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FCFM

Study of the event by event mean transverse momentum fluctuations in small collision systems at LHC energies with percolation color sources

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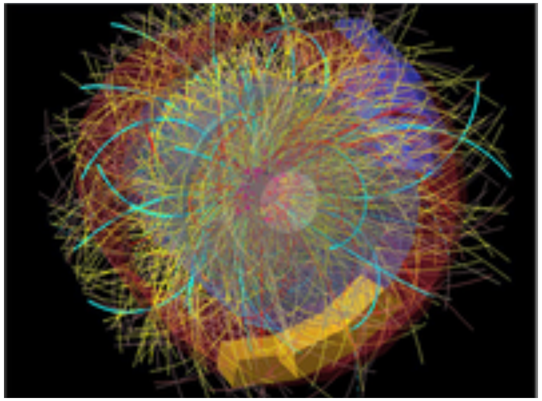
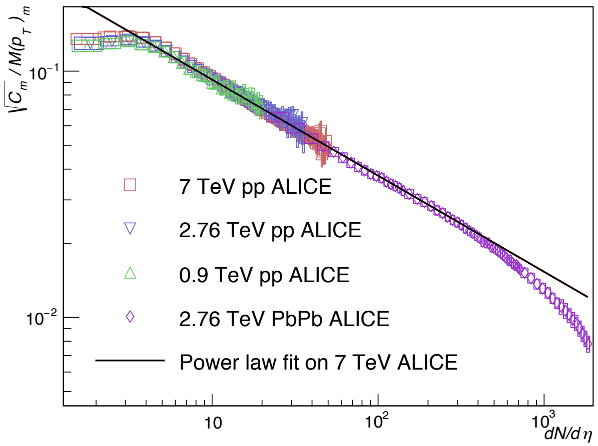
Motivation

- Event by event fluctuations of thermodynamic quantities were proposed as a probe for a phase transition from hadronic matter to Quark Gluon Plasma (QGP).

- Fluctuations in thermodynamic quantities, such as temperature can be reflected in dynamical event by event fluctuations of the mean transverse momentum $\langle p_T \rangle$ in high energy heavy ion collisions.

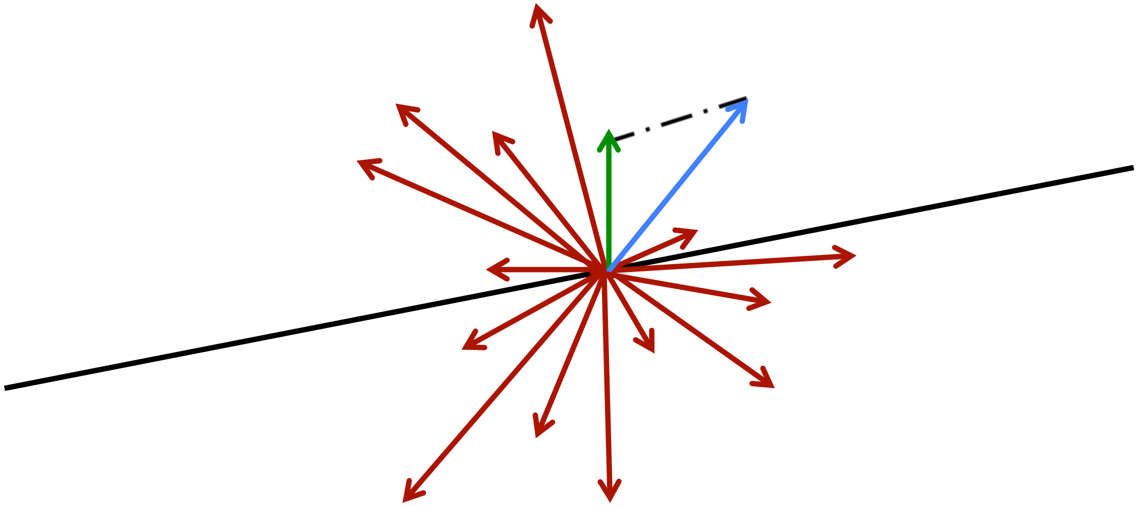
- Recently, collective signatures have been observed in small collision systems.





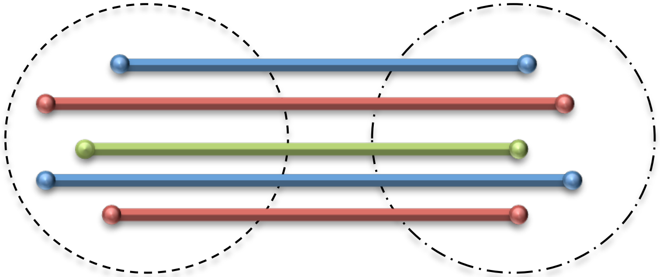
[1] S. T. Heckel [ALICE Collaboration],Phys. Rept. **599** (2015) 1.

- Dynamical fluctuations of the $\langle p_T \rangle$ increases by many kinds of correlations of the $\langle p_T \rangle$ of the final states of the generated particles (resonance decays, jets, etc.).

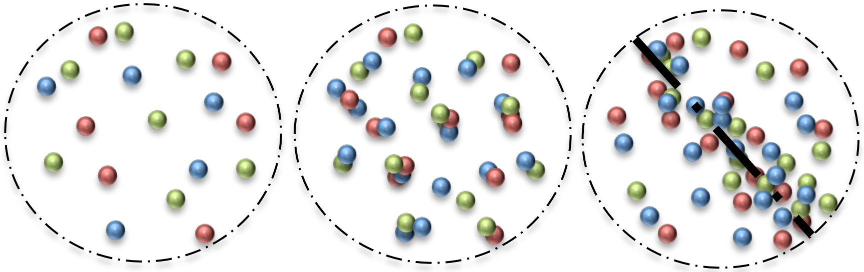


The Color String Percolation Model

- Phase transition can be described by percolation theory by using critical exponents and power laws. We use the transverse area of color flux tubes (strings) that represents the stretched color fields of the colliding partons.



- The stretched strings then break and more strings are produced, thus giving us particle emission (Schwinger mechanism).



- As the energy or the size of the systems increases the strings begin to percolate, thus marking a phase transition.

[2] M. A. Braun, J. Dias de Deus, A. S. Hirsch, C. Pajares, R. P. Scharenberg and B. K. Srivastava, Phys. Rept. **599** (2015) 1

[3] E. G.Ferreiro, F. del Moral and C. Pajares,Phys. Rev. C **69** (2004) 034901

- A critical parameter is the string density

  which is given by: $\zeta^t = \frac{S_1}{S_n} N_s$

- Given that we are interested in proton-proton collisions, the string density is now given by:

$$\zeta^t = \left(\frac{r_0}{R_P}\right)^2 N_s$$

Where r_0 is the radius of a single string and R_p is the proton radius.

[2] M. A. Braun, J. Dias de Deus, A. S. Hirsch, C. Pajares, R. P. Scharenberg and B. K. Srivastava, Phys. Rept. **599** (2015) 1

[3] E. G.Ferreiro, F. del Moral and C. Pajares,Phys. Rev. C **69** (2004) 034901

- A cluster is considered as a single string as the vectorial sum of the strings that compose it and thus having a factor that supresses color production called the color reduction factor (sacaling function).

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

- In the thermodynamical limit:

$$\langle \frac{nS_1}{Sn} \rangle = \frac{\zeta^t}{1-e^{-\zeta^t}} \equiv \frac{1}{F(\zeta^t)^2}$$

$$\mu_n = \sqrt{\frac{nS_n}{S_1}}\mu_1$$

$$\langle p_T^2 \rangle_n = \sqrt{\frac{nS_1}{S_n}}\langle p_T^2 \rangle_1$$

[2] M. A. Braun, J. Dias de Deus, A. S. Hirsch, C. Pajares, R. P. Scharenberg and B. K. Srivastava, Phys. Rept. **599** (2015) 1

Event by event $\langle p_T \rangle$ Fluctuations on the SPM

- Are measured with: $$F_{p_T} = \frac{\omega_{data} - \omega_{random}}{\omega_{random}}$$

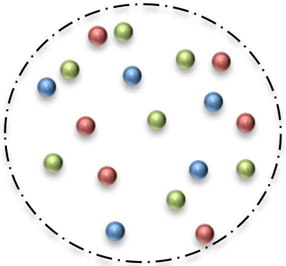
- With: $$\omega = \frac{\sqrt{\langle p_T^2 \rangle - \langle p_T \rangle^2}}{\langle p_T \rangle}$$

- F_{p_T} measures the fluctuations as a function of the number of participants in heavy ion collisions.

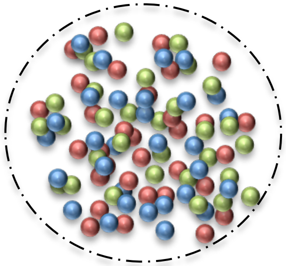
[3] E. G.Ferreiro, F. del Moral and C. Pajares,Phys. Rev. C **69** (2004) 034901

- We can understand EbE $\langle p_T \rangle$ fluctuations as following:

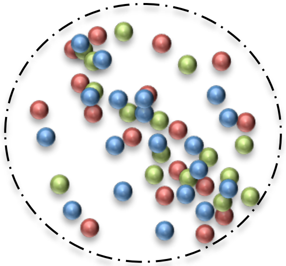
- At low ζ^t: we have very little fluctuations



- Over critical ζ^t: we have no fluctuations



- Below critical ζ^t: fluctuations are maximal



[3] E. G.Ferreiro, F. del Moral and C. Pajares,Phys. Rev. C **69** (2004) 034901

- With this in mind we can get the one particle variance and the event variance $z_i = p_{T_i} - \langle p_T \rangle$ and $Z_i = \sum_{j=1}^{N_i} z_j$ respectively.

- Thus:

$$F_{p_T} = \frac{\sqrt{\frac{\langle Z^2 \rangle}{\langle \mu \rangle}} - \sqrt{\langle z^2 \rangle}}{\sqrt{\langle z^2 \rangle}} = \frac{1}{\sqrt{\langle z^2 \rangle}} \sqrt{\frac{\langle Z^2 \rangle}{\langle \mu \rangle}} - 1$$

[3] E. G.Ferreiro, F. del Moral and C. Pajares,Phys. Rev. C **69** (2004) 034901

- By having $\langle p_T\rangle$ as a function of the number of participants:

$$\langle p_T\rangle = \frac{\sum^{N_{ev}}{}_{i=1}\sum_j \mu_{nj}\langle p_T\rangle_{nj}}{\sum^{N_{ev}}{}_{i=1}\sum_j \mu_{nj}} = \frac{\sum_{i=1}^{N_{ev}}\sum_j\left(\frac{n_jS_{nj}}{S_1}\right)^{1/2}\mu_1\left(\frac{njS_1}{S_{nj}}\right)^{1/4}\langle p_T\rangle_1}{\sum_{i=1}^{N_{ev}}\sum_j\left(\frac{njS_{nj}}{S_1}\right)^{1/2}\mu_1} = \frac{\langle\sum_j n_j^{3/4}\left(\frac{S_{nj}}{S_1}\right)^{1/4}\rangle}{\langle\sum_j\left(\frac{n_jS_{nj}}{S_1}\right)^{1/2}\rangle}\langle p_T\rangle_1$$

- And thus, we can write:

$$\left.\begin{aligned}
\frac{\langle Z^2\rangle}{\langle\mu\rangle} &= \frac{\sum_{i=1}^{N_{ev}}\left[\sum_j\left(\frac{n_jS_j}{S_1}\right)^{1/2}\mu_1\left[\left(\frac{n_jS_1}{S_{n_j}}\right)^{1/4}\langle p_T\rangle_1-\langle p_T\rangle\right]\right]^2}{\left[\sum_{i=1}^{N_{ev}}\sum_j\left(\frac{n_jS_{n_j}}{S_1}\right)^{1/2}\mu_1\right]} \\
\langle z^2\rangle &= \frac{\sum_{i=1}^{N_{ev}}\sum_j\left(\frac{n_jS_{nj}}{S_1}\right)^{1/2}\mu_1\left[\left(\frac{n_jS_1}{S_{nj}}\right)^{1/4}\langle p_T\rangle_1-\langle p_T\rangle\right]^2}{\sum_{i=1}^{N_{ev}}\sum_j\left(\frac{njS_{nj}}{S_1}\right)^{1/2}\mu_1}
\end{aligned}\right\} F_{p_T} = \frac{1}{\sqrt{\langle z^2\rangle}}\sqrt{\frac{\langle Z^2\rangle}{\langle\mu\rangle}}-1$$

[3] E. G.Ferreiro, F. del Moral and C. Pajares,Phys. Rev. C **69** (2004) 034901

- For this study the sums are taken as the average and the terms n_j and S_1/S_{n_j} are taken as N_s and S_1/S_n respectively.
- Thus having:

$$\frac{\langle Z^2\rangle}{\langle\mu\rangle} \simeq \frac{\left[\left(\frac{N_s S_n}{S_1}\right)^{1/2}\mu_1\left[\left(\frac{N_s S_1}{S_n}\right)^{1/4}\langle p_T\rangle_1 - \langle p_T\rangle\right]\right]^2}{\left[\left(\frac{N_s S_n}{S_1}\right)^{1/2}\mu_1\right]}$$

$$\langle z^2\rangle \simeq \frac{\left(\frac{N_s S_n}{S_1}\right)^{1/2}\mu_1\left[\left(\frac{N_s S_1}{S_{nj}}\right)^{1/4}\langle p_T\rangle_1 - \langle p_T\rangle\right]^2}{\left(\frac{N_s S_n}{S_1}\right)^{1/2}\mu_1}$$

- By exapnding the square powers and taking the square roots:

$$\sqrt{\frac{\langle Z^2\rangle}{\langle \mu_1\rangle}} \simeq \sqrt{N_s\langle p_T\rangle_1^2\mu_1 - 2N_s^{3/4}\left(\frac{S_n}{S_1}\right)^{1/4}\langle p_T\rangle_1\langle p_T\rangle\mu_1 + \left(N_s\frac{S_n}{S_1}\right)^{1/2}\mu_1\langle p_T\rangle^2}$$

$$\sqrt{\langle z^2\rangle} \simeq \sqrt{\left(N_s\frac{S_1}{S_n}\right)^{1/2}\langle p_T\rangle_1^2 - 2\left(N_s\frac{r_0}{R_p}\right)^{1/4}\langle p_T\rangle_1\langle p_T\rangle + \langle p_T\rangle^2}$$

- And finally we get the EbE $\langle p_T\rangle$ fluctuation as:

$$F_{p_T} = \sqrt{\frac{N_s\langle p_T\rangle_1^2\mu_1 - 2N_s^{3/4}\left(\frac{S_n}{S_1}\right)^{\frac{1}{4}}\langle p_T\rangle_1\langle p_T\rangle\mu_1 + \left(N_s\frac{S_n}{S_1}\right)^{\frac{1}{2}}\mu_1\langle p_T\rangle^2}{\left(N_s\frac{S_1}{S_n}\right)^{\frac{1}{2}}\langle p_T\rangle_1^2 - 2\left(N_s\frac{S1}{S_n}\right)^{\frac{1}{4}}\langle p_T\rangle_1\langle p_T\rangle + \langle p_T\rangle^2}} - 1$$

Finding the critical parameters

- In general, for comparing with experimental data we first need to make a fit on the minimum bias transverse momentum distributions using:

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

- Then we fit again with the values of the parameter to the transverse momentum distributions by multiplicty class using:

$$\frac{1}{N}\frac{d^2N}{d\eta dp_T} = \frac{a\left(p_0\sqrt{\frac{F(\zeta_{pp}^t)}{F(\zeta_{AA}^t)}}\right)^{\alpha-2}}{\left[p_0\sqrt{\frac{F(\zeta_{pp}^t)}{F(\zeta_{AA}^t)}}+p_T\right]^\alpha}$$

[4] I. Bautista, A. F. Téllez and P. Ghosh, Phys. Rev.D **92** (2015) no.7, 071504

- For *PbPb* collisions we took data from [5] to get a set of data given by centrality class.
- The $F(\zeta^t)$ is taken from [6]:

$$\frac{1}{N_A}\frac{dN}{d\eta}_{AA} = \kappa F(\zeta^t_{pp}) N^s_{pp}\left(1 + \frac{F(\zeta^t_{N_A})}{F(\zeta^t_{pp})}(N_A^{\alpha(\sqrt{s})} - 1)\right)$$

- With: $\kappa F(\zeta^t_{pp}) N^s_{pp} = \dfrac{dN}{d\eta}_{pp}$
- And: $\alpha(\sqrt{s}) = \dfrac{1}{3}\left(1 - \dfrac{1}{1 + \ln(\sqrt{s/s_0} + 1)}\right)$

[5] B. Abelev *et al.* [ALICE Collaboration], Phys. Rev. C **88** (2013) no.4, 044909

[6] I. Bautista, J. G. Milhano, C. Pajares and J. Dias de Deus, Phys. Lett. B 715 (2012)

- Thus having $F(\zeta^t)$ as:

$$F(\zeta^t_{N_A}) = \frac{\left[\frac{\left(\frac{1}{N_A}\frac{dN}{d\eta}_{AA}\right)}{\left(\frac{dN}{d\eta}_{pp}\right)} - 1\right]}{(N_A^{\alpha(\sqrt{s})} - 1)} F(\zeta^t_{pp})$$

- And by solving numerically the equation:

$$F(\zeta^t_{N_A}) = \sqrt{\frac{1 - e^{-\zeta^t_{N_A}}}{\zeta^t_{N_A}}}$$

$\zeta^t_{N_A}$ is known.

[6] I. Bautista, J. G. Milhano, C. Pajares and J. Dias de Deus, Phys. Lett. B 715 (2012)

- The area of a cluster is given by:

$$S_{N_A} = \pi R_p^2 A^{2/3} \left(\frac{N_A}{A} \right)^{\beta}$$

- And thus:

$$\frac{S_{N_A}}{S_1} = \left(\frac{R_p}{r_0} \right)^2 A^{2/3} \left(\frac{N_A}{A} \right)^{\beta}$$

- The number of strings is given by:

$$N^s_{N_A} = N^s_{pp} N_A^{1+\alpha(\sqrt{s})}$$

[6] I. Bautista, J. G. Milhano, C. Pajares and J. Dias de Deus, Phys. Lett. B 715 (2012)

- As shown before:

$$\langle p_T \rangle \propto \frac{1}{F(\zeta^t_{N_A})}$$

- Thus:

$$\langle p_T \rangle = \frac{k}{F(\zeta^t_{N A})}$$

- With k a proportionality constant given by:

$$k = \langle p_T \rangle_{data} F(\zeta^t_{N_A})$$

- With $\langle p_T \rangle_{data}$ taken from [7]

[7]P. Pujahari [ALICE Collaboration], PoS ICPAQGP 2015 (2017) 032.

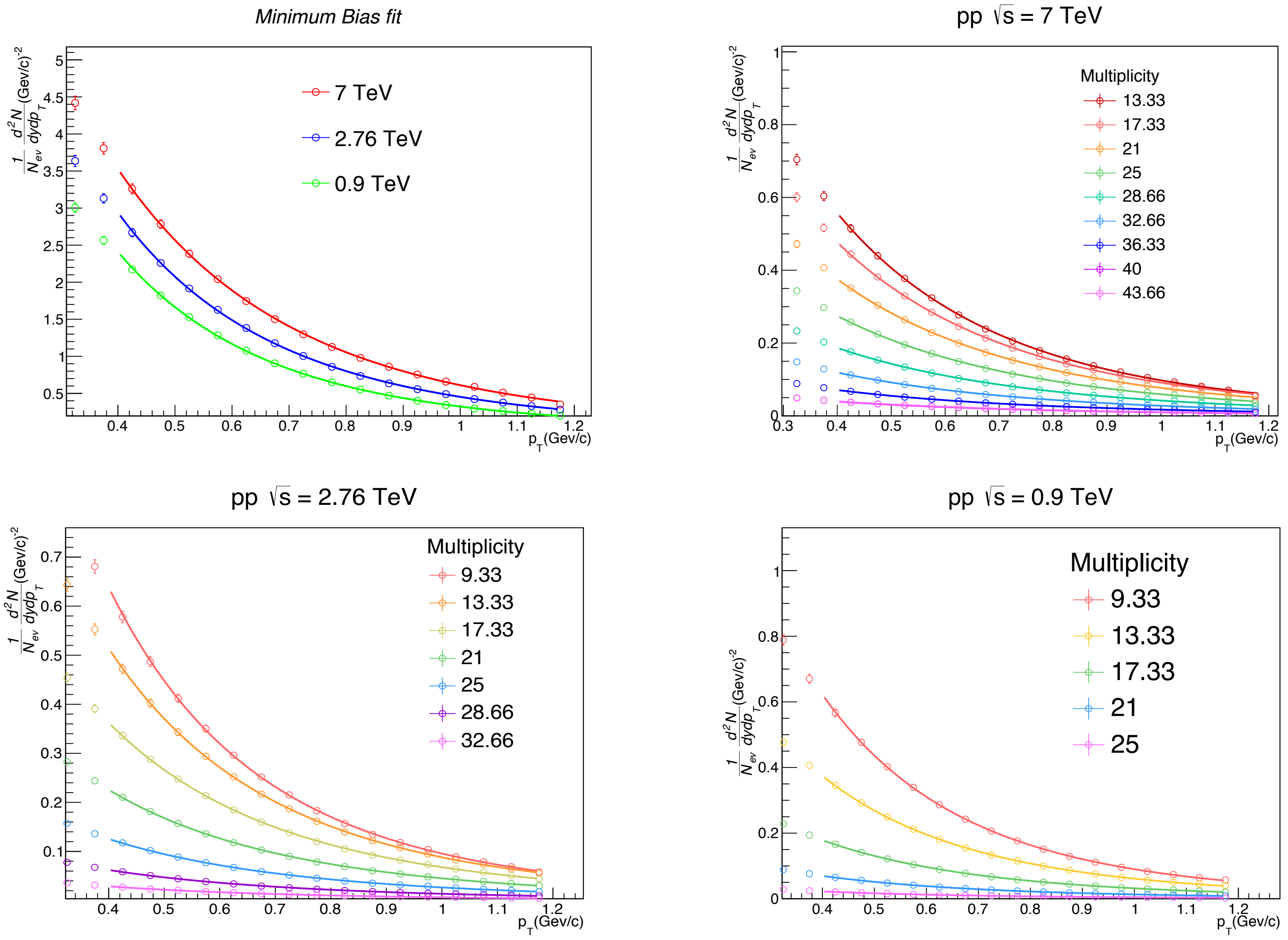
- Now we can calculate F_{p_T} for *PbPb* collisions as:

$$F_{p_T}^{AA} = \sqrt{\frac{N^s_{N_A}\langle p_T\rangle_1^2\mu_1 - 2{N^s_{N_A}}^{\frac{3}{4}}\left(\frac{S_{N_A}}{S_1}\right)^{\frac{1}{4}}\langle p_T\rangle_1\langle p_T\rangle\mu_1 + \left(N^s_{N_A}\frac{S_{N_A}}{S_1}\right)^{\frac{1}{2}}\mu_1\langle p_T\rangle^2}{\left(N^s_{N_A}\frac{S_1}{S_{N_A}}\right)^{\frac{1}{2}}\langle p_T\rangle_1^2 - 2\left(N^s_{N_A}\frac{S_1}{S_{N_A}}\right)^{\frac{1}{4}}\langle p_T\rangle_1\langle p_T\rangle + \langle p_T\rangle^2}} - 1$$

- For pp collisions we fit:

$$\frac{1}{N}\frac{d^2N}{d\eta dp_T}=\frac{a\left(p_0\sqrt{\frac{F(\zeta^t_{pp})}{F(\zeta^t_{HM})}}\right)^{\alpha-2}}{\left[p_0\sqrt{\frac{F(\zeta^t_{pp})}{F(\zeta^t_{HM})}}+p_T\right]^{\alpha}}$$

- Taking the string density for high multiplicity ζ^t_{HM} for pp instead of the string density for nuclear collisions ζ^t_{AA}.
- For we llok to calculate the color reduction factor por pp collisions by multiplicity class $F(\zeta^t_{pp})$.



- Fits [4] on the p_T distributions [8] on *pp* collisions at √s = 0.9, 2.76, 7 TeV

[4] I. Bautista, A. F. Téllez and P. Ghosh, Phys. Rev.D **92** (2015) no.7, 071504

[8] S. Chatrchyan *et al.* [CMS Collaboration], Eur. Phys. J. C **72** (2012) 2164

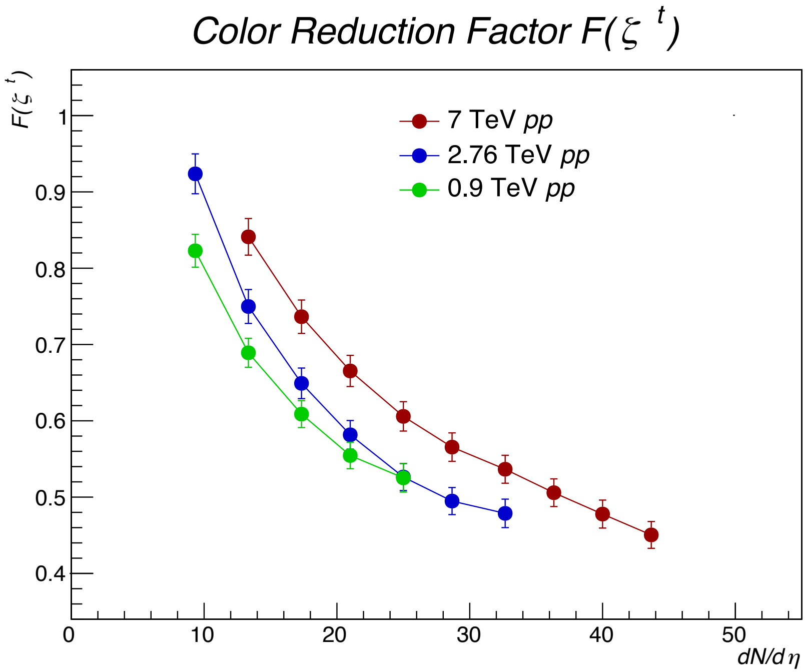
	$\sqrt{s}$(TeV)	a	p_0	α
pp	7	33.12±9.30	2.32±0.88	9.78±2.53
	2.76	22.48±4.20	1.54±0.46	7.94±1.41
	0.9	23.29±4.48	1.82±0.54	9.40±1.80

We can calculate the $\langle p_T \rangle$ and plot it, same with the color reduction factor.

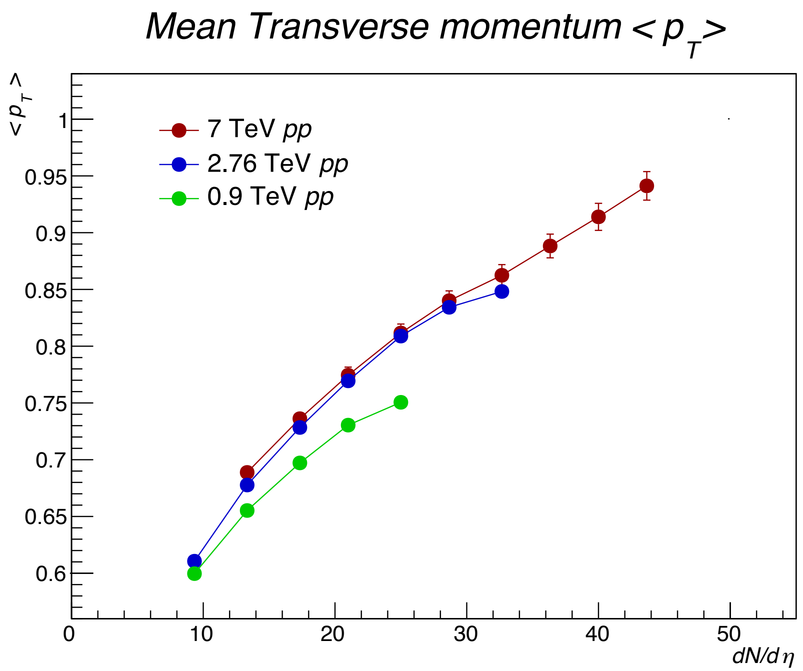
$$\langle p_T \rangle \simeq \frac{2p_0}{(\alpha - 3)} \sqrt{\frac{F(\zeta^t_{pp})}{F(\zeta^t_{HM})}}$$

[4] I. Bautista, A. F. Téllez and P. Ghosh, Phys. Rev.D **92** (2015) no.7, 071504

[8] S. Chatrchyan *et al.* [CMS Collaboration], Eur. Phys. J. C **72** (2012) 2164



Color Reduction Factor $F(\zeta^t)$



Mean Transverse momentum $<p_T>$

- Color reduction factor $F(\zeta^t)$ and $\langle p_T \rangle$ by multiplicity class with data from [5] and reported in [4].

[4] I. Bautista, A. F. Téllez and P. Ghosh, Phys. Rev.D **92** (2015) no.7, 071504

[8] S. Chatrchyan *et al.* [CMS Collaboration], Eur. Phys. J. C **72** (2012) 2164

- As seen before, the string density depends on centrality, thus for *pp* collisions we most propose an *effective centrality*
- ϵ is given by: $\zeta^t = \epsilon \left(\frac{r_0}{R_p} \right)^2 N_s^{max}$

$$\epsilon = \frac{\zeta^t}{\zeta^t_{max}}$$

- And the number of strings by:

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

- With these aproximation we can write the EbE $\langle p_T \rangle$ fluctuations for *pp* collisions as:

$$F_{p_T}^{pp} = \sqrt{\frac{N_s \langle p_T \rangle_1^2 \mu_1 - 2N_s^{3/4} \epsilon^{-1/4} \left(\frac{R_p}{r_0}\right)^{1/2} \langle p_T \rangle_1 \langle p_T \rangle + N_s^{1/2} \epsilon^{-1/2} \left(\frac{R_p}{r_0}\right) \mu_1 \langle p_T \rangle^2}{N_s^{1/2} \epsilon^{1/2} \left(\frac{r_0}{R_p}\right) \langle p_T \rangle_1^2 - 2N_s^{1/4} \epsilon^{1/4} \left(\frac{r_0}{R_p}\right)^{1/2} \langle p_T \rangle_1 \langle p_T \rangle + \langle p_T \rangle^2}} - 1$$

- However, in order to compare with the experimental data, we need to calculate the same quantity that was measured in [1], thus come the two particle correlator for multiplicity class.

$$C_m = \frac{1}{\sum_{k=1}^{n_{ev,m}} N_{acc,k}} \sum_{k=1}^{n_{ev,m}} \sum_{i=1}^{N_{acc,k}} \sum_{j=i+1}^{N_{acc,k}} (p_{T,i} - M(p_T)_m) \cdot (p_{T,j} - M(p_T)_m)$$

- That quantifies the dynamical fluctuations in units of the mean transverse momentum.
- With:

$$M(p_T)_m = \frac{1}{\sum_{k=1}^{n_{ev,m}} N_{acc,k}} \sum_{k=1}^{n_{ev,m}} \sum_{i=1}^{N_{acc,k}} p_{T,i}$$

[1] S. T. Heckel [ALICE Collaboration],Phys. Rept. **599** (2015) 1.

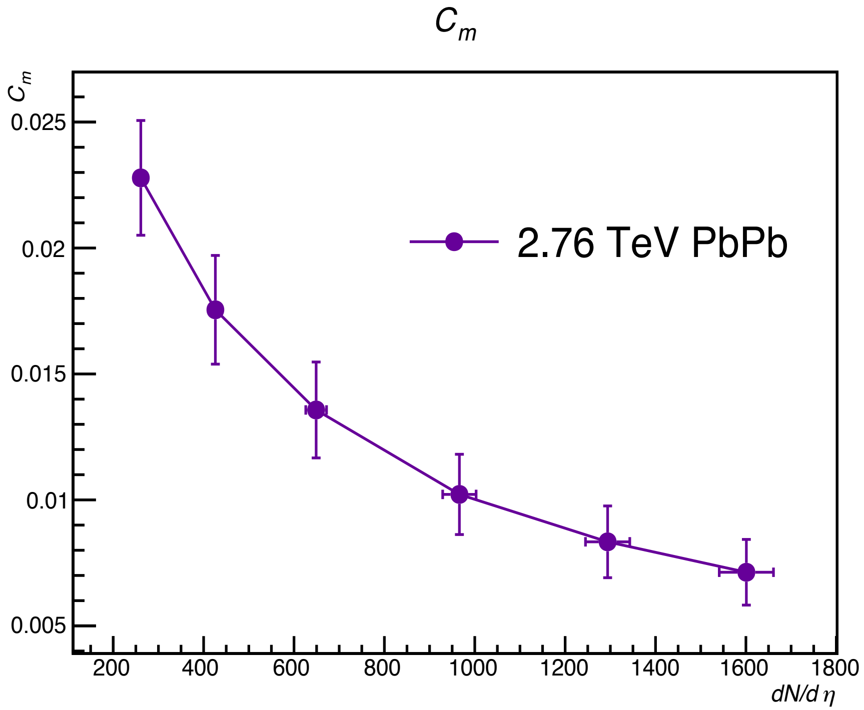
- In [1] the EbE $\langle p_T \rangle$ fluctuations are reported as that supresses statistical uncertanties:

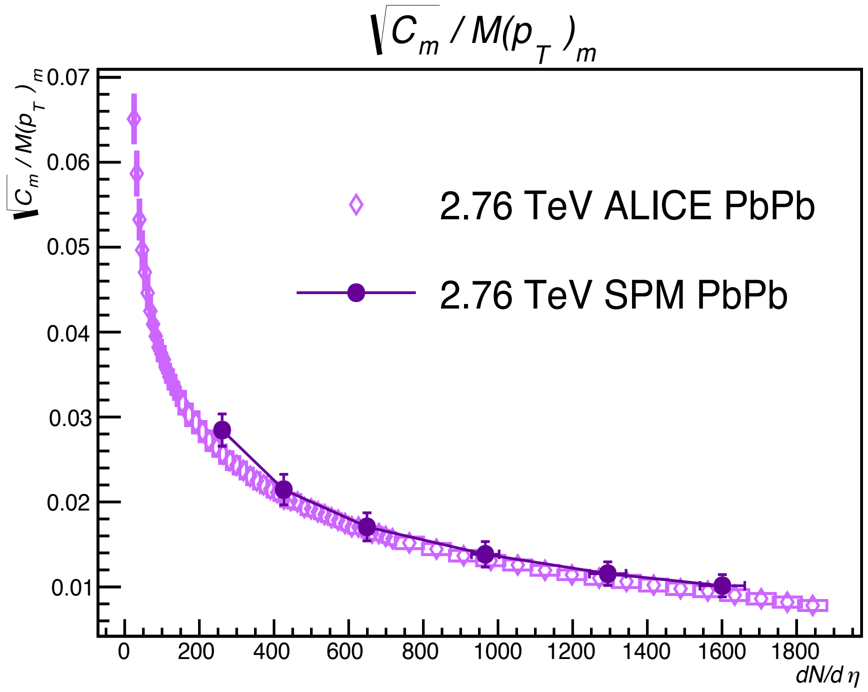
$$\sqrt{C_m}/M(p_T)_m$$

- However C_m relates with F_{p_T} as:

$$\langle \Delta p_{Ti}, \Delta p_{Tj} \rangle = C_m \simeq 2F_{p_T} \frac{var(p_T)}{\langle N \rangle}$$

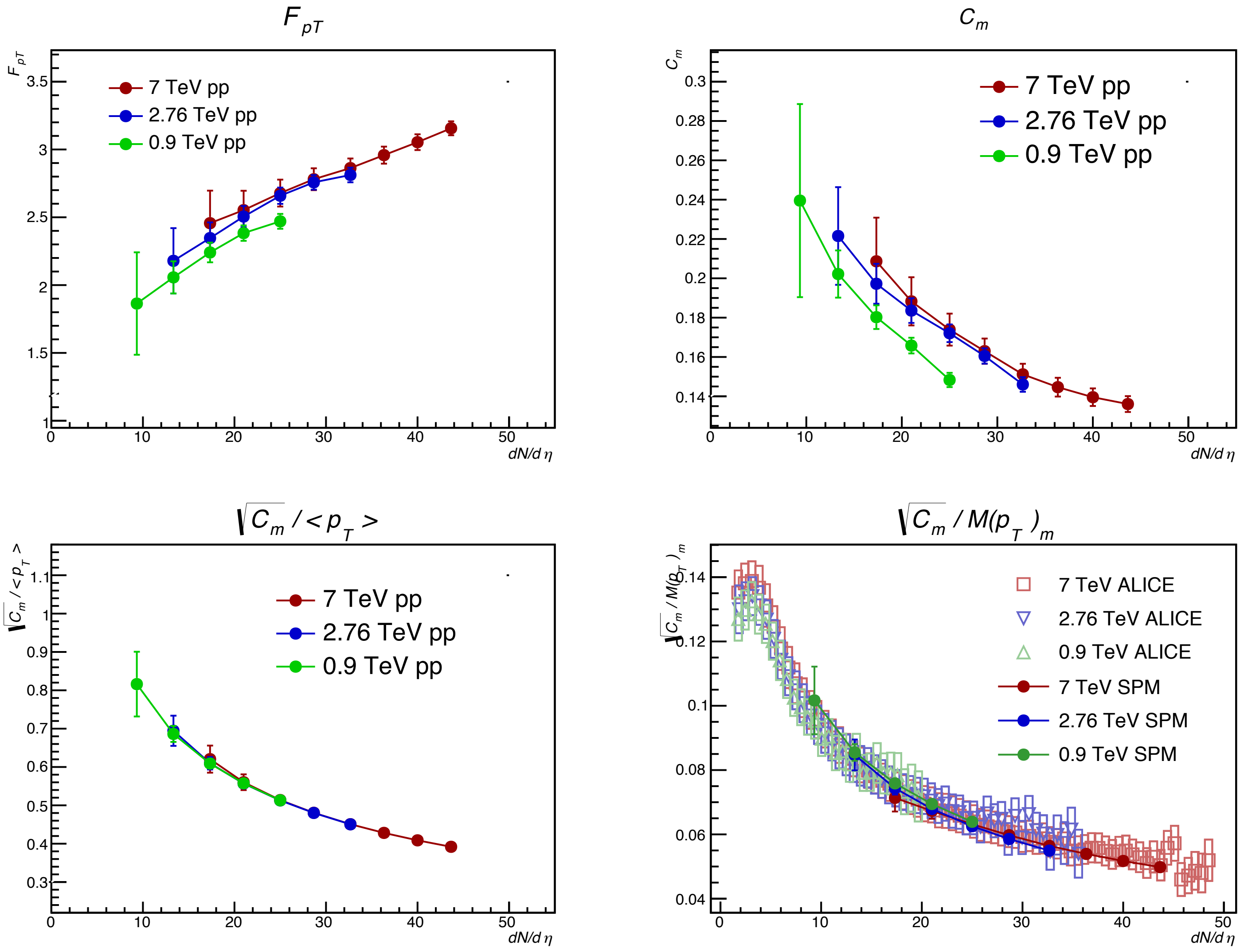
[1] S. T. Heckel [ALICE Collaboration],Phys. Rept. **599** (2015) 1.





- C_m for *PbPb* with data from [5] and $\sqrt{C_m}/M(p_T)_m$ measured and reported in [1] compared with our calculation.

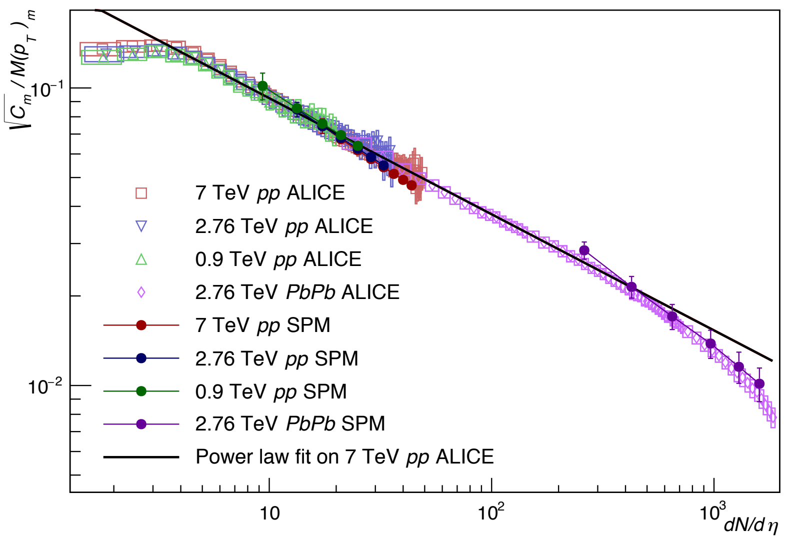
[1] S. T. Heckel [ALICE Collaboration],Phys. Rept. **599** (2015) 1.
[6] B. Abelev *et al.* [ALICE Collaboration], Phys. Rev. C **88** (2013) no.4, 044909

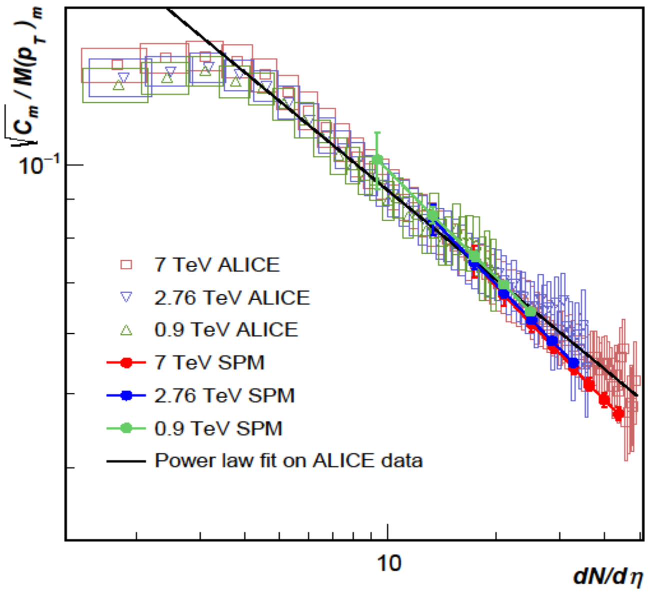


- $F_{p_T}^{pp}$, C_m and $\sqrt{C_m}/\langle p_T\rangle$ for *pp* with data from [5] and $\sqrt{C_m}/M(p_T)_m$ measured and reported in [1] compared with our calculation.

[1] S. T. Heckel [ALICE Collaboration],Phys. Rept. **599** (2015) 1.
[5] S. Chatrchyan *et al.* [CMS Collaboration], Eur. Phys. J. C **72** (2012) 2164

Conclusions

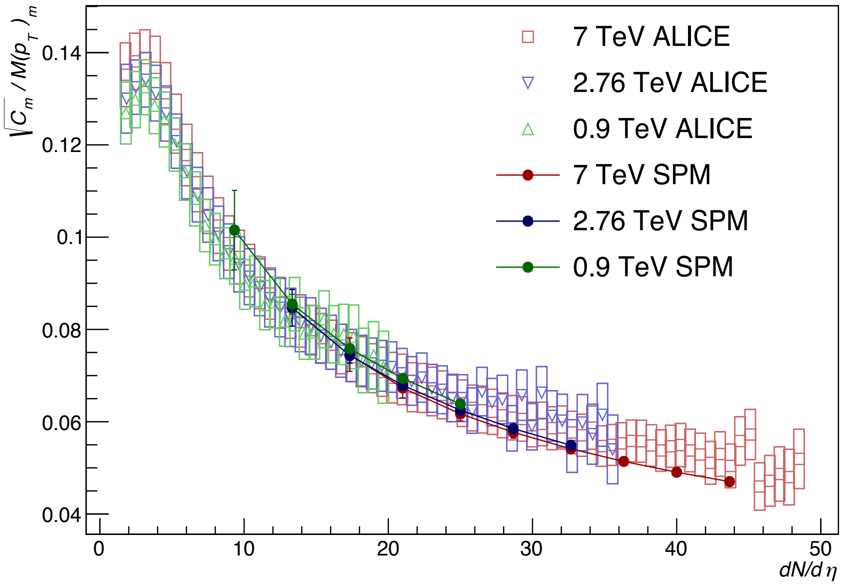


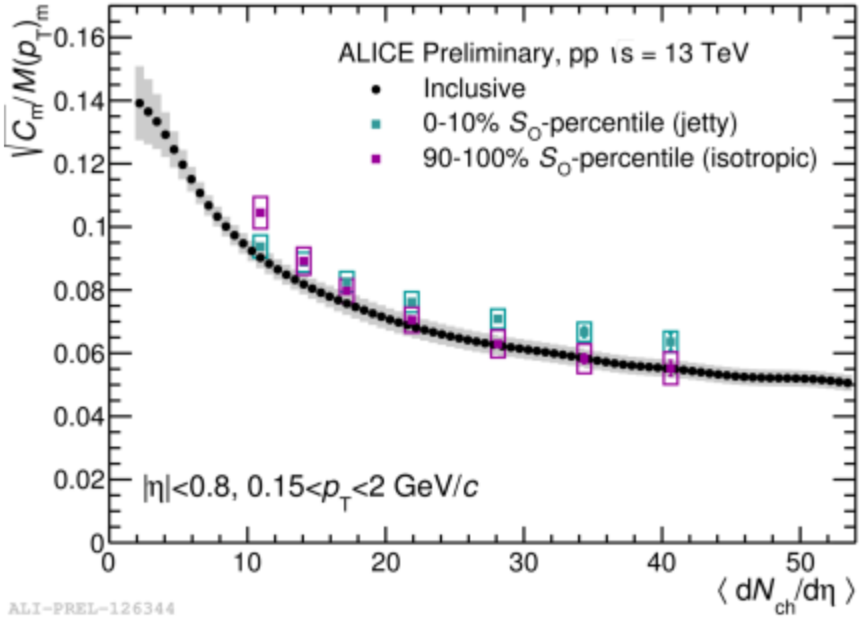


- A slight change of slope suggests the phase transition as seen in [1] (right side). This might be because of the system's size, not all correlations are destroyed and the systems have no time to thermalize.

- Where the power law fitted to 7 TeV pp ALICE is $f(x) = ax^b$ with *a* = 2.26 and b = -3.9 and b = -4.1 for the fit on 7 TeV SPM

[1] S. T. Heckel [ALICE Collaboration],Phys. Rept. **599** (2015) 1.





- Moreover we can see the SPM is in agreement with experimental results without jet bias (see Irais talk).

[1] S. T. Heckel [ALICE Collaboration],Phys. Rept. **599** (2015) 1.
[9] Quark Matter 2017 preliminar.

Thank you!