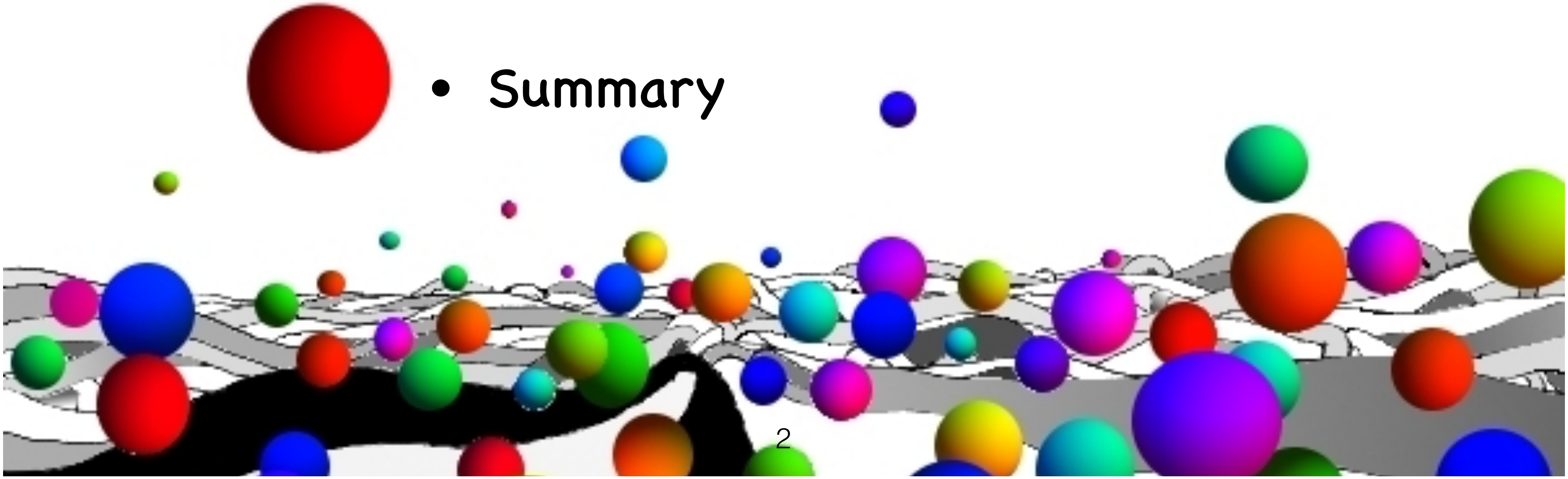
# String percolation model prediction for small systems at LHC energies

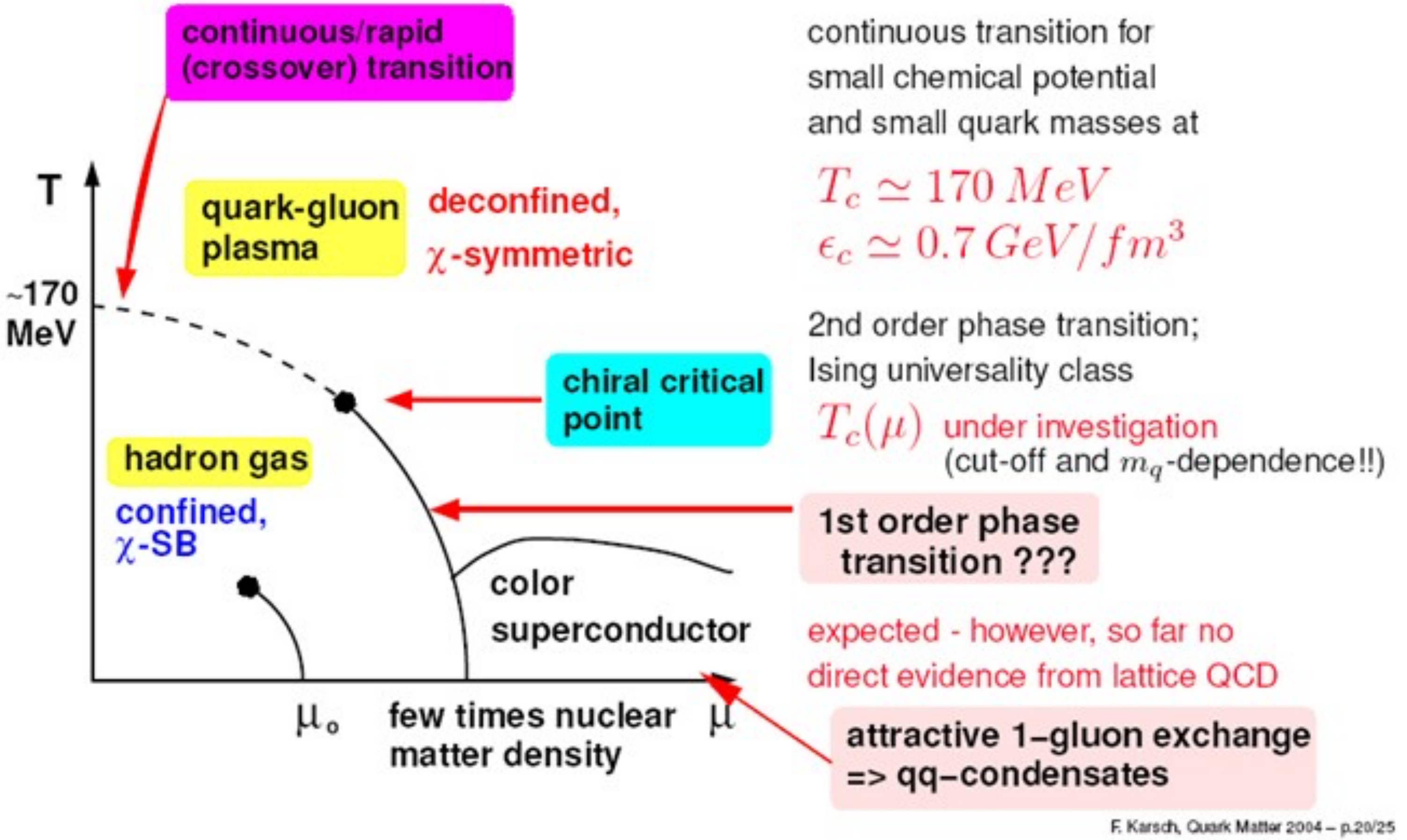
Iraís Bautista
CONACYT, FCFM-BUAP
A. Fernández, P. Ghosh, R. Vazquez, A. Sierra

**Jan 20th 2016, Taxco, Mexico**

# Outline

- Introduction to SPM
- Phase change signals
- p-p
- p-Pb
- Summary





continuous transition for
small chemical potential
and small quark masses at

$$T_c \simeq 170\,MeV$$
$$\epsilon_c \simeq 0.7\,GeV/fm^3$$

2nd order phase transition;
Ising universality class

$T_c(\mu)$ under investigation
(cut-off and $m_q$-dependence!!)

**1st order phase transition ???**

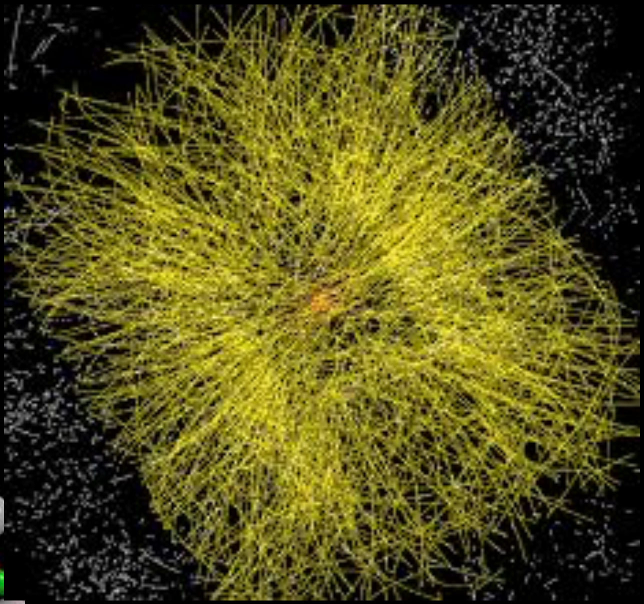
expected - however, so far no
direct evidence from lattice QCD

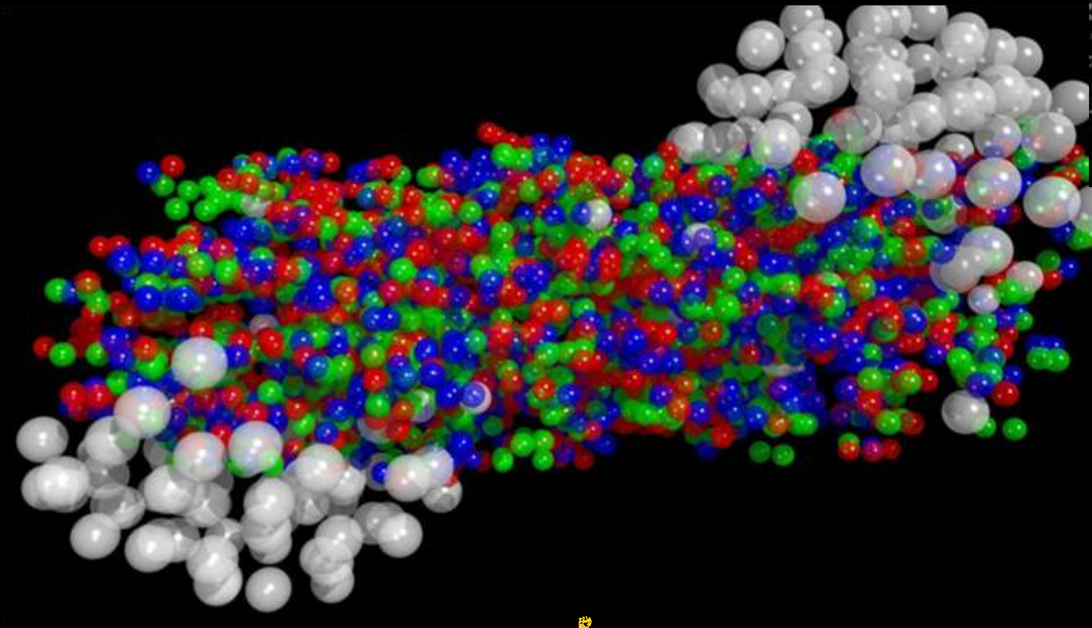
**attractive 1–gluon exchange
=> qq–condensates**

F. Karsch, Quark Matter 2004 – p.20/25

# Quark Gluon Plasma

sQGP

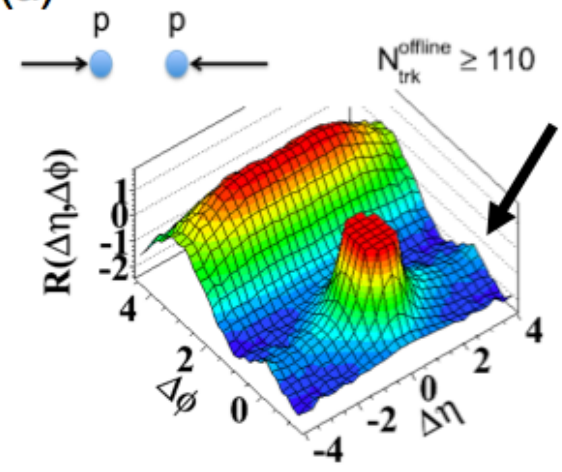




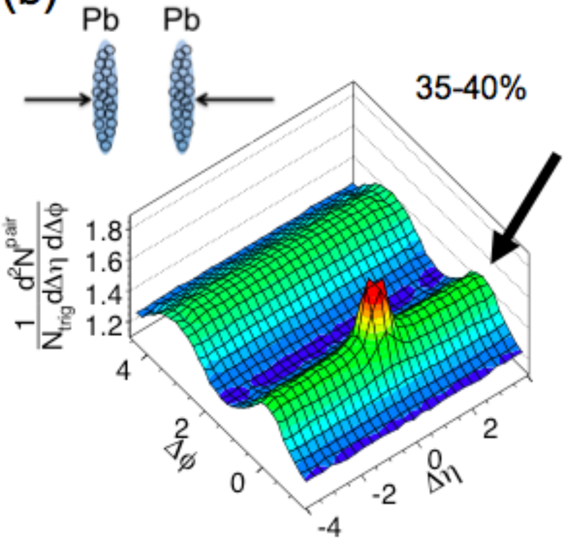
strong small

# “Ridge”

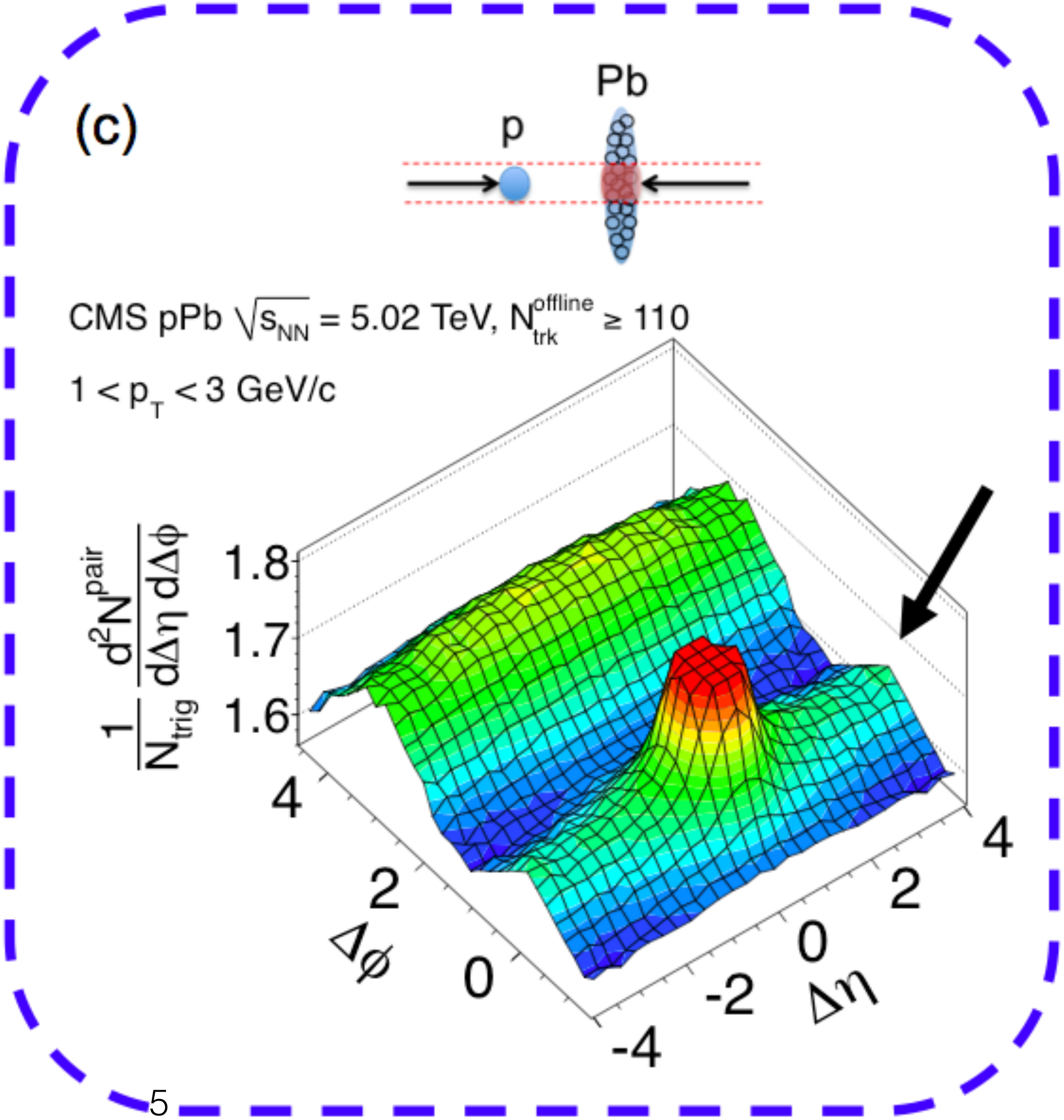
(a)


p
p
$N_{trk}^{offline} \geq 110$
$R(\Delta\eta,\Delta\phi)$
1
0
-1
-2
4
2
$\Delta\phi$
0
-4
-2
0
$\Delta\eta$
2
4

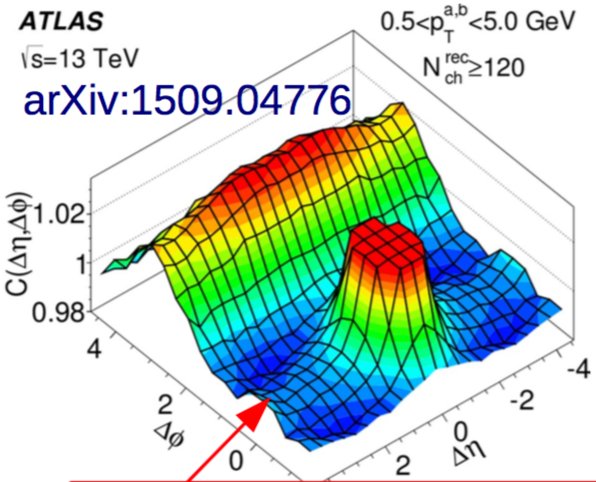
(b)


Pb
Pb
35-40%
$\frac{1}{N_{trig}}\frac{d^2N^{pair}}{d\Delta\eta\, d\Delta\phi}$
1.8
1.6
1.4
1.2
4
2
$\Delta\phi$
0
-4
-2
0
$\Delta\eta$
2

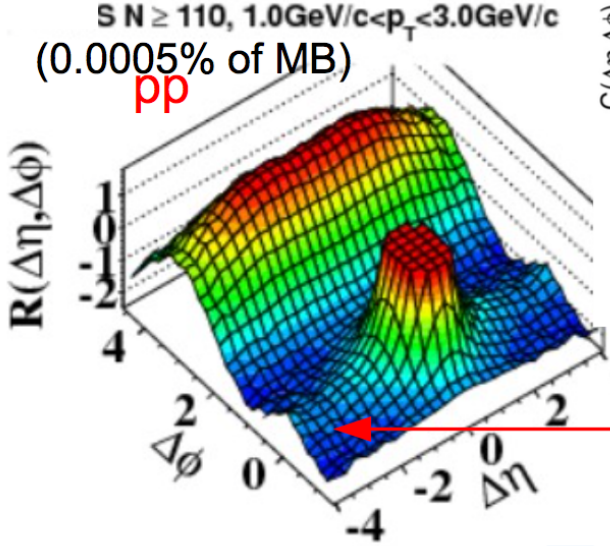
(c)


p
Pb
CMS pPb $\sqrt{s_{NN}}$ = 5.02 TeV, $N_{trk}^{offline} \geq 110$
$1 < p_T < 3$ GeV/c
$\frac{1}{N_{trig}}\frac{d^2N^{pair}}{d\Delta\eta\, d\Delta\phi}$
1.8
1.7
1.6
4
2
$\Delta\phi$
0
-4
-2
0
$\Delta\eta$
2
4

# 52 NS ridge str ar correlations

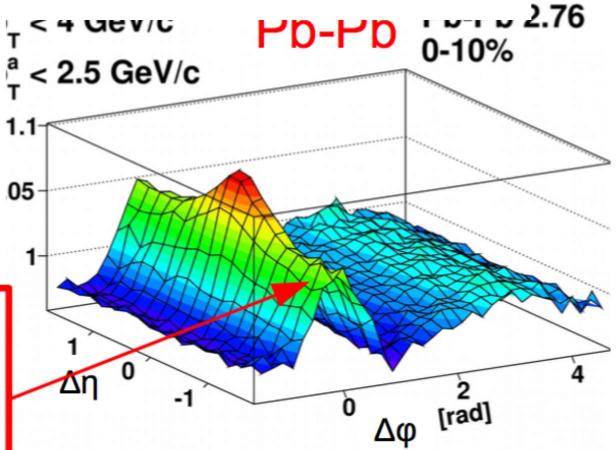


arXiv:1509.04776



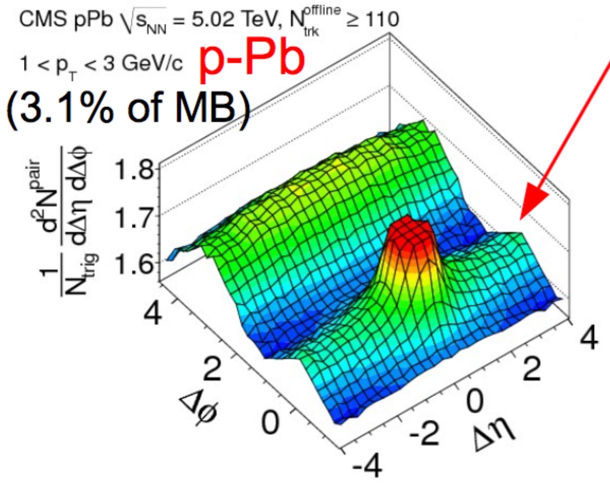
(0.0005% of MB)

CMS, JHEP 1009 (2010) 91



ALICE, PLB 708 (2012) 249

Near-side ridges
(direct exp. evidence
for long-range Δη
correlations at Δφ≈0)



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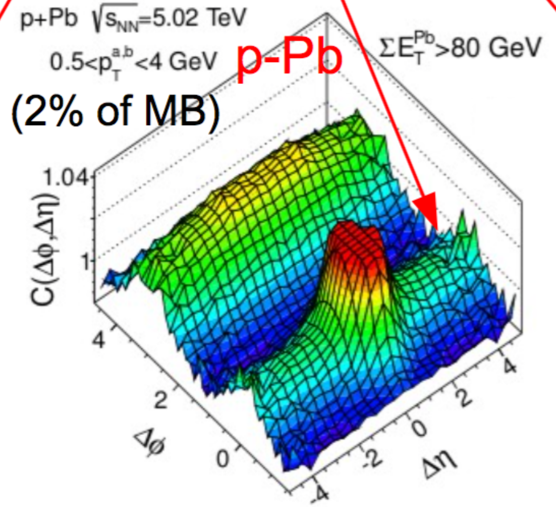
CMS, PLB 718 (2012) 795



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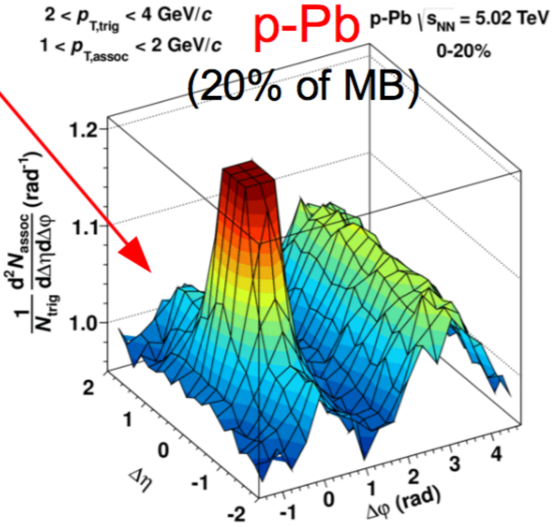
ATLAS, PRL 110 (2013) 182302



(20% of MB)

ALICE, PLB 719 (2013) 29

# String Percolation Model

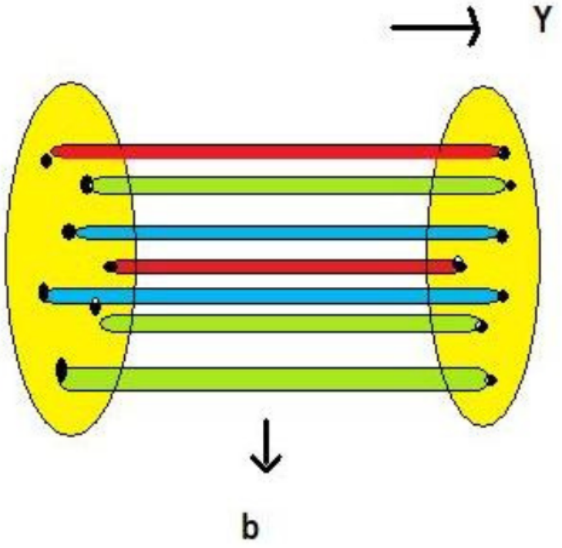
- Macroscopic system where we have the formation of related structures, which each time goes bigger by a random addition of links process between the components.

- For a given critical density of links one gets a macro-structure called cluster (dimension of the order of the total system).

# String Percolation Model

- In the transverse impact parameter plane the strings look like discs (2 dimensional percolation theory)

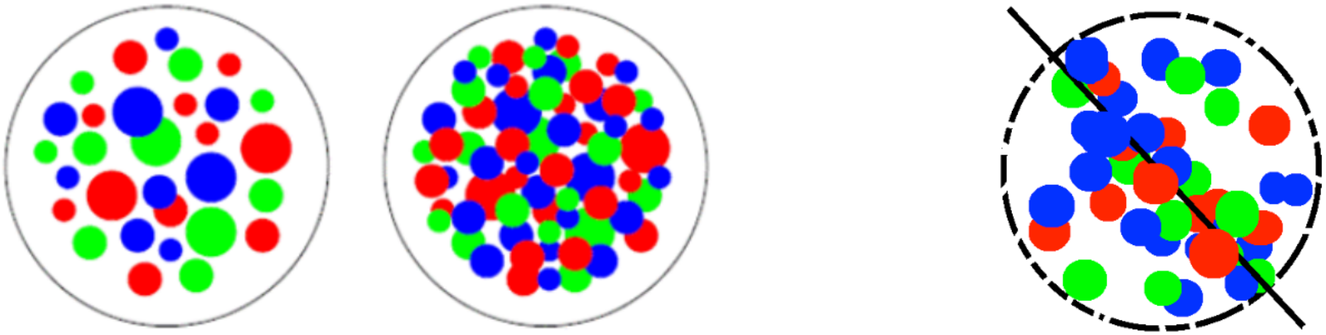
$S_1 = \pi r_0^2$ $\qquad$ $r_0 \sim 0.25 \text{ fm}$



$\sqrt{s},\ N_{part}$

- At a given density the strings will start to overlap forming clusters

- At the critical density a macroscopic cluster appears and marks a geometrical phase transition.



- Due to the color random summation of the color charges SU(3) the total change generates a reduction in multiplicity and an increase in the string tension $< p_T^2 >$

- The stretched strings between the partons decay into new pairs of partons and so new strings are formed. Subsequently, particles are produced from interaction of partons by the Schwinger Mechanism

- The critical parameter is the string density.
- $\xi = N_s \frac{S_1}{S_A}, \; \xi_c = 1.1 - 1.5$
- The area cover when a critical value is reached is given by

$$1 - e^{-\xi}$$

- We asume that a cluster behaves as a single string but with higher momentum and color
- In the n large limit the multiplicities and the transverse momentum can be express as:

$$< \mu_n > = \sqrt{\frac{nS_n}{S_1}} < \mu_1 > \; , \; < p^2_{Tn} > = \sqrt{\frac{nS_1}{S_n}} < p^2_{T1} >$$

$$\frac{dn}{dy} \sim F(\xi)\bar{N}_s$$

$$F(\xi) = \sqrt{\frac{1-e^{-\xi}}{\xi}}$$

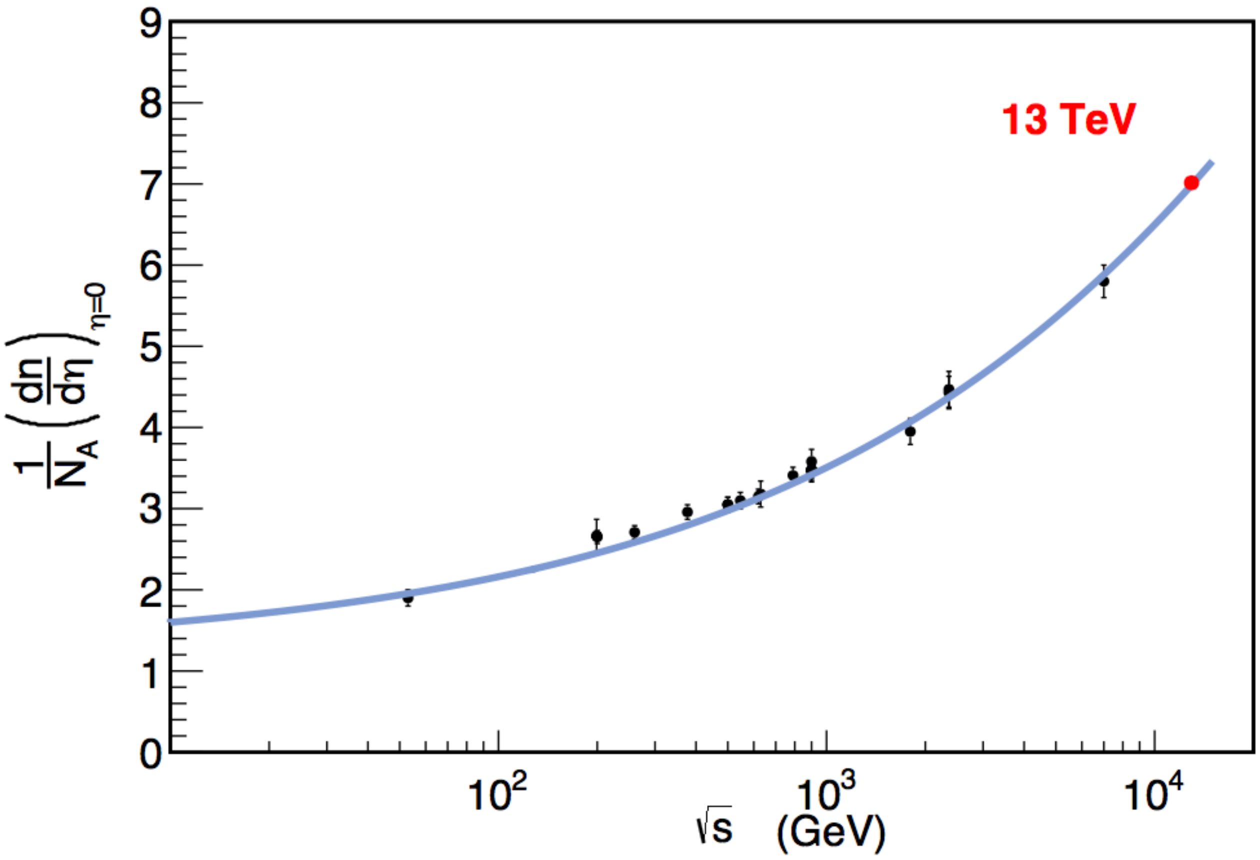
$$N_p^s = 2+4\left(\frac{r_0}{R_p}\right)^2\left(\frac{\sqrt{s}}{m_p}\right)^{2\lambda}$$

- mp-mass of the proton
- Rp -radius of the proton

$$\lambda = .201$$

- In pp $\xi = N_p^s(\frac{r_0}{R_p})^2$

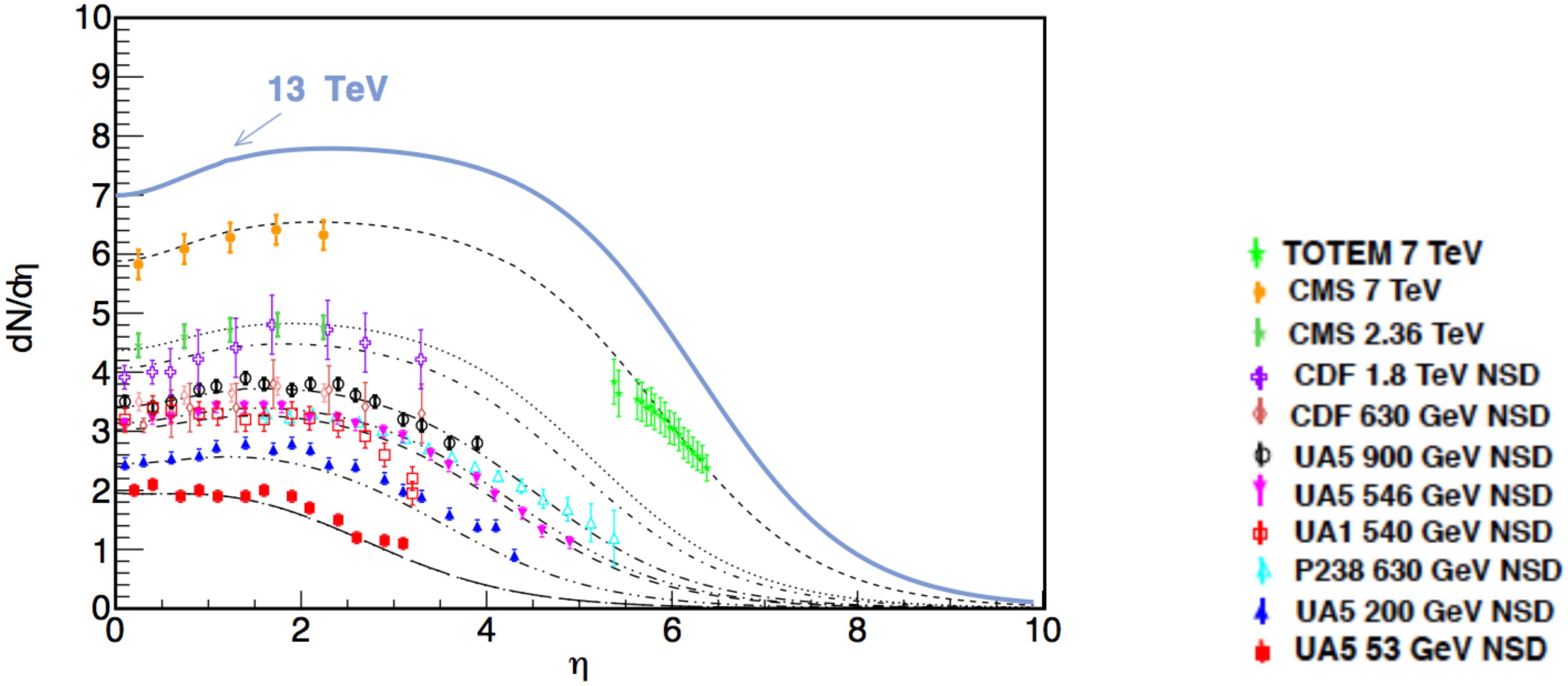
- $dn_{ch}^{pp}/dy|_{y=0} = \kappa F(\xi) N_p^s$ with $\kappa = .63$



Multiplicity dependence on $\sqrt{s}$. Data from $p-p$ PDG,

I. Bautista, J. G. Milhano, C. Pajares and J. Dias de Deus, Phys. Lett. B715, 230 (2012).

- $dn^{pp}_{ch}/d\eta|_{\eta} = \kappa' J F(\xi) N_p^s \frac{1}{\exp(\frac{\eta-(1-\alpha)Y}{\delta})+1}$



Comparison of the results from the evolution of the $\frac{dn_{ch}}{d\eta}$ with dependence in pseudorapidity for $p-p$ collisions at different energies (lines).

I. Bautista,J. Dias de Deus, C. Pajares, Phys.Rev. C86 (2012) 034909.

$$\frac{d^2N}{dp_T^2} = \omega(\alpha, p_0, p_T) = \frac{(\alpha-1)(\alpha-2)}{2\pi p_0^2}\frac{p_0^\alpha}{[p_0+p_T]^\alpha}$$

$$p_0 \to p_0\sqrt{\frac{F(\zeta)}{F(\zeta_{HM})}}$$

- Transverse momentum distribution

$$\frac{d^2N}{dp_T^2} = \frac{(\alpha-1)(\alpha-2)(p_0\sqrt{\frac{F(\zeta_{pp})}{F(\zeta_{HM})}})^{\alpha-2}}{2\pi[p_0\sqrt{\frac{F(\zeta_{pp})}{F(\zeta_{HM})}}+p_T]^\alpha}$$

$$\frac{1}{N}\frac{d^2N}{d\eta dp_T} = a'(\sqrt{s})\frac{dN}{d\eta}|^{pp}_{\eta=0}(\sqrt{s})\omega(\alpha, p_0, p_T) = \frac{a(p_0\frac{F(\zeta_{pp})}{F(\zeta_{HM})})^{\alpha-2}}{[p_0\sqrt{\frac{F(\zeta_{pp})}{F(\zeta_{HM})}}+p_T]^{\alpha-1}}$$

# pp collisions

$$\frac{1}{N}\frac{d^2N}{d\eta dp_T} = \frac{ap_0^{\alpha-2}}{[p_0+p_T]^{\alpha-1}},$$

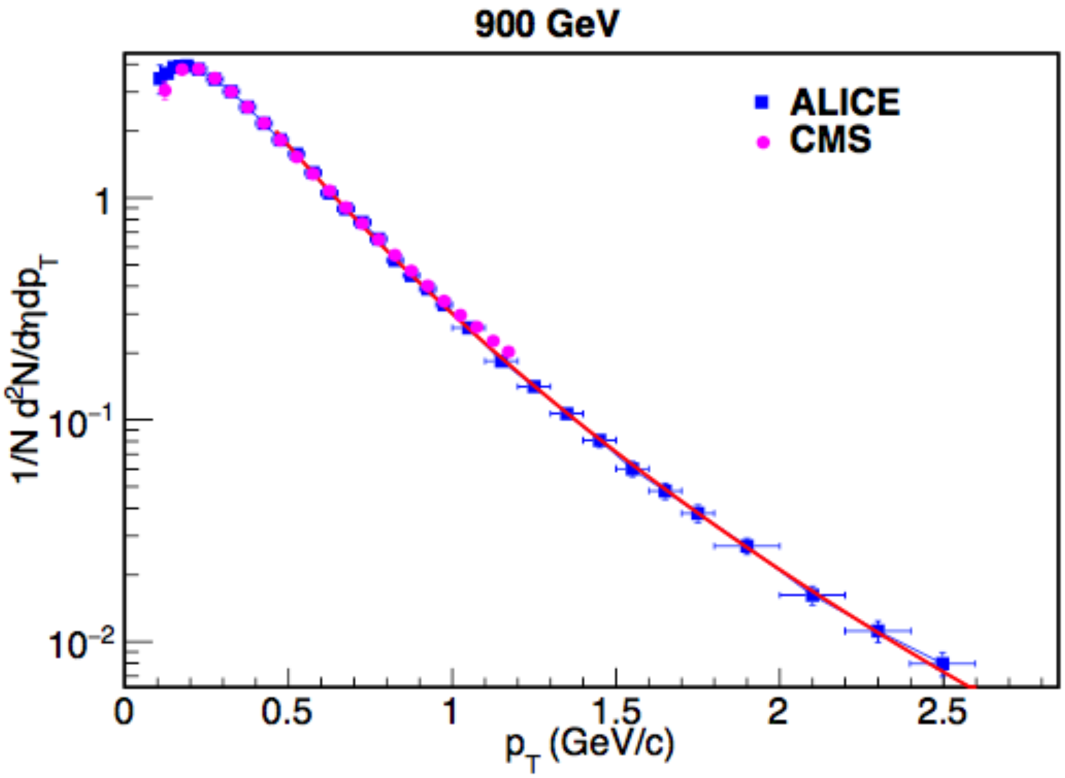


Figure: Fits to the transverse momentum distribution for energies $\sqrt{s} = 900$ GeV in $p-p$
Eur.Phys.J. C75 (2015) 226.

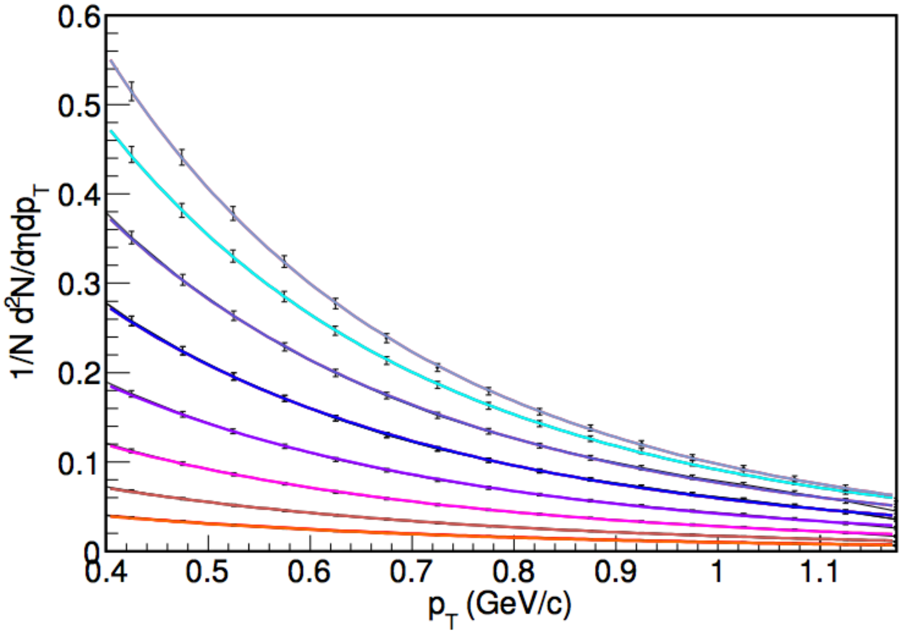


Figure: Fits to the transverse momentum distribution for energies $\sqrt{s} = 7$ TeV in $p - p$ collisions for different multiplicity classes from $N_{track} = 40$ grey line to $N_{track} = 131$ orange line. Data taken from http://hepdata.cedar.ac.uk/view/ins1123117 .

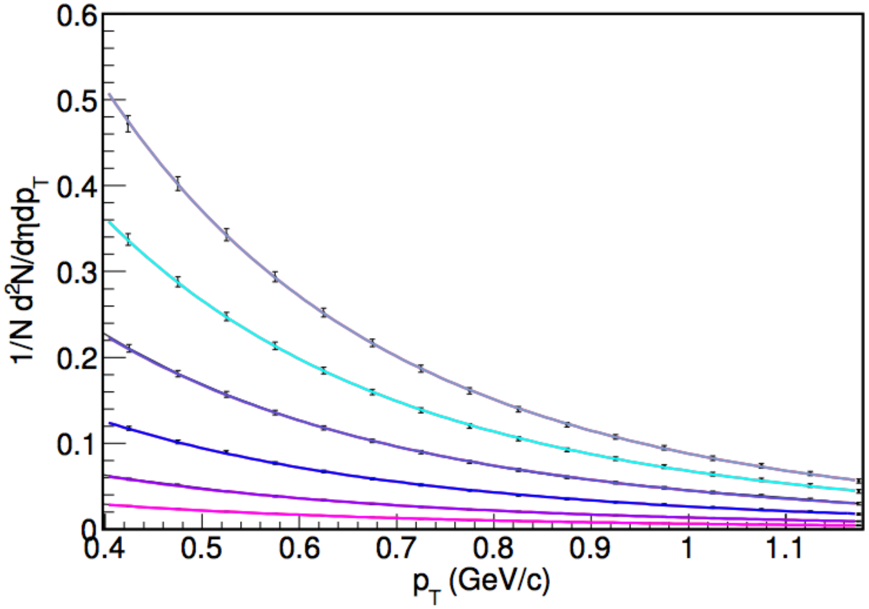


**Figure:** Fits to the transverse momentum distribution for energies $\sqrt{s} = 2.76$ TeV in $p-p$ collisions for different multiplicity classes from $N_{track} = 40$ grey line to $N_{track} = 98$ pink line. Data taken from http://hepdata.cedar.ac.uk/view/ins1123117 .

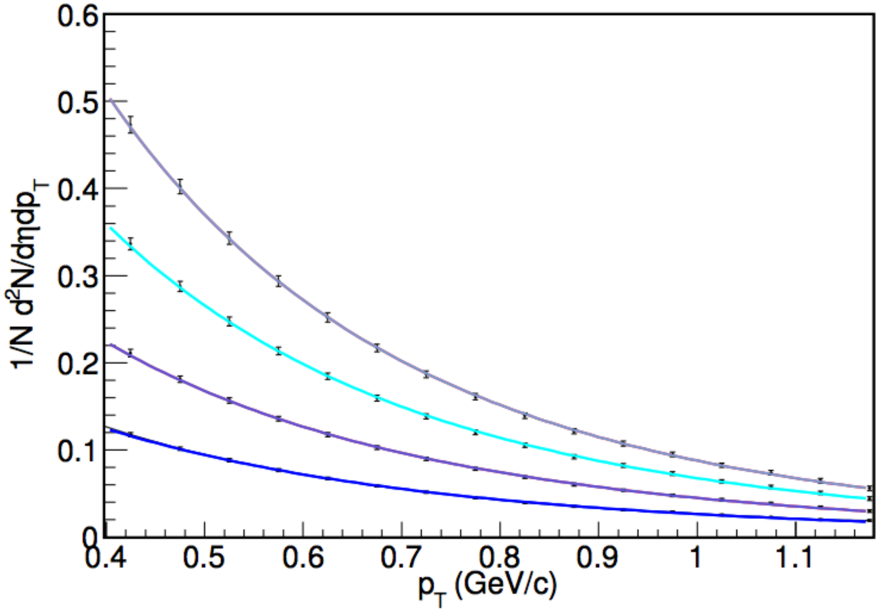


**Figure:** Fits to the transverse momentum distribution for energies $\sqrt{s} = 900$ GeV in $p-p$ collisions for different multiplicity classes from $N_{track} = 40$ grey line to $N_{track} = 75$ blue line. Data taken from http://hepdata.cedar.ac.uk/view/ins1123117 .

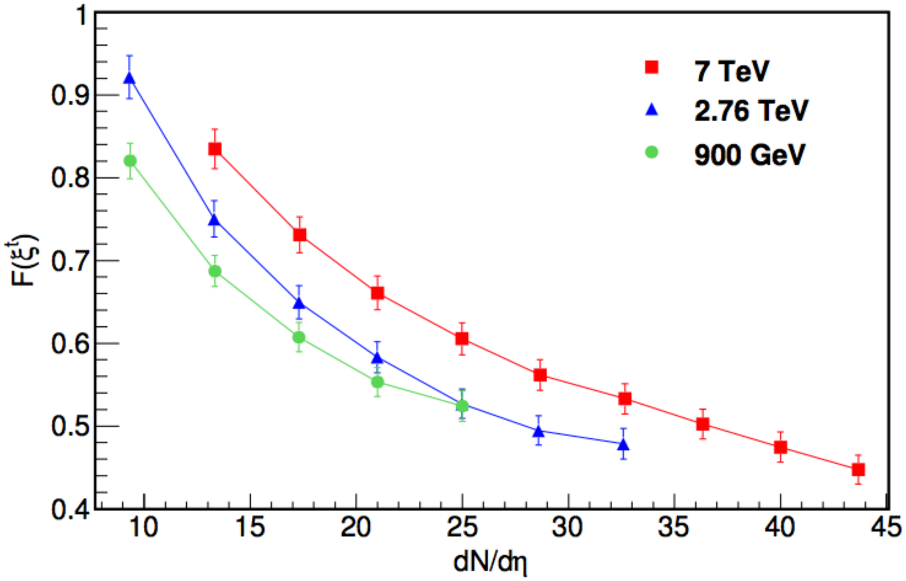


Figure: Color reduction factor at high multiplicities for different energies

- The Schwinger mechanism for massless particles

$$\frac{dN}{dp_T} \sim e^{-\sqrt{2F(\zeta^t)}\frac{p_T}{\langle p_T \rangle_1}},$$

- The average value of the string tension which value fluctuates around its mean value because the chromoelectric field is not constant

$$\langle x^2 \rangle = \pi \langle p_T^2 \rangle_1 / F(\zeta),$$

- The fluctuations of the chromo electric field strength lead to a Gaussian distribution of the string tension that transform it into a thermal distribution, where the temperature is given by

$$T(\zeta^t) = \sqrt{\frac{\langle p_T^2 \rangle_1}{2F(\zeta^t)}}$$

- We consider that the experimentally determined chemical freeze out temperature is a good measure of the phase transition temperature Tc

- We calculate the effective temperature, T, from the equation, for each multiplicity class for a critical density 1.2 and at the critical temperature Tc = 154 ± 9 MeV, as obtained by the latest LQCD results from the HotLQCD collaboration

$$T_c = 154 \pm 9 \text{ MeV}$$ [1]

- With the corresponding $\langle p_T \rangle_1 \sim 190.25 \pm 11.12 \text{ MeV/c}$ consistent with the measured of direct photon enhanced measured

[1] HotQCD: Phys. Rev. D85, 054503 (2012)

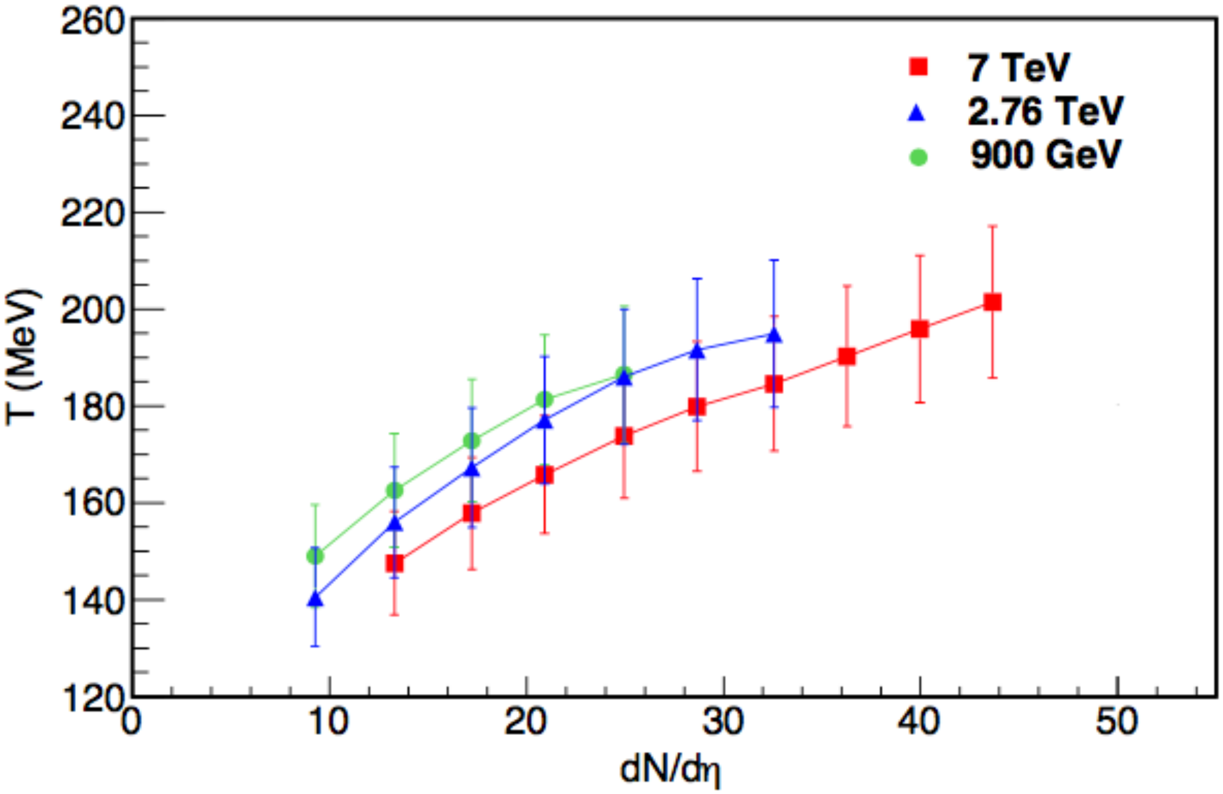


FIG. 3. Efective temperature vs $dn/d\eta$.

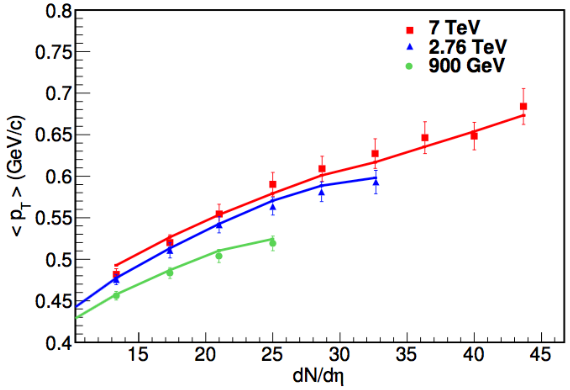
- The evolution of the mean transverse momentum can also described as an inverse function of the color reduction factor

$$\frac{1}{N}\frac{d^2N}{dp_T^2} = \omega(\alpha, p_0, p_T) = \frac{(\alpha-1)(\alpha-2)}{2\pi p_0^2}\frac{p_0^\alpha}{(p_T+p_0)^\alpha}$$

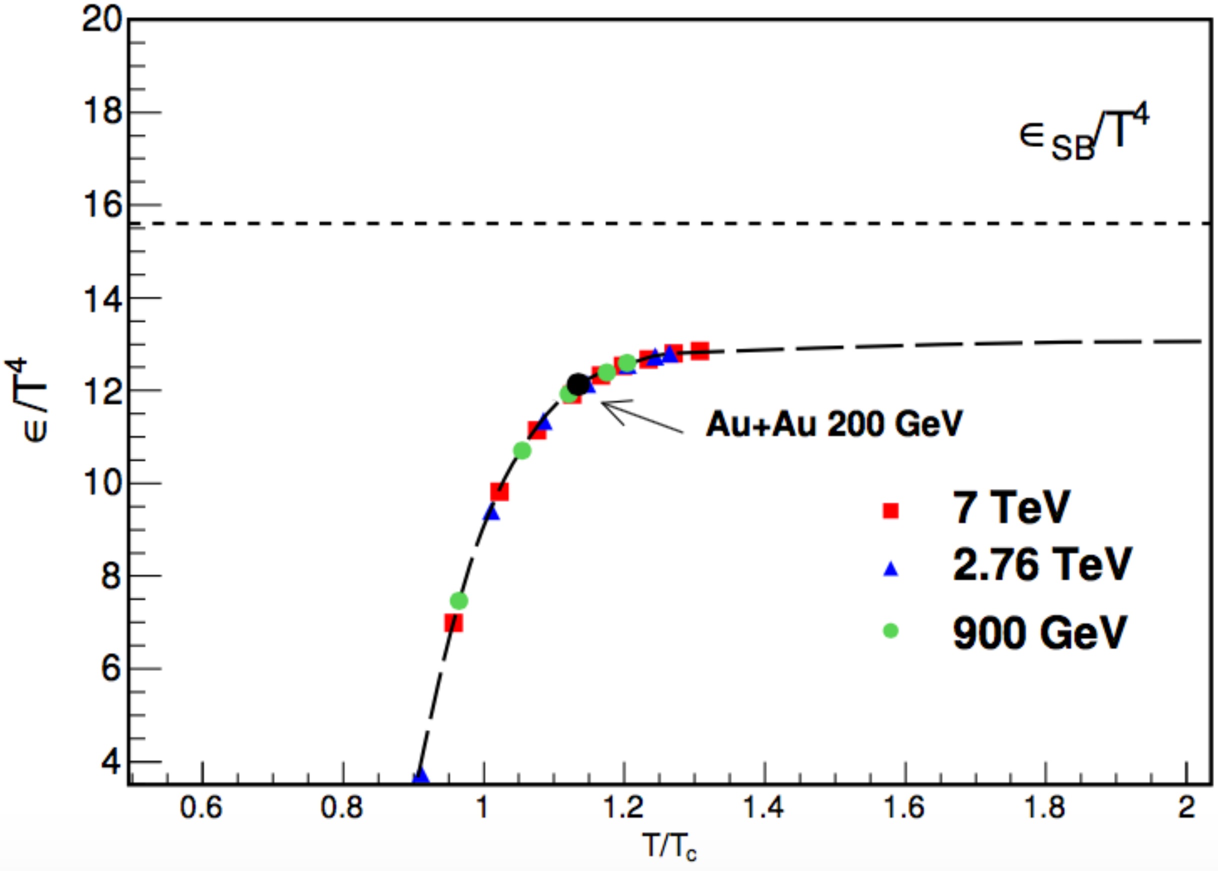
$$\langle p_T \rangle = p_0 \frac{2}{\alpha-3}$$

$$p_0 \rightarrow p_0\sqrt{\frac{F(\zeta)}{F(\zeta_{HM})}}$$

$$\langle p_T \rangle = p_0\sqrt{\frac{F(\zeta)}{F(\zeta_{HM})}}\frac{2}{\alpha-3}$$



$$\varepsilon_i = \frac{3}{2}\,\frac{\frac{dN_C}{dy}\langle p_T\rangle}{S_N\,\tau_{pro}}$$



where $S_n$ is the nuclear overlap area, $\tau_{pro}$ is the production time for a boson gluon which we will replace by $\tau = 2.405\bar{h}/ < m_t >$ the propagation time of the parton given in fermis. The results are

# Shear viscosity / entropy

- In the relativistic kinetic theory

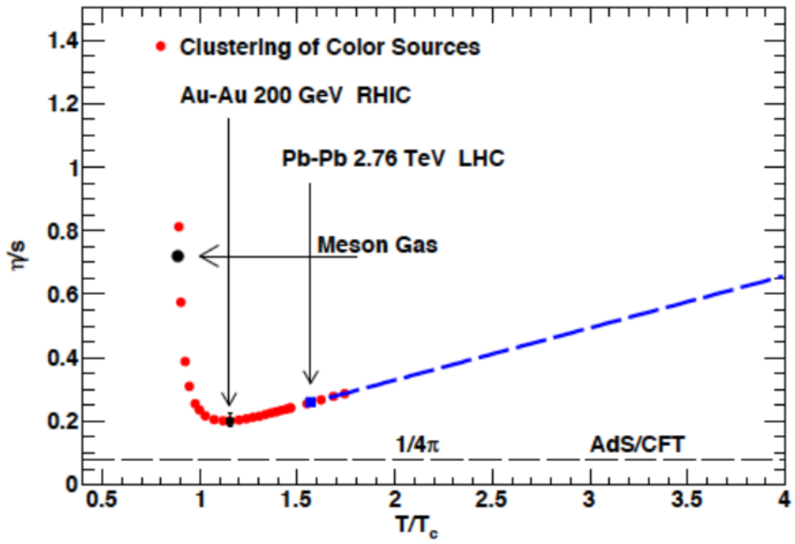
$$\frac{\eta}{s} \simeq \frac{T\lambda_{fp}}{5}$$

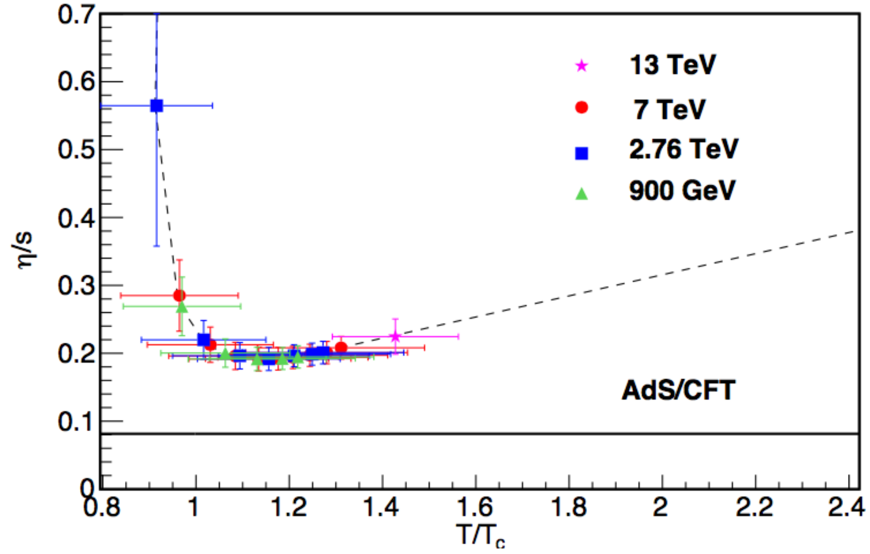
- $\lambda_{fp} \sim \frac{1}{n\sigma_{tr}}$ is the mean free path

- $n = \frac{N_{sources}}{S_N L}$ is the density of the effective number of sources per unit volume

- We considered $\frac{N_{sources}}{S_N L}\sigma_{tr} = (1 - e^{-\zeta^t})/L$ and L=1fm the longitudinal extension of the source.

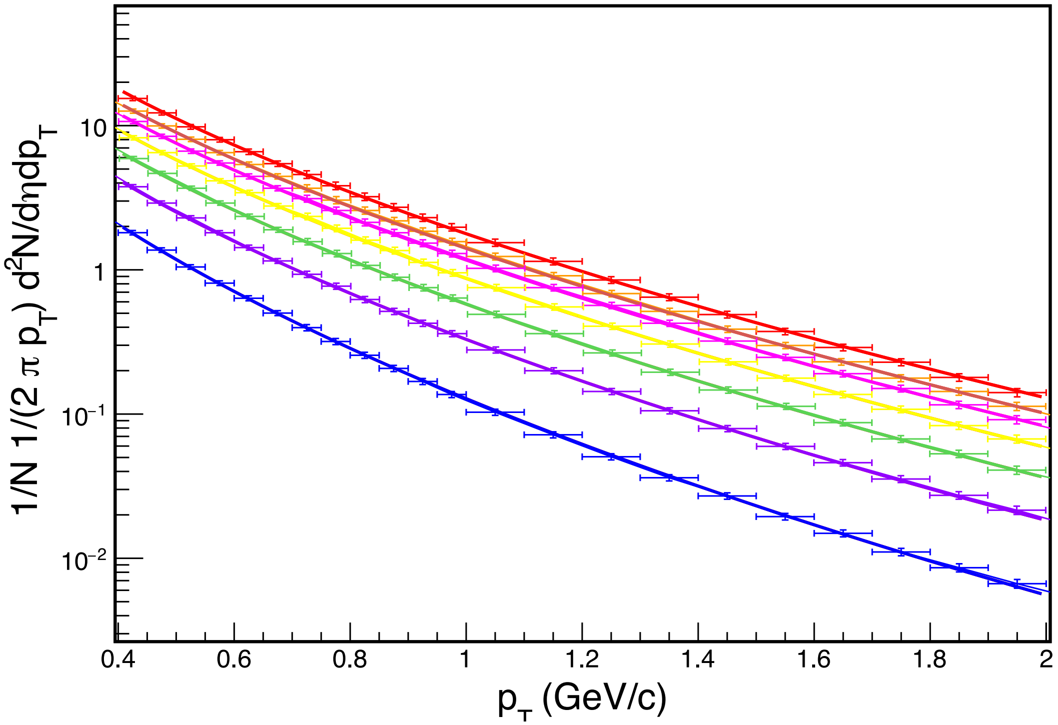
$$\frac{\eta}{s} = \frac{TL}{5(1 - e^{-\zeta^t})}$$





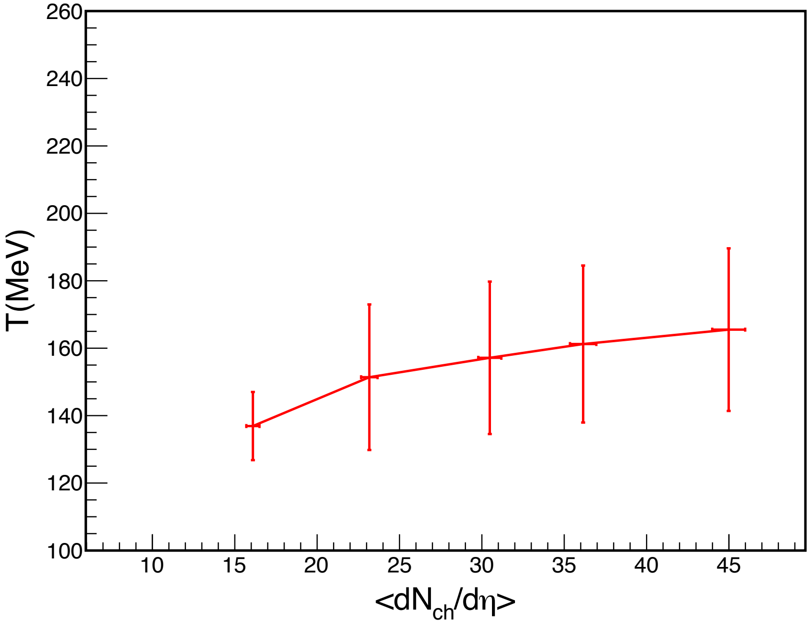
On the right Shear viscosity over entropy ratio for 7 TeV high multiplicity classes corresponding to $N_{track} = 40$ to $N_{track} = 131$, with the $T_c = 154 \pm 9$. In here we have plot the corresponding value corresponding to an approximate number of tracks $\sim 155 \pm 7$ corresponding to high multiplicity event in 13 TeV. Left side calculations the $T_c$ value was taken as 167 MeV for heavy ion B. K. Srivastava, Eur. Phys. J. C72.

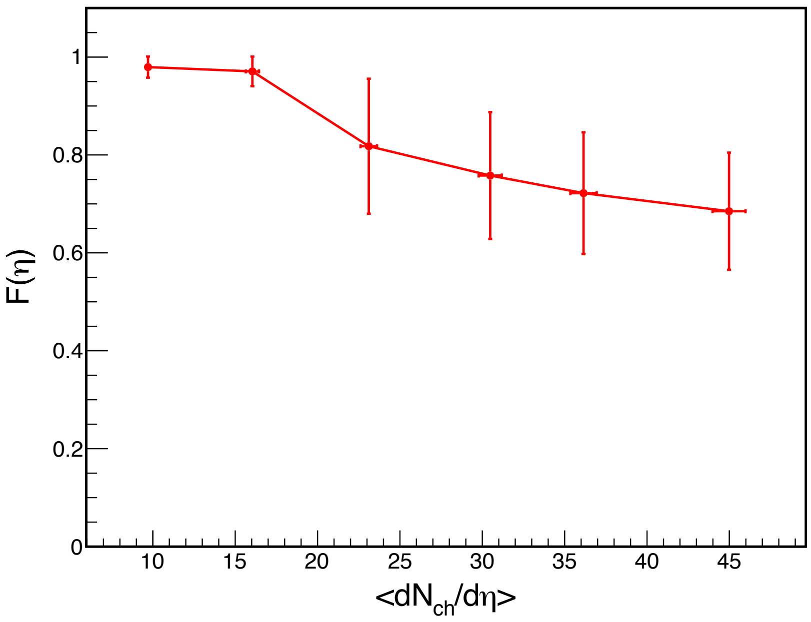
# pPb collisions at 5.02 TeV



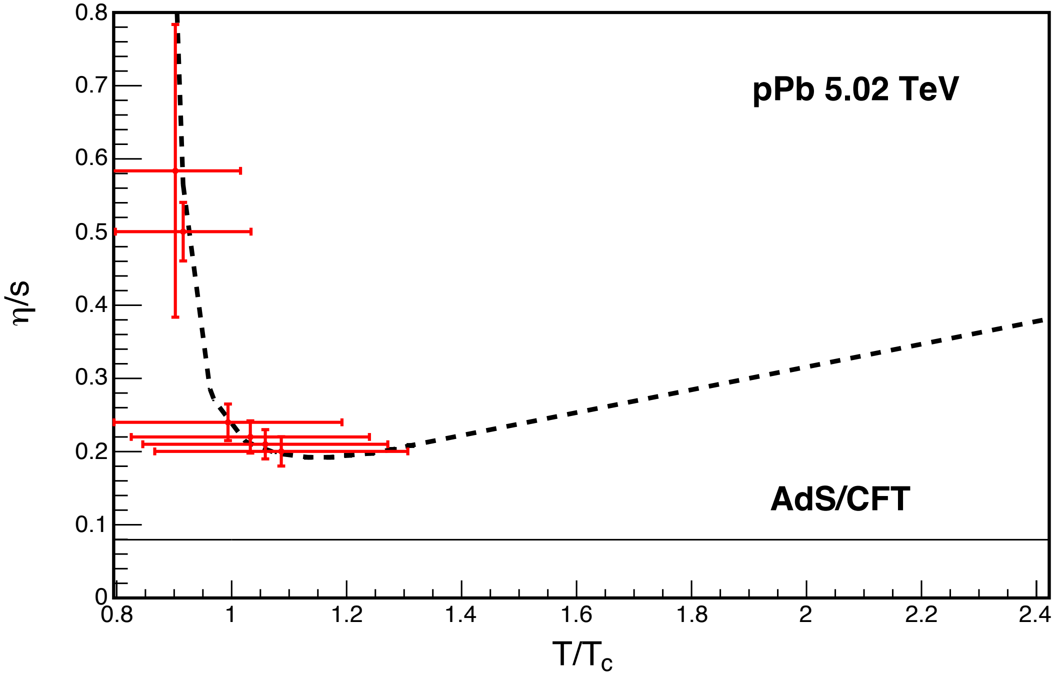
B. B. Abelev [ALICE Collaboration], Phys. Lett. B 728 (2014) 25

# pPb collisions at 5.02 TeV





**Data taken from: http://hepdata.cedar.ac.uk/view/ins1244523**


pPb 5.02 TeV
AdS/CFT
η/s
T/$T_c$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4

# Summary

The SPM gives a indication of the geometric phase transition for the highest multiplicity events on p-p and p-Pb collisions.

The SPM can give a qualitative explanation of the collective effects seen on small systems.

**I. Bautista, A. Fernandez, P. Ghosh, Phys. Rev D 92 (2015) 7, 0172504**

# Thank you !!!

| $\sqrt{s}$ (TeV) | a | $p_0$ | $\alpha$ |
|---|---|---|---|
| .9 | 23.29 ± 4.48 | 1.82 ± .54 | 9.40 ± 1.80 |
| 2.76 | 22.48± 4.20 | 1.54 ± .46 | 7.94± 1.41 |
| 7 | 33.12 ± 9.30 | 2.32 ± .88 | 9.78 ± 2.53 |

TABLE I. Parameters of the transverse momentum distribution (9) in *pp* collisions.

| $\sqrt{s}$ | 7 (TeV) | 2.76 (TeV) | 900 (GeV) |
|---|---|---|---|
| $dN/d\eta$ | $\zeta_{HM}$ | $\zeta_{MH}$ | $\zeta_{MH}$ |
| 13.33 | 0.77 ± .13 | 1.30 ± .15 | 1.75 ± .15 |
| 17.33 | 1.42 ± .15 | 2.09 ± .18 | 2.49 ± .19 |
| 21.0 | 1.98 ± .18 | .78 ± .21 | 3.13 ± .23 |
| 25 | 2.53 ± .21 | 3.52 ± .27 | 3.55 ± .28 |
| 28.67 | 3.02 ± .23 | 4.03 ± .31 | |
| 32.67 | 3.42 ± .26 | 4.33 ± .36 | |
| 36.33 | 3.89 ± .30 | | |
| 40. | 4.40 ± .36 | | |
| 43.67 | 4.98 ± .40 | | |

**Table:** Corresponding $dN/d\eta$ and $\zeta_{HM}$, and $R$ for the $\langle N_{track} \rangle$ in pp collisions high multiplicity clases

The single string average transverse momentum $\langle p_t \rangle_1$ is calculated at $\zeta_c = 1.2$ and $\zeta_c = 1.5$ with the universal chemical freeze out temperature of $167.7 \pm 2.6$ MeV and $154 \pm 9$ MeV both values corresponding to the old and new LQCD results from the HotLQCD collaboration. The values for the corresponding $\zeta^t$ and $T_c$ obtained:

$p_{T1} = 190.25 \pm 11.12$ for $\zeta^t = 1.2$ and $T_c = 154 \pm 9$
$p_{T1} = 184.76 \pm 7.80$ for $\zeta^t = 1.5$ and $T_c = 154 \pm 9$
$p_{T1} = 207.18 \pm 3.21$ for $\zeta^t = 1.2$ and $T_c = 167.7 \pm 2.3$
$p_{T1} = 201.19 \pm 3.12$ for $\zeta^t = 1.2$ and $T_c = 167.7 \pm 2.3$.

We compare the obtained temperature $T_i$ at the measured value of $\zeta = 2.88$ before the expansion of the QGP with the measured $T_i = 221 \pm 19_{stat} \pm 19_{sys}$ MeV from the enhanced direct photon experiment measured by PHENIX. All the values are consistent with the previously used value of $\sim 200$ MeV in the calculation of percolation transition of temperature with the exception of the one obtained at $T_c = 154$ with $\zeta_c = 1.5$.

A. Bazavov et al., Phys. Rev. D80, 014504 (2009), A. Adare et al., (PHENIX Collaboration), Phys. Rev. Lett. 104, 132301 (2010).