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An Event Generator for Drell-Yan Dilepton Production with Electroweak Radiative Corrections

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Abstract

We have implemented ZGRAD as an event generator compatible with the Run II CDF offline software environment. ZGRAD is a Monte Carlo cross section calculation code for Drell-Yan dielectron and dimuon production and includes full order alpha electroweak corrections. We discuss the implementation of ZGRAD as an event generator, its interface with the CDF offline environment, and present an initial comparison with PYTHIA. We also discuss the implications of these theoretical results for the measurement of the forward-backward asymmetry.

1 Introduction

Electroweak corrections to Drell-Yan production could be of interest to CDF anywhere that Z bosons are interesting. This could include: precision measurements such as the forward-backward asymmetry at the Z pole to measure the effective weak mixing angle; high mass tests of the Standard Model with the forward-backward asymmetry or searches for physics beyond the Standard Model in the dilepton invariant mass spectrum; or, general use of Z bosons as a calibration sample. In our work with ZGRAD our primary interest has been the forward-backward asymmetry [1] [2].

The QED corrections to Drell-Yan production are very important, especially at the generator level when ignoring effects such as the recombination of photons with leptons in the same calorimeter tower or electron object. The largest effect is from final-state radiation. Dileptons are produced abundantly on the Z pole, and when one of the leptons radiates a photon the invariant mass of the dilepton drops accordingly. So, for dielectrons just below the

Z pole the cross section increases by a factor of approximately 2.5 with QED radiation and no detector effects. Similarly, the forward-backward asymmetry changes from approximately -0.50 to approximately -0.20. Using a toy calorimeter grid, chosen to approximate the segmentation of the CDF calorimeter, to recombine some photons with electrons, the increase in the dielectron cross section is reduced to about 50% and the effect on the asymmetry is similarly muted.

Once the QED corrections are included the additional electroweak corrections are much smaller. Near the Z pole the correction to the cross section is about 1% and approximately 10% at high mass. The effect on the asymmetry is a few thousandths near the Z pole, where the asymmetry is near zero, and as large as one hundredth at high mass where the asymmetry is approximately 0.6.

The numbers in this section are taken from the original authors of ZGRAD. [3] [4]. We have reproduced many of the results from their papers, to satisfy ourselves that we knew how to operate ZGRAD, but we do not present those studies here. The pure electroweak corrections are quite small, but we may be able to probe them at the Tevatron when large integrated luminosity data sets become available.

So, our project has been to make this calculation of order alpha electroweak corrections available in the CDF offline environment as an event generator. This has involved taking the original ZGRAD cross section calculation program (section 2), converting it into an event generator (section 3), and using the LesHouchesModule to make the events available to PYTHIA and other parton shower codes (section 4). We have also made an initial comparison of samples from ZGRAD with ones generated by PYTHIA (section 5). Finally, we discuss some possible improvements to ZGRAD as a part of the CDF offline environment.

2 ZGRAD as Cross Section Calculation Program

ZGRAD, the cross section calculation program, was written by Baur *et al.*. [3] [4] It includes QED and electroweak order alpha corrections including initial and final-state radiation, their interference, self-energy and vertex corrections, W and Z box diagrams, and photon exchange. The Higgs boson contribution to the box diagrams and vertex corrections is neglected.

ZGRAD comes with a large number of configurable parameters (see Appendix) but has three primary different levels of theory. It turns out that, aside from real photon radiation, most of the order alpha electroweak corrections can be factorized into effective couplings. So, the basic mode of ZGRAD theory is what Baur *et al.* have christened the Effective Born Approximation (EBA). Below the threshold of the W and Z box diagrams it provides a good approximation of the full order alpha corrections, neglecting real photon radiation, while having the same computational complexity as the Born approximation. You can add photon radiation and run ZGRAD in EBA+QED mode. Or, you can include all corrections (including the non-factorizable corrections such as the W and Z box diagrams) and run ZGRAD in EBA+EW mode.

Internally, ZGRAD is configured as a something of a wrapper around two almost autonomous Monte Carlo integration sub-programs. The first handles the two-body final state events (no real photon in the final state) and so does the EBA, the soft and virtual photon effects (photons below user specified cutoffs) and the weak corrections. The second sub-program uses VEGAS, an adaptive Monte Carlo integration program to handle the three-body final state events. ZGRAD makes a number of passes through each of these sub-programs and fills histograms with the results from each.

The method used to calculate the two-body cross section is relatively robust, but the three-body code, because it uses an adaptive integration grid, is fairly sensitive to how it is used. In particular, if not enough weighted events are generated to produce a good integration grid then it may output unreliable results. ZGRAD does not report bin by bin errors on its calculations but, especially with small soft and virtual cutoffs, it is possible to use poor statistics, generate a bad integration grid, and get obviously non-physical cross sections with discontinuities, etc. Also, the two-body and three-body cross sections are separately dependent on the soft and virtual cutoffs used, but the sum should not be.

3 ZGRAD as Event Generator

ZGRAD originally produced only weighted events. So, the most obvious step necessary to implement ZGRAD as an event generator is to unweight the events. As a next to leading order (NLO) calculation ZGRAD also produces negative weight events which must be considered. Finally, since ZGRAD originally handled only weighted events it could take some computational short cuts, for instance in the way it handles different quark flavors, that require some translation to apply to unweighted events.

3.1 Unweighting Events

Currently ZGRAD has two internal parameters, NCALL1 and NCALL2, determining how many iterations through the code to process (equivalently, how many weighted events to attempt). In cross section calculation mode ZGRAD makes five passes of 2*NCALL1 iterations each through the two-body final state code. Then, ZGRAD makes ten passes of NCALL1 iterations each through the three-body final state code, with the idea that these are used to establish the integration grid, and three additions passes of NCALL2 iterations each. The idea is that NCALL2 will generally be much larger (at least a factor of ten) than NCALL1 and these last three passes will be the "production" passes when the bulk of the three-body calculation is carried out.

The unweighting strategy we have chosen is to first choose maximum weights for the two-body and three-body calculations. ZGRAD does this in an initial calculation of user-specified size (we usually choose NCALL1=NCALL2=20,000). Then, ZGRAD redoes the calculation with new user-specified NCALL1 and NCALL2 (generally larger) and compares the weight of each weighted event to the selected maximum. ZGRAD keeps the event when $\frac{|eventweight|}{maxweight}$ is greater than a random number chosen from a uniform distribution in the range zero to one. If the event had a negative weight the event is kept and assigned weight -1. If it had a positive weight it is assigned a weight of +1. If the event weight is greater than the maximum then multiple copies of the event are included. For instance, if an event is generated with 20.5 times the maximum weight, the event is kept twenty times and has a 50% chance of being kept a twenty-first time.

The basic compromise of the unweighting process is keeping an acceptably high unweighting efficiency while maintaining an acceptably low number of duplicated events. For example, you could multiply the maximum weight by ten before unweighting, and reduce the number of duplicated events. But, your unweighting efficiency would be reduced by the same factor of ten and so you would have to generate ten times as many weighted events to produce the same number of unweighted events.

Examples of the distribution of weights can be found in Figures 1 and 6. For a typical ZGRAD sample with full electroweak corrections you might have a two-body unweighting efficiency of 1% and a three-body unweighting efficiency of 0.05%. Graphically, in Figure 6 we can see the sharp high edge in the two-body weight spectrum which leads to a high unweighting efficiency, and the more gradual drop off in the high edge of the three-body weight spectrum which leads to a low unweighting efficiency. To give one particular example, a certain ZGRAD sample was generated with NCALL1=NCALL2=20,000 for the maximum weight selection calculation and NCALL1=300,000, NCALL2=30,000,000 for the unweighted event generation. We often keep NCALL1 at at least 1% of NCALL2 in an attempt to produce a good integration grid. Only the last three passes through the three-body code are used for unweighting, to try to ensure that the integration grid has settled out. Of these 90,000,000 attempts 29,500,000 weighted events were generated (due to internal cuts ZGRAD makes in cross section calculation mode) and of these 23,221 unweighted three-body events resulted (for an unweighting efficiency of 23,000 / 29,500,000 = 0.00077). Because we chose a large NCALL1 to get a good integration grid we have an abundance (36,000) of two-body events on hand. Matching the two-body to three-body ratio to that from the weighted calculation we keep 13,626 two-body and 23,221 three-body events. So, to produce 36,487 unweighted events we made a total of 3,200,000 iterations through the two-body code and 93,260,000 iterations through the three-body code. On a 1 GHz PC ZGRAD does about 250 two-body iterations per second or about 1,600 three-body iterations per second. So, for a typical electroweak sample ZGRAD takes about one second per unweighted event. But, this depends significantly on the parameters chosen (especially the mass range, and the soft and colinear cutoffs), on the particular maximum weight selected, and of course on CPU performance.

3.2 Comparing Weighted and Unweighted ZGRAD results

An important test of the event generator incarnation of ZGRAD is that the unweighted events correctly reproduce the distributions calculated by ZGRAD in cross section calculation mode. We include distributions from two different event samples. The first is 3,900,000 unweighted EBA events. The second is 780,000 unweighted events from a full order alpha electroweak calculation, but with final-state radiation turned off. This second sample was generated with 39 jobs using the input card found in the appendix. Both samples are generated with dielectron invariant masses from 30 to 600 GeV. These unweighted samples are compared with weighted samples, generated with ZGRAD in cross section calculation mode. For the EBA weighted sample we used the average of two jobs run with NCALL1=25,000,000. For the electroweak no final-state radiation sample we used the the average of two jobs run with NCALL1=NCALL2=3,000,000.

See Figures 1, 2, 3, 4, and 5 for comparisons of various kinematic quantities.

These samples should agree within statistical errors. The unweighted distributions have been normalized to the weighted distributions. ZGRAD does not keep track of errors for all histograms in cross section calculation mode. So, while the statistical errors on the weighted distributions should generally be small, they are not included. Since the electroweak no final-state radiation sample is dominated by two-body events we did not use a large NCALL2 for that sample, and so the errors on the three-body weighted electroweak no final-state radiation histograms may be somewhat larger than others. Statistical errors for the unweighted distributions are included but they are often inside the open boxes which are the data points.

3.3 Negative Event Weights

Negative weight events are a general characteristic of NLO Monte Carlos. The negative weight events cancel with positive weight events to give physical cross sections. Of course, the cancellation is statistical so with ZGRAD we generate events with weight -1 as well as +1. The Les Houches Accord (see Section 4) requires that parton shower codes, like PYTHIA, be able to accommodate positive and negative weight events. So, we are able to pass the event weights to PYTHIA. Unfortunately, the HEPG data format does not have an entry for event weight. So, for the time being, negative weight events from ZGRAD will actually be indistinguishable from positive weight events once they each emerge from PYTHIA. There are plans for the CDF offline environment to accommodate negative weights events in the future [5].

In ZGRAD the bulk of negative weight events are in three-body final state events. These three-body negative weight events result from the interference between the initial-state and final-state radiation diagrams. Since none of the samples we present in this note contain both initial-state and final-state radiation from ZGRAD, there are actually no negative weight events present.

The fraction of events with negative weights depends strongly on the soft and colinear cutoffs chosen. In ZGRAD these cutoffs are parameterized by user-specified quantities delta-s and delta-c. So for example photons with $E_\gamma < \frac{\delta_s\sqrt{\hat{s}}}{2}$ are integrated over and included as two-body final state events while photons with E_γ greater than this are included explicitly as three-body final state events. Since, after emerging from PYTHIA, negative and positive weight events are indistinguishable it is important to minimize the number of negative weight events [1]. In practice we often run ZGRAD with $\delta_s = 0.001$ (E_γ cutoff at about 50 MeV for

[1]Any user of ZGRAD will need to consider the issue of negative weights. For the forward-backward asymmetry analysis [2] we basically dodged the issue by using not-to-small soft and colinear cutoffs and by

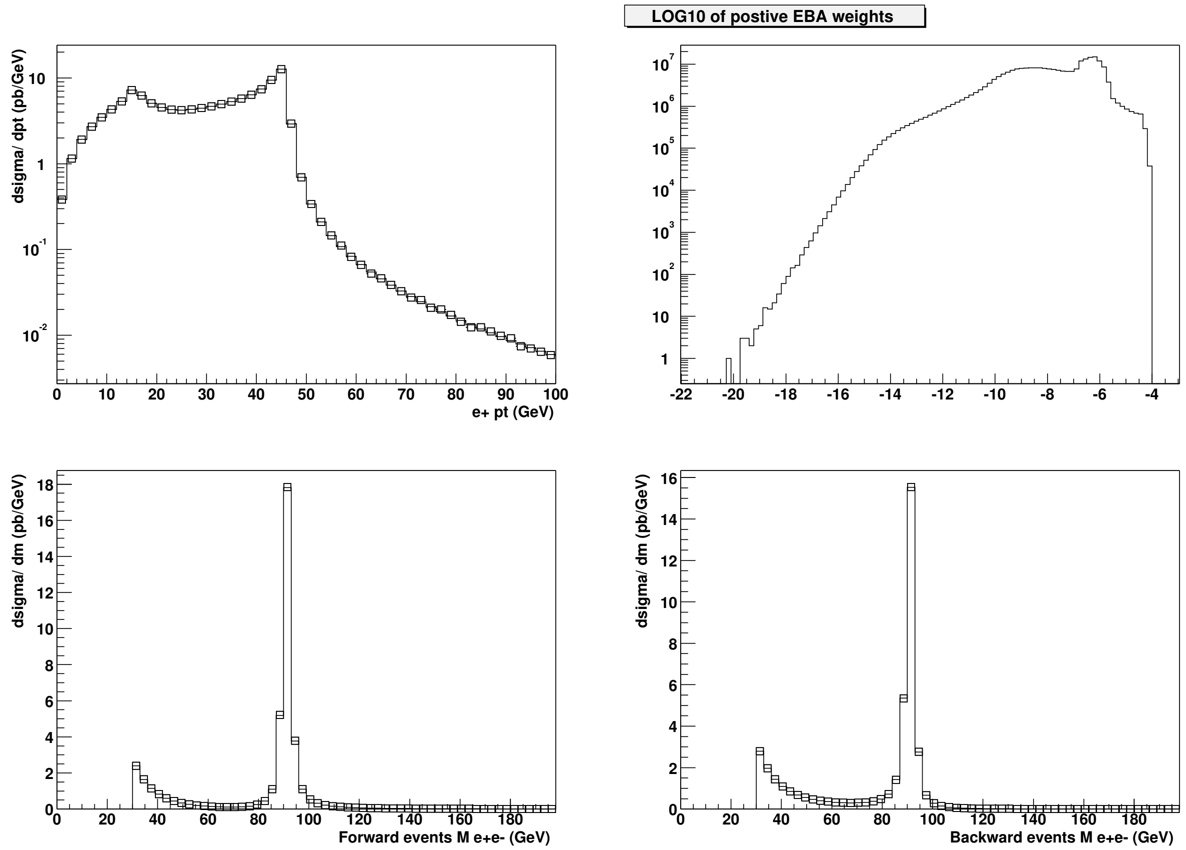

Figure 1: Weighted (histograms) and unweighted (boxes) distributions from an EBA sample. Statistical error bars are plotted for the unweighted distributions but are inside the boxes. Upper left: cross section vs. positron Pt. Upper right: $\log_{10}$ of EBA event weights. Lower left: Cross section of forward events vs. dielectron mass. Lower right: Cross section of backward events vs. dielectron mass. By forward and backward we are referring to the two hemispheres in the Collins-Soper frame as in the forward-backward asymmetry analysis [1] [2]. The weighted and unweighted histograms show good agreement.

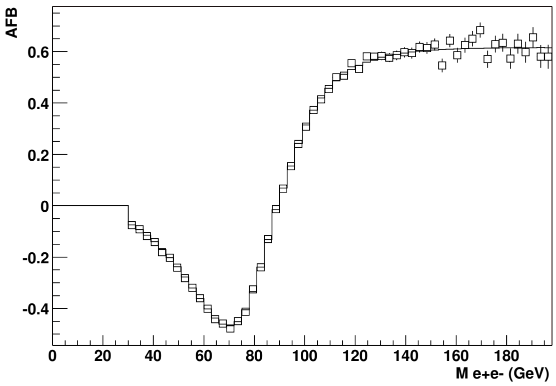

Figure 2: Weighted (histogram) and unweighted (boxes) distributions from an EBA sample. Forward-backward asymmetry as described in, for example, Veramendi *et al.* [2]. Statistical error bars are plotted for the unweighted distribution.

events on the Z pole) and $\delta_c = 0.0001$.

3.4 Flavor Fractions

In ZGRAD's cross section calculation incarnation each weighted event represents a particular choice of quark, lepton, and photon four-momenta. But, in this, its original mode, ZGRAD considers all compatible diagrams and quark flavors simultaneously. This means that a weighted ZGRAD event is a superposition of various Feynman diagrams and a statistical combination of different quark flavors. It should be possible to consult the fractions of the event weight that different flavor combinations contribute and statistically assign a flavor to any resulting unweighted event. Unfortunately, one weighted event can have positive and negative weight contributions from different quark combinations. So, correctly choosing quark flavor and event weight combinations has eluded our initial attempts.

For the time being, we choose quark flavors in the ZGRAD LesHouchesModule interface code (see Section 4). For two-body events we choose $u\bar{u}$ 80% of the time (u from the p, $\bar{u}$ from the $\bar{p}$) and $d\bar{d}$ 20% of the time. For three-body events ZGRAD handles two quark choice cases separately. For a particular weighted event, ZGRAD either considers matter, or anti-matter, quarks from the proton. For events that use matter (anti-matter) quarks from the proton we choose u and d ($\bar{u}$ and $\bar{d}$) with equal probability.

Different quark flavors do have, for instance, different forward-backward asymmetries. So, it is important to note that ZGRAD, when calculating cross sections, does handle the different combinations correctly. It's only the information we supply PYTHIA that uses the naive approximation. So, only the flavor content of the underlying event is affected and we expect the resulting effect on physical observables to be very small.

using some samples without initial state - final state interference.

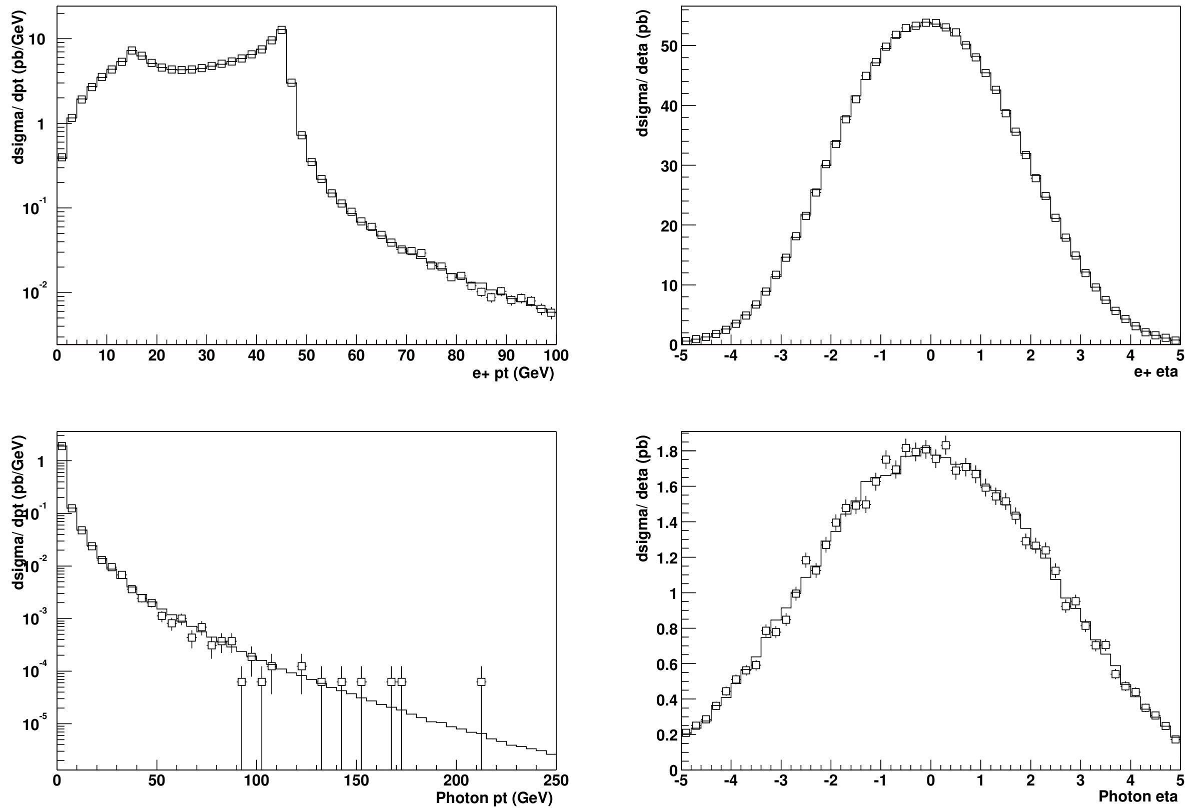

Figure 3: Weighted (histograms) and unweighted (boxes) distributions from an electroweak sample with no final-state radiation. Statistical error bars are plotted for the unweighted distributions but are often inside the boxes. Upper left: cross section vs. positron Pt. Upper right: cross section vs. positron eta. Lower left: cross section vs. photon pt. Lower right: cross section vs. photon eta. Since there are not many photons in the sample, the statistics are poor for the photon distributions. Given that, the weighted and unweighted histograms show good agreement.

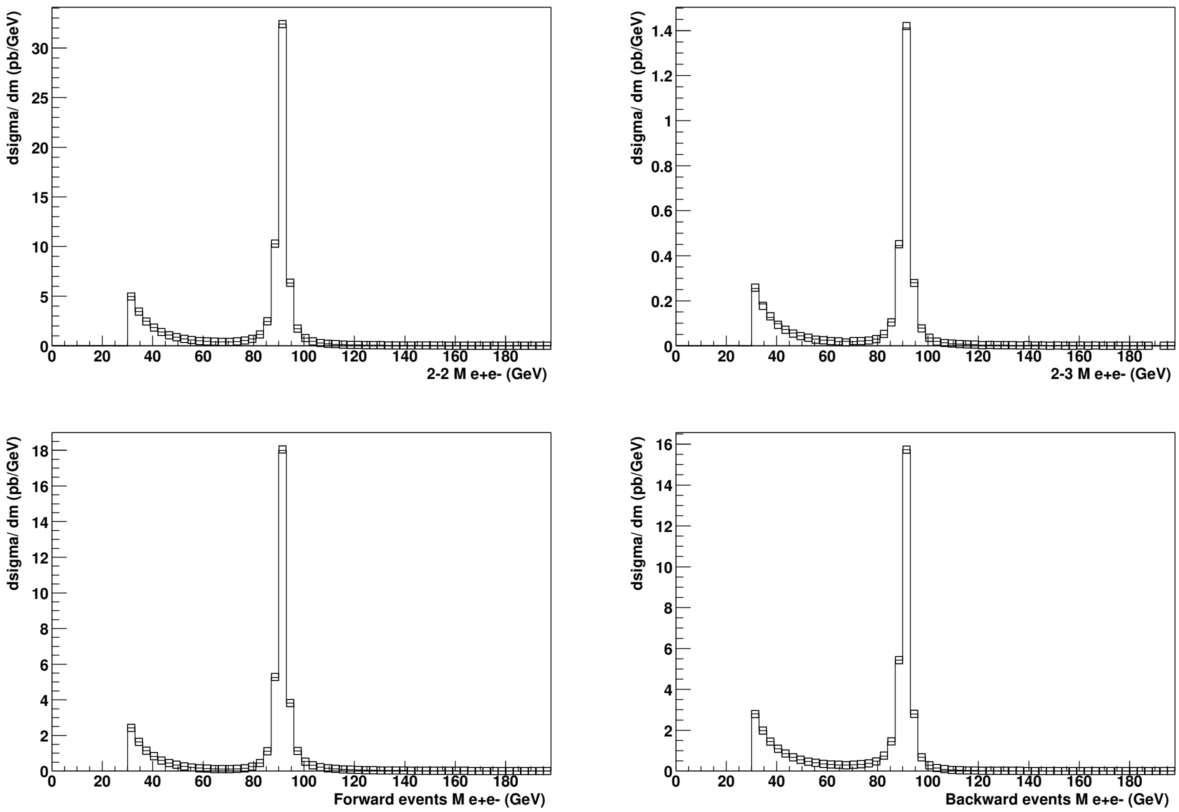

Figure 4: Weighted (histograms) and unweighted (boxes) distributions from an electroweak sample with no final-state radiation. Statistical error bars are plotted for the unweighted distributions but are often inside the boxes. Upper left: cross section of two-body final state vs. dielectron mass. Upper right: cross section of three-body final state vs. dielectron mass. Lower left: cross section of forward events vs. dielectron mass. Lower right: cross section of backward events vs. dielectron mass. By forward and backward we are referring to the two hemispheres in the Collins-Soper frame as in the forward-backward asymmetry analysis [1] [2]. Since there are not many photons in the sample, the statistics are poor for the 2-3 distributions. Given that, the weighted and unweighted histograms show good agreement.

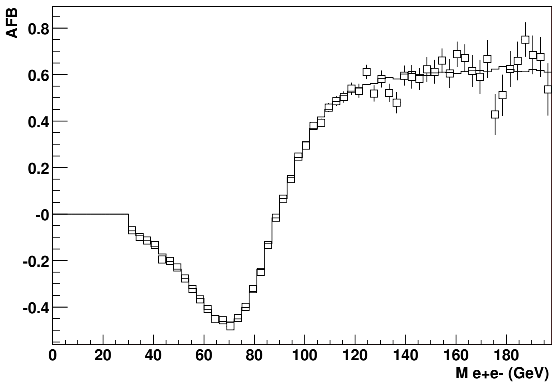

Figure 5: Weighted (histogram) and unweighted (boxes) distributions from an electroweak sample with no final-state radiation. Forward-backward asymmetry as described in, for example, Veramendi *et al.* [2]. Statistical error bars are plotted for the unweighted distribution.

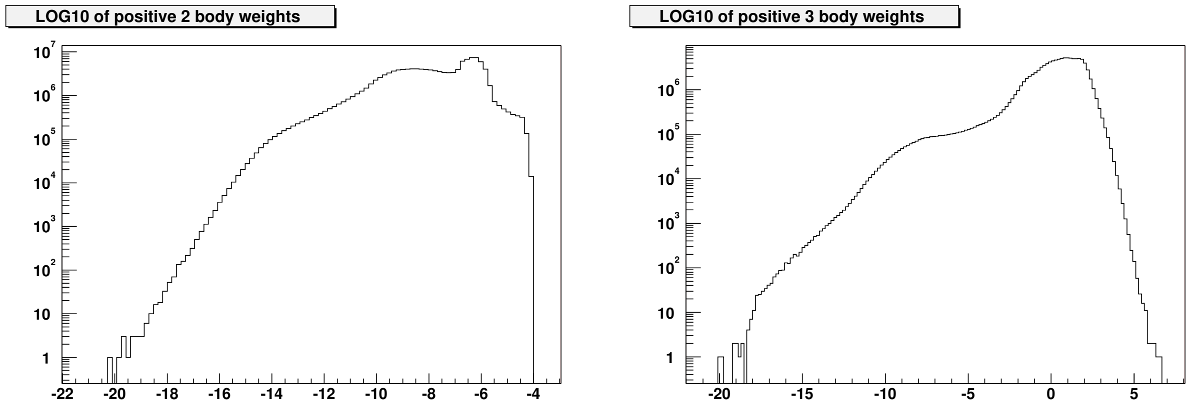

Figure 6: Event weights for electroweak events with no final-state radiation. Left: $\log_{10}$ of two-body event weights. Right: $\log_1 0$ of three-body event weights. The three-body final state events are from initial-state radiation. Since there is no final state - initial state interference in this sample there are no negative weights.

4 Interfacing with Parton Shower Codes

At the 2001 Les Houches *Physics at TeV Colliders Workshop* a common interface was agreed upon to facilitate connecting matrix element event generators to shower and hadronization event generators [6]. These are the so-called Les Houches Accords. So, a matrix element calculation code like CompHEP, MadGraph, VecBos, or in our case ZGRAD, fills FORTRAN common blocks with information about the process, and about the particular events. Then, a parton shower code like PYTHIA or HERWIG reads these common blocks and can add underlying events, parton showering, hadronization, etc.

In principal this should mean that any matrix element generator that is Les Houches compliant should be trivial to combine with any similarly compliant parton showering code. PYTHIA is compliant since version 6.2, but unfortunately the original version of ZGRAD was not.

S. Tsuno *et al.* are in the process of completing one additional step to implement the Les Houches framework at CDF [7]. They are writing a LesHouchesModule to facilitate the interface between matrix element codes and the CDF versions of parton shower generators like PYTHIA and HERWIG. The basic philosophy is that matrix element event generators like ZGRAD will output their events to a text file and someone will write a routine for LesHouchesModule to read in the text file and fill the appropriate common blocks so that LesHouchesModule can pass the information along to the chosen parton shower generator. LesHouchesModule has not yet been officially released but it seems to be far enough along to use with ZGRAD.

So, to use ZGRAD to generate events one begins by running ZGRAD as a stand alone program, with an ASCII input card, to generate a text file containing unweighted events. Then, one uses the LesHouchesModule to run a parton showering code over the ZGRAD events to provide initial-state gluon radiation, underlying events, hadronization, etc. The events can then be, if desired, run through the detector simulation and reconstruction as one would normally do with events produced by PYTHIA or HERWIG. One can also study generator level quantities using only the stand-alone ZGRAD program. It uses HBOOK routines to generate histograms with weighted and unweighted events and other histograms can be added by the user.

4.1 Particle Histories

There is at least one additional wrinkle when combining a matrix element event generator with a parton showering code. PYTHIA, at least, would like to know more information about particle histories than is usually available from a matrix element event generator. For instance, given a ZGRAD event with a real photon, PYTHIA would like to know where the photon came from. If PYTHIA decides to radiate a gluon from the initial state it would like to know how to correctly share that Pt among the final-state particles given by ZGRAD. But, the ZGRAD event was not generated from one particular Feynman diagram such that the photon came from, say, the positively charged lepton. Instead, it was generated from the combination of all of the diagrams.

In practice, we are just not telling PYTHIA where the photon came from. It is not clear how much of an effect this has on the events when they emerge from PYTHIA. Probably the best compromise would be, for each ZGRAD unweighted event, to compare the fractions of the event weight that came from the various diagrams, and their interference, and from this statistically assign a parent fermion for the photon.

5 Comparing PYTHIA to ZGRAD

By comparing the weighted and unweighted histograms from ZGRAD we gain confidence that we are correctly reproducing Baur *et al.*'s calculation. But, most ZGRAD users will probably want to use ZGRAD events that have also been showered by PYTHIA. The most obvious addition PYTHIA provides is a Pt kick from initial-state gluon radiation. Otherwise, the Z/γ^* in ZGRAD only has the, much more modest, Pt provided by photon radiation. The Pt distribution should not much affect, for instance, the forward-backward asymmetry (because of the Collins-Soper frame), but may be important for other measurements.

So, we have made an initial comparison of ZGRAD EBA events, sent through PYTHIA with the LesHouchesModule, to events generated by PYTHIA alone. The PYTHIA sample is 860,000 Drell-Yan dielectron events with no final-state radiation but otherwise with CDF default parameters (mostly Pythia defaults, but using, for example, Willis Sakumoto's Pt tune). The ZGRAD sample is 1,000,000 events from the previously described EBA sample (see Section 3.2). The PYTHIA parameters fed to the LesHouchesModule are the same as those given to PYTHIA for the PYTHIA sample. We would expect this to be a relatively direct comparison of whatever mechanism PYTHIA uses to generate Drell-Yan events (presumably starting with a Born-level calculation) to ZGRAD's EBA. See Figures 7 and 9 for comparisons of various kinematic quantities. In each plot, the ZGRAD and PYTHIA distributions have been normalized. So, the comparisons are of shapes only and not, for example, of absolute cross sections.

The Pt distribution of the dielectron is very different, PYTHIA's distribution having a long tail, and ZGRAD's cutting off rather more abruptly at about 100 GeV. It turns out that, for some processes including Z/γ^* production, PYTHIA includes results from NLO QCD matrix element calculations that significantly augment the high-Pt region [8]. Because Pythia sees events from ZGRAD as coming from an external process it assigns them a different process number than it uses for internally generated Z/γ^* events. So, the NLO QCD correction is not applied to ZGRAD events as they pass through Pythia. There is a PYTHIA switch, MSTP(68) , controlling this NLO QCD correction, so we also generated a PYTHIA sample without these effects (see Figure 8) and the agreement with ZGRAD is better at very high Pt. However, there is a significant disagreement at Pt's in the range 15-95 GeV. Despite the disagreement in the Pt spectrum we see good agreement for the forward-backward asymmetry among all three samples. This is not too much of a surprise since we adopt the Collins-Soper frame specifically to be insensitive to Pt kicks. The coarse binning, chosen to suit CDF's data 70 pb data sample so far in Run II, may also help mask

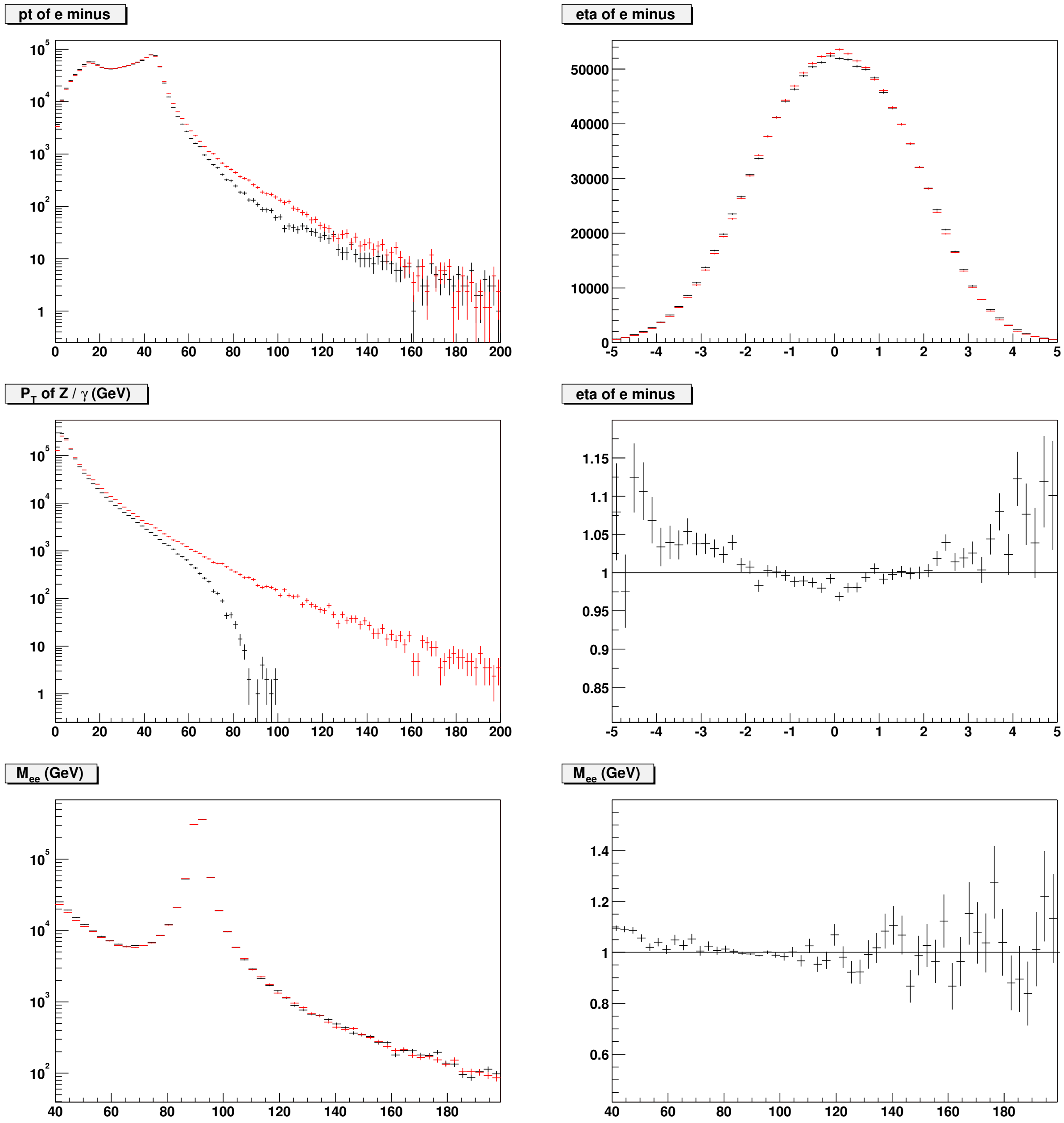

Figure 7: The red (light-colored) points are from a PYTHIA sample with no final-state radiation. The black points are from an EBA sample sent through PYTHIA. The distributions have been normalized to each other, so the comparisons are of shape only. Top left: electron Pt. Top right: electron eta. Middle left: dielectron Pt. Middle right: ZGRAD electron eta distribution divided by PYTHIA electron eta distribution. Lower left: dielectron mass. Lower right: ZGRAD dielectron mass distribution divided by PYTHIA dielectron mass distribution.

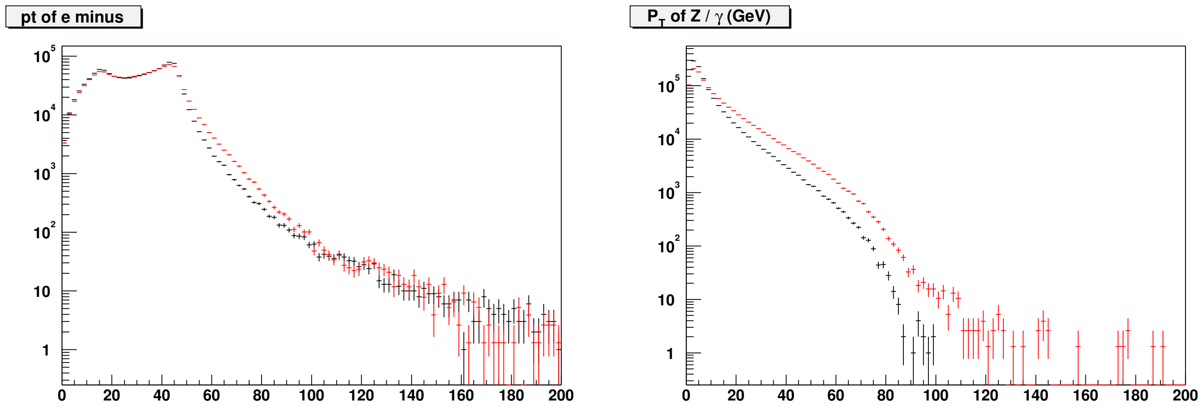

Figure 8: The red (light-colored) points are from a PYTHIA sample with no final-state radiation and no NLO QCD corrections. The black points are from an EBA sample sent through PYTHIA. Left: electron Pt. Right: dielectron Pt.

any differences.

PYTHIA can also produce events with final-state photon radiation. PYTHIA's method for this is basically the same as its method for gluon radiation. So, for example, PYTHIA first generates events with no photon radiation, and then showers the leptons. So, if you ask PYTHIA to generate events starting at a Z/γ^* mass of 30 GeV it will generate events that have Z/γ^* masses of 30 GeV or greater. But after final-state radiation some events will leak below this cut and have dielectron masses below 30 GeV. So, this complicates a comparison of ZGRAD events with real photons in the final-state to PYTHIA events.

So, for now, we present only the EBA to PYTHIA comparison. There are significant discrepancies in the dielectron invariant mass and Pt distributions. The discrepancies in the invariant mass distribution are not unlike those seen between the EBA and a "pure" Born approximation seen by Baur *et al.* [4]. We probably need to have a better understanding of PYTHIA's method of calculation to understand the differences in more detail.

6 Implications for the Forward-Backward Asymmetry

Beginning from the Born approximation, the largest perturbation to the forward-backward asymmetry comes from final-state photon radiation. Because the effect of such radiation is detector dependent measurements of the asymmetry are corrected to account for detector acceptance and final-state photon radiation, as we have done for the asymmetry measurement at CDF [2]. ZGRAD allows us to calculate all of the order alpha electroweak corrections, which also affect the asymmetry.

Unfortunately, we do not have a complete understanding of the Z/γ^* P_t distribution. From Figure 7 it is clear that we have not successfully reproduced PYTHIA's P_t distribution in the ZGRAD sample. Fortunately, for the asymmetry calculation in the Collins-Soper frame, this is not so important. In Figure 10 we compare the forward-backward asymmetry

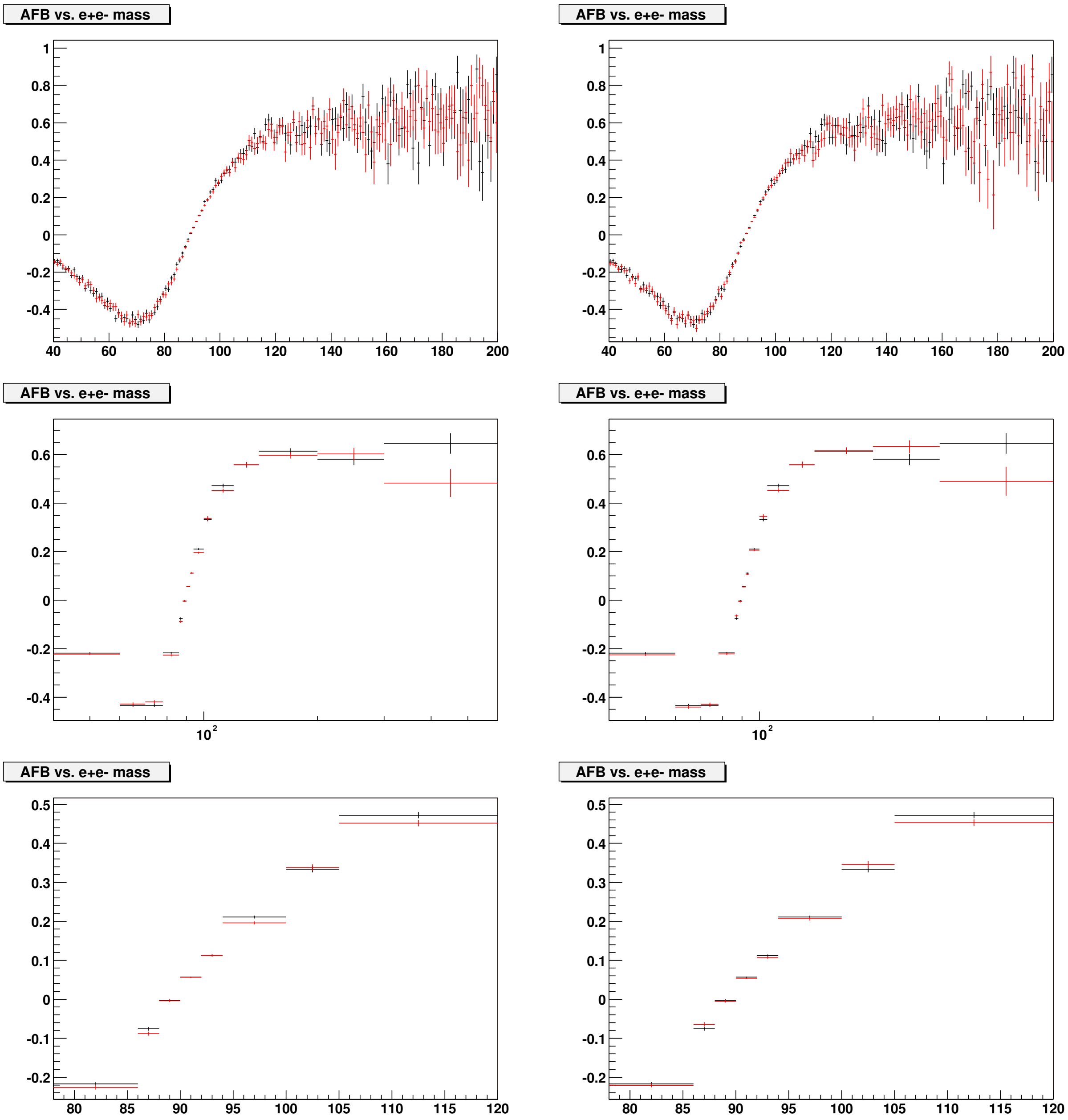

Figure 9: Forward-backward asymmetry as a function of the invariant mass of dileptons for various mass ranges and bin sizes. Left red (or light-colored) figures show results from a PYTHIA NLO + Parton Shower sample, and right red (or light-colored) figures show results from a PYTHIA LO + Parton Shower sample. They are compared to the results from the ZGRAD EBA calculation with P_T^Z obtained from PYTHIA (black). No QED final state radiation is included in these results.

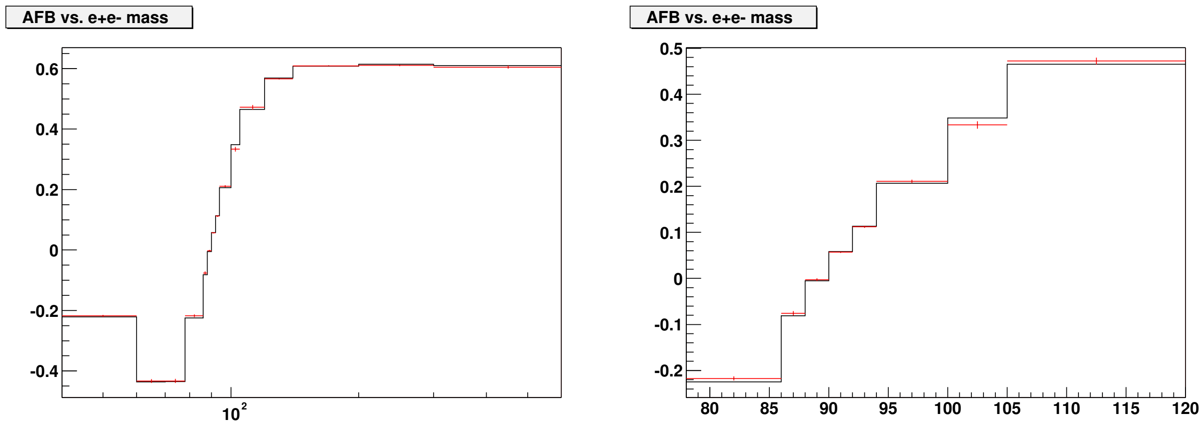

Figure 10: Forward-backward asymmetry from the ZGRAD EBA calculation as a function of the dilepton invariant mass for various mass ranges and bin sizes. Black figures show results from the stand alone calculation, thus $P_T^{Z/\gamma^*} \sim 0$, while red (or light-colored)figures show results from the ZGRAD EBA sample with P_T^{Z/γ^*} obtained from PYTHIA.

of a large ZGRAD EBA sample with and without the P_t kick provided by PYTHIA. Without the kick the ZGRAD EBA sample has 0 P_t and after the kick has on average P_t of 8.1 GeV. This makes almost no difference to the forward-backward asymmetry.

In Figure 11 we summarize a number of different theoretical calculations of the forward-backward asymmetry. We include stand-alone ZGRAD calculations: both EBA and full electroweak with no final-state radiation. We also plot an EBA sample that has been run through PYTHIA, a stand-alone PYTHIA sample with no final-state radiation, and the most recent data from CDF. The data is taken from Veramendi *et al.* [2]. In terms of Z/γ^* P_t these plots span the range from 0 (the stand-alone ZGRAD EBA sample) to 9.8 GeV (the stand-alone PYTHIA sample). So, our ignorance of the Z/γ^* P_t distribution is at least not much affecting our knowledge of the forward-backward asymmetry.

7 Conclusions

I'll come back to this after adding the AFB plots.

I need to rephrase this of course, but basically, my conclusion:

We have implemented Baur *et al.*'s ZGRAD cross section calculation program for use at CDF. Our modified version of the program appears to correctly reproduce Baur *et al.*'s calculation. Using Tsuno *et al.*'s LesHouchesModule we have interfaced our version of ZGRAD with PYTHIA. The Z/γ^* P_t distribution for the ZGRAD events passed through PYTHIA does not match PYTHIA's native Z/γ^* P_t distribution. But, at least for the forward-backward asymmetry this is not a pressing concern.

Acknowledgments We would like to thank Dave Waters for his advice and dis-

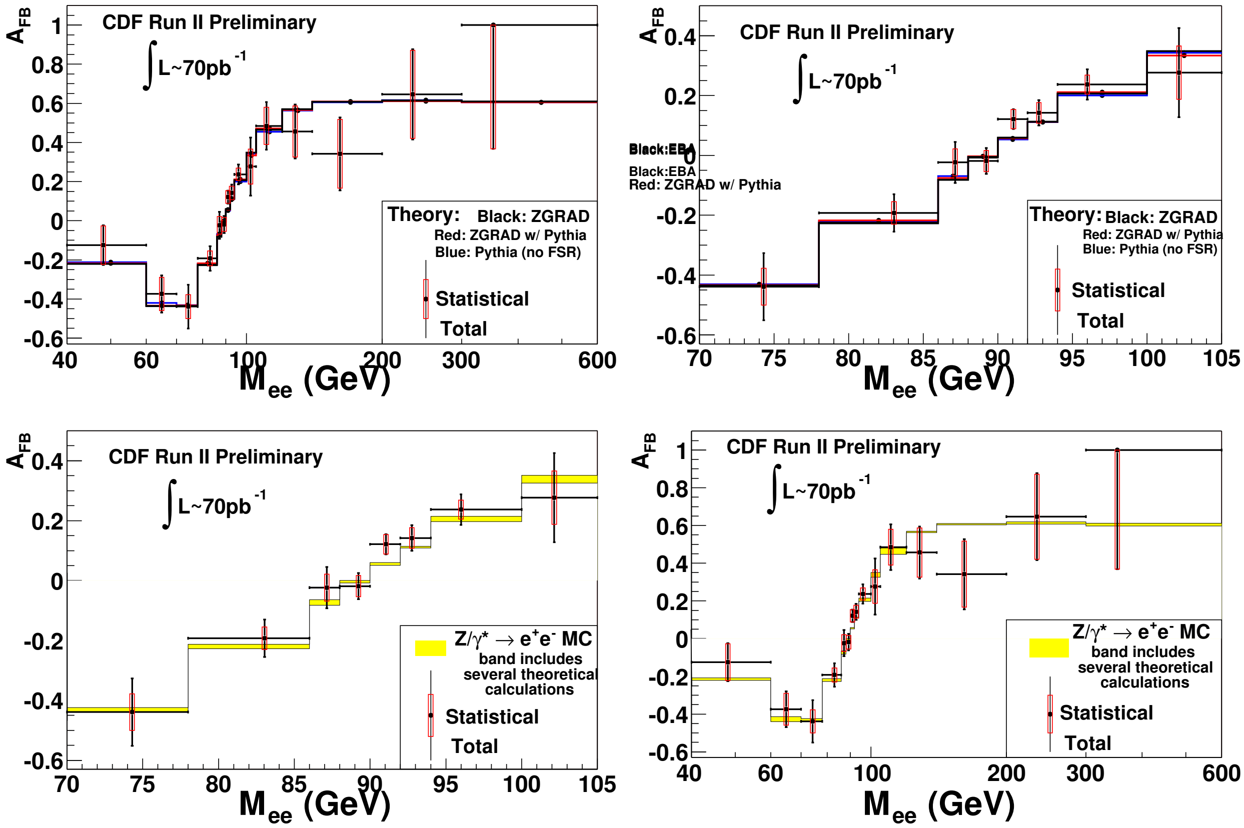

Figure 11: The top figure shows forward-backward asymmetry as a function of the dilepton invariant mass for the ZGRAD EBA stand alone calculation (black), and the ZGRAD electroweak no final-state radiation stand alone calculation (also in black and almost indistinguishable, on this plot, from the EBA line), ZGRAD EBA with P_T obtained from PYTHIA (red or light-colored), and PYTHIA stand-alone (blue). No QED final state radiation is included in these samples. The differences in these calculations and Monte Carlo statistical uncertainties are included in boxes in the bottom figure.

cussion. His implementation of WGRAD for CDF provided a pattern for our work.

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A Getting Up and Running with ZGRAD

In a later version of the note we may include some operational details in this appendix. For now, please refer to http://www-cdf.fnal.gov/internal/people/links/AdamGibson/zgrad/ .