Radiative Penguins and the CKM Matrix

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Outline

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Quark Decay in the Standard Model

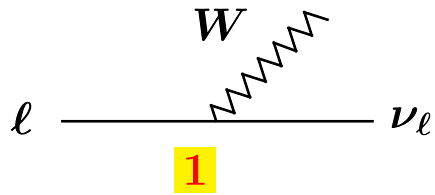
$$
\begin{array}{lcccc}
 & & & & Q/e \\
\text{Leptons} & \begin{pmatrix} \nu_e \\ e \end{pmatrix} & \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} & \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} & \begin{array}{c} 0 \\ -1 \end{array} \quad \updownarrow W \\
 & & & & \\
\text{Quarks} & \begin{pmatrix} u \\ d' \end{pmatrix} & \begin{pmatrix} c \\ s' \end{pmatrix} & \begin{pmatrix} t \\ b' \end{pmatrix} & \begin{array}{c} +2/3 \\ -1/3 \end{array} \quad \updownarrow W
\end{array}
$$

For $Q = -1/3$ quarks

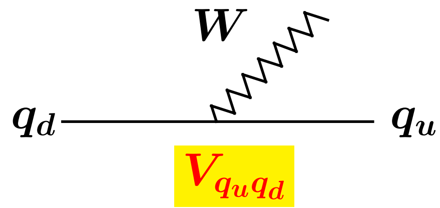
- the unitary CKM matrix V relates
  - q' – weak "eigenstates" to
  - q – strong "eigenstates"

$$
\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & \boxed{V_{ub}} \\ V_{cd} & V_{cs} & \boxed{V_{cb}} \\ \boxed{V_{td}} & \boxed{V_{ts}} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}
$$

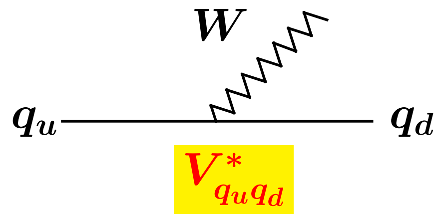
$\ell \rightarrow \nu_\ell W^-$



$q_d \rightarrow q_u W^-$



$q_u \rightarrow q_d W^+$



Leptons and quarks decay via W emission

- Relative couplings for quark decay are elements of the CKM matrix
- CP is conserved if V is real ($V_{q_u q_d} = V^*_{q_u q_d}$)

Wolfenstein Approximation of the CKM Matrix and the Unitarity Triangle

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cong \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix}$$

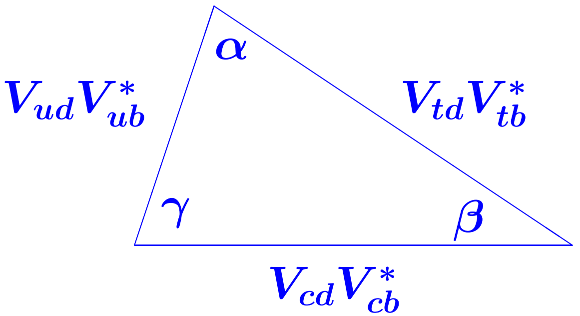
$\lambda \cong 0.22$

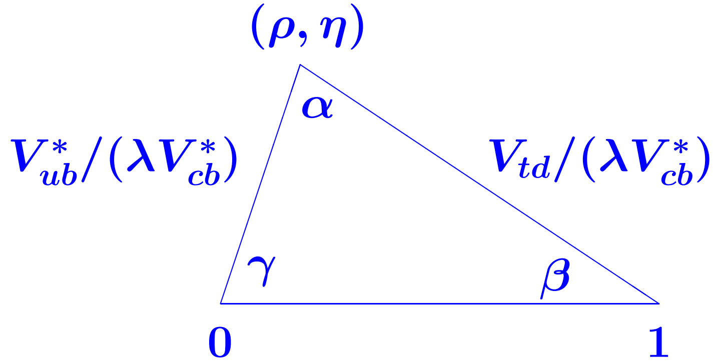
$A \cong 1$

$\eta \neq 0 \Leftrightarrow$ SM $\not{C}\not{P}$

Apply unitarity to columns 1 and 3:

- $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ defines a triangle in the complex plane:
- CP is conserved in the SM if the area of the triangle is zero
- The triangle apex is at (ρ, η) in the ρ–η plane in the Wolfenstein approximation

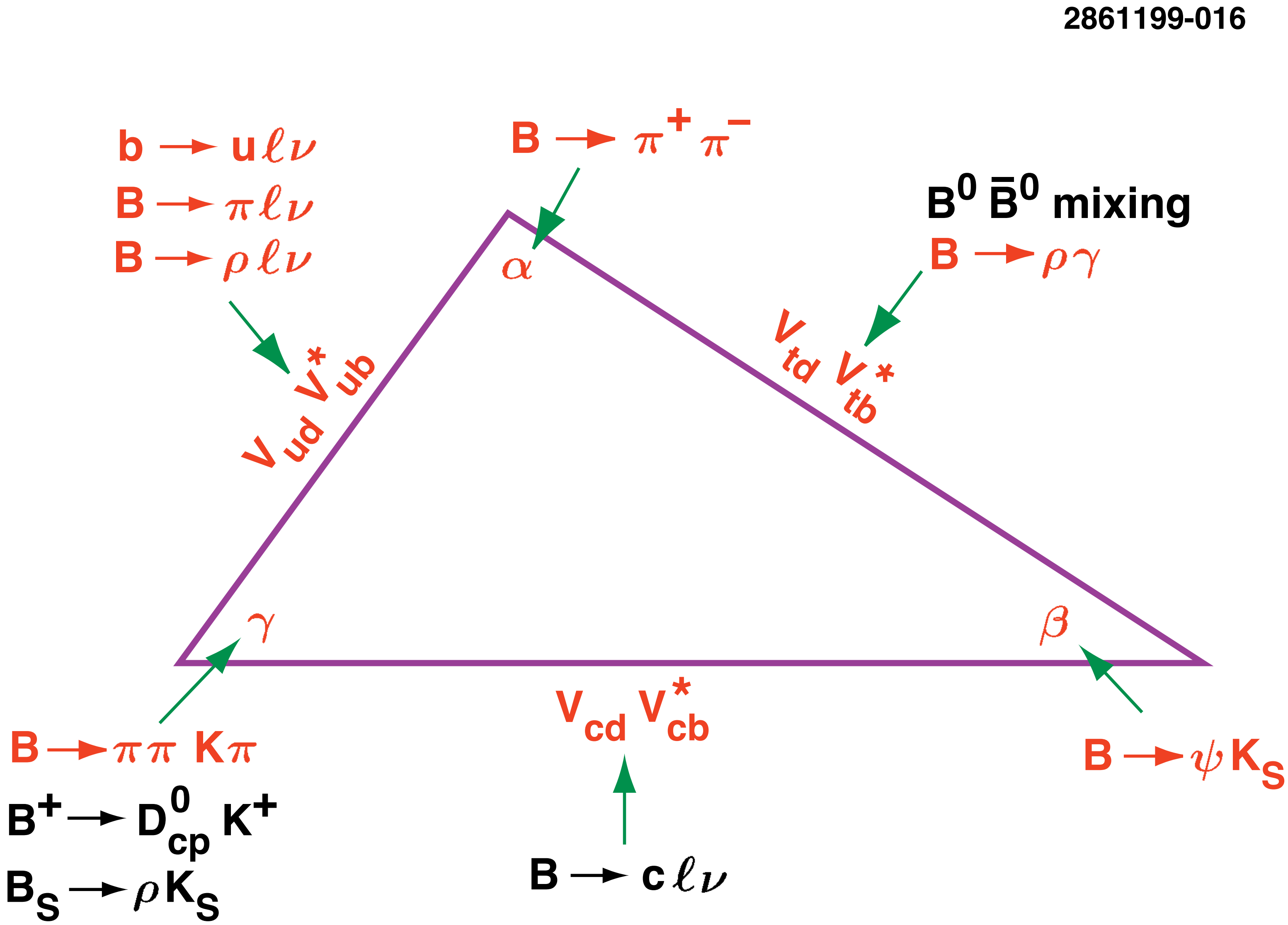




- Conventional B decay measurements determine the lengths of the nontrivial sides
- Some CP violation asymmetries in B decay determine angles of the triangle

Inconsistency between sides and angles would imply CP Violation beyond the SM

Determining the Unitarity Triangle



Determining $|V_{td}|$ from $B^0\bar{B}^0$ Mixing

The measured mass difference due to $B^0\bar{B}^0$ mixing is related to $|V_{td}|$ by:

$$\Delta m_d = \frac{G_F^2}{6\pi^2}\,\eta_{QCD}\,m_B\,f_B^2 B_B\,m_t^2\,F(\frac{m_t^2}{m_W^2})\,|V_{td}|^2\,|V_{tb}|^2$$

Everything in this expression, except the decay constant f_B and the bag constant B_B, is reasonably well known.

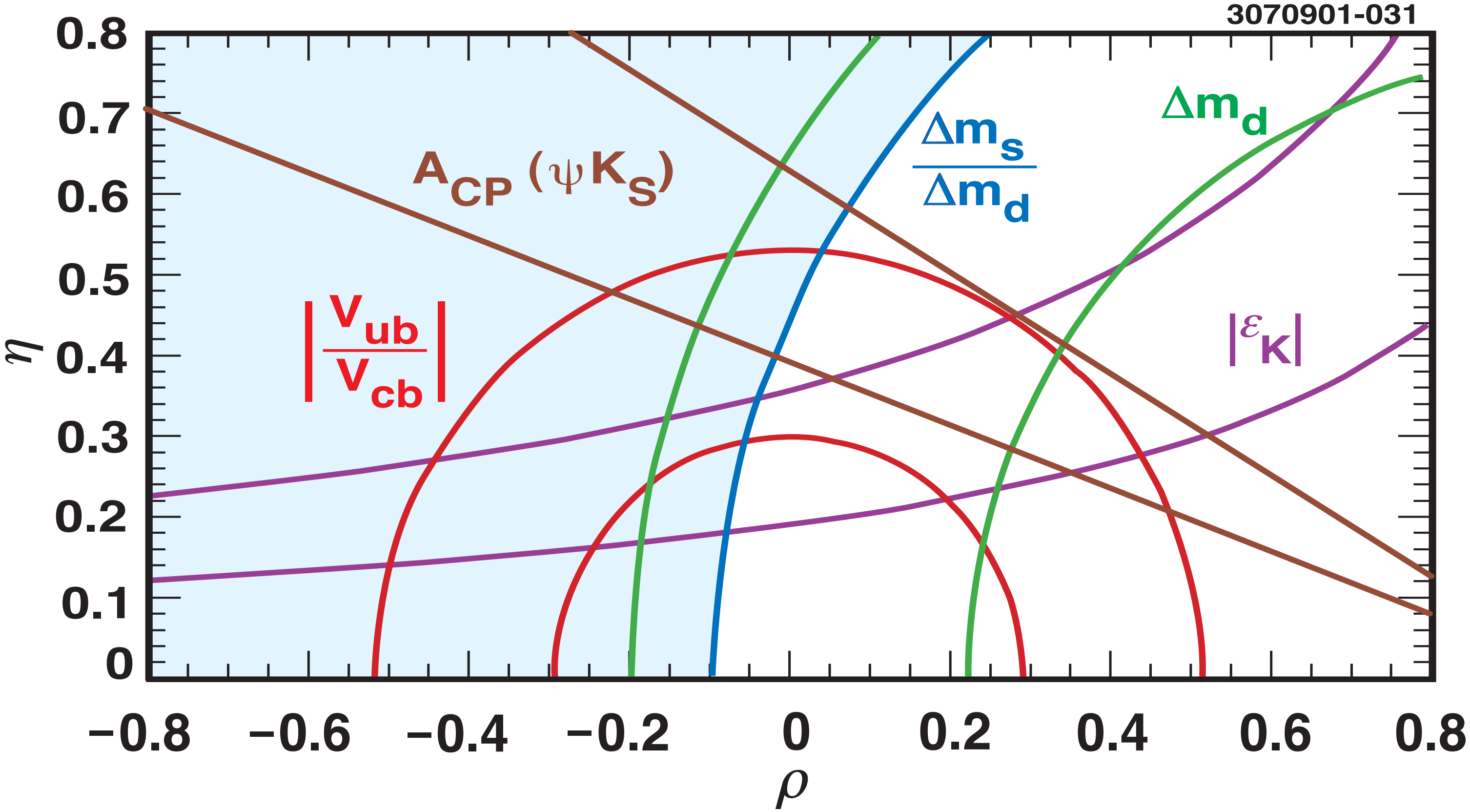
- Illustrate contributions to the uncertainty in $|V_{td}|$ using parameters from PDG 2000 and 2001 Update. (Uncertainties from other parameters are smaller.)

	Δm_d [ps^{-1}]	m_t [Gev]	$\sqrt{B_B} f_B$ [MeV]
Value	0.479 ± 0.012	166 ± 5	210 ± 40
$\Delta\|V_{td}\|$ [10^{-3}]	$^{+0.10}_{-0.11}$	$^{+0.20}_{-0.19}$	$^{+2.0}_{-1.3}$

The contribution from the theoretical uncertainty in $\sqrt{B_B} f_B$ is about an order of magnitude larger than the contribution from the experimental errors in Δm_d.

Allowed regions in the ρ-η Plane

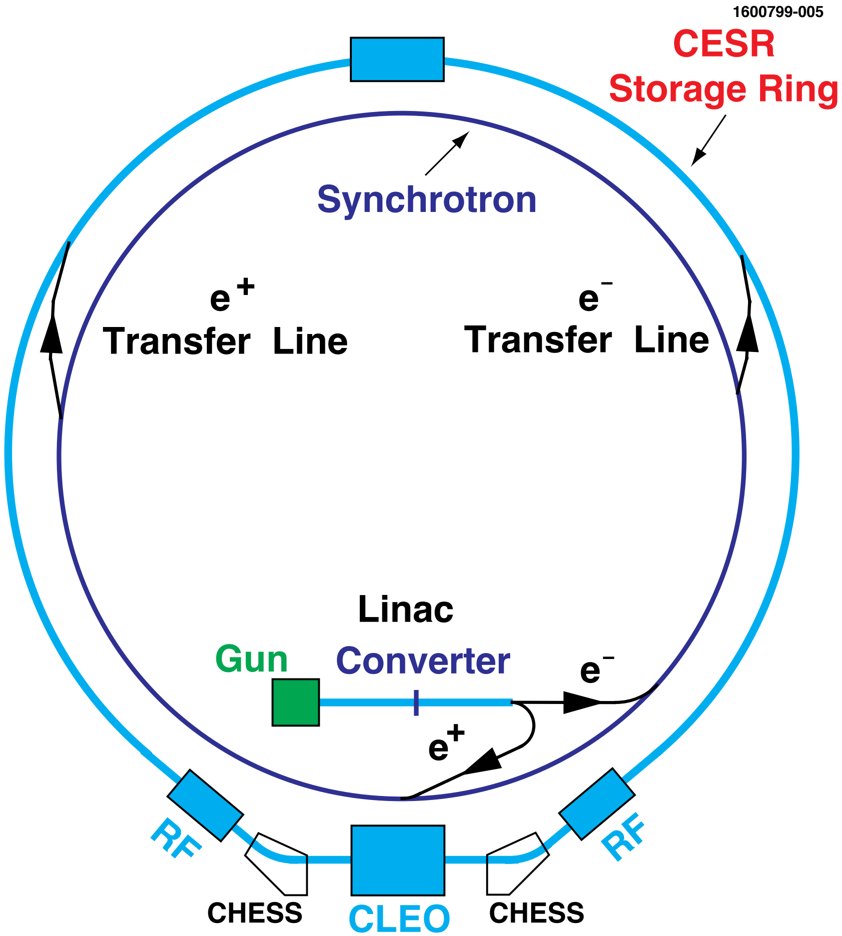
One illustration of regions in the ρ-η plane allowed by current experimental and *conservative* theoretical uncertainties, using a variant of the 95% scan method. Most input from PDG 2000 and 2001 Update.



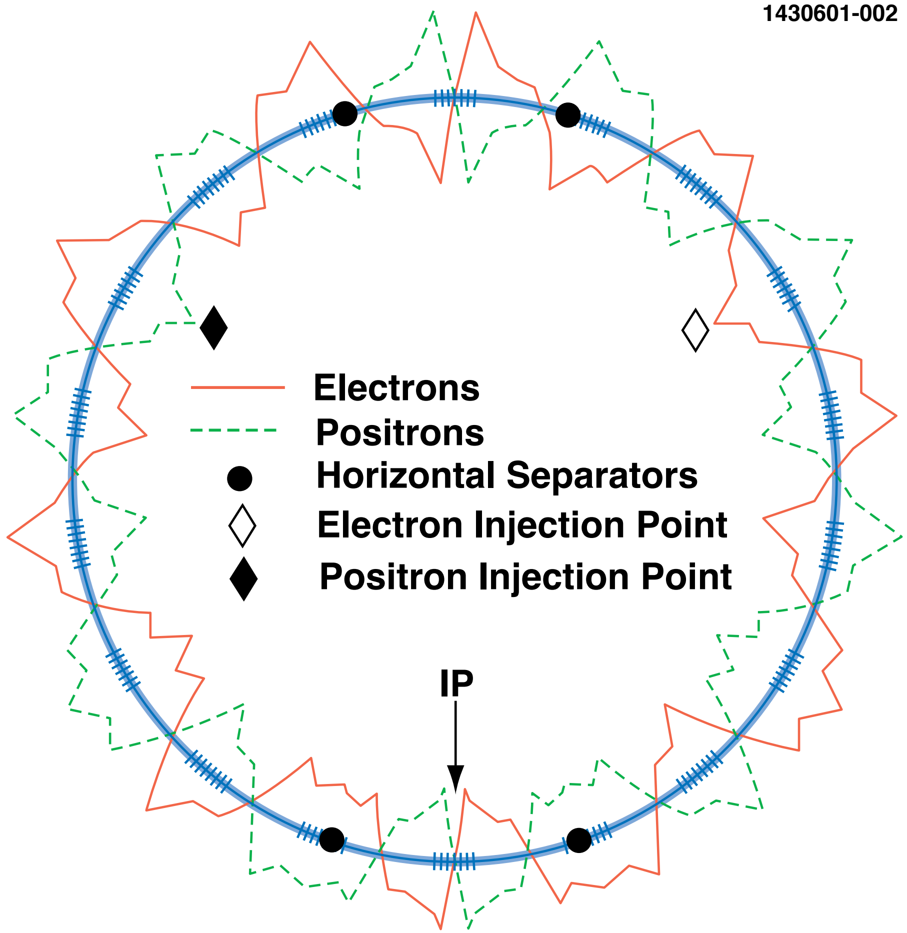
Theoretical uncertainties dominate the widths of all bands except $A_{CP}(\psi K_S)$.

CESR

Schematic CESR Layout



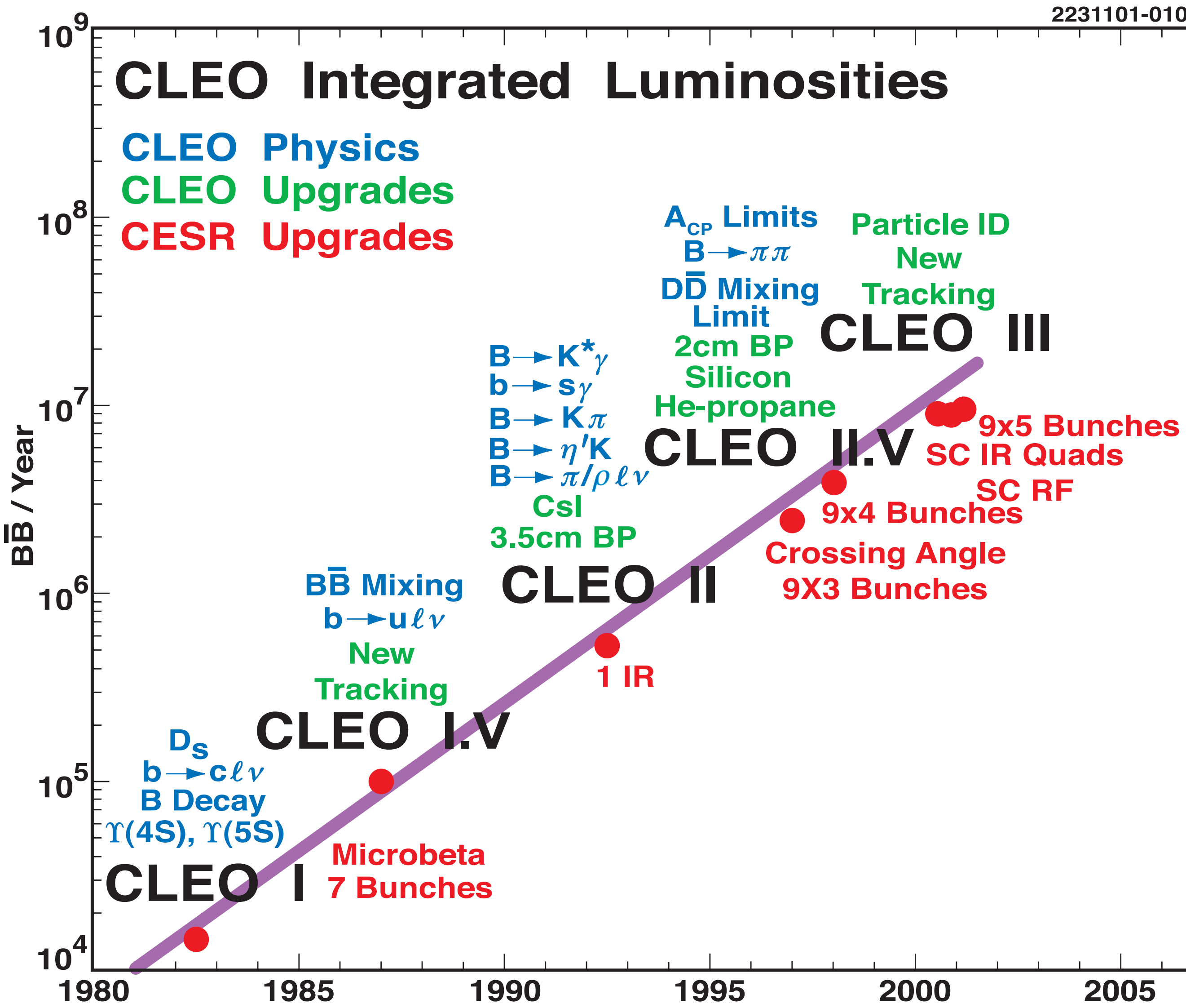
Bunch Trains in CESR



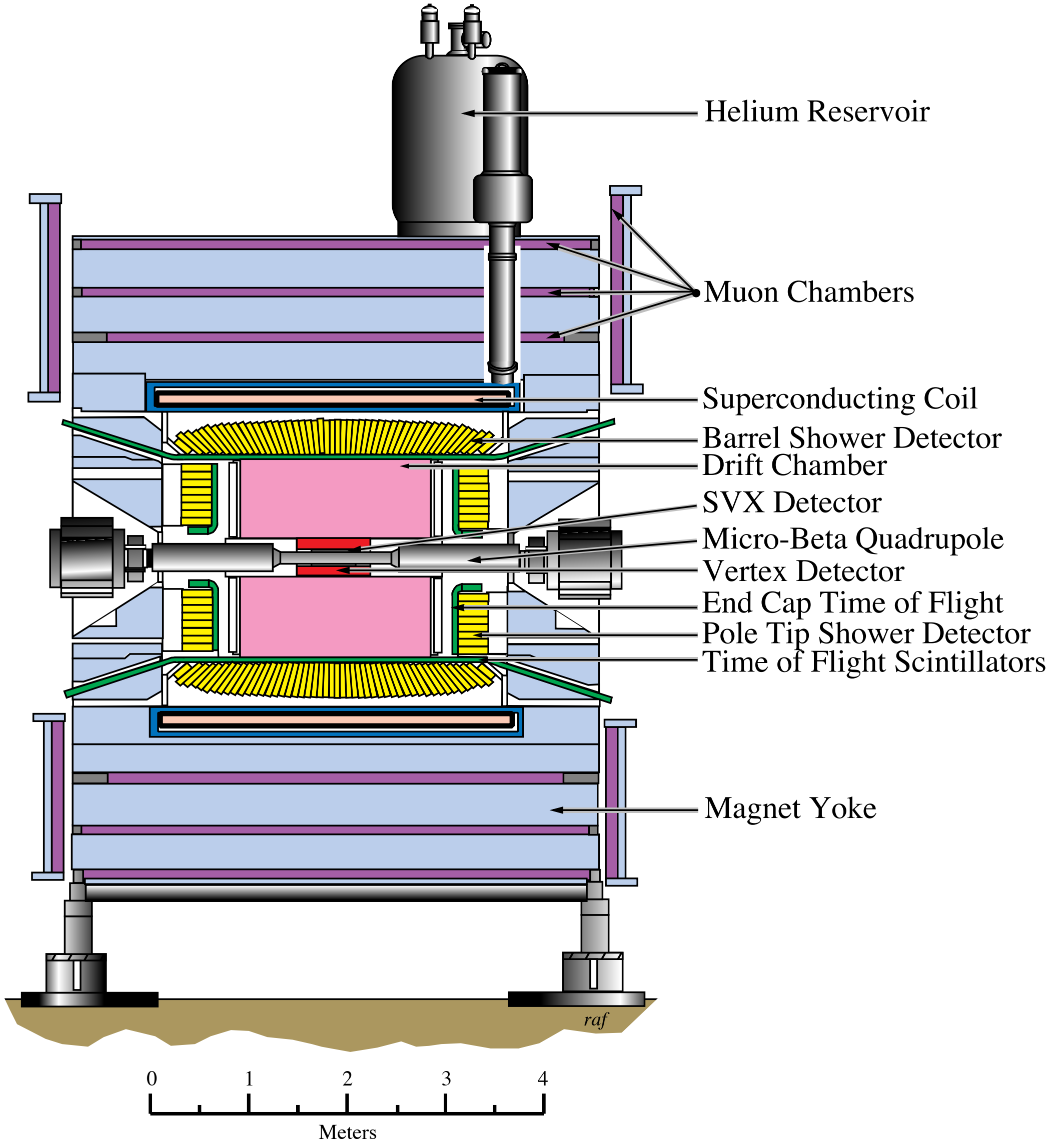
Cornell innovations (also used in LEP)

- Pretzel (brezel) orbits — Littauer 1985
- Bunch trains — Meller 1990

Brief History of CESR and CLEO



The CLEO II.V Detector and CLEO Collaboration

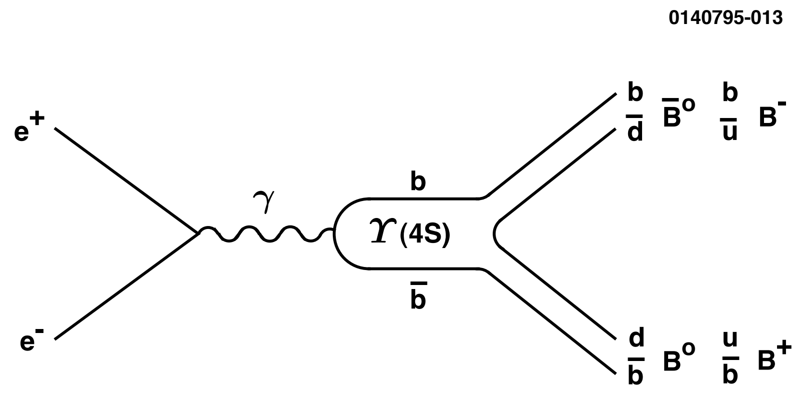


25 CLEO Institutions

CalTech, UC San Diego,
UC Santa Barbara,
Carnegie Mellon, Cornell,
Florida, Harvard, Illinois U-C,
Carleton, Ithaca College, Kansas,
Minnesota, SUNY Albany,
Ohio State, Oklahoma,
Pittsburgh, Purdue, Rochester,
Southern Methodist, Syracuse,
UT Austin, UT Pan American,
Vanderbilt, Virginia Polytechnic,
Wayne State

$\sim$ 160 Physicists

CLEO Data Samples



Detector	$\Upsilon(4S)$ fb^{-1}	Continuum fb^{-1}	$B\bar{B}$ Events (10^6)
CLEO II	3.1	1.6	3.3
CLEO II.V	6.0	2.8	6.4
Subtotal	9.1	4.4	9.7
CLEO III	6.9	2.3	7.4
Total	16.0	6.7	17.1

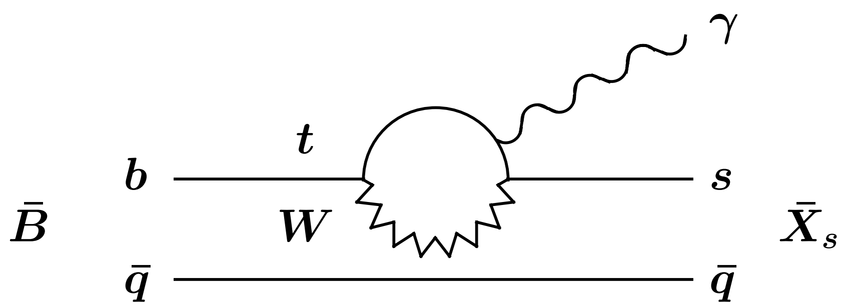
CLEO studies B mesons from:

- $e^+e^- \to \Upsilon(4S) \to B^+B^-$
- $e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0$
- No other particles are produced
- $E_{\pm} = 5.290$ GeV – beam energy
- $E(B) = E_{\pm}$

Data samples used in different analyses:

- CLEO II data are used in the $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ analysis
- CLEO II and II.V data are used in most other analyses
- CLEO III data are used in the new $B \to K\pi(\pi\pi)$ analyses

$b \to s\gamma$ Decays



Radiative penguin diagram

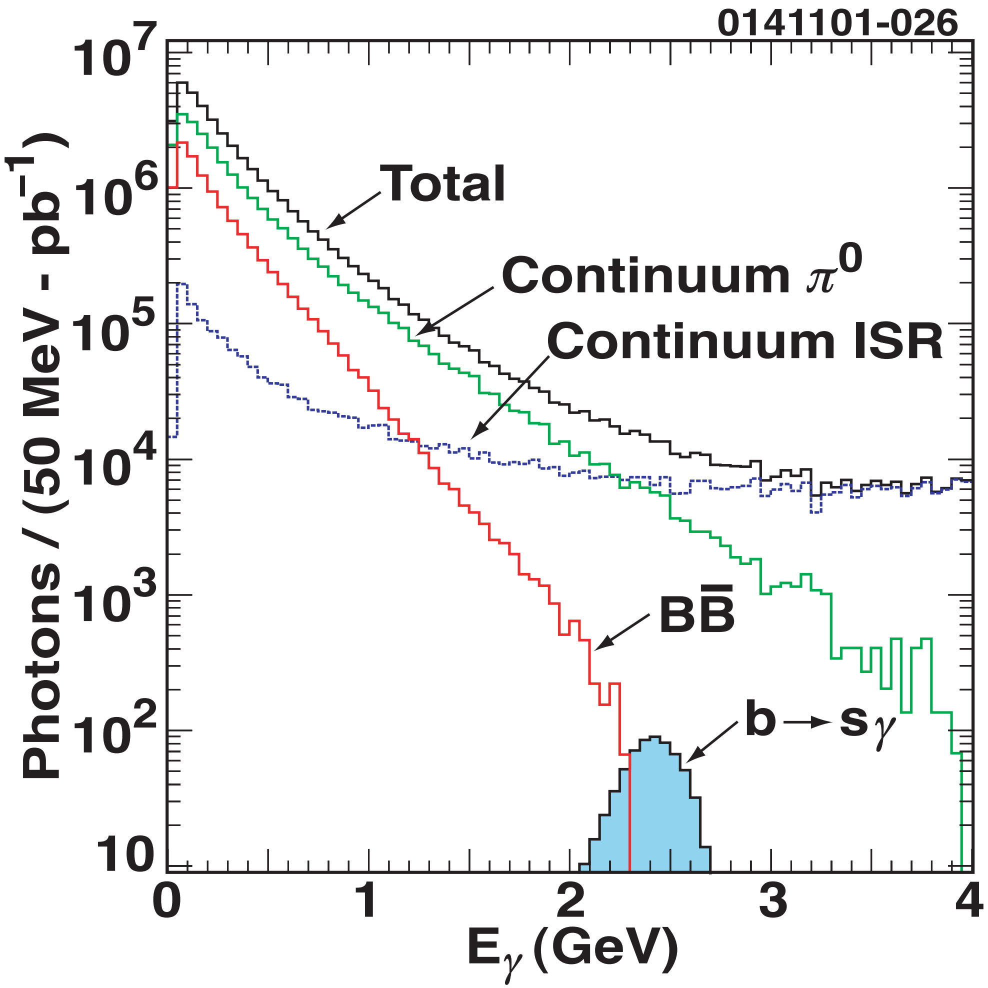
- Inclusive $\mathcal{B}(b \to s\gamma)$ is sensitive to charged Higgs, anomalous $WW\gamma$ couplings, and other New Physics (NP) beyond the Standard Model (SM)
  - NP can appear as additional contributions to the loop
- $\mathcal{B}(b \to s\gamma)$ calculated to next-to-leading-log order
  - $\mathcal{B}(b \to s\gamma)$ and the E_γ spectrum of $b \to s\gamma$ can be related to observed $B \to X_s\gamma$ decays with reasonable confidence
- Penguin diagrams (without radiation) were proposed $\sim$ 1970 to explain CP violation in K^0 decay
  - $B \to K^*\gamma$ (CLEO 1993) was the first definitive observation of a penguin process
- Exclusive $\mathcal{B}(B \to K^{*(*)}\gamma)$ are sensitive to hadronization effects and therefore insensitive to NP

$b \longrightarrow s\gamma$ Decays

CLEO published the first measurement of $\mathcal{B}(b \rightarrow s\gamma)$ in 1995

- **This update uses the full CLEO II and II.V data sample.**
  - **Factor of ~ 3 more data than the previous CLEO analysis**
- **Signal is an isolated γ with $2.0 < E_\gamma < 2.7$ GeV**
  - **Includes essentially all of the E_γ spectrum**
  - **Previously used $2.2 < E_\gamma < 2.7$ GeV**
  - **Much less model dependence now**

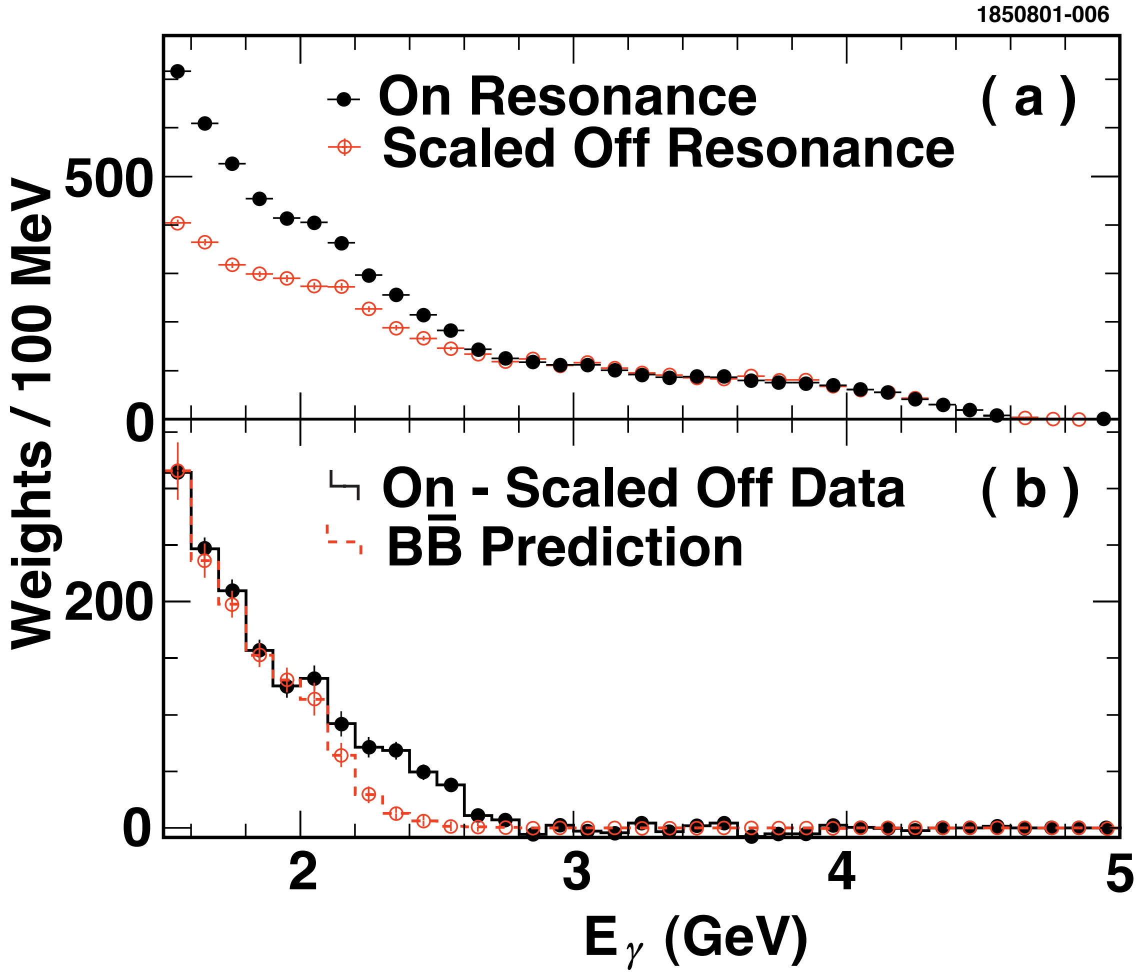
$b \longrightarrow s\gamma$ Decays



Search for an isolated γ with $2.0 < E_\gamma < 2.7$ GeV

- Above about 2.3 GeV most backgrounds are γs from Initial State Radiation or π^0s from continuum events
- Reduce huge background with
  - event shapes and energies in cones relative to p_γ
  - X_s pseudoreconstruction
  - presence of a ℓ in the event
- Combine all information into a single weight between
  - 0.0 (continuum) and
  - 1.0 ($B \longrightarrow X_s\gamma$)

$b \longrightarrow s\gamma$ Decays



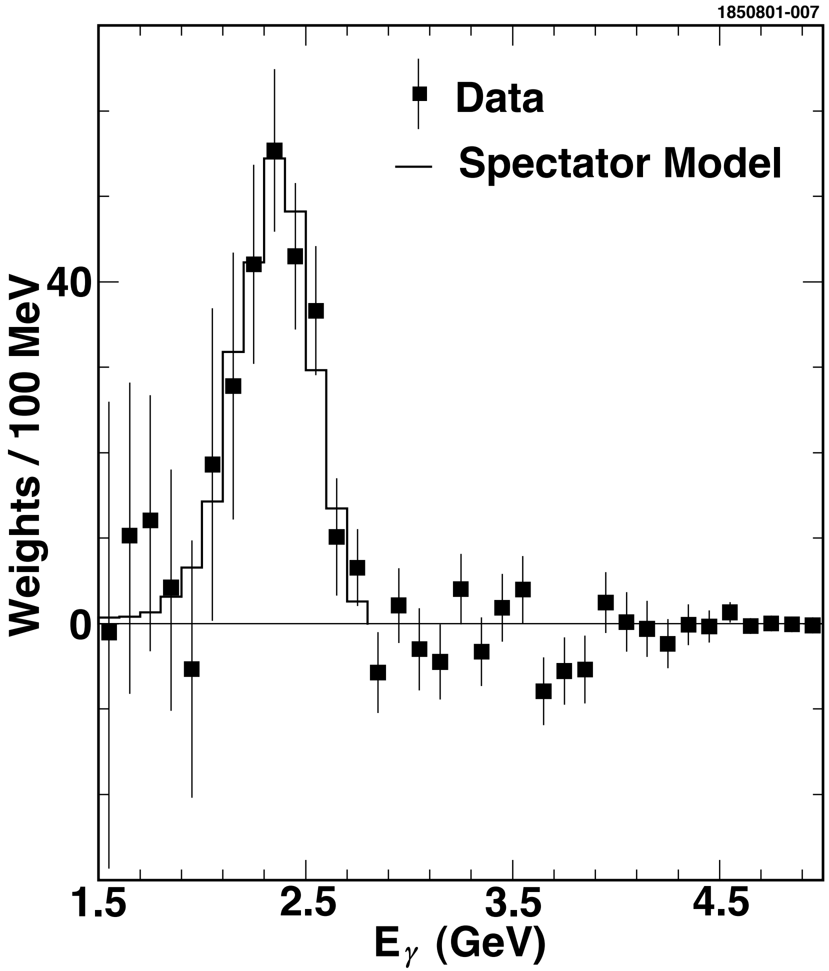
Utilizing weights:

- Subtract Off-$\Upsilon(4S)$ (continuum) data from On-$\Upsilon(4S)$ data
  - Note that subtracted data agree:
    - with $B\bar{B}$ background below 2 GeV and
    - with 0 above 3 GeV
- Then subtract $B\bar{B}$ background

Large continuum data sample is essential for this analysis

$b \longrightarrow s\gamma$ Decays

Weight distribution after subtracting continuum and $B\bar{B}$ backgrounds.



Ali-Greub Spectator Model

CLEO II and II.V Result:

- $\mathcal{B}(b \longrightarrow s\gamma) =$
  $(3.21 \pm 0.43 \pm 0.27^{+0.18}_{-0.10}) \times 10^{-4}$
  (stat) (sys)(thry)

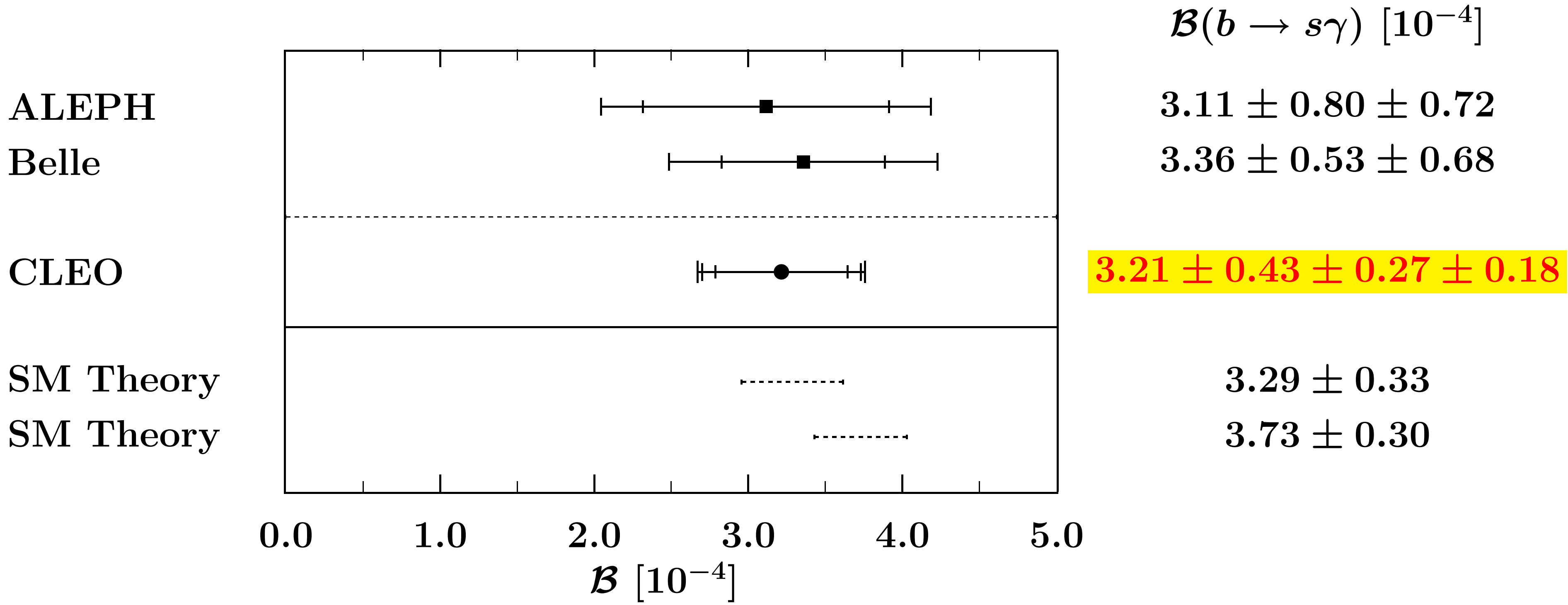
Theory:

- $\mathcal{B}(b \longrightarrow s\gamma) = (3.29 \pm 0.33) \times 10^{-4}$
  - (Chetyrkin-Misiak-Münz and Kagan-Neubert)
- $\mathcal{B}(b \longrightarrow s\gamma) = (3.73 \pm 0.30) \times 10^{-4}$
  - (Gambino-Misiak)

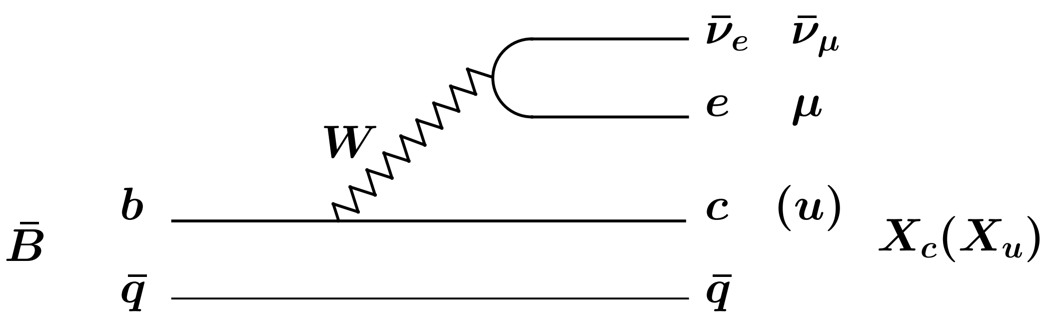
Conclusions:

- CLEO errors close to theoretical uncertainty.
- There is not much room for New Physics.

Summary of $\mathcal{B}(b \to s\gamma)$ Measurements and Theory



Determining $|V_{cb}|$ and $|V_{ub}|$



$|V_{cb}|$ and $|V_{ub}|$ can be determined from semileptonic decays

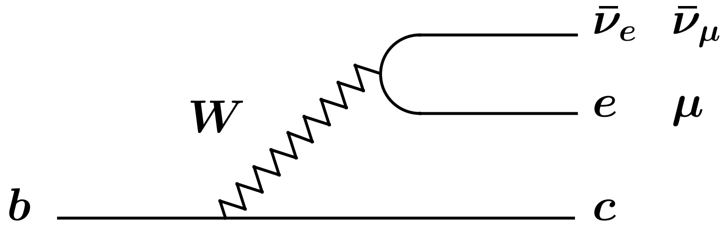
$$\Gamma^c_{SL} \equiv \Gamma(\bar{B} \to X_c \ell \bar{\nu}) = \frac{\mathcal{B}(\bar{B} \to X_c \ell \bar{\nu})}{\tau_B} = \gamma_c \, |V_{cb}|^2$$

[for $\Gamma^{\mathrm{u}}_{\mathrm{SL}}$ replace c with u]

- Measure $\mathcal{B}(\bar{B} \to X_c \ell \bar{\nu})$
  - Determine from fits to the inclusive p_ℓ spectrum
- The theoretical parameters γ_c and γ_u are a serious problem
  - Previously they were obtained from theoretical models
  - $b \to s\gamma$ decays can substantially reduce model dependence

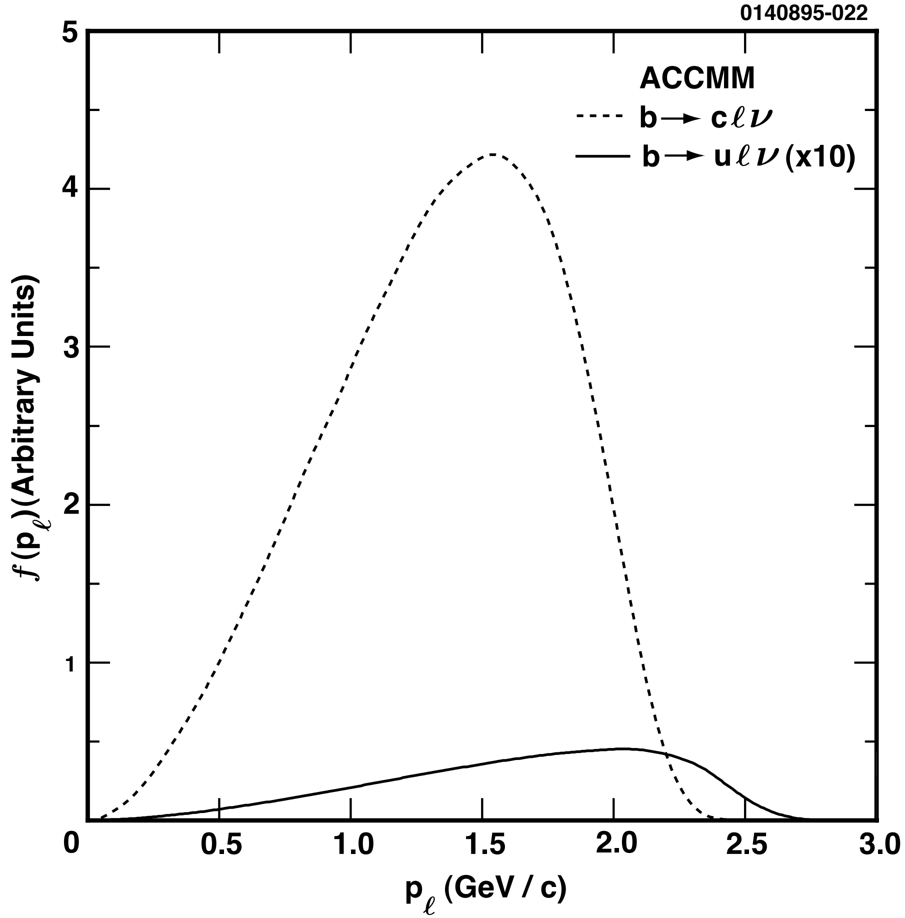
Ultimately we need an accurate and verified theory for γ_c and γ_u

Determining $|V_{cb}|$ from Inclusive Semileptonic B Decays



Free Quark Model with QCD corrections:

- Start with
  $$\gamma_c = \frac{G_F^2\, m_b^5}{192\,\pi^3}\, f(x_c) \quad \text{with}$$
  - G_F the Fermi constant
  - m_b the b-quark mass
  - m_c the c-quark mass
  - $f(x_c)$ phase-space ($x_c = m_c^2/m_b^2$)
- Add QCD corrections
- Includes all exclusive channels
- Problems:
  - No description of individual channels
  - Need model for $b\bar{q}$ binding
    - Fermi momentum p_F in ACCMM
  - Unknown m_b raised to fifth power!



Determining $|V_{cb}|$ from Inclusive Semileptonic B Decays

The Heavy Quark Expansion provides a potential solution to the m_b^5 problem:

- Inclusive observables are written in terms of a double expansion in α_S and $1/M_B$ (M_B is the observable B meson mass)
  - Nonperturbative QCD parameters enter at each order in the expansion
  - Current goal is to determine these parameters from experimental measurements
- The b quark mass is related to M_B and three nonperturbative QCD parameters:

$$\begin{aligned} M_B &= m_b + \bar{\Lambda} - \frac{\lambda_1 + 3\lambda_2}{2m_b} + \ldots \\ M_{B^*} &= m_b + \bar{\Lambda} - \frac{\lambda_1 - \lambda_2}{2m_b} + \ldots \end{aligned}$$

- Intuitively:
  - $\bar{\Lambda}$ is the energy of the light quark and gluon degrees of freedom
  - $-\lambda_1$ is the average of the square of the b quark momentum
  - λ_2/m_b is the hyperfine interaction of the b quark and light degrees of freedom
- Determine λ_2 from $M_{B^*} - M_B \approx 46$ MeV$/c^2$
- Determine $\bar{\Lambda}$ and λ_1 from hadronic mass moments in $\bar{B} \to X_c \ell \bar{\nu}$ decay and photon energy moments in $b \to s\gamma$ decay

$|V_{cb}|$ from Hadronic Mass Moments and $b \to s\gamma$

$\Gamma(\bar{B} \to X_c \ell \bar{\nu})$ can be written in the form:

$$\Gamma^c_{SL} = \frac{G_F^2 \, |V_{cb}|^2 \, M_B^5}{192\pi^3} \left[\mathcal{G}_0 + \frac{1}{M_B}\mathcal{G}_1(\bar{\Lambda}) + \frac{1}{M_B^2}\mathcal{G}_2(\bar{\Lambda}, \lambda_1, \lambda_2) \right.$$

$$\left. + \frac{1}{M_B^3}\mathcal{G}_3(\bar{\Lambda}, \lambda_1, \lambda_2 | \rho_1, \rho_2, \mathcal{T}_1, \mathcal{T}_2, \mathcal{T}_3, \mathcal{T}_4) + \mathcal{O}\left(\frac{1}{M_B^4}\right) \right]$$

- $\bar{\Lambda}, \lambda_1, \lambda_2, \rho_1, \rho_2, \mathcal{T}_1, \mathcal{T}_2, \mathcal{T}_3, \mathcal{T}_4$ are nonperturbative parameters,
- $\mathcal{G}_n$ are polynomials of order $\leq n$ in $\bar{\Lambda}, \lambda_1$,λ_2, and power series in α_S
- $\mathcal{G}_3$ is linear in $\rho_1, \rho_2, \mathcal{T}_1, \mathcal{T}_2, \mathcal{T}_3, \mathcal{T}_4$, and
- We use theoretical estimates of bounds for $\rho_1, \rho_2, \mathcal{T}_1, \mathcal{T}_2, \mathcal{T}_3, \mathcal{T}_4$.

There are similar expressions for the moments

- $\langle (M_X^2 - \bar{M}_D^2) \rangle$ of the $\bar{B} \to X_c \ell \bar{\nu}$ hadronic mass (M_X) spectrum (polynomials $\mathcal{M}_n$)
  - M_X is the mass of the hadronic system in $\bar{B} \to X_c \ell \bar{\nu}$ decay
  - $\bar{M}_D \equiv (M_D + 3M_{D^*})/4)$ – spin averaged $D^{(*)}$ mass
- $\langle E_\gamma \rangle$ of the $b \to s\gamma$ photon energy (E_γ) spectrum (polynomials $\mathcal{E}_n$).

$|V_{cb}|$ from Hadronic Mass Moments and $b \to s\gamma$

Moments of the $\bar{B} \to X \ell \bar{\nu}$ hadronic mass spectrum and $b \to s\gamma$ energy spectrum as functions of $\bar{\Lambda}, \lambda_1, \lambda_2, \rho_1, \rho_2, \mathcal{T}_1, \mathcal{T}_2, \mathcal{T}_3, \mathcal{T}_4$:

$$
\begin{aligned}
\frac{\langle (M_X^2 - \bar{M}_D^2) \rangle}{M_B^2} \;&=\; \mathcal{M}_0 + \frac{1}{M_B}\mathcal{M}_1(\boxed{\bar{\Lambda}}) + \frac{1}{M_B^2}\mathcal{M}_2(\boxed{\bar{\Lambda}, \lambda_1}, \lambda_2) \\
&+\; \frac{1}{M_B^3}\mathcal{M}_3(\boxed{\bar{\Lambda}, \lambda_1}, \lambda_2 | \rho_1, \rho_2, \mathcal{T}_1, \mathcal{T}_2, \mathcal{T}_3, \mathcal{T}_4) \\
&+\; \mathcal{O}\left(\frac{1}{M_B^4}\right)
\end{aligned}
$$

$$
\begin{aligned}
\frac{\langle E_\gamma \rangle}{M_B} \;&=\; \mathcal{E}_0 + \frac{1}{M_B}\mathcal{E}_1(\boxed{\bar{\Lambda}}) \\
&+\; \frac{1}{M_B^2}\mathcal{E}_2(\rho_1, \rho_2, \mathcal{T}_1, \mathcal{T}_2, \mathcal{T}_3, \mathcal{T}_4; C_2/(M_D^2 C_7)) + \mathcal{O}\left(\frac{1}{M_B^3}\right)
\end{aligned}
$$

$|V_{cb}|$ from Hadronic Mass Moments and $b \to s\gamma$

To extract $|V_{cb}|$ we

- determine λ_2 from $M_{B^*} - M_B$, and
- determine $\bar{\Lambda}$ and λ_1 from $\langle (M_X^2 - \bar{M}_D^2) \rangle$ and $\langle E_\gamma \rangle$.

Other experimental parameters:

- $\mathcal{B}(\bar{B} \to X_c \ell \bar{\nu}) = (10.39 \pm 0.46)\%$ from CLEO,
- τ_{B^-} and τ_{B^0} from PDG 2000, and
- $(f_{+-}\tau_{B^-})/(f_{00}\tau_{B^0}) = 1.11 \pm 0.08$ from CLEO.
  - $f_{+-} \equiv \mathcal{B}(\Upsilon(4S) \to B^+ B^-)$
  - $f_{00} \equiv \mathcal{B}(\Upsilon(4S) \to B^0 \bar{B}^0)$

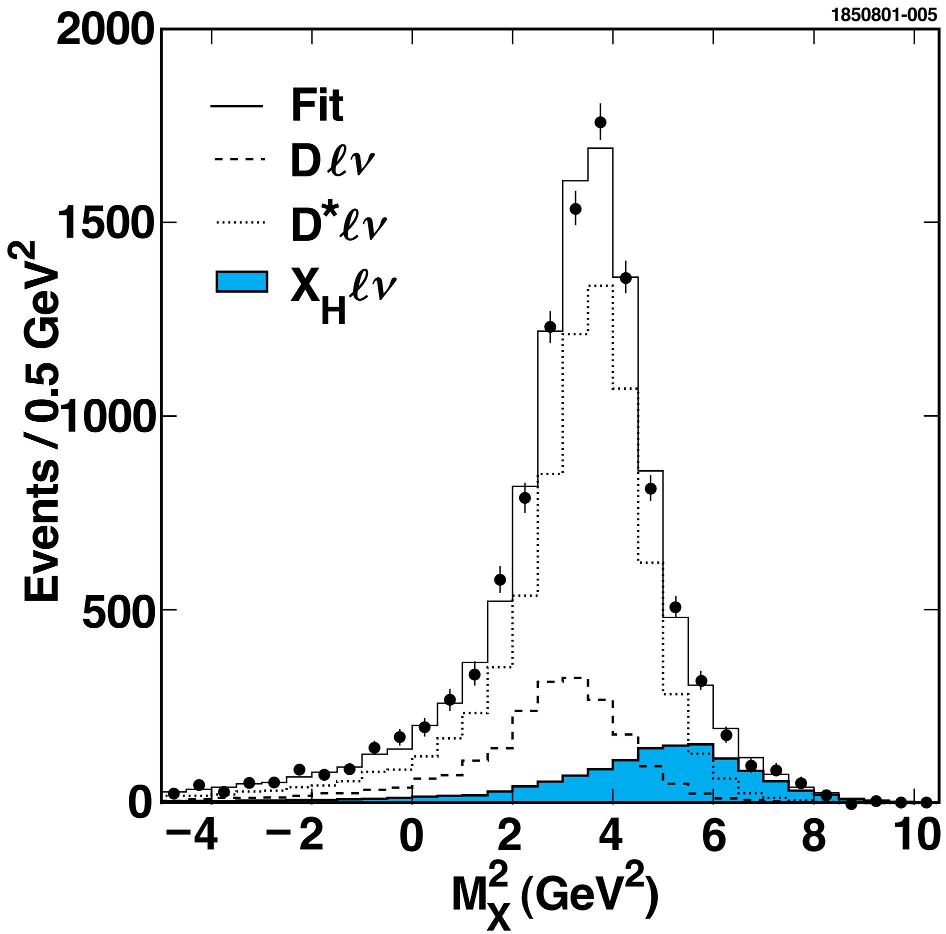
Theoretical functions:

- $\langle (M_X^2 - \bar{M}_D^2) \rangle$ are measured for $E_\ell > 1.5$ GeV,
- $\langle E_\gamma \rangle$ are measured for $E_\gamma > 2.0$ GeV, and
- $\mathcal{G}_n$, $\mathcal{M}_n$, and $\mathcal{E}_n$ calculated with same cuts using Falk-Luke, Phys. Rev. D 57, 1 (1998)

$|V_{cb}|$ from Hadronic Mass Moments and $b \to s\gamma$

Reconstructing M_X^2:

- reconstruct ν with $E_\nu = E_{\text{miss}}$ and $P_\nu = P_{\text{miss}}$,
- $M_X^2 = M_B^2 + M_{\ell\nu}^2 - 2(E_B E_{\ell\nu} - P_B P_{\ell\nu} \cos\theta_{B-\ell\nu})$ [$\cos\theta_{B-\ell\nu}$ unknown and P_B small]
- drop last term and use: $M_X^2 \approx M_B^2 + M_{\ell\nu}^2 - 2E_B E_{\ell\nu}$



Calculate M_X^2 moments by fitting the M_X^2 distribution to contributions from:

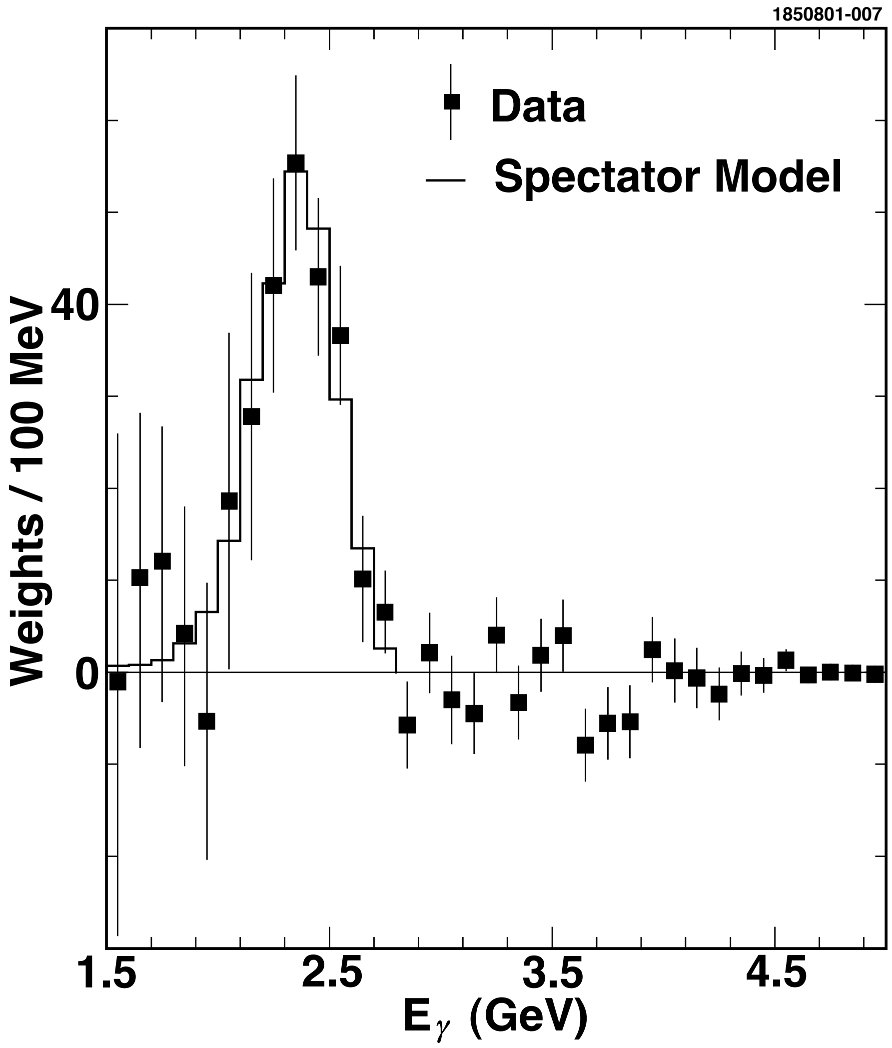
- $\bar{B} \to D\ell\nu$
- $\bar{B} \to D^*\ell\nu$
- $\bar{B} \to X_H\ell\nu$

For a wide variety of X_H models,

- the $X_H\ell\nu$ fraction is sensitive to the models and
- the M_X^2 moments are insensitive to the models.

The dispersion included in the systematic error

$|V_{cb}|$ from Hadronic Mass Moments and $b \to s\gamma$



Calculate E_γ moments using

- fits of the $b \to s\gamma$ data to the Ali-Greub and Kagen-Neubert spectra, and
- hadronization from Monte Carlos with JETSET and multiple $K^{*(*)}$.

Results of the four estimates agree and dispersion is included in the systematic error.

$|V_{cb}|$ from Hadronic Mass Moments and $b \to s\gamma$

Measured M_X^2 moments:

$$\begin{aligned}\langle (M_X^2 - \bar{M}_D^2) \rangle &= 0.251 \pm 0.023 \pm 0.062 \ \mathrm{GeV}^2 \\ \langle (M_X^2 - \langle M_X^2 \rangle)^2 \rangle &= 0.639 \pm 0.056 \pm 0.178 \quad \mathrm{GeV}^4\end{aligned}$$

Measured E_γ moments:

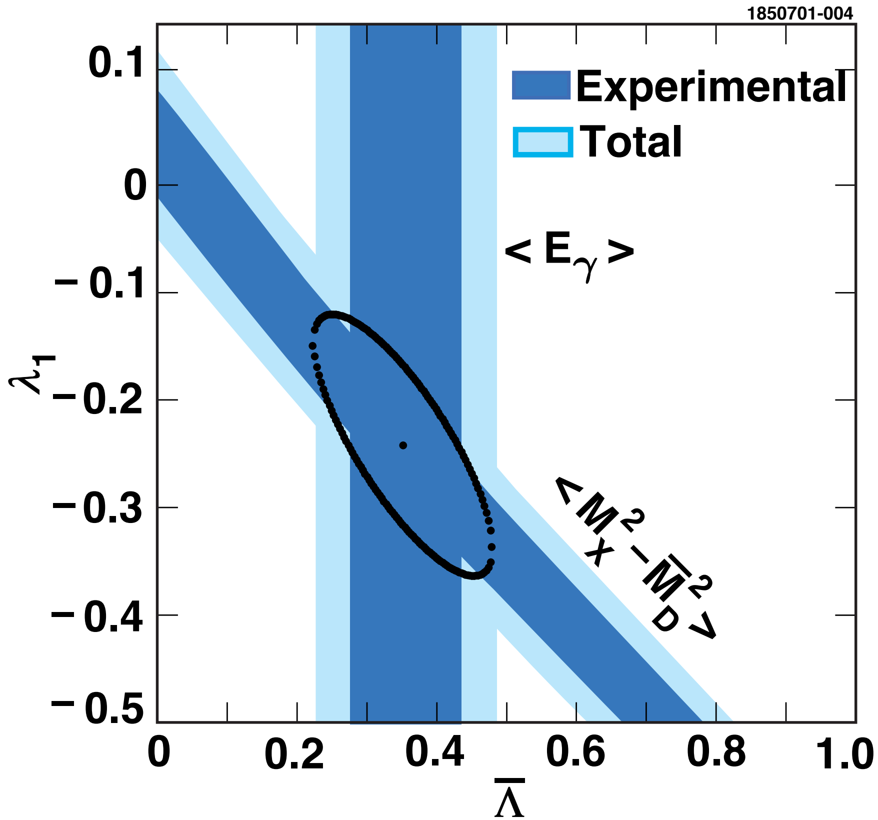
$$\begin{aligned}\langle E_\gamma \rangle &= 2.346 \ \pm 0.032 \ \pm 0.011 \quad \mathrm{GeV} \\ \langle (E_\gamma - \langle E_\gamma \rangle)^2 \rangle &= 0.0226 \pm 0.0066 \pm 0.0020 \ \mathrm{GeV}^2\end{aligned}$$

Use only $\langle (M_X^2 - \bar{M}_D^2) \rangle$ and $\langle E_\gamma \rangle$ to determine $\bar{\Lambda}$ and λ_1 since theoretical expressions for the next moments are much less reliable.

Determining $|V_{cb}|$ from Hadronic Mass Moments and $b \to s\gamma$

The intersection of the E_γ and M_X moments yields $\bar{\Lambda}$ and λ_1.

$$\begin{aligned} \bar{\Lambda} &= 0.35 \pm 0.07 \pm 0.10 \text{ GeV} \\ \lambda_1 &= -0.238 \pm 0.071 \pm 0.078 \text{ GeV}^2 \\ & \qquad\qquad\quad (\mathrm{M}) \qquad (\mathrm{T}) \end{aligned}$$



Then the expression for Γ^c_{SL} yields

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

Errors are due to

(M) moment uncertainties,

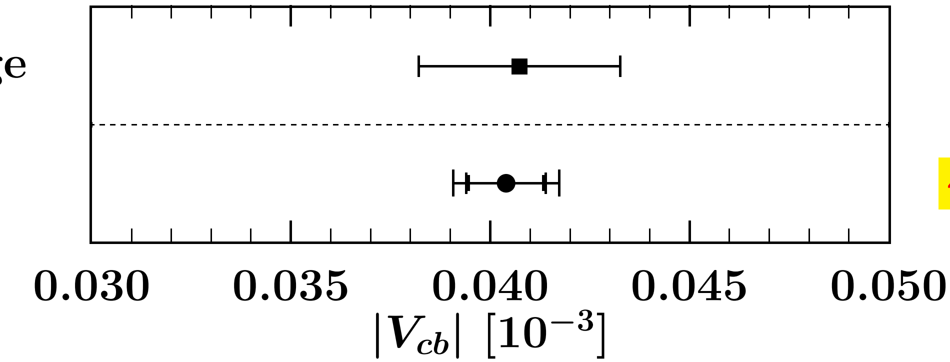
(Γ) Γ^c_{SL} uncertainties, and

(T) α_s scale and ignoring the $\mathcal{O}(1/M_B^3)$ term which contains the estimated parameters

Even with this measurement of QCD parameters, the theoretical uncertainties (T) are comparable to the experimental errors (M) and (Γ).

Summary of Inclusive Measurements of $|V_{cb}|$

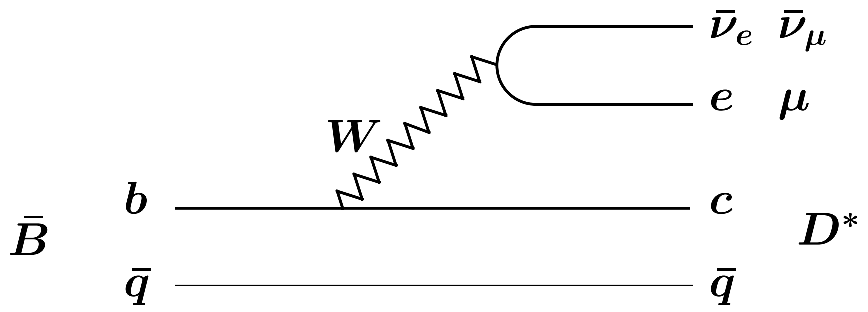
Experiment	$|V_{cb}|$ $[10^{-3}]$
LEP HFWG Average	40.7 ± 2.5
CLEO II & II.V	$40.4 \pm 0.9 \pm 0.5 \pm 0.8$



Note: LEP measurements were made with model values of γ_c

LEP now adopting CLEO nonperturbative parameters.

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



From Heavy Quark Effective Theory (Isgur-Wise symmetry) the differential decay width for $\bar{B} \to D^* \ell^- \bar{\nu}$ decay is

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

with $w \equiv v_B \cdot v_{D^*} = \dfrac{\mathcal{E}_{D^*}}{M_{D^*}} = \dfrac{M_B^2 + M_{D^*}^2 - q^2}{2M_B M_{D^*}}$

- v_B and v_{D^*} are the 4-velocities of the B and D^*,
- $\mathcal{E}_{D^*}$ is the energy of the D^* in the B rest frame.
- The w range is $(1.00 < w < 1.51)$ for $\bar{B} \to D^* \ell^- \bar{\nu}$ decay.
- $\mathcal{G}(w)$ is a known function of w.

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

The form factor $\mathcal{F}_{D^*}(w)$

- replaces the 3 form factors required without the Isgur-Wise symmetry,
- parameterizes the w dependence of the hadronic current, and
- is constrained by Heavy Quark Effective Theory (HQET)
  - $\mathcal{F}_{D^*}(1) \approx \eta_A[1 + \mathcal{O}(1/m_Q^2)]$ for large heavy quark masses

However $\mathcal{G}(1) = 0$ (phase space) so

- measure $d\Gamma(w)/dw$ over the full w range,
- extract $|V_{cb}|\mathcal{F}_{D^*}(w)$ and fit it over the full w range,
- extrapolate $|V_{cb}|\mathcal{F}_{D^*}(w)$ to $w = 1$ to get $|V_{cb}|\mathcal{F}_{D^*}(1)$.

Reduce w dependence of $\mathcal{F}_{D^*}(w)$ in the fit to a slope parameter ρ^2 using

- theory from Caprini-Lellouch-Neubert and
- the form factor ratios $R_1(1)$ and $R_2(1)$, previously measured by CLEO

We now have results for

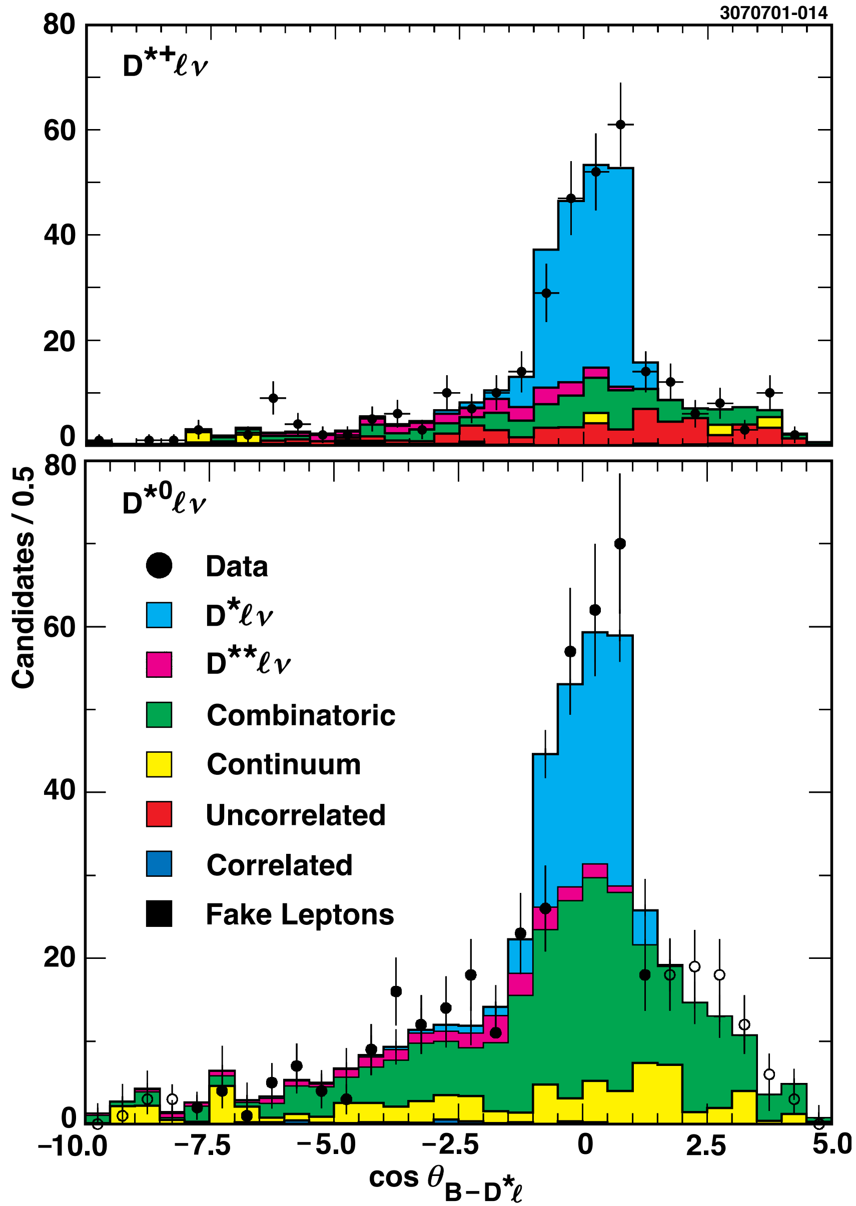
- $\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}$ *and* $B^- \to D^{*0} \ell^- \bar{\nu}$
- previously (e.g., ICHEP 2000 Osaka) only $\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}$

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

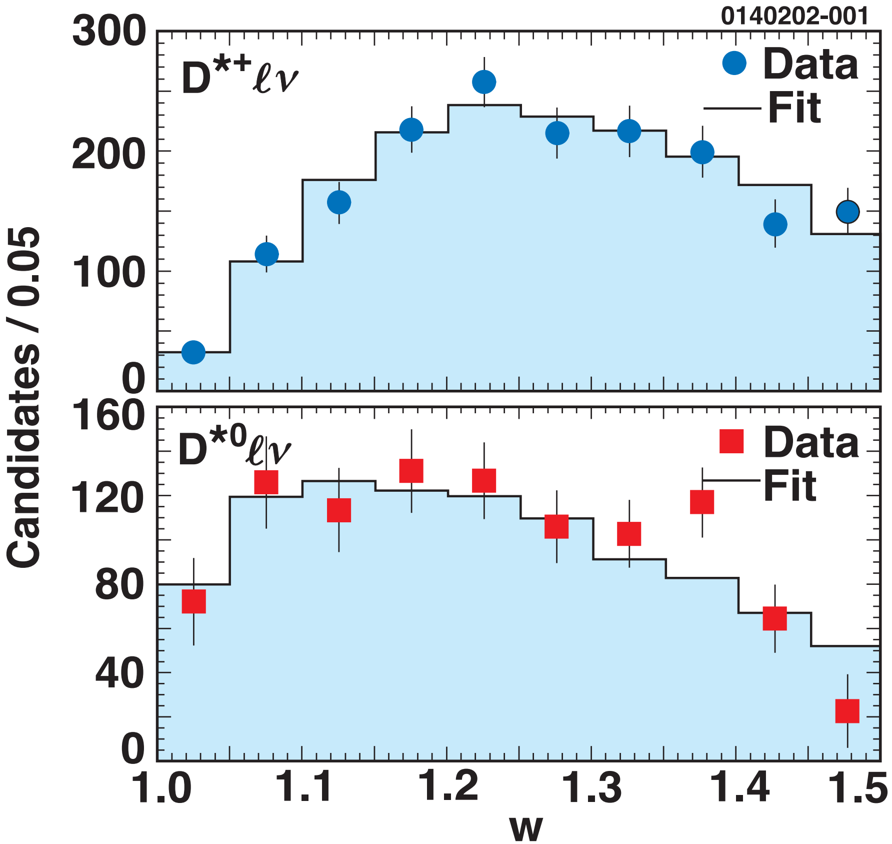
The strategy for reconstructing $\bar{B} \to D^*\ell^-\bar{\nu}$ is to:

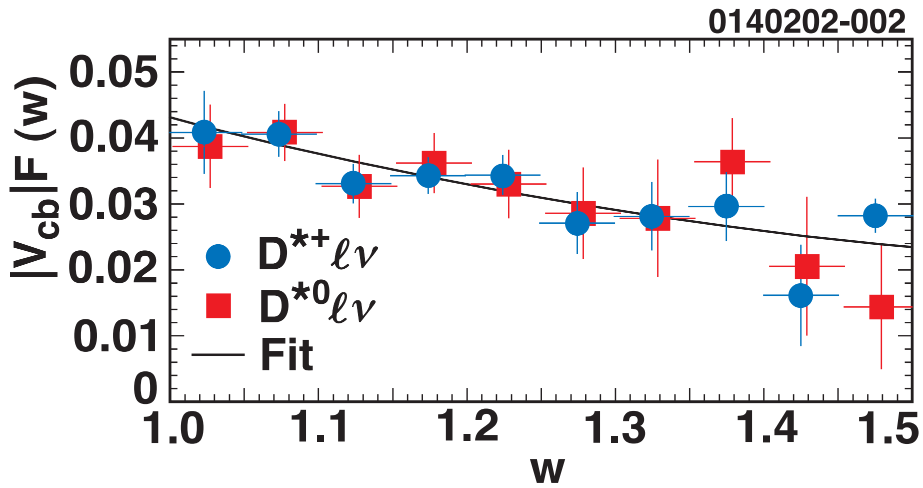
- find a D^* using $D^* \to D^0\pi$ and $D^0 \to K^-\pi^+$,
- find a lepton ℓ^- (e or μ) with the same sign as the K^-, and
- separate the $\bar{B} \to D^*\ell^-\bar{\nu}$ signal from background using the angle $\theta_{B-D^*\ell}$ between the momenta of the B and the $D^*\ell$ combination

$$\cos\theta_{B-D^*\ell} = \frac{2E_B E_{D^*\ell} - M_B^2 - M_{D^*\ell}^2}{2\,P_B\,P_{D^*\ell}}$$



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





The fit uses:

- $\mathcal{F}_{D^*}(w)$ from Caprini-Lellouch-Neubert
- $\mathcal{F}_{D^{*+}}(w) = \mathcal{F}_{D^{*0}}(w)$
- $\Gamma(D^{*+}\ell\bar{\nu}) = \Gamma(D^{*0}\ell\bar{\nu})$
- CLEO measurement of $(f_{+-}\tau_{B^-})/(f_{00}\tau_{B^0})$

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

From the $\bar{B} \to D^* \ell^- \bar{\nu}$ fit and systematic error estimates:

$$\begin{aligned} |V_{cb}|\mathcal{F}_{D^*}(1) &= (43.1 \pm 1.3 \pm 1.8) \times 10^{-3} \\ \rho^2 &= 1.61 \pm 0.09 \pm 0.21 \\ \Gamma(\bar{B} \to D^* \ell^- \bar{\nu}) &= (0.0394 \pm 0.0012 \pm 0.0026)\ \mathrm{ps}^{-1} \end{aligned}$$

Using PDG 2000 lifetimes and branching fractions

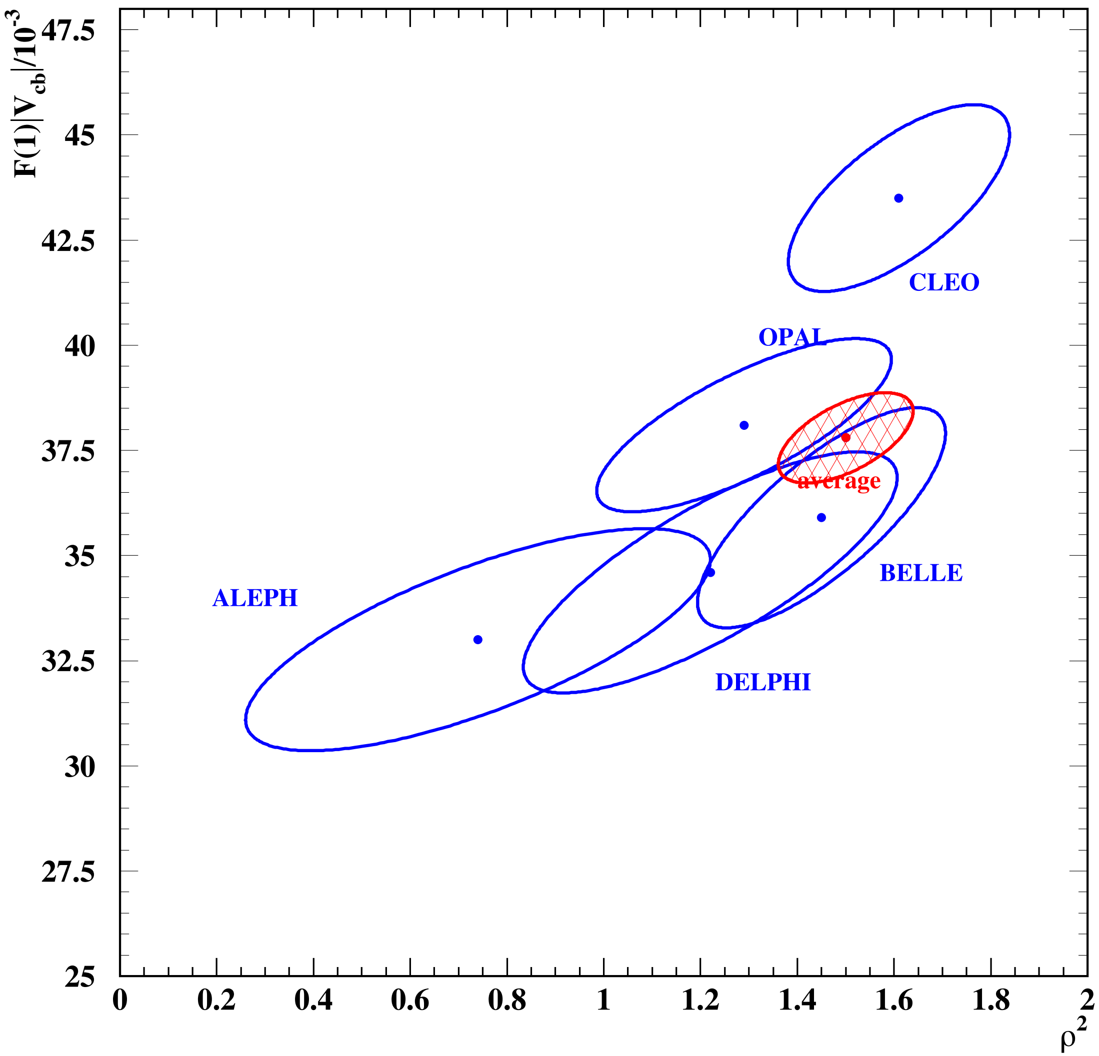
$$\begin{aligned} \mathcal{B}(B^- \to D^{*0} \ell^- \bar{\nu}) &= (6.09 \pm 0.19 \pm 0.40)\% \\ \mathcal{B}(\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}) &= (6.50 \pm 0.20 \pm 0.43)\% \end{aligned}$$

Using $\mathcal{F}_{D^*}(1) = 0.919^{+0.030}_{-0.035}$ (Lattice QCD – Hashimoto *et al.*)

$$\boxed{|V_{cb}| = (46.9 \pm 1.4 \pm 2.0 \pm 1.8) \times 10^{-3}}$$

(stat) (sys) (T)

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

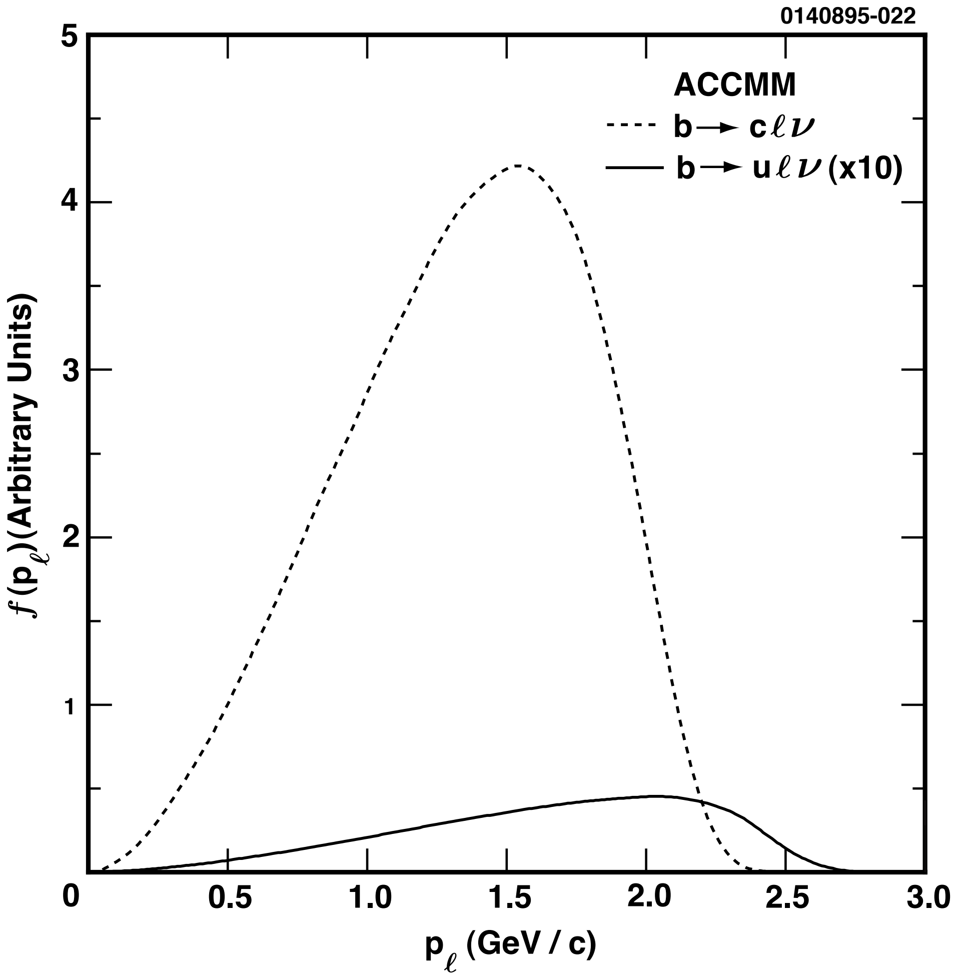


$\sim 6\%$ CL for consistency among the measurements

Possible sources of apparent discrepancy between CLEO and the LEP experiments

- $D^* X \ell \bar{\nu}$ component
  - CLEO fits
  - LEP and Belle use models

$|V_{ub}|$ from Inclusive Leptons and the $b \to s\gamma$ Spectrum



Determine $|V_{ub}|$ from:

- inclusive p_ℓ spectrum above or near the $\bar{B} \to X_c \ell \bar{\nu}$ endpoint or
- exclusive $\bar{B} \to \pi(\rho)\ell\bar{\nu}$ decays.

Either way need theory for fraction $f_u(p)$ of events in the momentum interval (p) above a p_ℓ cut

- leads to severe model dependence
- eliminate much of this uncertainty for inclusive $\bar{B} \to X_u \ell \bar{\nu}$ decays using the $b \to s\gamma$ spectrum
  - Still need theory for γ_u in

$$\Gamma(\bar{B} \to X_u \ell \bar{\nu}) = \gamma_u \, |V_{ub}|^2$$

Ultimately we need an accurate and verified theory for both $f_u(p)$ and γ_u

$|V_{ub}|$ from Inclusive Leptons and the $b \to s\gamma$ Spectrum

Measure $\bar{B} \to X_u \ell \bar{\nu}$ in a lepton momentum interval (p) at the $\bar{B} \to X \ell \bar{\nu}$ endpoint

- $\Delta\mathcal{B}_u(p)$ is the branching fraction for $\bar{B} \to X_u \ell \bar{\nu}$ in (p),
- $f_u(p)$ is the fraction of the $\bar{B} \to X_u \ell \bar{\nu}$ spectrum in (p), and
- $\mathcal{B}_u \equiv \mathcal{B}(\bar{B} \to X_u \ell \bar{\nu})$ is the $\bar{B} \to X_c \ell \bar{\nu}$ branching fraction.

New measurement of $f_u(p)$

- fit $b \to s\gamma$ data to a shape function (Kagan-Neubert)
- use shape parameters to determine $f_u(p)$ (De Fazio-Neubert)

Then get $\mathcal{B}_u$ from $\Delta\mathcal{B}_u(p) = f_u(p)\,\mathcal{B}_u$ and obtain $|V_{ub}|$ from

$$|V_{ub}| = \left[(3.07 \pm 0.12) \times 10^{-3}\right] \times \left[\frac{\mathcal{B}_u}{0.001}\frac{1.6\ \text{ps}}{\tau_B}\right]^{\frac{1}{2}}$$

(Hoang-Ligeti-Manohar and Uraltsev)

$|V_{ub}|$ from Inclusive Leptons and the $b \to s\gamma$ Spectrum

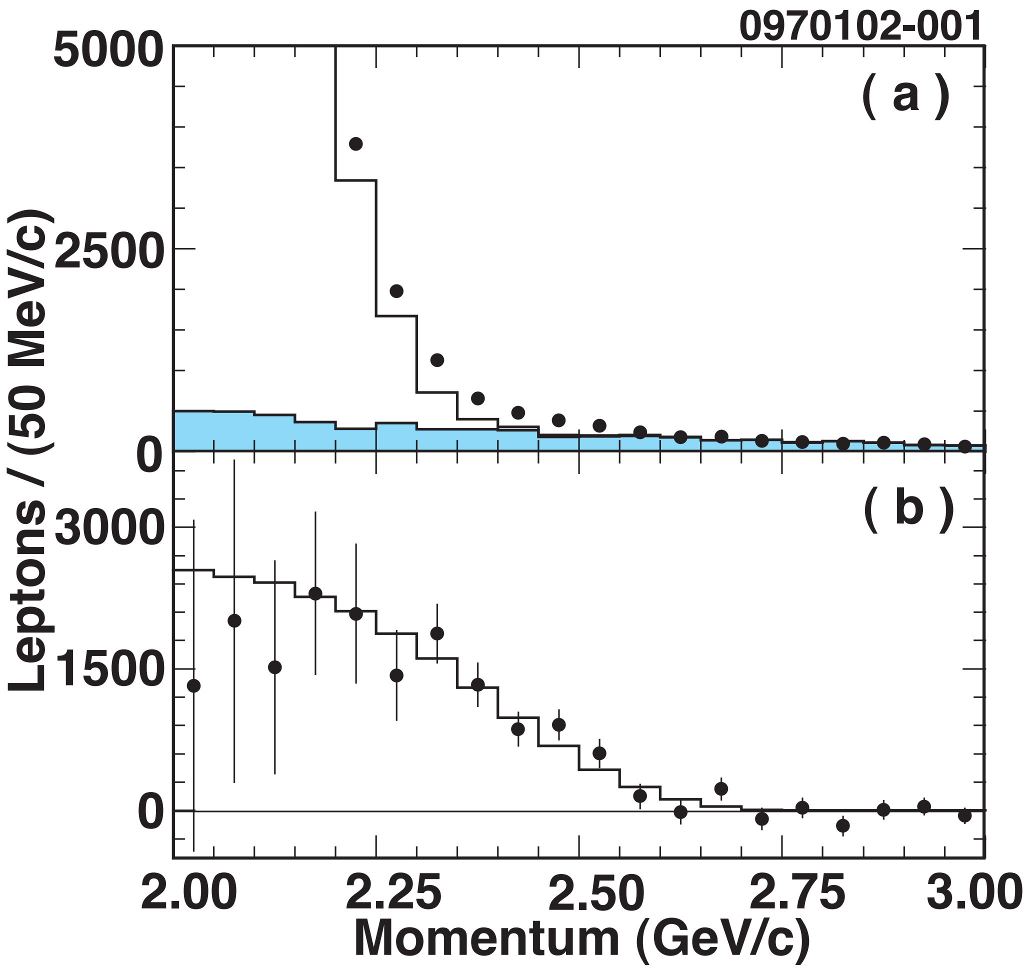


Figure (a)

- filled circles are data
- shaded histogram is scaled Off-$\Upsilon(4S)$
- histogram is sum of scaled Off and $\bar{B} \to X_c \ell \bar{\nu}$

Figure (b)

- filled circles are the total of e and μ data after subtraction of scaled Off-$\Upsilon(4S)$ and $\bar{B} \to X_c \ell \bar{\nu}$ backgrounds and correction for efficiencies
- histogram is $\bar{B} \to X_u \ell \bar{\nu}$ prediction from the $b \to s\gamma$ spectrum

$|V_{ub}|$ from Inclusive Leptons and the $b \to s\gamma$ Spectrum

For the momentum interval $(2.2 < p_\ell < 2.6)$ GeV

- $N_{ub} = 1,901 \pm 122 \pm 256$ $\bar{B} \to X_u \ell \bar{\nu}$ events (without efficiency correction)
- $\Delta\mathcal{B}_u = (2.30 \pm 0.15 \pm 0.35) \times 10^{-4}$
- $f_u = 0.130 \pm 0.024 \pm 0.015$ from the $b \to s\gamma$ spectrum
- $\mathcal{B}_u = (1.77 \pm 0.29 \pm 0.38) \times 10^{-3}$

The result for $|V_{ub}|$ is:

$$|V_{ub}| = (4.08 \pm 0.34 \pm 0.44 \pm 0.16 \pm 0.24) \times 10^{-3}$$

$(\Delta\mathcal{B}_u)$ (f_u) (γ_u) $(s\gamma)$

Errors are due to:

$(\Delta\mathcal{B}_u)$ measurement of $\Delta\mathcal{B}_u$

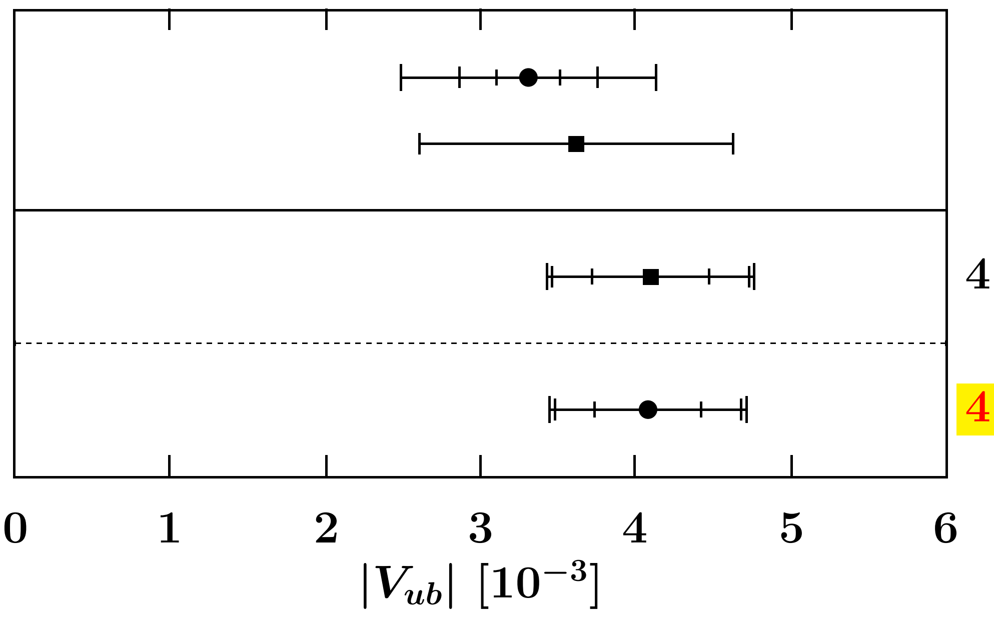
(f_u) determining f_u from $b \to s\gamma$ (includes some theoretical uncertainties)

(γ_u) theoretical uncertainties in γ_u ($\Gamma^u_{SL} = \gamma_u \, |V_{ub}|^2$)

$(s\gamma)$ theoretical uncertainties in the assumption that $b \to s\gamma$ can be used to compute the spectrum for $\bar{B} \to X_u \ell \bar{\nu}$

$|V_{ub}|$ from Inclusive Leptons and the $b \to s\gamma$ Spectrum

Source		$\lvert V_{ub}\rvert$ $[10^{-3}]$
CLEO Exclusive		$3.3 \pm 0.2 \pm 0.4 \pm 0.7$
PDG 2000		3.6 ± 1
LEP HFWG Avg.		$4.09 \pm 0.38 \pm 0.51 \pm 0.17$
CLEO Inclusive		$4.08 \pm 0.34 \pm 0.50 \pm 0.16$



Note: systematic errors are still under discussion.

Motivation for CLEO-c and CESR-c

CLEO has made substantial progress in measuring nonperturbative parameters that relate observables to underlying parton-level processes and CKM matrix elements.

- Much remains to be accomplished since we are rapidly approaching a situation where theoretical uncertainties will dominate all experimental CKM uncertainties.
  - Theoretical uncertainties already totally dominate the uncertainty in $|V_{td}|$.
  - Theoretical uncertainties are significant in measurements of $|V_{cb}|$ and $|V_{ub}|$, even with the recent CLEO measurements of some nonperturbative parameters using the E_γ spectrum in $b \to s\gamma$ decay and hadronic moments in $\bar{B} \to X_c \ell \bar{\nu}$ decay.
  - Experimental uncertainties will decrease significantly when the enormous BaBar and Belle data samples are fully understood, evaluated, and utilized.
    - To some extent, more precise measurements from BaBar and Belle will provide further constraints on theoretical uncertainties.
- Still, development of reliable theoretical methods for calculating nonperturbative parameters is essential for precise determination of CKM matrix elements.
- The methods must be technically correct and yield reliable results, and the methods and results must be accepted by the elementary particle physics community.
  - Experimental verification is an essential element for achieving such a consensus.
  - Precise data in the charm sector can motivate and validate theoretical progress in nonperturbative heavy quark physics that can be applied to b physics.

Motivation for CLEO-c and CESR-c

- **Lattice QCD (LQCD) is a candidate for a theory to satisfy these demands.**
  - **Verification will require comparison of LQCD results with a large number and wide variety of precision measurements in the c and b sectors.**

Providing precise charm data to motivate and validate theoretical progress in nonperturbative heavy quark physics is a major focus of the CLEO-c program.

CLEO-c and CESR-c

CLEO-c is a focused program of measurements and searches in e^+e^- collisions in the the $\sqrt{s} = 3 - 5$ GeV energy region, including:

- charm measurements
  - absolute charm branching fractions
  - the decay constants f_D and f_{D_s}
  - semileptonic decay form factors
  - $|V_{cd}|$ and $|V_{cs}|$
- searches for new physics including
  - CP violation in D decay
  - $D\bar{D}$ mixing without DCSD
  - rare D decays
- QCD studies
  - $c\bar{c}$ spectroscopy
  - searches for glue-rich exotic states: glueballs and hybrids
  - measurements of R
    - between 3 and 5 GeV – direct
    - between 1 and 3 GeV – indirect (Initial State Radiation)
- τ studies

A major emphasis is challenging nonperturbative QCD theory with precision measurements in the charm sector.

CLEO-c Run Plan

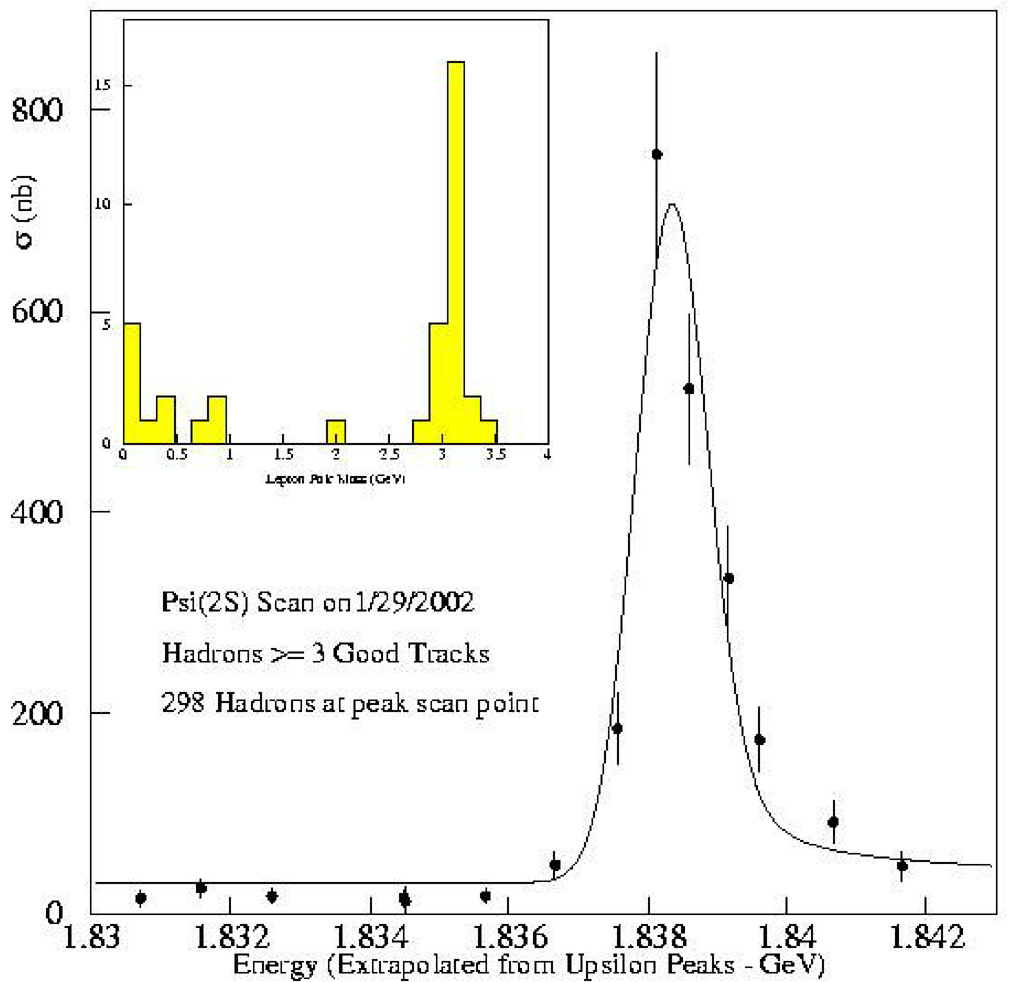
- 2002 – Prologue – Υ's $\gtrsim$1 fb^{-1} each
  - $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, ..., $\Upsilon(6S)$(?)
  - Matrix elements, Γ, Γ_{ee}, spectroscopy (η_b, h_b, D states, ...)
  - Compare with LQCD calculations
  - 10-20 $\times$ the existing world's data
- 2003 – Act I– $\psi(3770)$ 3 fb^{-1}
  - 30 M $D\bar{D}$ events, 6 M tagged D
  - 310 $\times$ MARK III
- 2004 – Act II – $\sqrt{s} \sim 4.1$ GeV – 3 fb^{-1}
  - 1.5 M $D_s\bar{D}_s$ events, 0.3 M tagged D_s
  - 480 $\times$ MARK III and 130 $\times$ BES II
- 2005 – Act III – J/ψ – 1 fb^{-1}
  - 1 G J/ψ decays
  - 170 $\times$ MARK III and 20 $\times$ BES II

The CESR-c Accelerator

Running at all energies from the J/ψ to above the $\Upsilon(4S)$ is possible with existing superconducting IR quads.

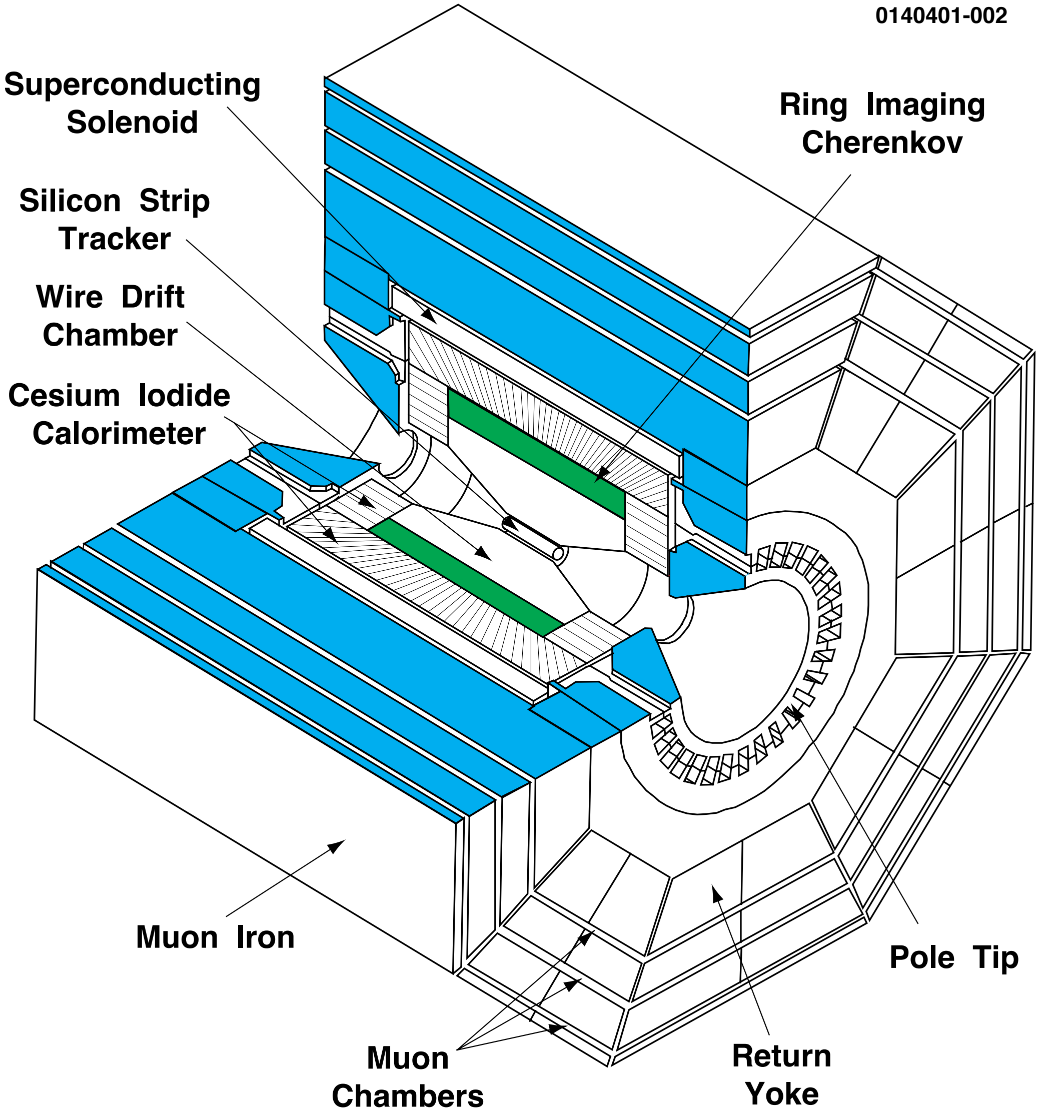
- $\psi(2S)$ already seen
- Loss of synchrotron radiation damping at low energies reduces luminosity
  - Compensate with wiggler magnets
  - Designed and built a superferric prototype (Fe poles & SC coils)
  - Excellent prototypes for Linear Collider damping ring wigglers.
  - The only substantial hardware upgrade in the program
- Expected luminosity

$\sqrt{s}$ (GeV)	$\mathcal{L}$ (10^{33} cm^{-2} s^{-1})
10	1
4.1	0.4
3.8	0.3
3.1	0.2



Psi(2S) Scan on 1/29/2002
Hadrons >= 3 Good Tracks
298 Hadrons at peak scan point
σ (nb)
Energy (Extrapolated from Upsilon Peaks - GeV)
0
200
400
600
800
1.83
1.832
1.834
1.836
1.838
1.84
1.842
0
5
10
15
0
0.5
1
1.5
2
2.5
3
3.5
4

The CLEO III Detector and CLEO-c



CLEO-c Institutions

Carnegie Mellon, Cornell, Florida, Illinois U-C, Kansas, Minnesota, Ohio State, Pittsburgh, Purdue, Rochester, Southern Methodist, SUNY Albany, Syracuse, UT Pan American, Vanderbilt, Wayne State

CLEO III Detector Performance

Component	Performance
Tracking	93% of 4π; $\sigma_p/p = 0.35\%$ at $p = 1$ GeV/c 5.7% dE/dx resolution for minimum-ionizing π
RICH	80% of 4π; 87% kaon efficiency with 0.2% pion fake rate at $p = 0.9$ GeV/c
Calorimeter	93% of 4π; $\sigma_E/E = 2.2\%$ at $E = 1$ GeV and $\sigma_E/E = 4.0\%$ at $E = 100$ MeV
Muons	85% of 4π for $p > 1$ GeV/c
Trigger	Fully pipelined, latency ~ 2.5 μs Based on track and shower counts, topology
DAQ	Event Size: ~ 25 kByte, Throughput ~ 6 MB/s

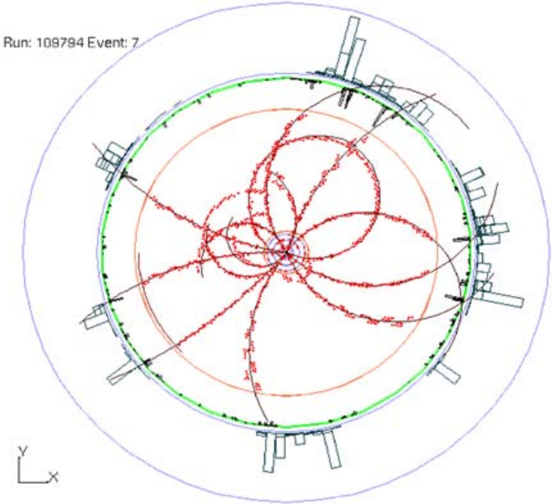
CLEO-c Detector Capabilities and CLEO-c Physics Reach

We will use the CLEO III detector in CLEO-c.

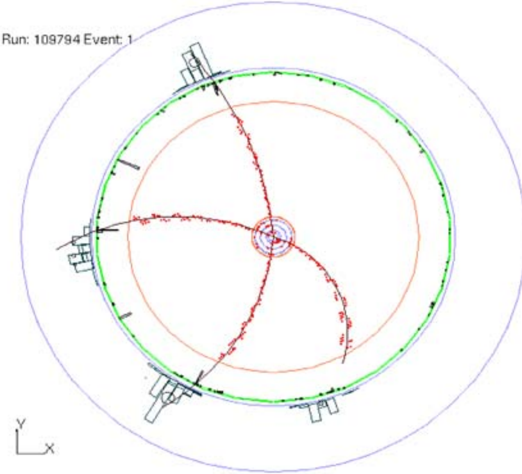
- **We will replace the silicon vertex detector (SVX) with a thin gaseous drift chamber.**
  - **The SVX is abnormally sensitive to radiation damage.**
  - **A thinner detector is better in this energy region anyway (The maximum momentum of a secondary from D decay is ~ 1 GeV/c.)**
- **The CLEO-c physics reach has been studied using a parameterized Monte Carlo simulation**
  - **The resolutions, acceptances, detection efficiencies, and particle identification efficiencies were carefully tuned to match *achieved* CLEO III performance.**
  - **uds background was included in all D decay simulations**
- **$D\bar{D}$ events near charm threshold are substantially simpler than $B\bar{B}$ events at the $\Upsilon(4S)$ due to significantly lower multiplicities.**

The capabilities and performance of the CLEO III detector are substantially beyond those of others that have operated in this energy region.

A typical $\Upsilon(4S)$ event:

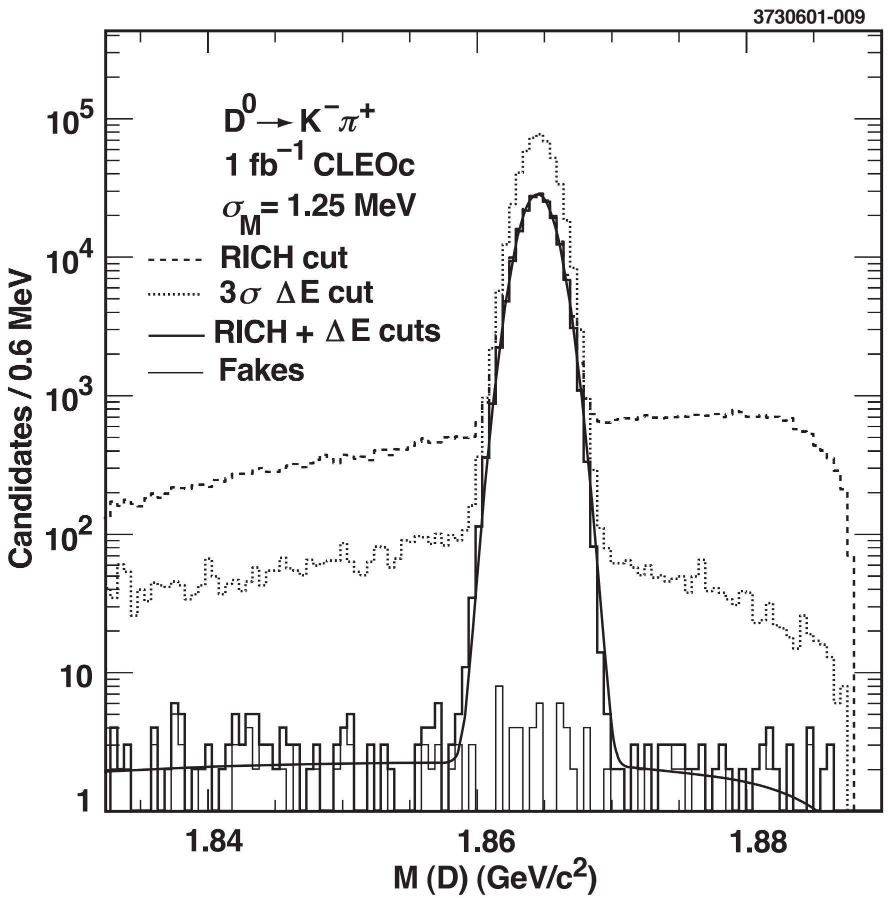


A typical $\psi(3770)$ event:

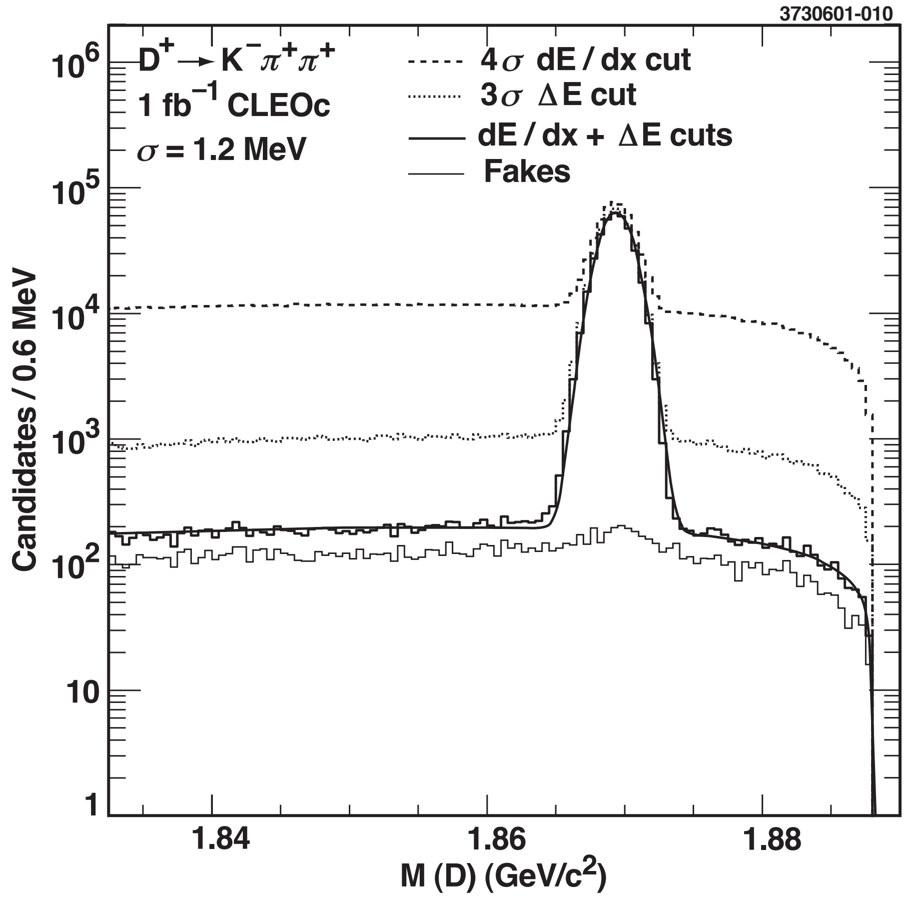


Detecting D Mesons in CLEO-c

$D^0 \to K^-\pi^+$

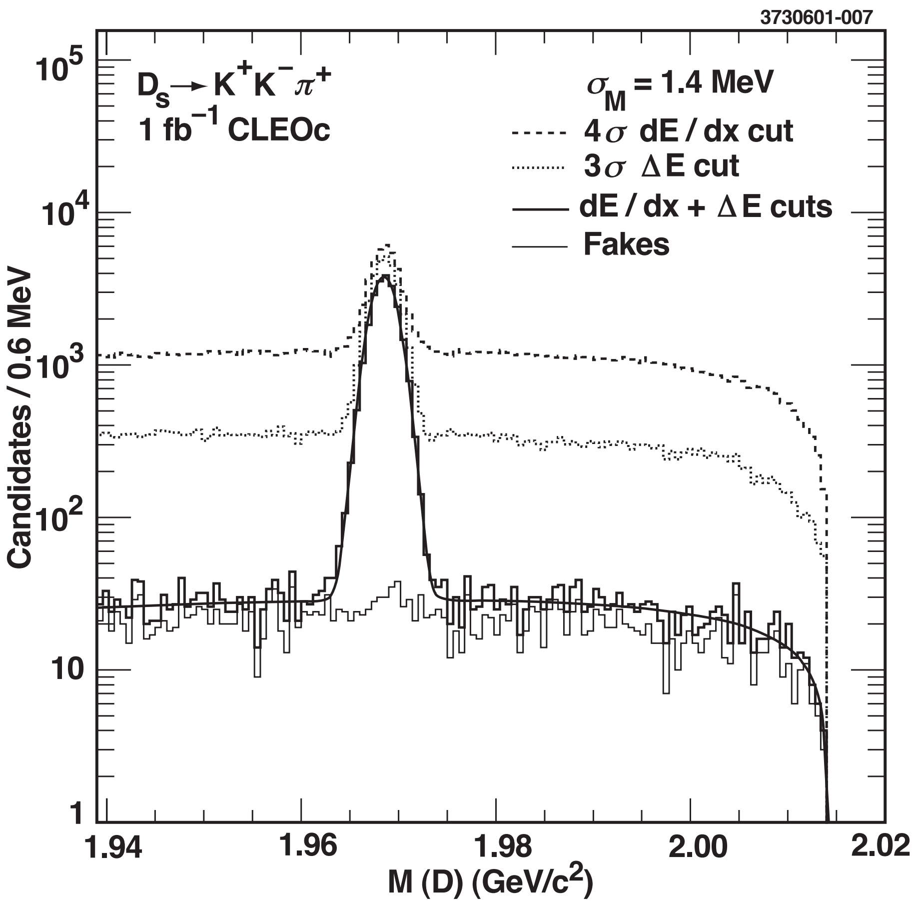


$D^+ \to K^-\pi^+\pi^+\pi^-$

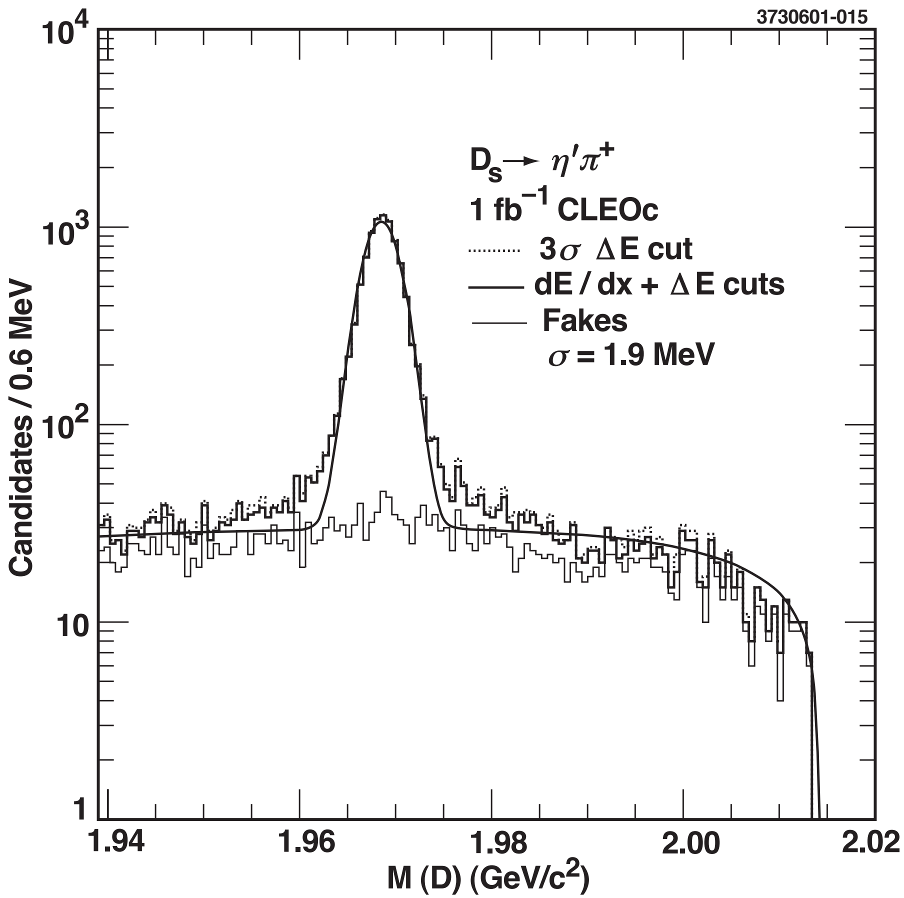


Detecting D Mesons in CLEO-c

$D_s^+ \to K^+K^-\pi^+$



$D_s^+ \to \eta'\pi^+$



Absolute Measurements of D Reference Branching Fractions

Absolute D branching fractions ($\mathcal{B}$) are essential for precision CKM measurements

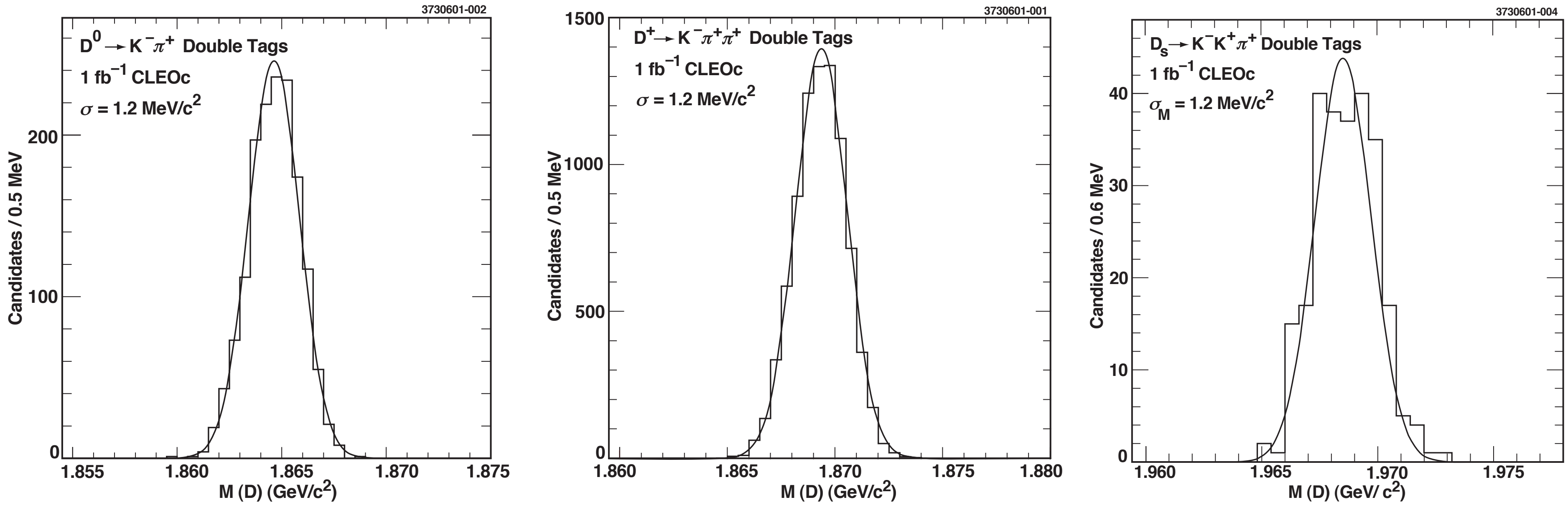
- Three D branching fractions
  - $\mathcal{B}(D^0 \to K^-\pi^+)$,
  - $\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$, and
  - $\mathcal{B}(D_s^+ \to \phi\pi^+)$

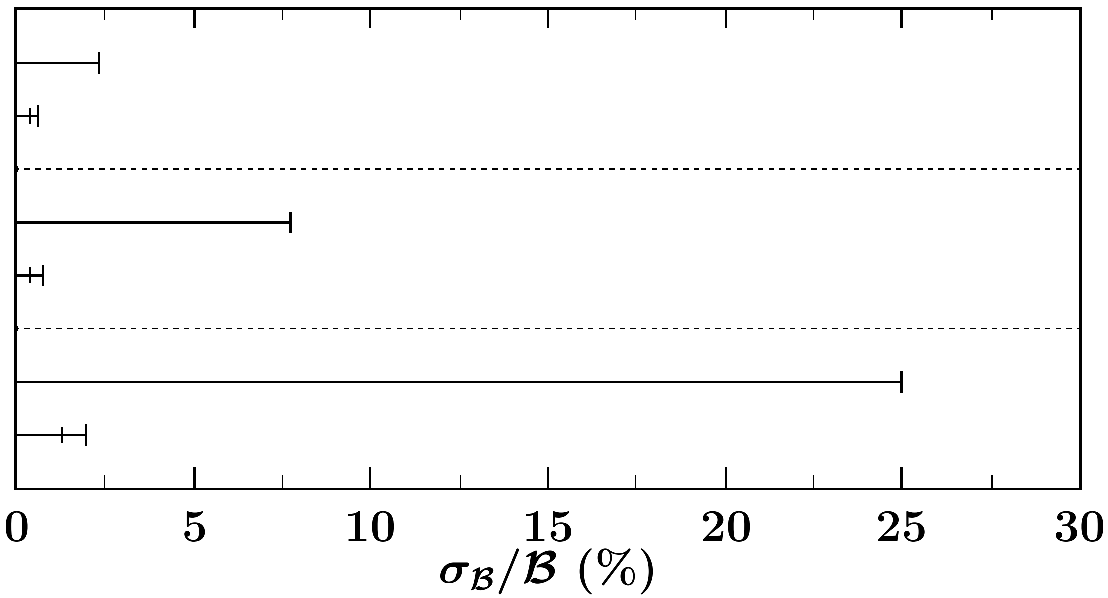
  set the scale of heavy quark branching fractions (e.g., $\bar{B} \to D\ell^-\bar{\nu}$ and $\bar{B} \to D^*\ell^-\bar{\nu}$)
- Necessary for precision measurements in the charm sector

Following Mark III, measure D absolute branching fractions by comparing
double tag ($D\bar{D}$) rates to
single tag (D or $\bar{D}$) rates

- Double tag events are very clean with little background
  - Backgrounds are very small in D^0 and D^+ single tags
  - Backgrounds are small in D_s single tags and manageable
- Most systematic errors cancel
  - We not need to know production rates.
  - Tracking uncertainties dominate systematic errors.
  - We can measure tracking efficiency with data with precision $\sim 0.2\%$ per track using missing mass reconstruction.

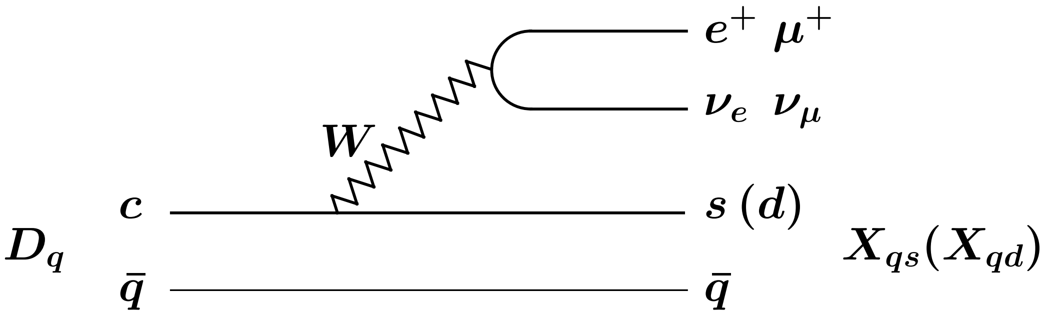
Absolute Measurements of D Reference Branching Fractions





Decay Mode		$\sigma_{\mathcal{B}}/\mathcal{B}$ (%)
$D^0 \to K^-\pi^+$	PDG	± 2.3
	CLEO-c	$\pm 0.4 \pm 0.4$
$D^+ \to K^-\pi^+\pi^+$	PDG	± 7.7
	CLEO-c	$\pm 0.4 \pm 0.6$
$D_s^+ \to \phi\pi^+$	PDG	± 25
	CLEO-c	$\pm 1.3 \pm 1.4$

Determining $|V_{cs}|$ and $|V_{cd}|$ in Semileptonic D Decays



- Semileptonic decay rates of D_q are proportional to $|V_{cd}|^2$ or $|V_{cs}|^2$

  $$\Gamma(D_q \to X_{qd}\,\ell^+\nu_\ell) = \frac{\mathcal{B}(D_q \to X_{qd}\ell^+\nu_\ell)}{\tau_{D_q}} = \gamma_{qd}\ \boxed{|V_{cd}|^2} \quad (\text{same for } s \leftrightarrow d)$$

  - γ_{qd} and γ_{qs} must come from theory

- Decays depend on the mass-squared (q^2) of the virtual W through form factors $f(q^2)$ which are related to γ_{qd} (γ_{qs})
- Decay to a pseudoscalar meson (P_d) involves only one form factor

  $$\frac{\Gamma(D_q \to P_d\,\ell^+\nu_\ell)}{dq^2} = \frac{\boxed{|V_{cd}|^2}\ p^3}{24\pi^3}\ |f_{qd}(q^2)|^2 \quad (\text{same expression for } s \leftrightarrow d)$$

- Decay to a vector meson (V) involves 3 form factors and a more complicated expression involving 3 decay angles (or 3 other variables) in addition to q^2

Determining $|V_{cs}|$ and $|V_{cd}|$ in Semileptonic D Decays

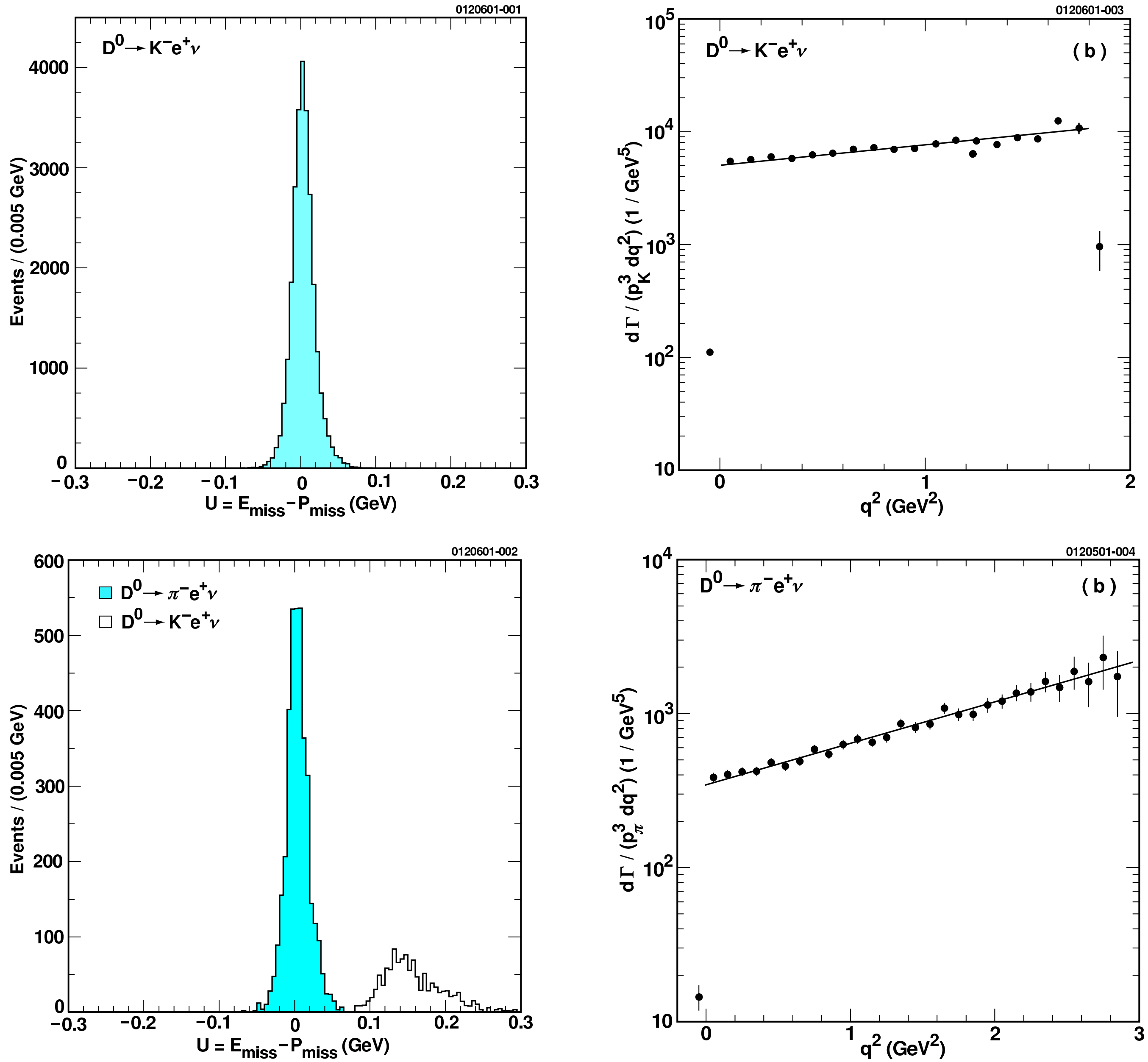
Measure semileptonic branching fractions and form factors

- Lifetimes, branching fractions, and γ_{qs} & γ_{qd} from theory determine $|V_{cs}|$ & $|V_{cd}|$
- Checks on theory:
  - Measurements of form factor slopes
  - Angular distributions in decays to vectors
  - Comparisons of $|V_{cs}|$ and $|V_{cd}|$ with CKM unitarity
    - From unitarity $\delta|V_{cs}|/|V_{cs}| \approx 0.1\%$ and $\delta|V_{cd}|/|V_{cd}| \approx 1.1\%$
- If theory meets the challenges:
  - Reinforces confidence in γ_{qs} and γ_{qd}
  - Reinforces confidence in theoretical calculations of quantities needed for determining $|V_{cb}|$ and $|V_{ub}|$.

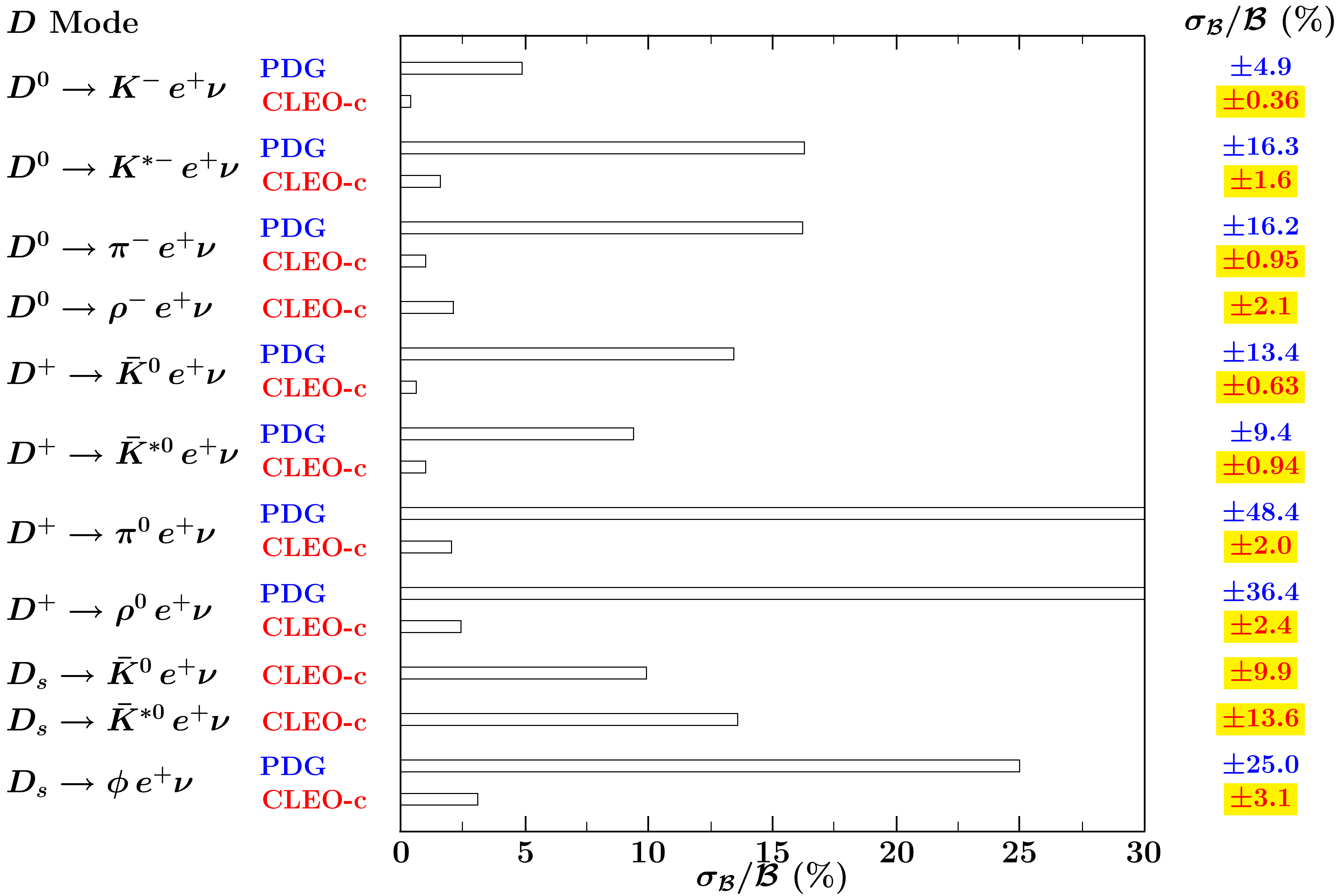
Detect semileptonic decays in events with a single hadronic tag and an $e^{\pm}$

- High rates due to high single tag rates
  - Single tags are very clean
- Excellent background rejection from kinematics and particle identification
  - Use $U \equiv E_{\text{miss}} - p_{\text{miss}}$ to separate signal from background efficiently

Semileptonic D Decays to Pseudoscalars (1 fb^{-1} Simulation)



Statistical Errors of D Semileptonic Branching Fractions



Exclusive Semileptonic D Decays

Results of Monte Carlo simulations:

- **Excellent separation of $D^0 \to \pi^- e^+ \bar{\nu}_e$ from $D^0 \to K^- e^+ \bar{\nu}_e$ even though $\mathcal{B}(D^0 \to K^- e^+ \bar{\nu}_e) \sim 10\mathcal{B}(D^0 \to \pi^- e^+ \bar{\nu}_e)$**
- **Semileptonic branching fractions can be measured with errors $\delta\mathcal{B}/\mathcal{B} \approx 1\%$.**
- **The exponential slopes (α) of the form factors can be measured with errors $\delta\alpha/\alpha \approx 4\%$.**
- **Angular distributions in semileptonic D decay to vectors can be measured accurately to to compare with form factor calculations.**

Determining $|V_{cs}|$ and $|V_{cd}|$ from Semileptonic D Decay

Since $|V_{cs}|^2 = \dfrac{\mathcal{B}(D_q \to X_{qs}\ell^+\nu_\ell)}{\tau_{D_q}\gamma_{qs}} = \dfrac{\mathcal{B}_{qs}}{\tau_q\gamma_{qs}}$

Then $\dfrac{\delta|V_{cs}|}{|V_{cs}|} = \dfrac{1}{2}\left[\left(\dfrac{\delta\mathcal{B}_{qs}}{\mathcal{B}_{qs}}\right)^2 + \left(\dfrac{\delta\tau_q}{\tau_q}\right)^2 + \left(\dfrac{\delta\gamma_{qs}}{\gamma_{qs}}\right)^2\right]^{\frac{1}{2}} = \dfrac{1}{2}\left[\left(\dfrac{\delta\Gamma_{qs}}{\Gamma_{qs}}\right)^2 + \left(\dfrac{\delta\gamma_{qs}}{\gamma_{qs}}\right)^2\right]^{\frac{1}{2}}$

Of course, similar expressions exist for $|V_{cd}|$

The purely experimental errors are obtained by setting $\delta\gamma_{qs} = 0$, so

$$\frac{\delta|V_{cs}|}{|V_{cs}|} = \frac{1}{2}\left(\frac{\delta\Gamma_{qs}}{\Gamma_{qs}}\right)$$

- These experimental errors then provide goals for the precision of theoretical γ_{qs} calculations
- Estimate experimental errors using D^0 and D^+ modes and assuming systematic errors:
  - $\delta\tau_{D^0}/\tau_{D^0} = 0.7\%$ (the current world average)
  - $\delta\tau_{D^+}/\tau_{D^+} = 1.2\%$ (the current world average)
  - $\delta\epsilon/\epsilon = 0.9\%$ (uncertainty in efficiency of 0.2% per track and 0.8% e identification)

Determining $|V_{cs}|$ and $|V_{cd}|$ from Semileptonic D Decay

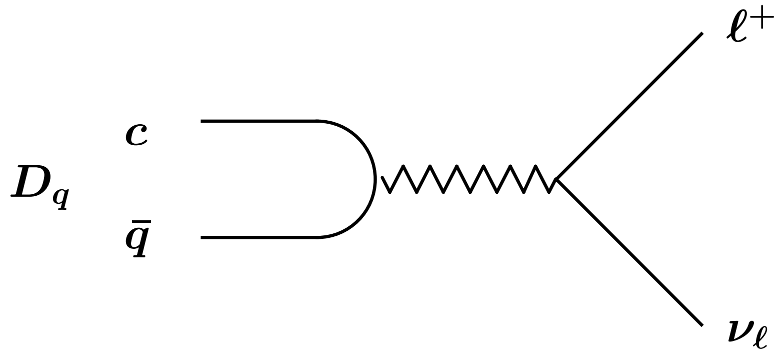
Contributions to errors in $|V_{cd}|$ and $|V_{cs}|$ expected
from 3 fb^{-1} of $D^0\bar{D}^0$ and D^+D^- CLEO-c data.

Decay Mode	V	$\frac{1}{2}(\delta\mathcal{B}/\mathcal{B})$	$\frac{1}{2}(\delta\tau/\tau)$	$\frac{1}{2}(\delta\epsilon/\epsilon)$	$\delta V/V$	Unitarity
$D^0 \to K^- e^+ \nu$	$\lvert V_{cs}\rvert$	0.2%	0.35%	0.45%	0.6%	0.1%
$D^+ \to \bar{K}^0 e^+ \nu$	$\lvert V_{cs}\rvert$	0.3%	0.6%	0.45%	0.8%	0.1%
$D^0 \to \pi^- e^+ \nu$	$\lvert V_{cd}\rvert$	0.5%	0.35%	0.45%	0.8%	1.1%
$D^+ \to \pi^0 e^+ \nu$	$\lvert V_{cd}\rvert$	1.0%	0.6%	0.45%	1.3%	1.1%

Experimental errors for $|V_{cs}|$ and $|V_{cd}|$ will be $\sim$ 1% from D^0 and D^+ modes

- Consistency of D^0 and D^+ measurements with unitarity and from a variety of modes will help to verify experimental systematic errors and theoretical calculations of form factors.
- Theory goal should be $\delta\gamma/\gamma \lesssim 2\%$ to take full advantage of experimental errors.

Determining D Meson Decay Constants



The factor $f_{D_q} V_{cq}$ occurs in the decay amplitude for the $c\bar{q}W$ vertex

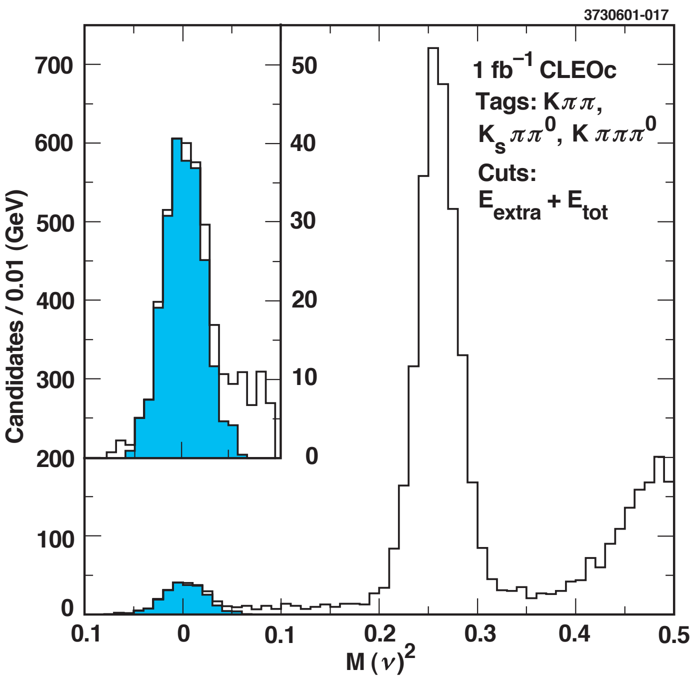
- The decay widths for leptonic D^+ and D_s^+ decays are:

$$\Gamma(D_q^+ \to \ell^+ \nu_\ell) = \frac{1}{8\pi} G_F^2 M_{D_q} m_\ell^2 \left(1 - \frac{m_\ell^2}{M_{D_q}^2}\right) f_{D_q}^2 |V_{cq}|^2$$

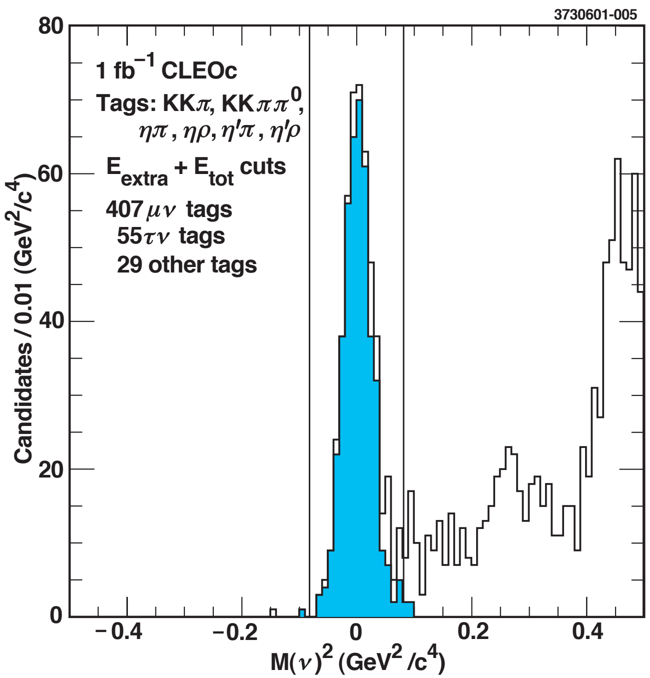
- Measurements of $\mathcal{B}(D^+ \to \ell^+ \nu_\ell)$ and $\mathcal{B}(D_s^+ \to \ell^+ \nu_\ell)$ Determine $f_{D^+}|V_{cd}|$ and $f_{D_s}|V_{cs}|$
- Conventionally measure $f_{D_q}|V_{cq}|$ and use unitarity for $|V_{cq}|$ to get f_{D_q}
  - We will also measure $|V_{cd}|$ and $|V_{cs}|$ accurately with semileptonic D decays
- Challenge theorists with values of f_{D^+} and f_{D_s} with errors $\mathcal{O}(1\%)$
  - Lead to understanding of the level of reliability of f_{B^0} and f_{B_s} calculations
  - f_{B^0} uncertainty dominates error in $|V_{td}|$ from value of Δm_d in $B^0\bar{B}^0$ mixing

Determining D Meson Decay Constants

$D^+ \to \mu^+\nu_\mu$ Decays



$D_s^+ \to \mu^+\nu_\ell$ Decays



Decay Mode	Signal	Bkg	$\frac{1}{2}(\delta\mathcal{B}/\mathcal{B})$	$\frac{1}{2}(\delta\tau/\tau)$	$\delta\lvert V_{cq}\rvert/\lvert V_{cq}\rvert$	$\delta f_{D_q}/f_{D_q}$		PDG
$D^+ \to \mu^+\nu$	672	90	1.9%	0.6%	1.1%	2.3%	f_{D^+}	—
$D_s^+ \to \mu^+\nu$	1,221	252	1.4%	1.0%	0.1%	1.7%	f_{D_s}	35%
$D_s^+ \to \tau^+\nu$	1,740	114	1.2%	1.0%	0.1%	1.6%	f_{D_s}	60%

How CLEO-c Could Contribute to CKM Measurements

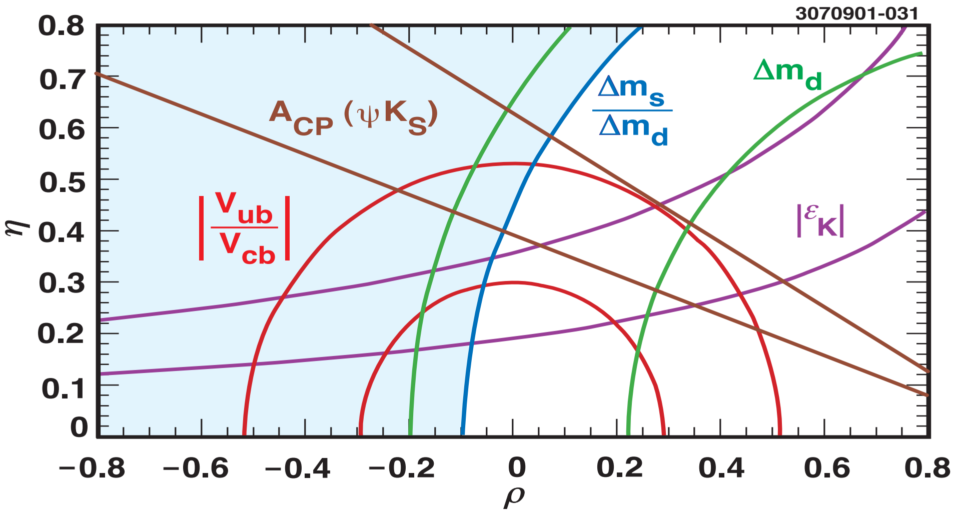
An illustration using a variant of the 95% scan method.

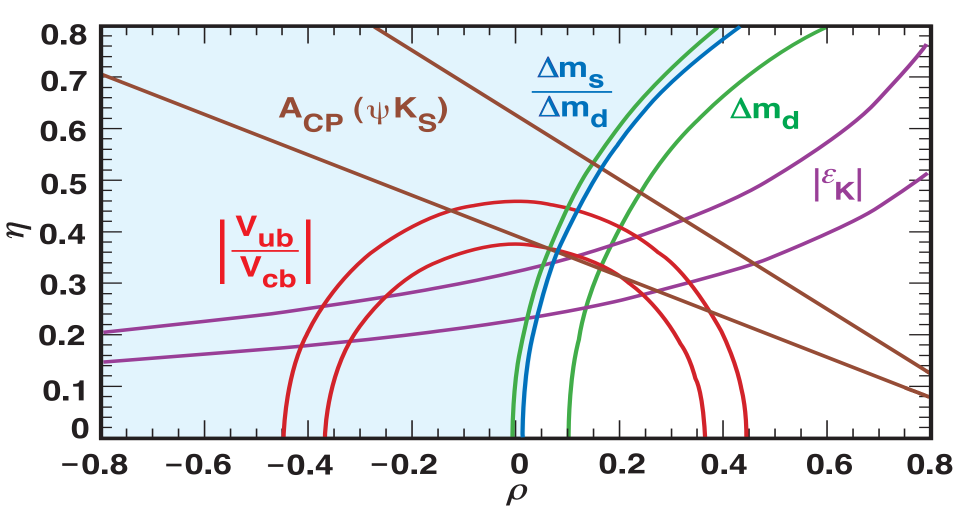
Allowed regions of the ρ-η plane using:

- current experimental results and
- conservative theoretical uncertainties

Allowed regions of the ρ-η plane using:

- current experimental results and
- theoretical uncertainties of $\mathcal{O}(1\%)$
  - 2% decay constants and bag parameters
  - 3% semileptonic form factors





Summary and Conclusions

New measurements using all CLEO II and II.V data

- $b \to s\gamma$ and E_γ spectrum
  - $\mathcal{B}(b \to s\gamma) = (3.21 \pm 0.43 \pm 0.27^{+0.18}_{-0.10}) \times 10^{-4}$
  - SM Theory $(3.28 \pm 0.33) \times 10^{-4}$
  - SM Theory $(3.73 \pm 0.30) \times 10^{-4}$
- $|V_{cb}|$ using hadronic mass and $b \to s\gamma$ energy moments
  - $|V_{cb}| = (40.4 \pm 0.9_{\mathrm{M}} \pm 0.5_{\Gamma} \pm 0.8_{\mathrm{T}}) \times 10^{-3}$
- Measurement of $|V_{cb}|$ from $\bar{B} \to D^* \ell^- \bar{\nu}$ decays
  - $|V_{cb}| = (46.9 \pm 1.4_{\mathrm{stat}} \pm 2.0_{\mathrm{syst}} \pm 1.8_{\mathrm{thry}}) \times 10^{-3}$
- $|V_{ub}|$ using the $b \to s\gamma$ spectrum to determine $f_u(p)$
  - $|V_{ub}| = (4.08 \pm 0.34_{\Delta\mathcal{B}_u} \pm 0.44_{f_u} \pm 0.29_{\mathrm{T}}) \times 10^{-3}$

Summary and Conclusions

Highlights of the CLEO-c program include:

- Precision $\mathcal{O}(1\%)$ measurements in the charm threshold region of
  - absolute reference hadronic branching fractions for D decay,
  - q^2 dependence of semileptonic decay form factors,
  - $\gamma_{qd}|V_{cd}|^2$ and $\gamma_{qs}|V_{cs}|^2$ from semileptonic D^0 and D^+ decays,
  - $|V_{cd}|f_{D^+}$ and $|V_{cs}|f_{D_s^+}$ from leptonic D^+ and D_s^+ decays, and
  - These measurements will challenge the ability of theorists to calculate decay constants and form factors for D decay, which will calibrate the utility of those theories for related calculations in B decay.
- No detector with the acceptance, resolution, and particle identification capability of the CLEO III detector has ever operated in the charm threshold region.
  - No other detector with these capabilities is likely to operate in the charm threshold region in the foreseeable future.
- CESR-c will provide much more luminosity than has been devoted to measurements in this region.

Summary and Conclusions

Unique features of the CLEO-c program in the charm threshold region include:

- *high event rates in an excellent well-understood detector,*
- *very small and well-controlled backgrounds,*
- *very small and well-understood systematic errors, and*
- *a large number of and wide variety of precision measurements to challenge and validate theory.*

We look forward to challenging our theoretical friends – whoever they may be – with precision data and we hope that they will meet the challenge!

More information is available in the CLEO-c/CESR-c project description:
CLEO-c and CESR-c: A New Frontier of Weak and Strong Interactions
Cornell Report No. CLNS 01/1742, Revised October 2001

- **Links to WWW versions at: http://www.lns.cornell.edu**
- **For a hard copy send a request to: preprint@lns.cornell.edu**

New collaborators are welcome!