Improved Measurement of $|V_{ub}|$ with Inclusive Semileptonic B Decays

Stefan Anderson
University of Minnesota
CLEO Collaboration

2002 Lake Louise Winter Institute

The CKM Matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

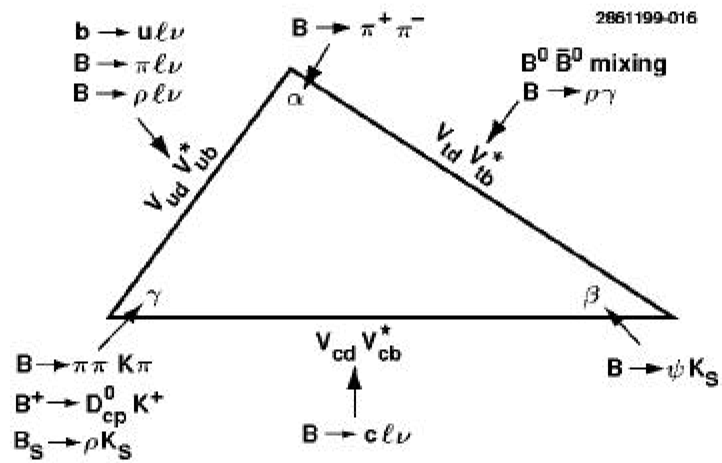
Parameterizes flavor mixing in weak decays

- Diagonal elements: near 1
- Off-diagonal: cross-generational, smaller
- Unitary
- Complex phase generates CP Violation

- Unitarity constraint on 1st and 3rd columns:

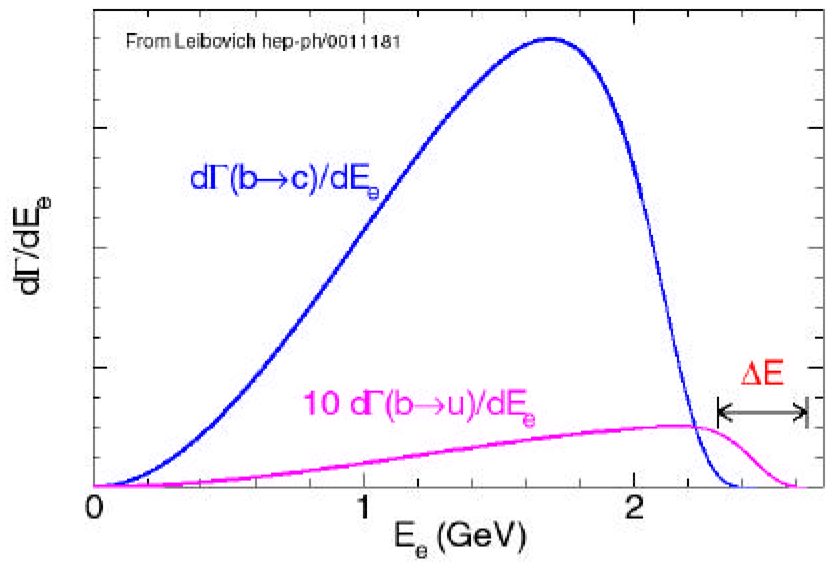
$$V_{ud}V_{ub}^{*} + V_{cd}V_{cb}^{*} + V_{td}V_{tb}^{*} = 0$$

  - Triangle: Sides and angles accessible experimentally
  - Goal: overconstrain and test SM



Inclusive Semileptonic B Decays

- B mesons can only decay across generations
- Semileptonic decays give most direct access to $|V_{ub}|$, $|V_{cb}|$
- $|V_{ub}|/|V_{cb}| \sim 0.1$: decays to charmed mesons ~100 times more likely



- Decays to charm overwhelm b→u signal everywhere but endpoint region

Lepton Energy Endpoint

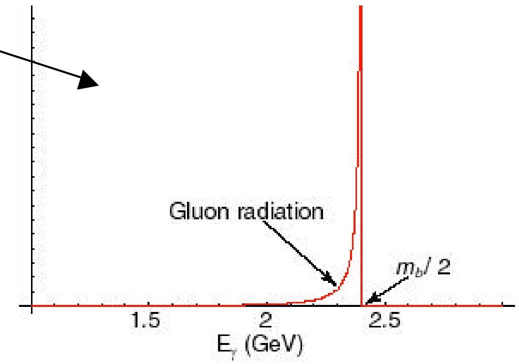
Approach: look for leptons in endpoint region

- Provided first evidence $|V_{ub}| \neq 0$
- $|V_{ub}|$ Measurement
  - Need fraction of spectrum measured ($f_u \sim 10\%$ for $2.3 \rightarrow 2.6$ GeV/c) to get $|V_{ub}|$ from partial Branching Fraction (BF)
  - Previous measurements relied on models $\rightarrow$ large error
- What's new in this measurement:
  - ~10x more data than 1993 measurement
  - Better understanding of $B \rightarrow X_c l$? bkg $\Rightarrow$ lower momentum cut and test stability of result
  - Heavy Quark Theory (HQT) and $B \rightarrow X_s \gamma$ photon-energy spectrum used in place of models

HQT, $B \rightarrow X_s\gamma$, and $B \rightarrow X_u l$?

- Parton level decays calculable w/ NLO QCD
- Meson level decays depend upon
  - m_b – mass of b quark
  - p_F – Fermi momentum; motion of b quark in B meson
- Not directly calculable; but can be described with a shape function $F(k_+)$
  - Convolute w/ parton spectrum
  - Universal for $b \rightarrow$ light transitions (to 1st order)

$b \rightarrow s\gamma$: 2-body & pertubative QCD



  - Quark-hadron duality assumed
- There are theoretical constraints on shape of $F(k_+)$
- Several parameterizations in literature (we use 3)

The Shape Function

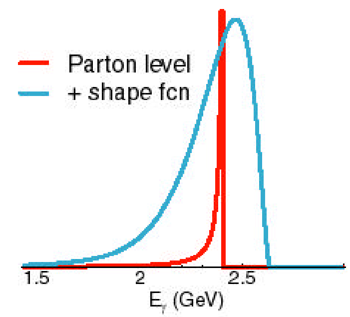
- One form (Kagan & Neubert):

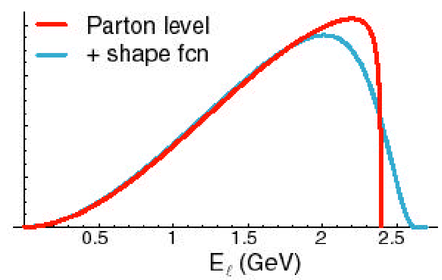
$$F(k_+) = N(1-x)^a e^{(1+a)x}; \qquad x = \frac{k_+}{\bar{\Lambda}} \leq 1$$

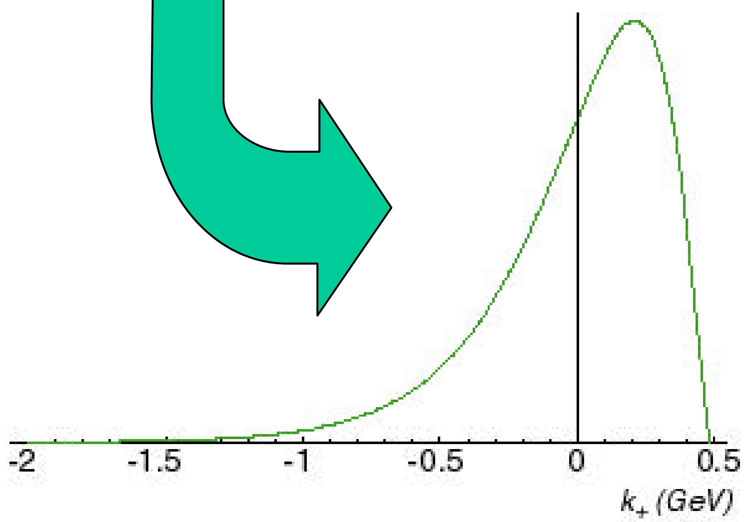
$$a = -3\frac{\bar{\Lambda}^2}{l_1} - 1$$

$$\bar{\Lambda} \approx M_B - m_b$$
$$- l_1^2 \approx \text{fermi momentum}$$

$b \to s\gamma$ $\qquad$ $b \to ul\,\nu$

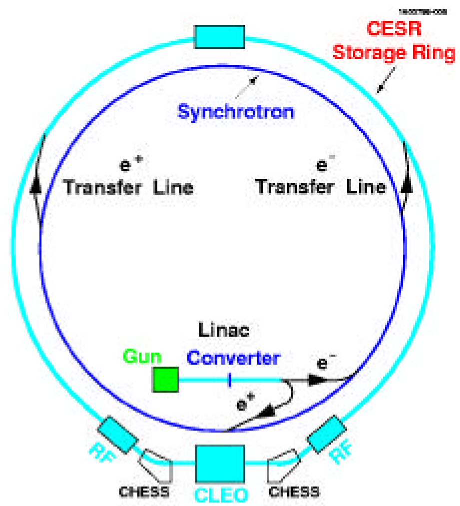


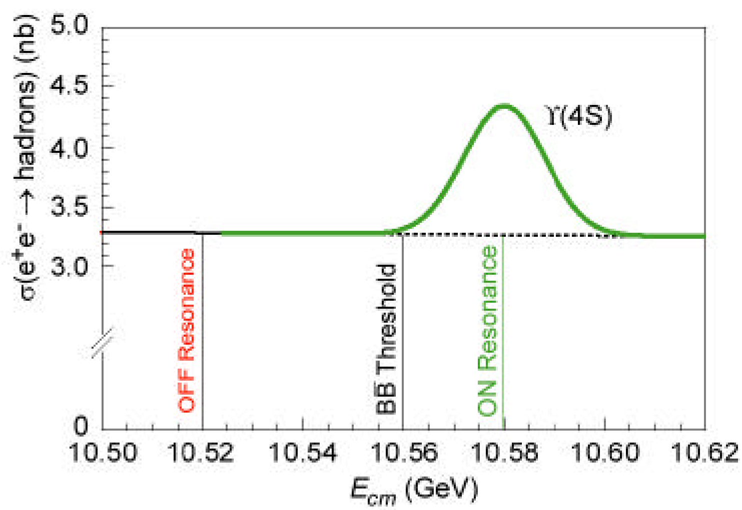




- Idea:
  - f_u depends on $F(k_+)$
  - Use $E_?$ spectrum to measure $F(k_+)$ params
  - Use result to calculate f_u

CESR & CLEO II Dataset

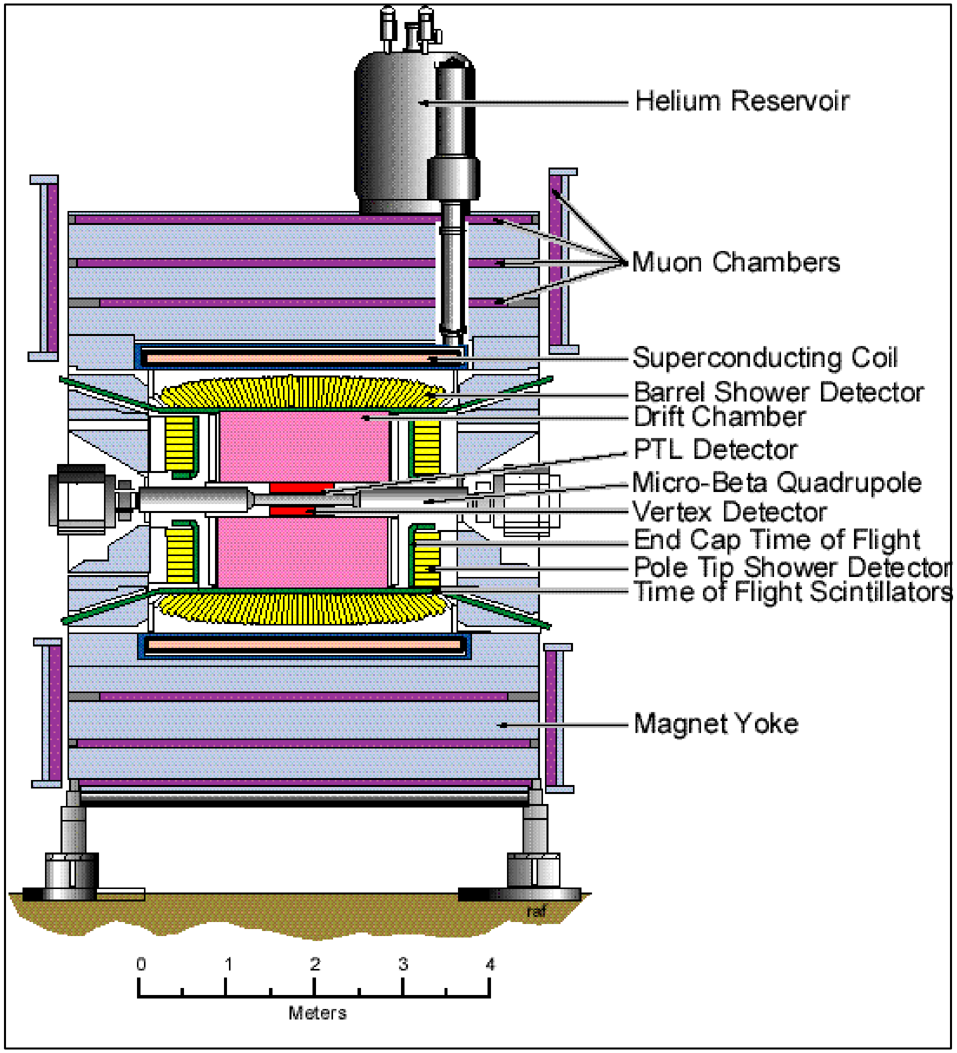




- CESR a Symmetric e^+e^- storage ring
- On the Υ*(4S)*:
  - e^+e^- ® ¡(4S) ® BB (s ~ 1 nb)
  - e^+e^- ® qq, (q = u, d, c, s) (s ~ 3 nb)
  - (P_B ~ 300 MeV/ *c*)
- 1/3 running at OFF Υ(4S) for continuum bkg subtraction
- CLEO II ('90-'99)
  ON: 9.1 fb^{-1} (9.7M *BB*)
  OFF: 4.4 fb^{-1}

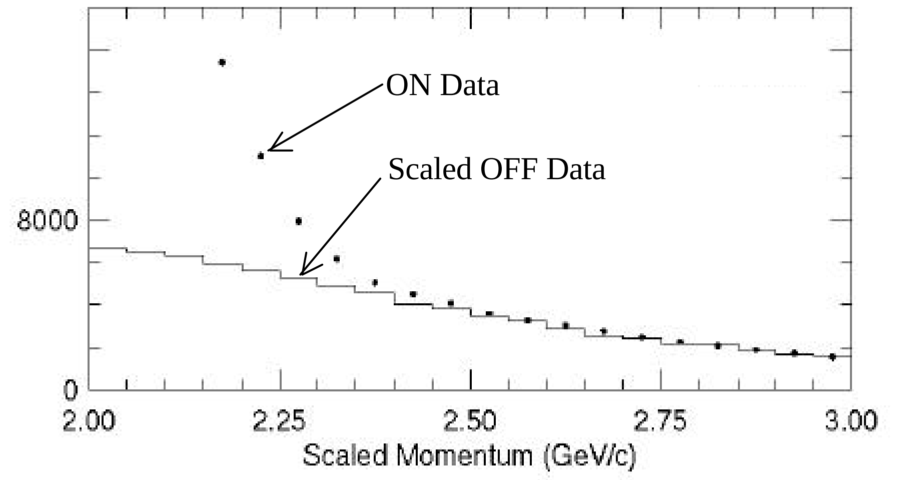
The CLEO II Detector

- Nearly Hermetic
- Tracking Chambers
  - 1.5 T **B** field
  - 95% solid angle
  - Provides *p* and dE/dx
- EM Calorimeter
  - Inside magnet
  - 98% solid angle
- Muon Detectors
  - 85% solid angle



$B \to X_u l$?: Analysis Strategy

- High Quality Tracks
  - Candidates restricted to central region of detector (~71% of solid angle)
  - Require excellent fits to reduce pollution from mismeasurement
- Lepton Identification
  - Electrons: combine E/p, dE/dx, other info into log-likelihood; fake rate < 0.1%
  - Muons: require hits at ≥ 7 nuclear interaction lengths; fake rate ≅ 0.5%

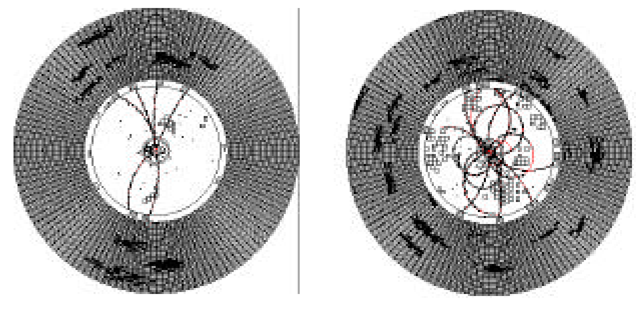


- Backgrounds
  - $B \to X_c l$? dominates below kinematic limit
  - Continuum production dominates above

$B\rightarrow X_u l$?: Analysis Strategy

- Continuum Background
  - Subtract with OFF data
  - Suppress w/ **neural net** (NN)
    - Uses event shape info

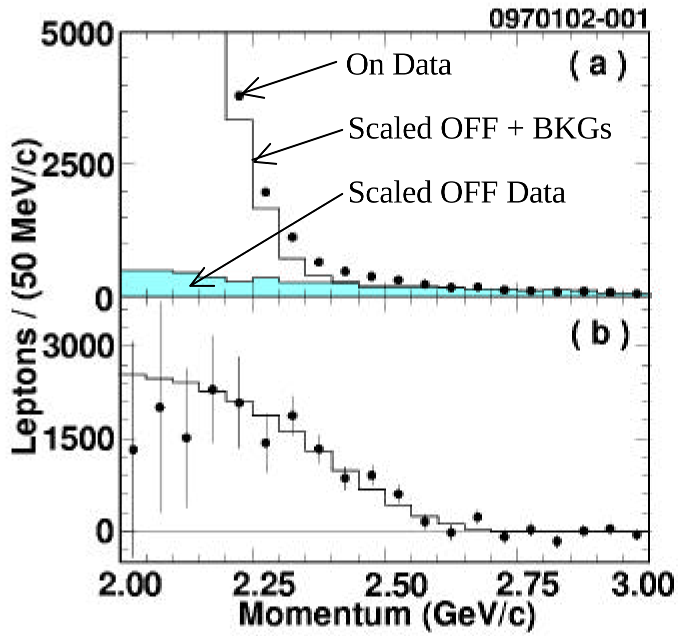
Continuum Signal



- $B \rightarrow X_c$ l ? Background

1. Use simulated spectra with $B\rightarrow D, D^*, D^{**}$ & D^{NR} components
2. Get mixture from fit to *e* spectrum without NN cut
3. Extend mixture to spectra with NN cut; minimal free parameters for data/MC differences
4. Systematics: Inner Brem., D/D* mix, $B \rightarrow D^{(*)}$ form factors, D** & D^{NR}

Lepton Yields & Partial BFs



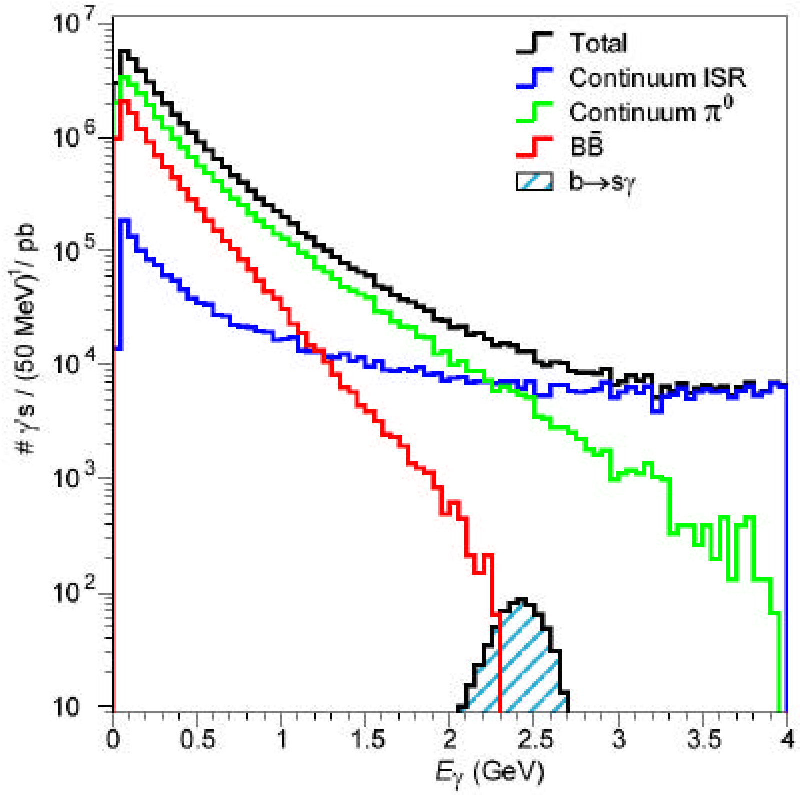
p [GeV/c]	Yield	$\Delta\mathcal{B}_u(p)[10^{-4}]$
2.0-2.6	$3538 \pm 279 \pm 1470$	$4.22 \pm 0.33 \pm 1.78$
2.1-2.6	$2751 \pm 191 \pm 584$	$3.28 \pm 0.23 \pm 0.73$
2.2-2.6	$1901 \pm 122 \pm 256$	$2.30 \pm 0.15 \pm 0.35$
2.3-2.6	$1152 \pm 80 \pm 61$	$1.43 \pm 0.10 \pm 0.13$
2.4-2.6	$499 \pm 57 \pm 14$	$0.64 \pm 0.07 \pm 0.05$

- Total e $\cong 0.21 \pm 0.015$
  - systematic error equal parts detector response and model dependence
- Measure yield in 5 overlapping intervals
- Need fraction of spectrum in each *p* interval (f_u) from $B \to X_s \gamma$

$B \to X_s \gamma$: Analysis Strategy

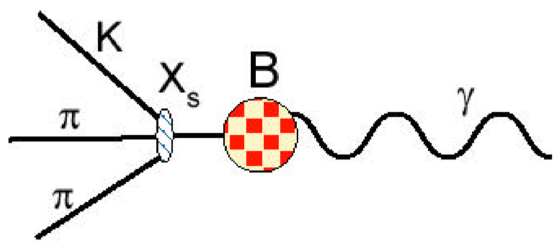
- ~2.0 < E_γ < ~2.7 GeV
- Continuum (qq) contributions HUGE
  - Subtract with OFF data
  - Must suppress to reduce error of subtraction
- Production from other B decays important below 2 GeV
- Distinguishing hard photons from continuum versus B decays is the task

Photon Spectrum at ϒ(4S)



$B \to X_s \gamma$: Analysis Strategy

- Shape Analysis
  - Combine many shape variables with Neural Net
- Pseudo-reconstruction



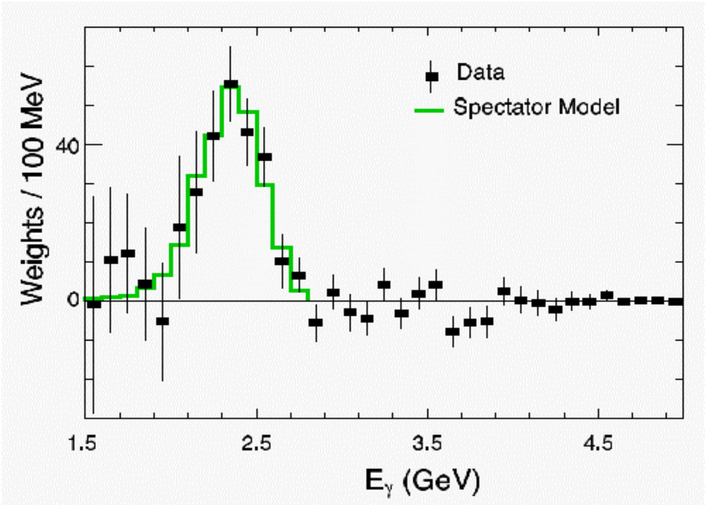
  - Identify the X_s System
    - K with up to 4 π's with at most 1 π^0
- Look for lepton
  - B-decay tag
  - Flavor tag

- Four Event Types:

Shape Analysis			
Reconstructable		**Non-Reconstructable**	
Lepton	**No Lepton**	**Lepton**	**No Lepton**

- Use all the available information
  - 4 Different Neural Nets
  - Rather than cut on the NN output, weight each event to minimize the statistical uncertainty

Fitting E? Spectrum



- Procedure:
  - Generate lab spectra for different $F(k_+)$ parameters
  - Fit E? spectrum over 1.5-2.8 GeV/c
  - Repeat to find minimum ?² and error ellipse

  - Use results to compute $B \rightarrow X_u l$? spectra and f_u's
  - Correct for electroweak radiative effects
- Systematics:
  - Other B decay processes
  - $a_s(\mu)$: vary μ from $m_b/2 \rightarrow 2m_b$
  - $F(k_+)$: 3 choices

Momentum Interval (GeV/c)	f_u
$2.0 \leq p_\ell < 2.6$	$0.266 \pm 0.041 \pm 0.024$
$2.1 \leq p_\ell < 2.6$	$0.198 \pm 0.035 \pm 0.020$
$2.2 \leq p_\ell < 2.6$	$0.130 \pm 0.024 \pm 0.015$
$2.3 \leq p_\ell < 2.6$	$0.074 \pm 0.014 \pm 0.009$
$2.4 \leq p_\ell < 2.6$	$0.037 \pm 0.007 \pm 0.003$

|Vub| calculation

$$\left|V_{ub}\right| = (3.07 \pm 0.12) \times 10^{-3} \times \left[\frac{\mathbf{B}(B \to X_u \ell \nu)}{0.001}\right]^{\frac{1}{2}} \times \left(\frac{1.6\ \mathrm{ps}}{\tau_B}\right)^{\frac{1}{2}}$$

(Hoang, Ligeti, Manohar; Uraltsev)

- Results:

Momentum Interval (GeV/c)	$V_{ub}(10^{-3})$
$2.0 \le p_\ell < 2.6$	$3.87 \pm 0.83 \pm 0.35 \pm 0.15 \pm 0.12$
$2.1 \le p_\ell < 2.6$	$3.95 \pm 0.46 \pm 0.40 \pm 0.16 \pm 0.16$
$2.2 \le p_\ell < 2.6$	$4.08 \pm 0.34 \pm 0.44 \pm 0.16 \pm 0.24$
$2.3 \le p_\ell < 2.6$	$4.27 \pm 0.24 \pm 0.47 \pm 0.17 \pm 0.34$
$2.4 \le p_\ell < 2.6$	$4.05 \pm 0.28 \pm 0.45 \pm 0.16 \pm 0.45$

- Uncertainties:
  1. Endpoint yield
  2. f_u measurement
  3. $|V_{ub}|$ expression
  4. Theoretical assumptions
- Dominant error depends upon lower limit:
  - Near 2.0: $b \to c$ subtraction
  - Near 2.4: f_u extrapolation
- We quote 2.2-2.6 GeV/c result as best compromise

Conclusions

- We find:

$$|V_{ub}| = (4.08 \pm 0.63) \times 10^{-3}$$

- Consitent with previous measurements
- New approach eliminates reliance on modeling
- Overall error smaller and better-measured than previous measurements

- Result stable as lower momentum limit varied: