Low-p_T QCD Physics with the CMS detector

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Outline

- Underlying Event analyses
- p_T, pseudorapidity and multiplicities of charged hadrons
- Short and long-range angular correlations
- Bose-Eistein Correlation

Underlying Events: reminders

- Hard process final state hadron-hadron interactions can be described as:
  - Products of partonic hard scattering; including ISR and FSR.
  - UE events (which cannot be uniquely separated from ISR and FSR):
    - + Hadrons produced in additional Multiple Parton Interactions (MPIs)
    - + Beam-Beam Remnants (BBR).

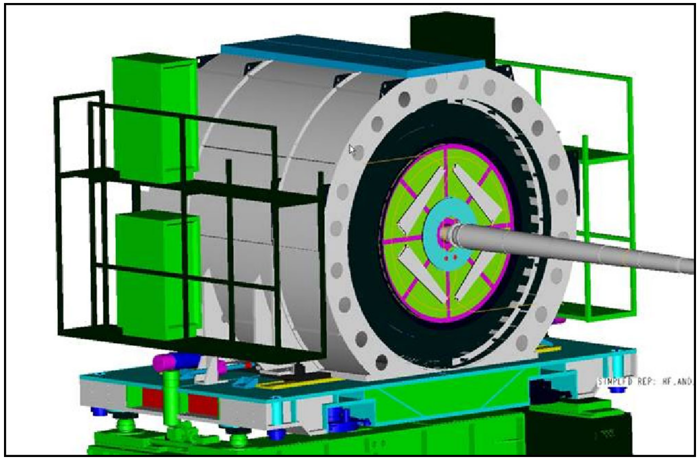
- Qualitative expectation on UEs:
  - Harder scale $\Leftarrow$ smaller Impact Parameter $\Rightarrow$ larger MPI activity (+plateau due to saturation)
  - Larger $\sqrt{s}$ $\Rightarrow$ increased Parton Density $\Rightarrow$ larger MPI activity

- In reference to the direction of the track or the jet with the leading p_T
  - "Toward" region $|\Delta\phi| < 60^\circ$ hard parton scattering and radiation
  - "Away" region $|\Delta\phi| > 120^\circ$ hard parton scattering and radiation
  - "Transverse" region $60^\circ < |\Delta\phi| < 120^\circ$ is dominated by UEs

Detectors

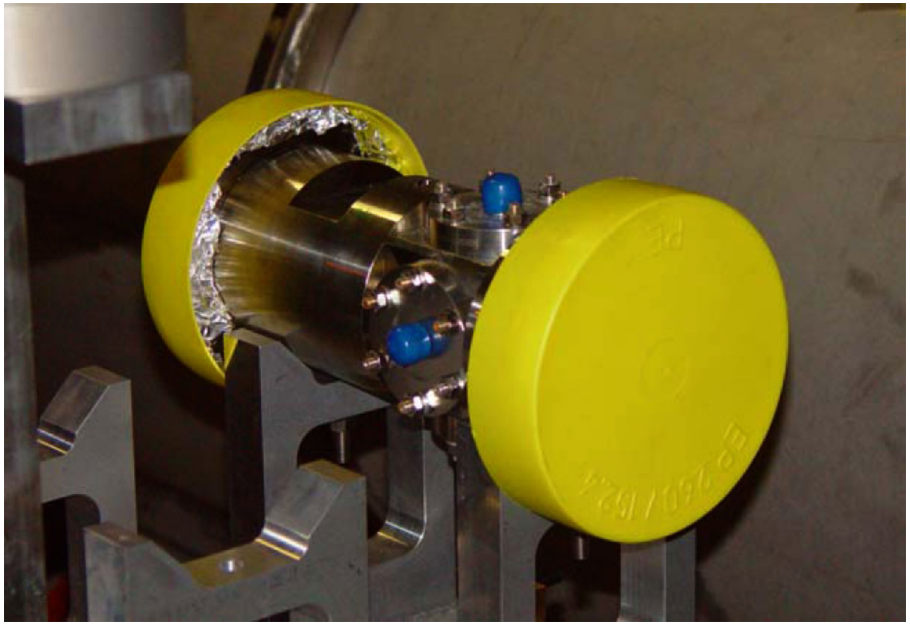
- Tracker
  - $|\eta| < 2.5$
  - p_T resolution 0.7% at $\eta = 0$ and 2% at $|\eta| = 2.5$
  - Alignment precision of 3-4 μm in the barrel region

BSC



- Beam Scintillator Counters (BSC)
  - IP distance 10.86 m
  - $3.23 < |\eta| < 4.65$
  - Time resolution 3 ns

- Beam Pick-up Timing for eXperiments (BPTX)
  - IP distance 175 m
  - Time resolution 0.2 ns



UE analyses: selections

- Signal in both BSCs

- in coincidence with BPTX signals from both beams ⇒ Beam-induced background negligible.
  Pile-up below % level.

- 1 Primary Vertex (PV)

- $|z| < 10$ (15) cm at 7 (0.9) TeV from the center of the beam collision (of rms 4 cm).
- fit d.o.f. > 4 (3) at 7 (0.9) TeV.

- Leading track-jet

- $|\eta| < 2$ and $p_T > 3$ GeV or 20 GeV.
- SISCone algo with R = 0.5.
- Constituents: charged particles with $p_T > 0.5$ GeV and $|\eta| < 2.5$ (to avoid a kinematic bias).

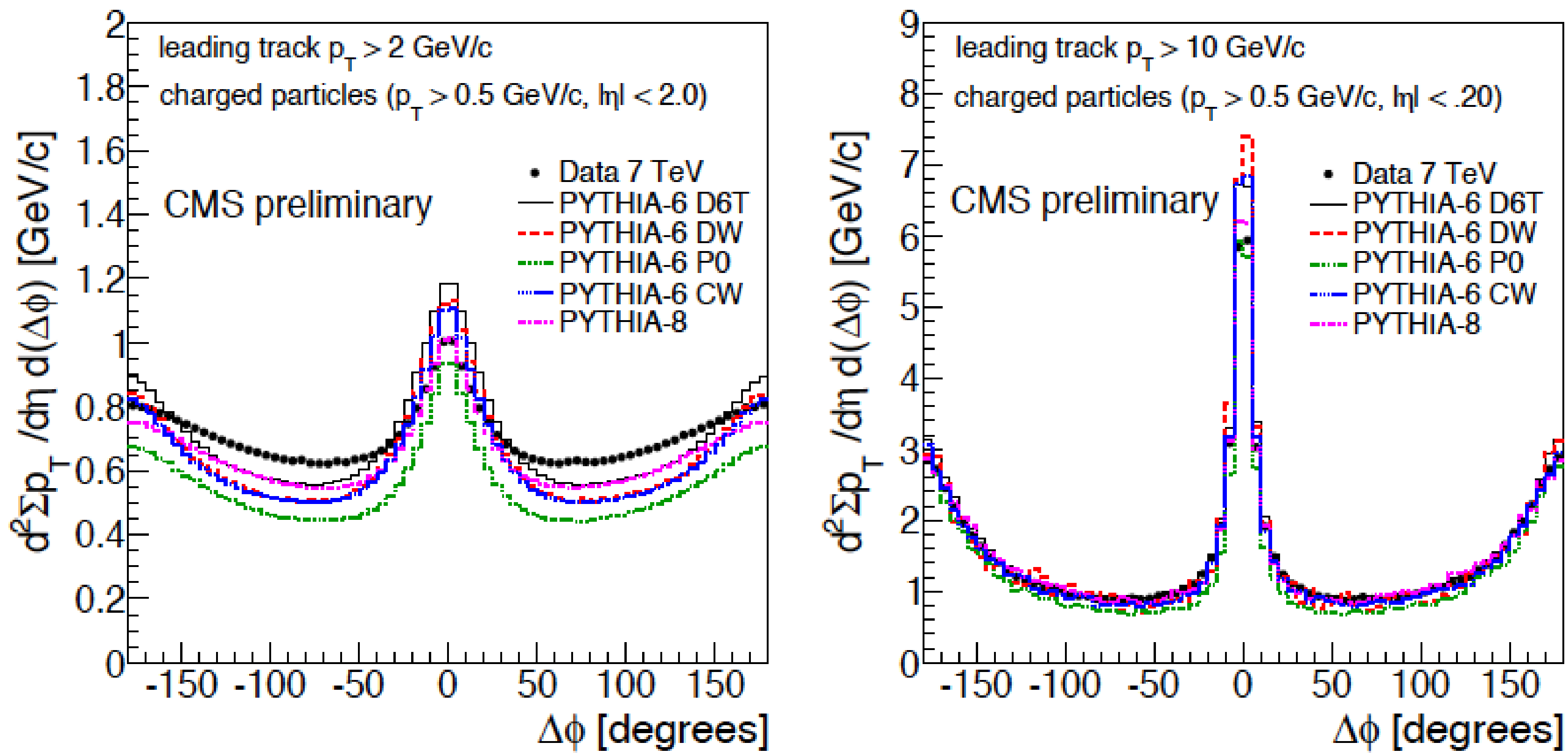
- Selected tracks

- $p_T > 0.5$ GeV and $|\eta| < 2$ belonging to PV.
- High purity tracks.
- $d_{xy}/\sigma(d_{xy})$ and $d_z/\sigma(d_z) < 3$ (5) at 7 (0.9) TeV
  ⇒ Reducing sec. tracks from long lived and γ-conversion.
- $\sigma(p_T)/p_T < 5\%$

⇒ Contamination: 1% K_S^0 and Λ^0 and 2% fake tracks.

Track selection	Data [nb. tracks]	Data [%]	MC [%]
reconstruction algorithm	491 228 197	100	100
$+ p_T > 0.5$ GeV/c	256 716 859	52.26	60.01
$+ \|\eta\| < 2.5$	254 290 734	99.05	98.94
$+ \|\eta\| < 2$	212 357 949	83.51	82.83
$+ d_{xy}/\sigma(d_{xy}) < 3$	181 128 780	85.29	85.72
$+ d_z/\sigma(d_z) < 3$	175 700 636	97.00	97.67
$+ \sigma(p_T)/p_T < 5\%$	170 834 393	97.23	96.96

UE analyses: $\Delta\phi$



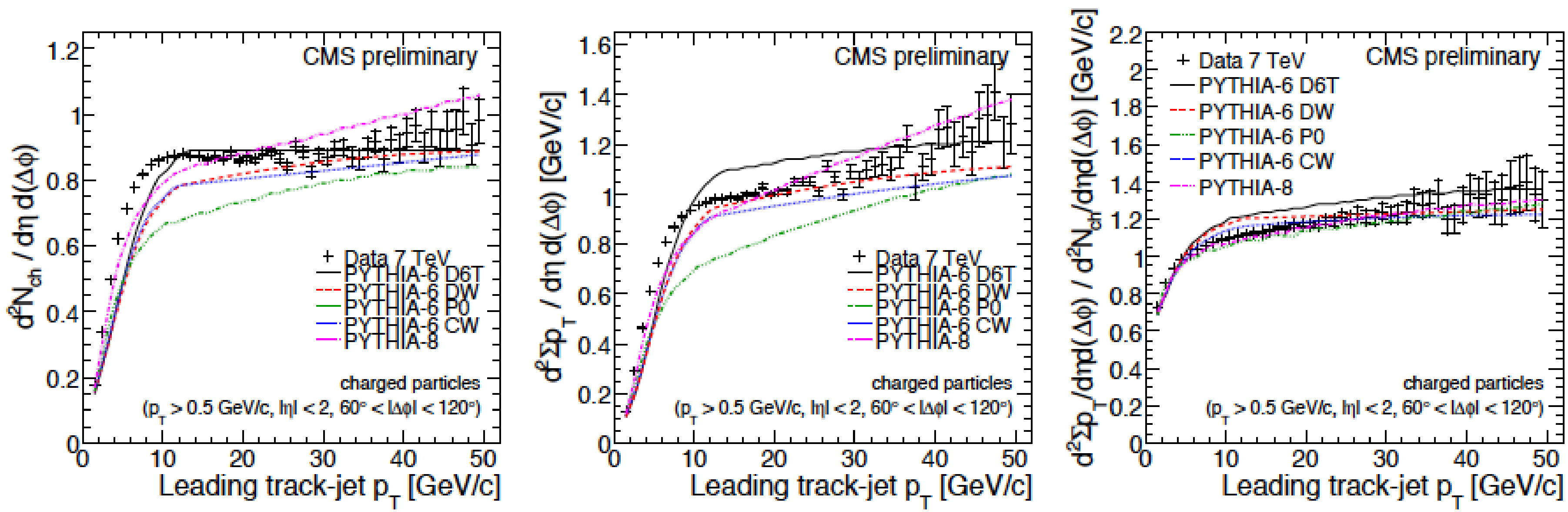
- The characteristic features of two-jet parton-parton production + UE activity are observed.

- Best descriptions from PHYTIA8 and P0 in the “toward” region for scale > 2 and 10 GeV respectively.
- All models well describe the “away” and “transverse” regions for scale > 10 GeV except P0.

UE analyses: transverse region

- Selected tracks
  - $p_T > 0.5$ GeV, $|\eta| < 2$ and $60^\circ < |\Delta\phi| < 120^\circ$

Inner error bars: statistical error
Outer error bars: statistical error + systematic error from MC



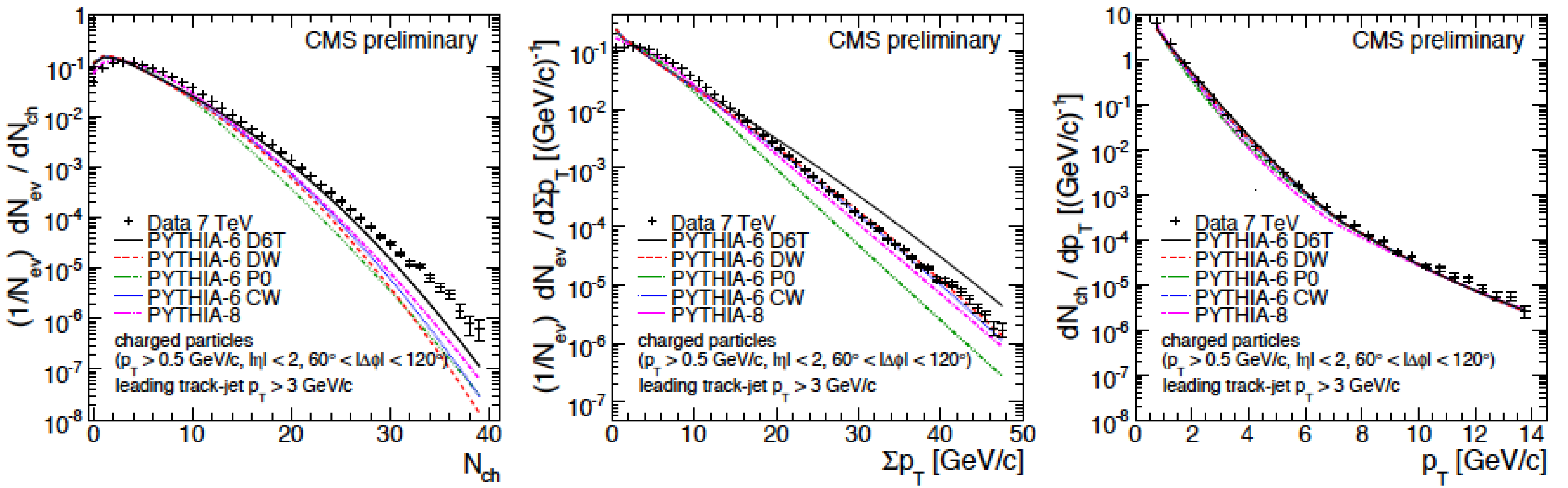
Fast rise at $p_T \leq 8$ GeV attributed to increase of MPI activity. Plateau region due to saturation.

- **$dN_{ch}/d\eta\ d(\Delta\phi)$ average multiplicity:** PYTHIA8 successful at low scale. D6T more successful in the plateau region. P0 systematically low.
- **$d\Sigma p_T/d\eta\ d(\Delta\phi)$ transverse activity:** DW successful in the plateau region.
- **Ratio of the two:** PYTHIA8 and P0 better. CW and DW too flat. D6T too high over most of the range.

UE analyses: transverse region

- Selected tracks
  - $p_T > 0.5$ GeV, $|\eta| < 2$ and $60^{\circ} < |\Delta\phi| < 120^{\circ}$

Inner error bars: statistical error
Outer error bars: statistical error + systematic error from MC



- Overall good agreement.
- Anyway, too soft **multiplicity distributions**.
- In the **transverse activity** distribution all tunes are below the data up to 10 GeV. For values > 10 GeV, CW and DW give a good description, while D6T overshoots the data.
- Good agreement for all models in the **p_T spectra**. Best agreement in P0 due to new MPI.
- N_{ch} up to 40 and $\sum p_T$ up to 50 GeV/c indicate an hard component in the transverse region.

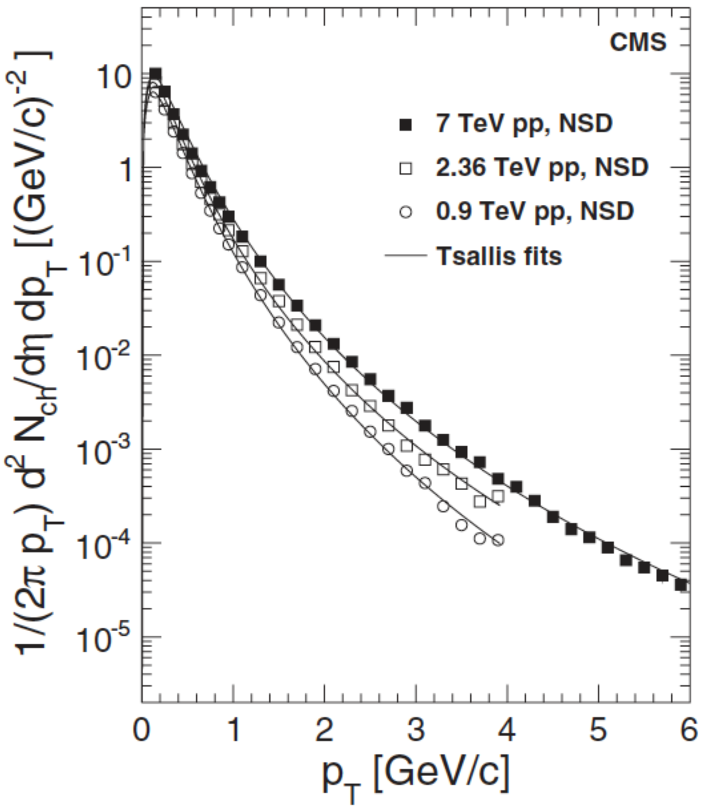
Charged hadrons: reminders

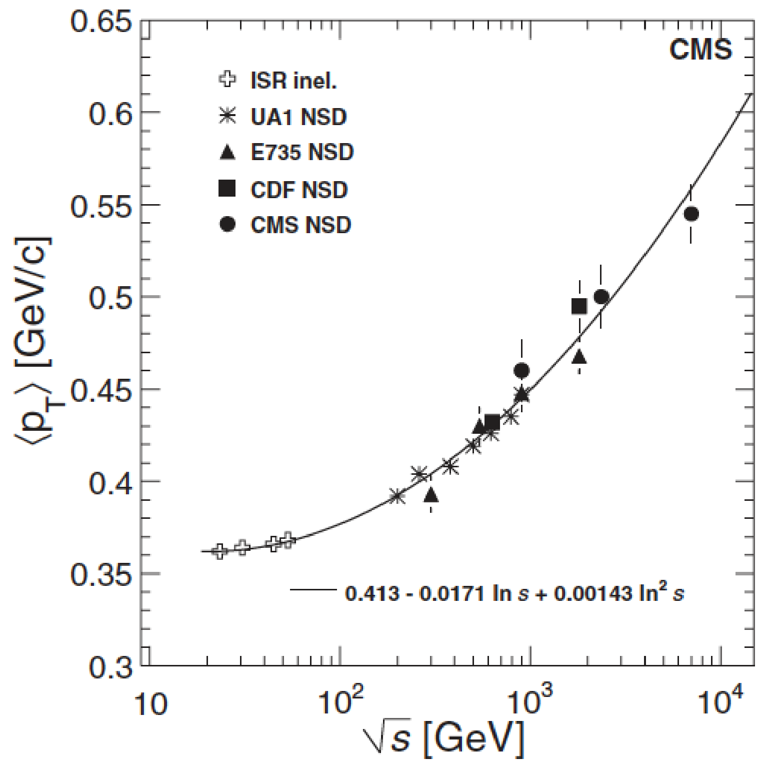
- Soft collisions are commonly classified as:
  - Elastic scattering.
  - Inelastic single-diffractive (SD) dissociation.
  - Inelastic double-diffractive (DD) dissociation (here we include Double-Pomeron exchange).
  - Inelastic non-diffractive (ND) scattering.

  - We can define also the non-single diffractive (NSD) interactions, which are based on event selection retaining large fraction of ND and DD, disfavoring SD.

- Charged hadrons:
  - Here we will focus on distributions from charged hadrons in NSD events
  - Charged particles are defined as decay products of particles with proper lifetime < 1 cm.
  - Products of secondary interactions are excluded
  - Correction is applied for prompt leptons.

Charged hadrons: p_T



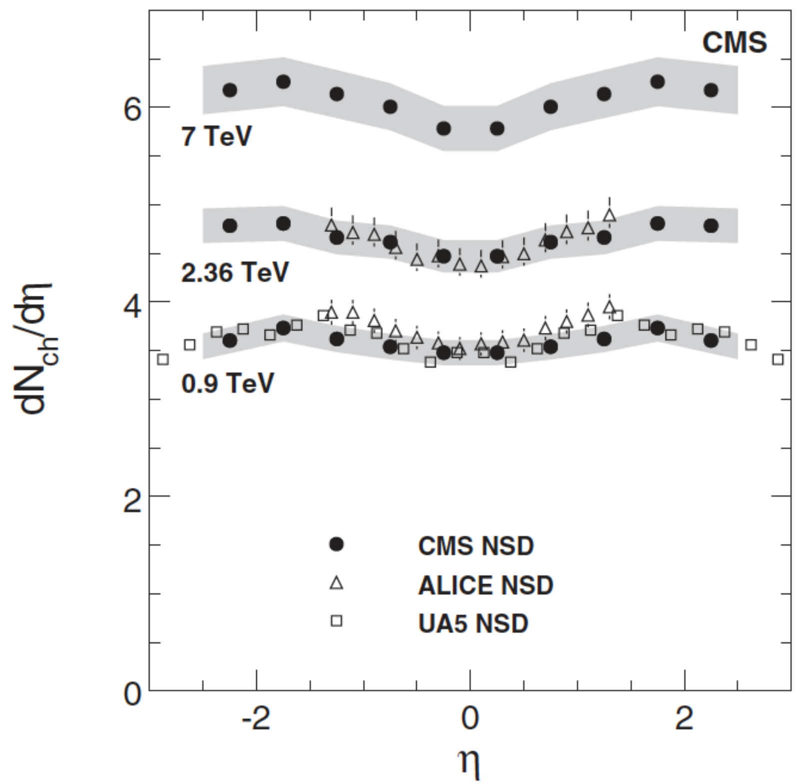


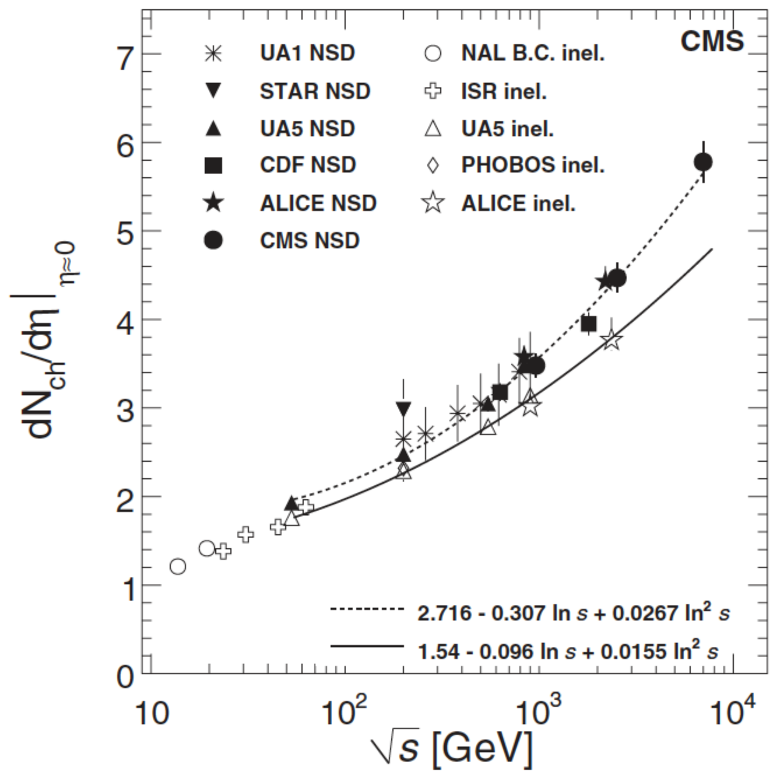
$<p_T>$ = 0.545 ± 0.005 (stat) ± 0.015 GeV/c (from measured points and low/high-p_T contributions form the fit).

- Uncertainties coming from: SD/DD fraction 1.4%/1.1%, selection efficiency (including BSC and HF efficiency) 3.5%, tracklet/track reco efficiency 3%/2%, extrapolation at p_T = 0 -> 1% and uncertainties in ref. [4]

- Final systematic uncertainties are: 5.7%, 4.6% and 4.3% for the barrel pixel, pixel tracklet and full tracker method respectively.

Charged hadrons: η





$<dN_{ch}/d\eta|_{=0}> = 5.78 \pm 0.01$ (stat) ± 0.23 (syst)

Models:

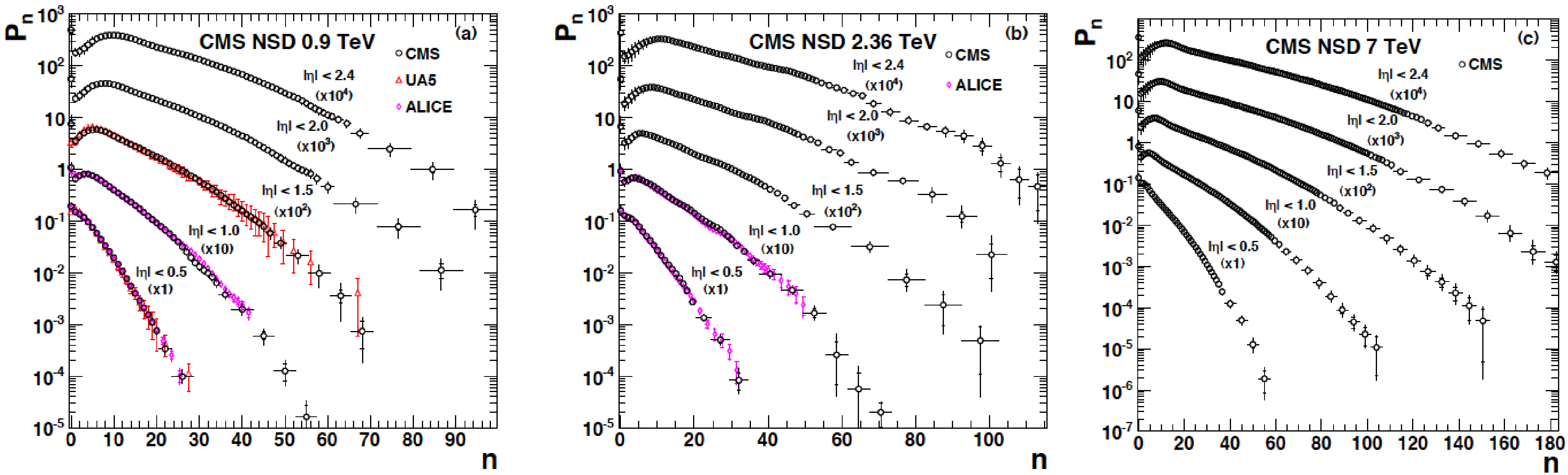
DW, PROQ20, P0 (of PYTHIA) and PHOJET are at: 3.99, 4.18, 4.34 and 4.57 respectively.

Experiments:

Increase between 0.9 and 7 TeV comparable to ALICE result using a somewhat different selection [5].

Charged hadrons: P_n

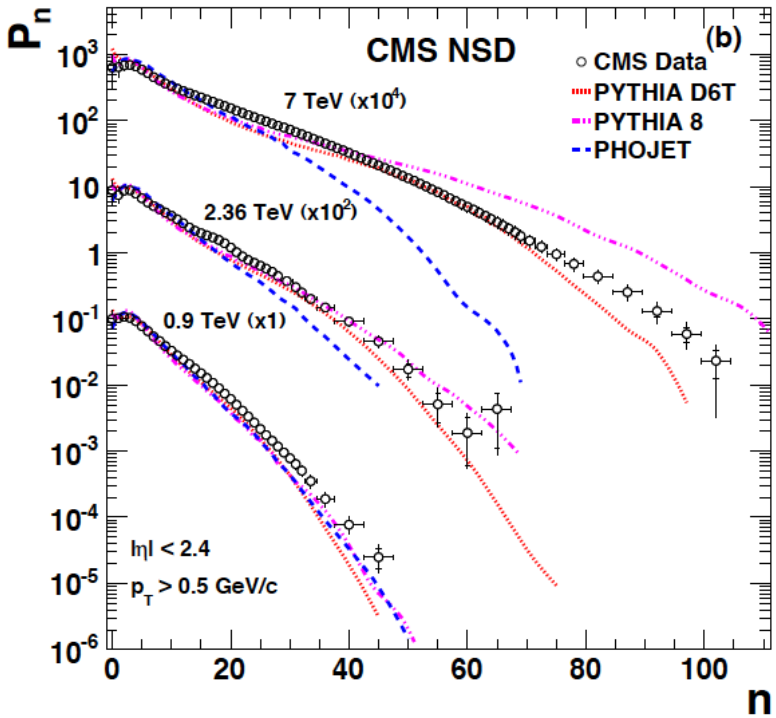
Comparison with experiments

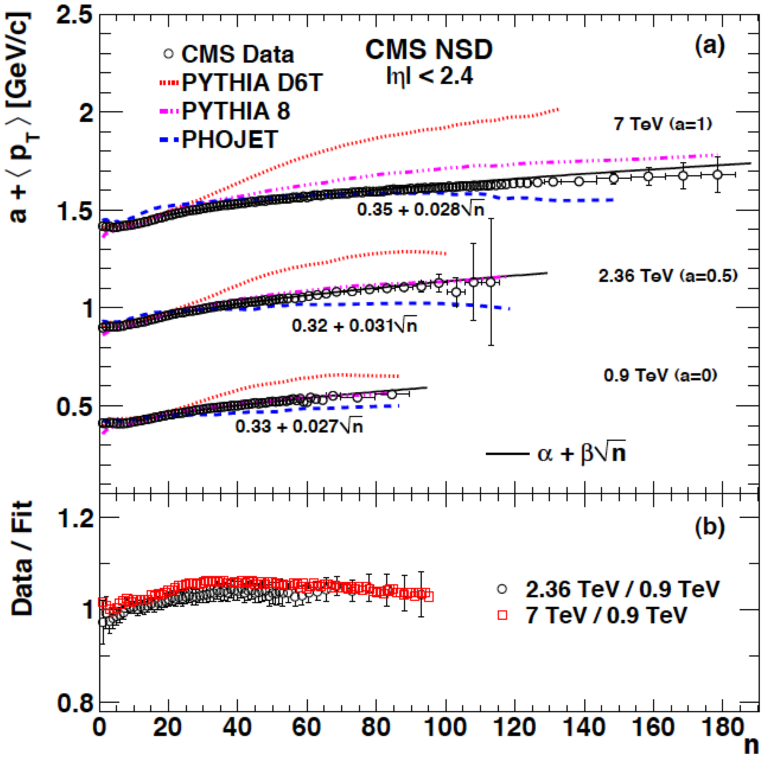


- Good agreement with previous measurements from UA5 and ALICE.
- For the range |η| < 2.4 change of slope for P_n > 20 indicating a multicomponent structure which could be explained in terms of mutliple-soft-Pomeron exchanges [7, 8].

Charged hadrons: P_n

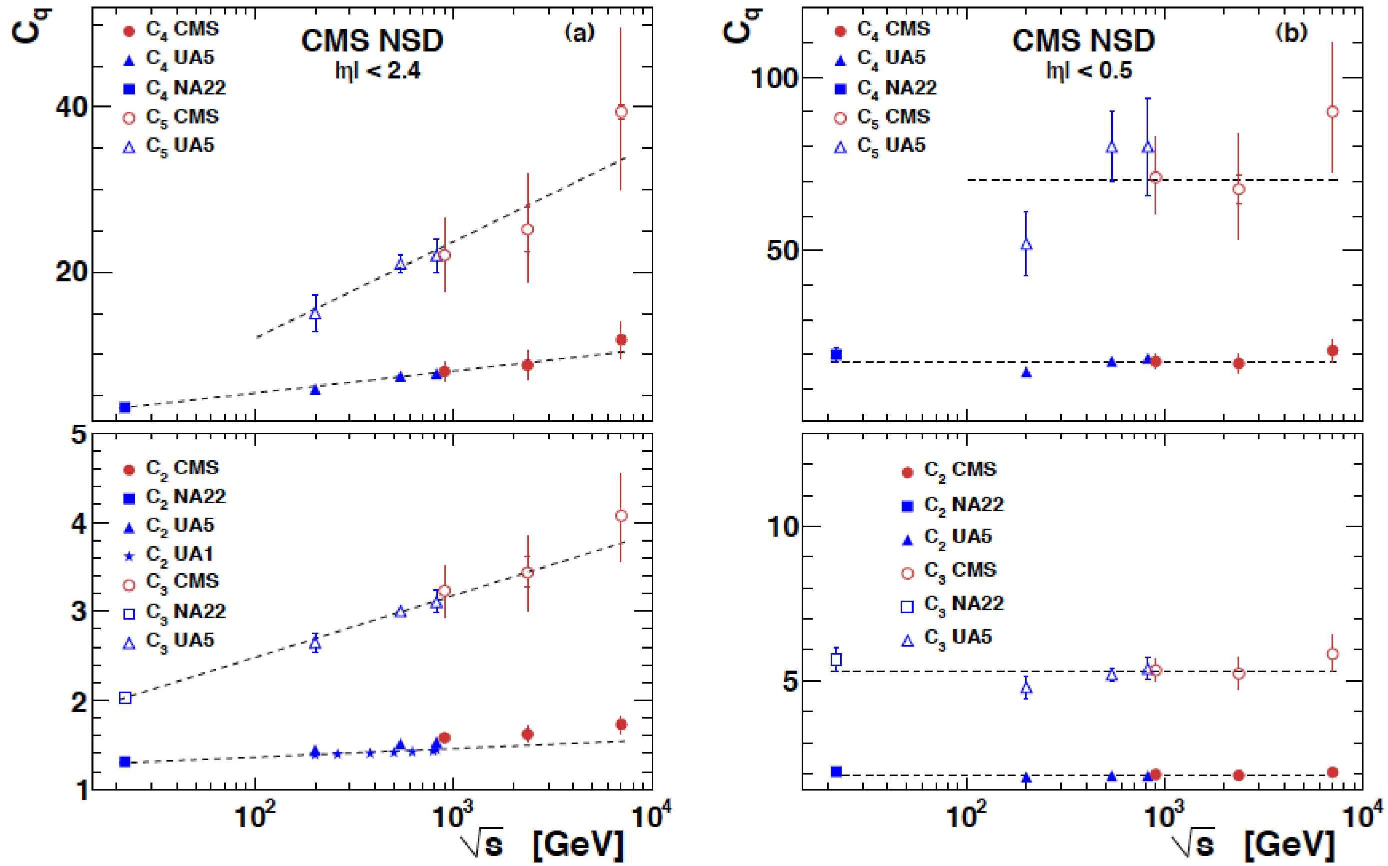
Comparison with models





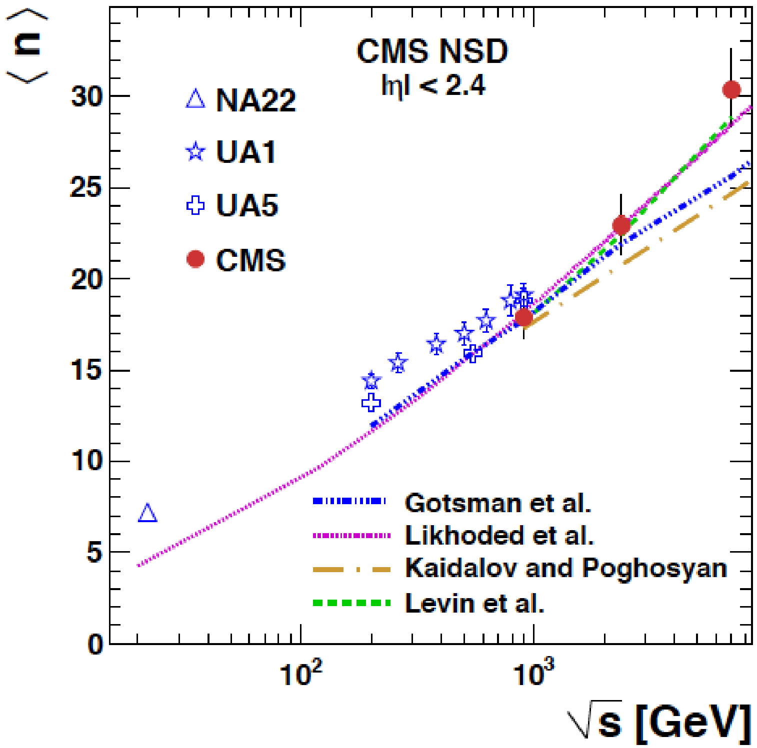
- PYTHIA D6T is in good agreement for $p_T > 0.5$ GeV, but it underestimates at all multiplicities for $p_T > 0$ (not shown here).
- PYTHIA8 gives a good description with the exception of large n for $p_T > 0.5$ GeV.
- PHOJET produce too few charged hadrons, but it gives a good description of $\langle p_T \rangle$ vs. n.
- In conclusion too few low p_T particles. PYTHIA tends to compensate with too many high p_T particles.

Charged hadrons: KNO scaling violation



- Here C_q are the normalized moments of the KNO function $\Psi(z) = \langle n \rangle P_n$ where $z = n/\langle n \rangle$ [9, 10].
- The KNO scaling hold for $|\eta| < 0.5$ and is violated for $|\eta| < 2.4$
- This confirms previous observations from UA5 which, together with the change of slope of P_n at high n is interpreted as evidence for a multi-component structure.

Charged hadrons: <n> vs. √s



$\sqrt{s}$ (TeV)	$\langle n \rangle$			
	Data	PYTHIA D6T	PYTHIA 8	PHOJET
0.9	$17.9 \pm 0.1^{+1.1}_{-1.1}$	14.7	14.9	17.1
2.36	$22.9 \pm 0.5^{+1.6}_{-1.5}$	16.7	17.8	18.7
7	$30.4 \pm 0.2^{+2.2}_{-2.0}$	21.2	25.8	23.2

- PYTHIA D6T underestimates <n> at all energies.

- PHOJET is consistent with data at 0.9 TeV, but not able to predict at *7* TeV.

- PYTHIA8 describes *7* TeV, but underestimates <n> at all energies.

- Recent Regge-inspired models predict a power-like behavior. Among these, the one in reference [11] gives a good description at high energy.

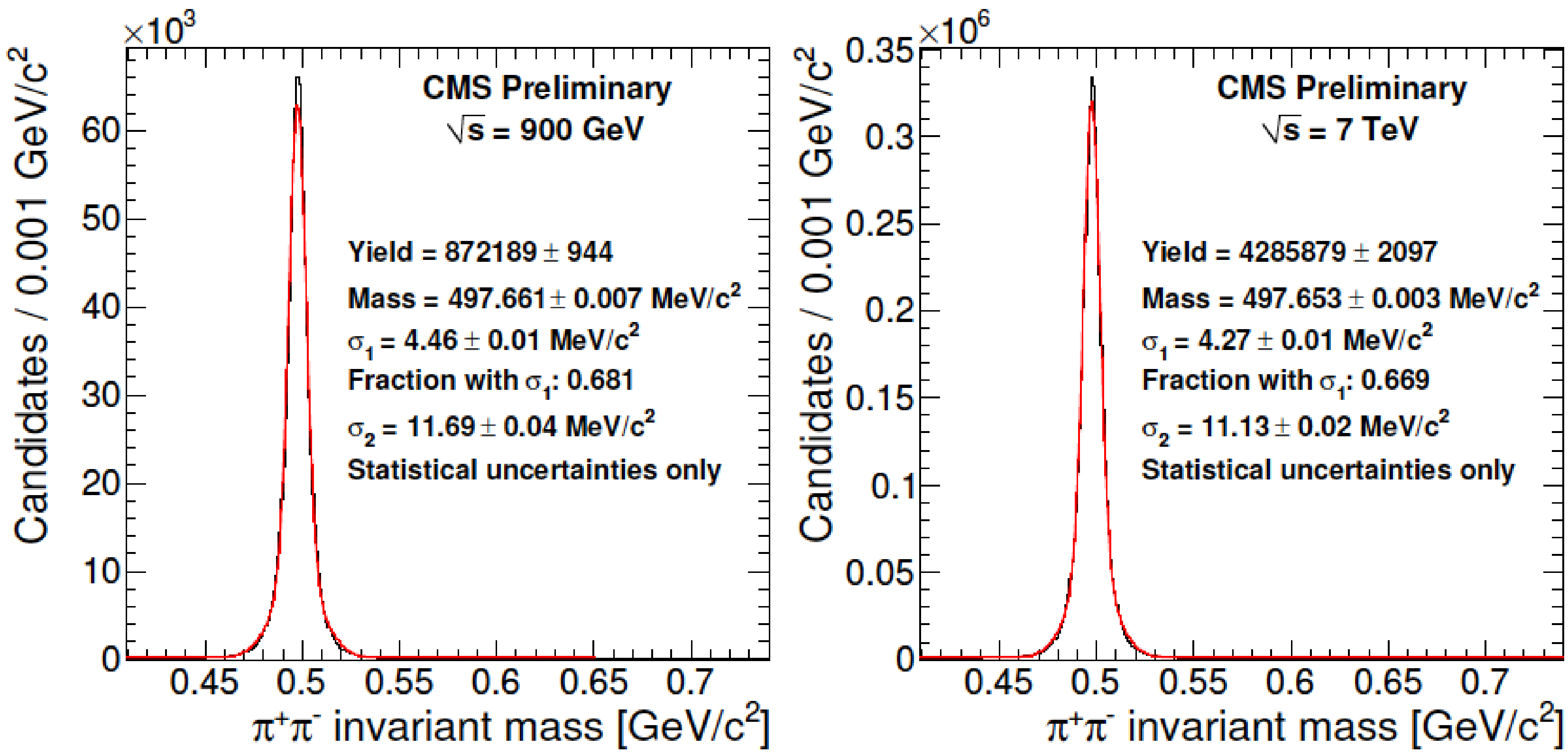
Strange particle production: reminders

- Strange mesons and baryons measurements aim at testing:
  - Interplay of soft and hard QCD at LHC.
  - Universality of fragmentation models.
  - Baryon transport mechanism.

- Strange particles here are:
  - Long-lived particles: $c\tau > 1$ cm.
  - $K_S^0 \rightarrow \pi^+\pi^-$, $\Lambda^0 \rightarrow p\pi^-$, $\Xi^- \rightarrow \Lambda^0\pi^-$

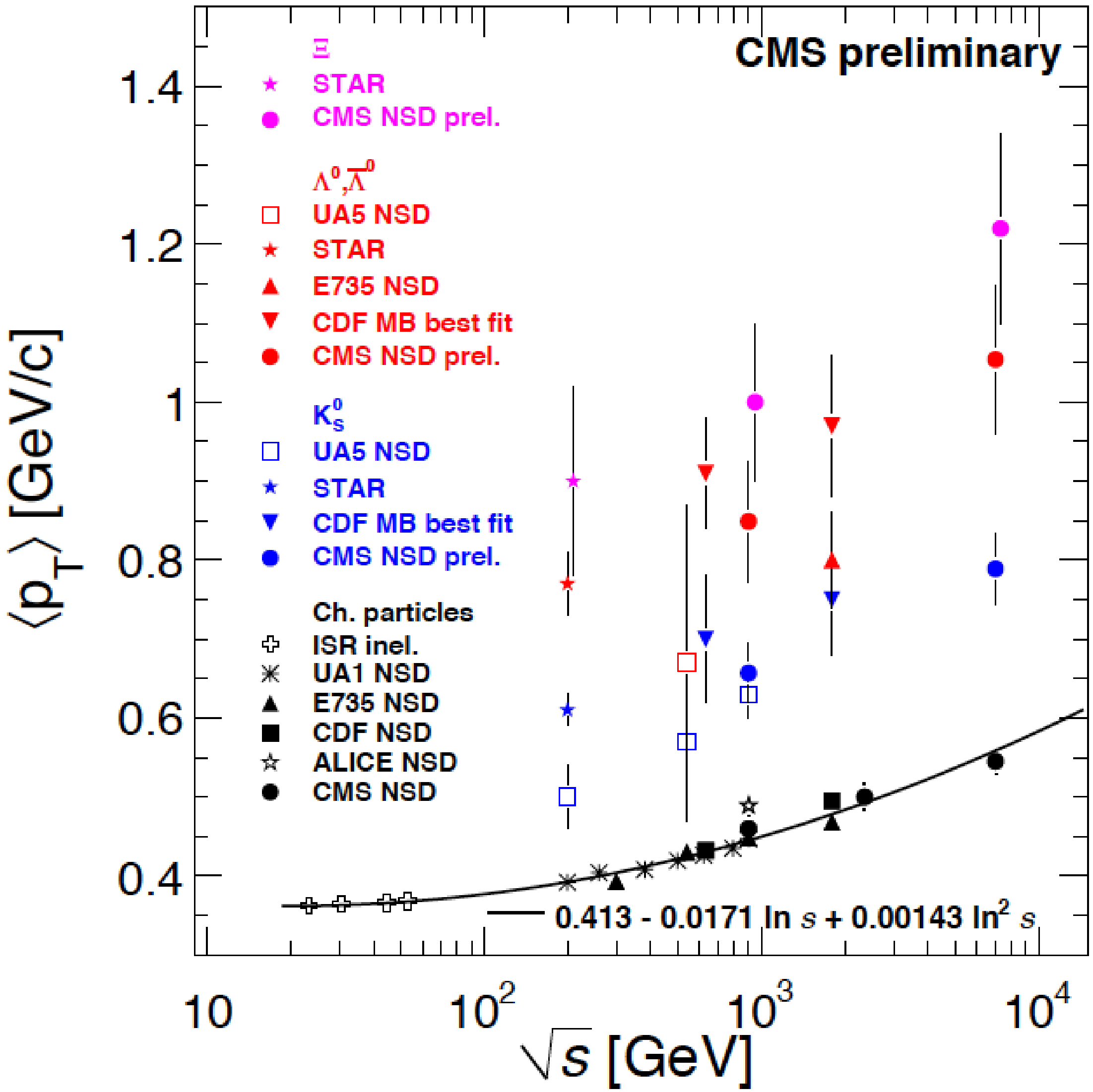
- Models are:
  - PYTHIA8
  - PYTHIA D6T and P0
  - For all the strange to down quark suppression factor was set to 0.3.

Strange particle production: K_S^0



Fit with a double gaussian for the signal + a second order polynomial for the background

Strange particle production: <p_T> vs. √s



- CMS: |y| < 2
- UA5: |y| < 2.5 at √s = 546 GeV
  |y| < 3.5 at √s = 0.2, 0.9 TeV
- E735: -0.36 < |η| < 1.0
- CDF: |η| < 1.0
- STAR: |y| < 0.5

Strange particle production: PYTHIA comparison

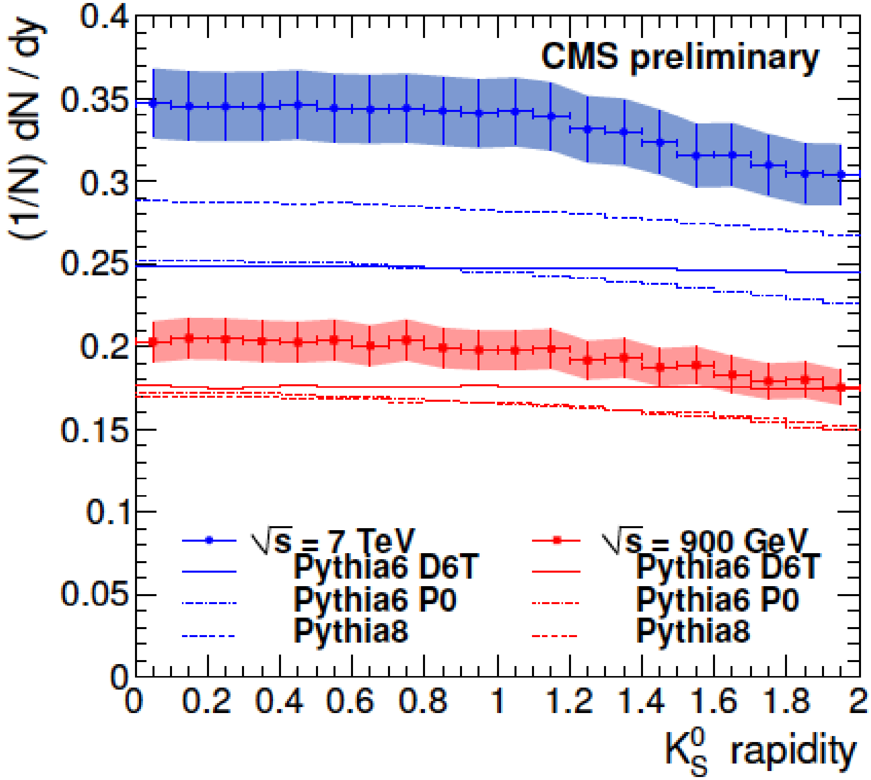


Table:

- Increase of x-sec with √s is not reproduced in MC.
- Deficit larger for larger masses.

Plot:

- All MC tunes are off.
- PYHIA8 and P0 reproduces better the dependence.

Particle	$\frac{\frac{dN}{dy}\|_{y=0}(7\text{ TeV})}{\frac{dN}{dy}\|_{y=0}(0.9\text{ TeV})}$ Data	PYTHIA D6T	$\frac{\frac{dN}{dy}\|_{y=0}(\text{PYTHIA D6T})}{\frac{dN}{dy}\|_{y=0}(\text{Data})}$ 0.9 TeV	7 TeV
K^0_S	$1.71 \pm 0.02 \pm 0.20$	1.41	$0.87 \pm 0.01 \pm 0.07$	$0.72 \pm 0.01 \pm 0.06$
Λ^0	$1.65 \pm 0.04 \pm 0.26$	1.48	$0.60 \pm 0.01 \pm 0.07$	$0.54 \pm 0.01 \pm 0.06$
Ξ^-	$2.09 \pm 0.09 \pm 0.27$	1.47	$0.48 \pm 0.05 \pm 0.09$	$0.33 \pm 0.02 \pm 0.05$

Two particle correlation function

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

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

$$B_N(\Delta\eta,\Delta\phi) = \frac{1}{N^2}\frac{d^2N^{\text{mixed}}}{d\Delta\eta d\Delta\phi}$$

This last distribution was constructed by randomly selecting two different events within the same multiplicity bin and pairing every particle from one event with every particle in the other.

<N> is the total number of offline tracks per event averaged over a multiplicity bin

$\Delta\eta$ and $\Delta\phi$ are always taken positive.

The signal S_N distribution represents the charged two-particle density function.

The background B_N distribution is a product of two single particle distributions.

S_N and B_N are both normalized to the unit.

Two particle correlation: selections and corrections

- Signal in both BSCs
  - in coincidence with BPTX signals from both beams ⇒ Beam-induced background negligible.
    Pile-up below % level.

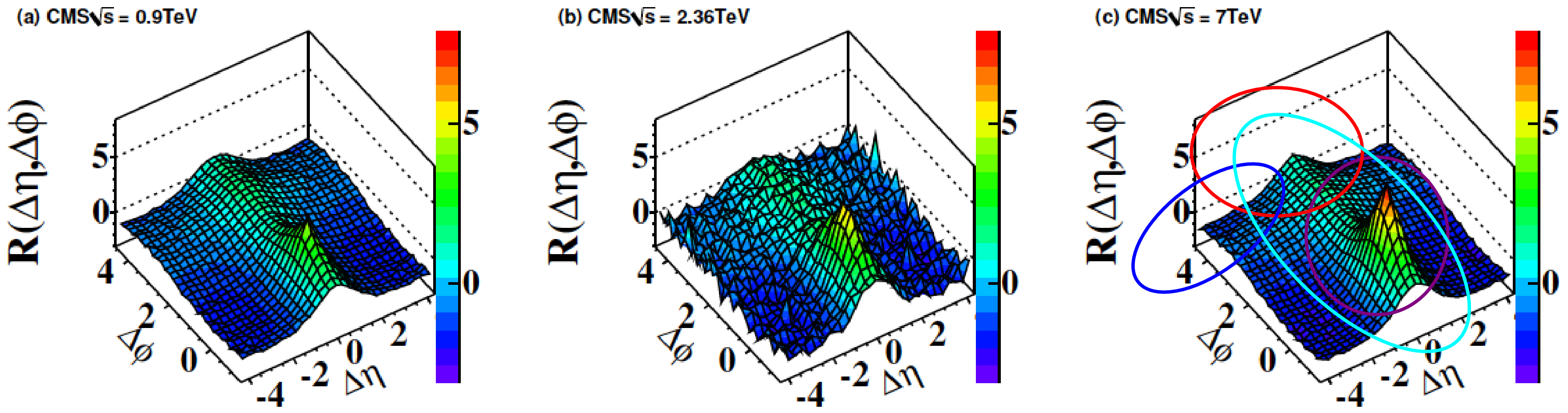
- Primary Vertex (PV)
  - $|z| < 4.5$ cm from nominal collision point.
  - in a radius perpendicular to beam axis < 0.15 cm from average vertex position.
  - containing 3 reconstructed tracks.

- Dedicated high multiplicity trigger
  - L1: $E_{ECAL+HCAL+HF} > 60$ GeV
  - HLT: $N_{trk}^{online} > 70$ for > 85 for the higher lumi runs.
    from pixel-tracks with z(origin) < 21cm and r(origin) < 0.5 cm
    $|\eta| < 2$, $p_T > 0.4$ GeV and
    d.o.c.a. from best vertex (the one with more tracks) < 0.12 cm.

- Corrections
  - Track efficiency vs. η, p_T, z_{vtx}
  - Event selection vs. N_{trk}^{true}
  - Event HLT selection vs. $N_{trk}^{offline}$ for high multiplicity

- Tracks
  - $5.0 > p_T > 0.1$ GeV (0.4 when classifying event multiplicity, in order to match online tracking)
  - $|\eta| < 2.4$
  - High purity
  - $d_{xy}/\sigma(d_{xy})$ and $d_z/\sigma(d_z) < 3$
  - $\sigma(p_T)/p_T < 10\%$

Two particle correlation: results



- Narrow peak at (0,0): can be understood as contribution from high p_T clusters (hard process like jets).
- Ridge at $\Delta\phi \approx \pi$: interpreted as due to away-side jets or momentum conservation.
- Ridge at $\Delta\eta \approx 0$: Gaussian ridge, extending over the whole range of $\Delta\phi$ and broader at lager values of $\Delta\phi$. This arises from low p_T cluster contribution (soft QCD string fragmentation).

Qualitatively the structure is reproduced by:
- PYTHIA.
- ISR experiment low mass resonance gas model.
- PHOBOS experiment isotropic cluster decay MC model.

Two particle correlation: results

- In the context of the ICM, the 1-dimensional correlation function obtained integrating over $\Delta\phi$, can be parametrized using the functional form:

$$R(\Delta\eta) = \alpha \left[\frac{\Gamma(\Delta\eta)}{B(\Delta\eta)} - 1 \right]$$

where the correlation strength depends on the cluster size K:

$$\alpha = \frac{\langle K(K-1)\rangle}{\langle K\rangle}$$

and is proportional to: $\exp\left[-(\Delta\eta)^2/(4\delta^2)\right]$

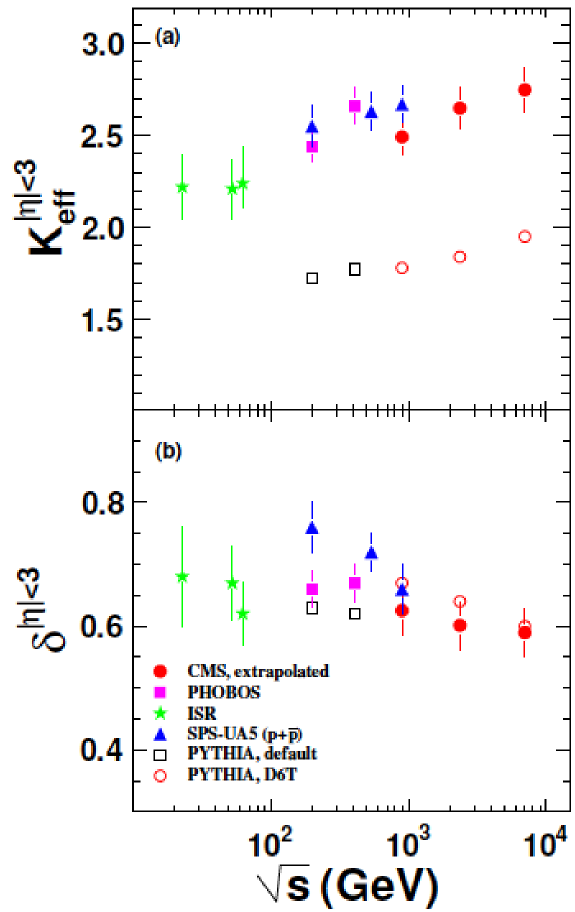
An effective cluster size can be defined using the extracted correlation strength via the relation:

$$K_{\text{eff}} = \alpha + 1 = \frac{\langle K(K-1)\rangle}{\langle K\rangle} + 1 = \langle K\rangle + \frac{\sigma_K^2}{\langle K\rangle}$$

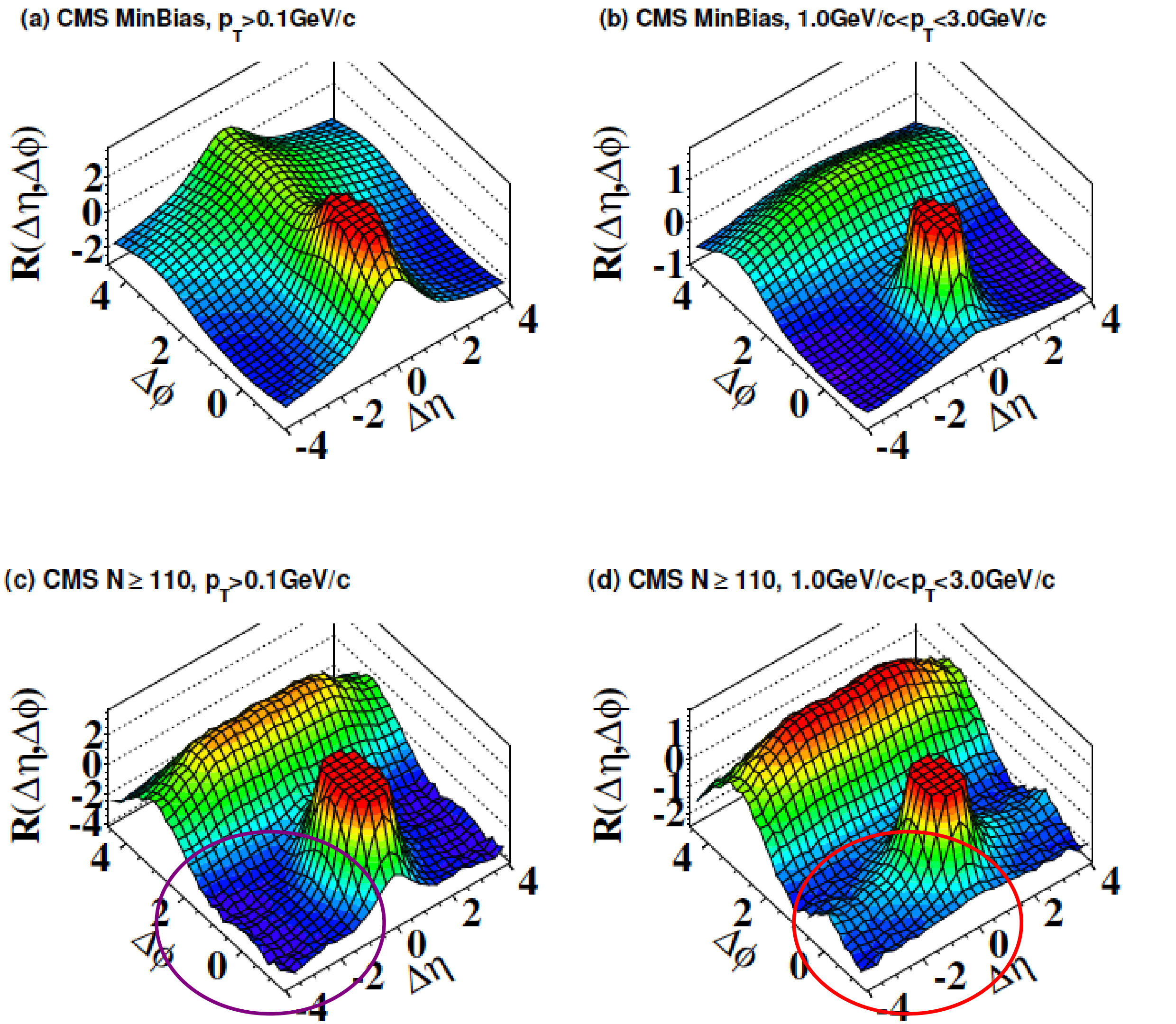
The functional form can be used to fit the 1-dimensional correlation function and to extract the effective cluster size K_{eff} and the cluster decay width δ.

The results were extrapolated to: $|\eta| < 3$ and $p_T \approx 0.1$ GeV/c, the last extrapolation made with a Tsallis fit.

- Expectations for <K> from resonance decay (close to PYTHIA values) cannot explain data.
- Additional sources of correlation are needed to explain data [12].
- Onset jets could play a more important role at high energies, resulting in bigger clusters.



Long-range correlation at 7 TeV: the "Ridge"



Typical ICM structures at low and intermediate p_T for minimum bias.

Shallow minimum less pronounced than in minimum bias.

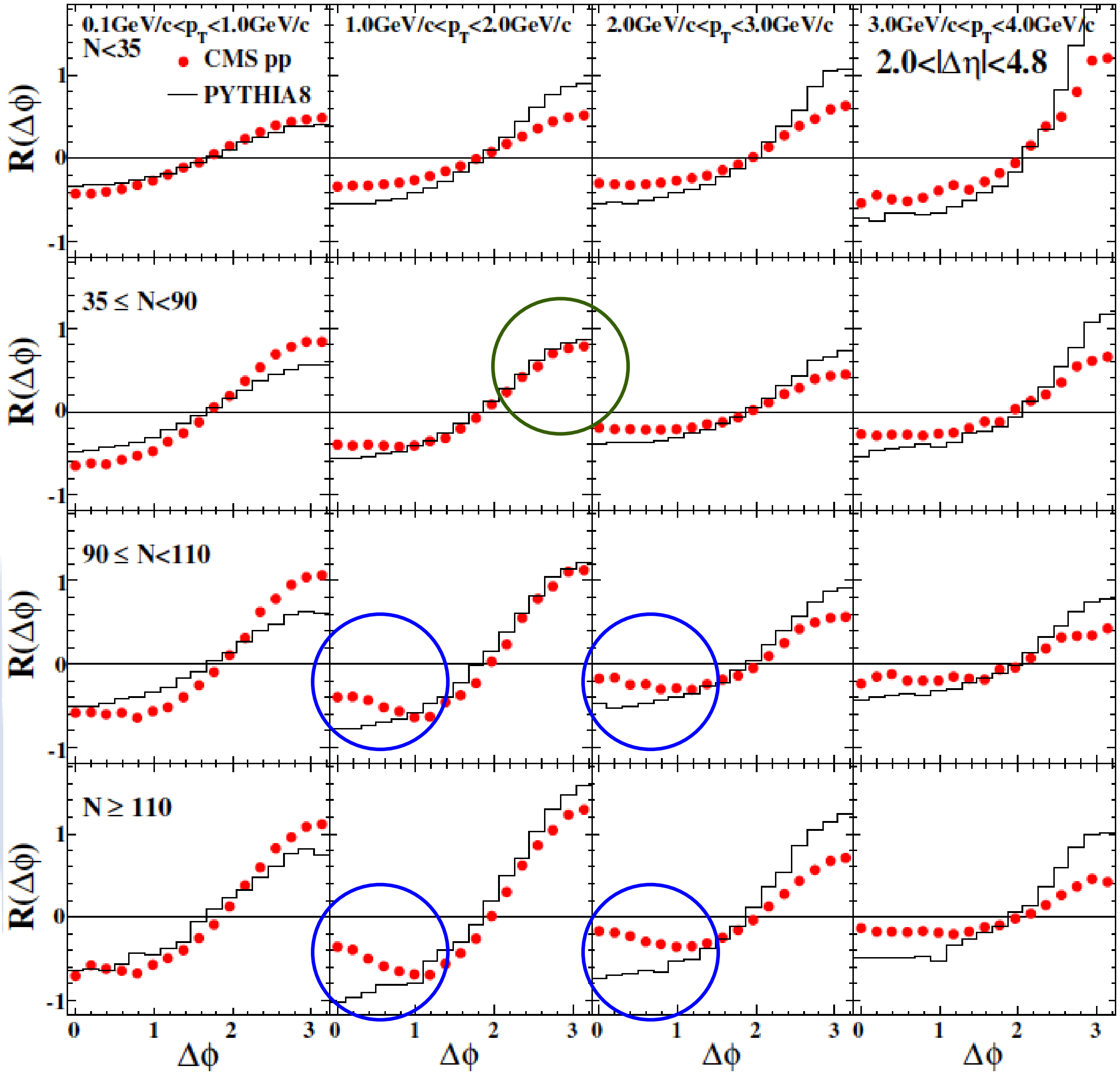
"Ridge"-like structure extending for at least four units of Δϕ: novel feature of data, never observed in pp or ppbar collisions.

Not reproduced by any MC model.

Reminiscent of correlations seen in relativistic heavy ion collisions (components of hydrodynamic flow of medium, interactions between hard scattering and medium and collective effects of interaction of nuclei).

Could be explained by additional color string connections, not yet implemented in MC models.

Long-range correlation at 7 TeV: the "Ridge"



Integrating the correlation function over $2.0 < |\Delta\eta| < 4.8$.

Away-side jet contribution present in all panels.

Local maximum in the region $\Delta\phi \approx 0$.

PYTHIA8:

- fails to predict the away-side correlation in many multiplicity and p_T ranges.
- soft particle production from string fragmentation, jet fragmentation, FSR and semihard MPI, fails to predict the novel long-range, near side particle correlation.

BEC effect

Constructive interference affects the joint probability for the emission of pair of identical bosons. The proximity is quantified by:

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

The BEC effect is observed as an enhancement at low Q of the ratio of the Q distribution for pairs of identical particles in the same event, to that of particles in a reference sample expected not to include the BEC effect by construction:

$$R(Q) = (dN/dQ)/(dN_{ref}/dQ)$$

which can be parametrized by:

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

In a static model $\Omega(Qr)$ is the Fourier transform of the phase-space region emitting bosons, characterized by an effective size r, λ measure the strength of the BEC for incoherent boson emission from independent sources, δ accounts for long distance correlations and C is a normalization factor.

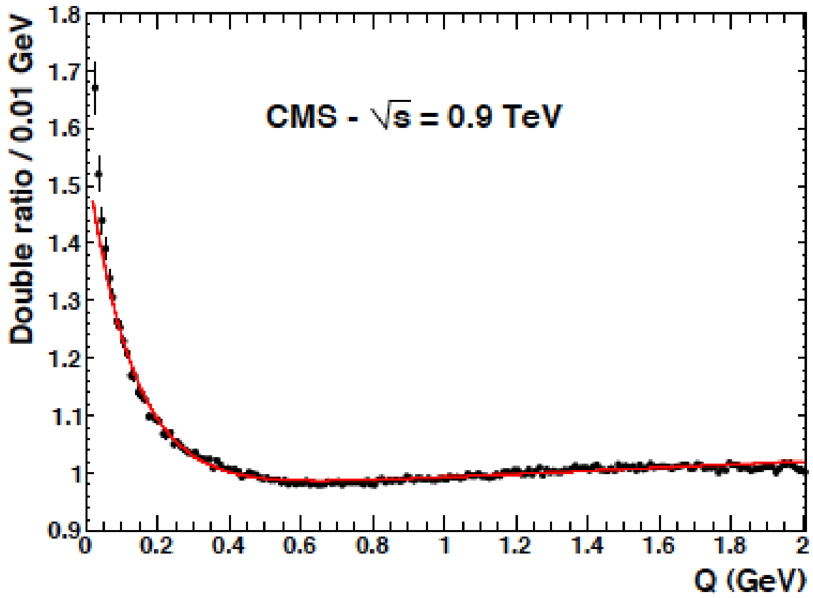
Reference samples

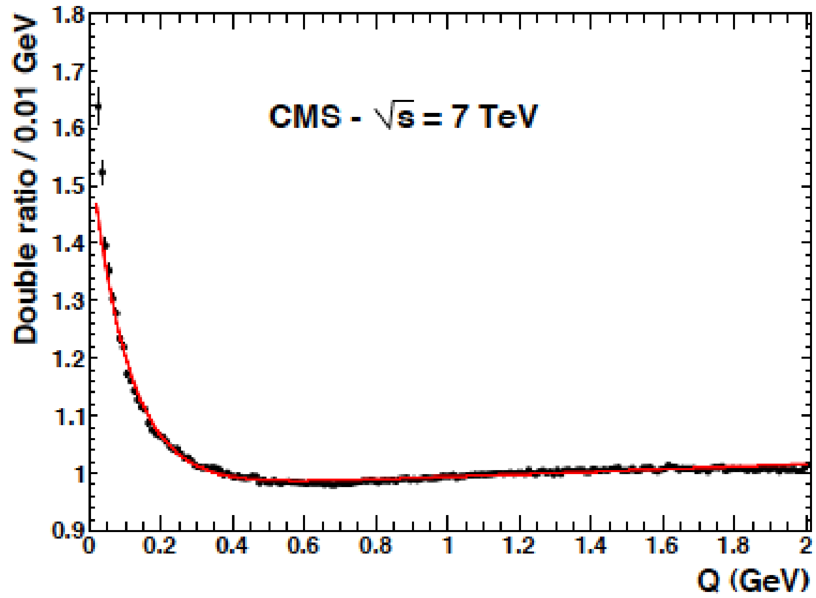
- **Opposite-charge pairs:** natural reference sample, but containing resonances.
- **Opposite-hemisphere pairs:** Pairing after the inverting of the 3-momenta of one of the two particles (for like- and unlike-sign).
- **Rotate particles:** pairing happen changing sign of x and y component of one particle.
- **Pairs from mixed events:** (i) random events, (ii) events w/ similar charge multiplicity in the same η region, (iii) events in the same invariant mass region of the signal.

To reduce biases a double ratio is defined:

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

BEC: measurement of parameters

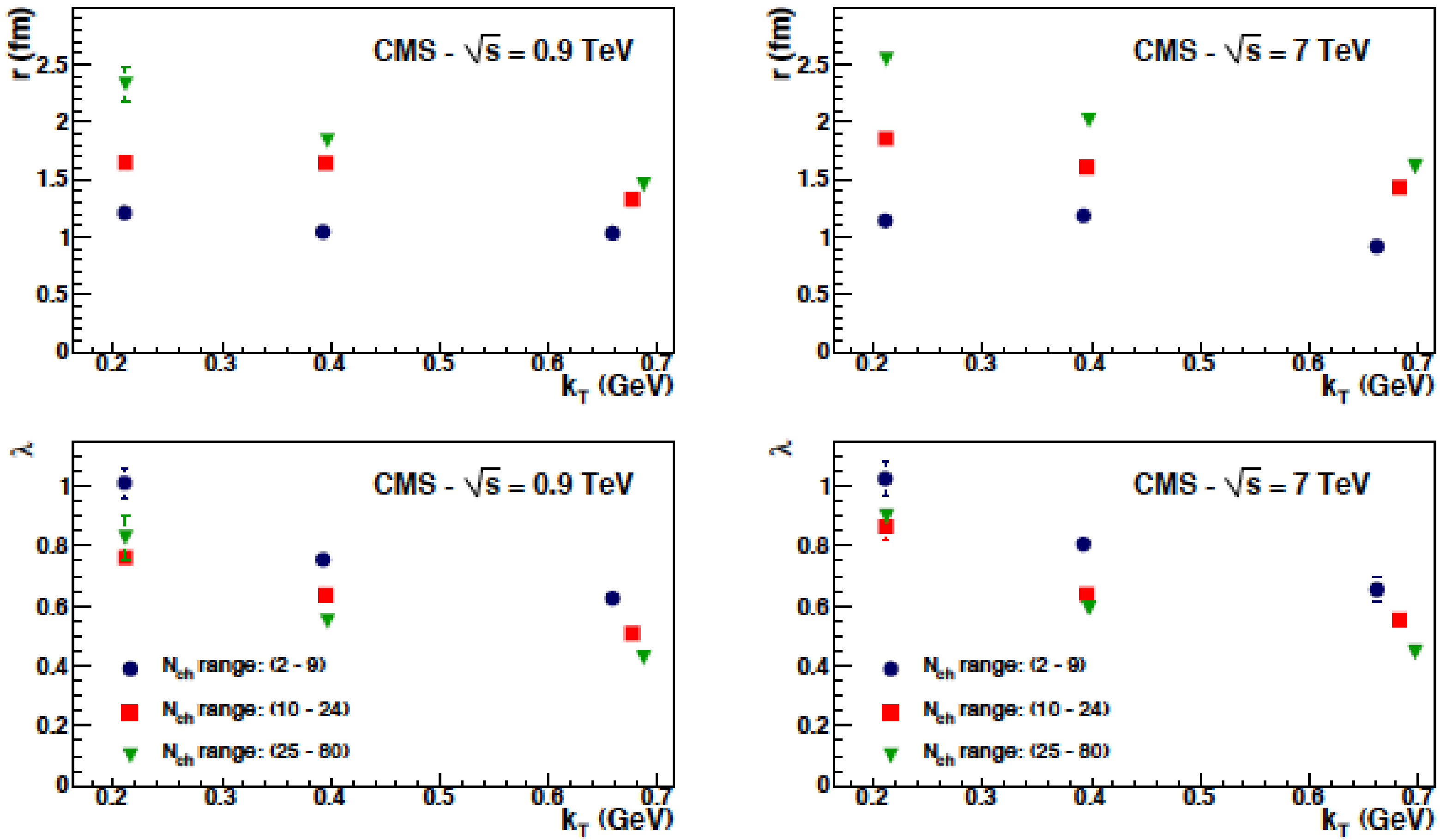




The shapes are fitted using an exponential parametrization of Ω(Qr) which fit better than a Gaussian but worse than a Lévy parametrization.

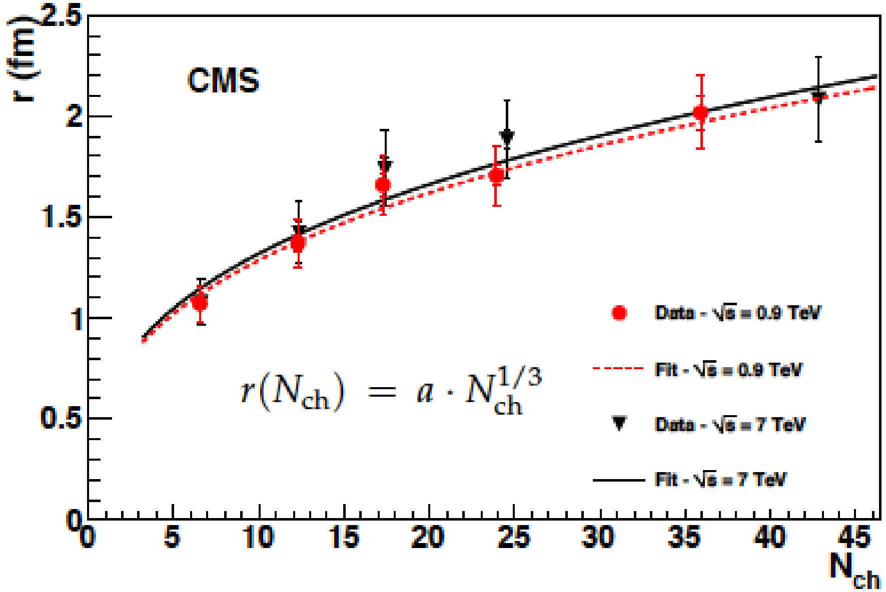
$\sqrt{s}$	χ^2/N_{dof}	C	λ	r (fm)	δ (10^{-2} GeV^{-1})
0.9 TeV	2.5	0.965 ± 0.001	0.616 ± 0.011	1.56 ± 0.02	2.8 ± 0.1
7 TeV	3.8	0.971 ± 0.001	0.618 ± 0.009	1.89 ± 0.02	2.2 ± 0.1

BEC: k_T dependence of parameters



- Uncertainties are point-to-point correlated: choices of different reference and MC are very similar.
- The 0.9 TeV results are compatible with ALICE results.

BEC: N_{ch} dependence of r

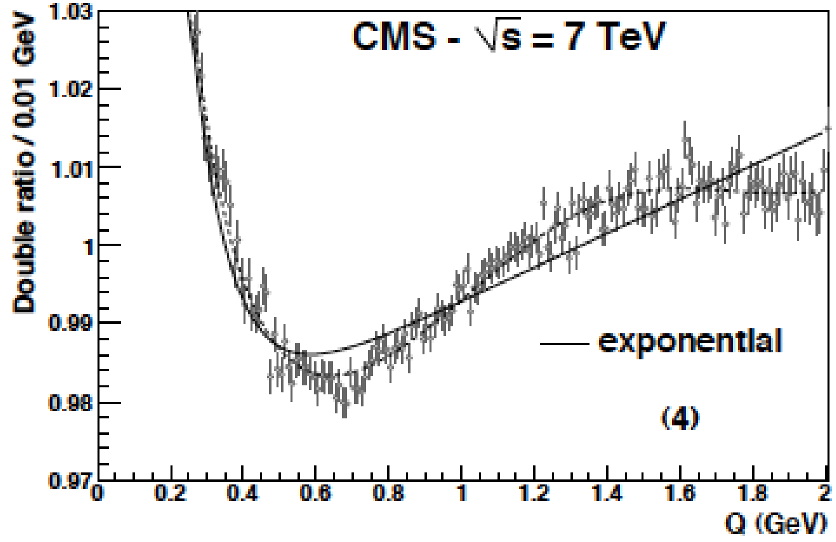


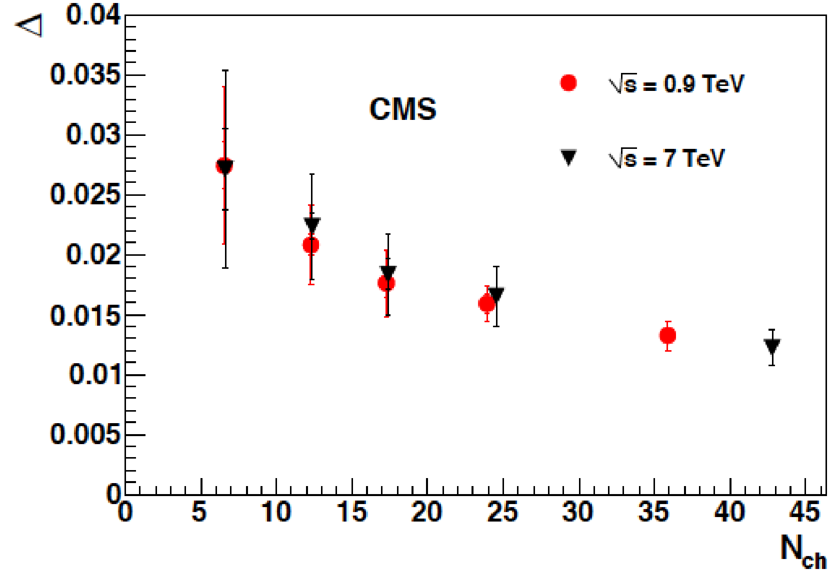
- Measurements at 0.9 and 7 TeV are consistent, indicating that the difference is accounted for by the different averaged charge multiplicities.

- Results of the fits are:

a = 0.597 ± 0.009 (stat) ± 0.047 (syst) fm at 0.9 TeV
a = 0.612 ± 0.007 (stat) ± 0.063 (syst) fm at 7 TeV

BEC: Same sign anti-correlation effect





$$R(Q) = C\left[1 + \lambda(\cos\left[(r_0 Q)^2 + \tan(\alpha\pi/4)(Qr)^\alpha\right] e^{-(Qr)^\alpha})\right] \cdot (1 + \delta Q)$$

- The presence of anti-correlation between same-sign charged particles has been explained in [14] and observed in e^+e^- collisions at LEP.

- The dip of the distribution can be defined as the difference between the actual value of the fit at its minimum and the baseline curve: C (1 + δQ)

Conclusions

- Various low p_T QCD analyses have been performed at center of mass energies of 0.9, 2.36 and 7 TeV.

- 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. Tuning of the model underway.

- Charged hadron distributions from NSD events have been compared to previous results. Results in agreement with empirical extrapolation from lower energies and with recent results from ALICE. Still tuning needed in MCs. KNO scaling violation observed.

- Strange particle production in good agreement with empirical extrapolation from lower energies. Tuning of models needed as for UEs and charged hadrons.

- 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. Reminiscent of correlations seen in relativistic heavy ion collisions.

- The BEC effect has been observed and quantified at 0.9 and 7 TeV. The exponential parametrization has been shown to better fit the data than the gaussian parametrization, confirming previous hints from data. Various parameter dependences have been investigated.

For more details

- "First Measurement of the Underlying Event Activity at the LHC with $\sqrt{s}$ = 0.9 TeV", Eur. Phys. J. **C 70** (2010) 555-572.

- "Measurement of the Underlying Event Activity with the Jet Area/Median Approach at 0.9 TeV", CMS-QCD-10-005.

- "Measurement of the Underlying Event Activity at the LHC with $\sqrt{s}$ = 7 TeV and comparison with $\sqrt{s}$ = 0.9 TeV", CMS-QCD-10-010.

- "Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s}$ = 7 TeV", Phys. Rev. Lett. **105** (2010) 022002.

- "Charged particle multiplicities in pp interactions at $\sqrt{s}$ = 0.9, 2.36, and 7.0 TeV", CMS-QCD-10-004

- "Strange Particle Production in pp collisions at $\sqrt{s}$ = 0.9 and 7 TeV", CMS-QCD-10-007

- "Observation of Long-Range, Near-Side Angular Correlations in Proton-Proton Collisions at the LHC", J. High Energy Phys. **09** (2010) 091.

- "First Measurement of Bose-Einstein Correlations in proton-proton Collisions at $\sqrt{s}$ = 0.9 and 2.36 TeV at the LHC", Phys. Rev. Lett. **105** (2010) 032001.

- "Measurement of Bose–Einstein Correlations in pp Collisions at $\sqrt{s}$ = 0.9 and 7 TeV at the LHC", CMS-QCD-10-023.

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Backup slides

Underlying Events: reminders

- UEs difficult to model (especially vs. √s)
  - UA5 measured multiplicity [1]
  - Detailed UE studies performed by CDF [2]
- Different MC tunings are used:
  - Differences are due to the different implementations of the regularization of the formal divergence of the leading order partonic scattering amplitude as the final state parton transverse momentum approaches 0. In PYTHIA:

$$1/\hat{p}_T^4 \;\rightarrow\; 1/(\hat{p}_T^2 + \hat{p}_{T_0}^2)^2 \qquad\qquad \hat{p}_{T_0}(\sqrt{s}) = \hat{p}_{T_0}(\sqrt{s_0}) \cdot (\sqrt{s}\,/\,\sqrt{s_0})^{\epsilon}$$

  - PYTHIA-6 tunes: DW -> ε = 0.25 from CDF
    (no default PYTHIA settings of weighting of color connections)
    Perugia-0/P0 (*) -> ε = 0.25
    D6T (CTEQ6LL) -> ε = 0.16 from UA5

    $\sqrt{s_0} = 1.8\,\text{TeV}$, $\hat{p}_{T_0} = 2.0\,\text{GeV}/c$

    CW (increase UE activity) -> ε = 0.30
    (weighting of color connections set to default PYTHIA values) $1.8\,\text{GeV}/c$

  - PYTHIA 8 tune uses new PYTHIA MPI model interleaved with parton showering.
    (Hard diffraction included: decreasing with scale faster than total inelastic cross-section.
    Soft diffraction suppressed for track-jet p_T > 3 GeV/c)
  - All tunes are using CTEQ5L (except where noted)

(*) P0 uses new PYTHIA MPI model [3] and LEP results to describe hadron fragmentation at high z

UE analyses: systematics

- Simulation of vertex and track selection
  - Obtained variating settings on data and MC. No uncertainty is assigned due to occupancy variation.
  - Tracker misalignment < 0.5 %
  - Inactive tracker material is 5% ⇒ 1% in tracking efficiency

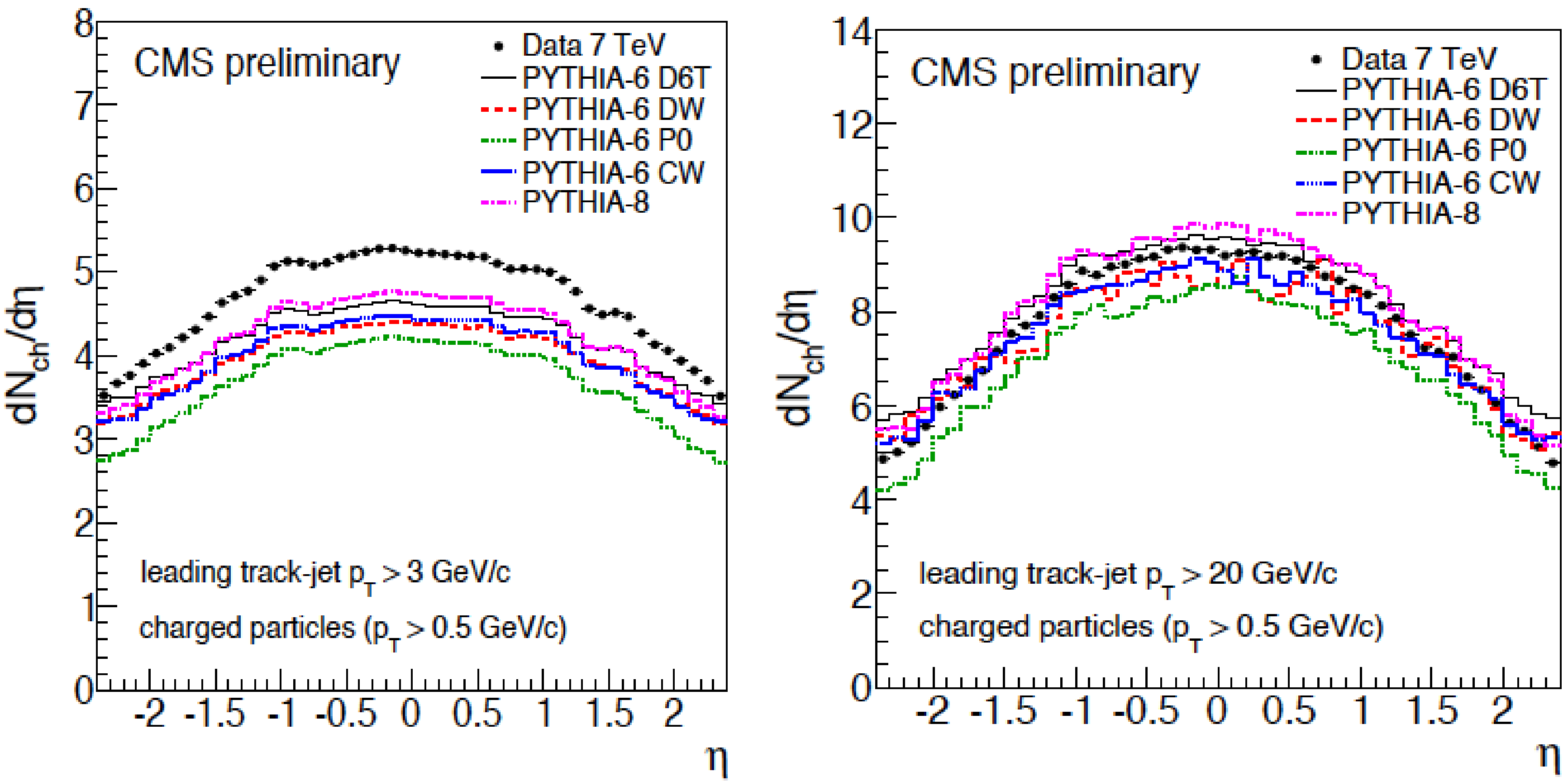
- Contaminations of neutral hadrons and photon conversion
  - Underestimated in MC by 0.5% ⇒ 0.8 % for a conservative 30%

- MinBias trigger
  - Half the difference between w/ and w/o trigger

- Inactive tracker channel variation (run-by-run)
  - 0.5%

- Beam collision region variation (run-by-run)
  - 0.5%

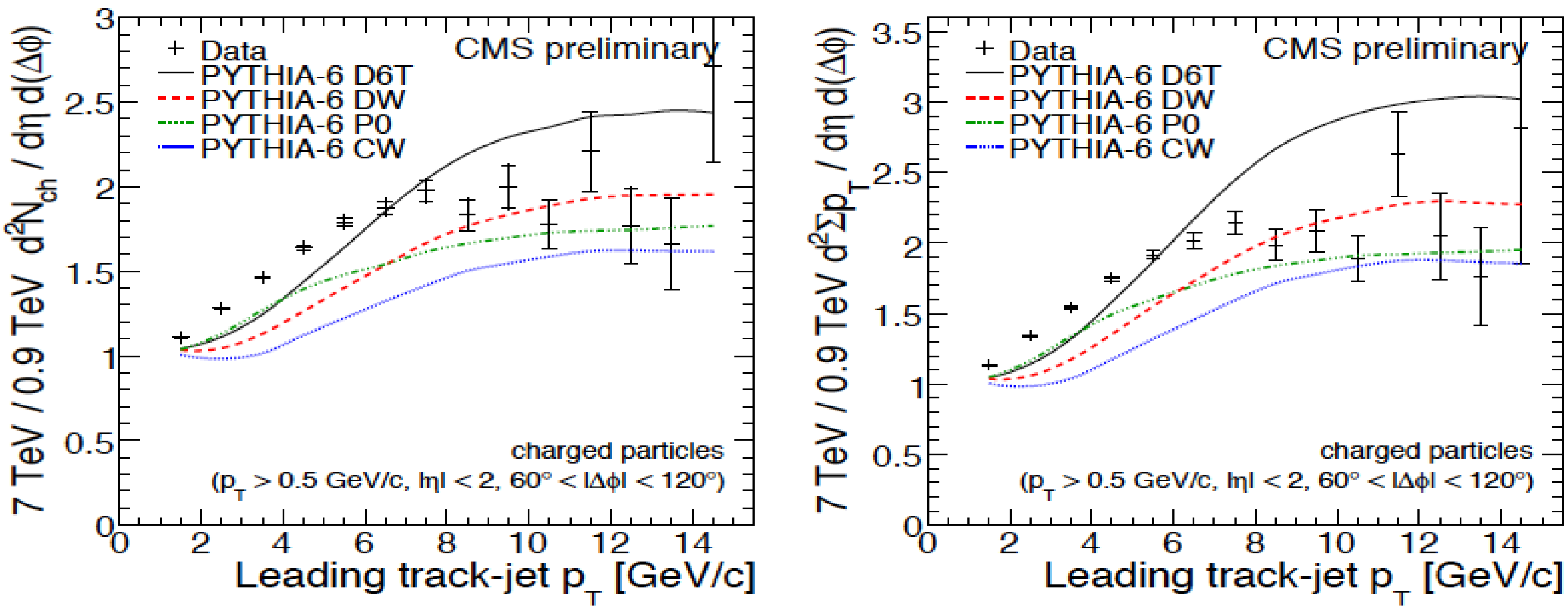
UE analyses: η



For both scales data are more central than MC. This can be due to shortcomings of the description of parton fragmentation and radiation (toward and away region) and UE description (transverse region).

UE analyses: transverse region

0.9 and 7 TeV datasets were taken with same detector and slightly different running condition.
A comparison of MC samples before/after simulation ⇒ difference smaller than the statistical error



- The ratio 7 TeV / 0.9 TeV is about 1 for p_T < 1 GeV and about 2 for p_T > 6 GeV.
- For the lower scales the disagreement is due to the inability of the models to reproduce well the multiplicity and transverse activity distributions at 7 TeV (while they describe them well at 0.9 TeV).
- At higher scales the best description is given by DW.

Area/median method: selections and systematics

- k_T jet algorithm
  - R = 0.6
  - $|\eta| < 1.8$

- Selected tracks
  - $p_T > 0.3$ GeV and $|\eta| < 2.3$ belonging to PV.
  - High purity tracks.
  - $d_{xy}/\sigma(d_{xy})$ and $d_z/\sigma(d_z) < 5$
  - $\sigma(p_T)/p_T < 5\%$

- Considered systematics
  - Tracker material budget (known at 5%) = negligible
  - Tracker alignement (considered different scenarios) = negligible
  - Tracker map of non operational channels = 2%
  - Vertex reconstruction (considered two set of minimal separation in z between PVs) = negligible
  - Track reconstruction efficiency and fake rate
    (known at 2% and 0.5% -> rejected and added a track in the event with a 2% probability) = 6%
  - Transverse momentum resolution of track-jets
    (conservative 5% smearing of the width in the simulation) = negligible
    (increase and decrease of track-jet p_T compatible with resolution) = 6%
  - Trigger efficiency bias = 3%

ρ϶ independent sources: for values compatible to 0, the offset is taken conservatively as the error.
ρ϶ dependent sources: results of a fit of the dependence are quoted bin-by-bin quoted uncetainties.

UE analyses: jet area/median method

- Catchment area k_T jet algos cannot be estimated as πR^2.
- Idea: uniform grid of ghosts ($p_T = 10^{-100}$ GeV).
- Ghosts are input for jet algorithm (k_T algo infrared- and collinear-safe).
- We can define the active area as:

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

- The total area can extend even up to $|\eta| = 5$.

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

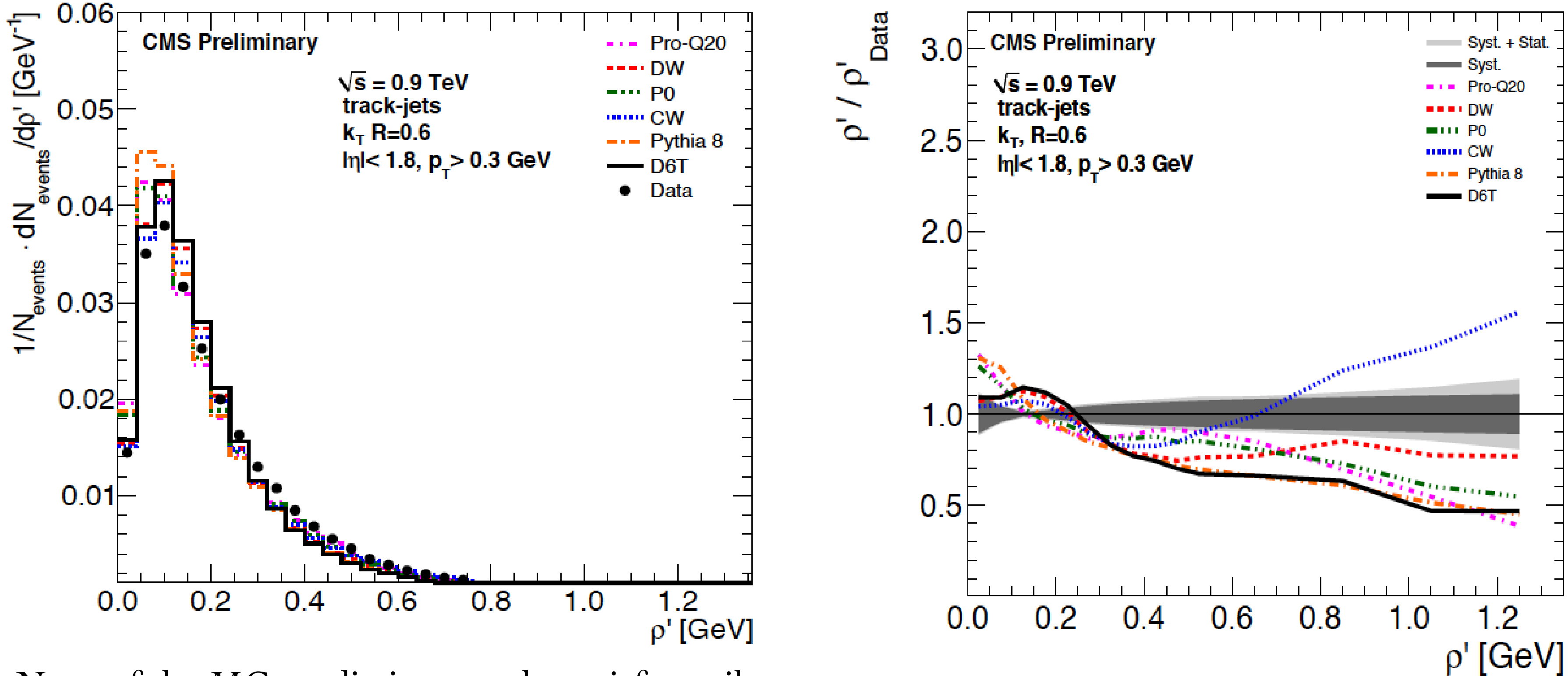
- The median is less sensitive to the outliers, i.e. leading jets in the event.
- If the number of ghost jets is larger than the number of physical jets $\rho = 0$.

$$\rho' = \underset{j \in \text{physical jets}}{\text{median}} \left[\left\{ \frac{p_{Tj}}{A_j} \right\} \right] \cdot C \qquad C = \frac{\sum_{j \in \text{physical jets}} A_j}{A_{\text{tot}}}$$

- This definition avoids to counting ghost jets as an estimate of the “emptiness” of the event.

Area/median method: results

Median of p_T over jet area is rather sensitive to UE activity



- None of the MC predictions works satisfactorily.
- CW and DW come closest: this is due to a better prediction of particle multiplicities.
- The general patter of deviations from data by the considered PYTHIA tunes looks rather similar to the one observed with traditional methods.

Charged hadrons: selections and corrections

- Signal in both BSCs
  - in coincidence with colliding proton beams was used for **triggering.**
- Primary Vertex (PV)
  - in coincidence with an HF tower > 3 GeV/c in each end.

TABLE II. Fractions of SD, DD, ND, and NSD processes obtained from the PYTHIA and PHOJET event generators before any selection, and the corresponding selection efficiencies determined from the MC simulation.

	PYTHIA		PHOJET	
	Fractions	Selection efficiencies	Fractions	Selection efficiencies
SD	19.2%	26.7%	13.8%	30.7%
DD	12.9%	33.6%	6.6%	48.3%
ND	67.9%	96.4%	79.6%	97.1%
NSD	80.8%	86.3%	86.2%	93.4%

- Corrections (according to method: barrel pixel, pixel tracklets or full tracker)
  - Geometrical acceptance: 2%
  - Efficiency and fake: 5%-10% and < 1%
  - Duplicate tracks < 0.5%
  - Loopers < 1%
  - Decay products of long lived: < 2%
  - Photon conversion: < 1%
  - Inelastic interactions in material: 1% - 2%

Charged hadrons: P_n

Dedicate systematic uncertainties

- Trigger and event selection efficiencies:
cross-check on zero-bias (by definition unbiased). A shift of the ε_n of +5%/-7%, covering the zero bias trigger, leads to 5% systematic uncertainty.

- Tracking efficiency and acceptance:
the overall effect is as high as 30% for high multiplicities.

- Model dependence:
The robusteness of the unfolding procedure was tested unfolding pseudo-data from PHOJET, using a response matrix constructed with PYTHIA. The effect is of 3%.

- SD subtraction:
Differences between PHOJET and PYTHIA in multiplicity distribution of SD events were taken into account. The impact is of 20% and 5% at low and high multiplicities, repectively.

- TOTAL:
10% almost everywhere, 40% at low and high multiplicities.

Charged hadrons: P_n

Dedicated corrections

- SD events are subtracted using MC
- Charged hadron multiplicity has to be normalized to NSD cross section.
- Correction from accepted to real multiplicity given by trigger and reco efficiency as function of n:

$$T_n = \epsilon_n \cdot P_n$$

- Correction to take into account effects of secondaries generated by the interaction of primaries in the beam pipe and presence of decay products of long-lived hadrons:

$$O_m = \sum_n R_{m,n} \cdot T_n$$

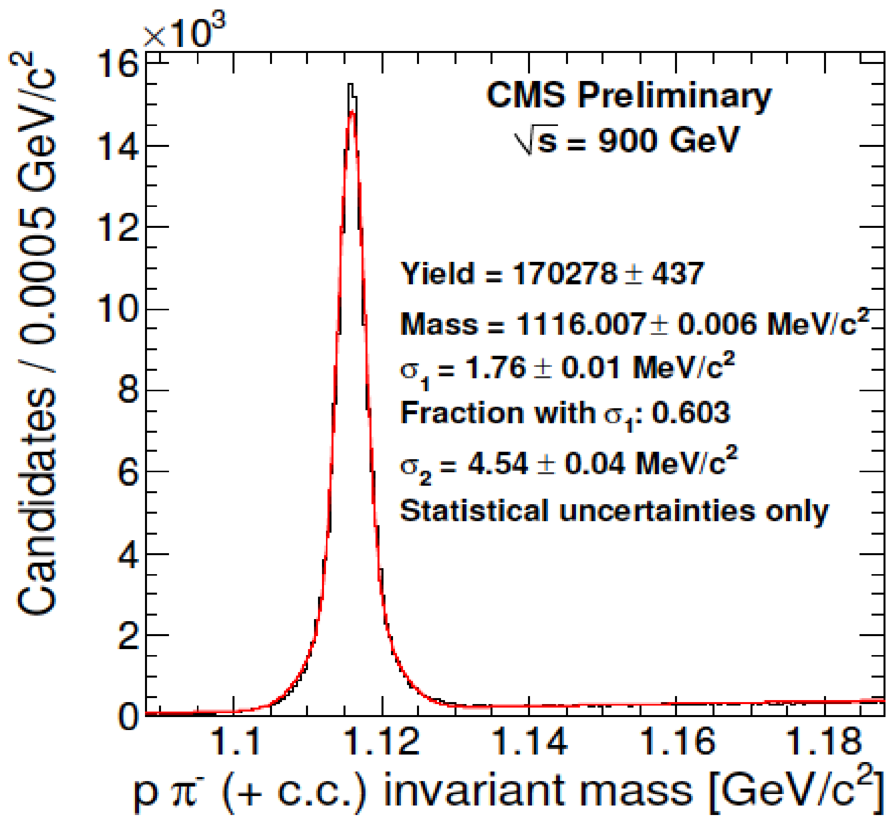
This matrix was inverted using Bayesian unfolding method [6].

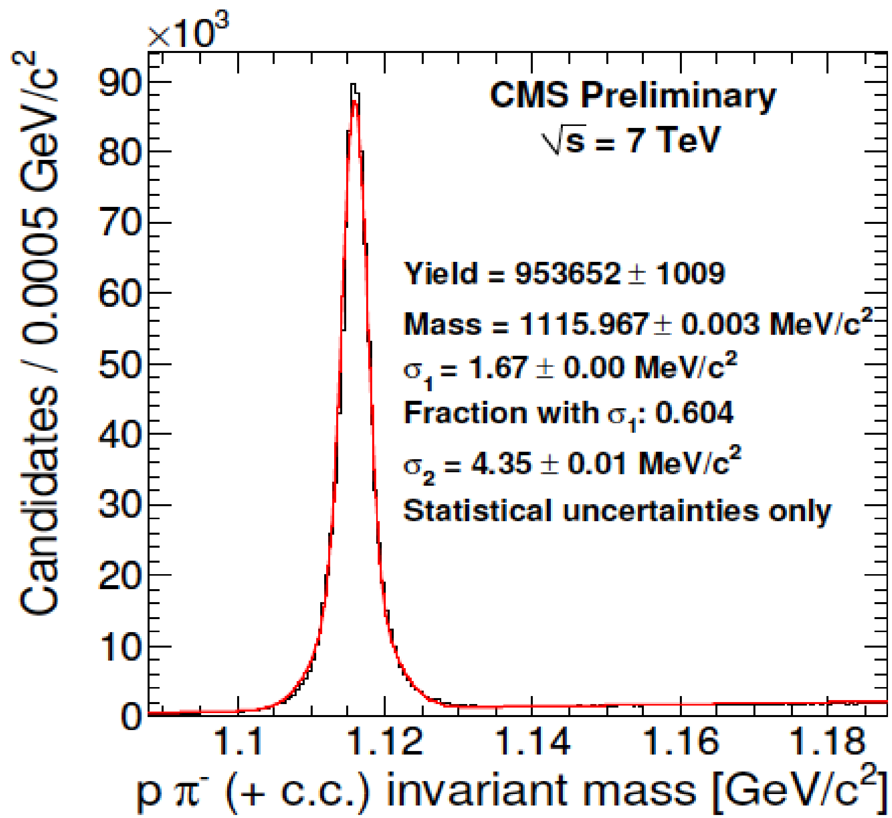
- A correction factor $\langle p_T^{gen} \rangle / \langle p_T^{reco} \rangle$ was applied for each bin of raw multiplicity.
- MinBias drop at $p_T < 100$ MeV/c was estimated by extrapolation with a polynomial form data.

Strange particle production: selection

- Candidates long-lived strange neutral particles:
  - Pairs of opposite charged tracks reconstructed from the inner tracker with $\chi^2/ndf < 5$.
  - Secondary tracks: distance of closest approach to PV < 3 σ (with based on the event-by-event error).
  - The SV < 4 σ from innermost hit of the two SV, further from the PV.
  - $|y| < 2$ in order to minimize corrections.
  - p_T ranges: 0-10 GeV (K_S^0), 0.2-10 GeV (Λ^0), 0.6-6 GeV(Ξ^-)
- Invariant mass reconstruction:
  - For K_S^0
    + both tracks were assumed to be pions.
    + to suppress Λ^0, the corresponding invariant mass was required to be > 2.5 σ than the Λ^0 mass value.
    + prompt were selected requiring momentum to point back to PV within 3 σ.
  - For Λ^0
    + at the charged track with lower momentum was assigned the pion mass.
    + Ξ, Ω^- were suppressed requiring requiring momentum to point back to PV within 3 σ.
    + to suppress K_S^0, the corresponding invariant mass was required to be < 2.5 σ than the K_S^0 mass value.
  - For Ξ^-
    + Λ^0 were selected as described above and combined with a negative track assumed to be a pion.
    + The three tracks were required to be separated of 3 σ from the PV.
    + Λ^0 and were fit to a common vertex with a probability > 1%. This vertex had to be 4 far from PV.
    + Trajectory of Ξ^- was required to be within 3 from PV.
    + Only exactly one Ξ^- reconstructed in the event was required.

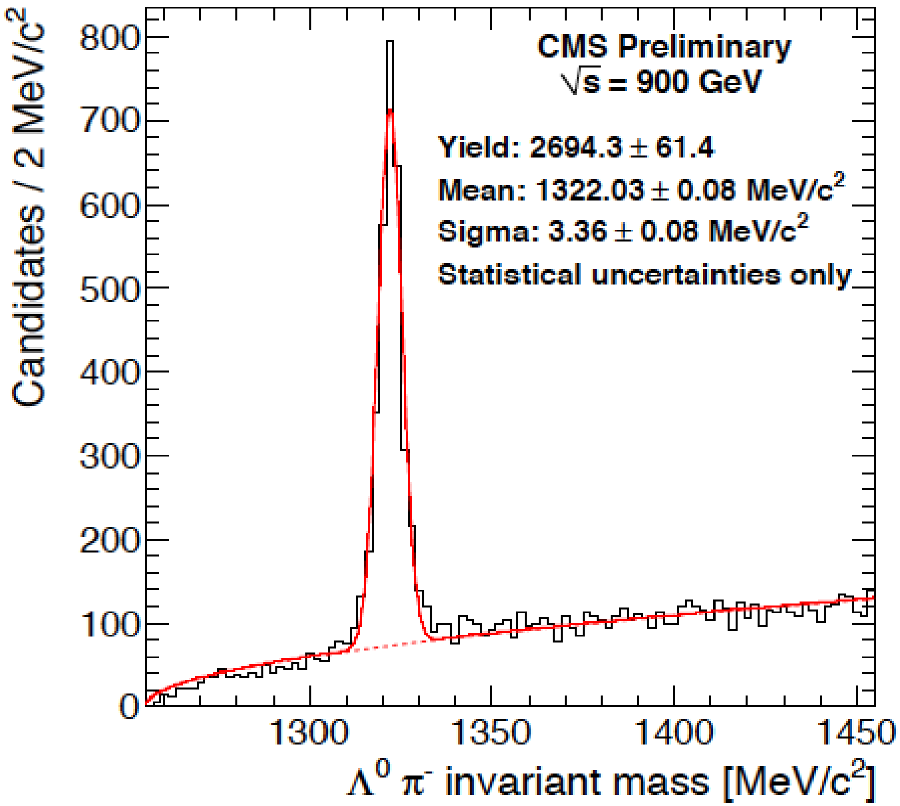
Strange particle production: Λ^0

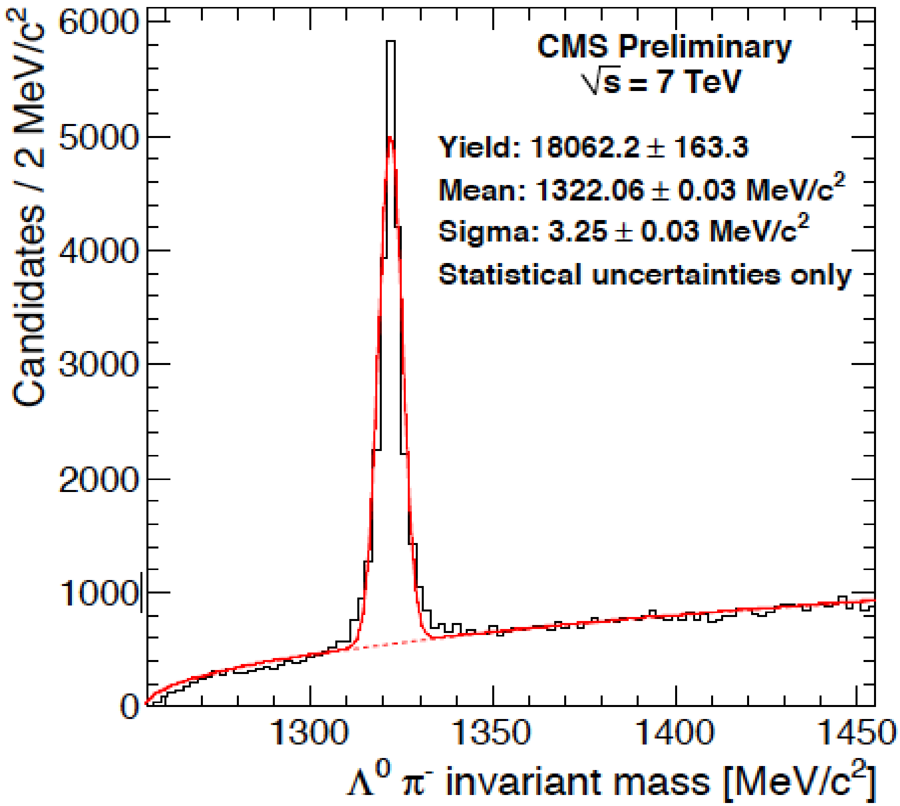




Fit with a double gaussian for the signal + $Aq^{B}e^{Cq+Dq^2}$ where $q = m_\Lambda - (m_p + m_\pi)$, for the background

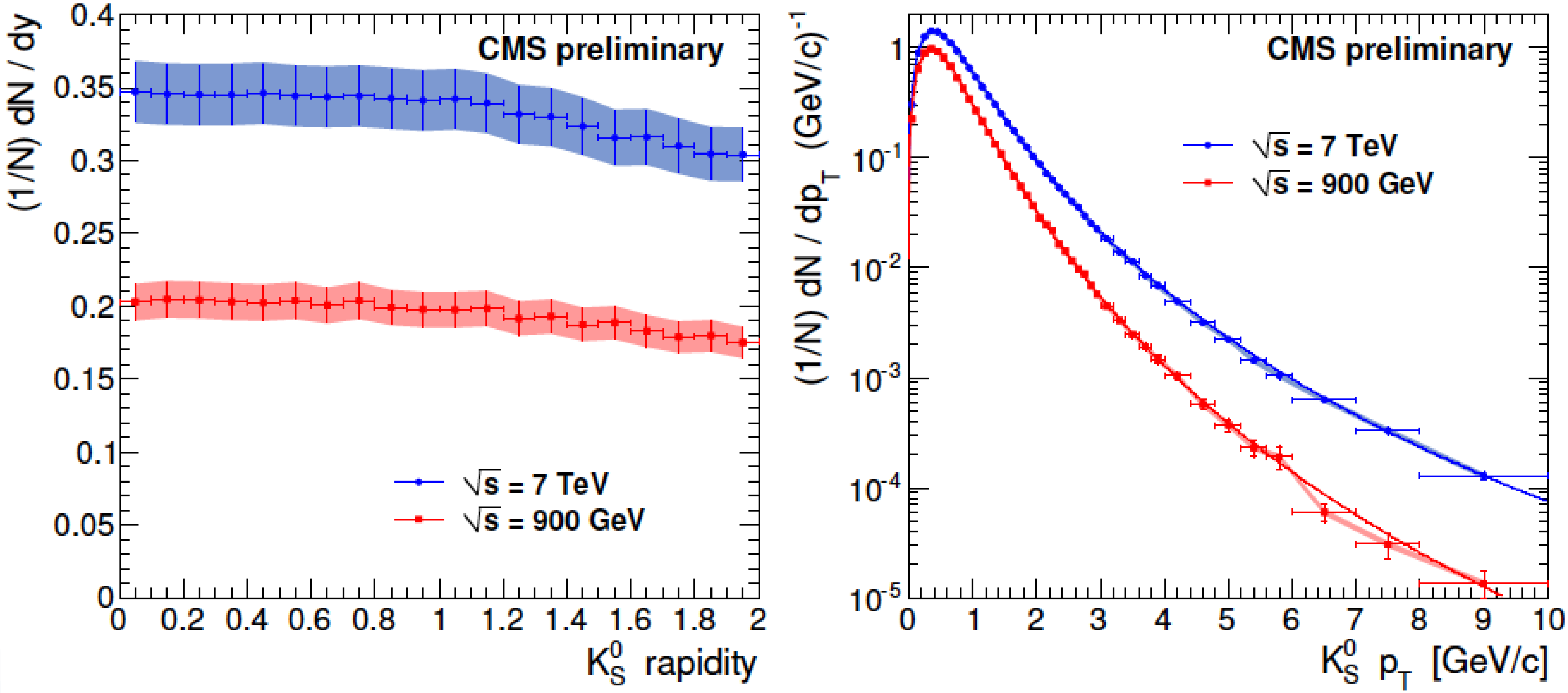
Strange particle production: Ξ^-





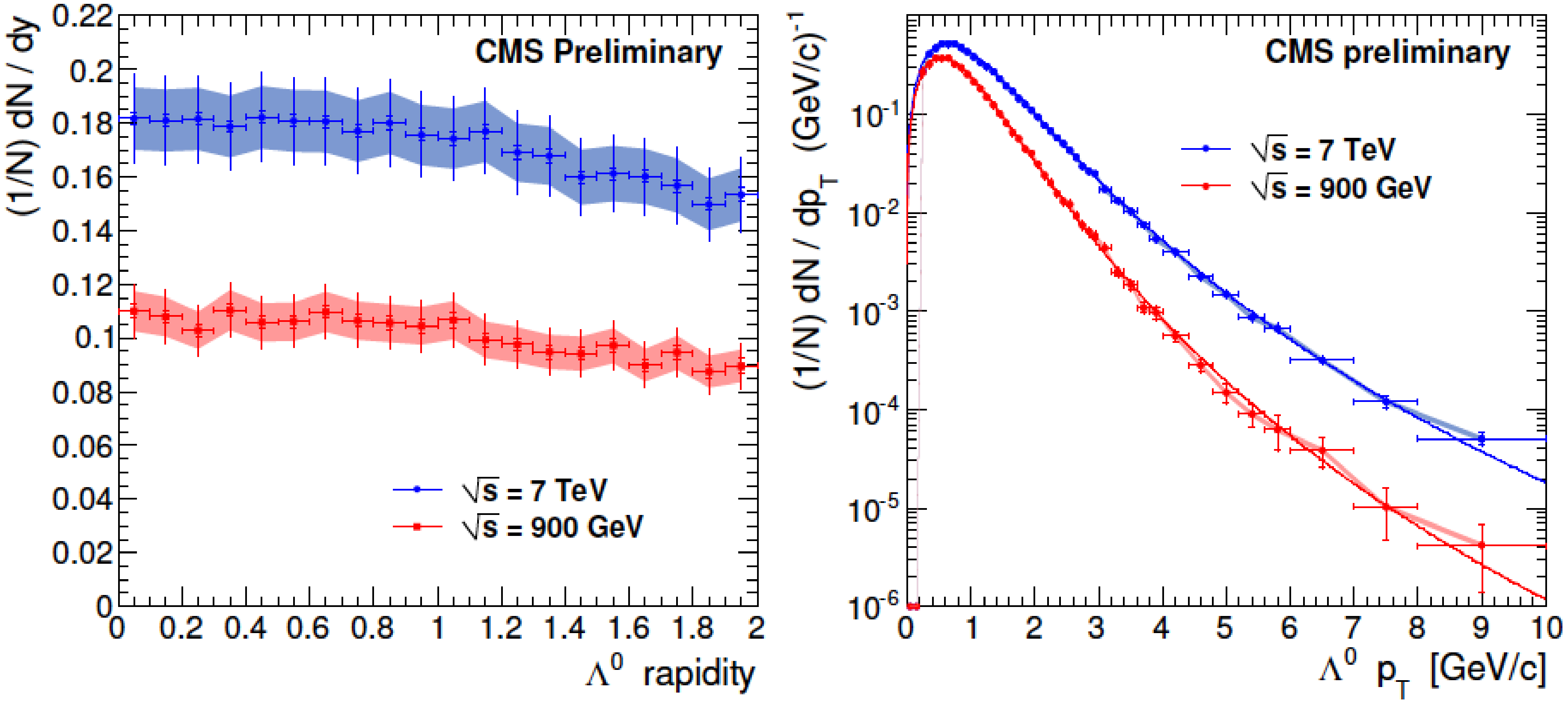
Fit with a single gaussian for the signal + Ae^{Bq} where $q = m_{\Xi} - (m_{\Lambda} + m_{\pi})$ for the background

Strange particle NSD production: K_S^0

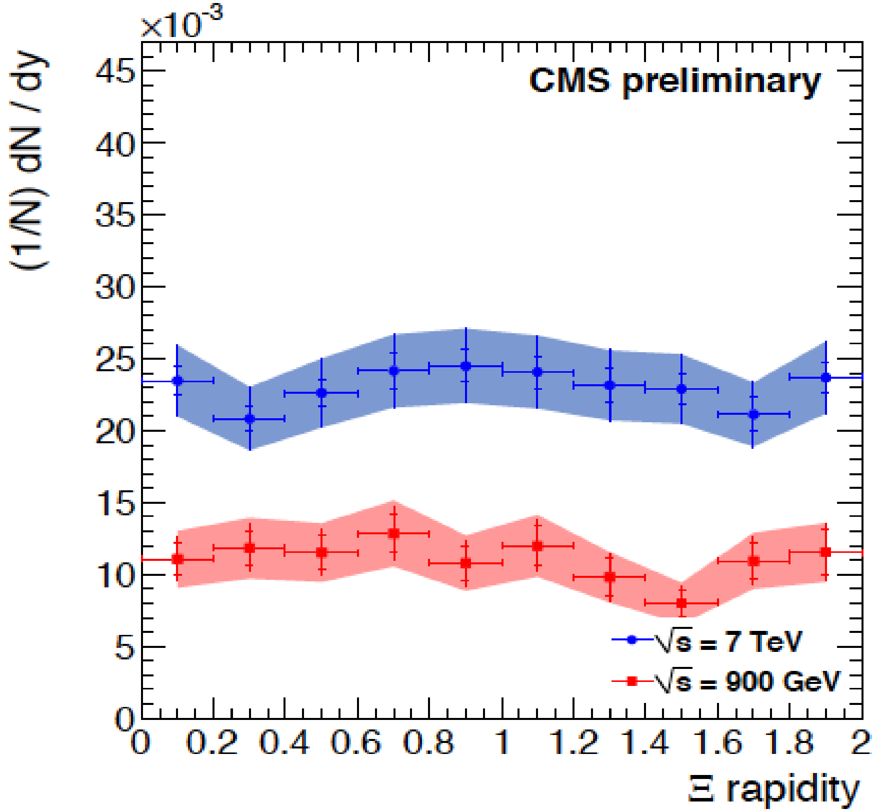


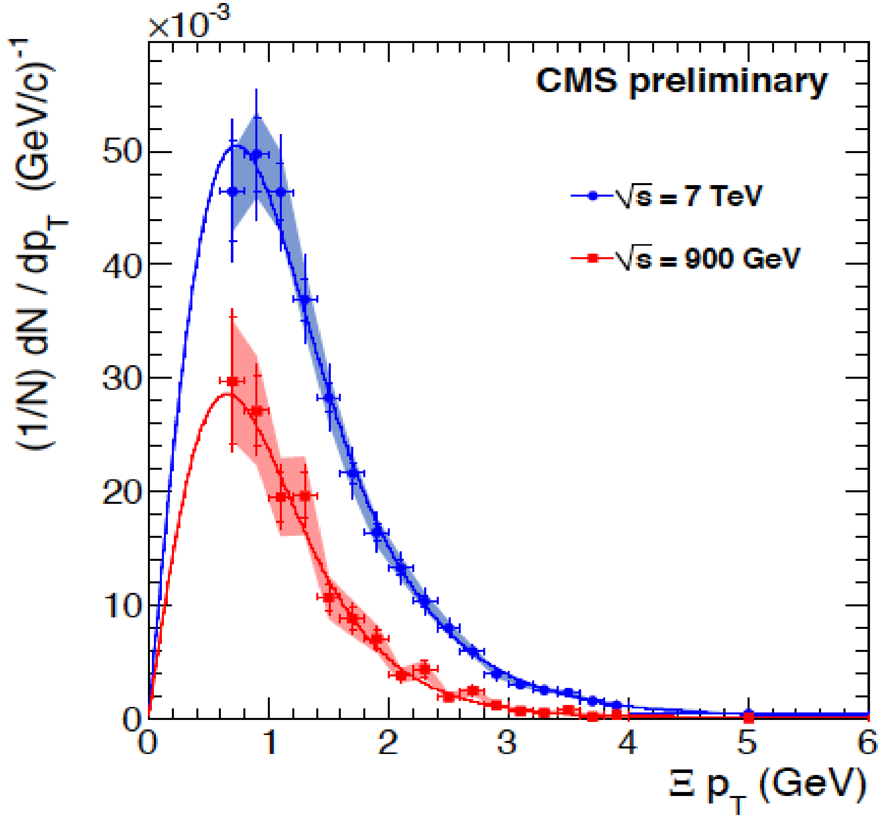
- Fit made with Tsallis function.
- Inner vertical bars: statistical error. Outer: uncorrelated systematic uncertainties.

Strange particle NSD production: Λ^0



Strange particle NSD production: Ξ^-





Strange particles: corrections and systematics

- Corrections for the yield:
  - Mass peak fit in each bin of a given variable (ct, p_T, y) to extract the yield .
  - Correction taking into account: trigger, selection and reco efficiencies (including acceptance and BR).
  - For Λ^0s a correction factor was applied for contribution coming from higher mass hyperon decays.
  - Correction factors were derived from PYTHIA8 and PYTHIA6 D6T (P0 used for systematics).
  - Non prompt Λ^0 production was increased by a factor of 2 in the MC.
  - Event-by-event re-weighting was applied to match multiplicities from data.
  - p_T(y) re-weighting was applied before correcting y(p_T).
- Systematic uncertainties:
  - PYTHIA8 vs. PYTHIA6 D6T and P0 ⇒ 2% for K_S^0 and 3% for Λ^0 and Ξ^-.
  - Track multiplicity re-weighting: PV and 2 tracks vs. HF only ⇒ 0.5%.
  - MC re-weighting 2D y and p_T vs. y fit and p_T fit ⇒ 1%.
  - With vs. w/o non prompt Λ^0 production factor ⇒ 2%.
  - Vertex significance and distance of closest approach variated by ± 1σ. and vertex fit probability by +1%,-0.9% ⇒ 4%.
  - Secondary track efficiency (measured – PDG) / PDG lifetime ⇒ 1% for K_S^0, 5% for Λ^0 and 8% for Ξ^-.
  - Fraction of tracks not originating from a true candidate (from MC) ⇒ 1%.
  - Track reconstruction ⇒ 2%/track, misalignment ⇒ 0.1%/track, acceptance ⇒ 1%.
  - Extrapolation p_T = 0, ½ diff. 2 different methods ⇒ 1.8% for K_S^0 at 7 TeV to 16% for Ξ^- at 0.9 TeV.
  - Fraction of NSD after cuts increased by 50% ⇒ 4.5%.

Two particle correlation: selections and corrections

- Signal in both BSCs

- in coincidence with BPTX signals from both beams ⇒ Beam-induced background negligible.
  Pile-up below % level.

- Primary Vertex (PV)

- |z| < 4.5 cm from nominal collision point.
- in a radius perpendicular to beam axis < 0.15 cm from average vertex position.
- containing 3 reconstructed tracks.

Resulting in:
168854 events (3.3 $\mu\beta^{-1}$) for 0.9TeV,
10902 events (0.2 $\mu\beta^{-1}$) for 2.36 TeV,
150086 events (3.0 $\mu\beta^{-1}$) for 7TeV ⇒
statistical error smaller than systematic error.

Multiplicity bin ($N_{trk}^{offline}$)	Event Count	$\langle N_{trk}^{offline} \rangle$	$\langle N_{trk}^{corrected} \rangle$
MinBias	21.43M	15.9	17.8
$N_{trk}^{offline} < 35$	19.36M	13.0	14.1
$35 \leq N_{trk}^{offline} < 90$	2.02M	45.3	53.1
$90 \leq N_{trk}^{offline} < 110$	302.5k	96.6	111.7
$N_{trk}^{offline} \geq 110$	354.0k	117.8	136.1

- Dedicated high multiplicity trigger

- L1: $E_{ECAL+HCAL+HF} > 60$ GeV
- HLT: $N_{trk}^{online} > 70$ for > 85 for the higher lumi runs.
  from pixel-tracks with z(origin) < 21cm and r(origin) < 0.5 cm
  $|\eta| < 2$, $p_T > 0.4$ GeV and
  d.o.c.a. from best vertex (the one with more tracks) < 0.12 cm.

Resulting in 980 nb^{-1}

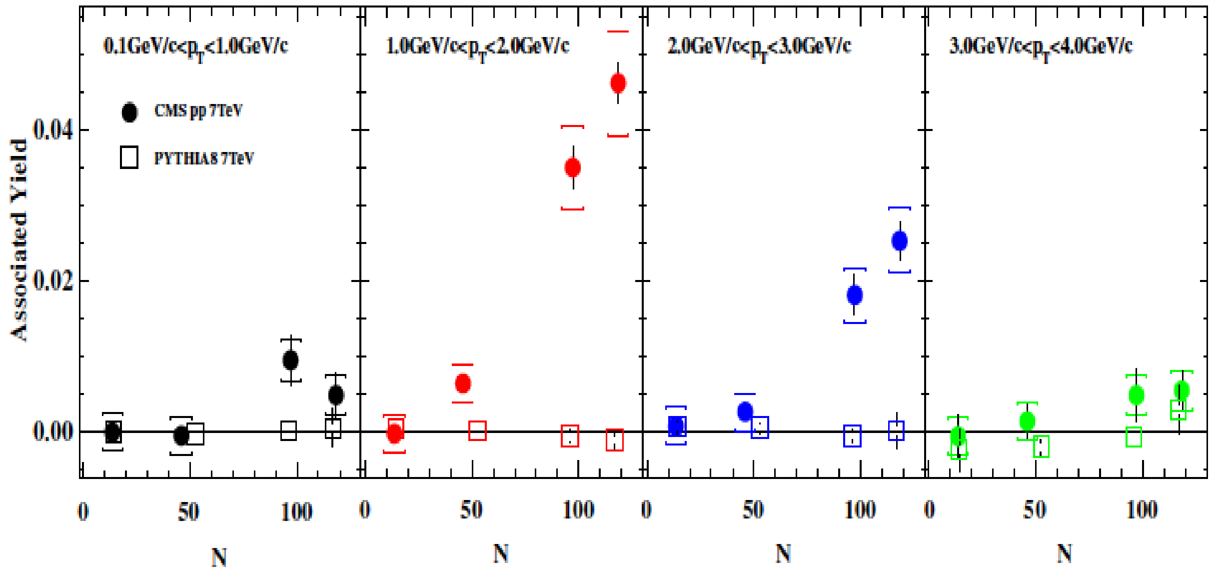
- Tracks

- 5.0 > p_T > 0.1 GeV (0.4 when classifying event multiplicity, in order to match online tracking)
- $|\eta| < 2.4$
- High purity
- $d_{xy}/\sigma(d_{xy})$ and $d_z/\sigma(d_z) < 3$
- $\sigma(p_T)/p_T < 10\%$

- Corrections

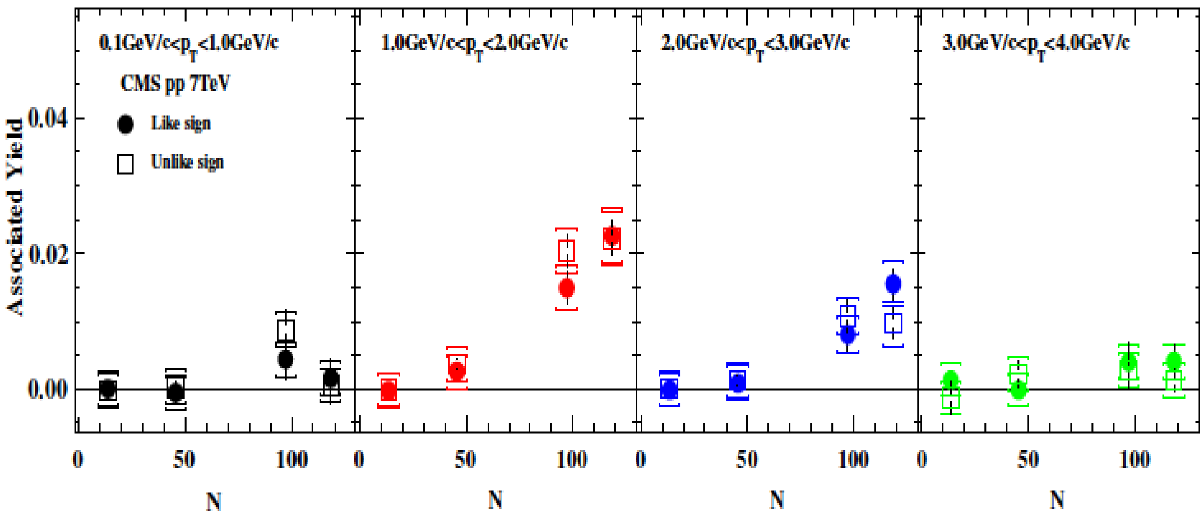
- Track efficiency vs. η, p_T, z_{vtx}
- Event selection vs. N_{trk}^{true}
- Event HLT selection vs. $N_{trk}^{offline}$ for high multiplicity

Long-range correlation at 7 TeV: the “Ridge”



Zero Yield At Minimum (ZYAM) method [13]: integrating over the range: $0 < |\Delta\phi| < \phi_{ZYAM}$ where ϕ_{ZYAM} is the minimum derived from the fit with a second order polynomial in the range $0.1 < |\Delta\phi| < 2.0$.

The long-range, near-side correlation is confirmed in the high multiplicity and moderate p_T bins.



Results in like-sign and unlike-sign were compared: possible problems in track reconstruction would affect differently the two subset.

PYTHIA8 (in open squares) cannot reproduce the data.

Bose-Eistein Correlation: selections

- Signal in both BSCs
  - in coincidence with BPTX signals from both beams

- Selected tracks
  - $p_T > 0.2$ GeV and $|\eta| < 2.4$ crossing all pixel layers (good separation).
  - High purity tracks: $\chi^2/nof < 5$.
  - Transverse impact parameter < 0.15 cm w.r.t. collision point.
  - $d_{xy} < 20$ cm w.r.t. beam axis.