Excited QCD 2022

Energy density of the formed medium in small collision systems at LHC energies

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Outlook

Model

- String Percolation Model
- Color Reduction Factor
- Intial geometry and size

Thermodynamic Observables

- Temperature
- Energy Density

Results

- Energy density, entropy density and Pressure evolution.

Conclusions

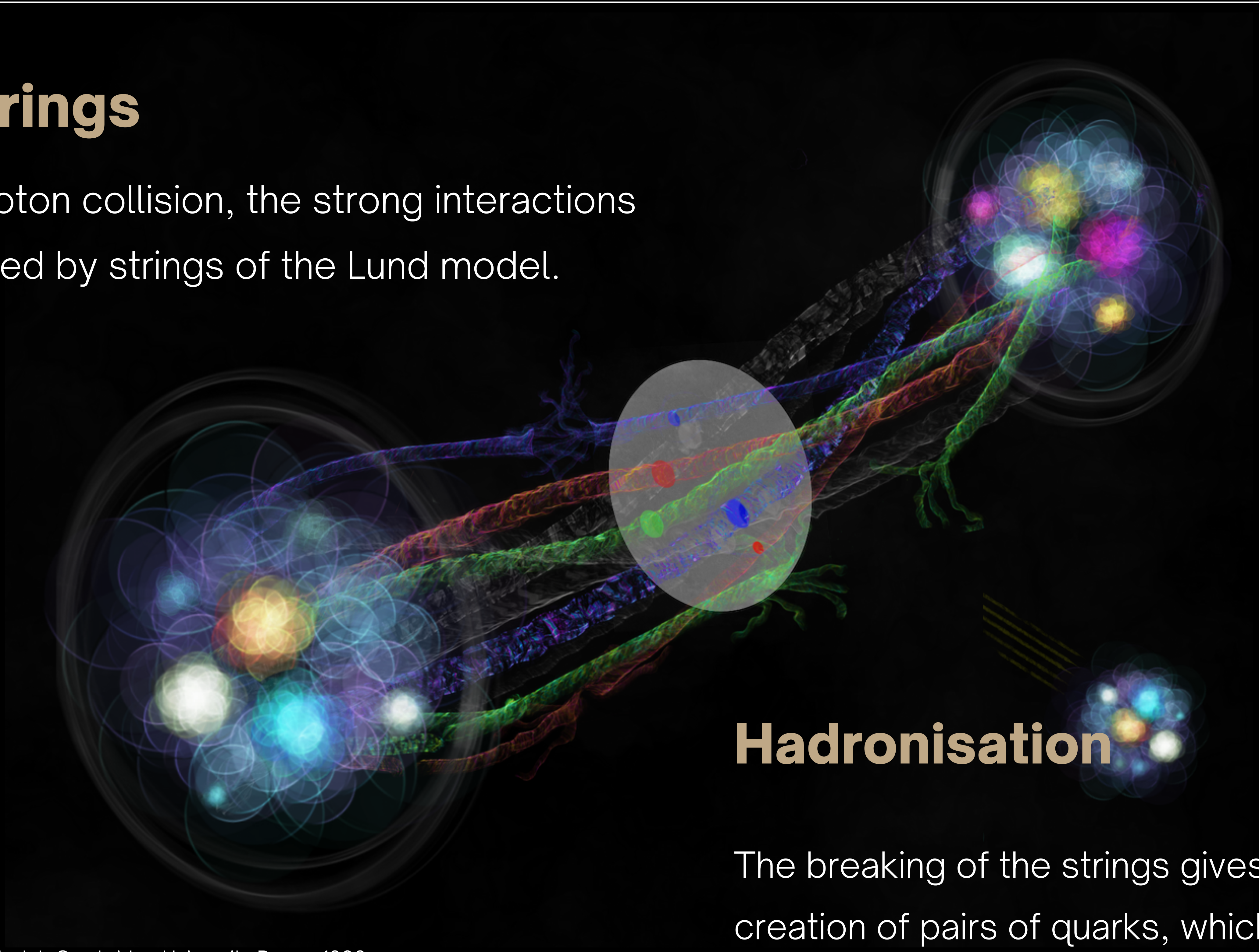
Abstract

Results on **small collision systems** are still under study to characterize whether a strongly interacting perfect fluid is formed or not. In this work we present an estimate of the **initial state energy density** on small collision systems. Results consider **effects of initial state fluctuations on geometry** and **finite volume** in a **clusterization of color sources** framework. The results are compared with Lattice QCD calculations. This work presents a perspective of how high energy densities can be reached in such small collision systems at the LHC energies. The results give a collective description of the system.

Color String Percolation Model

Color Strings

In a proton-proton collision, the strong interactions can be modeled by strings of the Lund model.

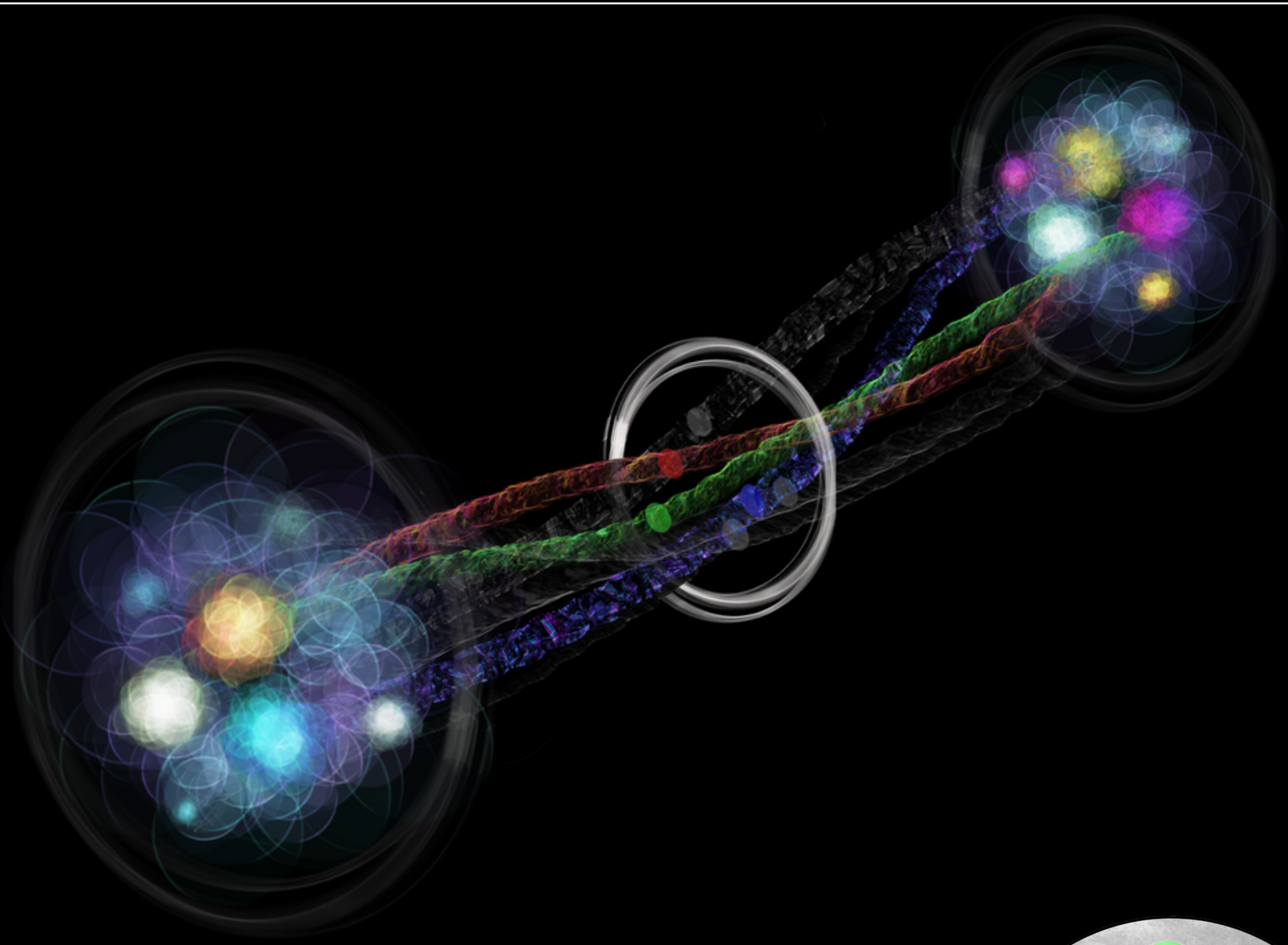


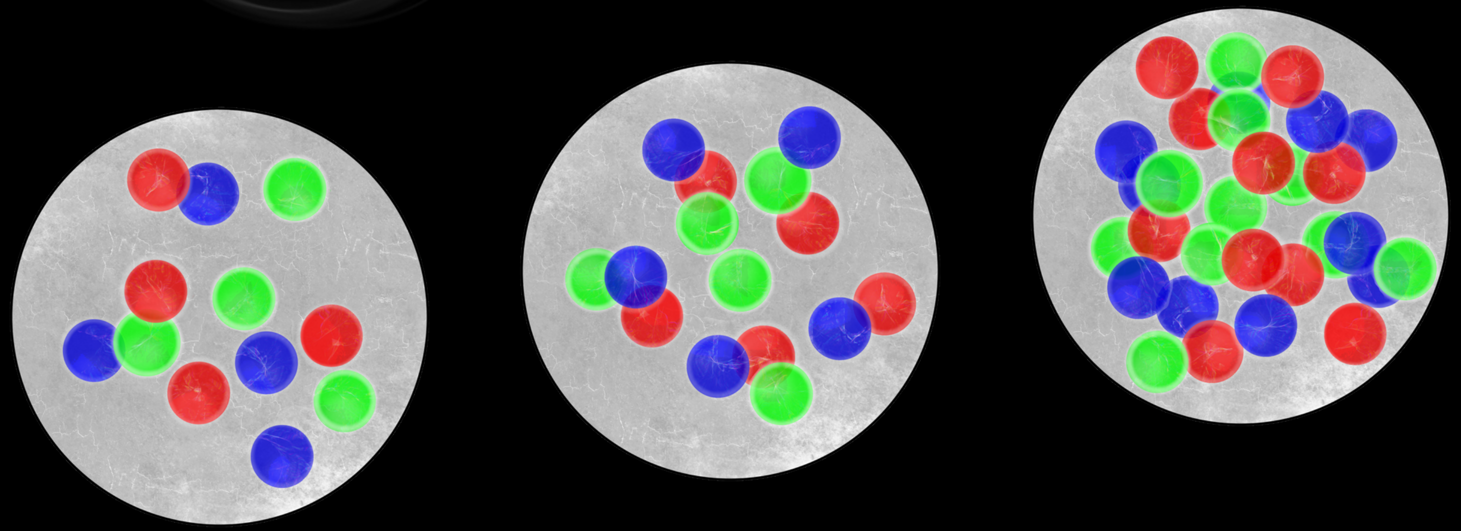
Hadronisation

The breaking of the strings gives rise to the creation of pairs of quarks, which then hadronize.

B. Andersson, The Lund Model, Cambridge University Press, 1998.

String density





The impact parameter plane

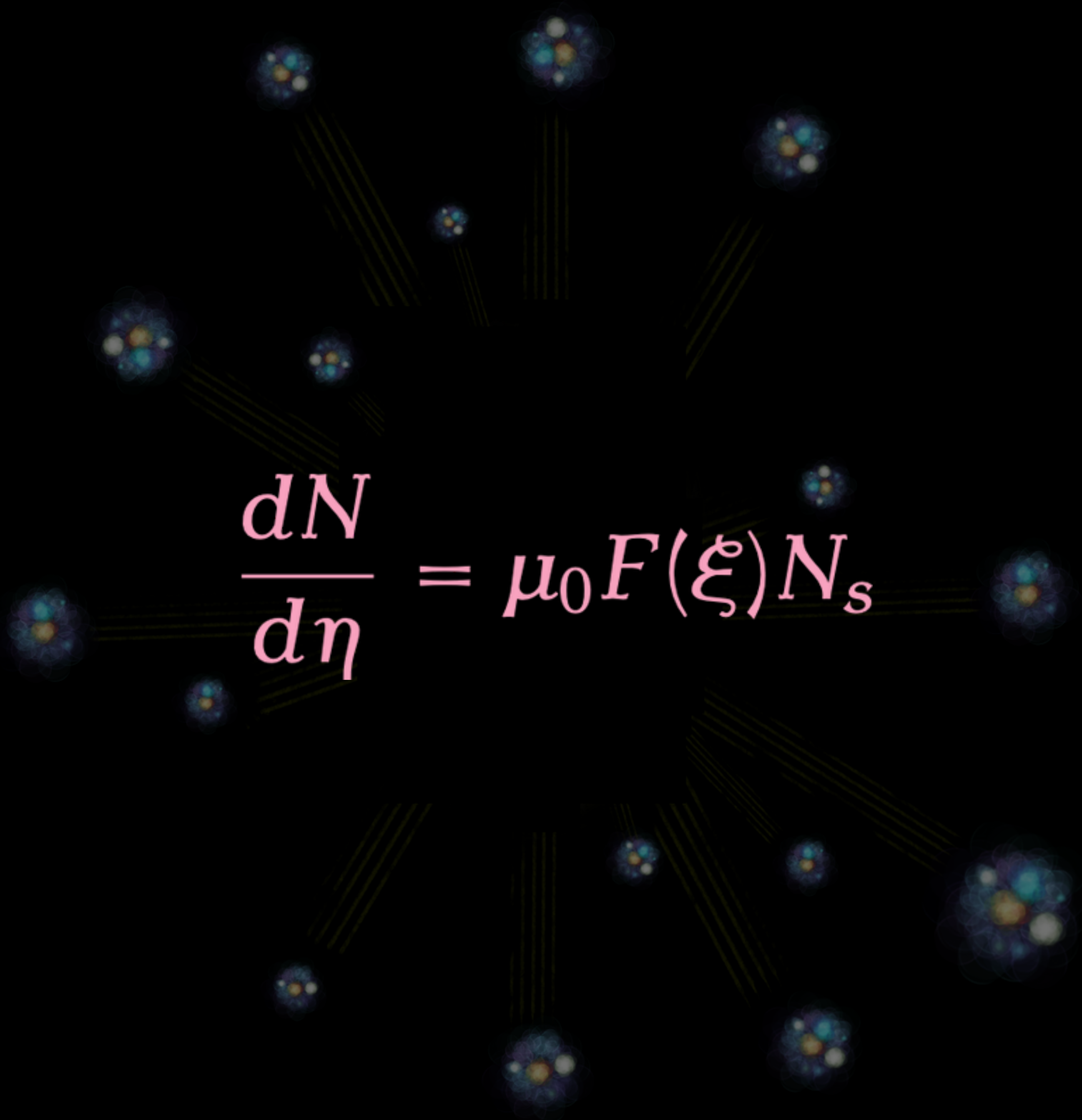
The strings project their area onto the overlap area of the colliding protons and define a certain distribution characterized by a **string density**

$$\xi = \frac{S_0}{S} N_s$$

where S_0 is the transverse area of a single string, S is the overlapping area over transverse plane and N_s is the number of strings.

I. Bautista, J. G. Milhano, C. Pajares and J. Dias de Deus, Phys. Lett. B 715 (2012) 230

Supression Factor



$$\frac{dN}{d\eta} = \mu_0 F(\xi) N_s$$

Saturation scale

Particle production is directly proportional to the number of strings and is suppressed by a string density-dependent geometric scaling function we call the Color Reduction Factor

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

For nuclear collisions in the thermodynamic limit the CRF has the form above.

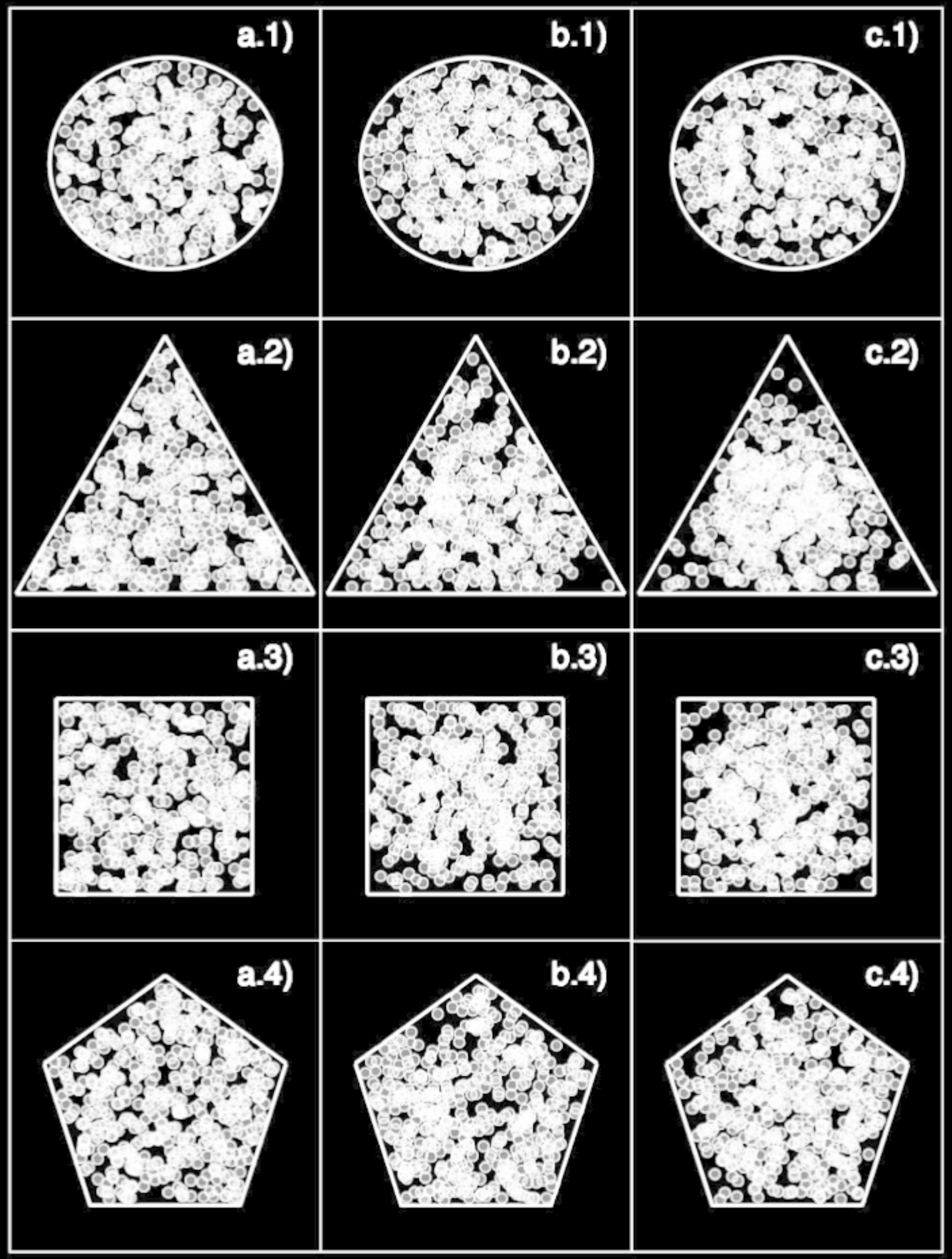
Phys. Rept. 599 (2015) 1–50. arXiv:1501.01524, doi: 10.1016/j.physrep.2015.09.003

Areas covered by disks

Effects for geometry

Different types of geometry and distribution profiles can cause the areas covered by discs to give rise to different saturations.

The initial shape of the distribution of color interactions is responsible of shifts in the percolation thresholds, therefore, in the phase transitions critical values.



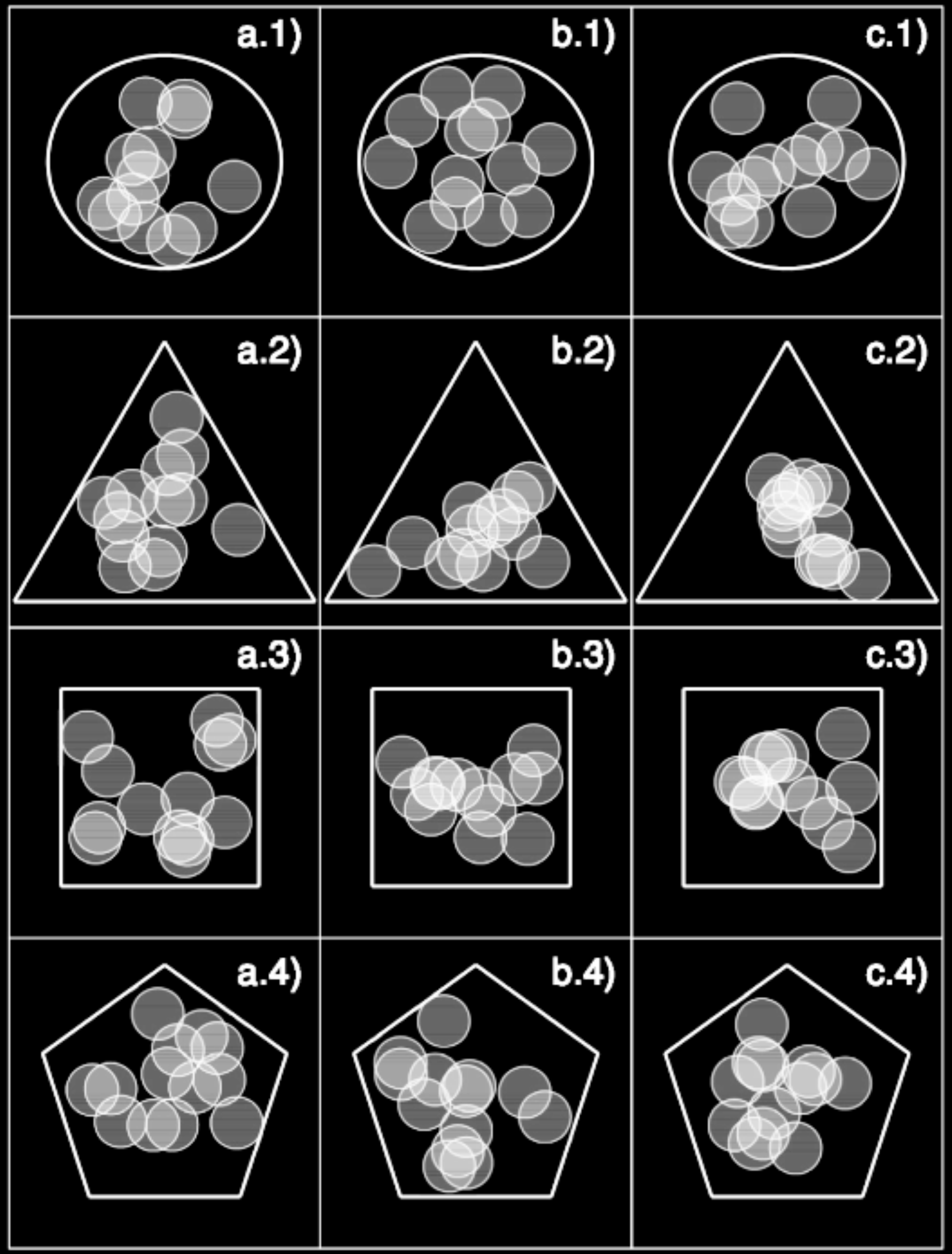
J. E. Ramírez and C. Pajares, Phys. Rev. E 100, 022123 – (2019)

Areas covered by disks

Effects for size

Boundary effects become especially relevant when there are few interactions at very high energies (small collisions systems at LHC energies).

In these cases, the CRF as a function of the **filling parameter** is far from the thermodynamic limit. There are multiple origins that give rise to modifications in the expressions applied to Heavy Ion Collisions.



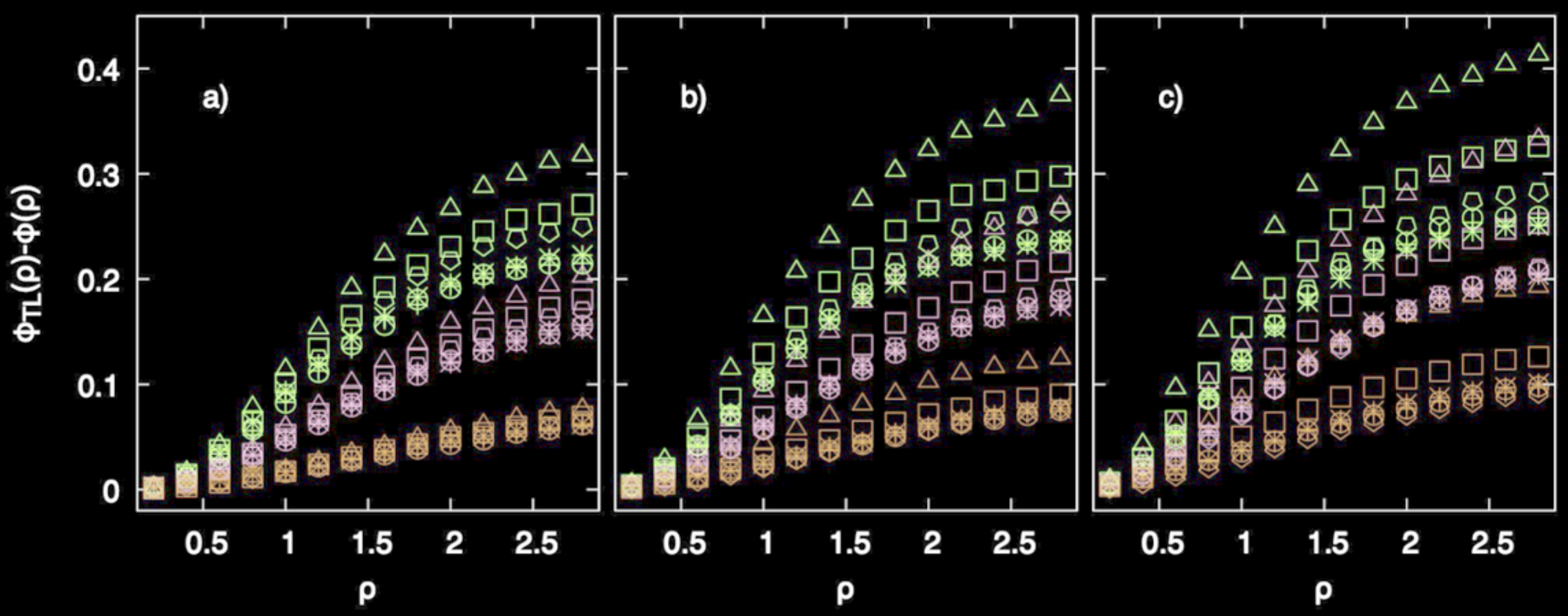
J. E. Ramírez and C. Pajares, Phys. Rev. E 100, 022123 – (2019)

Filling areas

Small areas

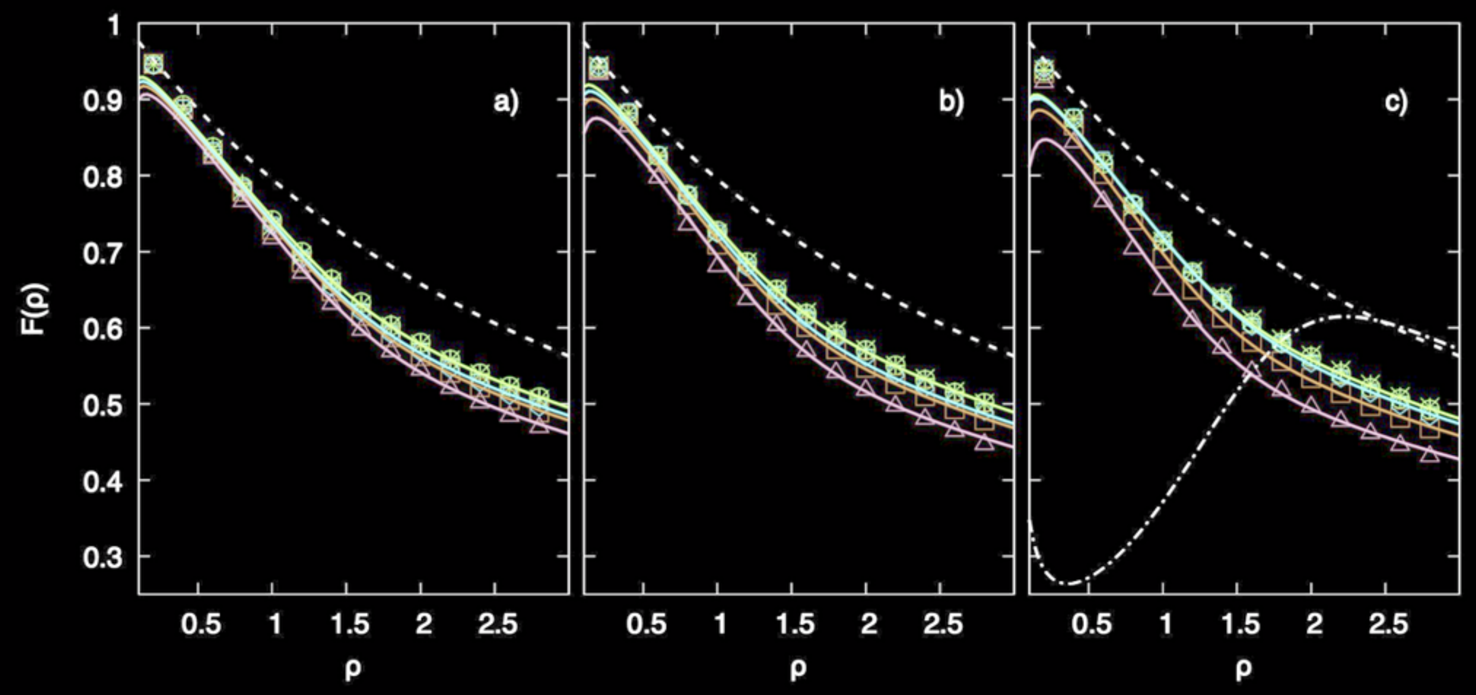
We consider areas close to that of a protor parameterized by an **impact parameter b**

$$S = \pi \left(R_p - \frac{b}{2} \right) \sqrt{R_p^2 - \left(\frac{b}{2} \right)^2} \simeq \pi R_p^2$$



The values of the reduction factor obtained show a **greater suppression** in the production of particles.

This additional contribution is expressed as an additive term in the color reduction factor formula.



J. E. Ramírez and C. Pajares, Phys. Rev. E 100, 022123 – (2019)

Small systems

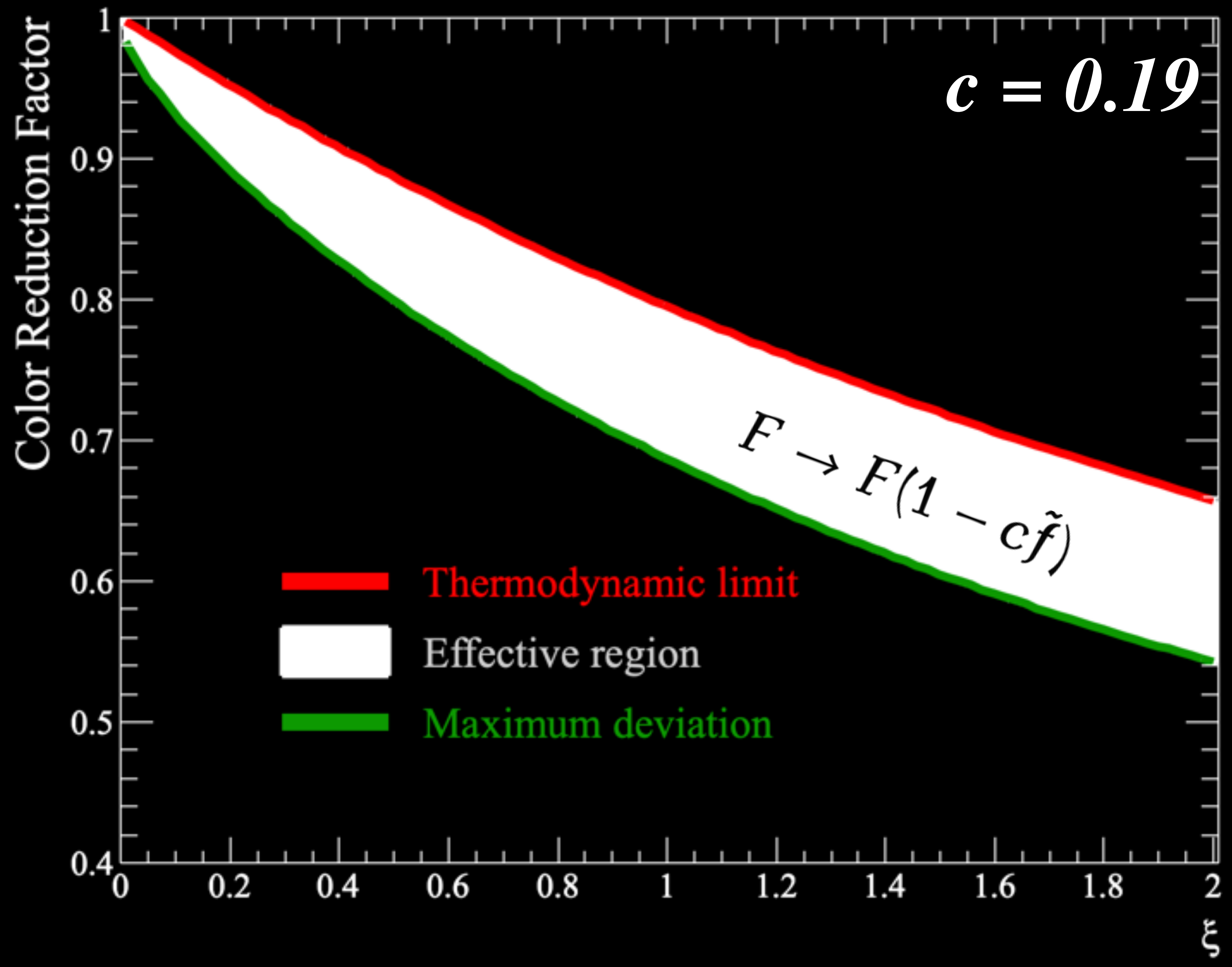
Small areas

We consider areas close to that of a proton parameterized by an impact parameter b

$$S = \pi \left(R_p - \frac{b}{2}\right)\sqrt{R_p^2 - \left(\frac{b}{2}\right)^2} \simeq \pi R_p^2$$

The values of the reduction factor obtained show a greater suppression in the production of particles.

This additional contribution is expressed as an additive term in the color reduction factor formula we use to describe MC data.



$$\tilde{f} = \sqrt{\tanh(\xi/2)}$$

Momentum spectra

Particle production

Particle production in the **low pT region** can be described by the Schwinger mechanism

$$\frac{dN}{dp_T^2} \sim \exp\left(-\pi \frac{p_T^2}{x^2}\right)$$

where *x* is the tensión of the strings.

Thermal distribution

Fluctuations in the chromo-electric field determine a thermal distribution of the form

$$\sim \exp\left(-p_T \sqrt{\frac{2F(\xi)}{\langle p_T^2 \rangle_0}}\right)$$

considering the average squared transverse momentum of a string.

Thermal temperature

From which we can estimate the average thermal temperature as

$$T(\xi) = \sqrt{\frac{\langle p_T^2 \rangle_0}{2F(\xi)}}$$

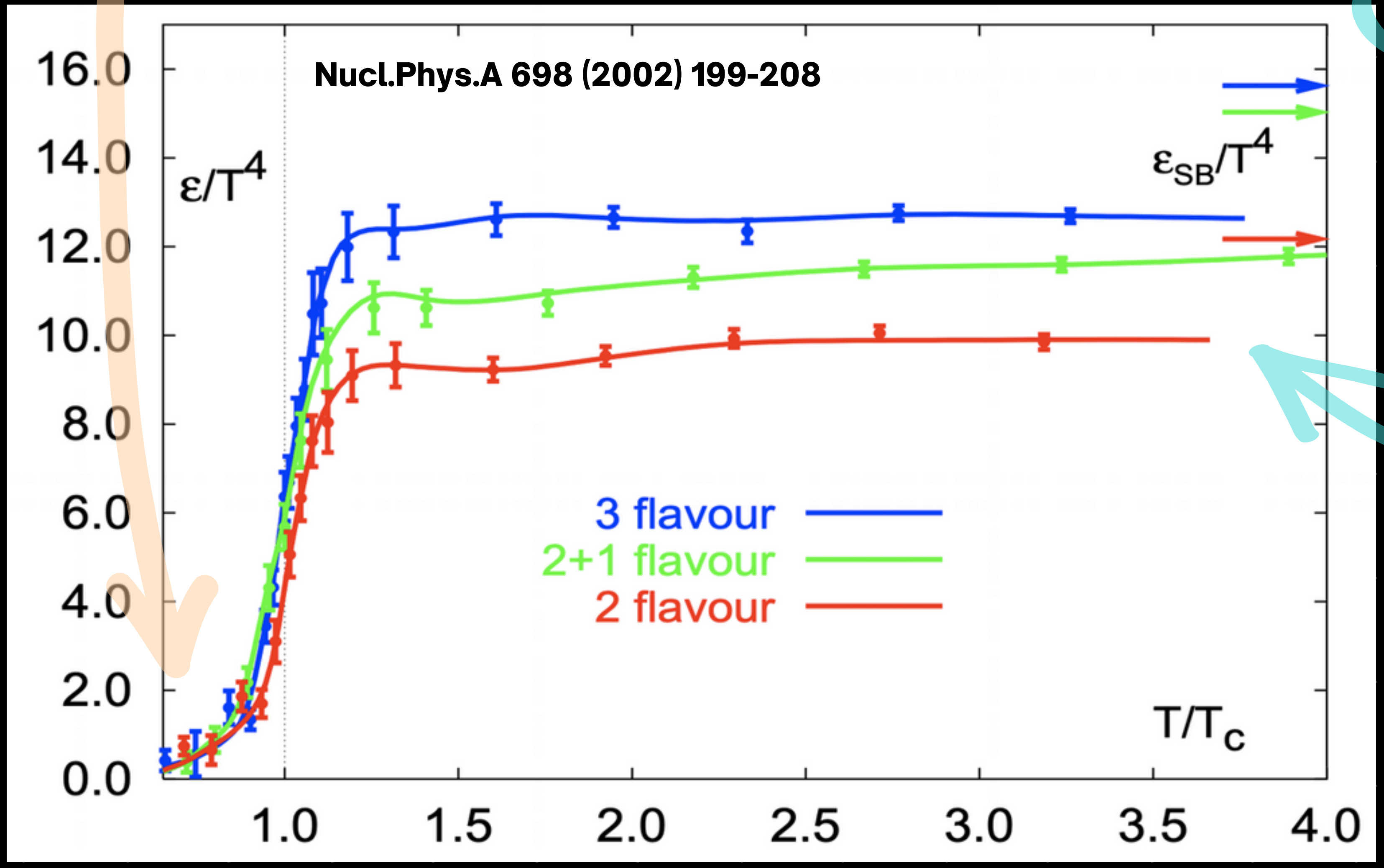
J. S. Schwinger, Phys. Rev. 128 (1962) 2425. doi:10.1103/PhysRev.128.2425;
I. Bautista, A. Fernadez, P. Ghosh, Phys. Re D 92 (2015) 7;

Energy density

Hadron Gas

$$\varepsilon = \frac{\pi^2}{30} 3T^4 \rightarrow \frac{\pi^2}{30}\left[2 \times 8 + \frac{7}{8} \times 2(3) \times 2 \times 2 \times 3\right] T^4$$

Quark-Gloun Plasma



Degrees of freedom count

A phase transition to a system with a high energy density is predicted for a certain critical temperature.

F. Karsch, Lect. Notes Phys. 583 (2002) 209 doi:10.1007/3-540-45792-5
T. D. Lee and G. C. Wick, Phys. Rev. D 9 (1974) 2291. doi:10.1103/PhysRevD.9.2291

Energy density

Order parameters

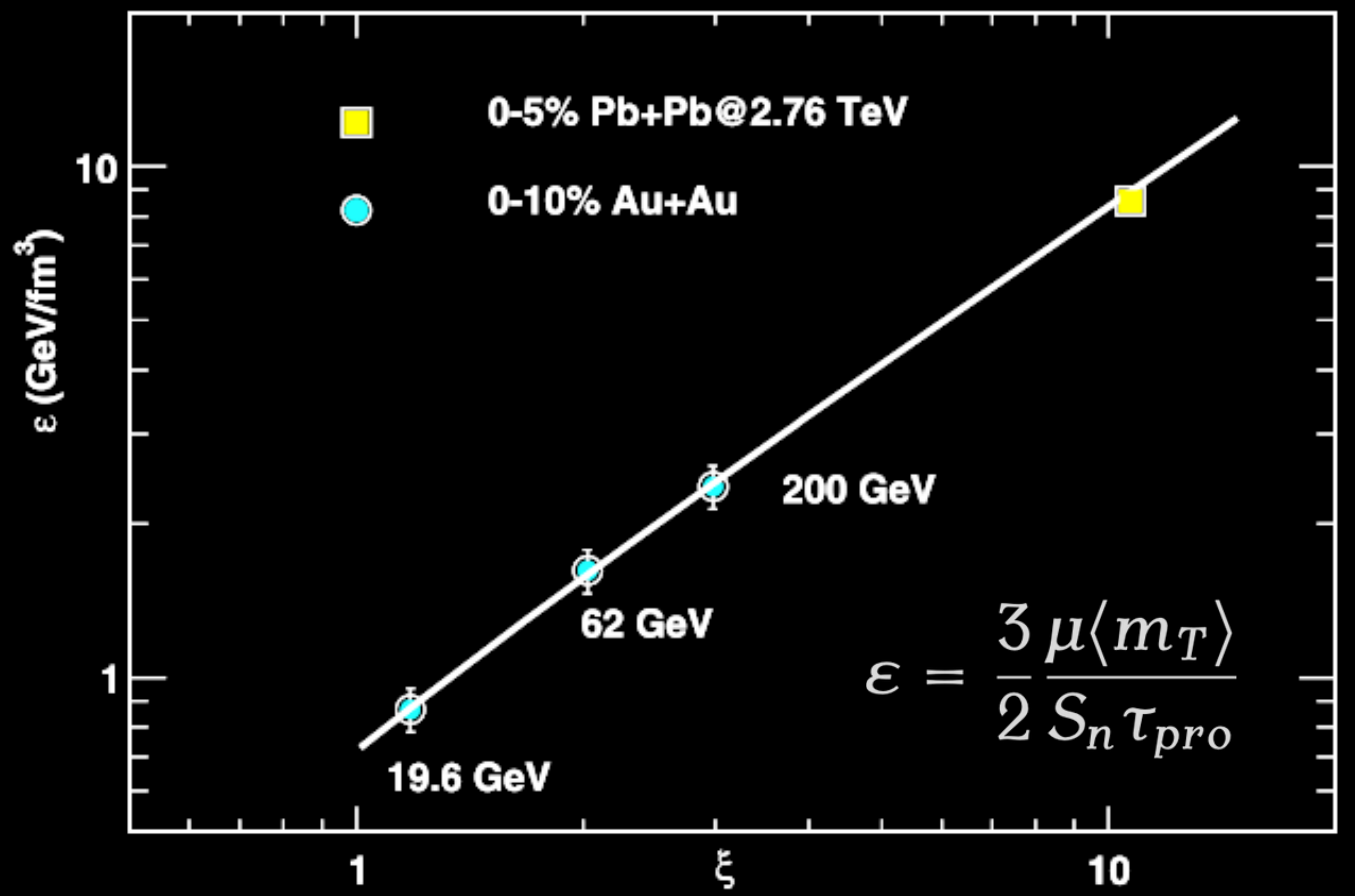
Energy density is the order parameter in the phase transition from HG to QGP, while the string density serves as the order parameter in the geometric phase transition in SPM.

It has been seen that both parameters share a direct relationship, in fact

$$\varepsilon = \varsigma\xi$$

where

$$\varsigma = \varepsilon_c/\xi_c = 0.5601 \ \mathrm{GeV/fm^3}$$

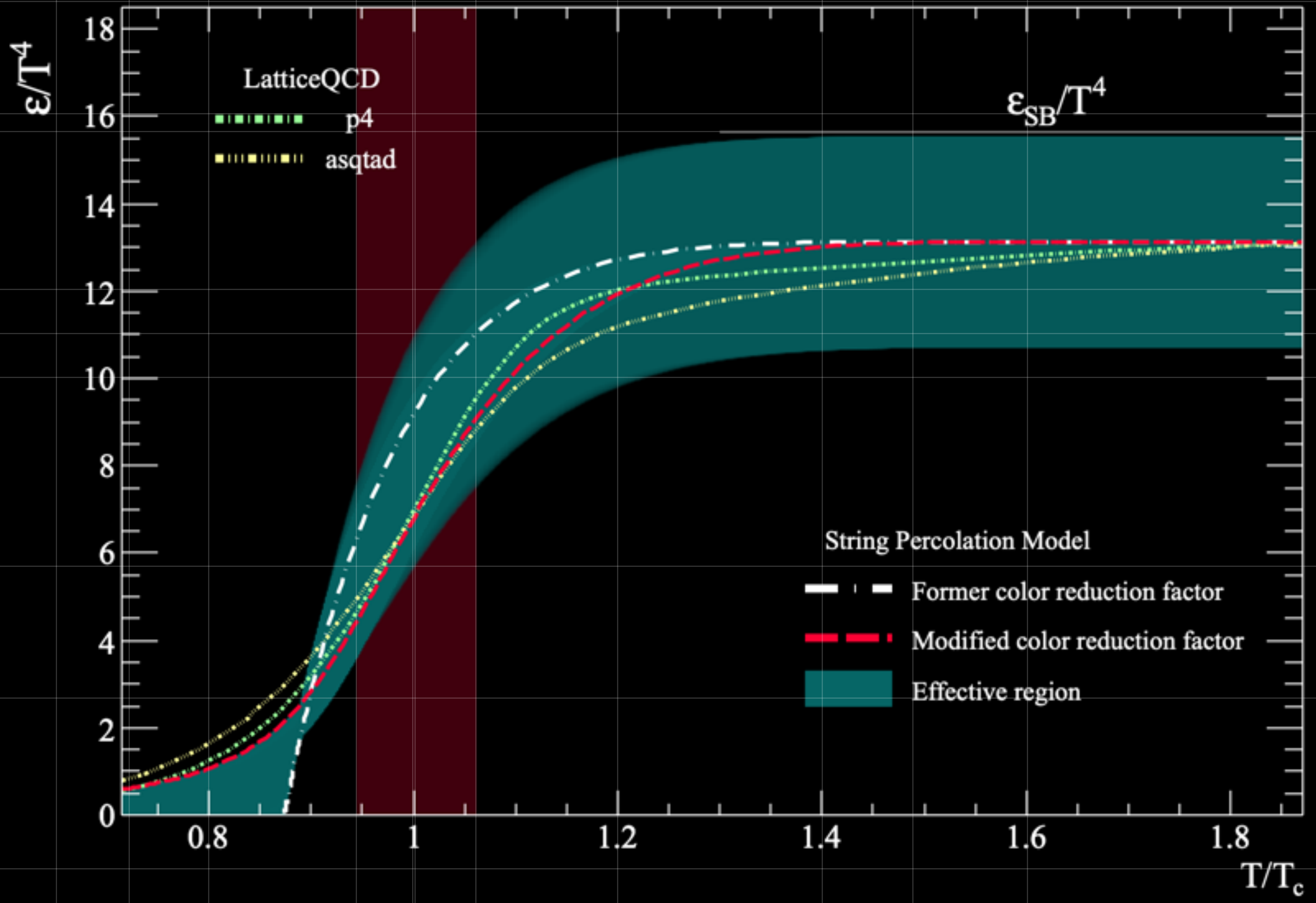


$$\varepsilon = \frac{3\,\mu\langle m_T\rangle}{2\,S_n\tau_{pro}}$$

Bjorken boost invariant 1D hydrodynamics

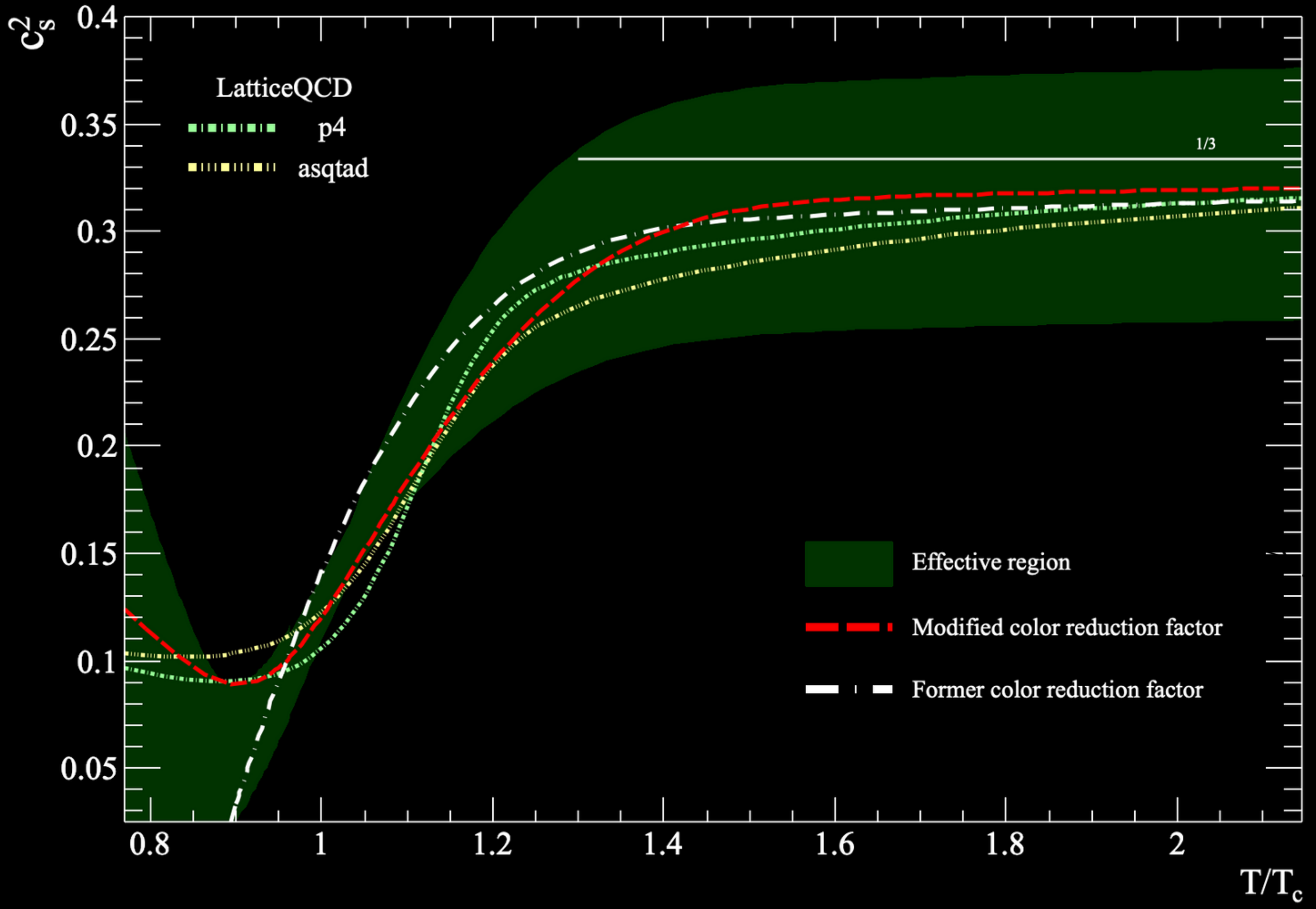
J. D. Bjorken, Highly relativistic nucleus-nucleus collisions: The central rapidity region, Phys. Rev. D 27 (1983) 140
J. Schwinger, Phys. Rev. 128 , 2425 (1962).
M. A. Braun, J. Dias de Deus, A. S. Hirsch, C. Pajares, R. P. Scharenberg, B. K. Srivastava, Phys. Rept. 599 (2015) 1–50. arXiv:1501.01524, doi: 10.1016/j.physrep.2015.09.003

Energy density



M. A. Braun, J. Dias de Deus, A. S. Hirsch, C. Pajares, R. P. Scharenberg, B. K. Srivastava, Phys. Rept. 599 (2015) 1–50. arXiv:1501.01524, doi: 10.1016/j.physrep.2015.09.003
A. Bazavov, et al., Equation of state and QCD transition at finite temperature, Phys. Rev. D 80 (2009) 014504. arXiv:0903.4379, doi:10.1103/PhysRevD.80.014504.

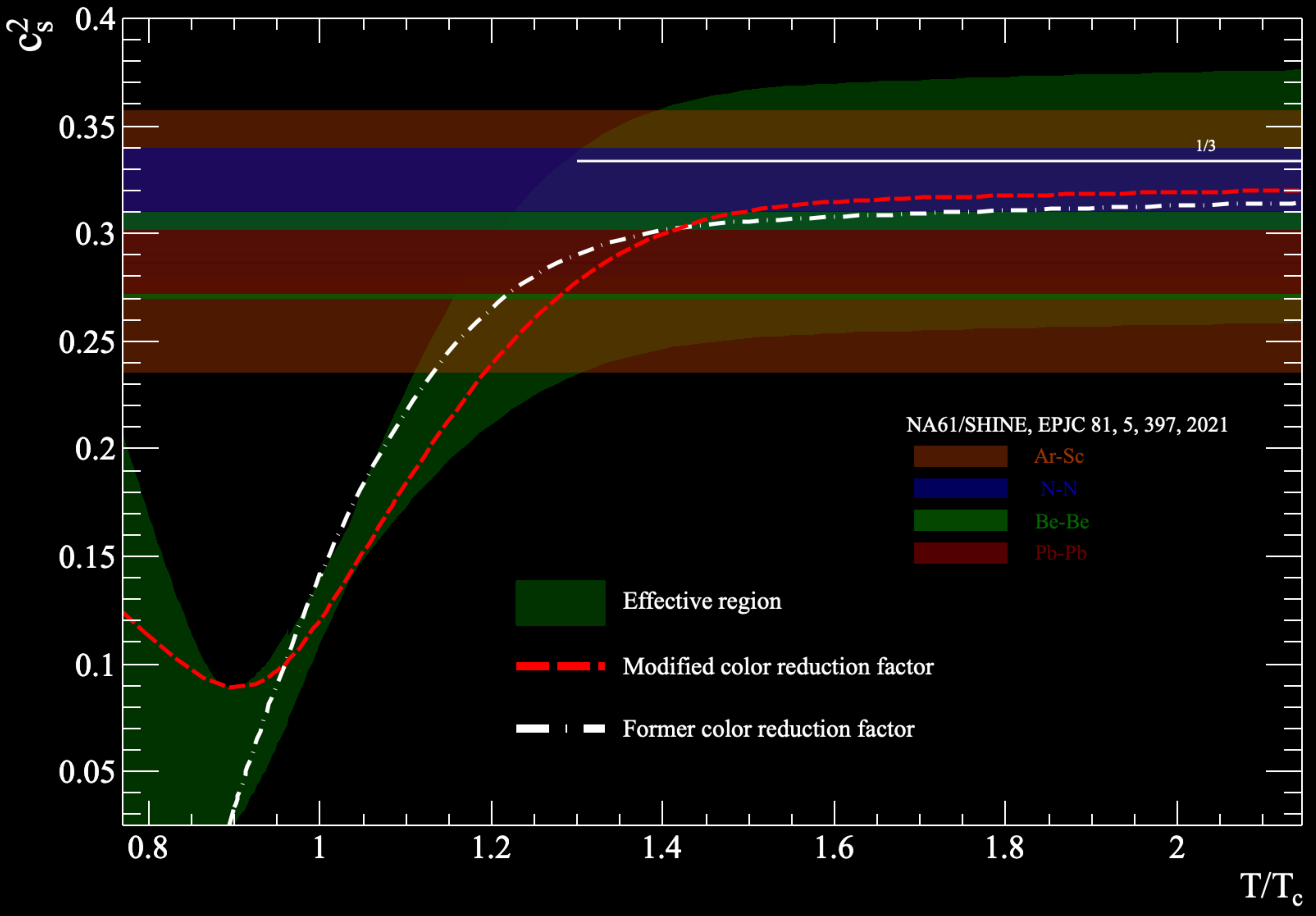
Speed of Sound



$$c_s^2 = \left(\frac{\partial P}{\partial \varepsilon}\right)_s = s\left(\frac{\partial T}{\partial \varepsilon}\right)_s = -\frac{sT}{2\varsigma F}\cdot\frac{dF}{d\xi}$$

Is derived directly from the previous formulaes

Speed of Sound

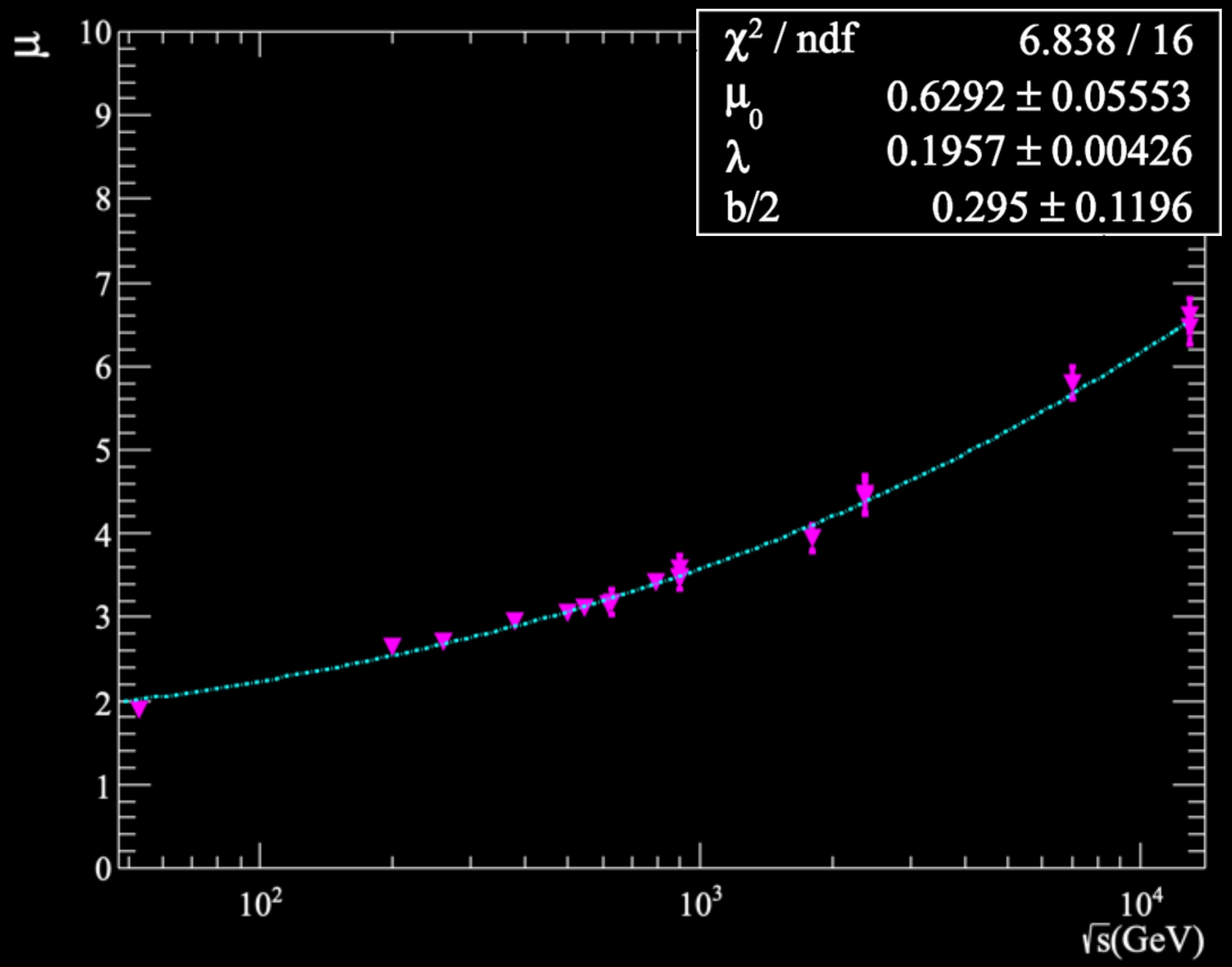


Energy dependence

$$\frac{dN}{d\eta} = \mu_0 F(\xi) N_s$$

$$N_s = 2 + 4\frac{S_0}{S}\left(\frac{\sqrt{s}}{m_p}\right)^{2\lambda}$$

$$S = \pi\left(R_p - \frac{b}{2}\right)\sqrt{R_p^2 - \left(\frac{b}{2}\right)^2} \simeq \pi R_p^2$$



C. Albajar *et al*. [UA1 Collaboration], Nucl. Phys. B 335 (1990) 261. doi:10.1016/0550-3213(90)90493-W
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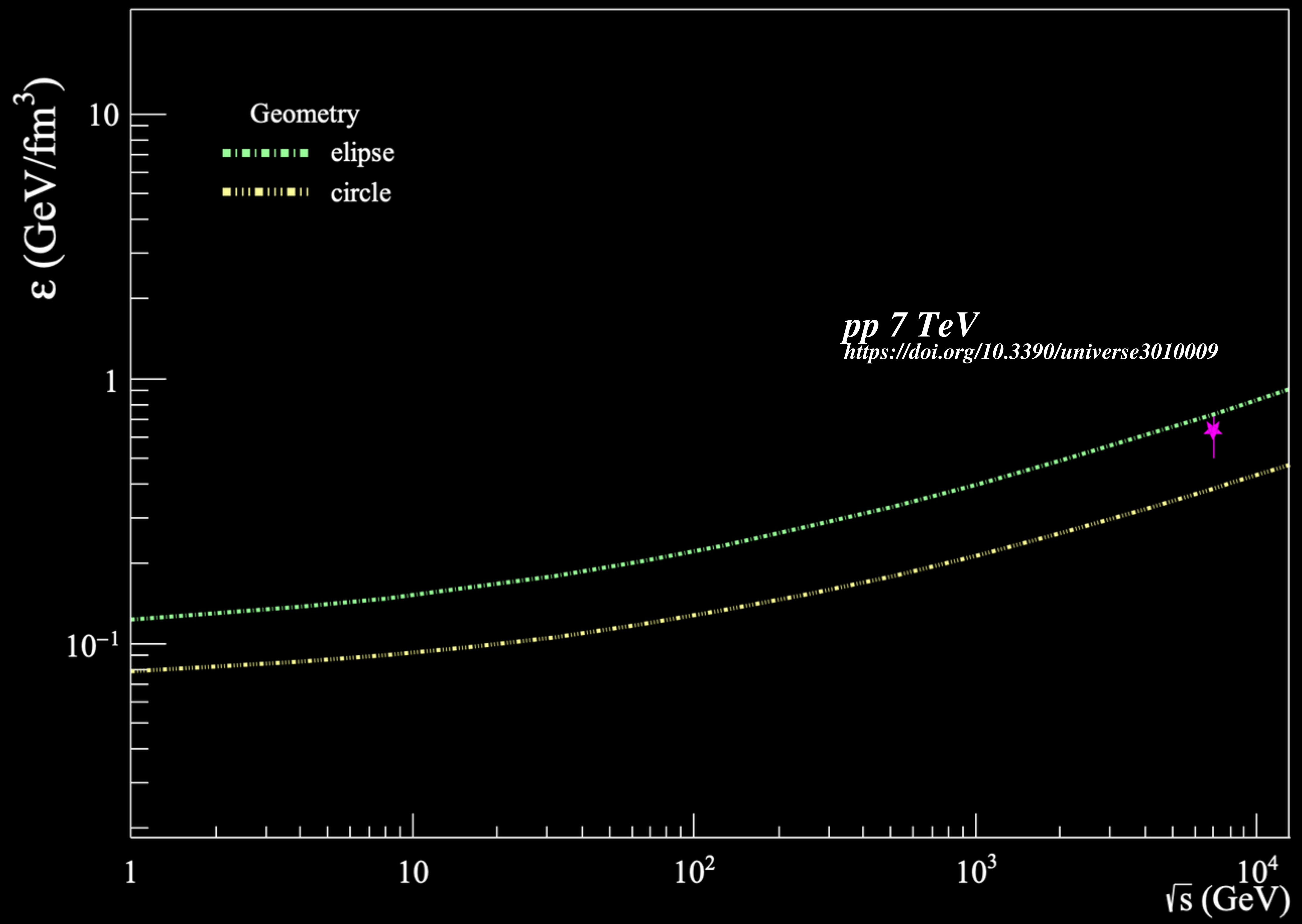
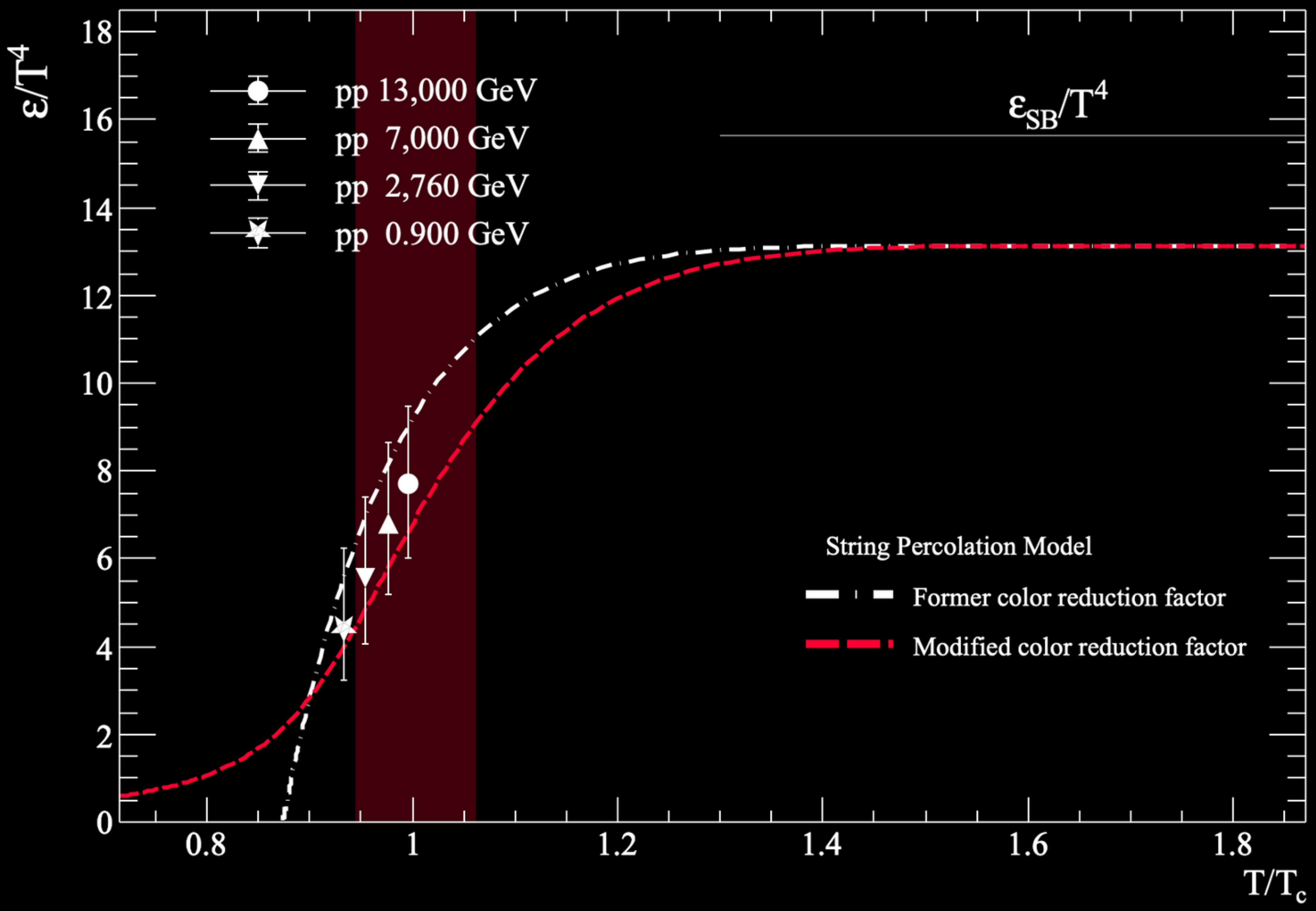
B. I. Abelev *et al*. [STAR Collaboration], Phys. Rev. C 79 (2009) 034909 doi:10.1103/PhysRevC.79.034909 [arXiv:0808.2041 [nucl-ex]].
F. Abe *et al*. [CDF Collaboration], Phys. Rev. D 41 (1990) 2330. doi:10.1103/PhysRevD.41.2330
K. Aamodt *et al*. [ALICE Collaboration], Eur. Phys. J. C 68 (2010) 89 doi:10.1140/epjc/s10052-010-1339-x [arXiv:1004.3034 [hep-ex]].
V. Khachatryan *et al*. [CMS Collaboration], JHEP 1002 (2010) 041 doi:10.1007/JHEP02(2010)041 [arXiv:1002.0621 [hep-ex]].
V. Khachatryan *et al*. [CMS Collaboration], Phys. Rev. Lett. 105 (2010) 022002 doi:10.1103/PhysRevLett.105.022002 [arXiv:1005.3299 [hep-ex]].
J. Adam *et al*. [ALICE Collaboration], Phys. Lett. B 753 (2016) 319 doi:10.1016/j.physletb.2015.12.030 [arXiv:1509.08734 [nucl-ex]].
V. Khachatryan *et al*. [CMS Collaboration], Phys. Lett. B 751 (2015) 143 doi:10.1016/j.physletb.2015.10.004 [arXiv:1507.05915 [hep-ex]].

Energy dependence



Energy dependence



Conclusions

- We have presented the calculation of energy density corresponding to the formed medium in small collisions systems based on LHC data, by including size and initial geometry fluctuation effects.
- The results indicate a clear phase transition which is consistent with the recent collective efects measured for high multiplicity events in small collision systems.

Thanks!

That's all

Viscosity limits

The shear viscosity of strongly coupled N=4 supersymmetric Yang-Mills plasma (AdS/CFT).

$$\frac{\eta}{s} \geq \frac{1}{4\pi}$$

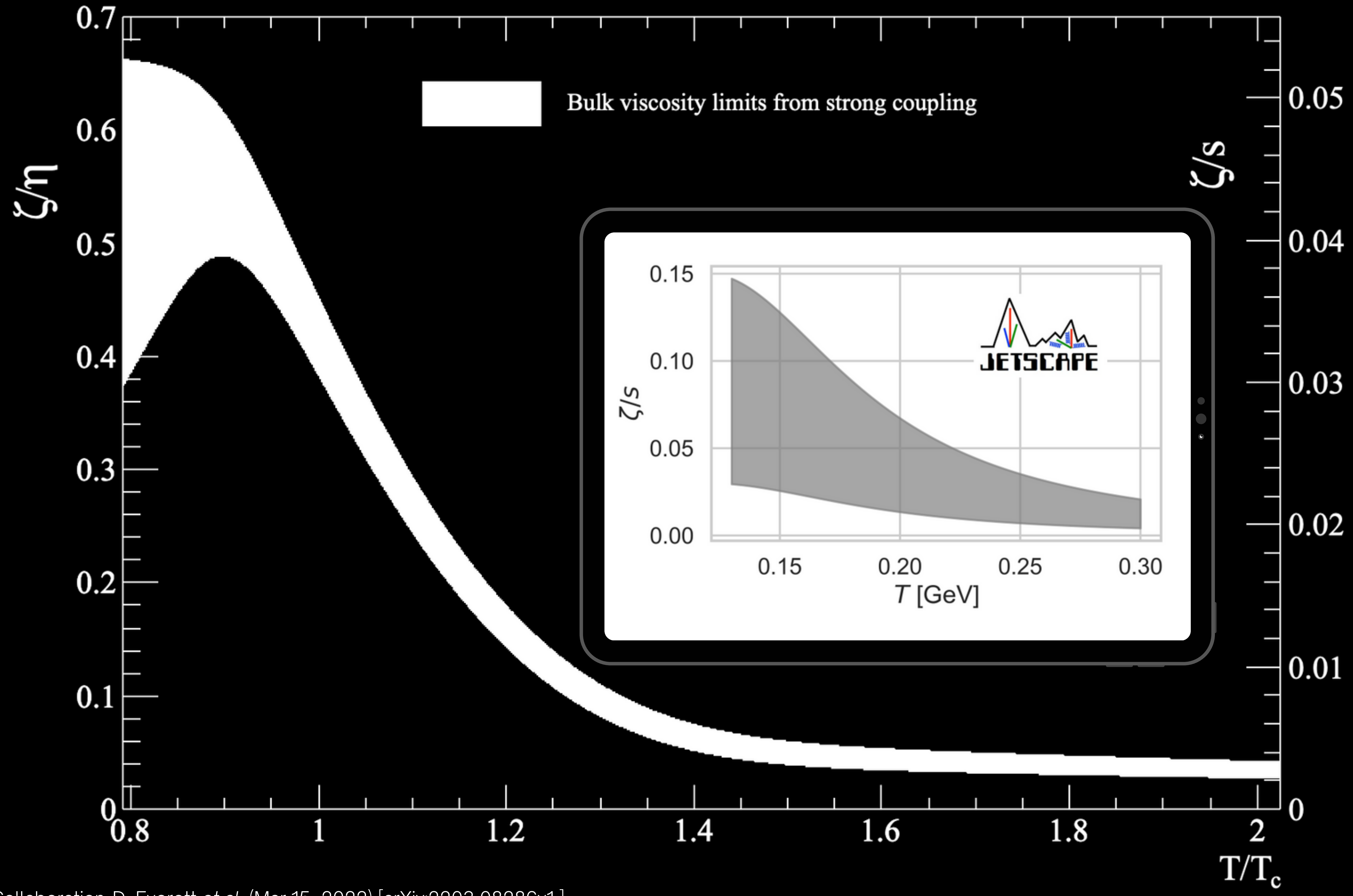
And the conformal of gauge theory plasma at strong coupling establish a lower limit of the bulk over shear viscosity coeficient:

$$\frac{\zeta}{\eta} \geq 2\left(\frac{1}{3} - c_s^2\right)$$

$$\frac{\zeta}{s} \geq 2\left(\frac{1}{3} - c_s^2\right)\frac{\eta}{s} \geq \frac{1}{2\pi}\left(\frac{1}{3} - c_s^2\right)$$

G. Policastro, D. T. Son, A. O. Starinets, Phys. Rev. Lett. 87 (2001) 081601. arXiv:hep-th/0104066, doi:10.1103/PhysRevLett.87. 081601
A. Buchel, Phys. Lett. B 663 (2008) 286–289. arXiv:0708.3459, doi:10.1016/j.physletb.2008.03. 069.

Viscosity limits



JETSCAPE Collaboration•D. Everett *et al*. (Mar 15, 2022) [arXiv:2203.08286v1]

Viscosity reported