Percolation approach applied to QCD

Dagmar Bendová

Faculty of Nuclear Sciences and Physical Engineering
Czech Technical University in Prague

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Color strings and confinement

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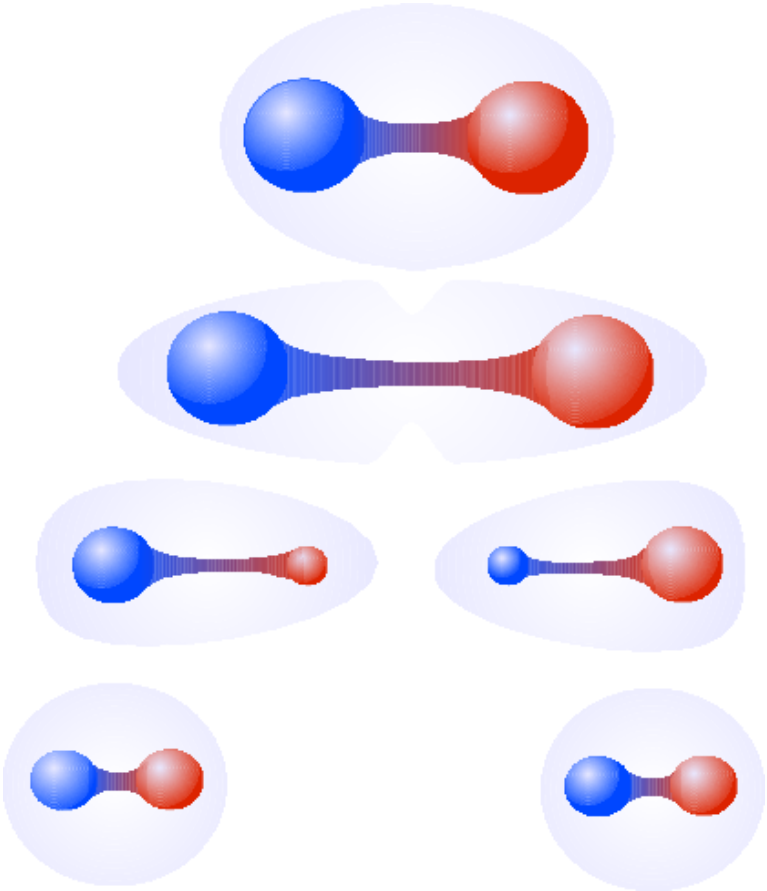
- Quarks and gluons are color-charged particles
- Single quarks and gluons are never seen isolated, always form colorless hadrons
- The gluon field between the quarks forms a narrow flux tube (string)
- With increasing separation the string stretches, the field does not weaken ($\alpha_S \to 1$)
- At large separation a new $q\bar{q}$ pair is created
- Several hadronization models

  $\to$ the best know is Lund string model

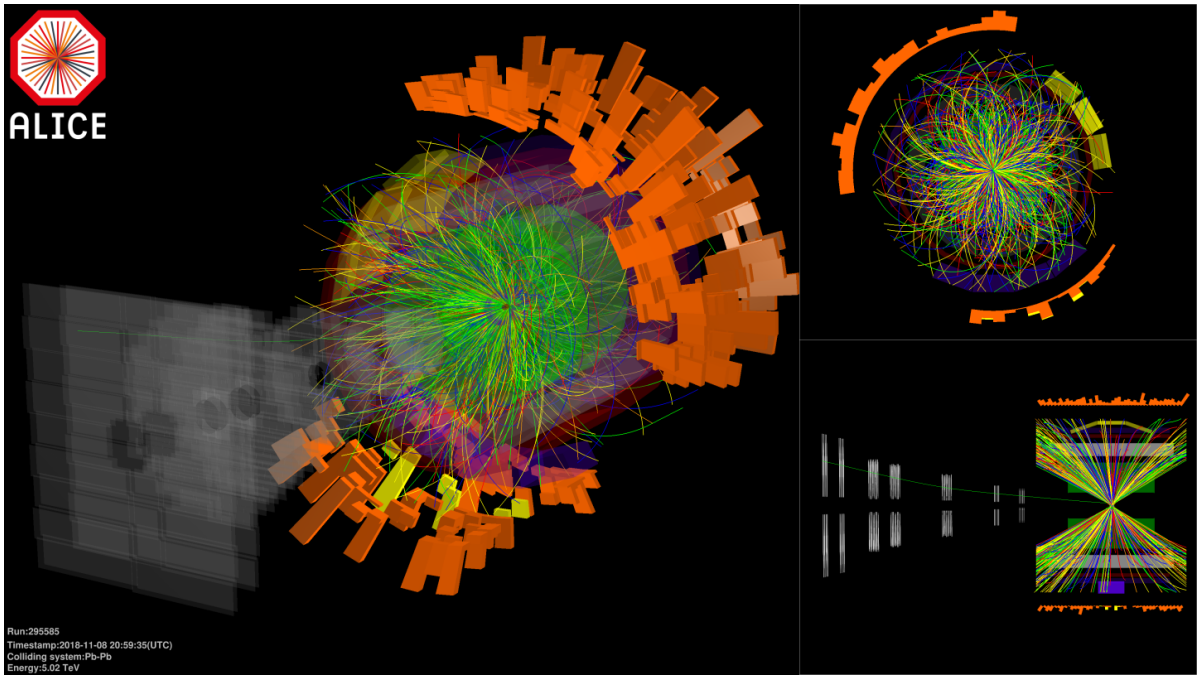


Multiparticle production at high energies

- Color strings stretched between the projectile and target

Multiparticle production at high energies

- Color strings stretched between the projectile and target
- Observed hadrons produced from hadronization of these strings
- Low energies – strings from valence quarks hadronize
- Number of strings grows with E and A



Clustering of color sources

- Color strings $\rightarrow$ small discs in the transverse space of area πr_0^2; $r_0 \approx 0.2\ \mathrm{fm}$
- Discs are filled with color field created by colliding partons
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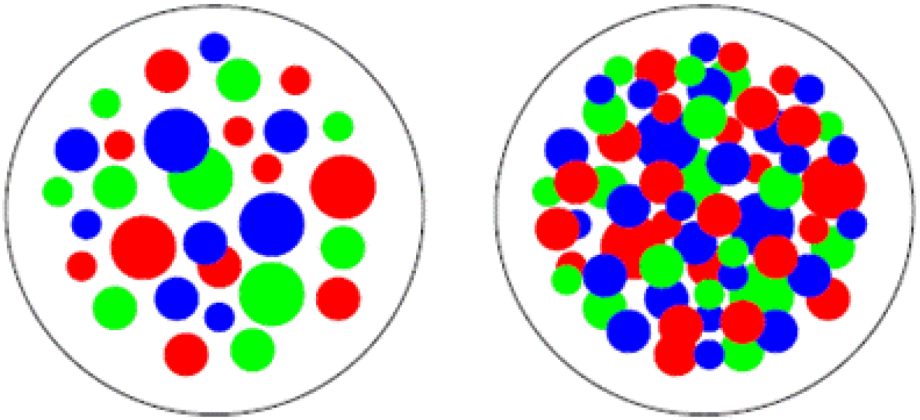
- Discs are filled with color field created by colliding partons
  $\rightarrow$ similar to discs in 2D percolation theory
- Growing E and A $\rightarrow$ number of strings grows and strings overlap
- Overlapping strings form clusters of color charge
- At some critical density of color strings, a macroscopic cluster appears
  $\rightarrow$ percolation phase transition



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- Resulting field covers area S_n of the cluster
- With more overlapping, multiplicity is suppressed and average transverse momentum squared is increased

$$\mu_n = \sqrt{\frac{nS_n}{S_1}}\mu_0; \qquad < p_T^2 >= \sqrt{\frac{nS_1}{S_n}} < p_T^2 >_1$$

Percolation of color strings

- Moreover

$$< \frac{nS_1}{S_n} >= \frac{\xi}{1 - \mathrm{e}^{-\xi}} \equiv \frac{1}{F(\xi)^2}$$

  - $F(\xi)$ – color suppression factor
  - $\xi = \frac{N_S S_1}{S_N}$ – percolation density parameter (finite for large N_S and S_N)
  - Critical cluster spanning over total interaction area S_N appears for $\xi_C \geq 1.2$

- Multiplicity and average transverse momentum squared:

$$\mu_n = F(\xi)\mu_0; \qquad < p_T^2 >_n = \frac{< p_T^2 >_1}{F(\xi)}$$

Percolation Approach to Quark-Gluon Plasma and J/ψ Suppression

N. Armesto, M. A. Braun, E. G. Ferreiro, and C. Pajares
Phys. Rev. Lett. **77**, 3736 – Published 28 October 1996

Article | References | Citing Articles (130) | PDF | Export Citation

ABSTRACT

It is shown that the critical threshold for percolation of the overlapping strings exchanged in heavy ion collisions can naturally explain the sharp strong suppression of J/ψ shown by the experimental data on central Pb-Pb collisions, which does not occur in central O-U and S-U collisions.

Received 3 July 1996

Some historical context

- Matsui & Satz – PLB 178 (1986) 416-422
  - High energy heavy-ion collisions lead to formation of hot QGP
  - Screening of color charges
  - $c\bar{c}$ can't bind in the deconfined strongly interacting matter
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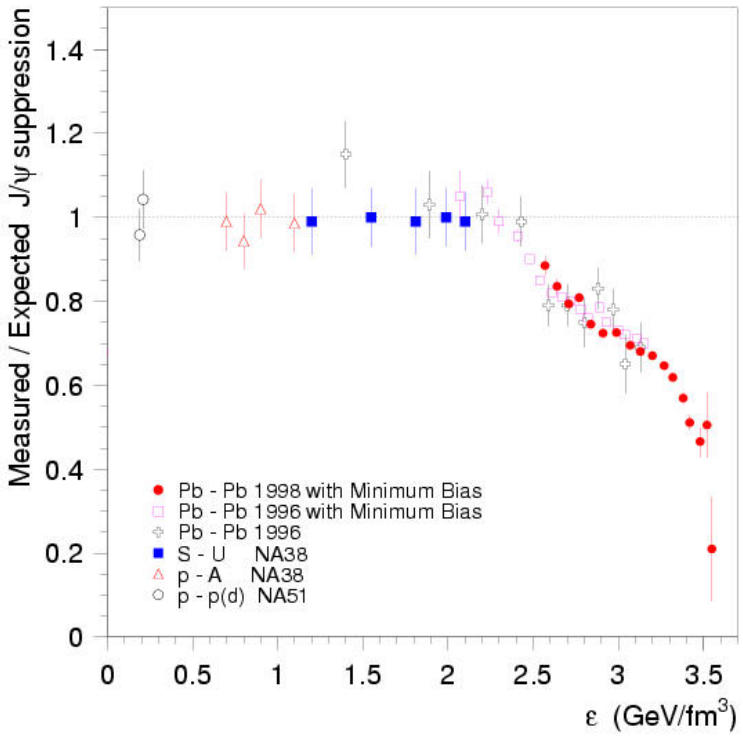
  - J/ψ suppression in nuclear collisions
- From 80s – experiments to create deconfined quark matter in CERN
- Formation of QGP confirmed at RHIC from several observables (flow, jet-quenching, comparison to dAu) in 2004 – Nucl.Phys.A757 (2005) 102-183

Some historical context

- NA50 collaboration – QM 1996, PLB 477 (2000) 28
  - Strong J/ψ suppression observed in central Pb-Pb at 158 AGeV/c per nucleon
  - Sharp enhancement of the suppression observed with increasing centrality
  - Suppression in peripheral Pb-Pb collisions comparable to central S-U
  - Evidence for deconfinement of quarks and gluons from the J/psi suppression pattern measured in Pb-Pb collisions at the CERN-SPS



Proposal

Continuum percolation of color strings can describe difference in J/ψ suppression between central O-U and S-U collisions, peripheral Pb-Pb, and central Pb-Pb collisions.

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Predictions for RHIC and LHC energies can be made.

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- For case of two-string fusion – effective radius $r = 0.36\ \mathrm{fm}$
- The region where many strings fuse – droplet of QGP
- Droplets overlap $\rightarrow$ QGP domain of size comparable to the nuclear size

  $\rightarrow$ **percolation**

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- Additional changes like repulsive interaction, hard core or different shape of strings

  don't change the result much

Results of the percolation approach to QGP

- At SPS energies, critical density reached only in central Pb-Pb collisions
- Strong suppression of J/ψ production observed only in central Pb-Pb at SPS
- Suppression also expected in central S-U at RHIC and S-S at the LHC

$\sqrt{s}$ (AGeV)	Collision			
	$p-p$	$S-S$	$S-U$	$Pb-Pb$
19.4	4.2	123	268	1145
	1.3	3.5	7.6	9.5
200	7.2	215	382	1703
	1.6	6.1	10.9	14.4
5500	13.1	380	645	3071
	2.0	10.9	18.3	25.6

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  - Fluctuations in the transverse momentum
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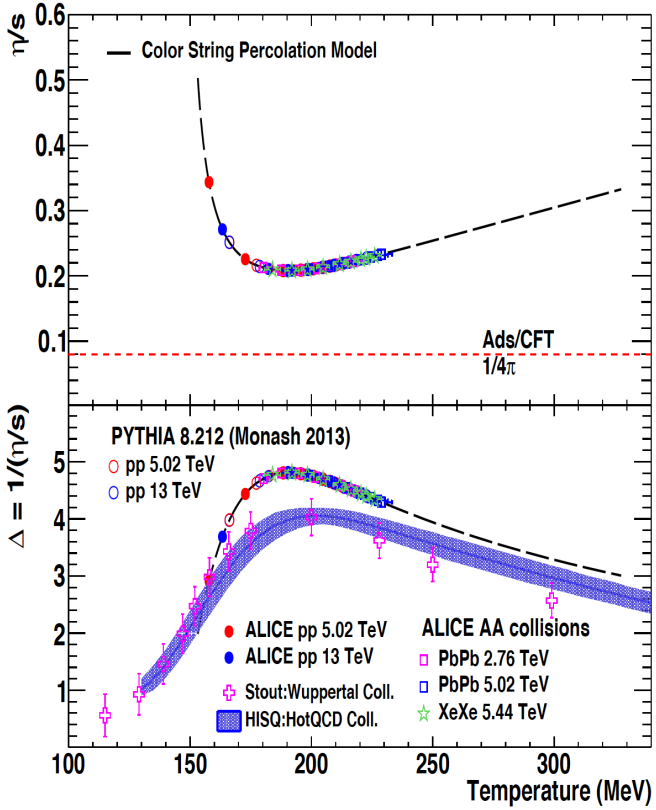
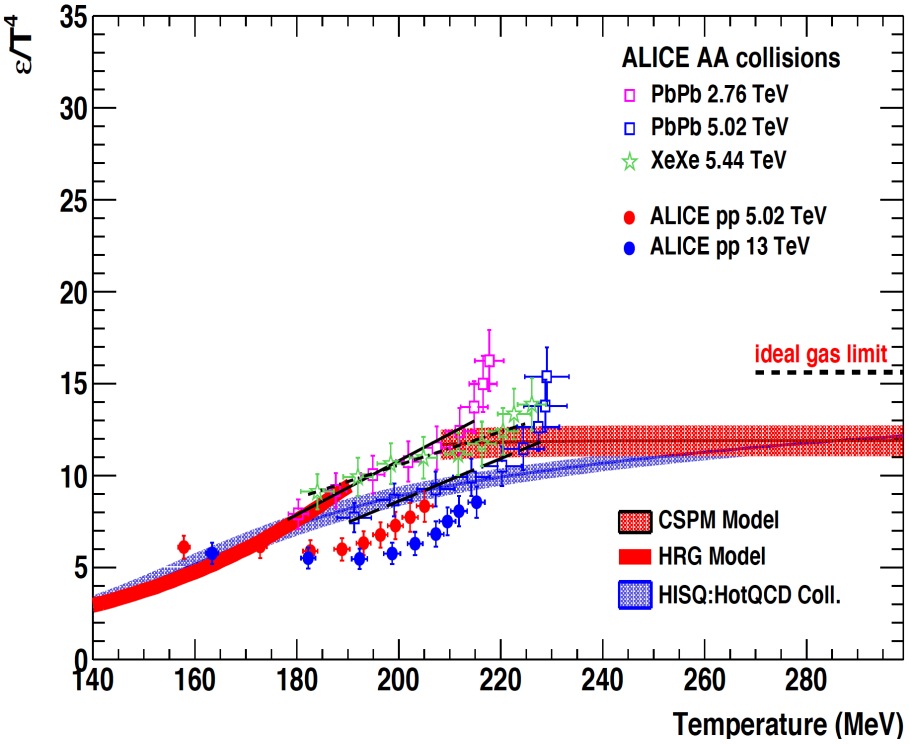
  - Correlations
  - QGP properties - temperature, energy density, trace anomaly, shear viscosity, EoS





Pajares et al., see e.g. Eur.Phys.J.C43:9-14,2005 or PoS(LHCP2019)004

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- Results in the suppression of particle multiplicity
- $\frac{<p_T^2>_1}{F(\xi)}$ plays the role of saturation scale Q_s^2 from CGC

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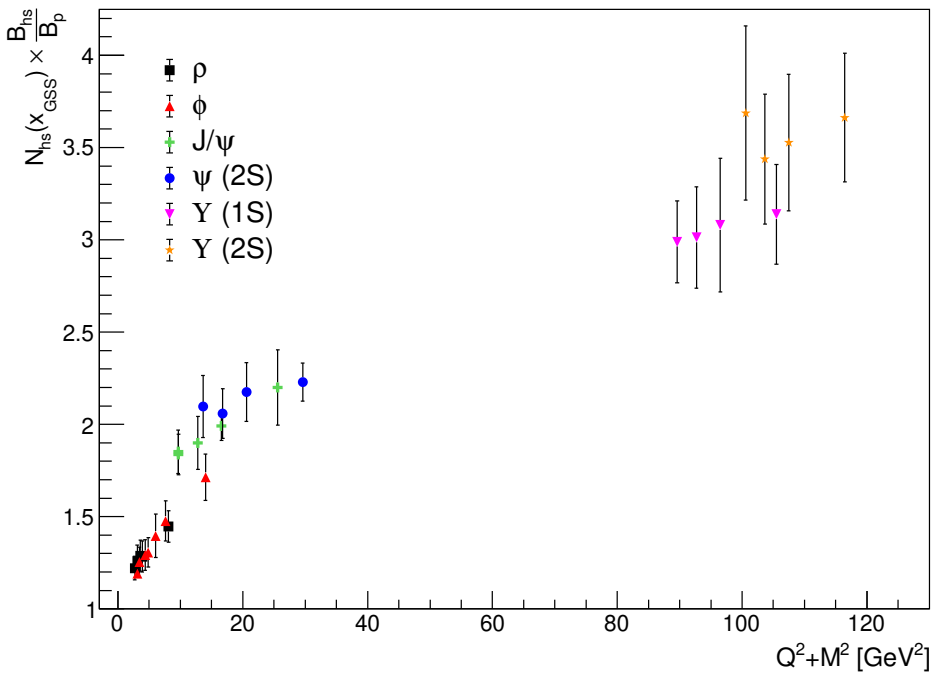
  - No satisfactory general agreement :(



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- There is an analogy/similarity to saturation model in CGC framework.