Available online at www.sciencedirect.com
ScienceDirect
Physics Procedia 17 (2011) 168–174
Physics Procedia

Physics of Fundamental Symmetries and Interactions - PSI2010

Muon Lifetime Measurement with the FAST Detector at PSI

E. Sánchez,
for the FAST Collaboration

CIEMAT, Avda. Complutense 22, E-28040 Madrid, Spain

Abstract

The Fibre Active Scintillator Target (FAST) experiment at the Paul Scherrer Institute was designed to measure the μ^+ lifetime to 4 ps precision and thereby to determine the Fermi coupling constant, G_F, to 1 part per million (ppm). In FAST, a π^+ beam was stopped inside a highly granular target which images the entire $\pi^+ \to \mu^+ \to e^+$ decay chain. To achieve the high statistics required, the detector has a modular structure which allows simultaneous measurements of several decay chains. The concept of the FAST detector provides strong intrinsic suppression of potential systematic effects and allows operation at high beam rates. In 2008 and 2009, FAST collected a total statistics of 4.2×10^{11} identified μ^+ decays, allowing a statistical sensitivity of 1.5 ppm on G_F. The current status on the analysis of these data is presented.

Keywords: Muon Lifetime - Fermi Constant - PSI - Pion beam

1. Introduction

The Standard Model has three free parameters in the bosonic sector: the electromagnetic coupling constant, α, the mass of the Z boson, m_Z, and the Fermi coupling constant, G_F. Only when these parameters have been experimentally determined the theory becomes fully predictive. Moreover, improving the precision of these parameters makes the theoretical prediction more precise, increasing the sensitivity of the experiments to new physics. Therefore, it is important to measure the fundamental parameters of the Standard Model with the highest possible precision.

The Fermi constant can be determined from the measurement of the muon lifetime, τ_μ, since both quantities are related:

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1 + \Delta q) \tag{1}$$

where m_μ is the muon mass and Δq includes the QED and hadronic radiative corrections [1, 2, 3]. The uncertainties in Δq have dominated the error in the determination of G_F until very recently, when the second-order QED corrections were computed [4, 5, 6, 7], reducing the theoretical uncertainty in G_F down to 0.21 ppm. This theoretical advance has motivated the realization of new precision experiments to measure τ_μ at the ppm level, whose preliminary results have been published elsewhere [8, 9, 10]. In this proceedings, the current status of the FAST [8] experiment is described.

doi:10.1016/j.phpro.2011.06.033

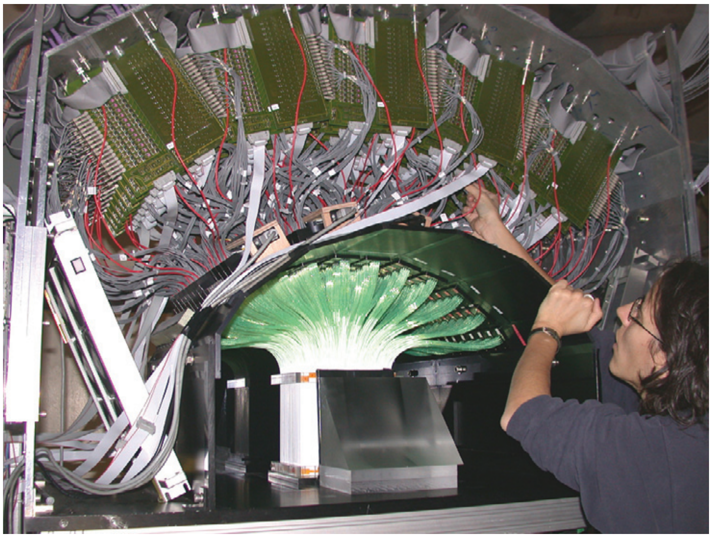

Figure 1: Image of the FAST target. The beam degrader, the fibers and the preamplifiers are also visible.

2. The FAST Experiment

2.1. The FAST Detector

The FAST detector was operated in the πM1 secondary beamline of the 590 MeV proton cyclotron at the Paul Scherrer Institute, which generates a 2 mA DC proton beam (100% duty cycle). The experiment has been designed to handle a rate which permits a measurement of the order of 1 ppm precision of the Fermi constant by measuring several muon decays in parallel. Moreover, the detector concept suppresses several systematics effects which were the limiting factor for previous measurements. First, the pile-up effects are reduced by means of a fast imaging detector. Second, gain shifts and event losses are avoided by operating a DC beam. And finally, the muon spin polarisation effects are highly suppressed by using a pion beam (spin 0), having a uniform detector with large angular acceptance and using a 80 G magnetic field across the target, which causes rapid precession of the muons.

The detector is a fast imaging target (Figure 1) of 32×48 pixels constructed from plastic scintillator bars of dimension $4 \times 4 \times 200$ mm^3. The target is read out by wavelength shifter fibres attached to Hamamatsu H6568-10 position sensitive photomultipliers (PMTs). There are 96 PMTs in total, each one viewing 4×4 pixels (Figure 2).

A DC π^+ beam of momentum 165 MeV/c is stopped in the target and the decay times of the full decay chain $\pi \to \mu \to$ e are registered. The wedge-shaped beam degrader makes the distribution of pion stopping points uniform through the target.

The PMT signals are passed through pre-amplifiers into custom-designed updating discriminators with two outputs, one of them for the data and the other for the trigger. The time measurement is performed with 16 CAEN V767 TDCs. The TDCs are driven by an external 30 MHz Rb atomic clock. The time window of the TDCs is set to measure decays between -8 μs and +22 μs relative to the pion stop time.

The level 1 (LV1) trigger defines an incident beam particle by a coincidence with the accelerator RF signal, defining the time origin for the event. The level 2 (LV2) trigger uses the high discrimination level data from the target to find the pion stopping pixel and identify the $\pi \to \mu$ decay, providing a strong rejection of backgrounds. It gives also the muon stopping pixel. The time windows used by the LV2 trigger are shown in Figure 3. Moreover, the LV2 trigger selects the interesting region of the target, given by the TDCs subtended by a 7×7 pixel array centred on the pion stop pixel. This selection reduces the bandwidth for the data acquisition (DAQ) system and allows the processing of multiple LV1 triggers in parallel.

2.2. Data analysis

The very high data rate of the FAST detector makes it impractical to store all events for later analysis offline. The requirements for the data storage were very large and, moreover, the time required for the reading and reprocessing

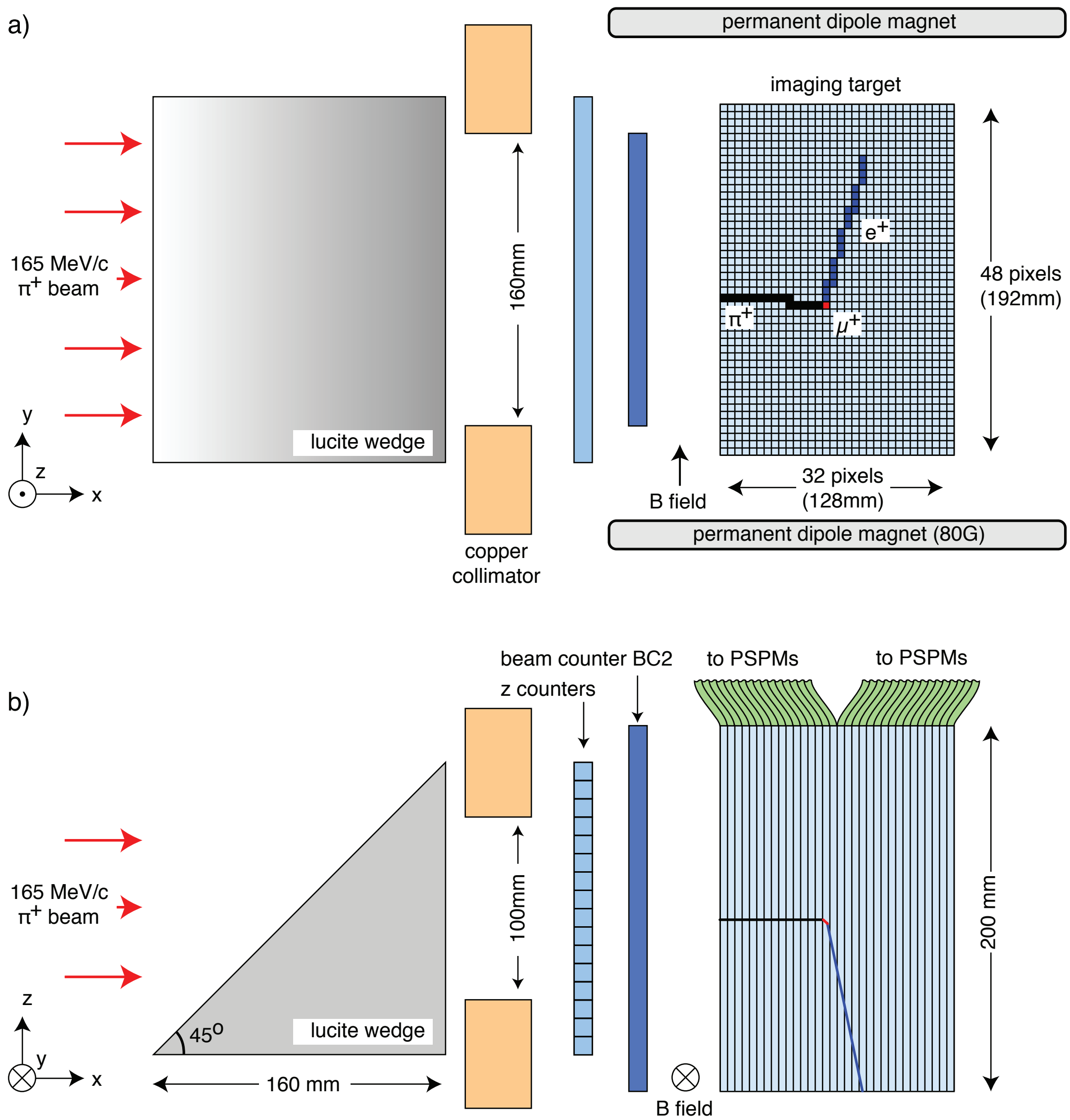

Figure 2: Scheme of the FAST target and associated instruments: Beam degrader, collimator, z-counters, BC2 scintillator and magnet. An example of FAST event is shown.

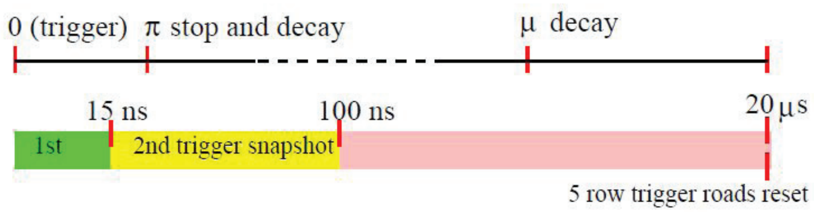

Figure 3: The time windows for the FAST trigger. The pion is located in the first snapshot, lasting 15 ns. The muon must appear in the second snapshot, which lasts from 15 to 100 ns.

of all the events required a time much longer than a new data taking period. Therefore, the data were fully analyzed online in real time, and only the relevant histograms for the muon lifetime measurement (around 3000) were stored on disk. In addition, a pre-scaled fraction of the raw events (around 1%), was recorded for monitoring, checks and study of systematic errors. The bulk of raw data was not stored on disk.

The raw data from the TDCs were transferred to several DAQ PCs. A Gigabit ethernet switch and collector PC then built the events from the DAQ PCs into time slices and passed these slices in turn to a farm of event analyser PCs. The event analyser PCs processed the events and wrote the histograms and other relevant information to disk. The full data treatment scheme can be seen in Figure 4.

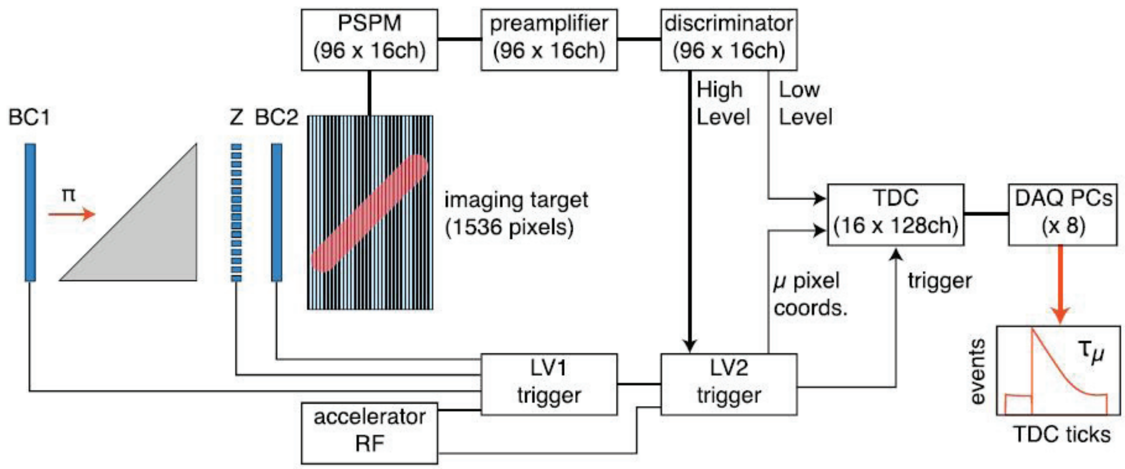

Figure 4: Scheme of the FAST experiment. Both the data hits, the trigger and the control signals were stored in the TDCs. All these signals were then analyzed online and the lifetime histograms were built and stored.

The analysis procedure uses the muon coordinates given by LV2 and identifies any positron candidate emerging from the muon pixel within the full TDC time window. The positron is identified using a set of 512 predefined pattern topologies, which were chosen to be highly efficient for accepting true positrons and reject false signals from overlapping tracks of beam particles or other decays. The positron time is taken as the average time of all the pixels in the candidate tracks. Only one positron candidate is allowed in the event, and complete matching between the predefined pattern and the measured track is required.

3. Data Sample and Muon Lifetime Measurement

The FAST experiment has completed its data taking phase. Two main samples were collected, during 2008 and 2009, for a total of 4.2×10^{11} muon decays. The data were taken at an average rate of around 65 kHz. The main differences between 2008 data and 2009 data were the replacement of 5 PMTs, and the settings for high voltage (HV),

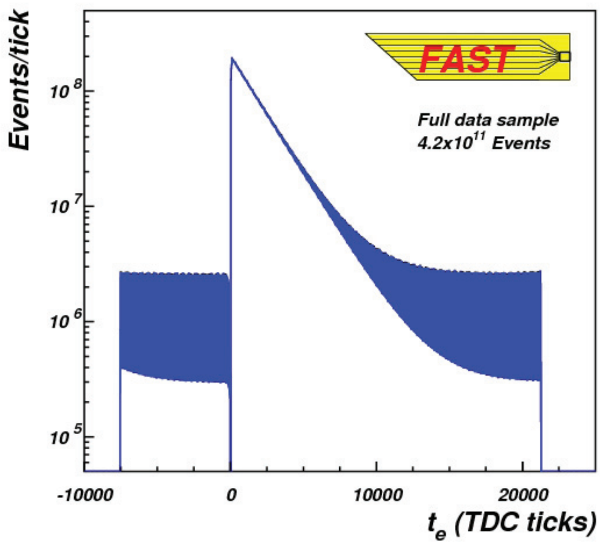

Figure 5: FAST full data sample, including 2008 and 2009 data. The total number of recorded muon decays is 4.2×10^{11}. The bin width is 1 TDC tick.

that were varied for the study of systematic errors, giving the periods 2009A and 2009B. The HV settings of the period 2009B are the same used for the 2008 sample, allowing consistency tests and evaluation of the systematic errors. In addition, new histograms were added to the 2009 data for the study of systematic errors.

The muon lifetime histogram for the full data sample (2008 and 2009) is shown in Figure 5. The region of negative decay times is populated by pure background events, where the true positron is lost and a fake positron is considered. The background contains a ~50% of beam particles, structured with the accelerator RF period. The composition of the beam, which includes electrons, muons and pions, fixes the shape of the beam background. It has three peaks of different intensities per period, each corresponding to one of the particle types in the beam. These events allow a precise description of the accidental background. The events with positive lifetime are used to perform the muon lifetime measurement. The structure of the lifetime histogram of FAST can be seen in Figure 6. The bin width is 1 TDC tick, which corresponds to ~1.04166 ns.

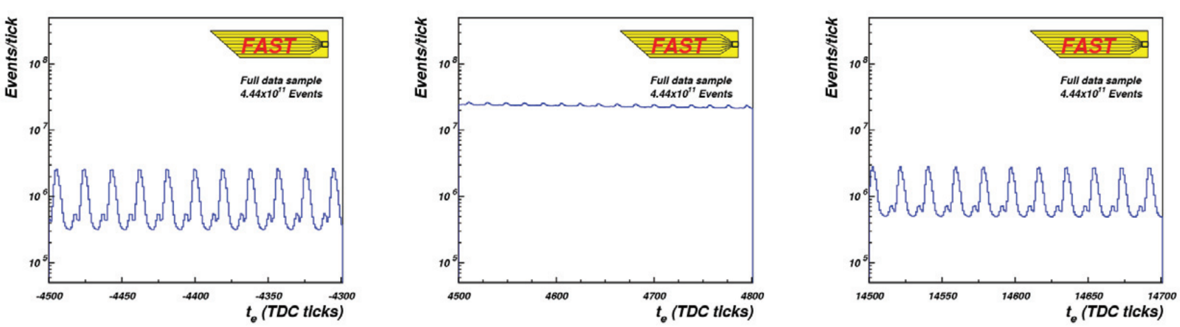

Figure 6: Structure of the FAST data. The negative decay times correspond to pure background (left). This zone allows a precise characterization of the accidental background, dominated by beam particles. The composition of the beam, which includes muons, electrons and pions is visible in the multiple peak structure of the background. This background is then propagated to the positive decay times. The signal dominated region still shows residual beam structure (center). The consistency of the description can be tested in the final region of the window (right).

The measurement of the muon lifetime is performed in three steps. First, the beam period is obtained with high precision from the negative decay region. Then, the lifetime histogram is rebinned using the measured beam period as the bin width. This rebinning absorbs the beam background structure, leaving a cleaner histogram, as can be seen in Figure 7 for the 2008 sample. The samples 2009A and 2009B have similar behaviour. The rebinning minimises the influence of the periodic background structure on the measurement of the lifetime.

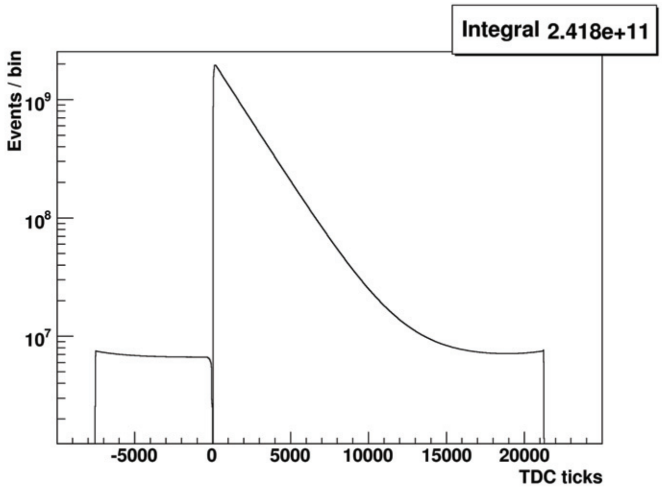

Figure 7: Data sample of 2008 after RF rebinning. The periodic background structure is absorbed by the rebinning, leaving a cleaner histogram.

Finally, a fit to the rebinned histogram is performed with the muon lifetime as one of the free parameters. The positive region of the lifetime distribution is fitted with the function

$$N(t_e) = f_{TDC}(t_e)\,(\,A\,e^{-t_e/\tau_\mu} + B\,e^{t_e/\tau_\mu} + C\,)$$

where t_e is the electron time relative to the RF bucket of the beam pion, $f_{TDC}(t_e)$ accounts for the TDC non-linearity, and the parameters A, B and C describe the amplitude of each component. The first term represents the muon decay signal, the second term accounts for the edge effect, due to the pions whose positron appears after the late time edge of the TDC window, which causes a small exponential rise of the background at the positive edge of the window, and the final term accounts for the flat, uncorrelated background. The free parameters of the fit are A, B, C and τ_μ.

The fit is started at 600 TDC ticks, and ended at 20000 TDC ticks. The statistical sensitivity of the FAST data to the muon lifetime is $\sim$3 ppm when the fit is performed in this region. The final results are still under study. The preliminary distributions of the residuals of the fits are shown in Figure 8.

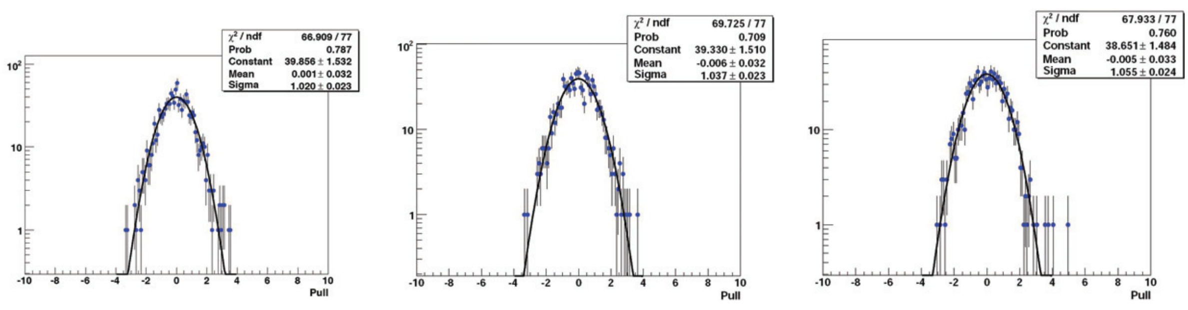

Figure 8: Residuals of the preliminary fit to the FAST data; left is 2008 sample, center is 2009A sample and right is 2009B sample. The distributions are well described by Gaussians, as shown by the fits.

4. Systematic errors

The study of the systematic errors is being done following the published analysis [8]. The result has been confirmed to be consistent versus beam background, TDC non-linearities, muon spin rotation and it is stable with time. Some of the systematic errors have been already studied, and are presented in Table 1.

There are still some contributions to the systematic errors under study, mainly the effect that the afterpulsing in the PMTs and the effect of the efficiency of hit registration in the TDCs have on the muon lifetime.

There is a preliminary estimation of the effect of the PMT afterpulsing. A correction of ~10 ppm towards smaller values must be applied to the fitted lifetime, depending on the sample, the starting point of the fit and the high voltage settings. The systematic error associated to this correction is always smaller than 2 ppm. The optimal fit range is still under study, and will result from a compromise between the uncertainty in the afterpulsing correction and the achieved statistical sensitivity.

The systematic error coming from the efficiency of registration of hits in the TDCs is still under study.

Source	$\Delta\tau_\mu$ (ppm)
TDC non-linearity	0.3
Rebinning Method	< 0.1
Fit method	< 0.1
RF Period Determination	0.1
Event Selection	< 1
Trigger Configuration	< 1
Muon Spin Rotation Description	0.1

Table 1: Sources of systematic errors which have been already studied. All of them stay within the expected range for FAST.

5. Conclusions

FAST has completed the data taking period. A total of 4.2×10^{11} muon decays have been recorded between 2008 and 2009, with a statistical sensitivity of ~3 ppm in the measurement of τ_μ, which translates to ~1.5 ppm in G_F.

The analysis of data is ongoing. The fitting procedure and method are well stablished, involving the rebinning using the RF period of the accelerator and the inclusion of TDCs non-linearities and muon spin rotation effects.

The systematic effects that have been already analyzed do not introduce errors larger than 1 ppm in the muon lifetime measurement. The systematic error coming from PMTs afterpulsing has been also studied and the preliminary conclusion is that it does not introduce errors larger than 2 ppm. The optimization of the final fit is being investigated, and depends on a compromise between afterpulsing corrections and statistical sensitivity. The effect of hit detection efficiency is still under study.

Bibliography

[1] S. M. Berman, Phys. Rev. 112 (1958) 267–270.
[2] T. Kinoshita, A. Sirlin, Phys. Rev. 113 (1959) 1652–1660.
[3] S. M. Berman, A. Sirlin, Annals of Physics 20 (1962) 20 – 43.
[4] T. van Ritbergen, R. G. Stuart, Nucl. Phys. B564 (2000) 343–390.
[5] T. van Ritbergen, R. G. Stuart, Phys. Rev. Lett. 82 (1999) 488–491.
[6] T. van Ritbergen, R. G. Stuart, Phys. Lett. B437 (1998) 201–208.
[7] A. Pak, A. Czarnecki, Phys. Rev. Lett. 100 (2008) 241807.
[8] A. Barczyk, et al., Phys. Lett. B663 (2008) 172–180.
[9] D. B. Chitwood, et al., Phys. Rev. Lett. 99 (2007) 032001.
[10] D. M. Webber, et al., Phys. Rev. Lett. 106 (2011) 041803.