Search for the $B^+ \to \eta\ell^+\nu$ decay

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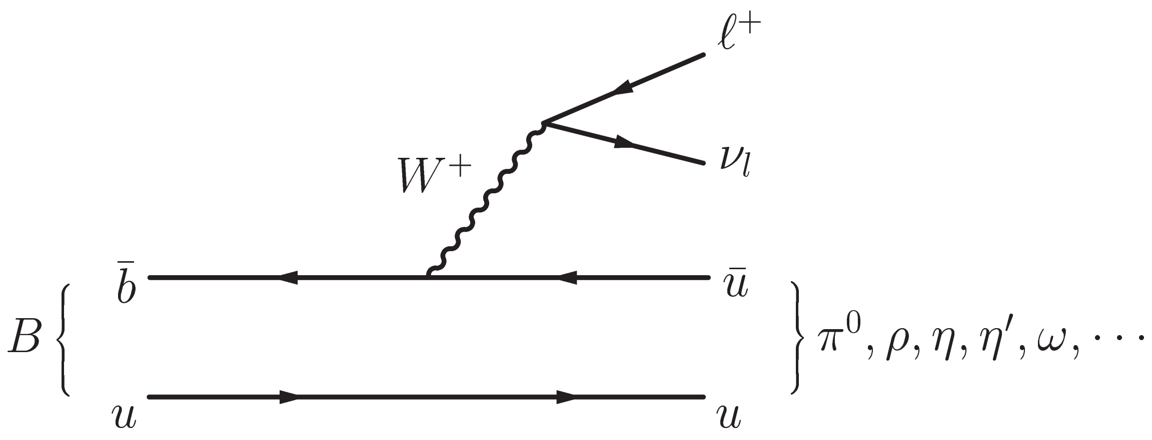
Introduction



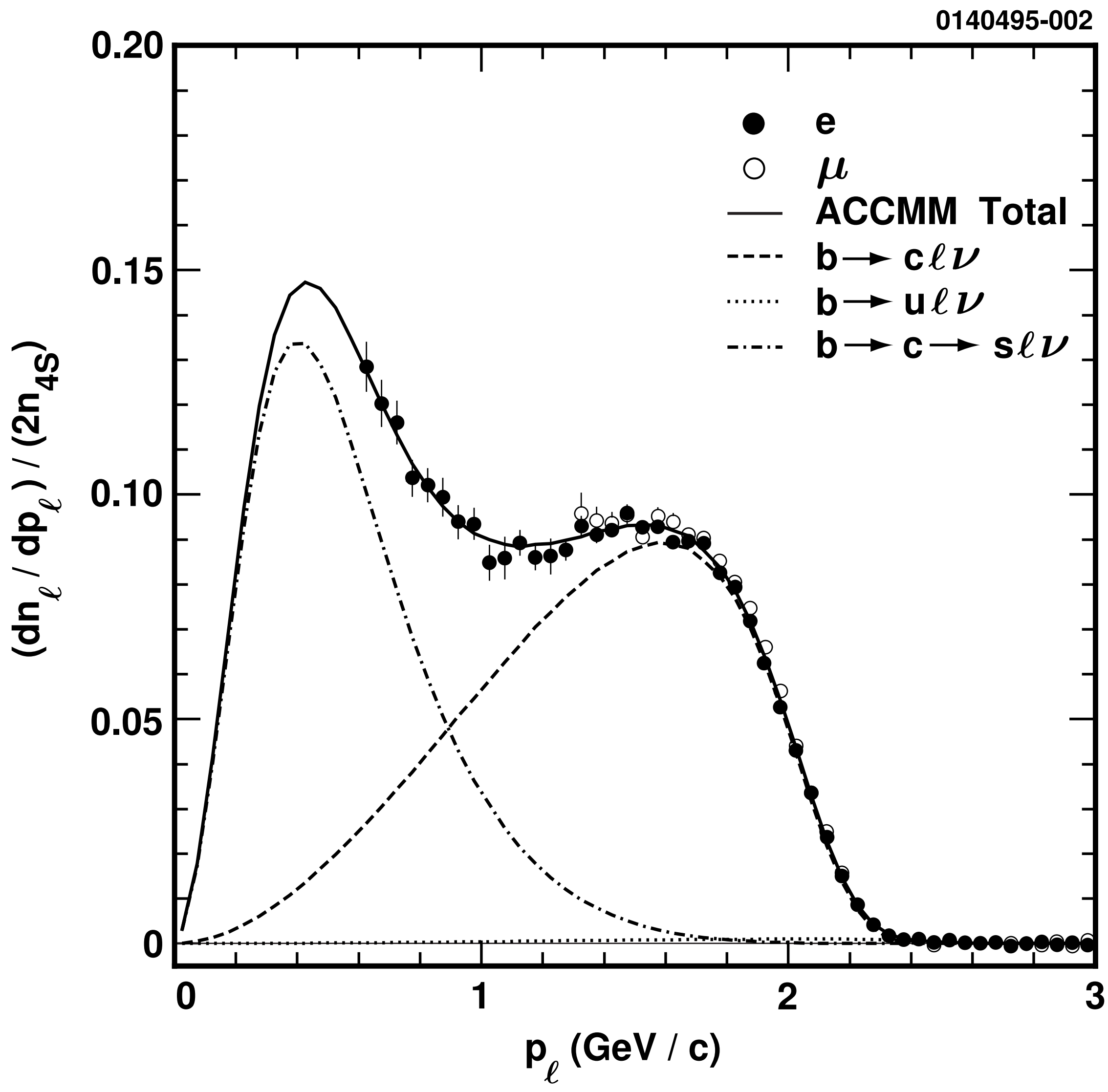
Quark level diagram for the decay $B^+ \to X_u \ell^+ \nu$

- The decay $B^+ \to \eta \ell^+ \nu$ is mediated by the highly suppressed transition $b \to u \ell \nu$. This decay is therefore sensitive to V_{ub}, the CKM element coupling the b and u quarks.

- Unlike the $b \to c \ell \nu$ decays which are dominated by $B \to \{D, D^*\} \ell \nu$, the X_u in $b \to u \ell \nu$ decays can be any mesons in the $u\bar{u}$ spectrum.

☞ Free quark estimate gives

$$\frac{\Gamma(b \to u\ell\nu\,)}{\Gamma(b \to c\ell\nu\,)} = (1.8 \text{ to } 2.5)|\frac{V_{ub}}{V_{cb}}|^2 \simeq 0.01 \text{ to } 0.02$$



The inclusive lepton momentum spectrum for semileptonic B decays

☞ CLEO has measured the decays $B^0 \to \rho^- \ell^+ \nu$ and $B^0 \to \pi^- \ell^+ \nu$:

$$\mathcal{B}(B^0 \to \rho^- \ell^+ \nu) = (2.57 \pm 0.29^{+0.33}_{-0.46} \pm 0.41) \times 10^{-4}$$
$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.8 \pm 0.4 \pm 0.3 \pm 0.2) \times 10^{-4}$$

☞ $B^+ \to \eta \ell^+ \nu$ is complementary to $B \to \{\rho, \omega, \pi\} \ell \nu$ analyses.

☞ ISGW2 (a form factor model) predicts:

$$B(B^+ \to \pi^0 \ell^+ \nu) = 1.1 B(B^+ \to \eta \ell^+ \nu)$$
$$B(B^0 \to \pi^- \ell^+ \nu) = 2.1 B(B^+ \to \eta \ell^+ \nu)$$

Testing these predictions and eventually measuring $d\Gamma/dq^2$ in $B^+ \to \eta \ell^+ \nu$ can provide valuable information on the form factors governing $b \to u \ell \nu$ decays, and hence lead to a reliable value of V_{ub}.

Sources of Background

☞ There are a number of sources of background.

- $b \to c\ell\nu$
- continuum
- fake η
- fake lepton
- other $b \to u\ell\nu$

☞ The cuts are optimized using three event samples:

- $B \to \eta\ell\nu$ signal Monte Carlo
- $b \to c\ell\nu$ Monte Carlo
- $e^+e^- \to q\bar{q}$ continuum data sample

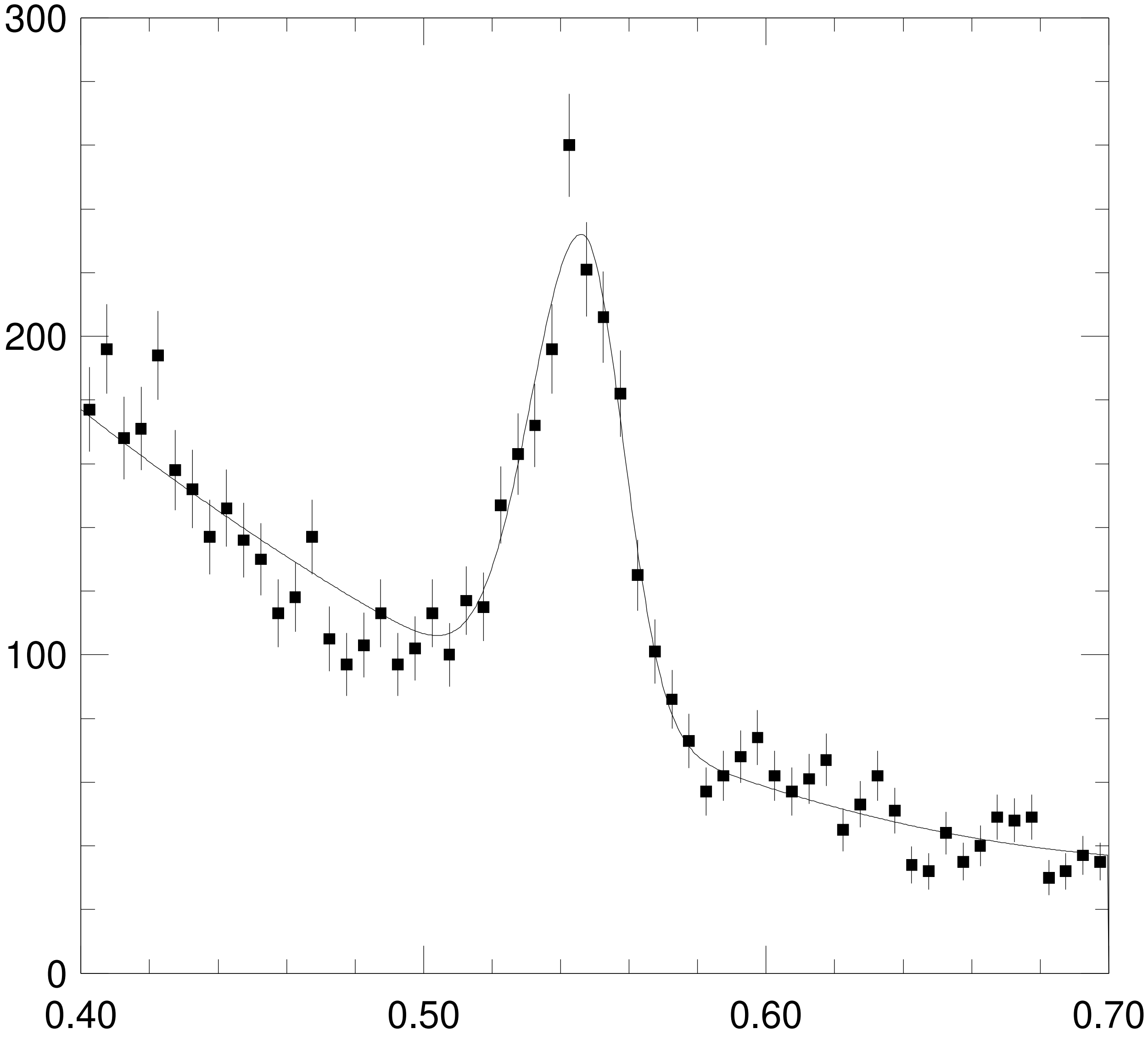
Event Selection

Technical Cuts

- Charged tracks must be well measured and originated at IP.
- Electrons are identified using dE/dx information and the ratio E/p. Where E is the calorimeter energy and p is the momentum measured in the drift chamber.
- Muon candidates are required to match the hits through at least five absorption length of iron.

η Candidates

- We use $\eta \to \gamma\gamma$ mode in the analysis.
- The η momentum is required to be greater than $1\mathrm{GeV}/\mathrm{c}$ to remove combinatorial background.
- π^0's are vetoed



The invariant $\gamma\gamma$ mass spectrum for CLEO $\Upsilon(4s)$ DATA after all the cuts have been applied.

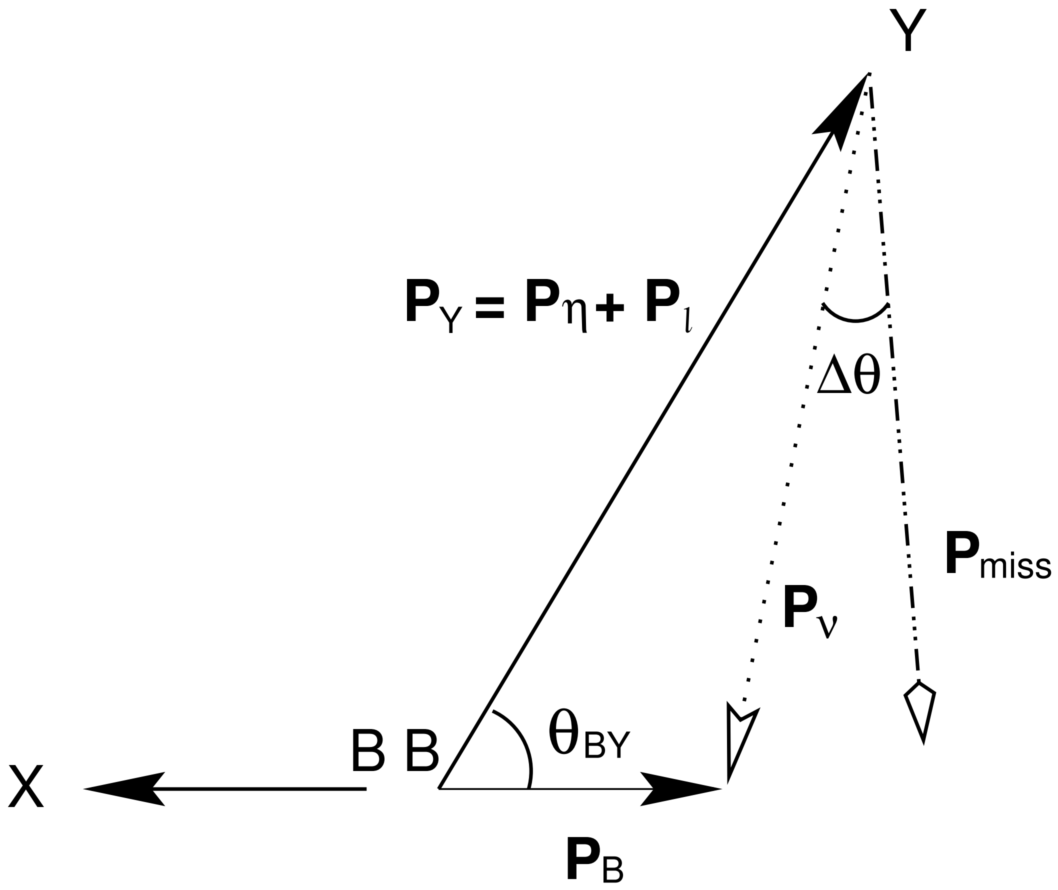
$B\bar{B}$ Events Selection

☞ $B\bar{B}$ events are spherical and $e^+e^- \to \tau^+\tau^-$ and $e^+e^- \to q\bar{q}$ backgrounds are jetty. We use shape variables to reduce jet-like continuum background.

Physics Cuts

☞ The momentum of primary lepton is required to be greater than $1.4\mathrm{GeV}/c$.

☞ $\cos\theta_{BY} = \dfrac{2E_B E_Y - M_B^2 - M_Y^2}{2|\boldsymbol{p_B}||\boldsymbol{p_Y}|}$



The Fisher Discriminant

☞ Given a set of N input variables, x_i, for both signal and background, we combine them into one, the Fisher discriminant $\mathcal{F}$, which has the best separation between signal and background:

$$\mathcal{F} = \sum_{i=1}^{N} \alpha_i x_i$$

where coefficients α_i can be calculated using large Monte Carlo samples:

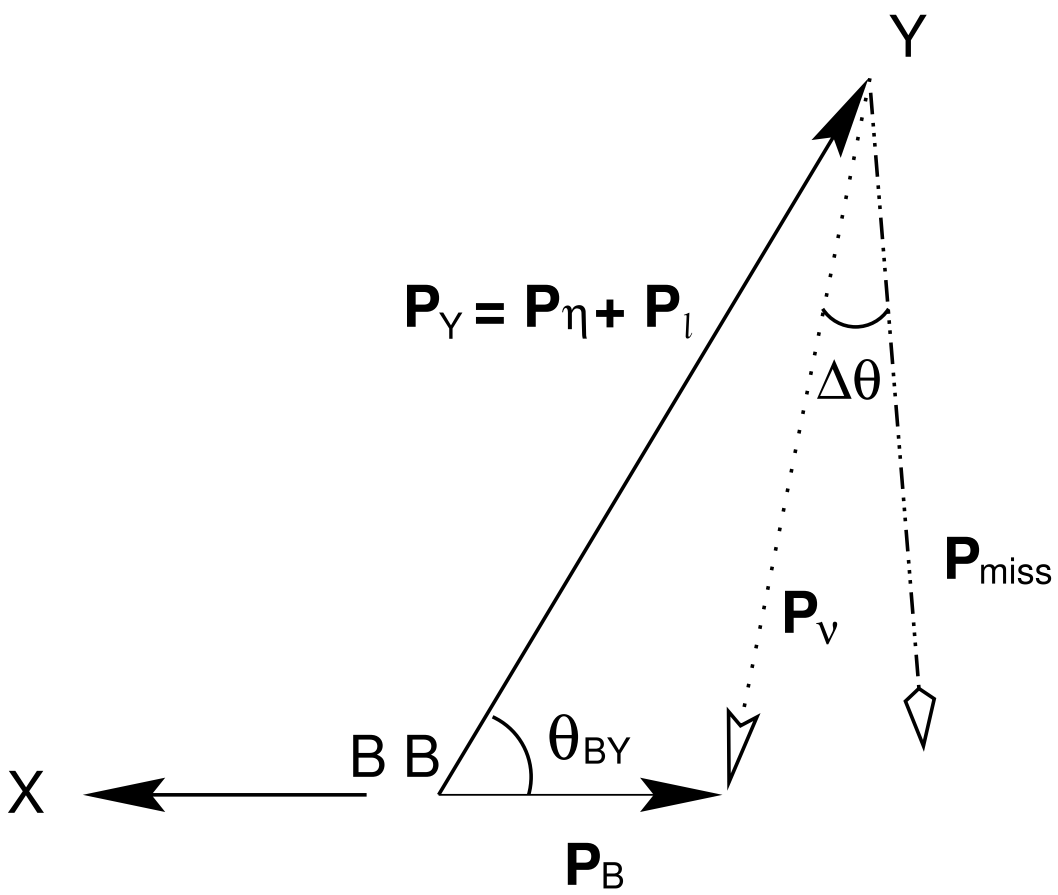
$$\alpha_i = \sum_{j=1}^{N} (U^S + U^B)^{-1}_{ij} \times (\mu^S_j - \mu^B_j)$$

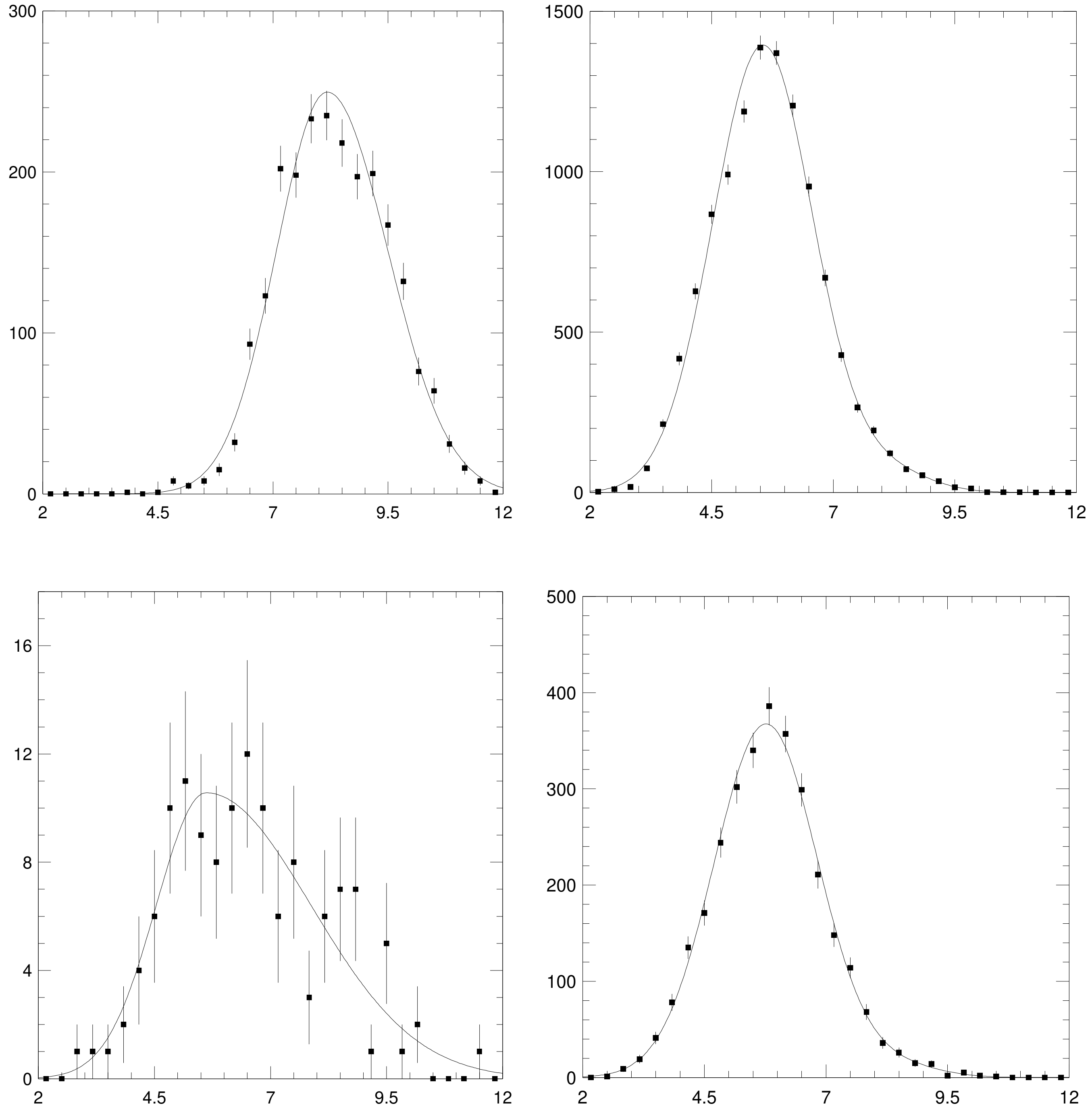
where U^S and U^B are the covariance matrices for the signal and background, and μ^S and μ^B are the corresponding mean values.

☞ We calculate the Fisher discriminant to achieve the maximal separation between signal and $b \to c\ell\nu$ background.

☞ Input variables:

- p_η, the momentum of the η
- p_ℓ, the momentum of the primary lepton.
- $\Delta\theta$, the angle between the direction of the missing momentum, $\boldsymbol{p}_{miss}$, and the momentum needed to close the $B - Y$ triangle.
- M^2_{miss}, the missing mass





The $\mathcal{F}$ discriminant for signal, $b \to c\ell\nu$, continuum and fake η

Maximum Likelihood Fit

- We extract signal yields from the data by performing an unbinned maximum likelihood (ML) fit, which increases the analysis efficiency since many cuts are unnecessary.
- Given a set of N events, each characterized by m observables $\boldsymbol{x}^i$, we would like to get an estimate for a set of θ parameters $\boldsymbol{P}$, such that the probability densities for observing each event is maximal.
- The likelihood function is defined as:

$$\mathcal{L}(\boldsymbol{P}, \boldsymbol{x}) = \prod_{i=1}^{N} \Gamma(\boldsymbol{P}, \boldsymbol{x}^i)$$

  The estimate of $\boldsymbol{P}$ is found by maximizing the likelihood function $\mathcal{L}$.
- The probability density function (PDF) of the i^{th} event, $\Gamma(\boldsymbol{P}, \boldsymbol{x}^i)$, is given by:

$$\Gamma(\boldsymbol{P}, \boldsymbol{x}^i) = \sum_{j=1}^{\theta} P_j \Gamma_j(\boldsymbol{x}^i)$$

☞ Observables ($m = 3$)

- M_B, the mass of the B meson
- ΔE, the difference between the beam energy and the energy of the candidate B meson:

$$\Delta E = E_{beam} - E_\eta - E_\ell - |\boldsymbol{p}_{miss}|$$

- $\mathcal{F}$, the Fisher discriminant

☞ Parameters ($\theta = 5$)

- P_{sig}: the fraction of signal events
- $P_{c\ell\nu}$: the fraction of $b \to c\ell\nu$ events
- P_{cont}: the fraction of continuum events
- $P_{u\ell\nu}$: the fraction of $b \to u\ell\nu$ events
- P_η: the fraction of fake η events

☞ Constraints on parameters:

- $P_{sig} + P_{c\ell\nu} + P_{cont} + P_{u\ell\nu} + P_\eta = 1$
- $P_{sig} + P_{c\ell\nu} + P_{cont} + P_{ulv} = \alpha = 0.43$

☞ PDF Calculation

- It's very difficult to obtain analytical PDF's in 3-D space. We use Monte Carlo events (continuum as well) to evaluate PDF's at each data point.
- We create a 3-D volume, V, centered on each data event and find how many Monte Carlo events fall into that volume. The probability that the data looks like the Monte Carlo in 3-D is then:

$$\Gamma_j(\boldsymbol{x}^i) = \frac{\sum \text{ of MC events in } V(\boldsymbol{x}^i)}{V(\boldsymbol{x}^i) \times N_j}$$

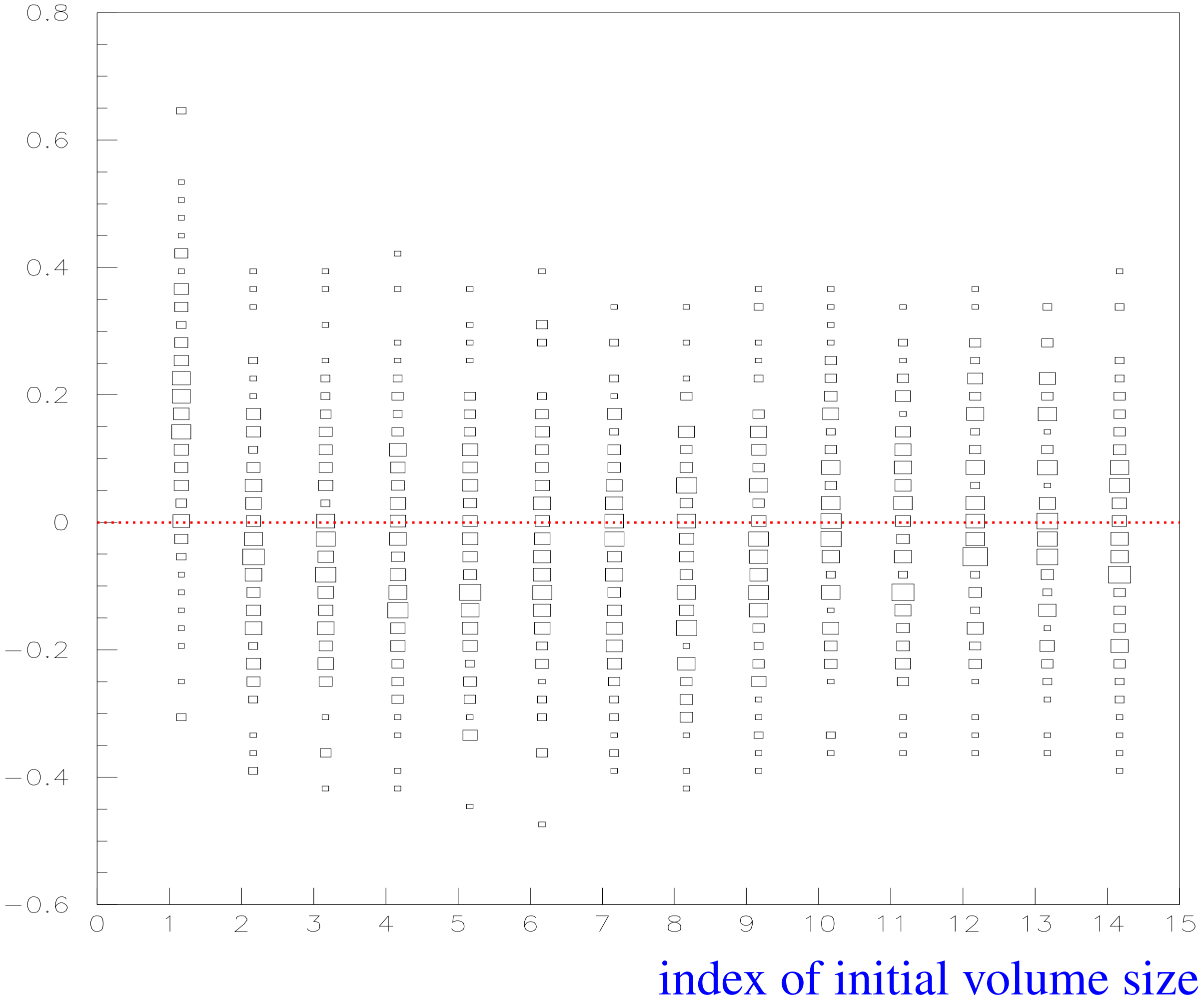
  where, N_j is the normalization, which equals to the total number of events in the Monte Carlo (or continuum data) sample.
- By centering the volume around the data point, a linear variation of PDF over the volume does not contribute any error to the fit result.

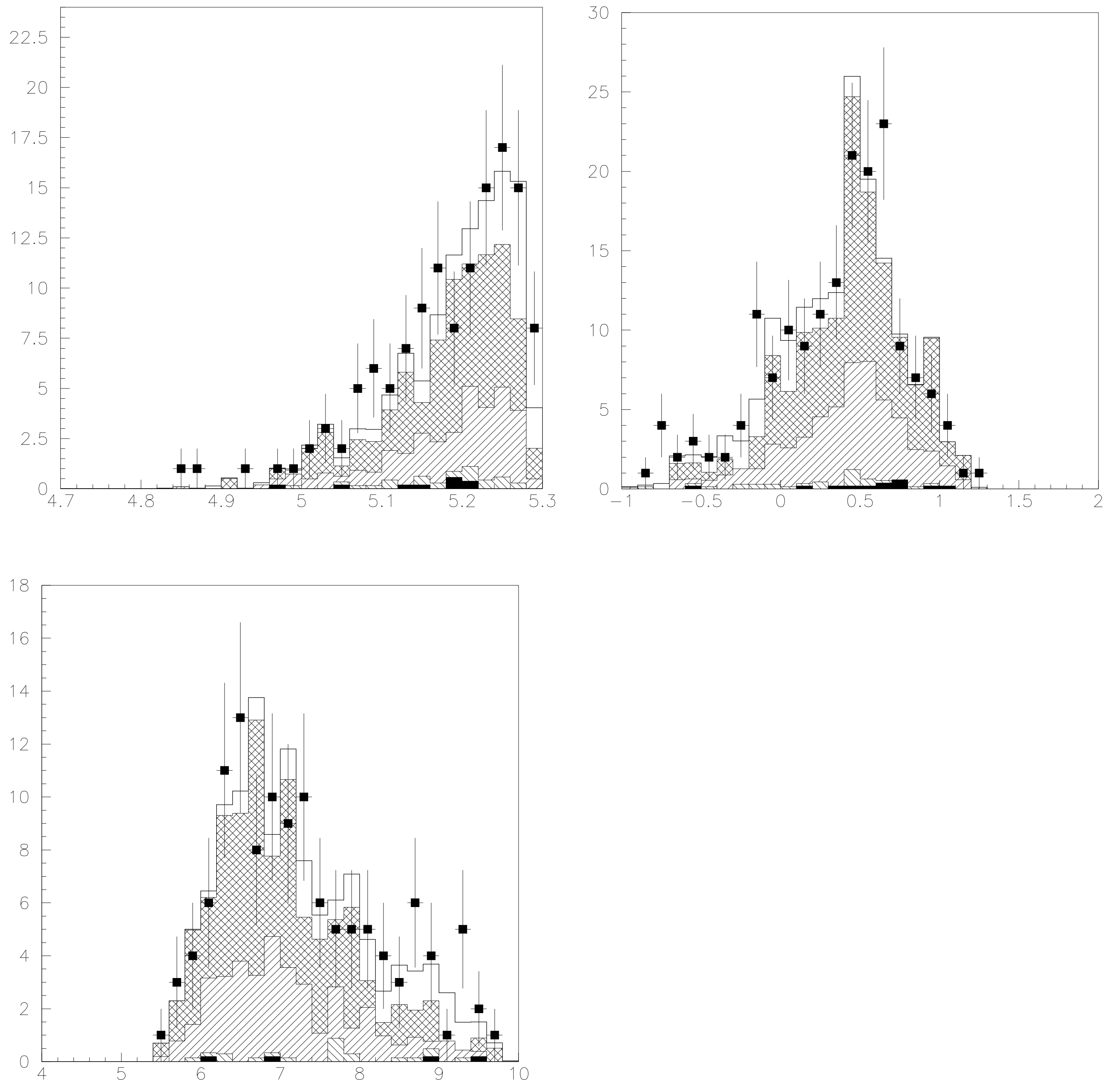
☞ Volume Size

- The volume should be relatively small, but not so small that there are not MC events falling into it. We choose the initial volume size according to the resolutions of observables.
- The volume size needn't to be fixed. For the data points near the boundary, we shrink the volume size so that the data point remains in the center. For other data points, we increase the volume size if the number of events in the volume is less than 4. We require that there are at least 4 events in the volume around the data point.

Monte Carlo Testing

- ☞ We test the method on mock data (signal and $b \to c\ell\nu$ from MC, continuum and fake η from data)
- ☞ $\frac{N_{sig}^{fit} - N_{sig}^{gen}}{N_{sig}^{gen}} \simeq 0 \pm 0.15 \sim$ independent of volume size





Projections of the ML fit sample onto M_B, ΔE and $\mathcal{F}$ variables

Analysis Sensitivity

- Combining theories (ISGW2 and Isospin and quark symmetry relations) with CLEO $\mathcal{B}(B^0 \to \pi^- \ell^+ \nu)$ result, we have the theoretical range:

$$\boxed{\mathcal{B}(B^+ \to \eta \ell^+ \nu) = (0.3 \text{ to } 1.3) \times 10^{-4}}$$

- We expect 18 to 76 events in the fit. We are currently evaluating the statistical and systematic significance of an excess of $\eta\ell$ pairs in our data.