Semileptonic Branching Ratios and Moments

Giuseppe Della Ricca
University and INFN – Trieste, Italy

9th International Conference on B Physics at Hadron Machines
October 14-18, 2003 – Pittsburgh, PA, USA
Motivations

- semileptonic decays are
  - relatively simple theoretically at parton level
  - accessible experimentally
  - sensitive to quark couplings to $W^\pm$
    (i.e. CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$)
  - probe the dynamics of the decay
  - probe the impact of strong interactions

- two possible approaches
  - exclusive measurements
    - need form-factors to describe the transition of the B meson to a lighter one
  - inclusive measurements
    - need OPE and b-quark mass to extract $|V_{xb}|$ from the total rate
Target

in naïve spectator picture the process is analogous to muon decay

\[ \Gamma(b \rightarrow u\bar{\nu}, c\bar{\nu}) \approx \frac{G_F^2m_b^5}{192\pi^3}|V_{ub,cb}|^2 \Rightarrow f(\text{parameters}) \times |V_{ub,cb}|^2 \]

but QCD (perturbative and non-perturbative) corrections are needed to extract weak decay physics

comparison of results from different measurements provides a test of the consistency of OPE predictions and of underlying assumptions

use many different approaches/techniques

CKM’02 @ CERN
measurements of $|V_{ub}|$ and $|V_{cb}|$ provide stringent tests of the unitarity triangle
Outline

- exclusive measurements
  - $\text{BR}(B \to \rho \ell \nu)$ [BaBar]
  - $\text{BR}(B \to \pi \ell \nu)$, $\text{BR}(B \to \rho'' \ell \nu)$, $\text{BR}(B \to \omega \ell \nu)$ [BaBar, Belle, Cleo]
  - $\text{BR}(B \to D^* \ell \nu)$ [BaBar]
    - $\text{BR}(B \to \pi \ell \nu)$ [Cleo]
  - $\text{BR}(B \to D^{**0} \ell \nu X)$ [Opal]

- inclusive measurements
  - $\langle M_{X}^{n} \rangle, \langle E_{i}^{n} \rangle$ in $B \to X_{c} \ell \nu$ [BaBar, Cleo, Delphi]
  - $\text{BR}(B \to X_{u} \ell \nu)$ [BaBar]
  - $\Delta \text{BR}(B \to X_{u} \ell \nu)$ [Belle]

far too much interesting material to include in 20 min [apologies in advance]

my own selection of recent result
\[ \text{BR}(B^0 \rightarrow \rho^+e^-\nu) \] \[ \text{[1]} \]

- signal (ISGW2)
- crossfeed
- \( b \rightarrow ue \nu \) downfeed (ISGW2+DeFazio Neubert)
- \( b \rightarrow ce \nu \) (HQET + Goity Roberts)

**HILEP:**

\[ 2.3 < E_{\text{electron}} < 2.7 \text{ GeV} \]
(large continuum backgrounds)

**LOLEP:**

\[ 2.0 < E_{\text{electron}} < 2.3 \text{ GeV} \]
(large \( b \rightarrow ce \nu \) backgrounds)

\[ \Gamma(B^0 \rightarrow \rho^-e^+\nu) = 2 \Gamma(B^+ \rightarrow \rho^0e^+\nu) \]
\[ \Gamma(B^0 \rightarrow \pi^-e^+\nu) = 2 \Gamma(B^+ \rightarrow \pi^0e^+\nu) \]
\[ \Gamma(B^+ \rightarrow \rho^0e^+\nu) = \Gamma(B^+ \rightarrow \omega e^+\nu) \]

(isospin-constrained average of \( \rho^\pm \) and \( \rho^0 \))
\( \text{BR}(B^0 \rightarrow \rho^+ e^- \nu) \) \[2\]

- Extrapolate partial branching fraction to entire lepton-energy spectrum using five different form-factor calculations.

**Combined result** (unweighted mean):

\[
\text{BR} = (3.29 \pm 0.42 \pm 0.47 \pm 0.55) \times 10^{-4}
\]

**Theoretical error on the combined result:**

Full spread seen between the different form-factors.

- ISGW2:
  \[2.76 \pm 0.34 \pm 0.40\]

- Beyer/Melikhov:
  \[3.64 \pm 0.46 \pm 0.52\]

- UKQCD:
  \[3.34 \pm 0.42 \pm 0.48\]

- LCSR:
  \[3.86 \pm 0.50 \pm 0.56\]

- Ligeti/Wise:
  \[2.86 \pm 0.37 \pm 0.41\]

**Combined result:**

\[
\text{Combined} = 3.29 \pm 0.42 \pm 0.47 \pm 0.60
\]

PRL 90 (2003) 181801
**BR(B→π^0lν, "ρ^0"lν, ωlν)**

very high purity but small statistics
loose cuts: small model dependence

"ρ^0" : 0.65<\(m_{ππ}\)<0.95 GeV/c^2

\[
\begin{align*}
BR(B→π^0lν) &= (0.78 \pm 0.32 \pm 0.13 ) \times 10^{-4} \\
BR(B→"ρ^0"lν) &= (0.99 \pm 0.37 \pm 0.19 ) \times 10^{-4} \\
BR(B→ωlν) &= (2.20 \pm 0.92 \pm 0.57 ) \times 10^{-4}
\end{align*}
\]

new CLEO results: see next talk !

Giuseppe Della Ricca – Semileptonic BRs and Moments
$B \rightarrow D^* \nu$: motivations

$B \rightarrow D^* \nu$ represents 10% (5% e + 5% $\mu$ channel) of the total $B^0$ decays, so a precise understanding of this decay improves the overall knowledge of the $B$ branching ratios.

The study of the differential decay rate can be used to extract $|V_{cb}|$

$D^{*\pm} \rightarrow D^0 \pi^\pm$

$D^0 \rightarrow K\pi, K_s\pi\pi, K\pi\pi^0, K\pi\pi\pi$

$\delta M \ [= M(D^*)-M(D^0)]$ used to fit signal and background components (except $D^{**}$)

Data control samples are used to estimate the background components (72 samples)
Background characterization: fit to $\delta M [= M(D^*) - M(D^0)]$

- Continuum from data control samples
- Fake D* from fake leptons
- Uncorrelated from background samples
Separation of $D^{**}$ component

Once other backgrounds are estimated from the global fit, $B^0(+) \rightarrow D^*Xl_\nu$ events are separated using the angle between the $B^0$ and the $D^*l$ direction.

can be written as:

$$\cos \theta_{B^0,D^*l} = \frac{-(m_{B^0}^2 + m_{D^*l}^2 - 2 E_{B^0} E_{D^*l}) + m_{X\nu}^2}{2 |P_{B^0}| |P_{D^*l}|}$$

$m_{X\nu}^2 = 0$ if $B^0 \rightarrow D^*l_\nu$

$m_{X\nu}^2 > 0$ if $B^0(+) \rightarrow D^*Xl_\nu$

$D^{**}$ shape different from the $D^*$ one fitted in each $D^0$ mode and $e/\mu$ subsample
Results for $BR(B \to D^* l \nu)$

$BR(B^0 \to D^* l^+ \nu) = (4.69 \pm 0.02_{\text{stat.data}} \pm 0.02_{\text{stat.MC}} \pm 0.24_{\text{syst.data}} \%)$

comparison with other results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>$5.75 \pm 0.26 \pm 0.36$</td>
</tr>
<tr>
<td>OPAL (excl)</td>
<td>$5.44 \pm 0.19 \pm 0.41$</td>
</tr>
<tr>
<td>OPAL (partial reco)</td>
<td>$6.15 \pm 0.27 \pm 0.58$</td>
</tr>
<tr>
<td>DELPHI (partial reco)</td>
<td>$5.02 \pm 0.13 \pm 0.36$</td>
</tr>
<tr>
<td>BELLE</td>
<td>$4.78 \pm 0.23 \pm 0.43$</td>
</tr>
<tr>
<td>CLEO</td>
<td>$6.25 \pm 0.19 \pm 0.39$</td>
</tr>
<tr>
<td>DELPHI (excl)</td>
<td>$5.70 \pm 0.20 \pm 0.41$</td>
</tr>
<tr>
<td>BABAR</td>
<td>$4.68 \pm 0.03 \pm 0.28$</td>
</tr>
<tr>
<td>Average</td>
<td>$5.20 \pm 0.19$</td>
</tr>
</tbody>
</table>

$\chi^2$/dof = 17.0/7 (CL = 1.8%)
Orbitally excited D mesons ($D^{**}$)

- $D^{**0}$ are $L=1$ orbitally excited charm mesons
  - narrow $J_q = 3/2, J^p=1^+,2^+$ states ($D_1^0, D_2^{*0}$)
  - wide $J_q = 1/2, J^p=0^+,1^+$ states (not visible with statistics)

motivation

- investigate the difference between measured inclusive and exclusive semileptonic branching ratios
- reduce uncertainty in $|V_{cb}|$
- test HQET predictions
Method

- identify high $p$ lepton ($\mu, e$)
  - high efficiency and purity for $p_{\mu} > 3$ GeV/c, $p_{e} > 2$ GeV/c
- exclusively reconstruct $D^{**0}$
  - $D^{**0} \rightarrow D^+ \pi^{**-}$
  - $D^0 \pi^+_{\text{slow}}$
  - $K^-\pi^+(\pi^+ \pi^-)$
- background cuts to remove fake $\pi^{**-}$ ($\pi$ from fragmentation)
  - main background from $b \rightarrow D^{*0}\ell\nu\chi$ decays plus fake $\pi^{**-}$
  - ANN ($p, p_T, d0/\sigma_{d0}$) to select $\pi^{**-}$
**D****0**−**D****+** mass difference

combine $D^0 \rightarrow K\pi$ and $K3\pi$ channels to reduce uncertainty due to background

unbinned ML fit to determine number of $D_1$ and $D_2^*$ events
(B.-W. ⊗ Gaussian)

$$\text{BR}(b \rightarrow \bar{B}) \times \text{BR}(\bar{B} \rightarrow D_1^0 \ell^+\nu X) \times \text{BR}(D_1^0 \rightarrow D^{**+}\pi) =$$

$$= (2.64 \pm 0.79\text{(stat)} \pm 0.39\text{(syst)}) \times 10^{-3}$$

$$\text{BR}(b \rightarrow \bar{B}) \times \text{BR}(\bar{B} \rightarrow D_2^{**0} \ell^+\nu X) \times \text{BR}(D_2^{**0} \rightarrow D^{**+}\pi) \leq 1.4 \times 10^{-3} \quad (95\% \text{ C.L.})$$

CERN-EP-2002-094
$B^0$ & $B^+$ semileptonic decays

Accurate, separate $BR_{sl}$ for $B^0$ & $B^+$, tagged by fully reconstructing one $B$

$BR(B^+ \rightarrow Xl\nu)/BR(B^0 \rightarrow Xl\nu)=1.14\pm0.04\pm0.01$

Preliminary

<table>
<thead>
<tr>
<th></th>
<th>$BR_{sl}(%)$</th>
<th>$\Gamma_{sl}(\text{ns}^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0$</td>
<td>10.32±0.32±0.29</td>
<td>67.0±2.8</td>
</tr>
<tr>
<td>$B^+$</td>
<td>11.77±0.26±0.32</td>
<td>71.1±2.5</td>
</tr>
<tr>
<td>$1/2(B^0+B^+)$</td>
<td>11.19±0.20±0.31</td>
<td>69.0±1.9</td>
</tr>
<tr>
<td>$Y(4S)$</td>
<td>10.89±0.24</td>
<td>67.7±1.8</td>
</tr>
</tbody>
</table>

$\Gamma_{sl}(B^+)/\Gamma_{sl}(B^0)=1.063\pm0.038$
Semileptonic B decays average BR_{sl}

on Y(4S), use high momentum lepton to tag flavor of 1\textsuperscript{st} B

CLEO

BR(B \rightarrow X e \nu) = (10.89 \pm 0.08\text{_{stat}} \pm 0.33\text{_{syst}})\%

preliminary, EPS'03 272

LEP (most recent EW fit) = (10.59 \pm 0.22)\% \rightarrow 10.76\% at Y(4S)
Parameters of HQE

Parameterization of decay rate in terms of Operator Product Expansion in HQET in powers of $\alpha_s(m_b)\beta_0$ and $\Lambda/m_B$:

$$\Gamma_{s\ell} = \frac{G_F V_{cb}^2}{192\pi^3} m_B^5 c_1 \{ 1 - c_2 \frac{\alpha_s}{\pi} m_p \lambda_1 (1 - c_4 \frac{\alpha_s}{\pi}) + c_5 \frac{\Lambda^2}{m_p^3} + \rho_1 \lambda_1 + \rho_2 \lambda_2 + \mathcal{O}(\frac{1}{m_p}) + \mathcal{O}(\frac{\alpha_s^2}{\pi}) \ldots \}$$

\(\bar{\Lambda}, \lambda_1, \lambda_2\), are non-perturbative parameters

- $\lambda_1$: (-) kinetic energy of the motion of the b-quark
- $\lambda_2$: chromo-magnetic coupling of b-quark spin to gluon (from $B^*-B$ mass difference, $\lambda_2 = 0.12$ GeV$^2$)
- $\bar{\Lambda} = m_B - m_b + (\lambda_1 - 3\lambda_2)/2m_B + \ldots$
  + additional parameters enter at higher orders ($\rho_1, \rho_2, \tau_1, \tau_2, \tau_3, \tau_4$)
  use theoretical estimates $-1/m_B^3$
OPE parameter extraction

first derivations of OPE parameters from spectral moments used the pole mass expansion and photon energy spectrum in $B \to X_{s\gamma}$, hadronic mass spectrum and lepton energy spectrum in $B \to X_{c\ell\nu}$

$$E_\gamma = \frac{m_B - \Lambda}{2} + \ldots$$

$$\frac{1}{m_B^2} \left( M_X^2 - m_D^2 \right) = M_0 + \frac{1}{m_B} M_1(\Lambda, \lambda_1, \lambda_2) + \ldots$$
Moments of lepton energy spectrum and hadronic mass spectrum in $Z\rightarrow b\bar{b}$ events

$B_{d}^{0} \rightarrow D^{*+}\nu$ decays exclusively reconstructed in three channels: $D^{*+} \rightarrow D^{0}\pi^{-}$, $D^{0}\pi^{+}$, $D^{+}\pi^{-}$.

- $D^{*+}$ decays into $D^{0}\pi^{+}$, $D^{0}\pi^{-}$, $D^{0}\pi^{0}$.

First measurements of moments performed at LEP exploiting advantage of $Z^0$ kinematics.

- Good secondary vertex reconstruction and signal/background separation.
- $\Gamma_{bb} / \Gamma_{hadrons} \sim 22\%$.
- $E_{B} \sim 0.7 E_{beam} \sim 30$ GeV.
Hadronic mass spectrum in $B \rightarrow D^{**} l \nu$

$\Delta M = M(D^{(*)}\pi) - M(D^{(*)})$ distributions fitted including contributions of resonant (narrow, broad) and non resonant states, $D^{*}Xl\nu$ floating

$BR(B^0 \rightarrow D^{**} l \nu) = (2.7 \pm 0.7 \pm 0.2) \%$

DELPHI’03-28
Interpretations

moments of hadronic mass spectrum and of lepton energy spectrum are sensitive to the non-perturbative parameters of the Heavy Quark Expansion.

at order $1/m_b^2 \Rightarrow \bar{\Lambda}, \lambda_1, \lambda_2 \ (\lambda_2 \approx 0.12 \text{ GeV}^2)$, at order $1/m_b^3 \Rightarrow \rho_1, \rho_2, T_{1-4}$

two possible approaches:

1) pole mass expansions

$$M_n = f_n (\lambda_1, \bar{\Lambda}, \lambda_2, T_1, T_2, \ldots)$$

(Falk, Luke, Gambino)

2) running quark masses

$$M_n = f_n (\mu_{\pi}^2, m_b (1 \text{ GeV}), \mu_G^2, \rho_D^3, \rho_{LS}^3, \ldots)$$

(Bigi, Shifman, Uraltsev, Vainshtein)
Pole mass scheme

multi-parameter fit:

\[ \bar{\Lambda} = 0.542 \pm 0.065_{\text{fit}} \pm 0.090_{\text{sys}} \text{ GeV} \]
\[ \lambda_1 = -0.238 \pm 0.055_{\text{fit}} \pm 0.030_{\text{sys}} \text{ GeV}^2 \]
\[ \rho_1 = 0.030 \pm 0.028_{\text{fit}} \pm 0.010_{\text{sys}} \text{ GeV}^3 \]
\[ \rho_2 = 0.066 \pm 0.025_{\text{fit}} \pm 0.192_{\text{sys}} \text{ GeV}^3 \]

good consistency of all measurements \((\chi^2/\text{d.o.f.}=0.4)\)
results compatible with CLEO

similar results with \(m_b^{1S-\lambda_1}\) formalism applied to CLEO and DELPHI data
Non-perturbative parameter extraction

makes use of low scale running quark masses and does not rely on a $1/m_c$ expansion

$$M_n(E_l) = \left( \frac{m_b}{2} \right)^n \left( \phi_n(r) + a_n(r) \frac{\alpha_s}{\pi} + b_n(r) \frac{\mu}{m_b^2} + c_n(r) \frac{\mu_G^2}{m_b^2} + d_n(r) \frac{\rho_D^3}{m_b^3} + s_n(r) \frac{\rho_{LS}^3}{m_b^3} + \ldots \right)$$

$m_b(\mu), m_c(\mu)$ are independent parameters and two operators only contribute to $1/m_b^3$ corrections: $\rho_D^3, \rho_{LS}^3$

first applied to fit DELPHI data

- multi-parameter $\chi^2$ fit to first three moments of lepton energy spectra and hadronic mass spectra (higher moments used to get sensitivity to $1/m_b^3$ parameters)

- use expressions for non-truncated lepton spectra

- simultaneous use of leptonic and hadronic moments in order to leave enough free parameters in the fit

Kinetic mass scheme

4-parameter fit

input constraints:
\[ \mu_G^2 = 0.35 \pm 0.05 \text{ GeV}^2 \]
\[ \rho_{LS}^3 = -0.15 \pm 0.15 \text{ GeV}^3 \]
\[ m_c = 1.05 \pm 0.30 \text{ GeV} \]
\[ m_b = 4.57 \pm 0.10 \text{ GeV} \]

equivalent to that derived from \( E_\gamma \) in \( B \to X_s \gamma \)

\[ m_{b,\text{kin}} \left( 1 \text{ GeV} \right) = 4.570 \pm 0.082_{\text{fit}} \pm 0.010_{\text{sys}} \text{ GeV} \]
\[ m_{c,\text{kin}} \left( 1 \text{ GeV} \right) = 1.133 \pm 0.134_{\text{fit}} \pm 0.030_{\text{sys}} \text{ GeV} \]
\[ \mu_\pi^2 \left( 1 \text{ GeV} \right) = 0.382 \pm 0.070_{\text{fit}} \pm 0.030_{\text{sys}} \text{ GeV}^2 \]
\[ \rho_D^3 \left( 1 \text{ GeV} \right) = 0.089 \pm 0.039_{\text{fit}} \pm 0.010_{\text{sys}} \text{ GeV}^3 \]

good consistency of all measurements (\( \chi^2/d.o.f. = 0.9 \))

within present accuracy no need to introduce higher order terms to establish agreement with data
using ratios of truncated lepton spectra (Gremm et al. PRL77 20 ’96)

\[ R_0 = \frac{\int_{1.7 \text{ GeV}} \frac{d\Gamma_{\ell}}{dE_\ell} dE_\ell}{\int_{1.5 \text{ GeV}} d\Gamma_{\ell} dE_\ell} \]

\[ R_1 = \frac{\int_{1.5 \text{ GeV}} \frac{E_\ell d\Gamma_{\ell}}{dE_\ell} dE_\ell}{\int_{1.5 \text{ GeV}} d\Gamma_{\ell} dE_\ell} \]

\[ R_0 = 0.6187 \pm 0.0014 \pm 0.0016 \text{ GeV} \]

\[ R_1 = 1.7810 \pm 0.0007 \pm 0.0009 \text{ GeV} \]

\[ \bar{\Lambda} = 0.39 \pm 0.03_{\text{stat}} \pm 0.06_{\text{sys}} \pm 0.12_{\text{th}} \text{ GeV} \]

\[ \lambda_1 = -0.25 \pm 0.02_{\text{stat}} \pm 0.05_{\text{sys}} \pm 0.14_{\text{th}} \text{ GeV}^2 \]

parameters extracted from lepton spectra are in agreement with those extracted from $M_X^2$ and $E_\gamma$
Hadronic mass moments \[^1\]

measured \(\tilde{M}_X\) differs from true \(M_X\)

for each interval in \(M_X\), full detector simulation gives \(<M_X>\) and \(<M_X>\)

 calibration curves applied to data: no model dependence!

\(p_{\text{min}}\) dependence study

\(\tilde{M}_X \sim <M_X> \sim <M_X>_{\text{TRUE}}\)
**Hadronic mass moments** \([^2]\)

Fit OPE for \(\langle M_x^2 \rangle\) to data and extract the two leading HQE parameters \(\Lambda\) and \(\lambda_1\) (MS scheme) → all correlations taken into account

---

![Graph showing OPE fit and data points](image)

**Graph Details:**
- **OPE fit**: Red line
- **CLEO data**: Green square
- **BABAR data**: Blue circle
- **DELPHI data**: Yellow triangle

**Legend:**
- **OPE prediction using CLEO data only**
- **\(\langle M_x^2 \rangle\) and \(\langle E_\gamma \rangle\) from \(b \rightarrow s\gamma\)**

---

All hadron mass moments are consistent (overlap from bands and BABAR ellipse) but \(\Delta \chi^2 = 1\) contour does not overlap with \(\langle E_\gamma \rangle\) band from CLEO \(b \rightarrow s\gamma\)
Hadronic mass moments $[^3]$ 

extraction of $m_b^{1s}$, and $\lambda_1^{1s}$ from a fit to the HQE in the 1s mass scheme ($O(1/m_b^3)$ parameters are fixed in the fit)

$\Delta \chi^2 = 1$ contour of hadron moments and lepton moments do not overlap

indication for large $O(1/m_b^3)$ corrections, duality violation, or maybe even more ...?

\[
m_b^{1s} = 4.638 \pm 0.094_{\text{exp}} \pm 0.062_{\text{dim} \oplus \text{BLM}} \pm 0.065_{1/m_B^3} \text{ GeV}
\]
\[
\lambda_1 = -0.26 \pm 0.06_{\text{exp}} \pm 0.04_{\text{dim} \oplus \text{BLM}} \pm 0.04_{1/m_B^3} \text{ GeV}^2
\]

hep-ex/0307046
Hadronic mass moments

the neutrino 4-vector is inferred using the detector hermeticity

\[ \langle M_x^2 - M_D^2 \rangle_{E_l > 1.0 \text{ GeV}} = 0.456 \pm 0.014 \pm 0.045 \pm 0.109 (\text{GeV}/c^2)^2 \]

\[ \langle M_x^2 - M_D^2 \rangle_{E_l > 1.5 \text{ GeV}} = 0.293 \pm 0.012 \pm 0.033 \pm 0.048 (\text{GeV}/c^2)^4 \]

hep-ex/0307081
Summary

- Huge efforts/progress in this area!!
- Large theoretical progress over the last decade (HQET & OPE)
- Fully reconstructed B meson recoil tag, neutrino reconstruction
- Many complementary observables
- Inclusive studies yield crucial informations for Heavy Quark physics, even for exclusive decays
Start of Backup Slides
The BaBar detector

Čerenkov Detector (DIRC)
- 144 quartz bars
- 11000 PMTs

ElectroMagnetic Calorimeter
- 6580 CsI(Tl) crystals

Instrumented Flux Return
- Iron/RPCs (muon/neutral hadrons)

Drift CHamber
- 40 stereo layers

Silicon Vertex Tracker
- 5 layers, double sided strips

SVT: 97% efficiency, 15 µm z hit resolution (inner layers, \( \perp \) tracks)
SVT+DCH: \( \sigma(p_T)/p_T = 0.13\% \times p_T + 0.45\% \)
DIRC: \( K-\pi \) separation \( 4.2\sigma \) @ 3.0 GeV/c \( \rightarrow \) \( >3.0\sigma \) @ 4.0 GeV/c
EMC: \( \sigma_E/E = 2.3\% \times E^{-1/4} \pm 1.9\% \)
The BELLE detector

SC solenoid
1.5T

CsI(Tl)
16X₀

TOF counter

Aerogel Cherenkov cnt.
n=1.015~1.030

8 GeV e⁻

Central Drift Chamber
small cell +He/C₂H₅

Si vtx. detector
3 lyr. DSSD

µ / K_L detection
14/15 lyr. RPC+Fe

vtx \( \sigma_{xy,z} \sim 55 \mu m @1GeV \)
mom \( \sigma_{pt}/p_t=0.19p_t (+) 0.34 \% \)
E \( \sigma_E/E \sim 1.8\% @E=1GeV \)

PID: ACC+TOF+dE/dx(CDC)
\( \varepsilon \sim 90\%, \eta \sim 6\% \) up to 3GeV

e-id: \( \varepsilon > 90\%, \eta \sim 0.3\% (>1GeV) \)
µ-id: \( \varepsilon > 90\%, \eta < 2\% (>1GeV) \)
\[ \varepsilon = \text{efficiency, } \eta = \text{fake rate} \]
The CLEO detector
The DELPHI detector

Giuseppe Della Ricca – Semileptonic BRs and Moments
The OPAL detector

Hadron calorimeters and return yoke
Electromagnetic calorimeters
Muon detectors
Jet chamber
Vertex chamber
Microvertex detector
Z chambers
Forward detector
Silicon tungsten luminometer
Presampler
Time of flight detector
Solenoid and pressure vessel
Inclusive $b \to c l \nu$

- rather than focusing on one hadronic final state, sum over all states and compare to quark level calculation

\[ \sum_i \Gamma(B \to X_c^{(i)} l \nu) = \Gamma(b \to c l \nu) \]

- relies on assumption of quark-hadron duality

- constrain theory parameters and test consistency
Inclusive $BR(B \to X_c l^{-}\nu)}$ and $\tau_B$

\begin{itemize}
  \item \textbf{ARGUS} \quad 9.73 \pm 0.50 \pm 0.39
  \item \textbf{CLEO} \quad 10.58 \pm 0.17 \pm 0.42
  \item \textbf{BELLE} \quad 10.94 \pm 0.12 \pm 0.50
  \item \textbf{BABAR (breno)} \quad 10.40 \pm 0.50 \pm 0.46
  \item \textbf{BABAR} \quad 10.89 \pm 0.18 \pm 0.29
  \item \textbf{BELLE (breno)} \quad 11.19 \pm 0.20 \pm 0.31
  \item \textbf{Average} \quad 10.83 \pm 0.25
\end{itemize}

\begin{itemize}
  \item \textbf{Y(4S)} \quad BR(B \to X_c l^{-}\nu)} = (10.83 \pm 0.25) \times 10^{-2}
  \item $\tau_B = (1.598 \pm 0.01) \text{ ps}$
  \item $\Gamma_{B \to X_c l^{-}\nu)} = 0.446 (1 \pm 0.023 \pm 0.007) \times 10^{-10} \text{ MeV}$
\end{itemize}

\begin{itemize}
  \item \textbf{LEP} \quad BR(B \to X l^{-}\nu)} = (10.59 \pm 0.22) \times 10^{-2}
  \item BR(B \to X_u l^{-}\nu)} = (0.17 \pm 0.05) \times 10^{-2}
  \item \textbf{BR(B \to X_c l^{-}\nu)} = (10.42 \pm 0.26) \times 10^{-2}
  \item $\tau_b = (1.573 \pm 0.01) \text{ ps}$
  \item $\Gamma_{B \to X_c l^{-}\nu)} = 0.436 (1 \pm 0.022 \pm 0.014) \times 10^{-10} \text{ MeV}$
\end{itemize}

\textbf{word average} \quad $\Gamma_{B \to X_c l^{-}\nu)} = 0.441 (1 \pm 0.018) \times 10^{-10} \text{ MeV}$
Reconstruction and cuts

D*/D^0 are reconstructed in the following modes:

<table>
<thead>
<tr>
<th>decay mode</th>
<th>BR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D^*± → D^0π±</td>
<td>67.7 ± 0.5</td>
</tr>
<tr>
<td>D^0 → Kπ</td>
<td>3.80 ± 0.09</td>
</tr>
<tr>
<td>D^0 → K_sππ</td>
<td>2.96 ± 0.18</td>
</tr>
<tr>
<td>D^0 → Kππ0</td>
<td>13.1 ± 0.9</td>
</tr>
<tr>
<td>D^0 → Kπππ</td>
<td>7.46 ± 0.31</td>
</tr>
</tbody>
</table>
Moments of lepton energy spectrum and hadronic mass spectrum in $Z \to b\bar{b}$ events

large momentum of $b$-hadrons ($E_B \sim 30$ GeV) gives sensitivity to full lepton energy spectrum in $B$ rest frame: measure first, second and third moment

lepton spectrum in $B \to X_c \ell^- \nu$

B system reconstructed from lepton+neutrino+charm vertex
lepton boosted in $B$ rest frame
Results for $M_n$

$$<m^n_H> = p_D m^n_D + p_{D^*} m^n_{D^*} + (1-p_D-p_{D^*})<m^{n*}_{D^{**}}>$$

moments of the hadronic mass

$M_1 = <m^2_H - \overline{m}^2_D> = 0.647\pm0.046\pm0.093 \ (GeV/c^2)^2$

$M_2 = <(m^2_H - \overline{m}^2_D)^2> = 1.98\pm0.23\pm0.29 \ (GeV/c^2)^4$

$M_2' = <(m^2_H - <m^2_H>)^2> = 1.56\pm0.18\pm0.17 \ (GeV/c^2)^4$

$M_3' = <(m^2_H - <m^2_H>)^3> = 4.05\pm0.74\pm0.31 \ (GeV/c^2)^6$

moments of the lepton energy spectrum

$$<E_i^*> = 1.383\pm0.012\pm0.009 \ GeV$$

$$<(E_i^* - <E_i^*>)^2> = 0.192\pm0.005\pm0.008 \ GeV^2$$

$$<(E_i^* - <E_i^*>)^3> = -0.029\pm0.005\pm0.006 \ GeV^3$$
Lepton endpoint

from the partial branching ratio

\[ \Delta B(B \rightarrow X_u e \nu) = (0.152 \pm 0.014 \pm 0.014) \times 10^{-3} \]

with \( f_u \) from CLEO (\( b \rightarrow s \gamma \) measurement)

\[ f_u(\Delta p) = \frac{\Delta B}{B} = 0.074 \pm 0.014 \pm 0.009 \]

\[ B(B \rightarrow X_u e \nu) = (2.05 \pm 0.27_{\text{exp}} \pm 0.46_{f_u}) \times 10^{-3} \]
## Hadronic moments - info

### DELPHI '03

<table>
<thead>
<tr>
<th></th>
<th>( \Lambda )</th>
<th>( \lambda_1 )</th>
<th>( \lambda_2 )</th>
<th>( \rho_1 )</th>
<th>( \rho_2 )</th>
<th>( \tau_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0.647 ± 0.046 ± 0.093 GeV</td>
<td>0.14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>1.98 ± 0.23 ± 0.29 GeV</td>
<td>0.16</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2'</td>
<td>1.56 ± 0.18 ± 0.17 GeV</td>
<td>0.11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M3'</td>
<td>4.05 ± 0.74 ± 0.31 GeV</td>
<td>0.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>1.383 ± 0.012 ± 0.009 GeV</td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>0.192 ± 0.005 ± 0.008 GeV</td>
<td>0.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E3</td>
<td>-0.029 ± 0.006 ± 0.006 GeV</td>
<td>0.21</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### DELPHI '02

<table>
<thead>
<tr>
<th></th>
<th>( \Lambda )</th>
<th>( \lambda_1 )</th>
<th>( \lambda_2 )</th>
<th>( \rho_1 )</th>
<th>( \rho_2 )</th>
<th>( \tau_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0.534 ± 0.041 ± 0.074 GeV</td>
<td>0.14</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>1.508 ± 0.200 ± 0.230 GeV</td>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2'</td>
<td>1.226 ± 0.168 ± 0.162 GeV</td>
<td>0.12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M3'</td>
<td>2.970 ± 0.673 ± 0.478 GeV</td>
<td>0.16</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E1</td>
<td>1.383 ± 0.012 ± 0.009 GeV</td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>0.192 ± 0.005 ± 0.008 GeV</td>
<td>0.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E3</td>
<td>-0.029 ± 0.006 ± 0.006 GeV</td>
<td>0.21</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Hadronic moments

- \( \Lambda \)
- \( \lambda_1 \)
- \( \lambda_2 \)
- \( \rho_1 \)
- \( \rho_2 \)
- \( \tau_1 \)

### Systematic errors

- \( m_b \)
- \( m_c \)
- \( \mu_\pi^2 \)
- \( \mu_G^2 \)
- \( \rho_D \)
- \( \rho_{CS} \)
- \( \rho_{LS} \)
End of Backup Slides