Looking back
Looking forward

NA60 was a very challenging experiment that delivered on all its promises and more. The work synthesized in this thesis is but a part of the whole.

What we have learnt

Firstly, NA60 has observed a dimuon excess yield in the IMR for In-In collisions, as compared to the superposition of expected sources, Drell-Yan and charm, with cross-sections which properly account for the IMR spectrum measured in proton-nucleus collisions by NA50. This strongly indicates that the IMR excesses previously seen by NA38 and NA50, in S-U and Pb-Pb collisions, are indeed something other than a simple underestimation of the background yields. Furthermore, an analysis *a la* NA50, leaving free the normalisation of the DY and charm contributions, shows that an enhancement of charm production, by a factor ~ 2, would lead to a proper description of the dimuon mass spectra, in qualitative and quantitative agreement with the previous observations.

Secondly, we have determined that the IMR excess is of a prompt nature, using the NA60 detector vertexing capabilities, which provide an accurate muon offset measurement. This result is essentially insensitive to the yield of the open charm contribution, given its much flatter dimuon offset distribution.

Finally, we have characterised the excess, not only in terms of yield, but also in terms of mass and centrality dependences. This is done with respect to the DY contribution, fixed by the same data set, using events at and above the J/ψ peak. The excess is seen to have a steeper mass distribution than Drell-Yan, and to increase faster with centrality.

What we can still learn

Charm is a way of getting the answer yes without asking a clear question. **Albert Camus**

Though Camus might be right about the role of charm in human issues, the conclusions reached in this work clearly show that charm is not responsible for the IMR excesses observed by NA38 and NA50 in S-U and Pb-Pb collisions.

This then leads people interested in the nature of the medium produced in nuclear collisions to the question: What prompt contribution can produce such an excess? This is a general question, and depending on our prior beliefs, *a la* Bayes, the question may take one of the following forms:

Persons believing that a QGP state is produced in heavy-ion collisions at $\sqrt{s} = 17$ GeV will ask if it could be direct radiation from the QGP phase. Can the excess be the result of thermally produced dileptons shinning off a QGP?

More sceptical readers will ask for the reliability of a leading order Drell-Yan calculation for dimuon masses below 3 GeV. While keeping in mind that this same shape properly describes the NA50 set of proton-nucleus data, can the excess be due to higher-twist effects in $q\bar{q}$ annihilation at low Q^2 in nuclear collisions?

We hope that the excess characterisation presented in this thesis will be a valuable input to the understanding of the aforementioned questions.

Finally, the understanding of the nature of the excess could dramatically gain from merging the traditional regions of low, intermediate and high masses into a single and consistent analysis procedure. Given its unprecedented precision and statistics, the NA60 data can provide a comprehensive, bird's eye view of dilepton production from mass threshold up to, and beyond, the J/ψ. Such a unified analysis procedure would bring about a richer picture, where patterns could be waiting to be uncovered.

Also the proton-nucleus data taken in 2004 will be crucial in the interpretation of the data collected in indium-indium collisions, since the detector will provide equally good accuracy and we need a robust reference baseline with respect to which we can identify "new physics" in the heavy-ion results. Furthermore, the proton-nucleus data of 2004 will hopefully provide a first measurement of the χ_c nuclear absorption, using the radiative decay into J/ψ, $\chi_c \rightarrow J/\psi\gamma$, and detecting the γ conversion into an e^+e^- pair. The χ_c is an important feed-down contribution to the J/ψ yield, and understanding its production in seven different nuclear targets will be an important piece in the J/ψ suppression puzzle.

What we would *still* like to learn

Never let the future disturb you. You will meet it, if you have to, with the same weapons of reason which today arm you against the present.
Marcus Aurelius Antoninus

The NA60 accurate measurements already provided concrete and final answers to some of the questions which motivated the experiment. But the value of a scientific discovery is also gauged by the number of important new questions it raises. Further high quality measurements should lead to a very significant step forward in our understanding of the QCD phase transition and chiral symmetry restoration. A new and significantly improved NA60-like experiment could be ready to take data from 2010 onwards, when the LHC in general and ALICE in particular will certainly be smoothly running in stable conditions. Besides addressing specific questions coming from previous results (from NA60 and from RHIC data), the new experiment could also contribute, as a by-product, to explore new ideas (such as the search for the critical point of the QCD phase diagram). We recall that the top SPS energy range seems to be particularly interesting for studies of the QCD phase *transition*, according to the existing observations and the present theory understanding. Besides, the fixed-target configuration allows for rather high luminosities, crucial for the study of rare processes, as long as production cross-sections are not too small.

Here is a "far-sighted wish list", for what we would like to see accomplished in the near future (including some dream quests).

- ▷ A clear "step-wise" J/ψ suppression pattern, with a well established understanding of the $c\bar{c}$ production in p-A collisions, the fractional contributions from higher state feed-downs, and the normal nuclear absorption cross sections for each charmonium state; complemented by a detailed study of open charm production rates. The dream part: to measure χ_c production in heavy-ion collisions.

- ▷ A clear confirmation of chiral symmetry restoration, through accurate data on the ρ spectral function, as a function of baryon density and temperature (several collision systems and energies). The dream part: measure the a_1 spectral function in heavy-ion collisions.

- ▷ A clear confirmation of thermal dimuon production, the "signature par excellence" of radiation from a QGP phase, with a well established understanding of the contribution from the hadronic phase and a solid link between the excesses seen in the low and intermediate mass ranges. The dream part: complement with a simultaneous measurement of direct (thermal) photons.

- ▷ An observation of anomalously high fluctuations in narrow ranges of temperature and baryon density (collision energy and system) in yields, particle ratios and average transverse momentum, of well identified particles (resonances) and in specific phase space windows... as an exploratory "by-product". The dream part: to have a clear theoretical connection between such observations and the existence of the critical point in the QCD phase diagram.

In order to reach these goals, we would need to put together an improved NA60-like experiment, which could operate in the period 2010–2014. It is important to keep in mind that, despite the very important guidance from theory, significant progress in the field crucially depends on high accuracy measurements. An accurate measurement at the SPS can be more useful to push progress than a "lousy" measurement at higher (or lower) energies. The new NA60-like experiment should collect data in the following conditions.

- ▷ Pb-Pb at 158 GeV/nucleon: improved study of charmonia with respect to the NA50 data and a completely new study of low and intermediate mass dimuons at the highest SPS energy densities.
- ▷ Pb-Pb at 50 GeV/nucleon: measure the ρ spectral function at higher baryon densities and lower temperatures; ideally it should be complemented by shorter runs (of about one week) with other A-A systems and/or energies.
- ▷ Cu-Cu at 158 GeV/nucleon: to establish the "normal J/ψ nuclear absorption" before new physics sets in and to confirm the location of the critical energy density (ϵ is not well defined in p-A collisions).
- ▷ Pb-Be at 158 GeV/nucleon: "inverse kinematics" experiment, to measure nuclear effects in charmonia production at negative x_F (down to around -0.7).

If and when the SPS will be upgraded in view of the LHC luminosity upgrade, the so-called SPS+ scenario, with two times higher energies, such a new experiment could also take Pb-Pb data at higher energies. In particular, this would be very interesting to confirm, with high statistics, that the J/ψ survival probability flattens out at 0.6, until it is further suppressed at the LHC due to the dissociation of the directly produced J/ψ mesons (if thermal regeneration of charmonia states does not take over).

Beyond the future

The only way to discover the limits of the possible
is to go beyond them into the impossible.
Arthur C. Clarke

Speaking of LHC, I cannot help expressing my personal dream of one day using the 7 TeV proton beam in a fixed-target setup, which coupled to a high-luminosity slow extraction could provide very interesting data on rare or forbidden decays in the Standard Model which involve muons, like the $D^0 \to \mu\mu$ decay. Setting limits on the branching fractions of these decays restricts the parameter space of many proposed extensions of the Standard Model, while an actual observation would be a manifestation of physics beyond the Standard Model.