B and D Spectroscopy at LEP

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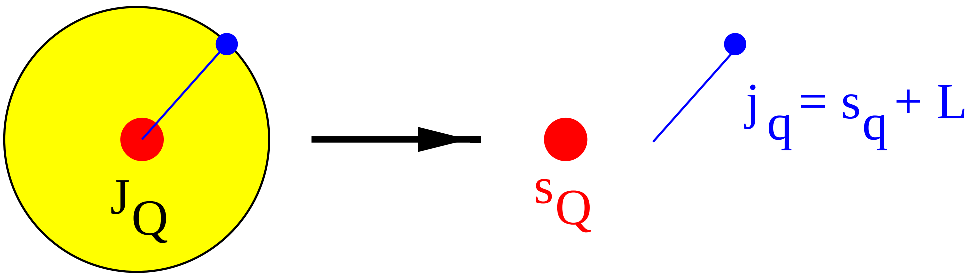
- ☞ **Introduction and Motivation**
- ☞ B^{**} **Spectroscopy**
- ☞ B_c^+ **Studies**
- ☞ D^{**} **Spectroscopy**
- ☞ $\mathrm{D}^{*'}$ **Studies**
- ☞ **Conclusions**

Acknowledgments: S.Goldfarb, O. Cooke, F. Simonetto

Fermilab, 12. Oct. 1988

HQET

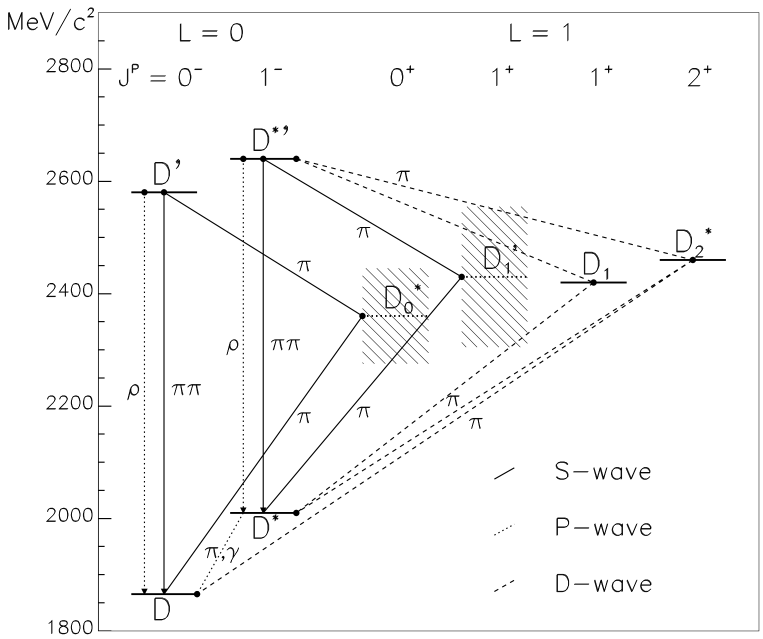
Heavy Quark Effective Theory



- **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* $\vec{j}_q = \vec{s}_q + \vec{L}$ *conserved independently*
- Corrections $(1/m_Q, 1/m_Q^2)$ calculable
  $\Longrightarrow$ **Effective theory (HQET)**
- Predictions expected to work better in B than in D system ($\Lambda_{\text{QCD}} < m_c < m_b$)

D Meson Spectroscopy

- Heavy quark spin $\vec{s}_Q$ and light quark $\vec{j}_q = \vec{s}_Q + \vec{L}$ are conserved separately $\Longrightarrow$ Doublets



- Ground states $L = 0$: $\quad \mathrm{D}$ and D^*

- Orbitally excited states $L = 1$:

  $L + s_Q \quad \mathrm{D}_1, \mathrm{D}_2^*$ narrow D wave

  $L - s_Q \quad \mathrm{D}_0^*, \mathrm{D}_1^*$ wide S wave

- 6 narrow $L = 1$ states $(c\bar{u}, c\bar{d}, c\bar{s})$ well established by ARGUS, CLEO, fixed Target, LEP

  wide $L = 1$ states hard to measure

HQET Predictions

B Meson Spectroscopy

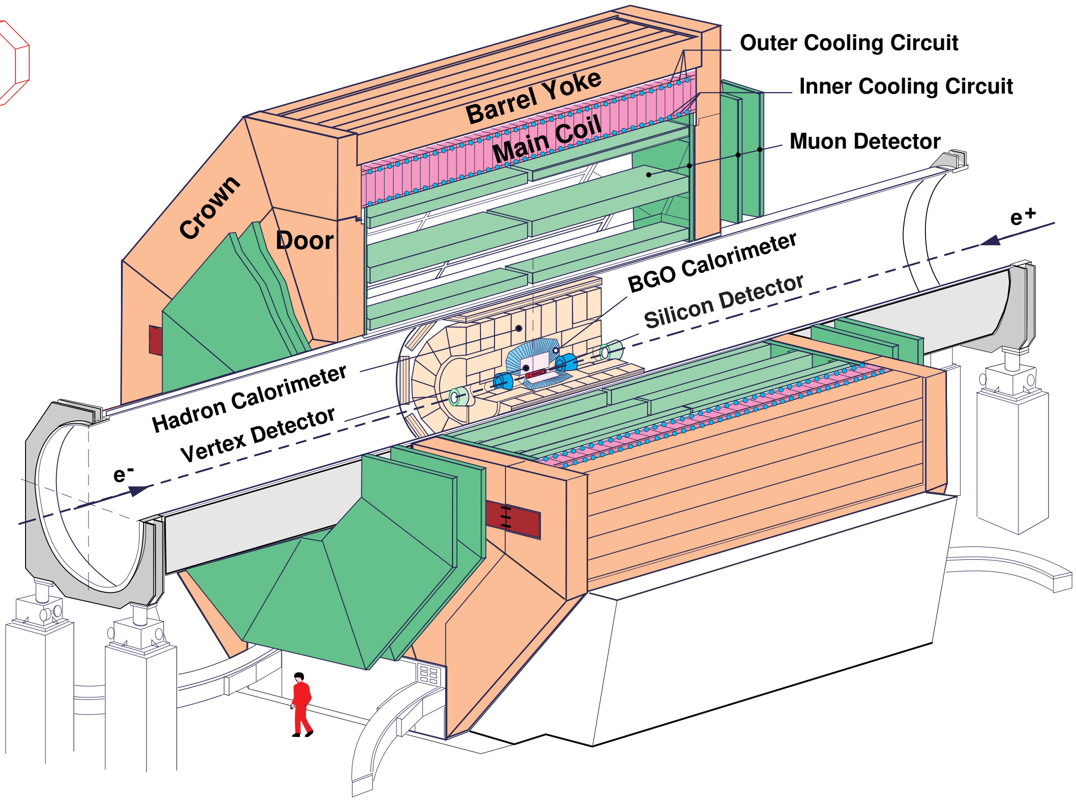
- Charm Measurements (masses and widths) are used to predict B system
- Predictions eg. (Eichten, Hill, Quigg - 1994)

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^*

LEP Detectors

ALEPH, DELPHI, L3 and OPAL

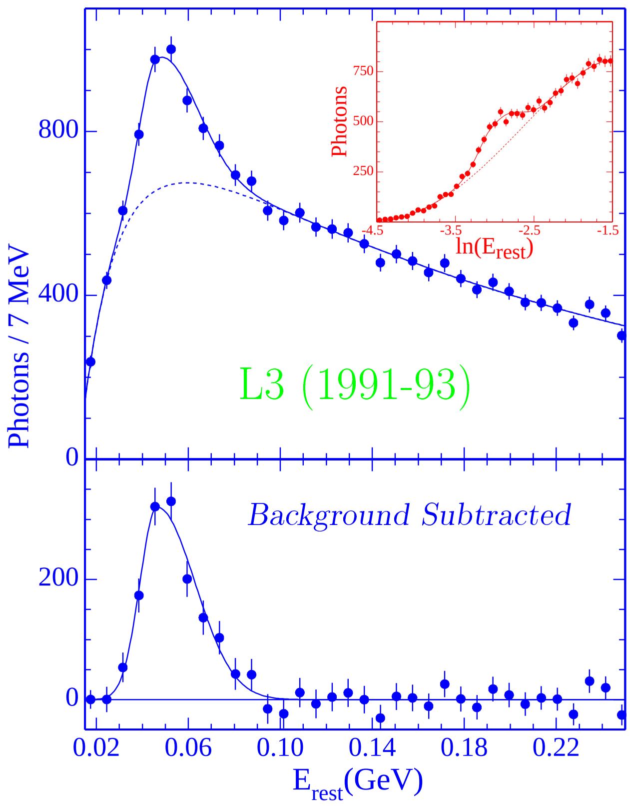


Data Sample

$$e^+e^- \to Z \to q\bar{q}$$
$$\to b\bar{b} \to B\bar{B}X$$

4×10^6 hadrons and 0.9×10^6 $B\bar{B}$ pairs per experiment

B^* at LEP



$B^* \to B\gamma$

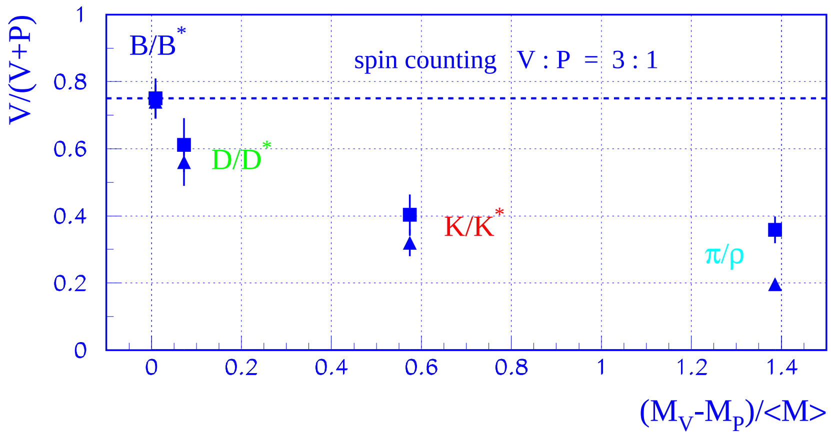
Measurements

by all 4 LEP

experiments

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

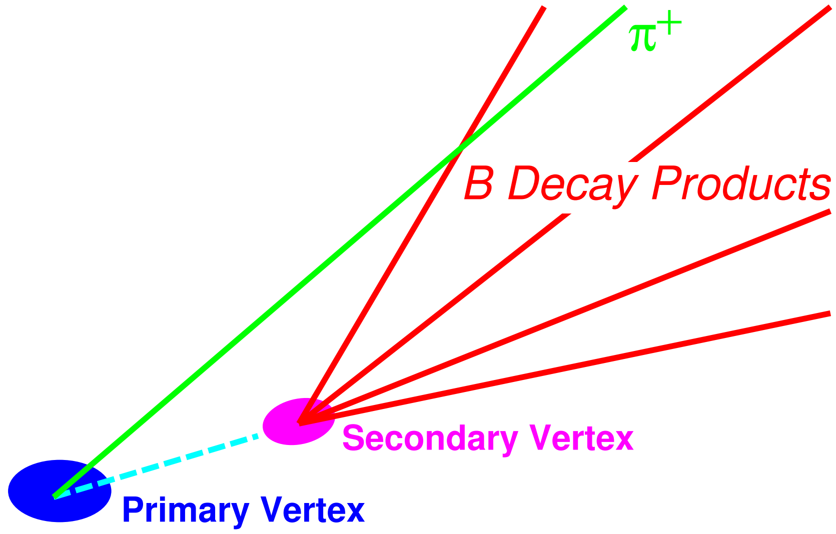
$\Longrightarrow$ Spin counting works well in B system



compiled by C. Kreuter

B^{**} Selection

$$\mathrm{B}^{**} \rightarrow \mathrm{B}^{(*)}\pi^{+}$$

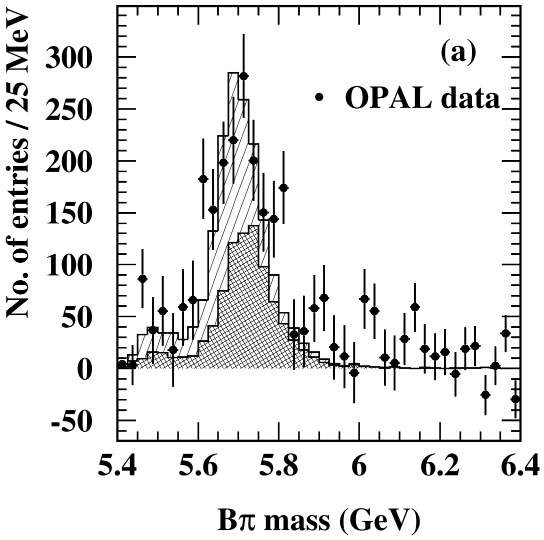


- $Z \rightarrow b\bar{b}$ **Selection:** Lifetime based event tag
- B **Reconstruction:** Inclusive (Vertex charge, Rapidity) or Exclusive Decays
- π^+ **Characteristics:** strong decay, points to primary vertex, small opening angle vs B direction, $p \approx 2$ GeV $\Longrightarrow p_L^{max}$

B^{**} at LEP

Inclusive Measurements

- OPAL vertex charge (Z. Phys. C 66 (1995) 19)



Background: wrong (like)-sign combinations

Signal: Single Breit-Wigner resonance

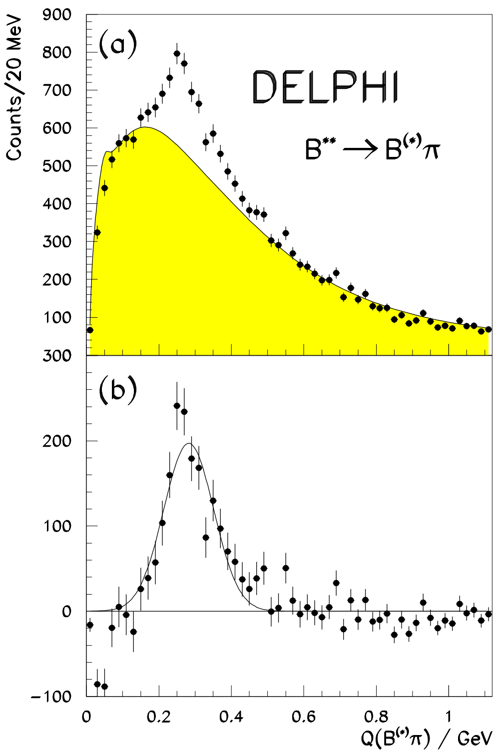
$1738 \pm 121\ \mathrm{B}^{(*)+}\pi^-$ and $149 \pm 30\ \mathrm{B}^{(*)+}\mathrm{K}^-$

Mass $M(\mathrm{B}^{**}_{u,d}) = 5681 \pm 11\ \mathrm{MeV}$

Production rate $f^{**} = 0.270 \pm 0.056$

B^{**} at LEP

- DELPHI (PLB 345(1995)598, EPS 1995)



B reconstruction:

rapidity

Background:

from Monte Carlo

Signal:

single Gaussian Fit

$$M(\mathrm{B}^{**}_{u,d}) = 5734 \pm 5 \pm 17\,\mathrm{MeV}$$
$$f^{**} = 0.32 \pm 0.018 \pm 0.06$$

- ALEPH

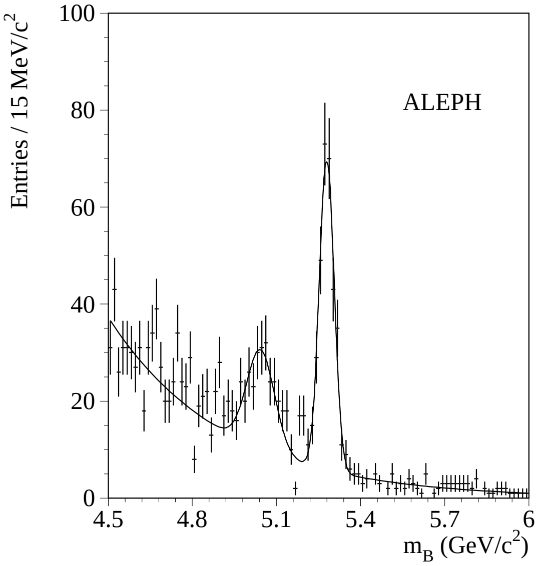
similar analysis (Z. Phys. C 69 (1996) 393)

$$M(\mathrm{B}^{**}_{u,d}) = 5703 \pm 4 \pm 10\,\mathrm{MeV}$$
$$f^{**} = 0.279 \pm 0.016 \pm 0.059\ {}^{+0.039}_{-0.056}$$

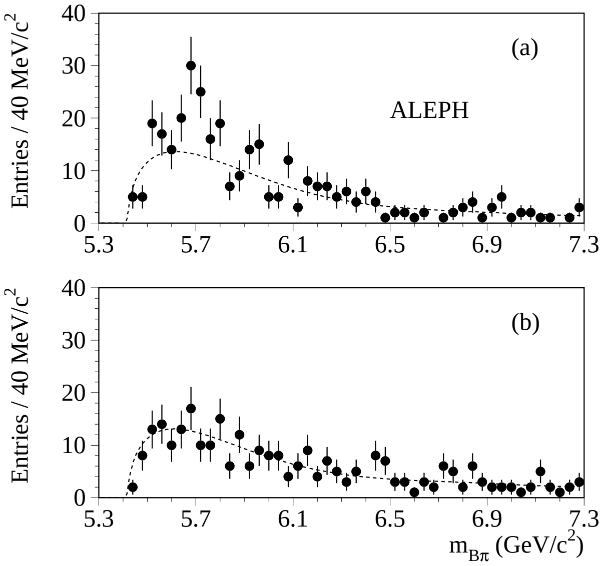
ALEPH B^{**}

Exclusive Measurement PLB 425 (1998) 215)

- Exclusive reconstruction of $\mathrm{B} \rightarrow \mathrm{D}^{(*)}X$, $X \in [\pi, \rho, a_1]$ and $\mathrm{B} \rightarrow J/\psi(\psi')K^{(*)}$



238 charged and 166 neutral B candidates (85 % purity)



$\mathrm{B}\pi$ mass distributions:

a) right-sign

b) wrong-sign

Excess events:

45 ± 13

ALEPH B^{**}

- Signal shape:

  5 Breit-Wigners assuming HQET predictions

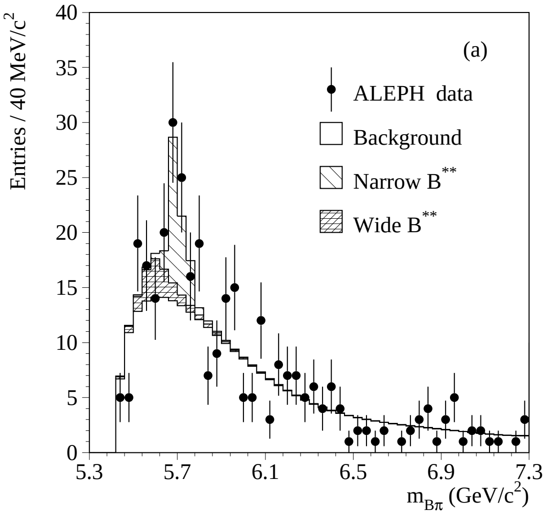
  for masses, widths, and production

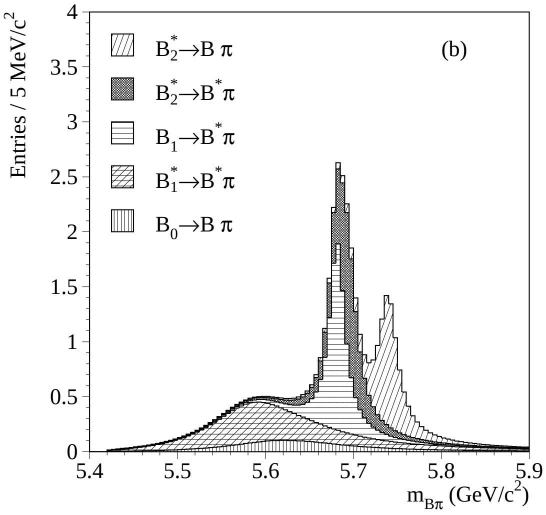
  $\Longrightarrow$ Fit for mass $M(\mathrm{B}_2^*)$ and rate f^{**}

- Background:

  high B mass sideband, Monte Carlo

  normalized to data above 6 GeV





$$M_{\mathrm{B}_2^*} = 5739 \,^{+8}_{-11}\,^{+6}_{-4}\ \mathrm{MeV}$$
$$f^{**} = 0.31 \pm 0.09 \,^{+0.06}_{-0.05}$$

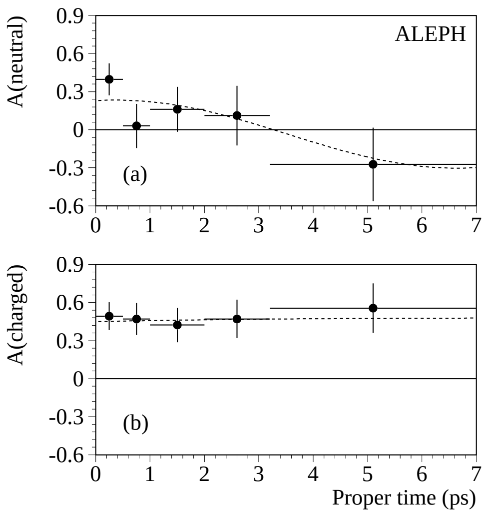
Tagging with B^{**}

Exclusive B^{**} from ALEPH

- Charge of prompt π tags b or $\bar{b}$ in $\mathrm{B}^{**} \to \mathrm{B}^{(*)}\pi^+$ decays

  $\Rightarrow$ Important for future CP violation studies

- Tagging efficiency: 89 %



Asymmetry between right-sign and wrong-sign tags vs B proper decay time for neutral and charged samples

- Mistag rate w from fit (Δm_d fixed)

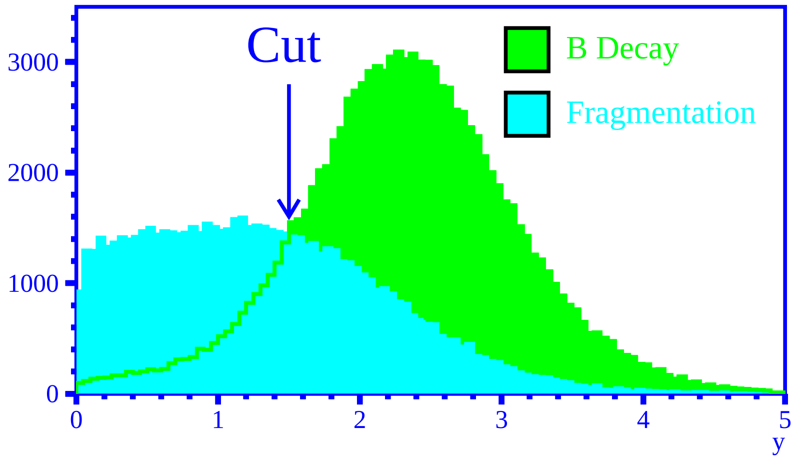
$$w(neutral) = 34.4 \pm 5.5 \pm 1.0\%$$
$$w(charged) = 26.0 \pm 3.6 \pm 0.7\%$$

- Difference due to strange quark fragmentation (limited π/K separation)

B^{**} from L3

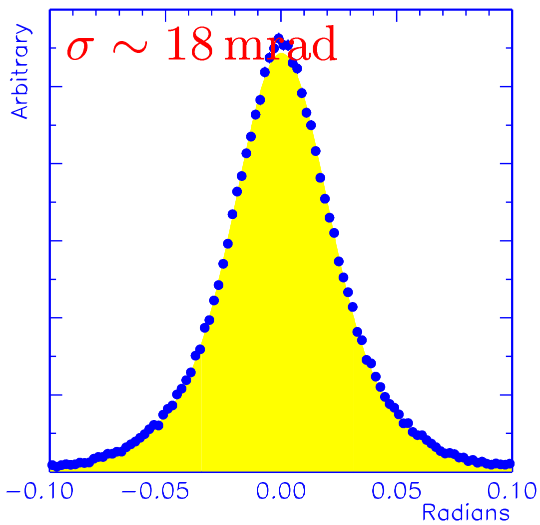
Inclusive B Reconstruction (ICHEP98)

- B decay products selected with rapidity

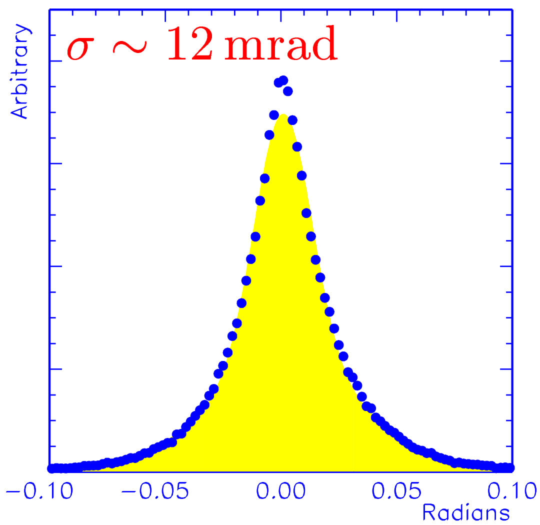


- B direction:

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



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



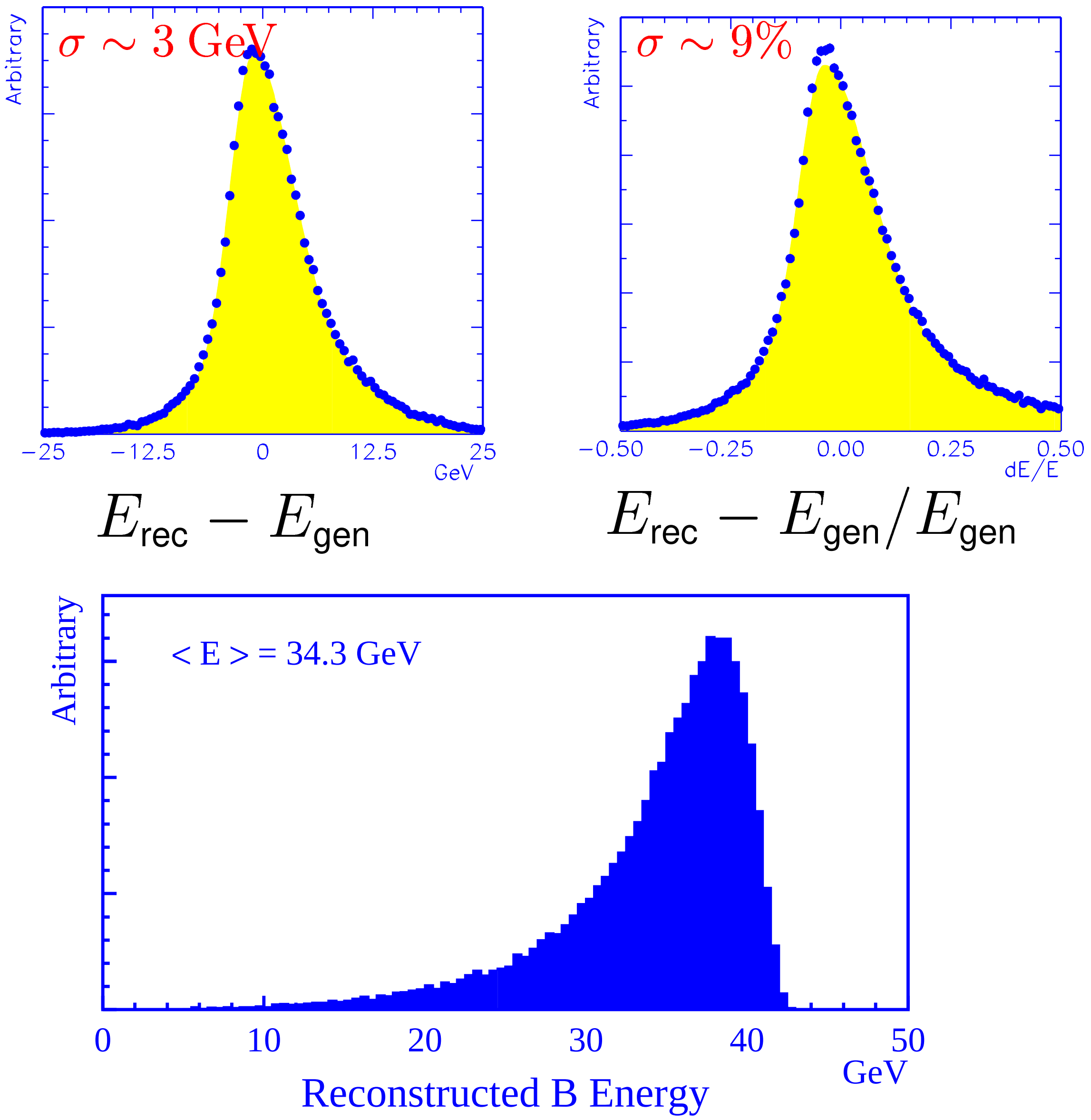
$\phi_{\text{rec}} - \phi_{\text{gen}}$

B^{**} from L3

- B energy:

Compute recoil mass with low rapidity particles

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

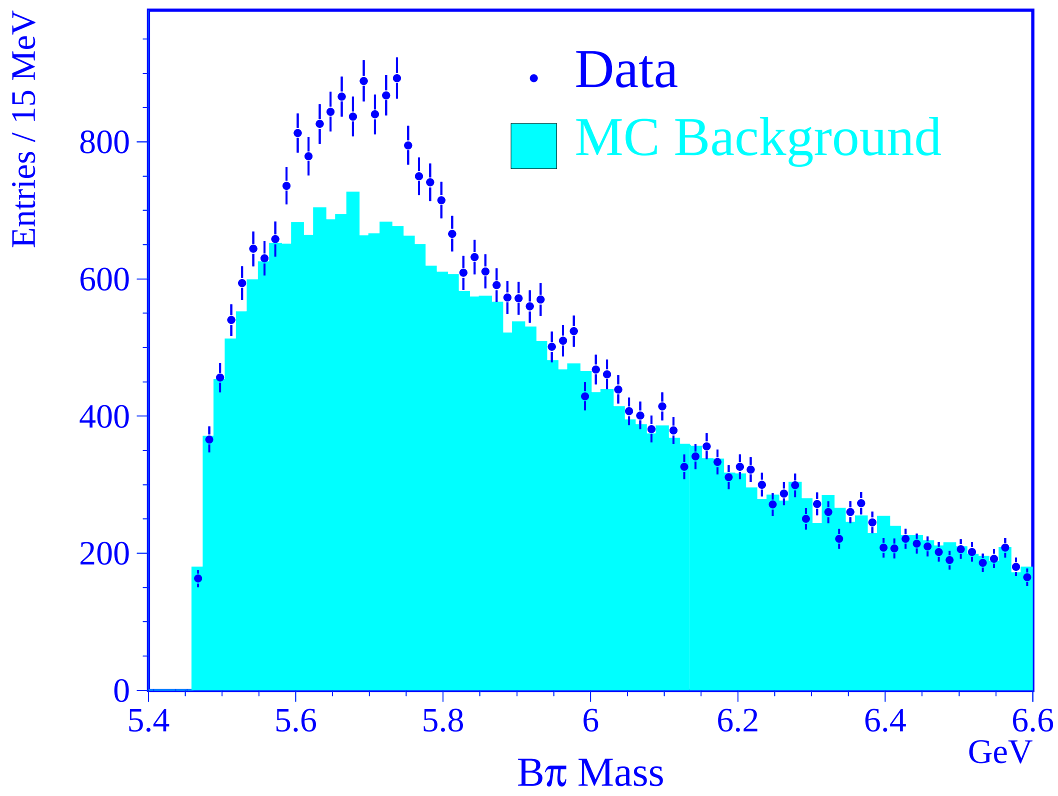


$B\pi$ Mass

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)	176980 events	0.828
π^+_{**} and sec. vertex	48,022 π-jet pairs	0.94

$B\pi$ Mass Spectrum



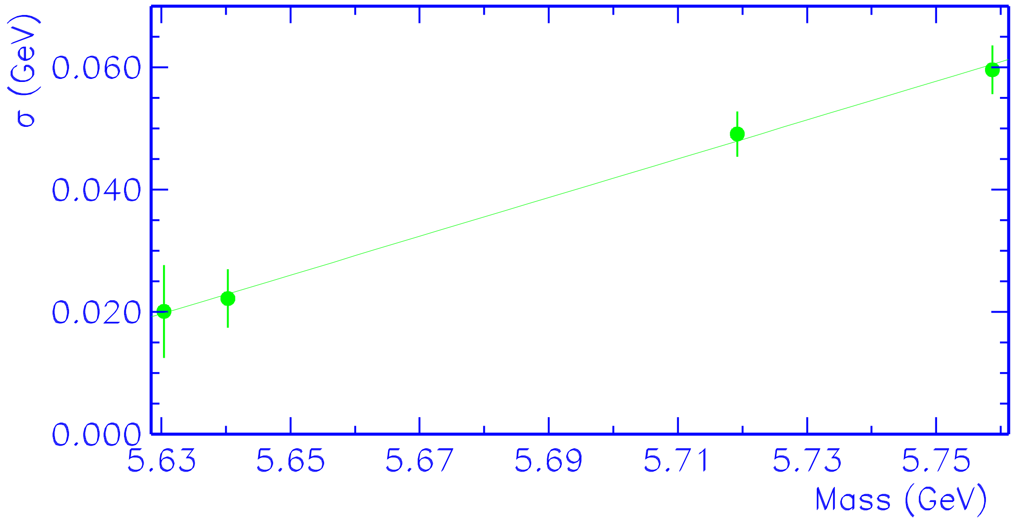
$$M_{B\pi} = \sqrt{M_B^2 + m_\pi^2 + 2E_B E_\pi - 2p_B p_\pi cos\alpha}$$

$B\pi$ Mass Fit

Signal Shape

- 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)

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

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

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

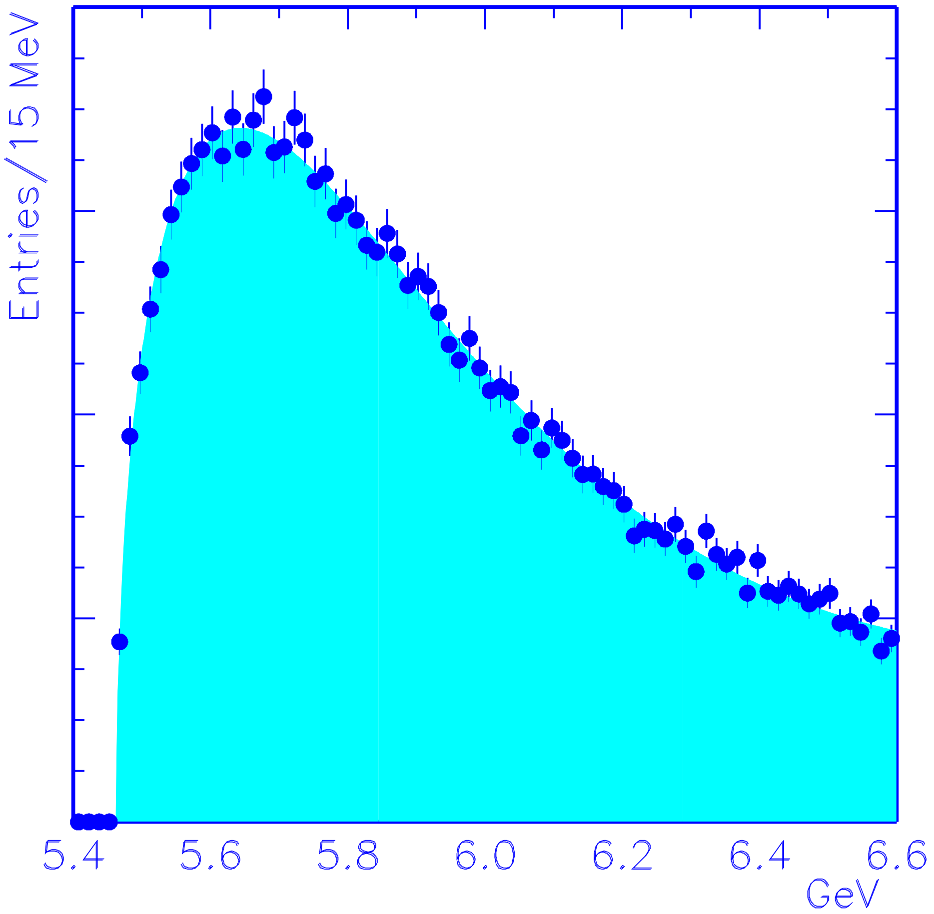
  $$\Gamma_{B_0^*} = \Gamma_{B_1^*}$$

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

$B\pi$ Mass Fit

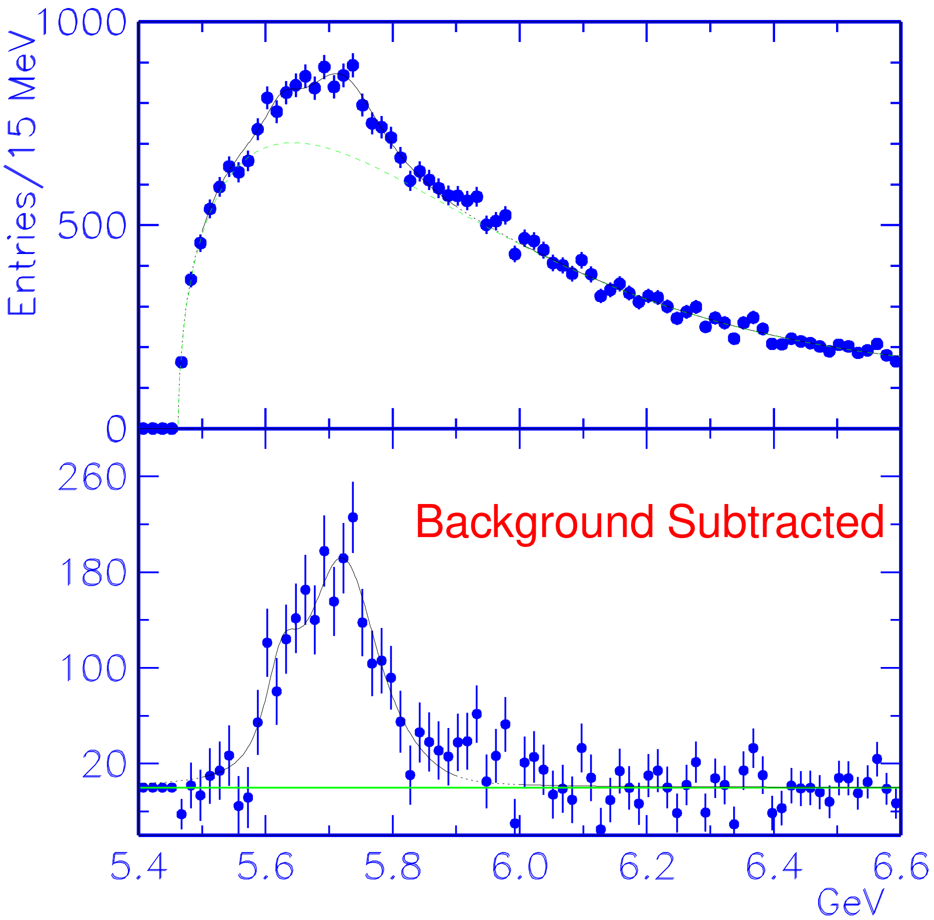
Background

- Threshold function: (6 parameters), shape from Monte Carlo, normalisation from data



$B\pi$ Mass Fit

HQET Signal Shape



$$N_{B^{**}} = 2652 \pm 232$$
$$M_{B_2^*} = 5770 \pm 6 \pm 4 \text{ MeV}$$
$$\Gamma_{B_2^*} = 21 \pm 24 \pm 15 \text{ MeV}$$
$$M_{B_1^*} = 5675 \pm 12 \pm 4 \text{ MeV}$$
$$\Gamma_{B_1^*} = 75 \pm 28 \pm 15 \text{ MeV}$$
$$f_{B^{**}} = 0.39 \pm 0.06 \pm 0.06$$

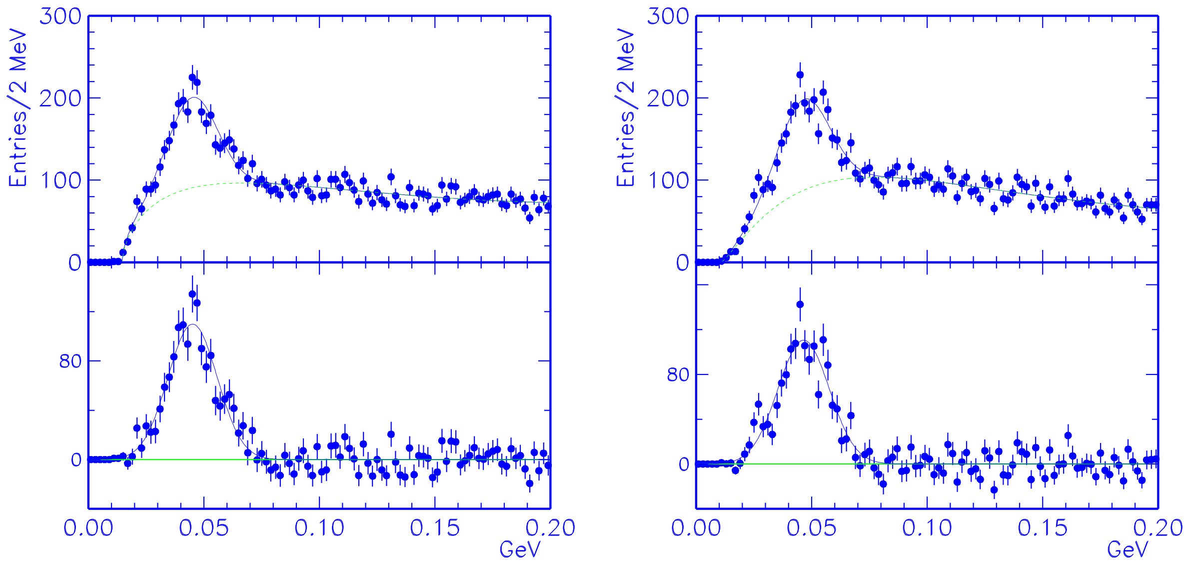
Systematic Errors

Sources of Uncertainty	$\delta M_{B_2^*}$	$\delta \Gamma_{B_2^*}$	$\delta M_{B_1^*}$	$\delta \Gamma_{B_1^*}$	δf^{**}
b purity: $0.92 - 0.96$	—	—	—	—	± 0.02
$B_{u,d}$ 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
state counting: $(1:1:1:1)$	$+13$	-26	$+3$	$+7$	-0.01
Total	± 4	± 15	± 4	± 15	± 0.06

Cross Checks

Mass Resolution

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

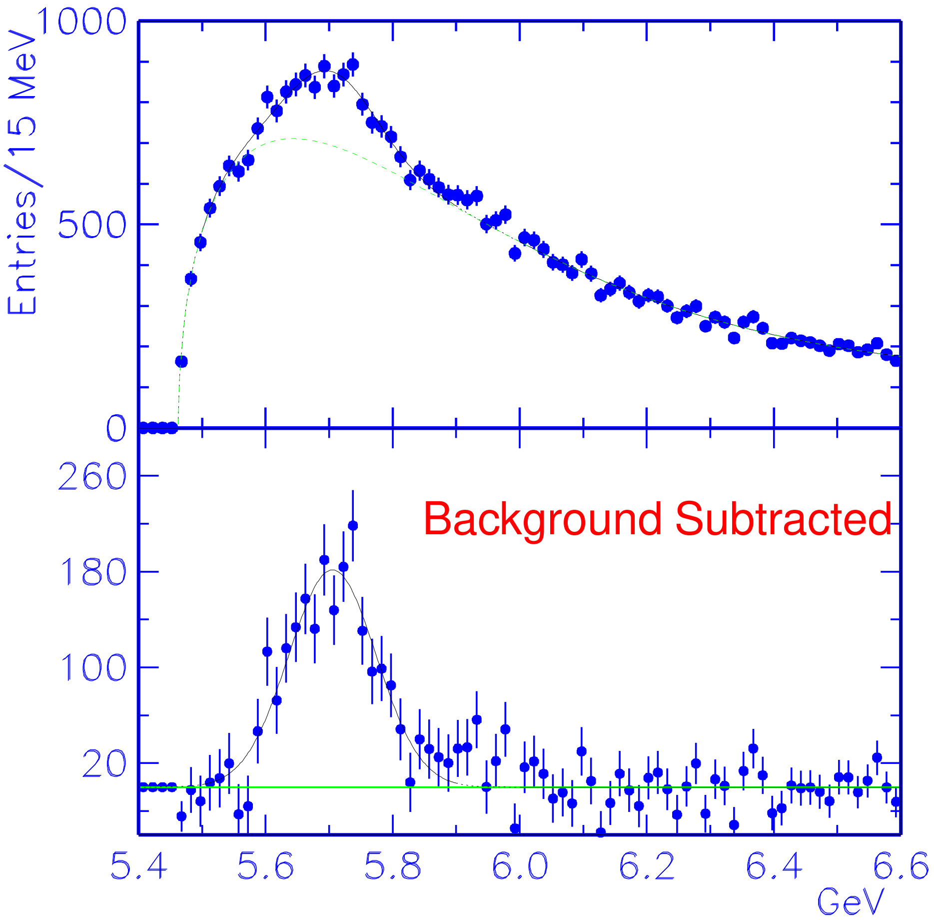


$M_{\mathrm{B}\gamma} - M_{\mathrm{B}}$ (Data) $M_{\mathrm{B}\gamma} - M_{\mathrm{B}}$ (MC)

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

Gaussian Signal Shape



$$\hat{M}_{\mathrm{B}^{**}} = (5705 \pm 5)\ \mathrm{MeV}$$

$$\hat{\sigma}_{\mathrm{B}^{**}} = (69 \pm 7)\ \mathrm{MeV}$$

$$N_{\mathrm{B}^{**}} = 2083 \pm 259$$

$$f_{\mathrm{B}^{**}} = 0.36 \pm 0.04$$

$\chi^2/\text{DoF} = 56/61 \quad (\text{prob} = 0.66)$

B^{**} Summary

- L3 measures $f^{**}, M_{B_2^*}, \Gamma_{B_2^*}, M_{B_1^*}, \Gamma_{B_1^*}$

$$\begin{array}{lcl} M_{B_2^*} & = & 5770 \pm 6 \pm 4\,\text{MeV} \\ \Gamma_{B_2^*} & = & 21 \pm 24 \pm 15\,\text{MeV} \\ M_{B_1^*} & = & 5675 \pm 12 \pm 4\,\text{MeV} \\ \Gamma_{B_1^*} & = & 75 \pm 28 \pm 15\,\text{MeV} \\ f_{B^{**}} & = & 0.39 \pm 0.06 \pm 0.06 \end{array}$$

- ALEPH measures $f^{**}, M_{B_2^*}$

$$\begin{array}{lcl} M_{B_2^*} & = & 5739\ ^{+8}_{-11}\ ^{+6}_{-4}\,\text{MeV} \\ f^{**} & = & 0.31 \pm 0.09\ ^{+0.06}_{-0.05} \end{array}$$

- OPAL, DELPHI and ALEPH measure

$$\begin{array}{rcll} M(B_{u,d}^{**}) & = & 5681 \pm 11\,\text{MeV} & \text{OPAL} \\ f^{**} & = & 0.270 \pm 0.056 & \\ M(B_{u,d}^{**}) & = & 5734 \pm 5 \pm 17\,\text{MeV} & \text{DELPHI} \\ f^{**} & = & 0.32 \pm 0.018 \pm 0.06 & \\ M(B_{u,d}^{**}) & = & 5703 \pm 4 \pm 10\,\text{MeV} & \text{ALEPH} \\ f^{**} & = & 0.279 \pm 0.016 \pm 0.059\ ^{+0.039}_{-0.056} & \end{array}$$

B_c^+ at LEP

DELPHI, ALEPH, OPAL $Z \to B_c^+ X$ Searches

	Candidates			Prod. Limit $[10^{-5}]$ at 90% CL		
Decay mode	DELPHI	ALEPH	OPAL	DELPHI	ALEPH	OPAL
$B_c^+ \to J/\psi\pi^+$	1	0	2	10.5 to 8.4	3.6	10.6
$B_c^+ \to J/\psi\ell^+\nu$	0	2	1	5.8 to 5.0	5.2	6.96
$B_c^+ \to J/\psi\pi^+\pi^-\pi^+$	1	-	0	17.5	-	5.53

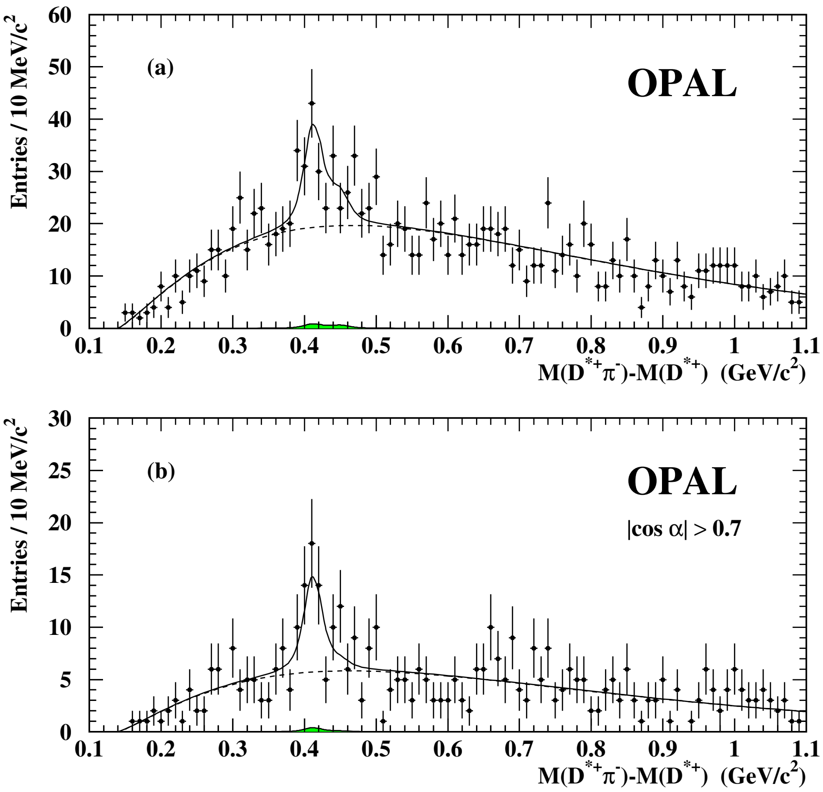
- $B_c^+ \to J/\psi\pi^+$ candidates have masses 6.342 ± 0.027 GeV (DELPHI) and 6.32 ± 0.06 GeV (OPAL average)
- Predictions for B_c^+ mass: 6.24 to 6.31 GeV
- Observation (CDF) $20.4\ {}^{+6.2}_{-5.8}$ events and $M(B_c^+) = 6.40 \pm 0.39 \pm 0.13$ GeV

D^{**}at LEP

OPAL L=1 Production (Z. Phys. C 76 (1997) 425)

- Reconstruct $\mathrm{D}^{**0} \to \mathrm{D}^{*+}\pi^-$, $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$, $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$
- $c\bar{c}$ enrichment: $x(\mathrm{D}^{**0}) > 0.5$ and $c\tau(\mathrm{D}^0) < 0.3$ mm
- $b\bar{b}$ enrichment: B and D vertexing

$b\bar{b}$ enriched sample with/without decay angle cut



D^{**} Results

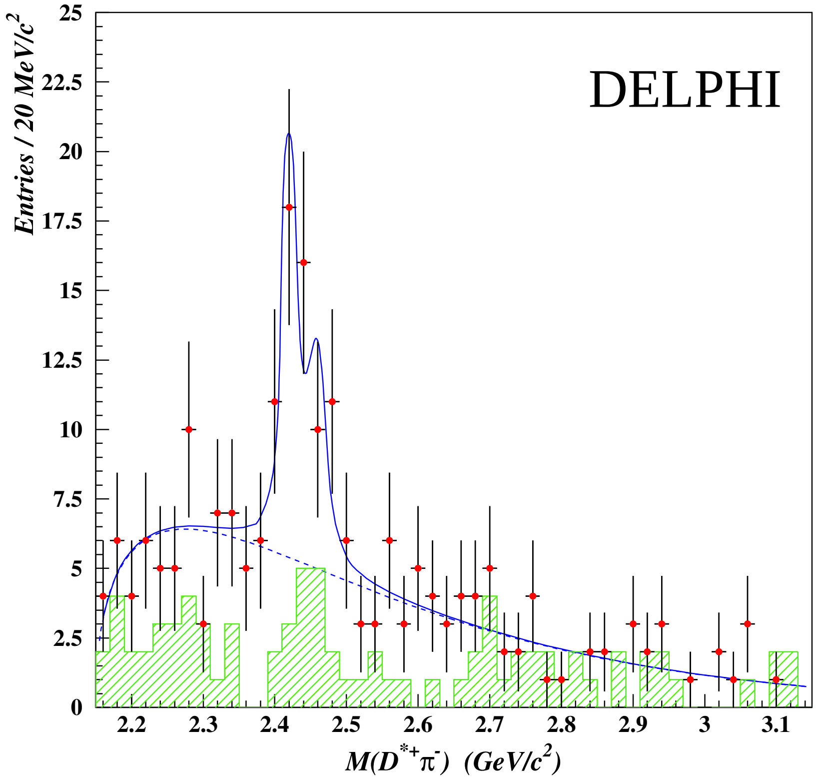
- Results (also for D_{s1}^{+} and D_{s2}^{*+})

$\mathcal{BR}[\%]$	OPAL	DELPHI (ICHEP98)	ALEPH (ICHEP98)
$b \to D_1^0$	$5.0 \pm 1.4 \pm 0.6$	2.0 ± 0.6	2.3 ± 0.7
$b \to D_2^{*0}$	$4.7 \pm 2.4 \pm 1.3$	4.8 ± 2.0	< 2.0
$c \to D_1^0$	$2.1 \pm 0.7 \pm 0.3$	1.9 ± 0.4	1.6 ± 0.5
$c \to D_2^{*0}$	$5.2 \pm 2.2 \pm 1.3$	4.7 ± 1.3	4.7 ± 1.0
$c \to D_{s1}^{+}$	$1.6 \pm 0.4 \pm 0.3$	-	$0.77 \pm 0.20 \pm 0.08$
$c \to D_{s2}^{*+}$	-	-	$1.3 \pm 0.5 \pm 0.2$
$b \to D_{s1}^{+}$	-	-	$1.1 \pm 0.3 \pm 0.2$
$b \to D_{s2}^{*+}$	-	-	$2.2 \pm 0.8 \pm 0.5$

$\mathrm{B} \to \mathrm{D}^{**}\ell\nu$

DELPHI (ICHEP98)

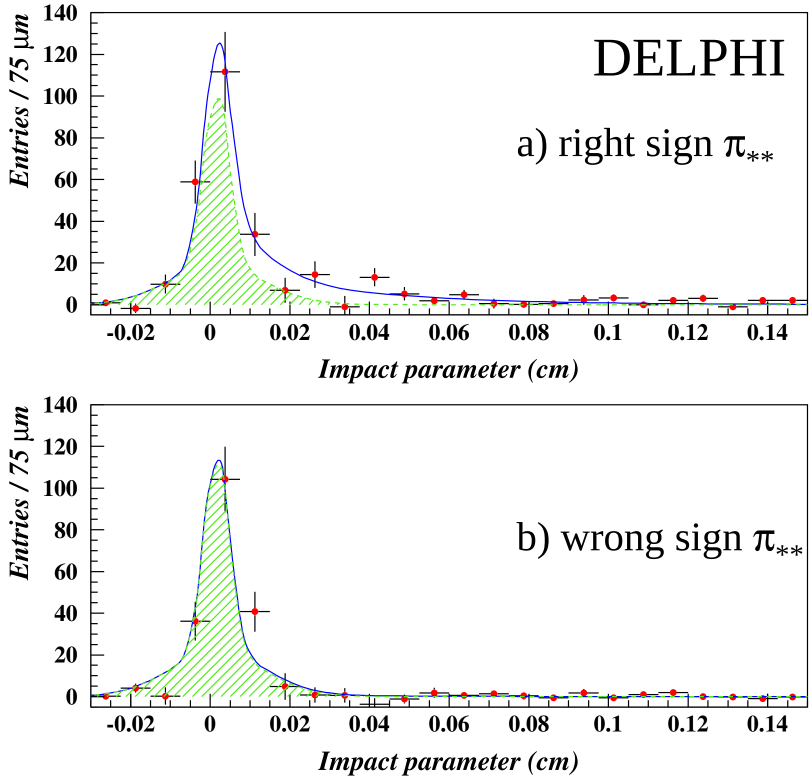
- Reconstruct $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$,
  $\mathrm{D}^0 \to \mathrm{K}^-\pi^+, \mathrm{K}^-\pi^+\pi^-\pi^+, \mathrm{K}^-\pi^+(\pi^0)$
- Fit $\mathrm{D}^{*+}\pi^-$ mass distribution to narrow D^{**} states



$$\boxed{\mathcal{B}(B^- \to \mathrm{D}_1^0\ell^-\bar{\nu}) = 0.72 \pm 0.22 \pm 0.13\%}$$

$B \to D^{**}\ell\nu$

- Fit impact parameter distribution to
  $B^- \to D^{*+}\pi^-\ell^-\bar{\nu}$



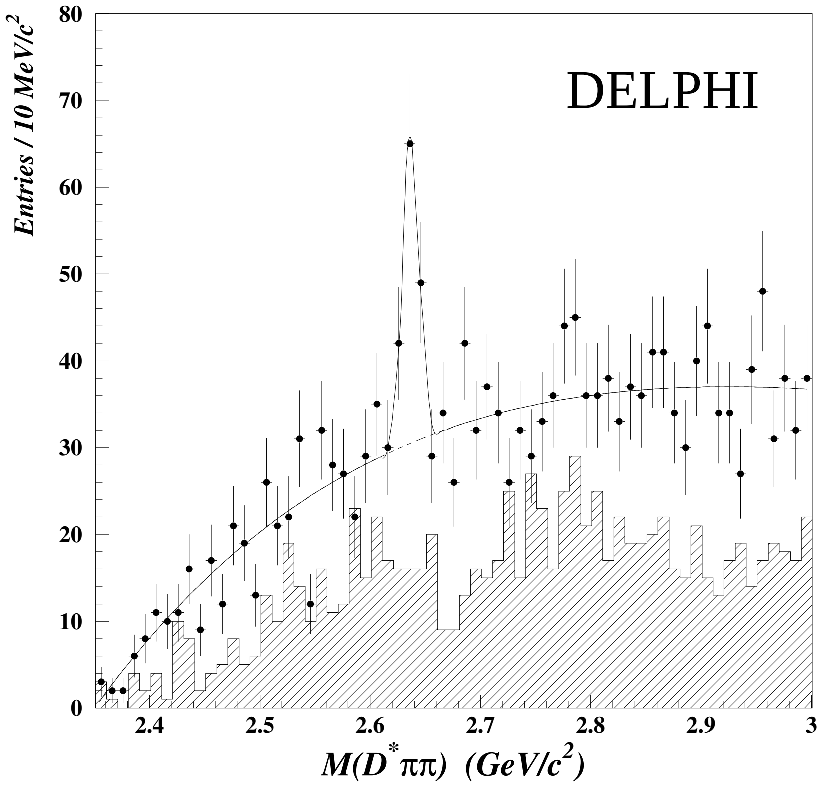
$$\mathcal{B}(B^- \to D^{*+}\pi^-\ell^-\bar{\nu}) = 1.15 \pm 0.17 \pm 0.14\%$$

- Results agree with previous LEP and CLEO measurements

DELPHI $\mathrm{D}^{*'}$ Evidence

(PLB 426 (1998) 231)

$\mathrm{D}^{*+}\pi^-\pi^+$ Mass Spectrum



- Excess $N = 66 \pm 14$ events

  Rate $f_{\mathrm{D}^{*'}}/f_{\mathrm{D}^{**}} = 0.49 \pm 0.18 \pm 0.10$

- Mass $M = 2637 \pm 2 \pm 6$ MeV

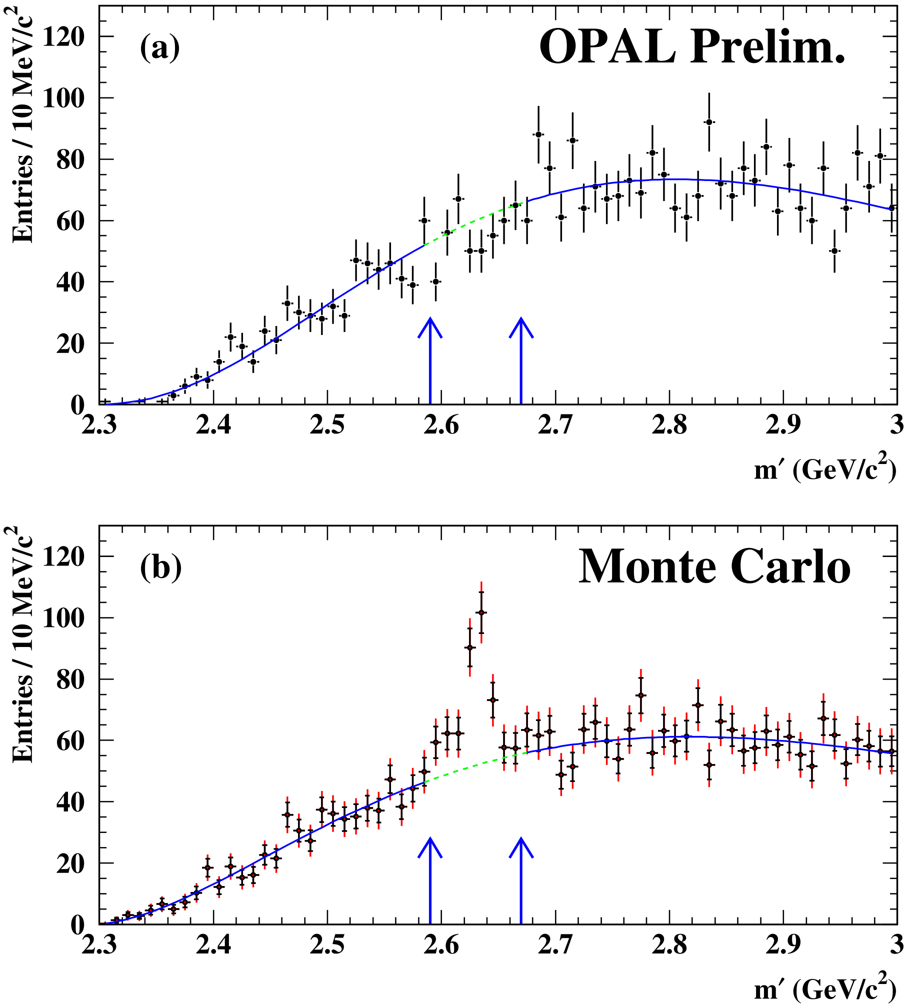
- Width $\sigma = 7 \pm 2$ MeV

- Mass consistent with radial excited $\mathrm{D}^{*'}$

OPAL $D^{*'}$ Search

(ICHEP98)

- Similar analysis as DELPHI



- No Excess $N < 32.8$ at 95 % CL

  Rate $f_{D^{*'}} / f_{D^{**}} < 0.21$ at 95 % CL

- CLEO sees also no excess

Conclusions

- Mass $M(\mathrm{B}_2^*)$ measured in HQET framework

$$M_{\mathrm{B}_2^*} = 5770 \pm 6 \pm 4\,\mathrm{MeV} \quad \text{L3}$$
$$M_{\mathrm{B}_2^*} = 5739\ ^{+8}_{-11}\ ^{+6}_{-4}\,\mathrm{MeV} \quad \text{ALEPH}$$

- L3 measures also mass $M_{\mathrm{B}_1^*}$ and widths $\Gamma_{\mathrm{B}_2^*}, \Gamma_{\mathrm{B}_1^*}$ in HQET framework
- HQET predictions (masses and widths) work in B system, Spin-Orbit inversion not supported
- Rate $f^{**} = 0.27$ to 0.39 measured by all LEP experiments
- Few B_c^+ candidates give mass to 27 MeV.
- New D^{**} production and $\mathrm{B} \to \mathrm{D}^{**}\ell\nu$ results
- Evidence for $\mathrm{D}^{*'}$ by DELPHI not supported by OPAL and CLEO