# $\Gamma_{ee}$ Paper Summary (for Paper Committee, not PRL)

## 1 The Goal

To measure $\Gamma_{ee}$, I will need to produce very accurate plots of $\Upsilon$ cross-section versus beam energy (lineshape scans). To get $\Gamma_{ee}$, I can fit the following function to the scans:

$$\sigma_{\text{apparent}}(E) = (\text{Breit-Wigner} \otimes \text{Radiative corrections} \otimes \text{Beam-energy resolution}) + \text{backgrounds} \quad (1)$$

where $\otimes$ is a convolution operator. Extracting the area of the Breit-Wigner, I can relate it to $\Gamma_{ee}$ through

$$\Gamma_{ee} = \left(\frac{{M_\Upsilon}^2}{6\pi^2}\right)(\text{area of the Breit-Wigner}). \quad (2)$$

The data for these scans are in the CLEO-III database (approximately November 2001 – September 2002), but what I need to do is produce a convincing argument that I know the $\Upsilon$ cross-section at every point very well. By "knowing well," I mean both that the uncertainty is small and that the argument justifying the uncertainty is rigorous. (This is why I had difficulty quoting partial results for the past few years: I didn't have a rigorous argument for even a large uncertainty.)

(To avoid large backgrounds that can distort the lineshape, I measure the hadronic cross-section and multiply by $(1 - 3\mathcal{B}_{\mu\mu})$. Although this features prominently in the PDG's description of this measurement (page 837 in the big orange book), it is a technical detail. Quoting the hadronic version of $\Gamma_{ee}$, written as $\Gamma_{ee}\Gamma_{\text{had}}/\Gamma_{\text{tot}}$, is a way of avoiding dependence on lepton universality until the last step. Even before Istvan's measurement, the fractional uncertainty in $(1 - 3\mathcal{B}_{\mu\mu})$ was only about half a percent.)

## 2 Relative and Absolute Cross-Section

I will break this argument into two parts. First, I argue that I understand the fractional differences in cross-section from one energy point to the next (this gives me lineshapes that I can fit), and I call this the relative cross-section. Second, I will argue that I understand the normalization of all energy points (to translate my fit result into the true area of the Breit-Wigner, and therefore the true $\Gamma_{ee}$). I call this the absolute cross-section.

These two arguments have been interleaved somewhat in the paper because they share a lot of technology. (The primary consideration in organizing the paper was to make it causal: I must never use terms that I haven't yet defined.) The luminosity calibration (turning a number of counts into a number of inverse nanobarns) and hadronic efficiency measurement are always absolute cross-section issues: the first sets the vertical axis in the lineshape scan plots and the second translates a fitted Breit-Wigner area into a true Breit-Wigner area. Backgrounds are an issue for relative cross-sections (subtracting the right amount from every run) and an issue for absolute cross-sections (subtracting the right amount from the data used to compare/check the hadronic efficiency measurement).

Once I believe that there are no backgrounds in my count of hadrons (other than what will be subtracted in the fit) or in my count of gamgams ($e^+e^- \to \gamma\gamma$), and that the efficiency of each of these is constant with respect to run number/energy, I can calculate relative cross-sections. I do this in the simplest way possible:

$$\sigma_{\mathrm{relative}} = \frac{\#\ \mathrm{hadrons}}{\#\ \mathrm{gamgams}} \times 1/s. \tag{3}$$

(The factor of $1/s$ is the "beam-energy correction.") The units of $\sigma_{\mathrm{relative}}$ are related to inverse nanobarns by a factor that can be determined by comparing my continuum gamgam count with a standard luminosity measurement for these events.

Here is how the two arguments figure into each chapter:

4. **Event Selection Criteria:** I define event types that I will count, preceded by motivation for why I need to count them. This is foundational, necessary for both arguments.

5. **Datasets, Scale Factors and Backgrounds:** This is where I describe the data that are available to me (datasets), how background samples are normalized before subtraction (scale factors), and what these scale factors imply about the size of the backgrounds I'm subtracting (backgrounds). The "database dataset" will be used to create

the lineshape scans, so scale factors and backgrounds in this dataset are important for the relative cross-section. The "unfiltered dataset" will be used in the argument justifying hadronic efficiency, so everything related to this dataset is relevant for absolute cross-section.

6. **Signal Monte Carlo:** It seemed to me that I should have a Monte Carlo chapter, so that I could defer Monte Carlo discussion to one place. (When I wrote it (last), I could find little to say, so this chapter has a dubious future.) Monte Carlo will only ever be relevant for absolute cross-section: for hadronic efficiency and for luminosity calibration.

7. **Upsilons from Di-Pion Cascades:** This is a special technique for measuring hadronic efficiency, which compliments the use of the unfiltered dataset. It therefore only concerns the absolute cross-section.

8. **Trigger Efficiency:** This chapter is split into two sections. The first is a set of in-depth studies of the trigger efficiency for hadrons, which is for absolute cross-section. The second is a study of how the trigger for gamgams varies from one run to the next, which is strictly for relative cross-section.

9. **Signal Efficiency:** Here is where I use the unfiltered dataset and collect what I have learned from the Di-Pion Cascades and Trigger studies to quote a final hadronic efficiency. It's for absolute cross-section.

10. **Search for Gamgam Backgrounds:** I chose to measure relative luminosity by counting gamgams because $\Upsilon \not\to \gamma\gamma$. But, in principle at least, $\chi_b$ can decay to $\gamma\gamma$ and $\Upsilon$ can decay to $\chi_b\gamma$, where the third photon is very small ($\sim$100 MeV). These three-photon events might be an energy-dependent background to the gamgam count, so I searched for them. I didn't find any.

11. **Run-by-Run Dependence of Hadronic Cross-Section:** This is a battery of tests to check for any bad runs that would distort the relative cross-section. The first two are concerned with the CC counting gamgams while the DR has ceased to count hadrons, and vice-versa. The rest are sanity checks of relative hadronic cross-section: it should be constant during each run, and constant for constant beam energy.

12. **Lineshape Fitting:** All that I need to fit the lineshapes, measure systematic errors in the lineshape, and determine if the beam energy calibration is varying during a scan is the relative cross-section. I've just completed this study and I'm writing it up now.

13. **Luminosity Calibration:** This is not yet written— I need to reconnect with Surik about the CLEO-III luminosity measurement. It's the last step in the absolute cross-section measurement which will translate my fit results into $\Gamma_{ee}$.

# 3 A summary of Hadronic $\Upsilon$ Counting

This involves only the database dataset and yields only relative cross-sections.

To make them easily understood, I made the hadronic cuts as loose and as simple as possible. A hadronic event must pass

- any relevant trigger line,
- the event vertex must be close to beamspot (cut well beyond $5\sigma$),
- $e^+e^-$ and $\mu^+\mu^-$ are rejected with a cut on the largest track momentum (very stable),
- two-photon and junk are rejected with visible energy $>$ 40% the center-of-mass energy (carefully studied), and
- the level 4 trigger, $\mathrm{L4}_{\mathrm{dec}}$ (very efficient after everything else).

These cuts were designed to be highly efficient for $\Upsilon \to$ hadrons; their efficiency for continuum hadrons is unknown. To gauge how the efficiency for continuum hadrons changes with beam energy, I fit for its dependence on the three continuum points (in Chapter 12, not yet written).

I count the number of hadrons in each run, the number of beam-gas events, and the number of cosmic rays. Because I have samples of no-beam and single-beam data (Chapter 5), I can translate these beam-gas and cosmic ray counts into a number of beam-gas and cosmic ray events expected to feed into my raw hadron count. The beam-gas background is small (0.3%) but poorly measured (it looks like two-photon events feed into my beam-gas cuts: Figures 5.2 and 5.6-b), and the cosmic ray background is somewhat larger (0.5%) and well-measured. Therefore, in subtracting non-beam-beam backgrounds from my hadron count, I apply all of the cosmic ray correction, propagating statistical errors only, and 50% $\pm$ 50% of the beam-gas correction. This is "# hadrons" in Equation 3 (of this document).

For relative luminosities, I count a subset of gamgams, avoiding regions with tiles that are unresponsive for part of the $\Upsilon$ running, so that the trigger efficiency is constant. I assume that the trigger efficiency is the only gamgam cut that may be susceptible to run-by-run variations: the rest are cuts on the geometry of the two largest showers (hot showers are not rejected) and a lower bound on the second-biggest shower energy. (An upper bound might suffer from intermittent inefficiencies if the photon lands in a noisy crystal. I haven't checked for the possibility that some crystals may intermittently fail to read out, but Brian assured me that this is remote.) In Chapter 10, I search for a background to gamgam counting, but don't find it. The raw gamgam count is "# gamgams" in Equation 3 (of this document). (I don't explicitly apply the run-by-run trigger efficiency correction described on page 75 for a technical reason.)

For every energy point, I calculate $\sigma_{\text{relative}}$ (for the continuum and high-energy points far from the resonance, I combine all available data). The background level is meaningless but allowed to float in the fit (and it is very well measured with 0.1 fb$^{-1}$ of data). The vertical scale is meaningless until luminosity is calibrated, and the areas of the $\Upsilon$ peaks need to be corrected for hadronic efficiency.

# 4 A Summary of the Hadronic Efficiency Measurement

This is the most difficult part of the work because a priori, half of all $\Upsilon$ decays might be to neutrinos, and if I didn't know that, $\Gamma_{ee}$ would be wrong by a factor of two. There are three major parts:

1. the study of $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ (di-pion cascades), which is used to put limits on these invisible decays in the form of "validity errors" on the Monte Carlo (Chapter 7).

2. Extra studies of $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ trigger efficiency, because the cascades study isn't conclusive enough. (While the cascades study

would find invisible decay modes, it can't be trusted to measure the details of the trigger, only an upper and a lower limit. Technical issue: if TriggerData were available after pass2, it would be possible.) This is the first of two sections in Chapter 8.

3. Comparisons of the unfiltered dataset with Monte Carlo, to argue that the validity of the Monte Carlo measured in $\Upsilon(1S)$ through cascades applies to the $\Upsilon(2S)$ and $\Upsilon(3S)$ as well. Here I explicitly assume that the invisible decays that prompted me to do the cascades study aren't peculiar to the $\Upsilon(2S)$ and $\Upsilon(3S)$. This is part of Chapter 9: the rest is a combination of these results and a summary.

The di-pion cascades study is an inclusive search for $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$, where very stringent requirements are placed on the two pions to guarantee that the event passed trigger and database filters solely because of the pions: the $\Upsilon(1S)$ can decay any way it likes. In choosing the two pion combination, I don't take the pair of tracks whose recoil mass is closest to $M_{\Upsilon(1S)}$, but randomly choose from those that are within 20 MeV of $M_{\Upsilon(1S)}$. This way, I can be sure that the combinatoric background is flat under the peak, and I fit it with a set of orthogonal polynomials. This fit is used to normalize the sideband events before subtracting them from the peak events, yielding unbiased distributions of $\Upsilon(1S)$. The fit uncertainties are a source of systematic error.

The cascades study was performed twice, with two datasets: a "little" dataset, which required the TwoTrack trigger (two tracks and a prescale), and a "big" dataset, which required the Hadron trigger (three tracks and a 150 MeV shower). The little cascades study is completely unbiased, and the big study requires that the $\Upsilon(1S)$ generated one track and a 150 MeV shower. This is actually desirable, since I want to measure cut efficiencies given the trigger, and this one track, one shower requirement is a necessary condition for the trigger. For a sufficient condition, to bound the trigger efficiency between a necessary and a sufficient condition, I had to do more work. This got complicated.

The bottom line for the cascades study was a comparison of data and Monte Carlo cut efficiencies for each of the cuts described on page 4 (of this document), applied cumulatively. Monte Carlo was generated for the di-pion mode and passed through all the same machinery as data. A "validity error" was assigned to each cut by adding the data–Monte Carlo difference to their errors in quadrature. Because of the large validity error for the trigger, and the fact that there were technical difficulties in defining it, I leave the trigger efficiency for the following chapter. The rest of the validity errors are added as systematic errors in the efficiency measurement, except for the cuts on visible energy and $L4_{dec}$, which are handled in a special way that I will describe later.

The trigger efficiency is studied by dividing the trigger into a tracking part and a calorimeter part. For the calorimeter part, I accept events using only the TwoTrack trigger, and then compare data and Monte Carlo efficiencies. Again, the systematic error is taken to be the data–Monte Carlo difference plus errors in quadrature. For the tracking part, there is no unbiased neutral trigger in CLEO-III, so I study the trigger efficiency by modeling it in a toy Monte Carlo. Input distributions to this toy Monte Carlo are varied to quantify all the systematic errors. Finally, I also plot data/Monte Carlo overlays of the four variables that are used in the trigger decision as a sanity check. Their distributions agree moderately well, and I have already claimed a trigger uncertainty which is 3 times its inefficiency.

The unfiltered dataset used to extend the $\Upsilon(1S)$ validity errors to the $\Upsilon(2S)$ and $\Upsilon(3S)$ is a set of runs that I have pass2'ed myself. I do this because events in the database have been filtered according to event type, and I want to do a fair data/Monte Carlo comparison. (This also gives me access to TriggerData, which I use to plot trigger variables in Chapter 8.) I subtract continuum, beam-gas, and cosmic rays from these datasets (this procedure is described in Chapter 5, with the other background subtractions), and overlay data and Monte Carlo for each cut variable, cumulatively.

The "special way" that the visible energy and $L4_{dec}$ cut efficiencies are measured also partially involves the unfiltered dataset. The fraction of events that fail the 40% visible energy cut is the sum of those that fail 0–30% and those that fail 30–40%. Because of large two-photon backgrounds in the 0–30% region (which are particularly hard to control because they upset the $1/s$ scaling in the continuum subtraction), the di-pion cascade study is preferred for measuring this part of the spectrum. Because the 30–40% part is significantly non-zero ($0.5\% \pm 0.1\%$) and varies a little from resonance to resonance, this part should be measured in the unfiltered dataset. These two disjoint contributions are added together. Since $L4_{dec}$ is very efficient after all other cuts ($100\% \pm 0.03\%$), it is simply measured by counting failures in the unfiltered dataset.

These efficiencies and systematic errors, derived from different techniques, are all combined in Tables 9.5 and 9.6.