Proton Charge Radius (PRad) Experiment at Jefferson Lab (JLab)

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The PRad experiment (E12-11-106) was recently performed with 1.1 and 2.2 GeV unpolarized electron beams in Hall B at Jefferson Lab (JLab), in order to investigate the proton radius puzzle. The experiment aims to extract the electric form factor and the charge radius of the proton in an unprecedentedly low four-momentum transfer squared region, $\sim 2\times10^{-4} < \mathrm{Q}^2 < 0.08$ $(\mathrm{GeV/c})^2$, with a sub-percent precision. In this proceeding, we will present our experimental method, apparatus, the status of the data taking and current analysis process.

1. INTRODUCTION

The electric and magnetic form factors are one of the most fundamental quantities of nucleons. They are related to the spacial distributions of the charge and the magnetization of nucleons. A precise knowledge of them is crucial in understanding how quantum chromodynamics works in the non-purturbative region. Taking from slopes of the electric and magnetic form factors as four-momentum transfer squared Q^2 approaches zero, one obtains the charge and magnetic radii of a nucleon, respectively. A traditional way to determine the proton charge radius is to measure the cross section of the electron-proton elastic scattering

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} \frac{1}{1+\tau}\left({G_E^p}^2(Q^2) + \frac{\tau}{\epsilon}{G_M^p}^2(Q^2)\right), \quad (1)$$

where $(d\sigma/d\Omega)_{\mathrm{Mott}}$ is the Mott cross section that represents a structureless proton, G_E^p and G_M^p are the electric and magnetic form factors of a proton, $\tau = Q^2/4M_p^2$ with M_p as the mass of a proton, and $\epsilon = [1+2(1+\tau)\tan^2(\theta/2)]$ with θ as the electron scattering angle in the lab frame.

The proton charge radius can also be obtained from the hydrogen Lamb shift measurement in the atomic spectroscopy. By 2010, the CREMA collaboration at PSI had made significant improvement on the precision of Lamb shift measurements using the muonic hydrogen. They reported a measurement on the proton charge radius with an unprecedented precision of <0.1 % [1],

$$r_p = 0.84184 \pm 0.00067 \text{ fm}. \quad (2)$$

The result was reinforced in 2013 by the same collaboration [2],

$$r_p = 0.84087 \pm 0.00039 \text{ fm}. \quad (3)$$

Nevertheless, the above results were 7σ away from the CODATA 2012 suggested value [3], which combined results of the proton charge radius from *ep* elastic scattering and ordinary hydrogen spectroscopy measurements. This discrepancy can be seen in Figure 1, which in addition to the CREMA and CODATA 2012 results, also includes the recent *ep* elastic scattering result from the Mainz Microtron [5], and other results obtained from reanalyses and global fits of *ep* elastic scattering data [6–8].

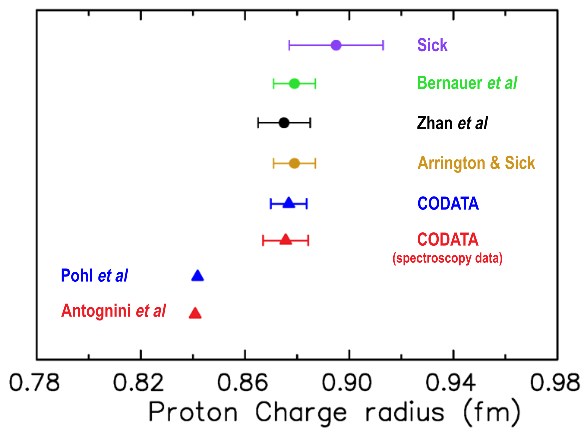

FIG. 1. Values of the proton charge radius from recent measurements and analyses [4].

A lot of efforts have been made in order to resolve this discrepancy, including a new muon-proton scattering experiment at PSI [9], and more precise measurements using the ordinary hydrogen [10, 11]. It is equally important as well to obtain a more precise result using the *ep* elastic scattering in a lower Q^2 region. With a dedicated detector setup and experimental method, the PRad experiment was recently performed at JLab, aiming to extract the proton charge radius with a sub-percent precision. The PRad setup allows the Q^2 to reach an unprecedentedly low value as 2×10^{-4} $(\mathrm{GeV/c})^2$. As the proton charge radius is extracted at the low Q^2 limit, the PRad experiment will be a unique piece for the proton charge radius puzzle. In the following sections, details and the current status of the experiment will be introduced.

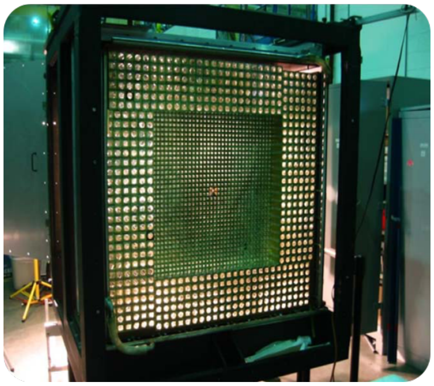

FIG. 2. The PRad hybrid calorimeter (HyCal).

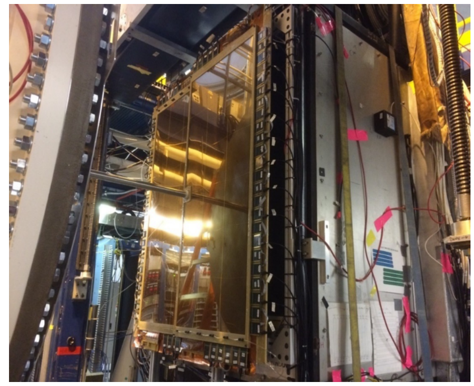

FIG. 3. Two GEM detectors mounted on the front face of the HyCal. Each GEM covers about half the area of the HyCal, with a small overlapping region in the middle.

2. EXPERIMENTAL APPARATUS

The PRad experiment was carried out during May and June in 2016 in Hall B at JLab, with both 1.1 and 2.2 GeV electron beams. As shown in Figure 4, the experiment utilizes a non-magnetic calorimetric setup. It uses a windowless hydrogen gas flow target in order to remove the elastic and the quasi-elastic background from the target window, which is one of the major background sources for many previous *ep* elastic scattering experiments. The target cell is placed inside a vacuumed target chamber, from where the leaked hydrogen gas from the windowless target is pumped away by vacuum turbos. A five meters long, two-stages vacuum box is connected to the target chamber in order to reduce possible background sources between the target and the main detectors. Three main detectors in the PRad apparatus are all located immediately after the vacuum box.

A hybrid calorimeter (HyCal) is located at the end of the setup. As shown in Figure 2, it consists of 1152 $PbWO_4$ crystal modules for the central part and 576 lead glass modules for the outer part. It served as a reliable and stable trigger for the experiment. The HyCal was calibrated module by module before the experiment using a high intensity and high energy photon beam tagged by the Hall B photon tagger. The data show that it has a very high and uniform trigger efficiency of better than 99.5 % for $E_\gamma > 500\,\mathrm{MeV}$. The same photon beam was also used to extract the energy resolution of the detector, which is around $2.6\,\%/\sqrt{E\,(\mathrm{GeV})}$ for the inner $PbWO_4$ part and $6.2\,\%/\sqrt{E\,(\mathrm{GeV})}$ for the outer lead glass part. With such a good resolution, the HyCal plays a major role for the event selection in the current data analysis.

Two large area Gas Electron Multipliers (GEM) are mounted on the front face of the HyCal (as shown in Figure 3) in order to have a more precise determination of positions. Each GEM covers about half the area of the HyCal with 44 mm overlapping area in the middle. With their excellent position resolution of about 70 μm, they improve the position resolution of the setup at least by a factor of 20, and significantly reduce the systematic uncertainty in the Q^2 determination.

The detector setup of PRad provides a 2π azimuthal angle coverage and a polar angle coverage from around 0.7° to 7.5°. Combining both 1.1 and 2.2 GeV data, the acceptance leads to a Q^2 range from an unprecedentedly low $\sim 2 \times 10^{-4}\,(\mathrm{GeV/c})^2$ up to $0.08\,(\mathrm{GeV/c})^2$. In order to have a better control of systematic uncertainties, the Møller scattering (*ee* scattering) data were collected simultaneously during the experiment with the same detector setting and similar kinematics. They will be used to calibrate the *ep* elastic scattering cross section, as the the Møller scattering is well known in quantum electrodynamic. Thus, systematic uncertainties from two major sources, namely the luminosity and the geometric acceptance, will be significantly reduced.

3. STATUS OF DATA TAKING AND CURRENT ANALYSIS PROCESS

During the PRad experiment, large amount of data were collected. From production runs, we collected over 600 M events with 1.1 GeV beam and over 750 M events with 2.2 GeV beam. Figure 5 shows very perliminary *ep* yields that were obtained immediately after the data taking of the experiment, using around 5% of the total data for both beam energies. Even though without corrections from the trigger efficiency, the detector efficiency, and the acceptance, one can already recognize the characteristic linear Q^2 dependence of *ep* yields in a log-log scale. Based on 5% of data showed in Figure 5, Figure 6 shows projected relative statistical uncertainties of all the Q^2 bins. At very low Q^2 region, our rich data will allow finer binnings while preserving a sub-percentage relative statistical uncertainty.

In addition, significant amount of events were also collected with an empty target for the purpose of the background subtraction and with a carbon foil target for the

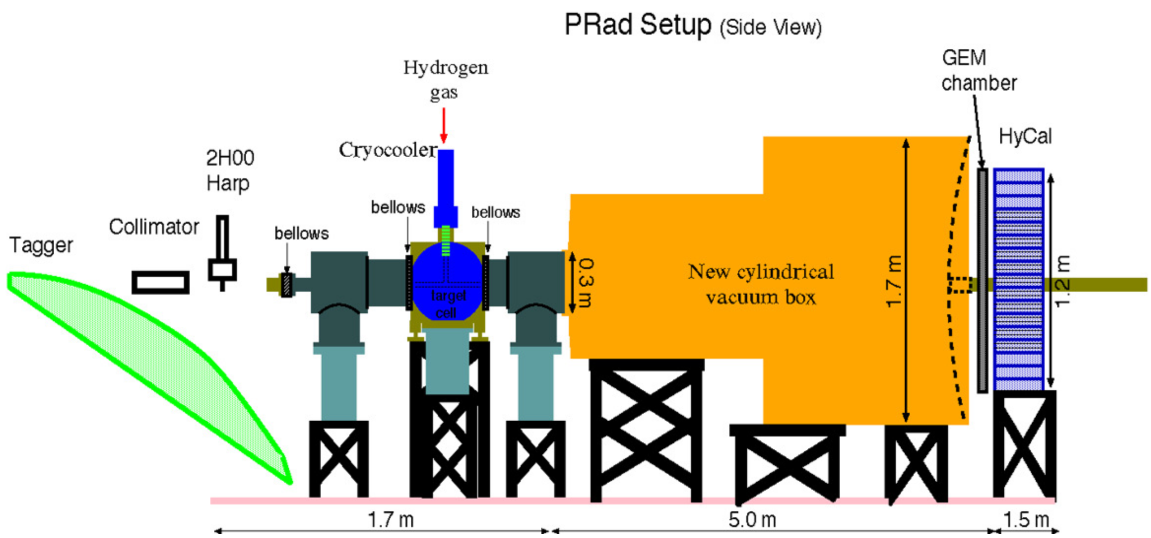

FIG. 4. PRad experimental layout (not in scale).

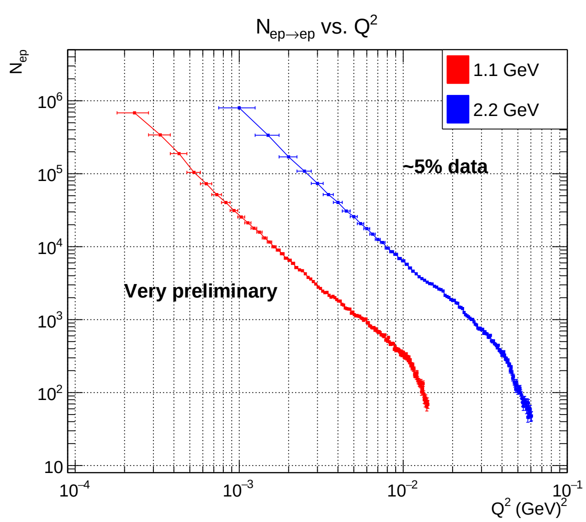

FIG. 5. *ep* yields for both 1.1 and 2.2 GeV beam energies, using around 5% of total data. No corrections related to acceptances and detection efficiencies are applied.

purpose of various calibrations.

Currently, we have accomplished the study of the alignment between detectors, the first-stage calibration of the calorimeter, and detection efficiency extractions for both the HyCal and the GEMs. Preliminary results are showed in Figure 7, from which the two major reaction channels, *ep* elastic scattering and Møller scattering, can be easily identified. The analysis for extracting the *ep* elastic scattering cross sections is ongoing.

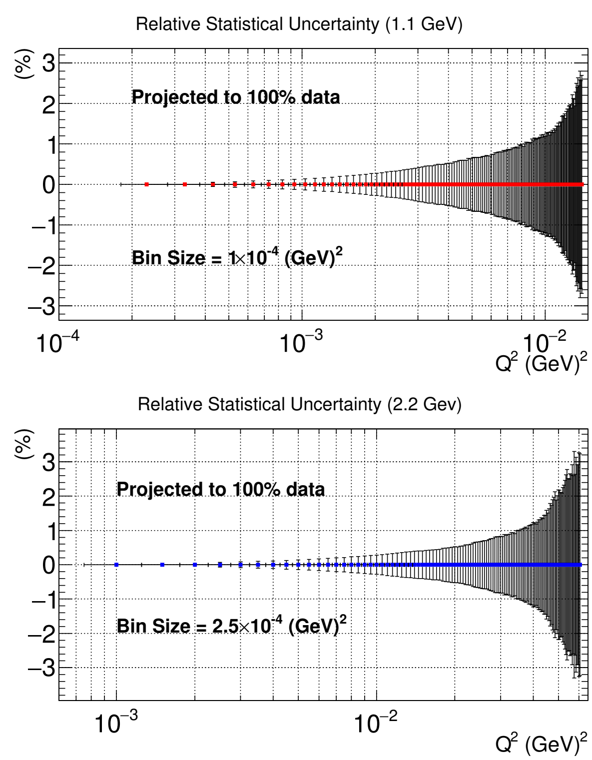

FIG. 6. Projected relative statistical uncertainties for 100% data, for each of the Q^2 bins in Figure 5.

4. SUMMARY

The PRad experiment was recently carried out in Hall B at JLab, aiming to resolve the proton charge radius puzzle. Due to its unprecedentedly low Q^2 coverage and the improvement on many systematic uncertainties, the PRad experiment will be a unique piece in un-

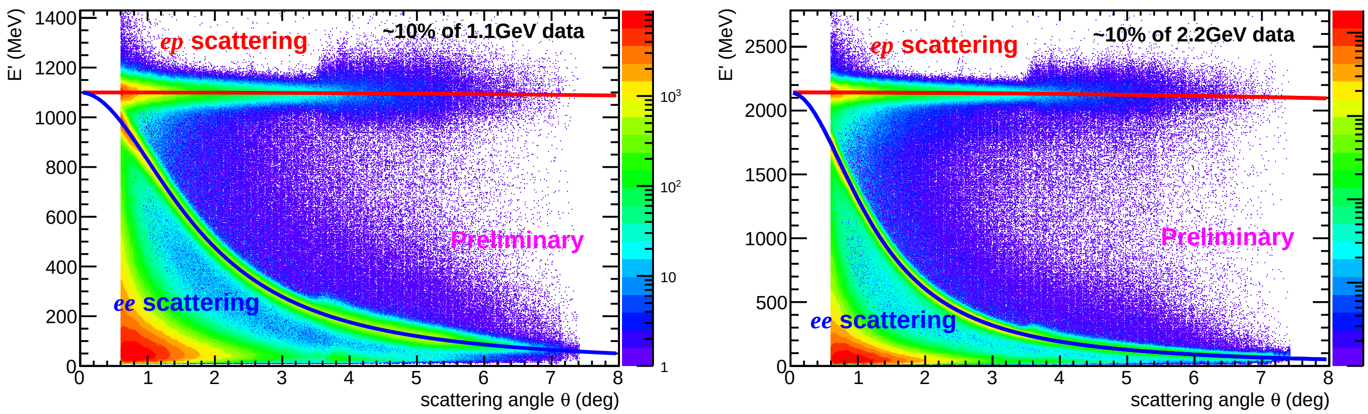

FIG. 7. HyCal cluster energy as a function of the scattering angle θ. The left(right) panel is for 1.1(2.2) GeV data. Solid lines over the distributions are calculated based on the *ep* and *ee* scattering kinematics.

derstanding the large discrepancy of the proton charge radius values between electronic and muonic measurements. Together with the high quality data with high statistics, the goal of the experiment is to extract the electric form factor and the proton charge radius with a sub-percent precision.

ACKNOWLEDGEMENT

This project is supported in part by U.S. Department of Energy under contract number DE-FG02-03ER41231 and NSF MRI award PHY-1229153.

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