Inclusive B Decays - Spectra, Moments and CKM Matrix Elements

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(**CLEO** Collaboration)

BNL Seminar
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Outline

- **Overview** of CESR/CLEO
- **The B Meson and HQET**
- **Moments Measurements and $|V_{cb}|$**
  - E_g spectrum in inclusive decays $B \to X_s g$
  - M_X^2 spectrum in inclusive decays $B \to X_c ln$
  - E_l spectrum in inclusive decays $B \to X_c ln$
- **Extraction of $|V_{ub}|$**
  - More from E_g spectrum and lepton energy endpoint ($|V_{ub}|$)
- **Summary**

CESR/CLEO

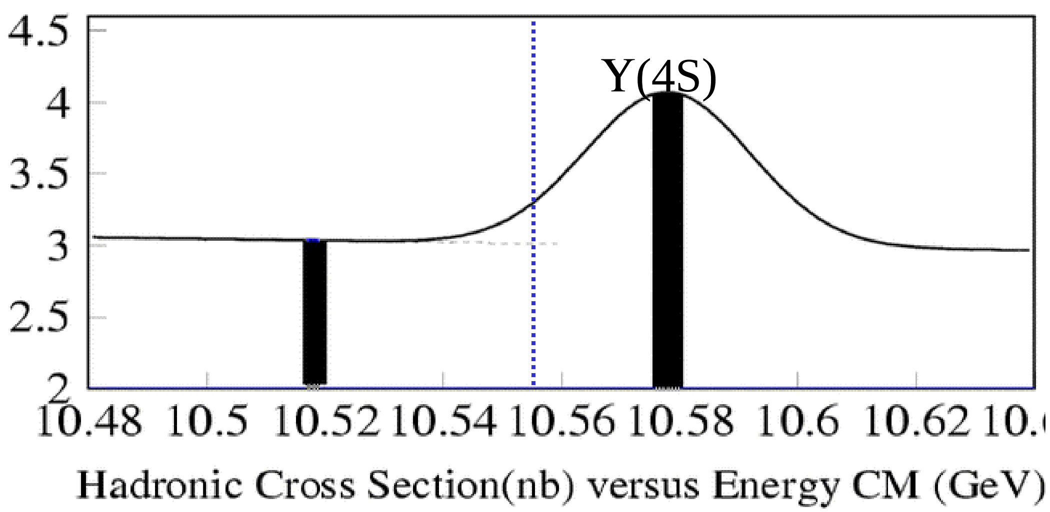
LEPP

Cornell **E**lectron-positron **S**torage **R**ing

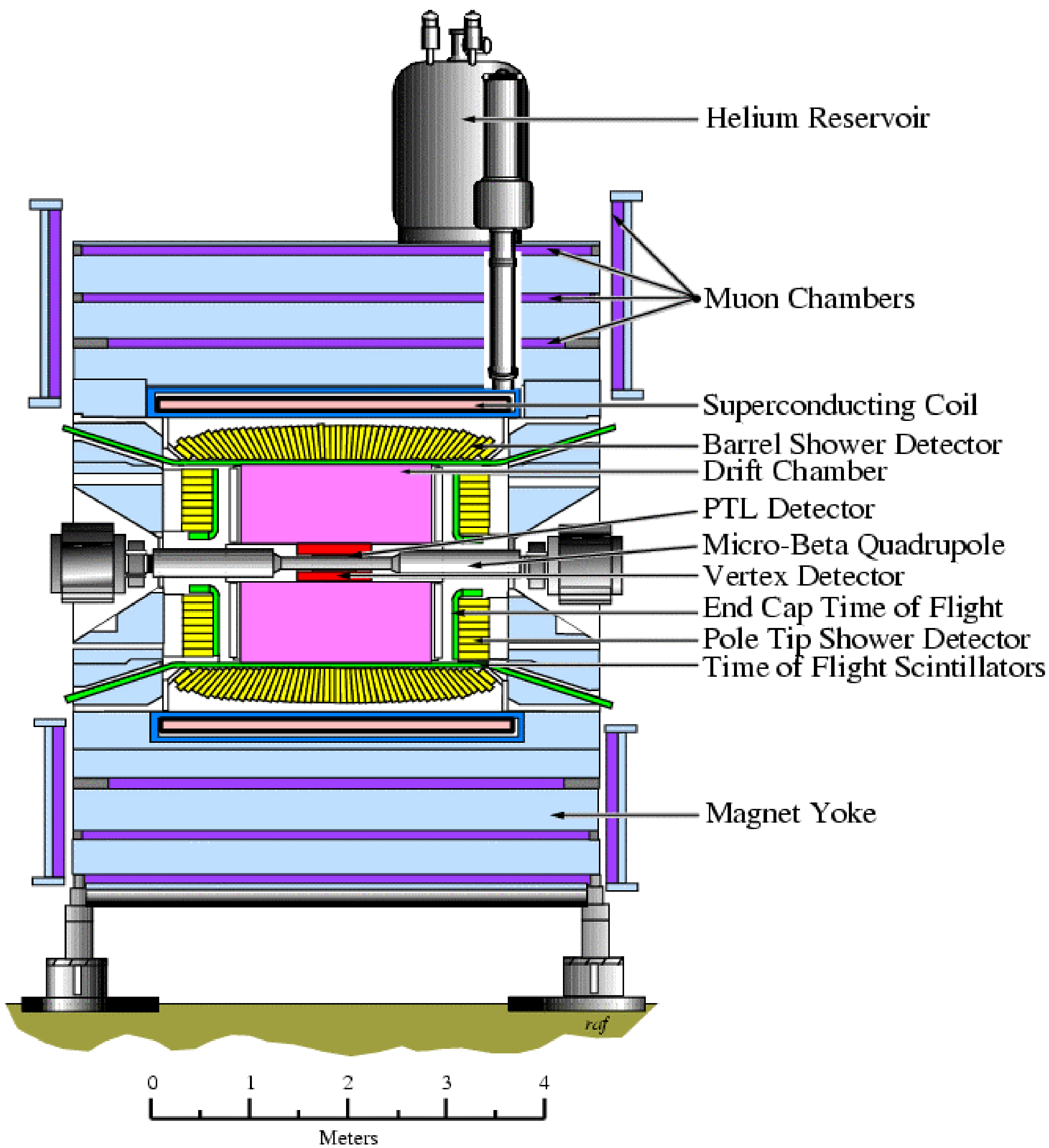
- ~ ¾ km circumference
- e^+e^- collisions
- E_{beam}: 1.5-5.6 GeV
- Most data collected near $\Upsilon(4S)$ resonance.

Operating Energies

- 2/3 data collected ON $\Upsilon(4S)$
  - $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ (σ ~ **1.0 nb**)
  - $e^+e^- \rightarrow q\bar{q}$ (σ ~ **3.0 nb**)
- 1/3 data collected OFF
  - 60 MeV below Resonance
  - Continuum only
  - Almost perfect $q\bar{q}$ background sample



CLEO



Photons: XtalCal (res=1.8%)

Electrons: XtalCal, Tracking

Muons: MuCh, Tracking

P K p e m: ToF+DeDx

Overview:

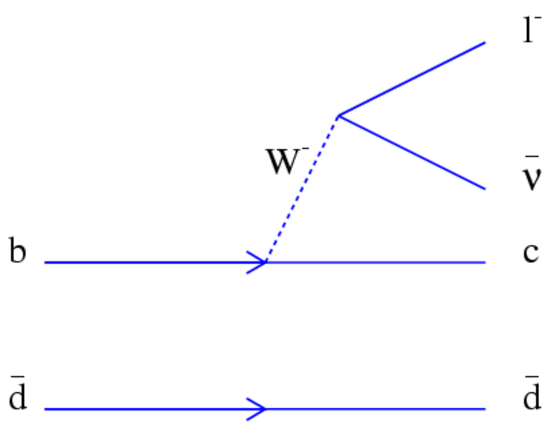
The Standard Model

&

The Heavy Quark Expansion

Overview

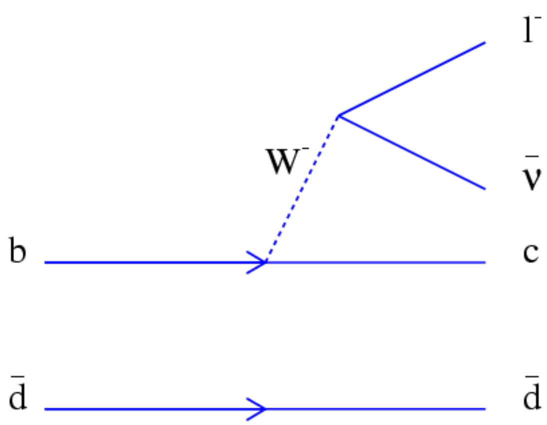
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



- CKM matrix relates quark mass eigenstates to weak eigenstates
- Fundamental Standard Model parameters – must be measured.
- Measurement of these electro-weak parameters complicated by QCD (we observe hadrons not quarks)
- The formalism that provides a viable framework for extracting CKM elements is Heavy Quark Effective Theory **HQET.**
- What is new in inclusive CKM extractions? **$B\rightarrow X_s$ g**

Overview

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} .975 & .223 & .004 \\ .223 & .974 & .041 \\ .009 & .041 & .999 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



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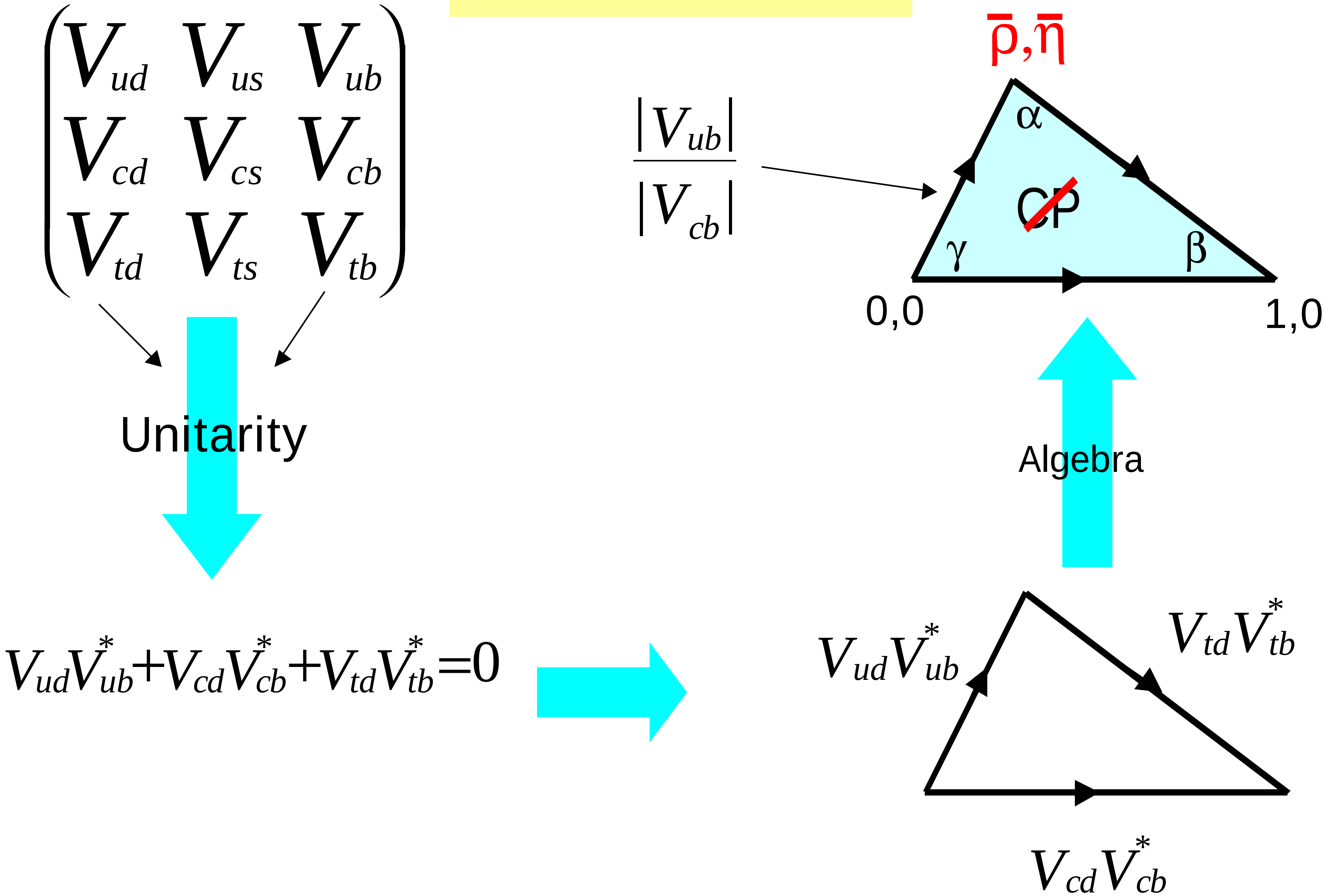
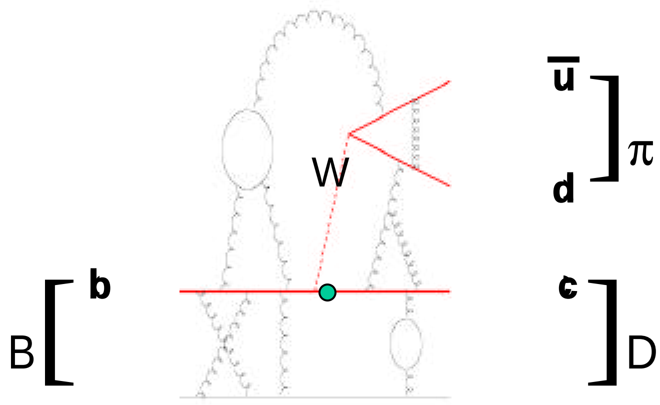
Overview



$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$
Unitarity
$V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}=0$
$V_{ud}V_{ub}^{*}$
$V_{td}V_{tb}^{*}$
$V_{cd}V_{cb}^{*}$
Algebra
$\bar{\rho},\bar{\eta}$
$\frac{|V_{ub}|}{|V_{cb}|}$
α
β
γ
CP
0,0
1,0

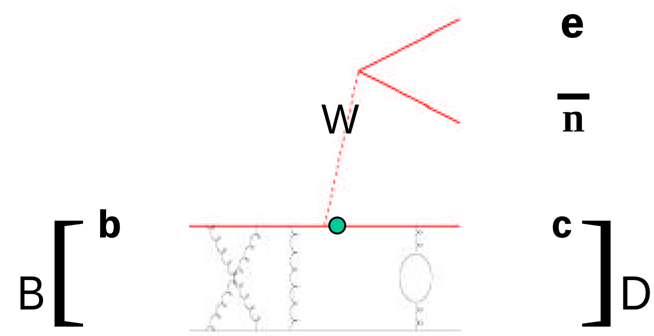
b → c Decay

B → D π



Very difficult

B → D e ν̄



Just right?

- Still need QCD corrections
- <u>Perturbative</u>
  - ✓ Hard gluon (Short distance)
  - ✓ a_s
- <u>Non-Perturbative</u>
  - ✓ Soft gluon (Long distance)
  - ✓ L, l_1 & l_2

HQET

- **HQET+OPE** allows any inclusive observable to be written as a double expansion in powers of α_s and $1/M_B$:

$$Observable = A(\alpha_s, \alpha_s^2) + B(\alpha_s)\frac{\overline{\Lambda}}{M} + C\frac{\overline{\Lambda}^2}{M^2} + D\frac{\lambda_1}{M^2} + E\frac{\lambda_2}{M^2} + O(\frac{1}{M^3})$$

O(1/M) $\overline{\Lambda}$ energy of light degrees of freedom

O(1/M^2) λ_1 -momentum squared of b quark

λ_2 hyperfine splitting (known from B/B* and D/D* ΔM)

O(1/M^3) $\rho_1, \rho_2, \tau_1, \tau_2, \tau_3, \tau_4$ ~(.5 GeV)^3 from dimensional considerations

- Γ_{sl} = **|V$_{cb}$|^2** $(A(\alpha_s, \beta_o\alpha_s^2) + B(\alpha_s)\overline{\Lambda}/M_B + C\lambda_1/M_B^2 + \ldots)$

- $\overline{\Lambda}, \lambda_1$ combined with the Γ_{sl} measurements ➔ better **|V$_{cb}$|^2**

Observables

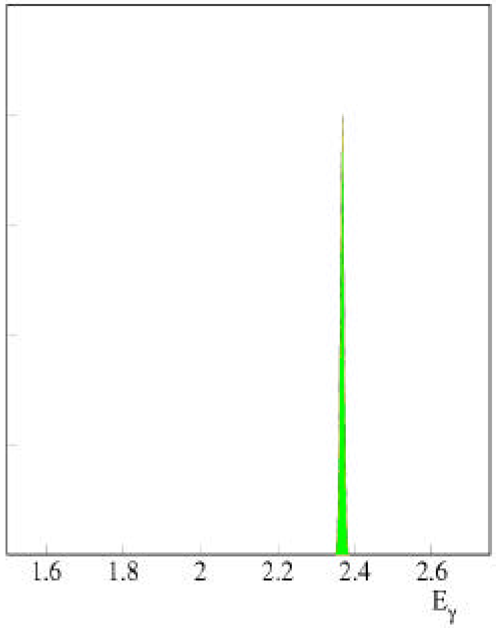
B→ X_s g : 1st and 2nd moments of Photon energy

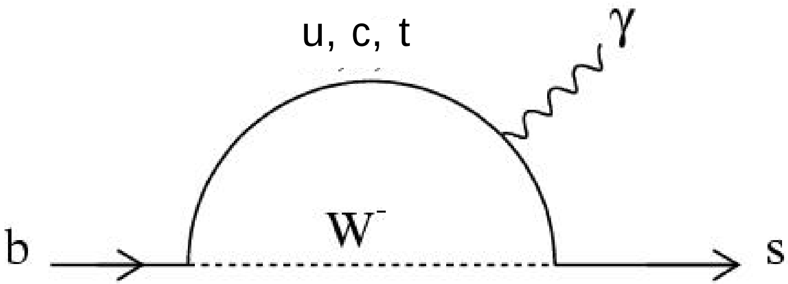
B→ X_c ℓ n: 1st and 2nd moments of hadronic recoil mass

B→ X_c ℓ n: Semileptonic Width (G_{sl})

B→ X_c ℓ n: lepton energy moments

b → *s* γ   Moments

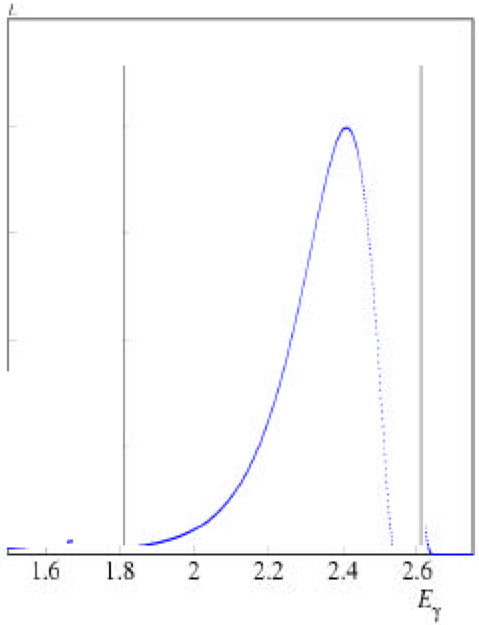


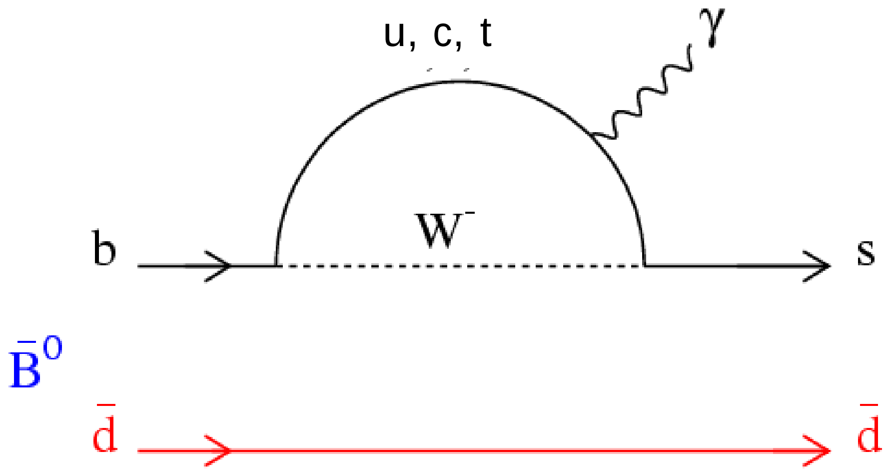


$$\langle E_g \rangle = \frac{m_b}{2}$$

$$\left\langle \left(E_g - \langle E_g \rangle \right)^2 \right\rangle =$$

$b \rightarrow s\,\gamma$ Moments

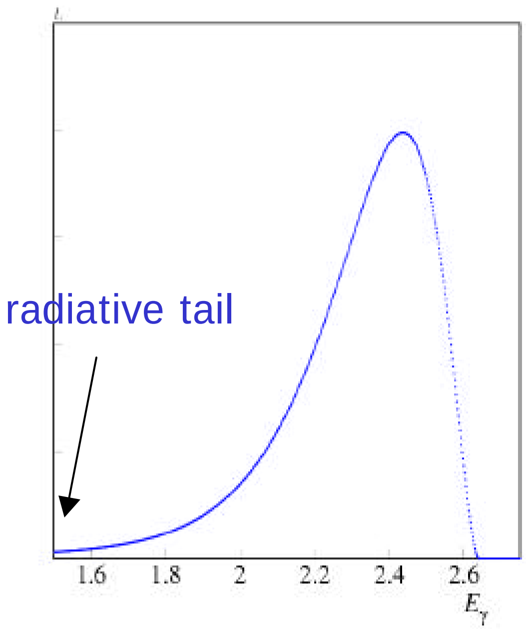


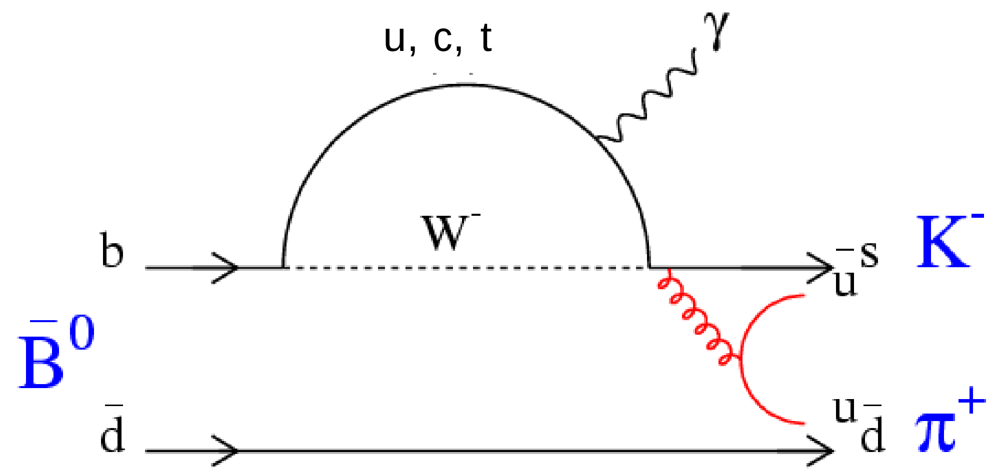


$$\langle E_g \rangle = \frac{M_B}{2}\left(1 - \qquad - \frac{\bar{\Lambda}}{M_B} \qquad \right)$$

$$\left\langle \left(E_g - \langle E_g \rangle\right)^2 \right\rangle = M_B^2\left(\frac{-l_1}{12 M_B^2} \qquad \right)$$

$b \rightarrow s\,\gamma$ Moments

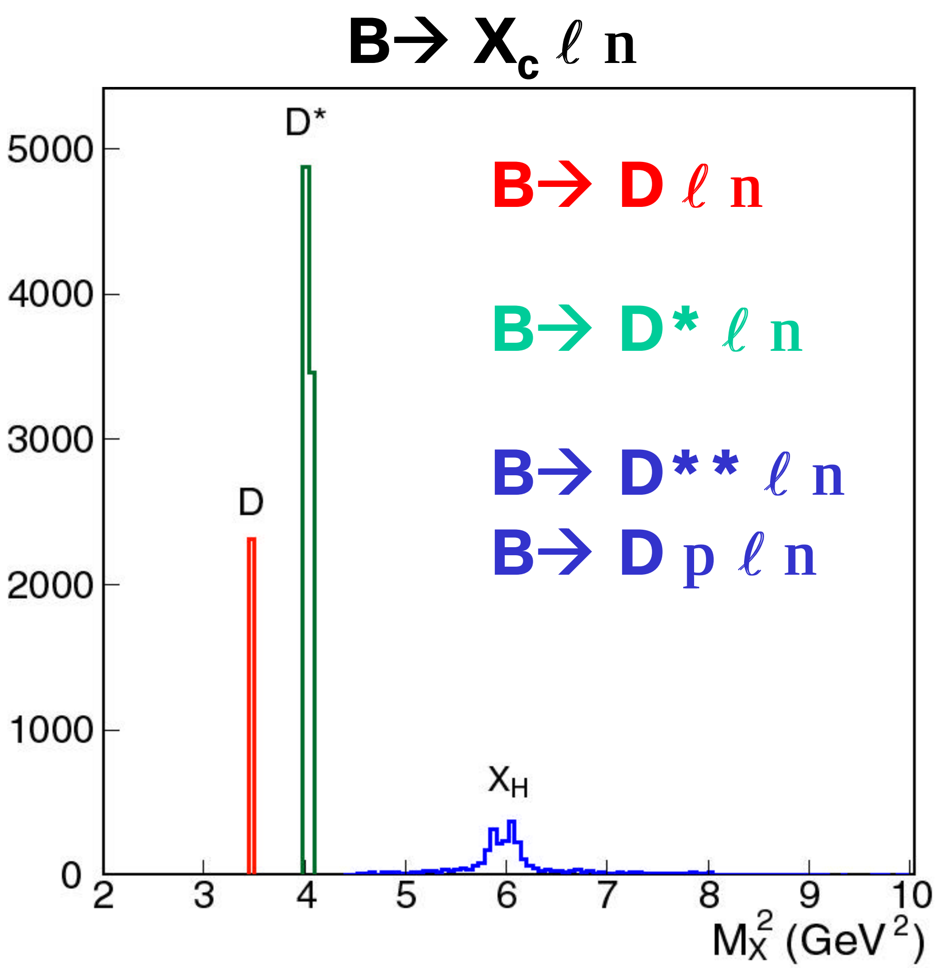




$$\langle E_g \rangle = \frac{M_B}{2}\left(1 - 0.385\frac{a_s}{p} - 0.620 b_0 (\frac{a_s}{p})^2 - \frac{\bar{\Lambda}}{M_B}(1 - 0.954\frac{a_s}{p} - 1.175 b_0 (\frac{a_s}{p})^2)\right)$$

$$\left\langle \left(E_g - \langle E_g \rangle\right)^2 \right\rangle = M_B^2\left(\frac{-l_1}{12 M_B^2} + 0.00815\frac{a_s}{p} + 0.01024 b_0 (\frac{a_s}{p})^2 - \frac{\bar{\Lambda}}{M_B}(0.05083\frac{a_s}{p} + 0.05412 b_0 (\frac{a_s}{p})^2)\right)$$

Hadronic Mass Moments



V

λ_2

$$\langle (M_X^2 - \overline{M}_D^2) \rangle$$

- Monte Carlo model shown
- Measure moments of recoil mass
- D and D* well measured
- Need to determine contribution to moments from high mass components
- Details of resonances not included in parton level calculation

Quark←→ Hadron

Semileptonic Decay Width

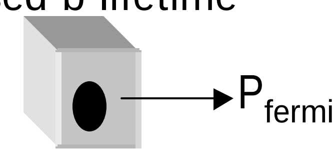
- Γ_{sl} (B Meson Semileptonic Decay Width)
  - Calculated from B meson branching fraction and lifetime measurements (CLEO, CDF, BaBar, Belle ...)
  - It is the first approximation to the b quarks decay width

$$\Gamma_{s\ell}(B \rightarrow X_u l\nu) = \frac{G_F^2 |V_{ub}|^2 m_b^5}{192\pi^3}\left[1 + \frac{\lambda_1}{2m_b^2} - \frac{9\lambda_2}{2m_b^2} + radiative + O(1/M_B^3)\right]$$

Free quark decay width

b quark motion – increased b lifetime

ΔM hyperfine splitting



$$\Gamma_{s\ell}(B \rightarrow X_c l\nu) = \frac{(0.3689)G_F^2 |V_{cb}|^2 M_B^5}{192\pi^3}\left[1 - 1.648\frac{\bar{\Lambda}}{M_B} - 0.946\frac{\bar{\Lambda}^2}{M_B^2} - 3.185\frac{\lambda_1}{M_B^2} - 7.474\frac{\lambda_2}{M_B^2} + O(1/M_B^3)\right]$$

Strategy

- At least two inclusive measurements needed in addition to the B branching fraction and B lifetime in order to extract $\mathbf{V_{cb}}$.

- Measure:
  - 1st and 2nd moments of Photon energy (b→ sγ)
  - 1st and 2nd moments of hadronic recoil mass ($B \to X_c \ell \nu$)
  - lepton energy moments ($B \to X_c \ell \nu$)

- *Many* measurements are needed to verify
  - Convergence of Expressions
  - Quark-Hadron Duality

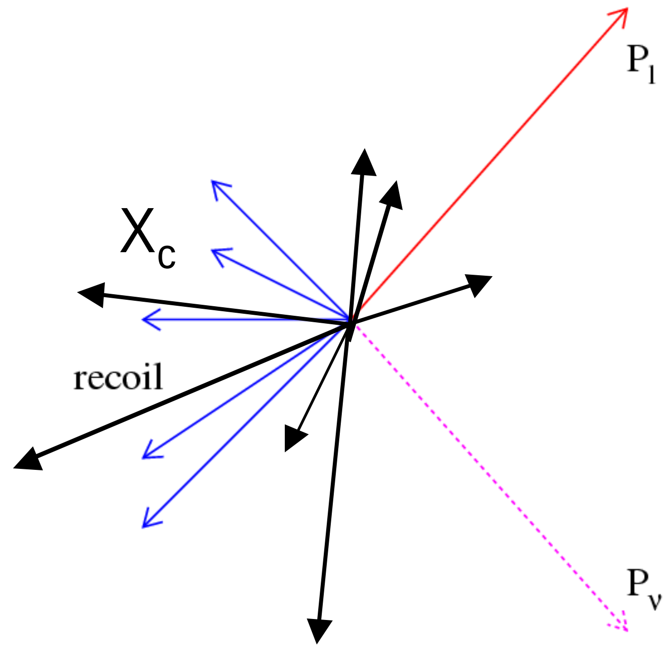
Measurements I

Moments & V_{cb}

Hadronic Mass Moments

- Want M_X^2 from $B \rightarrow X_c \ell \nu$ but can not use hadronic daughters

- Reconstruct mass with B, ℓ, and ν four-vectors



small (→ P_B) unknown (→ $\cos\theta_{B-\ell\nu}$, crossed out with X)

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

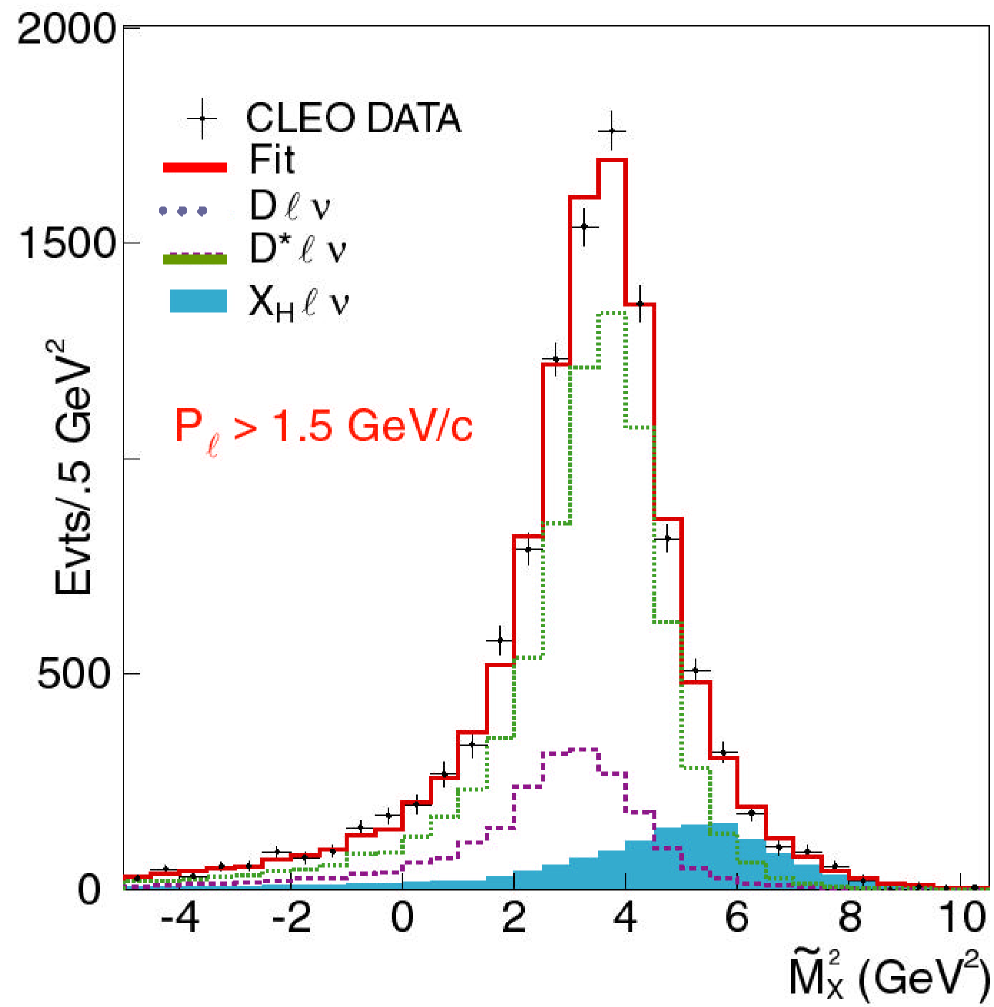
$$\tilde{M}_X^2 = M_B^2 + M_{\ell\nu}^2 - 2E_B E_{\ell\nu}$$

- **Lepton:** Select events with very high lepton momentum (1.5 GeV)
  - above lower momentum secondaries (*eg* D decays)

- **Neutrino:** Use all observed energy-momentum to calculate neutrino 4-vector
  - fakes arise from non-interacting neutrals (K_{long}, secondary neutrinos, neutrons)

Hadronic Mass Moments

– Fit spectrum with
  - *B® Dℓn*
  - *B® D*ℓn*
  - *B ® X*

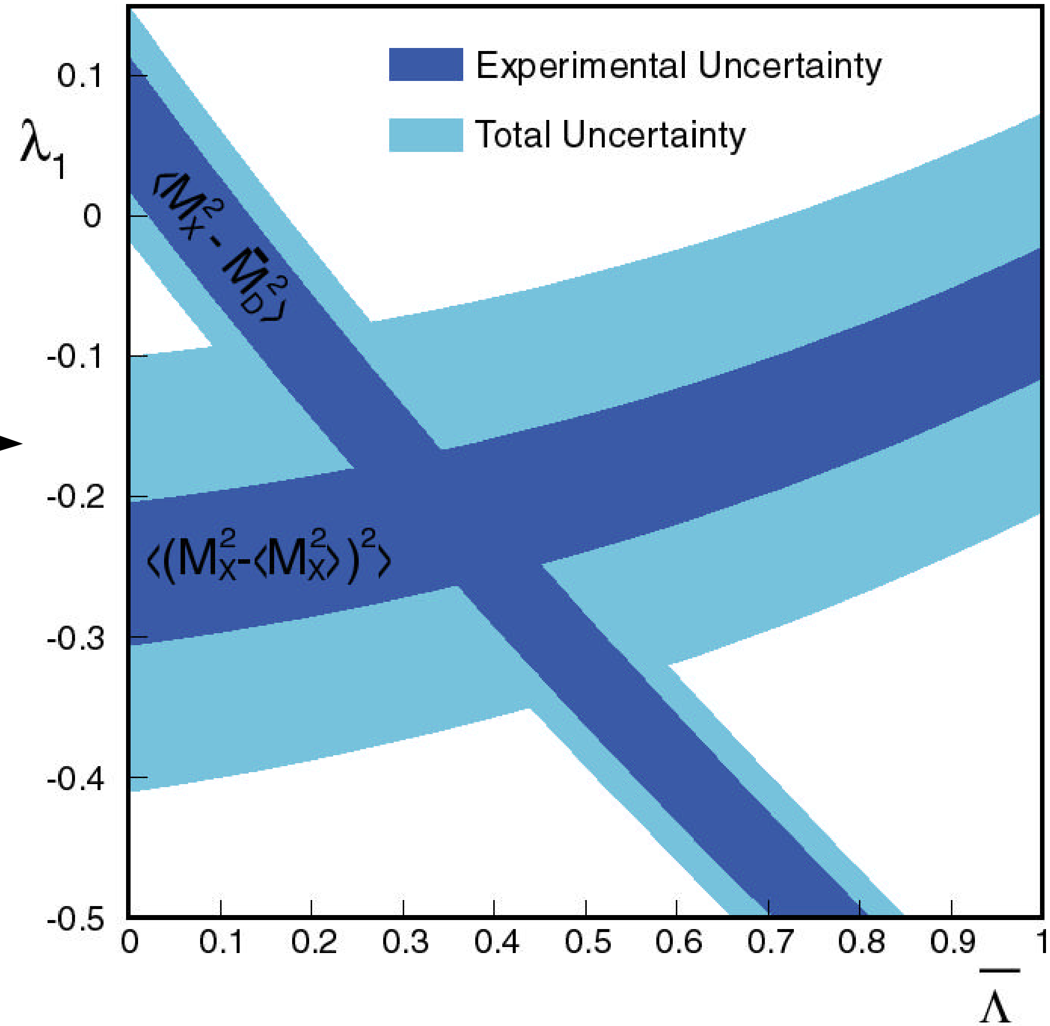


$$\left\langle (M_X^2 - \overline{M}_D^2) \right\rangle = 0.251 \pm 0.023 \pm 0.062$$

$$\left\langle (M_X^2 - \langle M_X^2 \rangle)^2 \right\rangle = 0.576 \pm 0.048 \pm 0.163$$

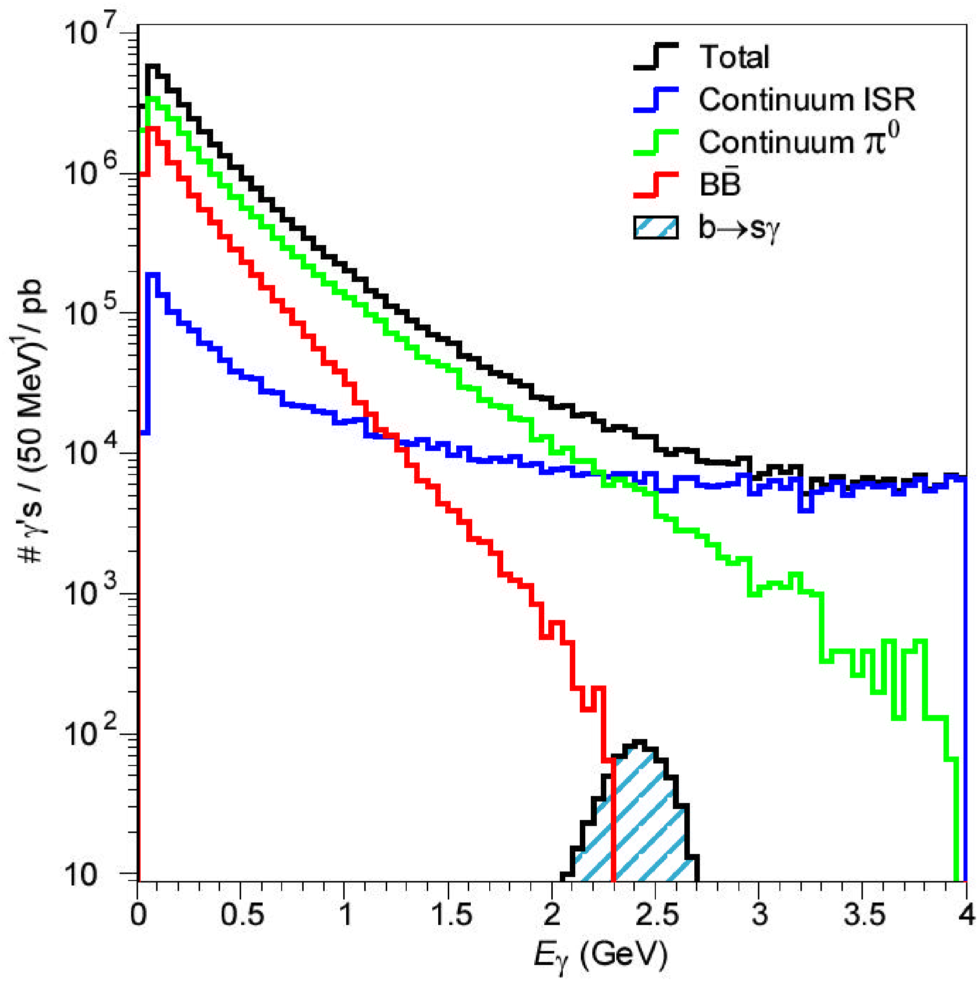
Hadronic Mass Moments

- If we believed the second moment expansion, we could get V_{cb} from this
- Use first moments from *b*® *sg* and hadronic *b*® *cℓn* instead…

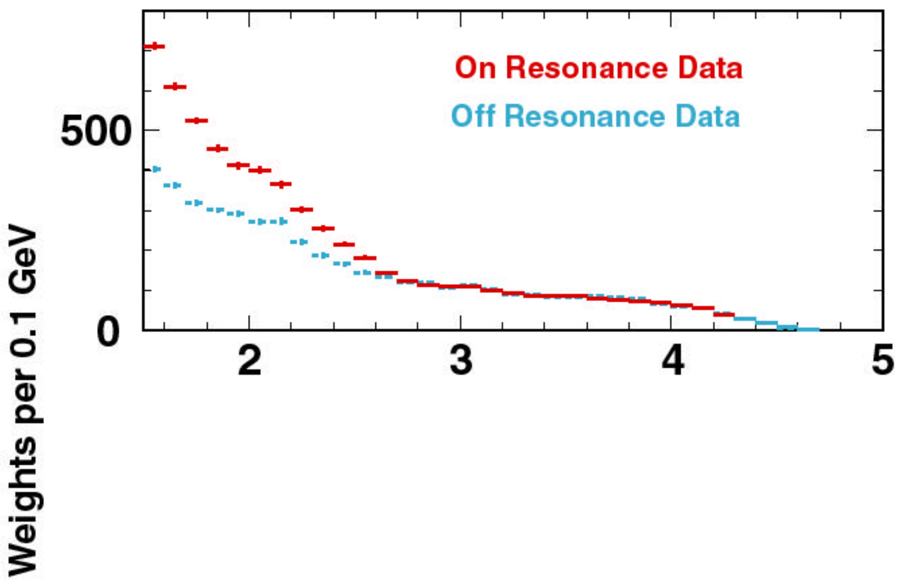


Photon Energy Moments

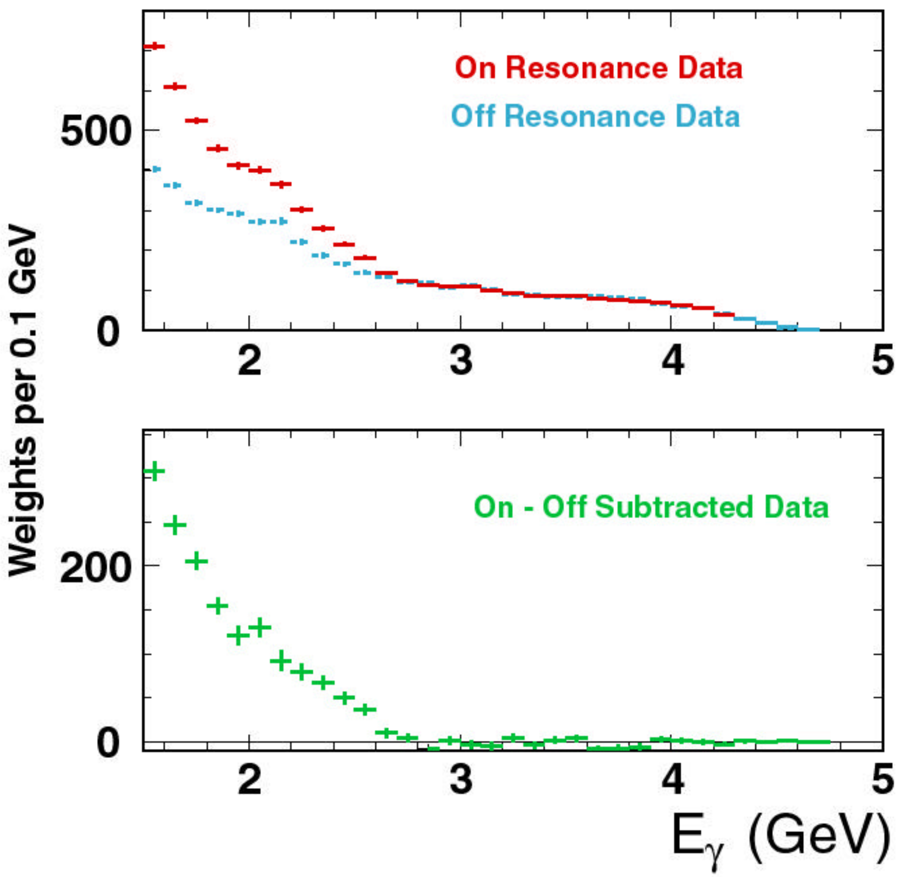
- Always require high energy photon $2.0 < E_g < 2.7$ GeV
  $|\cos q| < 0.7$
- Naïve strategy:
  Measure E_g spectrum for ON and OFF resonance and subtract
- But, must suppress **huge** continuum background!
  [veto is not enough]
  - π^0 ® $\gamma\gamma$ and η ® $\gamma\gamma$
- Three attacks:
  - Shape analysis
  - Pseudoreconstruction
  - Leptons



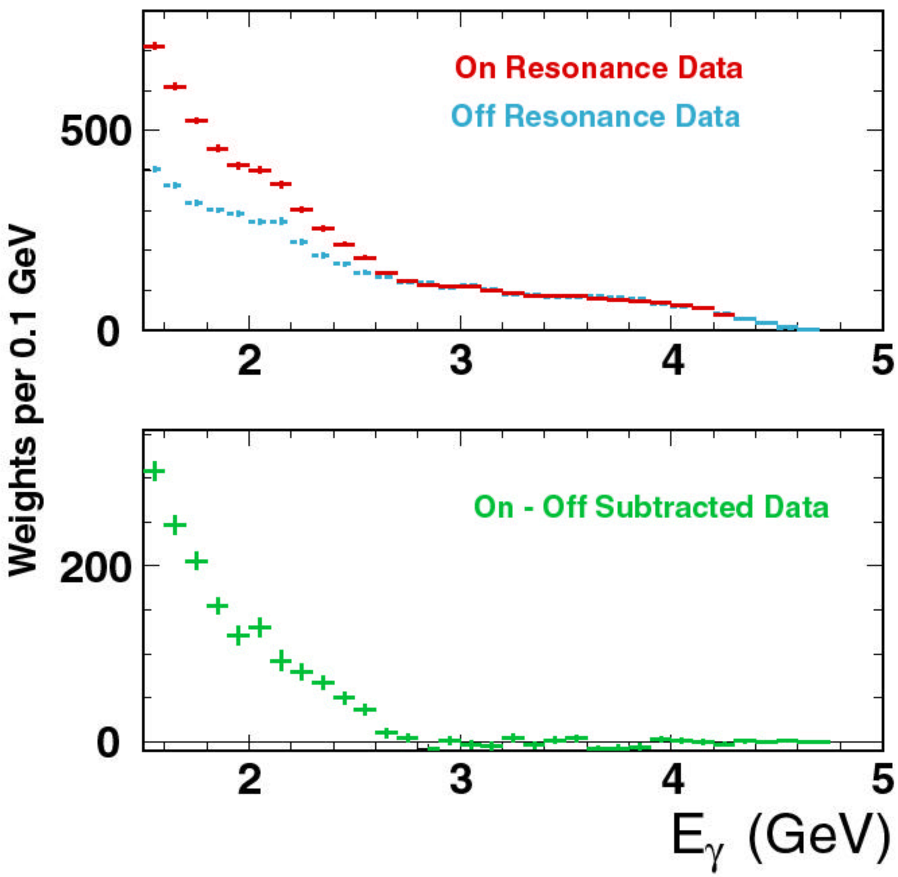
Photon Energy Moments

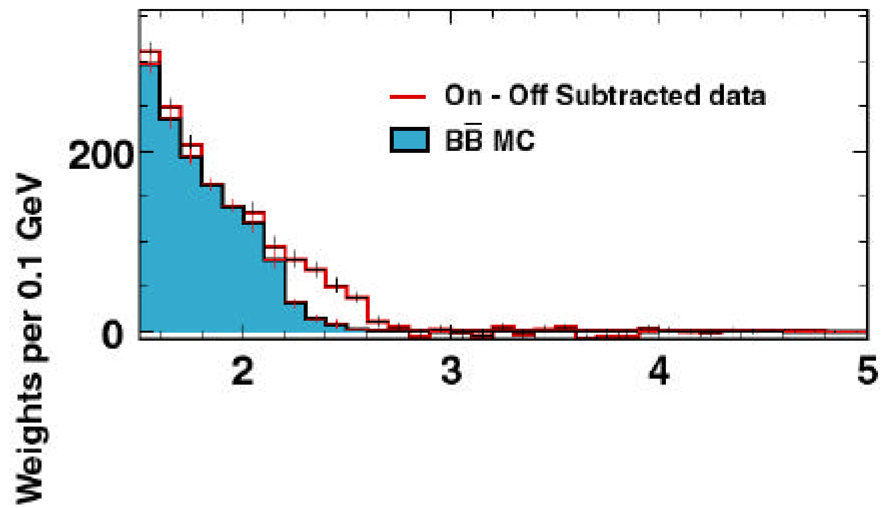


Photon Energy Moments

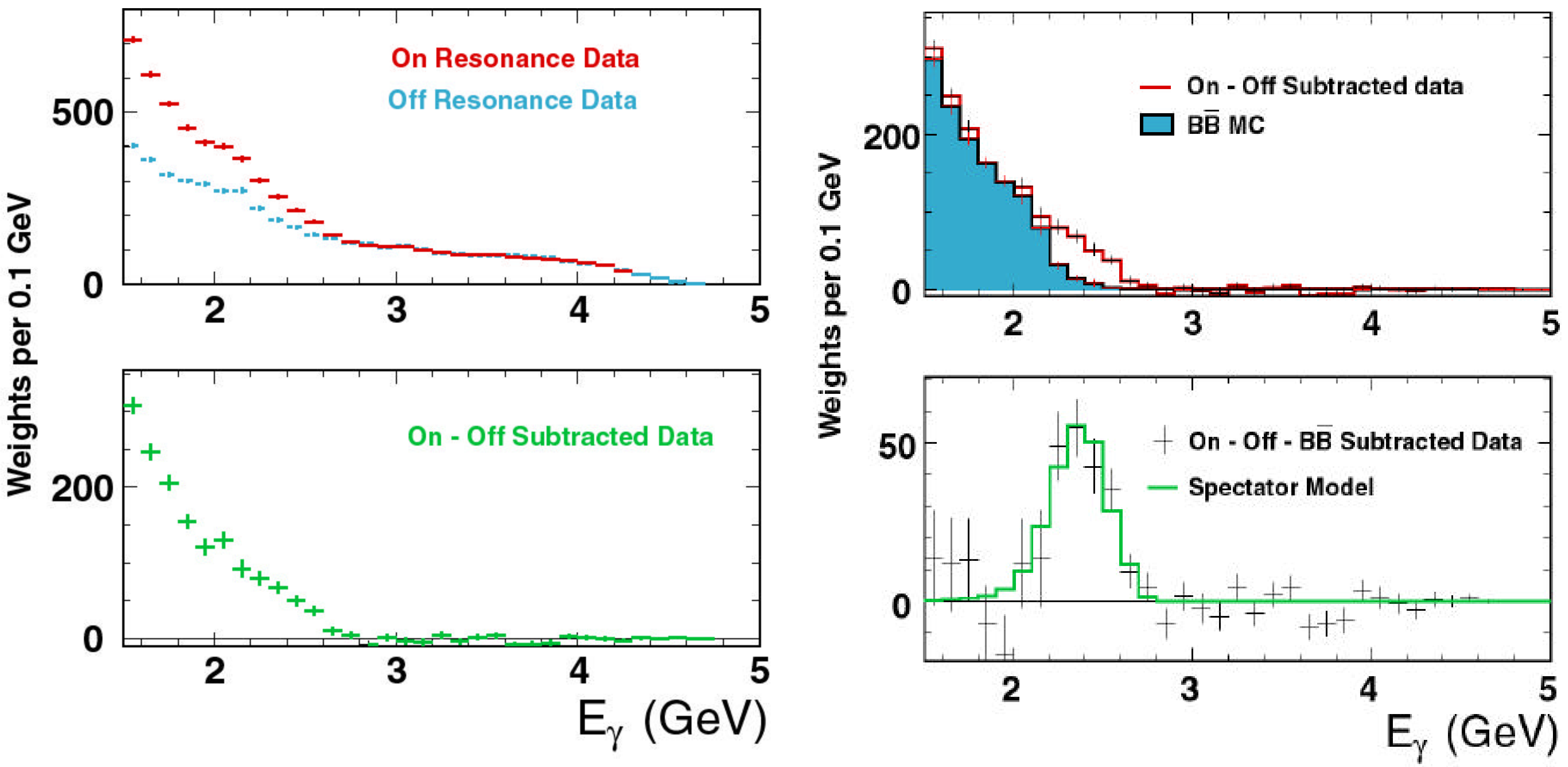


Photon Energy Moments

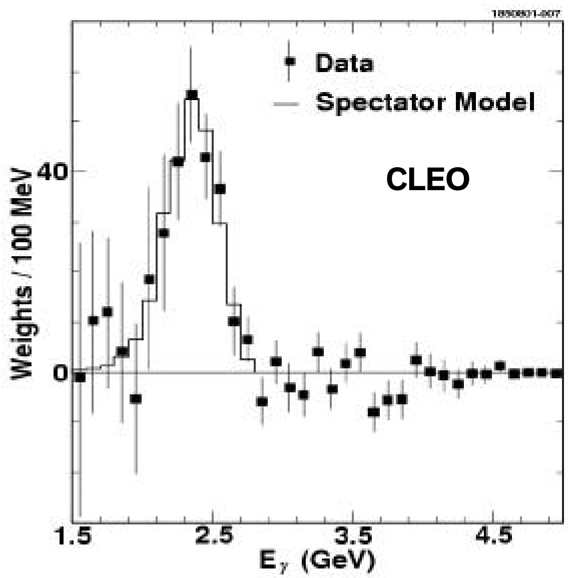


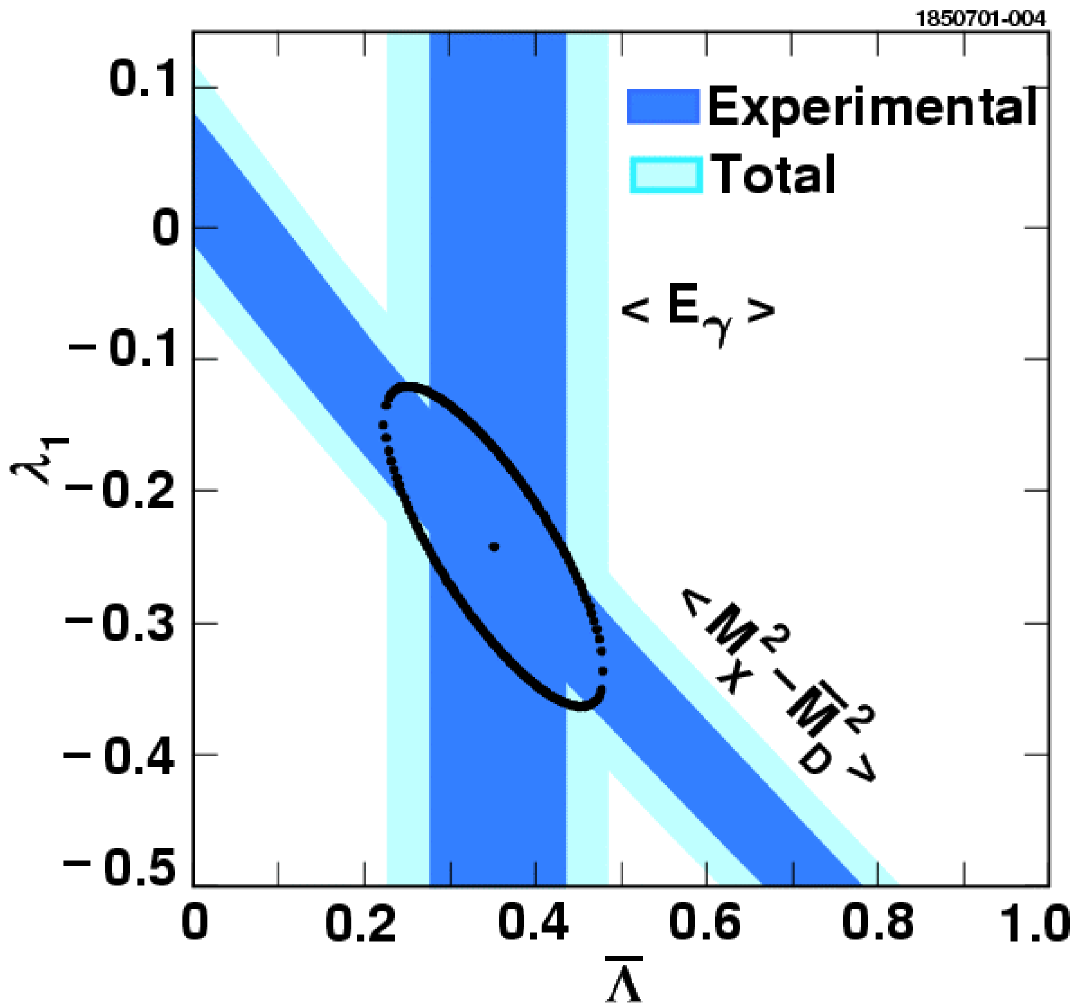


Photon Energy Moments



Hadronic Mass and Photon Energy





$$\langle E_g \rangle = 2.346 \pm 0.032 \pm 0.011\, GeV$$

$$\langle E_g{}^2 \rangle - \langle E_g \rangle^2 = 0.0226 \pm 0.0066 \pm 0.0020\ GeV^2$$

$$\langle (M_X^2 - \overline{M}_D^2) \rangle = 0.251 \pm 0.023 \pm 0.062\, GeV^2$$

$$\langle (M_X^2 - \langle M_X^2 \rangle)^2 \rangle = 0.576 \pm 0.048 \pm 0.163\ GeV^4$$

V_{cb}

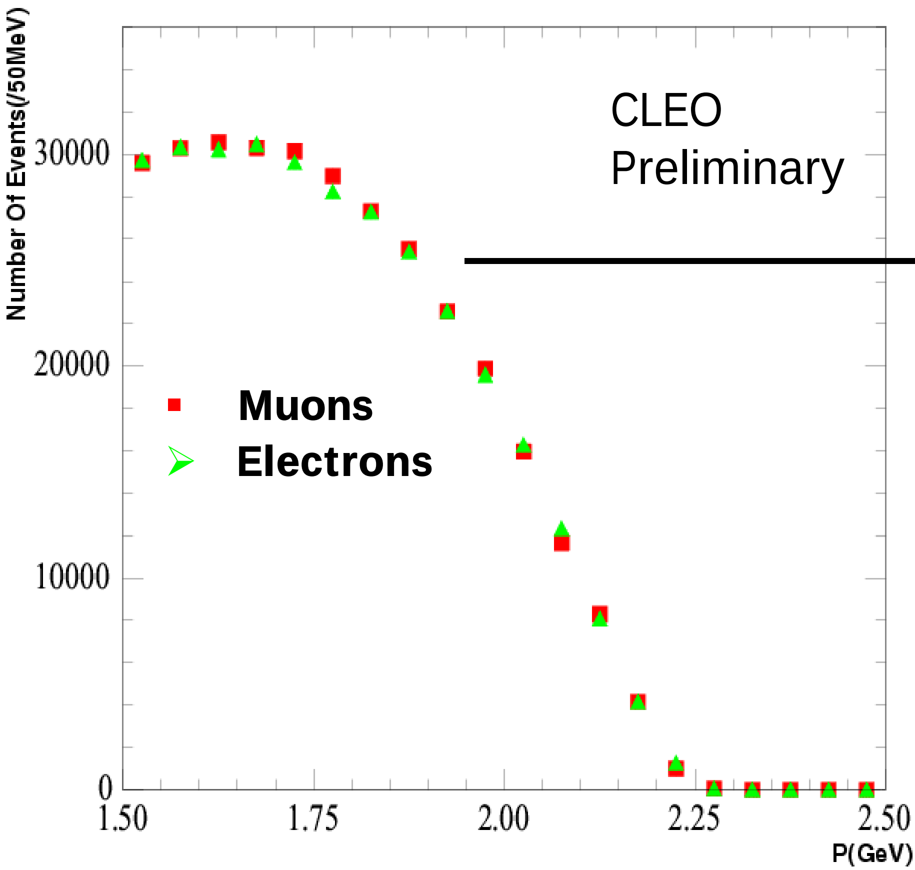
In $\overline{MS}$ scheme, at order $1/M_B^3$
and $\alpha_s^2\beta_o$

$\overline{\Lambda} = 0.35 \pm 0.07 \pm 0.10$ GeV
$\lambda_1 = -.236 \pm 0.071 \pm 0.078$ GeV^2

$|V_{cb}| = (4.04 \pm 0.09 \pm 0.05 \pm 0.08)\ 10^{-2}$

Γ_{sl} ↑ $\quad$ Λ, λ_1 ↑ $\quad$ Theory ↑

Lepton Energy Moments in $B \rightarrow X$ ln



Unfolded Lepton Energy Spectrum

for leptons from $B \rightarrow X$ ln

Measure lepton energy

From energy spectrum:

$$R_1 = \frac{\int_{1.5} E_l \frac{d\Gamma_{sl}}{dE_l} dE_l}{\int_{1.5} \frac{d\Gamma_{sl}}{dE_l} dE_l} \qquad R_0 = \frac{\int_{1.7} \frac{d\Gamma_{sl}}{dE_l} dE_l}{\int_{1.5} \frac{d\Gamma_{sl}}{dE_l} dE_l}$$

R_0 = 0.6187 $\pm$ 0.0014 $\pm$ 0.0016

R_1 = 1.7810 $\pm$ 0.0007 $\pm$ 0.0009 GeV

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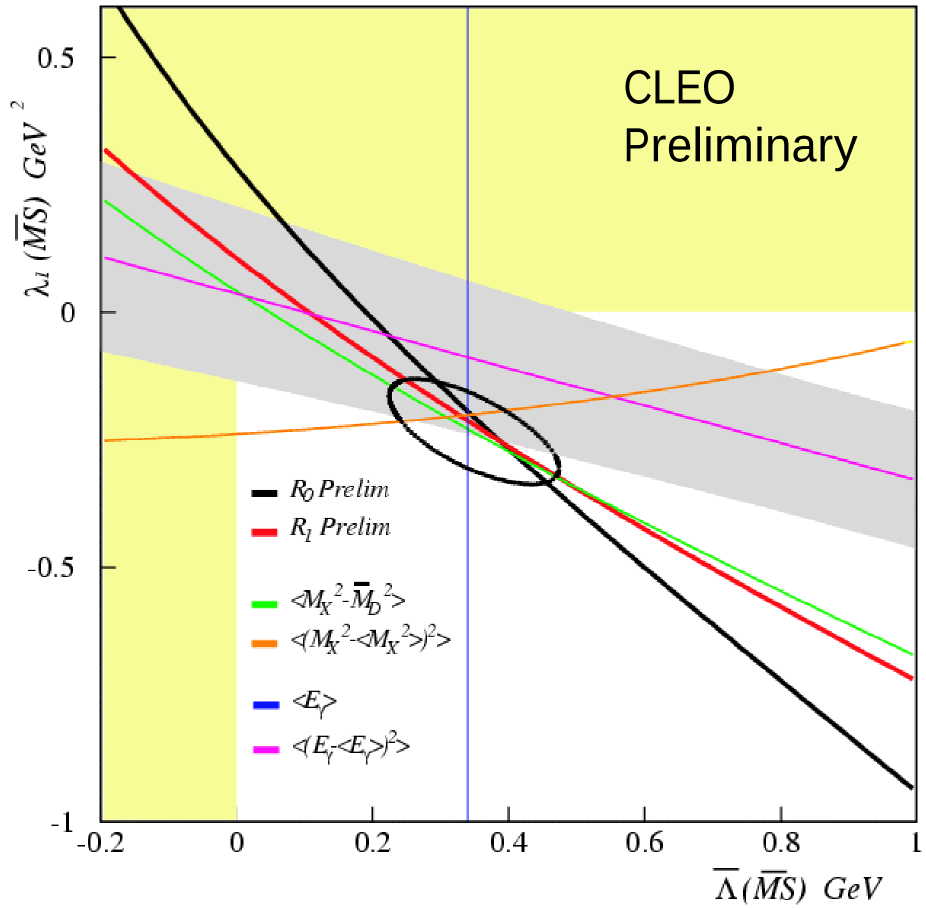
ICHEP02 ABS932

Consistency Among Observables



- Λ and λ_1 ellipse extracted from 1st moment of $B \to X_s$ g photon energy spectrum and 1st moment of hadronic mass² distribution($B \to X_c$ ln). We use the HQET equations in MS scheme at order $1/M_B^3$ and $\alpha_s^2\ \beta_o$.
  - **MS Expressions:** *A. Falk, M. Luke, M. Savage, Z. Ligeti, A. Manohar, M. Wise, C. Bauer*
- The red and black curves are derived from the new CLEO results for $B \to X$ ln lepton energy moments.
  - **MS Expressions:** *M.Gremm, A. Kapustin, Z. Ligeti and M. Wise, I. Stewart (moments) and I. Bigi, N.Uraltsev, A. Vainshtein(width)*
- Gray band represents total uncertainty for the 2nd moment of photon energy spectrum.

Moments Summary

- CLEO has measured six moments, two each from
  1) the photon energy distribution in $B \to X_s g$
  2) the hadronic mass^2 distribution in $B \to X_c ln$
  3) most recently the lepton energy spectrum in $B \to X_c ln$

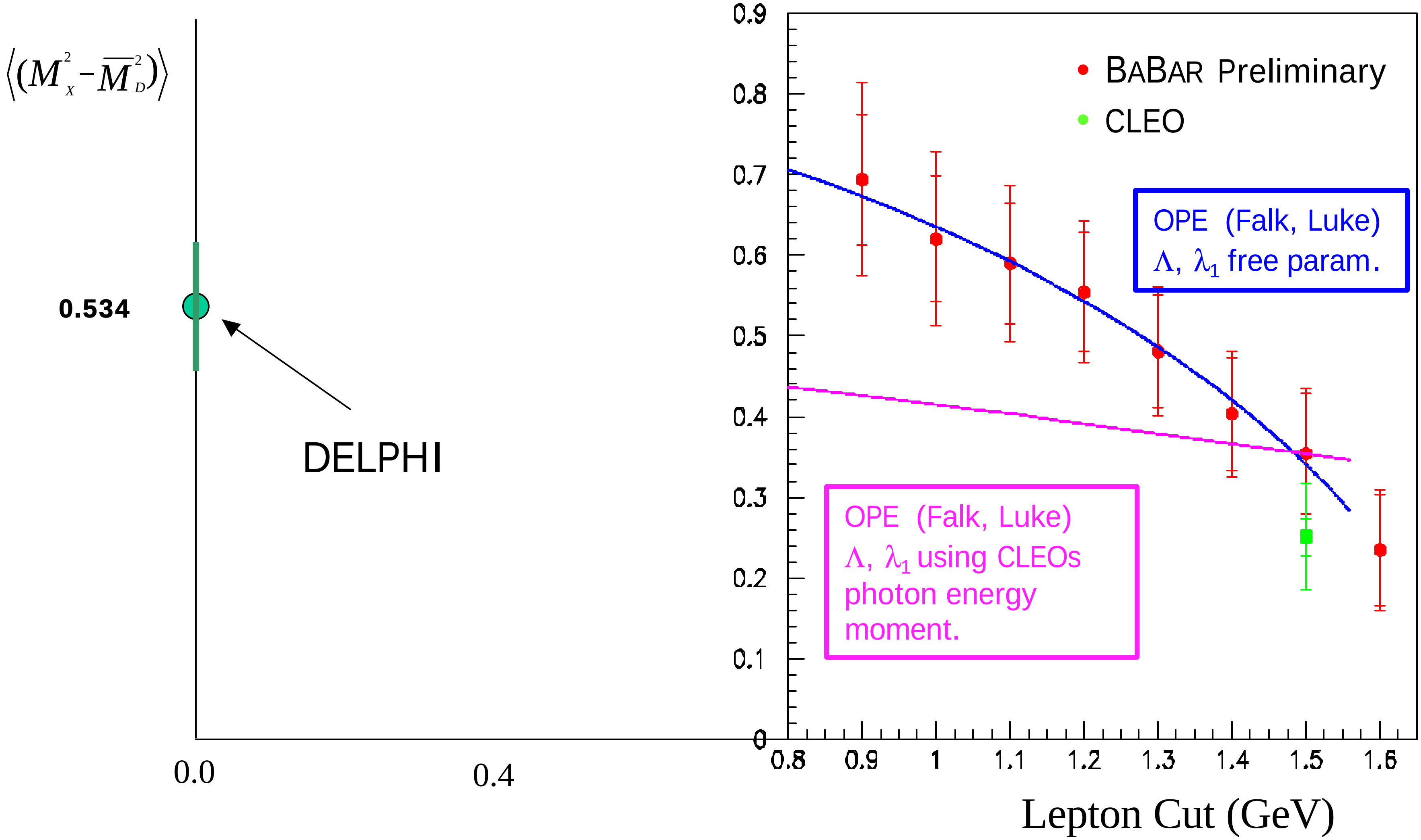
- The allowed values for HQET parameters $\overline{\Lambda}$ and λ_1 are in agreement for all measurements.

- $|V_{cb}|$ extracted at the level of 3%

Global Analysis: hep-ph/0210027 *Bauer,Ligeti,Luke & Manohar*

Moment	CLEO	DELPHI(*prelim*)	BABAR(*prelim*)
$<m^2_H - m^2_D>$	0.251±0.023±0.062 (E_l>1.5GeV)	0.534±0.041±0.074	Next Slide
$<(m^2_H - <m^2_H>)^2>$	.576±0.048±0.163 (E_l > 1.5GeV)	1.23±0.16±0.15	
$<(m^2_H - <m^2_H>)^3>$		2.97±0.67±0.48	
$<E_\gamma>$	2.346±0.032± 0.011		
$<(E_\gamma - <E_\gamma>)^2>$	0.0226±0.0066±0.0020		
$<E_\ell>$	1.7810±0.0007±0.0009 (E_l > 1.5 GeV)	1.383±0.012± 0.009	
$<(E_\ell - <E_\ell>)^2>$		0.192 ± 0.005± 0.008	
$<(E_\ell - <E_\ell>)^3>$		0.029 ±0.005±0.006	
R_0	0.6187±0.0014 ±0.0016 (E_l > 1.5 GeV)		

BaBar at ICHEP



Global Analysis: hep-ph/0210027 *Bauer,Ligeti,Luke & Manohar*

$|V_{cb}| = (4.08 \pm 0.09)\ 10^{-2}$

Abstract

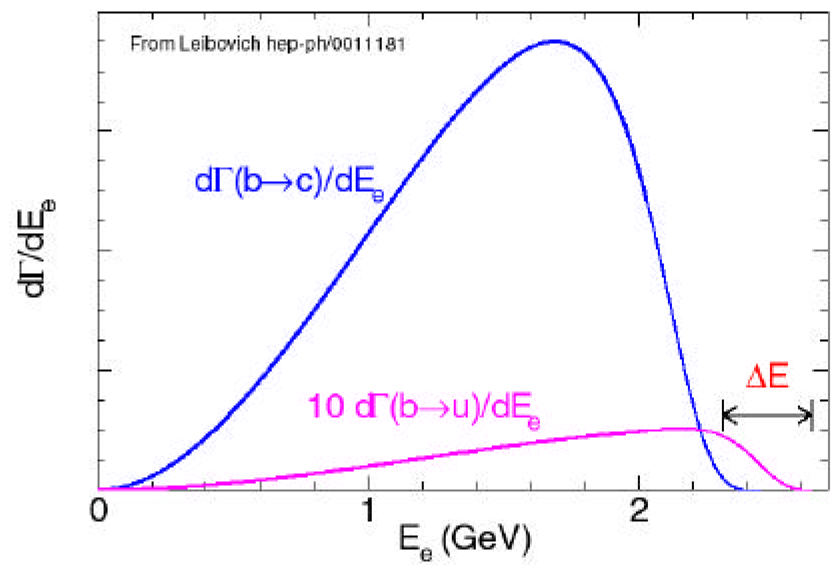
We present expressions for shape variables of B decay distributions in several different mass schemes, to order $\alpha_s^2\beta_0$ and $\Lambda^3_{\rm QCD}/m_b^3$. Such observables are sensitive to the b quark mass and matrix elements in the heavy quark effective theory, and recent measurements allow precision determinations of some of these parameters. We perform a combined fit to recent experimental results from CLEO, BABAR, and DELPHI, and discuss the theoretical uncertainties due to nonperturbative and perturbative effects. We discuss the possible discrepancy between the OPE prediction, recent BABAR results and the measured branching fraction to D and D^* states. We find $|V_{cb}| = (40.8 \pm 0.9) \times 10^{-3}$ and $m_b^{1S} = 4.74 \pm 0.10$ GeV, where the errors are dominated by experimental uncertainties.

Measurements II

V_{ub}

$|V_{ub}|$ from Lepton Endpoint (using $b \to s\gamma$)

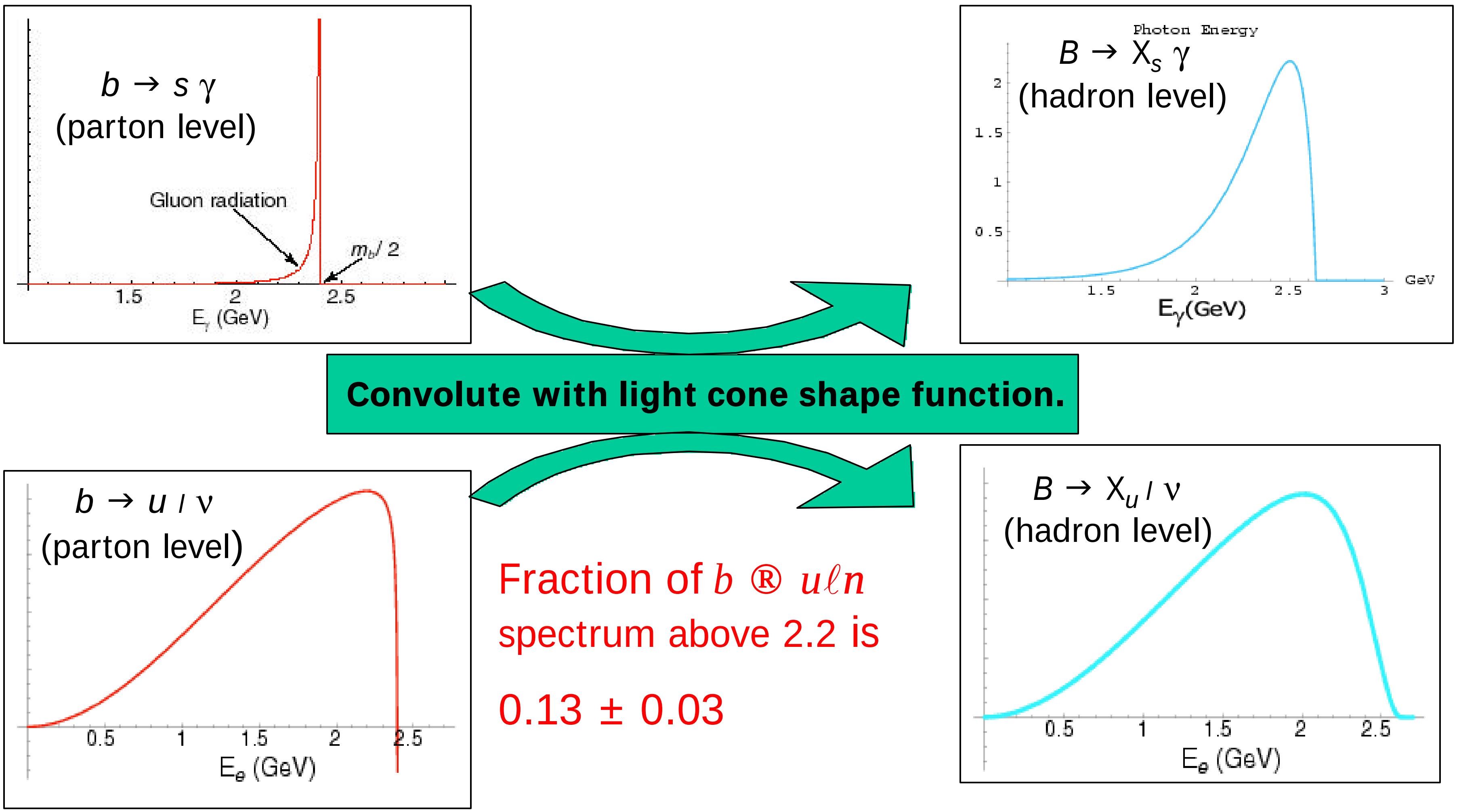
- $|V_{ub}|$ from $b \to u \ell \nu$
  - We measure the endpoint yield
  - Large extrapolation to obtain $|V_{ub}|$
  - High E cut leads to theoretical difficulties (we probe the part of spectrum most influenced by fermi momentum)



- **GOAL**: Use $b \to s\gamma$ to understand Fermi momentum and apply to $b \to u \ell \nu$ for improved measurement of $|V_{ub}|$

Kagan-Neubert
DeFazio-Neubert

B → lightquark shape function, SAME (to lowest order in Λ_{QCD}/m_b) for $b \to s\,\gamma$ ⇨ $B \to X_s\,\gamma$ and $b \to u\,l\nu$ ⇨ $B \to X_u\,l\nu$.



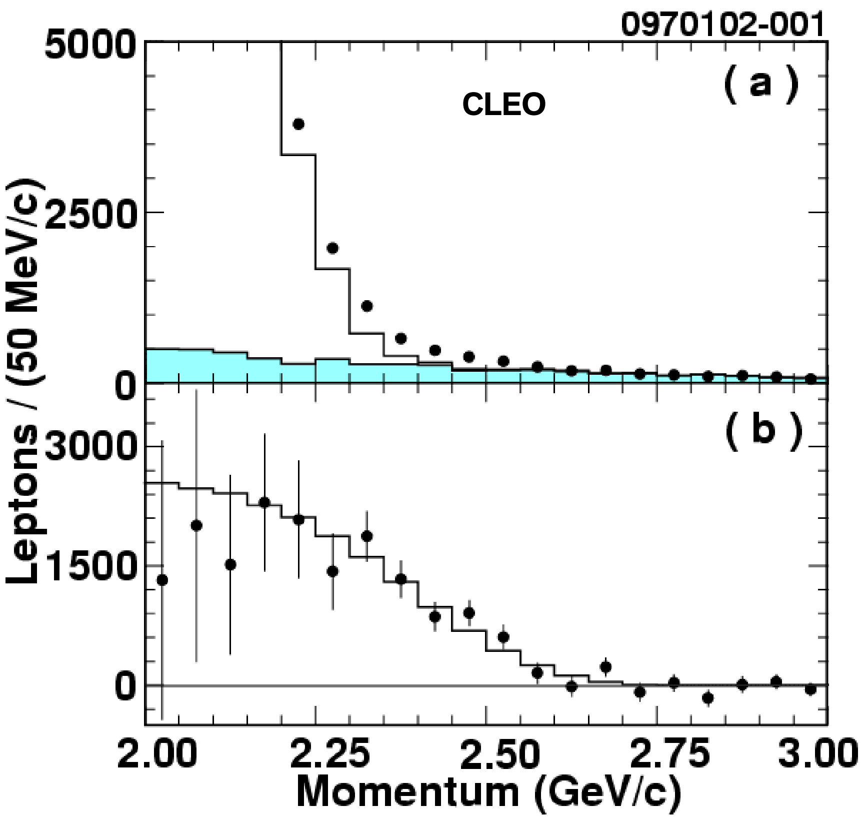
Fraction of b ® $u\ell n$
spectrum above 2.2 is

0.13 ± 0.03

$|V_{ub}|$ from Lepton Endpoint (using b ® sg)

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

The 1st two errors are from experiment and 2nd from theory



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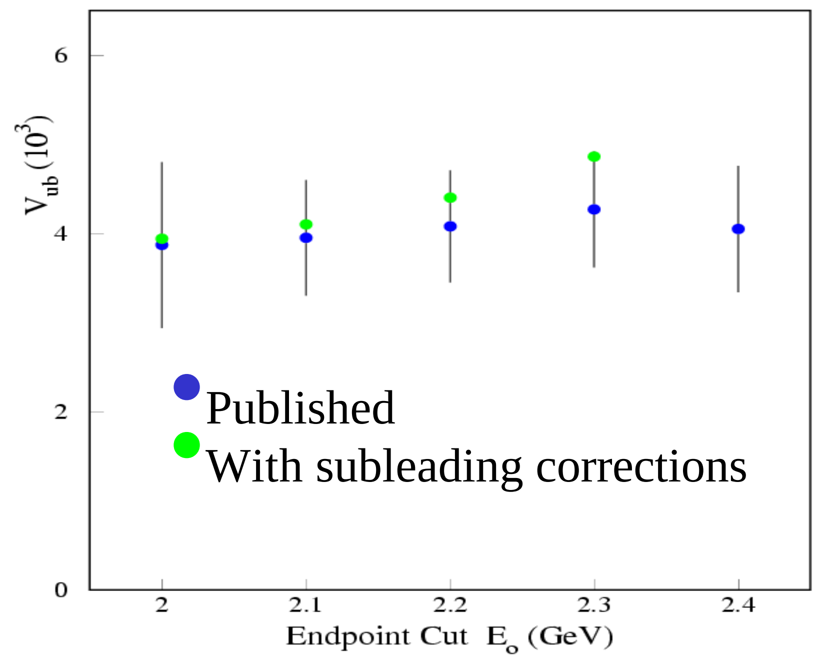
- Subleading corrections large

  C. Bauer, M. Luke, T. Mannel
  A. Leibovich, Z. Ligeti, M. Wise

- Method for partial inclusion of subleading corrections: *Neubert*



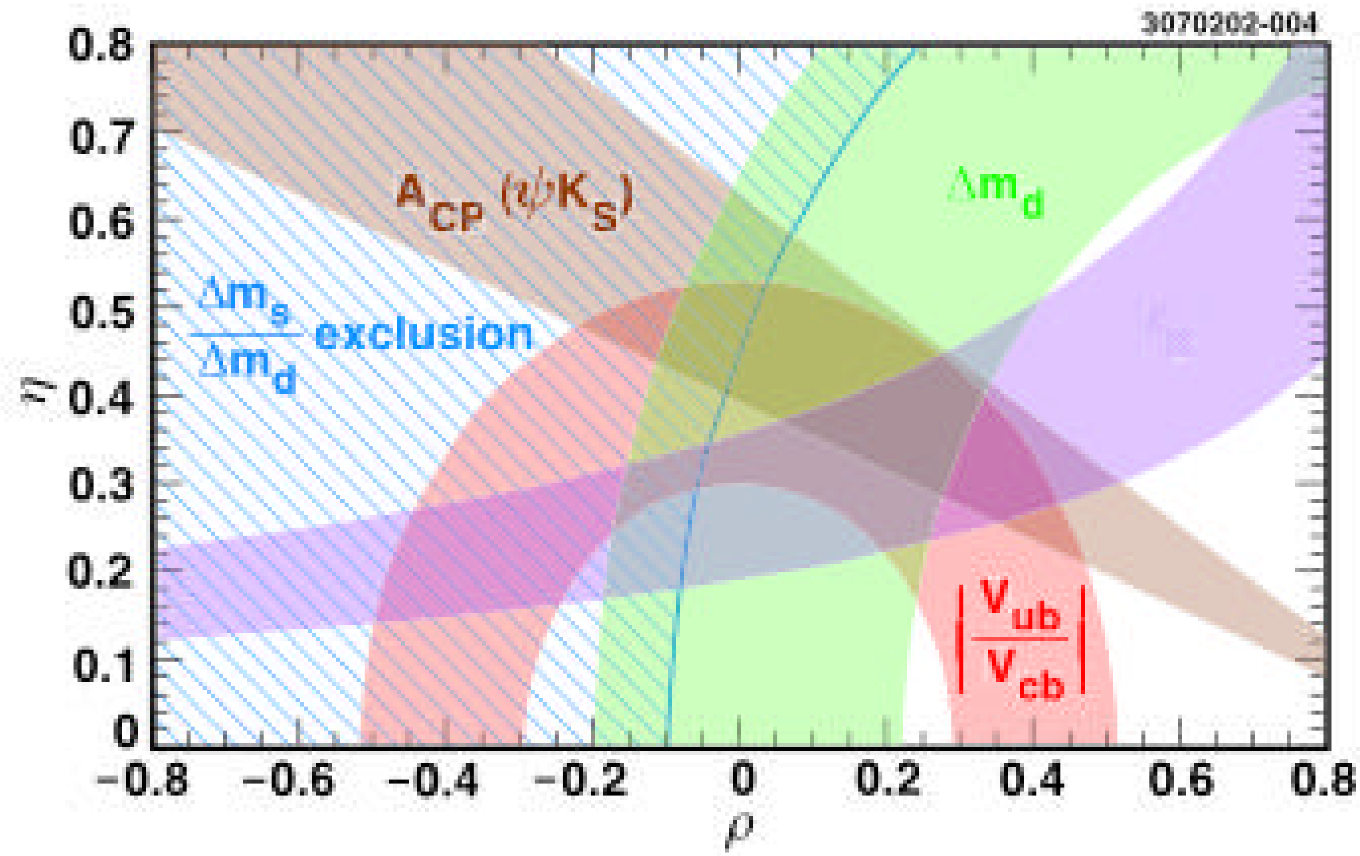
Conclusions

Summary

Endpoint $|V_{ub}| = (4.08 \pm 0.63)\ 10^{-3}$
Moments $|V_{cb}| = (4.04 \pm 0.13)\ 10^{-2}$

- **V_{cb}:**
  - Bound state corrections to the semileptonic width, predicted by HQET and measured by a number moments analyses have permitted the extraction of V_{cb} to a precision of a few %.
  - Are we seeing the first of Quark-Hadron Duality violations?
  - Improved hadronic mass measurements and lepton energy moments, are nearing completion and may help us understand.

- **V_{ub}:**
  - The photon energy spectrum in $b \rightarrow s\gamma$ provides a quantitative model for the bound state effects in $b \rightarrow u\, l\nu$.
  - This approach has not yet reached its full potential → We expect improved measurements from all 3 B factories.
  - The method does require additional theoretical refinements as well.


3070202-004
A_{CP} (ψK_S)
Δm_d
$\frac{\Delta m_s}{\Delta m_d}$ exclusion
$\left|\frac{V_{ub}}{V_{cb}}\right|$
η
ρ
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8