Recent Results from CLEO

Fourth Int. Workshop on B Physics and CP Violation

February 19 - 23, 2001

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What I'm NOT Talking About

Rare hadronic B decays
CP asymmetry in $b \to s\gamma$
(Adam Lyon, Tuesday morning)

$D^0 - \bar{D}^0$ **mixing**
CP violation in D^0 decays
Measurement of the D^* width
(Alex Smith, Tuesday afternoon)

$B \to D^*\ell\nu$ **decays, V_{cb}**
CP asymmetry parameter ϵ_B
(Karl Ecklund, Thursday afternoon)

CP violation in tau decays
(Tom Coan)

What I AM Talking About

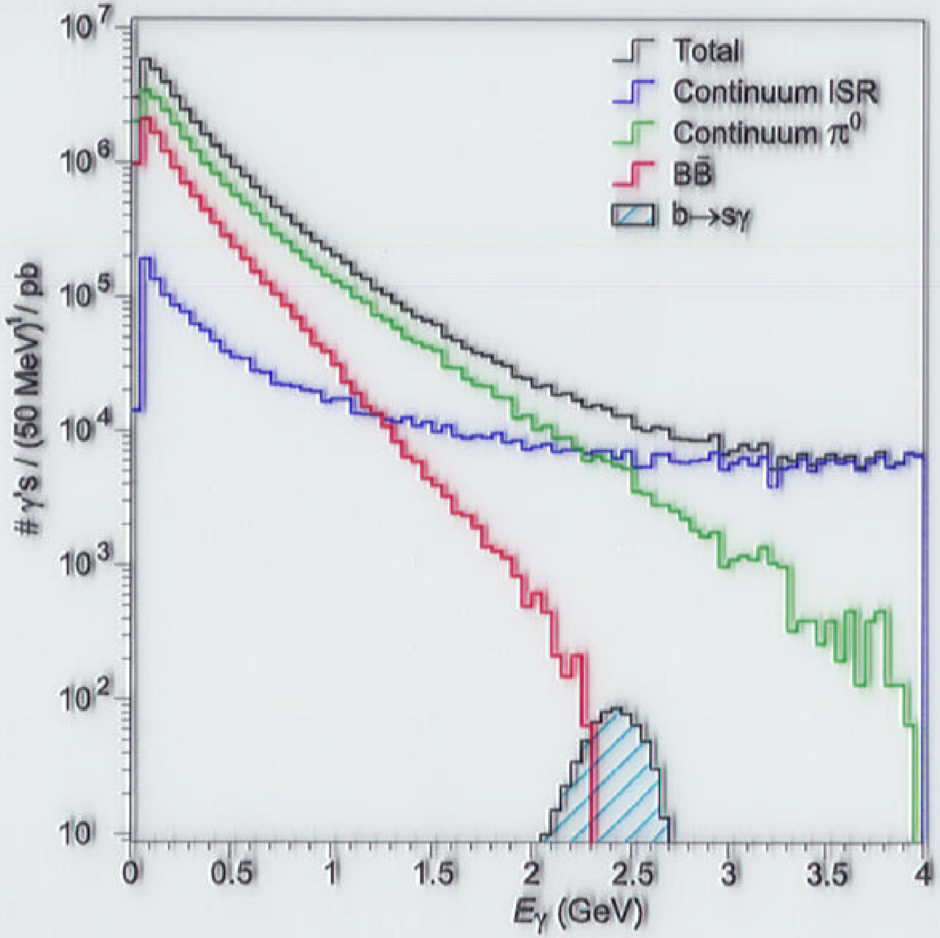
$b \to s\gamma$ branching fraction
and photon energy spectrum

Hadronic mass spectrum in $B \to X_c \ell \nu$

Interpretation of the spectra, giving
$\bar{\Lambda}$, λ_1, V_{cb}, and V_{ub}

Game plan for b $\rightarrow$ sγ

- Basic idea: Measure E_γ spectrum for ON and OFF resonance and subtract
- But, must suppress **huge** continuum background!
- Two attacks:
  - Shape analysis
  - Pseudoreconstruction



Background Suppression

π^0, η **veto** – helps with continuum and $B\bar{B}$ background.

Continuum Suppression

- Event shape variables
- Pseudoreconstruction
- Presence of lepton

We give each event with a high energy photon a weight $0.0 - 1.0$, depending on how much it is like continuum or $b \to s\gamma$.

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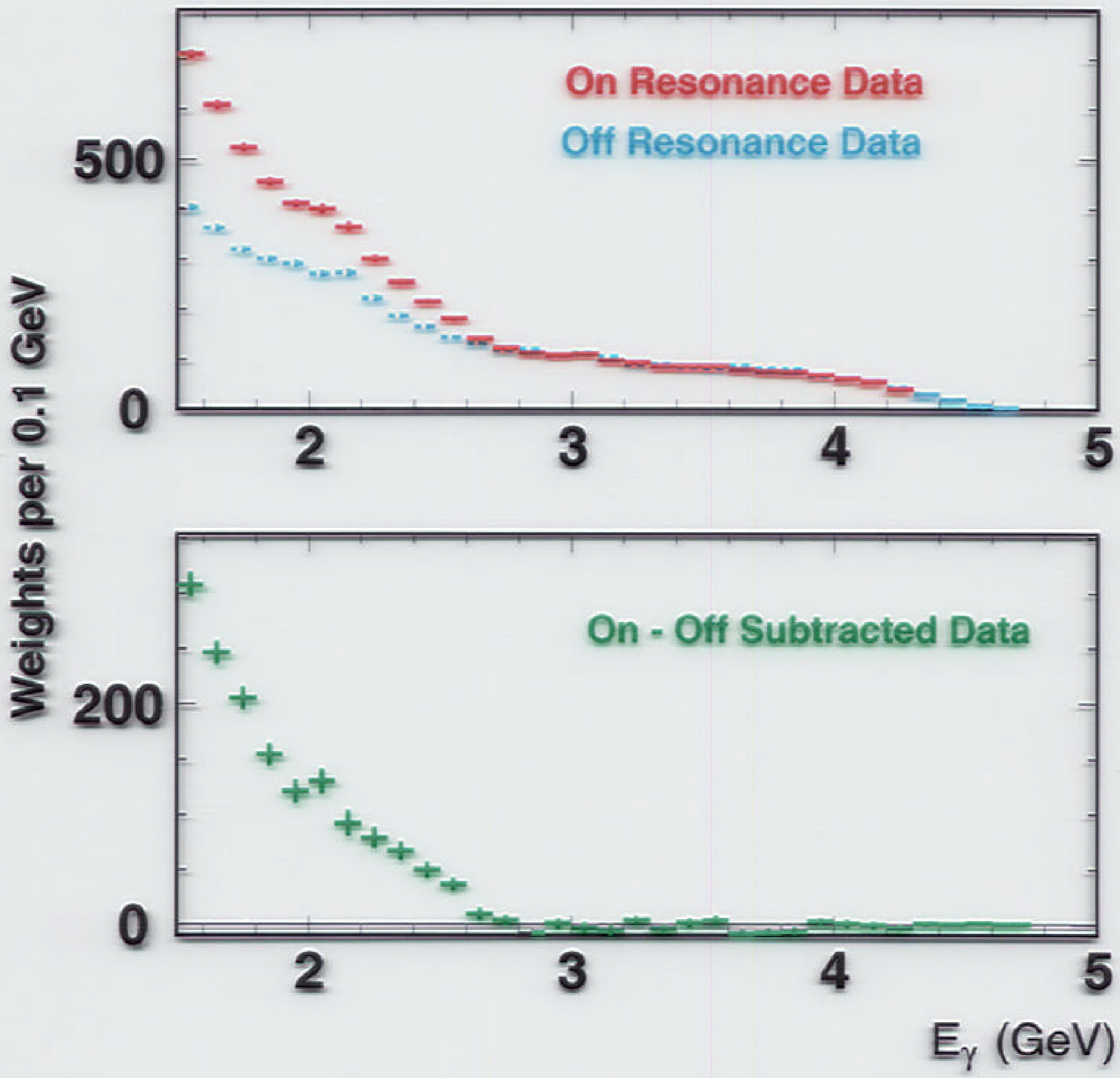

On Resonance Data
Off Resonance Data
500
0
2
3
4
5
Weights per 0.1 GeV
On - Off Subtracted Data
200
0
2
3
4
5
E_γ (GeV)

Background from Other $B\bar{B}$ Processes

Use Monte Carlo

TUNED to match

- π^0 yields
- η yields
- η' yields
- ω yields (approx)

INCLUDING

- radiative ψ decay
- final state radiation
- $a_1 \to \pi\gamma$, $\rho \to \pi\gamma$
- charmless hadronic decays
- $b \to u\ell\nu$
- $\Upsilon(4S) \to gg\gamma$
- Noise from random crossings

CORRECTED FOR

- Electrons that sneak through the track-matching requirement

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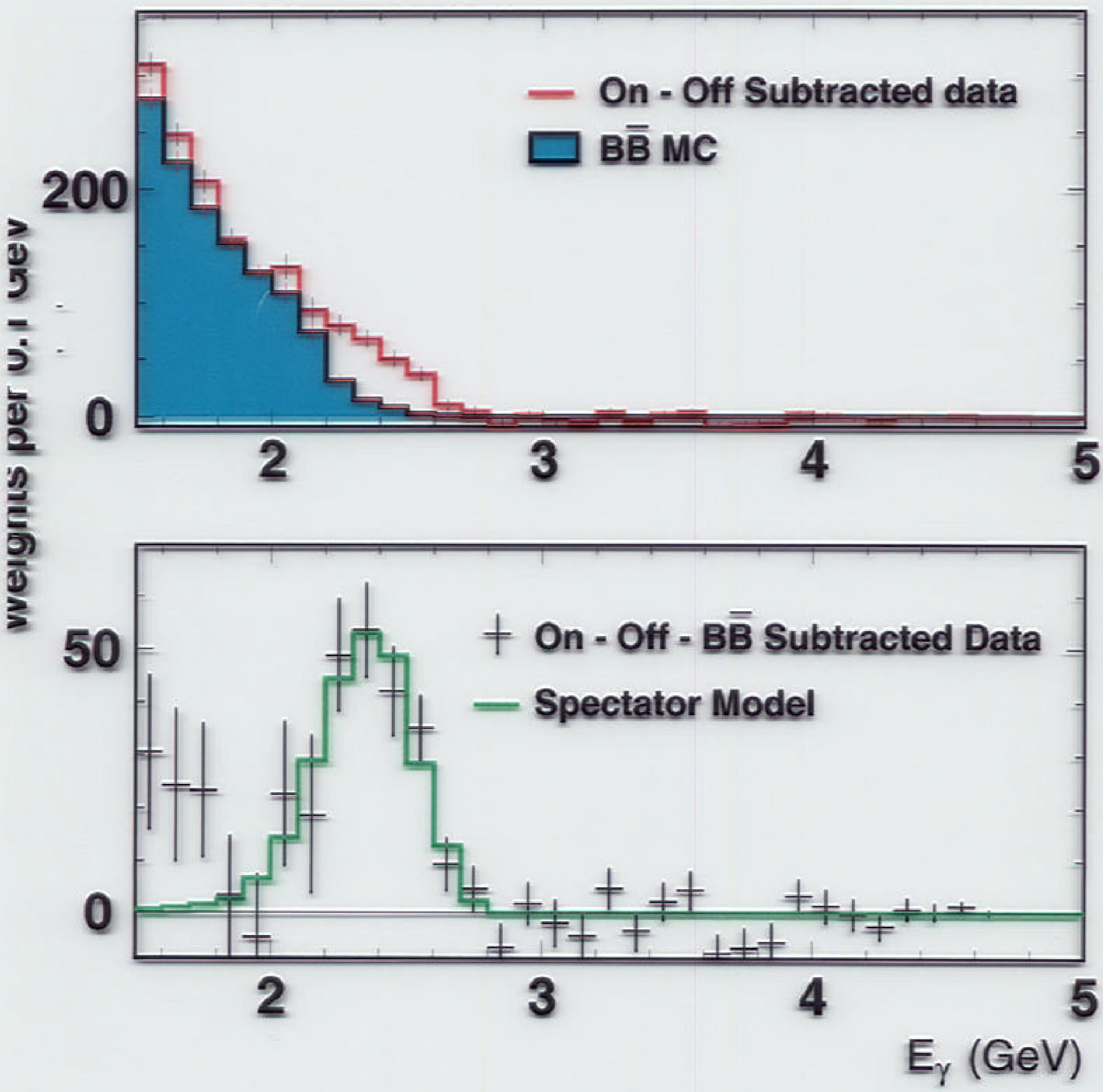
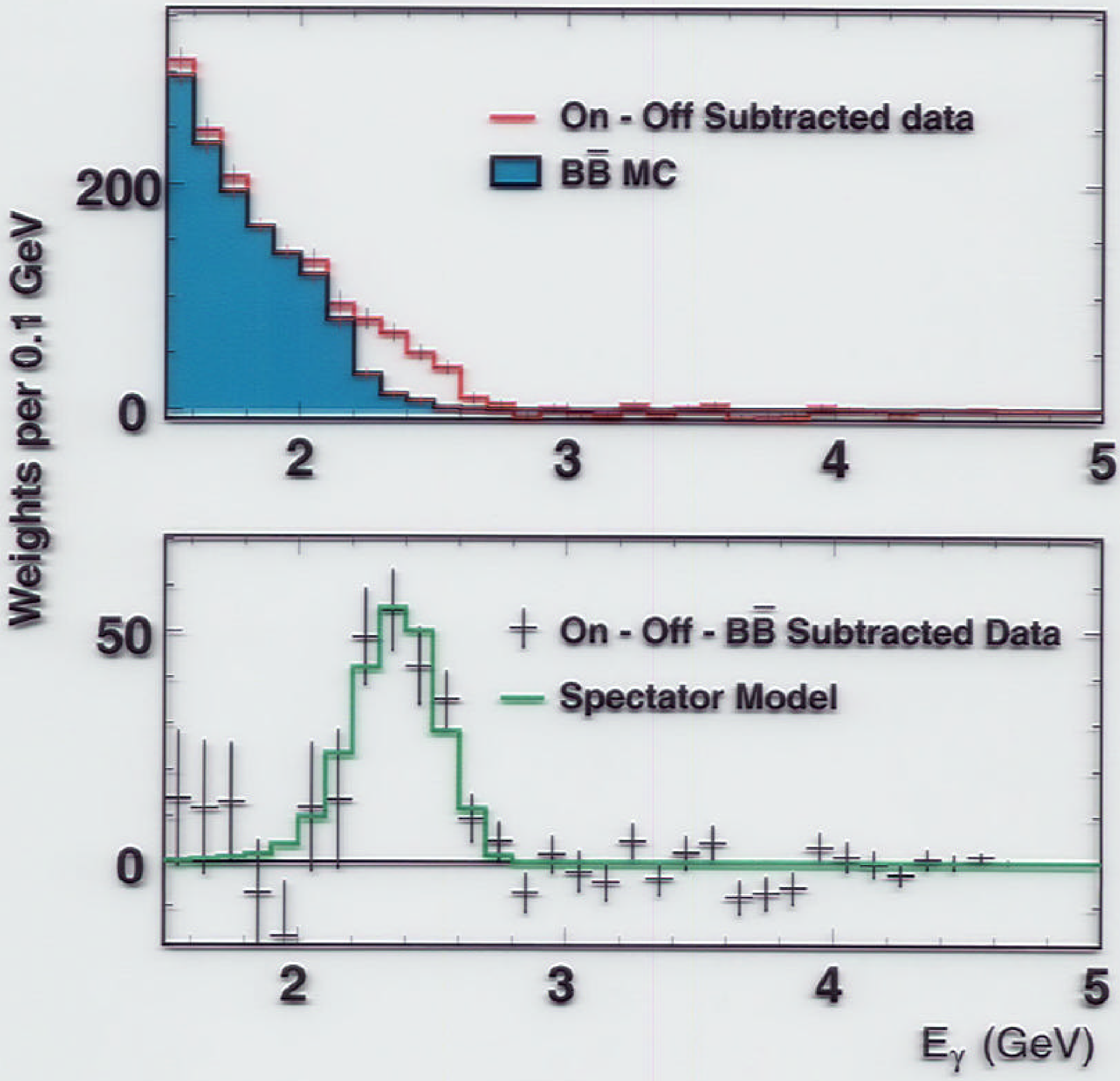


On - Off Subtracted data
B$\bar{B}$ MC
200
0
2
3
4
5
Weights per 0.1 GeV
On - Off - B$\bar{B}$ Subtracted Data
Spectator Model
50
0
2
3
4
5
E_γ (GeV)



On - Off Subtracted data
BB̄ MC
On - Off - BB̄ Subtracted Data
Spectator Model
Weights per 0.1 GeV
200
0
50
0
2
3
4
5
2
3
4
5
Eγ (GeV)

Branching Fraction

Yield between 2.0 and 2.7 GeV

$222.3 \pm 27.5 \pm 6.8 \pm 7.0$ weights

stat $B\bar{B}$ subtr Off

Efficiency

$(4.29 \pm 0.18)\%$

9.70M $B\bar{B}$ events

Fraction with E_γ above 2.0 GeV

0.94

$\Rightarrow \quad \mathcal{B}(b \to s\gamma) = [2.85 \pm 0.35 \pm 0.23] \times 10^{-4}$

Standard Model Prediction

$$\mathcal{B}(b \to s\gamma) = [3.29 \pm 0.33] \times 10^{-4} \ .$$

Our Result

$$\mathcal{B}(b \to s\gamma) = [2.85 \pm 0.41] \times 10^{-4} \ .$$

First and Second Moments
of
$b \to s\gamma$ Photon Energy Spectrum

- **In B rest frame**
- **With** $E_\gamma(restframe)$ **>2.0 GeV**

$$\langle E_\gamma \rangle = 2.360 \pm 0.027 \pm 0.014 \text{ GeV} ,$$

$$\langle (E_\gamma - \langle E_\gamma \rangle)^2 \rangle = 0.018 \pm 0.006 \pm 0.003 \text{ GeV}^2 .$$

(interpretation later)

$b \to c\ell\nu$ Inclusive

Study $B \to X_c \ell\nu$

Goal is the distribution in the mass of the hadronic system X_c.

Approach

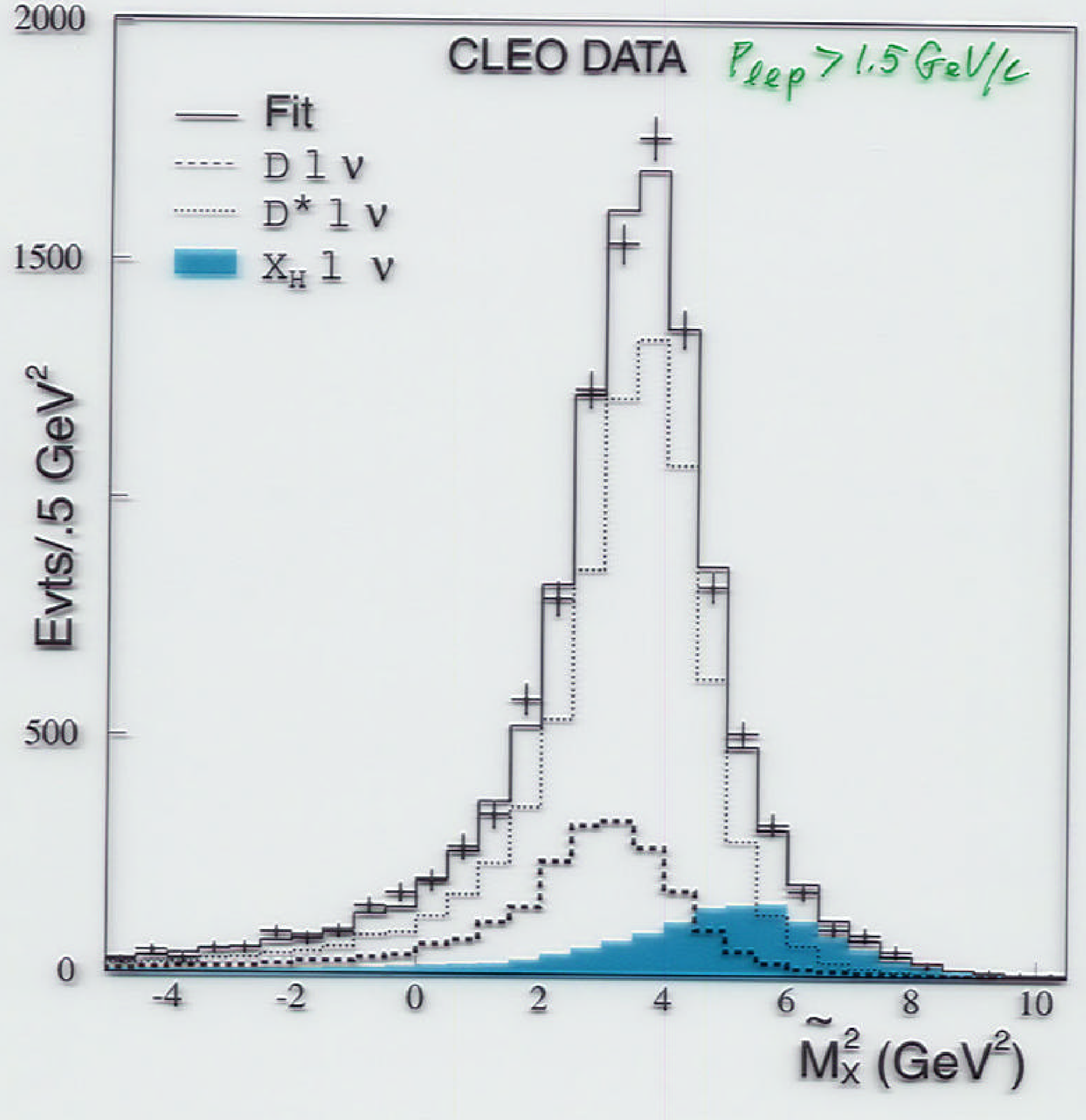
- **Detect and measure the charged lepton.**
- **"Detect and measure" the neutrino, via the missing 4-momentum in the event.**
- **From these (alone), calculate the hadronic mass.**

$$M_X^2 = M_B^2 + M_{\ell\nu}^2 - 2(E_B E_{\ell\nu} - P_B P_{\ell\nu} \cos\theta_{B-\ell\nu}) \ .$$

We don't know $\theta_{B-\ell\nu}$. But P_B is small. Drop that term.

$$\tilde{M}_X^2 \equiv M_B^2 + M_{\ell\nu}^2 - 2E_B E_{\ell\nu} \ .$$

(13)



CLEO DATA
$P_{lep} > 1.5$ GeV/c
Fit
D l ν
D* l ν
X_H l ν
2000
1500
500
0
-4
-2
0
2
4
6
8
10
Evts/.5 GeV²
$\tilde{M}_X^2$ (GeV²)

Fit the $\tilde{M}_X^2$ distribution, with

- $B \to D\ell\nu$
- $B \to D^*\ell\nu$
- $B \to X_{heavy}\ell\nu$, **with a wide range of models for** X_{heavy}

From the fit, extract first and second moments.

$$\langle M_X^2 - \bar{M}_D^2 \rangle = 0.287 \pm 0.065 \mathrm{GeV}^2 \ ,$$

$$\langle (M_X^2 - \langle M_X^2 \rangle)^2 \rangle = 0.63 \pm 0.17 \mathrm{GeV}^4 \ .$$

($\bar{M}_D$ = spin-averaged D, D^* mass.)

Inclusive Observables

- The Spectator Model has been made rigorous via HQET and OPE.
- Inclusive observables can be written as expansions in powers of $\frac{1}{M_B}$, calculable coefficients, and unknown parameters.

Semileptonic Width:

$$\Gamma_{sl} = \frac{G_F^2 |V_{cb}|^2 M_B^5}{192\pi^3} 0.3689 [1 - 1.54\frac{\alpha_s}{\pi} - 1.648\frac{\bar{\Lambda}}{M_B}(1 - 0.87\frac{\alpha_s}{\pi}) - 0.946\frac{\bar{\Lambda}^2}{M_B^2}$$

$$-3.185\frac{\lambda_1}{M_B^2} - 7.474\frac{\lambda_2}{M_B^2} - 0.298\frac{\bar{\Lambda}^3}{M_B^3} - 3.28\frac{\bar{\Lambda}\lambda_1}{M_B^3} + 7.997\frac{\bar{\Lambda}\lambda_2}{M_B^3} - 6.153\frac{\rho_1}{M_B^3}$$

$$+7.482\frac{\rho_2}{M_B^3} - 7.4\frac{\mathcal{T}_1}{M_B^3} + 1.491\frac{\mathcal{T}_2}{M_B^3} - 10.41\frac{\mathcal{T}_3}{M_B^3} - 7.482\frac{\mathcal{T}_4}{M_B^3} + \mathcal{O}(1/M_B^4)] \, .$$

b quark mass:

$$\frac{M_B}{m_b} = 1 + \frac{\bar{\Lambda}}{m_b} - \frac{\lambda_1 + 3\lambda_2}{2m_b^2} + \frac{\rho_1 + 3\rho_2}{4m_b^3} - \frac{\mathcal{T}_1 + \mathcal{T}_3 + 3(\mathcal{T}_2 + \mathcal{T}_4)}{4m_b^3} + \mathcal{O}(1/m_b^4) \, .$$

- Clearly important to determine the expansion parameters $\bar{\Lambda}$ and λ_1

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Hadronic Mass Moments

First Moment:

$$\frac{\langle M_X^2 - \bar{M}_D^2\rangle}{M_B^2} = [0.0272\frac{\alpha_s}{\pi} + 0.483\frac{\alpha_s^2}{\pi^2} + 0.207\frac{\bar{\Lambda}}{M_B}(1 + 0.43\frac{\alpha_s}{\pi}) + 0.193\frac{\bar{\Lambda}^2}{M_B^2}$$

$$+1.38\frac{\lambda_1}{M_B^2} + 0.203\frac{\lambda_2}{M_B^2} + 0.19\frac{\bar{\Lambda}^3}{M_B^3} + 3.2\frac{\bar{\Lambda}\lambda_1}{M_B^3} + 1.4\frac{\bar{\Lambda}\lambda_2}{M_B^3} + 4.3\frac{\rho_1}{M_B^3} - 0.56\frac{\rho_2}{M_B^3}$$

$$+2.0\frac{\mathcal{T}_1}{M_B^3} + 1.8\frac{\mathcal{T}_2}{M_B^3} + 1.7\frac{\mathcal{T}_3}{M_B^3} + 0.91\frac{\mathcal{T}_4}{M_B^3} + \mathcal{O}(1/M_B^4)].$$

Second Moment:

$$\frac{\langle (M_X^2 - \langle M_X^2\rangle)^2\rangle}{M_B^4} = [0.00148\frac{\alpha_s}{\pi} + 0.0210\frac{\alpha_s^2}{\pi^2} + 0.027\frac{\bar{\Lambda}}{M_B}\frac{\alpha_s}{\pi} + 0.0107$$

$$\frac{\bar{\Lambda}^2}{M_B^2} - 0.12\frac{\lambda_1}{M_B^2} + 0.02\frac{\bar{\Lambda}^3}{M_B^3} - 0.06\frac{\bar{\Lambda}\lambda_1}{M_B^3} - 0.129\frac{\bar{\Lambda}\lambda_2}{M_B^3} - 1.2\frac{\rho_1}{M_B^3} + 0.23\frac{\rho_2}{M_B^3}$$

$$-0.12\frac{\mathcal{T}_1}{M_B^3} - 0.36\frac{\mathcal{T}_2}{M_B^3} + \mathcal{O}(1/M_B^4)].$$

Inputs:

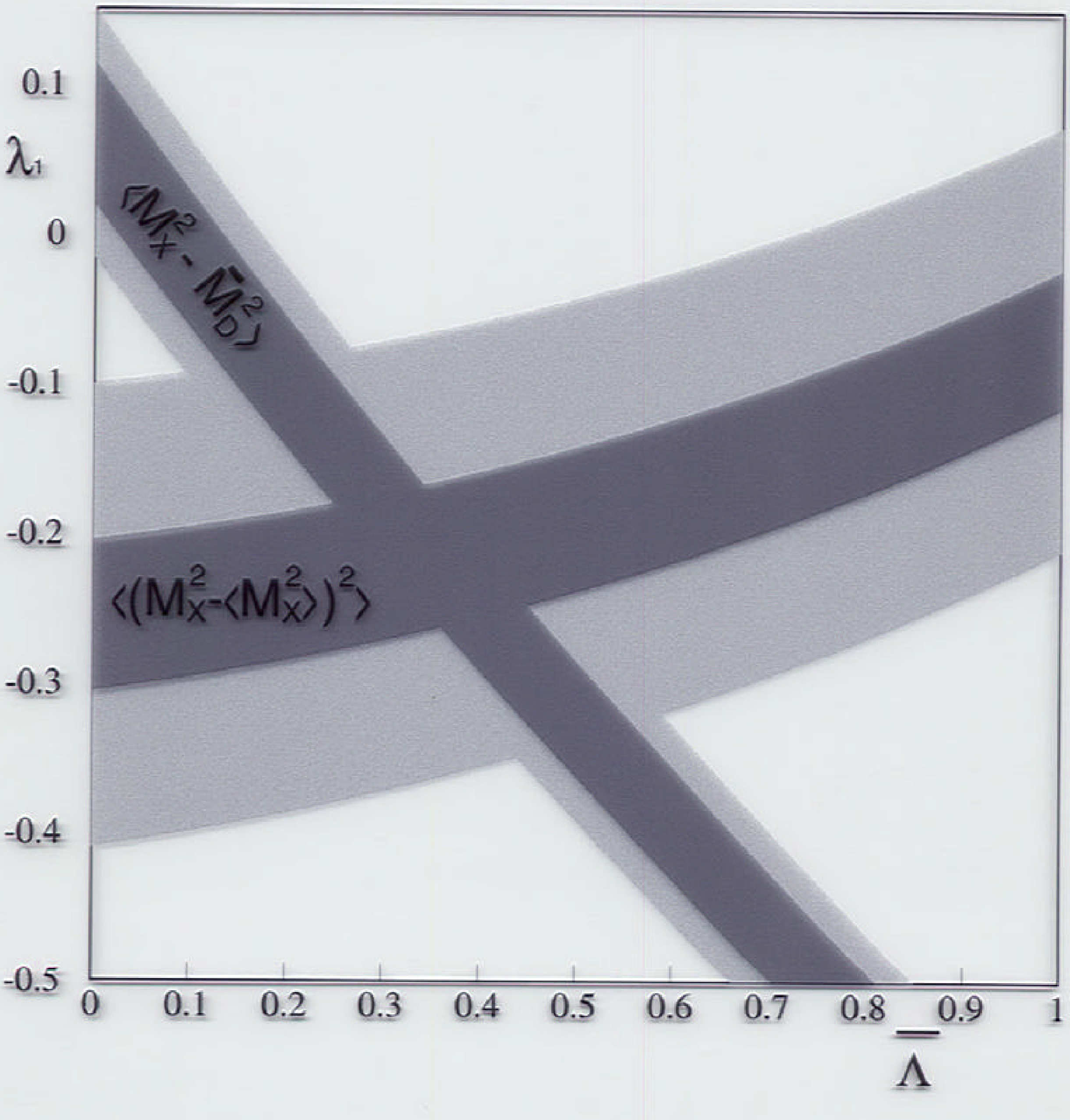
$\alpha_s = .22$

$\lambda_2 = 0.12\ GeV^2$

$M_B = 5.313\ GeV/c^2$

$p_\ell > 1.5$ GeV

Falk, Luke


0.1
λ_1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$\bar{\Lambda}$
$\langle M_X^2 - \bar{M}_D^2 \rangle$
$\langle (M_X^2 - \langle M_X^2 \rangle)^2 \rangle$

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$b \to s\,\gamma$ Moments

First Moment:

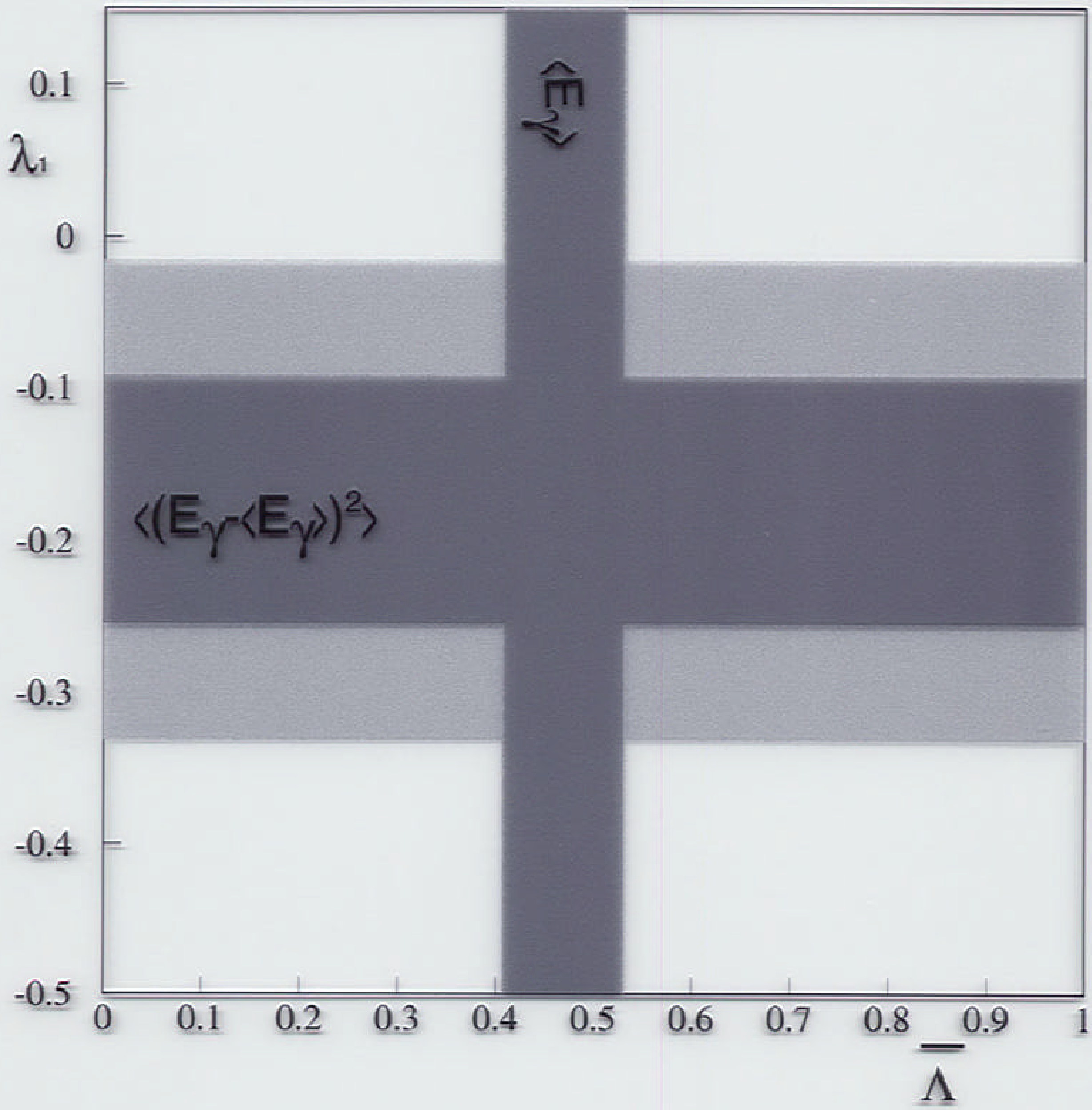
$$\langle E_\gamma \rangle_{E_0} = \frac{M_B - \bar{\Lambda}}{2}[1 + \delta m_1(\frac{2E_0}{m_b})] - \frac{13\rho_1 - 33\rho_2}{24 m_b^2} - \frac{\mathcal{T}_1 + 3\mathcal{T}_2 + \mathcal{T}_3 + 3\mathcal{T}_4}{8 m_b^2} - \frac{\rho_2 C_2}{18 m_c^2 C_7}.$$

Second Moment:

$$\langle (E_\gamma - \langle E_\gamma \rangle)^2 \rangle_{E_0} = \frac{-\lambda_1}{12}(\frac{m_b}{2})^2[\delta m_2(\frac{2E_0}{m_b}) - \delta m_1(\frac{2E_0}{m_b})] - \frac{2\rho_1 - 3\rho_2}{12 m_b} - \frac{\mathcal{T}_1 - 3\mathcal{T}_2}{12 m_b}.$$

↑ −

- E_0 is the photon energy cut inthe B rest frame.
- δm_i terms correct for the photon energy cut.



0.1
λ1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Λ̄
⟨Eγ⟩
⟨(Eγ-⟨Eγ⟩)²⟩

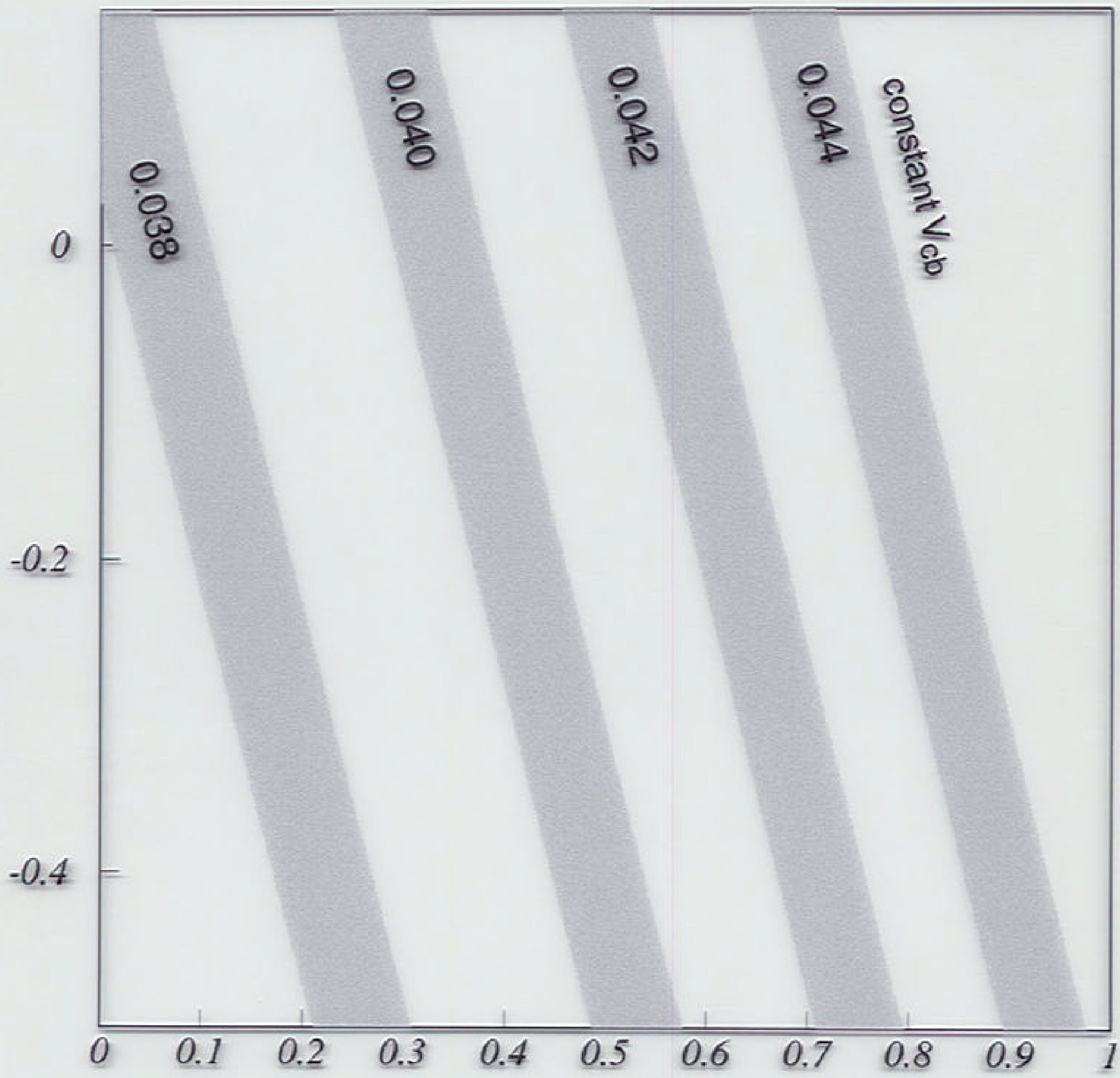
$|V_{cb}|$ from Inclusive Decays

$$\Gamma_{sl} = \frac{G_F^2|V_{cb}|^2 M_B^5}{192\pi^3} 0.3689[1 - 1.54\frac{\alpha_s}{\pi} - 1.648\frac{\bar{\Lambda}}{M_B}(1 - 0.87\frac{\alpha_s}{\pi}) - 0.946\frac{\bar{\Lambda}^2}{M_B^2}$$
$$-3.185\frac{\lambda_1}{M_B^2} - 7.474\frac{\lambda_2}{M_B^2} - 0.298\frac{\bar{\Lambda}^3}{M_B^3} - 3.28\frac{\bar{\Lambda}\lambda_1}{M_B^3} + 7.997\frac{\bar{\Lambda}\lambda_2}{M_B^3} - 6.153\frac{\rho_1}{M_B^3}$$
$$+7.482\frac{\rho_2}{M_B^3} - 7.4\frac{\mathcal{T}_1}{M_B^3} + 1.491\frac{\mathcal{T}_2}{M_B^3} - 10.41\frac{\mathcal{T}_3}{M_B^3} - 7.482\frac{\mathcal{T}_4}{M_B^3} + \mathcal{O}(1/M_B^4)]\ .$$

$$\mathcal{B}(B \to X_c \ell \nu) = (10.39 \pm 0.46)\% \quad \text{[CLEO]}$$
$$\tau_{B^\pm} = (1.548 \pm 0.032) \times 10^{-12}\text{sec} \quad \text{[PDG]}$$
$$\tau_{B^0} = (1.653 \pm 0.028) \times 10^{-12}\text{sec} \quad \text{[PDG]}$$
$$f_{+-}/f_{00} = 1.04 \pm 0.08 \quad \text{[CLEO]}$$

$$\Rightarrow \Gamma_{sl} = (0.427 \pm 0.020) \times 10^{-10}\text{MeV}$$

Determine $\bar{\Lambda}$, λ_1, from 1st moments of hadronic mass-squared, photon energy spectrum, obtain $|V_{cb}|$.


0.038
0.040
0.042
0.044
constant V_{cb}
0
-0.2
-0.4
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

The first moments of the hadronic mass-squared distribution in $B \to X_c \ell \nu$ and the photon energy spectrum in $b \to s\gamma$ give:

$$\bar{\Lambda} = 0.469 \pm 0.060 \pm 0.015\,,$$
$$\lambda_1 = -0.302 \pm 0.059 \pm 0.056\,.$$

moments $\quad 1/M^3$

cf FNAL lattice group calculations

These in turn give:

$$|V_{cb}| = 0.0401 \pm 0.0009 \pm 0.0006 \pm 0.0004\,.$$

$\Gamma_{sl} \quad \bar{\Lambda}, \lambda_1 \quad 1/M^3$

V_{ub} from the Lepton Spectrum Endpoint, Revisited

Years ago, CLEO measured the yield of leptons from $b \rightarrow u\ell\nu$ between 2.3 and 2.6 GeV/c, obtaining:

$$\mathcal{B}(b \rightarrow u\ell\nu, 2.3 - 2.6) = (138 \pm 31) \times 10^{-6}$$

Extracting a value of V_{ub} from that yield is problematic, because the fraction of $b \rightarrow u\ell\nu$ leptons that lie between 2.3 and 2.6 GeV/c is uncertain.

Years ago, Matthias Neubert (PRD 49, 4623 (1994)) showed us how to get around the problem, using the photon energy spectrum in $b \rightarrow s\gamma$.

$$\mathcal{B}(b \rightarrow u\ell\nu, E > E_c) \propto \left|\frac{V_{ub}}{V_{ts}V_{tb}}\right|^2 \int_{E_c}^{M_B/2} E_\gamma N(E_\gamma) dE_\gamma$$

More recently, Leibovich, Low, and Rothstein (hep-ph/9909404) have carried Neubert's calculation to a higher order, and estimate a 10% theoretical error on $|V_{ub}/V_{cb}|$ from their expression. Again, an integral over $N(E_\gamma)$, from E_c up, but with a slightly different weighting function.

We perform the integral over our measured photon energy spectrum, corrected to the B rest frame.

The accuracy of the integral, from the accuracy of the $b \to s\gamma$ spectrum, is $\pm 20\%$, implying an error of $\pm 10\%$ on V_{ub}.

The accuracy of $\mathcal{B}(b \to u\ell\nu, 2.3-2.6)$ is $\pm 22\%$, giving an error of 11% to V_{ub}.

L, L, R claim $\pm 10\%$ theoretical uncertainty in V_{ub} from their treatment.

These combine to an accuracy of $\pm 18\%$ on V_{ub}.

We're sorting out the constant of proportionality. Stay tuned.

CLEO and $\sin 2\phi_1$

What are the implications of a ±18% measurement of $|V_{ub}/V_{cb}|$?

For illustrative purposes, consider
$|V_{ub}/V_{cb}| = 0.100 \pm 0.018$ $\quad 0.060 \pm 0.011$

Then, at 90% c.l.
$\sin 2\phi_1 < 0.95$ $\quad \sin 2\phi_1 < 0.66$

Without assumptions about ϕ_3, one can say no more.

Now, assume $45° < \phi_3 < 110°$
then

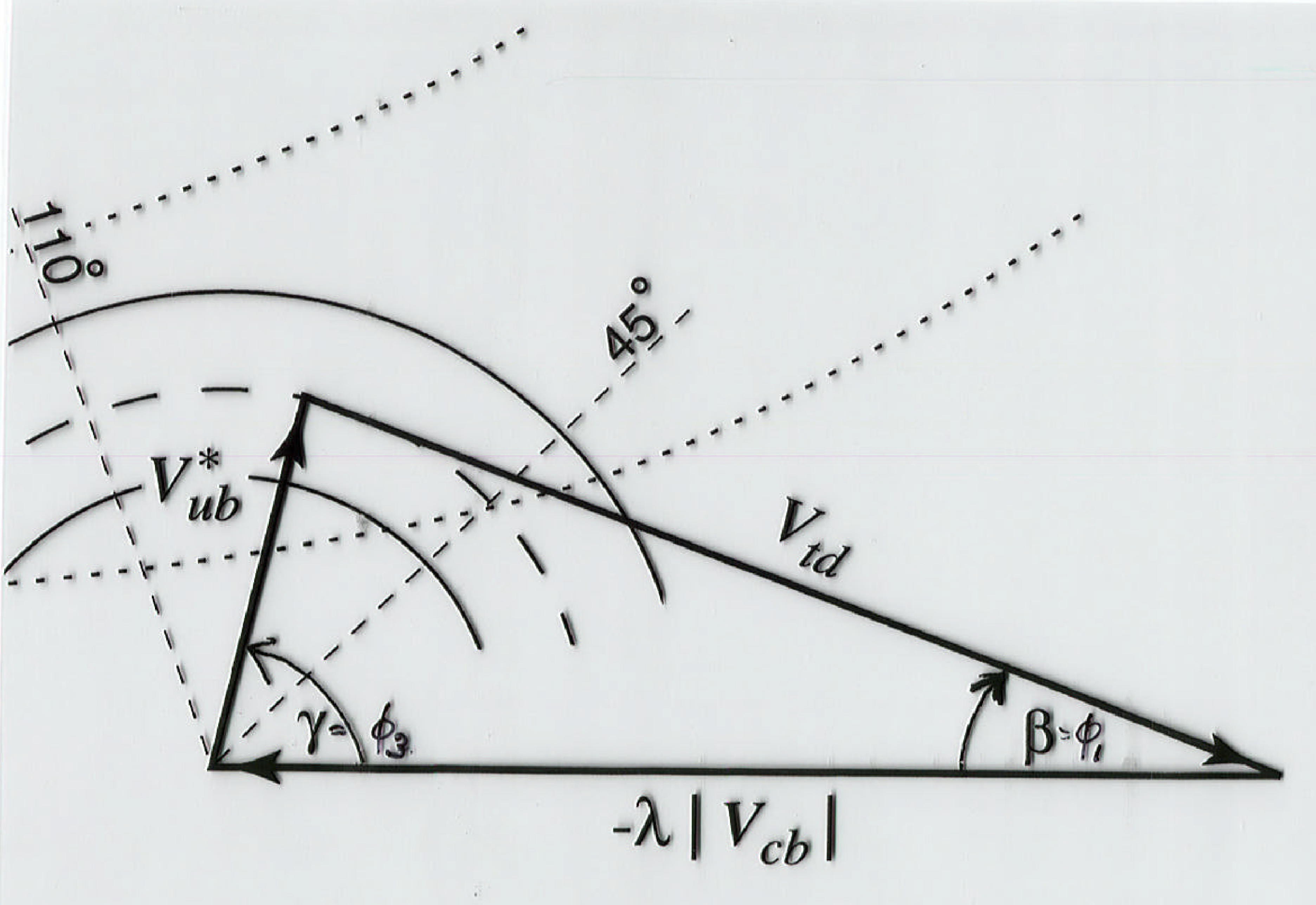
$$\sin 2\phi_1 = 0.73 \pm 0.11 \pm 0.08$$

OR

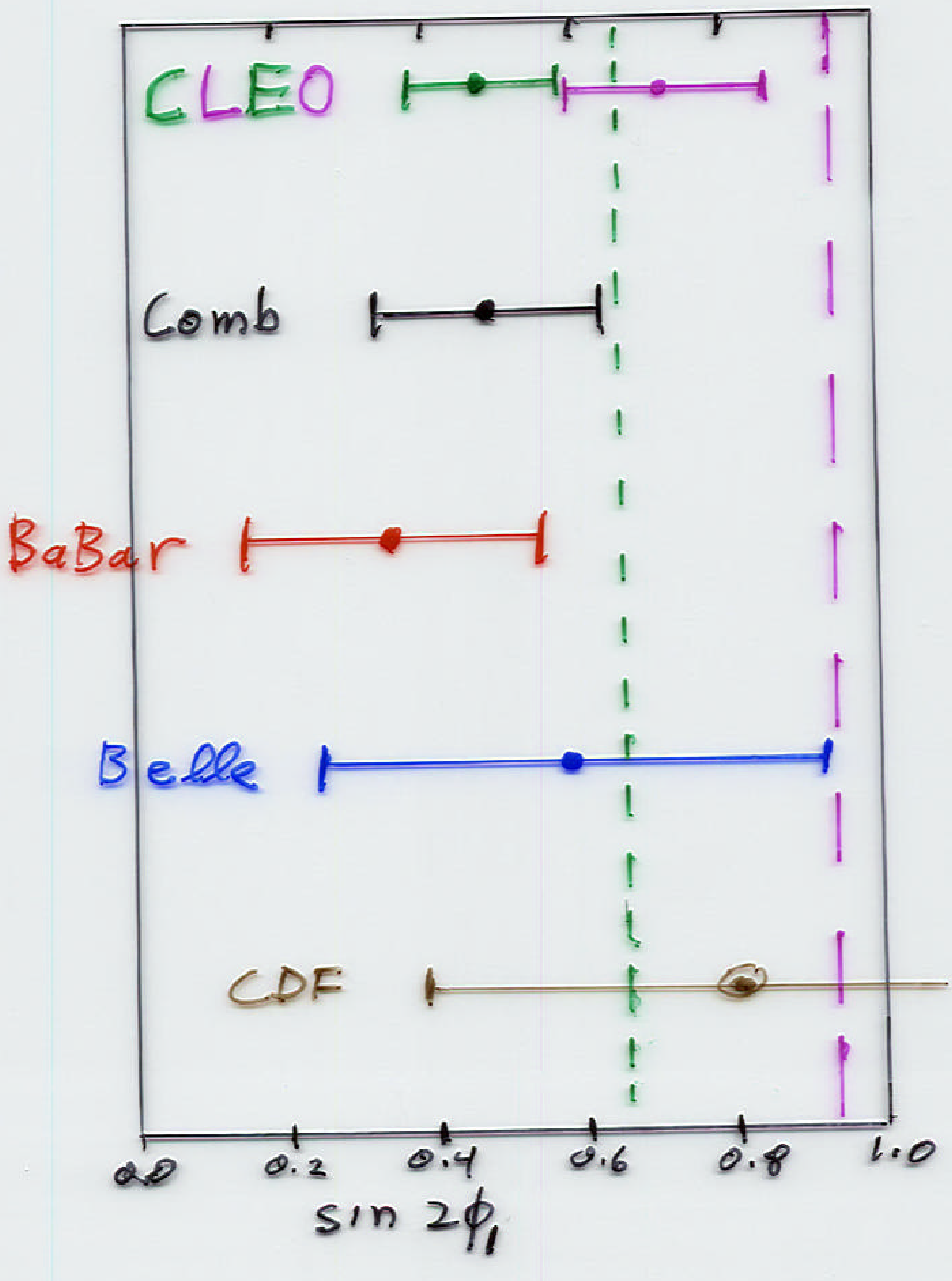
$$\sin 2\phi_1 = 0.48 \pm 0.09 \pm 0.04$$

from ±18% on $|V_{ub}/V_{cb}|$ (first error)

from 45°–110° range on ϕ_3 (second error)



110°
45°
V*ub
Vtd
γ= φ3
β= φ1
-λ | Vcb |



CLEO
Comb
BaBar
Belle
CDF
0.0
0.2
0.4
0.6
0.8
1.0
sin 2φ1

SUMMARY

$\mathcal{B}(b \to s\gamma) = [2.85 \pm 0.41] \times 10^{-4}$

in agreement with SM prediction $[3.29 \pm 0.33] \times 10^{-4}$

First and second moments of photon energy spectrum in $b \to s\gamma$

$$\langle E_\gamma \rangle = 2.360 \pm 0.030 \text{ GeV}$$

$$\langle (E_\gamma - \langle E_\gamma \rangle)^2 \rangle = 0.018 \pm 0.007 \text{ GeV}^2$$

First and second moments of hadron mass-squared distribution in $B \to X_c \ell \nu$

$$\langle M_X^2 - \bar{M}_D^2 \rangle = 0.287 \pm 0.065 \text{ GeV}^2$$

$$\langle (M_X^2 - \langle M_X^2 \rangle)^2 \rangle = 0.63 \pm 0.17 \text{ GeV}^4$$

First moments of the above two sets give

$$\bar{\Lambda} = 0.47 \pm 0.06 \text{ GeV}$$

$$\lambda_1 = -0.30 \pm 0.08 \text{ GeV}^2$$

$$|V_{cb}| = 0.0401 \pm 0.0011$$

$|V_{ub}|$

To compare $(\text{"}\sin 2\phi_1\text{"})_{Mixing}$ with $(\sin 2\phi_1)_{True}$, one needs to know $(\sin 2\phi_1)_{True}$ to reasonable accuracy.

That requires knowing $|V_{ub}/V_{cb}|$ to ± 20% or better.

All methods of measuring $|V_{ub}|$ entail big theoretical uncertainties.
So, one should measure $|V_{ub}|$ by 3 or more methods.

CLEO's measurement of the photon energy spectrum in $b \to s\gamma$ puts "V_{ub} from the $b \to u\ell\nu$ endpoint" back on the list.

Reminder of What I Didn't Talk About

Rare hadronic B decays
CP asymmetry in $b \to s\gamma$
(Adam Lyon, Tuesday morning)

$D^0 - \bar{D}^0$ mixing
CP violation in D^0 decays
Measurement of the D^* width
(Alex Smith, Tuesday afternoon)

$B \to D^*\ell\nu$ decays, V_{cb}
CP asymmetry parameter ϵ_B
(Karl Ecklund, Thursday afternoon)

CP violation in tau decays
(Tom Coan)