CLEO Results & Plans

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CLEO has pioneered many studies and measurements in the field of b-quark physics for over twenty years.

In 2002, CESR will broaden its range of operation at high luminosity to include the $\bar{c}c$ resonance & charm threshold regions as well as the Upsilon resonances.

I will present some recent CLEO results and then turn to the plans for the future.

CLEO & CESR at the $\Upsilon(4S)$

Features at the $\Upsilon(4S)$:

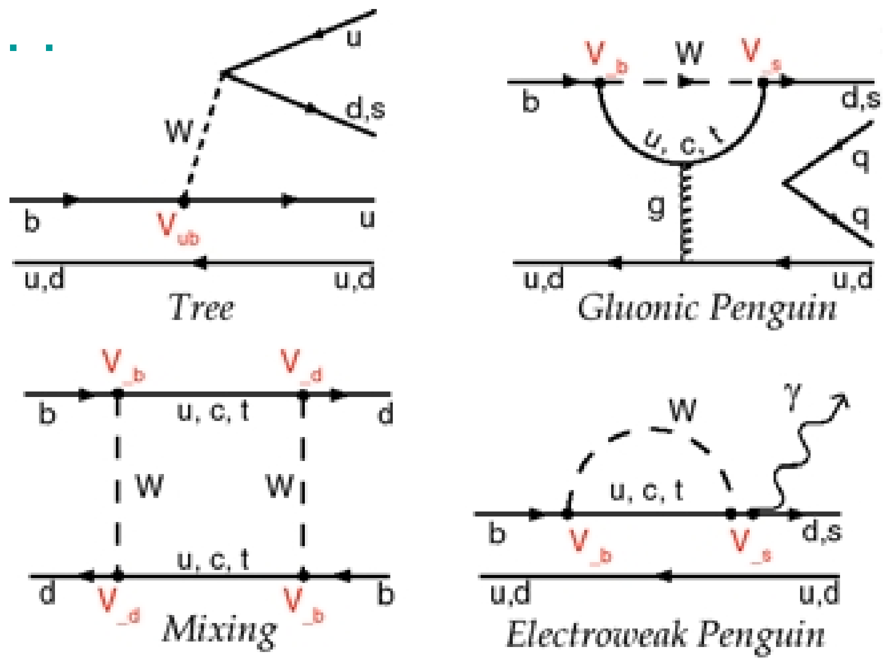
- Symmetric e^+e^- collisions at the $\Upsilon(4S)$, very close to $\bar{B}B$ threshold. $p_B \sim 300$ MeV/c, $E_B = E_{beam}$.
- $\sigma_{bb} \sim 1\text{nb}$; σ_{qq} (bkgnd.) ~ 3 nb. "Continuum" data obtained just below $\Upsilon(4S)$ for subtraction .
- All of the results presented here represent data collected in CLEO-II & CLEO-II.V configurations.
  - 9.1 fb^{-1} ON-4S, (9.7M $\bar{B}B$ evts.); 4.4 fb^{-1} below 4S.
- CESR has run with a peak luminosity of 1.3 x 10^{33} $cm^{-2}s^{-1}$ in the past year, collecting ~ 9.3 fb^{-1} in the CLEO-III configuration [see LP01].

Some Recent CLEO Results

- Rare *B* Decays & Direct *CP* Violation studies.
  - More than 60 Charmless *B*-decay modes measured by CLEO.
  - Electromagnetic & Gluonic Penguin- (loops) & box- diagrams: Measured Br ~ $10^{-6} - 10^{-4}$.
  - *CP* asymmetries and limits.
- Semileptonic *B* Decays & *CKM* matrix elements.
  - Inclusive & Exclusive leptonic decays, $|V_{ub}|$ & $|V_{cb}|$.
- Search for New Physics via Mixing & *CP* Violation in Charm Decays.
  - "*Wrong-sign*" decays and limits on mixing.
  - *CP* Asymmetries in D^0 Decays.
  - Lifetime Differences in D^0 Decays to *CP*-eigenstates: mixing.

Rare *B* Decays

- Rare *B* decays are a useful probe of new physics, & branching ratios are reasonable as V_{cb} is small. ($Br(\text{rare } B) \sim 10^{-6} - 10^{-4}$, while $Br(\text{rare } K) \sim 10^{-10} - 10^{-12}$.)
- Box & loop diagrams can involve new physics, Higgs, *SUSY* . . . replacing *W*.



Rare *B* Modes & bounds on *CP* Asymmetries

- Charmless hadronic modes:
  - $B \to \phi K$, ϕK^*, $\eta' K$, ηK^* : any surprises? ($\eta' K$ unusually large (CLEO 1997))
  - $B \to K\pi$, $\pi\pi$, KK : B r F & bounds on direct *CP* violation.
- Radiative Decays:
  - Inclusive $b \to s\,\gamma$: *CP* asymm.; γ–spectrum; *HQET* parameters; Fermi motion of *b* quark in *B* meson.
  - $B \to K^* \gamma$: *CP* asymmetry
  - $B \to K\ell\ell$, $K^*\ell\ell$: FCNC, new *u.l.* within 50% of SM.
  - $\bar{B}B \to \ell\ell$: *CP* asymmetry in dileptons (mixing).

Direct *CP* Violation in *B* decays

- Direct *CP* violation arises if there is a difference between amplitudes for ($\bar{B} \rightarrow \bar{f}$) & ($B \rightarrow f$).
  - Requires two or more interfering processes in the decay.
  - Non-zero differences in *both* weak & strong phases.
  - *CP*-violating weak phase may arise from *CKM* phase or from *new physics*.
  - Tree & loop diagrams can interfere in this way.
  - Hard to predict asymmetry as strong amplitudes & phases are unknown.
- Asymmetry parameter:

$$\mathcal{A}_{CP} \equiv \frac{\mathcal{B}(\bar{B} \rightarrow \bar{f}) - \mathcal{B}(B \rightarrow f)}{\mathcal{B}(\bar{B} \rightarrow \bar{f}) + \mathcal{B}(B \rightarrow f)}$$

Charmless hadronic modes

Typical analysis technique:

- Signal candidate variables:
  - Beam-energy constraint:

    $E_{Cand.} \approx E_{beam}$

    $$M_{Cand.} \equiv \sqrt{E_{beam}^2 - |\mathbf{p}_{cand.}|^2}$$

    σ_m ~ 2.5 MeV (3.0 MeV if π^0)

  - Energy difference

    $$\Delta E \equiv \left(E_{cand.} - E_{beam}\right)$$

    σ_E ~ 20-25 MeV, mode dependent.

    ~ 40-50 MeV if π^0 .

  - dE/dx and ΔE for PID.

- Background rejection:
  - Mainly $e^+e^- \rightarrow qq$ continuum,

    (negligible from other *B* decays.)

Continuum suppression variables:

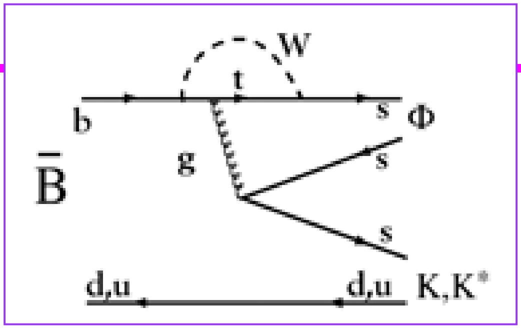
Two-jet *vs.* spherical *BB* event:

- *angle of Thrust axis*.
- *Fischer Discriminant F :*

  Linear combination of 11 shape variables:
  - *Angle of Sphericity axis* $\cos\vartheta$.
  - *Fox-Wolfram ratio* R_2.
  - *Energy flow into nine* (10^o) *cones around Sphericity axis.*

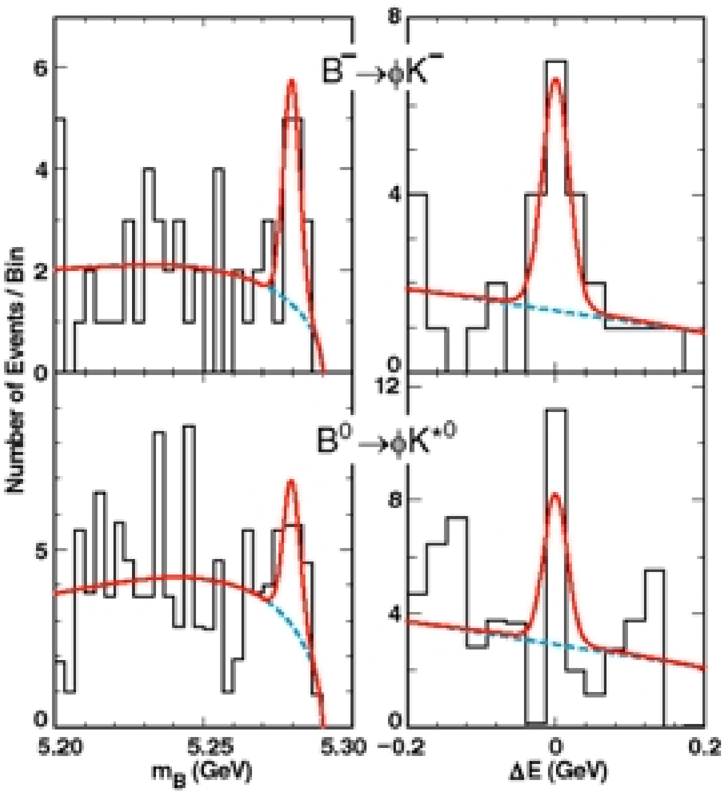
Maximum Likelihood fit using all variables.

B decays to ϕK & ϕK^* :



- A *gluonic penguin* with no $\bar{B}B$ bkgnd. ⇒ a *clean signature*.
- Maximum likelihood fits for each topology:
  - ϕK^- , ϕK^0 ,
  - ϕK^* with $K^* \to K^- \pi^+$
    $K^* \to K^- \pi^0$
    $K^* \to K^0 \pi^-$
    $K^* \to K^0 \pi^0$
  - *Variables:*
    - m_B, ΔE, $\cos\theta_B$, $\cos\theta_{Thrust}$
    - m_ϕ, m_{K*}, , $(dE/dx)_K$

:

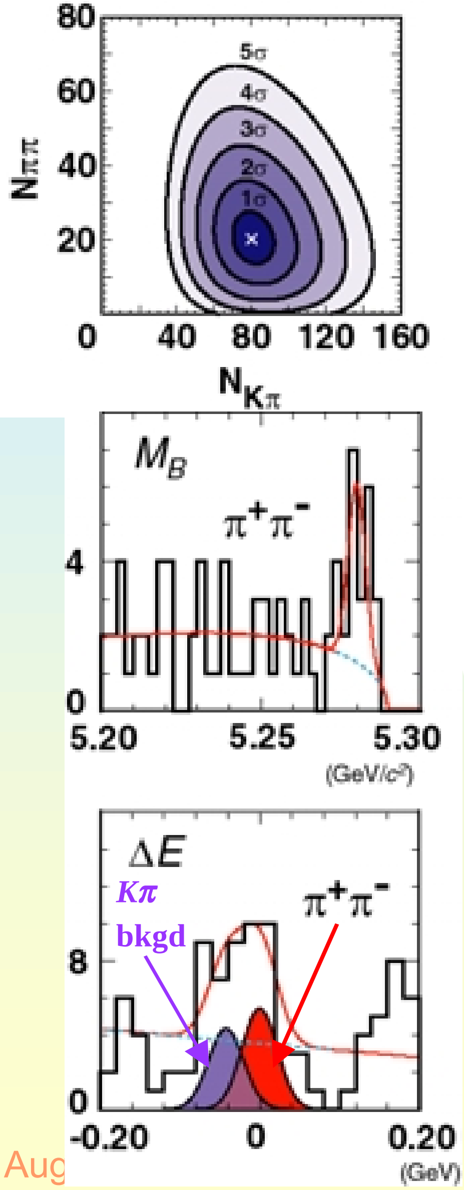


$B \rightarrow \phi K$ & ϕK^* : Results

- **CLEO 2001:** [hep-ex/0101032], PRL **86**, 3718 (2001)

Decay Mode	CLEO (9.7M $B\bar{B}$)				Theory BF(10^{-6})
	Yield	Eff. (%)	Stat. Signif.	BF (10^{-6})	
ϕK^-	$14.2^{+5.5}_{-4.5}$	54	5.4σ	$5.5\,^{+2.1}_{-1.8} \pm 0.6$	0.7 - 16
ϕK^0	$4.2^{+2.9}_{-2.1}$	48	2.9σ	< 12.3	0.7 – 13
$B \Rightarrow \phi K$			6.1σ	$5.5\,^{+1.8}_{-1.5} \pm 0.7$	
$\phi K^{*0}_{\to K^-\pi^+}$	$12.1^{+5.3}_{-4.3}$	38	4.5σ		
$\phi K^{*0}_{\to K^0\pi^0}$	$5.1^{+3.9}_{-2.8}$	20	2.7σ		
$B \Rightarrow \phi K^{*0}$			5.1σ	$11.5\,^{+4.5}_{-3.7}\,^{+1.8}_{-1.7}$	0.2 - 31
$\phi K^{*-}_{\to K^-\pi^0}$	$3.8^{+4.1}_{-2.8}$	25	1.5σ		
$\phi K^{*-}_{\to K^0\pi^-}$	$4.0^{+2.1}_{-2.2}$	32	2.7σ		
$B \Rightarrow \phi K^{*-}$			3.1σ	< 22.5	0.2 - 31
$B \Rightarrow \phi K^*$			5.9σ	$11.2\,^{+3.6}_{-3.1}\,^{+1.8}_{-1.7}$	

B decays to $\pi\pi$ & $K\pi$ modes:



CLEO: PRL **85**, 515 (2000)

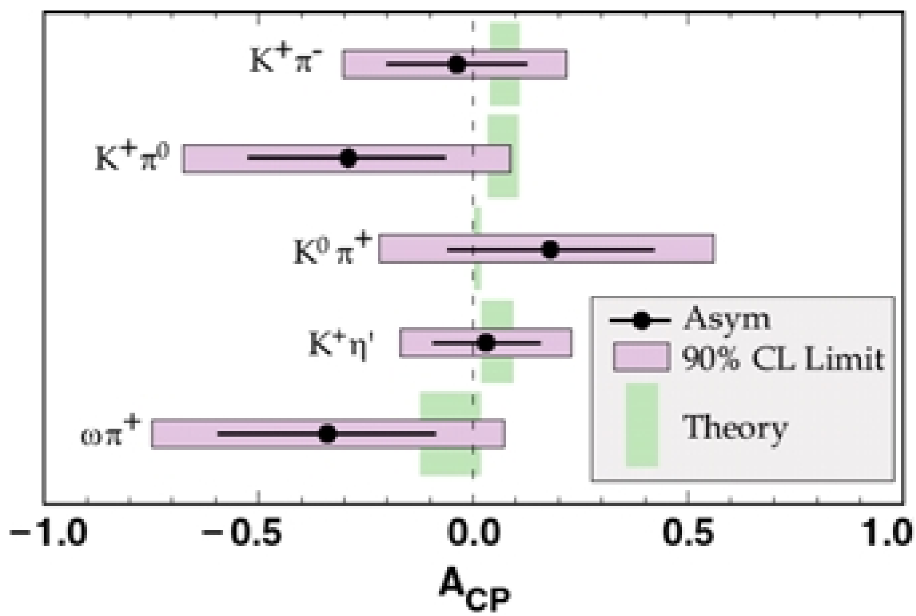
Decay Mode	CLEO (9.7M $B\bar{B}$)				Theory BF (10^{-6})
	N_{Signal}	Signif.	Effic. (%)	BF(10^{-6})	
$\pi^+\pi^-$	$20.0^{+7.6}_{-6.5}$	4.2σ	48	$4.3^{+1.6}_{-1.4} \pm 0.5$	8-26
$\pi^+\pi^0$	$21.3^{+9.7}_{-8.5}$	3.2σ	39	< 12.7	3-20
$\pi^0\pi^0$	$6.2^{+4.8}_{-3.7}$	2.0σ	29	< 5.7	0.3-4.6
$K^+\pi^-$	$80.2^{+11.8}_{-11.0}$	11.7σ	48	$17.2^{+2.5}_{-2.4} \pm 1.2$	7-24
$K^0\pi^+$	$25.2^{+6.4}_{-5.6}$	7.6σ	14	$18.2^{+4.6}_{-4.0} \pm 1.6$	3-15
$K^+\pi^0$	$42.1^{+10.9}_{-9.9}$	6.1σ	38	$11.6^{+3.0}_{-2.7}{}^{+1.4}_{-1.3}$	8-26
$K^0\pi^0$	$16.1^{+5.9}_{-5.0}$	4.9σ	11	$14.6^{+5.9}_{-5.1}{}^{+2.4}_{-3.3}$	3-9
K^+K^-	$0.7^{+3.4}_{-0.7}$	–	48	< 1.9	–
K^+K^0	$1.4^{+2.4}_{-1.3}$	1.1σ	14	< 5.1	0.7-1.5
$K^0\bar{K}^0$	0	–	5	< 17	–

BaBar & BELLE: recent new results confirm CLEO measurements ......

CP Asymmetries in $B \rightarrow hh$

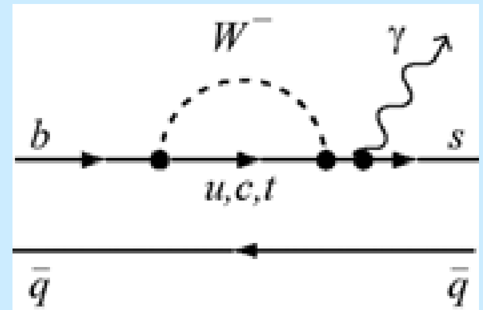
- Charge asymmetries measured in two-body hadronic "*self-tagging*" modes.[**CLEO** PRL **85**,525 (2000)]
- No significant asymmetry found.
- *SM* theory: Ali, Kramer & Lü, PRD 59,014005 (1999).

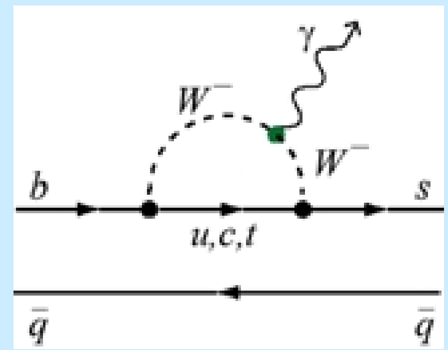
Mode	Yield	A_{CP}
$K^{\pm}\pi^{\mp}$	$80.2^{+11.8}_{-11.0}$	-0.04 ± 0.16
$K^{\pm}\pi^{0}$	$42.1^{+10.9}_{-9.9}$	-0.29 ± 0.23
$K^{0}\pi^{\pm}$	$25.2^{+6.4}_{-5.6}$	$+0.18 \pm 0.24$
$K^{\pm}\eta'$	100^{+13}_{-12}	$+0.03 \pm 0.12$
$\omega\pi^{\pm}$	$28.5^{+8.2}_{-7.3}$	-0.34 ± 0.25

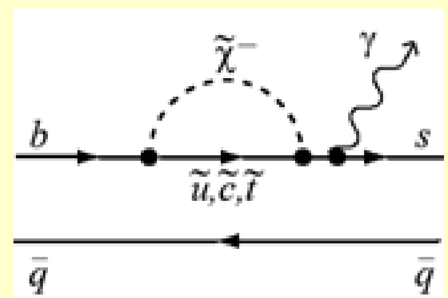


Radiative *B* Decays: $b \to s\,\gamma$

- FCNC $b \to s$ through loops
  - *SM* involves $V_{tb}V_{ts}$
  - New Physics?
    - Charged Higgs?
    - Chargino?
    - Anomalous $WW\gamma$ coupling?
    - ………?
- Theory (SM) predicts:
  - BF$(b \to s\,\gamma)$ = (3.73 ± 0.30)10^{-4}
    - [Gambino & Misiak, hep-ph/0104034]
- Measure *inclusive* γ spectrum:
  - Branching fraction & A_{CP}
  - Fermi motion of b quark in *B* meson
  - HQET parameter $\bar{\Lambda}$ from moments of E_γ spectrum.



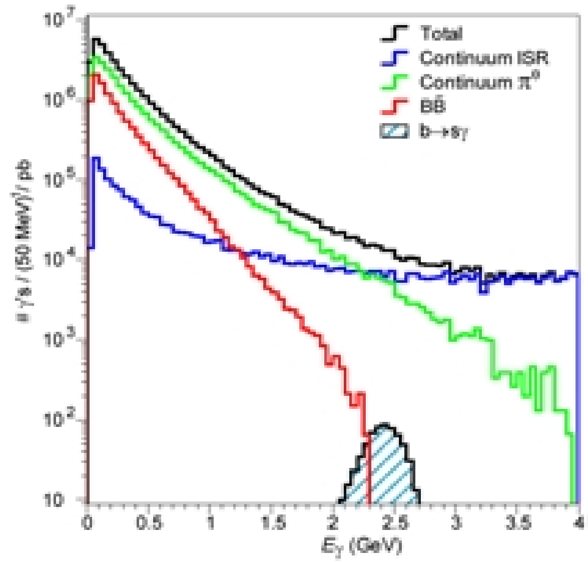




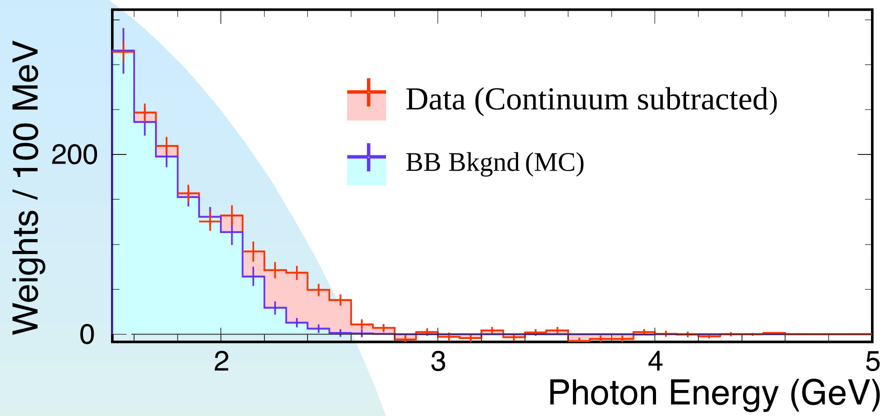
$b \rightarrow s\,\gamma$: Measuring the photon spectrum

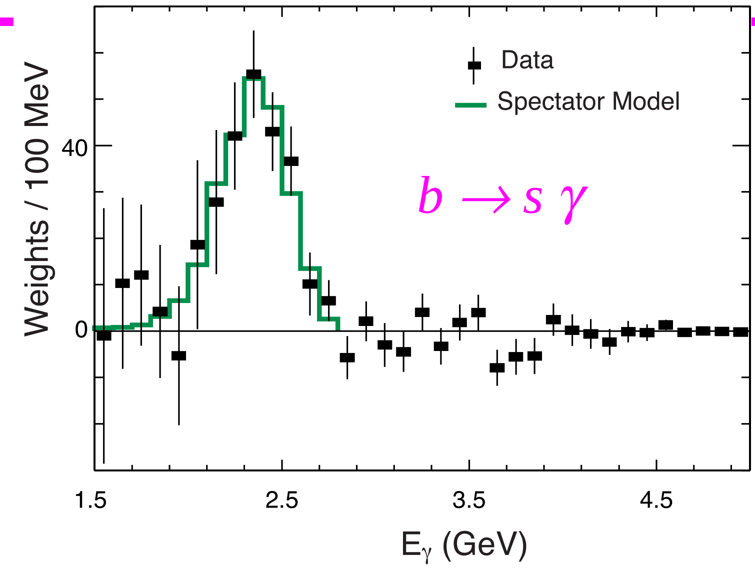
- Mono-energetic photon, $E_\gamma = m_B/2$, (smeared by Fermi motion of b quark in B).
- Measure E_γ spectrum ON-4S & OFF-4S ($e^+e^- \rightarrow q\bar{q}$ continuum).
- Huge $q\bar{q}$ bkgnd must be suppressed.
  - Veto photons from π^0 & η.
  - Eight shape variables combined.
  - "Pseudo reconstruction" of X_S :$(K+n\pi)$
  - High momentum $\boldsymbol{P}_{lepton}$ where available.
  - Combine available variables in neural nets, calculate weights $w(r_j)$
  - Sum w's for ON-4S and OFF-4S.
- Subtract surviving continuum spectrum.
- Model $B\bar{B}$ bkgnd & subtract.

Expected Raw Contributions



$b \to s\,\gamma$: Energy Spectrum





- Fit the energy spectrum for P_{Fermi} & $\langle m_b \rangle$ & obtain moments (E_γ>2GeV):

$$\langle E_\gamma \rangle = 2.346 \pm 0.032 \pm 0.011 \text{ GeV}$$

$$\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2 = 0.0226 \pm 0.0066 \pm 0.0020 \text{ GeV}^2$$

- HQET & O.P.Expansion: express moments in powers of α_s & $1/M_B$ to obtain $\bar{\Lambda} = 0.35 \pm 0.08 \pm 0.10$ GeV

Theory: Ligeti *et al.*, PRD **60** 034019 (1999) & C.Bauer, PRD **57**, 5611(1998)

$b \to s\,\gamma$: Branching Fraction

- Yield measured for ($2.0 < E_\gamma < 2.7$ GeV)
  - Signal efficiency (weight per event) from MC.
  - 5% subtraction for expected $(b \to d\,\gamma)$.

[hep-ex/0108032, submitted to PRL]

$$BF(b \to s\,\gamma) = (3.21 \pm 0.43 \pm 0.27) \times 10^{-4}$$

Theory: $BF(b \to s\,\gamma) = (3.73 \pm 0.30) \times 10^{-4}$

[Gambino & Misiak, hep-ph/0104034]

The CLEO result agrees with theory – theory & experimental errors are comparable.

$b \to s\,\gamma$ Bounds on CP Asymmetry

- Two types of flavor tags
  - Lepton tag: $(1.4 < p_\ell < 2.2\ \mathrm{GeV/c})$ from other B.

$$A_{CP}^{lepton} = +0.191 \pm 0.181$$

  - Pseudo-reconstruction of X_s in the same B.

$$A_{CP}^{pseudo} = -0.178 \pm 0.132$$

- Lepton & Pseudo-reconstruction analyses are statistically independent, so can combine using statistical weights:

$$A_{CP}^{combined} = -0.079 \pm 0.108$$

$$-0.27 < A_{CP} < +0.10$$

PRL **86**, 5661 (2001)

- The Asymmetry is consistent with Standard Model & can rule out some extreme models.

Semileptonic *B* decays: $|V_{ub}|$ & $|V_{cb}|$

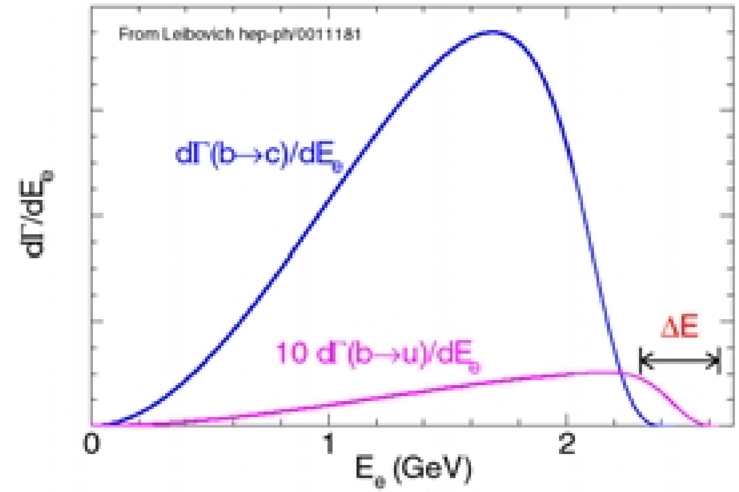
- Semileptonic *B* decays provide a clean method for extracting the CKM elements $|V_{ub}|$ & $|V_{cb}|$.

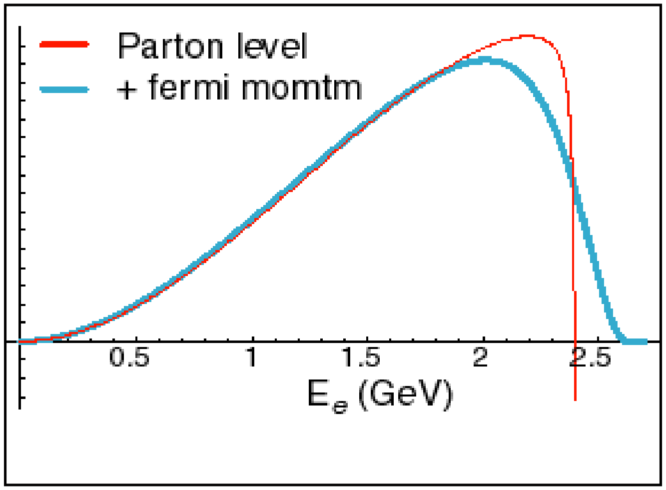
$$\Gamma(\bar{B} \to X_q \ell \nu) = \frac{\mathcal{B}(\bar{B} \to X_q \ell \nu)}{\tau_B} = \gamma_q \left| V_{qb} \right|^2$$

  - The BF and lifetime can be measured , but the factors γ_q must be understood from theory.
  - For $|V_{cb}|$, HQET & OPE provide expansions for γ_c in powers of $(1/M_B)$ with parameters $\bar{\Lambda}$, λ_1, λ_2, …. We can measure $\bar{\Lambda}$, λ_1, λ_2, and use theoretical estimates for the other parameters.
  - For $|V_{ub}|$, we use γ_u from theory.
    [Hoang,Ligeti & Manohar, PRD **59** 074017 (1999)]

$|V_{ub}|$ from the inclusive lepton spectrum.

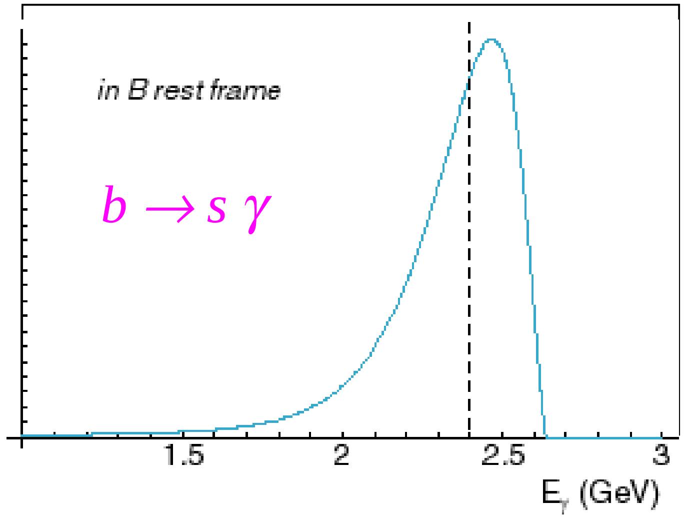
- Determine the BF $\bar{B}\to X_u \ell \nu$ by measuring the inclusive lepton spectrum near the endpoint, above the limit of $\bar{B}\to X_c \ell \nu$.
- A large extrapolation is needed to include the entire momentum range.
- The high momentum end is most influenced by Fermi motion of the b quark in the B meson.

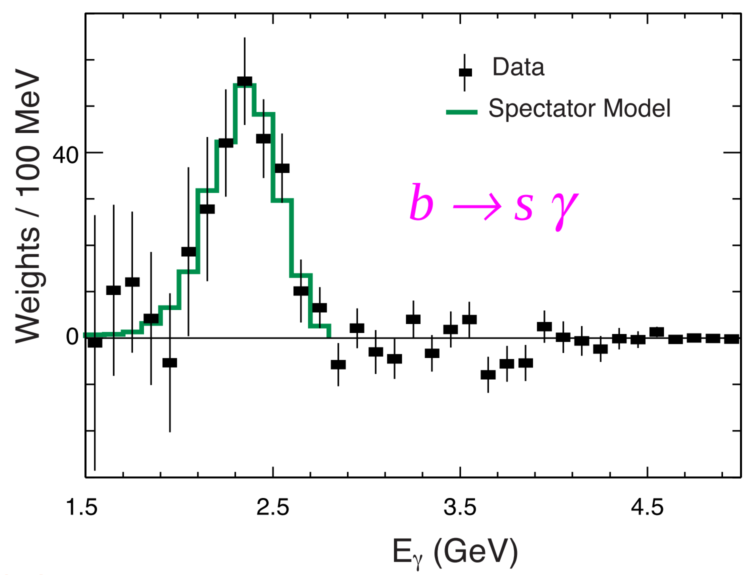




$|V_{ub}|$: Untangling the Fermi motion

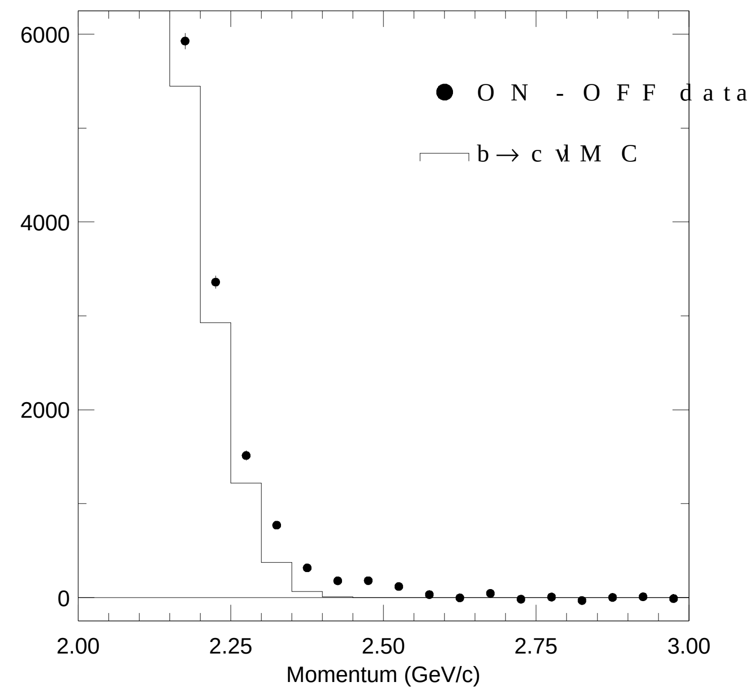
- Use the photon spectrum from $b \to s\,\gamma$ to understand Fermi motion.
  - Fermi motion broadens the simple, well understood photon spectrum.
  - Fit the *measured* spectrum of photons in $b \to s\,\gamma$ using shape function [Ali & Greub,1991]
  - Extract p_{Fermi} & m_b from the photon spectrum.
  - Apply the same parameters to the lepton spectrum & determine the fraction f(p) of the spectrum measured. [Kagan & Neubert, hep-ph/9805303]





$|V_{ub}|$ from the inclusive lepton spectrum.

- Lepton spectrum near the end-point (2.2 GeV/c < $p_l \leq$ 2.6 GeV/c) after suppressing & removing continuum & other backgrounds ⇒
- Subtract the yield for $B \to X_c \ell \nu$ (MC).
- Partial br.fr. (2.2 < $p_l \leq$ 2.6 GeV/c), $\Delta B_u = (2.35 \pm 0.15 \pm 0.45) \times 10^{-4}$.
- Apply the fraction $f(p) = 0.138 \pm 0.034$ obtained from Fermi motion analysis to get the BF for $\bar{B} \to X_u \ell \nu$. A 5% QED radiative correction is applied.



PRELIMINARY

$$|V_{ub}| = (4.09 \pm 0.14 \pm 0.66) \times 10^{-3}$$

$|V_{cb}|$ from $B \to X_c \ell \nu$: hadronic moments

- **HQET & OPE ¶ :** inclusive observables as expansion in powers of α_s & $(1/m_B)$:

$$|V_{cb}|^2 = \Gamma(b \to c \ell \nu) \times h(\bar{\Lambda}, \lambda_1, \lambda_2) \text{ to } \sim \Theta(m_B^{-3})$$

  - $\bar{\Lambda}$ ~ energy of light quark & gluon d.o.f.
  - λ_1 ~ rms momentum of b quark.
  - λ_2 ~ 0.13 GeV^2, extracted from $(m_{B*} - m_B)$

- $\bar{\Lambda}$, λ_1 can be determined from
  - Lattice QCD [Kronfeld & Simone, hep-ph/0006345]
  - CLEO: hadronic spectral moments in $b \to c \, \ell \nu$
  - CLEO: photon energy spectrum moments in $b \to s\gamma$

¶Theory: **A.Falk, M. Luke, & M. Savage, PRD53 (2491) 1996.**
M. Gremm & A. Kapustin, PRD55 (6934) 1997.
M. Voloshin, PRD51 (4934) 1995.
Z.Ligeti, M. Luke, A. Manohar and M. Wise PR D60, 034019(1999)

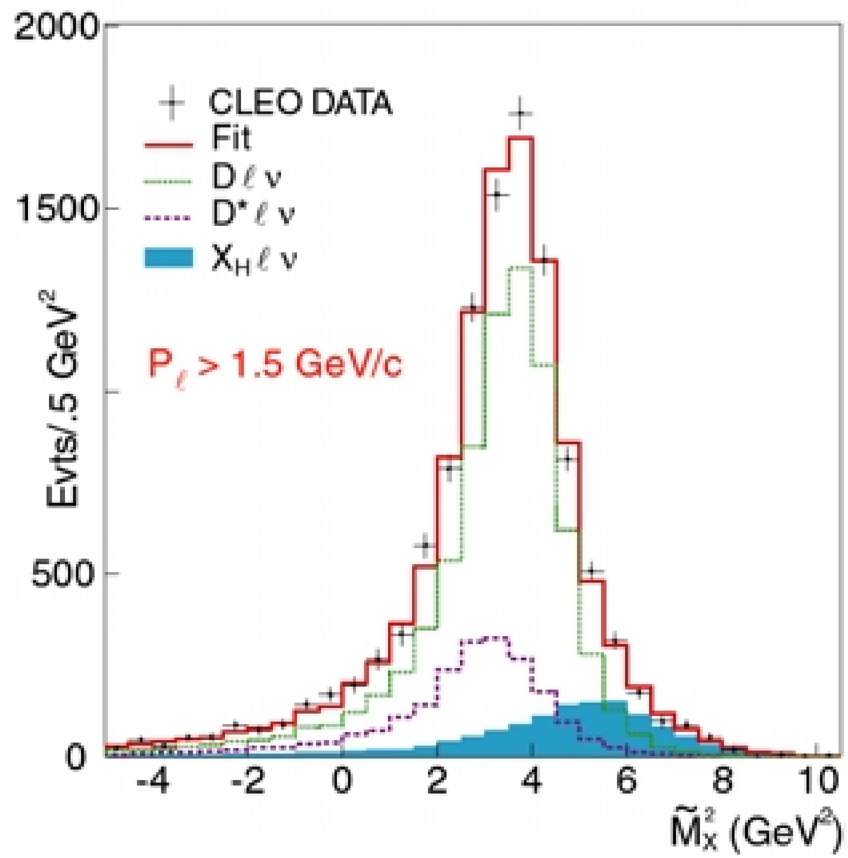
$B \to X_c \ell \nu$ Hadronic Mass Moments

- Reconstruct the neutrino p_ν & calculate the recoil mass M_X $(p_\ell > 1.5\ \text{GeV/c})$.
- Fit the M_X spectrum with D, D^* & X_h modes.
- Extract moments:

$$\langle M_X^2 - \bar{M}_D^2 \rangle = 0.251 \pm 0.066\ \text{GeV}^2$$

- Combine with $\langle E_\gamma \rangle$ from $(b \to s\gamma)$ to get $\bar{\Lambda}$, λ_1 .

$$\langle E_\gamma \rangle = 2.346 \pm 0.032 \pm 0.011\ \text{GeV}$$



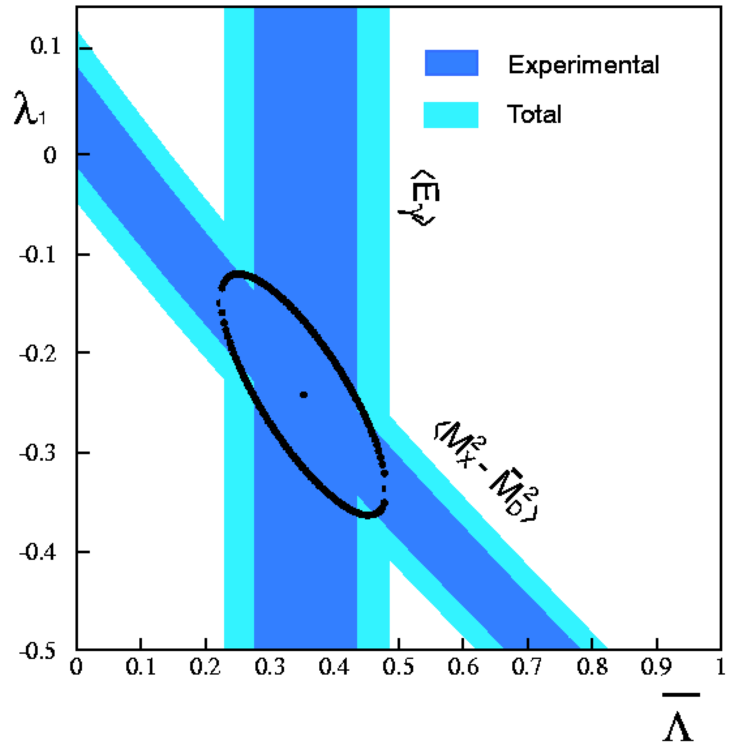
$|V_{cb}|$ from $\bar{\Lambda}, \lambda_1$

$$\bar{\Lambda} = 0.35 \pm 0.07 \pm 0.10\ GeV$$

$$\lambda_1 = -0.238 \pm 0.071 \pm 0.078\ GeV^2$$

- We use
  - **B**$(B \to X_c\, l\, \nu) = (10.39 \pm 0.46)\%$ (CLEO: PRL76 (1570) 1996)
  - $\tau_{\pm} = (1.548 \pm 0.032)$ psec(PDG)
  - $\tau_0 = (1.653 \pm 0.028)$ psec (PDG)
  - $f_{+-}/f_{00} = 1.04 \pm 0.08$

  (CLEO: PRL 86, 2737 (2001), hep-ex/0006002)



hep-ex/0108033, submitted to PRL:

$$\Gamma(b \to c l \nu) = (0.427 \pm 0.020) \times 10^{-10}\ \text{MeV}$$

$$|V_{cb}| = (40.4 \pm 0.9 \pm 0.5 \pm 0.8) \times 10^{-3}$$

$(\Lambda, \lambda_1)_{exp}$ Γ_{exp} $[\alpha_S, O(1/M_B^3)]$

Exclusive Semileptonic *B* decays: $|V_{cb}|$

- $|V_{cb}|$ from $B \to D^* \ell\, \nu$:

Decay width:

$$\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^3} \; G(w) \; F_{D^*}^2(w) \, |V_{cb}|^2$$

Strong interaction effects are in the form factor $F_{D^*}(w)$.

HQET: *D* boost in B rest-frame*

$$w = (m_B^2 + m_{D^*}^2 - q^2)/(2 m_B \, m_D^*)$$

($1 < w < 1.5$: $w = 1$ when D^* is at rest in B system)

HQET constrains form factor $F_M(1) \Rightarrow 1$ as $m_Q \Rightarrow \infty$.

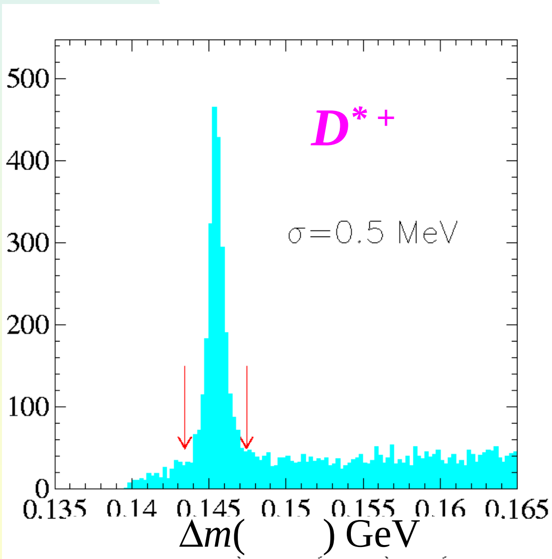
$G(w)$ is a known function, but $G(1) = 0$! (phase-space).

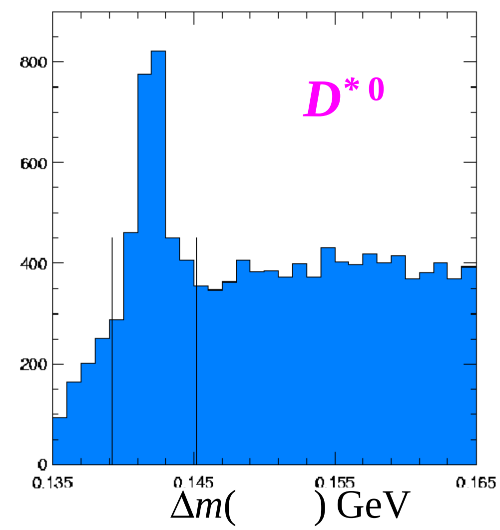
Measure the decay rate $d\Gamma/dw$ & extrapolate to $w = 1$

[Nearly linear extrapolation, but slope parameter ρ^2 at $w = 1$ can be measured.]

$|V_{cb}|$ from $B \to D^* \ell \nu$:

- 3.3 M $\bar{B}B$ events [3.1 fb^{-1} CLEO-II data ON $\Upsilon(4S)$]
- Reconstruct events:
  - *Leptons:* $(0.8 < p_e < 2.4$ GeV/c); $(1.4 < p_\mu < 2.4$ GeV/c).
  - $D^{*+} \to D^0 \pi^+$; $D^0 \to K^- \pi^+$. $\Delta m = (m_{K-\pi+\pi+} - m_{K-\pi+})$.
    $D^{*0} \to D^0 \pi^0$; $D^0 \to K^- \pi^+$. $\Delta m = (m_{K-\pi+\pi 0} - m_{K-\pi+})$.





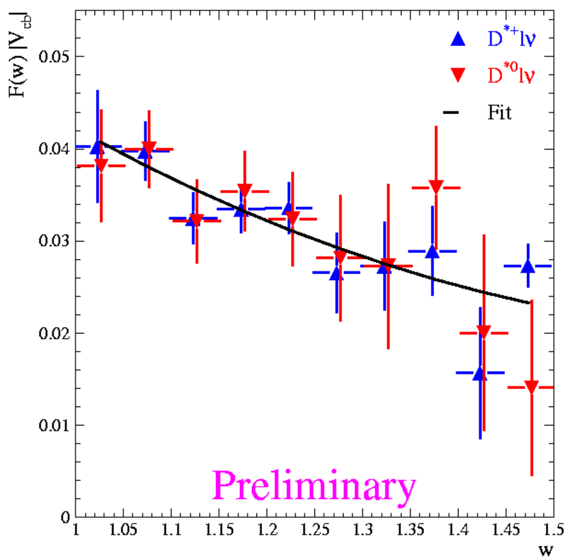
$|V_{cb}|$ from $B \to D^* \ell \nu$ (contd.):

- Backgrounds:
  - $B \to D^* \pi \ell \nu$ & $B \to D^{**} \ell \nu$: separate out using $\cos\Theta_{B-D^*\ell}$ & MM^2 distr.
  - Combinatorics; uncorr. D^* & ℓ; $B \to D^*(D_s \to X \ell \nu)$; continuum.
- Fit to signal & backgrounds in each w bin. (σ_w=0.03).
- Combine D^{*+} & D^{*0} to obtain single distribution in w.
  - Assume common $\Gamma_{B \to D \ell \nu}$; common $F(w)$;

    & CLEO (PRL 86): $(f_{+-} / f_{00})(\tau_{B^-} / \tau_{B^0}) = 1.11 \pm 0.08$

$$F(1)|V_{cb}| = (42.4 \pm 1.8 \pm 1.9) \times 10^{-3}$$

$$\rho^2 = 1.67 \pm 0.11$$



$|V_{cb}|$ from $B \to D^* \ell \nu$

PRELIM IN ARY

- Extracting $|V_{cb}|$:
  - using $F(1) = (0.913 \pm 0.042)$

CLEO

$$|V_{cb}| = (46.4 \pm 2.0 \pm 2.1 \pm 2.1) \times 10^{-3}$$

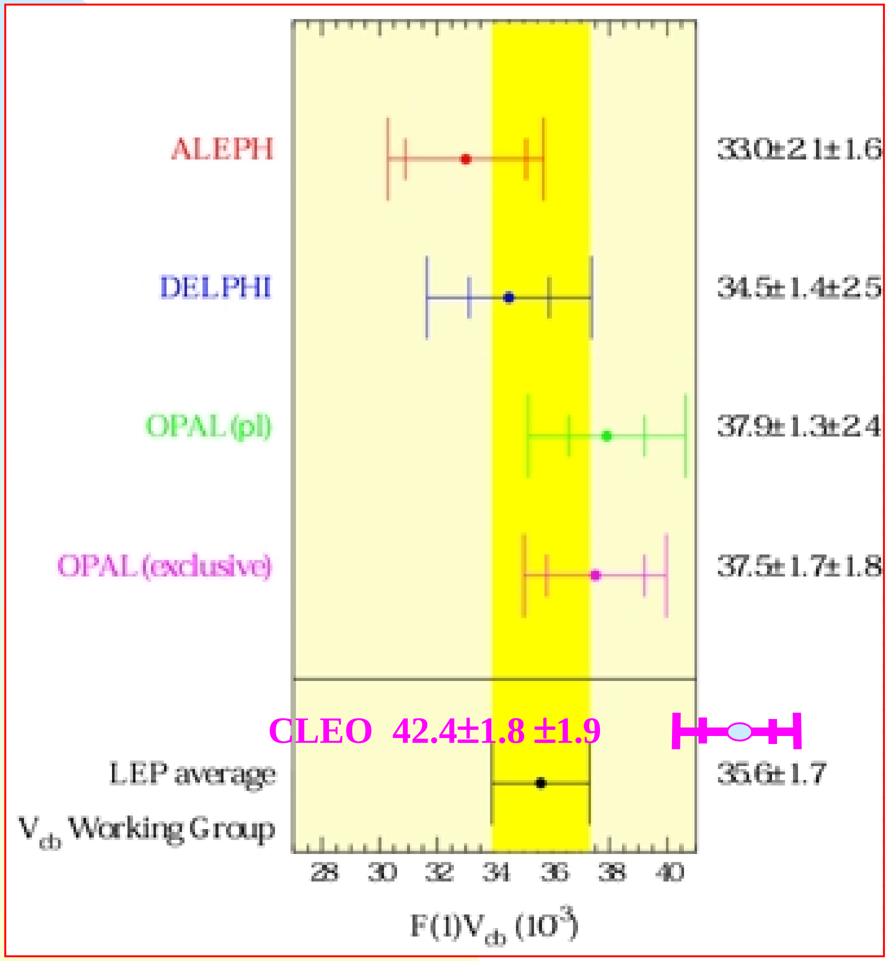
  - using $F(1) = (0.88 \pm 0.05)$

LEP gets $|V_{cb}| = (40.5 \pm 1.9 \pm 2.3) \times 10^{-3}$

- CLEO: $B(B \to D^* \ell \nu) = (5.66 \pm 0.29 \pm 0.33)\%$

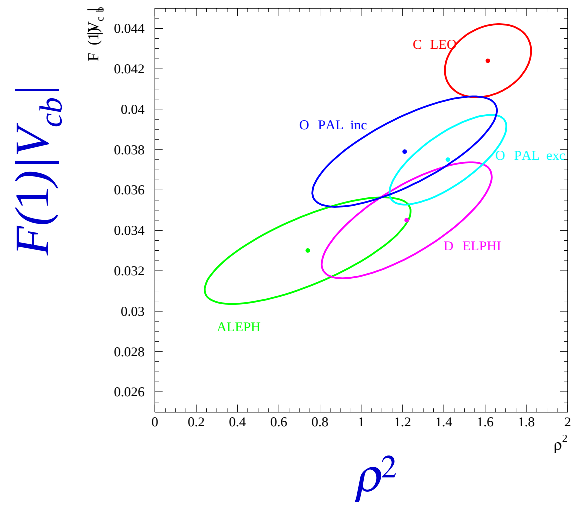
$F(1)^*|V_{cb}|$ from $B \to D^* \ell\ \nu$:

PRELIM IN ARY



$F(1)|V_{cb}|=(42.4 \pm\ 1.8 \pm\ 1.9) \times 10^{-3}$

- A Global fit to (CLEO + LEP) shows consistency @ 7% c.l.
- ALEPH, OPAL, DELPHI & CLEO show large correlation between $F(1)|V_{cb}|$ & ρ^2 values.



Charm Decays: Mixing & *CP* Violation

- Mixing & *CP* violation in Charm decays provide a unique opportunity to observe effects of new physics.
  - Within the Standard Model, mixing & CP violation are highly suppressed: ~ 0.1% – 1%

New **CLEO** Results: [$9\ fb^{-1}$ On & Off the Υ(4S)]

- First Measurement of $D^0 \rightarrow K^+\pi^-\pi^0$ & $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$
  - "Wrong sign": Doubly Cabibbo Suppressed Decay (DCSD) or $\bar{D}D$ mixing $\Rightarrow$ decay rates & A_{CP} ; & limits on Mixing & DCSD
- Mixing parameters & A_{CP} for decays to *CP*-eigenstates $D^0 \rightarrow K^+K^-, \pi^+\pi^-$; & A_{CP} for $D^0 \rightarrow K_S^0\pi^0, \pi^0\pi^0, K_S^0K_S^0$.

$D^0 \rightarrow K^+\pi^-\pi^0$ "Wrong sign" decays

- Can occur through mixing ($D^0 \rightarrow \bar{D}^0 \rightarrow K^+\pi^-\pi^0$ (CFD)) or as a *DCSD*.
- CLEO measures the ratio of "Wrong sign" to "Right Sign" decays integrated over time:

$$R_{WS} \equiv \frac{\Gamma\left(D^0 \rightarrow K^+\pi^-\pi^0\right)}{\Gamma\left(\bar{D}^0 \rightarrow K^+\pi^-\pi^0\right)}$$

  - Select $D^{*+} \rightarrow D^0\pi^+_{slow}$: D^0 flavor is tagged by sign of π_{slow} .
  - Two dimensional fits using $M_{cand.}(K\pi\pi^0)$

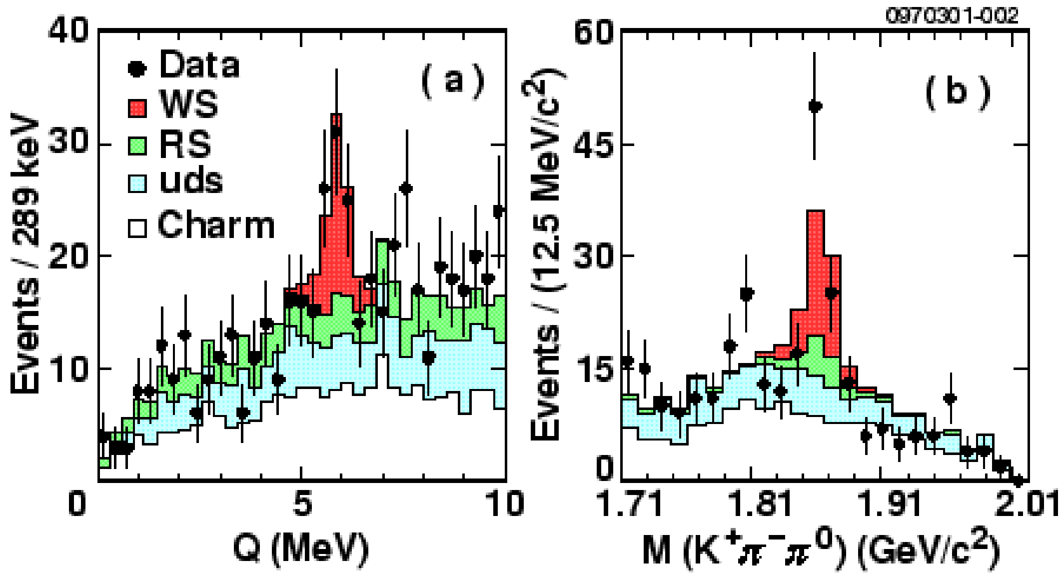
    & $Q \equiv M(K\pi\pi^0\pi_s) - M_{cand} - m_\pi$.

$D^0 \to K^+\pi^-\pi^0$ "Wrong sign" results

- Signal: 38±9 events
- Statistical 4.9σ

$$R_{WS} = \left(0.43\ ^{+0.11}_{-0.10} \pm 0.07\right)\%$$

PRL **87**, 071802 (2001)



- For Asymmetry: perform the analysis separately for D^0 & $\overline{D}^0$:

$$A_{CP} \equiv \frac{\Gamma\left(D^0 \to f\right) - \Gamma\left(\overline{D^0} \to \bar{f}\right)}{\Gamma\left(D^0 \to f\right) + \Gamma\left(\overline{D^0} \to \bar{f}\right)} = 8\ ^{+25}_{-22}\ \%$$

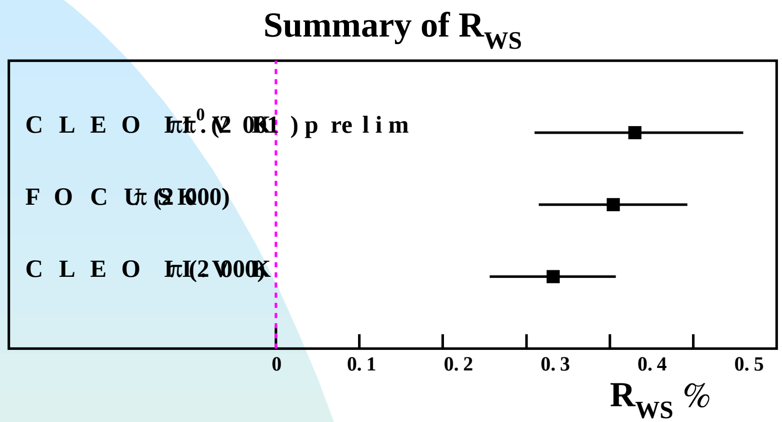
Limits on Mixing & DCSD

- Mixing amplitudes: $x \equiv 2M_{12}/\Gamma = \Delta M/\Gamma$: *via* virtual states
  $y \equiv \Gamma_{12}/\Gamma = \Delta\Gamma/2\Gamma$: *via* real states
  - SM: $|x|$ suppressed by $\tan^2\theta_C$ & GIM; *non-SM* $|x|$ could be >0.01.
- DCSD $(\sim V_{cd}V^*_{us})$ &CFD $(\sim V_{cs}V^*_{ud})$ ampls. w/ rel. phase δ:
  – define ratio of *rates* $\overline{R}_D \equiv (\Gamma_{DCSD}/\Gamma_{CFD})$.
- Mixing & DCSD combined: $y' \equiv (y\cos\delta - x\sin\delta)$ and $x' \equiv (x\cos\delta + y\sin\delta)$
- The ratio we measured can be expressed as:

$$R_{WS} \equiv \frac{\Gamma\left(D^0 \to K^+\pi^-\pi^0\right)}{\Gamma\left(\overline{D}^0 \to K^+\pi^-\pi^0\right)} = \overline{R}_D + y'\sqrt{\overline{R}_D} + \frac{1}{2}(x'^2 + y'^2)$$

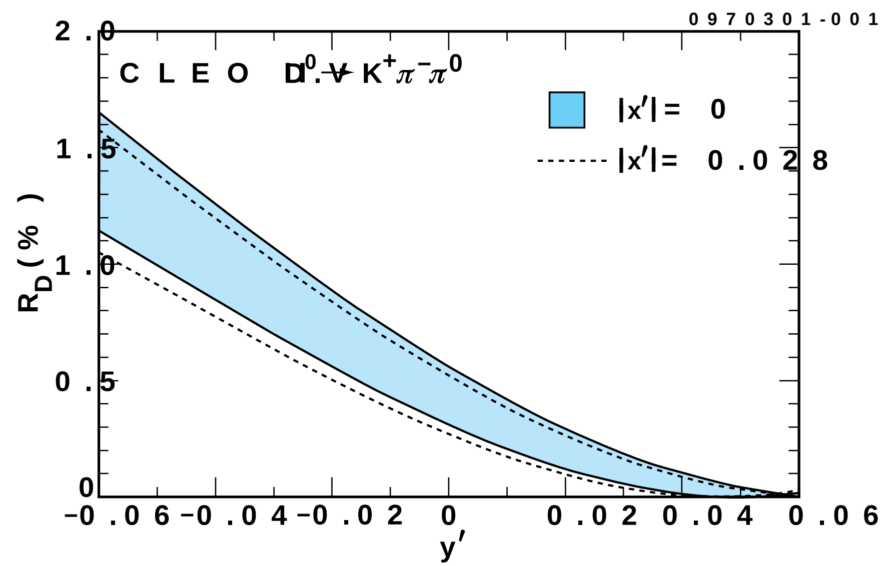
We can then plot $\overline{R}_D$ *vs* y' from our measurement, for limiting values of $|x'|$ measured by CLEO in $D^0 \to K^+\pi^-$.

Limits on Mixing & DCSD



- "Wrong sign" Mixing & DCSD measurements:
  - **FOCUS:** Phys. Lett.**B** 485, 62 (2000)
  - **CLEO ($K^+\pi^-$):** PRL **84**, 5038,(2000)
  - **CLEO ($K\pi\pi^0$):** PRL **87**, 071802 (2001)

CLEO: R_{DCSD} *vs* y'



Cabibbo Suppressed decays to *CP*-eigenstates: $D^0 \to K^+K^-,\ \pi^+\pi^-$

- What's the interest here?:
  - SU(3) predicts, in the absence of FSI: $R \equiv \frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to \pi^+\pi^-)} = 1$
    but measured value is 2.8 ± 0.2[PDG] due to *FSI* ?
  - Large FSI may include large strong phase differences δ_{strong} which may enhance *CP* violating terms.
- What do we measure?
  - Ratios to $D^0 \to K^-\pi^+$:

$$R_{KK} \equiv \frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to K^-\pi^+)},\quad R_{\pi\pi} \equiv \frac{\Gamma(D^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)}$$

  - $A_{CP}(KK)$ & $A_{CP}(\pi\pi)$
  - Mixing parameter $y \equiv \Delta\Gamma/2\Gamma$: *CP*-eigenstates propagate as pure mass-eigenstates ~ $\exp\{\Gamma(1-\eta_{CP}\,y)\}t$ if CP is conserved. [$\eta_{CP} = \pm 1$]
    - We measure lifetimes τ_+ for $KK_{(CP+)}$ & $\pi\pi_{(CP+)}$ & τ for $K\pi_{(CP\ mix)}$.
    - Then

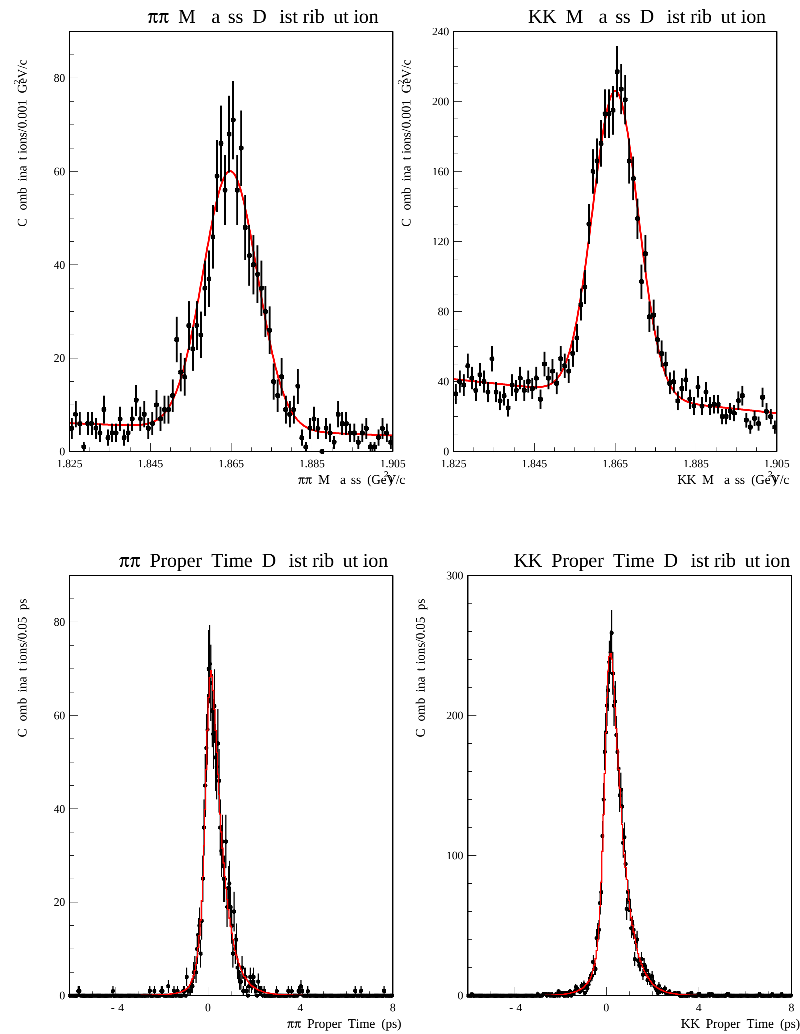
$$y_{CP\text{-}Eigenstate} = \eta_{CP}(\tau/\tau_{\pm} - 1)$$

$D^0 \to K^+K^-,\ \pi^+\pi^-$: CLEO Results *PRELIMINARY*

- Ratios:
  - $R_{KK} = (10.40 \pm 0.33 \pm 0.27)\ \%$
  - $R_{\pi\pi} = (3.51 \pm 0.16 \pm 0.1)\ \%$
  - $R = R_{KK} / R_{\pi\pi} = 2.96 \pm 0.16 \pm 0.15$
- No evidence for Asymmetries:

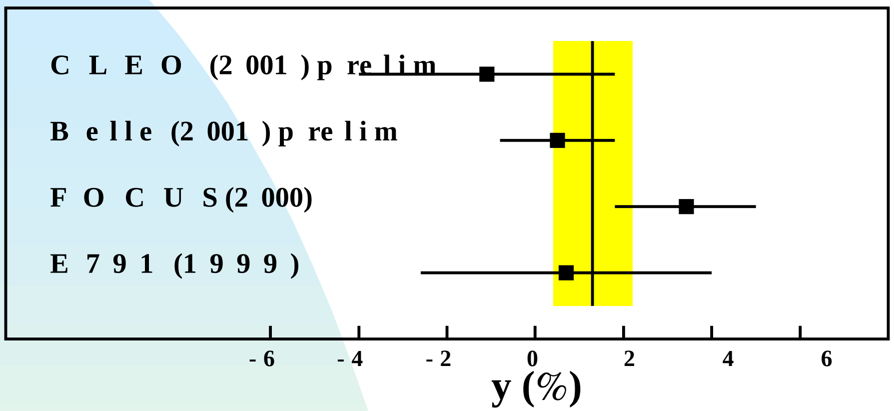
  Separating D^0 & $\bar{D}^0$ (using $D^* \to D\pi$) :
  - $A_{CP}(KK) = (0.0 \pm 2.2 \pm 0.8)\ \%$
  - $A_{CP}(\pi\pi) = (1.9 \pm 3.2 \pm 0.8)\ \%$
  - $A_{CP}(\pi^0 \pi^0)$, $A_{CP}(K_s^0 \pi^0)$, $A_{CP}(K_s^0 K_s^0)$,

    all consistent with zero [PRD63 (2001)]
- No evidence for Mixing:
  - $y_{CP+}(KK) = -0.019 \pm 0.029 \pm 0.016$
  - $y_{CP+}(\pi\pi) = +0.005 \pm 0.043 \pm 0.018$
  - $y_{CP}(\text{combined}) = -0.011 \pm 0.025 \pm 0.014$

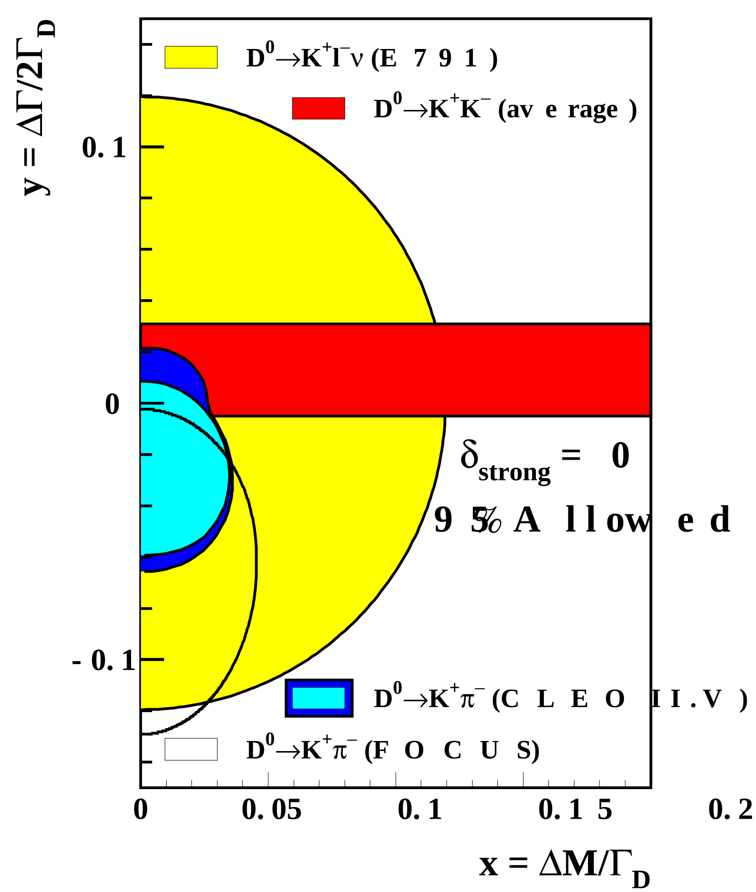


Mixing in the Charm Sector

y Values from Lifetime Differences



D^0-$\overline{D}^0$ Mixing Limits



- Compilation of recent results:
  - **E791:** PRL **77**, 2384 (1996);
    & PRL **83**, 32 (1999).
  - **FOCUS:** Phys Lett **B485**, 62 (2000)
    & **(preliminary):** hep-ex/0106093
  - **BELLE (preliminary):** hep-ex/0104053
  - **CLEO ($K^+\pi^-$):** PRL **84**, 5038, 2000
  - **CLEO (preliminary):** hep-ex/0102006

The CLEO-c Program

- The planned CLEO-c program is aimed at these specific areas in Electroweak & QCD Physics:
  - *Absolute branching ratios* of a large number of charm decays, measured to 1%–2%.
  - Precise measurements of *form-factors* and *decay constants*, to improve our understanding of strong dynamics & to test the predictions of Lattice QCD.
  - Precise measurements of $\bar{c}c$ & $\bar{b}b$ *quarkonia*, through spectroscopy & decay.
  - Physics beyond the standard model through $\bar{D}D$-mixing, *CP*-violation & rare decays of charm & tau.

The CLEO-c Program

The overall aim is to explore a broad set of weak and strong-interaction phenomena.

These measurements will help remove the constraints, complications and uncertainties of strong dynamics that now limit measurements & understanding of weak-interaction physics.

- $|V_{ub}|$ limited by form-factor uncertainties in $b \rightarrow u \ell^+ \upsilon$.
- $|V_{td}|$ limited by *B* decay constant and bag parameter.
- $|V_{cb}|$ extraction from $b \rightarrow c \ell^+ \upsilon$ restricted to $q^2 = q_{max}$

Strong coupling is to be *expected* in physics beyond the *SM* (e.g., SUSY & Technicolor) – we need a better understanding & theory for it.

The CLEO-c Data set

Here is what we propose:

- The CLEO-c program as a focused perspective for about three years of running, following an initial period of Upsilon data:
  - 2001-2002: 1–2 fb^{-1} each on $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, …

    We will start on this after the summer shutdown.

  After CESR-c is approved and upgraded:
  - 2003: 3 fb^{-1} on $\Psi(3770)$, 30M DD events.
  - 2004: 3 fb^{-1} at $\sqrt{s} \sim 4100$, 1.5M D_sD_s events.
  - 2005: 1 fb^{-1} on $\Psi(3100)$, 1 Billion J/Ψ decays.

What's unique about C L E O - c ?

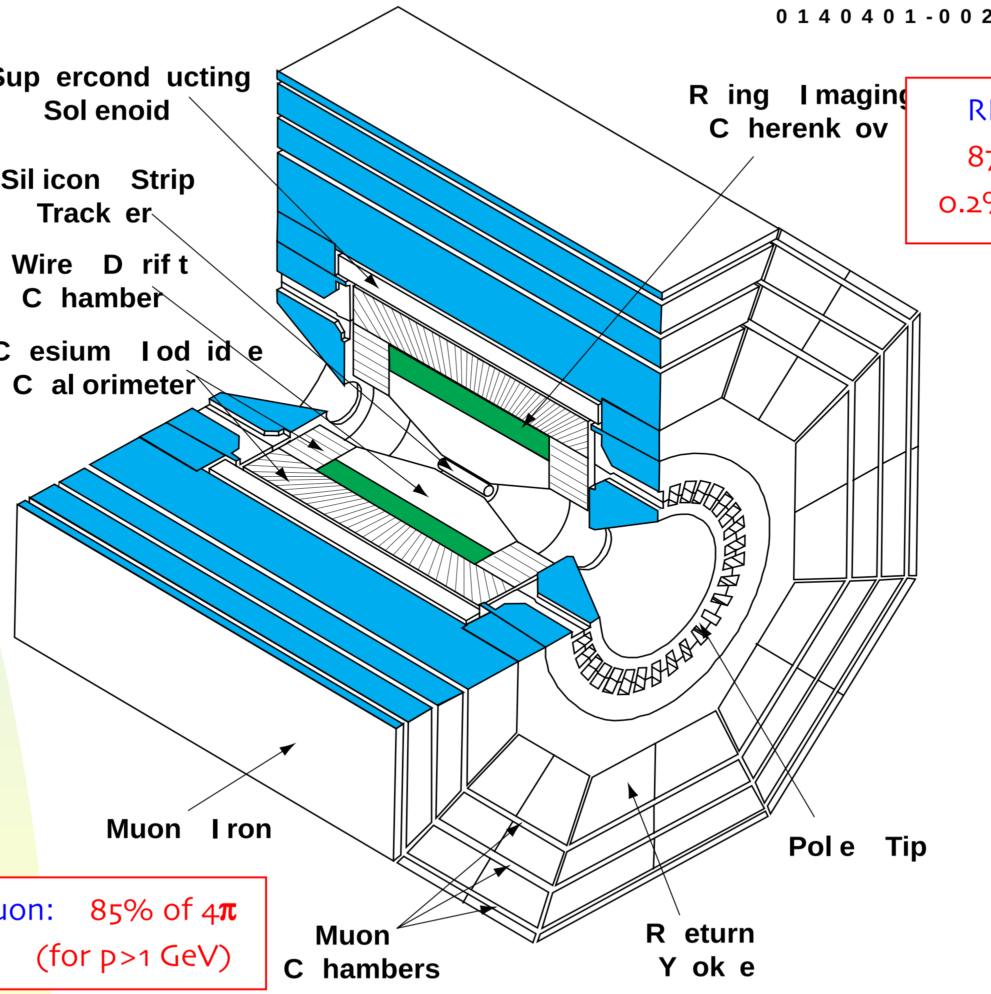
- A data set that is 20 to 500 times bigger than previous experiments.
- A state-of-the-art detector (CLEO-III) with
  - Excellent tracking resolution
  - Excellent shower resolution
  - RICH particle identification
  - Large solid angle
  - Flexible trigger and DAQ capability
- Parallel Data sets in the *same* detector:
  - Upsilon & Ψ resonances & $\gamma\gamma$ collisions

The CLEO III Detector

B-field: 1.5 T
[1.0 T for CLEO-c]

Tracking: 93% of 4π
σ_p/p = 0.35% @ 1GeV
dE/dx: 5.7% @ min-I

Calorimeter:
93% of 4π
σ_E/E = 2% @ 1GeV
= 4% @ 100MeV



RICH: 83% of 4π
87% Kaon ID with
0.2% π fake @ 0.9GeV

Muon: 85% of 4π
(for p>1 GeV)

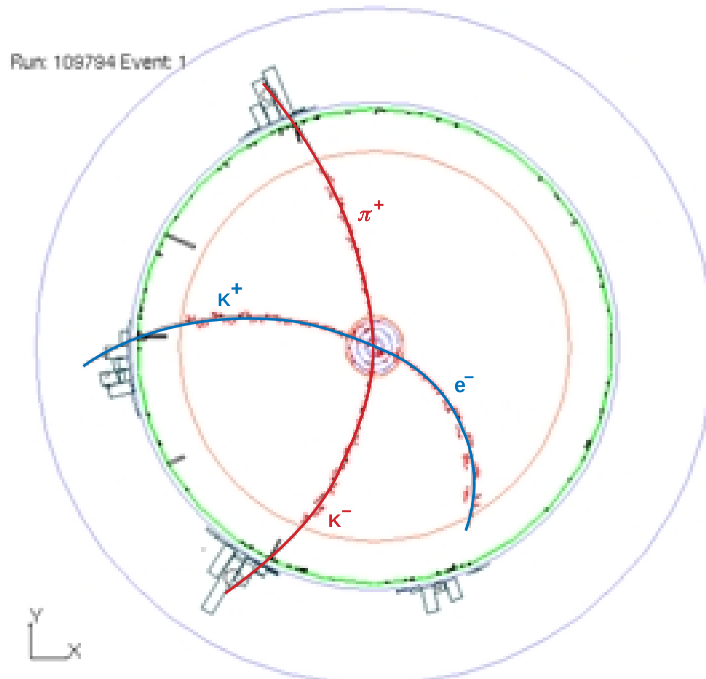
Data Set: Comparison with existing data.

- Upsilon resonances: 1– 2 fb^{-1} each will amount to ~ 10 – 20 times existing world data sets.
- Ψ(3770): 3 fb^{-1} ⇨ 30M *DD* events & 6M tagged *D* decays. [~ 300 times previous data set.]
- √s ~ 4100: 3 fb^{-1} ⇨ 1.5M $D_s D_s$ events, & 300K tagged D_s decays. [~ 480 times previous data set; ~ 130 times BES II data set.]
- Ψ(3100): 1 fb^{-1} ⇨ 1 Billion J/ Ψ decays. [~ 170 times previous data set; ~ 20 times BES II data set.]

Data At Charm Threshold

- Advantages [similar to $\bar{B}B$ studies at $\Upsilon(4S)$]:
  - Coherent initial state, with quantum numbers of the photon $\Rightarrow$ many favorable constraints.
  - Pure $\bar{D}D$ or $\bar{D}_s D_s$ initial state, no extra particles.
  - Tagged, fully reconstructed events, with no background.
  - Neutrino reconstruction.
- Better than charm studies at $\sqrt{s}$ = 10.6 GeV: at threshold $\Rightarrow$ large cross section & low multiplicity!
  - SIGNAL/BACKGROUND: On the $\Psi(3770)$, $\bar{D}D$:continuum is 1:1, while at 10.6 GeV, $\bar{c}c$ production is only a small part of the total hadronic cross section.

At Charm Threshold



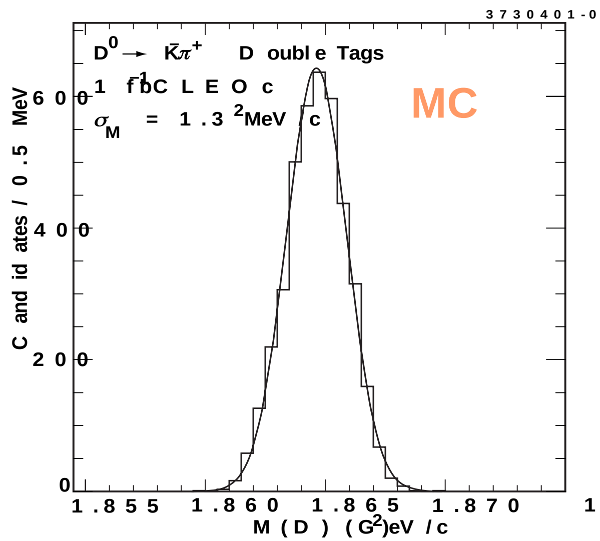
MC *simulation*
of expected events

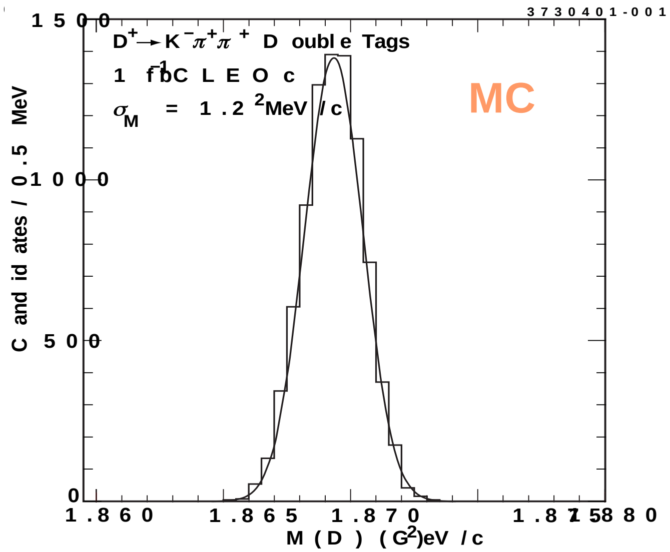
$D^0 \rightarrow K^- \pi^+$ $\qquad$ $D^0 \rightarrow K^+ e^- \nu$

Clean tagged events, no background in hadronic tag modes ⇨ *Absolute* branching ratios!

Branching ratios at Charm Threshold

- Background free hadronic tag modes:

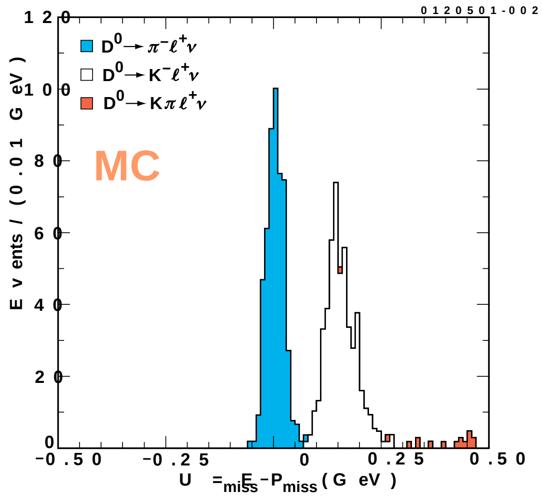


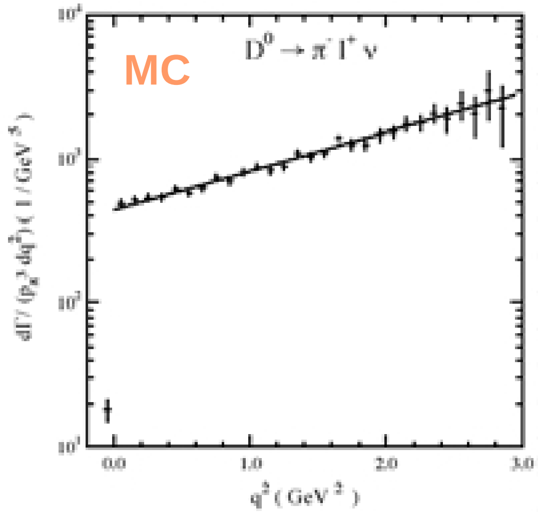


Branching ratio precision:	PDG2000	CLEO-c
$D^0 \to K\pi$	2.4%	0.5%
$D^+ \to K\pi\pi$	7.2%	1.5%
$D_s \to \varphi\pi$	25%	1.9%

Semileptonic D decays: $|V_{CKM}|^2, |f(q^2)|^2$

- $|V_{cd}|$ & $|V_{cs}|$ measured to ~ 1.5%; $|f(q^2)|$ at 1% level.

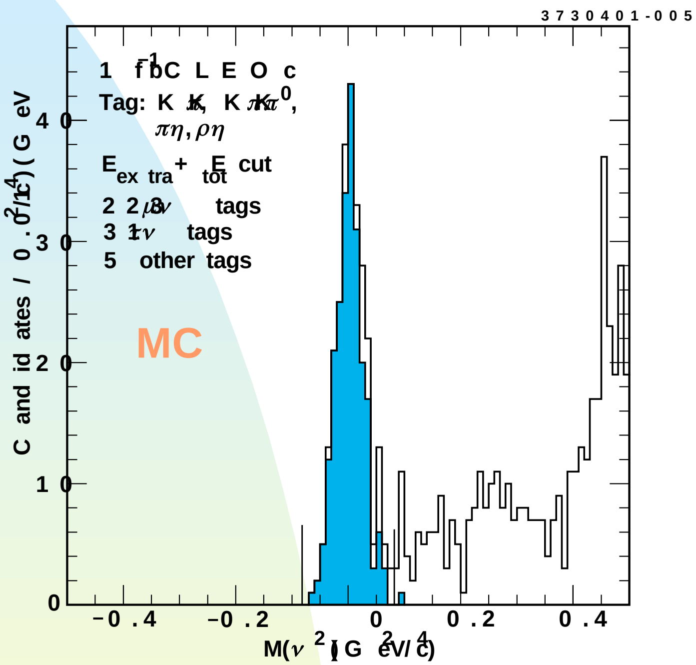


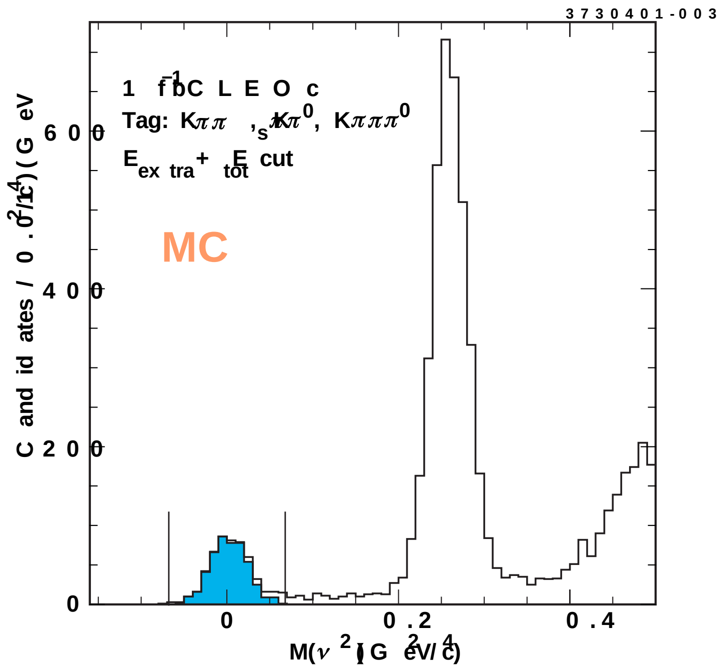


Branching ratio precision:	PDG2000	CLEO-c
$D^0 \to K \ell \nu$	5%	1.6%
$D^0 \to \pi \ell \nu$	16%	1.7%
$D^+ \to \ell \nu$	48%	1.8%
$D_s \to \varphi \ell \nu$	25%	2.8%

Pure Leptonic Decays: Decay Constant

$D_s^+ \to \mu^+\nu$	$D^+ \to \mu^+\nu$





	$\delta f_{Ds}/ f_{Ds}$	$\delta f_D/ f_D$
CLEO-c :	~± 2.1%	±~ 2.6%
PDG :	± 35%	± 100%

Quark onia & QC D

- One Billion J/Ψ decays (1 fb^{-1}) ⇨ a glue factory!
  - $J/\Psi \to \gamma gg \to \gamma X$: Look for glueballs (gg), hybrids (gqq) & other exotic states.
    - [1 Gev/c^2 < M_X < 3 Gev/c^2] , partial wave analysis.
    - Masses, spin-parity, decay modes, etc.
    - Inclusive γ spectrum (σ =20 MeV) for states with Br ~ 10^{-4}.
- Υ resonances:(~4 fb^{-1})⇨ Spectrosopy & transitions.
    - Masses; Leptonic widths; photon transitions; exotic states.
    - Compare with Lattice QCD predictions.
    - Corroborate or debunk glueball candidates.
- $\gamma\gamma \to X$: Corroborate or debunk glueball candidates ($\Gamma_{\gamma\gamma} < 1\text{eV}$)

Probing New Physics

Look for enhancements in phenomena expected to be highly suppressed in the *SM*.

- Rare Decays : Br > 10^{-6} accessible.
- $\bar{D}D$ mixing: highly suppressed in the *SM*.
  - Systematic studies exploiting *QM* coherence conditions at threshold.
  - Complementary constraints from $\psi(3770) \to \bar{D}D_{(C=-1)}$
    & $\psi(4140) \to \gamma\, \bar{D}D_{(C=+1)}$ decays.
  - DCSD is zero for $\psi(3770) \to \bar{D}D_{(C=-1)} \to (K^-\pi^+)\,(K^-\pi^+)$ Only Mixing!
- *CP* violation: direct $A_{CP} < 0.01$ in *SM*.
  - δ_{strong} (FSI) may allow enhanced A_{CP} (*New Physics*).
  - *QM* coherence: look for $\psi(3770)_{(CP=+1)} \to \bar{D}D \to (K^+K^-)_{(CP=+1)}\,(\pi^+\pi^-)_{(CP=-1)}$

CESR e^+e^-: collisions from Ψ to Υ

- If approved, CESR will be modified to provide high-luminosity colliding beams over an extended energy range.
- $\sqrt{s}$: 3.1 GeV – 11.2 GeV, covering the Ψ & Υ resonances.
- Luminosities will be large enough to increase the world's data sample by an order of magnitude and more.

Accel erator I ssues at l ow energy

- The energy range is usually limited by total synchrotron radiation (SR) power at the upper end (RF limit) & by *too little* radiation & damping at the lower end.

  SR Power ~ E^4 for fixed bend radius.

  - At low energy the horizontal beam emittance decreases ($\varepsilon_x \sim E^2$) & space charge density limits the charge per bunch & thus the total beam current.
  - The damping time increases significantly:

$$\tau_{\text{damping}}(1.88\ \text{GeV}) \approx 25 \times \tau_{\text{damping}}(5.3\ \text{GeV})$$

  and will inhibit the injection rate.

We have to increase radiation effects at low energies.

Accelerator Issues: scaling

- The beam-beam interaction may limit luminosity at lower beam energies (reduced damping between collisions).
- Overall, one can expect luminosity to scale as L ~ E^4, but typically, one sees L ~ E^4 to E^7 in various colliders without special efforts to maintain radiation damping at low energies.
- CESR will use enhanced radiation effects by adding *wigglers* operating at 2.1 Tesla.
- When wiggler radiation dominates, the scaling with energy is modified.

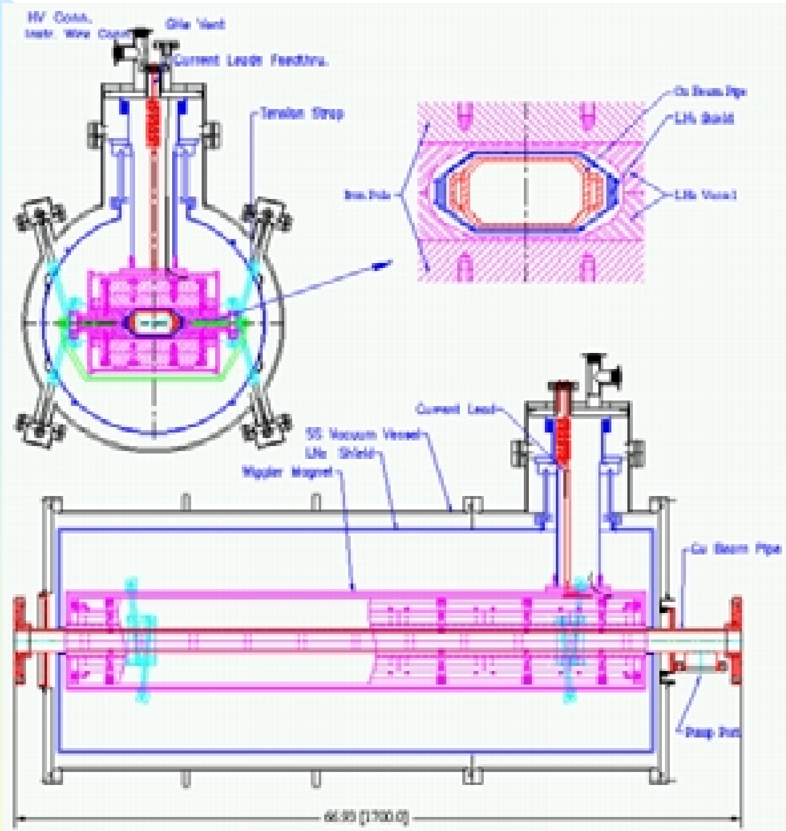
C E SR - c Parameters

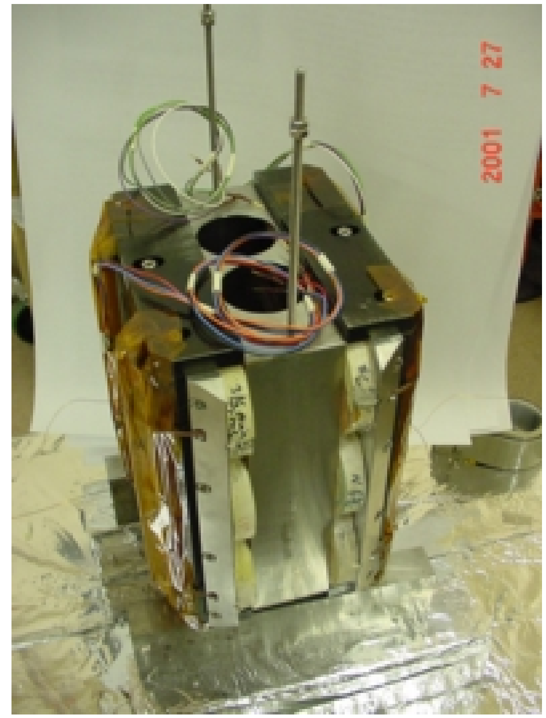
E_0 [GeV]	1.55	1.88	2.5	5.3
Luminosity [10^{33} cm^{-2} s^{-2}]	0.15	0.30	0.50	1.25
Beam current [mA/beam]	130	180	230	360
β_y^* [cm]	1.0	1.0	1.0	1.8
ξ_y	0.035	0.04	0.04	0.06
ξ_x	0.028	0.036	0.034	0.028
σ_E/E_0 [10^{-3}]	0.75	0.81	0.79	0.67
τ_{damp} [msec]	69	55	52	22
Wiggler Field [Tesla]	2.1	2.1	2.1	none
ε_x [nm-rad]	230	220	215	205

Planned Modifications to CESR

- Install 18 m of wiggler magnets with B_{pk}= 2.1 Tesla.
  - “Superferric” magnet construction.
  - Modular magnet length 1.33 m, 40 cm period.
  - Modular cryostat length 1.7m.
  - 14 units in south part of CESR ring, near utilities.
  - Prototype wiggler module construction in progress now.
- Complete *wiggler installation* by end of 2002.
- Install SC Quads in IR to decrease β^*– *in progress*.
- Upgrade RF to shorten bunch length – *in progress*.

Superferric Wigglers





3-pole test module

- Such wigglers are needed in wiggler-dominated damping rings for Linear Colliders: we can study non-linearities in CESR-c.