Understanding Light: Why We Need a Terascale Photon Collider

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We do not understand light. I argue that a terascale photon collider is necessary to determine the structure of the photon at 100 GeV. Uncertainties in photon parton distribution functions lead to cross section predictions that vary by a factor of 5. This limits our ability to predict how well we can perform precision measurements, e.g., extracting the width of Higgs into two photons. These uncertainties will only be resolved by measuring the gluonic structure of the photon *in situ*.

1. INTRODUCTION

A compelling motivation for a construction of a photon collider is the precision measurement of electroweak observables [1]. In particular, two of the most important are the measurement of the Higgs total width, and the width of Higgs into two photons. The later is directly proportional to the cross section through two photons, and hence a measure of the cross section is a measure of the partial width. A complete study of the cross section into two b jets ($\gamma\gamma \to h, A \to bb$) is presented at this workshop [2]. That analysis contains a full NLO treatment of backgrounds, a realistic photon spectrum, and detector simulation. They estimate that the "resolved" hadronic component of photons contributes about 15% to the background to Higgs production at a mass of 120 GeV. In this analysis, I demonstrate that the normalization and shape of this resolved-photon background to Higgs production are only known to a factor of 3–4. Hence, the photons are interesting in themselves, and not just as a tool to probe other physics.

The complete study of resolved photons near threshold is difficult to model properly. However, a simple leading order (LO) analysis of bb-dijet production is enough to quantify the uncertainties described in Sec. 2 below. We begin by plotting in Fig. 1 the bb-dijet cross section as a function of bb-invariant mass M_{bb}. The events were generated using a flat photon energy spectrum [2] of 25–200 GeV/beam. This is a good approximation to the full non-linear spectrum coming from photons back-scattered off of 250 GeV electrons. The two b jets each have $E_{Tb} > 40$ GeV, $|\eta_b| < 4$, and a separation $\Delta R > 0.1$. Looser cuts would slightly increase the $\gamma\gamma$ contribution near 80 GeV, but would greatly increase the γg contribution.

The lowest solid curve in Fig. 1 is the distribution for the "direct" collision of two real photons $\gamma\gamma \to b\bar{b}$. Rising above the real photon contribution is a large peak at the Z mass coming from resolved-resolved quark annihilation into

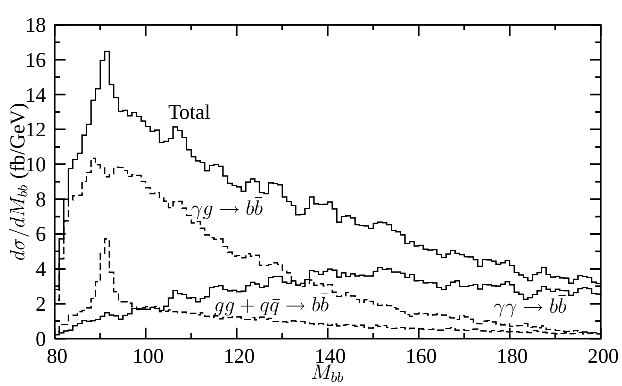

Figure 1: Breakdown of contributions to the bb-dijet cross section vs. dijet invariant mass M_{bb}.

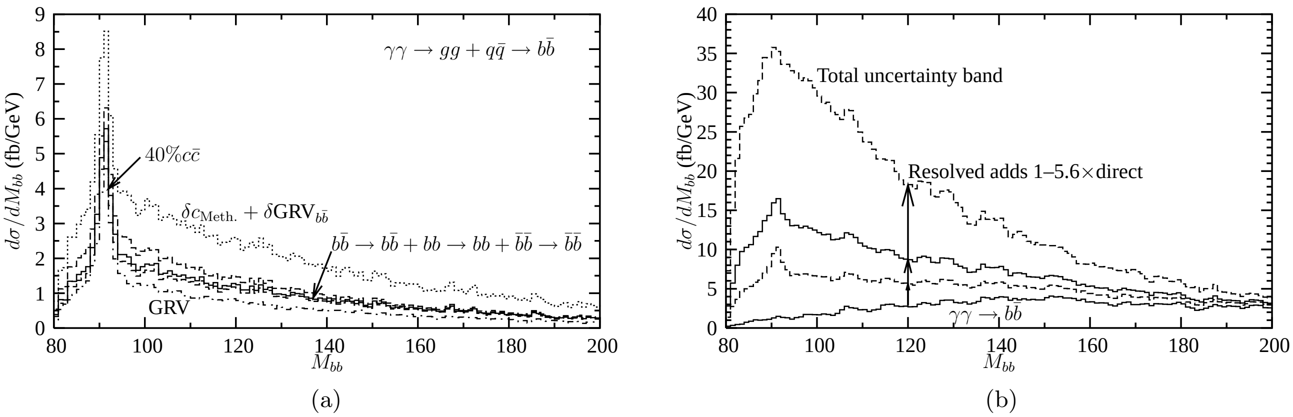

Figure 2: (a) Uncertainty in the resolved-resolved contribution to bb-dijet cross section vs. dijet invariant mass M_{bb}. (b) Range of theoretical predictions for bb-dijet cross section vs. dijet invariant mass M_{bb}.

a real Z boson. These quarks (and also gluons) come from hard interactions that "resolve" the hadronic structure of the photon. Both contributions are swamped by the single-resolved cross section from photon-gluon fusion $\gamma g \to b\bar{b}$. This is a generic feature at any photon collider where the final state invariant mass is less than $\sim W_{\max}/3$. Hence, a 120 GeV Higgs at a 500 GeV ee collider, which produces a $\gamma\gamma$ collider with $W_{\max} \approx 400$ GeV, would have a huge background from resolved photons.

The concern that resolved photons would be a large background to Higgs production was pointed out in Ref. [7], but was expected to be reduced by careful tuning of the electron beam energy and creation of polarized photons. More recent studies [2] have found a flatter spectrum of photon energies than previously assumed, and NLO effects appear to reduce the usefulness of polarized photon beams in reducing the background.

2. LARGE UNCERTAINTIES IN THE bb-DIJET CROSS SECTION

I turn to the estimation of the uncertainties for the resolved photon cross sections due purely to our understanding of the photon parton distribution functions (PDFs). The bb cross section is calculated using the 8 auxiliary PDFs given by the CJK group, and the "modified tolerance method" [3] with the default CJK2 tolerance of 10 [4, 5].

The results for the resolved-resolved contribution are shown in Fig. 2(a). The solid line is the central value from Fig. 1, and the dashed lines are uncertainty in the prediction using the modified tolerance method. Based on this calculation alone, it would appear that the cross section is well-constrained. Also shown with dash-dots is the prediction of using the GRV LO [6] PDFs. We notice that the GRV prediction is far below the supposed lower limit of the uncertainty. This indicates that we should be careful in interpreting these uncertainties.

In order to get a better estimate of the uncertainty, I focus on two features of Fig. 2(a). First, 40% of the peak of the distribution comes from $c\bar{c}$ annihilation through the Z pole. Second, the long tail to high invariant mass is mostly due to rescattering of real b quarks from the photon ($b\bar{b} \to b\bar{b}$, $bb \to bb$, and $\bar{b}\bar{b} \to \bar{b}\bar{b}$). Both the c and b PDFs are significantly larger at large x than the GRV PDFs. Furthermore, it was shown [4] that even at 4 GeV, the tolerance method used to produce the PDFs begins to diverge from a more accurate Lagrange multiplier result — implying that the some of the underlying assumptions used to calculate the PDF uncertainties are questionable. Therefore, a dotted curve also appears on Fig. 2(a) that estimates a rough upper limit on the error based on the difference between the GRV and CJK2 results. This corresponds to about a 50% uncertainty near the Z peak, and a factor of 2 in the tail.

While the uncertainty in the resolved-resolved cross section is interesting, the dominant cross section came from direct-resolved collisions. Unfortunately, the gluon is barely constrained. Much of this has to do with the need to subtract nonperturbative physics at low energy scales in order to get at the perturbative partons. One result is that the tolerance parameter T increases to over 100 for the g PDF near 100 GeV. This leads to at least a factor of 3 uncertainty in the $\gamma g \to b\bar{b}$ cross section.

Putting this all together, we see in Fig. 2(b) that the theoretical prediction for the bb-dijet cross section ranges from 5–20 fb/GeV at 120 GeV. In this figure I have used the tolerance method results, but a more conservative result would combine the differences between PDF fits to predict something like 3–25 fb/GeV. The uncertainties themselves are only approximate, given the poor PDF fits to the data.

The large uncertainty in the bb-dijet cross section should not be surprising. Measurements from experiments at both the HERA collider at DESY [8] and the LEP collider at CERN [9] exhibit a factor of 2–3 excess of events over the NLO theoretical predictions. It seems likely that at least a part of this excess may be attributed to a larger than expected gluon PDF. This can easily be determined at a real photon collider with cuts like those above, that give cross sections dominated by photon-gluon fusion.

3. CONCLUSIONS

The difficulty in predicting the bb-dijet cross section presents an exciting opportunity. Given the dominance of the photon-gluon fusion cross section, the first measurement of b production can quickly pin down the elusive gluonic component of the photon. If the Z peak can be observed, the charm PDF can also be pinned down. The b PDF might be measured from the resolved-resolved tail above the Z peak. One experimental challenge will be distinguishing charm quarks that fake b jets, but demanding two b tags may suppress it enough to pull out the physics. Once these PDFs are measured, an accurate measurement of the Higgs coupling to two photons can be made.

In this paper I have focused on a photon-photon collider, but another option may be to use a photon-electron collider to measure the photon structure. It is more difficult to cleanly extract the gluon PDF in a γ–e collision than a γ–γ collision, because the cross section at high invariant mass ($>$ 20 GeV) is smaller, the decay products tend to be boosted more forward into less-well instrumented regions of the detector, and an additional deconvolution must be performed to remove the effect of extracting an almost-real photon from the electron. Nevertheless, this option should be examined in detail as it may be simpler to construct a γ–e collider.

Today we do not understand light, but with a terascale photon collider, we will.

Acknowledgments

This work was supported by an FY2005 grant from the Argonne Theory Institute, and by the U. S. Department of Energy under Contract No. W-31-109-ENG-38.

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