Recent Heavy Meson Results from CLEO

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30 June 1998

- Introduction
- Rare B Decays :
  - $b \to s\gamma$
  - $B \to$ Baryons
- Hadronic B Decays: $B \to D^*\rho$
- Semi-leptonic B Decays : $B \to Dl\nu$
- Charm :
- Conclusions

Reconstructing B decays

- $\Upsilon(4S) \rightarrow B^0\overline{B}^0, B^+B^-$: B's nearly at rest.
- $M_B \approx 5.3$ GeV/c^2
- Two-body decays (such as $B \rightarrow \pi\pi$, $B \rightarrow K\pi$, $B \rightarrow \eta\,\prime K$ ...)

  $\Rightarrow$ back-to-back daughter particles

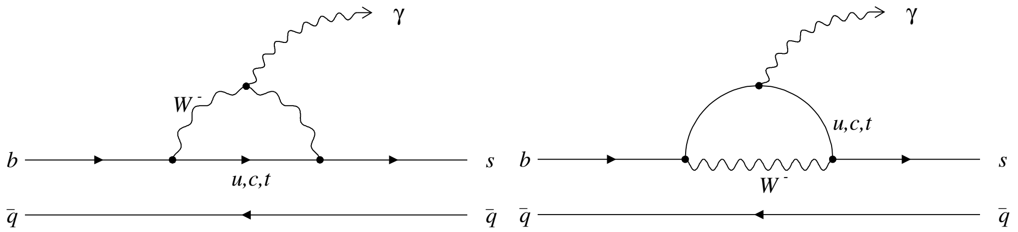
  $\Rightarrow$ each with $E \approx 2.6$ GeV$/c^2$
- Energy, Momentum conservation

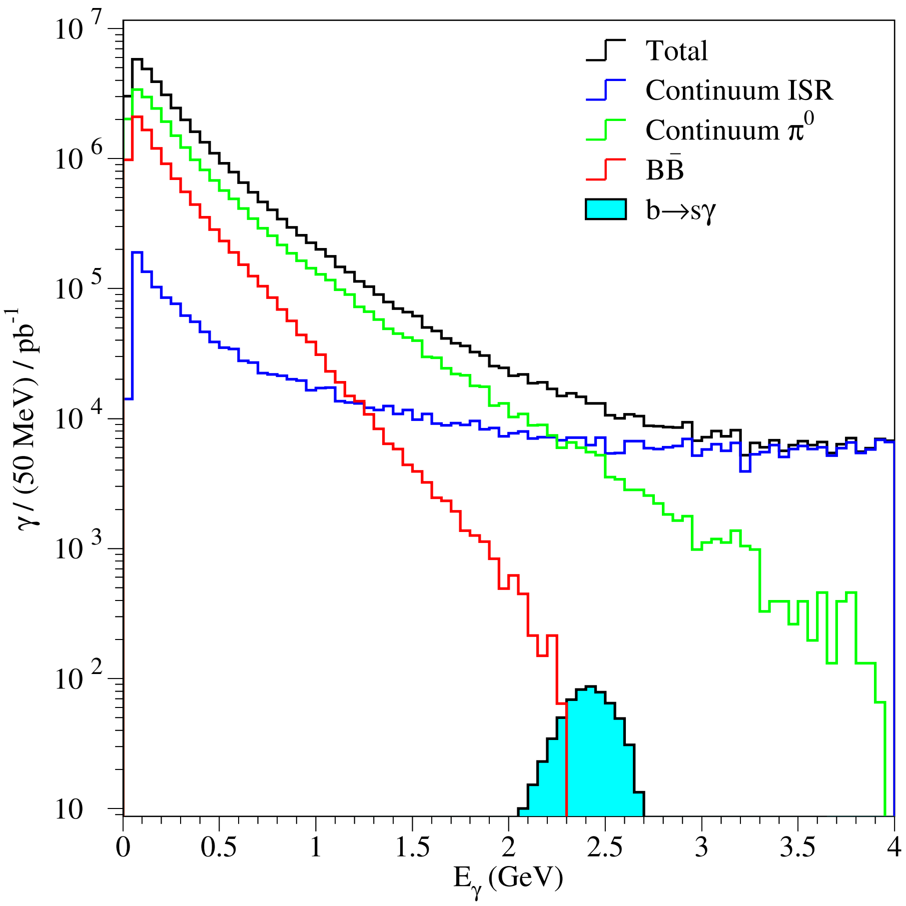
  $\Rightarrow$ $\Delta E \equiv \Sigma E_i - E_b = 0$ within resolution. E_b is the beam energy and E_i are the energies of the B daughters.

  $\Rightarrow$ $M_{BC} \equiv \sqrt{E_b{}^2 - |\Sigma\vec{p}_i|^2}$, where E_b is much better measured than ΣE_i ($\sim 10\times$ better resolution for h^+h^- for example)
- Continuum background(e.g. two $x = 0.5$ particles in opposite jets from $e^+e^- \rightarrow q\overline{q}$: $q = u, d, s$ or c):
  - Record data with $E_{CM} < B\overline{B}$ threshold.
  - Distinguish event shape.
  - B decay axis is uncorrelated with jet axis, while background is strongly correlated.
- CLEO II dataset: 1990-1995 $\Rightarrow$ 4.7 fb^{-1}
- CLEO II.5 dataset: 1996-1998 $\Rightarrow$ ~ 6 fb^{-1} so far

(Charge conjugate reactions implied throughout)

Inclusive $b \longrightarrow s\gamma$





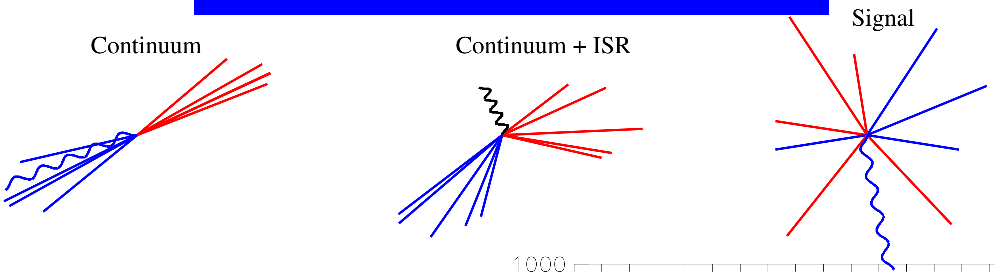
• At $\Upsilon(4S)$ CM energy, there are massive backgrounds from continuum ISR and continuum π^0 (η).

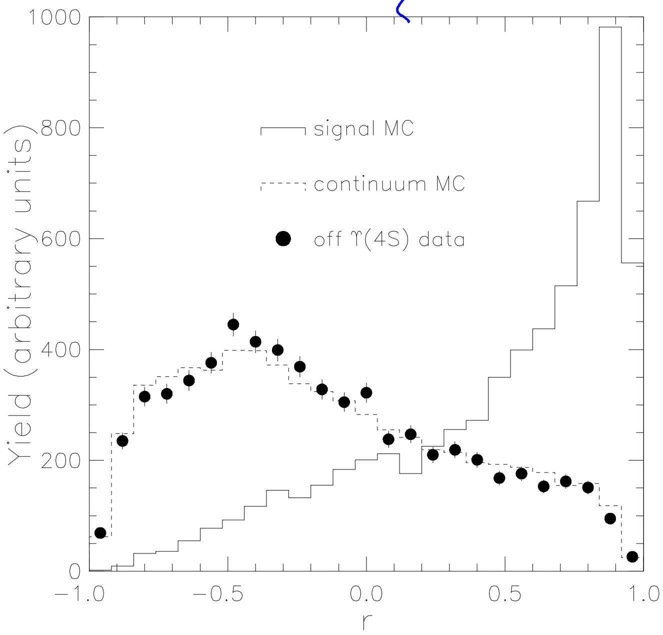
⇒ the photon energy spectrum alone is woefully inadequate to separate the signal from background.

⇒ Veto photons which when paired with others forms a π^0 or η mass. Still more needs to be done.

• CLEO has used two independent methods.

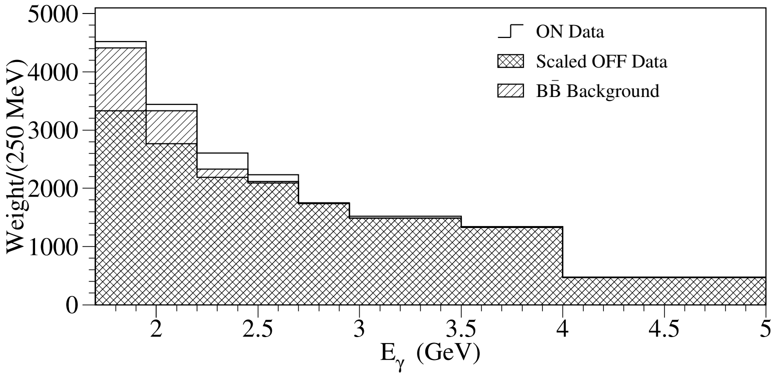
$b \longrightarrow s\gamma$ (Event Shape)

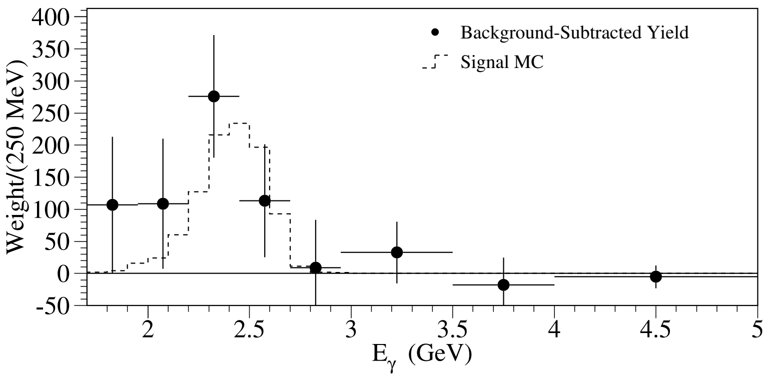




• Neural net: Eight input event shape variables each having some ability to separate signal from continuum. The net takes advantage of the correlations (not necessarily linear) to produce a new variable "r" with substantial discriminating power.

⇒ Signal efficiency: ∼30%

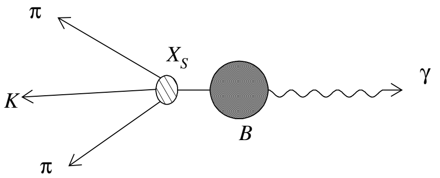




(CLEO Preliminary)
Full CLEO II dataset.
E_γ distribution for events weighted by "r".

$b \longrightarrow s\gamma$ (B Reconstruction)

Look for a K plus 1-4 π's recoiling against a photon.



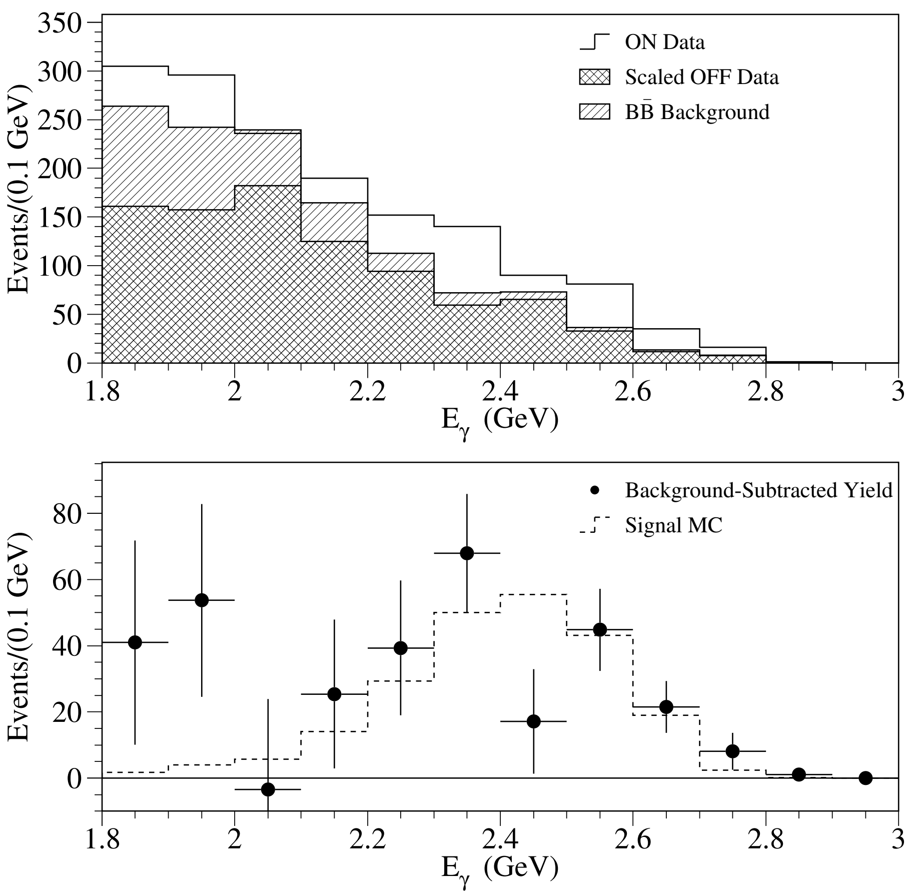
Define: $\chi^2 \equiv$
$$\left(\frac{E-E_b}{\delta E}\right)^2 + \left(\frac{M_{BC}-M_B}{\delta M}\right)^2$$

• Compare thrust axis for the candidate B to thrust axis for remaining event (θ_{tt}). Axes tend to align for continuum event.

• Cut on χ^2 and θ_{tt} to reject background.

• Signal efficiency ~10%, but background rejection is about 4 times higher than in the neural net analysis.

(CLEO II, Preliminary)



$b \longrightarrow s\gamma$

Restricting the photon energy to $2.2 < E_\gamma < 2.7$ GeV and correcting the yield by a factor of 0.85:

- Event-shape method (preliminary):
  $\mathcal{B} = (2.11 \pm 0.68(\mathrm{stat}) \pm 0.13(\mathrm{bkgd}) \pm 0.36(\mathrm{sys})) \times 10^{-4}$
- B Reconstruction method (preliminary):
  $\mathcal{B} = (2.89 \pm 0.50\ (\mathrm{stat})\ \pm 0.15\ (\mathrm{bkgd})\ \pm 0.35\ (\mathrm{sys})) \times 10^{-4}$
- Combining both methods, CLEO finds (preliminary full CLEO II dataset result):

$$\mathcal{B}(b \to s\gamma) = (2.50 \pm 0.47 \pm 0.39) \times 10^{-4}$$

Recent ALEPH result:

$$\mathcal{B}(b \to s\gamma) = (3.11 \pm 0.80 \pm 0.72) \times 10^{-4}$$

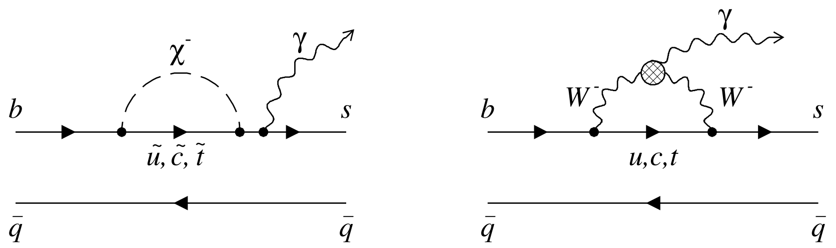
From a NLO calculation, Chetyrkin, Misiak, and Münz predict

$$\mathcal{B}(b \to s\gamma) = (3.28 \pm 0.33) \times 10^{-4}$$

—in good agreement with the measurements.

Currently analyzing CLEO II.5 data and expect to gain a factor of ~ 2 in statistics soon.

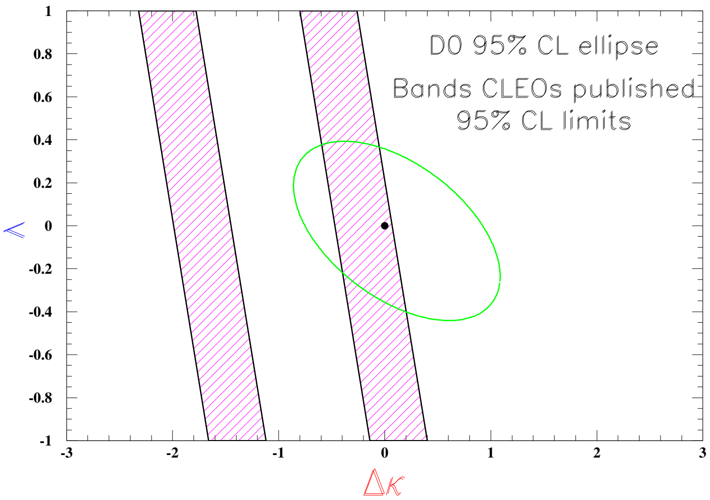
$b \longrightarrow s\gamma$



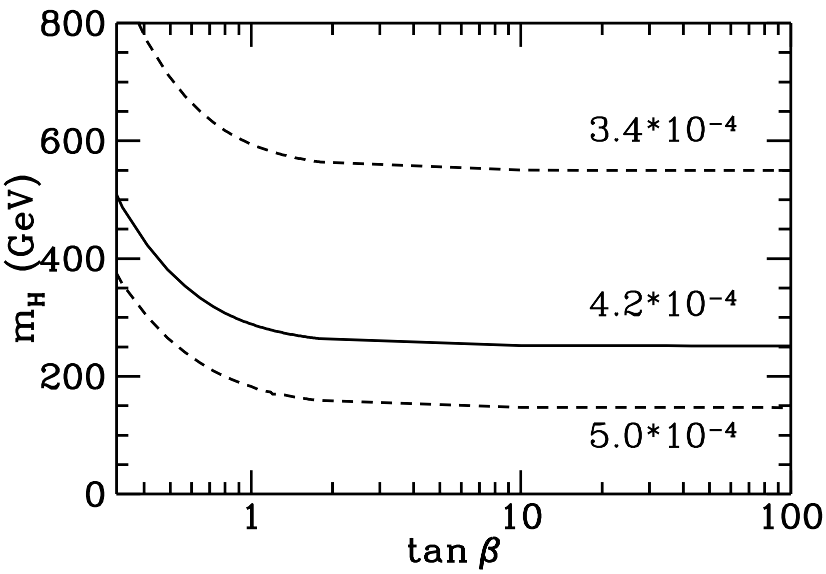
- Anomalous $WW\gamma$ couplings.

$$\mathcal{L}_{WW\gamma} = -ie[(W^{\dagger}_{\mu\nu}W^{\mu}A^{\nu} - W^{\dagger}_{\mu}A_{\mu}W^{\mu\nu}) + \kappa W^{\dagger}_{\mu}W_{\nu}F^{\mu\nu} + \frac{\lambda}{M_W^2}W^{\dagger}_{\alpha\mu}W^{\mu}_{\nu}F^{\alpha\nu}]$$

Ellipse from D0 assuming SM WWZ couplings



- Charged Higgs mass lower limit from $b \longrightarrow s\gamma$

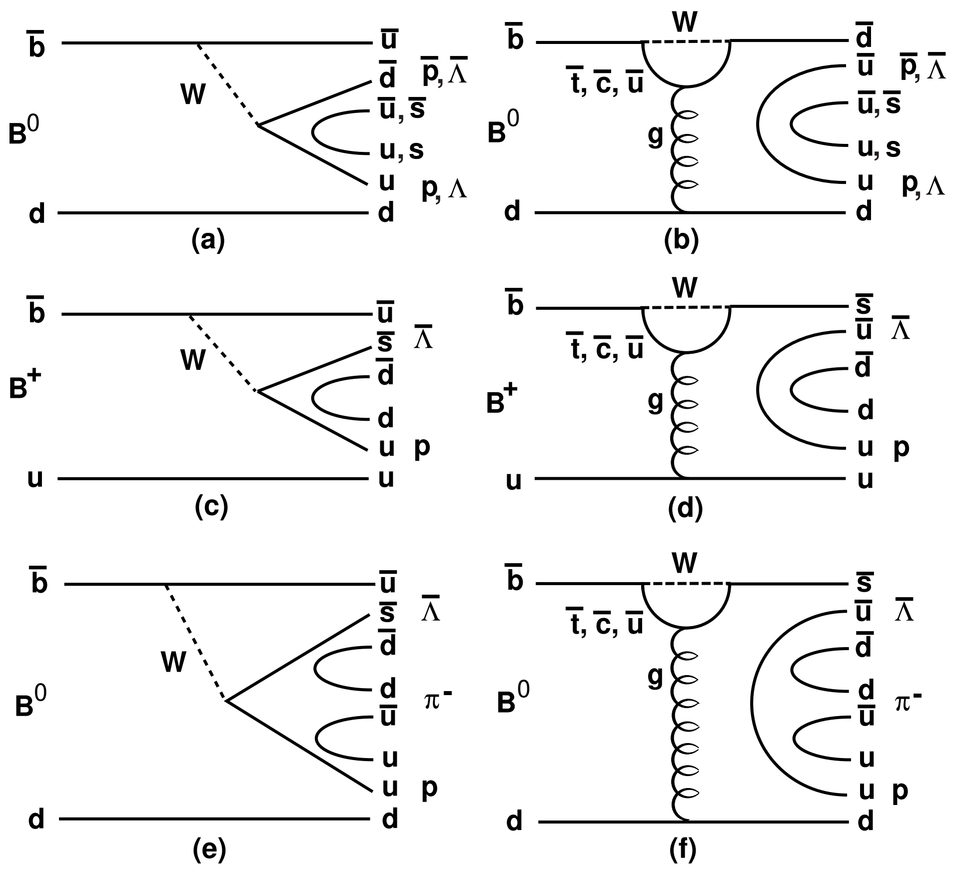


Allowed region for a given $\mathcal{B}(b \to s\gamma)$ upper limit. CLEO published 4.2×10^{-4} (95%CL)

NLO calculation by F. Borzumati and C. Greub

Limits on Higgs mass in Two Higgs Doublet Type II models as a function of VEV ratio $\tan\beta$.

Search for Exclusive Decays of B to Baryons



Tree Gluonic Penguin

- Most predictions assumed penguin contribution small.
- CLEO's observed $B \to K\pi$ rate $\Rightarrow$ large penguin contribution to those modes.
- Perhaps a surprise in the B decays to baryons as well ???

Search for Exclusive Decays of B to Baryons

Analyzing all CLEO II and first portion of CLEO II.5 data
(5.75×10^6 $B\overline{B}$ pairs)

Searching for $B^0 \to \Lambda\overline{\Lambda}$, $B^+ \to p\overline{\Lambda}$, $B^0 \to p\overline{\Lambda}\pi^-$ and $B^0 \to p\overline{p}$.

Beam-Constrained Mass $M_{BC} = \sqrt{E_b^2 - \mathbf{p}_B^2}$, where $\mathbf{p}_B$ is the B candidate momentum and E_b is the beam energy.

2.5 MeV/c^2 resolution on M_{BC}

Delta E $\equiv \Sigma E_i - E_b$, where E_i are the energies of the daughters that form the B meson candidate.
Centered at 0 MeV with a mode dependent width between 17-25 MeV.

Accept events with:

M_{BC} within 5.2-5.3 GeV/c^2

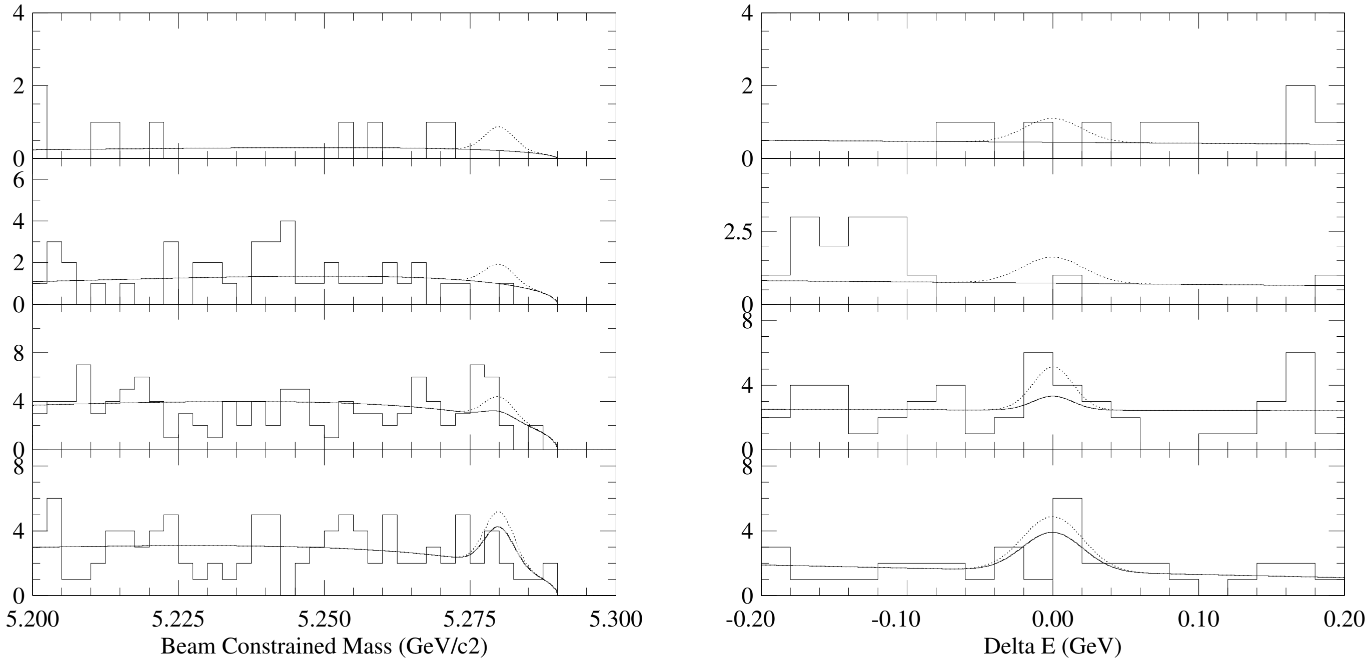
$|\Delta E| < 200$ MeV

$\Rightarrow$ B decay background $< 5\%$ of total

A likelihood fit used to determine yields. Inputs include: ΔE, M_{BC}, $\mathcal{F}$, Λ and $\overline{\Lambda}$ masses and dE/dx; $\mathcal{F}$ is the output of a Fisher discriminant based on energy and particle flow in the event. $\mathcal{F}$ provides $\sim 1.5\sigma$ of separation between $q\overline{q}$ background and signal.

Search for Exclusive Decays of B to Baryons

Projections of likelihood fit (solid) and 90% (CL) upper limit (dots)



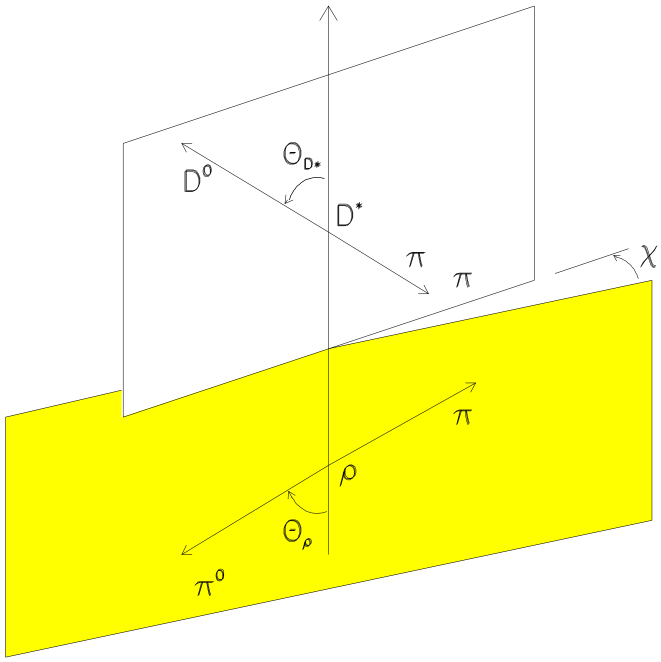
(a) $B^0 \to \Lambda\overline{\Lambda}$, (b) $B^+ \to p\overline{\Lambda}$, (c) $B^0 \to p\overline{\Lambda}\pi^-$ and (d) $B^0 \to p\overline{p}$

CLEO Preliminary

Observe no clear signal, so set 90% CL upper-limits:

Mode	CLEO	Theory
$\Rightarrow \mathcal{B}(B^0 \to \Lambda\overline{\Lambda})$	$< 3.9 \times 10^{-6}$	0.13×10^{-6}
$\Rightarrow \mathcal{B}(B^+ \to p\overline{\Lambda})$	$< 2.6 \times 10^{-6}$	$\simeq 3 \times 10^{-6}$
$\Rightarrow \mathcal{B}(B^0 \to p\overline{\Lambda}\pi^-)$	$< 13 \times 10^{-6}$	$\simeq 0.5 \times 10^{-6}$
$\Rightarrow \mathcal{B}(B^0 \to p\overline{p})$	$< 7.0 \times 10^{-6}$	$0.6 - 4.8 \times 10^{-6}$

Angular Distributions in $B \longrightarrow D^*\rho$



D^* and ρ helicity states:

$$|\mathbf{0},\mathbf{0}> \quad = \frac{3}{2\sqrt{2\pi}} cos\theta_{D^*} cos\theta_\rho$$

$$|\mathbf{1},\mathbf{1}> \quad = \frac{3}{4\sqrt{2\pi}} sin\theta_{D^*} sin\theta_\rho e^{i\chi}$$

$$|-\mathbf{1},-\mathbf{1}> \quad = \frac{3}{4\sqrt{2\pi}} sin\theta_{D^*} sin\theta_\rho e^{-i\chi}$$

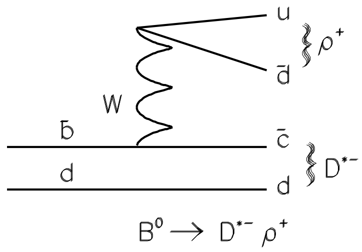
$\Rightarrow$ angular distribution, $\mathcal{D}(\theta_{D^*}, cos\theta_\rho, \chi)$, is the coherent sum

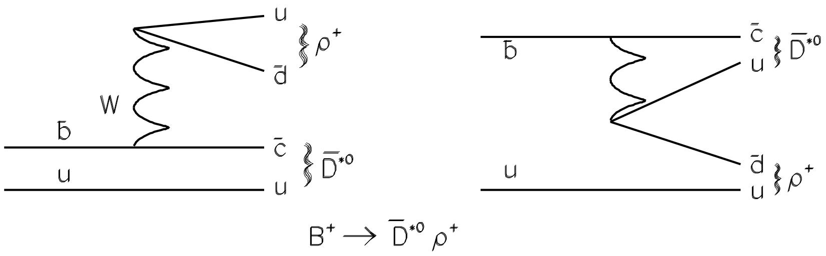
$$|\ H_0|\mathbf{0},\mathbf{0}> + H_+|\mathbf{1},\mathbf{1}> + H_-|-\mathbf{1},-\mathbf{1}>|^2$$

where H_0, H_+ and H_- are the complex amplitudes.

$$|H_0|^2 + |H_+|^2 + |H_-|^2 = 1$$

Angular Distributions in $B \longrightarrow D^*\rho$





$B^0 \rightarrow D^{*-}\rho^+$

$\quad D^{*-} \rightarrow \overline{D}^0\pi^-$

$B^+ \rightarrow D^{*0}\rho^+$

$\quad D^{*0} \rightarrow \overline{D}^0\pi^0$

In both cases: $\rho^+ \rightarrow \pi^+\pi^0$,

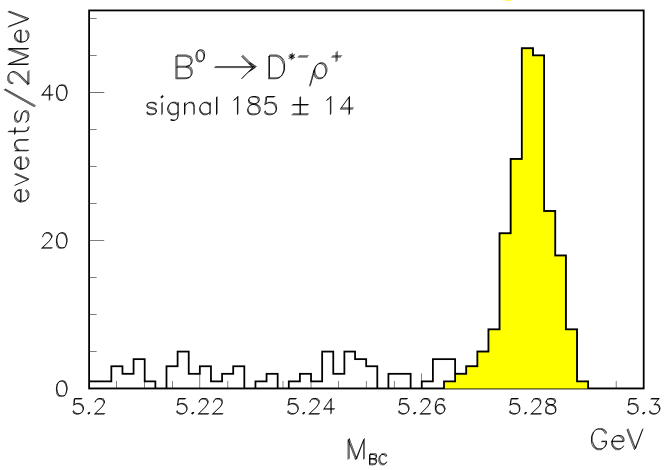
$\overline{D}^0 \rightarrow K^+\pi^-$

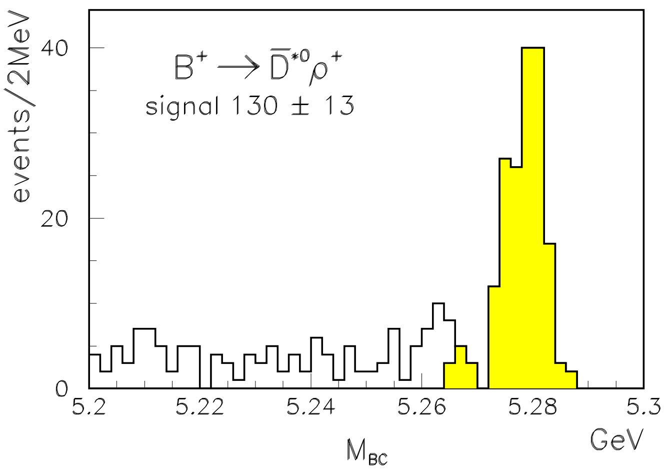
$\rightarrow K^+\pi^-\pi^0$

$\rightarrow K^+\pi^-\pi^+\pi^-$

A likelihood fit is performed using M_{BC} and the reconstructed M_ρ as well as the angular distribution $\mathcal{D}(\theta_{D^*}, cos\theta_\rho, \chi)$.

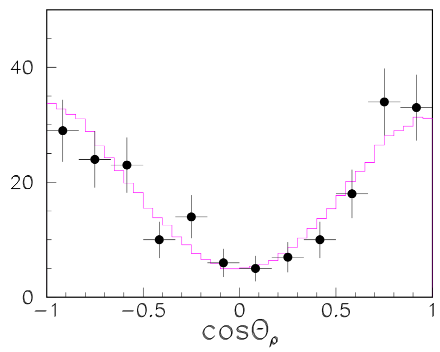
Shaded events used in the angular fit.

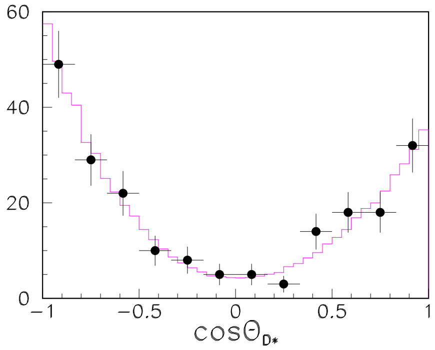




Angular Distributions in $B \longrightarrow D^*\rho$

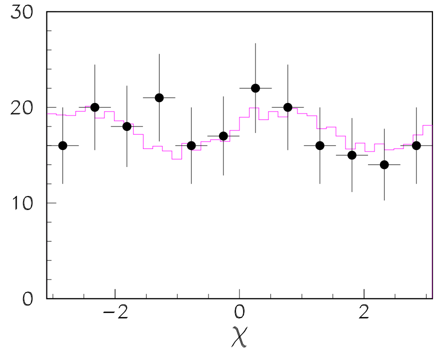
(CLEO Preliminary)





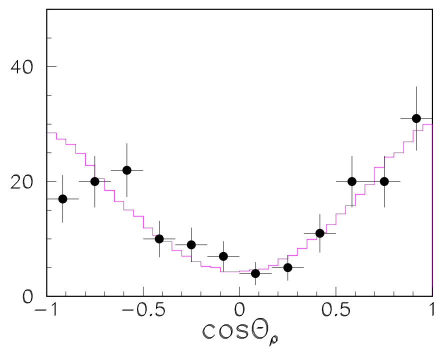
$B^0 \rightarrow D^{*+}\rho^-$

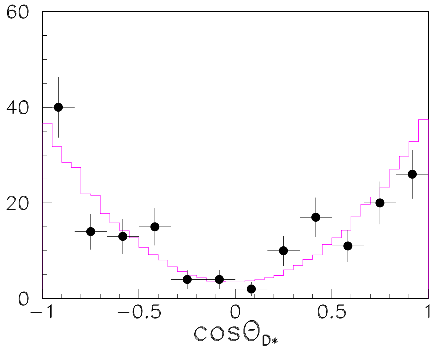
Likelihood fit projections on the angular distributions. (stat. errors)



$\lvert H_0 \rvert$	0.928	phase	0 (*reference*)
$\lvert H_+ \rvert$	0.165 ± 0.053	phase	1.56 ± 0.35
$\lvert H_- \rvert$	0.334 ± 0.059	phase	0.26 ± 0.22

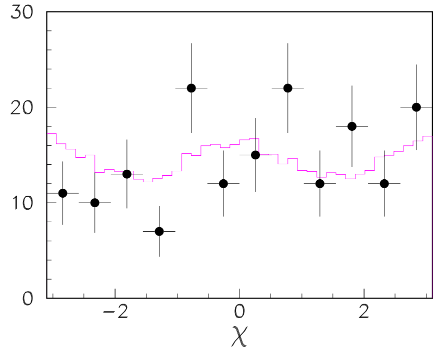
$$\frac{\Gamma_L}{\Gamma} = 0.86 \pm 0.05$$





$B^+ \rightarrow \overline{D}^{*0}\rho^+$

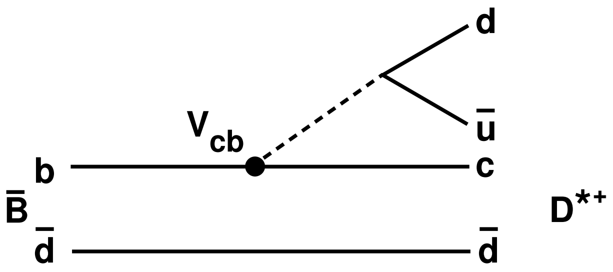
Likelihood fit projections on the angular distributions. (stat. errors)

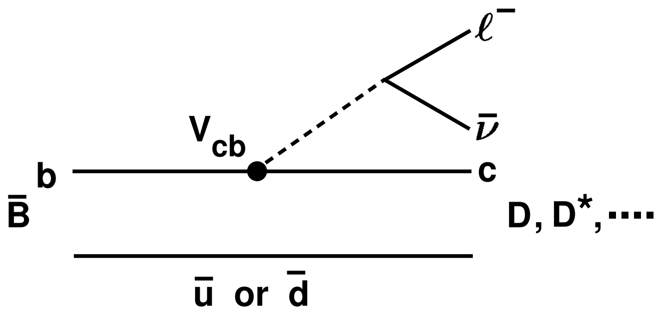


$\lvert H_0 \rvert$	0.923	phase	0 (*reference*)
$\lvert H_+ \rvert$	0.222 ± 0.069	phase	1.04 ± 0.33
$\lvert H_- \rvert$	0.306 ± 0.067	phase	1.18 ± 0.26

$$\frac{\Gamma_L}{\Gamma} = 0.86 \pm 0.06$$

Semi-leptonic Decays of B Mesons





- Test of factorization hypothesis - Longitudinal polarizations:
  - $B^0 \to D^{*+}\rho^-$ gave

$$\frac{\Gamma_L}{\Gamma} \equiv \frac{|H_0|^2}{|H_0|^2 + |H_+|^2 + |H_-|^2} = 0.86 \pm 0.05(stat)$$

  - CLEO measured the angular distributions of $B^0 \to D^{*-}l^+\nu$

$$\Rightarrow \left(\frac{\Gamma_L}{\Gamma}\right)_{q^2=m_\rho^2} = 0.914 \pm 0.152 \pm 0.089$$

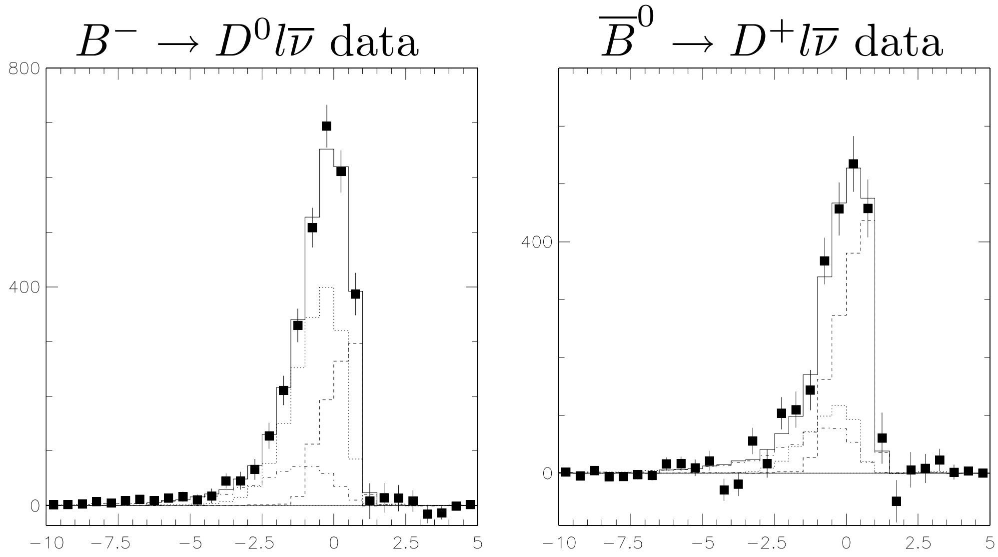
  - Theory predicts

$$\left(\frac{\Gamma_L}{\Gamma}\right)_{q^2=m_\rho^2} = 0.85 - 0.88$$

- Useful in determination of the CKM matrix elements.
  - No new $B \to D^*l\nu$ measurements from CLEO (yet)
  - No new $b \to u$ semileptonic measurements from CLEO
  - New $B \to Dl\nu$ measurements from CLEO
- Tests models of heavy quark decays

$B \longrightarrow Dl\nu$ Branching Ratios

(CLEO II Preliminary)



$\cos\theta_{B-Dl}$

$$\cos\theta_{B-Dl} = \frac{2E_B E_Y - M_B^2 - M_Y^2}{2|\vec{P}_B||\vec{P}_Y|}$$

- Fit for $Dl\overline{\nu}$ (*short dash*), $D^*l\overline{\nu}$ (*dots*) and $D^{**}l\overline{\nu} + D^{(*)}\pi l\overline{\nu}$ (*long dash-dots*) simultaneously, applying the isospin constraint that the vector to pseudo-scalar rates are the same for B^0 and B^+.
- Do not assume $f_{+-} = f_{00} = 0.5$ only $f_{+-} + f_{00} = 1$
- Assume $\Gamma_{B^-\to D^0 l\overline{\nu}} = \Gamma_{\overline{B}^0\to D^+ l\overline{\nu}} = \Gamma_{B\to Dl\overline{\nu}} \Rightarrow$

$$\Gamma_{B\to Dl\overline{\nu}} = (13.12 \pm 1.08 \pm 1,36)\mathrm{ns}^{-1}(\times\tau_{B^-}\ or\ \times\tau_{B^0})$$

$$\Rightarrow \mathcal{B}(B^- \to D^0 l\overline{\nu}) = (2.12 \pm 0.18 \pm 0.17)\%$$

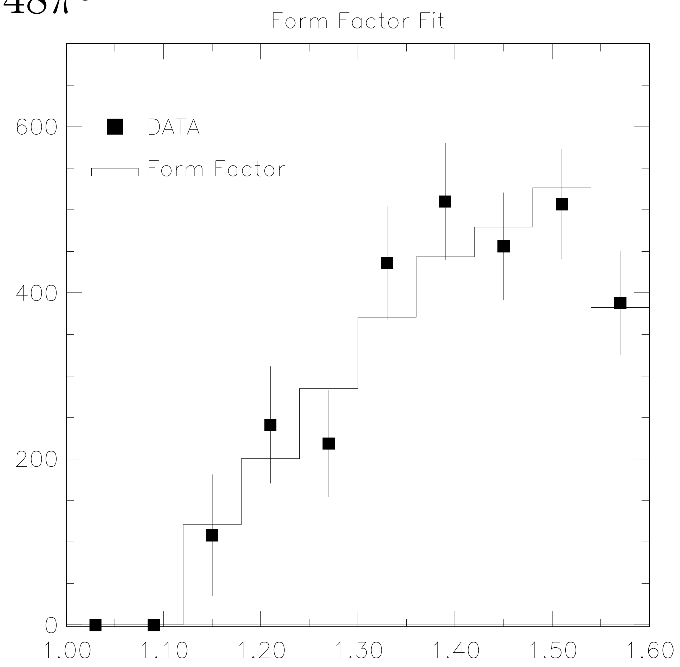
$$\Rightarrow \mathcal{B}(\overline{B}^0 \to D^+ l\overline{\nu}) = (2.05 \pm 0.18 \pm 0.20)\%$$

where the statistical errors on $\mathcal{B}$ are 100% correlated.

$B \longrightarrow Dl\overline{\nu}$ Form Factors and V_{cb}

Differential decay width:

$$\frac{d\Gamma}{dw} = \frac{G_F^2|V_{cb}|^2}{48\pi^3}(m_B + m_D)^2(m_D^3(w^2-1)^{3/2})F(w)^2$$



($\tilde{w}$ is the smeared version of w)

- $w \equiv v_B \cdot v_D = \frac{E_D}{M_D}$ in B rest frame ($w = 1$ at zero recoil).
- Form factor parameterized as:
  $F(w) = F(1)(1 - \hat{\rho}^2(w-1) + c(w-1)^2)$
- Theory $\Rightarrow$ slope is the same for $Dl\nu$ and $D^*l\nu$

$c = 0 \Rightarrow$ $\hat{\rho}^2 = 0.81 \pm 0.14$

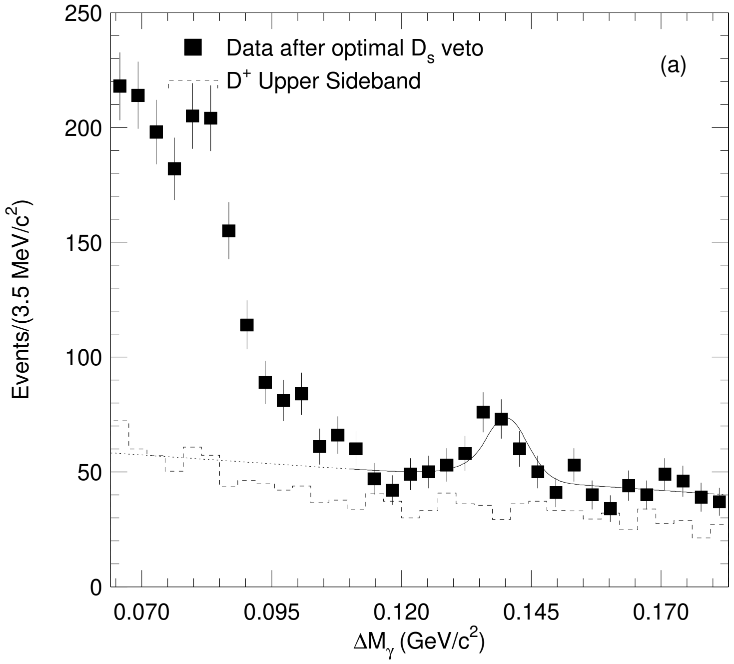
$$|V_{cb}|F(1) = (4.22 \pm 0.48) \times 10^{-2}$$

(with a correlation coefficient of 0.95 between the two quantities)

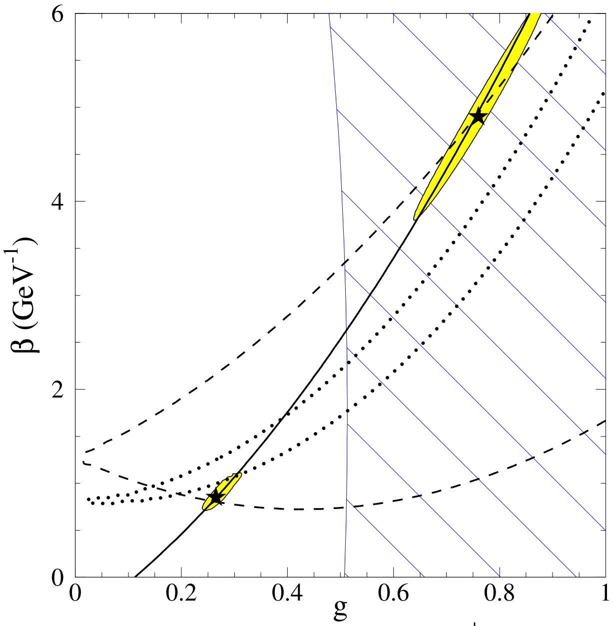
Consistent with CLEO's prior measurement based on reconstructing the neutrino. Form factor $\hat{\rho}^2$ is consistent with that from $B \rightarrow D^*l\nu$.

$D^{*+} \rightarrow D^+\gamma$

PRL May 4,1998



Iain Stewart hep-ph/9803227



Shaded area excluded by $\Gamma(D^{*+})$ limit

Measured the ratio $\frac{\mathcal{B}(D^{*+}\rightarrow D^+\gamma)}{\mathcal{B}(D^{*+}\rightarrow D^+\pi^0)} = 0.055 \pm 0.017$ which implies:

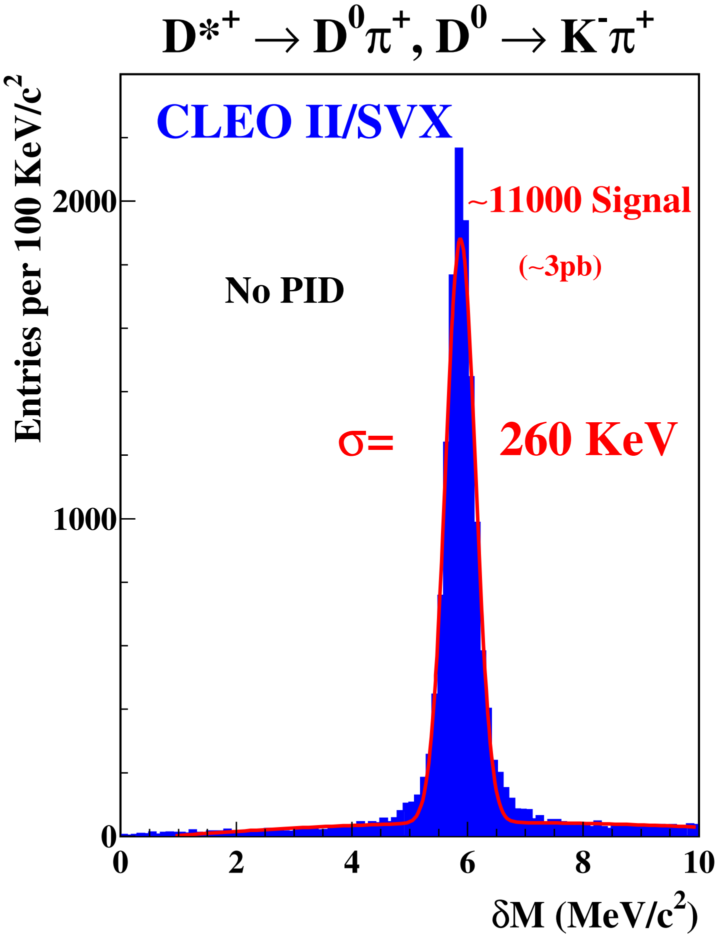
- $\mathcal{B}(D^{*+} \rightarrow D^+\gamma) = (1.7 \pm 0.5)\%$
- $\mathcal{B}(D^{*+} \rightarrow D^+\pi^0) = (30.7 \pm 0.6)\%$
- $\mathcal{B}(D^{*+} \rightarrow D^+\pi^+) = (67.6 \pm 0.7)\%$

When combined with the previously measured ratios $\frac{\mathcal{B}(D_s^{*+}\rightarrow D_s^+\pi^0)}{\mathcal{B}(D_s^{*+}\rightarrow D_s^+\gamma)}$ and $\frac{\mathcal{B}(D^{*0}\rightarrow D^0\gamma)}{\mathcal{B}(D^{*0}\rightarrow D^0\pi^0)}$ allows the extraction of the $D^*D\pi$ (g) and $D^*D\gamma$ (β) couplings within the framework of heavy meson chiral perturbation theory. The theory describes the data well and predicts $\Gamma(D^{*+}) = (22 - 39)$ keV or $(281 - 1157)$ keV (depending on which of the two solutions for g and β is used).

Perhaps CLEO can rule one of the solutions out in the future ???

CLEO II.5 Tracking and D^{*+}

δM is defined as $M(K^-\pi^+\pi_s^+) - M(K^-\pi^+) - M(\pi_s^+)$
Excellent resolution has already been achieved, but to push the limit on $\Gamma(D^{*+})$ (currently at 131 keV from the ACCMOR collaboration) will take a much better understanding of our charged particle tracking resolution on π_s^+.
⇒ This measurement will have to wait.

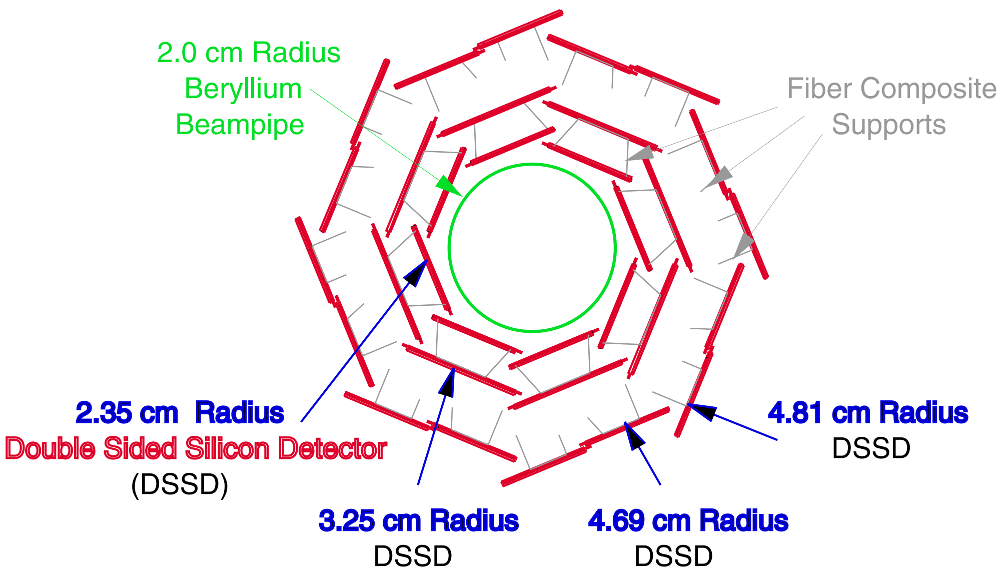


However, what has already been achieved is substantial. The improvements were made possible by three changes between CLEO II and CLEO II.5:

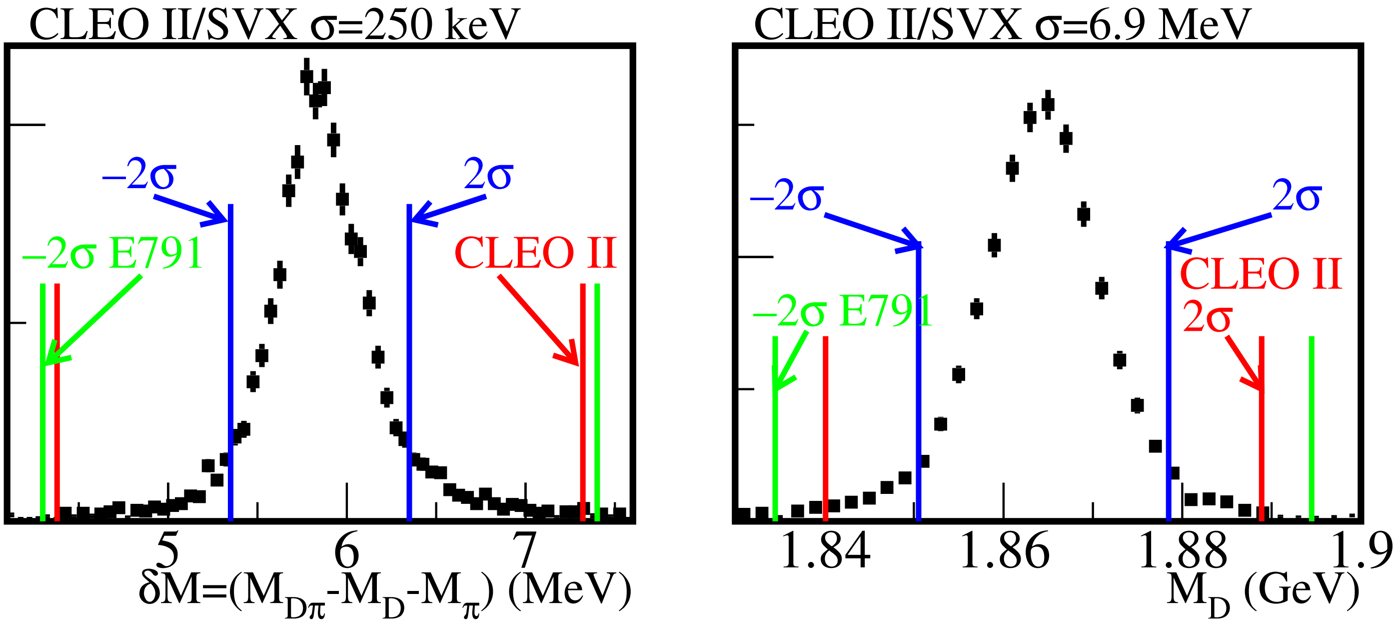
1. Kalman filter based tracking code
2. He-Propane drift gas
3. Silicon Vertex detector

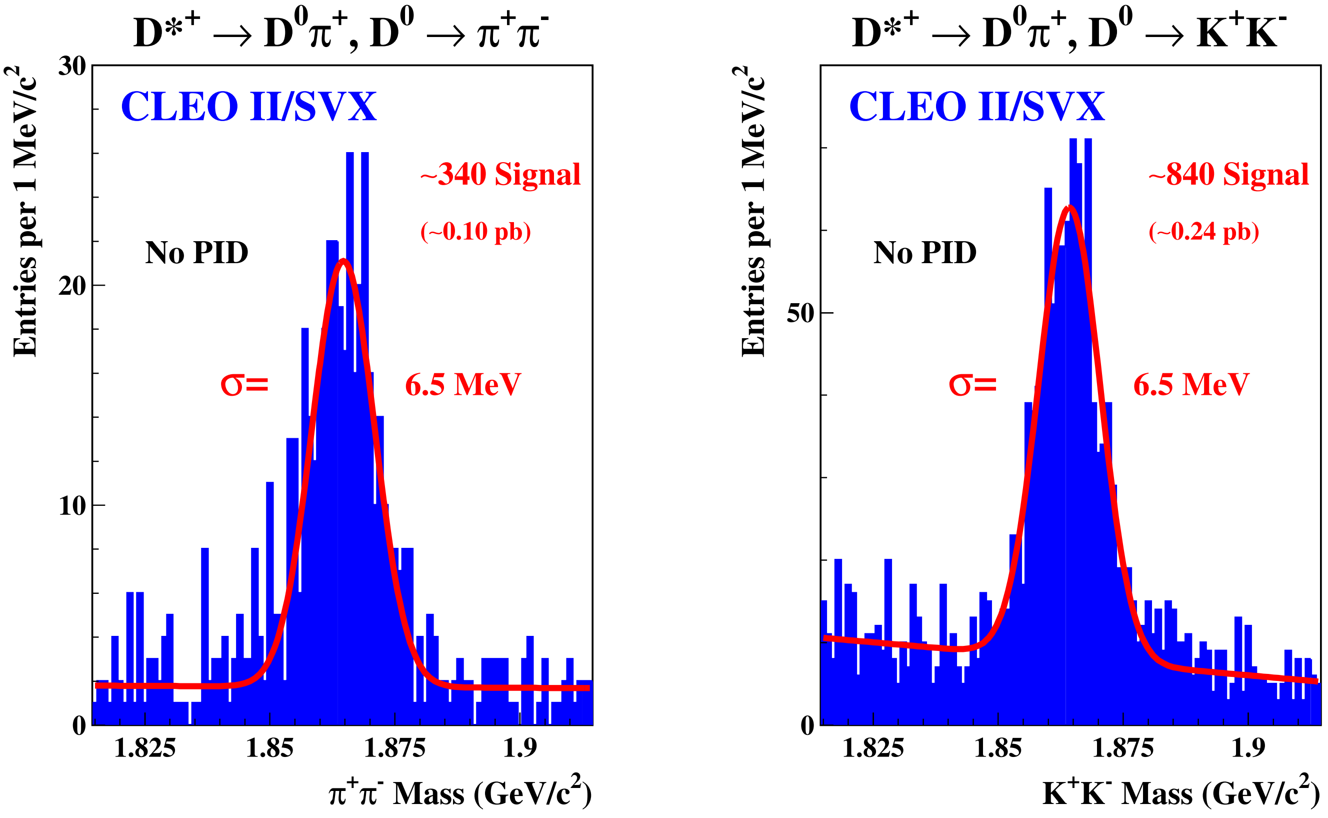
The CLEO II.5 Upgrade

- Kalman filter provides optimal fit for tracks taking energy loss and multiple scattering into account.
- He-Propane drift gas
  - reduces X_0 by a factor 0.61
  - increases hit efficiencies near edges of drift cells
- 3-layers of double sided silicon strip detectors
  - rϕ: S/N about 15/1, $\sigma = 24 \oplus 42/(psin^{3/2}\theta)$ μm
  - rz: S/N about 10/1, $\sigma = 54 \oplus (48/p)$ μm
  - Hit Efficiency: 95% per track for ≥ 2 hits in both coordinates



Background Reduction



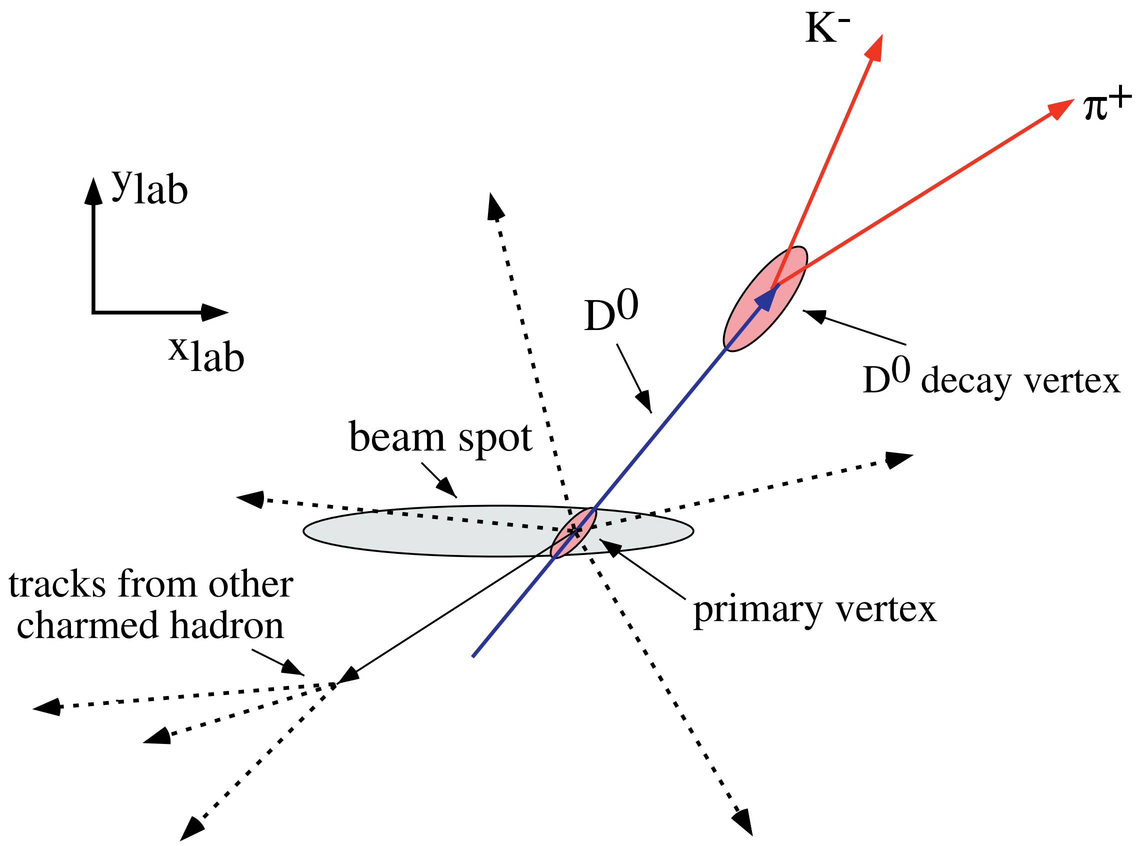


Cabibbo Suppressed Modes

Charm Meson Lifetimes

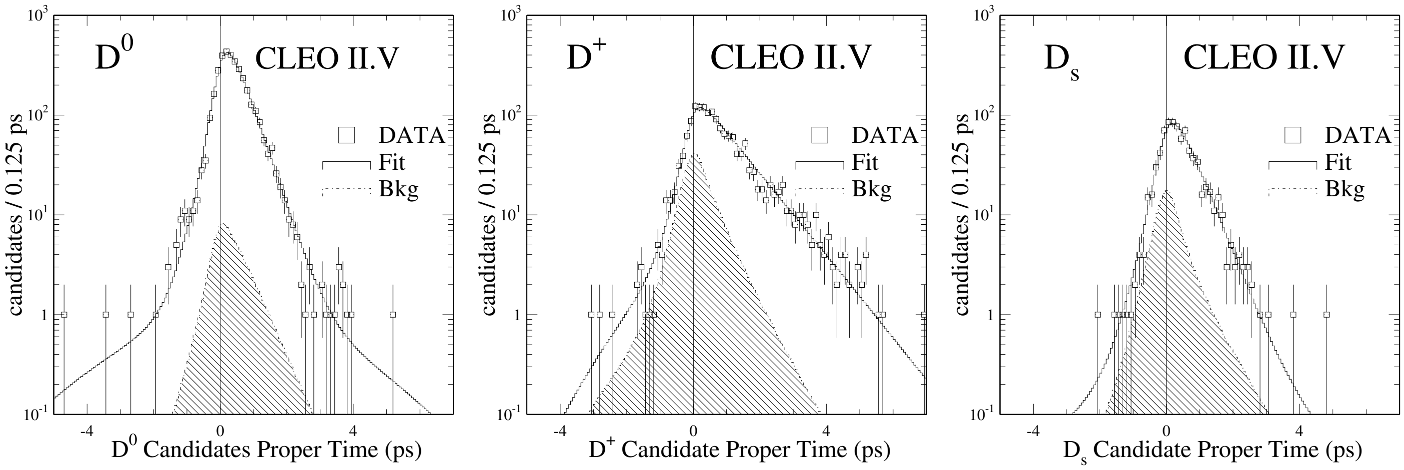
- $\approx 1.6\ \mathrm{fb}^{-1}$ or 1.9 million $c\bar{c}$ pairs of CLEO II.5 data.
- D^0 Lifetime ($D^{*+} \to D^0\pi_s^+, D^0 \to K^-\pi^+$):
  - $M(K\pi)$ within 48 MeV/c^2 of expected
  - δM within 0.8 MeV/c^2 of expected
  - $P_{K\pi\pi} > 2.5$ GeV/c
  - background $\sim 3\%$ within $\pm 2\sigma$ of $M(D^0)$
- D^+ Lifetime ($D^{*+} \to D^+\pi_s^0, D^+ \to K^-\pi^+\pi^+$):
  - $M(K\pi\pi)$ within 48 MeV/c^2 of expected
  - δM within 1.4 MeV/c^2 of expected
  - $P_{K\pi\pi\pi^0} > 2.5$ GeV/c
  - background $\sim 21\%$ within $\pm 2\sigma$ of $M(D^+)$
- D_s Lifetime ($D_s^+ \to \phi\pi^+, \phi \to K^+K^-$):
  - $M(KK)$ within 48 MeV/c^2 of expected
  - M_{KK} within 6 MeV/c^2 of M_ϕ
  - $P_{\phi\pi} > 2.5$ GeV/c
  - decay angle cuts
  - background $\sim 17\%$ within $\pm 2\sigma$ of $M(D_s)$
- χ^2 consistent with a common vertex
- Decay length uncertainty $< 200\mu$m.

Charm Meson Lifetimes



1. Reconstruct D^0 vertex in 2 dimensions and build D pseudo-track.
   - D^0 decay vertex resolution is $\sim$ 100 μm along D^0 flight direction.
   - mean D^0, D^+ and D_s flight distances are 200 μm, 480 μm and 250 μm respectively
2. Find intercept of D pseudo-track and beam spot ellipse ($\sigma_x = 350$ μm, $\sigma_y = 10$ μm).
   - unbiased measurement of interaction point (IP)
   - IP resolution depends on the D azimuthal angle ϕ

Charm Meson Lifetimes



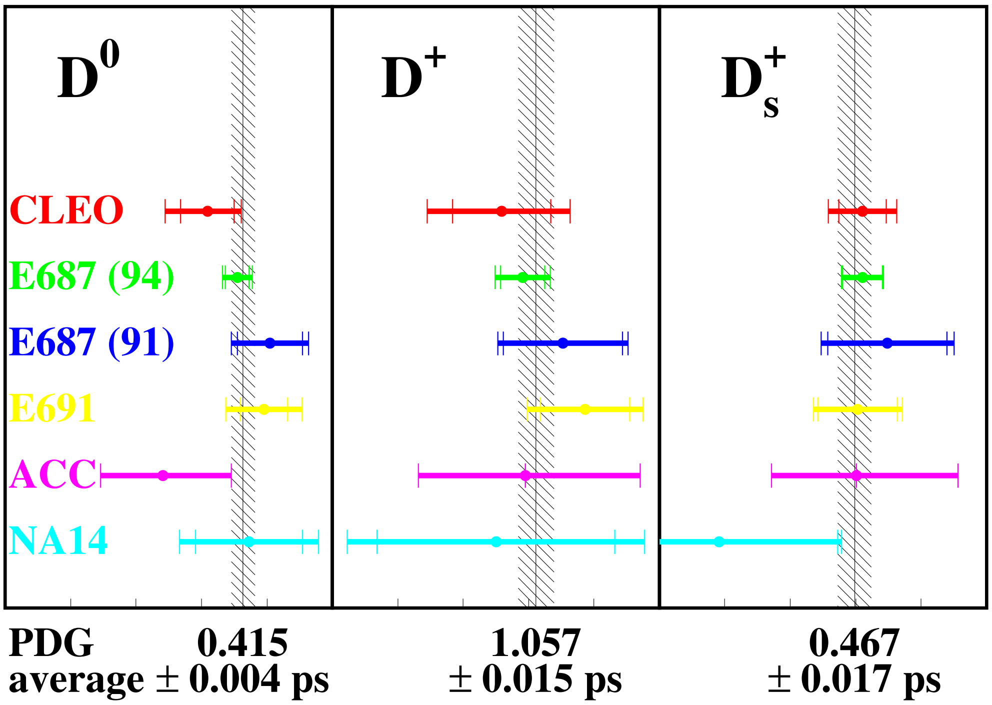
The average proper time uncertainty is **0.2 ps** for the candidates.

Charm Meson lifetimes extracted by a six parameter unbinned log-likelihood fit (all parameters obtained from data).

- τ_{Sig} - signal lifetime
- $f_{\tau-BG}$ - background fraction with non-zero lifetime
- τ_{BG} - background lifetime
- S - proper-time uncertainty scale factor
- f_{mis} - fraction of mis-measured candidates
- σ_{mis} - proper-time uncertainty for them

All Systematic uncertainties determined from data.
Results obtained with 1.6 fb^{-1} of CLEO II.5 data (by the end of the year $\sim$8 fb^{-1} will have been accumulated by CLEO II.5).

Charm Meson Lifetimes



(CLEO Preliminary)

Parameter	D^0	D^+	D_s^+
$\tau_{\rm Sig}$	0.403 ± 0.009 ps	1.034 ± 0.033 ps	0.475 ± 0.024 ps
$\tau_{\rm BG}$	0.530 ± 0.081 ps	0.529 ± 0.064 ps	0.704 ± 0.116 ps
$f_{\tau_{\rm BG}}$	0.67 ± 0.10	0.38 ± 0.04	0.22 ± 0.05
S	1.54 ± 0.04	1.47 ± 0.05	1.57 ± 0.06
$f_{\rm mis}$	0.014 ± 0.003	0.052 ± 0.014	0.009 ± 0.006
$\sigma_{\rm mis}$	2.8 ps $\pm$ 0.4 ps	1.66 ± 0.20 ps	2.7 ± 0.82 ps
χ^2/DOF	84/95	79/95	60/95

Conclusion

- Updated (using the full CLEO II dataset of 3.3×10^6 $B\overline{B}$ pairs) of CLEO's first measurement of $b \rightarrow s\gamma$.
- Searched for **rare barionic decays of B mesons** and set limits at or approaching theoretical expectations.
- First indications of final state interactions in $B \rightarrow D^*\rho$ from the measurement of the helicity amplitudes.
- New measurement of $B \rightarrow Dl\nu$ branching fraction and its form factor.
- Measurement of the **charm meson lifetimes** using a subset of the CLEO II.5 (CLEO II + Silicon) dataset.
- Many analyses are in progress and results are almost in hand.
  - Charmless two body modes ($\pi\pi$, $K\pi$ as well as modes involving η, η', ω, ...).
  - Update on $b \rightarrow s\gamma$ with $\approx 70\%$ more data and an improved method.
  - Competitive charm lifetimes ($> 2\times$ the luminosity and improved methods).
  - Measurement of the branching fractions and lifetimes of the D^0 to KK, $\pi\pi$ (and a little later $K_s\phi$).
- CLEO III scheduled to be installed early next year (RICH, 4-layer silicon, new drift chamber and yet higher luminosity).