

JOINT INSTITUTE  
FOR NUCLEAR RESEARCH

JOINT INSTITUTE FOR NUCLEAR RESEARCH

FINAL REPORT ON THE INTEREST PROGRAMME

Wave 4 : May 24th - July 2nd

**Generation and analysis of events for Au-Au  
collisions using the Monte Carlo generator  
Therminator 2**

Author

**Kitzia Michelle Hernandez Curiel**

Under the supervision of:

**Dr. Krystian Roslon**

July 1, 2021

# 1 Abstract

Femtoscopy analysis using two-particle correlation functions is a powerful tool to study space-time characteristics of Relativistic Heavy Ion Collisions. Using the Monte Carlo generator Therminator 2 we generated events corresponding to Au+Au collisions at RHIC energies of  $\sqrt{s_{NN}} = 200 GeV$  in a centrality range of [60-70%]. In addition, measurements of femtoscopic correlations for identical and non-identical particle pairs were carried out using the code FEMTO-THERMINATOR provided by Therminator 2.

# Contents

<b>1</b>	<b>Abstract</b>	<b>2</b>
<b>2</b>	<b>Introduction</b>	<b>4</b>
<b>3</b>	<b>Femtoscscopy</b>	<b>5</b>
3.1	Correlation Function . . . . .	6
<b>4</b>	<b>Therminator 2</b>	<b>6</b>
4.1	Installation . . . . .	6
4.2	Event Generation . . . . .	6
<b>5</b>	<b>Femtoscscopy Analysis Using Therminator 2</b>	<b>7</b>
5.1	Identical Particles . . . . .	8
5.2	Non-Identical Particles . . . . .	9
5.2.1	$\phi$ Meson Observation . . . . .	12
<b>6</b>	<b>Conclusion and Further Work</b>	<b>12</b>
<b>7</b>	<b>Acknowledgments</b>	<b>13</b>

## 2 Introduction

High Energy Physics is the field of Physics whose goal is to determine the most fundamental building blocks of matter and the forces interacting through these particles. The concept of "High energy" results from the fact that high energies are needed in order to break these fundamental particles apart to produce new particles which do not exist in the normal state of the matter.

Relativistic Heavy Ion Collisions is the part of High Energy Physics which deals with the Nuclear Physics of colliding nucleus. Studying these collisions we can recreate in the laboratory the properties of nuclear matter in a state close to the one that occurred shortly after the Big Bang.[6]

One of the main reasons to study these collisions in accelerators such as the Large Hadron Collider (LHC) at CERN or the Relativistic Heavy Ion Collider at Brookhaven National Laboratory is the exploration of the Quark-Gluon Plasma.

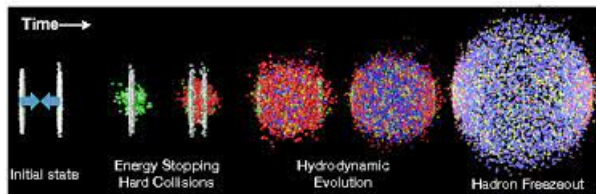


Figure 1: Relativistic Heavy-ion collision

The quarks and gluons produced in a collision are so strongly coupled that they form a collective medium that expands and flows as a relativistic hydrodynamic fluid. The so called Quark-Gluon Plasma (QGP).[3]

The notion of Quark-Gluon Plasma was introduced in 1978 by Shuryak([12]). Quark-Gluon Plasma is believed to be the state of matter which existed for some microseconds after the Big Bang and the constituent of neutron star cores.[4]

From statistical mechanics we can describe matter as a system in thermal equilibrium, with global observables such as net charge, temperature, and energy density. As these variables take on different values the system can manifest different phases of matter. Indeed, at high temperatures/densities a phase transition from hadronic matter to QGP should occur.

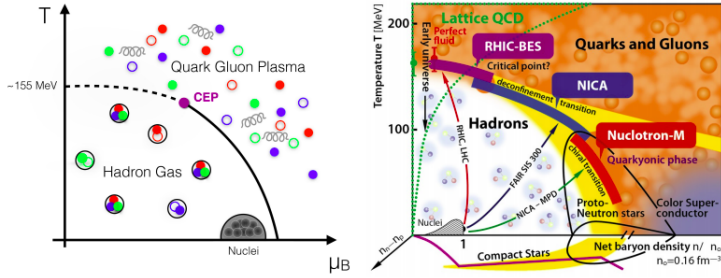


Figure 2: Phase diagram of the strong interacting matter

### 3 Femtoscopy

Femtoscopy correlation is a technique used in relativistic heavy-ion collisions that can give us an insight of the space-time characteristics of particle production at the *femtometer* scale ( $10^{-15}m$ ) using particle correlations.[1]

There are two types of correlations, for *identical* and *non-identical* particles. While the first can help us to study the size of two ion collision systems, the non-identical ones are used to study the time scale of nucleus fragments produced during the collision[8].

Another relevant physical concept used in the analysis of heavy-ion collisions is the centrality, which is closely related to the impact parameter and represents the size of the overlap region which corresponds to a different number of nucleons that take part in the collision (participants) and those that do not (spectators). However, experiments cannot directly measure the impact parameter of the collision and since it is an important metric for event selection and subsequent analysis, final state observables such as charged particle multiplicity and energy deposited by spectators are used to define centrality classes based on the predictions of a theoretical model. The centrality class allows us to have an estimate of how many nucleons take part in the collision.

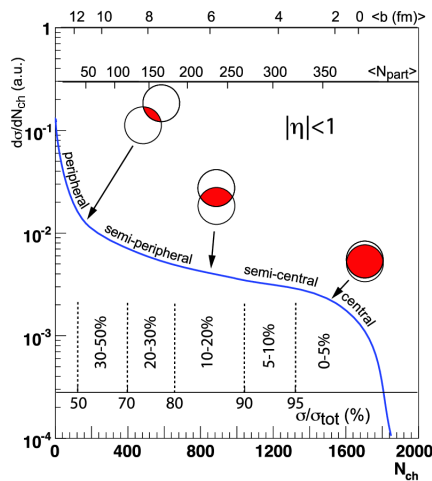


Figure 3: Determination of the centrality classes for a HIC

### 3.1 Correlation Function

The correlation function for two particles is defined as

$$C(\mathbf{p}_1 \cdot \mathbf{p}_2) = \frac{P(\mathbf{p}_1 \cdot \mathbf{p}_2)}{P_1(\mathbf{p}_1)P_2(\mathbf{p}_2)} \quad (1)$$

in which the numerator represents the measured momentum distribution difference ( $q = p_1 - p_2$ ) of the two particles from the same events and the denominator the distribution of two particles taken from different events. The results are normalized so the correlation function tends to 1 when there is no correlation between the particles. For the particles with equal masses we use the notation  $q_{inv} = 2\mathbf{k}^*$ , while the average transverse momentum of the pair will be denoted by  $\mathbf{k}_T$ . Calculating the correlation function for different particle pairs was the main purpose of this work, the details are given in the following sections.

## 4 Therminator 2

Event generators are software libraries that generate high energy particle physics events. They allow us to compare experimental results with theoretical predictions as well as to make predictions and preparations for future experiments. Therminator 2 is an extended version of the MC generator THERMINATOR (THERMal heavy IoN generATOR), created to carry out the statistical hadronization in relativistic heavy-ion collisions.[7]

### 4.1 Installation

We used a Linux based operating system (Ubuntu 18.04) as well as the ROOT Framework[5] package (version 6.24.0) and a C++ compiler. Then we proceeded to follow the installation instructions from the THERMINATOR 2 manual[7].

Before compiling the program some modifications in the source code and building instructions needed to be done. First it was necessary to add the line *using namespace std;* to the source file */therminator2/build/src/therm2\_events.cxx*. Secondly, in order for the libraries being linked correctly we modified the lines 119, 123 and 127 of the *MakeFile*,

```
$(LD)$(LFLAGS)$^~o$@ to $(LD)$^~o$@$(LFLAGS)
```

### 4.2 Event Generation

In order to generate events we first selected one of the hypersurfaces and velocity profiles that describe the data of Au+Au collisions at the highest RHIC energy  $\sqrt{s_{NN}} = 200\text{GeV}$  for different centralities. The anticipated profiles for the LHC Pb+Pb collisions at  $\sqrt{s_{NN}} = 5.5\text{TeV}$  are also incorporated in the "standard" library of hypersurfaces. The

*.xml* files containing the hypersurfaces descriptions and parameters are included in the **fomodel/lhyquid2dbi** folder, to run events we selected the *.xml* file corresponding to the type of collision and centrality we are interested in and replaced the name on the **lhyquid2dbi.ini** file. For this project we worked with Au+Au collisions at the RHIC energy of 200 GeV and the centrality of 60-70%. Once this was done we proceed to run 50,000 events using the **./therm2\_events** command. The configuration of the events is given in the **event.ini** file that includes the freeze out model to be used, the number of events that will be generated, the format of the output file and other parameters such as the multiplicity distribution, etc.

## 5 Femtoscopy Analysis Using Therminator 2

After generating the events as described before, the output was saved in the **events** folder that contains multiple root files with the name *event\*.root* with the information obtained from the simulation. These event files can be used to carry our multiple physical analysis. One of these is the analysis of the femtoscopic correlations, Therminator 2 has the advantage of providing a code (FEMTO-THERMINATOR) to calculate such correlation functions. They can be obtained through the **therm2\_femto** program, since the particles produced by Therminator 2 are grouped into events and recalling the equation 1 in each event every charged particle is combined with every other charged particle on what is called mixing. A more detailed description of the formalism of the process can be found in [8][9].

The main source file that performs all the calculation is **therm2\_femto.cxx**. All the physical processes according to the formalism mentioned earlier are defined there and some changes are necessary in order to run the program for different particle pairs. Some of those changes are mentioned in the following sections. The corresponding initialization file is **femto.ini** where some initial parameters are specified, like the type of particle pairs to correlate, number of particles to mix and enable the Coulomb Interaction.

The arguments necessary to make the program work are:

- the generated events (*event\*.root*).
- the transverse momentum bin of the pair ( $k_T$ ). It goes from 0 to 3, each one corresponds to a  $k_T$  range:
  1.  $k_T = 0$  corresponds to (0.15-0.25 GeV)
  2.  $k_T = 1$  to (0.25-0.35 GeV)
  3.  $k_T = 2$  to (0.35-0.45 GeV)
  4.  $k_T = 3$  to (0.45-0.60 GeV)
- the number of event files.

The output files consist of the **femto\*.root** files that contain the one-dimensional histograms of the numerator and denominator of a more generalized version of 1.

## 5.1 Identical Particles

As we mentioned before, it is possible to obtain the correlation function for identical particles and non-identical ones. We refer for identical particles as those that are from the same type, mass and charge, like the pairs  $\pi^+\pi^+$ ,  $K^+K^+$ ,  $pp$ . Identical particle femtoscopy can be useful to determine the relation between specific space-time information and the source radii.

To obtain the correlation function we divided the 1D histograms for the denominator and numerator included on the **femto\*.root** for each  $k_T$  bin.

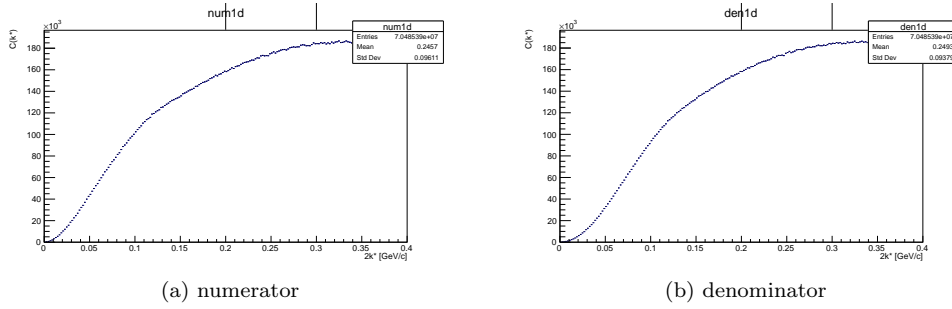


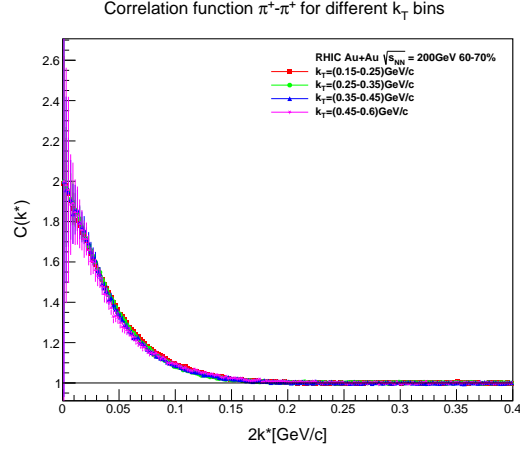
Figure 4: One dimensional histograms included in the femto\*.root files

The division and graphs were done using a root macro. An example of such macro used for one of the cases is showed below.

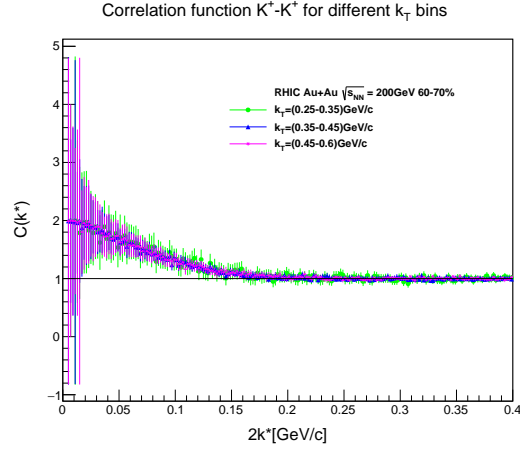
```
{
//load femto.root file
TFile* f = new TFile("AuAu50K/pi-pi/femtopipi0a.root");
//call histograms from file
TH1D *numq = new TH1D(*(TH1D*)f->Get("num1d;1")); //numerator
TH1D *denq = new TH1D(*(TH1D*)f->Get("den1d;1")); //denominator
TH1D*hc = new TH1D(*numq); //correlation function
hc->Reset();
hc->Divide(numq,denq,1.0,1.0);
hc->SetLineColor(kRed);
hc->SetMarkerStyle(21);
hc->SetMarkerColor(kRed);
hc->SetMarkerSize(1);
hc->Draw();
}
```

For the case of identical particles we calculated the correlation functions for the pairs  $\pi^+\pi^+$  and  $K^+K^+$  from the data obtained before, the results are shown in 5.





(a) Correlation function for pions



(b) Correlation function for Kaons

Figure 5: Correlation function from identical particles

## 5.2 Non-Identical Particles

For the case of non-identical particles we considered particles of different types,  $\pi^+K^+$ , or different charge like  $K^+K^-$ . For unlike-particles correlation is dominated by Coulomb Interaction[11] which is considered in the **therm2\_femto** code. We obtained the correlation functions for the following pairs:  $K^+K^-$ ,  $\pi^+\pi^-$ ,  $\pi^-K^+$ ,  $\pi^+K^+$  and  $\pi^+K^-$ . In order to run the program for some of the pairs we modified the **therm2\_femto.cxx** and **femto.ini** files.

- First we defined the missing pdg codes for  $\pi^-$  and  $K^-$ .
- In the part "Read parameters" we added the missing cases according to the pairs to use: `"else if (tPair == "kplus-kminus") pairtype = 8;"`
- In "Pair and particle cuts" we noticed that some of the particles combinations in the "switch(pairtype)" were already defined so we added the ones that were not like the following:

```

    case 8:
    ptmin1 = PTMIN;
    ptmin2 = PTMIN;
    ptmax1 = PTMAX;
    ptmax2 = PTMAX;
    break;

```

and at the end of that part we did:

```

    else if (pairtype == 8){
    partpid = KPID;
    partpid2 = KMPID;
    }

```

- Then in "Save Histograms to file", to save the data on under the given root file we added

```

    else if (pairtype == 8)
    sprintf(bufs,"%sfemtokpkm%i%s.root",sEventDir.Data(),

    nbin, onlyprim ? "p" : "a");

```

- Finally, in "Temporary file" we defined:

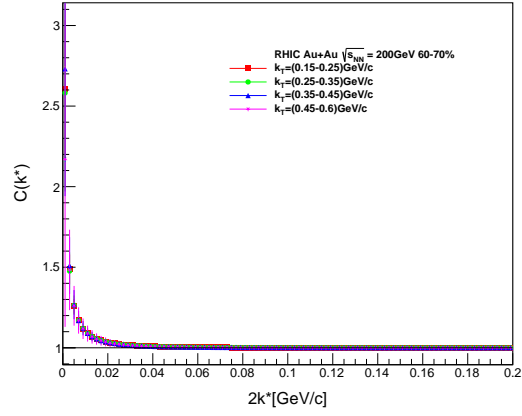
```

    else if (pairtype == 8) {
    pionac = -109.55 / 0.197327;
    partpid = KPID;
    partpid2 = KMPID;
    }

```

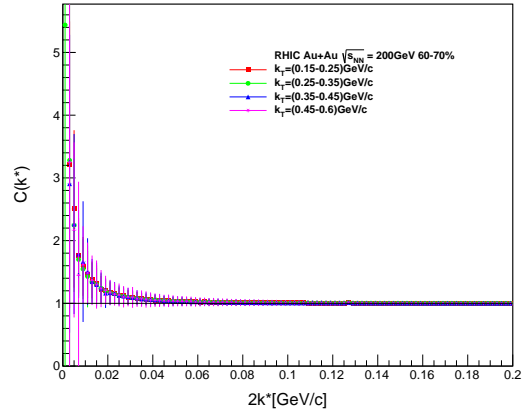
- It is also necessary to change the line 32 in the **femto.ini** file, from the name of the pair we are interested in and that we defined in the "Read Parameters" part.

Correlation function  $\pi^+\pi^-$  for different  $k_T$  bins



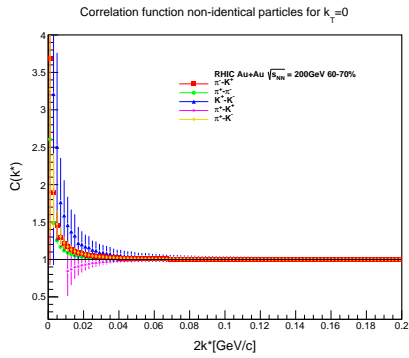
(a) Correlation function for  $\pi^+\pi^-$

Correlation function  $K^+K^-$  for different  $k_T$  bins

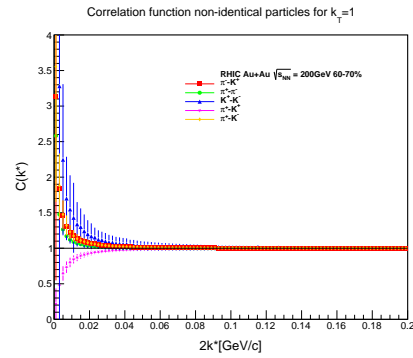


(b) Correlation function for  $K^+K^-$

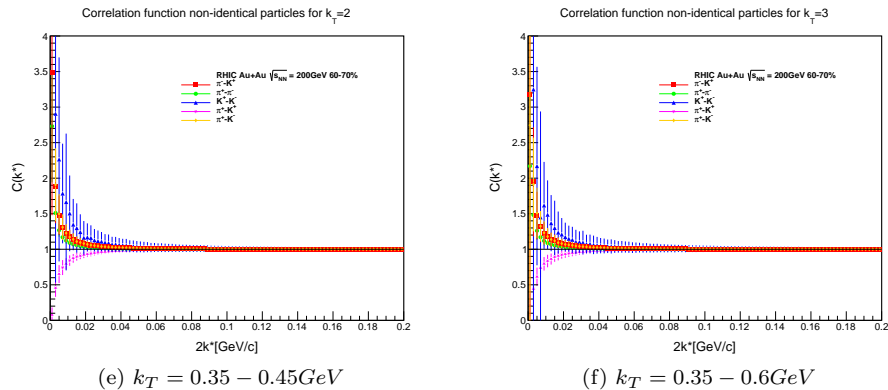
For each  $k_T$  bins.



(c)  $k_T = 0.15 - 0.25 GeV$



(d)  $k_T = 0.25 - 0.35 GeV$



### 5.2.1 $\phi$ Meson Observation

The  $\phi$  meson is considered as a good probe to study the QCD matter created in relativistic collisions[10] and according to [2] the  $\phi$  meson may be observed in the correlation for  $K^+K^-$  since it can decay in the channel  $\phi \rightarrow K^+K^-$ . Using the version of the code given in the previous section but selecting the histograms "num1dptrue;1" instead of "num1d;1" and "den1dptrue;1" instead of "den1d;1", it is possible to observe the  $\phi$  meson peak.

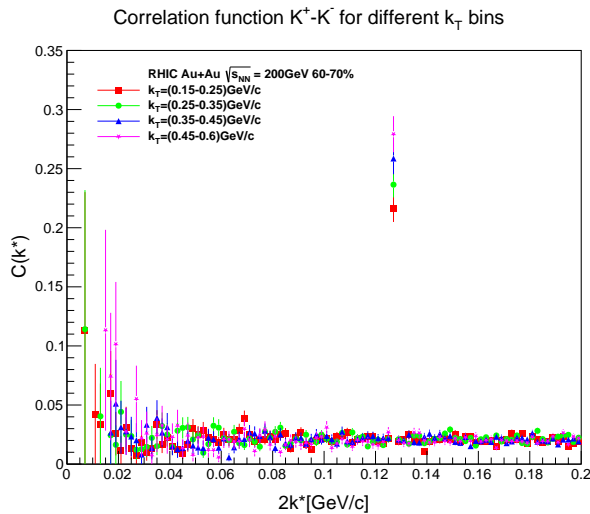


Figure 6:  $\phi$  meson peak in the  $K^+K^-$  correlation function.

## 6 Conclusion and Further Work

In conclusion, events for Au+Au collisions were generated with Therminator 2 for a centrality class of 60%-70% corresponding to peripheral collisions. Using femtoscopy analysis, the correlation function for identical particle pairs ( $\pi - \pi$ ,  $K - K$ ) as well as for non-identical ones were obtained. A special remark is made in the case of the  $K^+K^-$  correlation function since it can be used to search for presence of the  $\phi$  meson.

As a further extension of the project, a deeper analysis could be made comparing the results with the ones produced at other centrality ranges. It also would be interesting to perform the HBT analysis using the code implemented in Therminator 2.

## 7 Acknowledgments

I would like to thank Mr. Krystian Roslon for his guidance and feedback through the project and the JINR INTEREST team for organizing the training.

## References

- [1] Kaon femtoscopy in pb-pb collisions at  $\sqrt{s_{NN}} = 2.76$  tev. *Phys. Rev. C*, 96:064613, Dec 2017.
- [2] B. I. Abelev et al. Measurements of phi meson production in relativistic heavy-ion collisions at RHIC. *Phys. Rev. C*, 79:064903, 2009.
- [3] J. Bartke. *Introduction to Relativistic Heavy Ion Physics*. World Scientific, 2009.
- [4] Gordon Baym, Tetsuo Hatsuda, Toru Kojo, Philip D Powell, Yifan Song, and Tatsuyuki Takatsuka. From hadrons to quarks in neutron stars: a review. *Reports on Progress in Physics*, 81(5):56902, mar 2018.
- [5] R. Brun and F. Rademakers. ROOT: An object oriented data analysis framework. *Nucl. Instrum. Meth. A*, 389:81–86, 1997.
- [6] Wit Busza, Krishna Rajagopal, and Wilke van der Schee. Heavy Ion Collisions: The Big Picture, and the Big Questions. *Ann. Rev. Nucl. Part. Sci.*, 68:339–376, 2018.
- [7] Mikolaj Chojnacki, Adam Kisiel, Wojciech Florkowski, and Wojciech Broniowski. THERMINATOR 2: THERMal heavy IoN generATOR 2. *Comput. Phys. Commun.*, 183:746–773, 2012.
- [8] Adam Kisiel. Nonidentical-particle femtoscopy at  $\sqrt{s_{NN}} = 200$  gev in hydrodynamics with statistical hadronization. *Phys. Rev. C*, 81:064906, Jun 2010.
- [9] Richard Lednicky. Femtoscopic correlations of nonidentical particles. *Acta Phys. Polon. B*, 40:1145–1154, 2009.
- [10] James S. Lindsey and Gerald A. Smith. Production Properties and Decay Modes of the phi Meson. *Phys. Rev.*, 147:913–922, 1966.
- [11] Michael Annan Lisa, Scott Pratt, Ron Soltz, and Urs Wiedemann. Femtoscopy in relativistic heavy ion collisions. *Ann. Rev. Nucl. Part. Sci.*, 55:357–402, 2005.
- [12] Edward Shuryak. Strongly coupled quark-gluon plasma in heavy ion collisions. *Rev. Mod. Phys.*, 89:035001, Jul 2017.