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Preliminary Results from the PrimEx-II experiment at Jefferson Lab

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Properties of the neutral pion, as the lightest hadron in Nature, are most sensitive to the basic symmetries and their partial breaking effects in the theory of the strong interaction (QCD). In particular, the $\pi^o \to \gamma\gamma$ decay width is primarily defined by the spontaneous chiral symmetry breaking effect (chiral anomaly) in QCD. The next order corrections to the anomaly have been shown to be small and known to a 1% level precision. The PrimEx collaboration at JLab has developed and performed two Primakoff type experiments to measure the $\pi^o \to \gamma\gamma$ decay width with a similar precision. The published result from the PrimEx-I experiment, $\Gamma(\pi^0 \to \gamma\gamma) = 7.82 \pm 0.14\ (\text{stat.}) \pm 0.17\ (\text{syst.})$ eV, was a factor of two more precise than the average value quoted in PDG-2010. The second experiment was performed in 2010 with a goal of 1.4% total uncertainty to address the next-to-leading-order theory calculations. The preliminary results from the PrimEx-II experiment are presented and discussed in this note.

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1. Introduction

As the lightest hadron the properties of the neutral pion (π^0) are most sensitive to the symmetries and, most importantly, their partial violations in the theory of the strong interaction, quantum chromodynamics (QCD) ([1, 2] and references therein). The chiral symmetry spontaneous breaking effect is responsible for the existence of π^0 as one of the Goldstone pseudoscalar mesons. On the other hand, the chiral axial anomaly in the limit of vanishing quark masses primarily determines the $\pi^o \to \gamma\gamma$ decay width [3, 4]:

$$\Gamma(\pi^0 \to \gamma\gamma) = \frac{{\alpha_{em}}^2 M_\pi^3}{576\pi^3 {F_\pi}^2} {N_c}^2 = 7.725 \pm 0.044 eV$$

where α_{em} is the fine-structure constant, M_π is the π^0 mass, F_π is the pion decay constant, and N_c is the number of QCD colors (N_c = 3). This prediction is exact in the chiral limit when quark masses are assumed to be zero and has no free parameters or form factors that need to be determined phenomenologically. However, the current-quark masses are non-vanishing and have different values, $m_u \simeq 4$ MeV and $m_d \simeq 7$ MeV. That explicitly breaks the chiral symmetry, which adds corrections to the leading order (LO) prediction. The most important correction to the decay width is from the isospin breaking ($m_u \neq m_d$) effect, causing a mixing of the pure quantum states η and η' into the physical π^0 state [5, 6]. These corrections have been analyzed in the framework of the Chiral Perturbation Theory (ChPT) [5, 6, 7, 8] up to order p^6 (NLO in Fig. 1), and are shown to lead to an enhancement of about 4.5% in the π^0 decay width with respect to the leading order term (LO in Fig. 1). Corrections to the chiral anomaly have also been performed in the framework of QCD using dispersion relations and sum rules [9] (Ioffe07 in Fig. 1). The estimated uncertainty in the ChPT prediction is 1% [6]. The fact that the corrections to the chiral anomaly are small and they are known at the 1% level makes the $\pi^0 \to \gamma\gamma$ decay channel a benchmark process to test one of the fundamental predictions of QCD at low energies.

For the about fifteen years the PrimEx Collaboration at Jefferson Lab developed a new experimental setup in Hall B which is able to measure absolute photoproduction cross sections of neutral mesons to an accuracy of $\sim 1\%$. The collaboration, combining the high resolution and high intensity photon tagging facility in Hall B and a newly developed high resolution, large acceptance multi-channel electromagnetic calorimeter (HyCal), performed two Primakoff type experiments to test the prediction of the chiral anomaly and calculated corrections to it. The first experiment (PrimEx- I) was performed in 2004, following the commissioning of the newly developed experimental setup. The results from this experiment were published in 2011 [10]. The extracted value for the pion decay width, $\Gamma(\pi^0 \to \gamma\gamma) = 7.82 \pm 0.14\ (\text{stat.}) \pm 0.17\ (\text{syst.})$ eV, with its total uncertainty of 2.8% is the most precise Primakoff type measurement of the pion decay width to date (experiment number 5 in Fig. 1). It was a factor of two-and-a-half more precise than the average value quoted in the Particle Data Group (PDG) before our publication. As a single experimental result, it directly confirms the validity of the chiral anomaly in QCD at the few percent level. Within the error-bar it is also in agreement with the NLO calculations. To test the predictions of higher order corrections on the π^0 decay width, the PrimEx Collaboration upgraded the experimental setup and performed the second, PrimEx-II experiment in the fall of 2010 with the goal to reach an accuracy level of 1.4%. In this note a short description of the experimental improvements and analysis status are discussed. The preliminary results from one of the analysis groups are also presented and discussed.

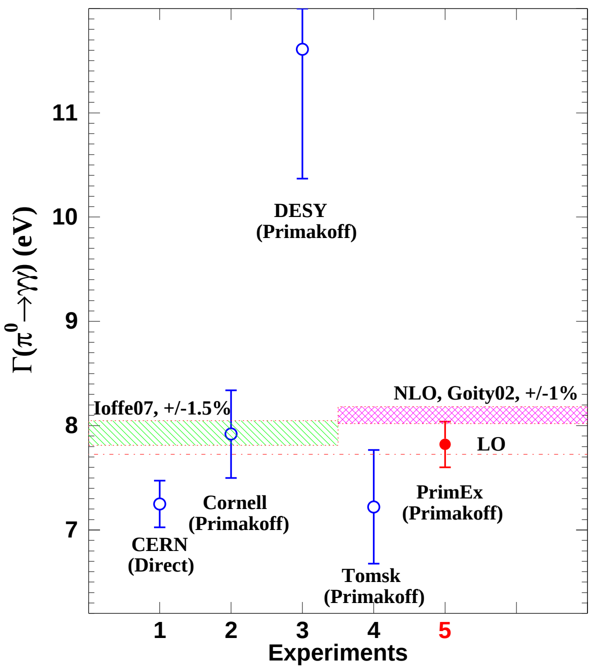

Figure 1: (color) Theoretical calculations and experimental results for $\Gamma(\pi^0 \to \gamma\gamma)$ included in the PDG average before 2011. The dashed horizontal line is the LO chiral anomaly prediction. NLO ChPT prediction [6] is shown as the shaded band on r.h.s. The l.h.s shaded band is the prediction from Ref. [9]. The experimental results, included in the PDG average, are for: (1) done with the direct method [11], (2, 3, 4) with the Primakoff method [12, 13, 14], and (5) is the result from the PrimEx-I experiment [10].

2. Primakoff Method

In past, three major experimental methods have been used to extract the π^0 lifetime: (1) the direct method; (2) the Primakoff method and; (3) collider experiments. In the direct method the distribution of the decay time is extracted by measuring the decay lengths of π^0 mesons. Since the π^0 lifetime is rather short ($\sim 10^{-16}$ s), to have measurable distances in these experiments highly relativistic π^0's are produced and used [11] (experiment number 1 in Fig. 1). The Primakoff method is an indirect method using the photoproduction of π^0's at forward angles in the Coulomb field of a heavy nucleus [15]. This is essentially a time-reversal process to the $\pi^o \to \gamma\gamma$ decay reaction, where the π^0's are being produced by "fusing" one real photon from the beam with a semi-real (having low virtuality) photon from the electromagnetic field of the nucleus. Three Primakoff type of experiments have been performed in past, before the PrimEx-I experiment. Typical uncertainties of these experiments are in 5 to 11% range (experiments number 2,3 and 4 in Fig. 1). In collider experiments a similar process is used for the production of π^0's from the electromagnetic field of electron and positron beams: $e^+e^- \to e^+e^- + \pi^o$. In these experiments the incident e^+ and e^- scatter in forward directions (undetected) to provide two semi-real photons for the π^0 production, which consequently are detected by their $\pi^o \to \gamma\gamma$ decay channel [16].

In general, in high energy photoproduction experiments at small angles the π^0's can be produced by two different elementary mechanisms: the Primakoff process (one photon exchange), T_{Pr}, and the strong process (hadron exchange), T_S. These amplitudes contribute both coherently, as well as incoherently in the π^0 photoproduction process. Therefore, the cross section of this process can be expressed by four terms [10]: Primakoff (*Pr*), nuclear coherent (*NC*), interference between strong and Primakoff amplitudes (*Int*), and nuclear incoherent (*NI*):

$$\frac{d\sigma}{d\Omega} = \mid T_{Pr} + e^{i\varphi} T_S \mid^2 + \frac{d\sigma_{NI}}{d\Omega} = \frac{d\sigma_{Pr}}{d\Omega} + \frac{d\sigma_{NC}}{d\Omega} + \frac{d\sigma_{Int}}{d\Omega} + \frac{d\sigma_{NI}}{d\Omega}$$

where φ is the relative phase between the Primakoff and the strong amplitudes.

The Primakoff cross section is directly proportional to the π^0 decay width, $\Gamma(\pi^0 \to \gamma\gamma)$, which needs to be extracted from these experiments [12]:

$$\frac{d\sigma_{Pr}}{d\Omega} = \Gamma(\pi^0 \to \gamma\gamma) \frac{8\alpha Z^2}{m^3} \frac{\beta^3 E^4}{Q^4} |F_{EM}(Q)|^2 \sin^2\theta_\pi$$

where Z is the atomic number; m, β, θ_π are the mass, velocity and production angle of the pion; E is the energy of the incident photon; Q is the four-momentum transfer to the nucleus; $F_{EM}(Q)$ is the nuclear electromagnetic form factor, corrected for the final state interactions (FSI) of the outgoing pion. The FSI effects for the photoproduced pions, as well as the photon shadowing effect in nuclear matter, need to be accurately included in the cross sections before extracting the Primakoff amplitude. To achieve this, and to calculate the *NC* and *NI* cross sections, a full theoretical description based on the Glauber method was developed in the past ten years, providing an accurate calculation of these processes in both light and heavy nuclei [17, 18].

3. PrimEx-I Experiment

In order to make a significant improvement in the accuracy of the Primakoff type of experiments and reach to the 1% level goal, we have implemented two basic improvements in the experimental technique. A tagged photon beam was used for the first time, allowing critical improvements in the background separation and the determination of the photon number. We also replaced the traditional Pb-glass based electromagnetic calorimeter, used in the previous experiments, with a newly developed $PbWO_4$ crystal based multi-channel, high resolution and large acceptance calorimeter (HyCal) [20]. This improved the energy and coordinate reconstruction of photons from π^0 decay by a factor of two-and-half times, allowing a more precise event selection in the experiment. In addition, the cross sections of two well-known electromagnetic processes, Compton scattering and e^+e^- pair production from the same target, were periodically measured to verify the validity of the extracted decay width and the estimated systematic uncertainties of it.

The schematic view of the PrimEx-I experiment is shown in Fig. 2. Tagged photons with known timing and energy [19] were incident on two 5% radiation length targets of ^{12}C and ^{208}Pb [21]. The photon relative tagging efficiencies were continuously measured during the experiment with a e^+e^- pair spectrometer (PS) consisting of a ~ 1.7 T·m large aperture dipole magnet and two telescopes of scintillating counters located downstream of the targets. The absolute normalization of the photon beam was measured periodically during the experiment with a total absorption counter (TAC), inserted in the beam line just behind the HyCal calorimeter. During these measurements the

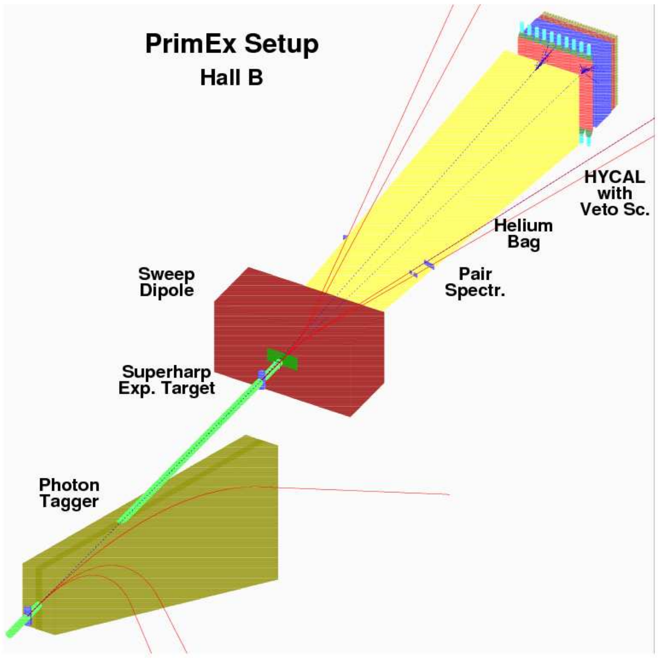

Figure 2: (color) Schematic layout of the PrimEx-I experimental setup (see text for explanations).

intensity of the photon beam was lowered up to $\sim$ 70 pA [22]. The decay photons from $\pi^0 \to \gamma\gamma$ were detected in a multichannel hybrid electromagnetic calorimeter (HyCal) [20] located 7.5 m downstream from the targets to provide a large geometrical acceptance ($\sim$70%). HyCal consists of 1152 $PbWO_4$ crystal shower detectors ($2.05 \times 2.05 \times 18.0$ cm^3) in the central part, surrounded by 576 lead glass Cherenkov counters ($3.82 \times 3.82 \times 45.0$ cm^3). Four crystal detectors were removed from the central part of the calorimeter (4.1×4.1 cm^2 hole in size) for passage of the high intensity ($\sim 10^7$ γ/s) incident photon beam through the calorimeter [20]. Twelve 5-mm-thick scintillator counters, located in front of HyCal, provided rejection of charged particles and effectively reduced the background in the experiment. To minimize the decay photon conversion in air, the space between the PS magnet to HyCal was enclosed by a helium bag at atmospheric pressure. The photon beam's position stability was monitored during the experiment by an X-Y scintillating-fiber detector located downstream of HyCal. The experimental trigger was formed by requiring coincidences between the photon tagger in the upper energy interval (4.9 - 5.5 GeV) and HyCal with a total deposited energy greater than 2.5 GeV.

3.1 Results from the PrimEx-I experiment

Two different university groups within the PrimEx Collaboration independently analyzed the experimental data set from the PrimEx-I experiment. Both groups used the information from the photon tagger and the calorimeter to define the main event selection criteria in the data analysis process: (1) timing between the incident photon and the decay photons in the calorimeter; (2) total energy conservation assuming an elastic event, the so called event "elasticity", defined as the ratio of the total energy in the calorimeter and the tagger energy; (3) reconstructed invariant mass of the two photons ($M_{\gamma\gamma}$) detected in the HyCal calorimeter.

The extracted differential cross sections for two targets, ^{12}C and ^{208}Pb are shown in Fig. 3.

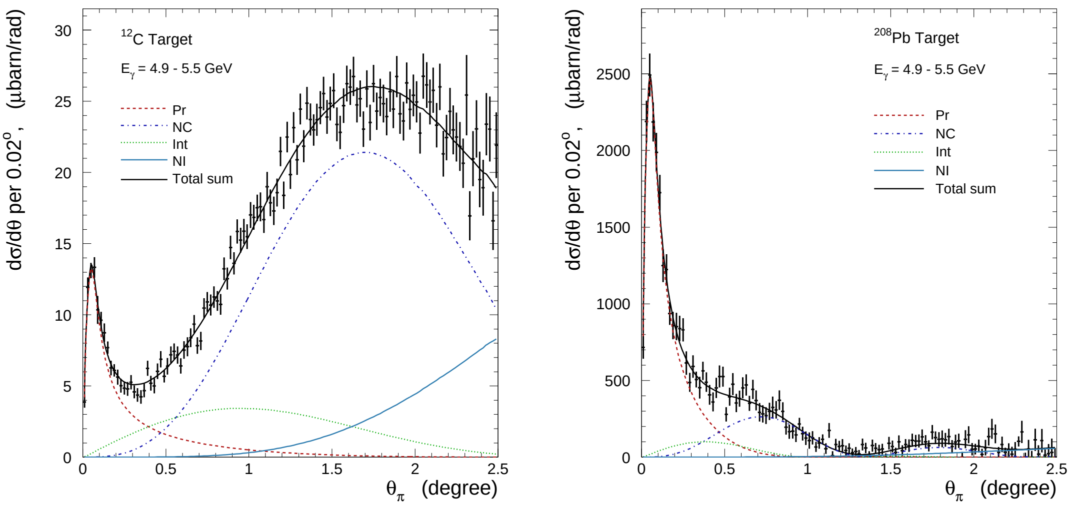

Figure 3: (color) Differential cross sections extracted from the PrimEx-I experiment as a function of π^0 production angle for: ^{12}C (left panel) and ^{208}Pb (right panel). Fit results for different physical processes are also shown.

To extract the $\Gamma(\pi^0 \to \gamma\gamma)$ decay width the experimental differential cross sections were fitted with the theoretical cross sections of the four processes mentioned above folded with the angular resolutions ($\sigma_{\theta_{\pi^0}}$ = 0.4 mrad) and the measured energy spectrum of the incident photons. In the fitting process, four parameters, $\Gamma(\pi^0 \to \gamma\gamma)$, C_{NC}, C_{NI}, φ, were varied to calculate the magnitude of the Primakoff, *NC*, *NI* cross sections and the phase angle, respectively. The result from the PrimEx-I experiment for decay width, weighted average for two targets, is [10]: $\Gamma(\pi^0 \to \gamma\gamma) = 7.82 \pm 0.14\ (\text{stat.}) \pm 0.17\ (\text{syst.})$ eV. The differential cross sections of two electromagnetic processes, Compton scattering and e^+e^- production, were also extracted from the same experimental data set. The extracted cross sections for these well-known processes agree with the theoretical predictions at the level of 1.5% therefore, verifying the measured value of $\Gamma(\pi^0 \to \gamma\gamma)$ and the estimated uncertainties of it. The PrimEx-I result, with a total experimental uncertainty of 2.8%, is the most precise Primakoff type measurement of the $\Gamma(\pi^0 \to \gamma\gamma)$ to date (Fig. 1).

The result from the PrimEx-I experiment was instrumental in significantly changing the landscape of the experiments used in the current PDG average (see Fig. 6). As a result, two Primakoff type of experiments, DESY [13] and Tomsk [14] have been excluded from the averaging process. Also, two new experiments, the DESY collider experiment CBAL [16] and the PIBETA π^+ radiative decay measurement PIBE [23] are included in the current PDG-2014. The PrimEx-I result helped to improve the accuracy of the PDG average value by a factor of 2.8 for this important fundamental quantity.

4. PrimEx-II Experiment

To test the predicted NLO and higher order corrections on the π^0 decay width, the PrimEx Collaboration upgraded the experimental setup and performed the second, PrimEx-II experiment in the fall of 2010 with a goal to reach an accuracy level of 1.4%.

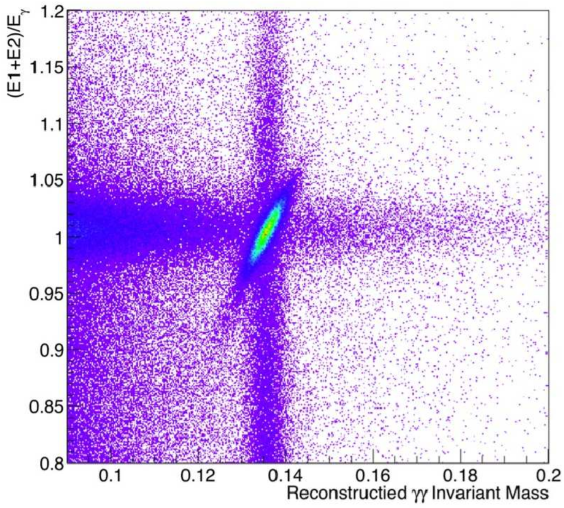

Figure 4: (color) Two-dimensional distribution of events, elasticity *vs.* $M_{\gamma\gamma}$.

Based on the PrimEx-I experience, our collaboration planed to improve the statistical uncertainty from 1.8% (PrimEx-I) down to 0.5%, combined for two targets, and reach similar improvements for the systematic uncertainty, from 2.2% down to 1.3%. To reach to such improvements in the statistics of the collected data we decided to: (1) increase the data acquisition (DAQ) rate by a factor of five, from 1 kHz to 5 kHz. (2) double the target thicknesses from 5% r.l. to 10% r.l.; (3) double the the tagged photon energy interval in the trigger. The systematic uncertainty in the PrimEx-I experiment in most part was dominated by the uncertainty in the event selection process (1.6%), which in turn was dominated by the uncertainty of the background extraction. For the PrimEx-II experiment we developed and implemented the following improvements for better control of the background: (1) optimization of the photon beam line between the Tagger and our physical targets to minimize the beam related background in the experiment; (2) add timing information for the HyCal individual channels (for about 500 central detectors); (3) add horizontal veto scintillator counters, on top of existing vertical counters, to improve the PID in the experiment and; (4) to take more so called "empty" target data to better control the shapes of the background processes. In addition, we have decided to use a new medium-Z, spin-zero 10% r.l. ^{28}Si target, which has an emphasized Primakoff production like the ^{208}Pb target but, in the mean time, a well-measurable nuclear coherent part (see Fig. 5, right panel) to better control the fitting process. The PrimEx-II experiment was performed in the fall of 2010 with a collection of high quality and large statistics data set.

4.1 Data Analysis and Preliminary Results

A typical two-dimensional distribution (elasticity *vs.* $M_{\gamma\gamma}$) of experimental events with two

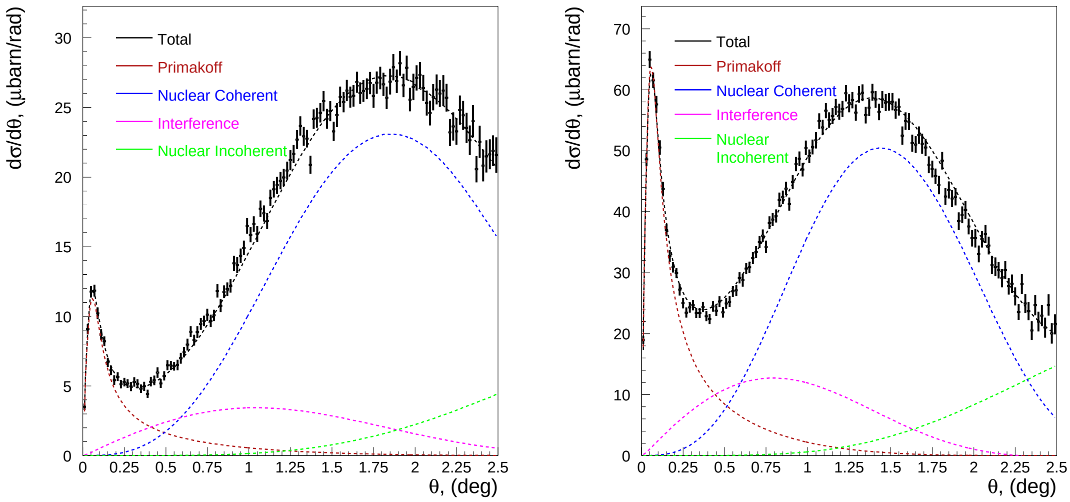

Figure 5: (color) Differential cross sections extracted from the PrimEx-II experiment as a function of π^0 production angle for: ^{12}C (left-hand panel) and ^{28}Si (right-hand panel). Fit results for different physical processes are also shown (Preliminary).

or more photons in HyCal is shown in Fig. 4. One of the main tasks for the data analysis process is to determine the number of elastic π^0s (experimental yields) for each angular bins at forward direction. Two groups from participating universities are currently analyzing the data set from the PrimEx-II experiment. At this stage of analysis work, these groups share the information about the total number of photons and the number of atoms in the targets, but differ significantly with their event selection criteria and some reconstruction software. Analysis Group 1 (NCA&T/UNCW/ITEP) for each angular bin applied a kinematical constraint on the energies of the two photons in HyCal to satisfy the elasticity condition for each event. The resulted more sharper $M_{\gamma\gamma}$ distributions were fit with a Gaussian plus polynomial functions to determine the π^0 yields for all angular bins. The analysis Group 2 (Duke University) implementing a more traditional method by slicing the experimental data into both angular and elasticity bins. Then, the $M_{\gamma\gamma}$ distributions are fit with individual polynomial background shapes [10, 1].

The extracted differential cross sections from analysis Group 1 for two targets, ^{12}C and ^{28}Si at forward angles are shown in Fig. 5. These cross sections are corrected for the effect of ω photoproduction in the forward direction on nuclei. The uncertainty in the π^0 decay width from this contamination is typically small ($\sim 0.25\%$). The extracted decay width from these cross sections, averaged for two targets, is: $\Gamma(\pi^0 \to \gamma\gamma) = 7.74 \pm 0.06\ (\text{stat.}) \pm 0.17\ (\text{syst.})$ eV, and it is shown in Fig. 6. The estimated individual systematic uncertainties are added quadraticaly giving the total systematic uncertainty of 1.6%. The two largest contributions to this systematic uncertainty result from: (1) the event selection process (1.0%), and (2) the measurement of the number of photons (0.7%). Work is in progress to include the timing information in the event selection process, which will significantly reduce the uncertainty on the background subtraction.

Within the 1.7% total uncertainty our current preliminary result is in a good agreement with the chiral anomaly leading order prediction and, however, it is 2.5 standard deviations lower than

NLO calculations (see Fig. 6).

We expect that the analysis work by the Group 2 will be finished by the end of this year. At that time the results from both Groups will be combined for the π^0 decay width's final value. To verify the measured value of the $\Gamma(\pi^0 \to \gamma\gamma)$ and associated uncertainties, The cross sections of two electromagnetic processes (atomic Compton scattering and e^+e^- pair production) need to be extracted from the data with an $\sim 1\%$ level precision and compared with the theoretical simulations. Active work is currently in progress on this part. There is an optimistic expectation that it will be finished by the beginning of the next year. Therefore, we expect to release the PrimEx-II final results in the first part of 2016.

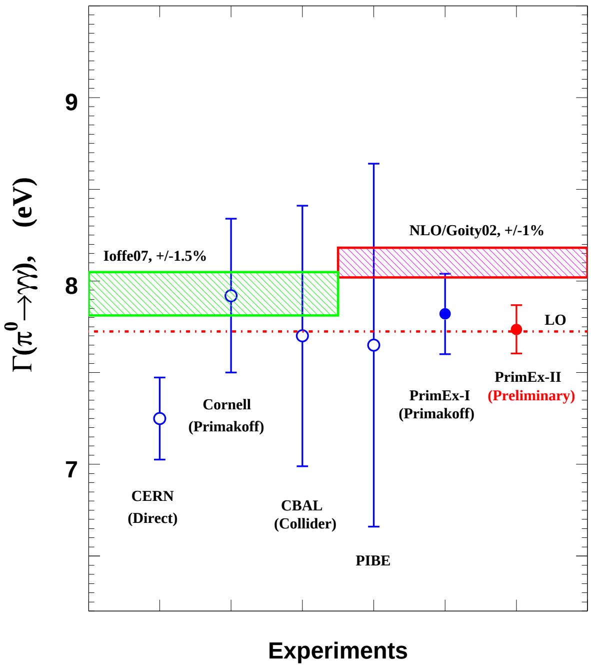

Figure 6: (color) Experimental results included in PDG-2014 for $\Gamma(\pi^0 \to \gamma\gamma)$ together with the preliminary result from the PrimEx-II experiment. Theoretical simulations are the same as in Fig.1. Three new experiments are included in the new decay width averaging (other than CERN [11] and Cornell [12]): PrimEx-I [10], CBAL [16] and PIBE [23].

5. Summary

The PrimEx Collaboration at the Jefferson Lab in the past fifteen years developed an experimental technique that is capable of measuring the absolute value of the neutral mesons photoproduction differential cross sections in the forward direction on a 1% level. It is based on a combination of the high precision photon tagging facility in Hall B at JLab and a newly developed stat-of-the-art multi-channel large acceptance and high resolution electromagnetic calorimeter (HyCal). The first experiment (PrimEx-I) was performed in 2004 to measure the π^0 radiative decay width with high precision. With its 2.8% total uncertainty the PrimEx-I result significantly changed the landscape of experiments included in the PDG averaging. It also played a critical role in reducing the uncertainty on the current PDG average value by a factor of 2.8 for this important fundamental quantity. The second upgraded experiment (PrimEx-II) was performed in 2010 to reach the projected 1.4% accuracy goal to test the higher order theory predictions. The preliminary result from the PrimEx-II experiment: $\Gamma(\pi^0 \to \gamma\gamma) = 7.74 \pm 0.06\ (\text{stat.}) \pm 0.12\ (\text{syst.})$ eV has already reached the 1.7% level in accuracy. This result is based on one analysis group only, that is currently continuing to analyze the data to further reduce the systematic error on this result. We expect to have the results from the second analysis group in the next few months. We are optimistic that the combined final result will reach to the 1.4% precision on π^0 decay width.

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