Collectivity in high-multiplicity *proton-proton* collisions 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

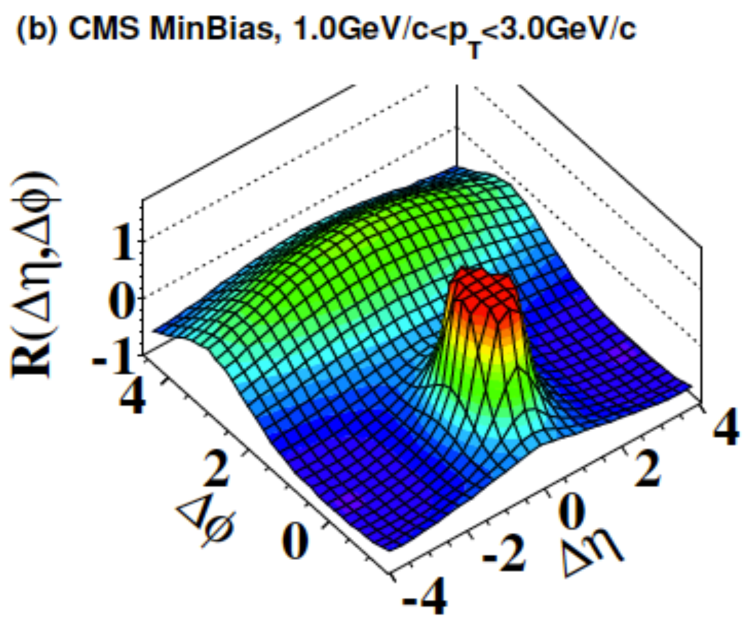
- **High energy collisions of heavy-ions (HI) in laboratory**
  CERN declared indication of formation of QGP-like new state (2000)
  RHIC, BNL presented convincing results on formation of QGP in laboratory NPA 757 (2005)

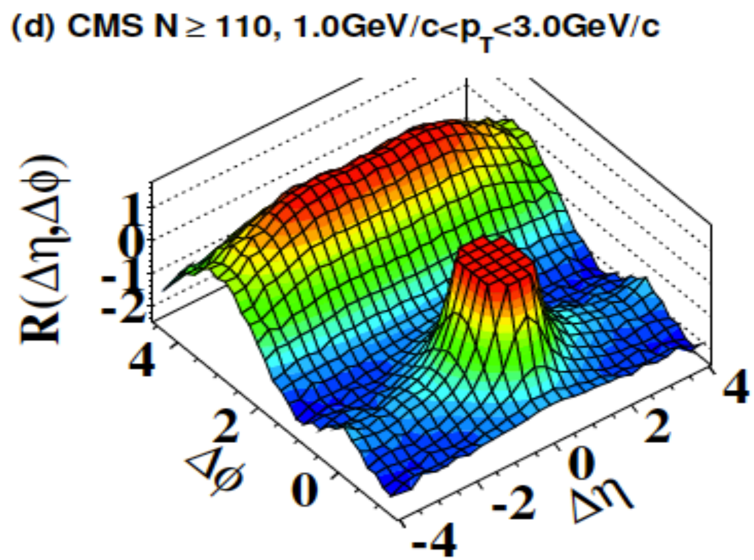
- **High energy proton-proton collisions: *consensus view !***
  Elementary collisions, no medium formation
  Experimentally, serve the base-line for the QGP study by HI collisions

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

pp - collisions at LHC show something different

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 !

Different thought prior to LHC – SPPS 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

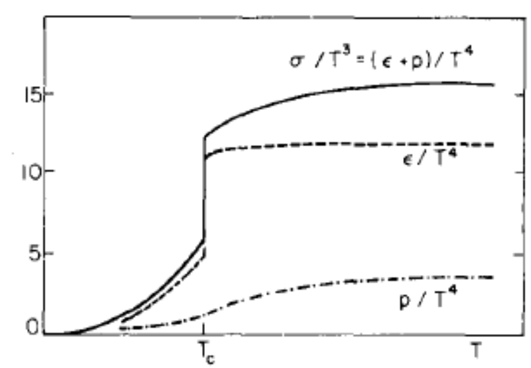
SPPS events of high transverse energy ....

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 thought prior to LHC – 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]

Measurable variables of importance ….

Characterization of QGP (thermodynamic) like medium

- thermodynamic variables like entropy, temperature

In high-energy collisions, measurable variables which reflect the bulk properties of the medium:

- **Multiplicity density – entropy density**
- **Transverse momentum distribution – temperature information**

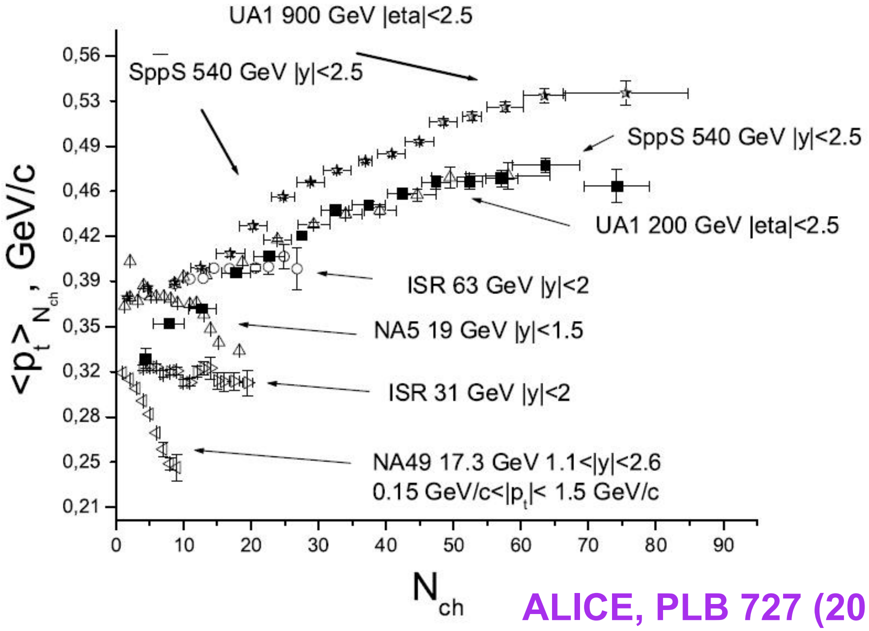
Experiments on *pp* & *(anti)pp* collisions before LHC

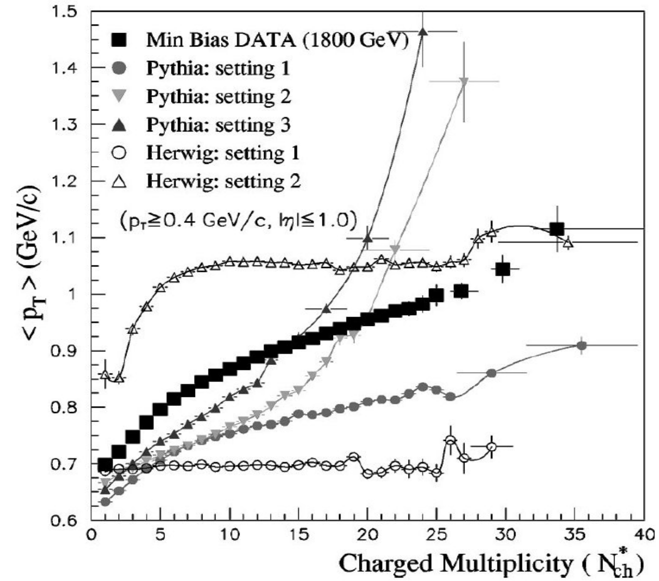
Slide from: Asryan, Spåtind, 06.01.2008
the 20th Nordic Particle Physics Meeting

Energy, GeV	Name of the machine	Name of experiment or detector	Type
17	SPS (Super Proton Synchroton), CERN	NA49, Large Acceptance Hadron Detector	LAB
19 22	SPS (Super Proton Synchroton), CERN	NA5 NA22	LAB
32 63 540	ISR (Intersecting Storage Rings), CERN	ABCCDHW (Ames, Bologna, CERN, College de France, Dortmund, Heidelberg, Warszawa), SFM (Split Field Magnet)	CMS
200 900	SppS (Super Proton Antiproton Synchroton), CERN	UA1 (Underground Area), a 4-pi Solid Angle Detector	CMS
1800	Tevatron, Fermilab	CDF (The Collider Detector at Fermilab)	CMS
1800	Tevatron, Fermilab	E375 (D0 at Fermilab)	CMS

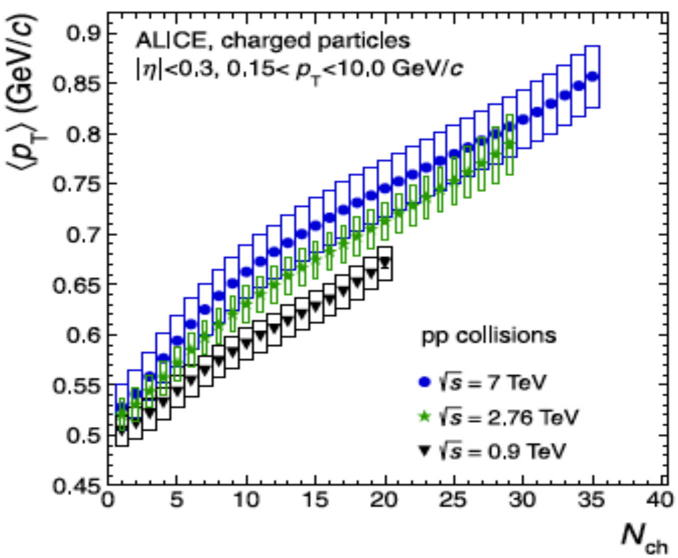
- ✓ NA49 collab. arXiv:hep-ex/0311009
- ✓ A. Breakstone et al. (ABCDHW Collaboration), Phys. Lett. 132B (1983) 463
- ✓ UA1 collab., Nucl Phys 335B (1990) 261
- ✓ F.Abe et.al, Phys.Rev.Lett. 61 (1988) 1819
- ✓ C.De Marzo et al. Phys. Rev. 29D (1984) 363
- ✓ V.V. Aivazyan et al., Phys.Lett. 209B (1988) 103
- ✓ T. Alexopoulos et al., Phys. Lett. 336B (1994) 599

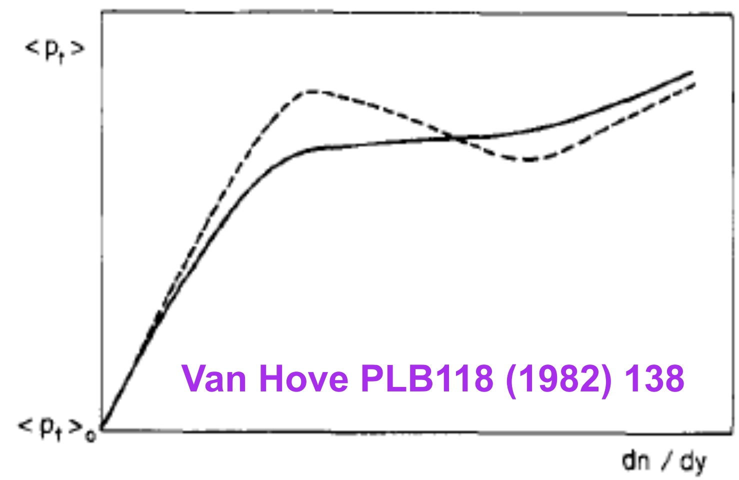
Correlations <pt> - <Nch>





ALICE, PLB 727 (2013) 371





Van Hove PLB118 (1982) 138

Scope of the talk

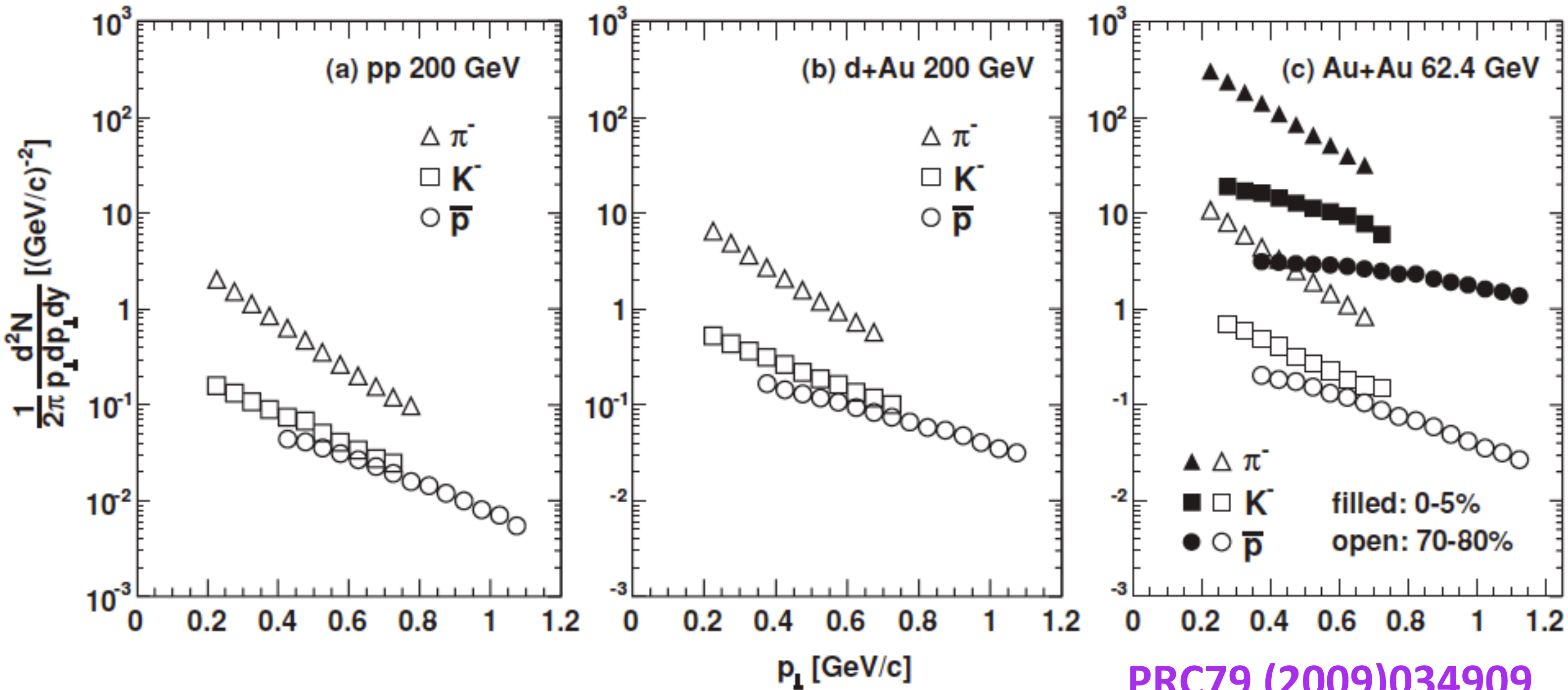
Discussions on "different" features of multi-particle production in pp collisions at LHC in terms of Transverse momentum

Don't intend to conclude on:

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

Transverse momentum distributions in *pp* at LHC

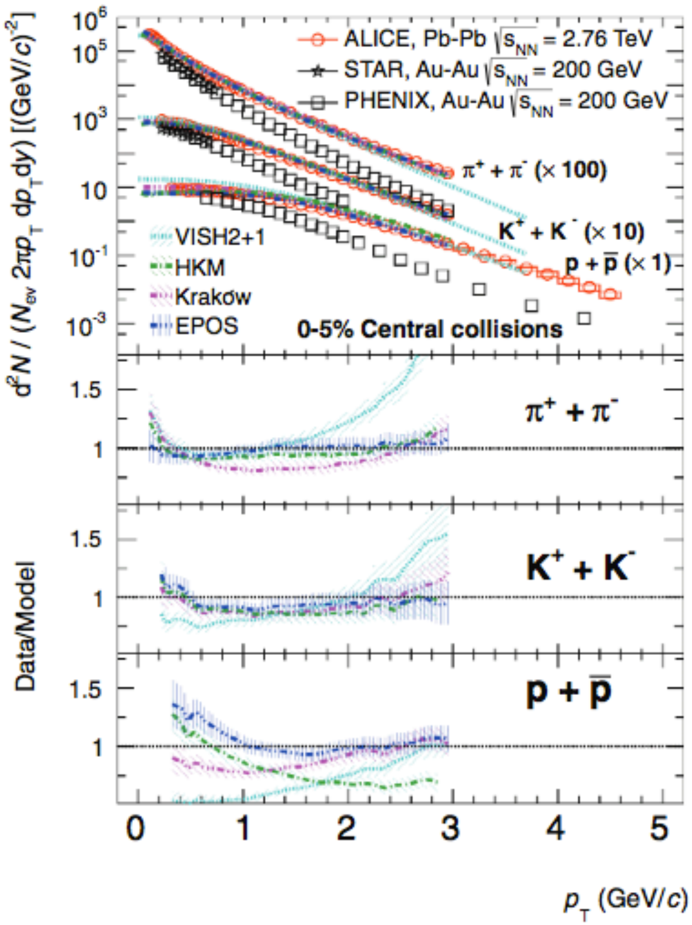
Let's start with identified hadron spectra at STAR@RHIC



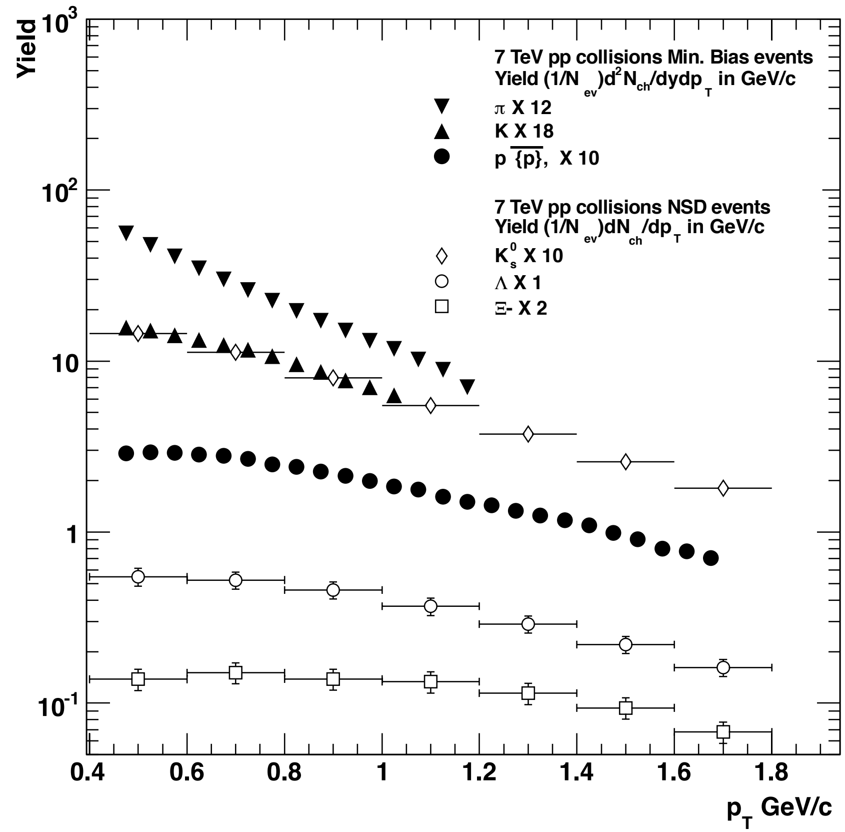
PRC79 (2009)034909

- **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



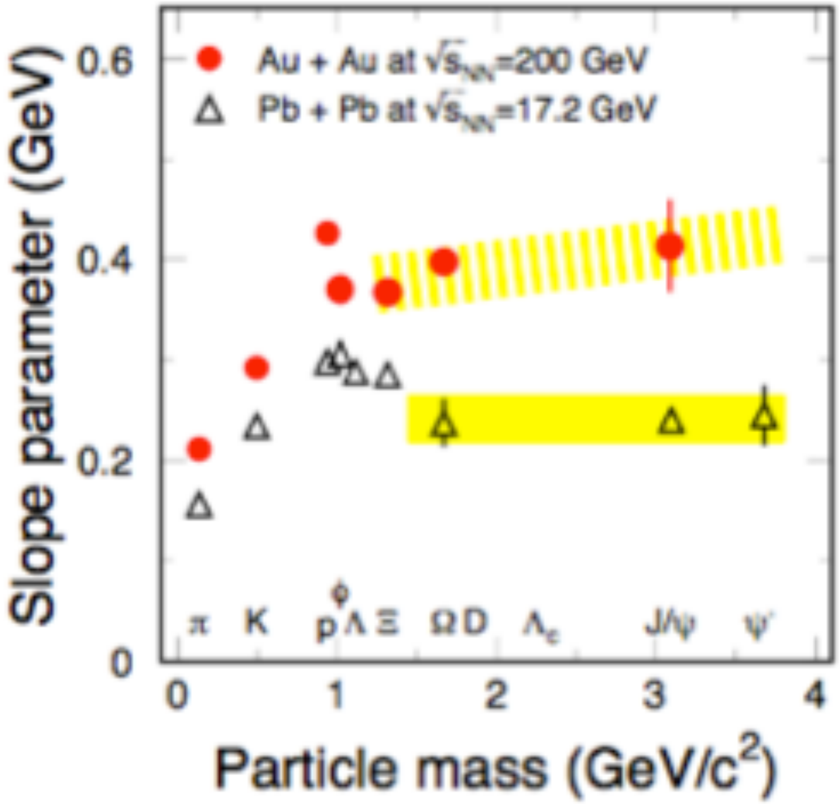
CMS, EPJC 72 (2012) 2164
CMS, JHEP 05 (2011)064
PG et al. JPG 41 (2014) 035106

Mass-dependent inverse slope parameter

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

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

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



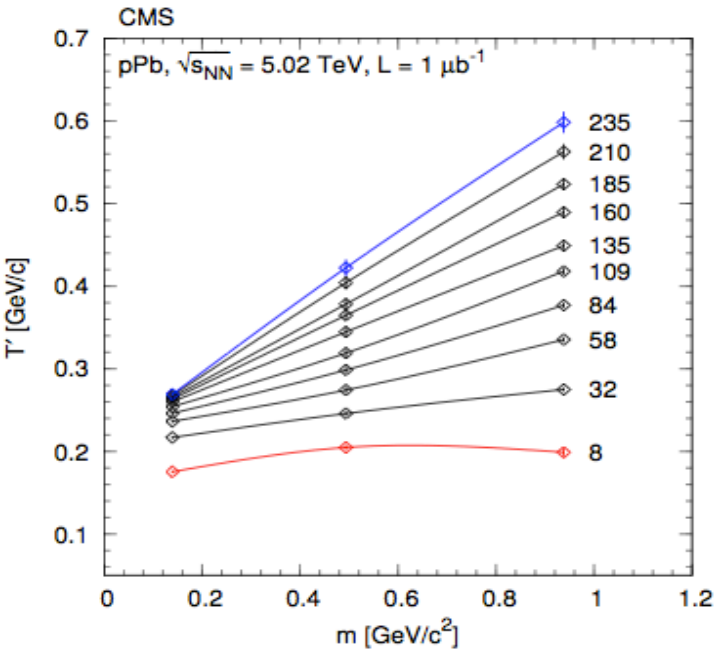
Hydrodynamical parameterization results:

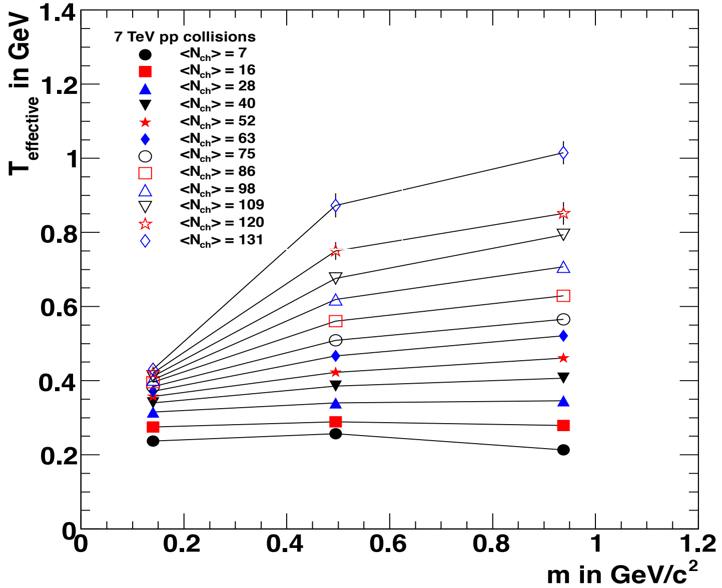
$$T_{eff} = T_{th} + \frac{1}{2} m \ < \beta_T >^2$$

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

$$\frac{dN}{p_T\,dp_T} \propto \int_0^R r\,dr\,m_T\,\mathrm{I}_o\left(\frac{p_T \mathrm{Sinh}\,\rho}{T_{\mathrm{kin}}}\right)\mathrm{K}_1\left(\frac{p_T \mathrm{Cosh}\,\rho}{T_{\mathrm{kin}}}\right),$$

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

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

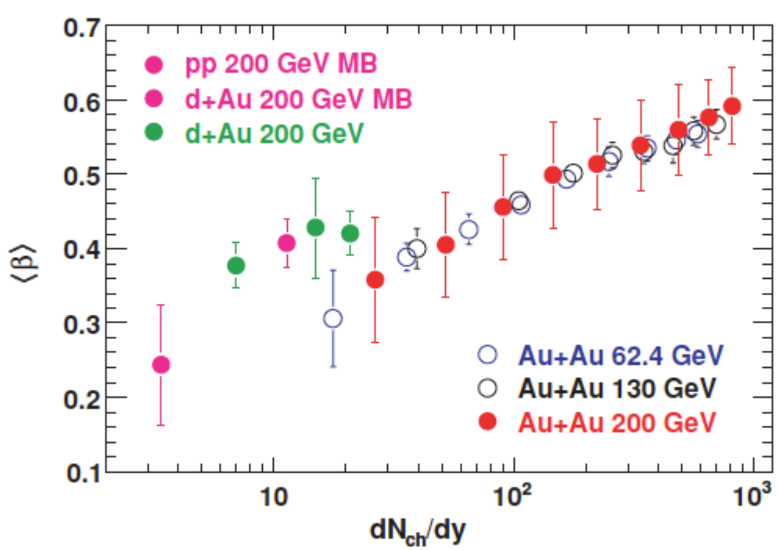
where β_s is the surface velocity

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

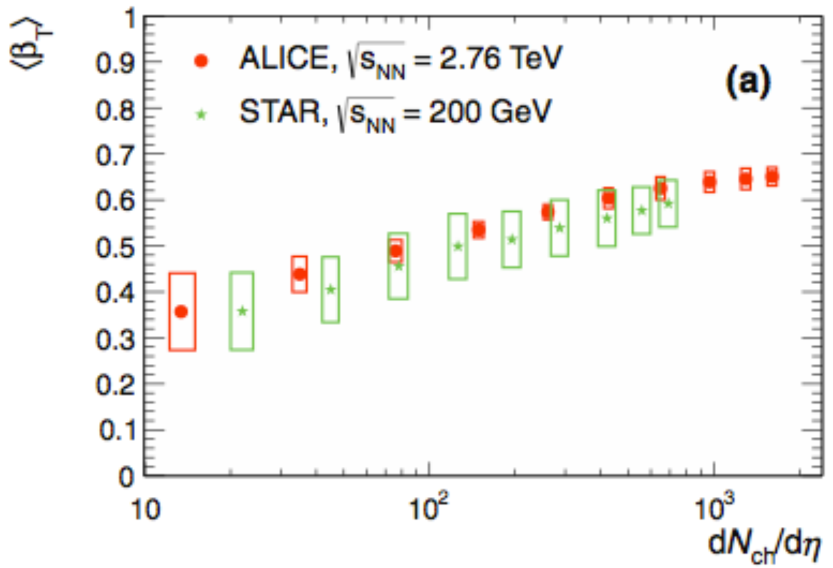
R is the transverse radius at freeze-out. Experimentally obtained from HBT radius for the lowest pair of transverse momentum. The profile parameter n is found to match hydrodynamic calculation with value 1 or 2, though in principle, it can take any positive value.

The average transverse flow velocity in heavy-ion collisions

STAR PRC79 (2009)034909



ALICE PRC88 (2013)044910

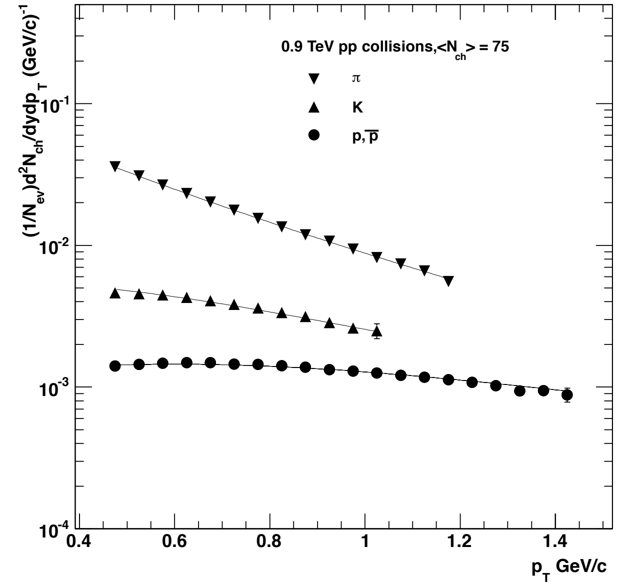


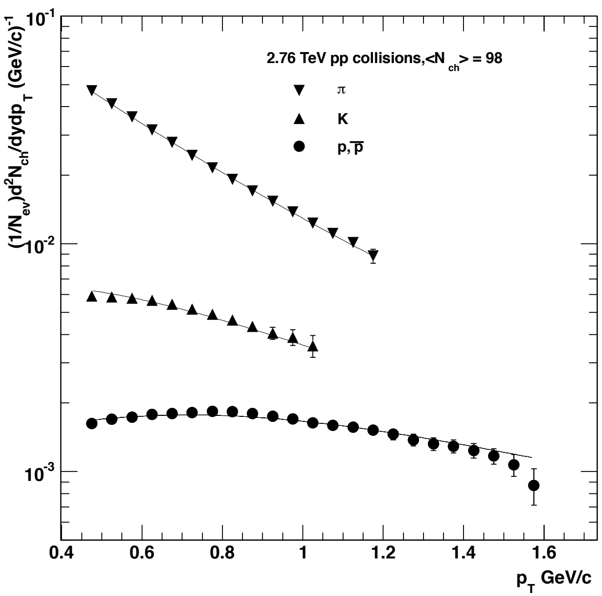
Blast-wave model has been very successful in establishing collectivity by extracting transverse flow velocity in heavy-ion collisions in SPS, RHIC and LHC

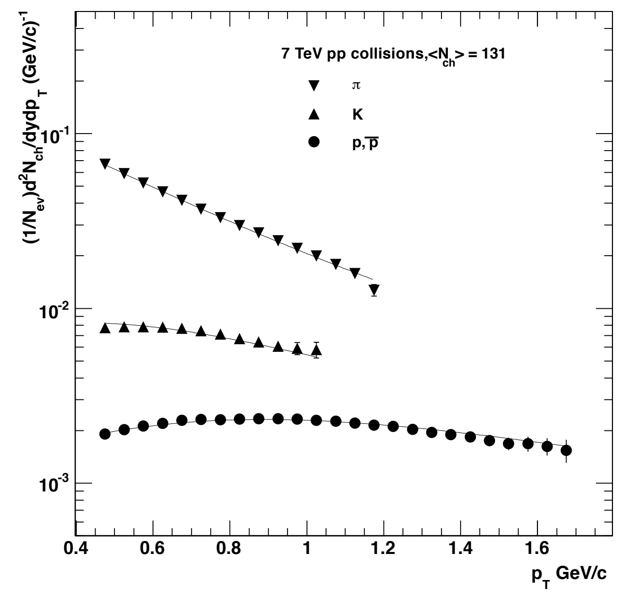
Transverse momentum spectra of $\pi^{\pm}$, $K^{\pm}$ and p(p-bar) from high multiplicity *pp* events at 0.9, 2.76 and 7 TeV.

- 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



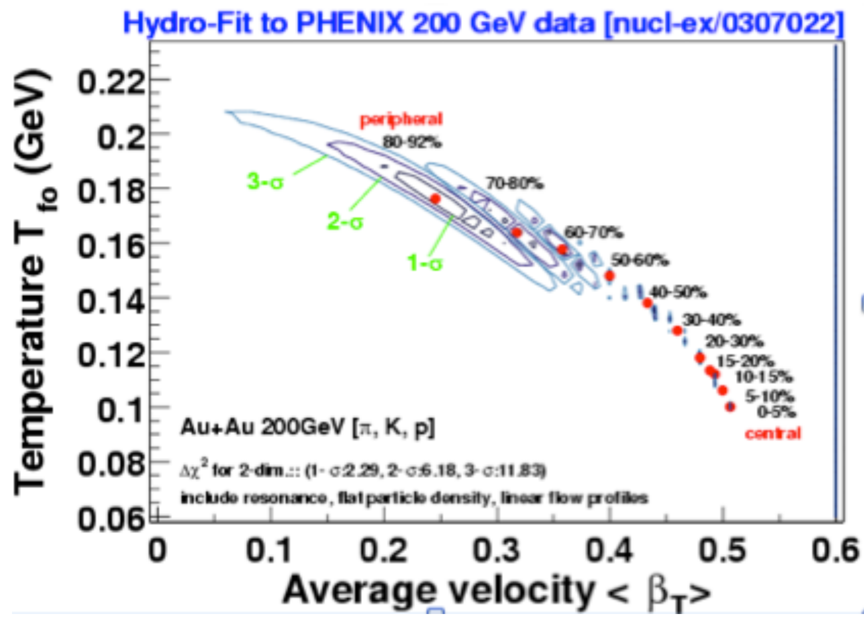




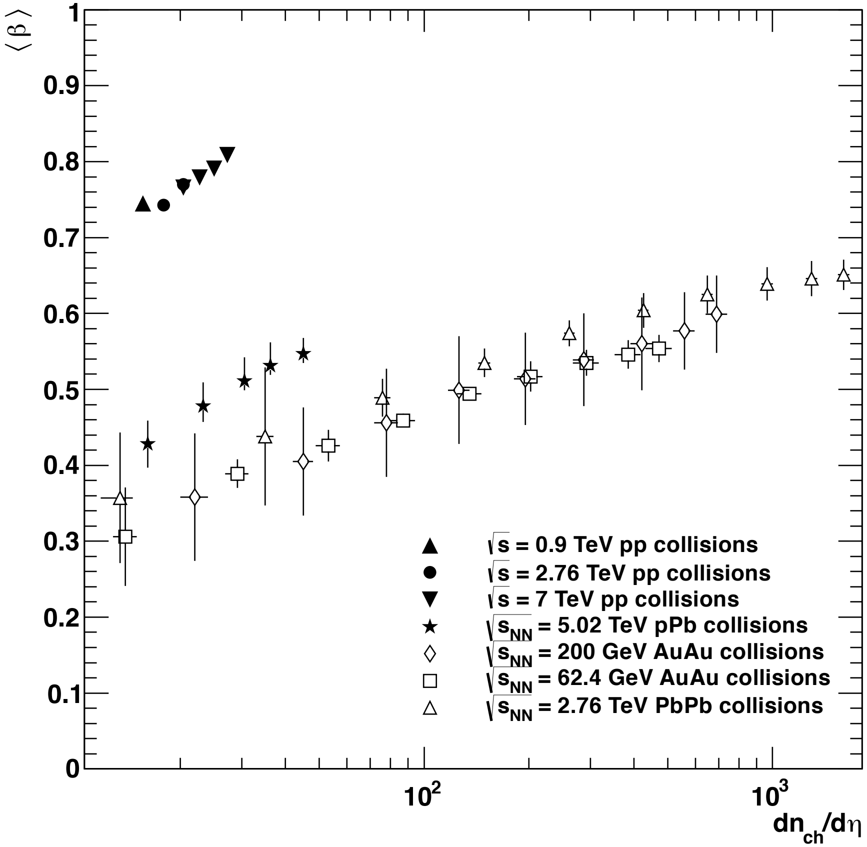
Simultaneous blast-wave fit parameters of transverse momentum spectra of $\pi^{\pm}$, $K^{\pm}$ and p(p-bar) from high multiplicity *pp* events at LHC

PG et al. JPG 41 (2014) 035106

$\sqrt{s}$(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

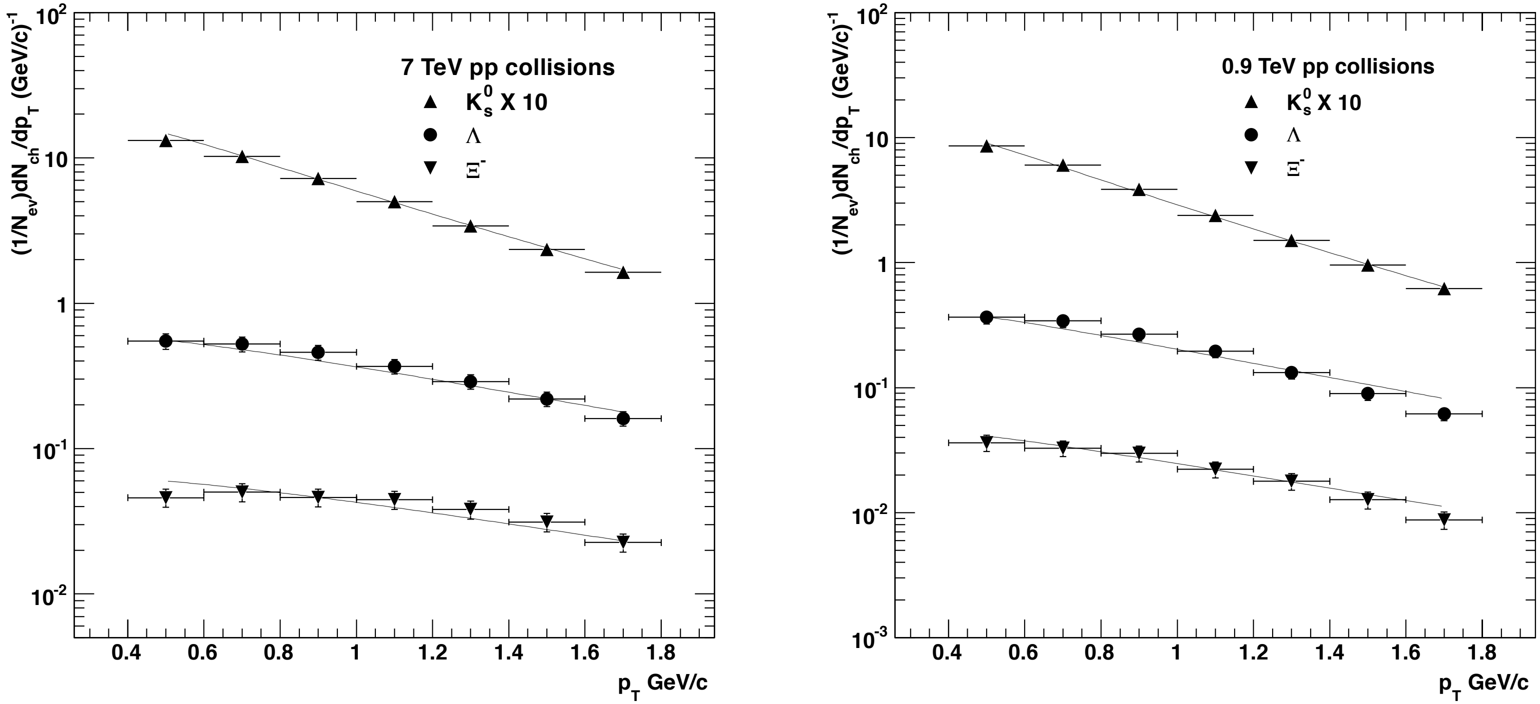
Stronger radial flow velocity for high multiplicity pp collisions as compared to pA and AA collisions is consistent with hydrodynamic picture :

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.**

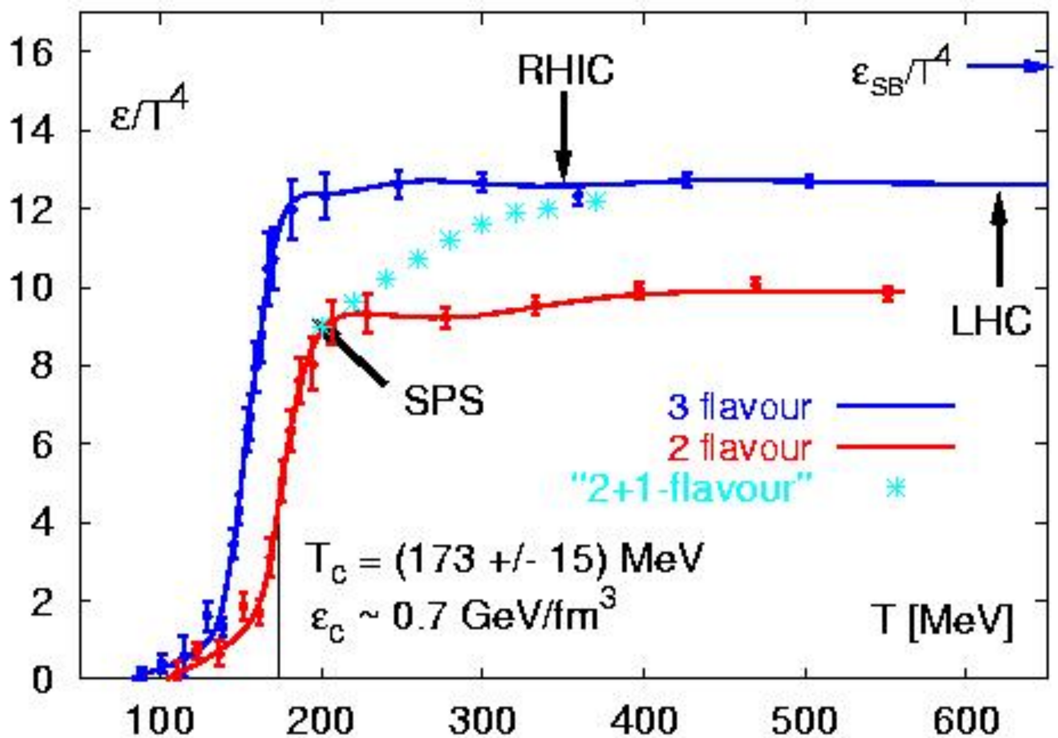
- **One may question if the mean free path of the constituent particles, the size and the lifetime of the produced medium, if any, in pp collisions is conducive to the formation of QGP or not.**

- **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.

The ε for an ideal gas Is proportional to T^4 – proportionality constant reflects the effective number of degrees of freedom.

- **Rapid increase in effective number of degrees of freedom indicates change in phase. Latest LQCD calculation results in a crossover.**
- **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 :

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

$dE = \langle E \rangle dN$ **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 : $dV = (R^2\pi)\tau_0 d\eta_0$

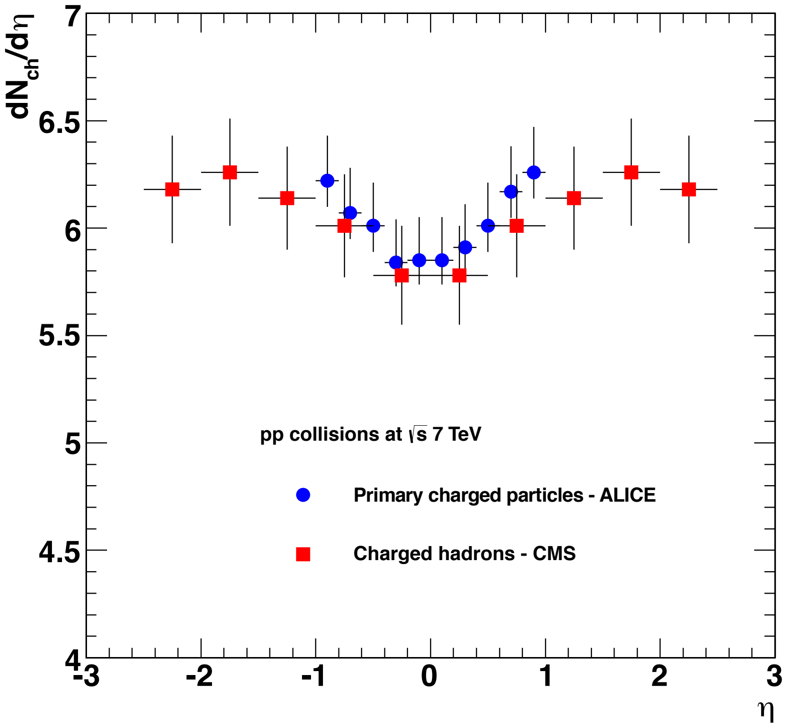
$\tau_0 d\eta_0$ is the longitudinal size of the fireball, R is radius of the Lorentz contracted colliding hadrons or nuclei. τ_0 is the proper-time of thermalization, estimated by Bjorken to be $\tau_0 \approx 1$ *fm*

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

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

Initial entropy density by hydrodynamic consideration : $\sigma = \varepsilon / \langle p_T \rangle$

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.

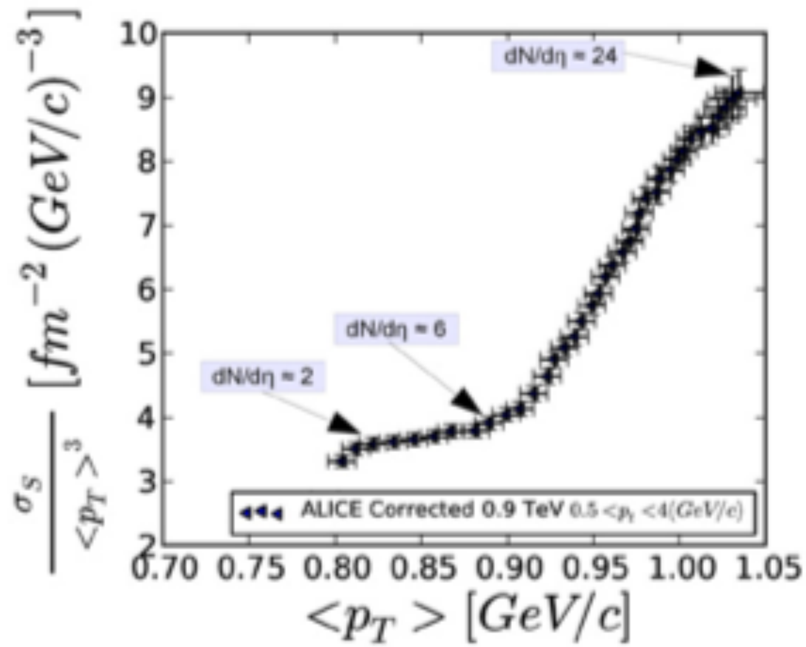
- Instead of exclusive measure of temperature, experimental analysis deal with parameters that reflect the temperature of the system.

- 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

Recent work : 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

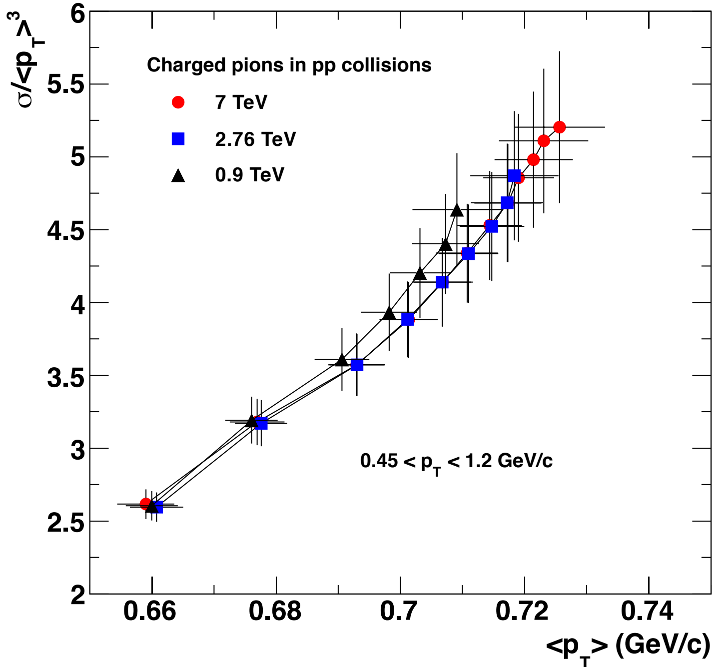
We consider

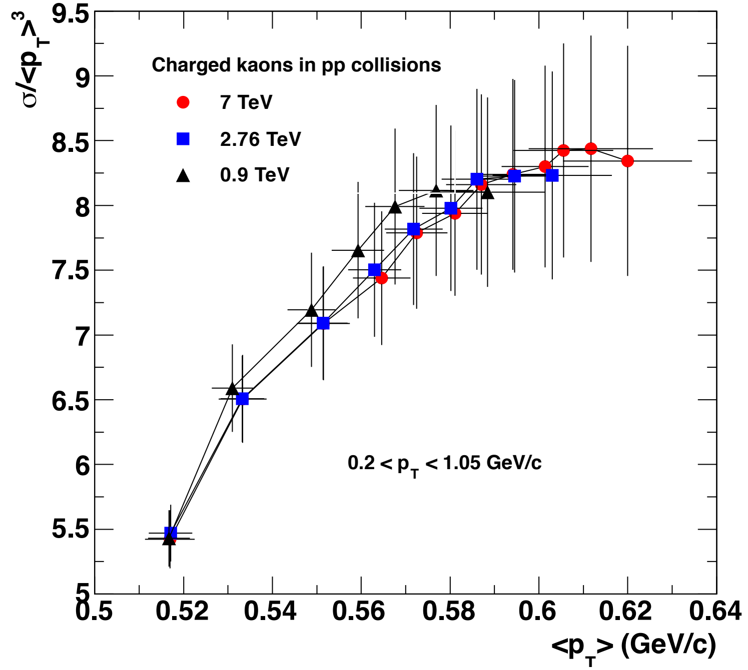
- The <p_T> of several particles together contains cumulative effect due to transverse expansion of varying magnitude.
- The <p_T> of individual species could be more meaningful in reflecting temperature related characteristics of the system.

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]

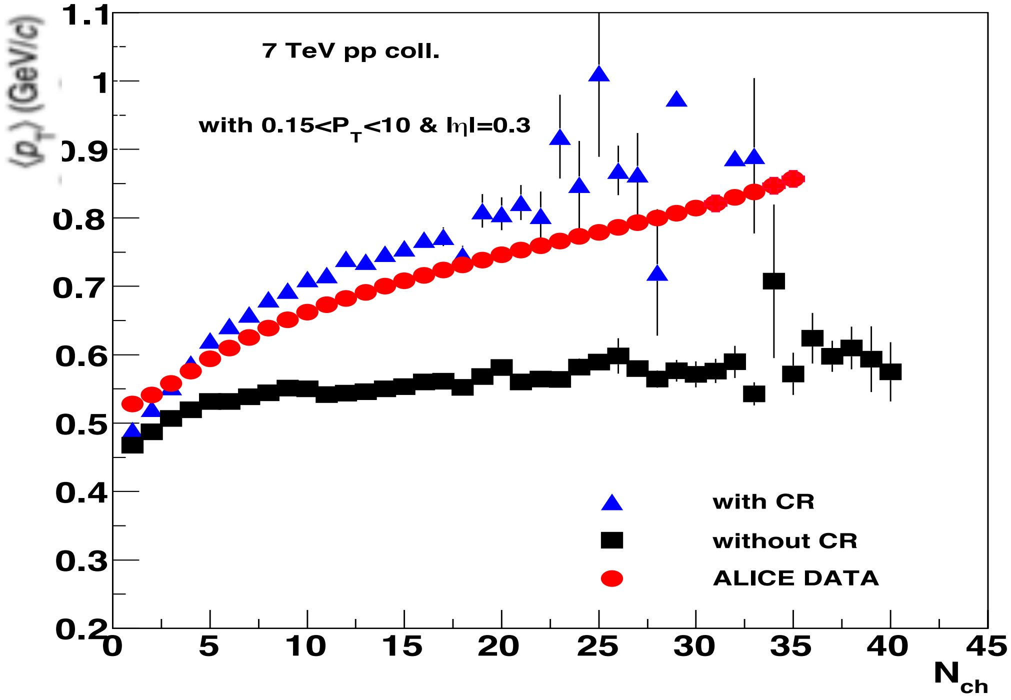




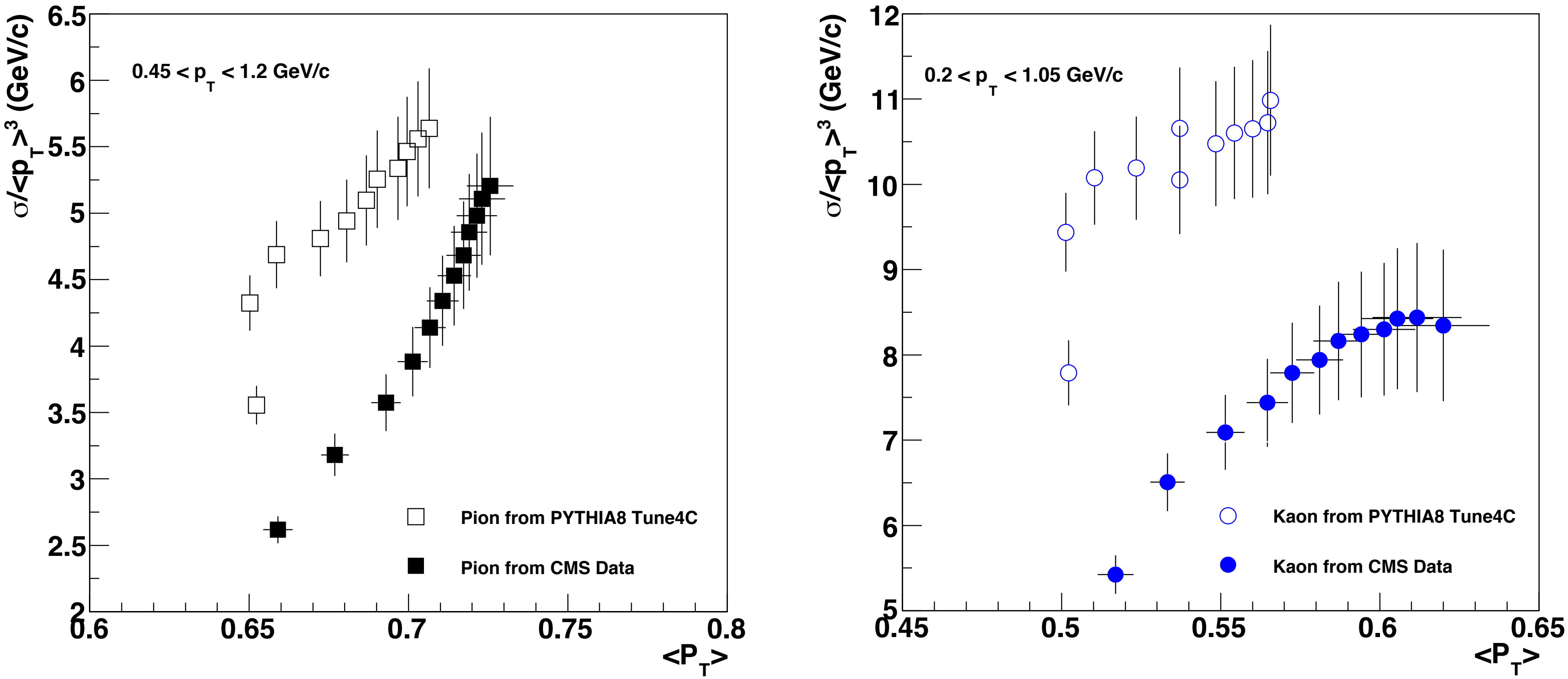
- **Rapid rise in $\sigma/\langle p_T\rangle^3$, indicating release of new degrees of freedom.**
- **The saturation of $\sigma/\langle p_T\rangle^3$ at high $\langle p_T\rangle$ indicates reaching of the highest possible no. of degrees of freedom at high temperature.**
- **For a given $|\eta|$ and p_T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

ALICE, PLB 727 (2013) 371

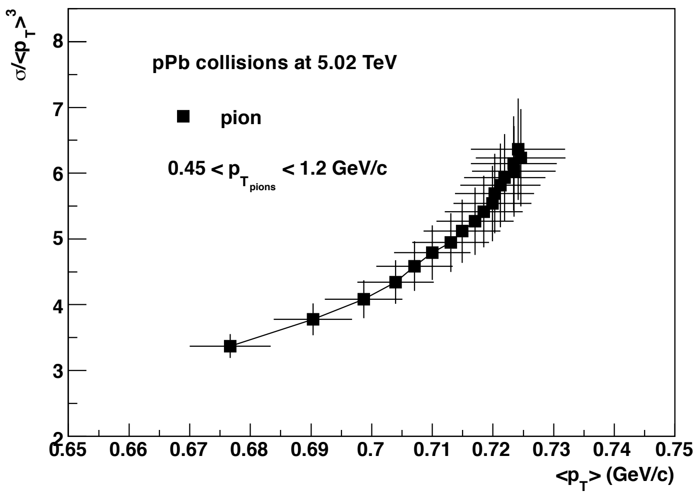


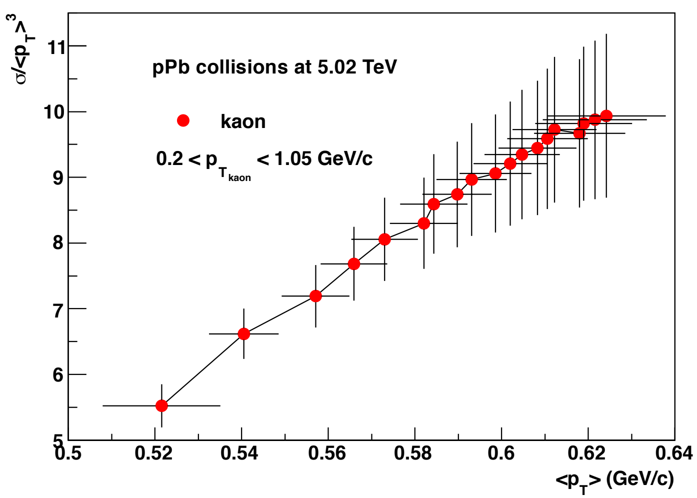
proton-proton collisions at √s = 7 TeV : CMS data compared with PYTHIA8 Tune 4C generator



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

proton-lead collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
CMS data





The CMS experiment has observed that the N_{ch} - dependence of radii in all k_T bins is remarkably similar for the pp and pPb collisions at the LHC

On the other hand, pPb collisions show stronger evidence of collectivity :

- **Ridge**
- **Mass-ordering of inverse-slope parameter**
- **Elliptic and triangular flow**

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

Back-up slide

Transition from hadronic matter to QGP : a simple model

H.Satz, arXiv:0903.2778 [hep-ph]

Ideal gas of massless pions: The pressure as a function of temperature
- Stefan-Boltzmann form

$$P_\pi = 3\frac{\pi^2}{90}T^4$$

Ideal QGP with 2 flavors and 3 colors:

$$P_{qg} = \{2 \times 8 + \frac{7}{8}(3 \times 2 \times 2 \times 2)\}\frac{\pi^2}{90}T^4 - B = 37\,\frac{\pi^2}{90}T^4 - B.$$

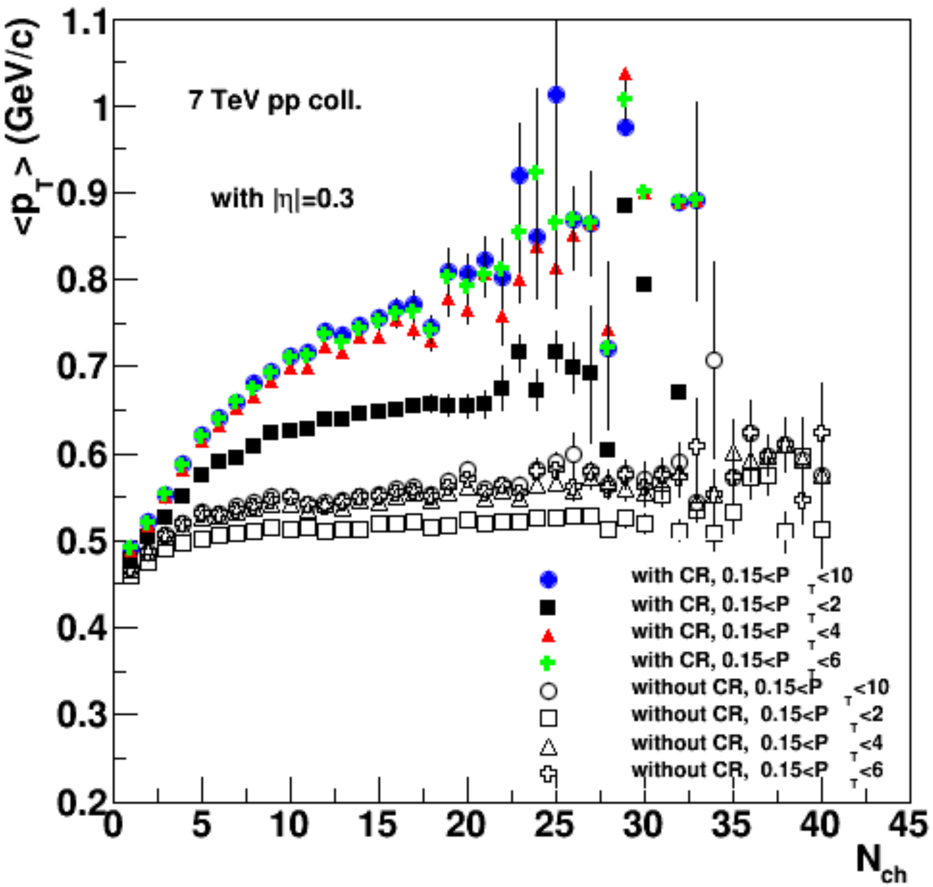
2 spin & eight color degrees of freedom of gluons.
3 colors, 2 flavors, 2 spin 2 particle-antiparticle degrees of freedom of quarks.
7/8 to obtain correct statistics
B, the bag pressure takes into account the non-perturbative difference
Between the physical vacuum and the ground state for colored quarks and gluons

The energy densities:

$$\epsilon_\pi = \frac{\pi^2}{10}T^4 \qquad \epsilon_{qg} = 37\frac{\pi^2}{30}T^4 + B.$$

$$B^{1/4} \simeq 0.2 \text{ GeV}$$

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



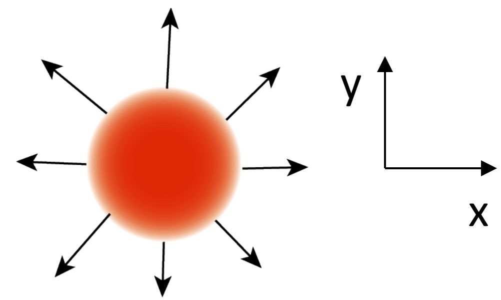
Color re-connection ON

p_T – range matters !

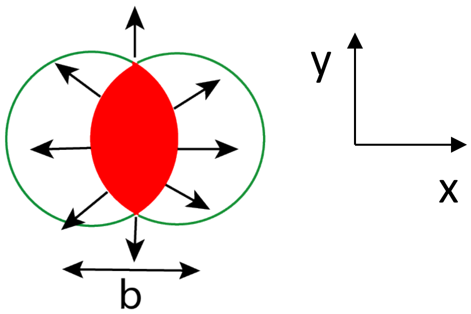
Back-up slide

Three Forms of Collective Motion

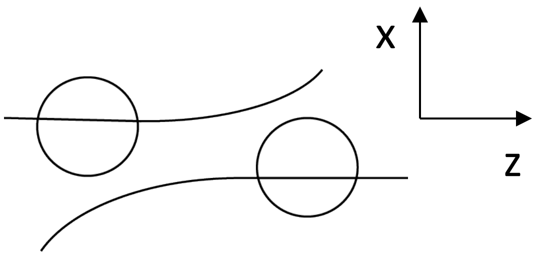
- Only type of transverse flow in central collision (b=0) is transverse flow.
- Integrates pressure history over complete expansion phase



- Elliptic flow, caused by anisotropic initial overlap region (b > 0).
- More weight towards early stage of expansion.

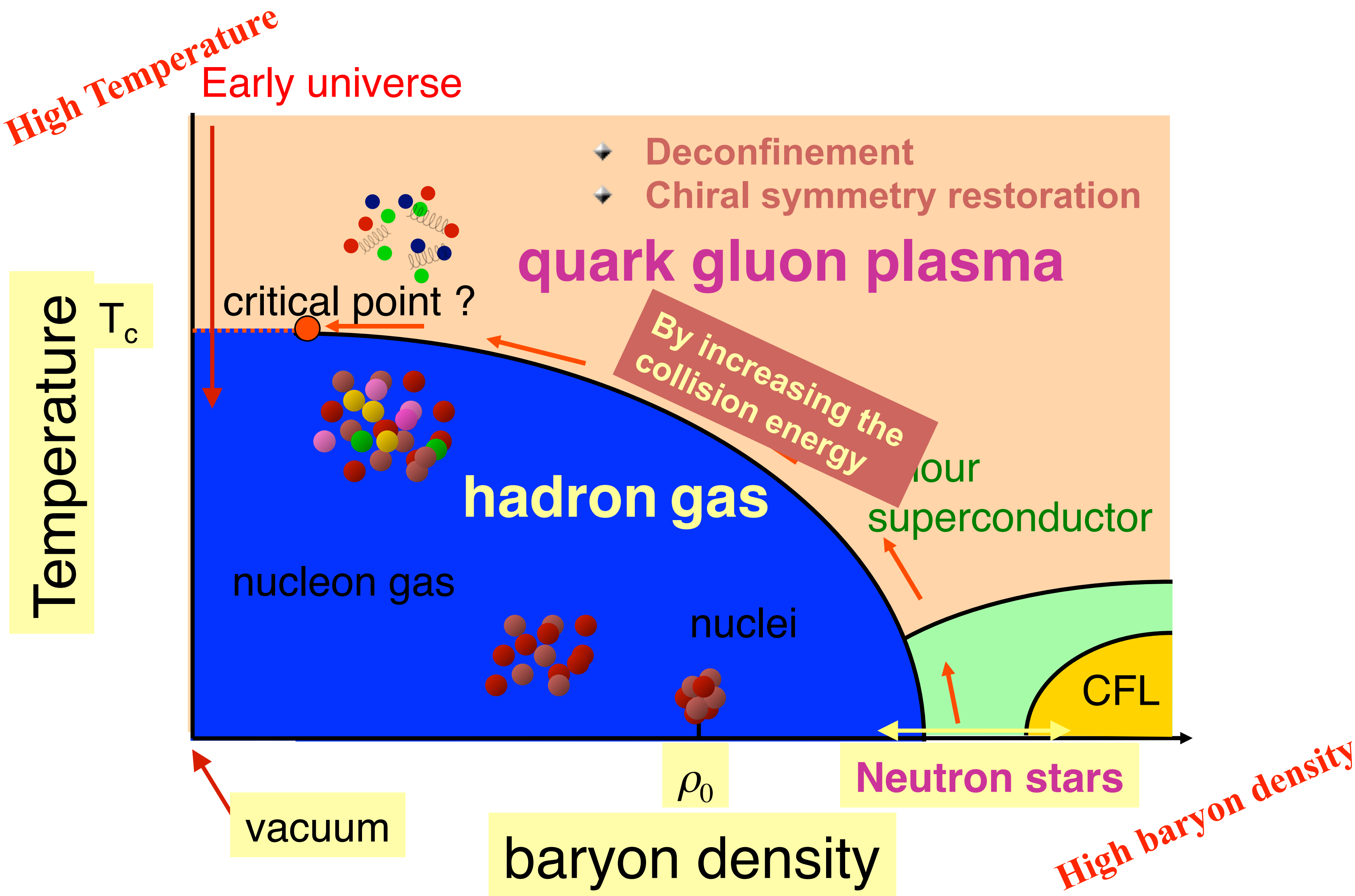


- Directed flow, sensitive to earliest collision stage (pre-equilibrium, b > 0)

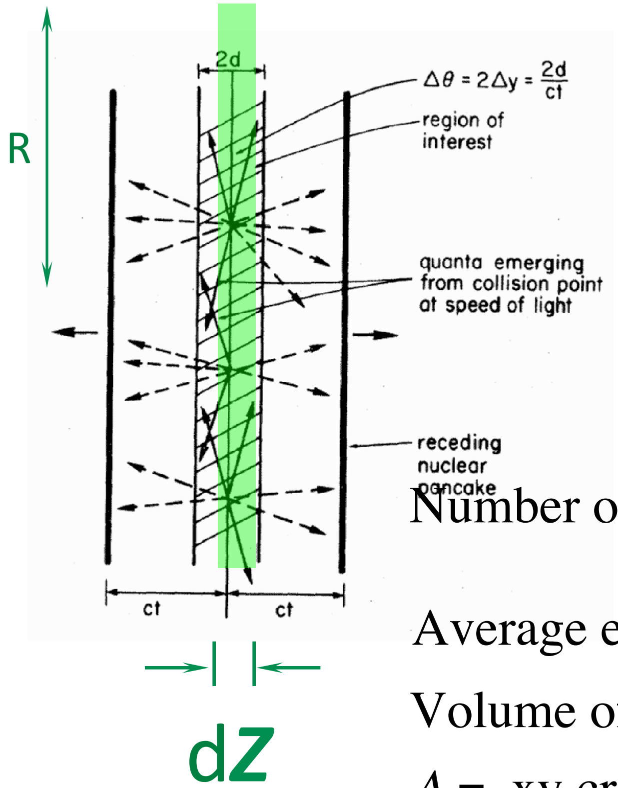


Back-up slide

The QCD Phase diagram



Bjorken's model – 1D



Exercise: Count particles in the green box at some time ***t***, add up their energies, and divide by the volume.

Particles in the box if $0<\beta_Z<dZ/t$ (limit of infinitely thin source)

Number of particles $dN = \dfrac{dN}{d\beta_Z}\dfrac{dZ}{t} = \dfrac{dN}{dy}\dfrac{dZ}{t}$

Average energy per particle $\langle E \rangle = \langle m_T \rangle$

Volume of the box $V = A \cdot dZ$

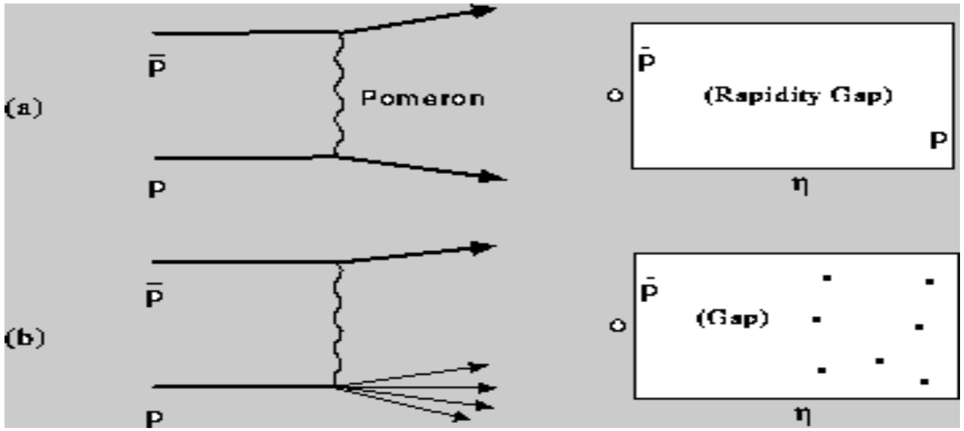
$A \equiv$ xy cross section area (limit $t << R$)

$$\langle \varepsilon(t) \rangle = \frac{\text{Energy}}{\text{Volume}} = \frac{\langle E \rangle dN}{V} = \frac{1}{t\,A}\frac{dN(t)}{dy}\langle m_T \rangle (t) = \frac{1}{t\,A}\frac{dE_T(t)}{dy}$$

Valid for material at *any* rapidity and for *any* shape in $dE_T(t)/dy$! A plateau in $dE_T(t)/dy$ is *not* required.

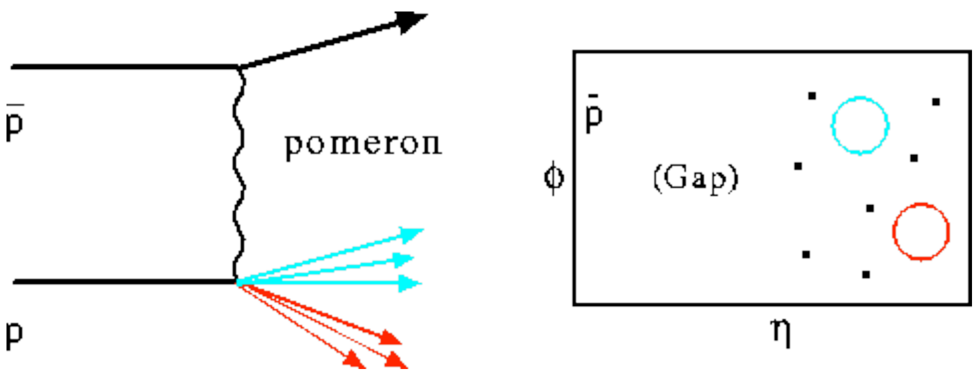
Back-up slide

Types of pp collisions

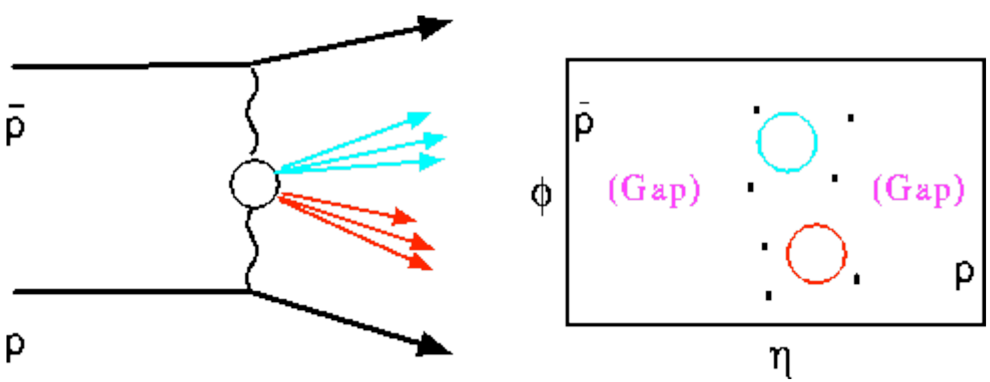


Elastic Scattering

Single Diffractive



Hard Single Diffractive



Hard Double Diffractive