Orbitally excited B mesons in Z decays

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on behalf of the L3 collaboration

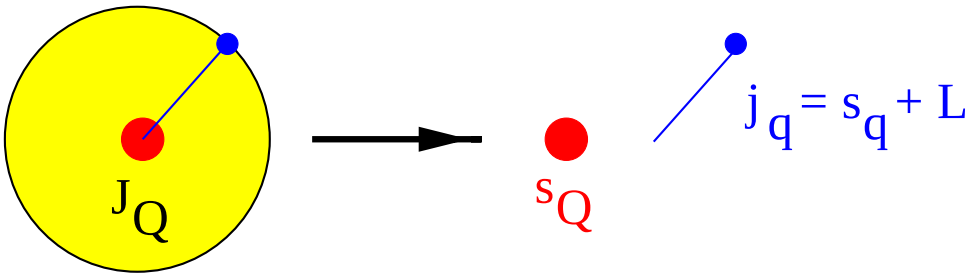
- **Motivation**
- $\mathrm{B}^{**} \to \mathrm{B}\pi$ **reconstruction**
- $\mathrm{B}\pi$ **Mass Fit**
- **Conclusions**

DPF'99

UCLA, 5-9 January 1999

Motivation

Heavy Quark Effective Theory



- **Heavy Quark Symmetry** at $\Lambda_{QCD}/m_Q \to 0$
  - Decoupling of heavy quark Q from light degrees of freedom

    $\Longrightarrow \vec{s}_Q$ *and* $\vec{j}_q = \vec{s}_q + \vec{L}$

    are conserved independently
  - Corrections $(1/m_Q, 1/m_Q^2)$ calculable

    Effective theory (HQET)
  - Best test by looking at B system

    ($m_c \sim 3\Lambda_{\text{QCD}}$ whereas $m_b > 10\Lambda_{\text{QCD}}$)

HQET Predictions

Spin counting

$$\vec{J} = \vec{s}_b \oplus \vec{j}_q$$

$L = 0$ states (B and B^*)

$$\vec{j}_q = \frac{1}{2} \oplus 0 \Longrightarrow \vec{J} = \frac{1}{2} \oplus \frac{1}{2}$$

$J^P = 1^-$	(3 B^* states)
$J^P = 0^-$	(1 B state)

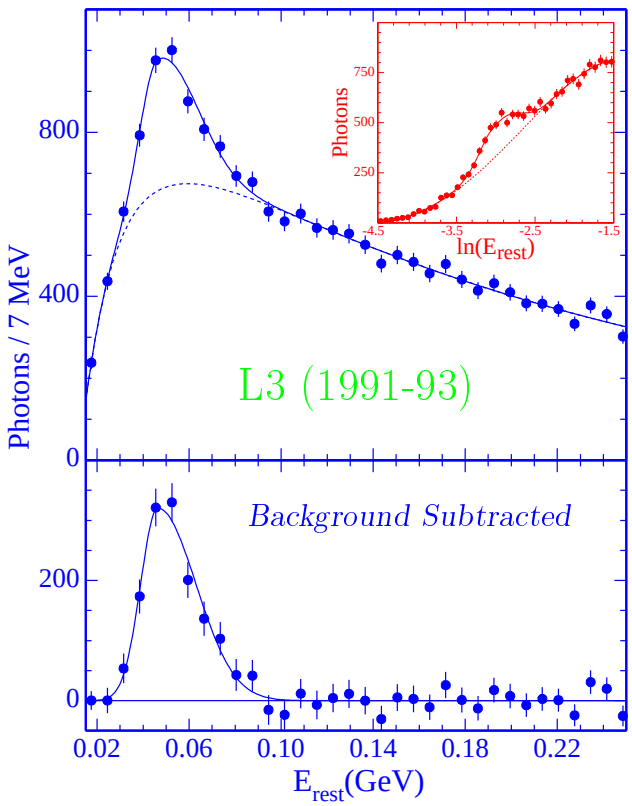
$$\Longrightarrow \text{expect } \frac{V}{(V+P)} = \frac{\sigma^*_{\mathrm{B}}}{(\sigma^*_{\mathrm{B}}+\sigma_{\mathrm{B}})} = \frac{3}{4}$$

$L = 1$ states (B^{**})

$$\vec{j}_q = \frac{1}{2} \oplus 1 \Longrightarrow \vec{J} = \frac{1}{2} \oplus \frac{1}{2} \quad \text{and} \quad \vec{J} = \frac{1}{2} \oplus \frac{3}{2}$$

$J^P = 2^+$	(5 B^*_2 states)
$J^P = 1^+$	(3 B_1 states)
$J^P = 1^+$	(3 B^*_1 states)
$J^P = 0^+$	(1 B^*_0 state)

B^* at LEP



$B^* \to B\gamma$

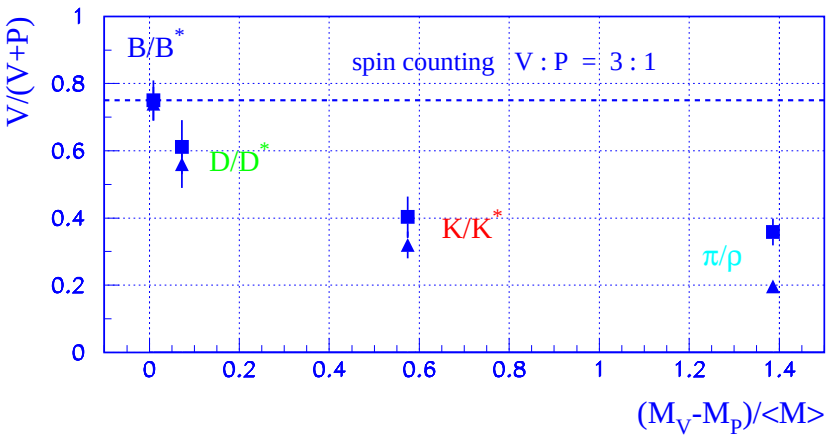
Measurements

by all 4 LEP

experiments

$$\frac{\sigma_{B^*}}{(\sigma_B + \sigma_{B^*})} = 0.75 \pm 0.04 \quad \text{(Combined LEP)}$$

$\Longrightarrow$ Spin counting works well in B system



compiled by C. Kreuter

HQET Predictions

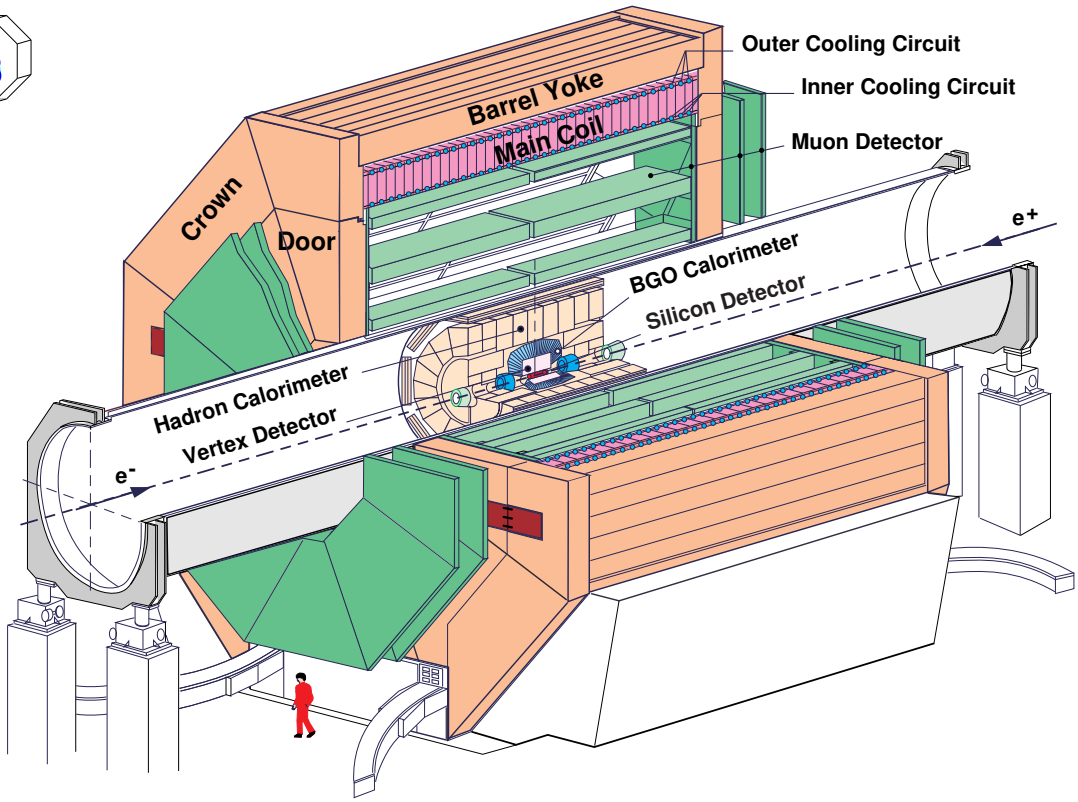
B^{**} Spectroscopy

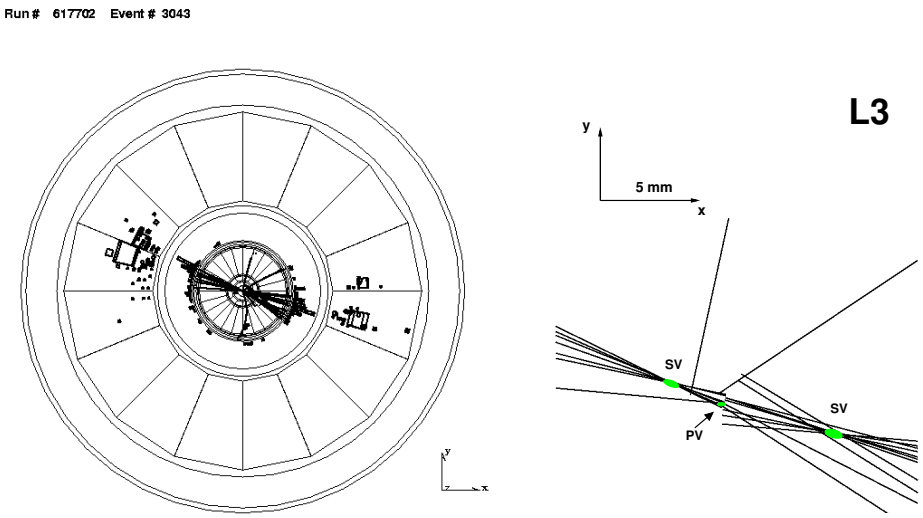
- Charm Measurements (masses and widths) are used to predict B system
- Predictions eg. (Eichten, Hill, Quigg - 1994)

J^P	Name	Mass [MeV]	Width [MeV]	Decay
2^+	B_2^*	5771	25	$\mathrm{B}\pi, \mathrm{B}^*\pi$
1^+	B_1	5759	21	$\mathrm{B}^*\pi$
1^+	B_1^*	$M_{\mathrm{B}_2^*} - 100$	~ 150	$\mathrm{B}^*\pi$
0^+	B_0^*	$M_{\mathrm{B}_1^*} - 12$	~ 150	$\mathrm{B}\pi$

- Other papers (Isgur, Ebert *et al.*) predict spin-orbit inversion, ie. $M_{\mathrm{B}_2^*} < M_{\mathrm{B}_1^*}$
- Production rate $f_{\mathrm{D}^{**}} = 20 - 40\%$
  Expect same for B system
- Spin-counting 5:3:3:1 predicted for relative production of B_2^*, B_1, B_1^*, B_0^*

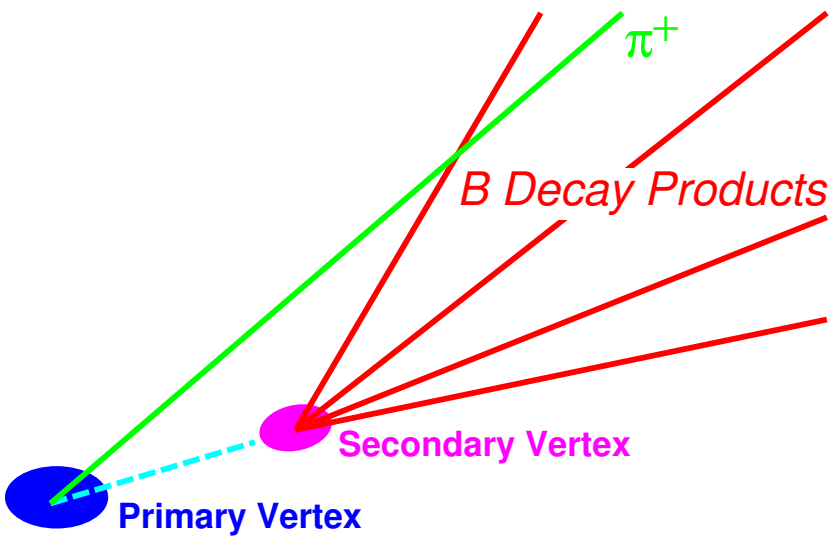
The L3 detector





$B^{**} \to B^{(*)}\pi$ Selection

$$B^{**} \to B^{(*)}\pi^+$$



- $Z \to b\bar{b}$ **Selection:** Lifetime based event tag
- B **Selection:** Energetic jet with with decay vertex: $l > 3\sigma_l$
- π^+ **Selection:** strong decay

  $\Rightarrow$ points to primary vertex.

  Small opening angle to B direction,

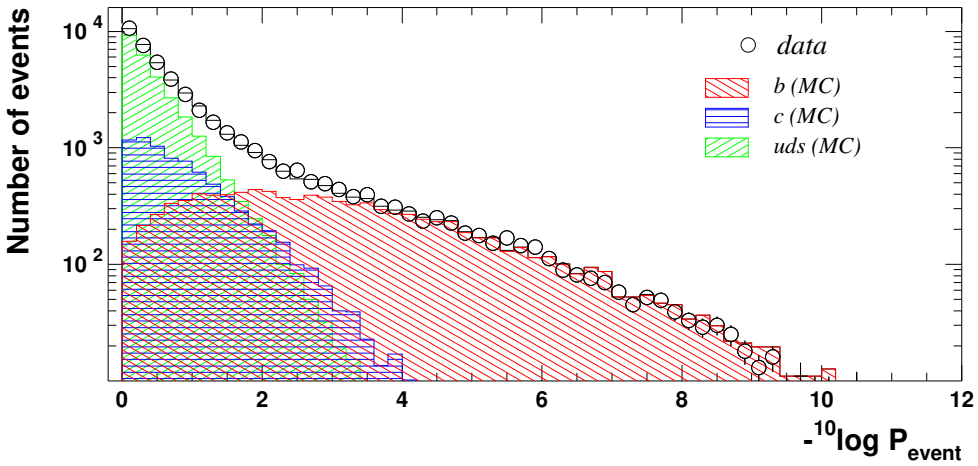
  $p \approx 2$ GeV

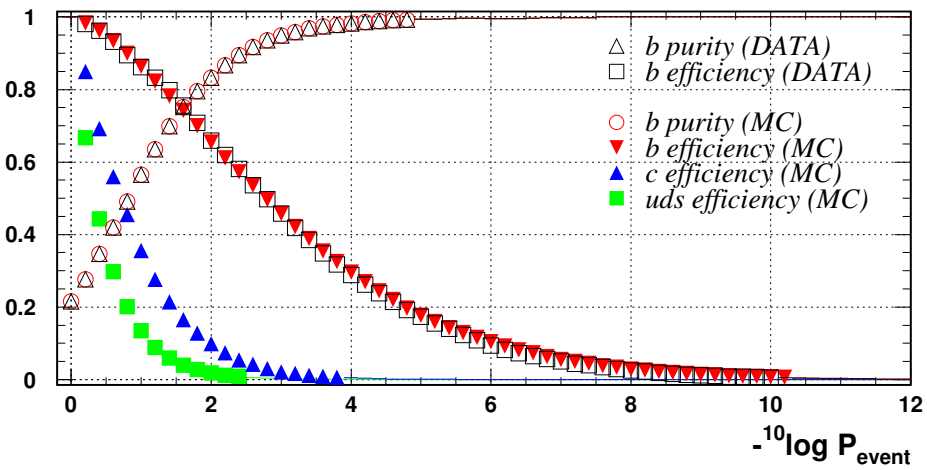
  $\Longrightarrow$ Select track with maximum p_L^B

$B^{**} \to B^{(*)}\pi$ Selection

Selection of $Z \to b\bar{b}$ events

Build discriminant variable with track decay lengths.





Cut : $-\,^{10}\log \mathrm{P}_{\mathrm{event}} > 2.2$

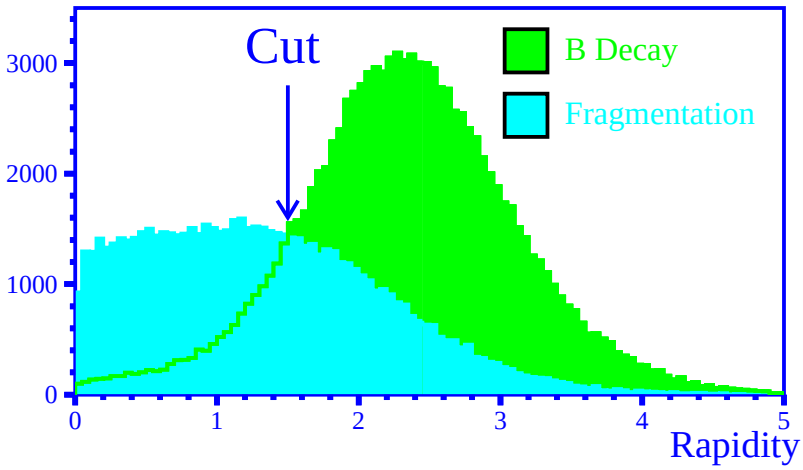
$176'980$ Data events

$\pi_b = 83\%$ $\epsilon_b = 65\%$

B Reconstruction

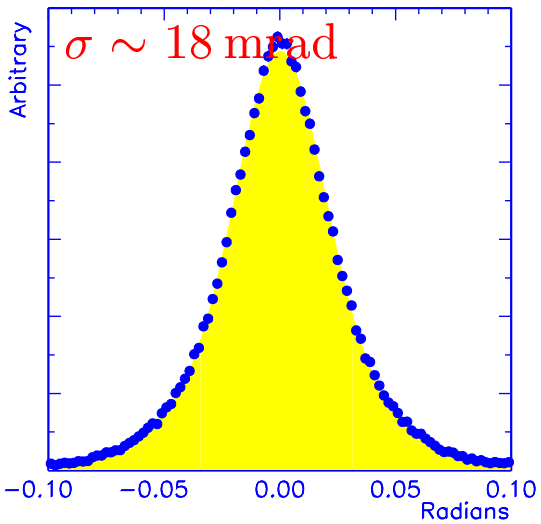
Inclusive B Reconstruction

- B decay products selected with rapidity

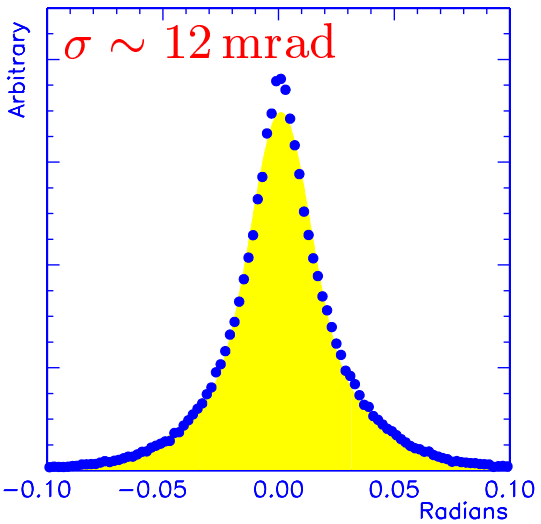


- B direction:

  Error-weighted average in θ and ϕ from decay vertex and high rapidity particles



$\theta_{\text{rec}} - \theta_{\text{gen}}$



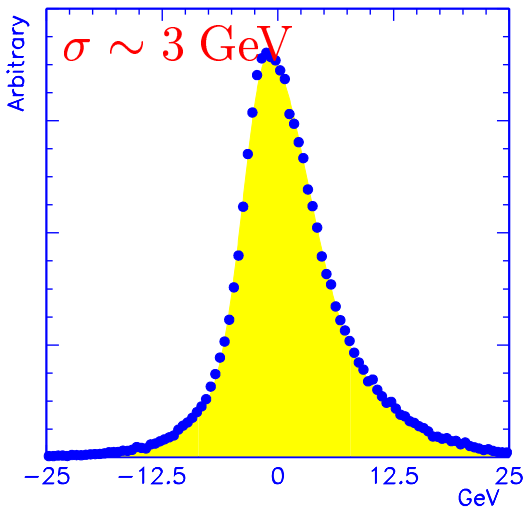
$\phi_{\text{rec}} - \phi_{\text{gen}}$

B Reconstruction

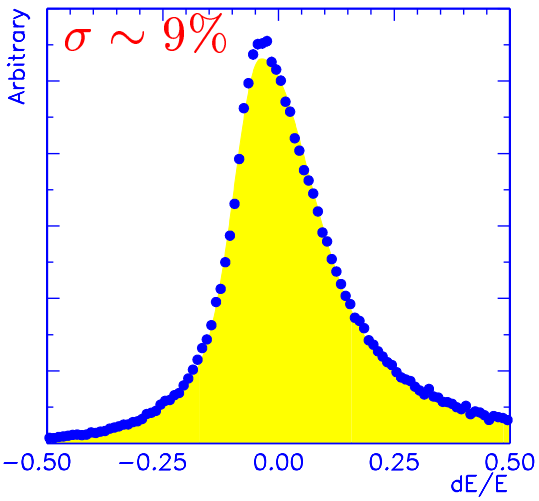
- B energy: use Beam Constraint

  Compute recoil mass with low rapidity particles

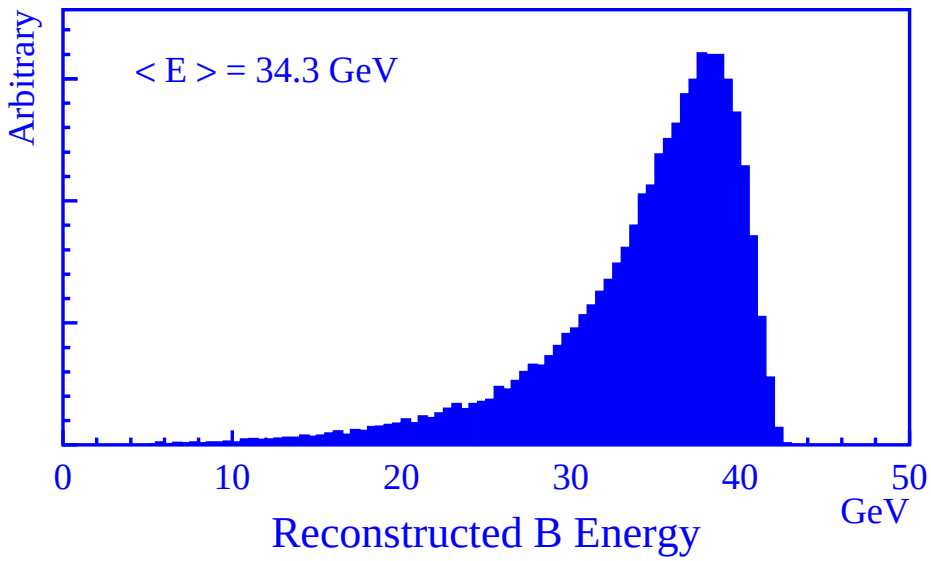
$$E_B = \frac{M_Z^2 + M_B^2 - M_{\text{recoil}}^2}{2M_Z}$$



$E_{\text{rec}} - E_{\text{gen}}$



$E_{\text{rec}} - E_{\text{gen}}/E_{\text{gen}}$

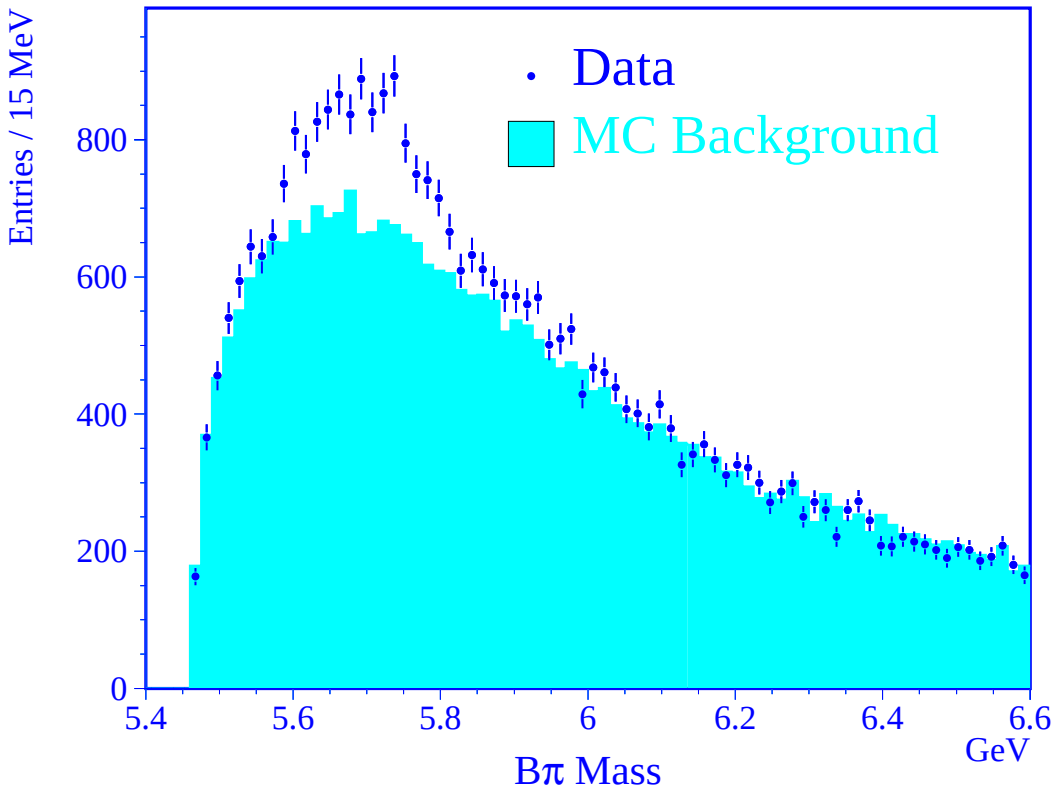


$B\pi$ Mass

Data Sample

Selection	Data 1994/95	b-purity
$Z \to q\bar{q}$	1'248'350 events	0.215
$Z \to b\bar{b}$ tag (3-dim)	176'980 events	0.828
π^+_{**} and sec. vertex	48'022 π-jet pairs	0.94

$B\pi$ Mass Spectrum



$$M_{B\pi} = \sqrt{M_B^2 + m_\pi^2 + 2E_B E_\pi - 2p_B p_\pi cos\alpha}$$

$B\pi$ Mass Fit

Fitting HQET Signal Shape

- HQET Predictions

(Eichten, Hill and Quigg *et al.* / Isgur, Ebert *et al.*)

j_q	Name	Mass [MeV]	Width [MeV]	Decay
$\frac{3}{2}$	B_2^*	5771 / 5733	25	$B\pi, B^*\pi$
$\frac{3}{2}$	B_1	5759 / 5719	21	$B^*\pi$
$\frac{1}{2}$	B_1^*	5671 / 5757	~ 150	$B^*\pi$
$\frac{1}{2}$	B_0^*	5669 / 5738	~ 150	$B\pi$

- 5 Breit-Wigners $\otimes$ Gaussian Resolution

Unfold $\sigma(M)$ from Monte Carlo

- HQET Constraints:

Spin counting: (5:3:3:1 for B_2^*: B_1: B_1^*: B_0^* rates)

$$M_{B_2^*} - M_{B_1} = 12\,\text{MeV}$$

$$M_{B_1^*} - M_{B_0^*} = 12\,\text{MeV}$$

$$\Gamma_{B_1} = \Gamma_{B_2^*}$$

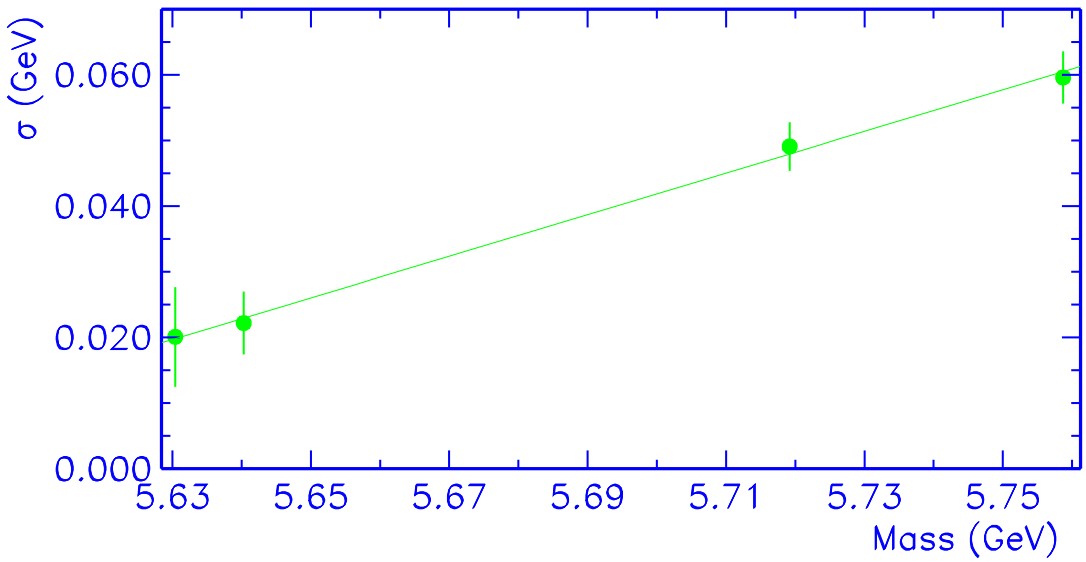
$$\Gamma_{B_0^*} = \Gamma_{B_1^*}$$

$\Longrightarrow$ **Measure** $f^{**}, M_{B_2^*}, \Gamma_{B_2^*}, M_{B_1^*}, \Gamma_{B_1^*}$

$B\pi$ Mass Fit

Resolution and efficiency functions

- Fit Several Simulated Decay Spectra
  - Breit-Wigner $\otimes$ Gaussian
  - Fix Γ to Γ_{gen}
  - Extract $\sigma(M)$ and $\epsilon(M)$

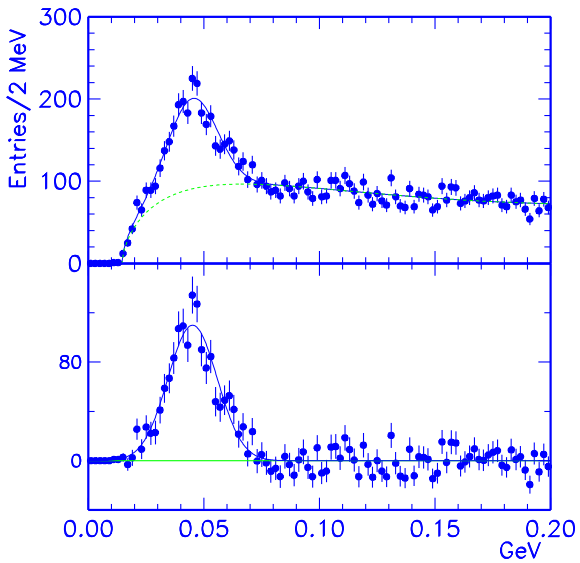


$$\sigma(M) = 0.448M - 2.496\ \text{GeV}$$
$$\epsilon(M) = 0.925M(\ \text{GeV}) - 4.307$$

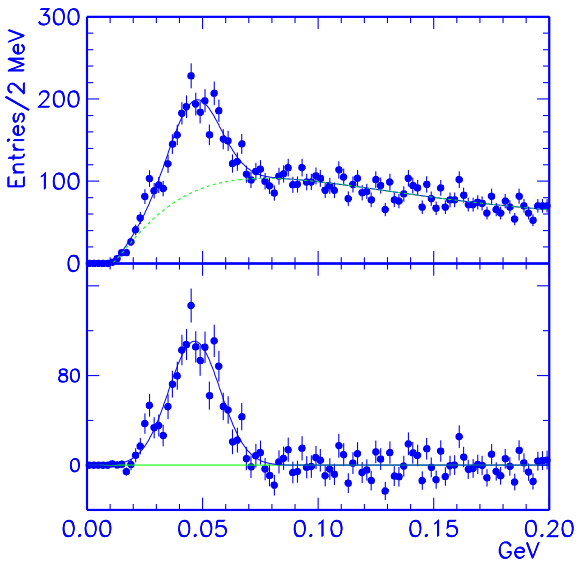
Cross Checks

Mass Resolution

- Mainly from B Reconstruction
- Same uncertainty as for $\mathrm{B}^* \to \mathrm{B}\gamma$ analysis



$M_{\mathrm{B}\gamma} - M_{\mathrm{B}}$ (Data)



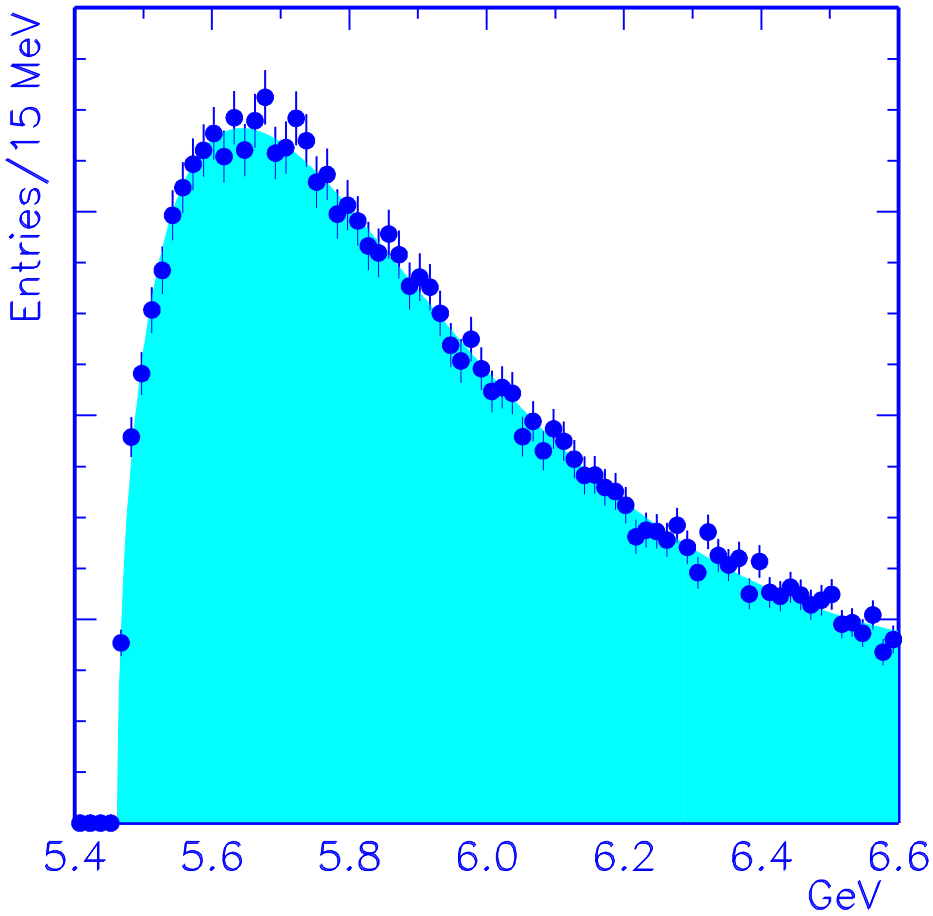
$M_{\mathrm{B}\gamma} - M_{\mathrm{B}}$ (MC)

Quantity	Monte Carlo	Data
$M_{\mathrm{B}^*} - M_{\mathrm{B}}$	(46.5 ± 0.6) MeV	(45.1 ± 0.6) MeV
$\sigma(\mathrm{B}^*)$	(11.1 ± 0.7) MeV	(10.7 ± 0.6) MeV

$B\pi$ Mass Fit

Background

Shape from Monte Carlo, normalisation from data.

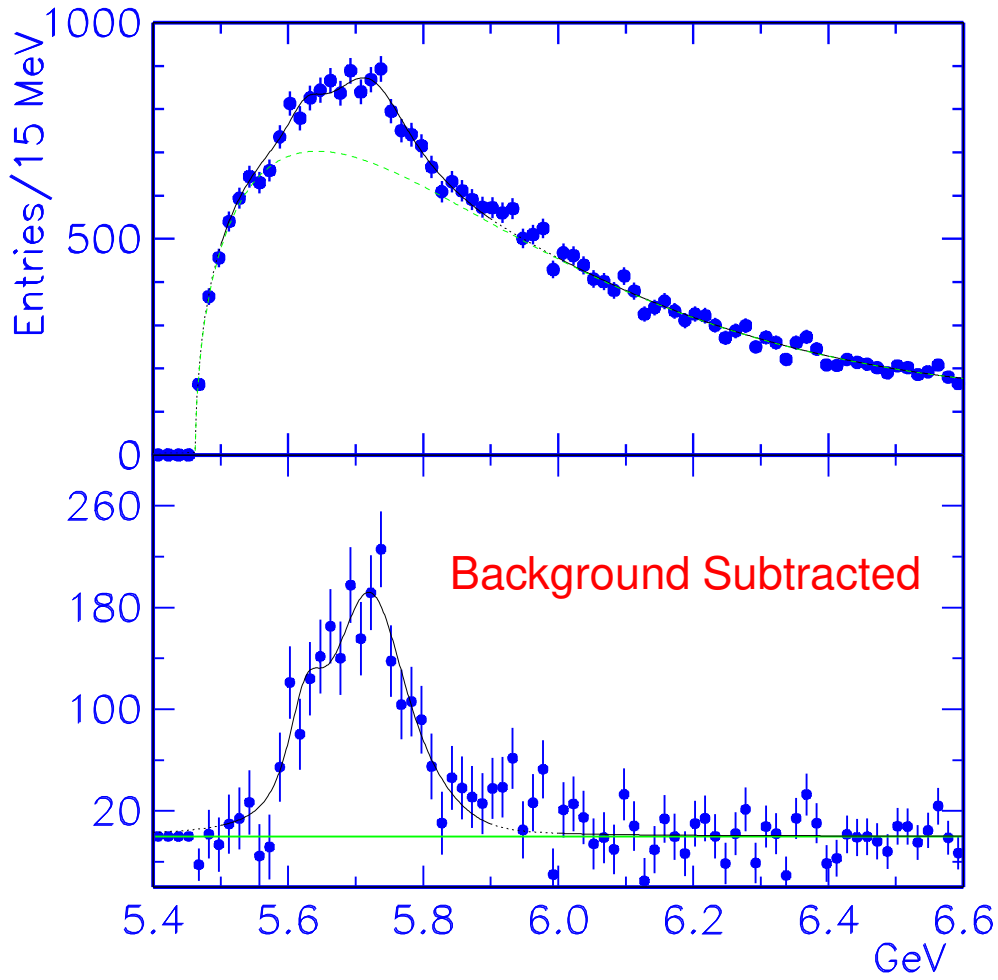


Fit 6 parameters Threshold Function:

$$p_1 \times (x - p_2)^{p_3} \times e^{(p_4 \times (x-p_2) + p_5 \times (x-p_2)^2) + p_6 \times (x-p_2)^3}$$

$B\pi$ Mass Fit

HQET Signal Shape



$N_{B^{**}}$	$= 2652 \pm 232$
$M_{B_2^*}$	$= 5770 \pm 6$ MeV
$\Gamma_{B_2^*}$	$= 21 \pm 24$ MeV
$M_{B_1^*}$	$= 5675 \pm 12$ MeV
$\Gamma_{B_1^*}$	$= 75 \pm 28$ MeV
$f_{B^{**}}$	$= 0.39 \pm 0.06$
$\chi^2/\text{DoF} = 39/74$	(prob $= 1.00$)

$\mathrm{B}\pi$ Mass Fit

Systematic Errors

Sources of Uncertainty	$\delta M_{\mathrm{B}_2^*}$	$\delta\Gamma_{\mathrm{B}_2^*}$	$\delta M_{\mathrm{B}_1^*}$	$\delta\Gamma_{\mathrm{B}_1^*}$	δf^{**}
b purity: $0.92 - 0.96$	—	—	—	—	± 0.02
$\mathrm{B}_{u,d}$ fraction: $0.74 - 0.83$	—	—	—	—	± 0.03
background modelling	± 2	± 9	± 3	± 9	± 0.05
signal resolution	± 2	± 9	± 1	± 9	± 0.01
signal efficiency	< 1	± 1	< 1	± 1	± 0.01
mass constraints: $6 - 18$ MeV	± 3	± 7	± 3	± 7	< 0.01
width constraints: $0.8 - 1$	< 1	± 2	< 1	± 2	< 0.01
Total	± 4	± 15	± 4	± 15	± 0.06

Results

This measurement yields:

$$
\begin{aligned}
M_{\mathrm{B}_2^*} &= (5770 \pm 6\ \textbf{(stat.)} \pm 4(\textbf{syst}))\ \mathrm{MeV} \\
\Gamma_{\mathrm{B}_2^*} &= (21 \pm 24\ \textbf{(stat.)} \pm 15(\textbf{syst}))\ \mathrm{MeV} \\
M_{\mathrm{B}_1^*} &= (5675 \pm 12\ \textbf{(stat.)} \pm 4(\textbf{syst}))\ \mathrm{MeV} \\
\Gamma_{\mathrm{B}_1^*} &= (75 \pm 28\ \textbf{(stat.)} \pm 15(\textbf{syst}))\ \mathrm{MeV} \\
f^{**} &= 0.39 \pm 0.06\ \textbf{(stat.)} \pm 0.06(\textbf{syst})
\end{aligned}
$$

- Consistent with HQET.
- Spin-Orbit inversion is not confirmed:
  $M_{\mathrm{B}_2^*} > M_{\mathrm{B}_1^*}$.
  - Constraint $M_{\mathrm{B}_2^*} \leq M_{\mathrm{B}_1^*}$ results in bad fit.
  - Disfavours predictions of Isgur, Ebert *et al.*.
  - Supports predictions of Eichten, Hill and Quigg.

Conclusions

- L3 measured the production of orbitally excited B mesons.
- The observed signal is consistent with HQET.
- The Masses and Widths of the states B_2^* and B_1^* were measured in the HQET framework.
- Spin-Orbit inversion is not supported.
- We measured the total B^{**} production rate $f^{**} = 0.39 \pm 0.06 \pm 0.06$ in the HQET framework.

Many thanks to my colleagues S.Goldfarb and F. Muheim!

Other LEP B^{**} measurements

Analysis	Measurement
OPAL Inclusive *(Vertex Charge)*	$M(\mathrm{B}^{**}_{u,d}) = (5681 \pm 11)\ \mathrm{MeV}$ $\mathrm{Br}(\bar{b} \to \mathrm{B}^{**0} \to \mathrm{B}^{(*)+}\pi^-)/\mathrm{Br}(\bar{b} \to \mathrm{B}^+)$ $= 0.18 \pm 0.01$ (stat.) ± 0.04(syst) $\Rightarrow f^{**} = 0.27 \pm 0.06$ (isospin)
DELPHI Inclusive *(Rapidity)*	$M(\mathrm{B}^{**}_{u,d}) = (5734 \pm 5$ (stat.) ± 17(syst)$)\ \mathrm{MeV}$ $\sigma(\Delta M) = (72 \pm 5$ (stat.) ± 8(syst)$)\ \mathrm{MeV}$ $\sigma_{\mathrm{B}^{**}_{u,d}}/\sigma_{b-\mathrm{jet}} = 0.26 \pm 0.015$ (stat.) ± 0.05(syst) $\Rightarrow f^{**} = 0.32 \pm 0.018$ (stat.) ± 0.06(syst)
ALEPH Inclusive *(Rapidity)*	$M_{\mathrm{B}\pi} - M_{\mathrm{B}} = (424 \pm 4$ (stat.) ± 10(syst)$)\ \mathrm{MeV}$ $\Rightarrow M(\mathrm{B}^{**}_{u,d}) = (5703 \pm 4$ (stat.) ± 10(syst)$)\ \mathrm{MeV}$ $\sigma(\Delta M) = (53 \pm 3$ (stat.) ± 9(syst)$)\ \mathrm{MeV}$ $f^{**} = 0.279 \pm 0.016$ (stat.) ± 0.059(syst) $^{+0.039}_{-0.056}$(model)
ALEPH Reconstructed	$M_{\mathrm{B}^*_2} = (5739\ ^{+8}_{-11}$ (stat.) $^{+6}_{-4}$(syst)$)\ \mathrm{MeV}$ $f^{**} = 0.31 \pm 0.09$ (stat.) $^{+0.06}_{-0.05}$(syst)