Addendum to the proposal P330

Further Information Requested in the Proposal Review Process

By NA61 Collaboration

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Z. Włodarczyk, A. Wójtaszek

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A. Aduszkiewicz, W. Dominik, D. Kielczewska, M. Posiadała, E. Skrzypczak

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Rudjer Boskovic Institute, Zagreb, Croatia
T. Anticic, K. Kadija, V. Nikolic, T. Susa

ETH, Zurich, Switzerland
A. Marchionni, A. Meregaglia, A. Rubbia

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the participation of the following group is under discussion:
-INFN Sezione di Milano Bicocca, Milano, Italy (contact: M. Bonesini),
-INFN Sezione di Padova, Padova, Italy (contact: M. Mezzetto).
This documents presents additional information on the proposal [1] requested by the SPSC in the review process.

1 Task, responsibility and manpower lists

Tables 1, 2, 3, 4 and 5 show lists of hardware and software tasks, responsibilities and manpower of the NA61 Collaboration. The NA49 experts are indicated by italic font.

<table>
<thead>
<tr>
<th>Task</th>
<th>Responsible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety Beam</td>
<td>Zoltan Fodor [70%] (Budapest)</td>
</tr>
<tr>
<td>Beam line and beam profile</td>
<td>CERN, Zoltan Fodor [70%] (Budapest)</td>
</tr>
<tr>
<td>Beam Position Detectors</td>
<td>Zbigniew Majka [20%] (Cracow)</td>
</tr>
<tr>
<td>Trigger Detectors</td>
<td>Zoltan Fodor [70%] (Budapest)</td>
</tr>
<tr>
<td>Detector configuration/logic</td>
<td>Alberto Marchionni [30%] (ETH Zurich)</td>
</tr>
<tr>
<td>Magnets</td>
<td>CERN, Zoltan Fodor [70%] (Budapest)</td>
</tr>
<tr>
<td>TPC Gas system, gas</td>
<td>Wojtek Dominik [20%] (UW Warsaw)</td>
</tr>
<tr>
<td>Power supplies</td>
<td>Edward Gornicki [10%] (IFJ Cracow)</td>
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<tr>
<td>Read-out</td>
<td>Wolfgang Rauch [30%] (FH Frankfurt)</td>
</tr>
<tr>
<td>FE electronics</td>
<td>Rainer Renfordt [10%] (UF Frankfurt)</td>
</tr>
<tr>
<td>cooling, air condition</td>
<td>CERN, Rainer Renfordt [10%] (UF Frankfurt)</td>
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<tr>
<td>He beam pipe</td>
<td>Grigori Fedinov [20%] (St. Petersburg)</td>
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<td>TPC read-out upgrade</td>
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<tr>
<td>Read-out electronics</td>
<td>Tivadar Kiss [20%] (Budapest)</td>
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<tr>
<td>New DAQ</td>
<td>Ervin Demes [20%] (Budapest)</td>
</tr>
<tr>
<td></td>
<td>Zoltan Fodor [70%] (Budapest)</td>
</tr>
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</table>

Table 1: List I of tasks and responsibilities: NA61 detector and its infrastructure. The NA49 experts (post-docs and seniors) are indicated by italic font. The numbers in square brackets show the fraction of time devoted to NA61 activities.

2 2007 run: data calibration and analysis

The first NA61 run is expected to take place in October 2007. During the 30-day long running period we will set up and test the NA49 apparatus (15 days) and take physics data for the T2K
<table>
<thead>
<tr>
<th>Task</th>
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</tr>
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<tbody>
<tr>
<td><strong>TOF (Dubna and Marburg)</strong></td>
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<tr>
<td>Detectors</td>
<td>Vadim Kolesnikov [80%] (Dubna)</td>
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<tr>
<td>New read-out</td>
<td>Ferenc Sikler [10%] (Budapest)</td>
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<tr>
<td><strong>forward TOF</strong></td>
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<tr>
<td>Detectors</td>
<td>Alessandro Bravar [40%] (Geneva)</td>
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<tr>
<td></td>
<td>Marcelo Messina (Bern)</td>
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<tr>
<td>Electronics</td>
<td>Alessandro Bravar [40%] (Geneva)</td>
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<tr>
<td>Read-out</td>
<td>Zoltan Fodor [70%] (Budapest)</td>
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<td></td>
<td>Marcelo Messina (Bern)</td>
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<td><strong>PSD</strong></td>
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<td>Detector</td>
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<td>Read-out</td>
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<td><strong>GEM</strong></td>
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<tr>
<td>Detector</td>
<td>Andras Laszlo [80%] (Budapest)</td>
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<td>Read-out</td>
<td>Andras Laszlo [80%] (Budapest)</td>
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<tr>
<td><strong>Targets</strong></td>
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<td>Targets/installation</td>
<td>Herbert Stroebel [10%] (UF Frankfurt)</td>
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<td></td>
<td>Takashi Kobayashi [10%] (KEK Tsukuba)</td>
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<tr>
<td><strong>DAQ</strong></td>
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<tr>
<td>DAQ software</td>
<td>Wolfgang Rauch [30%] (FH Frankfurt)</td>
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<tr>
<td>Data recording</td>
<td>Wolfgang Rauch [30%] (FH Frankfurt)</td>
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<td><strong>DCS</strong></td>
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<td>Detector control system</td>
<td>Wiktor Peryt [30%] (WUT Warsaw)</td>
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<tr>
<td><strong>Database</strong></td>
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</tr>
<tr>
<td>Database</td>
<td>Wiktor Peryt [30%] (WUT Warsaw)</td>
</tr>
<tr>
<td><strong>Detector geometry</strong></td>
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<tr>
<td>Measurements</td>
<td>CERN Tatjana Susa [40%] (Zagreb)</td>
</tr>
<tr>
<td>Input to database</td>
<td>Tatjana Susa [40%] (Zagreb)</td>
</tr>
</tbody>
</table>

Table 2: List II of tasks and responsibilities: NA61 detector and its infrastructure. The NA49 experts (post-docs and seniors) are indicated by italic font. The numbers in square brackets show the fraction of time devoted to NA61 activities.

part of the program. We plan to register $3 \times 10^6$ p+C interactions at 30 GeV/c. In this section the strategy of data calibration and analysis is presented.

The calibration procedure of the NA61 data will be based on the procedure developed for the NA49 data and it will consist of two sequential steps: reconstruction of the raw data needed to determine a given set of calibration constants. A following reconstruction step will then use the previously determined calibration constants for evaluation and test. The calibration procedure will require about $2 \times 10^6$ interactions on the thin ($<\text{several \% interaction probability}$) carbon target with the magnetic field turned on. The details of the procedure are given below.

1. Reconstruction of several samples of about 100k events each for determining the corrections to the detector geometry and drift velocity.
Table 3: List I of tasks, responsibilities and manpower: NA61 software, data calibration and analysis. The NA49 experts (post-docs and seniors) are indicated by italic font. The analysis will be performed by Ph. D. and M. Sc. students from the indicated institutes with participation/supervision by the NA49 experts: dE/dx - Zoltan Fodor (Budapest), TOF - Georgi Melkumov, Vadim Kolesnikov (Dubna), V5s - Tatjana Susa (Zagreb) high p_T - Andras Laszlo, fluctuations/correlations - Katarzyna Grebieszkow (WUT Warsaw), Maciej Rybczynski (Kielce), Agnieszka Wojtaszek (Kielce), HBT - Paul Chung (Stony Brook), anisotropic flow - Grzegorz Stefanek (Kielce).

<table>
<thead>
<tr>
<th>Task</th>
<th>Manpower</th>
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<tbody>
<tr>
<td>Software</td>
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<tr>
<td>DSPACK library</td>
<td>Grzegorz Stefanek [75%] (Kielce)</td>
</tr>
<tr>
<td>ROOT61 library</td>
<td>Anselmo Meregaglia [30%] (ETH Zurich)</td>
</tr>
<tr>
<td>Reconstruction chain</td>
<td>Tatjana Susa [40%] (Zagreb)</td>
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<td></td>
<td>Grzegorz Stefanek [75%] (Kielce)</td>
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<td></td>
<td>Boris Popov [50%] (Dubna)</td>
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<tr>
<td>Simulation chain</td>
<td>Alessandro Bravar [40%] (Geneva)</td>
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<td>Boris Popov [50%] (Dubna)</td>
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<tr>
<td>Calibration</td>
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<tr>
<td>Geometry/drift velocity</td>
<td>Tatjana Susa [40%] (Zagreb)</td>
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<tr>
<td></td>
<td>Tome Anticic [30%] (Zagreb)</td>
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<tr>
<td>Magnetic field</td>
<td>Agnieszka Wojtaszek [75%] (Kielce)</td>
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<tr>
<td>Residual correction</td>
<td>Katarzyna Grebieszkow [40%] (WUT Warsaw)</td>
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<tr>
<td>TPC point resolution</td>
<td>Antoni Aduszkiewicz [100%] (UW Warsaw)</td>
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<td>dE/dx</td>
<td>Zoltan Fodor [70%] (Budapest)</td>
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<td></td>
<td>Geneva group</td>
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<tr>
<td>TOF (Dubna and Marbug)</td>
<td>Georgi Melkumov [80%] (Dubna)</td>
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<td></td>
<td>Vadim Kolesnikov [80%] (Dubna)</td>
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<td></td>
<td>Aleksandr Sadovsky [40%] (Moscow)</td>
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<tr>
<td>forward TOF</td>
<td>Alessandro Bravar [40%] (Geneva), Boris Popov [50%] (Dubna)</td>
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</table>

Responsible: Tatjana Susa (Zagreb).
Estimated time: 5 days.

2. Evaluation and test of the corrections to the detector geometry and drift velocity.
Responsible: Tatjana Susa (Zagreb).
Estimated time: 15 days.

3. Reconstruction of 1M events for determination of the magnetic field calibration constants.
Responsible: Tatjana Susa (Zagreb).
Estimated time: 10 days.

4. Evaluation and test of the magnetic field calibration constants.
Responsible: Agnieszka Wojtaszek (Kielce).
<table>
<thead>
<tr>
<th>Task</th>
<th>Manpower</th>
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<tbody>
<tr>
<td><strong>Analysis:</strong></td>
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<td>2007/2008 data</td>
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<td>beam and cross section normalization</td>
<td>ETH Zurich</td>
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<tr>
<td>charged pions and kaons (TOF)</td>
<td>Dubna, Geneva, Paris, Moscow</td>
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<td>charged kaons (kinks)</td>
<td>Geneva, Dubna, Paris</td>
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<td>charged kaons (dE/dx)</td>
<td>Geneva and FZK Karlsruhe</td>
</tr>
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<td>charged pions (dE/dx, h–)</td>
<td>Geneva, SINS and UW Warsaw and Karlsruhe</td>
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<td>K_S</td>
<td>WUT Warsaw</td>
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<tr>
<td>hyperons</td>
<td>Zagreb and WUT Warsaw</td>
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<td>high p_T</td>
<td>Budapest and Zagreb</td>
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<tr>
<td><strong>Analysis:</strong></td>
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<tr>
<td>2009-2011 data</td>
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<td>charged pions and kaons (TOF)</td>
<td>Dubna and UW Warsaw</td>
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<td>charged pions and kaons (dE/dx)</td>
<td>Budapest and SINS Warsaw</td>
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<td>neutral strange hadrons</td>
<td>Zagreb, WUT Warsaw</td>
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<td>fluctuations/correlations</td>
<td>Athens, Frankfurt, Kielce, Moscow</td>
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<td>St. Petersburg, WUT Warsaw</td>
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<tr>
<td>HBT</td>
<td>Stony B-ook</td>
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<tr>
<td>anisotropic flow</td>
<td>Kielce, WUT Warsaw</td>
</tr>
</tbody>
</table>

Table 4: List II of tasks, responsibilities and manpower: NA61 software, data calibration and analysis. *The NA49 experts (post-docs and seniors) are indicated by italic font.* The analysis will be performed by Ph. D. and M. Sc. students from the indicated institutes with participation/supervision by the NA49 experts: dE/dx - Zoltan Fodor (Budapest), TOF - Georgi Melkumov, Vadim Kolesnikov (Dubna), V^0's - Tatjana Susa (Zagreb) high p_T - Andras Laszlo, fluctuations/correlations - Katarzyna Grebieszkow (WUT Warsaw), Maciej Rybczynski (Kielce), Agnieszka Wojtaszek (Kielce), HBT - Paul Chung (Stony Brook), anisotropic flow - Grzegorz Stefanek (Kielce).

Estimated time: 10 days.

5. Reconstruction of 1M events for determination of the residual distortion correction.
   Responsible: Tatjana Susa (Zagreb).
   Estimated time: 10 days.

6. Evaluation and test of the residual distortion correction.
   Responsible: Katarzyna Grebieszkow (WUT Warsaw).
   Estimated time: 10 days.

7. Reconstruction of the full statistics of the thin target p+C interactions (≈ 2M events).
   Responsible: Tatjana Susa (Zagreb).
   Estimated time: 20 days.
<table>
<thead>
<tr>
<th>Institute</th>
<th>Supervisor name</th>
<th>Number of students</th>
</tr>
</thead>
<tbody>
<tr>
<td>Athens</td>
<td>Apostolos Panagiotou [20%]</td>
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<tr>
<td>Bari</td>
<td>Emilio Radicioni [20%]</td>
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<tr>
<td>Bergen</td>
<td>Dieter Roelich [20%]</td>
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<tr>
<td>Budapest</td>
<td>George Vesztergombi [40%]</td>
<td>2</td>
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<tr>
<td>Cape Town</td>
<td>Jean Cleymans [20%]</td>
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<td>Cracow</td>
<td>Zbigniew Majka [20%]</td>
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<td>Dubna</td>
<td>Stepan Bunyatov [50%] / Boris Popov [50%]</td>
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<tr>
<td>UF Frankfurt</td>
<td>Marek Gazdzicki [70%]</td>
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<td>Geneva</td>
<td>Alain Blondel [20%] / Alessandro Bravar [40%]</td>
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<tr>
<td>Karlsruhe</td>
<td>Ralph Engel [20%]</td>
<td>1</td>
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<tr>
<td>Kielce</td>
<td>Stanislaw Mrowczynski [20%] / Grzegorz Stefanek [75%]</td>
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<tr>
<td>Moscow</td>
<td>Fedor Guber [30%] / Alekandr Ivashkin [30%]</td>
<td>1</td>
</tr>
<tr>
<td>Paris</td>
<td>Jacques Dumarchez [20%]</td>
<td>1</td>
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<tr>
<td>Pusan</td>
<td>In-Kwon Yoo [20%]</td>
<td>1</td>
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<td>Sofia</td>
<td>Roumen Tsiev [20%]</td>
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<td>St. Petersburg</td>
<td>Grigori Feofilov [30%]</td>
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<td>Stony Brook</td>
<td>Roy Lacey [20%]</td>
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<td>WUT Warsaw</td>
<td>Wiktor Pryt [30%]</td>
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<td>WU Warsaw</td>
<td>Wojtek Dominik [20%] / Danka Kielczewska [20%]</td>
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<td>SINS Warsaw</td>
<td>Ewa Rondio [10%] / Joanna Stepaniak [20%]</td>
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<td>Zagreb</td>
<td>Kreso Kadija [30%]</td>
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<tr>
<td>ETH Zurich</td>
<td>Alberto Marchionni [30%] / Anselmo Meregaglia [30%]</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5: Supervisors and the expected number of students devoted to the analysis of the NA61 data.

8. Preliminary dE/dx calibration needed for the TOF calibration procedure.
   Responsible: Zoltan Fodor and Geneva. Estimated time: 15 days.

9. Evaluation and test of the geometrical and time TOF calibrations.
   Responsible: Vadim Kolesnikov and INR Moscow. Estimated time: 60 days.
   Evaluation and test of the dE/dx calibration.
   Responsible: Zoltan Fodor and Geneva. (Estimated time: 60 days (new gas mixture), 20 days (NA49 gas mixtures))
   Evaluation and test of the potential point calibration.
   Responsible: Tatjana Susa. Estimated time: 10 days.
   Evaluation and parametrization of the TPC point reconstruction resolution.
   Responsible: Antoni Aduszkiewicz. Estimated time: 30 days.
   Estimated time: 60 days.

The calibrations 1-8 should be done sequential, whereas the calibrations listed in 9 in parallel.

The total time of the whole calibration procedure is about 150 days (about 5 months). This
estimate is based on the assumption, supported by the results from the test run, that there are no unexpected problems. Consequently, the fully calibrated data will be copied to the ROOT minidists not earlier than at the end of March 2008.

Thus the physics analysis of the data will start in spring 2008. Clearly the data used for the calibration will also be used for physics analysis. The inclusive spectra of charged pions, charged kaons and $K^0_S$ requested for T2K physics will be obtained by different groups, see Table 2 for details. In addition hyperon production will be studied. The results will allow to correct the pion spectra for the feed-down from decays of $\Lambda$ hyperons. The analysis will be based on the existing NA49 procedures and the ROOT49 analysis classes will be used. The corrections for the limited detector acceptance and efficiency will be calculated using the NA49 simulation chain. The analysis will be performed by the NA49 experts and non-NA49 members of the NA61 collaboration. The experts will supervise the work of inexperienced members of the collaboration. The preliminary physics results are expected by the fall of 2008.

In order to accelerate the learning process of the non-NA49 members of the collaboration two software/analysis schools will be organized. The first one took place from April 30 - May 4, 2007 in Frankfurt, the second is foreseen during the October 2007 data taking run. Furthermore weekly VRVS/EVO meetings on the NA49 and NA61 software and analysis already take place.

3 Experimental uncertainties in the search for the critical point

In this section statistical and systematic uncertainties relevant for the search for the critical point of strongly interacting matter by energy and system size scan with nucleus-nucleus collisions are presented and discussed. The following uncertainties are quantified:

- statistical errors,
- systematic error due to variation of the background fluctuations,
- systematic error due the uncertainty in the measurement of the number of projectile spectators and
- systematic error due to reconstruction efficiency and the small contribution of non-vertex tracks.

Finally, the effect of experimental acceptance on the measured fluctuations is discussed.

The critical point is expected to lead to an increase of multiplicity and transverse momentum fluctuations [2]. The scaled variance $\omega$ of the multiplicity distribution is expected to increase by more than 0.1 and the $\Phi_{P_T}$ measure of transverse momentum fluctuations by about 10 MeV/c in the standard NA49 acceptance [2, 3].

3.1 Statistical error

The statistical error on the scaled variance and $\Phi_{P_T}$ are inversely proportional to the square root of the number of analyzed collisions, $N_{EV}$. Their dependence on the particle multiplicity
and on the actual values of $\omega$ and $\Phi_{pT}$ is weak and can be neglected.

Figure 1: Expected statistical error of the $\Phi_{pT}$ measure of fluctuations for $2 \cdot 10^6$ events as a function of the collision energy and system size.

The statistical error on $\Phi_{pT}$ is shown in Fig. 1 as a function of the collision energy and the system size. The expected number of $2 \cdot 10^6$ events for each reaction was assumed. The statistical errors measured by NA49 were propagated using the $1/\sqrt{N_{EV}}$ dependence. For 10$A$ GeV a smooth extrapolation from higher energies was used. The expected statistical errors are about 0.1 MeV/c.

The expected statistical errors of the scaled variance for the 1% most central collisions (as used in the multiplicity fluctuation analysis by NA49) is smaller than 0.5 %.

### 3.2 Background fluctuations

The systematic error due to variation of background fluctuations with changing collision energy and size of the colliding nuclei was studied using simulations performed within two independent relativistic transport approaches which employ hadronic and string degrees of freedom, i.e. the UrQMD [4] and HSD [5] models. Unlike for other models the validity range of the UrQMD and HSD approaches covers the whole SPS energy domain. The models include numerous effects which influence event-by-event fluctuations and which are not related to the critical point. In particular these are variation in the collision geometry, conservation laws and resonance decays.
The energy and system size dependence of $\omega$ and $\Phi_{p_T}$ in central nucleus-nucleus (C+C, S+S, In+In and Pb+Pb) collisions at $20A$, $30A$, $40A$, $80A$ and $158A$ GeV calculated within the UrQMD model is shown in Fig. 2. Results for negatively charged hadrons in the NA49 experimental acceptance are presented. The events were selected according to the NA49 selection criteria applied in the study of multiplicity and $p_T$ fluctuations.

![Figure 2: Energy and system size dependence of multiplicity (left) and transverse momentum (right) fluctuations calculated within the UrQMD model for reactions to be taken by NA61. For more details see text.](image)

The performed simulation demonstrates that background fluctuation sources lead to only weak variation of the studied measures of multiplicity and $p_T$ fluctuations when the collision energy and system size are changed.

In Fig. 3 the same UrQMD results as presented in Fig. 2 are plotted but the plotted values of $\omega$ and $\Phi_{p_T}$ for S+S collisions at 80A GeV were increased by 0.1 and 10 MeV/c, respectively. This allows for a visual judgment of the significance of the expected increase in fluctuations due to the critical point with respect to the background fluctuations.

In the case of the $\Phi_{p_T}$ measure point-to-point changes of about 1 MeV/c seen in Fig. 2 are dominated by the statistical fluctuations. Thus an upper limit of systematic uncertainty due to the background changes can be estimated to be 1 MeV/c. This upper limit is significantly smaller than the expected increase of $\Phi_{p_T}$ due to the critical point and thus a more precise estimate of the systematic error due the background variation is not necessary.

Point-to-point changes up to about 0.05 are seen for the scaled variance of the multiplicity fluctuations calculated within the UrQMD model, whereas the critical point signal is expected to lead to an increase of $\omega$ by more than 0.1. Thus in this case more detailed analysis of the background variation is necessary. The systematic uncertainty of detection of the increased scaled variance of the multiplicity distribution due to the critical point was quantified by the
Figure 3: Energy and system size dependence of multiplicity (left) and transverse momentum (right) fluctuations calculated within the UrQMD model for reactions to be taken by NA61. The values of $\omega$ and $\Phi_{PT}$ for S+S collisions at 80A GeV were increased by 0.1 and 10 MeV/c, respectively. For more details see text.

following procedure. The value of $\omega$ for S+S collisions at 80A GeV was calculated by a linear interpolation in $A$ of the values for C+C and In+In interactions at the same energy and by a linear interpolation in $\sqrt{s_{NN}}$ of the values for S+S at 40A GeV and 158A GeV. The obtained values were compared with the value of $\omega$ resulting from simulations of S+S collisions at 80A GeV. The calculations were performed independently for the UrQMD and HSD models. The differences between the interpolated and the actual value of $\omega$ for S+S collisions at 80A GeV are -0.011(UrQMD), 0.002(HSD) and 0.026(UrQMD), 0.001(HSD) for the interpolations in $A$ and $\sqrt{s_{NN}}$, respectively. The corresponding difference for the arithmetic mean of the two interpolated values is 0.007(UrQMD) and 0.0015(HSD). Thus in the case of the planned two-dimensional scan the systematic error of $\omega$ due to the background variation is about 0.01. For the one dimensional scan in collision energy the systematic error may be as large as 0.026 (maximum of the UrQMD and HSD values).

3.3 Measurement of the number of projectile spectators

Multiplicity fluctuations are strongly influenced by fluctuations in the number of interacting nucleons. In order to minimize this influence only events with fixed energy from projectile spectators are selected for the analysis. In NA49 this energy is measured by the VETO calorimeter. The resolution of this detector is poor and it can be estimated only in a model dependent way. This is caused by the large non-uniformity of the VETO calorimeter. The response of it changes by a factor of about 2 depending on the impact point of the particle. In order to
Figure 4: The correction, $\delta$, to the scaled variance of the multiplicity distribution calculated for the NA49 VETO calorimeter (two upper curves) and the NA61 Projectile Spectator Detector (two lower curves) for nucleus-nucleus collisions at 20$A$ GeV (dashed) and 158$A$ GeV (solid). The correction is plotted as a function of the ratio of the number of projectile participants $N_p^{PROJ}$ to the nuclear mass number of the projectile nucleus $A$. For more details see text.

calculate its resolution a nuclear fragmentation model is needed. The correction $\delta$ which has to be subtracted from the measured scaled variance of the multiplicity distribution for negatively charged hadrons in the NA49 acceptance is plotted in Fig. 4 as a function of the ratio of the number of projectile participants $N_p^{PROJ}$ to the nuclear mass number of the projectile nucleus $A$. The correction $\delta$ scales in good approximation with the ratio $N_p^{PROJ}/A$, and therefore the curves shown in Fig. 4 are valid for all colliding nuclei. The vertical lines show the ratio which corresponds to 1% of the inelastic cross section for the most central collisions of C+C, S+S and In+In from left to right, respectively.

The two upper curves indicate the correction calculated for the NA49 VETO calorimeter for interactions at 20$A$ GeV (dashed line) and 158$A$ GeV (solid line). For the 1% of the most central collisions the correction ranges between 0.005 and 0.1. The systematic error of this correction is estimated to be as large as 50% of its value.

The two lower curves indicate the correction calculated for the NA61 PSD detector. The
PSD correction is typically smaller by a factor of about 30 than the NA49 VETO correction. For the 1% of the most central collisions it ranges between 0.0001 and 0.003 and due to the high uniformity of the PSD its systematic error will be reduced to about 5% of its value.

3.4 Reconstruction efficiency and contribution of non-vertex tracks

![Graph](image)

Figure 5: The relative difference between results on the scaled variance of the multiplicity distribution obtained using the standard track quality cuts and the opened impact parameter and $dE/dx$ cuts (open points) as well as the point cut (closed points). Results are shown for central Pb+Pb collisions at 20A, 30A, 40A, 80A and 158A GeV. For further details see text.

In order to estimate an upper limit of the systematic error of \( \omega \) due to track reconstruction inefficiency and contributions of tracks from weak decays and secondary interactions the stability of the results with respect to changes of the track quality cuts were studied using NA49 data on central Pb+Pb collisions at 20A, 30A, 40A, 80A and 158A GeV. The impact of the following cuts were studied:
- cut on the specific energy loss (the $dE/dx$ cut) applied in order to reduce the electron contamination,
- cut on the distance between the reconstructed interaction point and the track in the target plane (the impact parameter cut) applied in order to reduce the contamination of tracks from secondary interactions and weak decays,
-cut on the ratio of the number of TPC points on a track and the maximum number of the TPC points (the point cut) calculated for this track applied to reduce non-main-vertex tracks and split tracks. All these cuts reduce the contamination from background tracks, but also change the efficiency of acceptance of the signal tracks (charged hadrons produced at the main vertex in strong and e-m processes). Results using standard NA49 track cuts were compared with corresponding results obtained for opened track quality cuts. The relative differences shown in Fig. 5 are smaller than 2%. This data-based estimate of the systematic error is consistent with an estimate performed using a simulation, where the results from the analysis of the simulated and reconstructed events were compared to the corresponding results obtained directly from the event generator.

Thus the systematic uncertainty of $\omega$ due to the reconstruction efficiency and the contribution of non-vertex tracks is smaller than 0.02.

The relative systematic error on the $\Phi_{p_T}$ measure was studied in detail in [3]. It was found to be about 1.2 MeV/c for p+p, C+C, S+S at 158 A GeV and 1.6 MeV/c for Pb+Pb collisions at 158 A GeV. These uncertainties correspond to a single point error. The relative systematic error was estimated by studying the statistical significance of the structure in the system size dependence of $\Phi_{p_T}$ as a function of the used analysis cuts. No significant change of the statistical significance was found, which indicates that the relative systematic error is smaller than the typical statistical error ($<1$ MeV/c) of the data points used in this analysis.

### 3.5 Critical point signal significance

The results concerning statistical and systematic errors on $\Phi_{p_T}$ and $\omega$ in NA61 are summarized in Table 6. The corresponding values for NA49 are given for comparison. The magnitude of the expected critical point signal as expressed by the number of statistical and systematic errors is presented in Table 6 (signal significance).

### 3.6 Acceptance dependence

The discussed results refer to the NA49 acceptance as used in the multiplicity and transverse momentum fluctuation analysis. This acceptance region covers the rapidity interval $1 < y < y_{\text{beam}}$, where the rapidity is given in the center of mass system. In general, fluctuation and correlation results depend on the selected acceptance. In order to illustrate this dependence for the NA61 case results of two models were studied as a function of the acceptance in rapidity. First, the scaled variance and $\Phi_{p_T}$ for negatively charged hadrons were calculated within the UrQMD model changing the acceptance interval $\Delta y$ from 0 to 2 around the approximate center of the NA49 interval, $y = 1.78$. The results for central S+S collisions at 80 A GeV are shown in Fig. 6 by full squares. Second, clusters (fireballs) decaying into hadrons were added to the UrQMD events. The position of the cluster (fireball) in rapidity was generated according to the inclusive hadron distribution from UrQMD and the cluster transverse momentum was assumed to be zero. A cluster (fireball) emits hadrons with a thermal spectrum assuming temperature
Multiplicity fluctuations, \( \omega \)

<table>
<thead>
<tr>
<th>NA49</th>
<th>NA61</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical error</td>
<td>( \leq 0.05 )</td>
</tr>
<tr>
<td>Systematic error</td>
<td>( \approx 0.005 \text{ MeV/c} )</td>
</tr>
<tr>
<td>Systematic error (other sources)</td>
<td>( \leq 10^{-5} ) (PSD)</td>
</tr>
<tr>
<td>Signal significance</td>
<td>( 2 \cdot \Delta_{\text{stat}} ) and ( 2 \cdot \Delta_{\text{sys}} )</td>
</tr>
</tbody>
</table>

Transverse momentum fluctuations, \( \Phi_{p_T} \)

<table>
<thead>
<tr>
<th>NA49</th>
<th>NA61</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical error</td>
<td>( \leq 1 \text{ MeV/c} )</td>
</tr>
<tr>
<td>Systematic error</td>
<td>( \approx 0.1 \text{ MeV/c} )</td>
</tr>
<tr>
<td>Signal significance</td>
<td>( 10 \cdot \Delta_{\text{stat}} ) and ( 10 \cdot \Delta_{\text{sys}} )</td>
</tr>
</tbody>
</table>

Table 6: Statistical and systematic errors of \( \Phi_{p_T} \) and \( \omega \) measurements in central nucleus-nucleus collisions in NA49 and NA61. The critical point signal significance was calculated assuming an increase of \( \Phi_{p_T} \) by 10 MeV/c and \( \omega \) by 0.1.

\( T = 40 \text{ MeV} \) and the multiplicity of the cluster particles was taken to be 10\% of the mean UrQMD multiplicity. The results obtained within the UrQMD model are shown by full circles in Fig. 6. As expected the scaled variance approaches one (Poisson distribution) and \( \Phi_{p_T} \) approaches zero in the limit \( \Delta y = 0 \). The UrQMD results are weakly dependent on \( \Delta y \). A significantly different behavior is observed for the UrQMD+cluster model. The scaled variance and \( \Phi_{p_T} \) significantly increase with \( \Delta y \) up to about \( \Delta y = 1 \) (the width of the rapidity spectrum of the particles from a cluster decay) and remain approximately constant for \( \Delta y > 1 \).

The above example clearly shows that by changing the acceptance used for the analysis one can distinguish between different possible sources of correlations.

4 Strategy of data taking with ions

The proposed [1, 6] (collision energy)-(system size) scan with ion beams at the CERN SPS is necessary for conclusive and comprehensive results on the critical point and the onset of deconfinement. The originally suggested sequence of data taking can be, however, further optimized in order to increase the probability to observe indications of the new physics in the shortest time.

From this point of view the most promising strategy is to start ion data taking in 2009 with S+S interactions and continue in 2010 with In+In interactions. The 2011 run with C beam will
Figure 6: Left: Scaled variance of the multiplicity distribution for negatively charged hadrons in central S+S collisions at 80A GeV calculated within the UrQMD model (full squares) and the UrQMD+cluster model (full circles). The results are plotted as a function of the width of the rapidity interval $\Delta y$ centered at $y = 1.78$. Right: The corresponding results for the transverse momentum fluctuations expressed in terms of the $\Phi_{P_T}$ measure.

then close ion data taking. The arguments for this ion data taking strategy are given below.

The pilot data on hadron production at the top AGS (see Fig. 25 (left) in [1]) and SPS [7] energies indicate that the ratio of yields of pions and strange hadrons is approximately independent of the size of the colliding nuclei for central collisions of nuclei with $A \geq 30$. Furthermore, results obtained within statistical models [8, 9] show that for these collisions calculations using an infinite volume approximation are valid. For average quantities this means that simple thermodynamical models can be used already for central S+S collisions in the whole SPS energy domain. The interpretation of the experimental results within statistical approaches is significantly simplified for collisions of large enough nuclei.

On the other hand the duration of the expansion stage with purely hadronic degrees of freedom increases with increasing mass of the colliding nuclei. Consequently, the thermal and chemical freeze-out temperatures decrease with increasing size of the colliding nuclei (see Fig. 18 in [1]). The matter freezes out further away from the transition line. In order to minimize the role of hadronic re-scattering collisions of small nuclei are preferred.

Consequently collisions of nuclei of about the size of sulfur seem to be optimal for the study of the properties of the transition between quark-gluon-plasma and hadron gas.
5 Additional justification for neutrino running

In this chapter, we summarize the impact of the proposed hadron production measurements with the NA61 apparatus on the T2K neutrino oscillation experiment.

5.1 Purpose of T2K hadron production measurements at NA61

The main goals of the NA61 hadron production measurements for T2K are the following [10]:

1. predict the far to near neutrino energy spectrum ratio (F/N ratio) at the required precision;

2. predict the near neutrino energy spectrum ($E_{\nu}$) to be compared with near detector measurements at the required precision.

5.2 Requirements on the F/N ratio from the T2K physics goal

In T2K, neutrino oscillations are probed by comparing observations at Super-Kamiokande (SK) with predictions with or without oscillations. Predictions of all the SK observables depend on the $\nu_{\mu}$ and $\nu_{e}$ fluxes at SK ($\Phi_{\mu}^{SK}$ and $\Phi_{e}^{SK}$). They are predicted as products of the spectra at the near site ($\Phi_{\mu}^{ND}$ and $\Phi_{e}^{ND}$) measured by the near detector (ND280) with the far to near ratios (F/N), denoted $R_{\mu}$ and $R_{e}$ respectively, as defined by the equation:

$$\Phi_{\mu,e}^{SK} (E_{\nu}) = R_{\mu,e} (E_{\nu}) \cdot \Phi_{\mu,e}^{ND} (E_{\nu})$$  (1)

If the neutrino source is point-like and isotropic, the F/N ratio is given by the ratio of the distances from the neutrino source squared (solid angle), and is energy independent. In reality, due to the finite size of the source, the F/N ratio depends on the neutrino energy and is determined by:

- the momentum distributions of hadrons (pion and kaons) at production,
- the geometry of the neutrino source.

Thus, in order to evaluate the central value and error of the F/N ratio and, hence, of the SK observables, a detailed information on the pion and kaon production off the T2K target is needed.

5.2.1 Search for $\nu_e$ appearance

One of the T2K goals in its first phase is to search for $\nu_{\mu} \rightarrow \nu_{e}$ oscillations down to $\sin^2 2\theta_{13} \sim 0.008$ (90% CL), which is an improvement by more than an order of magnitude with respect to
present limits. The background ($N_{BG}$) predominantly consists of $\nu_\mu$ NC $\pi^0$ interactions ($N_{BG}^{\pi0}$) and intrinsic beam $\nu_e$ contamination ($N_{BG}^e$):

\[
N_{BG} = N_{BG}^{\pi0} + N_{BG}^e = \Phi_{\mu}^{SK} \cdot \sigma_{NC\pi0} \cdot \varepsilon_{SK}^{\pi0} + \Phi_{e}^{SK} \cdot \sigma_{e} \cdot \varepsilon_{SK}^e \\
= R_{\mu} \Phi_{\mu}^{ND} \cdot \sigma_{NC\pi0} \cdot \varepsilon_{SK}^{\pi0} + R_{e} \Phi_{e}^{ND} \cdot \sigma_{e} \cdot \varepsilon_{SK}^e ,
\]

where $\varepsilon$ denotes efficiency and an energy integral is omitted for simplicity. To achieve the T2K goal, the systematic error on the prediction of background events has to be less than 10% \[
\delta(N_{BG}) \leq 10\%
\]

Figure 7: Fractional change of expected number of BG events in the $\nu_e$ appearance search when the content of one bin in the true $E_\nu$ spectrum is increased by 20% (red) or 10% (black). Left plot is for $\nu_\mu$ NC backgrounds and right plot is for $\nu_e$ CC background events.

In Figure 7, the effects of changes in the F/N ratio (or equivalently the SK spectrum) on the expected number of background events are plotted. For example, the left plot shows that if the height of the neutrino spectrum in the 1.0 - 1.2 GeV energy bin is increased by 20% (red curve), then the number of background events caused by $\nu_\mu$ NC interaction increases by about 1%. According to these studies we find that:

- overall 10% error on $R_{\mu}$ (or $\Phi_{\mu}^{SK}$) in $0 - 1$ GeV range \(\rightarrow \delta(N_{BG}^{\pi0}) = 5.4\%\),
- overall 10% error on $R_{\mu}$ (or $\Phi_{\mu}^{SK}$) in $1 - 10$ GeV range \(\rightarrow \delta(N_{BG}^{\pi0}) = 4.6\%\),
• overall 10% error on $R_e$ (or $\Phi_{e^{SK}}$) in $0 - 1$ GeV range → $\delta (N_{BG}^e) = 8.9\%$
• overall 10% error on $R_e$ (or $\Phi_{e^{SK}}$) in $1 - 10$ GeV range → $\delta (N_{BG}^e) = 1.2\%$

The sources of background errors are not only uncertainties of the F/N ratio, but also those from the ND280 spectrum measurements, cross-sections, efficiencies, etc. Therefore, our aim is to bring the contribution to the error $\delta (N_{BG})$ from the F/N ratio down to a negligible level compared with other contributions to the systematic error. Therefore the goal is to reach a precision on the F/N ratio of

$$\delta (R_{\mu,e}) \approx 2 - 3\%,$$

which corresponds to the error contributions $\delta (N_{BG}^{\mu}) < 1.6\%$ ($0 - 1$ GeV interval), $\delta (N_{BG}^{\pi^0}) < 1.4\%$ ($1 - 10$ GeV), $\delta (N_{BG}^e) < 2.7\%$ ($0 - 1$ GeV), and $\delta (N_{BG}^e) < 0.4\%$ ($1 - 10$ GeV).

### 5.2.2 Precision measurement of $\nu_\mu$ disappearance

The nominal T2K statistical power, assuming 5 years of running with 0.75 MW on target, is $\delta(\sin^22\theta_{23}) \approx 0.01$, $\delta(\Delta m^2_{23}) \leq 3 \times 10^{-5}$ eV$^2$ ($\approx 1\%$), which has to be compared with the present precision of $\delta(\sin^22\theta_{23}) \approx 0.04$ and $\delta(\Delta m^2_{23}) \leq 2 - 3 \times 10^{-4}$ eV$^2$ (SK, K2K, MINOS).

Observations at SK are predicted as follows:

$$N_{sig} (E_\nu) = P_{osc} \cdot \Phi_{\mu}^{SK} (E_\nu) \cdot \sigma_{\nu_\mu CC} (E_\nu) \cdot \varepsilon^{\nu_\mu CC}_{SK} (E_\nu)$$

$$= P_{osc} \cdot R_{\mu} \Phi_{\mu}^{ND} (E_\nu) \cdot \sigma_{\nu_\mu CC} (E_\nu) \cdot \varepsilon^{\nu_\mu CC}_{SK} (E_\nu)$$

and depend on the $\nu_\mu$ F/N ratio (the effect of energy resolution is not explicitly shown for simplicity).

The effects of the variation of the F/N ratio (equivalently the SK spectrum) on the oscillation parameter determination are plotted in Figure 8 [11]. Sources of systematic errors related to the F/N extrapolation in Figure 8 are shown by Red, Pink and Light blue curves. Red is the SK flux normalization error of 10%. Pink is the energy dependent bias on the spectrum with a weighting factor $w(E_\nu) = 1 + 0.2(1 - E_\nu)$, which roughly represents the difference of spectra predicted by MARS and FLUKA hadron production models ($w$ is +20% at 0 GeV, +0% at 1 GeV and -20% at 2 GeV) and Light blue corresponds to a 10% width change. The Green curve shows the error increase, if the ratio of inelastic $\nu$ scattering events (non-QE) to the quasi-elastic ones (QE) is increased by 20% (since the $\nu$ energy for non-QE events cannot be measured) and the Blue curve corresponds to a 4% variation in the energy measurement at SK. The $\Delta m^2$ region of interest is $\Delta m^2 = 2 - 3 \times 10^{-3}$ eV$^2$. Within this region the above changes give an error on the oscillation parameters of:

$$\delta (\sin^2 \theta_{23}) \approx \pm 0.015,$$

$$\delta (\Delta m^2_{23}) \approx \pm 5 \times 10^{-5} \text{eV}^2.$$
Figure 8: Effects of systematic uncertainties on determination of oscillation parameters as a function of true $\Delta m^2$ (2.5° off-axis beam). [Red]: effect when the flux is changed by 10%, [Green]: non-QE/QE ratio changed by 20%, [Blue]: energy scale changed by 4%, [Pink]: multiplication of the neutrino spectrum by a weighting factor $w(E_\nu) = 1 + 0.2(1 - E_\nu) + \text{const}$, [Lightblue]: width of spectrum changed by 10%. The dashed curve indicates the $1\sigma$ statistical error.

A combination of several of these errors can yield a further increase of the systematic error by a factor of 2, which already exceeds the T2K goal.

In order not to limit the precision by the F/N extrapolation, we set our precision goal for the F/N ratio to be

$$\delta (R_{\mu,e}) \approx 2 - 3\%, \quad (8)$$

which roughly corresponds to a contribution to the systematic error of

$$\delta (\sin^2 \theta_{23}) \leq \pm 0.005, \quad \delta (\Delta m^2_{23}) \leq \pm 1.5 \times 10^{-5}\text{eV}^2. \quad (9)$$

5.2.3 Summary of requirements for the F/N ratio to achieve the original T2K goals:

$$\delta R_{\mu} \leq 2 - 3\%, \quad (10)$$

$$\delta R_{e} \leq 2 - 3. \quad (11)$$
5.3 Sensitivity without NA61

Without NA61 data, there are few possible methods to constrain the hadron production rates and spectra, such as:

1. The energy spectrum has to be measured at the near site (ND280) with different beam settings by changing the target-horn parameters or different detector positions. This requires additional mechanisms to produce the different energy spectra. The method also suffers from the uncertainty of the neutrino cross-sections and systematics of the near detector measurements. Therefore, this will not be our primary choice to extract physics results. The expected T2K sensitivities, if we were to take this option, have not been estimated.

2. Another method is to purely rely on the hadron production model fitted to data taken at different energies and target materials. This method suffers from several factors:
   - the nearest data of proton on Carbon were taken at 12 GeV (HARP) and 158 GeV (NA49);
   - no model reproduces very well the observed K/π ratios measured in these data and other nearby nuclei.

Therefore the validity of the models has not been established. Figure 9 shows a comparison of the F/N ratios predicted by different hadron production models (see also Figures 18 and 19).

![Figure 9: Ratio of the F/N ratio for different hadron production models as a function of $E_\nu$: (Left) F/N(MARS) / F/N(G-FLUKA); (Right) F/N(FLUKA) / F/N(G-FLUKA).](image-url)
As can be seen in Figure 9, the differences are as large as ±20% around the peak of the neutrino energy spectrum (0.2 – 1 GeV). If we take this difference as the error on the F/N ratio, i.e. \( \delta R_\mu \sim 20\% \), we can estimate the error on the oscillation parameters from the F/N ratio by scaling the errors related to the F/N ratio shown in Figure 8 as

\[
\delta \left( \sin^2 \theta_{23} \right) \approx (0.015 - 0.030), \tag{12}
\]
\[
\delta \left( \Delta m^2_{23} \right) \approx (5 - 10) \times 10^{-5} \text{eV}^2. \tag{13}
\]

These errors would be much larger than the statistical errors, and poorly known. They would already compromise the achievement of the T2K physics goals.

From the studies described in Section 5.2, a 20% error on the F/N ratio for the \( \nu_e \) appearance search results in:

- overall 20% error on \( R_\mu \) (or \( \Phi^{SK}_\mu \)) in 0 – 1 GeV range → \( \delta (N^0_{BG}) \sim 10\% \),
- overall 20% error on \( R_\mu \) (or \( \Phi^{SK}_\mu \)) in 1 – 10 GeV range → \( \delta (N^0_{BG}) \sim 10\% \),
- overall 20% error on \( R_e \) (or \( \Phi^{SK}_e \)) in 0 – 1 GeV range → \( \delta (N^0_{BG}) \sim 20\% \),
- overall 20% error on \( R_e \) (or \( \Phi^{SK}_e \)) in 1 – 10 GeV range → \( \delta (N^0_{BG}) \sim 2\% \).

Therefore the error contribution coming ONLY from the F/N ratio error gives a larger error on \( N_{BG} \) than the required error of ≤ 10%, leading to a situation which is not acceptable.

### 5.4 Requirements on the NA61 measurements from F/N ratio requirements

Here, we study the requirements on the accuracy of hadron production measurements in order to achieve a precision of 2 – 3% on the F/N ratio.

First, we investigate which parts of the momentum/production-angle phase-space of produced secondary particle influence the F/N ratio. We increased the number of particles in a given momentum (angle) bin by +30% and then evaluated the resulting change in the F/N ratio. Figure 10 shows the results of \( \delta (F/N \text{ ratio}) \) as a function of momentum and angle for the bin in which the number of particles was increased. From these studies we conclude that we need to measure hadron production particularly in the region \( 0.5 < p(\text{GeV}/c) < 5 \) and \( 0 < \theta(\text{mrad}) < 250 \).

Secondly, we consider the required statistical precision of the hadron production measurement by dividing the momentum-angle region into 1000 bins (Figure 11). A 10% uncorrelated uncertainty (i.e. 10% statistical fluctuations) in each of the momentum-angle bins leads to an uncertainty in the F/N ratio of typically 1%. Therefore, we need to measure hadron production with a statistical accuracy of about 10% in each momentum-angle bin. For a sample consisting of 200k reconstructed \( \pi^+ \) tracks in the phase-space of the T2K neutrino beam the number of entries in each momentum-angle bin satisfies this requirement (Figure 12).
Figure 10: $\delta(F/N$ ratio) as a function of momentum (left) and angle (right) for the bin in which the number of particles was increased by 30%. The “non-smoothness” is due to the limited statistics of the beam MC simulation.

Figure 11: Momentum-angle bins: the error on $F/N$ as a function of $E_{\nu}$ from a 30% (top) and 10% (bottom) uncorrelated uncertainty (statistical fluctuation) for each $p-\theta$ bin.
Figure 12: Momentum distribution of $\pi^+$'s detected in NA61 yielding $\nu$'s in T2K for different $\theta$ intervals. The plots are normalized to 200k $\pi^+$ tracks.

5.5 Requirements for predicting the energy spectrum at the near site

We evaluated the accuracy of the predicted $E_\nu$ spectrum at the near detector assuming measurements of hadron production with a 10% statistical uncertainty for each $p-\theta$ bin. Figure 13 shows the predicted $E_\nu$ spectrum (top plot) and the size of the error for each bin (bottom plot). The size of the error ($<2\%$) is smaller than the expected systematic uncertainties of T2K from the response of the ND280 detector ($\sim 4\%$) and from the neutrino interaction cross section ($\sim 3-4\%$).

Statistics wise, therefore, we need to measure the pion production ($p-\theta$ distribution) with an accuracy (equal or) better than 10% for each $p-\theta$ bin. To achieve this the 200k $\pi^+$ tracks necessary to perform the study of the F/N prediction will be adequate. Detailed study of the required $K^+$ meson statistics was still not performed, but we expect a several thousand $K^+$ tracks to be measured in the event sample which yields 200k $\pi^+$ tracks (about 1M p+C interactions). This should allow a statistical precision of 3-5% on the integral of the high energy
part of the spectrum. The systematic uncertainty of the K/π ratio measurement in NA49 was 5% for central Pb+Pb collisions. We expect even higher precision for the lower multiplicity p+C interactions at 30 GeV.

The absolute normalization of the hadron production cross-section measurements and the overall systematic error (correlated errors) should be ≤ 3% in order to be smaller compared to the T2K errors mentioned above. NA49 has published cross-section measurements with a typically precision of 3%, both in absolute and in the K/π ratio. This is also the required precision for the NA61 measurements.

![Graph](image_placeholder)

Figure 13: Predicted $E_\nu$ spectrum (top plot) and the size of the error for each $E_\nu$ bin (bottom plot) from 10% uncorrelated statistical fluctuations.

### 5.6 Impact of the K/π ratio on backgrounds to the $\nu_\mu$ appearance search

As discussed in Section 5.2, the requirement on the accuracy for $R$ is 2 – 3% in both the high energy region (1 – 10 GeV) and low energy region (< 1 GeV). Since the high energy part of the $\nu_\mu$ spectrum comes from kaon decays (Figure 14), we need to measure the ratio of the number of K$^+$ to the number of π$^+$. We studied how the accuracy of the K/π ratio impacts the accuracy of $R$. When we varied the K/π ratio by ±10% we found that the uncertainty on $R$ is ±2% as shown in Figure 15.

Moreover, only the K$^+$'s in the momentum range of $1 < p_K$(GeV/c) < 10 and production angle range of $0 < \theta$(mrad) < 250, contribute to the $\nu_\mu$ flux accepted by ND280 and SK.
Figure 14: Top plots: $\nu_\mu$ spectra in the near detector (ND280) and Super-Kamiokande (SK) as a function of $E_\nu$. The $\nu_\mu$ origin from different parent decays is also shown. Bottom plots: Relative contributions to the energy spectrum of $\nu_\mu$'s from $\pi^+$'s and $K^+$'s decays.

Figure 15: F/N sensitivity on the $K/\pi$ ratio.
detectors (Figure 16). Therefore, we need to measure the total K\(^+\) yield and the K/\(π\) ratio in this kinematic region with a 10% accuracy. Thus several hundred K\(^+\) tracks will satisfy the statistical requirement. Event statistics needed for 200k \(π^+\) tracks includes a few thousand K\(^+\) tracks. The K\(^+\)/\(π^+\) ratio is between 3-7% but the efficiency for K\(^+\) is lower than for pions due to Kaon decays in flight.

![Figure 16: \(p \text{ vs. } θ\) distribution of K\(^+\) mesons that contribute to the observed neutrino flux at ND280 (left) and at SK (right). The K\(^+\) production cross-section is weighted with the probability that the daughter neutrinos will interact in SK.](image)

### 5.7 Longer term goals: absolute cross-sections and precision measurement of \(\nu_μ \rightarrow \nu_e\) oscillation

The two arguments in the following are not part of the immediate program of T2K but may become extremely important in the future. They emphasize the fact that in the longer term there will be a potentially important usage for high precision particle production measurements.

The measurements of low energy neutrino cross-sections leave much to be desired. The energy spectrum of T2K is a nearly narrow band beam with a peak at 600 MeV. Neutrino cross-sections at that energy have been measured in the ANL bubble chamber with a precision of 20 – 30%. The T2K near detector ND280 has the possibility to improve these measurements considerably. Statistics of several 100k events will be available, and systematic uncertainties will clearly dominate the errors.

A measurement of hadron production with a precision of \(\sim 3\%\), as possible with the NA61 apparatus, will allow a determination of the absolute neutrino flux, and thus of the absolute
cross-sections with a much improved precision. Other errors coming from the modeling of the flux and from the detector response have not been fully estimated, but it is clear that the knowledge of particle production by 30 GeV protons on carbon will allow measurements of inclusive and exclusive neutrino cross-sections at this energy with a precision in the 5% range, which represents a large improvement over existing data.

Once and if the $\nu_\mu \to \nu_e$ transition is observed, the precise measurement of the oscillation probability will allow, by comparison with other measurements with different baselines or energies, to have access to the matter effects, and by comparison with anti-neutrino runs or reactor experiments, to the CP violating phase. The hadron production data needed for anti-neutrino runs ($\pi^-$ and $K^-$) will be taken by NA61 at the same time. These measurements require precise knowledge of the ratio of final state to initial state cross-section $\times$ efficiency, which, even with the assumptions of lepton universality, are affected by a combination of lepton mass, nuclear effects and pion thresholds. A measurement free of theoretical assumptions and uncertainties will require careful measurements of electron neutrino events as well as muon neutrino events, and this can only be performed with a good knowledge of the ratio of $\nu_e$ to $\nu_\mu$ fluxes, and therefore of the $K/\pi$ ratio in the neutrino beam line.

5.8 Impact of the HARP experiment on the K2K experiment

Figure 17 shows the difference between the F/N ratio obtained with the HARP data and that obtained without the HARP data. To demonstrate the contribution of HARP to the K2K oscillation analysis, we compare the three oscillation analyses, which differ in the estimated uncertainty due to the F/N ratio. The precision of the oscillation analysis in K2K is limited by the statistical error. Thus we performed the oscillation analysis using a virtual experiment with much higher statistics (100 times larger than K2K) in order to clearly see the differences of the systematic errors from the F/N ratio. Then we compared the measurement precision of $\Delta m^2$, where the input value of $\Delta m^2$ and $\sin^22\theta$ in the virtual experiment are $2.76 \times 10^{-3}\text{eV}^2$ and 1.0, respectively. (The size of the statistical error in K2K was $\delta(\Delta m^2) = \pm0.35(\text{stat}) \times 10^{-3}\text{eV}^2$ and 10 times smaller in the virtual experiment).

5.8.1 Analysis using the F/N ratio obtained by HARP (HARP F/N) [The method adopted for the K2K final result]

The F/N flux ratio in K2K is estimated using the beam MC simulation based on the pion production cross-section measured by HARP. The systematic uncertainty on the F/N ratio is due to the Sanford-Wang parameterization of HARP data and gives the following error on $\Delta m^2$:

$$\delta(\Delta m^2) = \pm0.041(\text{F/N syst}) \times 10^{-3}\text{eV}^2.$$  \hspace{1cm} (14)
Figure 17: Comparison between neutrino fluxes and the F/N ratio with and without the HARP data. The empty circles with error bars show the central values and systematic errors based on the HARP measurement. The empty squares with shaded error bars show the central values and systematic errors based on the PIMON measurement. The dotted histograms show the values obtained with the Cho-CERN compilation. Beam MC predictions for (Left) the neutrino flux at the near detector location, (Center) the neutrino flux at the far detector position, and (Right) the F/N ratio.

5.8.2 Analysis using the F/N ratio obtained without the HARP data (Non-HARP F/N) [The method adopted to obtain the K2K result prior to HARP]

For $E_\nu > 1.0$ GeV the F/N ratio is based on the measurement of the pion monitor (PIMON) installed in the K2K beam line. The dominant source of the uncertainty of the F/N ratio is the error of the PIMON measurement.

For $E_\nu < 1.0$ GeV the F/N ratio is estimated using the “Cho-CERN compilation” for the pion production model, which is based on p-Be interaction measurements. The uncertainty on F/N is due to the parameterization error of the Sanford-Wang formula and the extrapolation of p+Be data to p+Al interactions. The resulting error on $\Delta m^2$ is

$$\delta (\Delta m^2) = \frac{+0.052}{-0.053} \text{ (F/N syst) [Unit : } 10^{-3}\text{eV}^2].$$

(15)

It should be noted that there are no cross-section measurements at the energy of the T2K proton beam. Extrapolations to the T2K beam energy are not very reliable, since they would be based on parameterizations of existing data taken at different energies (HARP at 12 GeV and NA49 at 158 GeV), which have limited predictive power. For the K2K beam some cross-section measurements off a Be target, though not very accurate, existed prior to the HARP measurement. In general, the Cho-CERN parameterization is:

i) based on a set of scattered, several unpublished and not necessarily accurate data,

ii) phenomenological; it is very hard to estimate the systematic errors associated with this parametrization.
Moreover, in T2K there will be no monitoring of the T2K pion beam generated off the T2K target. Because of the 100× higher beam intensity compared to K2K, a detector similar to the PIMON of K2K would not function with the T2K beam. In K2K the PIMON detector was based on a Cherenkov detector with a 2 GeV threshold for pions. This threshold was set in order to reject 12 GeV beam protons. Therefore, only pions decaying to neutrinos with \( E_\nu > 1 \text{GeV} \) were measured. Most of the relevant neutrino flux, however, had \( E_\nu < 1 \text{GeV} \) and was not monitored. The Cho-CERN compilation was used instead. The main purpose of PIMON was to verify the Cho-CERN parameterization for \( p_\pi > 2 \text{GeV}/c \). In T2K the threshold would be even higher in order to reject beam protons, leaving out most of the relevant hadron beam phase space.

5.8.3 Analysis using the F/N ratio based on Monte Carlo (Pseudo-T2K non-NA61) [Situation similar to the analysis of T2K without the NA61 data]

The F/N ratio is estimated by relying on the hadron production model in the beam MC. The uncertainty due to the hadron production model is estimated from the comparison between GEANT, FLUKA and MARS (~ 20% level) in addition to the Non-HARP F/N case. The resulting error on \( \Delta m^2 \) is

\[
\delta \left( \Delta m^2 \right) = \pm 0.11 \text{ (F/N syst) [Unit : } 10^{-3}\text{eV}^2 \right].
\]

(16)

It can be seen that the error on the beam uncertainties was reduced by a factor of more than two by using hadron production data and especially the HARP measurement. Moreover, the errors were data based, and thus much more reliable than those obtained from ‘comparisons between Monte Carlos’. While in K2K the statistical error on the far detector event sample dominated the errors, the systematic uncertainty due to the F/N ratio will become very significant in the oscillation analysis with higher statistics as in the T2K experiment. Therefore, it is critical to understand the hadron production well for the oscillation analysis with large statistics.

5.9 Pion momentum and angular distributions, \( \nu_\mu \) energy spectrum for different production models.

Figure 18 shows the predictions of different hadron production models of the angular distributions of pions originating from the T2K target for two different momentum ranges. Figure 19 shows the pion momentum and neutrino energy distributions predicted by the same hadron production models.

5.10 Hardware for the T2K related measurements

The hadron production measurement for T2K requires good particle identification (\( \pi/K \) and K/p separation) over the whole phase space of the T2K beam (see for example Figure 16).
Figure 18: Pion angular distributions for two different momentum ranges predicted by different hadron production models: Red is G-FLUKA, Green is MARS and Blue is FLUKA.

Figure 19: (Left) Pion momentum distributions and (Right) energy spectra of $\nu_e$'s for different hadron production models: Red is G-FLUKA, Green is MARS and Blue is FLUKA.
The particle identification (PID) will be based on time of flight (ToF) measurements up to 3 – 4 GeV/c, and by a combined ToF – dE/dx (TPC) analysis up to 8 GeV/c.

Figure 20 (left) shows the acceptance of the existing NA61 ToF system. Clearly the acceptance is not sufficient to cover all the phase space required. At the proposal level we addressed this issue indicating that in principle by changing the magnetic field and/or target location one could cover most of the kinematic region of interest. The disadvantage of this approach is that for each change of the setup one would need to reconfigure the experiment (different settings), the systematics of different data samples would not be necessarily the same, and it would require a two times longer running time to acquire the desired statistics.

Figure 20: Acceptance of the existing ToF system (left) and of the new ToF wall combined with the existing ToF (right).

The best solution is to fill the gap in the ToF acceptance with a new ToF wall (Figure 21). Figure 20 (right) shows the acceptance of the new ToF system, consisting of a new ToF wall combined with the existing ToF detectors. This solution provides full ToF coverage over the whole phase space of the T2K beam.

Figure 21 shows the setup of the existing NA61 ToF detectors (left) and of the new ToF configuration (right). The current setup consists of two highly segmented ToF walls (TOF-L and TOF-R in the figure) and two ToF counters at very large angles (Buda-L and Buda-R, Buda stands for Budapest, where these counters were built). The new ToF wall will be installed just downstream of the main TPCs (MTPC-L and MTPC-R in the Figure) and in front of TOF-L and TOF-R, filling the gap between the TOF-R and TOF-L walls (Figure 21 right). The new ToF wall will consist of 64 scintillator bars, oriented vertically, and read out on both sides with Hamamatsu R1828 photo-multipliers. The size of each scintillator bar is 120 × 10 × 2.5 cm³. The expected resolution of the new ToF wall is ≤ 120 ps. This resolution will provide a 5 σ π/K separation at 3 GeV/c. The electronic chain (constant fraction discriminators, TDCs and ADCs) and power supplies will be inherited from the Buda ToF walls in the existing ToF system. The acceptance of the Buda ToF walls is marginal. We already planned not to use the
Buda ToF walls in NA61.

Figure 21: NA61 ToF system: existing detectors (left) and new configuration (right). The new ToF wall is shown in red. TOF-L and TOF-R are the highly segmented NA49 ToF walls (left), that have been shifted to a new position (right), and Buda-L and Buda-R are two additional ToF counters at large angles. MTPC-L and MTPC-R are the main TPC detectors used also for dE/dx measurements.

The construction of the new ToF system has already started. We expect that the system will be ready this fall, in time for the 2007 run. As a backup plan for the 2007 run we can use the counters in the Buda walls. These counters could cover most of the required phase-space, however, with an almost three times lower acceptance due to the smaller vertical extension of the detector (45 cm vs. 120 cm).

5.11 Beam request

The proton beam energy at which the J-PARC accelerator will start operating is 30 GeV. Contingent on the accelerator performance and in particular the beam intensity, in a second phase the beam energy could be increased to 40 GeV and to 50 GeV. The off-axis neutrino beam intensity is essentially proportional to the beam power dumped in the target. Therefore there will be an optimization process of the J-PARC proton beam intensity and energy to achieve the maximum beam power. As discussed in the proposal and earlier in this addendum, we would like to make all the measurements necessary for the T2K experiment, including those concerning
the longer range plans of T2K, so that we do not need to plan additional measurements at a later time. For this reason we would like to measure \( \pi \) and K production at 30 GeV, 40 GeV, and 50 GeV incident proton energy.

We plan to take data with:

- a 1 cm thick graphite target (2% \( \lambda_{\text{int}} \)) to study the \( p + C \rightarrow \pi^+(\pi^-) + X \) and \( p + C \rightarrow K^+(K^0, K^-) + X \) cross-sections in detail and

- the 90 cm long T2K replica target (180% \( \lambda_{\text{int}} \)) to study in detail the secondary interactions, which become more and more important as the beam energy increases, and to characterize the T2K hadron beam.

The pion and kaon spectra measured with the replica target can also be used as input to the beam MC simulation. Given the concerns about the systematics between the thin and the long targets, uncertainties related to the spread of the interaction point (primary vertex) in the long target, multiple scattering, multiple interactions, etc. we are also envisaging measurements using a 10 cm long (intermediate) target (20% \( \lambda_{\text{int}} \)) to address these issues. Based on the outcome of the measurements with the thin and the replica targets, we might need to make measurements also with the intermediate target.

For each target we would like to collect 200k \( \pi^+ \) tracks in the phase space of the T2K beam. Since the apparatus acceptance is symmetric for positive and negative particles, at the same time we will collect a similar number of \( \pi^- \) tracks. That is already addressing the longer range running of T2K, when T2K will change to an anti-neutrino beam. The expected number of kaons in these data samples will be sufficient to measure the \( K/\pi \) ratio to an accuracy better than 10%, as required for the T2K physics. Given the overall acceptance of the NA61 apparatus of about 15% (Figure 20), around 1.0 – 1.5 million triggers will be required to collect 200k \( \pi^+ \) tracks.

In 2007 we expect that NA61 will register about 70 events per SPS cycle assuming the standard cycle with a 4.8 s flattop. This data rate will result in about 270k events per day provided the NA61 and SPS efficiencies are 80%. Thus in two weeks of physics data taking we expect to collect about 3.8 million events. It is possible that during the NA61 run the SPS will be operated with the 40 s cycle needed for the CNGS running. In this case NA61 will register only about 2 million events due to the limited depth of the DAQ buffers. Thus the 2007 pilot run should allow to collect the required statistics for \( p + C \) interactions at 30 GeV on two targets (thin and replica). The data for the remaining target/energy configurations will be registered in the 2008 run. The upgraded read-out electronics will allow to run the DAQ at a speed of 100 Hz. The number of registered events will depend on the duty cycle and not on the cycle length. This will result in about 2 million events per day. Including setup time for the beam/target/trigger about 14 days of data taking during the 2008 run will be required to collect the T2K statistics.
6 Further justification of runs for the cosmic-ray experiments

6.1 Astroparticle physics motivation

The current knowledge of the all-particle cosmic-ray flux at high energy is shown in Fig. 22. The flux is scaled with $E^{2.5}$ to make some characteristic features easily visible. At the knee, at about $3 \times 10^{15}$ eV, the index of the power law changes from approximately $-2.7$ to $-3$. At higher energy the spectrum flattens again somewhat in the energy region of the ankle at about $3 \times 10^{18}$ eV. Also there seems to be a suppression of the flux at ultra-high energy. The physical origin of both the knee and the ankle are not yet understood. It is also not clear whether the flux suppression at ultra-high energy is related to the Greisen-Zatsepin-Kuzmin (GZK) energy loss process or to an intrinsic energy cutoff of cosmic ray sources.

For understanding these key features of the cosmic-ray spectrum, the elemental composition of cosmic rays has to be measured. Due to the low flux of particles, cosmic rays can only be measured at high energy by detecting the extensive air showers they produce in the atmosphere. The indirect nature of this detection technique leads to a strong dependence of the interpretation of the data on the detailed modeling of extensive air showers.

In the following we discuss only two representative examples that are related to the knee and the ankle to illustrate the need of and the methods applied for measuring the elemental composition of high-energy cosmic rays. Detailed presentations of the current status of composition measurements and open problems can be found in [29, 30, 31].

6.1.1 The knee in the cosmic-ray spectrum

Many theories have been put forward for explaining the knee of the cosmic ray spectrum, for example, see [32, 30]. In the following we will present some characteristic predictions of different classes of models rather than discussing the individual models directly.

In acceleration models, the knee is a feature of the cosmic ray sources in our Galaxy. For example, assuming that cosmic rays are accelerated in shock fronts of supernova remnants, the knee could be a feature of the acceleration process. The knee energy would correspond to the energy above which the acceleration process is much less efficient due to source-specific properties such as the magnetic field strength in supernova shock fronts.

In propagation models, the knee is the imprint of the change of the characteristics of cosmic ray propagation in our Galaxy above $3 \times 10^{15}$ eV. The change of the power-law index of the observed flux is the result of a rapidly decreasing time over which cosmic rays are confined to the Galaxy due to galactic magnetic fields.

The deflection of a particle in a magnetic field is inversely proportional to the ratio of momentum over charge, called rigidity $R = p/Z$. In particular, the confinement radius (Larmor radius) scales with $R$. Therefore, in acceleration and propagation models of the knee, it is expected that the knee of the cosmic ray flux is the result of the superposition of different
Figure 22: All-particle cosmic-ray energy spectrum as obtained by direct measurements above the atmosphere by the ATIC [12, 13], PROTON [14, 15], and RUNJOB [16] as well as results from air shower experiments. Shown are KASCADE data (interpreted with two hadronic interaction models) [17] and Akeno data [18, 19] in the knee energy range. The measurements at high energy are represented by HiRes-MIA [20, 21], HiRes I and II [22, 23, 24, 25], AGASA [26, 27], and Auger [28]. The flux is shown as function of the total nucleus energy and not energy per nucleon as typically used in heavy ion physics.

Elemental knees. The characteristic energy of the individual knees should correspond to the same rigidity and hence scale in energy with the charge $Z$, see Fig. 23 (left panel).

There are a number of models in which new interaction channels, changing the characteristics of multi-particle production at the knee energy, or new energy loss processes are proposed. With the knee energy being slightly higher than the equivalent c.m.s. energy of the Tevatron collider, such assumptions are not in contradiction with available data. Another alternative scenario is the cannon ball model of cosmic ray acceleration [33], which is based on the assumption that blobs of matter (called cannon balls) are ejected in jets of supernova explosions. In this model, cosmic rays gain energy due mainly to elastic scattering. Both the models proposing new hadronic physics and the cannon ball model predict a scaling of the knee energy of different elements with mass number $A$, see Fig. 23 (right panel).
Figure 23: Schematic presentation of different model predictions: scaling of knee energy for different elements with charge number (left panel) and mass number (right panel).

Figure 24: Correlation of electron and muon numbers with primary particle mass and shower energy [34]. Each point corresponds to one shower simulated with the CONEX code [35] using the hadronic interaction models QGSJET 01 [36] at energies $E_{\text{lab}} > 80\text{ GeV}$ and GHEISHA [37] at energies $E_{\text{lab}} < 80\text{ GeV}$.

Determining the cosmic ray composition in the knee energy region is the most promising method to distinguish between different classes of models and to learn more about the origin of the cosmic ray knee. The currently best measurement in this energy range has been performed by the KASCADE Collab. [17]. For each detected air shower, the number of muons and electrons is measured with an array of ground detectors. Using detailed simulations of extensive
air showers, the muon and electron numbers are used to estimate the energy and mass number of the shower-initiating particle. The relation between the muon and electron numbers and the primary particle is illustrated in Fig. 24 for the hadronic interaction models GHEISHA [37] (used for the simulation of interactions with $E_{\text{lab}} < 80 \ \text{GeV}$) and QGSJET 01 [36] ($E_{\text{lab}} > 80 \ \text{GeV}$).

![Diagrams showing energy spectra for different elements](image)

Figure 25: Energy spectra for five groups of elements derived from electron and muon number measurements with the KASCADE air shower array [17]. The shaded bands indicate the systematic uncertainty of the unfolding method.

The results of an unfolding analysis of the KASCADE data [17] is shown in Fig. 25 for the two hadronic interaction models QGSJET 01 [36] and SIBYLL 2.1 [38, 39]. GHEISHA was used as low-energy interaction model for both analyses. For some of the five elemental groups used in the analysis, individual knees can be clearly seen, however, no clear trend of a scaling with either charge or mass number can be discerned. The strong dependence of the results on the used hadronic interaction model is apparent. Moreover, both sets of models are found to provide an inadequate description of the KASCADE data [17] (see also Fig. 8 in [40]). Currently the limited knowledge of simulating hadronic interactions in extensive air showers is the largest source of uncertainty in determining the primary mass of cosmic rays.
6.1.2 The ankle in the cosmic-ray spectrum

Traditionally the ankle has been interpreted as the signature for the transition from galactic to extragalactic cosmic rays. Protons with an energy greater than $\sim 10^{18}$ eV are no longer confined to the Galaxy by the magnetic fields (field strength $\sim 3\, \mu G$). The transition from diffusive to almost rectilinear propagation depends on energy and charge number. An enhancement of heavier elements just at the upper limit of the galactic confinement energy range is expected. If extragalactic cosmic rays are dominated by light elements, a transition from a heavy to a light elemental composition of cosmic rays should take place in the energy range of the ankle around $3 \times 10^{18}$ eV [41].

In a recently proposed, alternative model, the ankle is interpreted as a signature of extragalactic cosmic ray propagation [42, 43]. If the extragalactic cosmic ray flux is consisting almost entirely of protons and extends to energies well below $10^{18}$ eV, production of $e^+e^-$-pairs in interactions with the cosmic microwave background naturally lead to a dip in the spectrum similar to that observed in data. This model predicts a transition from an iron-dominated composition to protons already at much lower energy than expected in the conventional ankle model [44, 45].

![Graphs showing mean depth of shower maximum and density measurements.](image)

Figure 26: Mean depth of shower maximum (left panel) and muon density at 600 m lateral distance (right panel) as measured by the HiRes-MIA Coll. [21]. The black solid lines are fits to the data.

The data from the HiRes prototype fluorescence telescope and the MIA muon detector array (HiRes-MIA) [46] cover the lower part of the energy range that is of interest for the transition from galactic to extra-galactic cosmic rays. Both detectors were operated in coincidence, al-
lowing the measurement of the shower depth of maximum and the muon density at 600m from
the shower core for the same events [21]. In Fig. 26, the data were compared with predic-
tions calculated with CORSIKA [47] using the hadronic interaction models QGSJET 98 and
GHEISHA. The measured mean depth of shower maximum indicates a rapid transition from a
mixed to a very light elemental composition. However, the muon measurements, although also
showing a transition towards a lighter composition, are not compatible with the interpretation
of the depth of shower maximum [21]. The muon densities would correspond to elements even
heavier than iron, see Fig. 26 (right panel).

Due to this inconsistency of the interpretation of the HiRes-MIA data, which is most likely
related to shortcomings in the simulation of hadronic interactions, the composition has to be re-
garded as unknown in this energy range. Again, the limited knowledge of hadronic multi-particle
production turns out to be the most important uncertainty in deriving the mass composition
from air shower data.

6.2 Importance of measuring low-energy interactions

The muon component of air showers is directly connected to the hadronic core of the shower.
About 90% of the muons produced in hadron-induced air showers are decay products of charged
pions and kaons.

The number of pions and kaons produced in an air shower is related to hadronic interactions
over a wide energy range from the primary particle energy down to few tens of GeV. Detailed
simulations show that typically five consecutive hadronic interactions, including the primary
particle interaction, take place before a charged hadron decays to a muon [48]. Therefore a
good knowledge of hadronic interactions in the entire energy range will be needed to predict
muon production reliably.

The sensitivity of the muon multiplicity to the characteristics of hadronic interactions at
very high energy is not as high as one would naively expect. For example, doubling the
secondary particle multiplicity of the primary interaction leads only to a less than 10% increase
of the muon number at ground [50]. In case of a very high secondary particle multiplicity, the
energy of the produced pions is lower and the interplay between interaction and decay of pions
leads to a reduction of the number of consecutive interactions.

The number of low-energy muons cannot be measured close to the shower core with air
shower arrays. First of all, the dynamic range of the detectors does not allow counting such
high particle numbers. Secondly, a separation between the em. and muonic components is not
possible close to the shower core. The “punch-through” of the dominating em. component would
be too strong for deriving a reliable muon number. Therefore muon densities are measured only
at detector-specific distances from the core (for example, 40 – 200 m in the knee energy range,
400 – 600 m for energies below the ankle and 1000 m at the highest energies).

The muon density in air showers at large lateral distance is very sensitive to the characteristics of low-energy interactions. This is illustrated in Fig. 27 by showing the energy distribution
of the last interaction in which the pion is produced that finally leads to the observed muon.
Figure 27: Energy distribution of the “last” hadronic interaction in which a secondary pion or kaon is produced that in turn decays to an observed muon [48]. Left panel: Energy distribution for different particle types that initiate the “last” interaction. Right panel: Energy distribution for different lateral distance ranges (lateral distances) for muon detection. The step at 80 GeV is caused by the differences of the predictions of the low- and high-energy interaction models GHEISHA and QGSJET 01.

Muons that are detected at large lateral distance are typically produced by pions and kaons with large angles to the shower axis. With an almost energy-independent mean transverse momentum of about 350 to 400 MeV of the secondary particles produced in hadronic interactions, low-energy particles are more likely to produce observable muons [51, 52]. It should also be noted that pion-induced interactions account for more than 70% of all produced muons [48].

Already moderate changes of the hadronic interaction model used for simulating low-energy interactions lead to important changes of the muon density at large distance from the shower core. In Fig. 28 (left panel) the predicted relative muon density as function of the distance to the shower core (lateral distance) is shown for $10^{19} \text{eV}$ showers [52]. The model dependence of the muon density is much larger than that of the em. components which are also shown. The difference between the G-FLUKA and GHEISHA predictions is about 20%. This has to be compared with the difference expected for proton and iron-induced showers which is about 40%. In other words, observed showers could be interpreted as proton showers if compared to a simulation with GHEISHA as low-energy model or carbon-induced showers if FLUKA is used. Predictions of different low-energy interaction models for p-N interactions are shown in Fig. 28 (right panel). In the relevant phase space region (see Fig. 9 of proposal), FLUKA and GHEISHA differ by up to 30%.

Another very important advantage of fixed target measurements at energies greater than 100 GeV is that the data can be used not only to tune low-energy interaction models but also for testing high-energy models. Most high-energy interaction models have an energy threshold for
Figure 28: Left panel: Ratio of particle densities (electrons, photons and muons) as function of the lateral distance to the shower core in vertical, proton-induced showers of $10^{19}$ eV. Interactions at laboratory energies below 80 GeV were simulated with the models G-FLUKA [53], UrQMD [54], and GHEISHA [37]. The model QGSJET [36] was used for simulating high energy interactions. Shown is the ratio of the particle densities relative to the prediction of UrQMD (from [52]). Right panel: Predictions of different models for pion production in proton-nitrogen interactions at 20 and 100 GeV lab. energy (from [55]).

applicability of about 100 GeV. For example, predictions of the high-energy interaction models QGSJET and SIBYLL are shown in Fig. 28 (right panel) together with that from low-energy models. A comparison of model prediction with recent NA49 data on pion production in p+C interactions at 158 GeV is given in Fig. 10 of the proposal, demonstrating the importance of data in this energy range. Currently only fixed target experiments provide the needed coverage of the forward phase space.

6.3 Quantitative estimates

Detailed simulations and their analysis needed for the interpretation of data sets like that of the KASCADE Collab. are very time-consuming and typically take several months. Therefore we will discuss here the required data statistics on the basis of scaling considerations.

The mean number of muons $N_\mu$ in showers of a primary nucleus with energy $E$ and mass
number \( A \) can be written as

\[
N_\mu \propto A \times \left( \frac{E}{A} \right)^\alpha, \quad \alpha \approx 0.9
\]  

(17)

For example, iron-induced showers are expected to contain about 1.4 times more muons than proton showers of the same energy.

Ultimately, it is desired to distinguish the most important (abundant) groups of elements in the cosmic-ray flux, which are H, He, C/N/O, Si, and Fe/Ni. This will only be possible if the number of muons in hadronic showers can be predicted with less than 5% systematic uncertainty, see Eq. (17).

The uncertainty due to the limited knowledge of hadronic interactions at very high energy cannot be quantified reliably. In the following estimates we do not include this uncertainty. It is understood that measurements at LHC will significantly reduce the uncertainty of high-energy interaction models.

Regarding muons produced by pions in low-energy interactions, the secondary particle yield has to be known with less than 10% overall uncertainty. The analysis of p+C data taken with the NA49 detector at 158 GeV [56] can be taken as a reference and shows that a data set of about 600k minimum bias triggers (about 400k inelastic events after cuts) is sufficient to obtain statistical uncertainties of less than 10% for the relevant phase space region with a systematic uncertainty of about 5%.

Two dedicated runs are proposed to collect 1M minimum bias triggers of \( \pi^- + C \) interactions at 158, and also at 350 GeV. The requested run time including beam and trigger set-up is 3 days assuming the event rate expected after the TPC read-out upgrade.

The data will be analyzed to measure the production cross sections of secondary charged pions and kaons. The leading role in the analysis of these data will be assumed by the group from Forschungszentrum Karlsruhe, Germany. The FZK manpower devoted to the analysis of the NA61 data is Ralph Engel (senior scientist, 20%), Michael Unger (Post. Doc., 33%), N. N. (Post. Doc., 100%, starting end of 2007), Florin Ionita (Ph. D., 50%), N. N. (Ph. D. student, starting 2008).

Recently pion production cross sections for p+C interactions measured with the HARP detector at 12 GeV became available [57]. The corresponding analysis for \( \pi^- + C \) interactions at the same energy is in progress (results will be presented at the Int. Cosmic Ray Conference in July).

At 158 GeV, high statistics p+C data from NA49 allow a direct comparison of the pion yields of proton and pion induced interactions. The comparison of pion- and proton-induced interactions at the same energy will be used to improve the modeling of the difference between pion and proton beams. Understanding this difference is important to (a) extrapolate from measured high energy pp and pp collider interactions to pion-induced interactions and (b) to study the leading particle effect that is of outstanding importance for cosmic ray simulations. Similarly, we will be able to learn something about p-C data at 350 GeV simply by rescaling the pi-C data taken at this energy by the relation found for 158 GeV.
Note that the data of Barton et al. [49] of π-C interactions at 100 GeV is not suited for such a comparison. This data set is characterized by low statistics, small phase space coverage, and large systematic uncertainties.

The data set at 350 GeV is needed to estimate pion production at high energy. The aim is to have a beam energy as high as possible to allow a high statistics measurement. Regarding the air-shower physics, both positive or negative pions could be used as beam for π-C interactions. A beam energy of 350 GeV for π− is a good compromise regarding purity and beam intensity. A high beam energy is important to use the data points for extrapolating to very high energies as needed in air shower simulation. At this energy it is possible to tune both low and high energy interaction models. There is no data set with pion beams on nuclear targets available in this energy range.

The data taken with thin carbon targets for T2K are filling the gap to the low-energy HARP measurements. After completion of the NA61 measurement programme we will have high statistics and quality p-C data at 12 (HARP), 30, 40, 50 GeV (NA61), 158 GeV (NA49). The corresponding pion-beam data sets will be π−C at 12 GeV (HARP, the π+−C has very low statistics), 158, and 350 GeV (NA61). Having a direct comparison between π−C and p-C data sets available at 12 and 158 GeV will allow us to make use of the p-C data sets at ∼ 40 GeV to derive not only information on pion production in p-C but also π−-C.

7 Strategy concerning software and IT resources

The computing model of the NA61 experiment is based on the NA49 model which has been successfully used for more than 10 years. The model assumes processing real and simulated data and storing the results after every major step. The NA61 data will consist of real and simulated Monte-Carlo events stored as RAW data, as reconstructed DSTs and as ROOT mini-DSTs. The RAW data as recorded by the DAQ will be migrated by the CDR system to CASTOR, the CERN developed mass storage system. This first stage of the processing and storing scenario requires tapes, tape slots and tape drives. All parts of the infrastructure will be provided by the CERN IT division and the cost will be shared between NA61 and CERN IT (for details see Appendix). The RAW data require a storage volume up to 250 TB. Raw data will be processed off-line. In the estimate of the required resources it was assumed that all RAW data will be reconstructed two times. The required NA61 resources like CPU requirements and storage volume will grow successively in the first years of data taking, 2007-2011. The reconstruction of all NA61 events both p+p, p+A and A+A collisions will be done at CERN on the lxbatch cluster. The processing of simulated events which needs reconstruction and database info will also take place on the CERN lxbatch machines. The DSTs will be stored in CASTOR. DSTs will be converted to ROOT mini-DSTs which will be analyzed using ROOT based software, ROOT61. ROOT61 will be an updated version of the ROOT analysis classes used by NA49 (ROOT49). The ROOT mini-DSTs data require significantly smaller storage volume than the RAW and DST data. They will be stored on CERN IT disks and transferred to disks
of clusters at participating institutes. The ROOT mini-DST data will be partly analyzed at CERN (20%) but mostly in the collaborating institutes. The detailed list of resources provided by the collaboration institutes is shown in Table 7.

<table>
<thead>
<tr>
<th>Institute</th>
<th>IT Resources for NA61</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS, Kielce</td>
<td>6 CPUs, 1 TB</td>
</tr>
<tr>
<td>Geneva</td>
<td>12 CPUs, 5 TB</td>
</tr>
<tr>
<td>JINR, Dubna</td>
<td>15 CPUs, 10 TB</td>
</tr>
<tr>
<td>Jagiellonian U., Cracow</td>
<td>6 CPUs, 0.5 TB</td>
</tr>
<tr>
<td>FZK Karlsruhe</td>
<td>10 CPUs, 0.5 TB</td>
</tr>
<tr>
<td>INR Moscow</td>
<td>5 CPUs, 1.5 TB</td>
</tr>
<tr>
<td>LPNHE, Paris</td>
<td>10 CPUs, 10 TB</td>
</tr>
<tr>
<td>Pusan University, Korea</td>
<td>20 CPUs, 5 TB</td>
</tr>
<tr>
<td>University of Sofia</td>
<td>18 CPUs, 0.3 TB</td>
</tr>
<tr>
<td>WUT, Warsaw</td>
<td>29 CPUs, 4 TB</td>
</tr>
<tr>
<td>ETH Zurich</td>
<td>8 CPUs, 2.5 TB</td>
</tr>
</tbody>
</table>

Table 7: List of resources provided by collaborating institutes for NA61.

Cost of CERN IT resources to be covered by NA61 will be payed from the resources of the participating groups.

Concerning global strategy for software tools, the NA61 collaboration will use the same software as the NA49 collaboration at least during the 2-3 first years of data taking. Minor changes to the software are connected with the inclusion of new detectors in the data base and in the reconstruction chain and slightly modified geometry in the database and simulation program. The database itself is planned to be migrated from the NA49 computers to a machine located at CERN IT.

Conversion of the NA49 software to the SLC4 version LINUX has been completed. SLC4 should be operational at CERN for at least 4 years. In parallel the collaboration considers converting the NA49 software to a modern environment. In particular, a software based on the system developed for ALICE is under discussion.
8 Updated beam request

The updated beam request is given in Table 8.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Energy (A GeV)</th>
<th>Year</th>
<th>Days</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>30, 40, 50</td>
<td>2008</td>
<td>14</td>
<td>Data for T2K, C-R</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>158, 350</td>
<td>2008</td>
<td>3</td>
<td>Data for C-R</td>
</tr>
<tr>
<td>p</td>
<td>158</td>
<td>2008</td>
<td>19</td>
<td>High $p_T$</td>
</tr>
<tr>
<td>S</td>
<td>10, 20, 30, 40, 80, 158</td>
<td>2009</td>
<td>30</td>
<td>CP&amp;OoD</td>
</tr>
<tr>
<td>p</td>
<td>10, 20, 30, 40, 80, 158</td>
<td>2009</td>
<td>30</td>
<td>CP&amp;OoD</td>
</tr>
<tr>
<td>In</td>
<td>10, 20, 30, 40, 80, 158</td>
<td>2010</td>
<td>30</td>
<td>CP&amp;OoD</td>
</tr>
<tr>
<td>p</td>
<td>158</td>
<td>2010</td>
<td>30</td>
<td>High $p_T$</td>
</tr>
<tr>
<td>C</td>
<td>10, 20, 30, 40, 80, 158</td>
<td>2011</td>
<td>30</td>
<td>CP&amp;OoD</td>
</tr>
<tr>
<td>p</td>
<td>10, 20, 30, 40, 80, 158</td>
<td>2011</td>
<td>30</td>
<td>CP&amp;OoD</td>
</tr>
</tbody>
</table>

Table 8: The NA61 beam request.
9 Appendix: Computing requirements and costs for NA61.

This appendix contains the results of the IT (Bernd Panzer-Steindel) analysis of the SPSC addendum to the P330 proposal (NA61 experiment).

Data taking according to the proposal:

- proton runs in 2007 and 2008,
- ion and proton runs from 2009 to 2011,
- one/two months running in each year,
- for ion runs 6 times 5 days running periods, high data rate during 3 out of the 5 days.

Expected amount of data collected and derived data produced

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw data [TB]</td>
<td>2.1</td>
<td>52.5</td>
<td>74.8</td>
<td>73.1</td>
<td>53</td>
</tr>
<tr>
<td>DST+ [TB]</td>
<td>1.5</td>
<td>30.7</td>
<td>45.3</td>
<td>51.8</td>
<td>37.9</td>
</tr>
<tr>
<td>Sum [TB]</td>
<td>3.6</td>
<td>83.2</td>
<td>129.1</td>
<td>124.9</td>
<td>90.9</td>
</tr>
<tr>
<td>Cost [KCHF]</td>
<td>1.8</td>
<td>41.6</td>
<td>60</td>
<td>62.5</td>
<td>45.4</td>
</tr>
<tr>
<td>Cost tape slots [KCHF]</td>
<td>0.6</td>
<td>13</td>
<td>18.5</td>
<td>19.2</td>
<td>14</td>
</tr>
</tbody>
</table>

The 75 TB raw data are produced during 30 days of running, but there are only 18 effective days. From this one can derive CDR data rates of 50 MB/s (4.2 TB per day). This would require 2 tape drives during the running period, one to absorb the data rate and one 'spare' drive. With sufficient disk space available (which is very strongly recommended), one can reduce the number of drives to less than one on average during the reprocessing and analysis periods over the year. The costs for this would be about 20 KCHF (once to be paid at the end of 2007, next time in 2011).

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>RECO [KSI2000]</td>
<td>10</td>
<td>20</td>
<td>35</td>
<td>110</td>
<td>75</td>
</tr>
<tr>
<td>Analysis [KSI2000]</td>
<td>10</td>
<td>10</td>
<td>35</td>
<td>180</td>
<td>240</td>
</tr>
<tr>
<td>Sum [KSI2000]</td>
<td>20</td>
<td>30</td>
<td>70</td>
<td>290</td>
<td>315</td>
</tr>
<tr>
<td>Cost [KCHF]</td>
<td>14</td>
<td>5</td>
<td>21</td>
<td>45</td>
<td>3</td>
</tr>
</tbody>
</table>

The following plot shows the CPU capacity used by the NA49 experiment during 2006. The NA61 paper did not mention any disk space needed. The current NA49 experiment has 12.5 TB of disk space for their analysis. To be able to use CDR efficiently, continue to do
data processing and analysis plus minimizing the restage of data during the year a minimum of 50 TB of disk space is required. For 2007 about 5 TB would be sufficient. Thus the costs would be 10 KCHF in 2007 and an additional 72 CHF in 2008. This would last for 3 years.

**Total cost estimate per year:**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU</td>
<td>14</td>
<td>5</td>
<td>21</td>
<td>45</td>
<td>3</td>
</tr>
<tr>
<td>Tape</td>
<td>1.8</td>
<td>41.6</td>
<td>60</td>
<td>62.5</td>
<td>45.4</td>
</tr>
<tr>
<td>Tape slot</td>
<td>0.6</td>
<td>13</td>
<td>18.5</td>
<td>19.2</td>
<td>14</td>
</tr>
<tr>
<td>Tape drive</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Disk</td>
<td>10</td>
<td>72</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Sum</td>
<td>46.4</td>
<td>131.6</td>
<td>99.5</td>
<td>126.7</td>
<td>72.4</td>
</tr>
<tr>
<td>NA61 costs</td>
<td>24.4</td>
<td>93.1</td>
<td>89</td>
<td>104.2</td>
<td>65.9</td>
</tr>
</tbody>
</table>

IT would offer to pay 50% of the CPU, disk space and tape drive costs per year for the next 2 years (further budget discussion on non-LHC experiments in 2008-9)
References


