

*Event by event  
mean  $p_T$   
fluctuations from  
small to large  
systems with  
percolation color  
sources*



**KKFM**

**\*Pablo Fierro**  
Irais Bautista  
Cristal Robles

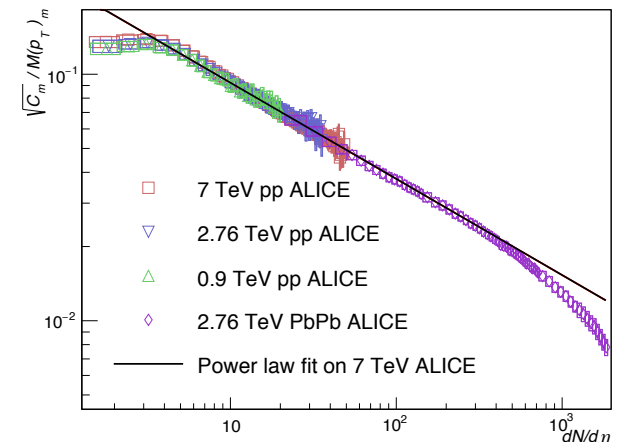
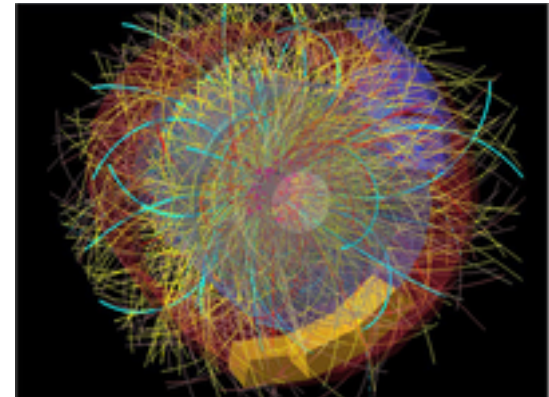


3 al 4 de Noviembre del 2017  
Hotel Colonial, Puebla. Mexico

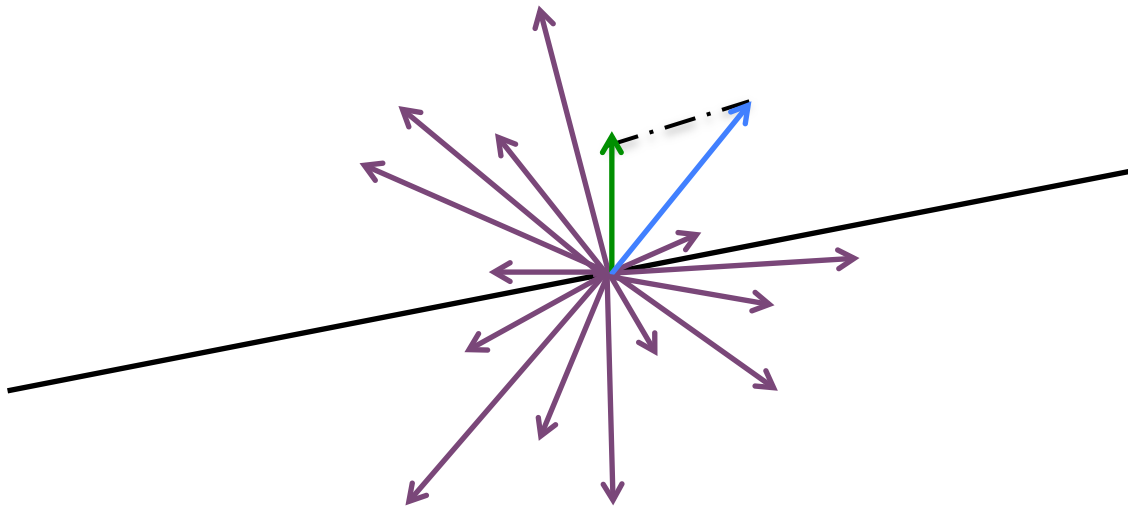
**4ta Reunion Anual**

# 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.

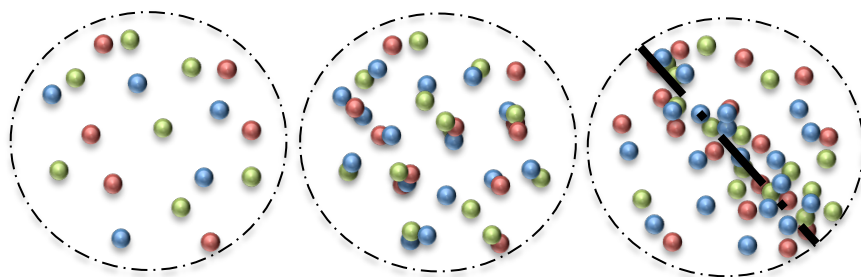
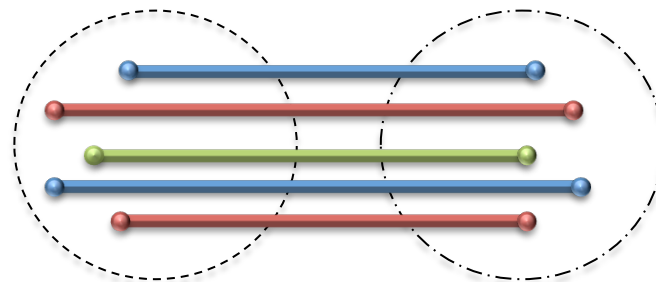


- Dynamical fluctuations of the  $\langle p_T \rangle$  increases by many kinds of correlations of the  $\langle p_T \rangle$  of the final states of the generated particles (resonance decays, jets, etc.).



# 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. Ferreira, 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.

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

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

[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

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

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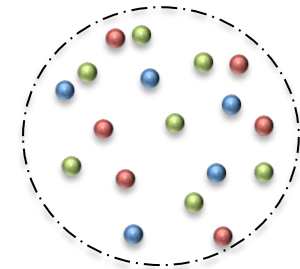
- Are measured with: 
$$F_{p_T} = \frac{\omega_{data} - \omega_{random}}{\omega_{random}}$$

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

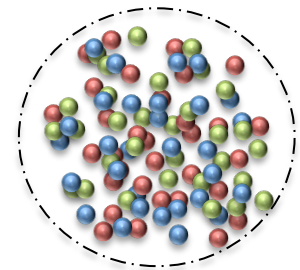
- $F_{p_T}$  measures the fluctuations as a function of the number of participants in heavy ion collisions.

- We can understand E<sub>bE</sub>  $\langle p_T \rangle$  fluctuations as following:

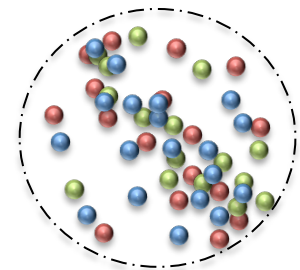
- At low  $\zeta^t$  we have very little fluctuations



- Over critical  $\zeta^t$  we have no fluctuations



- Below critical  $\zeta^t$  fluctuations are maximal



- 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:

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



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

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

- And thus, we can write:

$$\frac{\langle Z^2 \rangle}{\langle \mu \rangle} = \frac{\sum_{i=1}^{N_{ev}} \left[ \sum_j \left( \frac{n_j S_j}{S_1} \right)^{1/2} \mu_1 \left[ \left( \frac{n_j S_1}{S_{nj}} \right)^{1/4} \langle p_T \rangle_1 - \langle p_T \rangle \right] \right]^2}{\left[ \sum_{i=1}^{N_{ev}} \sum_j \left( \frac{n_j S_{nj}}{S_1} \right)^{1/2} \mu_1 \right]^2}$$

$$\langle z^2 \rangle = \frac{\sum_{i=1}^{N_{ev}} \sum_j \left( \frac{n_j S_{nj}}{S_1} \right)^{1/2} \mu_1 \left[ \left( \frac{n_j S_1}{S_{nj}} \right)^{1/4} \langle p_T \rangle_1 - \langle p_T \rangle \right]^2}{\sum_{i=1}^{N_{ev}} \sum_j \left( \frac{n_j S_{nj}}{S_1} \right)^{1/2} \mu_1}$$

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

# *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:

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

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

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

- 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]:

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

- With:

$$\alpha(\sqrt{s}) = \frac{1}{3} \left( 1 - \frac{1}{1 + \ln(\sqrt{s/s_0} + 1)} \right)$$

[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)

- As shown before:

$$\langle p_T \rangle \propto \frac{1}{F(\zeta_{N_A}^t)}$$

- Thus:

$$\langle p_T \rangle = \frac{k}{F(\zeta_{N_A}^t)}$$

- With  $k$  a proportionality constant given by:

$$k = \langle p_T \rangle_{data} F(\zeta_{N_A}^t)$$

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

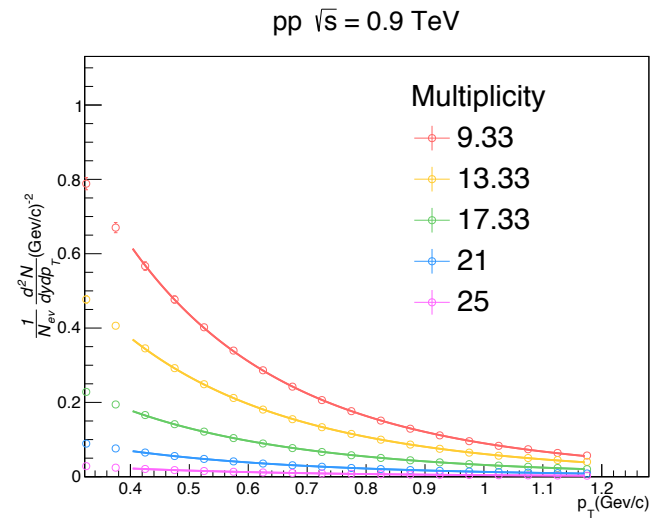
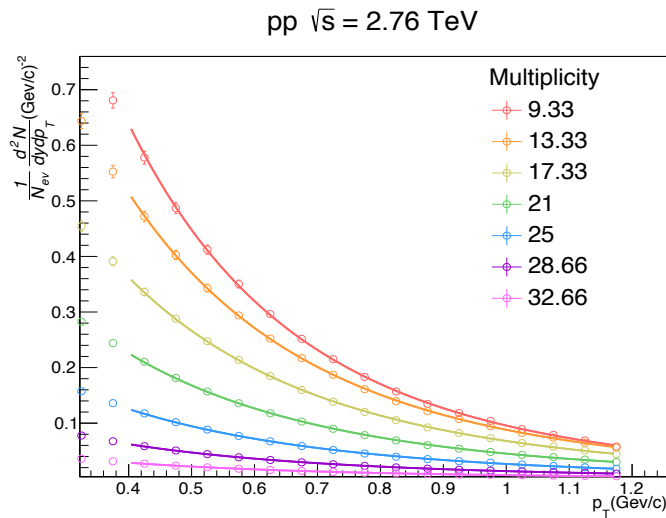
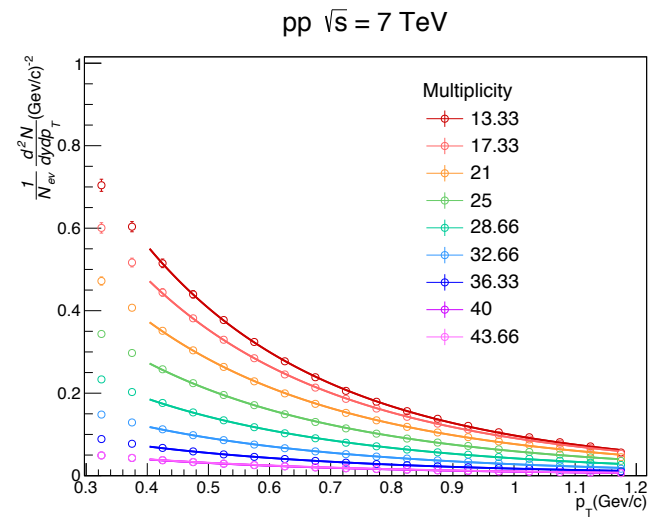
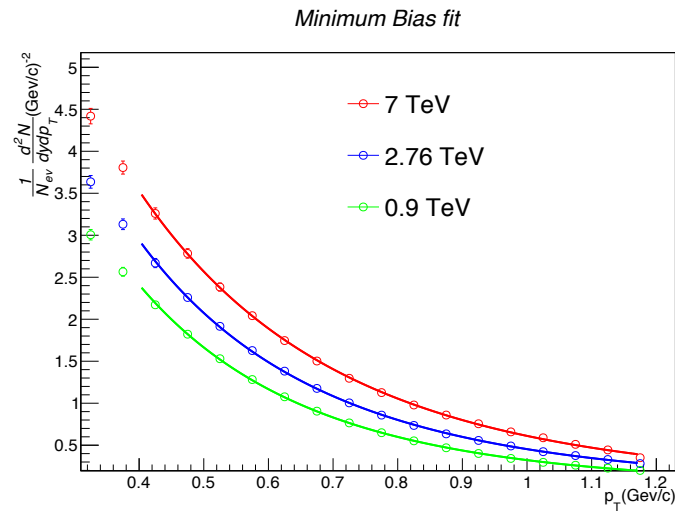
- Now we can calculate  $F_{p_T}$  for  $PbPb$  collisions as:

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

- For pp collisions we fit:

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

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



- Fits [4] on the  $p_T$  distributions [8] on  $pp$  collisions at  $\sqrt{s} = 0.9, 2.76, 7$  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

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

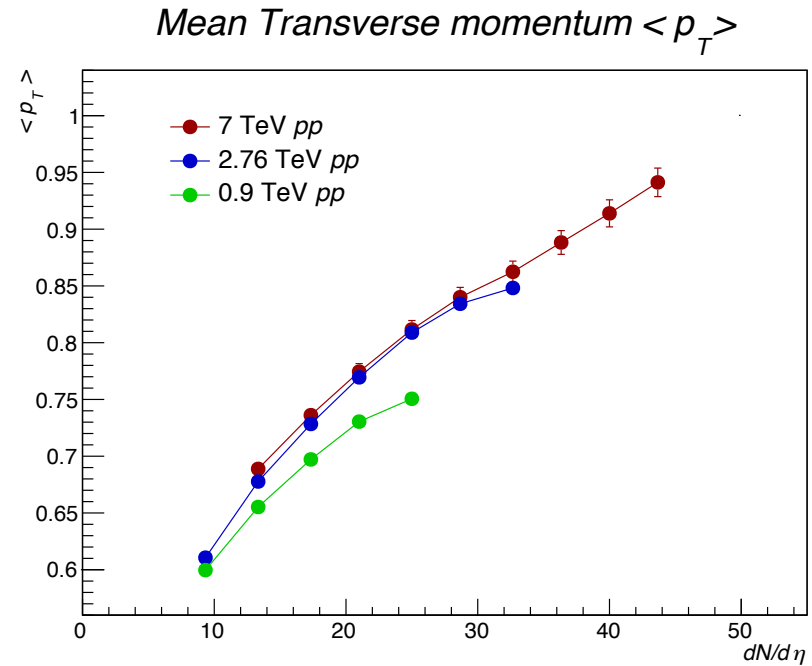
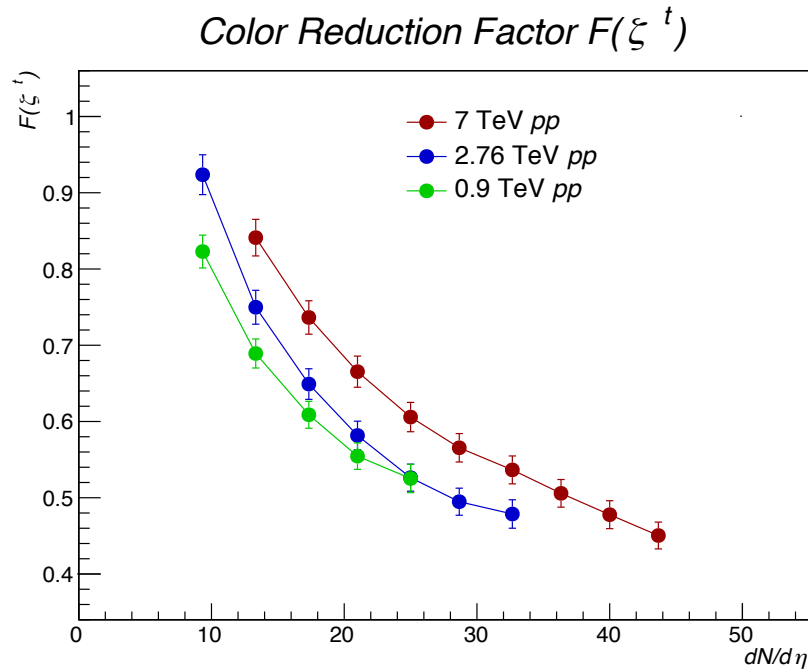
We can calculate the  $\langle p_T \rangle$  and plot it, same with the color reduction factor.

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

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

- As seen before, the string density depends on centrality, thus for  $pp$  collisions we must propose an *effective centrality*

- is given by: 
$$\zeta^t = \epsilon \left( \frac{r_0}{R_p} \right)^2 N_s^{max}$$

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

- 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 approximations we can write the  $E_b E$  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.

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

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

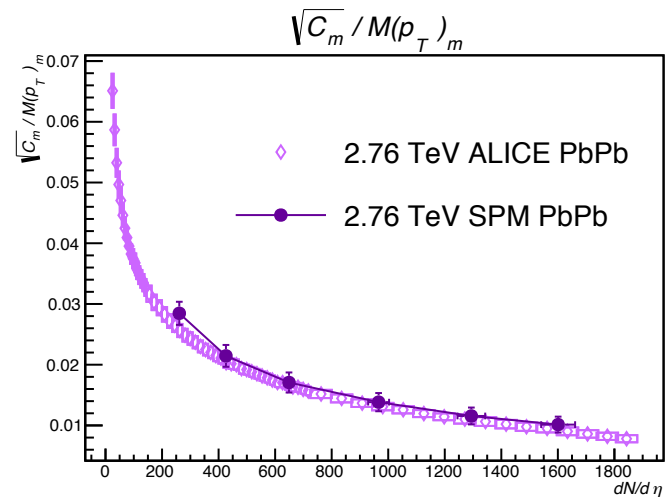
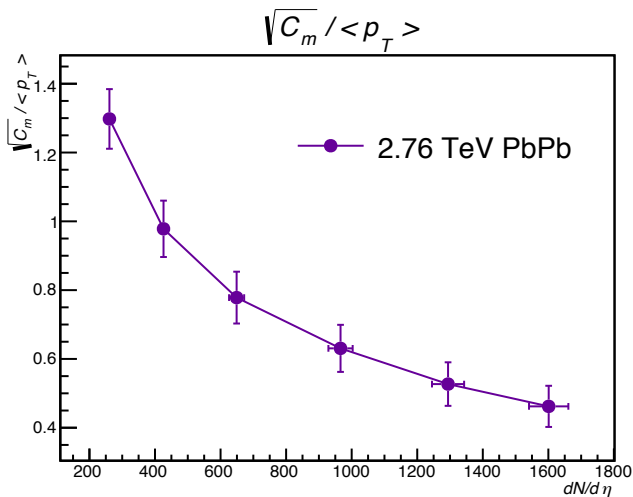
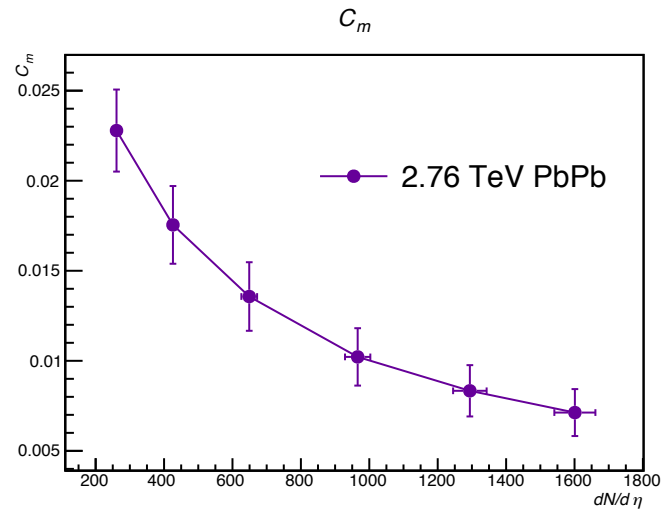
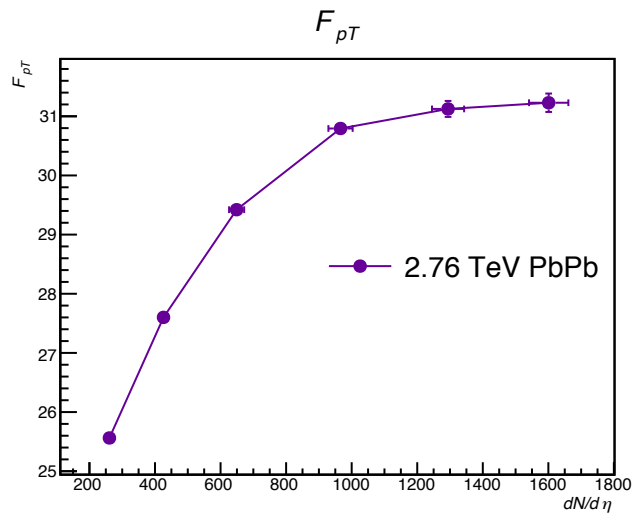
$$M(p_T)_m = \frac{1}{\sum_{k=1}^{n_{ev,m}} N_{acc,k}} \sum_{k=1}^{n_{ev,m}} \sum_{i=1}^{N_{acc,k}} p_{T,i}$$

- In [1] the  $\text{EbE}\langle p_T \rangle$  fluctuations are reported as that suppresses statistical uncertainties:

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

- However  $C_m$  relates with  $F_{p_T}$  as:

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

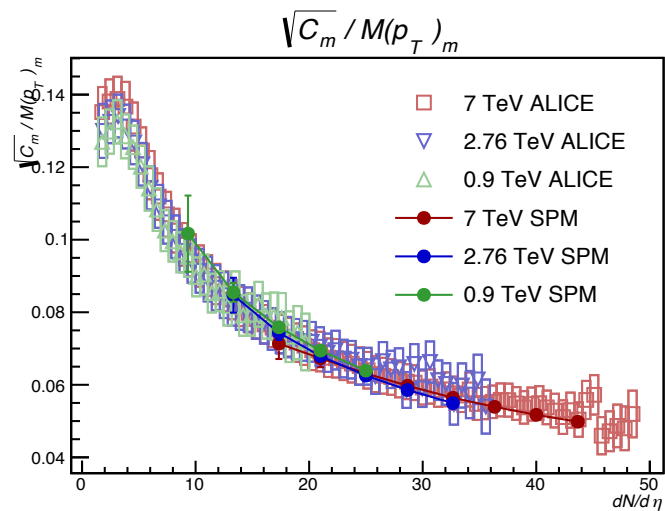
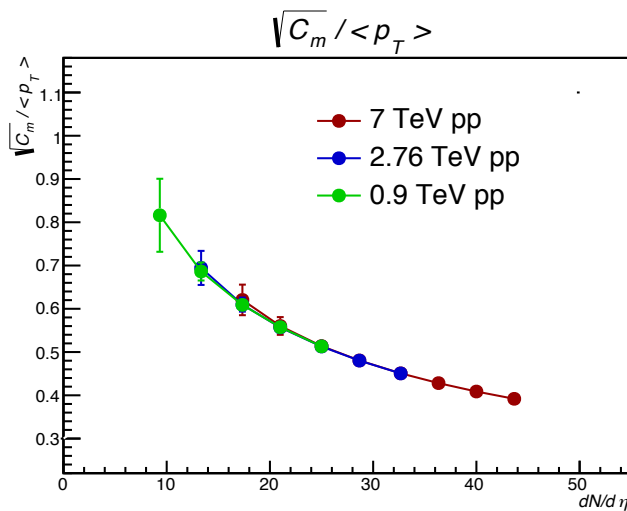
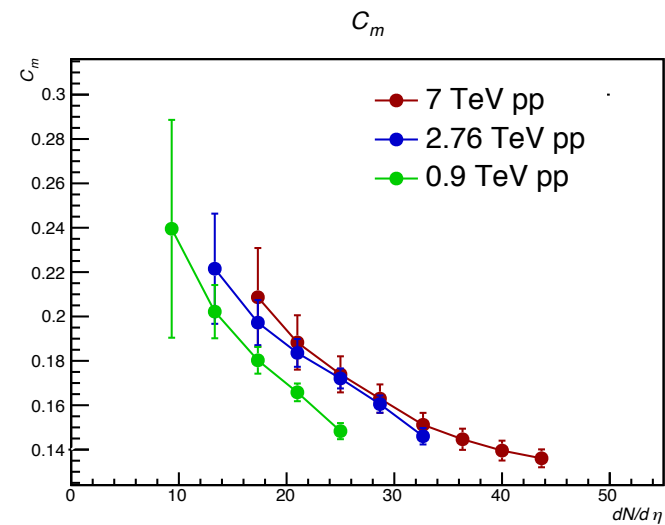
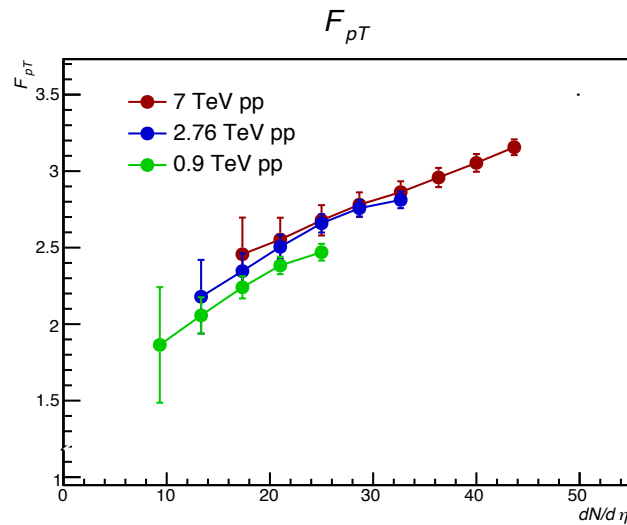


- $F_{pT}^{AA}$ ,  $C_m$  and  $\sqrt{C_m} / \langle p_T \rangle$  for PbPb with data from [5] and reported in [1] compared with our calculation.

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

[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

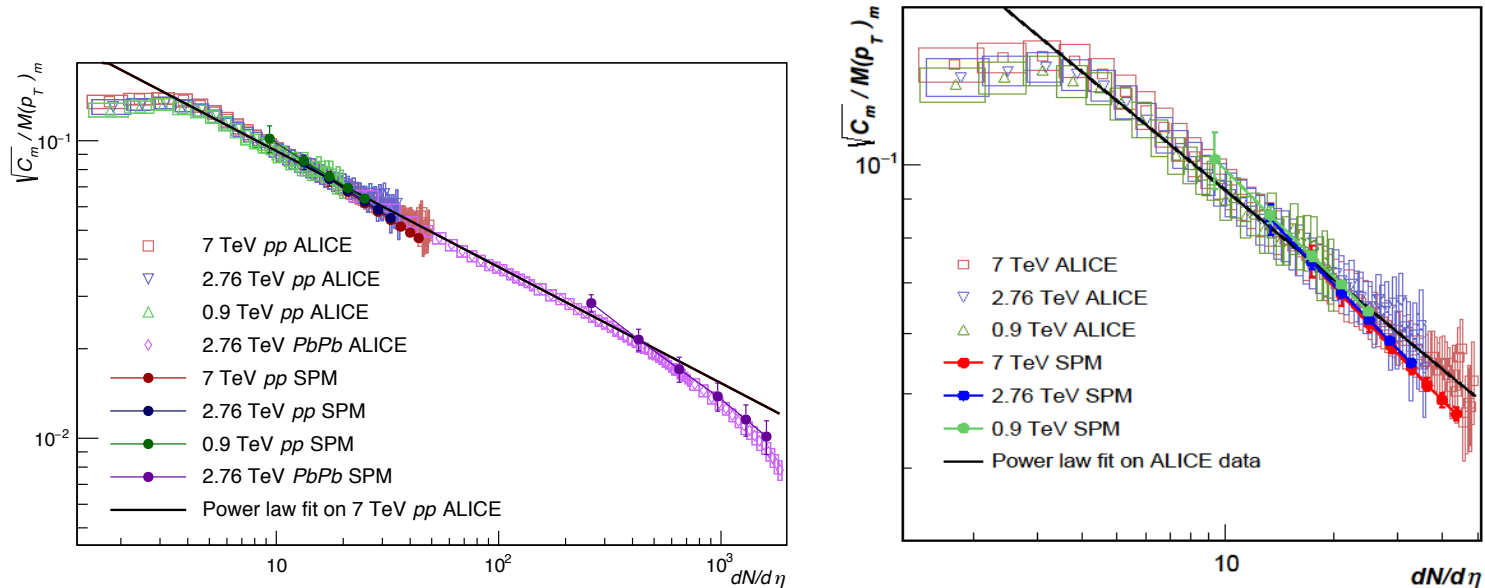


- $F_{pT}^{pp}$ ,  $C_m$  and  $\sqrt{C_m / \langle p_T \rangle}$  for pp with data from [5] and  $\sqrt{C_m / M(p_T)_m}$  measured and reported in [1] compared with our calculation.

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

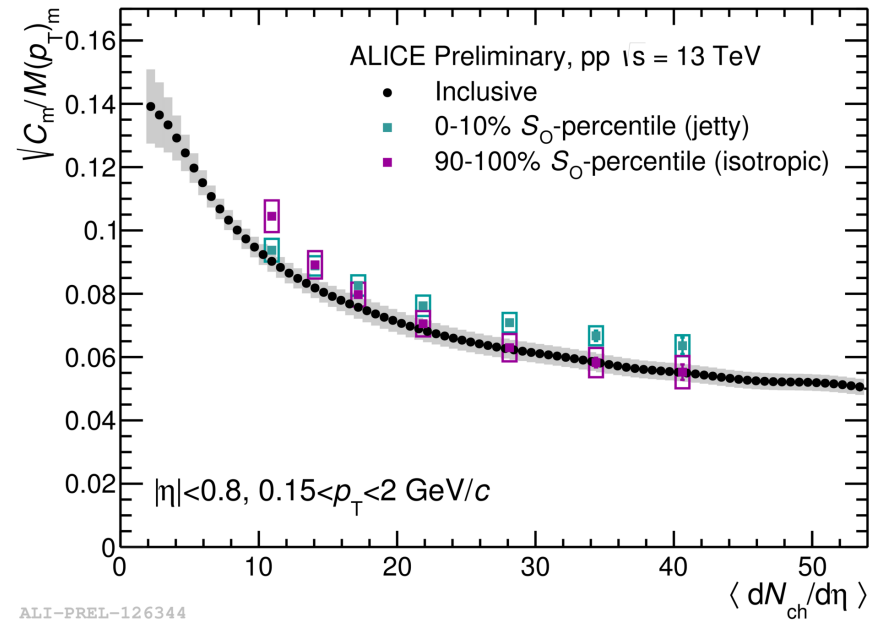
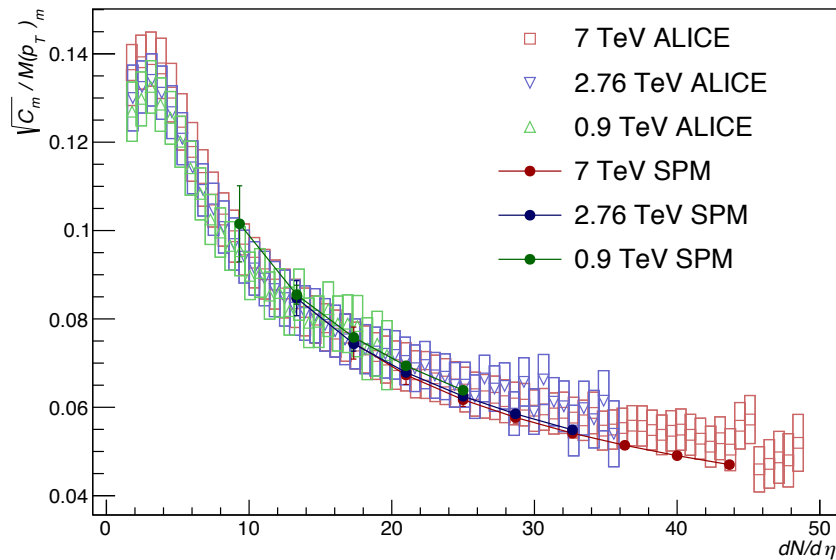
[5] S. Chatrchyan *et al.* [CMS Collaboration], Eur. Phys. J. C **72** (2012) 2164

# 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  $b = -3.9$  and  $b = -4.1$  for the fit on 7 TeV SPM





- 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!