# 1 Research Programme — Hadron Physics and Developments for PANDA


## Abstract

I am applying for a junior research position grant to be held at the University of Uppsala. During the tenure of this grant I would like to promote the fascinating field of hadron physics and, in particular, the PANDA experiment at the future FAIR facility, which is one of the most promising projects in the field. I am already strongly involved with this programme both physics-wise as well as experimentally.

One crucial experimental task is to complete the development of a pellet target for the use at PANDA. There is unique technical expertise on this topic available at the The Svedberg Laboratory (TSL), and this should be promoted and exploited in future developments. Initial achievements have been made in this direction but a significant amount of work is still required in order to be able to implement such a target within the PANDA detector by 2010.

I have additionally been involved in the R&D work for the PANDA electromagnetic calorimeter. This includes both the testing of crystals and electronics as well as simulation studies and I would like to continue with such an involvement.


## 1.1 Introduction

Quantum Chromo Dynamics (QCD) is generally accepted to be the correct underlying theory of the strong interaction. However, our knowledge of the behaviour at large distances is still rather primitive. To shed light onto this field the gluon-rich environment of proton-antiproton annihilations at beam momenta of $1.5-15\,\mathrm{GeV/c}$ is optimally suited. This is because this is the range in which – if existing – glueballs, charmed hybrids, charmonium states, *etc* are produced. Due to their decay particles showing a pronounced zero degree enhancement, it is also mandatory to measure those states in a fixed-target experiment. Currently the planned PANDA detector is the only facility, at which such studies would be feasible.

I am, hence, convinced that this is not only a field attracting growing interest but, in particular, the PANDA project at FAIR is highly capable to bring new insights into this field. Thus I am planning to devote my studies to the field and technical developments for the realisation of the project. I have already started this activity within a fellowship within the $6^{\mathrm{th}}$ EU Framework Programme. Some tests have been done helping to specify the crystals to be used for the electromagnetic calorimeter (EMC). Furthermore, simulations were performed, showing the feasibility of the reconstruction of a charmed hybrid, and defining parameters for the EMC. Vacuum studies with a redesigned pellet target and dedicated vacuum system show the feasibility for an operation at PANDA. Finally, a large workload was spend to coordinate and write the Technical Progress Report [1], which was the basis for a very positive evaluation of the project by the QCD-PAC at FAIR.

A lot of work has to be done still to complete the design of the detector, such that a full Technical Design Report could be written and the production of components could start. I would like to continue my successful work at the University of Uppsala after the end of my current EU fellowship, which ends on February the $16^{\mathrm{th}}$, 2006.

## 1.2 Specific Aims

The main aims of my work are to:

- develop a unique pellet target further,
- define crystal properties and geometries for the PANDA electro-magnetic calorimeter,
- detailed planning for measurements at PANDA,

- promote hadron physics in Sweden,
- strengthen the participation in the FAIR project.

A technically challenging task would be the further development of the only pellet target in operation [2, 3] in order to use it at the future PANDA experiment. Such a system is probably the only way how to provide a high luminosity proton target for an internal $4\pi$ detector in a storage ring. This is because high density, very limited out-gassing, and almost no space consumption near the interaction point is a prerequisite for such a set-up.

The electromagnetic calorimeter is a not less challenging device, as it is severely constraint by the resolutions required from the physics side and the technical design imposed by installation inside the PANDA solenoid. In order to define an optimal design, simulations and experimental tests on arrays of crystals would be carried out in close collaboration with Stockholm University. A detailed planning for first measurements at PANDA would be done using the output from Monte Carlo simulations on certain reactions and expected background.

I would like to promote the field of hadron physics in Sweden, as I believe that basic questions, like the formation of mass in hadrons, are yet not understood and need investigation. Here the FAIR project yields an excellent opportunity to do forefront experiments in the medium-term future.

## 1.3 Survey of the Field

The strong force governs the microscopic structure of matter. It dominates the interaction between the nucleons, i.e. the protons and neutrons within the atomic nucleus, and it is the key force that determines the interaction between the quarks within the nucleon and within other hadrons (strongly interacting particles). Achieving a fully quantitative understanding of matter at this level is one of the most challenging and fascinating areas of modern physics. During the last two decades hadronic physics has moved from phenomenological to fundamental understanding. The theory of Quantum Chromodynamics (QCD) is regarded as the basic theory of the strong interaction. While being elegant and deceptively simple, the theory generates a most remarkable richness and complexity of phenomena. The possible forms of matter range from the spectrum of strongly interacting hadrons and nuclear species to compact stars of extreme density and to the quark-gluon plasma, a state of matter in the early universe and, possibly, in the interior of very heavy stars.

The fundamental building blocks of QCD are the quarks which interact with each other by exchanging particles, the gluons. QCD is simple and well understood at short-distance scales, much shorter than the size of a nucleon ($< 10^{-15}$ m). In this regime, the basic quark-gluon interaction is sufficiently weak. Here, perturbation theory can be applied, a calculation technique of high predictive power yielding accurate results when the coupling strength is small. In fact, many processes at high energies can quantitatively be described by perturbative QCD within this approximation.

The perturbative approach fails when the distance among quarks becomes comparable to the size of the nucleon, the characteristic dimension of our microscopic world. Under these conditions, the force among the quarks becomes so strong that they cannot be further separated, in contrast to the electromagnetic and gravitational forces which fall off with increasing distance. This unusual behaviour is related to the self-interaction of gluons: gluons do not only interact with quarks but also with each other, leading to the formation of gluonic flux tubes connecting the quarks. As a consequence, quarks have never been observed as free particles and are confined within hadrons, complex particles made of 3 quarks (baryons) or a quark-antiquark pair (mesons). Baryons and mesons are the relevant degrees of freedom in our environment. An important consequence of the gluon self-interaction and – if found – a strong proof of our understanding of hadronic matter is the predicted existence of hadronic systems consisting only of gluons (glueballs) or bound systems of quark-antiquark pairs and gluons (hybrids).

In the evolution of the universe, some microseconds after the big bang, a coalescence of quarks to hadrons occurred associated with the generation of mass. The elementary light quarks, the up and down quarks, that make up the nucleon have very small masses amounting to only a few percent of the total mass of the nucleon. Most of the nucleon mass, and of the visible universe stems from the QCD interaction. The generation of mass is associated with the confinement of quarks and the spontaneous breaking of chiral symmetry, one of the fundamental symmetries of QCD in the limit of massless quarks.

The phenomena of the confinement of quarks, the existence of glueballs and hybrids, and the origin of the mass of strongly interacting, composite systems related to confinement and the breaking of chiral symmetry are long-standing puzzles and represent the intellectual challenge in our attempt to understand the nature of the strong interaction and of hadronic matter. The future PANDA experiment will enable the new FAIR facility to play a significant role in strong interaction physics, providing a link between nuclear physics and hadron physics. For further reading please refer to Refs. [4, 5, 6, 7, 8, 9, 10, 11, 12, 13] and references therein.

## 1.4 Project Description

The project comprises:

- investigation of physics topics in hadron physics and experimental opportunities for measurements,
- the further development of a pellet target for the operation at PANDA,
- testing of components for the electromagnetic calorimeter,
- using simulations for feasibility studies on certain reactions optimising detector geometry and layout,
- contributing to the design and writing of the corresponding Technical Design Reports for PANDA.

The activities are described briefly in the following and a time schedule is given in Table 1.

### 1.4.1 Physics Studies

This topic lies in my natural interest and I would be glad to have the chance to pursue it within the project. I cannot give a detailed description and time planning here, as this is very much dependent on findings and new developments. I can, however, say that I will concentrate myself mainly on topics as: the creation of mass, exotic states, their interpretation and measurement, and charmed hadrons.

### 1.4.2 Pellet Target Development

A pellet target is a stream of frozen droplets with diameters of 20 to 30 $\mu$m. Using this technology high density hydrogen or deuterium targets can be operated at storage ring experiments, with no space for pumps or other equipment directly at the interaction point. At the CELSIUS/WASA experiment such a target is successfully in use for production runs [2, 3, 14].

The currently existing target set-up is not designed for the operation at PANDA. However, first steps have been made to study the modifications needed. An additional pellet target, the Pellet Test Station (PTS) is fully operational now, and has been equipped with a PANDA-like vacuum system and simple diagnostics (see Sec. 1.5). Currently the vacuum measurements are going on, an advanced pellet tracking system is tested for the first time; and beam-pellet interactions are studied at CELSIUS.

Major improvements have to be done concerning the properties of the pellet train, to meet the requirements for the operation at PANDA. This is because the count rate in the experiment would vary strongly in time, if it cannot be ensured that always one pellet is inside the antiproton beam. The case of no pellet in the beam would appear if the beam does not cover at least the transversal

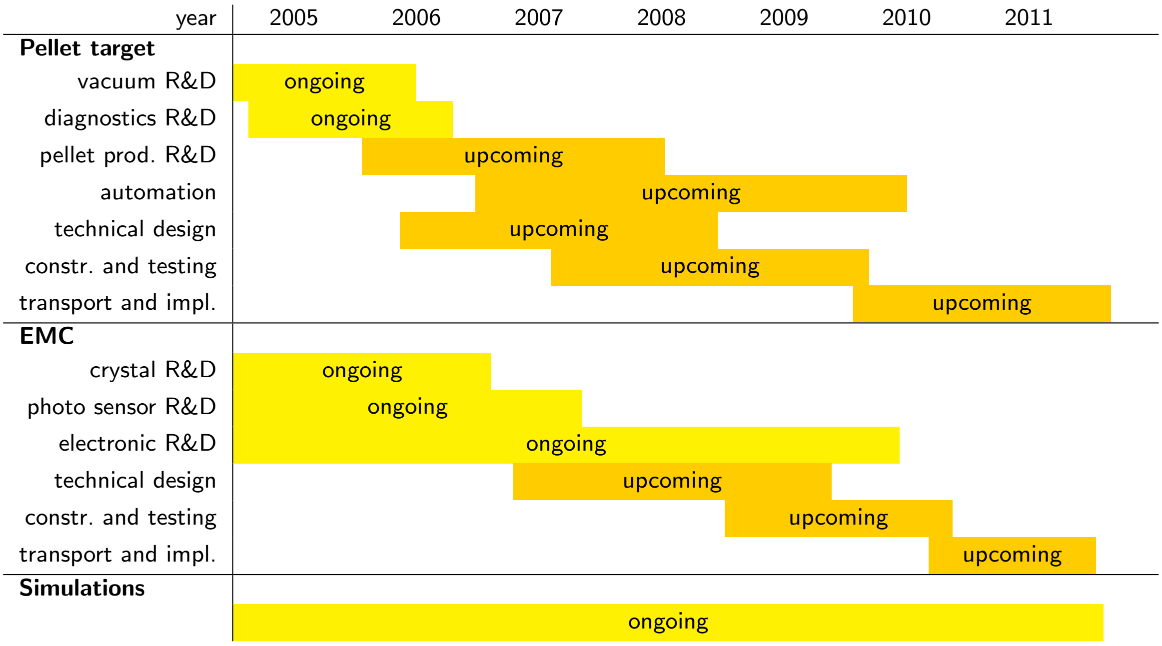



Table 1: Time Schedule for the activities planned within this project. Marked in yellow are ongoing activities, whereas upcoming parts are shown using orange bars. The technical design includes writing the Technical Design Reports.

spread and longitudinal distance between the pellets. For the beam optics, however, it would be very advantageous to have a beam as small as possible at the target. In order to achieve the necessary improvement, the production scheme of the pellets has to be reconsidered. The simulation work, redesign, experimental testing, and optimisation will be a challenging task. Another task is the automation of all the procedures, as it will no longer be feasible to do all those steps by hand.

At the end of the period of the project the detailed design, build-up, transport, and implementation of the system at the FAIR facility has to be pursued (see Table 1).

### 1.4.3 Electromagnetic Calorimeter

The PANDA electromagnetic calorimeter is one of the most demanding developments for the detector, as a $4\pi$, high resolution crystal spectrometer has to be built inside the coils of the solenoid. A detailed description of this project, in which several institutes are involved, can be found in Ref. [1].

Within this project the properties of several crystal types, their packaging, photo sensors and read-out electronics would be studied. This is important as, apart from the differences between PWO and BGO, also different producers provide different types of doping, *etc.* The energy resolution additionally depends on other factors which will have to be studied, like temperature, size, sensor, and arrangement.

### 1.4.4 Simulation Studies

Monte Carlo simulations are performed to understand the required detector properties for the measurement of certain reactions at PANDA. Here first studies on the charmed hybrid channel have been done. But more detailed simulations are necessary to optimise, in particular, the design of the electromagnetic calorimeter. As the crystals and their readout electronics amount most to the overall costs, any optimisation may also lead to significant savings. Thus these investigations may provide important information for the project planning.

The simulations are, however, not finalised by defining the mechanical design of the detector. Precise information on the settings, trigger, measurement times and required on-line information have to be obtained before the measurements can actually start.

### 1.4.5 Design for PANDA

For the Technical Design Reports a detailed design of all the detector parts is needed. I intend to participate in both defining this design as well as compiling the information on the corresponding parts in written documents.

## 1.5 Preliminary Results

Several results have been obtained from a large variety of measurements and investigations. However, here I limit myself to a few examples, which show the general progress of the project.

### 1.5.1 Vacuum Studies with a Pellet Target

In order to further improve the pellet target and to evaluate whether such a target could be operated in PANDA, a second independent target (Pellet Test Station – PTS) has been build up at the The Svedberg Laboratory (TSL), Uppsala, Sweden.

This system is designed taking into account the experiences from the WASA system. However, a maximum of compatibility with this system is kept, such that an interchange of nozzles, capillaries, *etc* is feasible between the systems. The objective is to provide a set-up where tests and modifications are easily possible giving access for the measurement of all variables, like beam diameter, distribution, vacuum, *etc*. It may, however, be used in large parts for the installation at the future FAIR facility.

Below the pumping block (see Fig. 1) an additional vacuum system has been designed and completed, which simulates the situation at PANDA. Furthermore, it also allows the monitoring of crucial variables like vacuum and beam shape, especially also at the so-called "interaction chamber", which is the point which simulates the beam intersection at PANDA.

Several test and measurements were performed using this system. The results of a vacuum measurement and its comparison to vacuum calculations using VAKLOOP [15] described in more detail in Ref. [1] are shown in Fig. 2(a). Applying the same calculations to the current PANDA design a vacuum of below than $2 \times 10^{-5}$ mbar is expected inside the beam line around the interaction point. This is a value acceptable from the point of view of both the accelerator as well as the experiment.

This system is well suited to be used for all the planned developments. Currently the system is equipped with a pellet tracking system and further tests on the divergence and pellet rate will follow. The modifications to the pellet production can also be performed there.

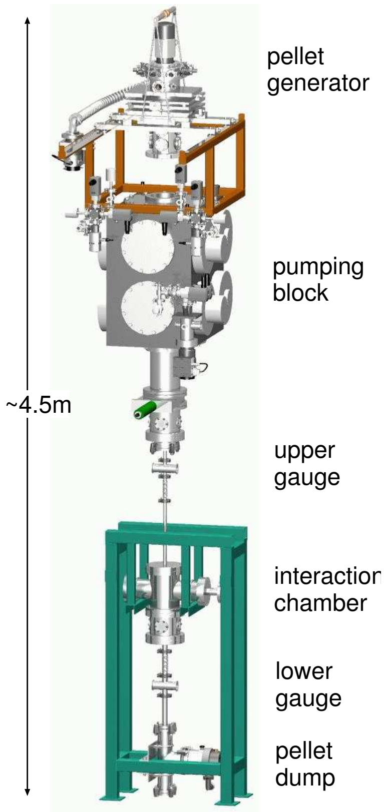
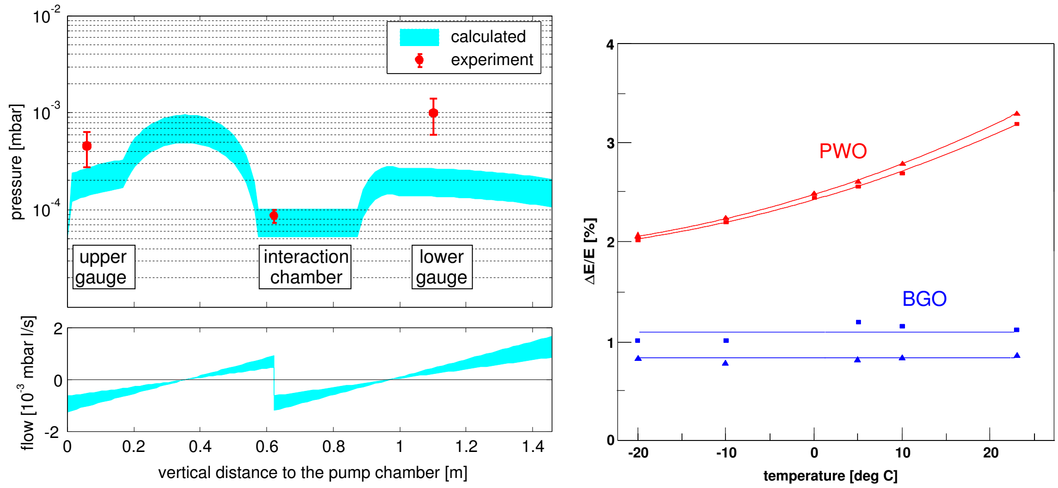



Figure 1: Pellet Test Station PTS designed for testing and further development of the target. On this drawing vacuum gauges, diagnostic tools, several pumps, and fittings are omitted.




(a) Comparison of experimental (red points) and calculated vacuum (light blue band) in the target pipe of the PTS. The errors indicate a $1\sigma$ uncertainty. The experimental points lie factors 2 to 4 above the calculated band but agree within $2\sigma$. The lower part shows the calculated gas flow, which is below zero if the gas flows to the left the figure and positive if the flow is to the right, i.e. upwards and downwards respectively at the experiment.

(b) Energy resolution *versus* temperature using PWO or BGO crystals from studies with protons at KVI. It is clearly visible that the resolution of PWO crystals is strongly temperature dependent, while BGO shows no such behaviour.

### 1.5.2 Experiments with Crystals for the EMC

First measurements with lead tungstate, $PbWO_4$ (PWO) and bismuth germinate, $Bi_4Ge_3O_{12}$ (BGO) have been made. The resolution of PWO and BGO crystals have been compared at several temperatures using the proton beam at KVI, Groningen, Holland (see Fig. 2(b)). The resolution, obtainable with a new type of PWO crystals in a cooled $3 \times 3$ array has been studied using the tagged photon beam at MAMI, Mainz, Germany. The same studies have been done with an array of BGO crystals. Furthermore studies on radiation hardness and several read-out concepts have been performed (see Ref. [1]). Such studies are the basis of decisions on the choice of materials and technical design of the calorimeter.

### 1.5.3 Simulations on the Exotic Charmed Hybrid: $p\bar{p} \to \psi_g \eta \to \chi_c \pi^0 \pi^0 \eta$

The lowest charmonium hybrid is generally believed to be a $J^{PC} = 1^{-+}$ state, which is particularly interesting due to its exotic spin quantum numbers. LQCD predicts masses in the range 4.1–4.4 GeV/c$^2$ this study uses a mass of 4.29 GeV/c$^2$ and a width of 20 GeV/c$^2$ [10, 11]. Particles with exotic spin quantum numbers can be reached only in production in $p\bar{p}$-collisions. Here we assume production in association with a light meson, a $\pi^0$ or an $\eta$.

Non-relativistic flux-tube calculations predict suppression of decays into open charm for hybrid masses below the $D^0\overline{D_1^0}$-threshold [16]. Non-relativistic OZI-allowed decay into hidden charm would give a $\chi_{c1}$ state reached through emission of light hadrons, where scalar particles are preferred to isoscalars [17], the lightest scalar being composed of two neutral pions in an s-wave. The total branching ratio to 7 photons and an electron pair of 3.6% is calculated under the optimistic assumption of having BR$(\psi_g \to \chi_{c1}\pi^0\pi^0 = 1)$.

The final state has a restrictive signature and trigger in the $e^+e^-$-pair at the narrow $J/\psi$-resonance. Possible background channels all contain a $J/\psi$ and a large number of photons; single photons, photons from neutral pions, $\eta$ mesons, $\omega$ mesons or from electromagnetic interactions within the detector material. Production in association with a $\pi^0$ instead of an $\eta$ as well as other decay channels, as for example $J/\psi \to \mu^+\mu^-$, are subject of ongoing investigation, as is background misidentification into the hybrid channel.

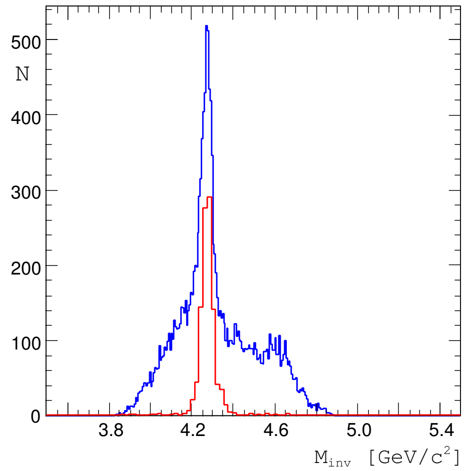



Figure 2: Mass distribution of all reconstructed charmed hybrid candidates (dotted blue) and of unambiguously reconstructed events only (solid red). Please note that the binning differs by a factor of 3.

Having a final state with seven photons, it is clear that the EMC plays the major role. With high multiplicities, it has to cover almost completely $4\pi$ to enable detection and reconstruction of this reaction. Therefore the reaction has been studied using several scenarios on crystal length, geometry, and thresholds. The results are discussed in more detail in Ref. [1].

The overall efficiency and background reduction, however, also depends on geometries of other detectors and materials which may degrade the photon energy or produce showers. Hence, full Monte Carlo studies with different setups have been done and further investigations are to follow.

## 1.6 Significance

The pellet target, electromagnetic calorimeter, and investigations on benchmark channels are essential to the development of the PANDA detector. To achieve the required luminosities with an internal hydrogen target at PANDA, the use of a pellet target seems to be a unique possibility. Since the only operational pellet target worldwide is in use at the CELSIUS/WASA facility, Uppsala, the further development of this target is an exclusive opportunity for PANDA.

Apart from the physics topics addressed (see Sec. 1.3), the PANDA project is one of the key experiments at FAIR, and has received very high credits in all evaluations so far. Due to the significance of the topics addressed in this work, they also become essential to the Swedish contribution to the FAIR project as a whole. With the acknowledged investment costs of about one billion Euro, this facility is one of the leading projects worldwide in the field of nuclear and hadron research.

## 1.7 Equipment

The equipment required for those studies is mostly already available at the ISV and TSL. Further equipment is partially foreseen in the material budgets of these institutes or is part of independent applications to funding agencies. Grants of about 1400 kSEK in total are already approved for the EMC and target development, ensuring the possibility to buy additional hardware and consumables in the coming years.

Though the CELSIUS ring closes down middle of 2005, the experimental facilities to continue the pellet studies will be available at the TSL for a longer time. Thereafter the access is foreseen to be ensured by transferring equipment and part of the staff to the ISV. That especially concerns the Pellet Test Station (PTS) and vacuum equipment. Also minimum two staff members, most knowledgeable to working with pellet targets, are supposed to be transferred to the ISV. Thus they would assist those developments with part of their time.

### 1.8 International and National Collaboration

The developments are all pursued in national and international collaboration. The development of the electro-magnetic calorimeter is performed in close collaboration with the University of Stockholm, the Justus-Liebig-Universität Gießen, and the Ruhr Universität Bochum, just to name the most important ones. Simulations are done within the framework of the PANDA simulation group. This international group has set up an infrastructure with multiple sites to ensure enough computing power for the calculations. The number of institutions contributing to this group in various ways is almost comprising all 47 members institutes of PANDA. All the simulations have been done and will be done within this framework.

The pellet target is being developed in very close collaboration with the staff from the The Svedberg Laboratoriet, Uppsala, which has build up and is operating the current WASA target. This development has been performed within the $6^{\text{th}}$ EU Framework Programme, Research Infrastructure – Integrated Infrastructure Initiative, Hadron Physics and further work will be continued collaborating closely within this project.

## References

[1] PANDA collaboration, Technical Progress Report, Technical report, FAIR-ESAC, 2005, http://www.ep1.rub.de/∼panda.

[2] C. Ekström et al., Phys. Scripta **T99**, 169 (2002).

[3] J. Zabierowski et al., Phys. Scripta **T99**, 159 (2002), http://www5.tsl.uu.se /wasa.

[4] H. S. Group, HESR-Project, Contributions to the Scientific Case, Darmstadt, 1999, http://www.ep1.ruhr-uni-bochum.de/gsi/part2.ps.gz.

[5] D. M. Asner et al., Phys. Rev. Lett. **92**, 142001 (2004), hep-ex/0312058.

[6] F. Fang et al., Phys. Rev. Lett. **90**, 071801 (2003).

[7] M. Ambrogiani et al., Phys. Rev. **D62**, 052002 (2000).

[8] S. K. Choi et al., Phys. Rev. Lett. **91**, 262001 (2003).

[9] A. Abele et al., Eur. Phys. J. **C19**, 667 (2001).

[10] C. Bernard and J. Hetrick, Phys. Rev. **D56**, 7039 (1997).

[11] F. Close, Phys. Rev. **D57**, 5653 (1998).

[12] J. A. Minahan, JHEP **01**, 020 (1999).

[13] J. Sexton, A. Vaccarino, and D. Weingarten, Phys. Rev. Lett. **75**, 4563 (1995).

[14] C. Ekstroem et al., Nucl. Instrum. Meth. **A371**, 572 (1996).

[15] V. Ziemann, Vacuum tracking, SLAC-PUB-5962, 1993.

[16] P. Page, Phys. Lett. **B402**, 183 (1997).

[17] C. Michael, 2002, International Conference on Quark Nuclear Physics.