Progress toward Publishing HPS Results

The HPS Collaboration

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The HPS Collaboration Meeting at JLAB on November 16-18, 2016, gave us an opportunity to assess progress toward publishing our first physics results. At the time of our previous meeting, in April at SLAC, the Collaboration hoped and expected to be able to present its first physics results by late summer 2016. That optimism was based on the near completion of the first HPS thesis on the bump hunt in the 2015 Engineering Run data and the good performance of the trigger, ECal, and SVT. Other propitious signs included the near-design level momentum and invariant mass resolution, and the good agreement between data and MC vertex distributions (including the all-important tails). All these factors contributed to JLAB management's granting full approval to HPS for our original request of 180 PAC days (minus the 15 days already allotted), at the end of April.

Two problems have delayed our first publication. First, discrepancies between data and MC, which were already known at the time of the April meeting, have since been recognized as critically important. The most glaring of these was the failure of trident MC to predict the shape and normalization of the measured distribution of the sum of the energies of the electron and positron (called Esum). Rough agreement between data and MC was (fortuitously) seen in the region $x > 0.8$, HPS's signal region, but MC exceeded data by a factor 3 or so at low x. It was not clear if the MC generator was at fault, if the trigger had been inefficient at low energies, if the tracking was inefficient, or if something else was wrong. Secondly, it became clear that an important background to the trident signal had been overlooked in the simulations. Wide Angle Bremsstrahlung (WAB) appears prominently in our data, with an electron and photon summing to the beam energy in the ECal. It also contributes to the "e^+e^- trident sample" whenever a WAB photon converts in the target or an early layer of the tracker and the resulting positron receives most of the photon's energy. In these cases, the conversion electron is usually missed because of its low momentum, but the original electron is detected. Thus converted WABs produce an e^+e^- pair in HPS just like the tridents and so constitute a background.

After a good deal of study and simulation, we have come to understand that "converted WABs" occur at a rate comparable to the tridents, constitute a significant background for our heavy photon search, and so significantly impact the agreement of data and MC. This background was missed not because our event generator (EGS5) didn't have WABs, but because EGS5 implemented them incorrectly. The photon was generated with the right energy and angle but, for the sake of simplicity, the electron was propagated at zero degrees. Such events don't trigger in HPS. Consequently, converted WABs did not appear in the MC as they do in the data. Previous heavy photon searches may also have overlooked this background. The situation has been remedied by implementing an accurate simulation of WABs which incorporates form factor effects using Madgraph 4. The addition of this component to the trident sample has significantly improved agreement between many MC and data distributions, including the shapes of the electron and positron spectra and the shape of the invariant mass distribution. But it did not explain the low Esum behavior.

Converted WABs can be largely removed from the trident sample with cuts which retain most of the tridents, so this background will have little impact on our ultimate reach.

To return to other possible sources of data/MC discrepancy, we have studied the efficiency of the HPS trigger, worried that an incomplete simulation of all the details of energy deposits near the edges of crystals could lead to significant distortions in the simulated ESum distribution. Studies of trident candidates found with the SVT alone, using a sample of random triggers, have demonstrated that the ECal and trigger are fully efficient at even the lowest ESum energies. Ecal and trigger response are not a source of the Esum discrepancies.

Studies of the SVT tracking efficiency have also been performed. They show that the tracking efficiency in MC is somewhat greater than that in data, especially at the lowest momenta. Differences there are in the range of 10-20%. While the observed tracking inefficiencies will somewhat modify the predicted shape of the Esum distribution, they are not nearly large enough to account for the low ESum discrepancies.

The question of the validity of the MC simulations remains. We have been investigating the validity of the simulation, first by comparing the HPS Madgraph 4 trident generator to a newer Madgraph 5 generator and to the Madgraph 4 generator used by the APEX experiment in the past. Our original Madgraph 4 generator was in agreement with that of the APEX experiment and predicted their observed trident rate (into a very much smaller acceptance and in a different region of phase space) within 10%. However, the Madgraph 4 generator differs substantially with Madgraph 5 in its predictions of the shape of the Esum distribution, Madgraph 4 showing many more low Esum events than Madgraph 5. Independent estimates of the ESum spectral shape based on the analytic calculation by Beranek and Vanderhaegen agree with Madgraph 5 and with the data. The preponderance of evidence in fact supports the Madgraph 5 calculation, indicating at least partial resolution of the ESum puzzle. The original data/MC discrepancy occurred because Madgraph 4 considerably overestimated the number of low ESum events, converted WABs were not unaccounted for, and small variations in the tracking efficiency with Esum were not included. Using Madgraph 5 tridents and Madgraph 4

WABs, which now also include corrections for form factor and spin state counting effects, gives good agreement between the shapes of the predicted and measured ESum distributions.

There remained, however, a discrepancy between the overall rates observed in data and Monte Carlo. The MC predicted rates higher than observed in the data by a factor ~ 1.5. Just recently, we have discovered an error in the trident and WAB rates in MC. Both rates are normalized by the value of the electromagnetic coupling constant, tridents by α^4 and WABs by α^3. The value of α found in our programs was suitable for processes at the Z pole, not our experiment. When the value α=1/137 is restored, both the trident and WAB cross sections decrease, and bring the data and MC into reasonable agreement. The data is still ~10% low, presumably because of tracking and other small inefficiencies. But the “trident problem” is solved.

To summarize a protracted journey, the sum of Madgraph 5 tridents and Madgraph 4 WABs now accounts for the shape and normalization of the measured Esum distribution as well as other key distributions. We are now confident that our data is in accord with theoretical expectation, and are ready to proceed with the bump hunt and vertex searches. To analyze HPS data in our signal region, we need to know: (1) how many e+e- events are detected with x>0.8 (we do, directly from the data); (2) the fraction of those events that are really tridents (we do, both from the predicted normalizations from MC and from independent measures of the fraction of converted WABs); and (3) the fraction of the real tridents which are “radiative” tridents. This last fraction, determined from simulation, is needed because the heavy photon production at a given mass is proportional to radiative trident production.

Substantial progress has been made in analyzing HPS data. Omar Moreno, now graduated from UCSC and an HPS post doc, produced a full bump hunt analysis on 10% of the 2015 Engineering Run data for his thesis. He is updating this analysis in preparation for unblinding the whole 2015 data set and has derived limits on heavy photon production for a range of masses. His limits on ε^2 are roughly a factor 2 worse than we had projected in our proposal. Much of this can be accounted for by a factor 2 error in acceptance (see below) and data/MC rate discrepancy discussed above. Recall that the limit goes as the square root of these factors. The analysis of the full 2015 data set is proceeding. We should have a result in Spring 2017. The present HPS bump hunt results quantitatively demonstrate the HPS reach. The 2015 results will not explore new parameter space, given advances from other experiments, but our bump hunt results at higher energies will.

Sho Uemura, then a Stanford PhD candidate, completed the first vertex analysis on the 10% sample of the 2015 data. His analysis has uncovered two mistakes in our vertex reach projections: we failed to account properly for the reduction in efficiency affecting long lived decays and we failed to model the ECal acceptance correctly, omitting a “hole” in the ECal coverage which is close to the electron beam’s trajectory. The latter mistake costs a factor 2 in acceptance. In Sho’s analysis, both tracks are required to have hits in the first tracking layer which is situated just 10 cm downstream of the target. This results in a considerable fall-off in efficiency for decays which occur more than 3 cm downstream of the target. The effect is most pronounced for low mass events, since their decay products are produced at the smallest angles, and it biases the experiment’s current sensitivity to masses around 45 MeV, in contrast to that in the proposal, 22 MeV. After including events which have tracks which miss Layer 1 but hit Layer 2, which future HPS nalyses will do, the efficiency fall-off will cost a factor ~2 compared to our proposal (which had erroneously assumed constant efficiencies for decay lengths out to 10 cm). Sho’s analysis projects a sensitivity that is roughly a factor 2 x 2 x 1.5 = 6 worse than the projections in our proposal, the final factor of 1.5 coming primarily from the error in WAB and trident cross sections mentioned above. The overall factor of 6 is large enough that the present vertex analysis of the 2015 data will not exclude any region of canonical A’ coupling/mass parameter space. It may still, however, exclude other models of long-lived hidden sector particles. Recent work by a number of theorists (Schuster, Toro, Blinov, and Berlin) indicates there is explorable parameter space for so-called SIMP models of dark matter, with the present data sets. We need to confirm their estimates, but are encouraged that HPS may be able to exploit the 2015 data to explore new physics targets.

The deficiencies in vertex reach can be mitigated. Moving Layers 2 and 3 slightly closer to the beamline but still in regions of acceptable occupancy, will gain a factor 1.5 in sensitivity, just from improved geometric acceptance. The addition of a new Layer 0, placed 5 cm downstream of the target (our present layer 1 is at 10 cm), will further boost the efficiency by doubling the vertexing resolution. This halves the width of the vertex distribution and thereby allows detection of decays which are twice as close to the target, providing access to new regions of parameter space and better than a factor 2 improvement in the optimal sensitivity. Modifications to the HPS trigger could buy us another factor of 2. The present trigger requires detection of both the e+ and e- in the Ecal. The Ecal has a large “hole” to avoid the high background rates encountered close to the beam, and many trident electrons are lost in this “hole”. Studies indicate that by triggering only on the positron, instead of requiring both the positron and electron, it is possible to recover many of the events where the electron is lost. Initial studies of the background rates for such a trigger make this look feasible, especially if a veto can be developed for WAB photons which hit on the “positron side.” Studies of the performance of such a trigger with full simulation are underway. Taken together, these factors could improve HPS vertex sensitivity by a factor of at least 1.5 x 2 x 2 = 6, offsetting the current shortfall. Further studies are needed to make this estimate robust, but it is clear that substantial improvements are possible with modest upgrades.

Even with such improvements, taking data for periods significantly longer than the one or two weeks proposed for the engineering runs will be needed to fully exploit HPS’s capability. The

2015 data represents just 1.7 PAC days of data. Longer running times *and* the remediations listed above will result in robust limits (or discovery) over a large region of virgin A’ parameter space. Runs of 4 PAC weeks at each of 1.1, 2.2, 4.4, and 6.6 GeV, would allow a comprehensive search and can be accommodated in our remaining 165 PAC days.

To conclude, we are behind where we had hoped to be in terms of publishing our data, but this is because real and unanticipated problems arose which have demanded investigation and solution. These issues, particularly with event generators widely used by the community that have not been tested in our kinematics, have been resolved. Our focus has turned again to completing the bump hunt analysis of the 2015 data, presenting the results publicly, and publishing them. The reach of the present bump hunt is worse than predicted in our 2013 proposal, but still appreciable. We plan to present the results from the 2015 run in Spring 2017 and publish later in the year. The vertexing analyses are HPS’s unique contribution to dark photon searches, and they will cover a good deal of virgin parameter space. Our present vertex reach is a factor of 6 below our earlier projections, but this factor will be recovered by running for longer periods, making modest upgrades to the SVT, and installing a new trigger. We expect to have robust reach estimates in the next few months. Vertexing results on the full 2015 data set should be available later in 2017.

HPS has demonstrated its capability to search for heavy photons with its bump hunt. Future running at higher energies will explore new bump hunt territory. HPS is also poised to search a large region of virgin heavy photon parameter space in the vertex region. An extended run in 2018 will generate exciting physics results from HPS in both regions.