89 ± 0.02 ± 0.21
λ	0.616 ± 0.011 ± 0.029	0.618 ± 0.009 ± 0.042

→ **BEC effective emission region grows with $\sqrt{s}$ while strength is similar**



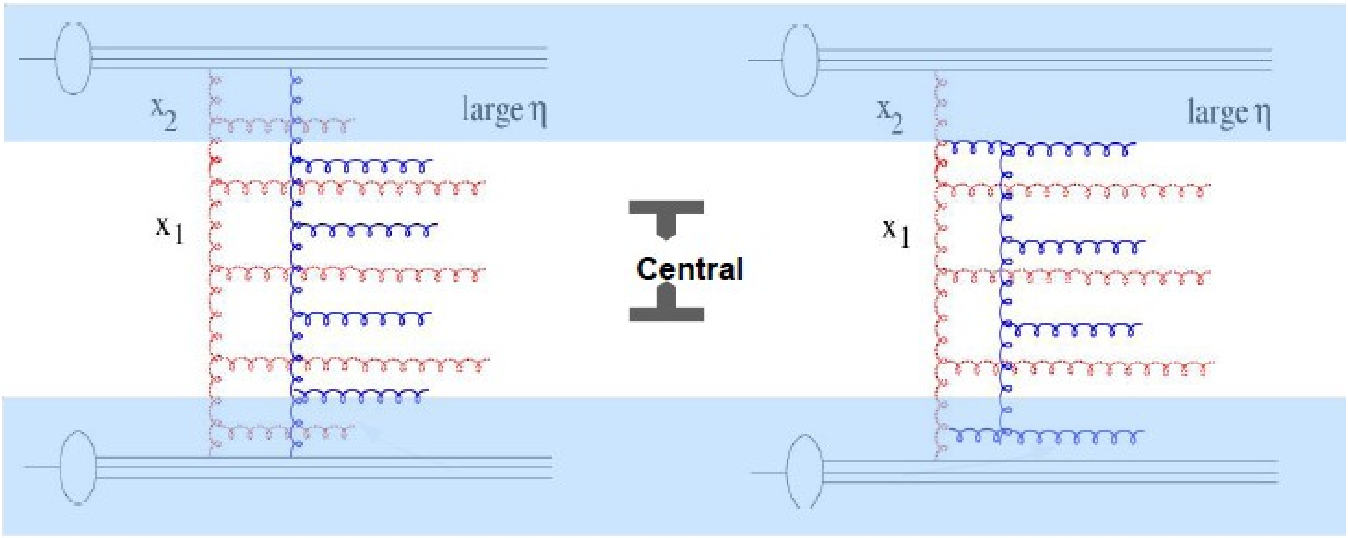
→ **BEC effective emission region grows with N as observed by previous experiments**

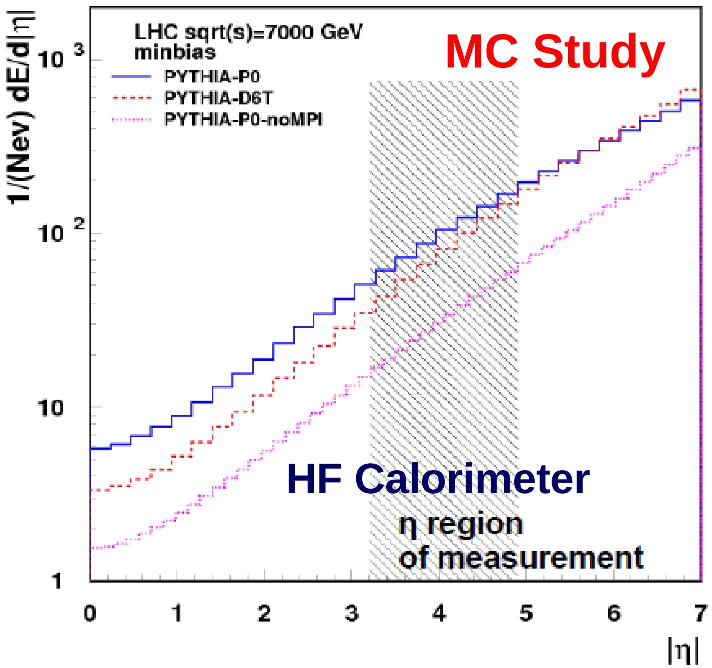
→ **This accounts for the grow with $\sqrt{s}$ (cf. dN/dη)**

Forward Physics

See B. Roland talk (Tuesday)

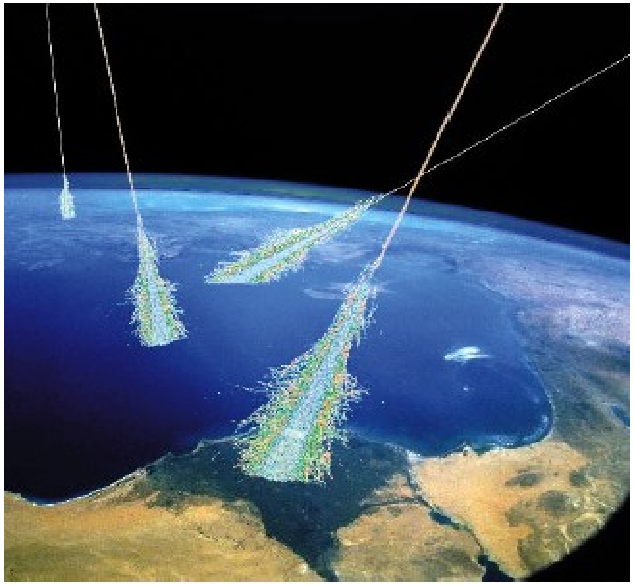
Forward Energy Flow





- High energy collisions - large parton densities important:
  → MPI, low x physics and possible saturation effects.
- Long range in rapidity between forward and central activity
  → Opens up for higher order reactions
- Energy flow in the forward region
  → Information about color (re)connections to the proton remnant

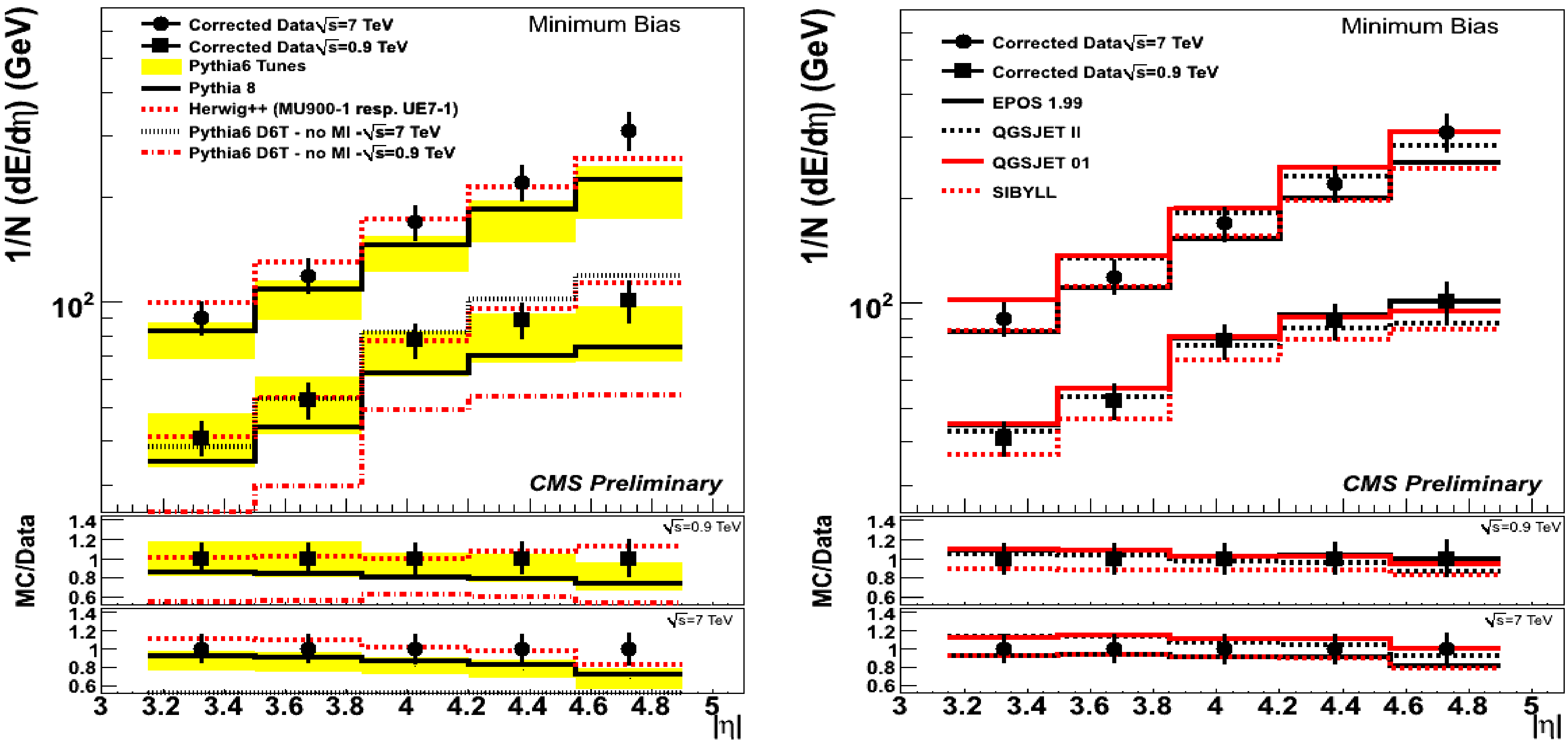
→ High sensitivity to QCD and MC generators (PYTHIA)



- Forward particle production important in air shower models
  → Majority of the energy carried by the forward particles

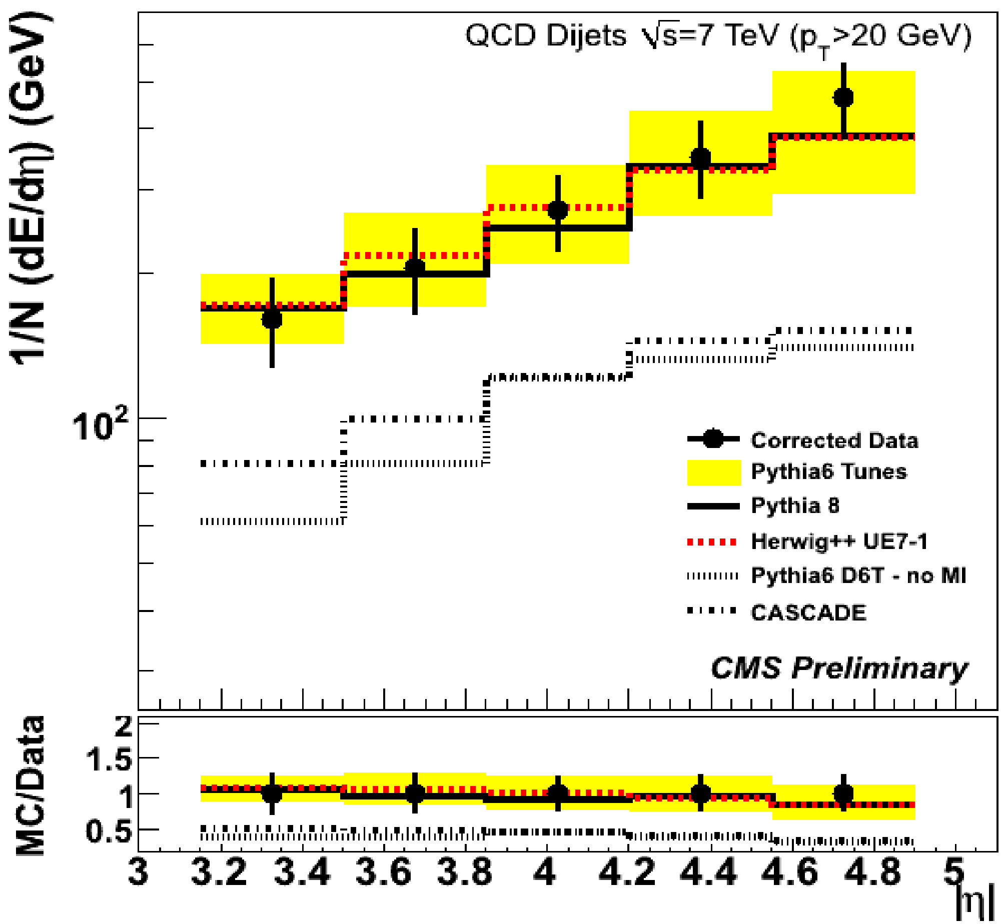
→ Test of cosmic ray MC: QGSJET, SIBYLL and EPOS

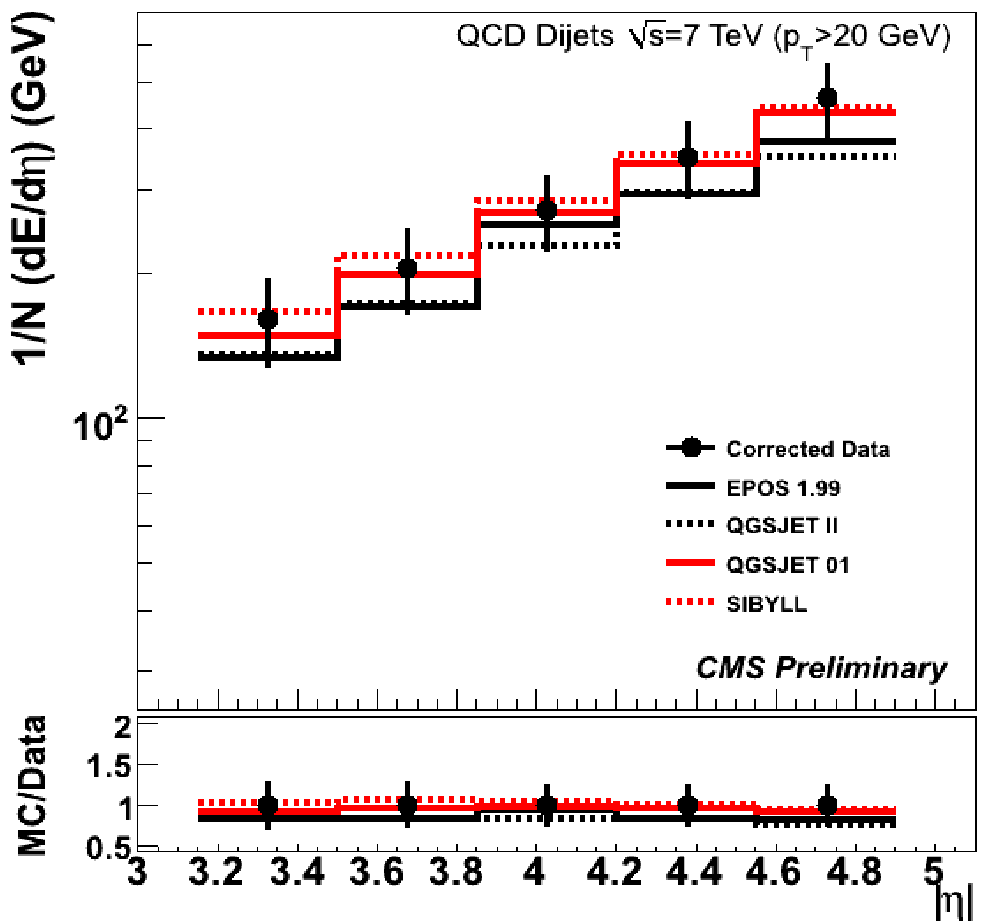
Forward Energy Flow: MinBias



- Strong dependence of forward energy flow with $\sqrt{s}$ reproduced by all MC
- Strong contributions from MPI (PYTHIA6-no MI fails)
- PYTHIA 6 (Z2,CW,D6T,P0,..) and PYTHIA 8 with MPI fails at high η (color reconnection)
- HERWIG++ describes the data (but different tunes for both $\sqrt{s}$)
- Cosmic ray generators provide a very good description of data (some still failing at high η)

Forward Energy Flow: Dijets





- Significantly higher forward energy flow in dijets events than in MinBias
- Good description by PYTHIA6 & PYTHIA8
- MPI required (PYTHIA6-no MI & CASCADE failing)
- HERWIG++ describes the data (but different tunes for both $\sqrt{s}$)
- Cosmic ray generators again providing a good description of data

  → High sensitivity to MC and tunes → Data to be used for the MC tuning effort

CMS Monte-Carlo Tuning

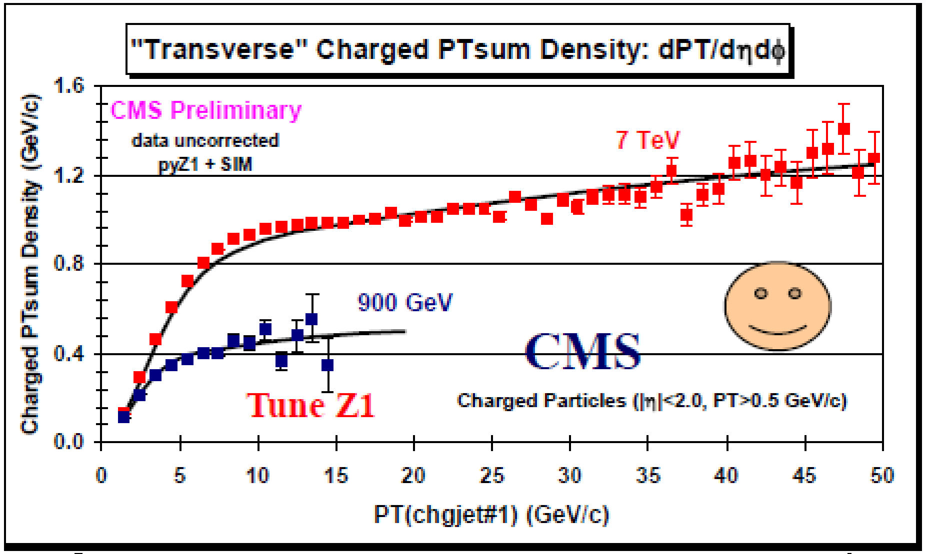
See R. Field talk (Thursday)

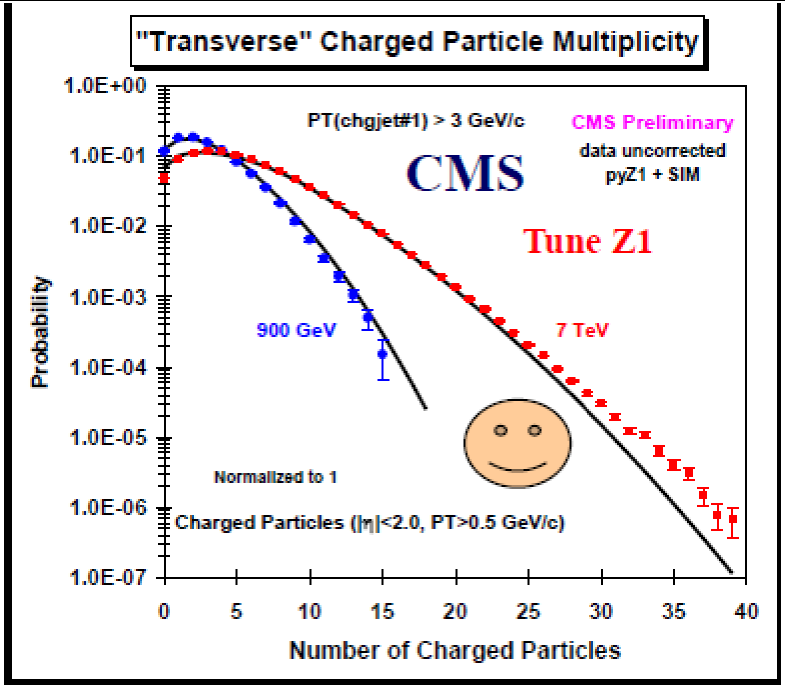
CMS UE PYTHIA Tune Z1

R. Field, MBUEWG Sept '10

- All my previous tunes (A, DW, DWT, D6, D6T, CW, X1, and X2) were PYTHIA 6.4 tunes using the old Q^2-ordered parton showers and the old MPI model (really 6.2 tunes)!
- I believe that it is time to move to PYTHIA 6.4 (p_T-ordered parton showers and new MPI model)!
- Tune Z1: I started with the parameters of ATLAS Tune AMBT1, but I changed LO* to CTEQ5L and I varied PARP(82) and PARP(90) to get a very good fit of the CMS UE data at 900 GeV and 7 TeV.

Parameter	Tune Z1 (R. Field CMS)	Tune AMBT1 (ATLAS)
Parton Distribution Function	CTEQ5L	LO*
PARP(82) – MPI Cut-off	1.932	2.292
PARP(89) – Reference energy, E0	1800.0	1800.0
PARP(90) – MPI Energy Extrapolation	0.275	0.25
PARP(77) – CR Suppression	1.016	1.016
PARP(78) – CR Strength	0.538	0.538
PARP(80) – Probability colored parton from BBR	0.1	0.1
PARP(83) – Matter fraction in core	0.356	0.356
PARP(84) – Core of matter overlap	0.651	0.651
PARP(62) – ISR Cut-off	1.025	1.025
PARP(93) – primordial kT-max	10.0	10.0
MSTP(81) – MPI, ISR, FSR, BBR model	21	21
MSTP(82) – Double gaussion matter distribution	4	4
MSTP(91) – Gaussian primordial kT	1	1
MSTP(95) – strategy for color reconnection	6	6



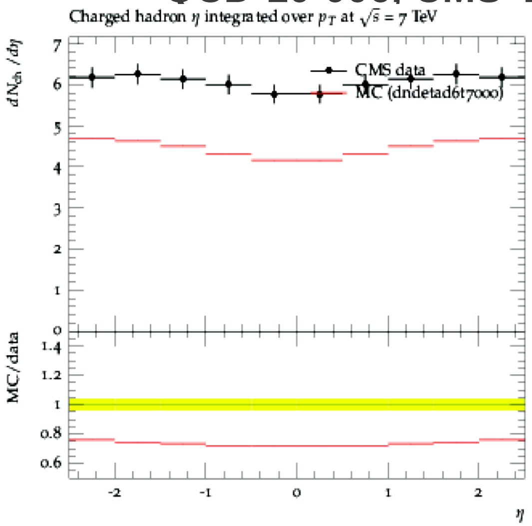


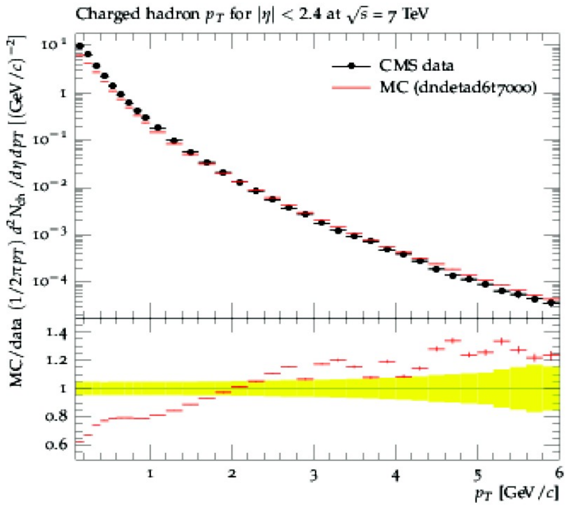
→ CMS use Z2 tune (Same as Z1 +CTEQ6L) for new round of MC production

Status of CMS Soft QCD/FWD analysis in Rivet

dN/dη and dN/dp$_T$ at 0.9, 2.36, and 7 TeV

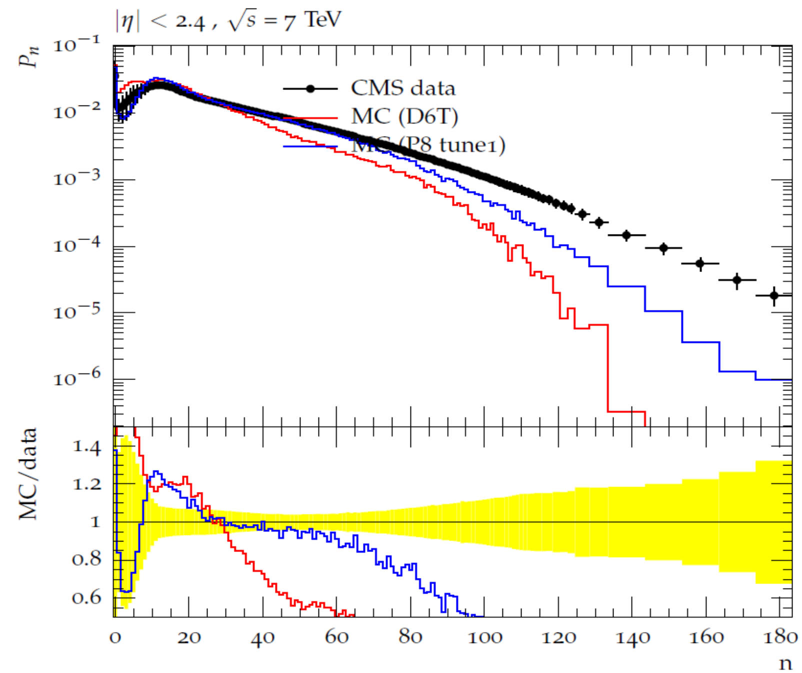
QCD-09-010: CMS_2010_S8547297
QCD-10-006, CMS_2010_S8656010





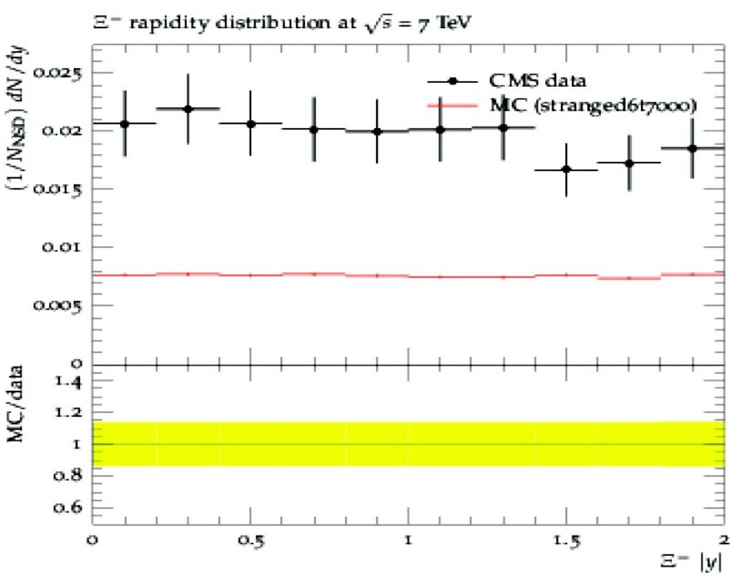
Multiplicities at 0.9, 2.36, and 7 TeV

QCD-10-004, CMS_2011_S8884919



Strange Partcicles at 0.9 and 7 TeV

QCD-10-007, CMS_2011_S8978280



TODO:

- UE leading jet (being validated)
- Other UE: DY, jet area.
- dN/dp$_T$: “extended p$_T$ range”
- dN/dη with central particles
- Bose-Einstein correlations
- Forward: energy flow, fwd jets, jet kT factors, ...

CONCLUSIONS

Inelastic cross-section:

New method exploiting the pile-up at LHC !

$$\sigma_{inel}(pp) = 68 \pm\ 2.0\ (\mathrm{Syst}) \pm\ 2.4\ (\mathrm{Lum})\ \pm\ 4(\mathrm{Ext.})\ \mathrm{mb}$$

Particle spectra and correlations:

- Understanding of soft QCD contributions is crucial for new physics searches and precision measurements of Standard Model processes
- Pre-LHC Monte Carlo tunes do not describe the data well in all aspects → Monte Carlo tuning effort ongoing
- Strangeness production has been investigated showing similar discrepancy
- Bose-Einstein correlations have been studied in detail
- Long-range correlations has been observed in proton data

Forward physics:

- Need of MPI to describe the forward energy flow and jets
- Forward energy flow provides further constraints for Monte Carlo tuning and a validation of cosmic ray generators