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Project Report

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# Study of the final state particle composition in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as a function of centrality

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# 1 Introduction

Quarks and gluons, as described by Quantum chromodynamics (QCD), can only exist as constituents of hadrons and cannot be isolated. This property, known as confinement, is due to the fact that gluons can interact with each other, causing the strong force to increase with distance. At high temperatures and short distances, the strong force weakens, allowing partons (quarks and gluons) to move freely. Such a behaviour is known as asymptotic freedom and the phase of deconfined partons is called a Quark-Gluon Plasma (QGP). A Large Ion Collider Experiment (ALICE) at CERN studies the QGP by colliding lead (Pb) nuclei at ultra-relativistic energies.
When Pb ions collide in the Large Hadron Collider (LHC), an extremely dense and hot fireball is produced and quickly equilibrates to a QGP [1]. The QGP then expands and cools down until it reaches the critical temperature $T_c$, at which it goes through a phase transition during which the quarks and the gluons agglomerate to form hadrons. Once the phase transition has occurred and the QGP has become a hadron gas, at temperature $T_{ch}$, the abundances of each hadron species is fixed. This moment is called chemical freeze-out. The produced hadrons can then reach the detectors and the yields of the different species are measured.
The yields of hadrons can be precisely predicted by statistical thermal models, such as THERMUS [2] which was used in this project. By fitting the measured yields with THERMUS, $T_{ch}$ and the volume of the QGP fireball can be estimated.
The production yields of particles depend, among other factors, on the centrality of the Pb-Pb collision, which is described by a percentage. A collision is said to be central if two Pb ions collide head-on. The most central collisions have centrality comprised between $0 - 10\%$. The more peripheral the collision, the bigger the percentage describing the centrality. As expected, production yields of central collisions are higher that those of peripheral collisions.

In this project, production yields and freeze-out parameters are studied as a function of centrality for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using the THERMUS package. THERMUS is briefly presented and a more recent version of the package is tested in section 2. In section 3, THERMUS is used to fit a first set of ALICE data for the most central collisions (0-10%), including or not the proton yields in the fit. The chemical freeze-out temperature and volume are then evaluated as a function of centrality using data from a new ALICE analysis in section 4.

# 2 Extra loop THERMUS

## 2.1 Thermal description

In strong interactions, the baryon number $B$, strangeness $S$ and charge $Q$ are conserved. Three ensembles to treat the conservation of these numbers in particle collisions are implemented in THERMUS [2].
In the canonical description, $B$, $S$, and $Q$ are conserved exactly, which is adequate for high energy elementary collisions such as $pp$, $p\bar{p}$ and $e^+e^-$.

In the mixed canonical description, $Q$ and $B$ are conserved on average while $S$ is conserved exactly. $Q$ and $B$ are described using chemical potentials, $\mu_Q$ and $\mu_B$, that allow small fluctuations about their average values. This approach is used when there is a low production of strange particles.
Finally, in the grand-canonical ensemble, energy, $B$, $Q$ and $S$ are all only conserved on average. This requires the number of particles involved in the description of each quantum number to be large and the temperature to be high. In heavy-ion collisions, $B$ and $Q$ can be considered to be conserved on average due to the large number of charged particles and baryons produced in the collision. In Pb-Pb collisions, all three ensembles lead to similar results [3]. In this report, THERMUS is used with the grand-canonical ensemble.

## 2.2 Original version of THERMUS

Among the hadrons produced in heavy-ion collisions, some, called resonances, have very short lifetimes and can decay before reaching the detector. In the case of Pb-Pb collisions, resonances measured are $K^*(892)^0$ and $\phi(1020)$ [4] with main decay channels : $K^*(892)^0 \rightarrow \pi^{\pm} + K^{\mp}$ , $\phi(1020) \rightarrow K^+ + K^-$. Therefore, when calculating the yields of the produced hadrons, one has to take into account that detected pions can come from a decayed $K^*$ and detected kaons can come from decayed $K^*$ and $\phi$.

THERMUS fits the observed yields of final state particles and returns predictions about what these yields should be according to the ensemble used, as well as the chemical freeze-out temperature and the volume of the QGP fireball. In its original version, particles in the hadron list used for predictions and fits are marked as either stable (1) or unstable (0). When predicting a ratio of the type $\frac{\text{resonance}}{\text{longer-lived particle}}$, one must fit the data or predict the yields twice :

- A first time, by marking the resonance as stable to obtain the proper yield for the numerator.
- A second time, by marking the resonance as unstable, and letting it decay into its daughters and to get the yield for the denominator right.

## 2.3 Extra loop THERMUS

V. Vovchenko [5] modified THERMUS so that running the fit twice is not needed anymore and the resonances are taken care of due to an extra loop. In the extra loop THERMUS, a new variable is introduced, called *fDecayChainProcessed*, which can take the value *True* or *False*. This variable keeps track of whether or not the hadron's daughters have been taken into account in the final yields predictions. Each hadron starts with *fDecayChainProcessed = False*. If the particle is stable, the variable takes the value *True*. If the particle is unstable, the yields of the daughter, possible granddaughters and other generations are evaluated. The fit stops and the yields of final state particles are returned only once *fDecayChainProcessed = True* for all particles studied, that is, only once all the decay chains have been taken into account.
If the modifications from Vovchenko are implemented properly, the two versions of THERMUS should return the exact same values for the ratios of type $\frac{\text{resonance}}{\text{longer-lived particle}}$. We eval-

uated the values of different such ratios using both the two-step method with the original version of THERMUS and the one-step method with the extra loop one. The results obtained are presented in Table 1.

**Table 1:** Comparison of ratios of the yields of resonances to those of long-lived particles obtained with two different versions of THERMUS.

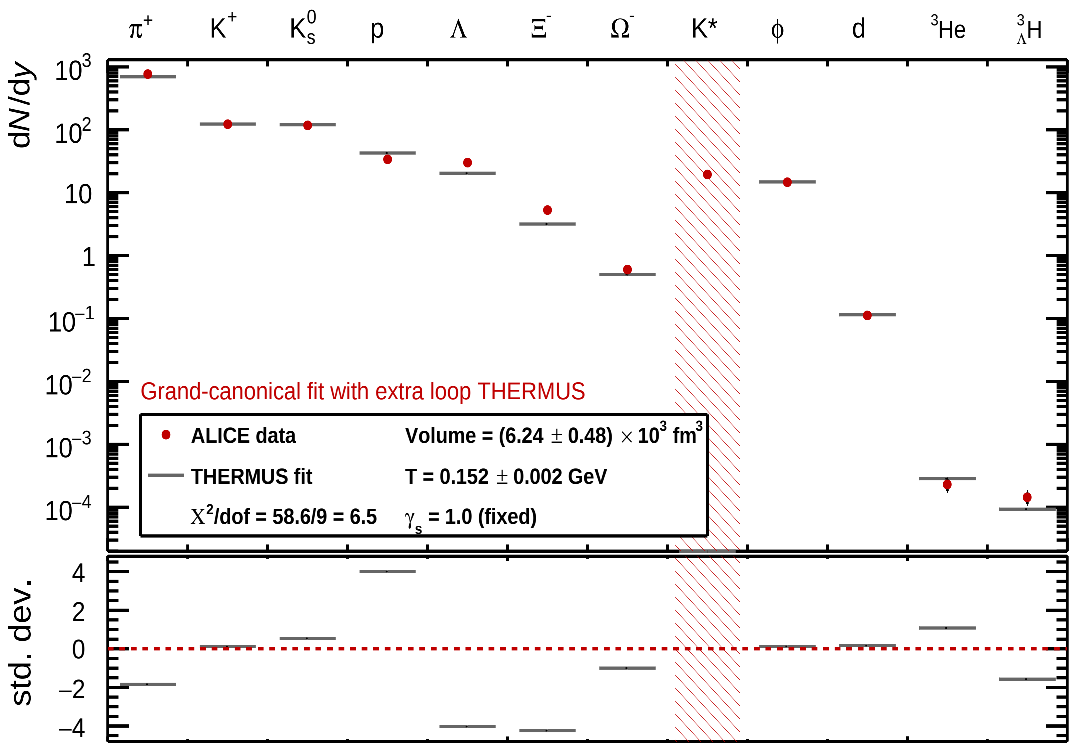
| Ratio | Original THERMUS | Extra loop THERMUS | Relative difference (%) |
|---|---|---|---|
| $\Delta^{++}/p$ | 0.2001 | 0.2001 | 0.0002 |
| $\phi(1020)/K^-$ | 0.1258 | 0.1258 | 0.0002 |
| $K^*(892)^0/K^-$ | 0.29770 | 0.29770 | 0.00006 |
| $\Lambda(1520)/\Lambda$ | 0.0800 | 0.0800 | 0.0003 |
| $\Sigma^{*+}/\Lambda$ | 0.1373 | 0.1373 | 0.0003 |
| $\Sigma^{*+}/\Sigma^+$ | 0.5087 | 0.5087 | 0.0001 |
| $\Xi^{*0}/\Xi^-$ | 0.3611 | 0.3611 | 0.0003 |

From Table 1, we can see that the original and the extra loop versions of THERMUS return the same values for the evaluated ratios. The differences observed are at the level of the last digit, which is due to computing and rounding approximations. The extra loop implemented evaluates the decays of the resonances in a way that is compatible with the original version of THERMUS. Now that we checked the validity of the extra loop, we can use the modified code to fit ALICE data in Section 3.

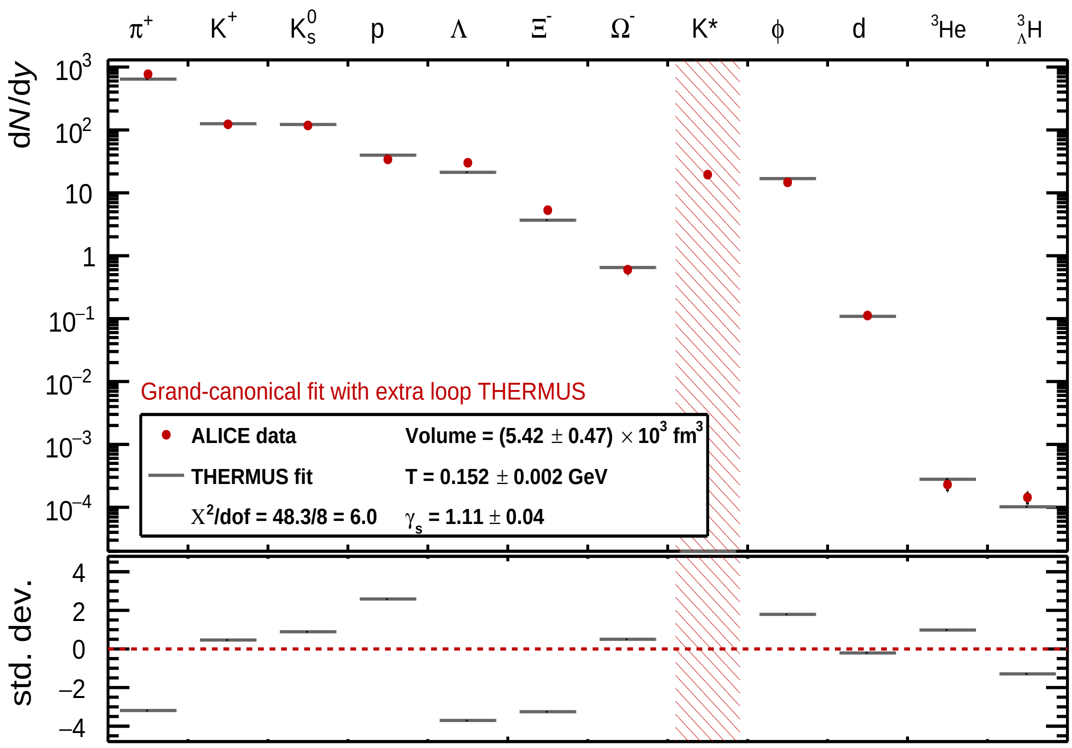
# 3 Fitting to experimental data

We fit the yields of final state particles in Pb-Pb collisions of centrality $0-10\%$ at $\sqrt{s_{NN}} = 5.02$ TeV detected in ALICE as reported by J. Bang [1]. The fits are realized using the extra loop version of THERMUS for different particle configurations as presented in Fig.1. For each configuration, the chemical freeze-out temperature and volume of the fireball are estimated, by comparing the observed yields to those predicted by the theoretical model. An additional parameters is studied, $\gamma_s$, the strangeness saturation factor. $\gamma_s$ describes the deviation of strange particles from a completely chemically equilibrated hadron gas [6]. $\gamma_s$ is typically a number between 0 and 1, where $\gamma_s = 1$ refers to a gas where the strange particle production is fully equilibrated and $\gamma_s < 1$ refers to a gas where the strange particle production is not equilibrated.

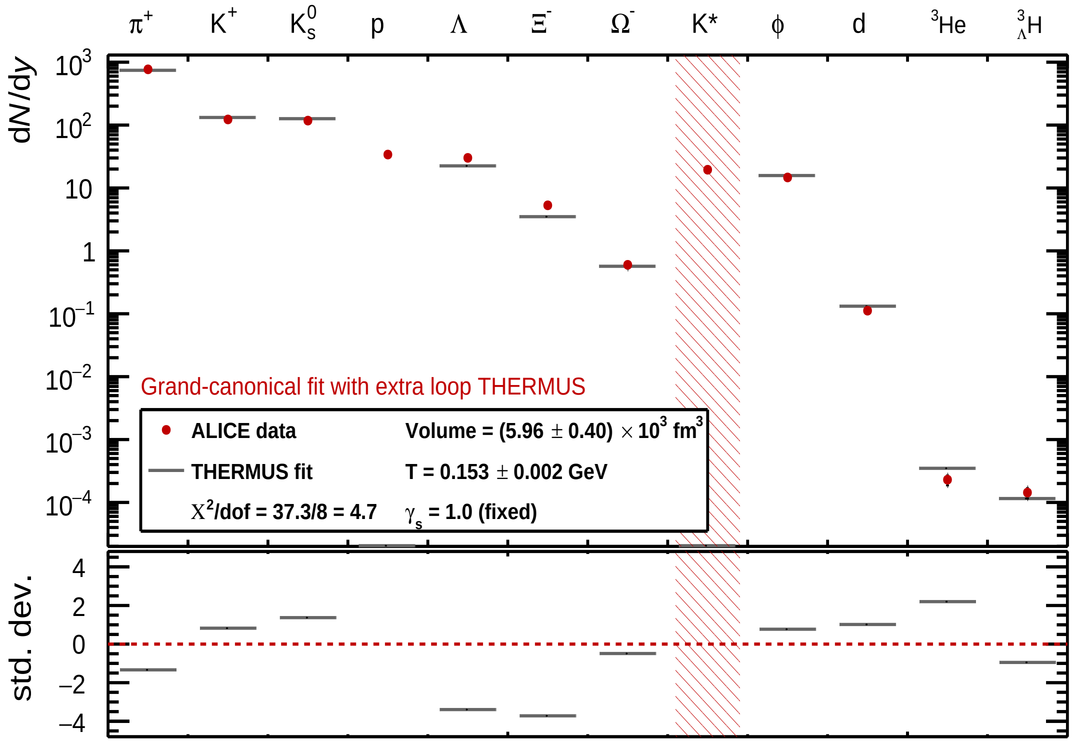
The extra-loop version of THERMUS is used for convenience in the realisation of the fits as $\phi$, which is a resonance, is included. Using the original version of THERMUS would mean having to run THERMUS twice to obtain the correct predictions of the yields for all the studied particles.
$K^*$ has a very short lifetime, which means its daughters have time to scatter before being detected by the detector. Hence it is very difficult, when detecting particles of the species of the daughters, to know whether they where produced at the time of chemical freeze-out, or due to the decay of a $K^*$. This is why the $K^*$ are excluded from all the fits.




**(a)** Fit result without $K^*$ and with $\gamma_s$ fixed to unity. There are 9 degrees of freedom: 11 particles fitted - 2 parameters evaluated ($T_{ch}$ and $V$ of the fireball).




**(b)** Fit result without $K^*$ and with $\gamma_s$ free. There are 8 degrees of freedom: 11 particles fitted - 3 parameters evaluated ($T_{ch}$, $V$ of the fireball and $\gamma_s$).




**(c)** Fit result without $K^*$ and $p$, with $\gamma_s$ fixed to unity. There are 8 degrees of freedom: 10 particles fitted - 2 parameters evaluated ($T_{ch}$ and $V$ of the fireball).

**Figure 1:** Fit results of the yields of the final state particles for the most central Pb-Pb collisions $(0-10\%)$ at $\sqrt{s_{NN}} = 5.02$ TeV using extra loop THERMUS.

The fits were also realized with and without $\phi$, but removing $\phi$ only leads to differences of the order $\pm 0.0001$ GeV in the temperature and $\pm 50$ fm$^3$ for the volume. As $\phi$, even though it is a resonance, does not seem to perturb the fit the way $K^*$ does, it was decided to keep it in the fit.
We assume chemical equilibrium of the QGP fireball in the fits and hence $\gamma_s$ is fixed to unity in Fig.1 (a) and (c). However, in (b), $\gamma_s$ if left free and becomes larger than unity. This effect is explained by Bugaev et al. [6] by supposing that strange particles have a different chemical freeze-out temperature $T_{ch}$ from other non-strange hadrons.
In (c), the protons are not fitted, which leads to a very slightly higher temperature and higher predicted yields, that are closer to the observed ones. The reduced $\chi^2$ is hence smaller and the fit more accurate compared to the two other fit results. This could be explained by supposing again different $T_{ch}$ for the different species of hadrons, and especially a smaller $T_{ch}$ for the protons. At this lower $T_{ch}$, all the protons are formed but other species are not yet, and hence if the fit stops at this $T_{ch}$, the predicted yield for the protons is accurate but the ones for the other species are smaller than what is actually being observed.

Overall, however, the fits do not seem to be drastically affected by any of the changes when considering only the most central collisions. In the next section, we study how the fits evolve for more peripheral collisions.

# 4 Freeze-out parameters as a function of centrality

We now consider the evolution of the chemical freeze-out temperature and the volume of the fireball with centrality. We use the observed hadronic yields from two recent ALICE collaboration analysis for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [7] [8]. Data is only available for $\pi$, $K$, $p$, $K^0_S$, $\Lambda$, $\Xi$ and $\Omega$, and thus they are the only particles considered in the following analysis.

## 4.1 Comparison of the two sets of data

We first compare the observed produced yields between the preliminary values from J. Bang and the recent ALICE publications to look for any discrepancies. To do so, we plot the total error in the yield over the observed yield for all the particles considered for the most central bin.
In the data set from J. Bang, the total error is given as such. However, in the two ALICE publications, the systematic and statistical errors are given separately. Furthermore, in the ALICE Analysis notes [8], the yields and their associated systematic and statistical errors are given for the bin $0-10\%$ for $\Xi$ and $\Omega$ whereas for all the other particles, the bins $0-5\%$ and $5-10\%$ are given.
In order to consistently evaluate the total uncertainties on the yields, we decided to merge the $0-5\%$ and $5-10\%$ bins when given to form a $0-10\%$ bin for all particles, consistent with the data available for $\Xi$ and $\Omega$. We added the systematic errors for the two bins linearly and the statistical ones in quadratures. Then we added the obtained total systematic error and the total statistical error in quadratures to obtain the total uncertainty on the $0-10\%$ bin. Data was available for all the particles for all the remaining bins : $10-20\%$, $20-30\%$, $30-40\%$, $40-50\%$, $50-60\%$, $60-70\%$, $70-80\%$ and $80-90\%$.
To obtain the total uncertainty for each particle in each bin, we added the systematic and the statistical error in quadratures. Finally, to get the relative error for each particle in each centrality bin, we divided the total uncertainty for that bin, by the corresponding observed yield.
Since the data from J. Bang is only for collisions with centrality $0-10\%$, we plotted its calculated relative errors alongside those for the most central bin in the two ALICE papers in Fig.2.

We can see on Fig.2 that for all particles, apart from $K^0_S$, the relative errors vary very little, at most one set of data gives a relative error higher of 1.5%. Such a small variation means that the two sets of data are compatible with each other and nothing new is happening between the older set of data and the newer one. The exception is for $K^0_S$, where the relative error predicted by the ALICE Analysis notes is a bit more than 2% higher than that predicted by the preliminary values. Since there is no major discrepancy between the two sets of data, we can use the recent one to study the thermal parameters as explained in the next section.

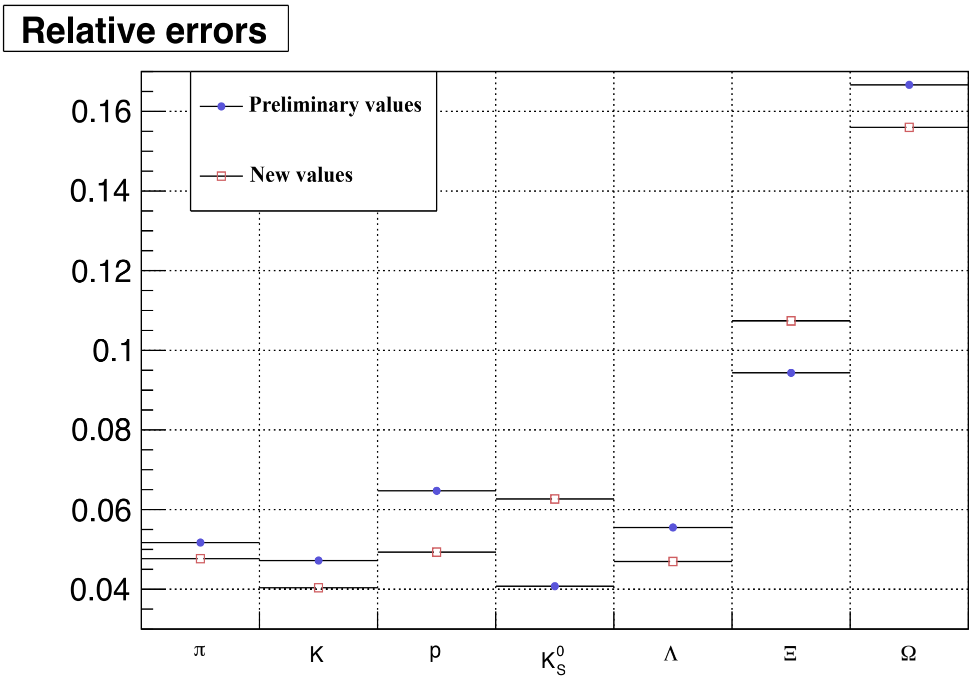



**Figure 2:** Relative error for the observed yields of particles produced in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with centrality $0-10\%$ for two sets of data. *Preliminary values* represent the set of data from J. Bang and *New values* represent the data from the two more recent ALICE Analysis.

## 4.2 Evolution of $T_{ch}$ and $r$ with centrality

We fit the observed yields given by the ALICE papers using THERMUS for all the centrality bins and for three different configurations:

a. Free parameters : $T_{ch}$, radius of the fireball.

   Fixed parameter : $\gamma_s = 1$

   Particles excluded : None

b. Free parameters : $T_{ch}$, radius of the fireball, $\gamma_s$

   Particles excluded : None

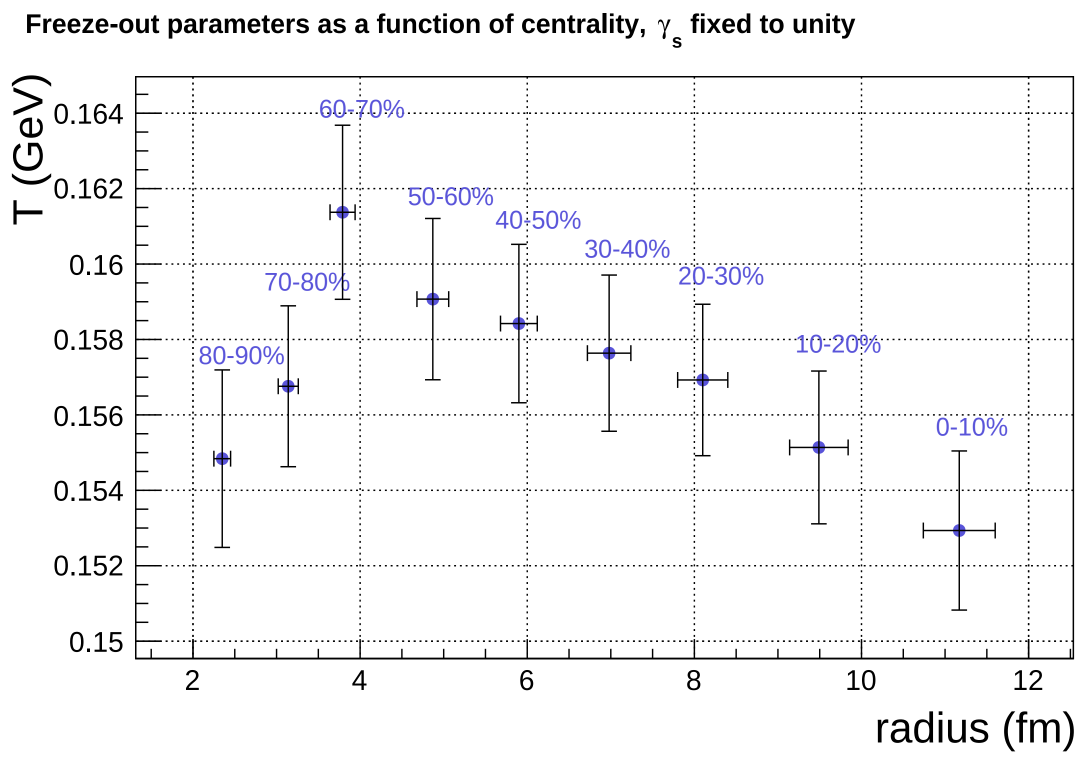
c. Free parameters : $T_{ch}$, radius of the fireball

   Fixed parameter : $\gamma_s = 1$

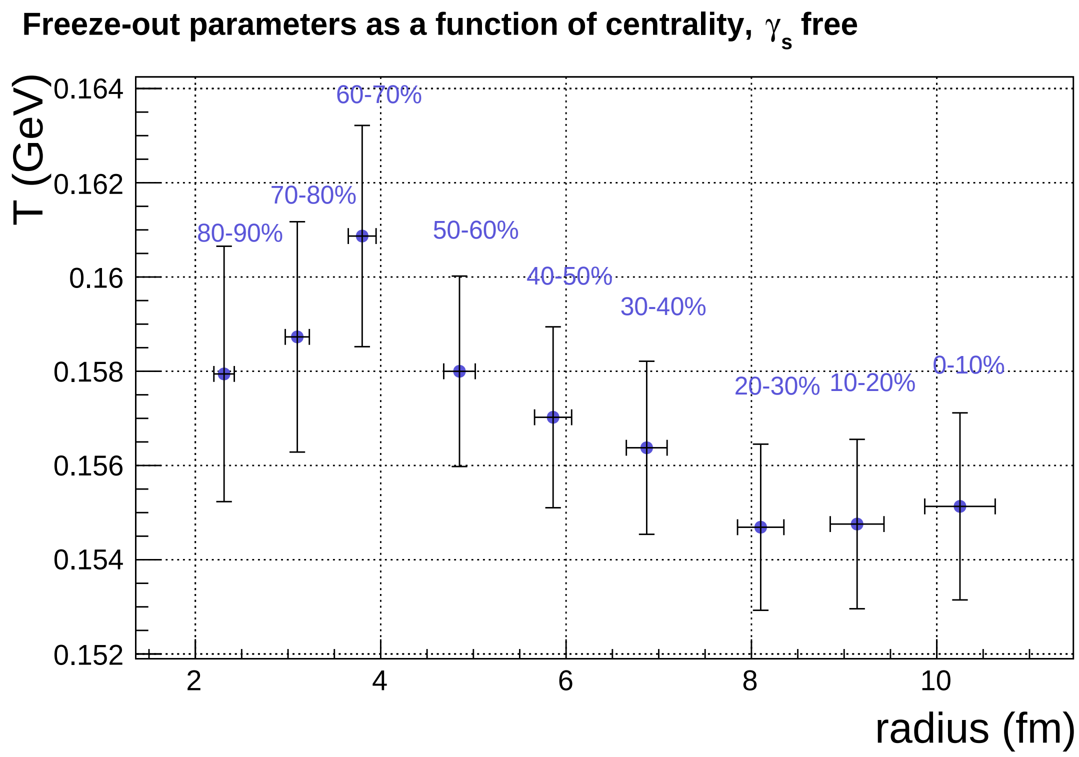
   Particles excluded : protons

Where $T_{ch}$ and the radius of the fireball are the predicted temperature and the radius of the fireball at chemical freeze-out respectively. $\pi$, $K$, $p$, $K^0_S$, $\Lambda$, $\Xi$ and $\Omega$ are all fitted each time unless otherwise specified. $T_{ch}$ vs radius as a function of centrality is then obtained and plotted in Fig.3.

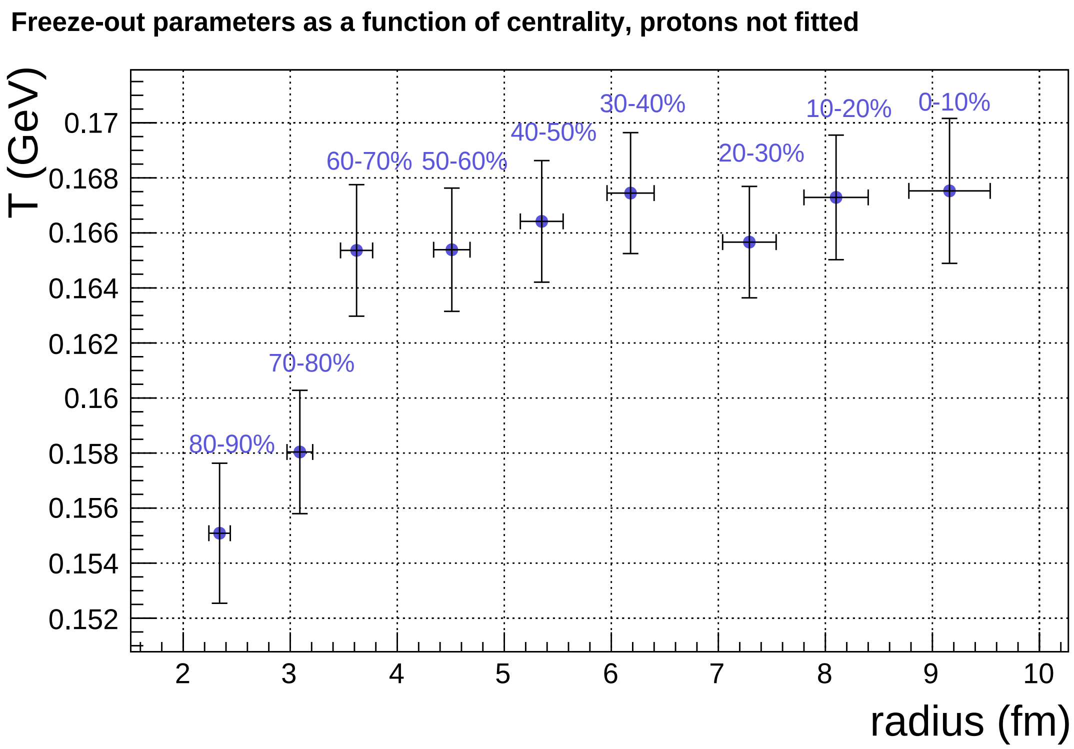
Overall, we can see on the different plots of Fig.3 that the chemical freeze-out temperature does not vary too much as a function of centrality, as it is theoretically expected. It varies the least for case (b) where $\gamma_s$ is free and the highest and lowest temperatures are 0.161 and 0.155 GeV respectively. On the contrary, it varies the most for case (c) where protons are not fitted and $\gamma_s$ is fixed to unity. In that case, the highest and lowest predicted temperatures are 0.168 and 0.155 GeV respectively.




(a)




(b)




**(c)**

**Figure 3:** Freeze-out parameters of the QGP fireball for different configurations for Pb-Pb collisions at different centralities between 0 to 90%. The centrality bin is indicated above each predicted point.

As it was noticed in the previous section, not fitting the protons leads to higher temperatures, no matter what centrality bin is considered.
The radius parameter of the fireball decreases as the centrality percentage increases. That is, the more central the collision, the bigger the fireball at chemical freeze-out. This is expected, since the less central the collision, the less energy, quarks and gluons involved and available to create particles, hence the smaller the fireball. In the continuation of that reasoning, the less quarks and gluons in the QGP fireball, the smaller the yields of the final state particles, which is indeed what has been observed [7] [8].
The radius parameter of the most central fireball differs depending on the configurations of the fit: it is about 11 fm for case (a), 10 fm for case (b) and 9 fm for case (c). This difference carries on for the next most central bin $10 - 20\%$ , with the radius being the smallest when the protons are not fitted and being the bigger when $\gamma_s$ is fixed to unity. For more peripheral collisions, until bin $50-60\%$, the two fits including the protons return the same radius, while the fit excluding them returns a smaller radius for each bin. All three configurations return the same radii for the most peripheral collisions.

The evolution of the reduced $\chi^2$ with centrality is also plotted in Fig 4. for the three cases considered in this section.

For the most central collisions, not fitting the protons returns a much smaller $\chi^2$ than the two other cases. However, the reduced $\chi^2$ for this configuration increases with centrality until it gets higher than that of the two other configurations. For both cases including all

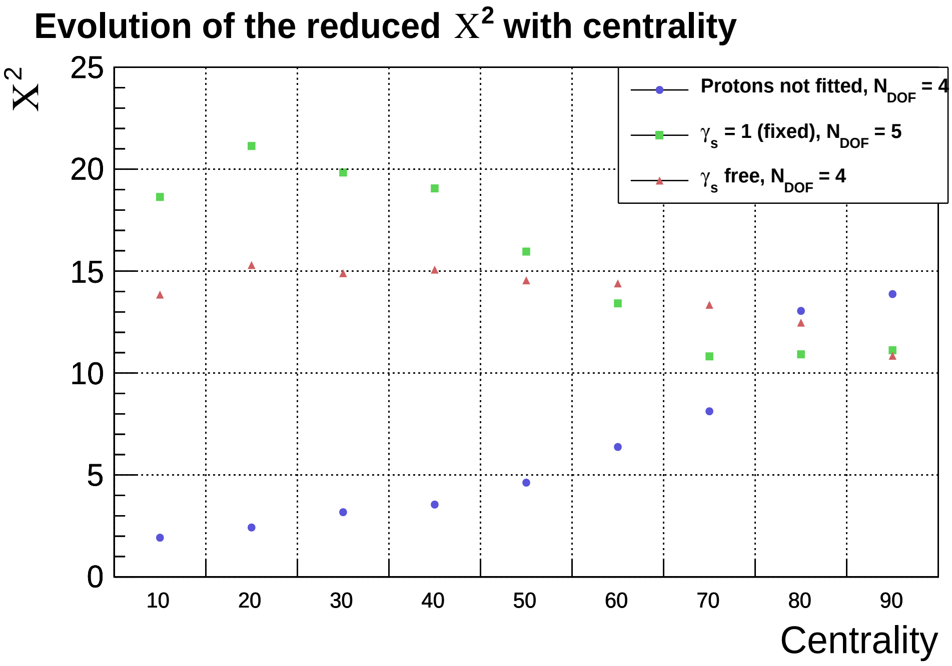



**Figure 4:** $\chi^2/N_{DOF}$ for each centrality bin for the three configurations considered. The green squares represent case 1 where all the particles are fitted and $\gamma_s$ is fixed to unity. The red triangles represent case 2 where all the particles are fitted but $\gamma_s$ is let free. The blue dots represent case 3 where the protons are excluded from the fit and $\gamma_s$ is fixed to unity. The centrality bins are indicated on the x-axis in such a way that the first bin corresponds to centrality $0-10\%$, the second one to centrality $10-20\%$ and so on until the last bin which is $80-90\%$.

the particles, the $\chi^2$ start at high numbers and decreases with centrality. As we mentioned before, we can suppose that $T_{ch}$ is different for the different hadron species produced, and in particular, is lower for the protons. THERMUS returns a single $T_{ch}$ for all the particles and hence fitting the protons forces THERMUS to find a temperature that could satisfy both the protons and the other hadrons. The $T_{ch}$ it returns is then somewhere in between the actual $T_{ch}$ of the protons and that of the other species which leads to a high reduced $\chi^2$. Not fitting the protons means that the $T_{ch}$ returned by THERMUS corresponds more to that of the species fitted and hence the $\chi^2$ improves. As the centrality increases, and the number of particles produced becomes smaller, the fit becomes less accurate and $\chi^2$ for the case without the protons increases. On the other hand, when fitting the protons, the smaller the amount of particles produced, the smaller the amount of protons produced and hence the less they "drag" the predicted $T_{ch}$ to smaller values. $T_{ch}$ can then be closer to the value corresponding to the other hadron species and $\chi^2$ improves.

## 4.3 Contour study of $T_{ch}$ and $r$

The correlation between the chemical freeze-out temperature and the radius is better understood when a contour plot is obtained. Fig 5. shows the contour plot in the case of protons no being fitted for all the centrality bins (equivalent of case (c)) in Fig.3).

At the very center of the $1\sigma$ contour for each centrality bin in Fig.5, is the result of the

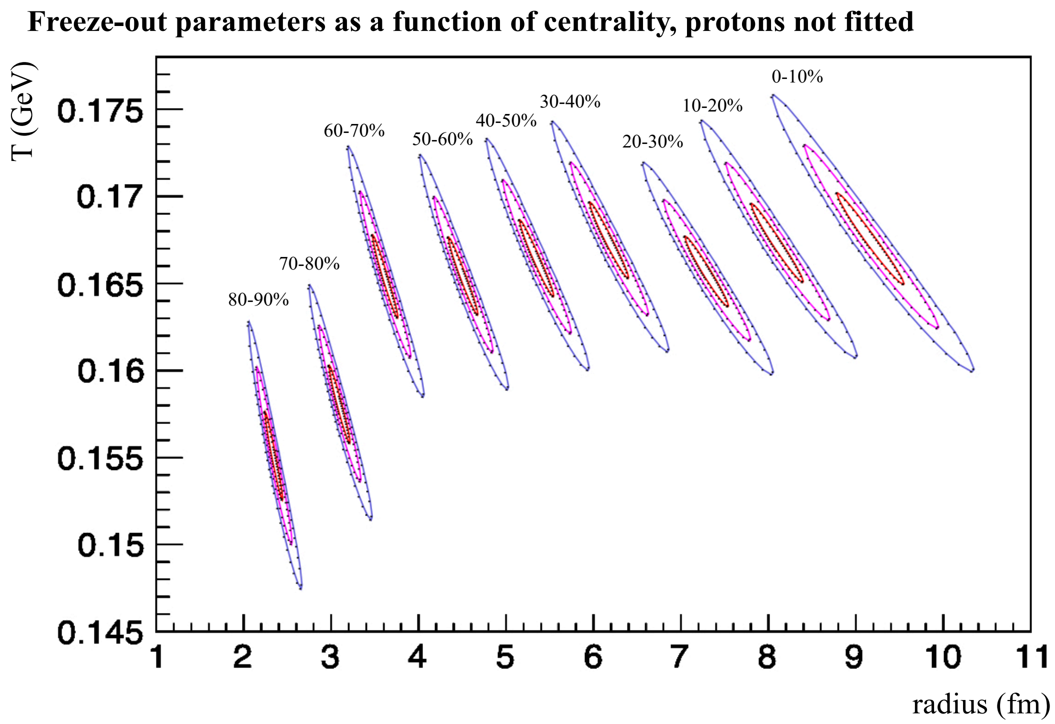



**Figure 5:** Contour plot of the chemical freeze-out temperature versus the radius of the QGP fireball as a function of centrality for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The $1\sigma$, $2\sigma$ and $3\sigma$ contours are represented in red, pink and purple respectively. The corresponding centrality bins are specified above each set of contours.

fit, so the predicted $T_{ch}$ and radius. If we assume the uncertainties on the temperature and the radius to be gaussian, then the observed $T_{ch}$ and radius have a probability of 68% to be somewhere within the $1\sigma$ contour, 95% to be within the $2\sigma$ contour and 99.7% to be within the $3\sigma$ one.
On Fig.5, we can see that the contours are not vertical, but are instead inclined, meaning that $T_{ch}$ and the radius are correlated. More specifically, since the contours are inclined from left to right, the two parameters are anti-correlated, meaning that the fireball can have a slightly higher $T_{ch}$ but then the radius must be slightly smaller.

The contour plot is also obtained for case (b), where $\gamma_s$ is free in Fig.6. This time, only the $1\sigma$ contour is plotted due to a lack of time : plotting all three contours takes about 45 minutes for each centrality bin. Again, we can see that the radius and the temperature are anti-correlated from the inclination of the contours. The inclination varies with centrality as the contour for the $0-10\%$ bin is more inclined than the contours of the more peripheral bins, getting almost vertical for the $80-90\%$ centrality bin : the correlation between the temperature and the radius decreases as the centrality percentage increases.

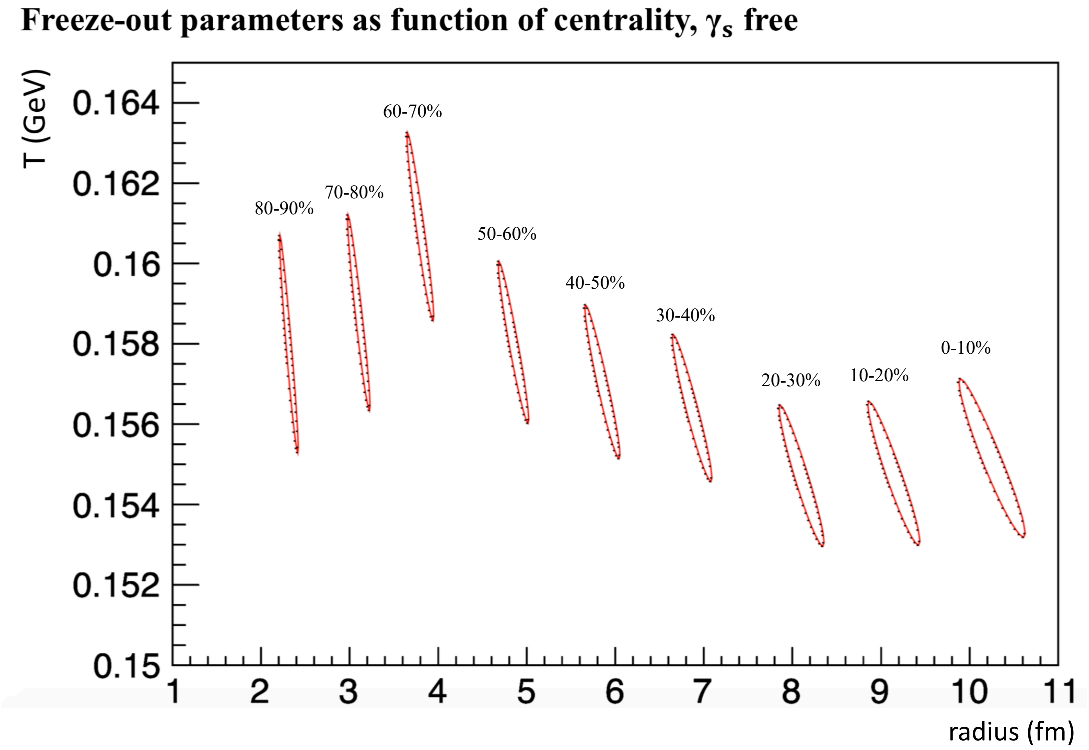



**Figure 6:** Contour plot of the chemical freeze-out temperature versus the radius of the QGP fireball as a function of centrality for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Only the $1\sigma$ contour is represented in red. The corresponding centrality bins are specified above each contour.

# 5 Conclusion

In this project, we studied the final state particle composition in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in order to evaluate the behaviour of the freeze-out parameters of the QGP fireball as a function of the centrality of the collision. We started by verifying the implementation of an extra loop in THERMUS to make it more convenient to deal with resonances. Using the extra-loop version of THERMUS, we then fitted the production yields of particles in the most central collisions $(0 - 10\%)$ with a first set of ALICE data for different configurations. We studied how $T_{ch}$, the volume of the fireball and $\gamma_s$ behave depending on the particles included and the fixed and free parameters in the fit. Obtaining $\gamma_s$ superior to 1 and higher chemical freeze-out temperature when the protons are not fitted comforts the hypothesis that different species of hadrons have different $T_{ch}$. Finally, using two recent sets of ALICE data, we fitted the yields of the produced particles for different centrality bins ranging from 0 to 90%. As expected, $T_{ch}$ doesn't vary much with centrality while the radius decreases. As for the most central collisions, for all centrality bins, the chemical freeze-out temperature is higher when the protons are not fitted. By obtaining the contour plot for the case excluding the protons from the fit, we confirm that, as expected, $T_{ch}$ and $r$ are anti-correlated.

## Acknowledgments

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