Effects of initial state fluctuations on non-equilibrium phase transition on pp collisions at LHC energies

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in collaboration with

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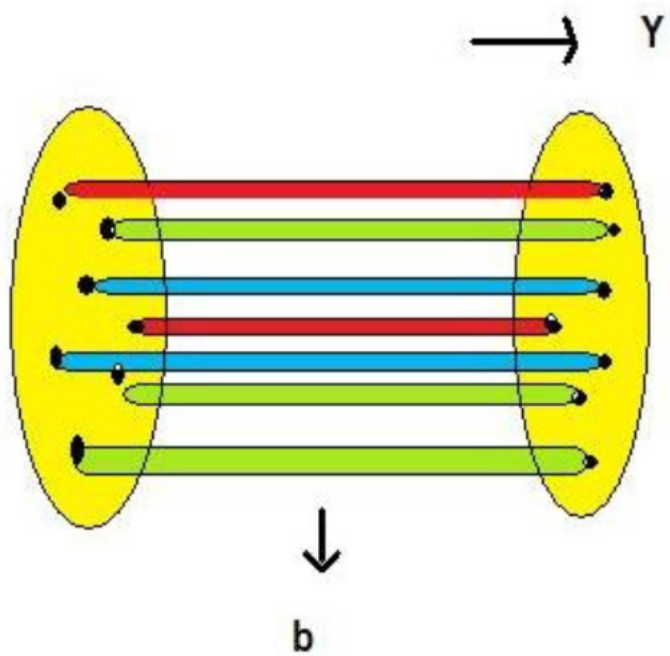
pp collisions

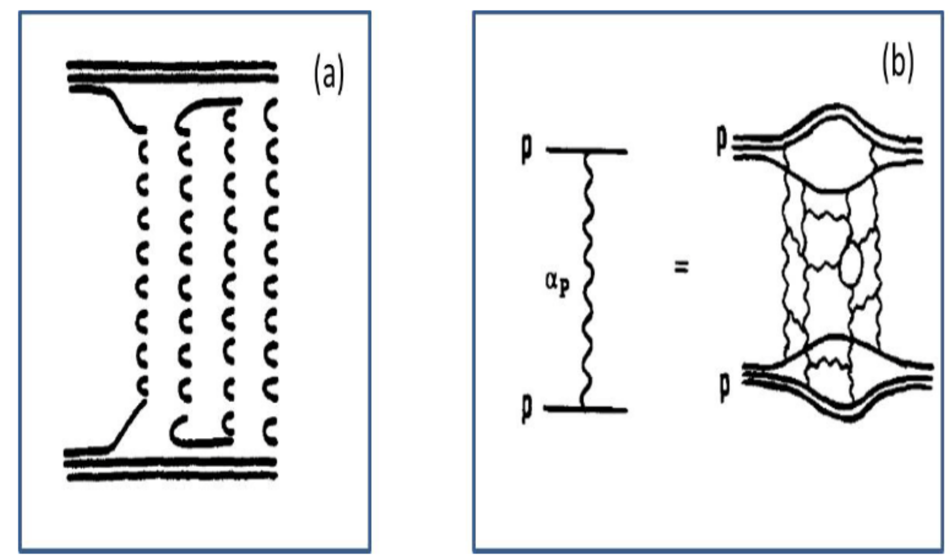
- In small systems, the finite-size and fluctuation effects become relevant
- Fast expansion and cooling with a lifetime of a few fm/c.

- T. S. Biro, G. G. Barnafoldi, G. Biro and K. M. Shen, J. Phys. Conf. Ser. 779 (2017) no.1, 012081
- G. Bíró, G. G. Barnaföldi, T. S. Biró and K. Ürmössy, AIP Conf. Proc 1853 (2017) 08000
- C. Gale, S. Jeon, and B. Schenke, Int. J. Mod. Phys.
- N. Armesto and E. Scomparin, Eur. Phys. J. Plus 13, 52 (2016)

Color sources

In the transverse impact parameter plane the strings look like small disk where we can apply 2 dimensional percolation theory



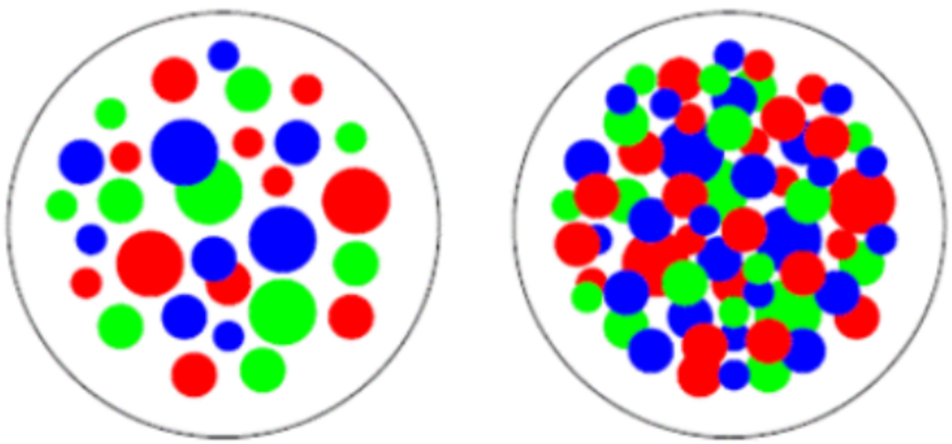


Multi particle production at high energies is currently described in terms of color strings stretched between the projectile and target. These strings decay into new ones by ($q - \bar{q}$) production and subsequently hadronize to produce the observed hadrons.

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

$$S_1 = \pi r_0^2$$

$r_0 \sim 0.25$ fm

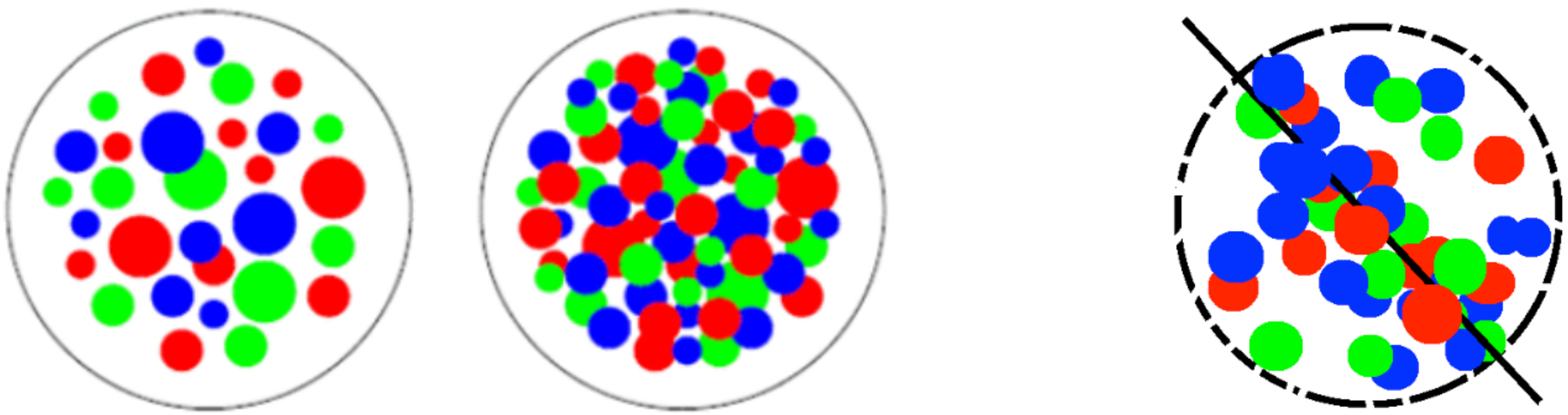


De-confinement is expected when the density of quarks and gluons becomes so high that would overlap strongly.

We have clusters within color is not longer confined : De-confinement is thus related to cluster formation very much similar to cluster formation in percolation theory and hence a connection between percolation and de-confinement seems very likely.

Parton String Percolation Model

- At a critical density, a macroscopic cluster appears and mark a geometric phase transition.



- Due to the random sum of the color charges in SU(3) the total color charge decrease the particle multiplicity and gives an increase on the average tension of the strings
- A cluster of n strings that occupies an area Sn behaves as a single color source with a higher color field corresponding to a vectorial sum of color charges of each individual string

$$\vec{Q_n}^2 = n\vec{Q_1}^2 \longrightarrow$$ If strings are fully overlap

$$\vec{Q_n}^2 = n\frac{S_n}{S_1}\vec{Q_1}^2 \longrightarrow$$ Partially overlap

- The extended string between partons decays to new pairs of strings that latter form new partons which eventually hadronize (fragmentation). The particles are produce by the parton interactions via the Schwinger mechanism

Multiplicity and <p_T^2> of particles produced by a cluster of n strings

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

color reduction factor ⟶ $F(\xi) = \sqrt{\frac{1-e^{-\xi}}{\xi}}$

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

string density in pp collisions ⟶ $\xi = N_p^s \left(\frac{r_0}{R_p}\right)^2$

$\lambda = .201$

proton mass

proton radius

M. A. Braun and C. Pajares, Eur. Phys. J. C16,349 (2000)
M. A. Braun et al, Phys. Rev. C65, 024907 (2002)

- 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 one reach the critical density $1 - e^{-\xi}$

- We assume that the cluster behaves like a single string but with higher color field and momentum

- In the large (n) limit the multiplicities and momentum sums:

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

Similar scaling laws are obtained for the product and the ratio of the multiplicities and transverse momentum in CGC

Both provide explanation for multiplicity suppression and $\langle p_T \rangle$ scaling with dN/dy.

Momentum Qs establishes the scale in CGC with the corresponding one in percolation of strings

The no. of color flux tubes in CGC and the effective no. of clusters of strings in percolation have the same dependence on the energy and centrality. (implications in Long range rapidity correlations and the ridge structure).

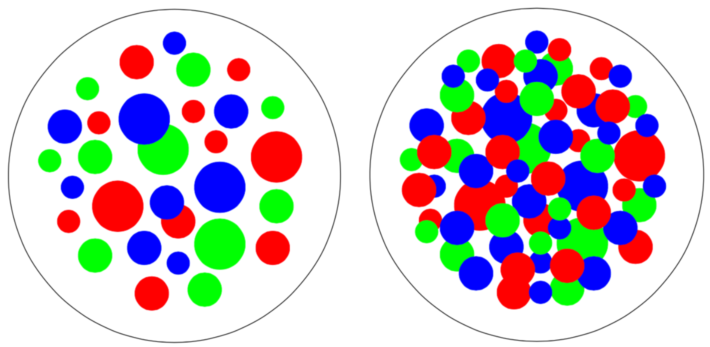
Clustering strings ~gluon saturation

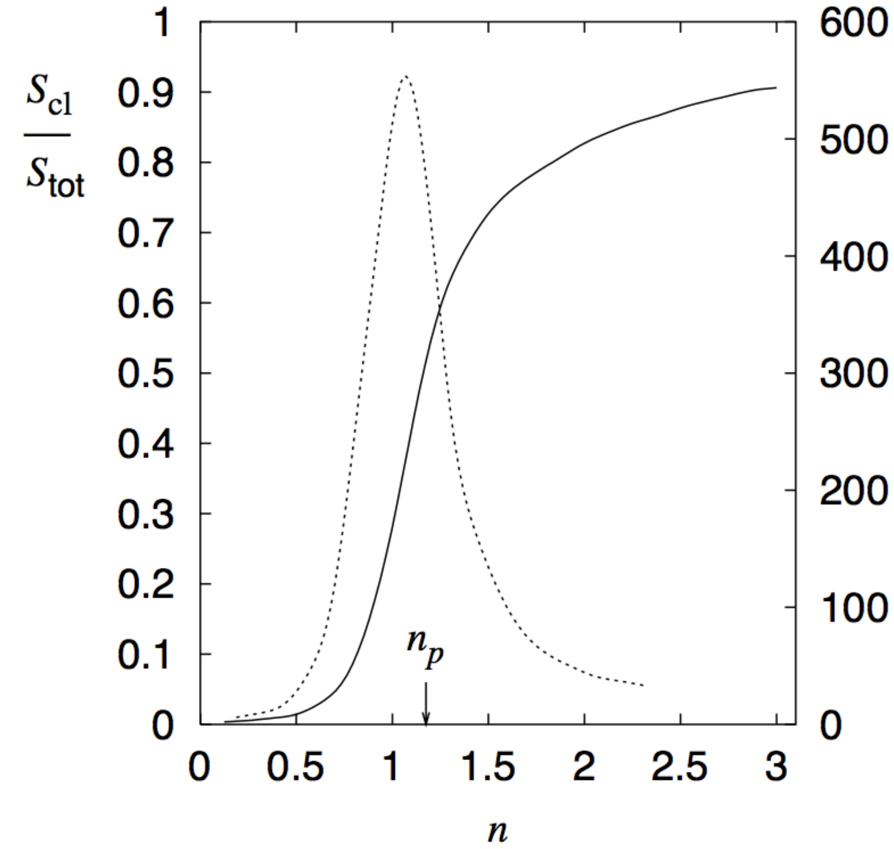
$$Q_s^2 = \frac{k\langle p_T^2 \rangle_1}{F(\xi)}$$

$$Q_s^2 \sim \sqrt{(\xi)}$$

Y. V. Kovchegov, E. Levin, L. McLerran, Phys. Rev. C 63, 024903 (2001).
I. Bautista, J. Dias de Deus, C. Pajares, AIP Conf.Proc. 1343 (2011) 495-497

Monte Carlo



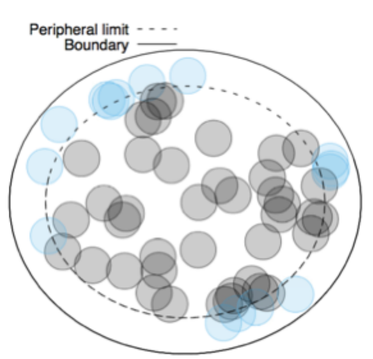


$$\varepsilon = \sqrt{1 - \frac{b^2}{a^2}}$$

$$\eta = \frac{r_0^2 N}{ab}. \qquad a^2 = \frac{r_0^2 N}{\eta\sqrt{1-\varepsilon^2}}; \qquad b^2 = \frac{r_0^2 N\sqrt{1-\varepsilon^2}}{\eta}$$

Once determined a and b, we take a random point (x, y) distributed in the rectangle $[-(a - r_0), a - r_0] \times [-(b - r_0), b - r_0]$ according with a density profile. This point is the center of the string and it is included in the string population if satisfies the following condition

$$\frac{x^2}{(a - r_0)^2} + \frac{y^2}{(b - r_0)^2} \leq 1.$$



Boundary conditions were taken into account to define the spanning closer, we have performed a 10^7 generated positions for each case of profile function.

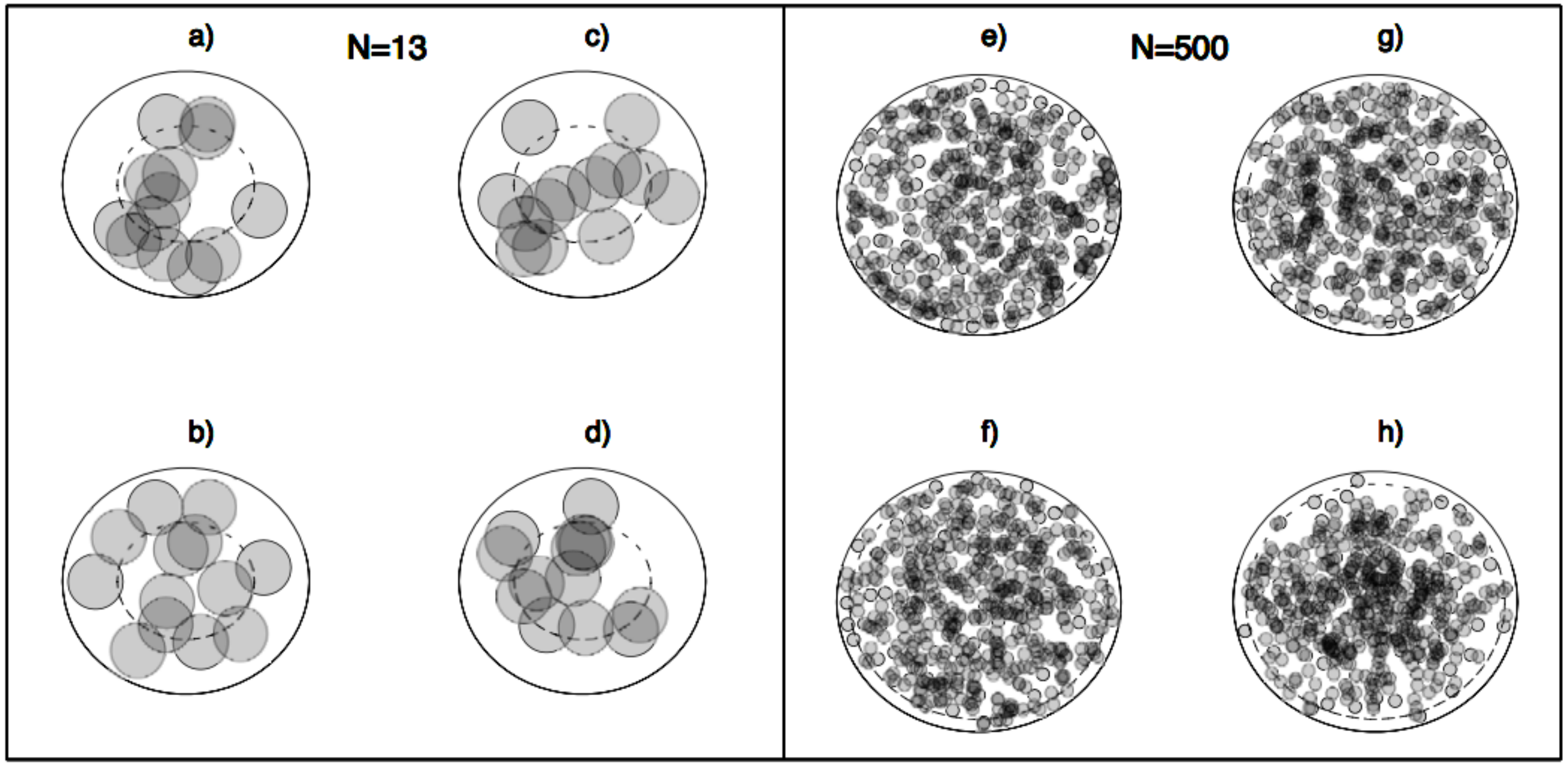
Density Profiles

$$f(x,y) = \frac{1}{2\pi\sigma_a\sigma_b}\exp\left[-\frac{1}{2}\left(\frac{x^2}{\sigma_a^2}+\frac{y^2}{\sigma_b^2}\right)\right]$$

$$\sigma_a = (a - r_0), \quad \sigma_b = (b - r_0);$$
$$\sigma_a = (a - r_0)/2^{1/2}, \quad \sigma_b = (b - r_0)/2^{1/2};$$
$$\sigma_a = (a - r_0)/2, \quad \sigma_b = (b - r_0)/2.$$

σa and σb are standard deviations over the semi-axis of the ellipse

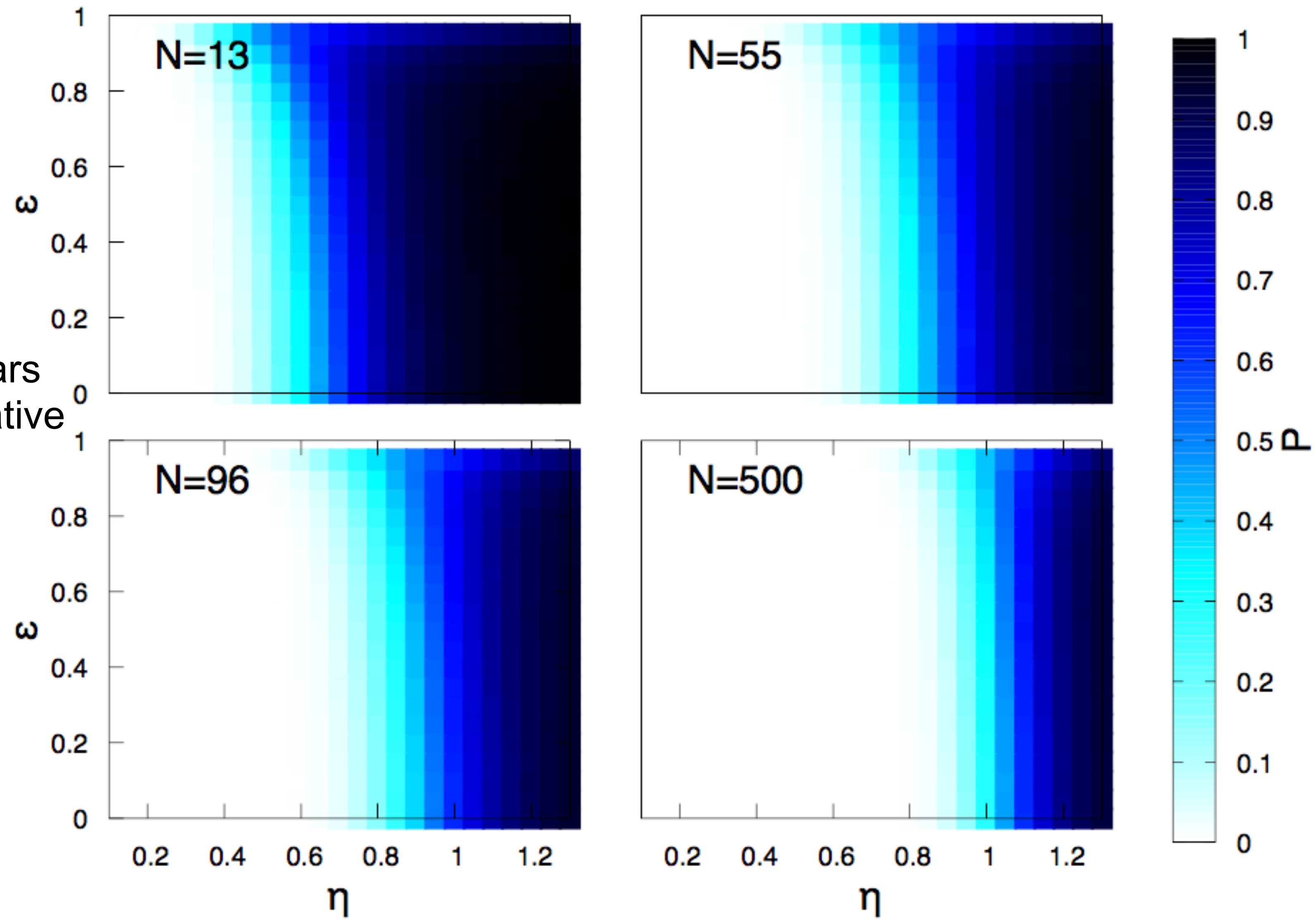
1s, $2^{1/2}$s y 2s



Samples of a percolating system for different density profiles. Left box: String systems at $N = 13$, $\eta = 0.7$ and $\varepsilon = 0.4$, for the models a) Uniform, b) $1s$, c) $2^{1/2}s$ and d) $2s$; Right box: String systems at $N = 500$, $\eta = 1.1$ and $\varepsilon = 0.4$, for the models e) Uniform, f) $1s$, g) $2^{1/2}s$ and h) $2s$.

String percolation threshold for elliptically bounded systems, I. Bautista, A. Fernández. J. E Ramirez, Physica 488 (2017) 8-15.

The percolation threshold appears when the derivative ∂P/∂η takes its maximum value



The percolation probability shows an evident shift as a function of N and high eccentricity dependence associated with a finite size effect.

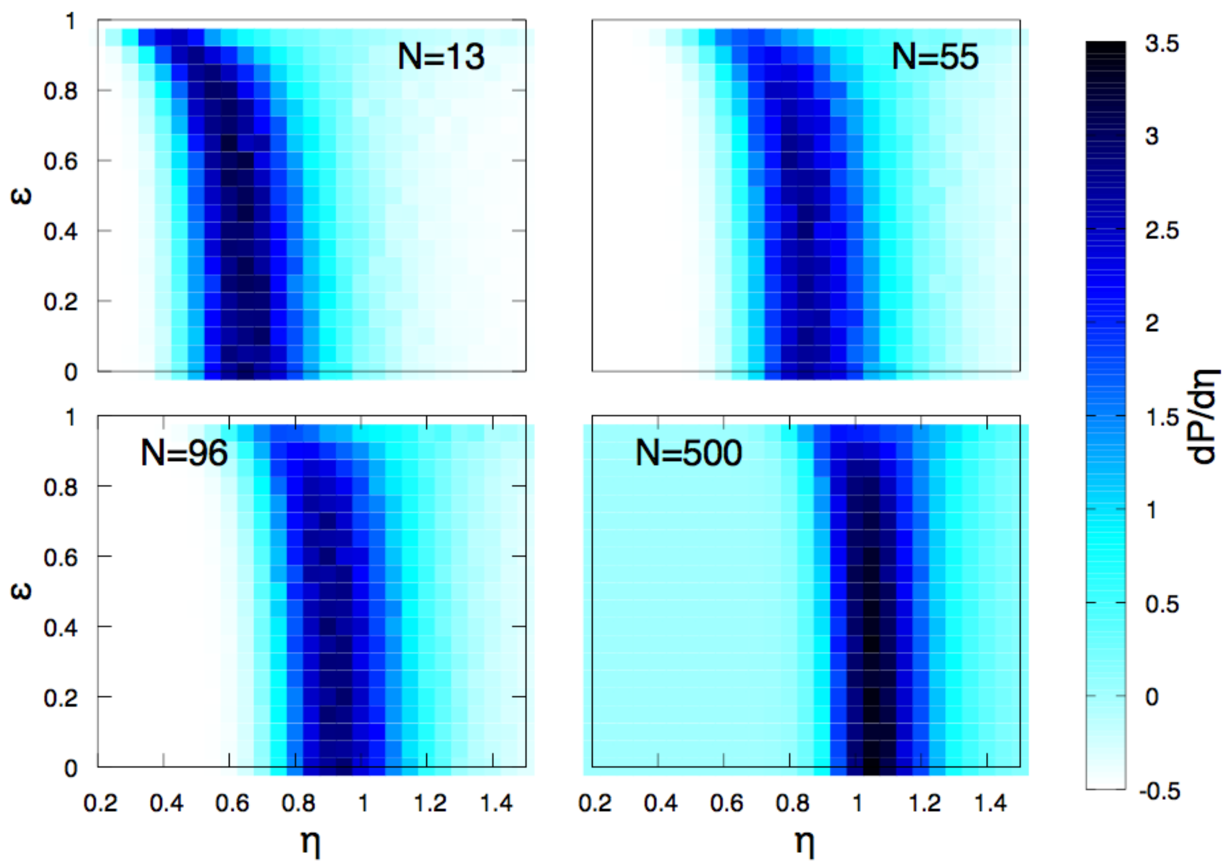
Percolation probability P as a function of filling factor η and eccentricity ε for different values of a number of strings N with Uniform density profile.

For largest values of N, the percolation probability becomes independent of the eccentricity and the phase transition appears around the percolation threshold for the continuum percolation in the thermodynamic limit.

String percolation threshold for elliptically bounded systems, I. Bautista, A. Fernández. J. E Ramirez, Physica 488 (2017) 8-15.

$$P(\eta) = \frac{1}{1 + \exp\left(-\sum_{k=0}^{4} a_k \eta^k\right)}$$

the fraction of occupied/connected sites belonging to the spanning cluster



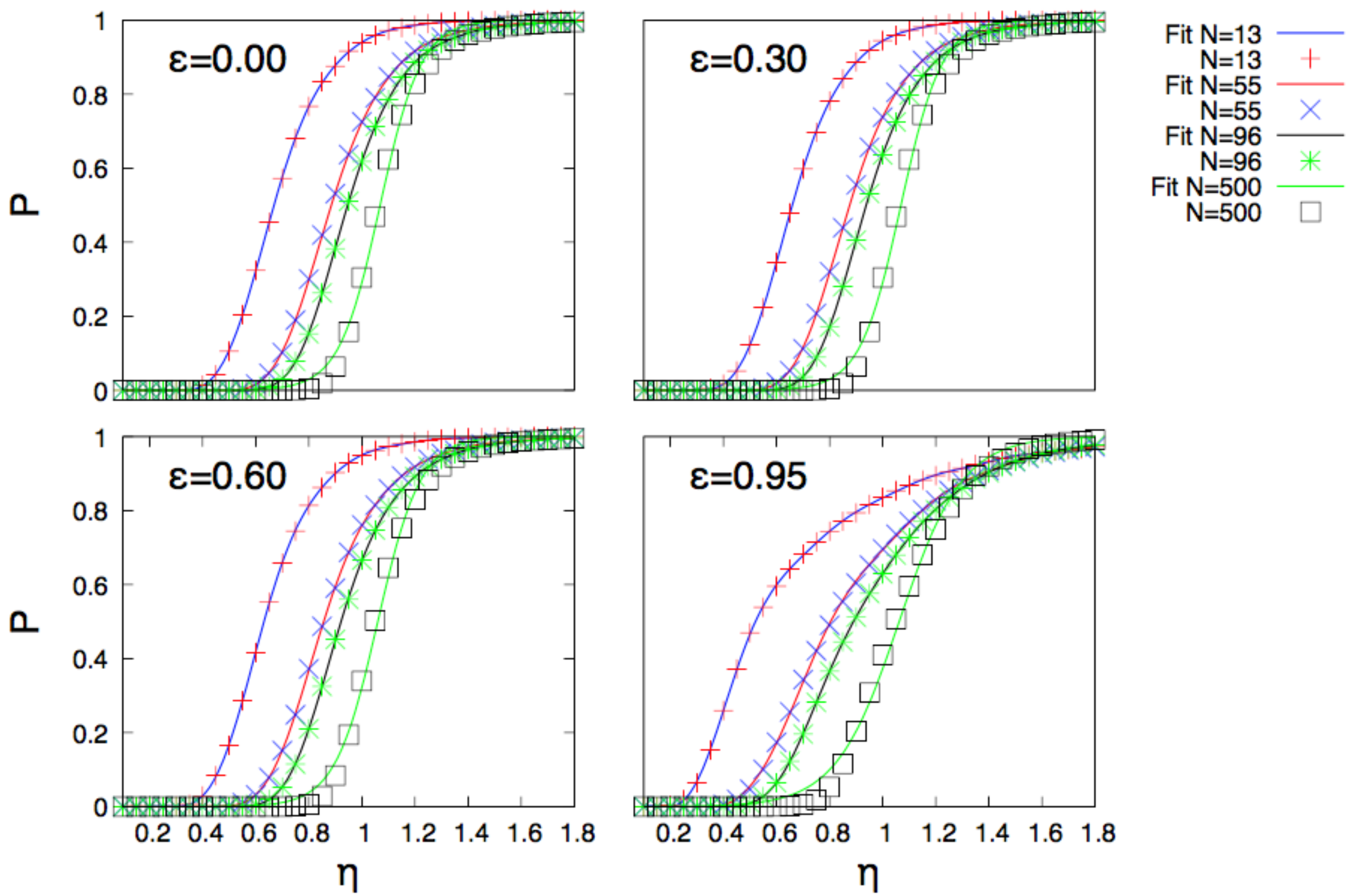
A derivative of the percolation probability with respect to filling factor η in the Uniform model.

To obtain the value of η_c, the equation $P(\eta_c) = 0.5$ has to be solved. However, for N = 500 and the model with Gaussian density profiles, we use

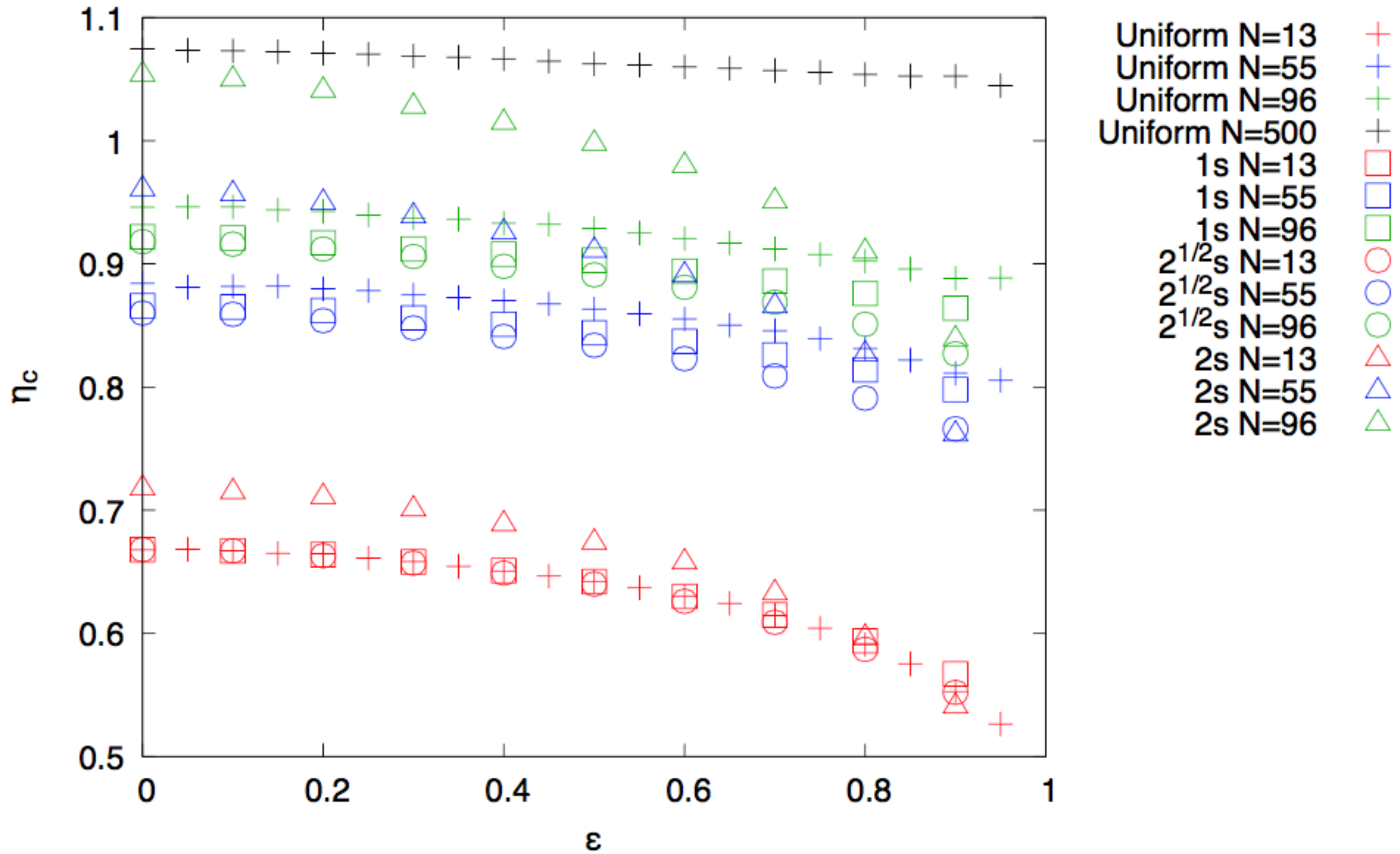
$$P(\eta) = \frac{1}{2}\left[1 + \tanh\left(\frac{\eta - \eta_c}{\Delta L}\right)\right]$$

where η_c is the percolation threshold and ΔL is the width of the percolation transition. In Fig. 7, we show the best fit obtained for the percolation probability as a function of filling factor for different values of η and N in string percolating systems with Uniform density profile

String percolation threshold for elliptically bounded systems, I. Bautista, A. Fernández. J. E Ramirez, Physica 488 (2017) 8-15.



String percolation threshold for elliptically bounded systems, I. Bautista, A. Fernández. J. E Ramirez, Physica 488 (2017) 8-15.

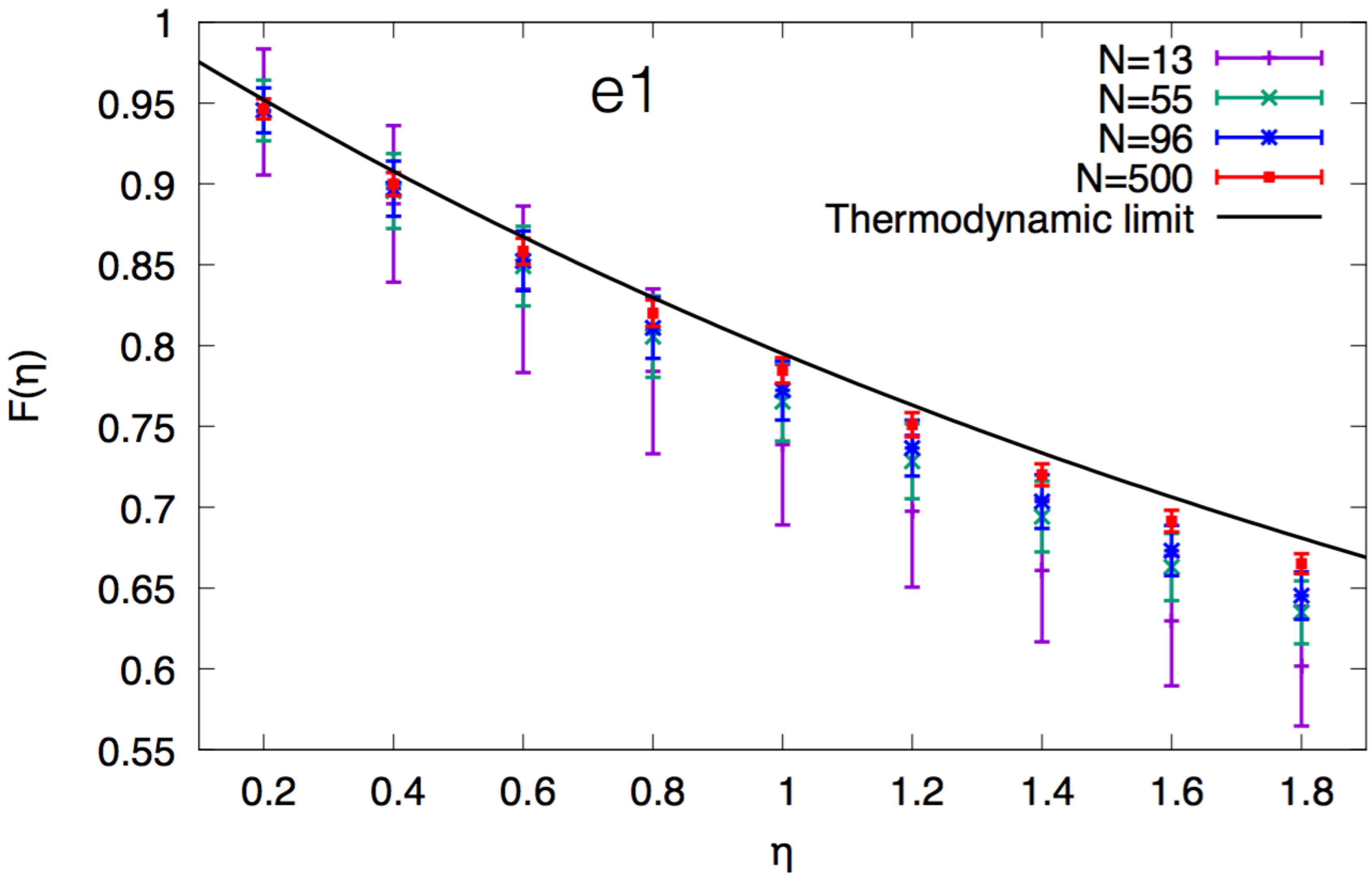


Percolation threshold η_c as a function of eccentricity (ε) for different values of N with the different density profiles: Uniform (crosses), and Gaussian: $1s$ (squares), $2^{1/2}s$ (circles) and $2s$ (triangles).

String percolation threshold for elliptically bounded systems, I. Bautista, A. Fernández. J. E Ramirez, Physica 488 (2017) 8-15.

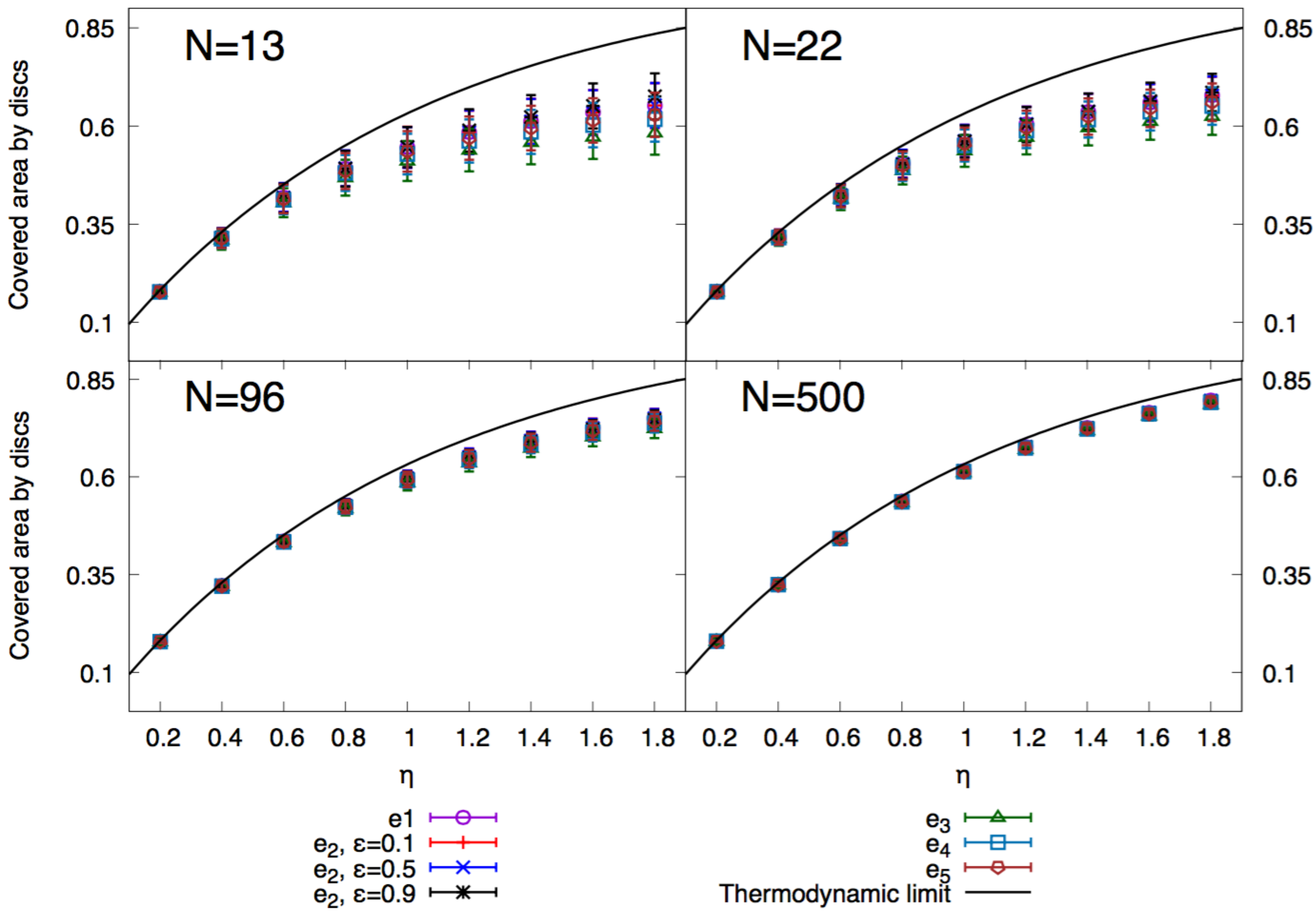
How far from the thermodynamic limit?

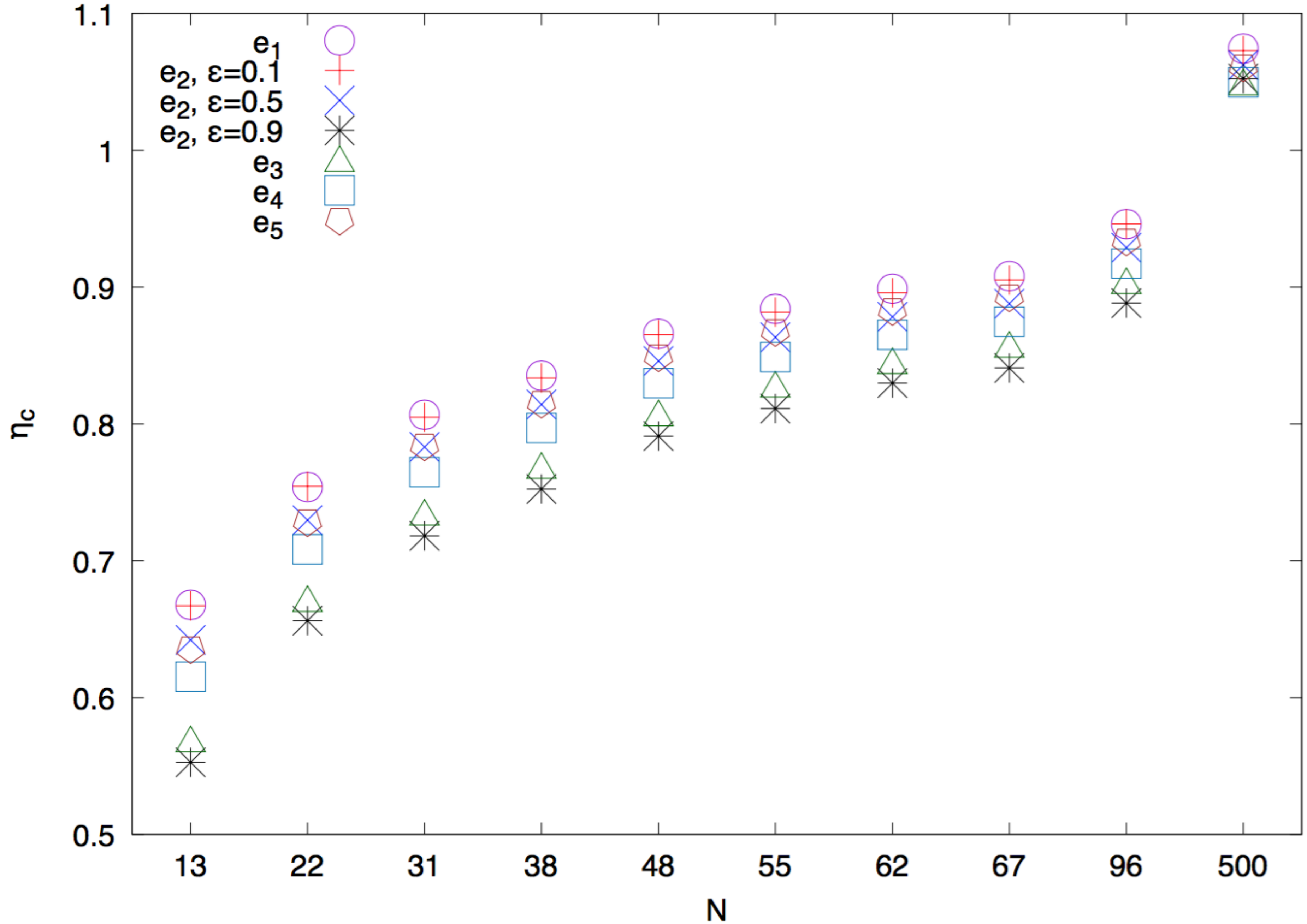
$$\frac{\eta}{1-\exp(-\eta)} \equiv \frac{1}{F^2(\eta)} \longrightarrow \mu = N_S F(\eta)\mu_1 \; ; \; \langle p_{\mathrm{T}}^2 \rangle = \langle p_{\mathrm{T}}^2 \rangle_1 / F(\eta)$$



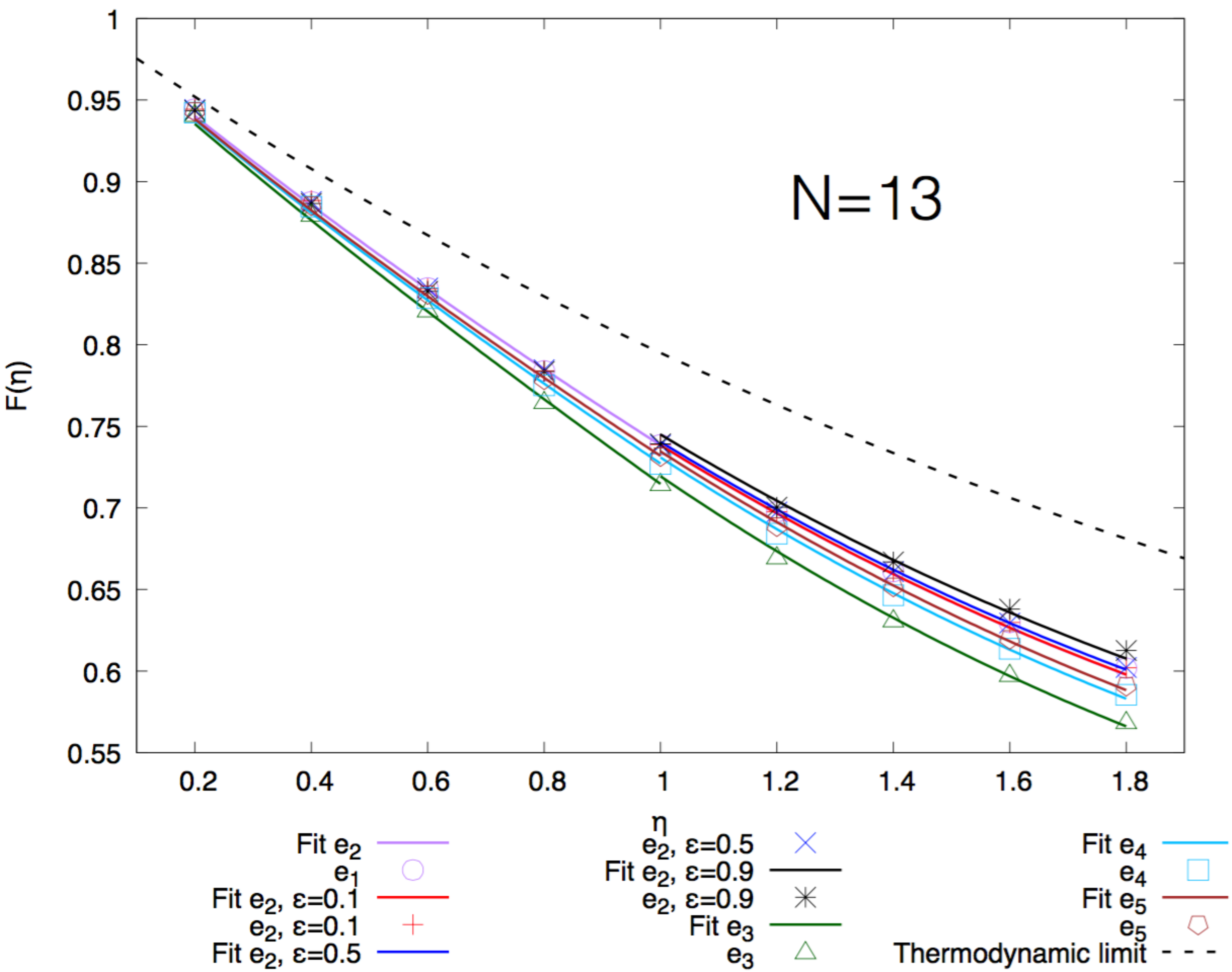
Geometric scaling function ~control Saturation (color reduction factor)

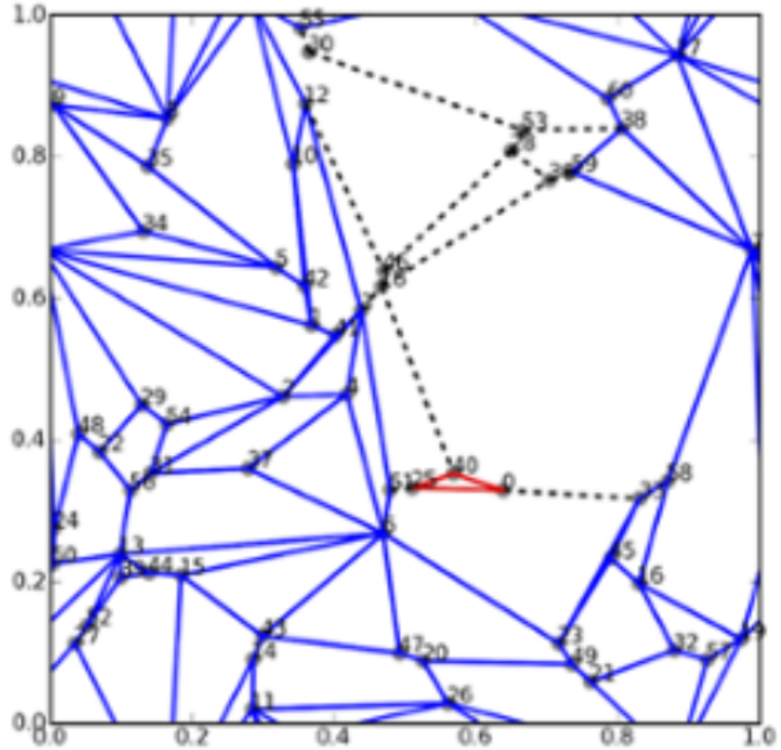
Initial geometry fluctuations

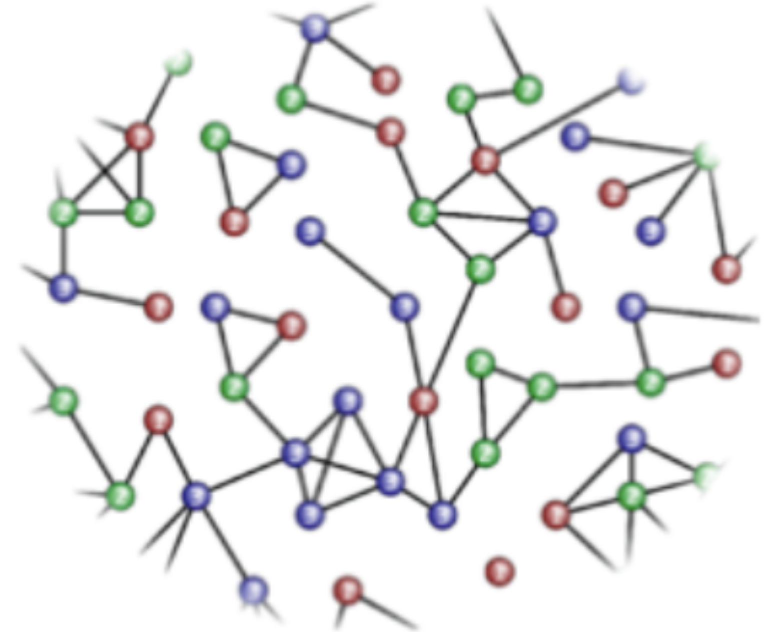




1.1
1
0.9
0.8
0.7
0.6
0.5
η_c
13
22
31
38
48
55
62
67
96
500
N
e_1
e_2, ε=0.1
e_2, ε=0.5
e_2, ε=0.9
e_3
e_4
e_5


N=13
F(η)
η
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Fit e2
e1
Fit e2, ε=0.1
e2, ε=0.1
Fit e2, ε=0.5
e2, ε=0.5
Fit e2, ε=0.9
e2, ε=0.9
Fit e3
e3
Fit e4
e4
Fit e5
e5
Thermodynamic limit





disordered systems -> often have fractal structure

lead to anomalous diffusive transport

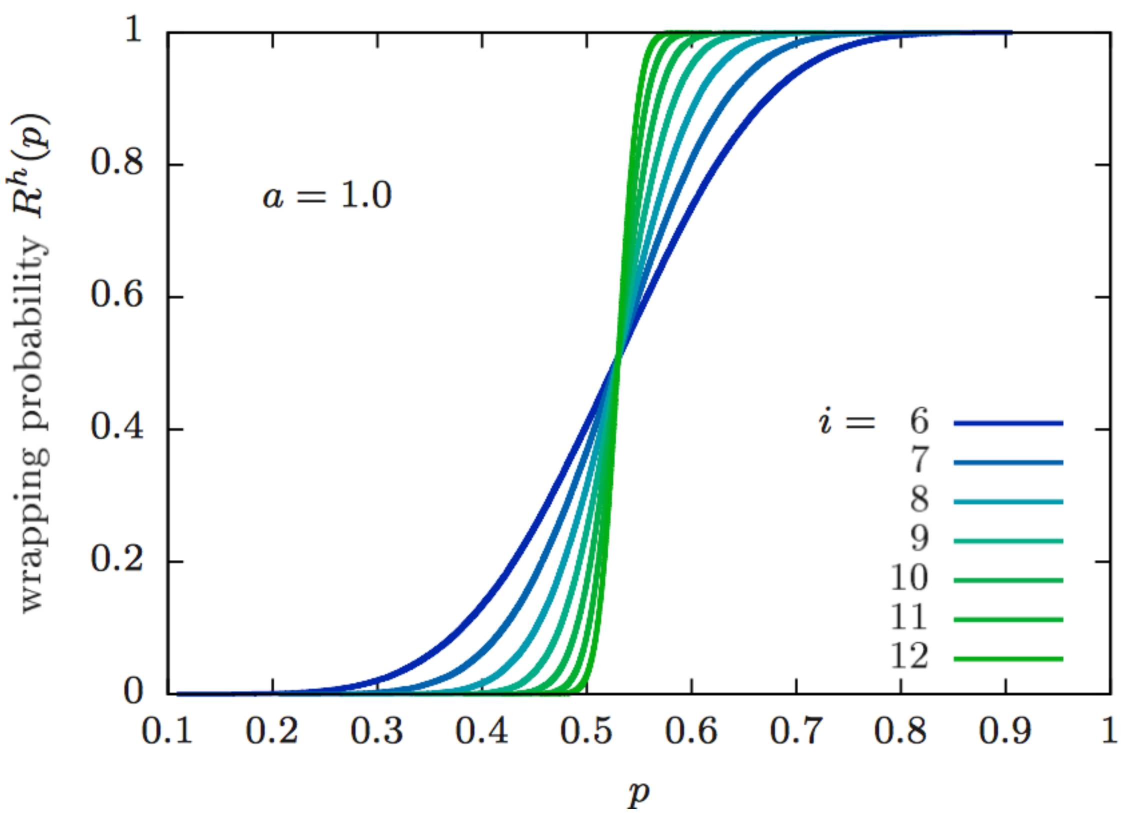
dynamics of fluids in disordered media

In the framework of lattice models with randomly positioned defects

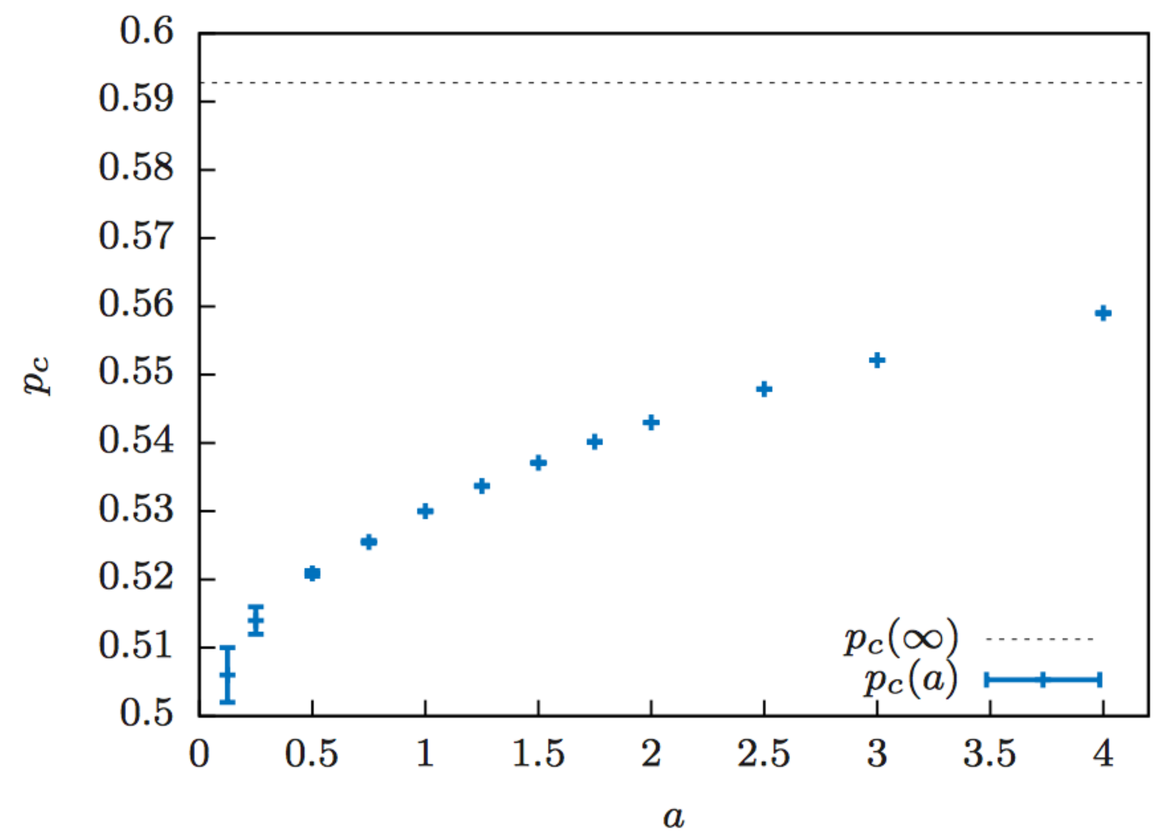
inhomogeneities are frequently not distributed totally at random but tend to be correlated over large distances. To understand the impact of this, it is useful to consider the limiting case where correlations decay asymptotically as a power law with distance

r : $C(r) \sim r^a$

If the correlation exponent a is smaller than the spatial dimension d, the correlations are considered as long-range or “infinite”

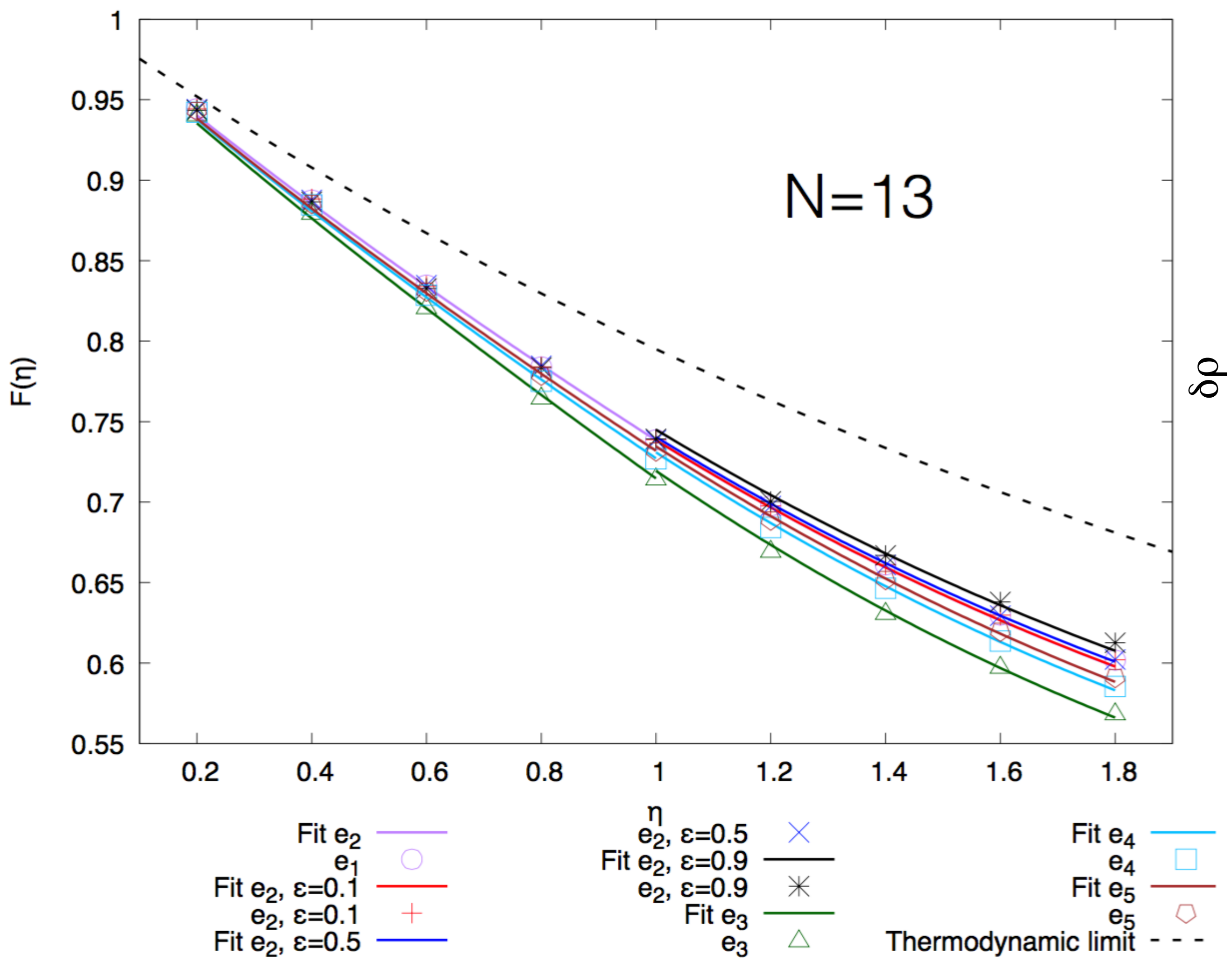


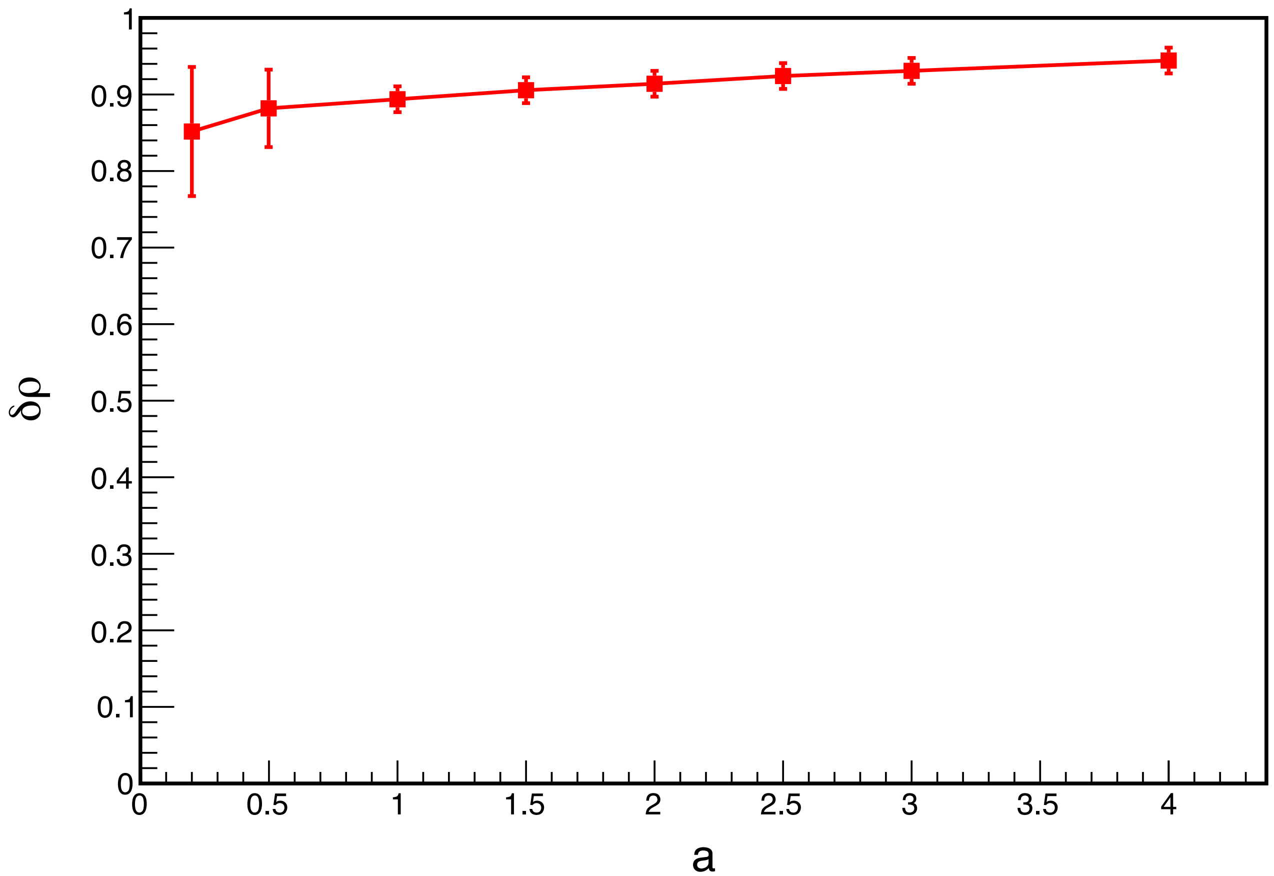
Example for finite-size scaling of the percolation threshold for a = 1 and lattice sizes L = 2i , i = 6, . . . , 12. Horizontal wrapping probabilities (left-hand) and critical concentrations (right- hand) obtained from the quenched disorder average of the occupation numbers



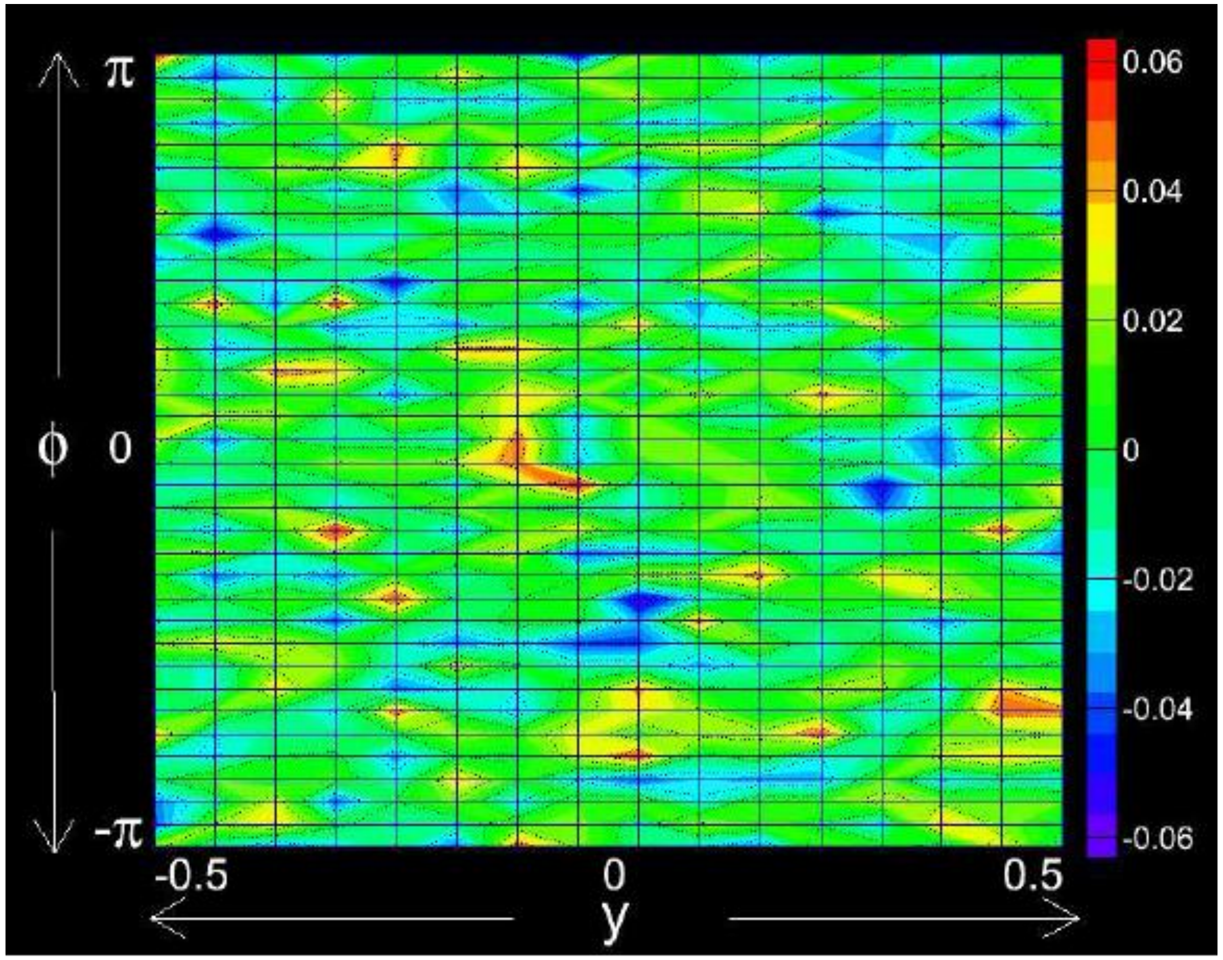
Blue line results of the percolation threshold pc from the finite-size scaling extrapolation as a function of the correlation strength for the square lattice. The dashed line indicates the value for the uncorrelated case which is recovered for a → ∞.

Phys. Rev. E 88, 052102 (2013)

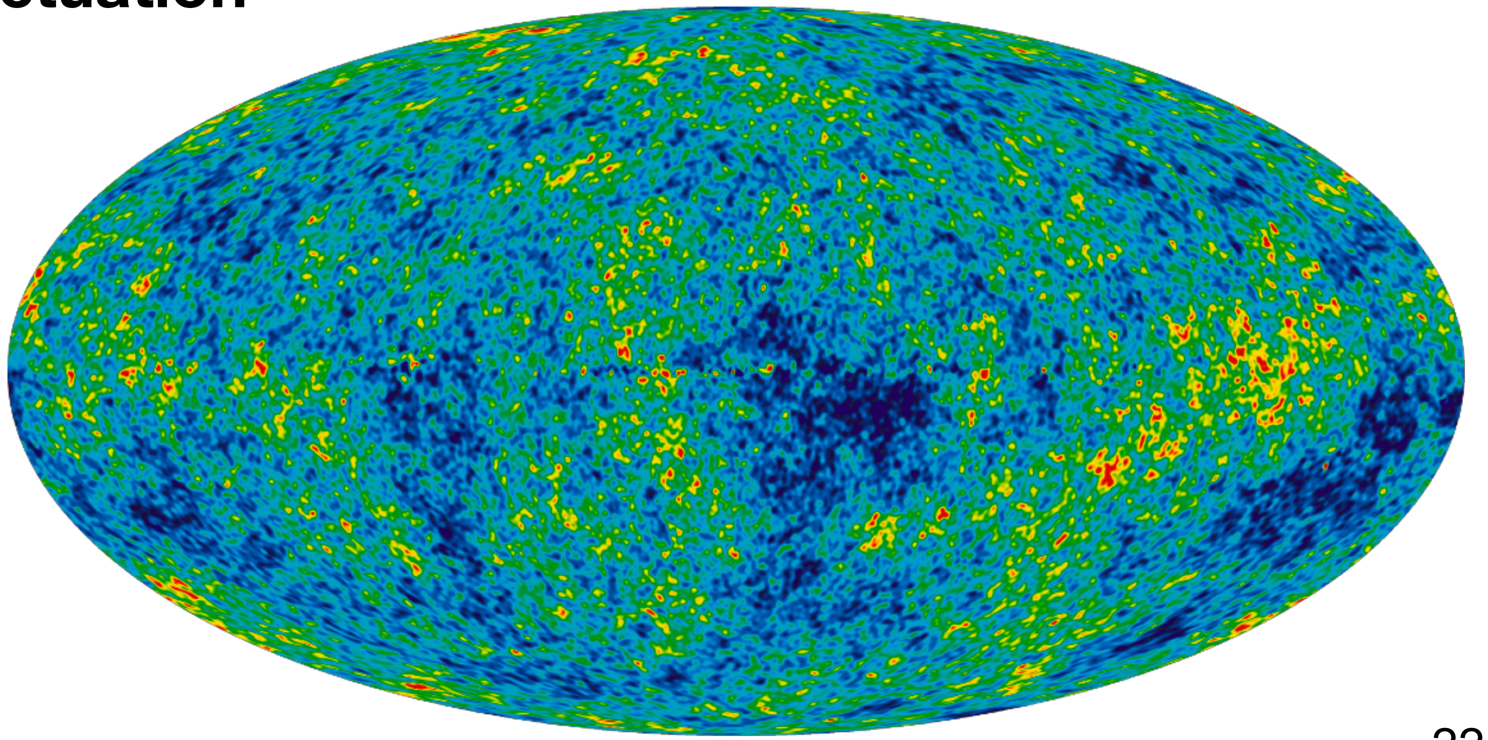


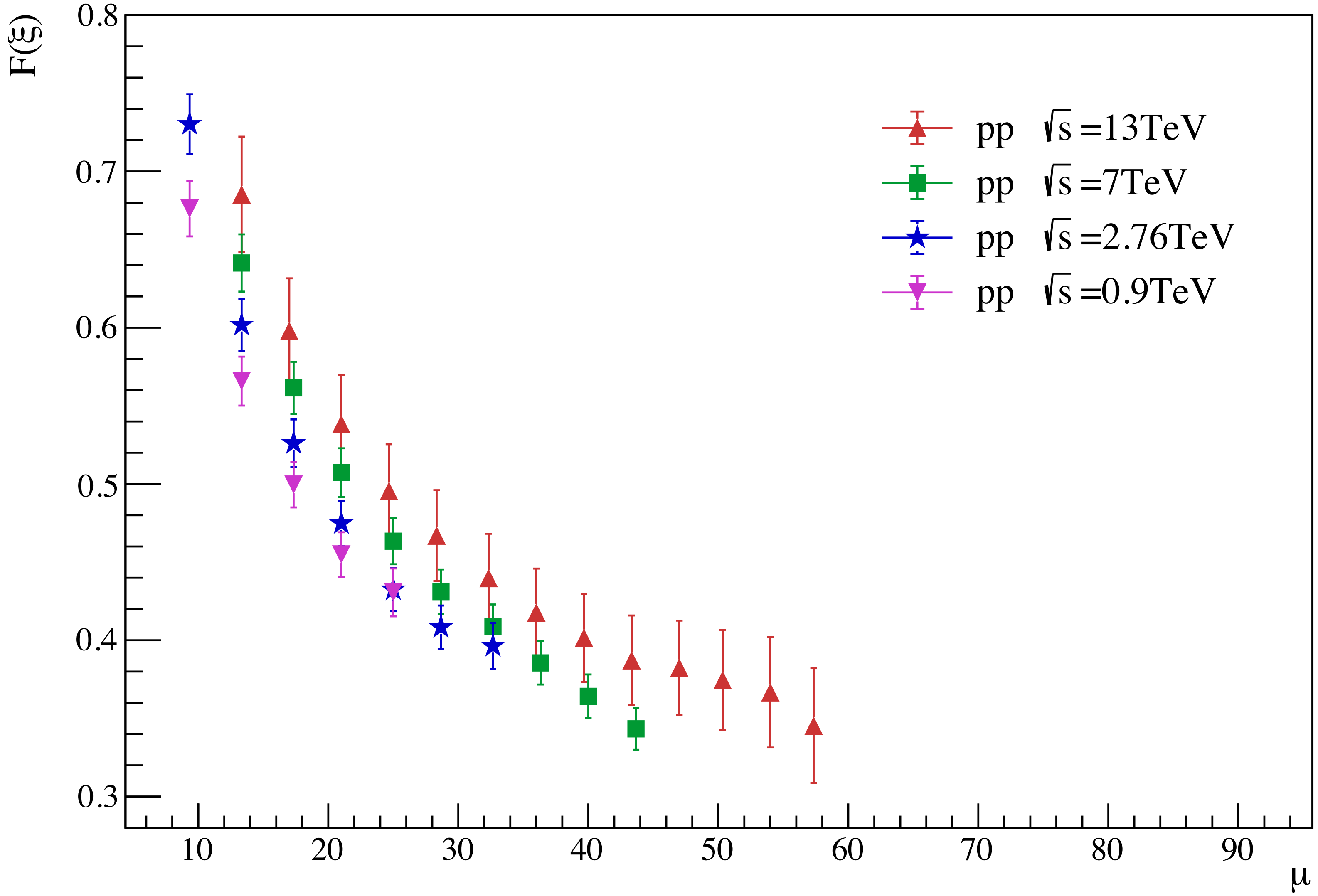


Results of the effects on the scaling function as a function of the correlation strength.



Map of Temperature fluctuation





$$F(\eta') = a\sqrt{\frac{1-\exp -\eta}{\eta}} + b\sqrt{\frac{1+\exp -\eta}{\eta}}$$

with a=0.7714 +/- 0.0146, and b=0.0609 +/- 0.0075

Thermodynamics on SPM

The model allows to relate concepts like temperature, entropy, and viscosity among other quantities as a function of the parameters

$$\zeta^t \,\&\, F(\zeta^t)$$

The Schwinger mechanism for no massive particles is given by:

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

which can be related with the average value of the string tension of the strings $\langle x^2\rangle = \pi\langle p_T^2\rangle_1/F(\zeta)$

These value fluctuates around its mean value since the chromo electric filed is not constant, and the fluctuations gives a Gaussian distribution of the string tension which can be seen as a thermal distribution.

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

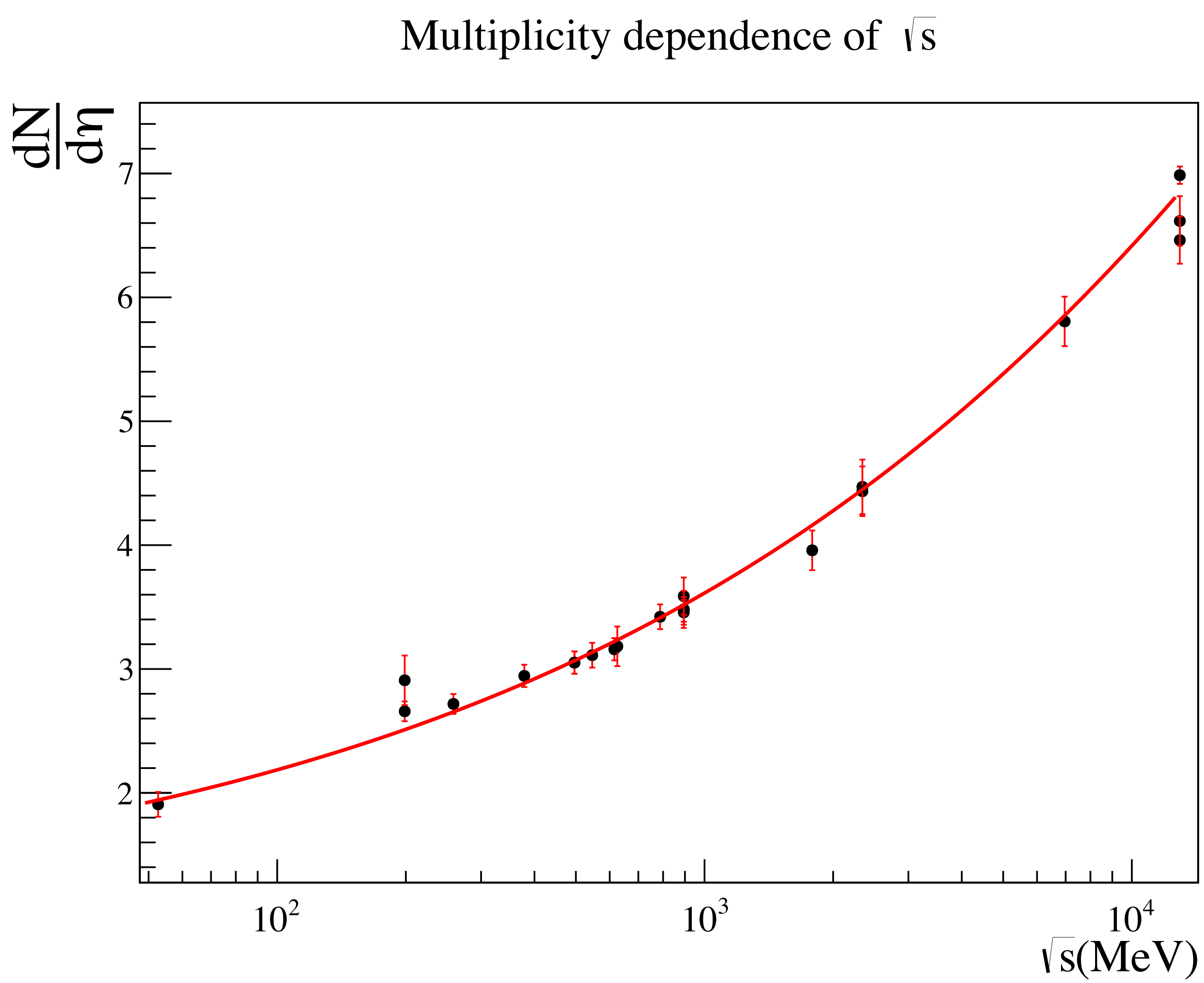
H. G. Dosch, Phys. Lett. 190 (1987) 177 A. Bialas, Phys. Lett. B 466 (1999) 301

Braun, Dias de Deus, Hirsch, Pajares, Scharenberg and Srivastava Phys. Rep. 599 (2015)

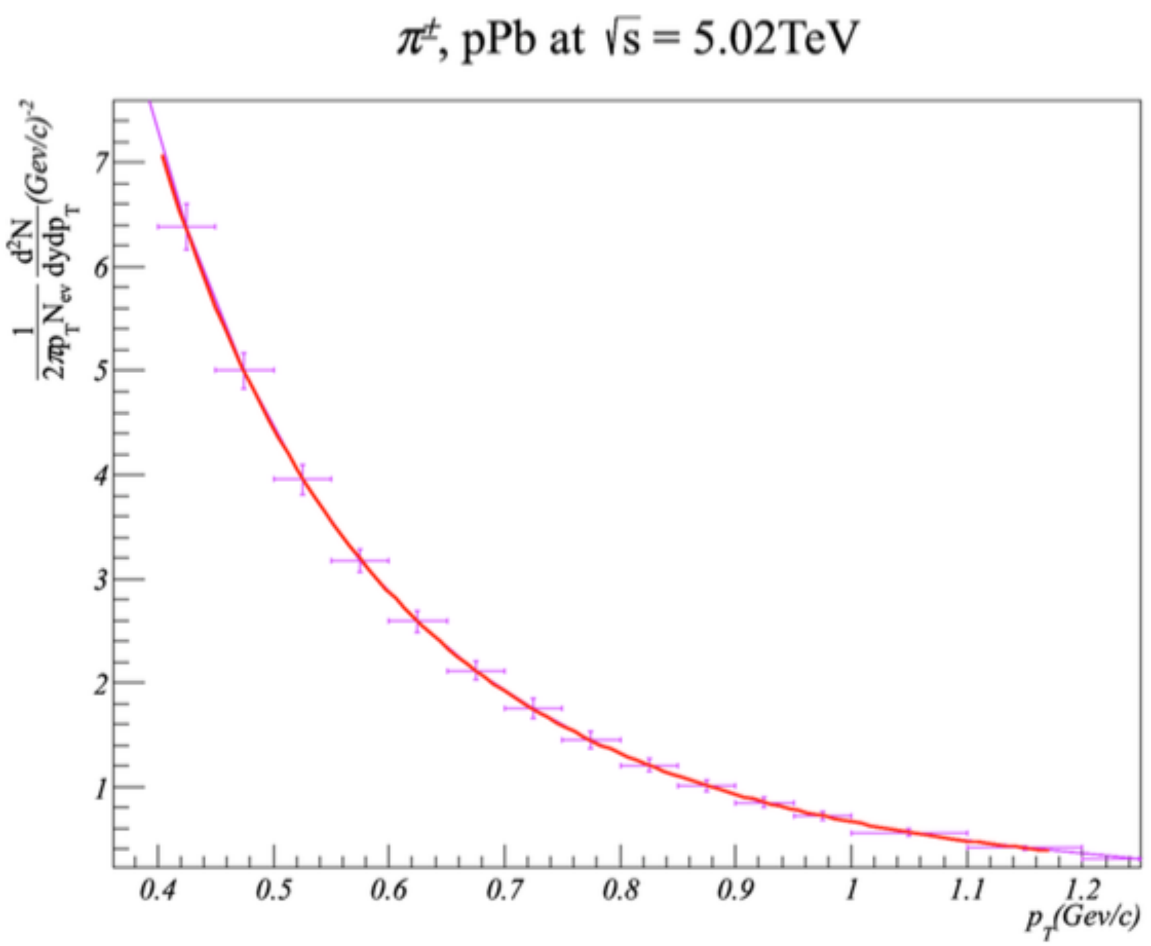
Power law for the transverse momentum distribution

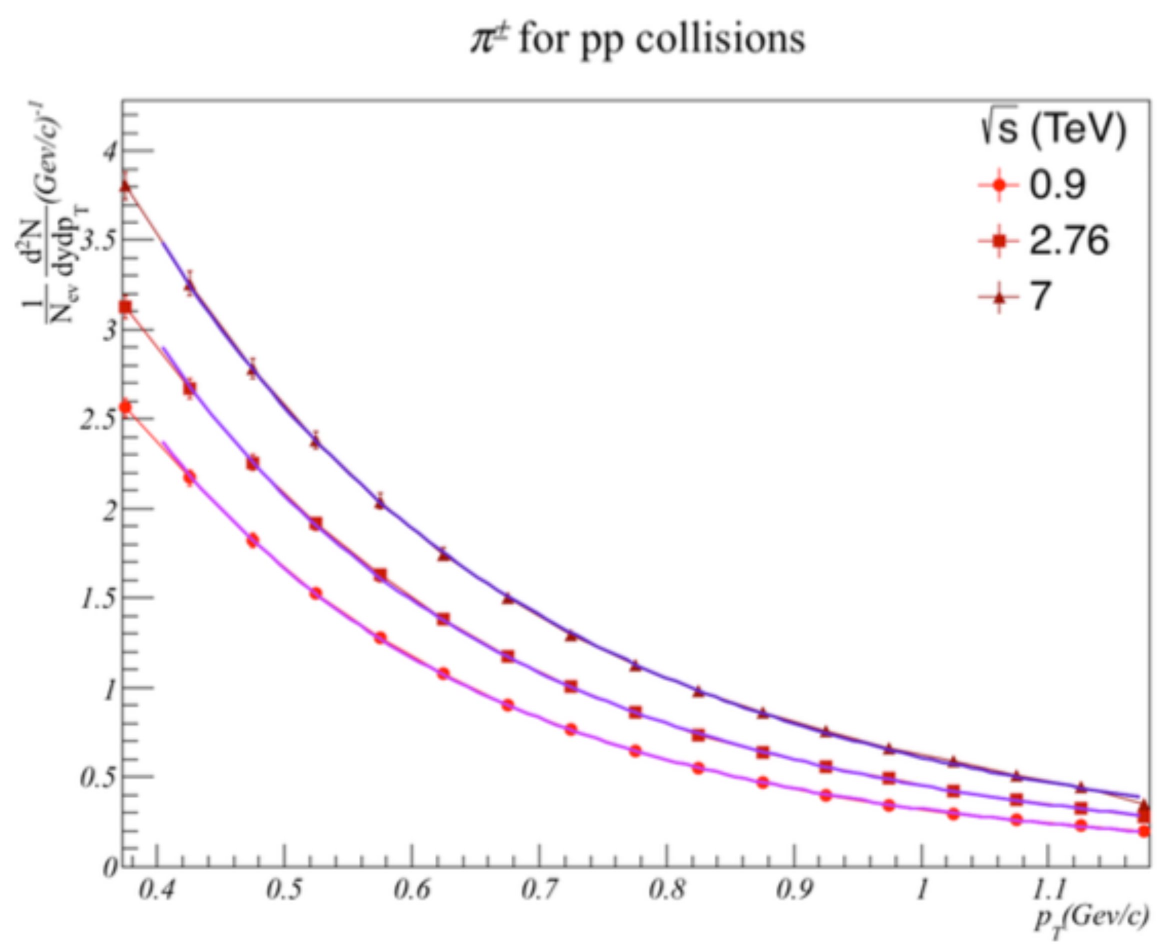
$$\frac{d^2N}{dp_T^2} = \omega(\alpha, p_0, p_T) = \frac{(\alpha-1)(\alpha-2)}{2\pi p_0^2}\frac{p_0^\alpha}{[p_0+p_T]^\alpha}$$

Nucl. Phys. A 698, 331 (2002)



I. Bautista, C. Pajares, J. G. Milhano and J. Dias de Deus, Phys. Rev. C **86** (2012) 034909





$\sqrt{S}(TeV)$	a	p_0	α
5.02	29.63±67.6	3.35±9.14	10.83±22.02
7	33.48±9.3	2.32±0.88	9.78±2.53
2.76	22.48±4.2	1.54±0.46	7.94±1.41
0.9	23.29±4.48	1.82±0.54	9.4±1.8

B. B. Abelev *et al.* [ALICE Collaboration], Eur. Phys. J. C **74** (2014) no.9, 3054

S. Chatrchyan *et al.* [CMS Collabora- tion], Eur. Phys. J. C **72**, 2164 (2012)

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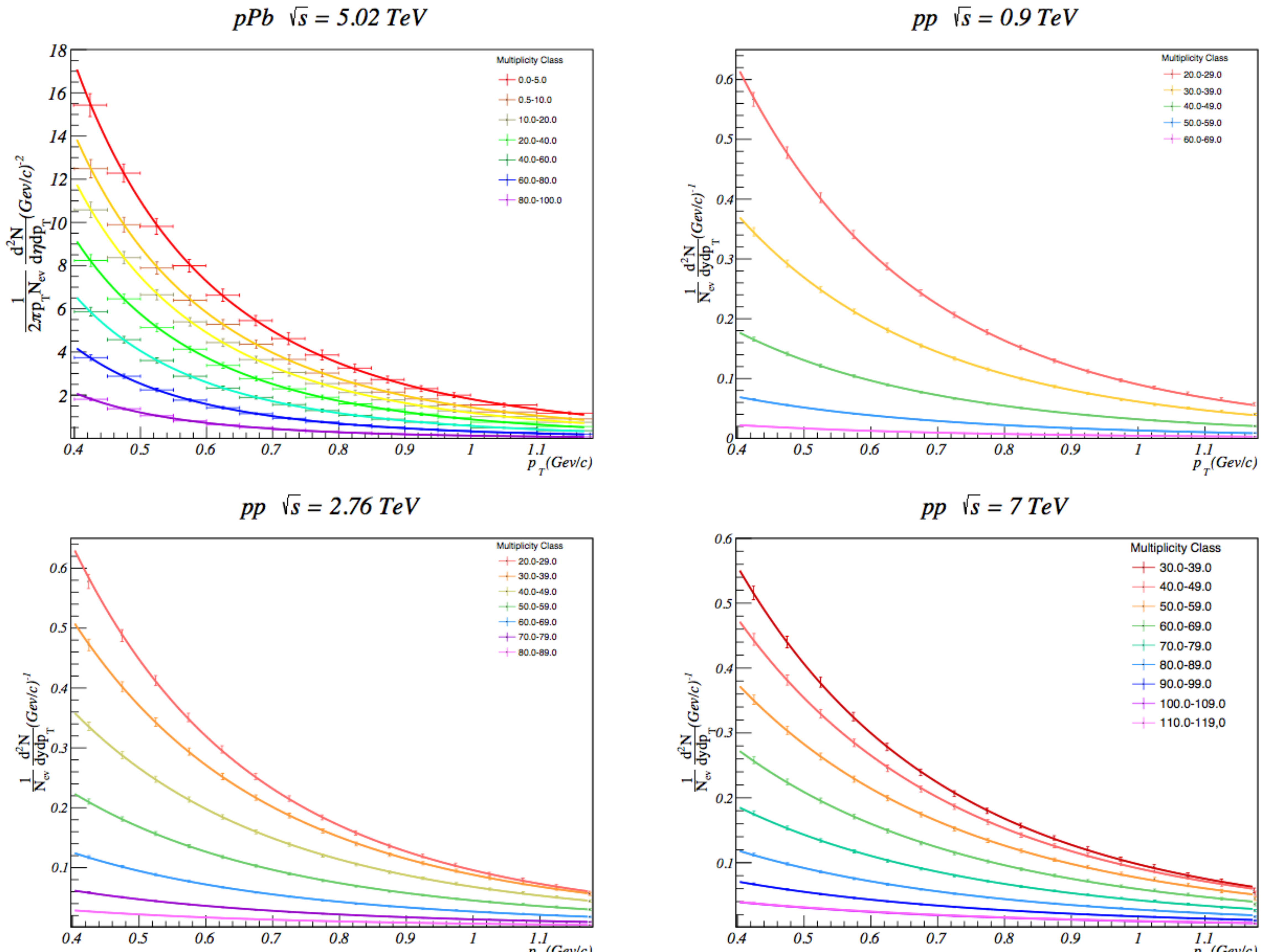
$$\frac{d^2N}{dp_T^2} = \omega(\alpha, p_0, p_T) = \frac{(\alpha-1)(\alpha-2)}{2\pi p_0^2}\frac{p_0^\alpha}{[p_0+p_T]^\alpha}$$

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

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

Nucl. Phys. A 698, 331 (2002)



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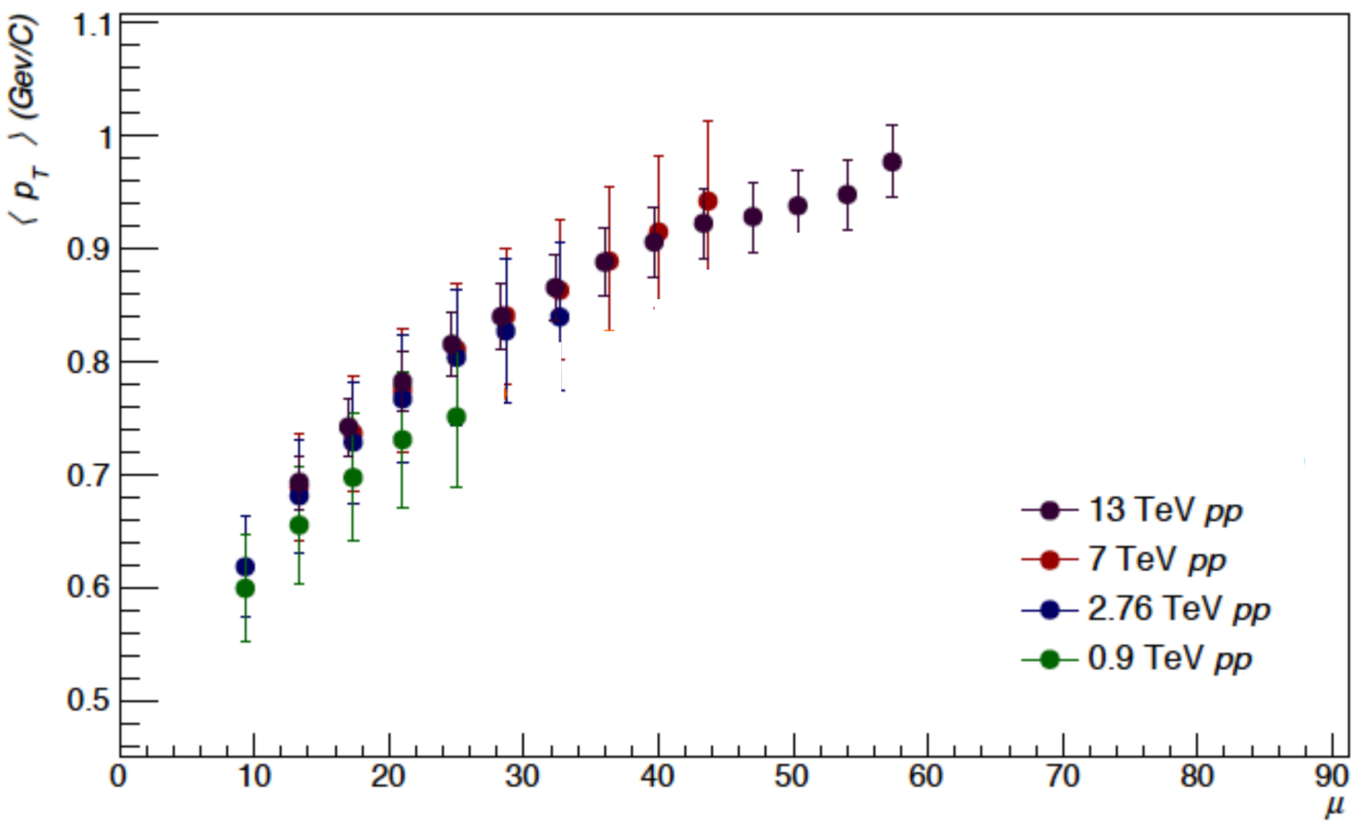
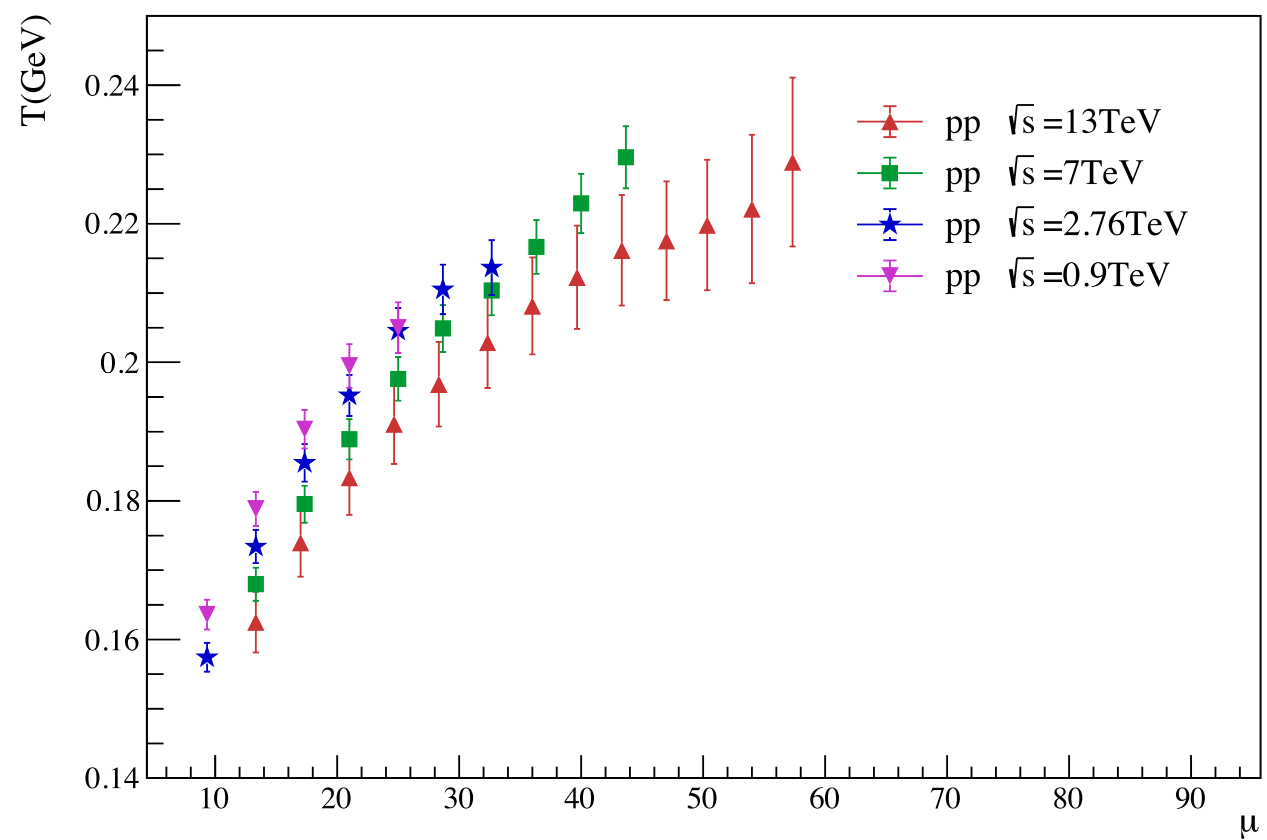

⟨ p_T ⟩ (Gev/C)
μ
13 TeV pp
7 TeV pp
2.76 TeV pp
0.9 TeV pp


T(GeV)
μ
pp √s =13TeV
pp √s =7TeV
pp √s =2.76TeV
pp √s =0.9TeV

EbE <pT> Fluctuations

$$F_{p_T} = \frac{\omega_{\rm datos} - \omega_{\rm random}}{\omega_{\rm random}}, \qquad \omega = \frac{\sqrt{\langle p_T^2\rangle - \langle p_T\rangle^2}}{\langle p_T\rangle},$$

$$\langle p_T\rangle = \frac{\sum_{i=1}^{N_{\rm eventos}} \sum_j \mu_{n_j} \langle p_T\rangle_{n_j}}{\sum_{i=1}^{N_{\rm eventos}} \sum_j \mu_{n_j}},$$

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

$$\langle p_T\rangle = \frac{\sum_{i=1}^{N_{\rm eventos}} \sum_j \left(\frac{n_j S_{n_j}}{S_1}\right)^{1/2} \mu_1 \left(\frac{n_j S_1}{S_{n_j}}\right)^{1/4} \langle p_T\rangle_1}{\sum_{i=1}^{N_{\rm eventos}} \sum_j \left(\frac{n_j S_{n_j}}{S_1}\right)^{1/2} \mu_1}.$$

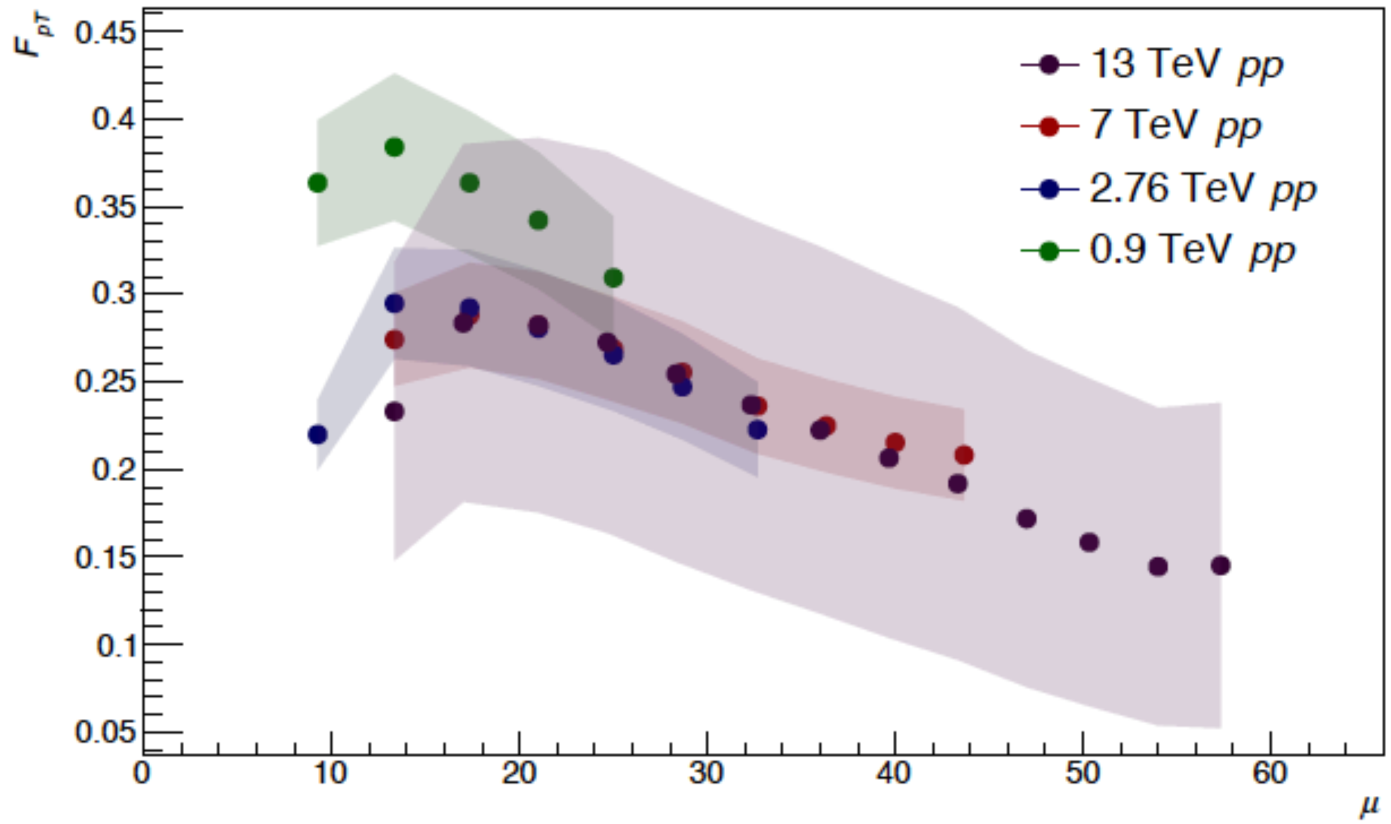
sum of all strings in a given event (i)

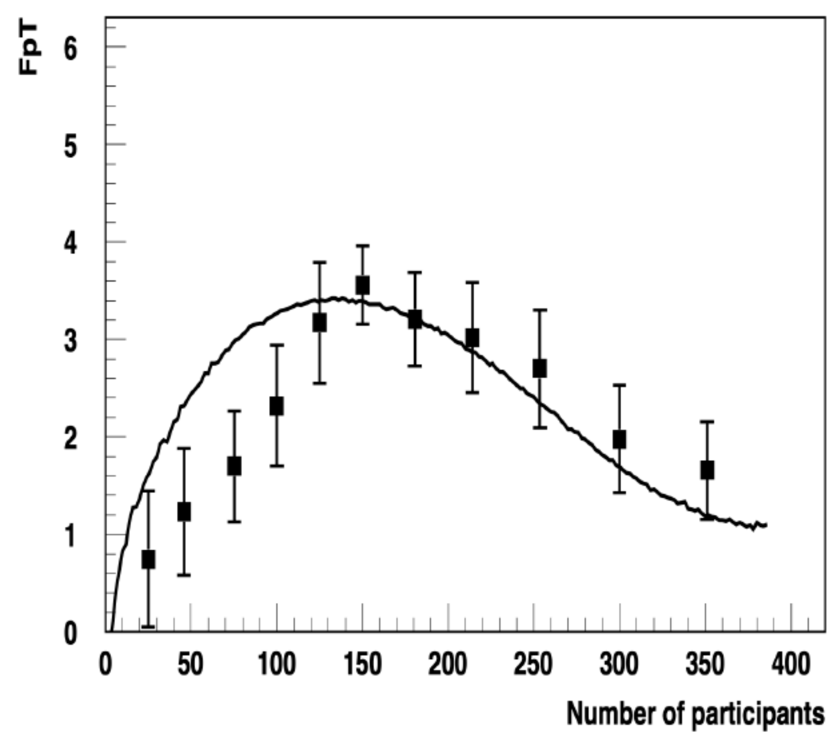
$$z_i = p_{Ti} - \langle p_T\rangle, \qquad Z_i = \sum_{j=1}^{N_i} z_j. \qquad F_{p_T} = \frac{\phi}{\sqrt{\langle z^2\rangle}} = \frac{1}{\sqrt{\langle z^2\rangle}}\sqrt{\frac{\langle Z^2\rangle}{\langle \mu\rangle}} - 1.$$

for a single string

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

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





Au-Au 200 GeV

S. S. Adler et al. [PHENIX], Phys. Rev. Lett. 93 (2004), 092301 doi:10.1103/PhysRevLett.93.092301.

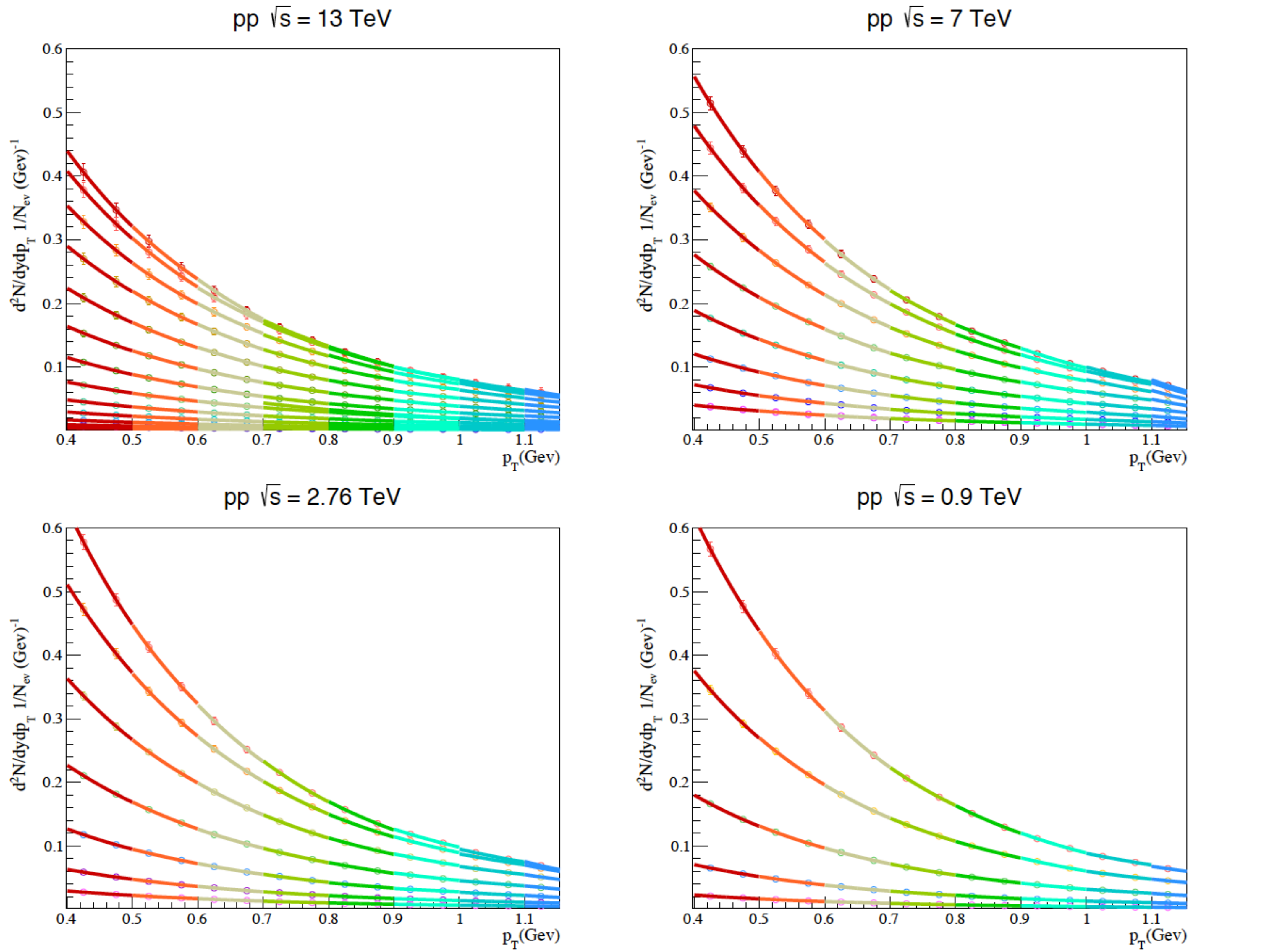
Temperature fluctuations can also increase with pT fluctuations and their correlations are given by

$$T(\xi) = \sqrt{\frac{\langle p_T^2 \rangle_1}{2F(\xi_{HM})}}$$

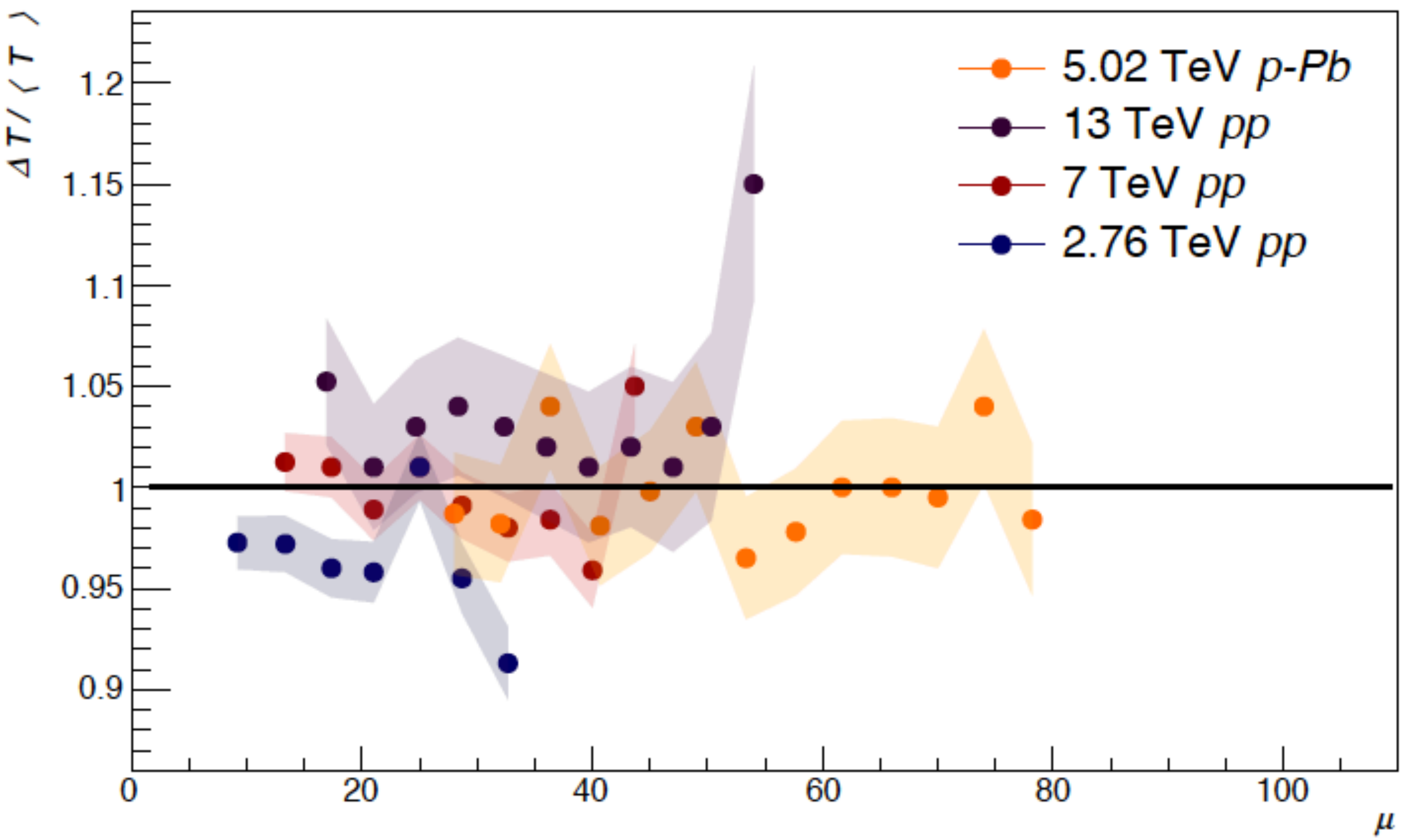
$$\frac{\Delta T}{\langle T_{eff} \rangle_{overall}} = \frac{\sum_i \langle T_{eff} \rangle - T_i}{\langle T_{eff} \rangle_{overall}}$$

$$\frac{\Delta T}{\langle T \rangle} = \frac{1}{\langle T \rangle} \frac{\sqrt{T_1^2 + T_2^2 + ... + T_i^2}}{n_i},$$

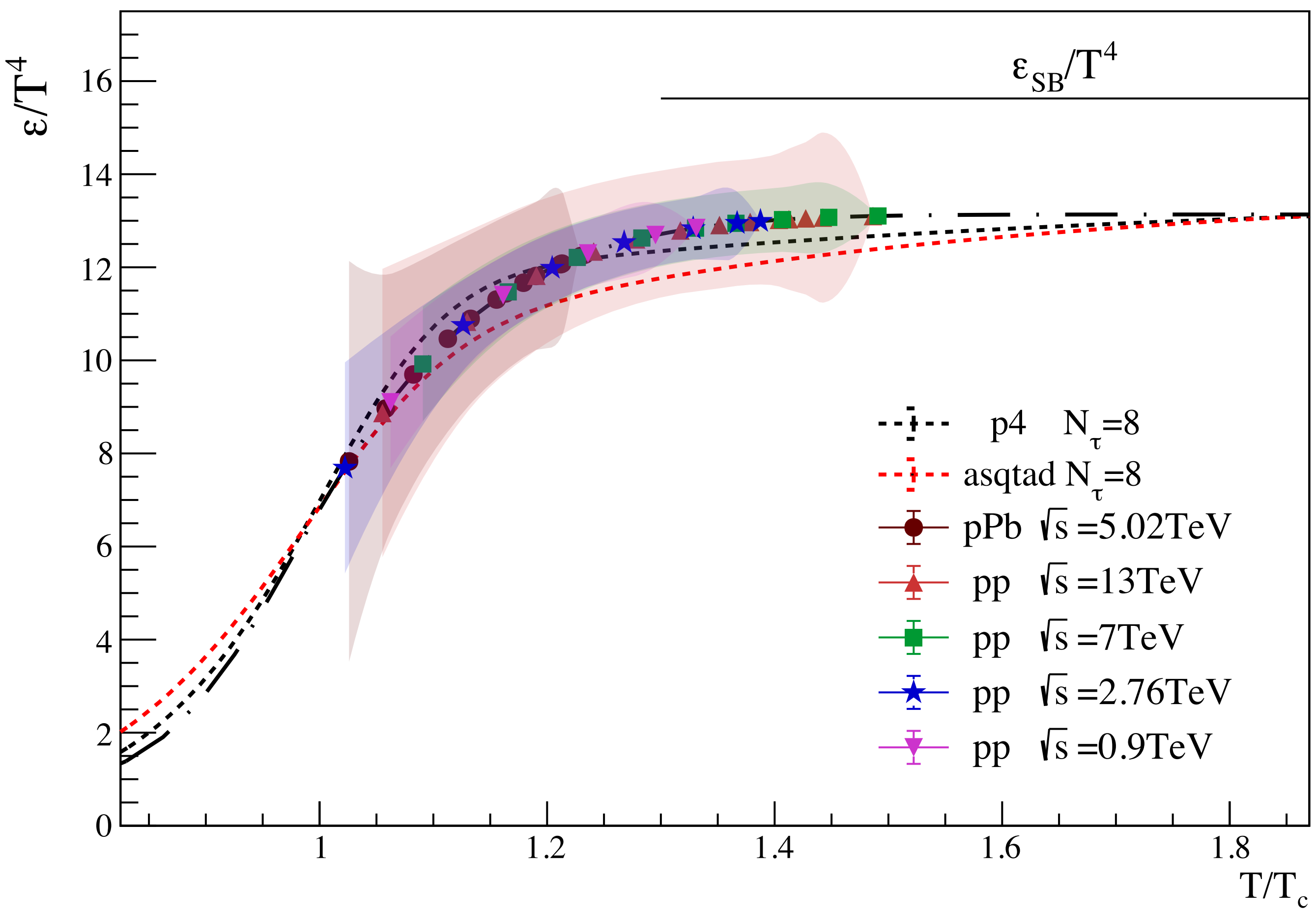
[5] S.~Basu, R.~Chatterjee, B.~K.~Nandi and T.~K.~Nayak, AIP Conf.\ Proc. **1701** (2016) no.1, 060004, doi:10.1063/1.493866



Fit over pT intervals, data taken from CMS []

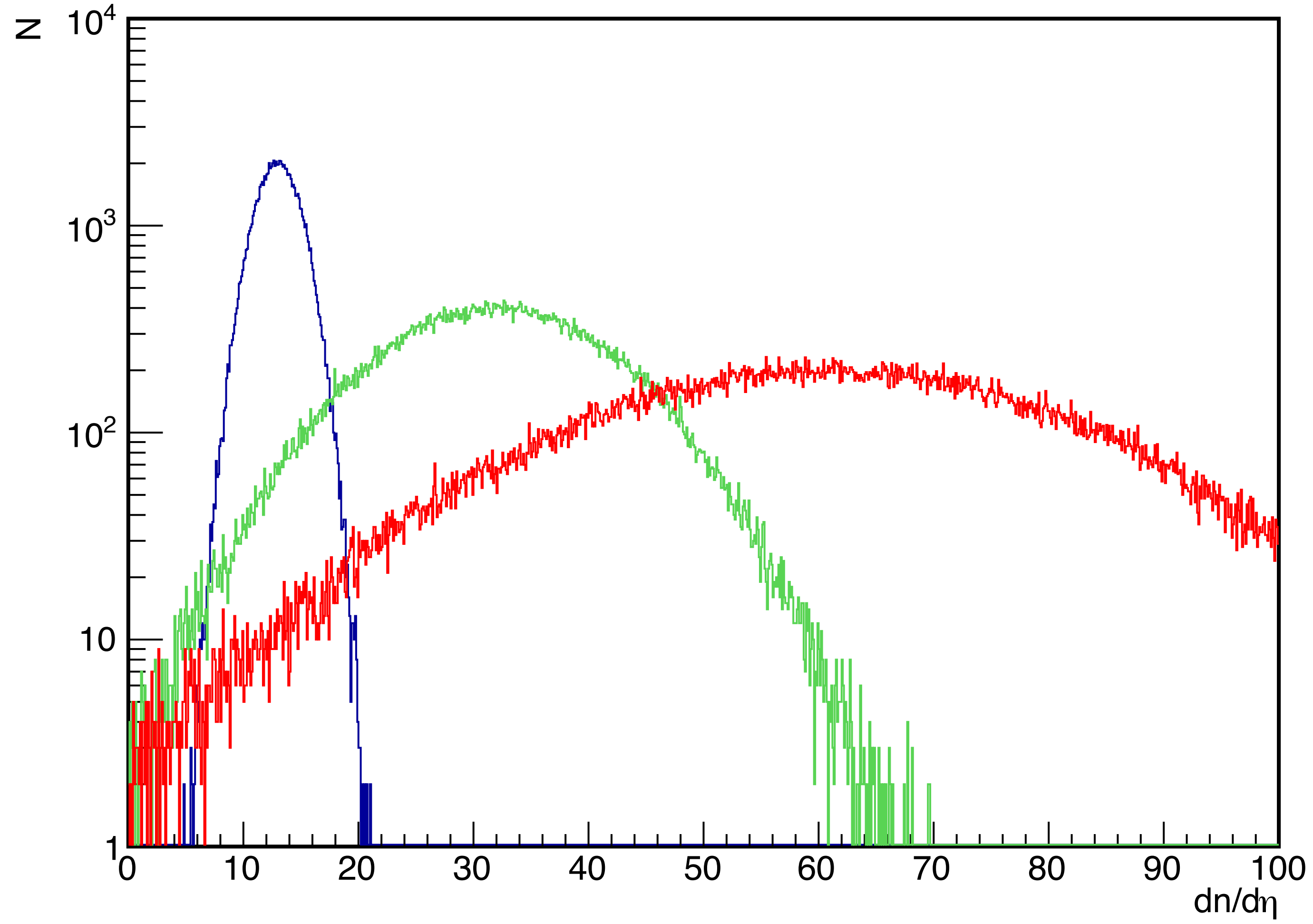


There is no global temperature stability reached, do to the temperature fluctuations, which segues if there is a phase transition it happens in a non-thermalized system.

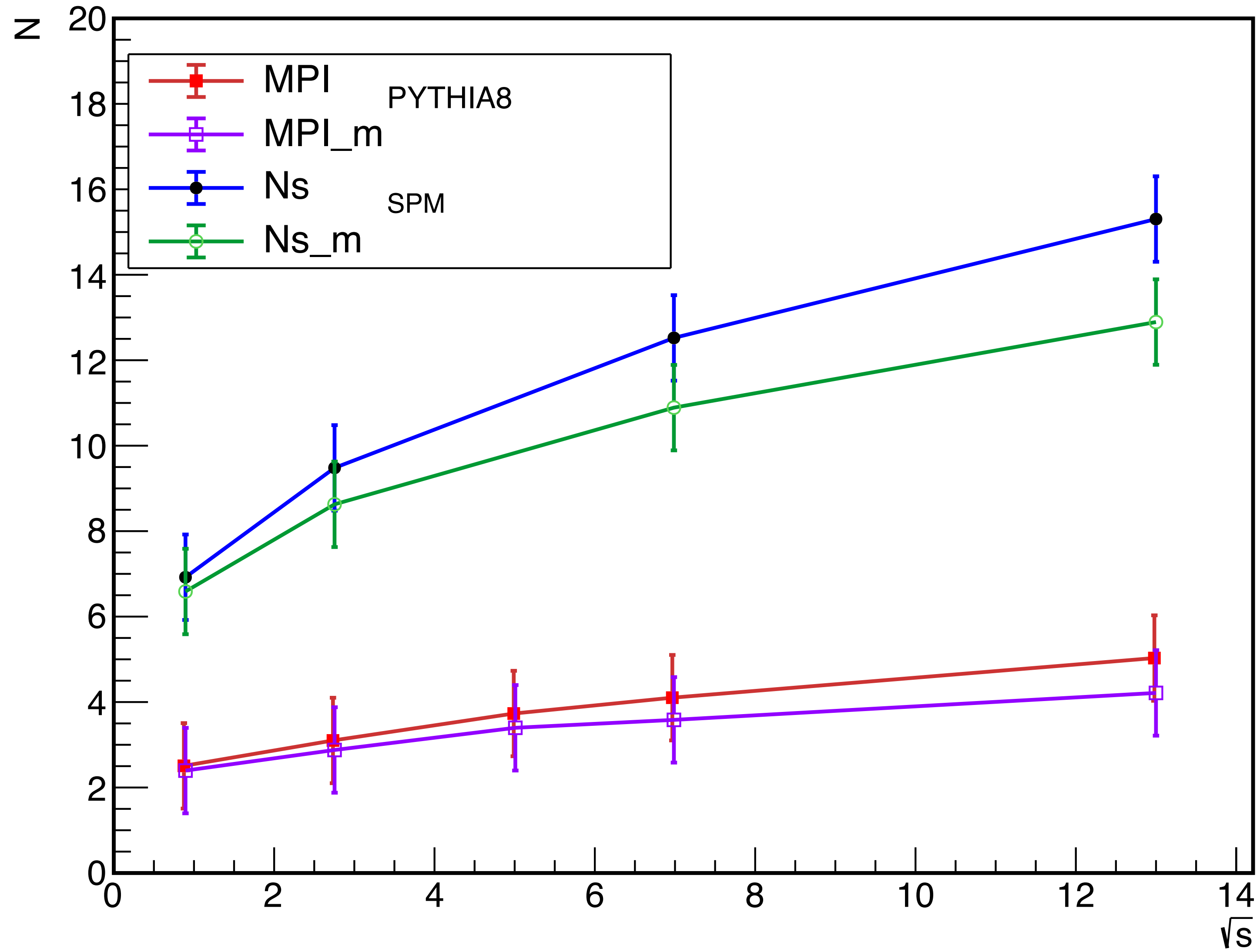


Energy density as a function of Temperature for pp and pPb collisions at LHC energies, with initial fluctuation effects, compared with Lattice QCD with 2 + 1 flavors with actions p4 in blue and y asqtad in red. [A. Bazavov et al., Phys. Rev. D 80 (2009) 014504 doi: 10.1103/PhysRevD.80.014504]

pp 13 TeV



Simulation of the corresponding distribution for dN/deta = 61, 32, 13 corresponding to red, green and blue lines respectively for pp collisions at 13 TeV.



Reduction on the number of sources given by the effect of the initial fluctuations, given in the SPM model (Ns) and PYTHIA 8 (MPI)

A. Ortiz et al, aXiv: 2004.03800 [hep-ph]

Summary

In our MonteCarlo toy Model, we had calculated the contribution percentage of the initial state fluctuation effects due to initial geometry, system size, and presence of inhomogeneities, depending on the multiplicity and energy of the event. When taking into account these effect on data it gives us a lower initial number of sources. A wider distribution of the fluctuation is observed to increase for higher multiplicity events, increasing with higher energy density, or collision energy. The effect may be associated with the enhanced the probability of pair creation, due to the effects of the fluctuations as in the modification of the Schwinger mechanism from the initial state as study on the Glasma picture [H. Fujii (Tokyo U., Komaba), K. ItakuraNucl.Phys.A809:88-109,2008].