Particle production in relativistic *proton-proton* collisions - new (!) features at the LHC

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Multi-particle production in relativistic collisions of heavy-ions and proton-proton

Primary goal – to study Quark-gluon plasma (QGP) – thermally equilibrated matter of de-confined quarks and gluons.

- **Super-dense astrophysical and cosmological situations:**
  A few micro-seconds after the Big Bang
  Core of the Neutron star Collins & Perry PRL 34 (1975) 1353

- **High energy collisions of heavy-ions (HI) in laboratory**
  CERN declared indication of formation of QGP-like new state (2000)
  RHIC, BNL presented convincing results on formation of QGP in laboratory NPA 757 (2005)

- **High energy proton-proton collisions: *consensus view !***
  Elementary collisions, no medium formation
  Experimentally, serve the base-line for the QGP study by HI collisions

$$R_{AA} = \frac{\text{Yield}_{\text{AuAu}}}{\langle N_{\text{binary}} \rangle_{\text{AuAu}} \times \text{Yield}_{\text{pp}}}$$

pp collisions - there had always been a different school of thought !

SPS regime

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

FERMILAB-Pub-82/59-THY
August, 1982

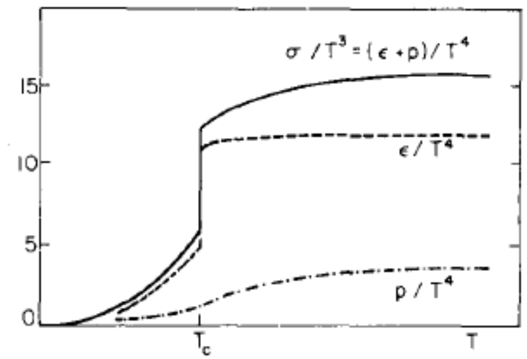
SPPS events of high transverse energy …………

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Volume 118B, number 1, 2, 3 PHYSICS LETTERS 2 December 1982

MULTIPLICITY DEPENDENCE OF p_t SPECTRUM AS A POSSIBLE SIG
FOR A PHASE TRANSITION IN HADRONIC COLLISIONS

L. VAN HOVE
CERN, Geneva, Switzerland



Different school of thought (contd.)

Tevatron regime

VOLUME 67, NUMBER 12 PHYSICAL REVIEW LETTERS 16 SEPTEMBER 1991

Transverse Baryon Flow as Possible Evidence for a Quark-Gluon-Plasma Phase

Péter Lévai[(a)] and Berndt Müller

Department of Physics, Duke University, Durham, North Carolina 27706
(Received 13 March 1991)

In order to investigate the coupling between the collective flow of nucleons and pions in hot pion-dominated hadronic matter, we calculate the pion-nucleon drag coefficient in linearized transport theory. We find that the characteristic time for flow equalization is longer than the time scale of the expansion of a hadronic fireball created in high-energy collisions. The analysis of transverse-momentum data from $p+\bar{p}$ collisions at $\sqrt{s}=1.8$ TeV reveals the same flow velocity for mesons and antinucleons. We argue that this may be evidence for the formation of a quark-gluon plasma in these collisions.

ELSEVIER

Physics Letters B 528 (2002) 43–48

PHYSICS LETTERS B

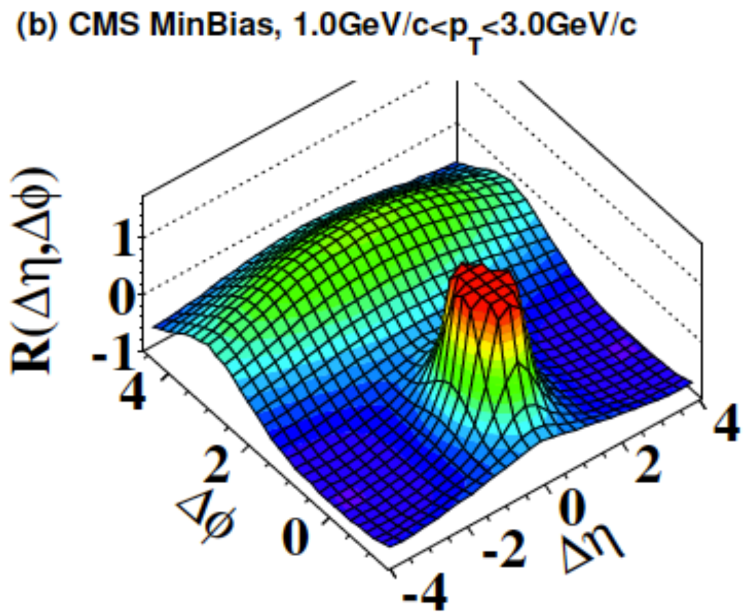
www.elsevier.com/locate/npe

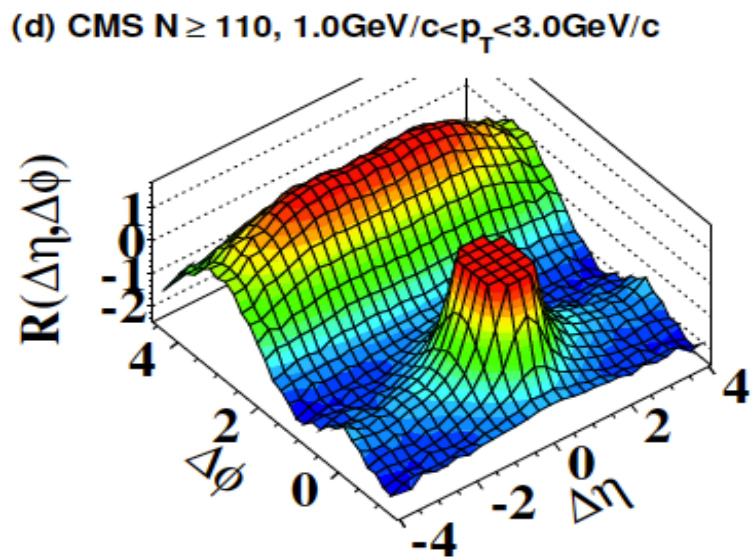
Evidence for hadronic deconfinement in $\bar{p}$–p collisions at 1.8 TeV

T. Alexopoulos[a,1], E.W. Anderson[b], A.T. Bujak[c], D.D. Carmony[c], A.R. Erwin[a], L.J. Gutay[c], A.S. Hirsch[c], K.S. Nelson[a,2], N.T. Porile[d], S.H. Oh[f], R.P. Scharenberg[c,*], B.K. Srivastava[d], B.C. Stringfellow[c], F. Turkot[g], J. Warchol[e], W.D. Walker[f]

Different school of thought (contd.)

Most striking observation, so far ! ***Ridge.*** **CMS, JHEP 09 (2010) 091** **LHC regime**





Near-side long-range correlation in high multiplicity events.
Resembles effects seen in heavy-ion collisions !

Dependence of HBT radii on multiplicity and pair transverse momentum – Similar as observer in heavy-ion collisions

CMS, JHEP 05 (2011) 029
ALICE, PRD 84 (2011) 112004

High multiplicity pp events comparable to RHIC and SPS HI events

Several Hydrodynamics-motivated models !

Scope of the talk

Discussions on some features of multi-particle production in pp collisions at LHC in terms of

- ***Multiplicity***
- ***Transverse momentum***

Don't intend to conclude on:

Hydrodynamics, Color Glass Condensate, Color Re-connection ……..????

Charged hadron Multiplicity Distributions in *pp* collisions at LHC

Prior to LHC, the Negative Binomial Distribution (NBD) function has played a major role in describing multiplicity distributions (MD) in hadronic collisions for a wide range of collision energy.

We report a detailed analysis of the measured multiplicity distributions for pp collisions at so far available LHC energies, in terms of NBD.

Multiplicity distributions in pp collisions by ALICE

ALICE, EPJC68(2010)89

Primary charged particles from NSD events for pseudorapidity intervals, η_c < 0.5, 1.0 and 1.3 at energies 900 GeV and 2360 GeV.

Matched fairly well with a single NBD function.
Sum of two NBDs did not improve description of data.

ALICE, EPJC68(2010)345

For 7000 GeV collisions, multiplicity distribution is measured only in the pseudorapidity interval, η_c <1.0 for the class of events having at least one charged particle in the interval.

NBD-fit to the distribution slightly underestimates the data at low multiplicity (n<5) and slightly overestimates at high multiplicity (n > 55).

MD measured in pp collisions by CMS and LHCb

CMS, JHEP1101(2011)079

CMS has measured MD of charged hadrons from NSD events for pseudorapidity intervals, η_c < 0.5, 1.0, 1.5, 2.0 and 2.4 at all the available LHC energies : 900, 2360 and 7000 GeV.

Change in slope in the measured multiplicity distributions for n>20 in the pseudorapidity interval, η_c <2.4. The feature becomes more prominent with increasing centre-of-mass energy. The paper does not on NBD.

LHCb, EPJC 72 (2012) 1947

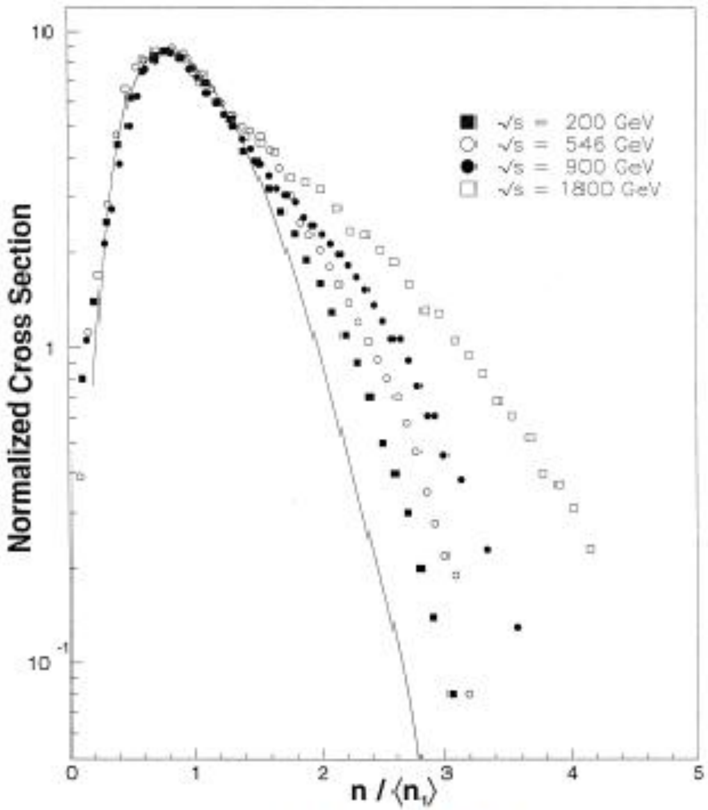
LHCb has analyzed multiplicity distributions for hard interaction events (at least one long track with p_T > 1 GeV/c) for 7000 GeV cms energy in non-overlapping psedorapidity interval of $|\eta| < 0.5$ in the pseudorapidity range 2.5 < $|\eta|$ <4.5.

Shoulder-like structure in multiplicity distributions at pre-LHC energies

PLB435(1998)453.

Comparative study: charged particle multiplicities arising from NSD events of hadronic collisions at energies from 30 GeV to 1800 GeV.

Observed: Data of collider energies (200 to 1800 GeV) deviate in the form of a shoulder-like structure, apparently due to superposition of distribution of particles from other process, different from KNO-producing process that is valid up to ISR energies



A comparison of multiplicity distributions at different values of $\sqrt{s}$. The distributions have been normalized at the maximum value of $d\sigma/dx$ where $x = n/\langle n_1 \rangle$. The solid curve is the KNO distribution from the ISR data. The actual cross section $d\sigma/dx$ may be obtained by integrating the overall curves as presented in the figure and equating the result to the measured value of σ_{NSD} to determine the scale constant.

Two-NBD model explains shoulder-like structure

PRD59 (1999)094020

Model by Giovannini and Ugoccioni

Sub-structure in multiplicity distributions at collider energies could be well explained by weighted superposition of two NBDs, representing two classes of events:

"semi-hard" – events with mini-jets or jets.
"soft" – events without mini-jets or jets.

PRD60(1999)074027

The model for the full phase space was extended to limited η – intervals, only after classification of events into "soft" and "semi-hard" to ensure that the weight factors for the components are maintained.

Negative Binomial Distribution (NBD) Function

$$P(n, \langle n \rangle, k) = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)} \left[\frac{\langle n \rangle}{k+\langle n \rangle}\right]^n \times \left[\frac{k}{k+\langle n \rangle}\right]^k,$$

where $\langle n \rangle$ is the average multiplicity and the parameter k is related to dispersion D, $(D^2 = \langle n^2 \rangle - \langle n \rangle^2)$ by

$$\frac{D^2}{\langle n \rangle^2} = \frac{1}{\langle n \rangle} + \frac{1}{k}.$$

Weighted superposition of Two-NBDs

$$\begin{aligned} P_n(\sqrt{s}, \eta_c) &= \alpha_{\text{soft}}(\sqrt{s}) \\ P_n[\langle n \rangle_{\text{soft}}(\sqrt{s}, \eta_c), k_{\text{soft}}(\sqrt{s}, \eta_c)] &+ [1 - \alpha_{\text{soft}}(\sqrt{s})] \\ P_n[\langle n \rangle_{\text{semihard}}(\sqrt{s}, \eta_c), k_{\text{semihard}}(\sqrt{s}, \eta_c)], \end{aligned}$$

α_{soft} = fraction of soft events

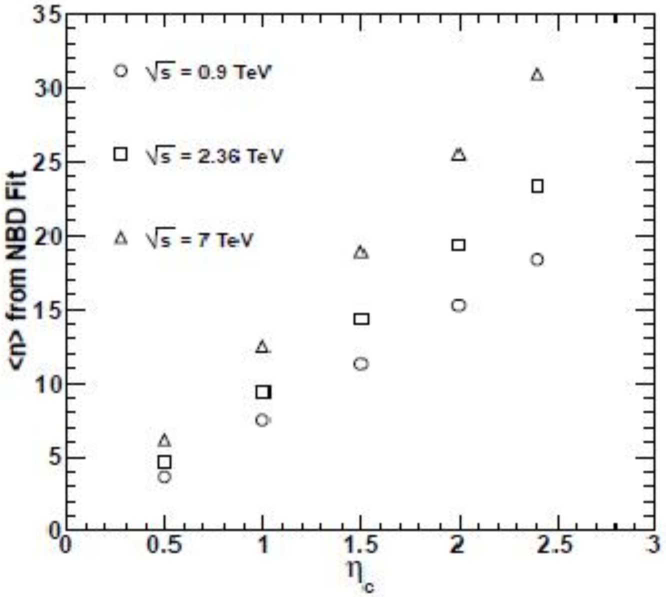
Measured <n> & corresponding NBD parameter for MDs at LHC-energies

$\sqrt{s}$ (TeV)	η_c	$\langle n \rangle_{NBD}$	$\langle n \rangle$	$\chi^2/d.o.f$
0.9	0.5	3.66 ± 0.04	$3.59^{+0.15}_{-0.15}$	6.12/22
	1.0	7.49 ± 0.08	$7.26^{+0.16}_{-0.15}$	53.35/38
	1.5	11.32 ± 0.10	$10.95^{+0.18}_{-0.16}$	49.55/50
	2.0	15.26 ± 0.13	$14.83^{+0.21}_{-0.18}$	36.69/60
	2.4	18.36 ± 0.14	$17.86^{+0.23}_{-0.20}$	46.29/66
2.36	0.5	4.70 ± 0.08	$4.60^{+0.16}_{-0.15}$	6.38/21
	1.0	9.42 ± 0.11	$9.26^{+0.19}_{-0.17}$	55.30/38
	1.5	14.35 ± 0.16	$14.01^{+0.28}_{-0.21}$	24.79/48
	2.0	19.35 ± 0.21	$18.93^{+0.29}_{-0.27}$	29.11/58
	2.4	23.35 ± 0.25	$22.63^{+0.35}_{-0.33}$	29.76/68
7	0.5	6.16 ± 0.05	$5.98^{+0.14}_{-0.13}$	83.36/39
	1.0	12.49 ± 0.08	$12.18^{+0.15}_{-0.13}$	152.65/68
	1.5	18.89 ± 0.10	$18.53^{+0.18}_{-0.15}$	226.57/93
	2.0	25.47 ± 0.14	$25.10^{+0.21}_{-0.19}$	208.56/113
	2.4	30.90 ± 0.16	$30.32^{+0.24}_{-0.21}$	129.37/125

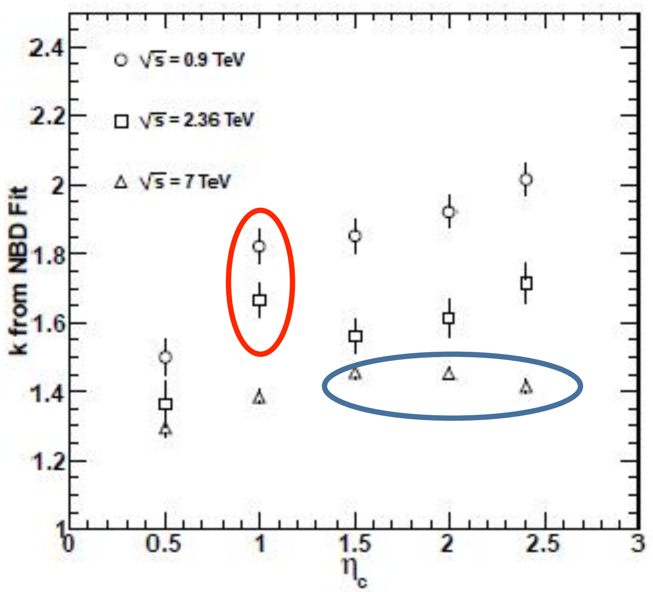
PG PRD 85 (2012)054017

NBD parameters for MDs at LHC-energies

PG PRD 85 (2012)054017



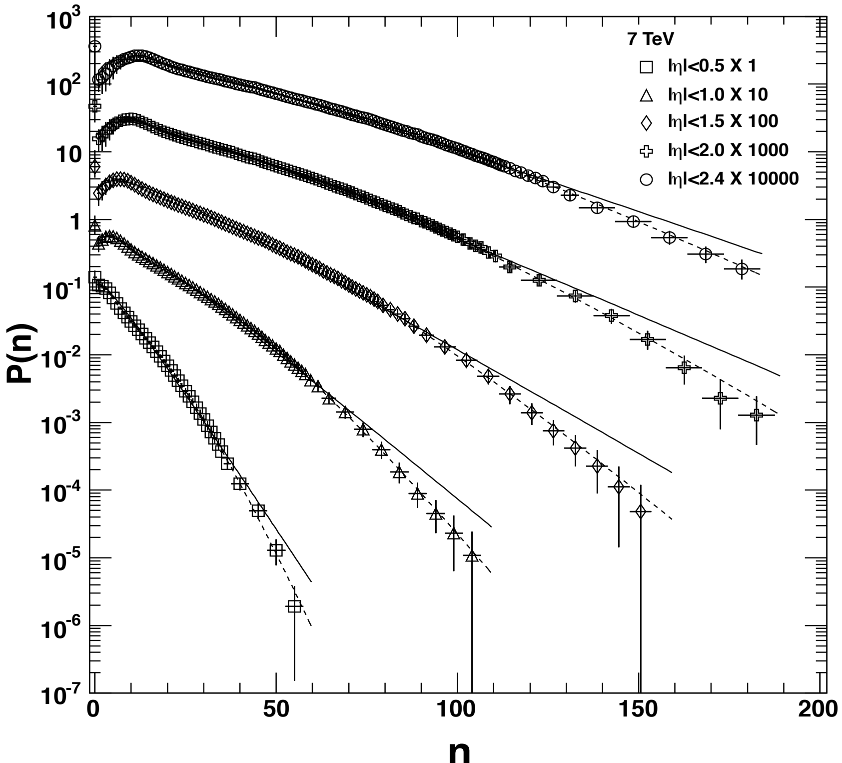
Parameter $\langle n \rangle$ from NBD for $|\eta|$ <0.5 to 2.4 for $\sqrt{s}$ = 0.9, 2.36 and 7 TeV. The error-bars associated with the data-points are not visible as the corresponding magnitudes are smaller than the dimension of symbol-size in the plots.



Parameter k of NBD for $|\eta|$ <0.5 to 2.4 for $\sqrt{s}$ = 0.9, 2.36 and 7 TeV.

Two–NBD explains 7 TeV data better

PG PRD 85 (2012)054017



pp collisions @ 7 TeV

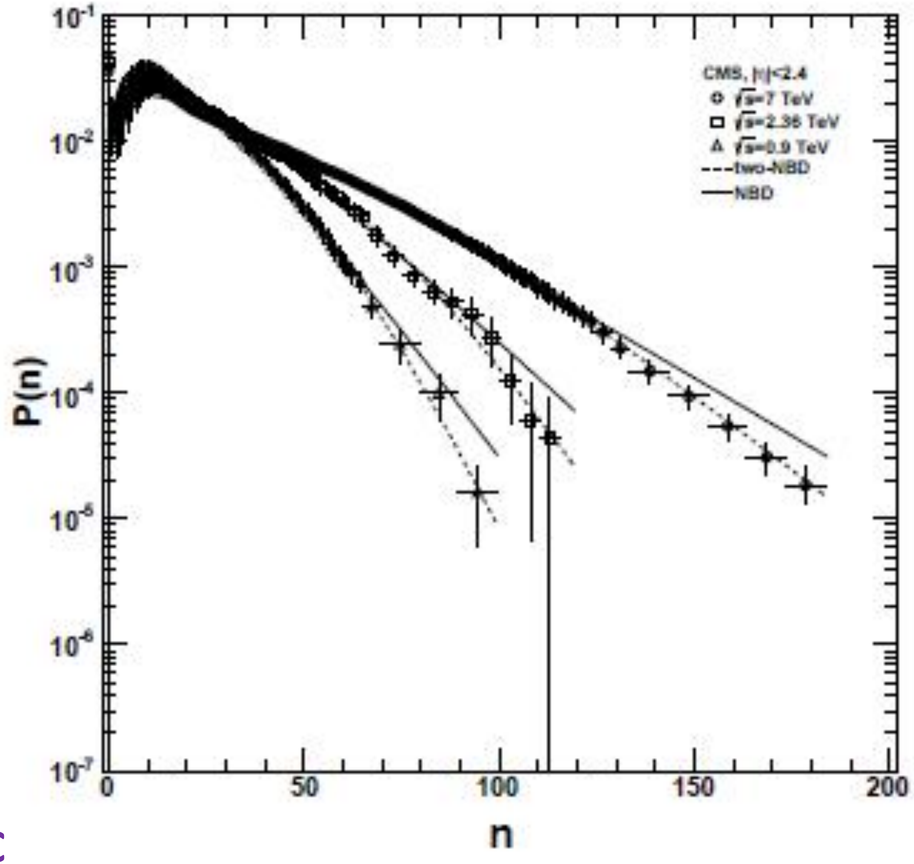
η_c <2.4

Energy-invariance of "soft" events !

$\sqrt{S}$ (GeV)	k_{soft}	$<n>_{soft}$	$k_{semihard}$	$<n>_{semihard}$
900	2.44+0.32	14.78+1.99	8.13+2.34	35.11+3.90
2360	2.57+0.52	15.74+2.98	6.27+2.21	41.92+6.21
7000	2.38+0.34	15.06+1.48	3.25+0.49	46.86+3.45

Energy-invariance of "soft" component of events @ LHC

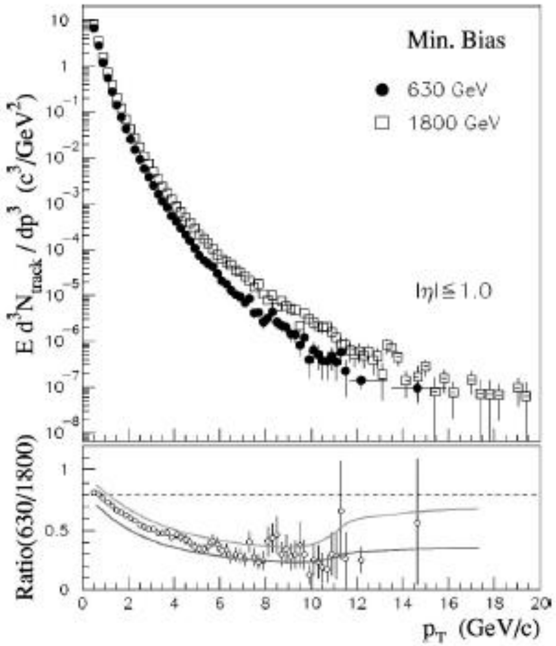
Indication slide - 1



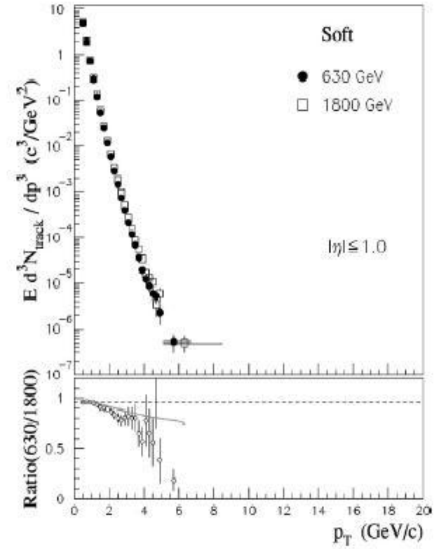
pp collisions @ LHC
η_c <2.4

Plots of multiplicity distributions of charged hadrons in η_c <2.4 at $\sqrt{s}$ = 0.9 TeV, $\sqrt{s}$ = 2.36 TeV and $\sqrt{s}$ = 7 TeV. The continuous lines correspond to fits to a single NBD function and the dotted lines correspond to fits to weighted superposition of two NBDs. The error-bars include both the statistical and the systematic uncertainties

Energy-invariance ……….. at Tevatron



Transverse momentum distributions for the full MB samples at 1800 and 630 GeV. In the bottom panel the ratio of the two distributions is shown. The two continuous lines delimit the band of all systematic uncertainties (see Sec. VI of text). N_{track} refers to the number of charged tracks in a unit η interval.



Same for the *soft* samples. The continuous line in the ratio plot shows the upper limit of the systematic uncertainties. The lower limit overlaps the data points.

CDF Collaboration, PRD65 (2002)072005.

Analyzed: isolated sub-samples of "soft" and "semihard" events of proton-antiproton collisions at 630 and 1800 GeV.

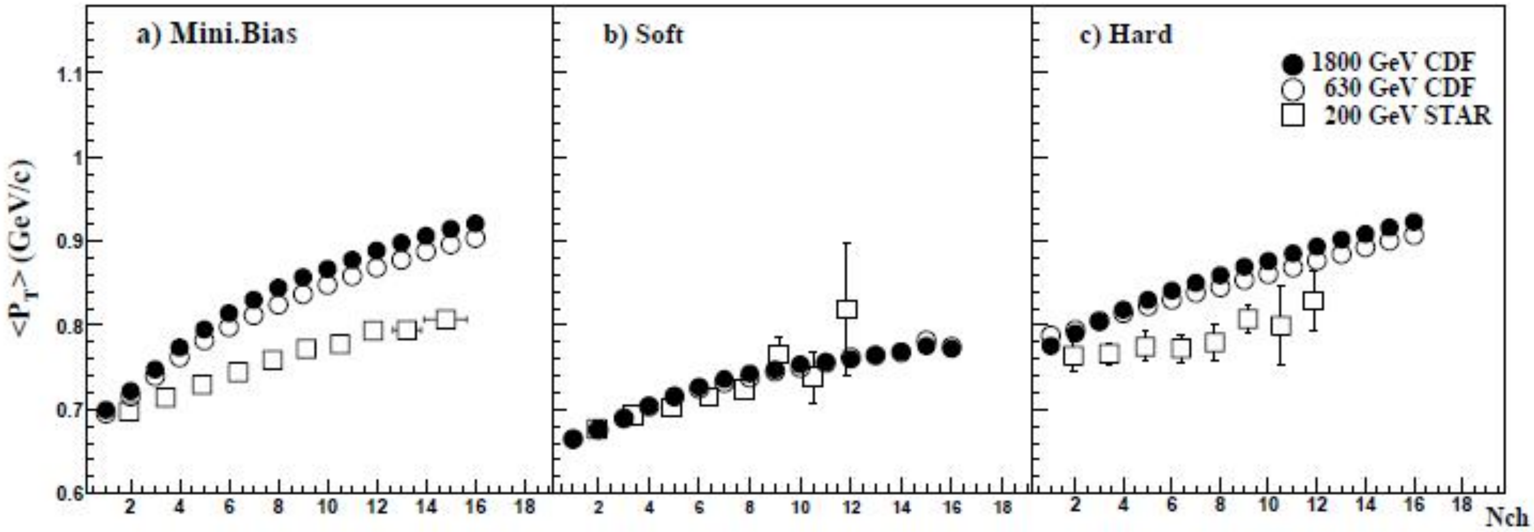
Observed: energy-invariance of properties of "soft" sub-samples.

Energy-invariance ……………… at RHIC

STAR Collaboration, arXiv:hep-ex/0403038v1 (2004)072005.

Analyzed: isolated sub-samples of "soft" and "hard" events of proton-proton collisions at 200 GeV.

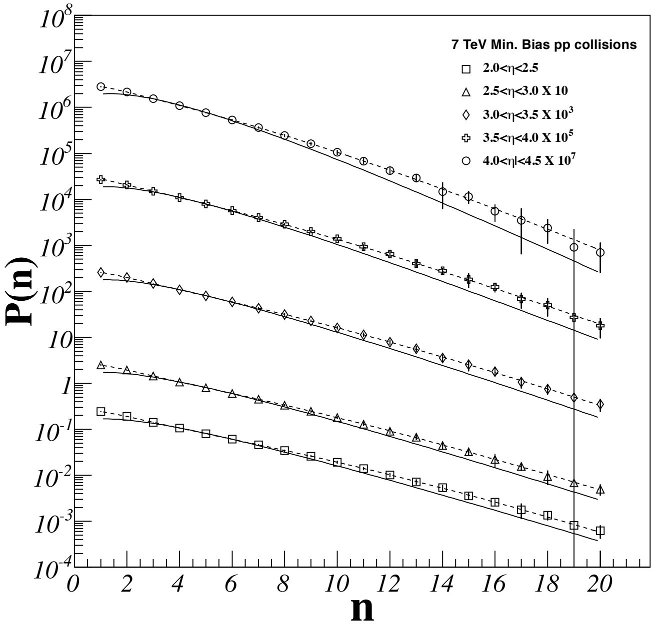
Observed: energy-invariance of dynamical mechanism of inelastic multiparticle production in "soft" collisions.

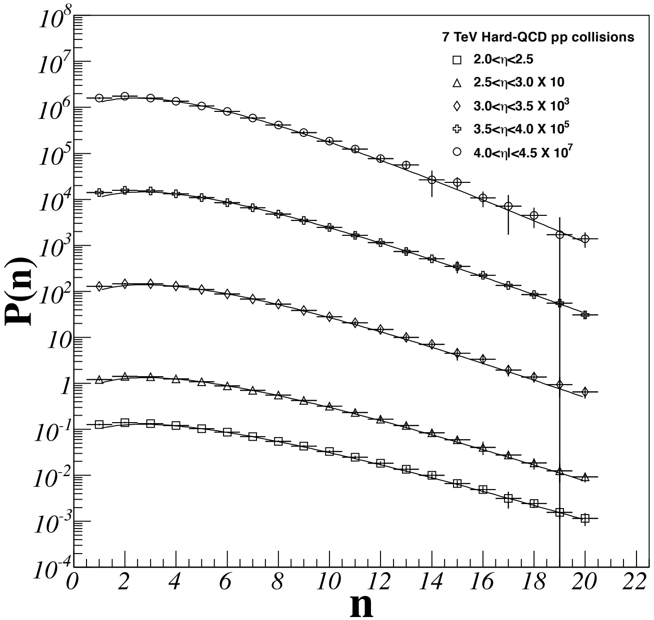


The mean transverse momentum $<P_T>$ dependence on the multiplicity Nch in minimum bias, soft and hard events. The errors bars are statistical errors only. The STAR acceptance is extended from $|\eta|<0.5$ to $|\eta|<1.0$ by HIJING to compare the results with CDF.

NBD in *pp* collisions in the forward pseudorapidity by LHCb

PG & S. Muhuri PRD 87 (2013) 094020

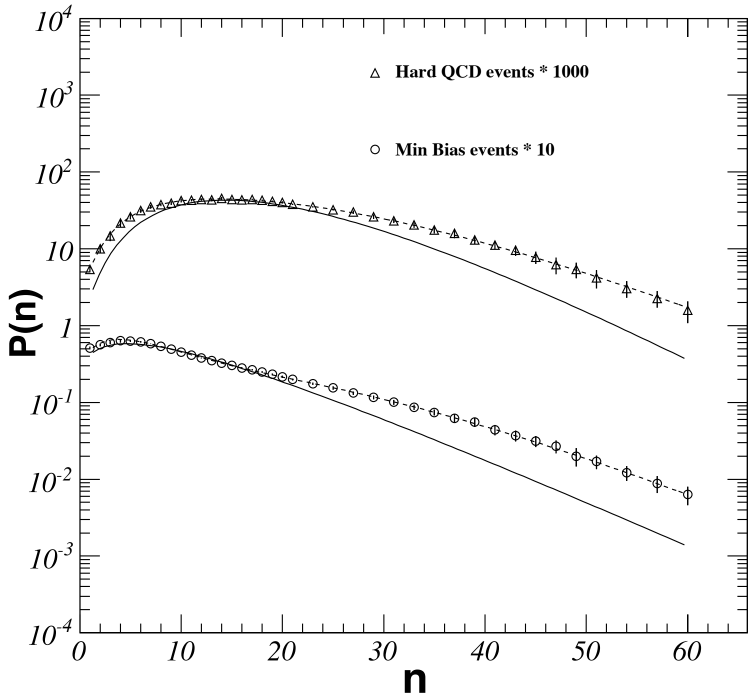




***Two-NBD fits and single-NBD fits to the minimum-bias and "hard" events respectively, in the small pseudo-rapidity windows appear consistent with the two-component model*.**

NBD in *pp* collisions in the forward pseudorapidity by LHCb (contd.)

PG & S. Muhuri PRD 87 (2013) 094020



In the large pseudo-rapidity window, for both the minimum-bias and hard events, two-NBD gives better descriptions !

- ***The selection criterion of "soft" and "hard" events needs to be reviewed!***
- ***Different physics of particle production in mid and forward rapidity regions!***

CDF – "soft" event : no particle of transverse energy, E_T > 1.1 GeV
LHCb – "hard" event : at least one particle with transverse momentum p_T > 1 GeV/c

Summary – multiplicity distributions at LHC

The energy-invariance of the two-NBD parameters related to the "soft" component of LHC pp events the mid-rapidity is indicative to the possibility of validity of the energy-invariance of soft particle production in pp collisions at LHC

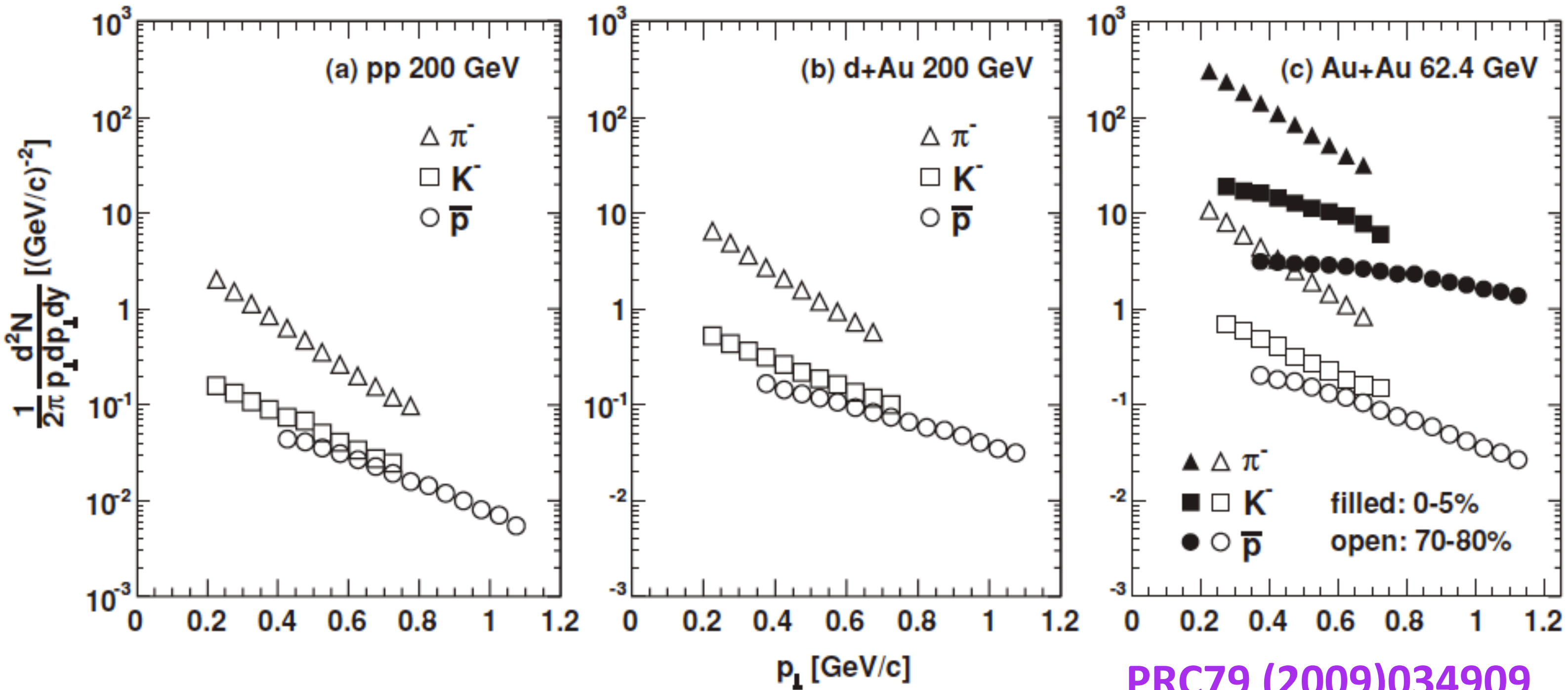
One needs to look into the global properties of the isolated sub-samples of the "soft" and the "hard" events of pp collisions.

Analysis of LHCb – data indicates the importance of reviewing "soft" and "hard" events selection criterion. Transverse Sphericity!!

The study of properties of exclusive "soft" events will be complementary to the study of Underlying Event properties, already addressed by ALICE and the other two experiments, CMS and ATLAS.

Transverse momentum distributions in *pp* at LHC

Let's start with identified hadron spectra at STAR@RHIC

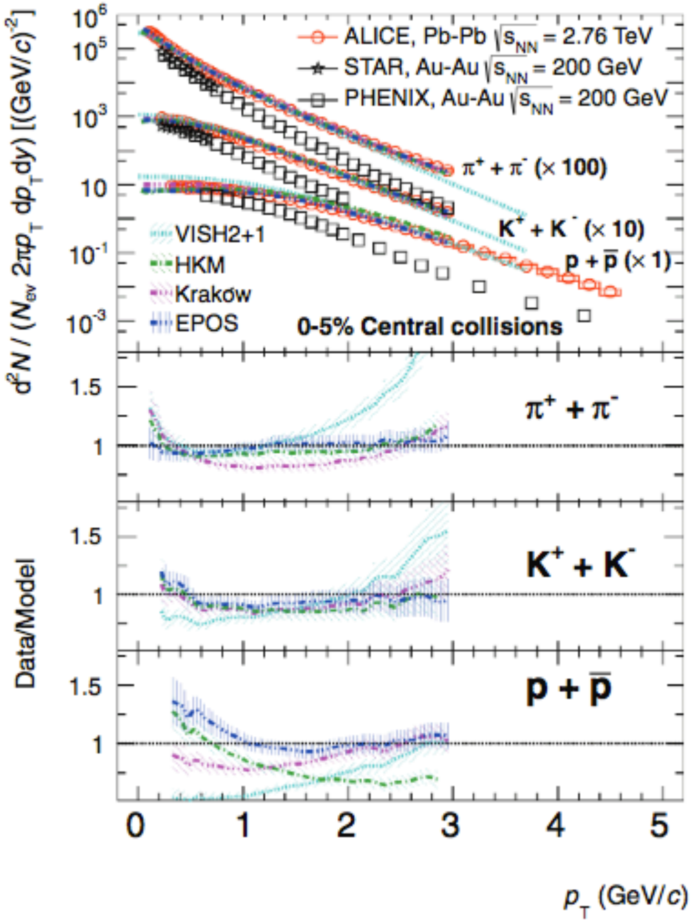


PRC79 (2009)034909

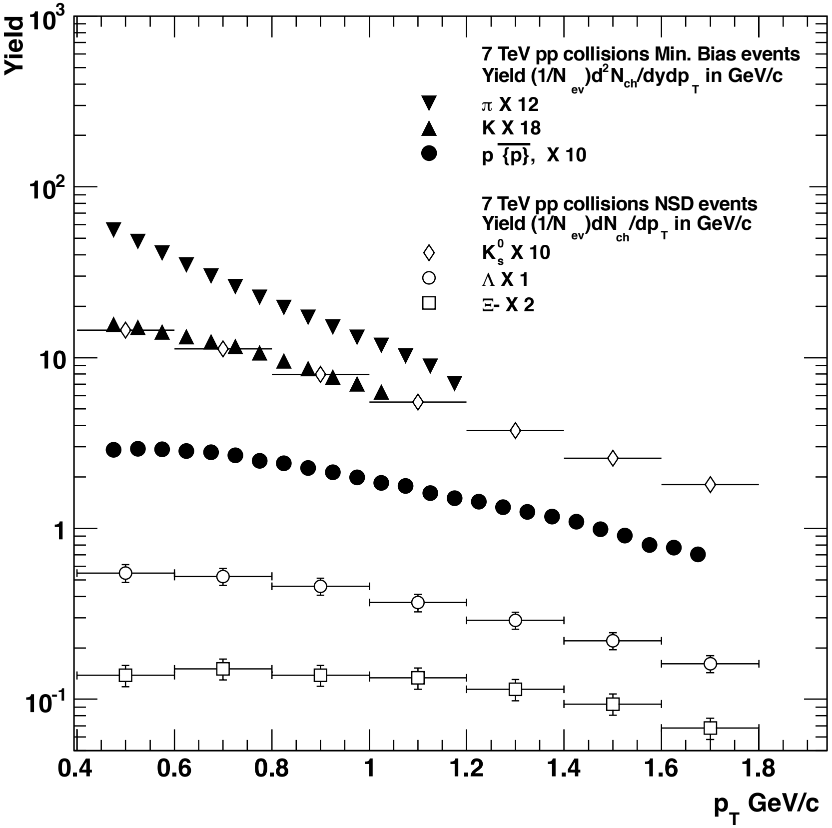
- **Flattening of spectra with increasing mass indicates collectivity**

- **Collectivity is associated with 'soft' particle production – particles in the low p_T part of the p_T - spectra**

Transverse momentum distributions of identified hadrons in heavy-ion & *pp* collisions at LHC



ALICE, PRC88 (2013)044910



CMS, EPJC 72 (2012) 2164

CMS, JHEP 05 (2011)064

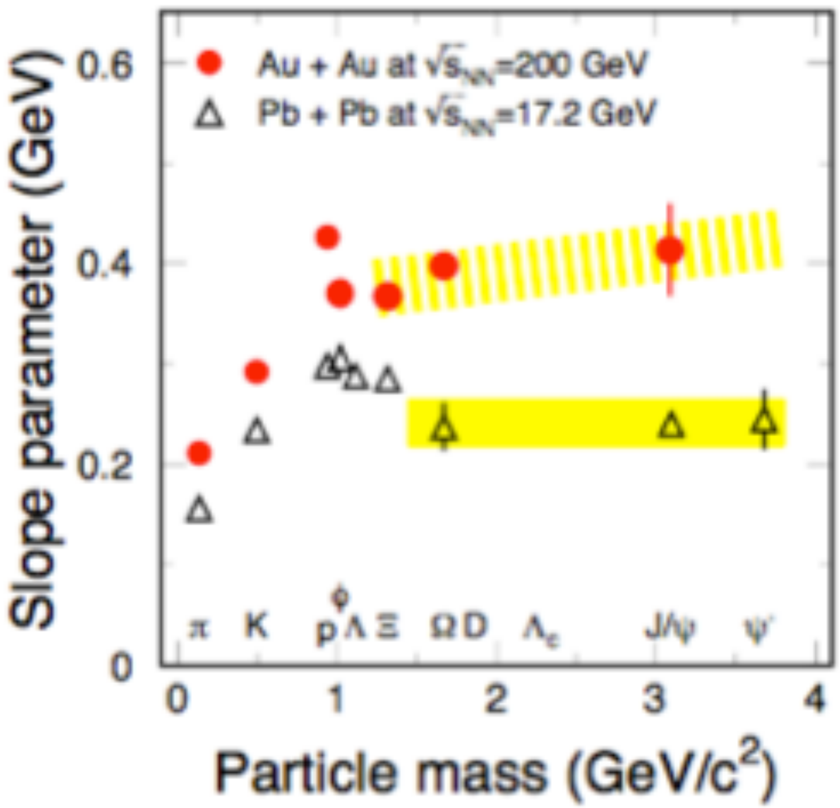
PG et al. JPG 41 (2014) 035106

Mass-dependent inverse slope parameter

$$m_T = \sqrt{p_T^2 + m^2}$$

$$\frac{dN}{m_T\, dm_T} \sim C \exp\left(-\frac{m_T}{T_{eff}}\right),$$

$$\langle m_T \rangle = T_{eff} + m + \frac{(T_{eff})^2}{m + T_{eff}}.$$



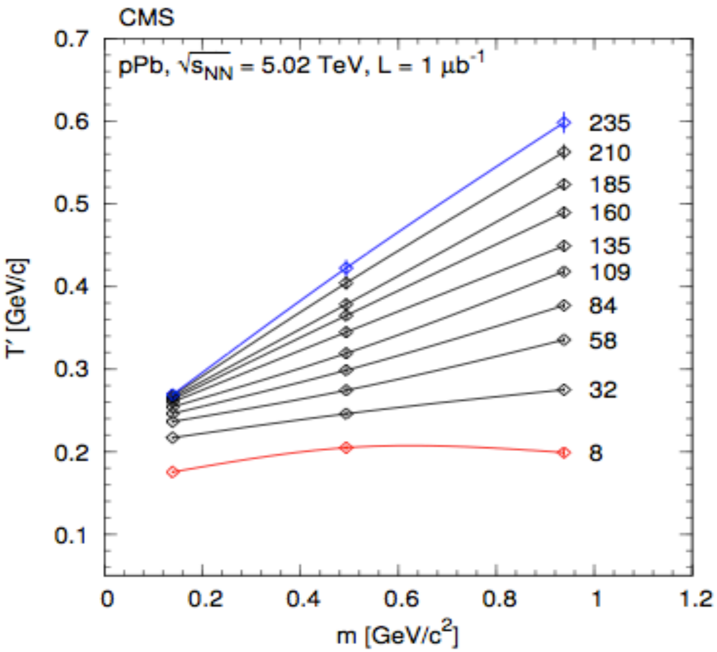
Hydrodynamical parameterization results:

$$T_{eff} = T_{th} + \frac{1}{2} m < \beta_T >^2$$

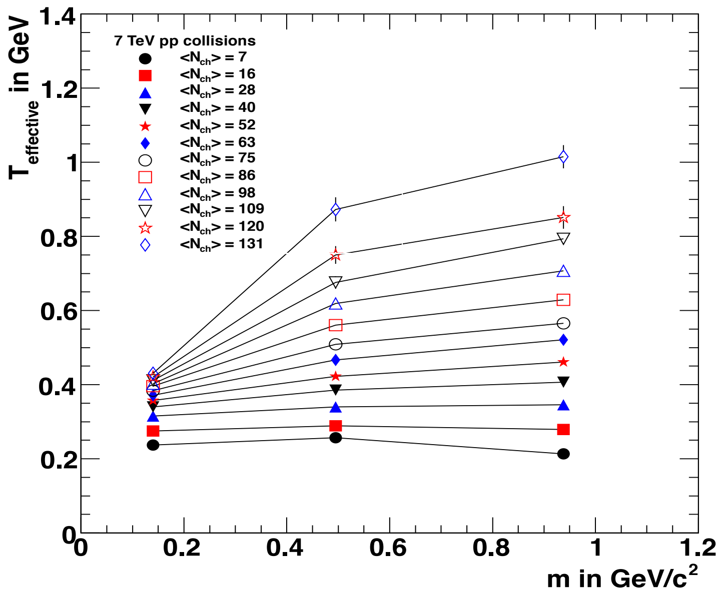
Absence of the mass-ordering with strange and heavy-flavor hadrons is attributed to non-effective participation of these heavy particle in hadronic re-scattering – due to their heavy mass or early freeze-out of strange particles

Mass dependent inverse slope parameter for *pp* & *pPb* collisions at LHC

CMS, EPJG 74 (2014) 2847



PG & S. Muhuri arXiv:1406.5811 [hep-ph]



Mass ordering of inverse slope parameter in high multiplicity *pp* and *pPb* events – similar feature as observed in HI collisions

Indication of collectivity in high multiplicity *pp* and *pPd* collisions at LHC

Hydrodynamics-motivated Boltzman-Gibbs blast-wave model

Blast-wave model assumes an instantaneous common freeze-out at kinetic freeze-out temperature T_{kin} and a common transverse flow velocity.

E. Schnedermann et al. PRC48 (1993) 2462

$$\frac{dN}{p_T\,dp_T} \propto \int_0^R r\,dr\, m_T\, I_o\left(\frac{p_T \mathrm{Sinh}\,\rho}{T_{\mathrm{kin}}}\right) K_1\left(\frac{p_T \mathrm{Cosh}\,\rho}{T_{\mathrm{kin}}}\right),$$

where $\rho = \tanh^{-1}\beta$, I_0 and K_1 are modified Bessel functions.

The flow velocity profile is given by $\beta = \beta_s\left(\frac{r}{R}\right)^n$

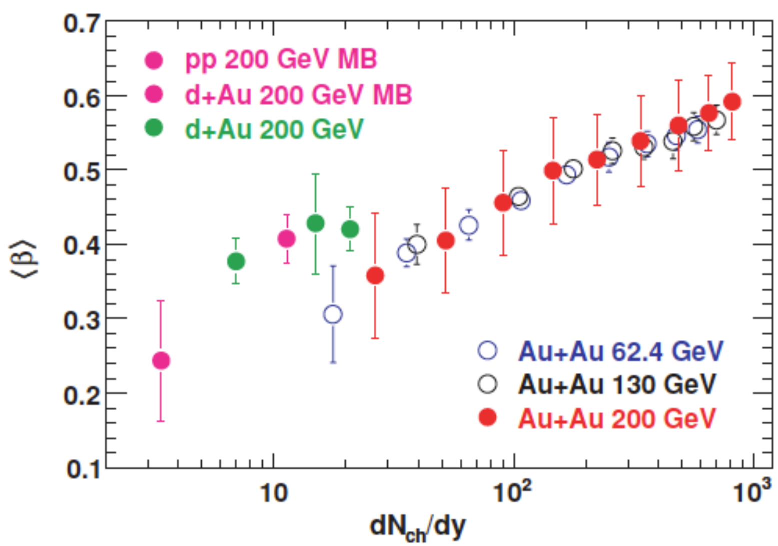
where β_s is the surface velocity

The average transverse flow velocity $\langle\beta\rangle = \frac{2}{(2+n)}\beta_s$

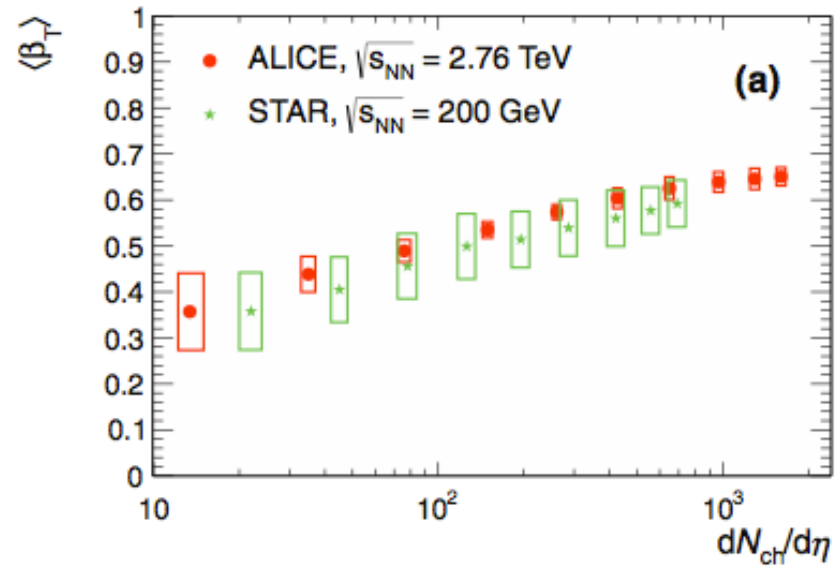
R is the transverse radius at freeze-out. Experimentally obtained from HBT radius for the lowest pair of transverse momentum. The profile parameter n is found to match hydrodynamic calculation with value 1 or 2, though in principle, it can take any positive value.

The average transverse flow velocity in heavy-ion collisions

STAR PRC79 (2009)034909



ALICE PRC88 (2013)044910

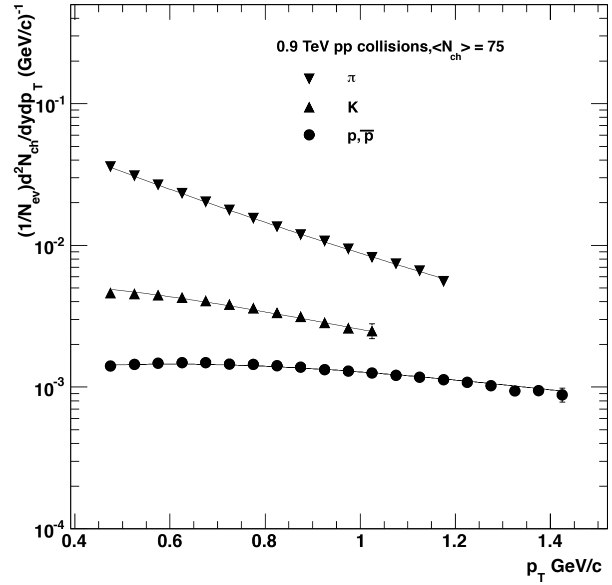


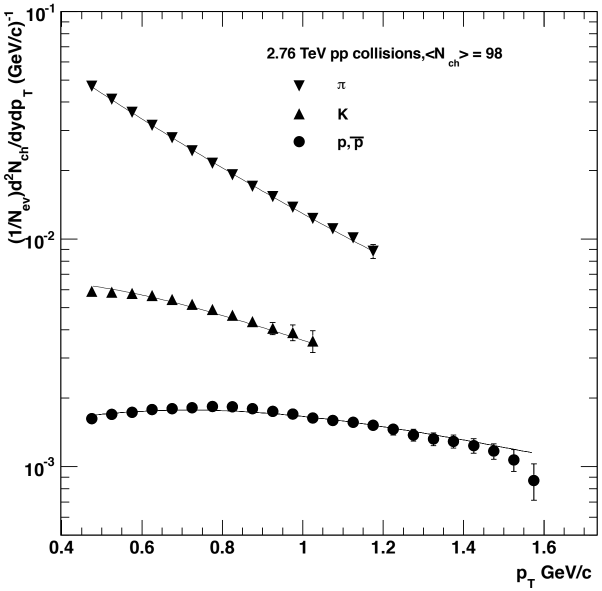
Blast-wave model has been very successful in establishing collectivity by extracting transverse flow velocity in heavy-ion collisions in SPS, RHIC and LHC

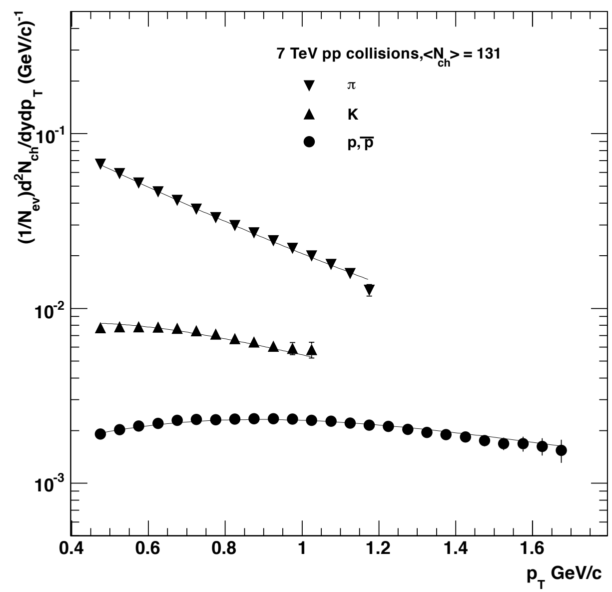
Transverse momentum spectra of $\pi^{\pm}$, $K^{\pm}$ and p(p-bar) from high multiplicity *pp* events at 0.9, 2.76 and 7 TeV.

- **Solid lines represent the blast-wave description.**
- **Minimum bias or low multiplicity events do not fit blast-wave.**

PG et al. JPG 41 (2014) 035106







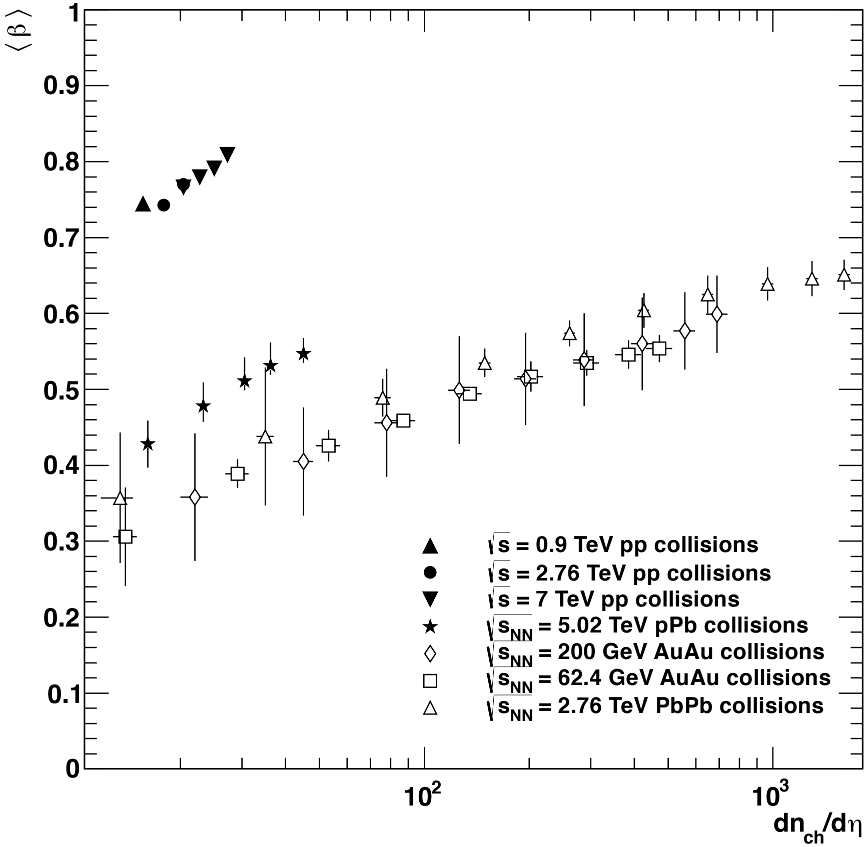
Simultaneous blast-wave fit parameters of transverse momentum spectra of $\pi^{\pm}$, $K^{\pm}$ and p(p-bar) from high multiplicity *pp* events at LHC

PG et al. JPG 41 (2014) 035106

T_{kin}, $\langle\beta\rangle$ and n, the parameters of the BGBW, obtained from the simultaneous fit to tne published spectra of $\pi^{\pm}$, $K^{\pm}$ and $p(\bar{p})$ and respective $\chi^2/n.d.f$ for pp collisions at $\sqrt{s} = 0.9, 2.76$ and 7 TeV for different event classes depending on average multiplicity, $\langle N_{ch}\rangle$, in the range $|\eta| < 2.4$.

$\sqrt{s}$(TeV)	$\langle N_{ch}\rangle$	T_{kin}(MeV)	$\langle\beta\rangle$	n	$\chi^2/n.d.f$
0.9	75	106.43 ± 0.10	0.745 ± 0.004	0.584 ± 0.010	0.29
2.76	86	115.55 ± 0.11	0.742 ± 0.005	0.605 ± 0.007	1.25
2.76	98	110.39 ± 0.13	0.769 ± 0.005	0.521 ± 0.009	0.43
7	98	115.57 ± 0.11	0.766 ± 0.004	0.540 ± 0.006	1.02
7	109	113.09 ± 0.12	0.779 ± 0.004	0.503 ± 0.006	0.61
7	120	110.84 ± 0.15	0.790 ± 0.004	0.480 ± 0.006	0.34
7	131	104.29 ± 0.15	0.809 ± 0.005	0.436 ± 0.005	0.44

Comparison with *pPb* and heavy-ion collisions



PG et al. JPG 41 (2014) 035106

A stronger radial flow (than in HI) in pPb collisions at LHC has been reported by ALICE

ALICE PLB 728 (2014) 25

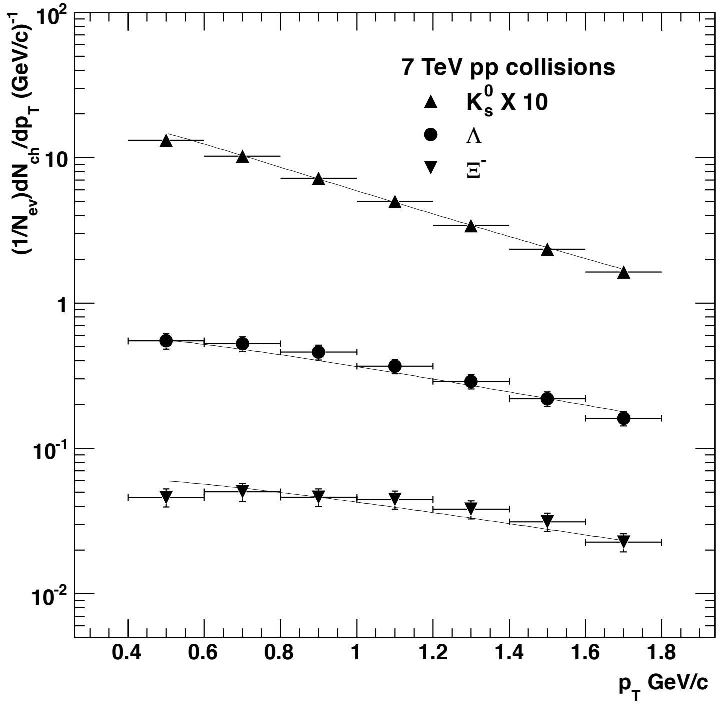
Stronger radial flow velocity for high multiplicity pp collisions as compared to pA and AA collisions is consistent with hydrodynamic picture :

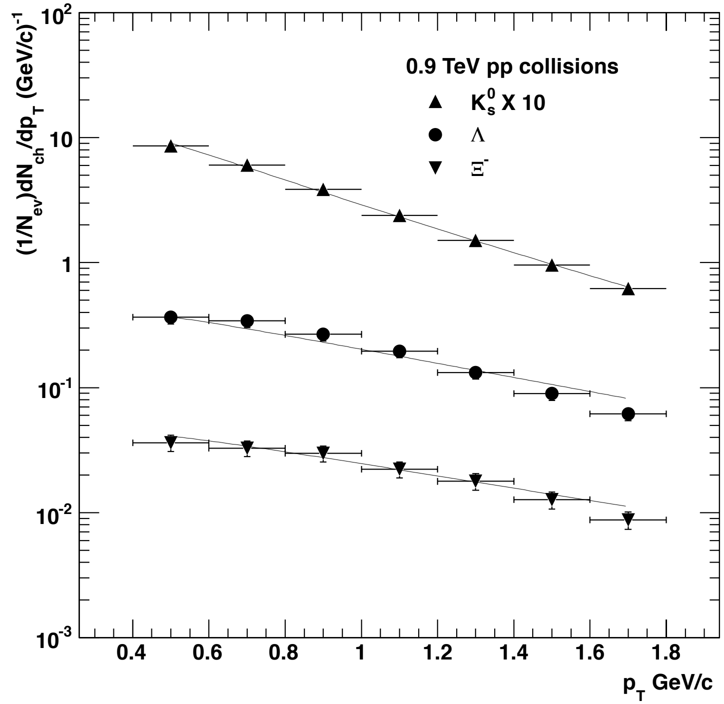
E. Shuryak and I. Zahed
PRC 88 (2013) 044915

Indication of formation of collective medium in high multiplicity proton-proton events at the LHC

Transverse momentum spectra of K^0_s, Λ and Ξ^- *pp collisions NSD* events at 0.9 and 7 TeV.

PG et al. JPG 41 (2014) 035106





$\sqrt{s}$(TeV)	T_{kin}(MeV)	$\langle\beta\rangle$	n	$\chi^2/n.d.f$
7	149 ± 0.59	0.62 ± 0.006	1.0 ± 0.02	0.85
0.9	140 ± 0.53	0.54 ± 0.01	1.27 ± 0.12	0.62

The simultaneous BW fit to K^0_s, Λ and Ξ^- in contrast to the group of particles $\pi^{\pm}$, $K^{\pm}$ and p(p-bar) may be due to early freeze-out of strange particles

Could there be a change of phase in pp collisions ?

- **Topical models do not endorse formation of any medium, whatsoever, in *pp* collisions. But, we see an indication of collectivity in *pp* collisions.**

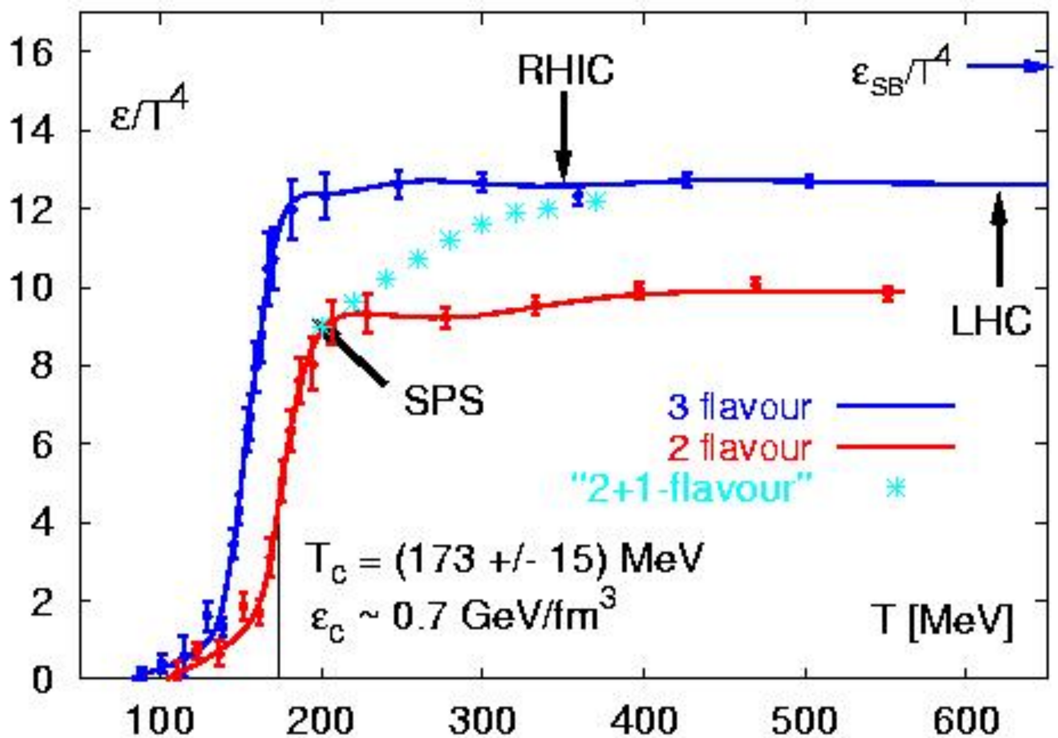
- **One may question if the mean free path of the constituent particles, the size and the lifetime of the produced medium, if any, in pp collisions is conducive to the formation of QGP or not.**

- **What is wrong in following the approach adopted in search for the QGP in heavy-ion collisions - assume local thermal equilibrium and search for QGP?**

- **We attempt [PG & Muhuri, S. arXiv:1406.5811 [hep-ph]] to search for a signal of change of phase as predicted by LQCD calculations: in terms of change in effective number of degrees of freedom of the system formed in the collision as a function of temperature.**

Signal for change of phase – LQCD calculations

Lattice QCD, $\mu_B = 0$



Both statistical and lattice QCD predict that nuclear matter will undergo a phase transition at a temperature of, T ~ 170 MeV and energy density, ε ~ 1 GeV/fm^3.

- **Experimental search of LQCD prediction involves connecting thermodynamic variables with measurable observables.**

Measuring energy density or entropy density

According to the relativistic hydrodynamics, the rapidity or the pseudo-rapidity density reflects the entropy-density created early in the collision.

Bjorken's formula for Initial energy density from experimental data :

$$\epsilon_{\rm Bj} = \frac{\langle E \rangle dN}{(R^2\pi)\tau_0 d\eta_0} = \frac{\langle E \rangle}{(R^2\pi)\tau_0} \left. \frac{dN}{d\eta} \right|_{\eta=\eta_0}$$

$dE = \langle E \rangle dN$ **Where dN is the number of particles and <E> is their average energy near *y = 0*.**

Initially produced collision fireball is a cylinder of volume : $dV = (R^2\pi)\tau_0 d\eta_0$

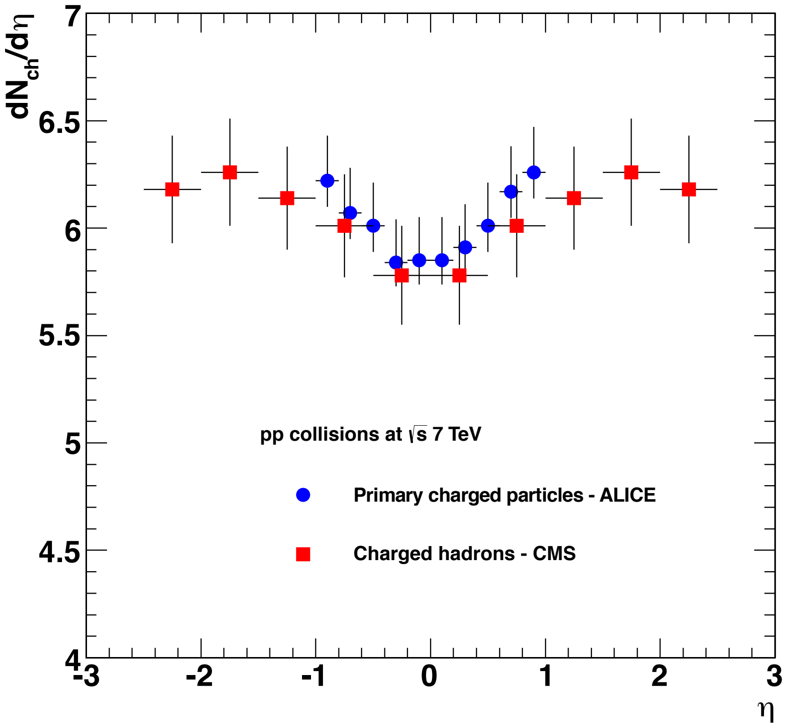
$\tau_0 d\eta_0$ is the longitudinal size of the fireball, R is radius of the Lorentz contracted colliding hadrons or nuclei. τ_0 is the proper-time of thermalization, estimated by Bjorken to be $\tau_0 \approx 1$ *fm*

$\langle E \rangle \approx \langle m_T \rangle \approx (3/2) . T \approx (3/2) . \langle p_T \rangle$

$$\epsilon_{BJ} \simeq \frac{\frac{dN_{ch}}{d\eta} \cdot \frac{3}{2} \langle p_T \rangle}{V}$$

The entropy density : $\sigma = \varepsilon / \langle p_T \rangle$

Energy density in *pp* collisions at LHC



CMS, PRL 105 (2010) 022002

ALICE, EPJC 68 (2010) 345

Csnad, M. & Csorgo, T
arXiv: 1307.2082v2 [hep-ph] (2013)

- A detailed, conservative estimate of initial energy-density shows that even for $dN_{ch}/d\eta \approx 6$, the energy density is sufficient to form a non-hadronic medium in *pp* collisions at 7 TeV.

- In agreement with 1.8 GeV data.
  T. Alexopoulos et al. PLB 528(2002) 43.

CMS EPJC 72 (2012) 2164

- CMS experiment has recorded sufficient statistics of high multiplicity pp events with $dN_{ch}/d\eta \approx 30$.

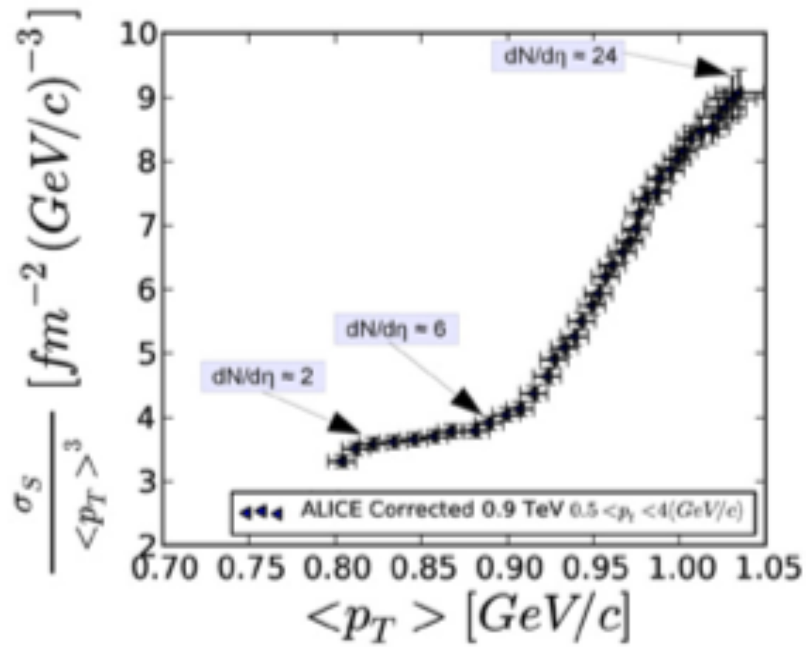
Measuring temperature in high energy collisions

- The p_T - spectra of produced particles from high energy collisions contain information on temperature as well as on transverse expansion of the system.
- No straightforward method of disentangling the effect of the temperature and the contribution from the transverse expansion.
- Instead of exclusive measure of temperature, experimental analysis deal with parameters that reflect the temperature of the system.
- Besides the inverse slope parameter, the mean transverse momentum, $\langle p_T \rangle$ as proposed by Van Hove [PLB 118 (1982) 138], can be used for comparing thermal states of system.

Change of phase in pp collisions – previous attempt

Besides the work by T. Alexopoulos et al. PLB 528(2002) 43 at 1.8 TeV

R.Campanini & G. Ferri PLB703 (2011) 237



ALICE at √s = 0.9 TeV, 0.5<pT<4 GeV/c, |η|<0.8, Minimum Bias.

- ***Proposed to study the LQCD prediction on change of phase in terms $\varepsilon/<p_T>^4$ or $\sigma/<p_T>^3$ (effective number of degrees of freedom) as a function of $<p_T>$ (reflecting temperature).***

Mass-dependent flow effect

Change in <p_T> due to transverse expansion is mass-dependent – pions lose some <p_T> .

S.Bass & A. Dumitru PRC61 (2000) 064909

Being weekly affected by re-scattering of hadrons and resonance decay, kaons are better observable than pions.

M.I.Gorenstein et al PLB567 (2003) 175

We consider

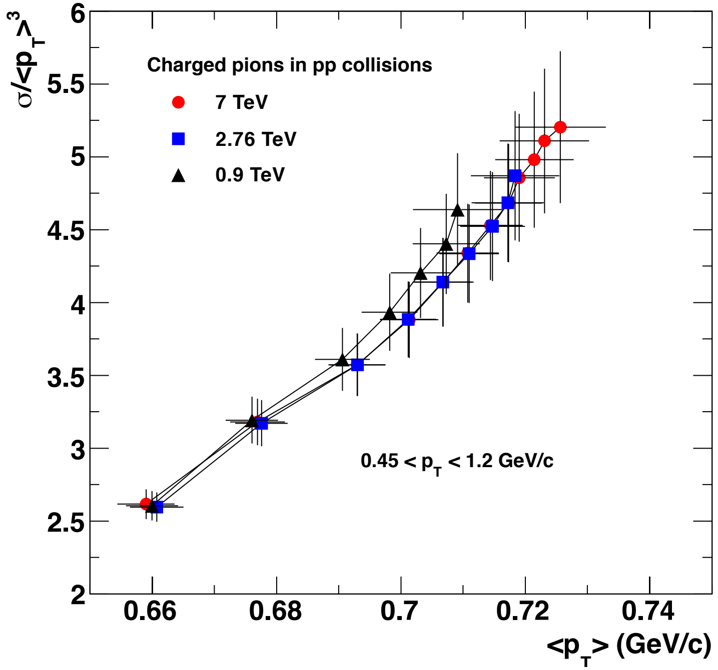
- **The <p_T> of several particles together contains cumulative effect due to transverse expansion of varying magnitude.**

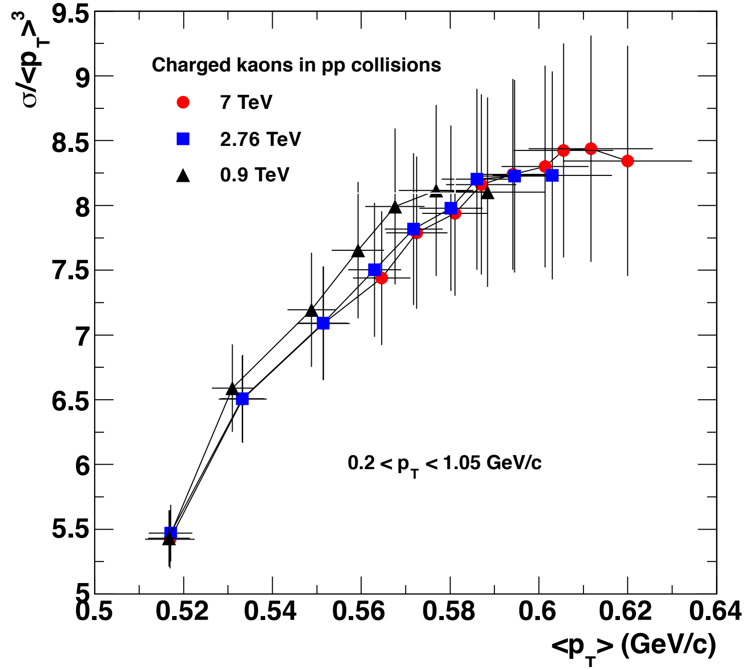
- **The <p_T> of individual species could be more meaningful in reflecting temperature related characteristics of the system.**

and extend the study to the high multiplicity pp events at the LHC energies.

proton-proton collisions at $\sqrt{s}$ = 0.9, 2.76 and 7 TeV CMS data

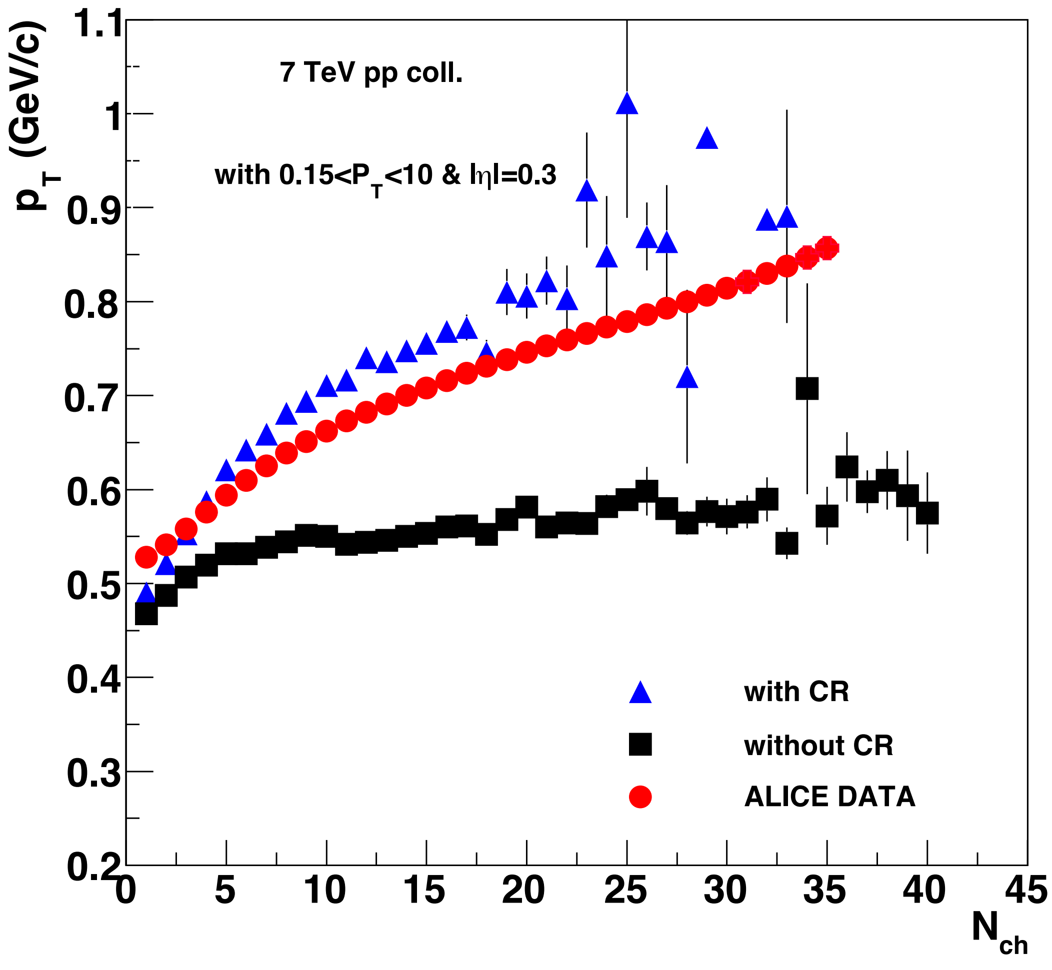
PG & S. Muhuri, arXiv:1406.5811 [hep-ph]



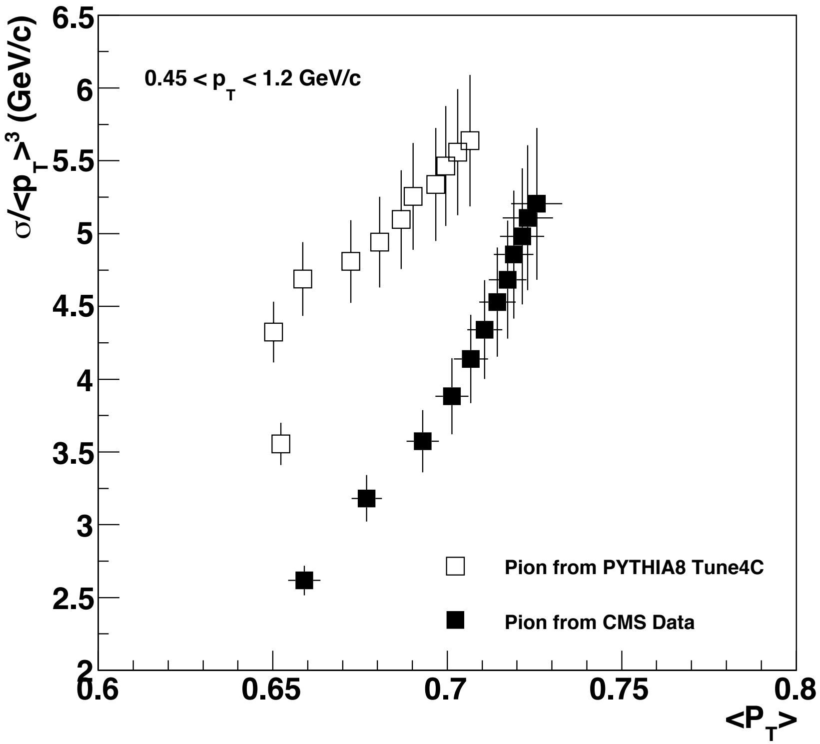


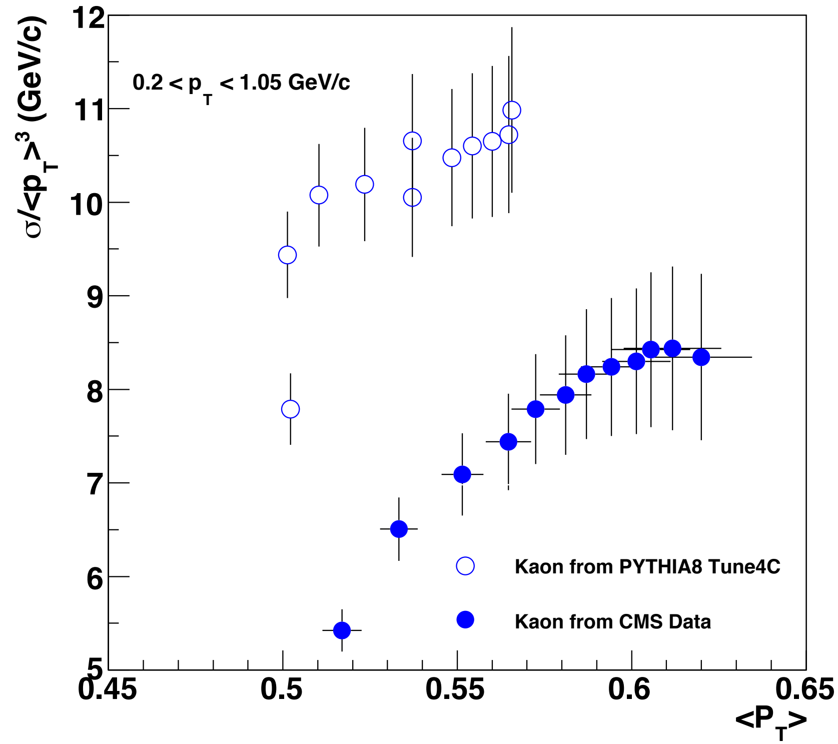
- **Rapid rise in $\sigma/\langle p_T\rangle^3$, indicating release of new degrees of freedom.**
- **The saturation of $\sigma/\langle p_T\rangle^3$ at high $\langle p_T\rangle$ indicates reaching of the highest possible no. of degrees of freedom at high temperature.**
- **For a given |η| and p_T – range, the rise in $\sigma/\langle p_T\rangle^3$ is independent of $\sqrt{s}$.**

proton-proton collisions at √s = 7 TeV : ALICE data compared with PYTHIA8 Tune 4C generator



proton-proton collisions at √s = 7 TeV : CMS data compared with PYTHIA8 Tune 4C generator





PYTHIA8 Tune 4C with (color re-connection on) does not match the data

Change of phase in pp collisions – do we see it ?

The $<p_T>$ only reflect T, does not give the absolute measure of T.

Similarly, $\sigma/<p_T>^3$ reflects effective number of degrees of freedom and need not match σ / T^3 .

Loss of $<p_T>$ by pions could be the reason for the disappearance of the saturation effect of $\sigma/<p_T>^3$ at high $<p_T>$.

Early freeze-out, due to differential elastic cross-section of hadrons, the kaons are likely to be less affected by flow, that develops with time.

Nevertheless, qualitative agreement with the LQCD-predicted change of phase in pp collisions invites further investigation.

Thank you