A SONIC TIME PROJECTION CHAMBER. SONIFIED PARTICLE DETECTION AT CERN.

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ABSTRACT

In a short-term research project at CERN, an auditory display of elementary particle tracks has been developed. Data stems from simulations of the Time Projection Chamber (TPC) in ALICE experiment. Particle detection there is based on pattern recognition algorithms, but is still today double checked with visualization tools. The sonification works with cluster data of the TPC and was designed in analogy to the physics behind the measurement device. Thus it is possible to listen directly to the otherwise silent detector.

1. INTRODUCTION - SOUNDING CERN

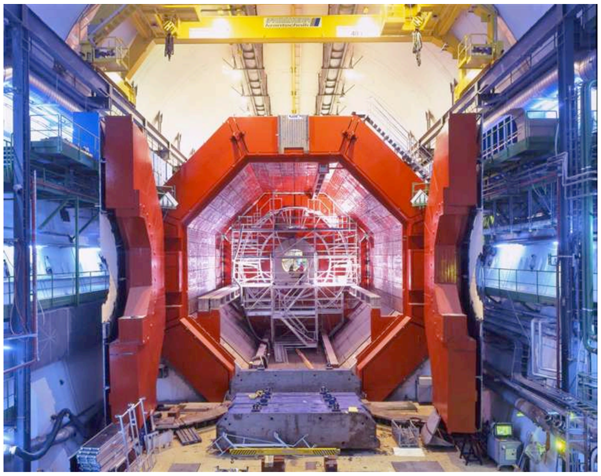


Figure 1: The cavern of the ALICE experiment - a 50 m high dome, 50 m under ground. The huge magnet doors are closed and the beam pipe is mounted and shielded today, as particle beams are circulated since November 2009 from where the photo was taken. In the middle of the detector, the TPC was installed - one read-out chamber at the front, where the doors are, the other at the back. *Photo: A. Saba, http://aliceinfo.cern.ch.*

During a three months research visit at the European Organization for Nuclear Research CERN, the principal author of this paper had the opportunity of getting insights into this scientific community. Around 3500 physicists, engineers, other scientists and staff are working at CERN. At the time of this stay the newest experiment was started, the Large Hadron Collider (LHC). The dimensions of CERN are impressive in every respect: Particle beams are accelerated in a tunnel of 27 kilometers length to nearly the speed of light. Two counterrotating beams collide at four possible sites, where different detectors are mounted. They detect traces of the particles they are specialized at, that have been produced in the collisions. (One of the collision points is ALICE, A Large Ion Collider Experiment, see Fig.1). The LHC experiment has been planned for two decades and will run for 10 to 20 years. In the planning of the beam acceleration and the various detector facilities, simulations were done for experiments that have been realized much later.

CERN is naturally a very open community, as there is a high fluctuation of scientists from all over the world and a melting pot of all kinds of technologies. Sonification has not been known to any of the physicists we spoke to before. Often, sonification was put into context with sounds occurring in experiments or simple analysis: from alarms in the control room to the fine-tuning of parts of detectors to listening to the beam spectra *"because there was nothing else to do and you just had to plug in headphones"*. Thus the idea of using sound was not so new to many, though systematic studies of sonification have not been conducted at CERN.

In our short term project, we gained an overview over sounds and CERN. It can never be complete, as the organization is wide spread and diverse, with thousands of collaborations with external institutions. Still, a few interesting projects have been found: the sonification of beam spectra, referred to above; or for instance the mounting of microphones in the LHC tunnel, in order to monitor the performance of collimators, devices for the so-called cleaning of the beam (for a pilot project on sound measurements on a prototype for the collimator, see [1]). The analysis of beam spectra is worth mentioning in some detail, as it is an ideal application of sonification – while their makers didn't even know this term.

Parameters of both LHC particle beams, like horizontal and vertical position in the vacuum chamber, are measured at many places in the tunnel. The particles are grouped in bunches, that have transversal and longitudinal oscillation modes. These oscillations can be described in phase space and should stay outside resonances, otherwise beam oscillations grow and the beams might get lost. The oscillation modes are measured accurately, as they are very important for keeping the beam on a stable orbit for the 27 kilometer circumference. The resulting transversal (β-tron) and longitudinal (synchrotron) oscillation frequencies range from a few tens of Hz to a few kHz, therefore they are audible without any further processing. With this sonification, many details of beam dynamics can be monitored by listening, in parallel to standard observation usually done in the frequency domain by performing real-time Fourier analysis of the beam signals. As full performance of the LHC is expected only in 2010, sonification results from this machine will be published in the future. Sonification of beam oscillation signals from other machines - the Super Proton Synchrotron at CERN - have also been tried out, but without any regular studies. Information and soundfiles can be found at [2, 3].

In our sonification approach, we chose data from one experiment, ALICE, and focused on its main detector, the TPC. The data we worked with is still simulated proton-proton collisions, but the sonification can be used for real measurement data as well. For this data, a well-developped visualization tool exists, which is called AliEve [4].

2. PARTICLE DETECTION AS A PATTERN RECOGNITION PROBLEM

The search for subatomic particles always depends on indirect measurement. Obviously, no direct perception is possible. Still, since the electron was detected in 1897, physicists tried to find traces of ever harder detectable particles. Usually, a huge amount of noisy raw data has to be assessed, and patterns in the data - tracks - give evidence of elementary particles having passed.

The history of particle detection is one of technological and theoretical achievements on the one hand side and the (re-) organization of scientific labour on the other, starting from single physicists in small laboratories to research groups of hundreds of scientists. But, for a big part, it is also the story of human pattern recognition. P. L. Galison argues in his book *Image and Logic* [5], that two rivaling methods have been developed in the 19th and 20th century. Logic, in the form of logic circuits, with many events treated statistically, stood against the golden event of the image tradition, where one single picture could proof a new particle. Particle detection is an inherently stochastic process, thus was the argument of the statistical approach of the logic community. During the last century, the big experimental particle research organizations were still largely led or influenced by individuals, who supported one or the other school.

The image tradition always relied mainly on the human being. "Alvarez [a leading proponent of the image tradition] wanted the 'human operator' to be 'the black box pattern recognizer'" [5, p.391]. But they had to struggle with the ever rising amounts of data being produced by the latest detectors. In the 1940s human operators (the 'scanner girls') assessed the pictures of bubble chambers according to certain criteria, before physicists would analyze only the more interesting events. Different technologies were developed in order to aid and accelerate the human scanning process. The logic tradition was pursued at CERN (amongst other institutions). One of its leading persons, L. Kowarski, put the idea in 1960 as "[t]he evolution is towards the elimination of humans, function by function." [5, p.371]. The more measurement devices produced data, and the more pattern recognition algorithms were refined, the logic tradition prevailed. Still, a combination with the fine-coarse measurement data of the image tradition with obvious and pervasive results could not be achieved for a long time.

During the long development of detectors, a few times sound was used implicitly or explicitly. Very early versions of the Geiger-Mueller counter had such a large voltage supply that a sparkover caused a bang as well. Today still, the typical Geiger counter display is an auditory one. Eyes-free conditions in radio-active environments has of course huge advantages for physicists and engineers. When they work on the machinery, they get information on what humans cannot perceive with their senses.

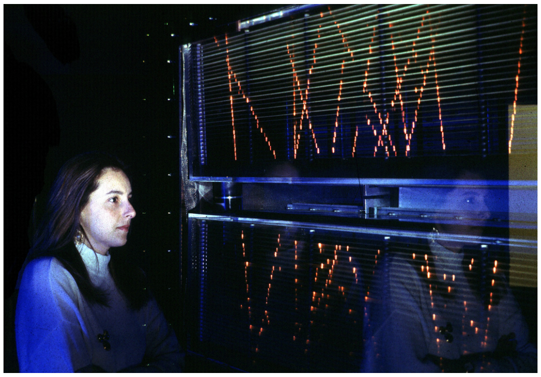


Figure 2: *Spark chamber at CERN's permanent exhibition Microcosm, source: http://cdsweb.cern.ch/record/39277.*

The logic of the Geiger counter was pursued in spark chambers. The sonic chamber was a device used in the 1960s at CERN and one example is still shown in their main exhibition called *Microcosm* (Fig.2). In a spark chamber, an energetic retort is produced between two plates. If a spark crackles through air, a loud *bang* is produced, which is recorded by microphones and thus can be counted. These detectors were called sonic chambers. A next development step was the wire chamber, which uses a similar but 'silent' technique. An external electrical field accelerates electrons towards highly charged wires, where they can be detected.

The first detector finally fusing the logic and image tradition is the TPC, invented in 1974. It is an extension of the (logic) wire chamber for the read out part, but with all benefits from the image tradition chambers. Many events can be recorded and studied by statistical means, while the tracks are reconstructed 3-dimensionally. Details are discussed in the next session.

While any particle detection is today based on algorithmic logics and statistics, visualization has still a standing. Data from the ALICE experiment is, e.g., finally cross-checked by human 'scanners' in organized shifts. Today, the goal of visualization is different than 50 years ago. Particle measurements became even more complicated with the reliance on computers. Thus the human scanners double check the functionality of the detection machinery and pattern algorithms and help debugging the extensive code. Furthermore there are applications for non-experts: firstly, newcomers -future experts- can become acquainted with all parts of the experiment. Secondly, outreach becomes more important also in high energy physics, where the energy (in terms of electron volt) as well as funding (in terms of money) are of high orders of magnitude.

Arguments of the image tradition, some 50 years ago, are remarkably similar to sonification arguments of today. Humans shall be presented with data with the least hypothesis applied in the display and search them for patterns in order to allow for the formulation of new hypothesis. Pattern recognition is very quick when comparing for instance real data to simulated one. All those arguments can as well be applied in favor of sonification, with all known additional advantages, but also drawbacks, of hearing vs.

seeing [6].

3. THE TPC - A PARTICLE DETECTOR

At the heart of the ALICE experiment there is a TPC installed – the most exact and with 5 m diameter the biggest which has ever been built. It is a detector consisting of a cylindrical gaseous volume mounted around the collision spot. If particles are produced in the collision, they cross the gas and ionize it by hitting the gas molecules. The freed electrons are lead in an electric field parallel to the beam direction, to the left or right. At both sides, read out chambers are situated. They consist of different layers of wires at high potential producing an electrical field and accelerating the electrons towards them. In an avalanche process electrons are multiplied and the induced current can be read out. From the time, they are hit by the collision particles, the electrons move (ideally) straight and with a constant drift velocity towards the read-out chambers. Thus the information on their impact time and location on the circular read-out chamber suffices to reconstruct the particle path exactly.

Depending on the energy deposit on the wires and the shape of the tracks, physicists and algorithms can deduce which particles were produced in the collision. This is not as straight forward as simple plots or sonifications of the raw data suggests. our perception groups single events that form a shape automatically. In the measurement, single signals from the read out pads behind the wires have to be combined to find the center of a freed electron cloud (cluster). These clusters are then grouped to a complete track. Analysis of the shape of the track makes it possible to associate a certain particle with it – the one that must have caused it. In a second step, 'the physics' can be studied and interpreted. Each collision is only measured partially, as very short lived particles and decay products do not leave a trace.

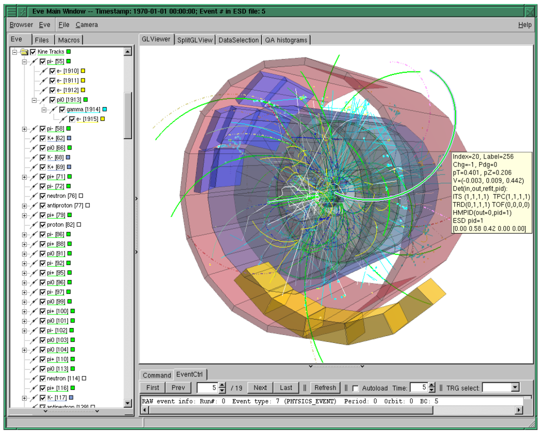
4. SONIFICATION

4.1. Methodology and goals

This sonification was developed in a short-time visit at CERN. We wanted to achieve an intuitive sonification of basic cluster data, not yet grouped tracks, which is based on analogies to the measurement.

One goal of the sonification is to extend the visualization. The primary visualization tool of ALICE is AliEve [4]. It allows 3-dimensional display of all the detector's data. The display is freely moveable. AliEve is a full software package, and our sonification can of course not compete with the functionality. Still, it could be a first step towards an additional auditory display.

The provided data sets are simulated *events* of p-p collisions, containing up to 35 tracks comprising a few 100.000 single electron impacts, each given at a certain time (t_i) and location ($\phi_i,\ r$), with an energy deposit (e_i). These are the simulated raw data expected in the measurements; further information is given from a second level of pattern recognition, i.e. which single electron impacts form a track caused by one particle. The data files are usually smaller than the ones of lead-lead collisions, that contain each around 80 MB of data or 60000 primary tracks. Still, it was challenging to stick with the raw data: hundreds of thousands of single electron impacts, each with a certain time, location and energy deposit.



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Index=20, Label=256
Chg=-1, Pdg=0
pT=0.401, pZ=0.206
V=(-0.003, 0.009, 0.442)
Det(in,out,refit,pid):
ITS (1,1,1,1)  TPC(1,1,1,1)
TRD(0,1,1,1) TOF(0,0,0,0)
HMPID(out=0,pid=1)
ESD pid=1
[0.00 0.58 0.42 0.00 0.00]
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RAW event info: Run#: 0  Event type: 7 (PHYSICS_EVENT)  Period: 0  Orbit: 0  BC: 5
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Figure 4: *A screenshot of AliEve [4], the visualization tool of the ALICE offline group. The reddish surface gives the volume of the TPC (yellow and blue are other detectors). Each line is the track of this one event -a certain time of measurement after a collision with a certain amount of particles produced.*

4.2. A sonic time projection chamber

The sonification is a parameter mapping that uses the raw data of single electron hits, allowing for a perceptual grouping into tracks, following auditory grouping principles [9].

Based on the fact, that 'electrons' (in fact electron clouds) hit the wires with a certain charge (the number of electrons), the wires are taken as analog to *strings*, which are hit and resonate with their basic frequency depending on their length.

It was a natural choice to place the listener at the collision point and let the time evolve towards the left and right read-out chambers. The time in the raw data is given *inversely*, as it is the time of the electrons freed by the particles passing nearly at the speed of light. Those electrons reach the read-out chambers first that are closest to them, and the time in the raw data thus evolves from outside back to the collision point. The sonification time is inverse to the data time, as it is more natural to follow the tracks from the collision point outwards.

In order to enhance the perceptual grouping and separation of tracks, we had to disambiguate those which are in the same height of radius but at a different azimutal position (given by ϕ in spherical coordinates). Determined by this angle, we add different sets of overtones to the base frequency. In order to achieve different timbres, the base frequency is either played solely for $\phi = 0°$ (where the amplitudes of all even and odd overtones are 0), or with just one set of overtones (odds = 0, evens =1 for $\phi = 90°$ or vice versa if $\phi = 270°$), or as a full sound at $\phi = 180°$ (evens and odds = 1). See Fig. 6.

For angles in between these extreme positions, there is a linear mapping of rising or falling of overtones, introduced as a weighting factor $w_i(\phi)$. The amplitudes are in the first place weighted with $w_k = 1/n$ for n being the harmonics. Finally, the sum of all amplitudes was normalized to 1 in order to avoid clipping.

This differentiation of timbres allows the correct grouping in human perception: following the *gestalt* psychological principle of *similarity*, similar sounds are grouped together and believed as coming from the same track. Pitch is a very strong grouping fac-

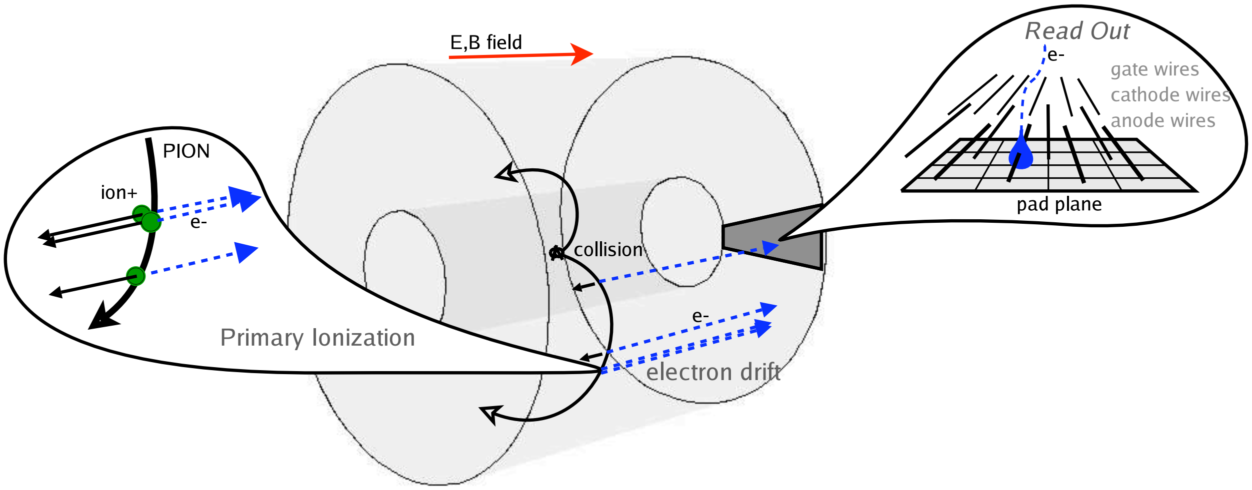

Figure 3: *Schematic plot of the working principle of a TPC, at the example of a pion track. Charged particles transverse the volume of the drift chamber and ionize the gas. The created electrons follow the applied electrical field (E) and are collected in the wire chambers, where they are read out. Three layers of fine copper and wolfram wires are strained on top of each other with some mm between the layers (gate wires, cathode wires and anode wires). The triangular elements are mounted on each of the two read out chambers. The inner wires are shorter than the outer ones, ranging from 27 cm to 84 cm (in total, there are 656 wires from inside to outside.). Calculating the real frequency range for these wires results to 0.0028 and 0.0089 Hz. All technical details of the ALICE TPC can be found in [7]. Source: [8]*

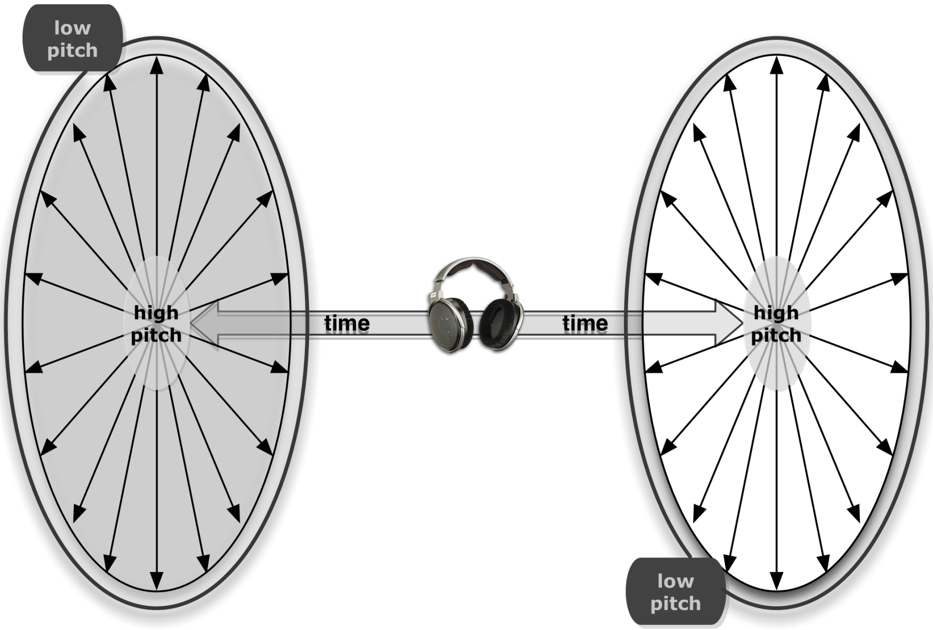

Figure 5: *Scheme of the sonification: the listener is virtually placed in the center, where the beams collide. The two read-out chambers are situated to the left and right hand side. The strings in the center of the read-out chamber are shorter and higher pitched. The tracks start playing in the point of collision and evolve simultaneously to the left and right hand side. The volume of the sounds represents the charge deposit of the electrons. And finally, in order to not confuse tracks that are close to each other, they sound slightly different - as different instruments of an orchestra. If more electrons are hitting wires within a short time, the sounds overlap and auditory grouping happens. Thus we hear a continuous and coherent sound for each track rather than single tones for each single hit.*

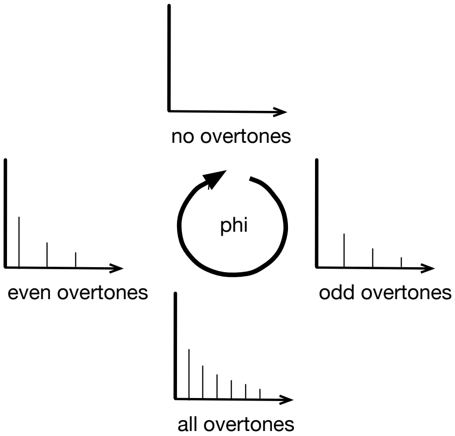

Figure 6: Simplified scheme of the overtone structure in the TPC sonification depending on the angle ϕ. It helps disambiguating the correct grouping and separation for single sounds into coherent tracks, even if these tracks have similar pitches.

tor. As additional cues, similar sounds always follow close to each other (principles of *proximity* and in *good continuation*).

Each sound consists of a bank of resonators $\mathcal{F}_{band}$ with frequencies $f_{i,k}$ specified according to the pitch mapping. The filter bank is excited with an impulse, and enclosed by an envelope $a(\mathring{t}, e_i)$. The level of the impulse and thus the amplitude of the resulting sound are determined by the charge deposit of the electron. Tracks with only few single electron impacts or very weak ones fall silent.

The sonification operator[1] is given as:

$$\mathring{y}(\mathring{t}) = \begin{pmatrix} \mathring{y}_L(\mathring{t}) \\ \mathring{y}_R(\mathring{t}) \end{pmatrix} \tag{1}$$

The $\mathring{y}(\mathring{t})$ denotes the sonification signal, depending on a sonification (listening) time. $\mathring{y}_L(\mathring{t})$ and $\mathring{y}_R(\mathring{t})$ denote the left and right channel of a stereo or binaural rendering.

$$\mathring{y}(\mathring{t})_{L,R} = \sum_i Trig_{t_i} \left[y_i(\mathring{t}, d_i) \right] \tag{2}$$

The sonification consists of a sum over all i (each a single electron impact) of single sounds $y_i(\mathring{t}, d_i)$, that are triggered at respective times t_i as given in the data.

$$y_i(\mathring{t}, d_i) = a(\mathring{t}) \sum_k w_k w_i(\phi) \mathcal{F}_{band, f_{i,k}} [\mathcal{I}(e_i)] \tag{3}$$

Each of these single sounds is a weighted filtered impulse.

$$f_{i,0}(d_i) \in [200, 800]^{exp}\ Hz \tag{4}$$

The frequencies are mapped exponentially between 200 and 800 Hz.

We rendered stereo files and also a binaural version, but the latter seemed not to work well with ‘imaginary’ paths (as the perception has no fix references, but virtual ‘flying’ objects close around the head). Simple stereo panning was less effort to render but even clearer perceived in addition to the visual cues of the screenshots.

In the current setting, each event takes 10 seconds of sonification time. This span can be shortened, of course, but is a good length to disambiguate tracks even in the more complicated events.

As it is difficult to listen to many tracks at once, all tracks can be chosen and played individually. In Fig.7, you see a screenshot for one sound example on the homepage. One track is marked, which is played solely. In this case, the particle did not come from the collision, but stemmed from background radiation or some secondary process of disintegration. It is a charged particle, as it is whirling around in the exterior magnetic field of the ALICE experiment. The pitch is rising and falling, which matches the idea of a turning flying object.

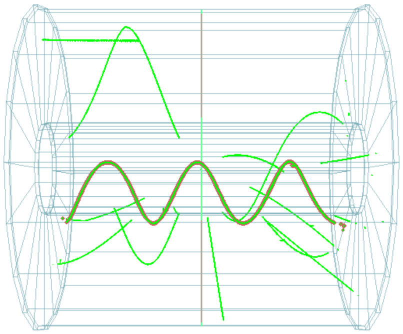

Figure 7: Screenshot of a sound example of the TPC sonification (event number 6), which can be listened to at www.qcd-audio.at/tpc.

Some remarks have to be made with regard to sound files of single tracks. Some tracks are clearly visible but nearly silent in the sonification. This is because the charge deposit of the electrons was very small, and indicates a low energy particle. Another reason may be that only very few electrons constitute a track - either this is a measurement or track counting error or the passing elementary particle really only kicked out a few electrons.

Sound examples can be accessed at: www.qcd-audio.at/tpc.

5. DISCUSSION AND OUTLOOK

The sonification as described in this paper has advantages as well as short-comings. First of all, the outcome is very simple - which we regard as a huge benefit. The mapping is made in analogy to the measurement, thus easy to understand. Also, raw data is sonified, and all pattern recognition of grouping tracks is done automatically by auditory perception.

A ‘normal’ event will mainly include tracks from the collision. If they start at the height of the beam axis, their pitch is falling.

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[1] Recently, J. Rohrhuber [10] suggested the formalization of the sonificaiton operator, to make the mapping between the domain science and the sound synthesis more explicit. We take up this idea and extend the formalization by notation suggestions, as used in Eq. (1-4)

This sound matches very well a real-world sounding object which is thrown away. Still, many other things might happen, where the real-world association does not make sense any more. As it was shown in Fig.7, particles might also stem from background radiation or secondary derivation (the particles stemming from the collision were e.g. neutral and thus could not be detected, but they launched other particles at different places than the collision spot). This creates also problems for the timing, as it is assumed to start in the collision point and evolve towards the read-out chambers. Still, the time is the reversed but otherwise 1:1 measured time of the TPC and thus represents the measurement.

The example shown above, and also most examples on the webpage have rather few tracks. There is also data for other types of collisions, e.g., between two heavy lead nuclei, as pb-pb, which produce thousands of particles in a collision. For such a data set, we did not apply the sonification. We assume, that a sonification of a full such event would not be of much use. This is also true for a visualization. In such a case both sonification and visualization can only provide a very rough overview and tell the scanning person that *a lot* was going on. In AliEve, such plots for raw data are only used for outreach pictures, otherwise some kind of automatized data reduction is done instead of visualizing the raw data. Such a strategy would also be applicable for the sonification.

During the configuration of the sonification, we remarked that 3d plots are often very counter-suggestive. At least in the case, where one sees a bunch of lines on an else empty surface, that gives only scarce cues of dimensionality and perspective, one often interprets the real position of a track wrongly. Different viewpoint angles that can be interactively rotated, as it is possible with AliEve, make the estimate much more accurate. Sound, on the other hand, has other disambiguities. Even with binaural recordings, a cone of confusion stays at the very left or right hand side, and frontal and rear sound events are confused as well. This is addressed as tracks usually are not always in such a confusing area, but rather evolve somehow. This gives our brain an additional cue about the movement and real location of the particle.

The outcome of the project has been presented in two meetings at CERN (weekly meetings of the Offline group and the TPC group) in November 2009. For the physicists attending the meetings, this project clearly presented an interesting variety. Furthermore the sonification is presented as interactive installation in the permanent exhibition of the ALICE experiment at Point 2 of the LHC. This shows, that the idea of sonification was taken serious for didactic and outreach reasons. A continuation in research would imply an interactive bridge to AliEve, which would make *real-time* audio synthesis necessary. Until now, the rendering of an event takes between 10 to 20 minutes.

This project was ended with the stay of the main author at CERN. A continuation depends on time and financial resources. A second project was implemented, where physicists were questioned about their expectance on how particles *should* sound like. This would allow a different mapping, which is also intuitive to the people who can work with it, but provides much more information. As the methodology was completely different, this project was treated in another paper.

Remark on nomenclature.

We used the software SuperCollider3 [11] to sonify the data from the LHC. The LHC is a *super collider*. It was decided to build it only after the US government had abandoned the Superconducting Super Collider (SSC). The SSC would have studied even higher energetic particles. The programming language was called *super collider* after the SSC, as its initiator James McCartney lived in the same region where the SSC was built. In this project, we used super collider to sonify super collider data.

Acknowledgments.

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