Jefferson Lab PAC 35 Update

Measurement of the Charged Pion Form Factor to High Q^2

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On behalf of the F_π Collaboration

An update to the Pion Form Factor experimental proposal is presented. Please see the E12-06-101 proposal for full details on the scientific justification, experimental method, and projected uncertainties.

I. SCIENTIFIC MOTIVATION: SUMMARY AND UPDATE

The π^+ electric form factor is a topic of fundamental importance to our understanding of hadronic structure. In contrast to the nucleon, the asymptotic normalization of the pion wave function is known from pion decay. The hard part of the π^+ form factor can be calculated within the framework of pQCD as the sum of logarithms and powers of Q^2, which in the $Q^2 \to \infty$ limit becomes [1, 2]

$$F_\pi(Q^2)\xrightarrow[Q^2\to\infty]{}\frac{16\pi\alpha_s(Q^2)f_\pi^2}{Q^2}, \quad (1)$$

where $f_\pi = 93$ MeV is the pion decay constant [3].

Because the pion's $\bar{q}q$ valence structure is relatively simple, the transition from "soft" (non-perturbative) to "hard" (perturbative) QCD is expected to occur at significantly lower values of Q^2 for F_π than for the nucleon form factors [4]. Some estimates [5] suggest that pQCD contributions to the pion form factor are already significant at $Q^2 \geq 5$ GeV^2. On the other hand, a recent analysis [6] indicates that non-perturbative contributions dominate the pion form factor up to relatively large values of Q^2, giving more than half of the pion form factor up to Q^2=20 GeV^2. Thus, there is an ongoing theoretical debate on the interplay of these hard and soft components at intermediate Q^2, and high quality experimental data are needed to help guide this discussion.

The pion form factor can be calculated relatively easily in a large number of theoretical approaches. In this sense, F_π plays a role similar to that of the positronium atom in QED. All of these approaches yield essentially identical F_π predictions consistent with the measured π^+ charge radius at low Q^2, and then progressively diverge. A detailed discussion on the theoretical motivations for the measurement of the pion form factor are given in our 2006 PAC proposal [8] and in our recent article [9].

As an example of the theoretical investigations underway, we indicate the calculations of Bakulev, Passek-Kumericki, Schroers and Stefanis [11], which present the π^+ and π^0 electromagnetic structures in a common framework. The π^0 has been generally understood in terms of a dominant hard contribution arising from the chiral anomaly, while the π^+

contains both hard and soft contributions. Bakulev et al. investigated the constraints upon the pion distribution amplitude (DA) posed by $\pi\gamma\gamma$ transition form factor data from CLEO [12] and CELLO [13], as well our F_π data from JLab. They found that the data are particularly sensitive to the shape of the DA near $x = 0,\ 1$, but insensitive to the shape near $x = 1/2$. Their resulting hard contribution to the π^+ form factor, shown as F_π^{hard} in the left panel of Fig. 1, is far below our data. The drop at low Q^2 is due to their choice of infrared renormalization, which is not necessarily shared by other calculations. To bring the calculation into agreement with the experimental data, a soft component must also be added. The authors estimate this soft contribution using a local quark-hadron duality model. This soft estimate, along with the sum of the hard and soft contributions, are also shown in Fig. 1.

In 2009, the Babar Collaboration published new data on the $\gamma\gamma^* \rightarrow \pi^0$ transition form factor [14] which has raised the issue of the role of soft contributions in the π^0 as well. These data, along with those from Refs. [12, 13] are shown in the right panel of Fig. 1. While the previous data were consistent with a leveling off of the transition form factor near the pQCD asymptotic limit, as expected if hard contributions dominate, the Babar data indicate a continuing rise of the transition form factor, which must approach the asymptotic limit from above at much larger Q^2. This is a very difficult measurement, as Babar was not designed to perform spacelike measurements of this nature. Radyushkin [15] and Polyakov [16] argue that if these data are correct, they indicate a nearly flat shape of the pion DA, in contradiction of most theoretical expectations. This would have implications for the charged

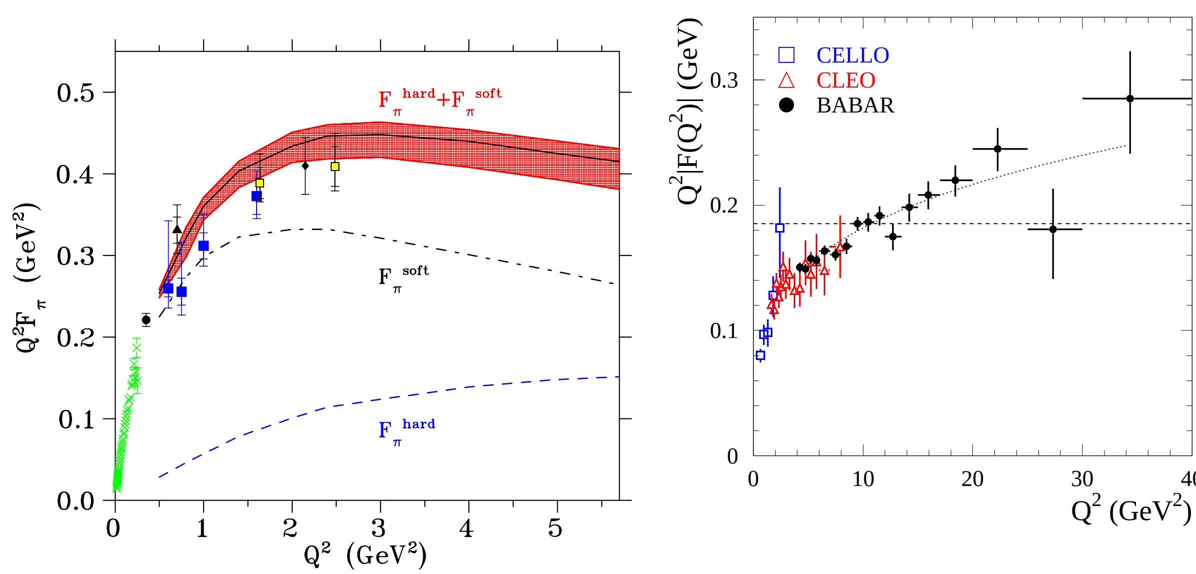

FIG. 1: **Left:** F_π data compared with a hard LO+NLO contribution by Bakulev, Passek-Kumericki, Schroers and Stefanis [11] based on an analysis of the pion-photon transition form factor data from CLEO [12] and CELLO [13]. A soft component, estimated from a local quark-hadron duality model, is added to bring the calculation into agreement with the experimental data. The band around the sum reflects nonperturbative uncertainties from nonlocal QCD sum rules and renormalization scheme and scale ambiguities at the NLO level.
Right: $\gamma\gamma^* \rightarrow \pi^0$ transition form factor as published by the Babar Collaboration [14]. The dashed line indicates the asymptotic limit predicted by pQCD, $Q^2 F_{\gamma\gamma^*\pi^0} = 2f_\pi$. The dotted curve is a power law interpolation of the experimental data.

pion form factor as well. These measurements only strengthen the case for reliable charged pion form factor data at values of Q^2 beyond where they exist now.

The most interesting question, as far as Jefferson Laboratory is able to address, is the description of $F_\pi(Q^2)$ in the gap between the "soft" and "hard" regions. The difficult intermediate Q^2 regime is a vital one where one can gauge the success of a variety of calculations of hadron structure, and the pion is the first test case that all must consider as the situation for the nucleonic form factors is even more complicated. Firstly, their asymptotic behavior is not predicted in such an unequivocal manner. Secondly, the greater number of valence quarks in the nucleon means that the asymptotic regime will be reached at much higher values of Q^2. Finally, the lower power of Q^2 in the pion form factor means that the relevant cross section will be more easily accessible, and less sensitive to experimental uncertainties in Q^2. Because of these reasons, if one believes that it is worthwhile to pursue the measurement of a hadronic form factor where perturbative effects may become apparent, the pion form factor is the obvious first choice.

II. THE DETERMINATION OF F_π FROM ELECTROPRODUCTION DATA

The experimental determination of the pion form factor from low $-t$ electroproduction data, the interpretability issues which affected the high Q^2 data from Cornell, and how these issues may be controlled, are explained at length in our 2006 proposal [8]. We briefly summarize that the separated $p(e, e'\pi^+)n$ cross sections versus t over some range of Q^2 and W are the actual observables measured by the experiment, and the extraction of the pion form factor from these data is inherently model dependent. Ideally, one would like to have a variety of reliable electroproduction models to choose from, so that the model dependence of the extracted F_π values can be better understood. Since the VGL Regge model [17] is able, without fitted parameters, to provide a good description of both π^+ and π^- photoproduction data, and of $\sigma_{\rm L}$ electroproduction data over a range in W, t, and Q^2, it has been used to extract pion form factor values from the JLab $\sigma_{\rm L}$ data up to a maximum Q^2 value of 2.45 GeV^2 (see Fig. 2).

Since our 2006 PAC submission, several other electroproduction models have begun development [18–21]. At present, the respective authors have concentrated their efforts on the improved description of $\sigma_{\rm T}$, since $\sigma_{\rm L}$ is already well described by the VGL model. We are in close contact with these authors and we are hopeful that alternative models of $\sigma_{\rm L}$ useful for the extraction of the pion form factor will eventually be available. Access to more models would allow a better understanding of the model dependence of the F_π result to be made. Since it remains our intent to publish the $\sigma_{\rm L}$ values obtained by our experiment, other F_π values may result when better models become available in the future.

III. PROPOSED KINEMATICS

The rationale and justification for each of the proposed kinematic settings are explained at length in our 2006 proposal [8]. To briefly summarize, the data to be acquired falls into the following categories:

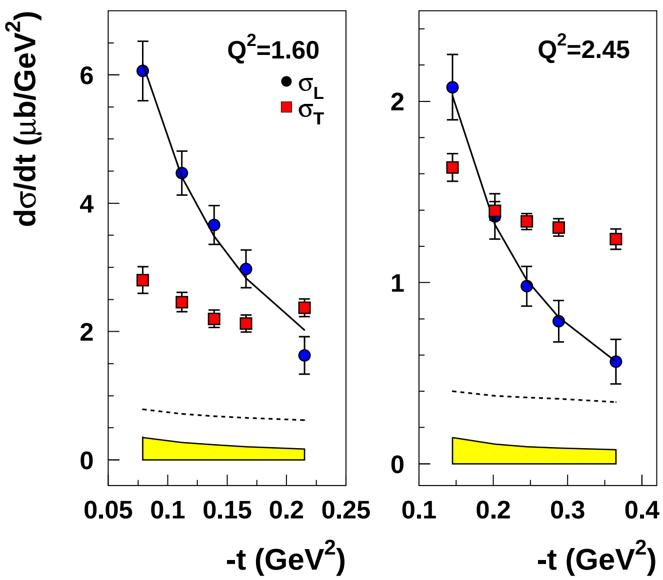

FIG. 2: Separated cross sections $\sigma_{\rm L}$ and $\sigma_{\rm T}$ from E01-004 compared to the VGL Regge model (full curve for L, dashed curve for T) with parameters $\Lambda_\pi^2 = 0.513(0.491)$ GeV^2 and $\Lambda_\rho^2 = 1.1$ GeV^2. Because of the various kinematic correlations, each t-bin has its own average $\overline{W}$ and $\overline{Q^2}$ which differ slightly from the nominal values. The error bars indicate the statistical and uncorrelated systematic uncertainty in both ϵ and t combined in quadrature; the error band denotes the correlated part of the systematic uncertainty by which all data points move collectively.

1. $p(e, e'\pi^+)n$ L/T separated data for $Q^2 = 1.6$-6.0 GeV^2 and W near 3 GeV. The data at Q^2=1.60 and 2.45 GeV^2 will be 70% closer to the pion pole than our earlier E93-021 (Fpi-1) and E01-004 (Fpi-2) data taken at much lower W, and so will be an excellent probe of the model-dependence of the extracted F_π result in this Q^2 range. The $Q^2 = 3.50$-6.00 GeV^2 data will probe the onset of pQCD in a simple quark system. These data will be of dramatically higher quality than the existing Cornell data in this region.

2. Low $Q^2 = 0.30$ GeV^2 data taken extremely close to the pion pole, $-t_{min} = 0.005$ GeV^2, to cross check the extracted F_π values using the electroproduction method against those obtained without approximation from elastic π^+e^- scattering at the CERN SPS [22]. Our data will have 50% smaller $-t$ than any previous electroproduction data, and hence be a sensitive test of the electroproduction method.

3. Exclusive π^-/π^+ ratio measurements using a liquid deuterium target at Q^2=1.6, 3.5 GeV^2, as a test of the t-channel dominance of the σ_L data.

4. Extensive elastic scattering measurements to calibrate the spectrometer detectors and acceptances, and to measure kinematic offsets. Elastic ep scattering is proposed to be used in both singles and coincidence modes. Additional (inelastic) data from thin carbon targets will be taken for spectrometer pointing studies and optics checks.

The proposed 'near parallel' kinematics settings are unchanged from our 2006 submission with one exception. In their approval of the "Pion Scaling" experiment E12-07-105 [23], PAC 32 wrote: *"A detailed study to determine whether or not meson electroproduction can provide information on GPDs is important. The PAC believes that the kinematics might not be fully optimized. The experiment could better overlap the F_π experiment."* The proponents of both experiments have met to address this issue, and as a result the point planned at Q^2=4.50 GeV^2 has been moved to Q^2=4.46 GeV^2 to contribute to the Q^2-scan planned in E12-07-105 at $x = 0.311$. This is only a minor change and the lab cross section for this setting is expected to increase by only ∼1%. More details on how the kinematics of the two experiments fit together are presented in the Appendix.

Rate estimates for most runs are 13% higher than our 2006 proposal. This is primarily due to design changes in the SHMS which have increased the solid angle from 3.5 msr to about 4.5 msr (slightly smaller once an acceptance defining collimator is added). We have checked the kinematic coverage and rates via simulation and have found that the new SHMS design offers comparable t–ϕ coverage, while offering an increase in rate that scales almost directly with the increase in solid angle (see Fig. 3). This increase is partially offset by the decrease in the maximum assumed beam current from 90 μA to 85 μA, required by the maximum current limits at 12 GeV. For the most part, the increased solid angle of the SHMS will have negligible effect on random coincidences due to increased singles rates in the SHMS. In most cases, the singles rates were already quite small, usually on the order of at most 50 kHz.

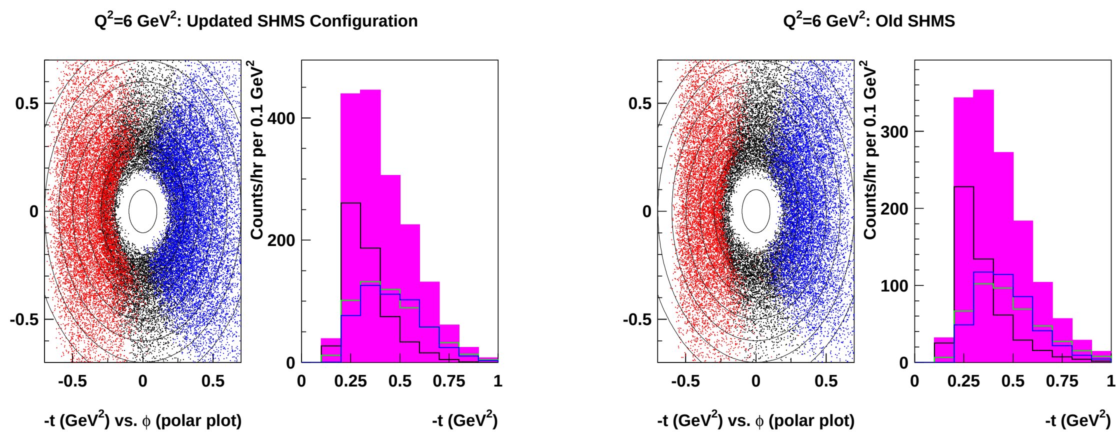

FIG. 3: Coverage of $-t$ (radial coordinate) versus azimuthal angle ϕ for the HMS+SHMS combination at $Q^2 = 6$ GeV^2. Cuts were placed to match the W-Q^2 range of the lowest ϵ setting. Each radial division corresponds to $-t = .10$ GeV^2. The plots are for the high ϵ runs at 10.90 GeV, with the SHMS set at 0 and $\pm 2.00^o$ degrees left and right of the nominal q-vector. The superposition of the three SHMS settings shows good ϕ coverage for the range $0.16 < |t| < 0.60$ GeV^2. Comparison of the left and right panels indicates the effect of SHMS design changes.

One exception is the proposed π^- data taking at Q^2=1.6 and 3.5 GeV^2. Previously, we tried to keep electron singles rates in the SHMS to ≈1 MHz, which required that we limit the maximum beam current to only 15 μA for these runs. The increased solid angle of the SHMS thus necessitates that we further reduce this maximum current to 12 μA, thus keeping fixed the total data–taking time for the π^- running. The other exception is the π^+ running at Q^2=0.3 GeV^2, which was proposed to use 30 μA beam because of expected high random coincidence rates. The increased solid of the SHMS necessitates a reduction in beam current for these runs to 25 μA, keeping the time request for this setting unchanged. The beamtime request for the single-arm elastic, coincidence elastic, and optics running is also unchanged from the original proposal. This portion of the program is dominated by the overhead required in changing targets and spectrometer settings. The run times themselves are typically rather short – even the longest runs taking on the order of 2 hours to complete.

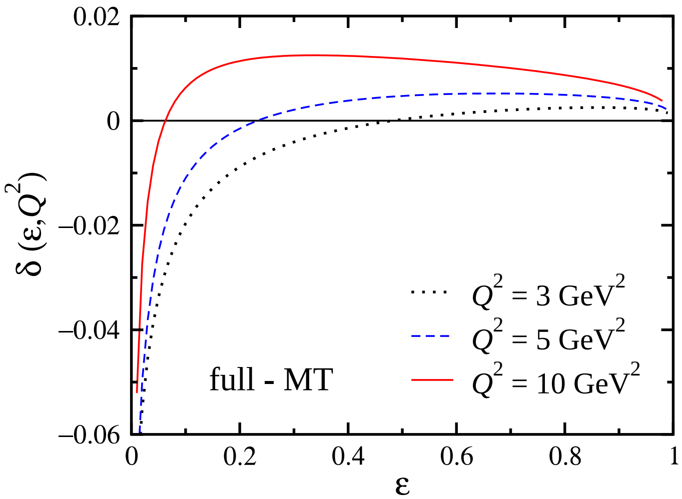

FIG. 4: Two-photon exchange correction to the square of the pion form factor as a function of ϵ for various Q^2 relative to the Mo & Tsai contribution, as calculated by Blunden, Melnitchouk and Tjon [24].

IV. TWO-PHOTON EXCHANGE EFFECTS

In the Rosenbluth separation of the proton electric form factor, two photon contributions cannot be neglected because the electric cross section is much smaller than the magnetic cross section. In this case, a few percent correction to the total cross section has a potentially large impact upon the electric cross section. Forward angle π^+ electroproduction is expected to be much less sensitive to two photon effects, since $\sigma_{\rm L}$ is expected to be larger than $\sigma_{\rm T}$ at low $-t$. Blunden, Melnitchouk and Tjon have recently published a calculation of two-photon exchange effect corrections to the pion form factor [24] in the context of elastic electron scattering from a real pion. In this calculation, two-photon exchange effects are not large and are in fact comparable to the point-to-point systematic error typically assigned to the radiative corrections procedure (Fig. 4). Except for the extreme backward region ($\epsilon \to 0$) which is inaccessible to measurement, the corrections to the square of the pion form factor are well under 1% for the kinematics proposed here. It should be noted, however, that this calculation is not directly applicable to the extraction of the pion form factor from electroproduction data since the fundamental process is different. It does, however, clearly demonstrate that in the limit of pure t–channel dominance, with t very close to the pion pole, there is no fundamental problem with two-photon exchange effects.

V. BEAM REQUEST

As in 2006 [8], we assume that 30,000 good events per ϵ setting are used to determine the $-t$ dependence of the reaction. These 30,000 events are divided between 5 t-bins, yielding a statistical accuracy of 1.3%, to which is added the uncorrelated systematic error estimate of 0.6%. This will allow the $-t$ dependence of σ_L to be carefully compared to the VGL Regge (or other) model. The final uncertainty on F_π will be limited by the t-correlated uncertainty, which is common to all $-t$-bins at fixed ϵ, but varies randomly between ϵ settings. Since the final extraction of F_π will be dominated by the lowest $-t$ bin, the statistical precision of 1.3% per bin is well matched to the 1.6% t-correlated uncertainty. The resulting projected error bars, including all statistical, systematic, and model fitting uncertainties, are displayed in Fig. 5. The proposed measurement is easily able to distinguish between at least a number of the models.

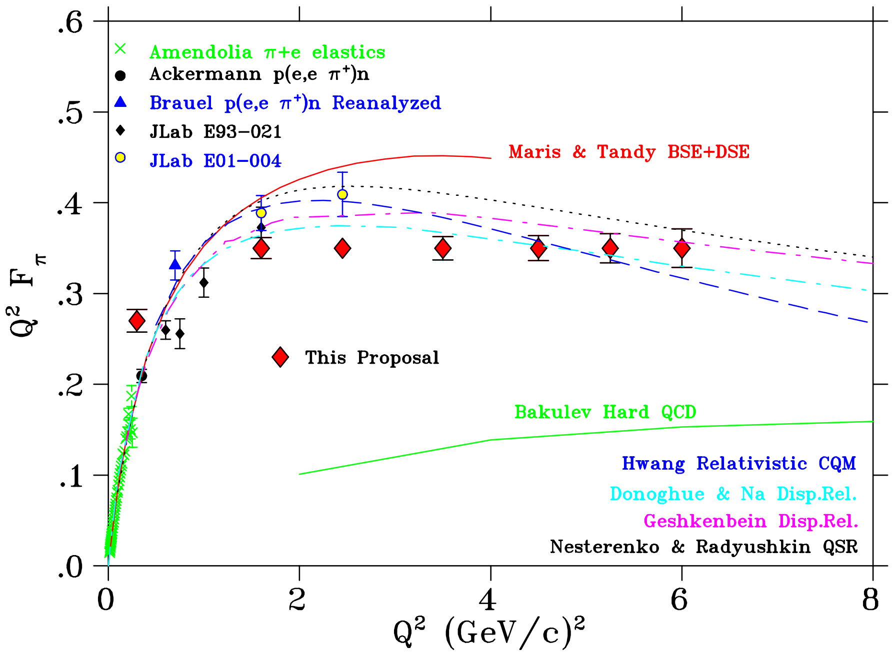

FIG. 5: Projected error bars for this proposal, in comparison with a variety of theoretical models, and existing precision data. The error bars include all projected statistical and systematic uncertainties, as well as an additional 1% model uncertainty in the form factor extraction added in quadrature.

The estimated beam time in Table I assumes 30,000 events per LH and LD(π^+) kinematic setting, and 20,000 events per LD(π^-) setting,[1] including detection inefficiencies and cut inefficiencies. Running times include a 10% allowance to account for data taking from the aluminum "dummy" target, needed to subtract contributions from the target cell walls. The beam current is assumed to be 85 μA for SHMS positive polarity runs, and 12 μA for SHMS negative polarity runs, with the exception of the $Q^2 = 0.3$ GeV^2 runs, which are 25 μA. The cryogenic target length is taken to be 8 cm, as explained in the 2006 proposal [8]. Rates were estimated using SIMC, the Hall C Monte Carlo incorporating a parameterization of the ^{1}H$(e, e'\pi^+)$ cross section constrained by existing data at lower Q^2 but which asymptotically approaches VGL Regge predictions at larger Q^2. The overhead listed in the table will be used for target and momentum changes (extra time is allotted at points where we will take π^- data to allow time to change the SHMS polarity). We have also allocated ≈ one shift at each beam energy for elastic and optics data taking. An additional shift has been set aside for each beam energy change that will be required.

[1] Because of the neutron's smaller transverse cross section, the π^- data should have a L/T ratio at least two times larger than the π^+ data. The error amplification in the L/T separation will be smaller, hence, even with reduced statistics, the π^- longitudinal cross sections are expected to have uncertainties comparable to the π^+ data.

TABLE I: Beam time request for hydrogen and deuterium running. The number of hours per setting is for three $\theta_{\pi q}$ settings at high and medium ϵ and for two $\theta_{\pi q}$ settings at low ϵ (except at Q^2=0.3 GeV^2) as listed in the 2006 proposal [8]. Times include aluminum "dummy" target running needed for cell wall subtraction.

Q^2 (GeV^2)	ϵ	LH_2 Hours $p(e,e'\pi^+)n$	LD_2 Hours $d(e,e'\pi^+)nn$	LD_2 Hours $d(e,e'\pi^-)pp$	Overhead (Hours)	Total (Hours)
6.00	0.177	176	0	0	4	180
	0.298	94	0	0	4	98
	0.435	63	0	0	4	67
5.25	0.188	127	0	0	4	131
	0.401	46	0	0	4	50
	0.498	31	0	0	4	35
4.46	0.224	66	0	0	4	70
	0.404	26	0	0	4	30
	0.524	18	0	0	4	22
3.50	0.304	20	20	127	8	175
	0.587	8	0	0	4	12
	0.671	8	8	26	8	50
2.45	0.265	17	0	0	4	21
	0.505	8	0	0	4	12
	0.625	8	0	0	4	12
	0.702	8	0	0	4	12
1.60	0.387	8	8	13	8	37
	0.689	8	0	0	4	12
	0.765	8	8	8	8	32
0.30	0.341	8	0	0	4	12
	0.657	8	0	0	4	12
	0.747	8	0	0	4	12
Subtotals		772	44	174	104	
$p(e,e'p)$ + optics						80
9 beam energy changes						72

Grand Total: 1246 hours (52 days)

VI. SUMMARY

The high quality, continuous electron beam of Jefferson Lab makes it the only place to seriously pursue a program of F_π measurements. However, a challenge of the QCD-based models in the most rigorous manner requires the electron beam upgrade and construction of the SHMS.

The flexibility afforded by an 11 GeV maximum beam energy will allow measurements to be obtained sufficiently close to the π^+ pole that σ_L will be dominated by the t-channel process, and that backgrounds to σ_L will be minimized. The requirements upon the spectrometer are small forward angle capability, good angular reproducibility (to control systematic errors in the L/T separation) and sufficient missing mass resolution to cleanly separate $p(e,e'\pi^+)n$ events from $p(e,e'\pi^+)n\pi^0$. This combination will allow F_π to be determined in the best manner allowable by current models, and would provide a very significant advance in the understanding of the pion form factor.

Our proposed measurement of the pion form factor is a good match to the anticipated characteristics of the spectrometers and focal plane package and is a natural application of the proposed SHMS+HMS spectrometer system. Jefferson Lab can make a unique contribution to our knowledge of hadronic structure via this charged pion form factor experiment.

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APPENDIX A: DETAILS ON THE COMBINED F_π AND "PION SCALING" RUN PLANS

The "Pion Scaling" experiment E12-07-105 [23] plans three scans of the $p(e, e'\pi^+)n$ reaction versus Q^2 at x =0.311, 0.400 and 0.550. The experiment proposes to acquire 5,000 $(e, e'\pi^+)$ coincidences per setting in each of the lower two x scans, and 10,000 coincidences per setting in the higher x scan. This is in contrast to F_π, which requires 30,000 coincidences per setting to determine the $-t$ dependence of σ_L with the necessary statistical precision. Hence the "Pion Scaling" envisions a larger number of settings in a survey-type experiment, while F_π requires precision over a narrower range of x and $-t$.

The total time requested by E12-07-105 for each x scan is 1.8 days, 3.4 days and 29.3 days, respectively. The scan at x =0.550 comprises 70% of the total E12-07-105 beam request and is at $-t_{min}$ values of 0.5-0.55 GeV^2, which are much larger than the settings proposed for the F_π experiment. Thus, any savings by combining kinematic settings are restricted to the other two x scans (which take only 4% and 8%, respectively, of that beam request).

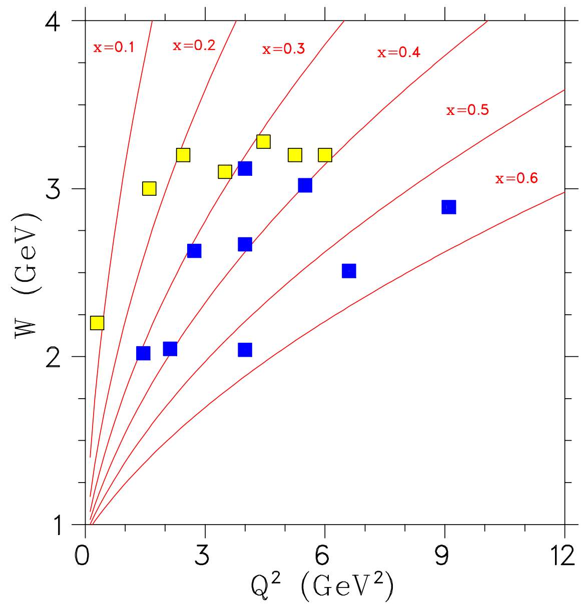

FIG. 6: W versus Q^2 settings planned for the F_π experiment (yellow squares; higher statistics) and the "Pion Scaling" experiment E12-07-105 (blue squares; lower statistics). The red lines indicate fixed x values from 0.1 to 0.6.

The Q^2=6.0 GeV^2 point needed by F_π is at $x = 0.39$. Thus, it has been agreed to move the x-value of the middle scan from x =0.40 to x =0.39. This does not save significant beamtime, but it positively benefits the "Pion Scaling" experiment by extending the upper range of the planned Q^2-scan from 5.50 GeV^2 to 6.0 GeV^2, reducing the uncertainty in the determination of the $1/Q^n$ scaling exponent accordingly.

To benefit the planned x =0.311 scan, the Q^2=4.50 GeV^2, W=3.28 GeV point originally listed in the F_π proposal has been moved to Q^2=4.46 GeV^2, W=3.28 GeV. $-t_{min}$ is nearly unchanged, decreasing from 0.122 to 0.121 GeV^2. The lab cross sections are similarly nearly unchanged, so there is no impact upon the F_π request. However, this positively benefits the "Pion Scaling" experiment by extending the upper Q^2 range of this scan from 4.00 to 4.46 GeV^2.

The combined Q^2, W, x coverage of both experiments are shown in Fig. 6. Subject to beam scheduling constraints, we think it likely that both experiments will run concurrently, and we expect both experimental collaborations to work together to optimize the physics output of both experiments. For example, two days of beam could be potentially saved by sharing $e + p$ elastics and optics calibration runs. However, there is no way to know at this point how the two experiments will be scheduled, and therefore we separately request the full elastics and calibration runs required for each experiment.