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Evidence for hadronic deconfinement in p̄–p collisions at 1.8 TeV

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Abstract

We have measured deconfined hadronic volumes, $4.4 < V < 13.0\ \mathrm{fm}^3$, produced by a one-dimensional (1D) expansion. These volumes are directly proportional to the charged particle pseudorapidity densities $6.75 < dN_c/d\eta < 20.2$. The hadronization temperature is $T = 179.5 \pm 5$(syst) MeV. Using Bjorken's 1D model, the hadronization energy density is $\epsilon_F = 1.10 \pm 0.26$(stat) $\mathrm{GeV/fm}^3$ corresponding to an excitation of 24.8 ± 6.2(stat) quark–gluon degrees of freedom.

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The observation of high total multiplicity, high transverse energy, non-jet, isotropic events [1] led Van Hove [2] and Bjorken [3] to conclude that high energy density events are produced in high energy p̄–p collisions [4]. These events have a far greater cross section than jet production. In these events the transverse energy is proportional to the number of low transverse momentum particles. This basic correspondence can be explored over a wide range of the charged particle pseudorapidity density $dN_c/d\eta$ in p̄–p collisions at center of mass energy $\sqrt{s} = 1.8$ TeV. The various measurements from the Fermilab quark–gluon plasma search experiment E-735 have already

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been published. In this Letter we present for the first time a coherent picture based on the relationship between the volume V, temperature T, energy density ϵ_F, and pions per fm^3 n_π emitted from V. Spectra of identified particles, π, K, φ, p, $\bar{\text{p}}$, Λ^0 $\overline{\Lambda^0}$, Ξ^-, $\overline{\Xi^-}$ are used to extract the V, ϵ_F, and n_F values and to determine the strange quark content and relative yields of the hadrons.

Previously the various individual measurements did not provide an overall understanding of these $\bar{\text{p}}$–p collisions. Prompted by the new analysis of the initial collision, we have developed a self-consistent picture of hadronic deconfinement. This letter discusses: (1) The role of parton–parton (gluon) scattering; (2) The volume at decoupling, resulting from the one-dimensional longitudinal expansion; (3) The number of pions per fm^3 emitted by the source; (4) The hadronization temperature of the source; (5) The hadronization energy density of the source; (6) The number of quark–gluon degrees of freedom in the source; (7) The deconfined volumes and plasma lifetimes, estimates of initial energy densities and temperatures.

Experiment E-735 [5] was located at the CØ interaction region of the Fermi National Accelerator Laboratory (FNAL). The $\bar{\text{p}}$–p interaction region was surrounded by a cylindrical drift chamber which in turn was covered by a single layer hodoscope including endcaps. This system measured the total charged particle multiplicity $10 < N_c < 200$ in the pseudorapidity range $|\eta| < 3.25$. A magnetic spectrometer with tracking chambers and time of flight counters, provided particle identified momenta spectra in the range $0.1 < p_t < 1.5$ GeV/c. The spectrometer covered $-0.37 < \eta < +1.00$ with $\Delta\varphi \sim 20^\circ$ (φ is the azimuthal angle around the beam direction).

1. Recently the E-735 collaboration has analyzed the charged particle multiplicity distributions arising from p–p and $\bar{\text{p}}$–p collisions over a range of center of mass energies $0.06 \leqslant \sqrt{s} \leqslant 1.8$ TeV [6]. Results at 1.8 TeV support the presence of double (σ_2) and triple (σ_3) parton interactions. These processes increase the non-single diffraction cross section (NSD) from ~ 32 mb at $\sqrt{s} = 0.06$ TeV to ~ 48 mb at $\sqrt{s} = 1.8$ TeV. The variation of the double encounter and triple encounter cross sections σ_2 and σ_3 with center of mass energy $\sqrt{s}$ is shown in Fig. 1.

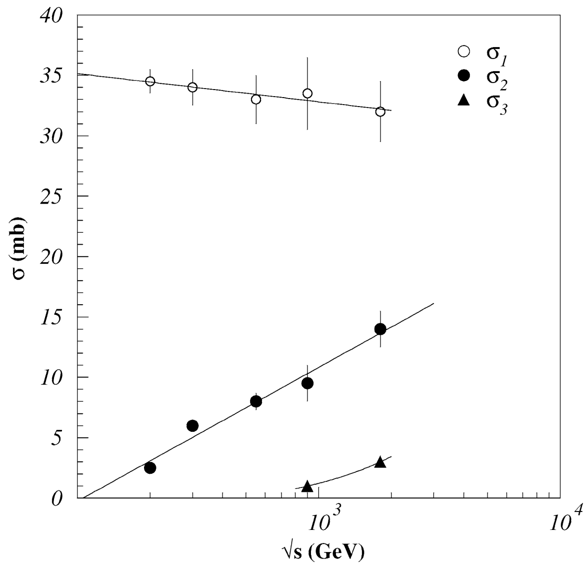

Fig. 1. Comparison of the cross-sections for single, double, and triple encounter collisions which increase σ_{NSD} above 32 mb as a function of $\sqrt{s}$.

The multiplicity distribution is made up of three contributions corresponding to single, double and triple parton–parton collisions. Our work on multiparton interactions shows that the increase in the p–p inelastic cross-section with energy is nearly completely accounted for by the increase in multiparton interactions. Previously this increase in the p–p inelastic cross-section was ascribed to copious minijet production [7]. As the energy is increased, a decreasing fraction of the center of mass energy appears in the NSD part of the inelastic cross-section. This may be due to the decrease of the Feynman x of the partons involved in these collisions. It is thus likely that gluons become more involved with increasing energy leading to rapid thermalization [8].

2. To measure the hadronization volume V, pion HBT (Hanbury Brown, Twiss) correlation measurements were made as a function of both $\vec{P}_{\pi\pi} = \vec{p}_1 + \vec{p}_2$ the total momentum of the pion pair and of $dN_c/d\eta$. The $\vec{P}_{\pi\pi}$ momentum dependent results are shown in Table 1 [9]. R_G is the Gaussian radius parallel to the beam, τ the Gaussian lifetime, and λ the chaoticity pa-

Table 1
Fitted values of radius R_G, lifetime τ, and chaoticity λ in the Gaussian parameterization with respect to q_t and q_0. Values are a function of average two-pion total momentum $P_{\pi\pi}$ or average two-pion transverse momentum P_t. The total momentum interval containing the data is listed in column 1. Momentum is in GeV/c. The errors are statistical

$P_{\pi\pi}$	$\langle P_{\pi\pi}\rangle$	R_G (fm)	τ (fm)	λ	$\langle P_t\rangle$
0.2–0.5	0.404	1.20 ± 0.05	0.95 ± 0.06	0.24 ± 0.01	0.369
0.2–0.7	0.503	1.05 ± 0.08	0.71 ± 0.05	0.25 ± 0.01	0.462
0.5–1.0	0.708	0.80 ± 0.07	0.67 ± 0.07	0.23 ± 0.02	0.650
0.7–1.2	0.900	0.60 ± 0.06	0.64 ± 0.05	0.26 ± 0.03	0.832
0.9–1.7	1.175	0.58 ± 0.06	0.53 ± 0.07	0.26 ± 0.02	1.087
>1.0	1.403	0.48 ± 0.06	0.45 ± 0.05	0.21 ± 0.02	1.285
>1.2	1.600	0.43 ± 0.06	0.41 ± 0.06	0.23 ± 0.02	1.479

Table 2
Fitted values of the (longitudinal) radius R_G (transverse) lifetime τ and corrected chaoticity λ in the Gaussian parameterization with respect to q_t and q_0. Values are a function of the average charged multiplicity per unit of pseudorapidity. Charged particle multiplicity intervals containing the data are listed in column 1. The errors are statistical

N_c	$\langle dN_c/d\eta\rangle$	R_G (fm)	τ (fm)	λ
0–60	6.75	0.62 ± 0.09	0.53 ± 0.07	0.39 ± 0.05
0–80	9.00	0.70 ± 0.09	0.65 ± 0.06	0.32 ± 0.03
60–100	12.5	1.00 ± 0.08	0.86 ± 0.12	0.25 ± 0.01
80–120	15.5	1.10 ± 0.10	0.89 ± 0.12	0.23 ± 0.01
100–240	18.2	1.52 ± 0.14	0.99 ± 0.15	0.21 ± 0.02
120–240	20.17	1.86 ± 0.35	0.88 ± 0.20	0.19 ± 0.03

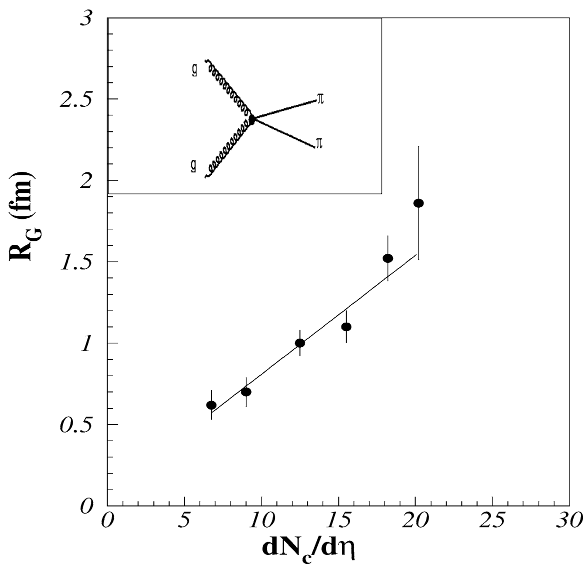

Fig. 2. Dependence of the Gaussian radius R_G on $dN_c/d\eta$. The gluon diagram indicates that two gluons are required to form two pions.

rameter. The lifetime τ can be viewed as a measure of the radius perpendicular to the beam [10]. The increase of R_G and τ with decreasing $P_{\pi\pi}$ is the characteristic signature for the expansion of the pion source [11]. The dependence of R_G and τ on $dN_c/d\eta$ is shown in Table 2 [9]. A clear increase of R_G with $dN_c/d\eta$ is evident. The dependence of R_G and τ on $P_{\pi\pi}$ and $dN_c/d\eta$ is consistent with a one-dimensional (1D) longitudinal expansion of the pion source. The effect of a 1D-expansion on the Bose–Einstein correlation has been calculated for a massless relativistic ideal gas [12]. This calculation provides correction factors ℓ_R and ℓ_τ to our values of R_G and τ obtained from the HBT analysis. Both ℓ_R and ℓ_τ are a function of $P_{\pi\pi}$ and $\Delta\eta$, where $\Delta\eta$ is the spectrometer aperture. The cylindrical volume V of the pion source is $V = \pi(\ell_\tau\tau)^2 2\ell_R R_G$, where R_G varies with $dN_c/d\eta$ and $\ell_\tau\tau$ reaches an asymptotic value for the larger $dN_c/d\eta$ values. From our data $R_G = e + h\,dN_c/d\eta$, where $e = (0.0788 \pm 0.013)$ fm and $h = (0.0730 \pm 0.011)$ fm and $\chi^2/\mathrm{NDF} = 3.09/4.00$ as shown in Fig. 2. We neglect e since $h\,dN_c/d\eta$ is 6 to 20 times larger than e. The cylindrical volume becomes

$$V = \pi \ell_\tau^2 \tau^2 2\ell_R h \frac{dN_c}{d\eta}. \tag{1}$$

The largest measured value of $\tau = 0.95$ fm is used to evaluate V. We estimate the ℓ factors using the extrapolation procedure ($P_{\pi\pi} \to 0$) outlined in Ref. [12]. (See, in particular, Fig. 4 and Eq. (7) in Ref. [12]). For our $P_{\pi\pi}$ values and a 1D-expansion, $\ell_\tau = 1$ is independent of $P_{\pi\pi}$. For the data in Table 2 $\ell_R = 1.56$. Thus $V = (0.645 \pm 0.130)\,dN_c/d\eta$ fm^3

and the range of V is $4.4 \pm 0.9 < V < 13.0 \pm 2.6$ fm^3 for $6.75 < dN_c/d\eta < 20.2$.

3. We assume that for $dN_c/d\eta > 6.75$ the system is above the deconfinement transition. The hot thermalized system expands, cools and then hadronizes. We attribute all of the measured volume to the expansion before hadronization. We neglect the subsequent expansion of the hadronic phase. Following Bjorken's derivation, we further assume that hydrodynamics of a massless relativistic ideal gas can describe the 1D expansion and that the observed number of pions/fm^3 are *proportional to the entropy density s at hadronization*. To estimate the pions/fm^3 emitted by the source, the Bjorken 1D boost invariant equation becomes

$$s \propto n_\pi = \frac{(3/2)(dN_c/d\eta)}{A\,2\mathcal{T}}, \tag{2}$$

where A is the transverse area and $\mathcal{T}$ is the proper time [13]. The collisions occur at longitudinal coordinate $z = 0$ and time $t = 0$. Eq. (2) describes an isentropic expansion $s(\mathcal{T})/s(\mathcal{T}_0) = \mathcal{T}_0/\mathcal{T}$ and

$$\mathcal{T} = \left(t^2 - z^2\right)^{1/2}, \tag{3}$$

where $\mathcal{T}_0$ is the initial proper time when thermalization has occurred. For a relativistic massless ideal gas above the phase transition the maximum expansion velocity, responsible for most of the longitudinal expansion, is likely to be the sound velocity, $v_s^2 = 1/3$ [13]. The expansion time $t = z/v_s = \ell_R R_G/v_s$ and $\mathcal{T} = (3z^2 - z^2)^{1/2} = \sqrt{2}\,z$. We note that $\mathcal{T}_f$ is the proper time at hadronization.

$$\mathcal{T}_f = \sqrt{2}\,\ell_R R_G = \sqrt{2}\,\ell_R h \frac{dN_c}{d\eta}, \tag{4}$$

and Eq. (2) becomes

$$n_\pi = \frac{(3/2)(dN_c/d\eta)(1/\sqrt{2})}{\pi\tau^2\,2\ell_R h\,dN_c/d\eta} = \frac{(3/2)(1/\sqrt{2})}{\pi\tau^2\,2\ell_R h}, \tag{5}$$

where $1/\sqrt{2}$ is the effective $\Delta\eta$ slice. Thus n_π is independent of $dN_c/d\eta$ and one obtains

$$n_\pi = 1.64 \pm 0.33(\text{stat})\ \text{pions fm}^{-3}. \tag{6}$$

This n_π value indicates that the deconfinement transition occurs at a definite entropy density. Since $s \propto n_\pi$ is constant we can directly evaluate n_π using the total number of pions emitted divided by the total volume for the data set in Table 1. We choose the lowest $P_{\pi\pi}$ value, where $\tau = 0.95$ fm, $R_G = 1.2$ fm, and $\ell_R = 1.43$. Here the average pseudorapidity density is $\langle dN_c/d\eta\rangle = 14.4$ and Eqs. (2) and (4) become

$$n_\pi = \frac{(3/2)(dN_c/d\eta)(1/\sqrt{2})}{\pi\tau^2\,2\ell_R R_G} = 1.57 \pm 0.25(\text{stat})\ \text{pions fm}^{-3} \tag{7}$$

which has a smaller statistical error than (6).

4. The negative particle p_t spectrum is used to measure the temperature. A slope parameter b^{-1} is obtained from a fit of the invariant cross section $d^2N_c/dy\,d^2p_t$ to the function $A\exp(-bp_t)$ for $0.15 \leqslant p_t \leqslant 0.45$ GeV$/c$ [14]. The b^{-1} value is constant to $\pm 1\%$ for $6.75 < dN_c/d\eta < 20.2$. Transverse flow has not been seen in p–p reactions at lower energies [15, 16]. In heavy ion reactions the transverse flow is attributed to final state interactions of the hadrons which presumably are not important in $\bar{\text{p}}$–p collisions. The fact that R_G increases by a factor of three and b^{-1} remains constant to $\pm 1\%$, suggests that the transverse flow is negligible. The components σ_2, σ_3 in the NSD cross section indicate that the parton–parton mean free paths are shorter in high energy collisions. Since gluon–gluon interactions dominate in the initial encounters, early thermalization ~ 0.5 fm$/c$ when $T \sim 200$ MeV is likely [8]. We interpret $b^{-1} = T = 179.5 \pm 5$(syst) MeV as the hadronization temperature. We neglect the expansion of the hadronic phase following hadronization, i.e., decoupling is associated with hadronization. The systematic error estimate is based on possible kaon (K_s^0) misidentification in the negative particle spectrum at low p_t. We have not made a correction for the effect of resonance decays on the negative particle p_t spectrum. We note that the negative particle temperature is significantly higher than the temperature based on the spectra of idenitified pions which include resonance particle decay pions ($T \simeq 168$ MeV). A hadronization inverse slope parameter T_m can be estimated from our measurement of the relative yields of mesons and hyperons as shown in Fig. 3, using all the events with $dN_c/d\eta > 6.75$. The hadron yield versus rest mass inverse slope parameters indicates $162 < T_m < 173$ MeV. Similar $T_m \sim$

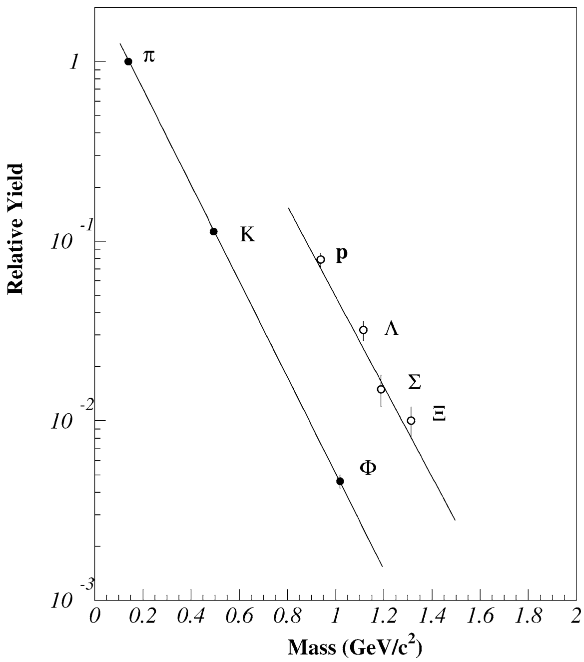

Fig. 3. Relative meson and hyperon yields versus rest mass [19,20]. For the mesons, the inverse slope parameter $T_m = 162 \pm 5$ MeV, and for the hyperons $T_m = 173 \pm 12$ MeV.

168 MeV values, based on thermal model analyses of hadron yield ratios, have been seen in high energy $\bar{p}p$, pp, e^+e^- and heavy ion reactions [17]. This has been interpreted as evidence for a universal limiting temperature T_m for hadrons, the Hagedorn temperature [18].

5. We can also use the average measured energies to estimate the hadronization energy density ϵ_F [19]. Since $\epsilon_F = 3/4Ts_F$, ϵ_F is also constant versus $dN_c/d\eta$ [13],

$$\epsilon_F = \frac{\sum_h F_h (m_h)_\perp (1/\sqrt{2})}{\pi\tau^2\, 2\ell_R h}, \tag{8}$$

where $(m_h)_\perp = (m_h^2 + p_t^2)^{1/2}$ is the average transverse mass of hadron h, F_h is a hadron abundance factor which also accounts for the neutral hadrons of each species. We have determined F_h for π, K, φ, p, n, Λ^0, Ξ, etc. For $\tau = 0.95$ fm, $\ell_R = 1.56$, $h = 0.073$, ϵ_F becomes

$$\epsilon_F = 1.10 \pm 0.26(\text{stat})\ \text{GeV/fm}^3. \tag{9}$$

6. We can estimate the average number n_c of constituents in volume V at temperature T, for a system without boundaries [21]

$$n_c = V\frac{G(T)\cdot 1.202(kT)^3}{\pi^2\hbar^3c^3}, \tag{10}$$

where $G(T)$ are the number of degrees of freedom (DOF). For a pion gas $G(T) = 3$, $V = 1\ \text{fm}^3$, and $T = 179.5$ MeV. The average number of pions (pion gas) *in the source* is $n_\pi = 0.28$ pions/fm^3. We observe 1.57 pions/fm^3, emitted from the source at temperature $T = 179.5$ MeV, which requires many more DOF.

For a quark–gluon plasma $G(T) = G_g(T) + G_q(T) + G_{\bar{q}}(T) = 16 + (21/2)(f)$, where f are the number of quark flavors [13]. $G_g(T)$ are the gluon DOF; $G_q(T)$ and $G_{\bar{q}}(T)$ are the quark and antiquark DOF. We *assume* that pion emission from the source can be determined by the number of constituents in the source at hadronization, that one pion is a quark–antiquark (q, $\bar{\text{q}}$) pair and that two gluons (2g) are required to produce two pions (see insert Fig. 2)

$$n_\pi = n_\text{g} + (n_\text{q} + n_{\bar{\text{q}}})/2. \tag{11}$$

Our data indicates that $\sim 6\%$ strange quarks are present at hadronization [19,20]. Thus we use $f = 2$ to evaluate Eq. (10) where $V = 1\ \text{fm}^3$ and

$$n_\pi = (1 + 2\cdot 21/64)G_\text{g}\cdot 16.1\,T^3\ (\text{GeV}), \tag{12}$$

where G_g are the effective number of gluon DOF. For $n_\pi = 1.57/\text{fm}^3$ and $T = 0.1795$ GeV, we obtain $G_\text{g} = 10.18$. The total number of DOF are,

$$\begin{aligned} G(T) &= n_\text{g} + n_\text{q} + n_{\bar{\text{q}}} \\ &= (1 + 21/16)G_\text{g} = 23.5 \pm 6\ \text{DOF}, \end{aligned} \tag{13}$$

nearly eight times the DOF for a pion gas. A second method for estimating the DOF is to use the energy density and temperature at hadronization. For the isentropic expansion, the energy E in the volume V at temperature T is [21]

$$E = V\frac{G(T)\pi^2k^4}{30\hbar^3c^3}T^4. \tag{14}$$

For $\epsilon_F = 1.10 \pm 0.22(\text{stat})\ \text{GeV/fm}^3$ and $T = 179.5 \pm 5$ MeV, we find $G(T) = 24.8 \pm 6.2(\text{stat})$ quark–gluon DOF, in good agreement with the DOF using the number of constituents (Eq. (13)).

7. Two Lorentz-contracted nucleons collide at $t = 0$, $z = 0$ and the thermalized constituents are assumed to emerge at $\mathcal{T}_0$. Suppose we choose $\mathcal{T}_0 = 1.0\ \mathrm{fm}/c$. For a given expansion velocity, the data determines the hadronization proper time $\mathcal{T}_f$ and $1.09 < \mathcal{T}_f < 3.25\ \mathrm{fm}/c$. For $6.75 < dN_c/d\eta < 20.2$, the deconfined volumes V, determined by the data, range between $4.4 < V < 13.0\ \mathrm{fm}^3$. For $dN_c/d\eta > 6.75$ and using $G(T)$ from Eq. (14)

$$\frac{\epsilon}{T^4} = \frac{\pi^2}{30\,G(T)} = 8.15 \pm 2.0(\mathrm{stat}) \tag{15}$$

in general agreement with lattice gauge calculations [22]. The ratio of the initial temperature T_i to the final T_f is $T_i/T_f = (\mathcal{T}_f/\mathcal{T}_0)^{1/3}$ and $185 < T_i < 266$ MeV. The ratio of the initial energy density ϵ_i to the final energy density ϵ_f is $\epsilon_i/\epsilon_f = (\mathcal{T}_f/\mathcal{T}_0)^{4/3}$ and ϵ_i is $1.23 < \epsilon_i < 5.30\ \mathrm{GeV/fm}^3$ for $6.75 < dN_c/d\eta < 20.2$. Note a different choice of $\mathcal{T}_0$ would change the T_i and ϵ_i estimates.

In summary, the HBT analysis and the constant temperature versus $dN_c/d\eta$ are consistent with a model in which a pion source undergoes a 1D expansion with total longitudinal dimension $2l_R R_G$ directly proportional to $dN_c/d\eta$. We have used the Bjorken 1D model to analyze our data. We find that there is a unique hadronization entropy density and temperature at which the pions are produced independent of $dN_c/d\eta$. We have used phase space estimates of the average number of thermalized constituents in volume V at temperature T and the measured energy density ϵ_F to compute the number of DOF in the source. However, we note that reducing the average expansion velocity from $v^2 = 1/3$ to $v^2 = 1/5$ reduces the DOF estimate by 30%. Then the lower limit for the DOF is 16.6 ± 4.2, still substantially larger than the pion gas DOF of 3. This lower limit allows a more conservative argument that quark–gluon constituents are present in the large deconfined volumes. Our estimate of the number of DOF in the source (23.5 ± 6, 24.8 ± 6.2) is in general agreement with those expected for a quark–gluon plasma. The n_π, ϵ_F, and T values characterize the quark–gluon to hadron thermal phase transition. We expect that these hadronization conditions will be observed in p–p collisions at the CERN Large Hadron Collider where higher pseudorapidity density $dN_c/d\eta$ values will produce even larger deconfined volumes and longer plasma lifetimes.

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