B Spectroscopy and Heavy Quark Production at LEP

Déborah Sciarrino
University of Geneva

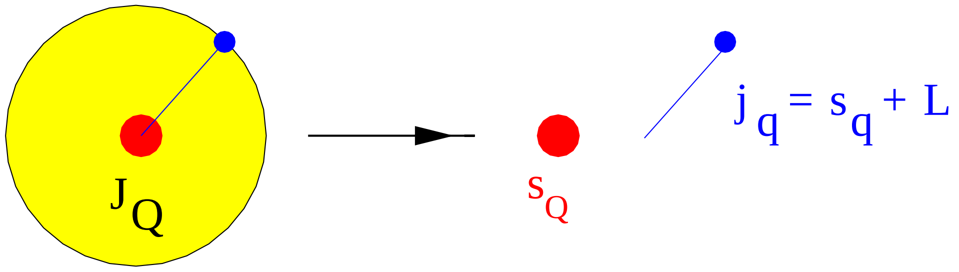
July 15-21, 1999

EPS-HEP99, Tampere

- Motivation
- $\mathbf{B}^{**} \longrightarrow \mathbf{B}^{(*)}\pi$ Studies (abs. 5_7, 5_285)
- Heavy Quarkonium Production (abs. 5_286)
- Conclusion

Motivation

Heavy Quark Effective Theory



- **Heavy Quark Symmetry** at
  $$\Lambda_{QCD}/m_Q \rightarrow 0$$

- 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 with **Effective theory (HQET)**

- Predictions expected to work better in B than in D system :
  $$\Lambda_{QCD} < m_c < m_b$$

Motivations - HQET Predictions

B Meson Spectroscopy

- Charm Measurements (masses and widths) are used to predict B system

- Predictions eg. (Eichten, Hill, Quigg - 1994)

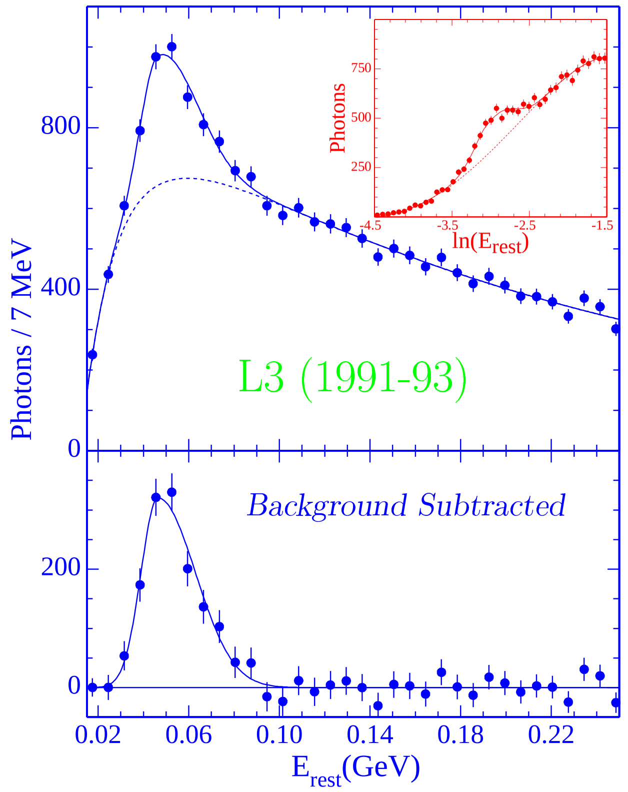
J^P	Name	Mass [MeV]	Width [MeV]	Decay
2^+	B_2^*	5771	25	$\mathrm{B}\pi, \mathrm{B}^*\pi$
1^+	B_1	5759	21	$\mathrm{B}^*\pi$
1^+	B_1^*	$M_{\mathrm{B}_2^*} - 100$	~ 150	$\mathrm{B}^*\pi$
0^+	B_0^*	$M_{\mathrm{B}_1^*} - 12$	~ 150	$\mathrm{B}\pi$

- Other papers (Isgur, Ebert *et al.*(1998)) predict spin-orbit inversion, i.e. $M_{\mathrm{B}_2^*} < M_{\mathrm{B}_1^*}$

- 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^*

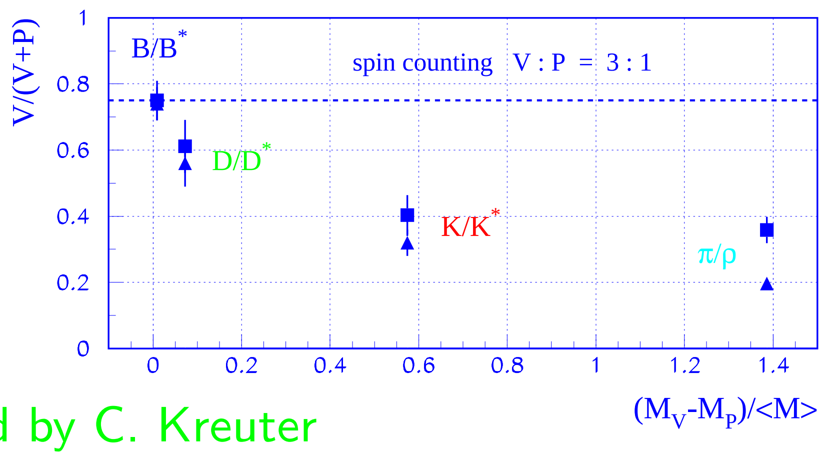
B^* at LEP



$B^* \to B\gamma$ Measurements by all 4 LEP experiments

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

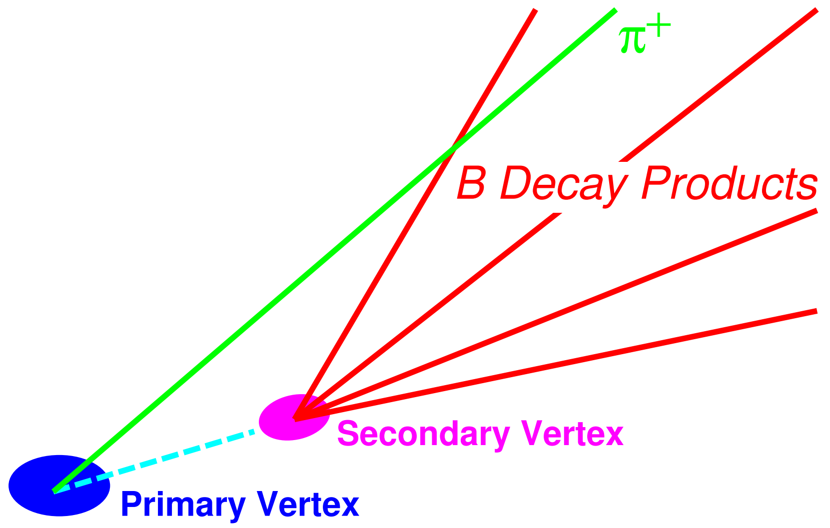
$\Longrightarrow$ Spin counting works well in B system



compiled by C. Kreuter

B^{**} Selection

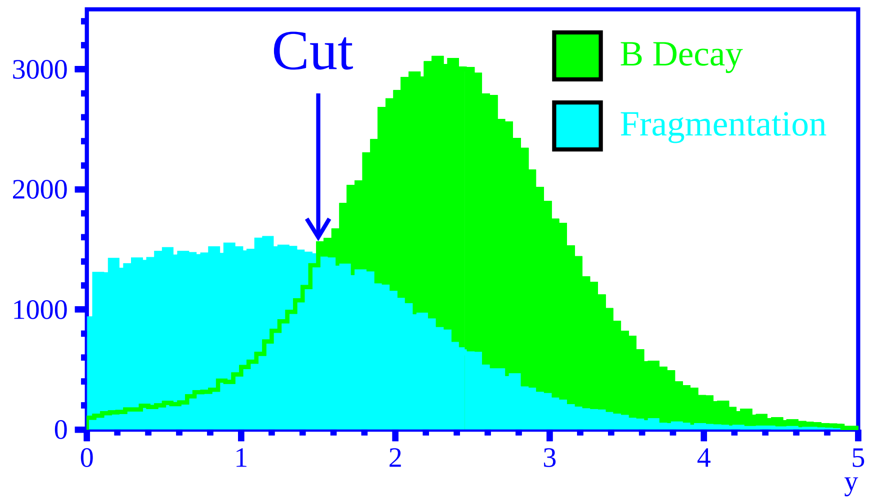
$$\mathrm{B}^{**} \longrightarrow \mathrm{B}^{(*)}\pi^{+}$$



- **$Z \longrightarrow b\bar{b}$ 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, $p \approx 2\,\mathrm{GeV} \Longrightarrow p_L^{max}$

L3 Inclusive B**

- B Decay products : Rapidity



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

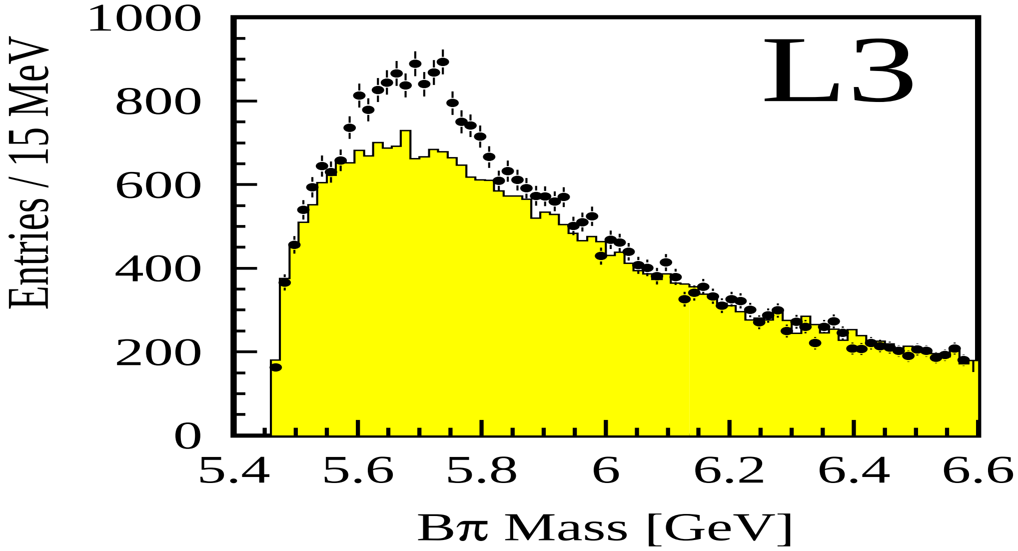
- $B\pi$ invariant mass :

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

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

Selection	Data 94/95	b-purity
$Z \longrightarrow q\bar{q}$	1,250,000 evts	0.215
$Z \longrightarrow b\bar{b}$ tag (3-dim)	177000 evts	0.828
π^+_{**} and sec. vertex	48,000 π-jet	0.94

L3 B**



Background

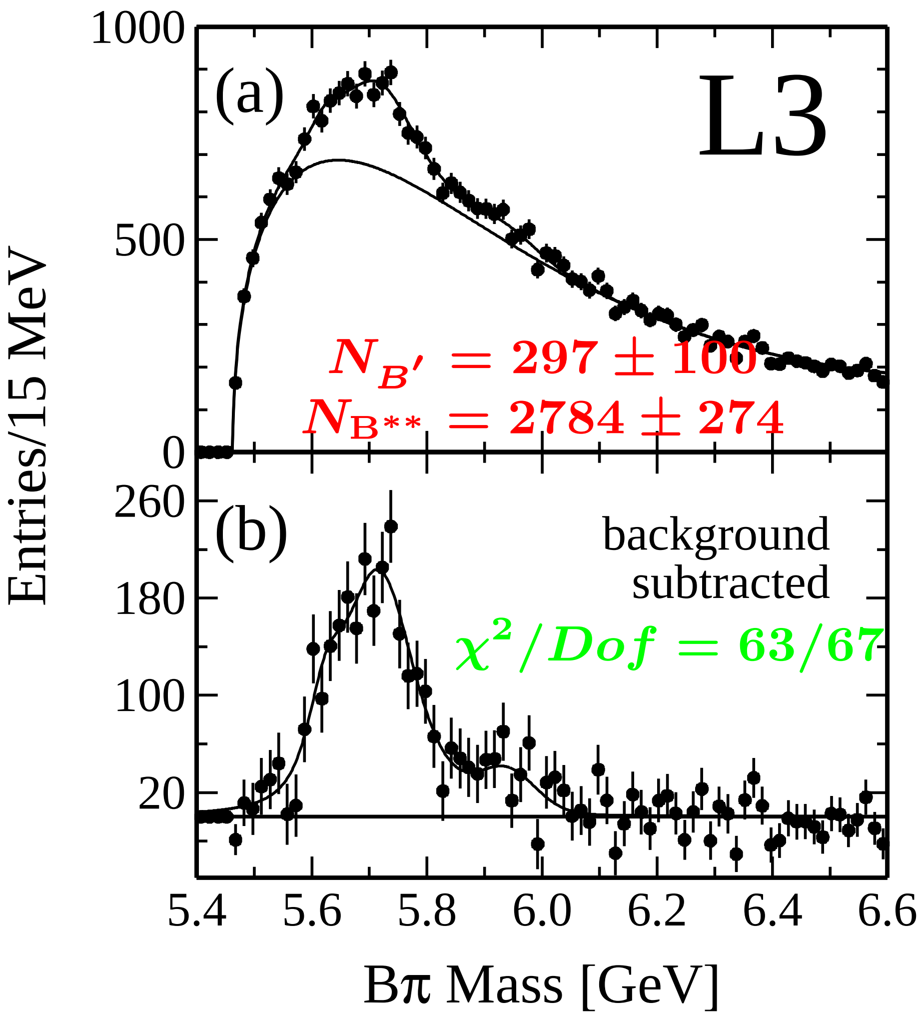
- Threshold function: (6 parameters), shape from Monte Carlo, normalisation from data

Signal

- 5 Breit-Wigners $\otimes$ Gaussian Resolution
  Unfold $\sigma(M)$ from Monte Carlo
- HQET Constraints:
  5:3:3:1 for B_2^*: B_1: B_1^*: B_0^* rates
  $M_{\mathrm{B}_2^*} - M_{\mathrm{B}_1} = 12\,\mathrm{MeV}$ and $\Gamma_{\mathrm{B}_1} = \Gamma_{\mathrm{B}_2^*}$
  $M_{\mathrm{B}_1^*} - M_{\mathrm{B}_0^*} = 12\,\mathrm{MeV}$ and $\Gamma_{\mathrm{B}_0^*} = \Gamma_{\mathrm{B}_1^*}$

$\Longrightarrow$ Measure $f^{**}, M_{\mathrm{B}_2^*}, \Gamma_{\mathrm{B}_2^*}, M_{\mathrm{B}_1^*}, \Gamma_{\mathrm{B}_1^*}$

L3 B**



$$M_{\mathrm{B}_2^*} = 5768 \pm 5 \pm 6\,\mathrm{MeV}$$
$$M_{\mathrm{B}_1^*} = 5670 \pm 10 \pm 13\,\mathrm{MeV}$$
$$\Gamma_{\mathrm{B}_2^*} = 24 \pm 19 \pm 24\,\mathrm{MeV}$$
$$\Gamma_{\mathrm{B}_1^*} = 70 \pm 21 \pm 25\,\mathrm{MeV}$$
$$f_{\mathrm{B}^{**}} = 0.32 \pm 0.03 \pm 0.06$$

$$Br(B \to B' \to B\pi) = 0.034 \pm 0.011$$
$$M_{B'} = 5936 \pm 22\,\mathrm{MeV}$$
$$\sigma_{B'} = 50 \pm 22\,\mathrm{MeV}$$

OPAL B^{**}

- Select only $B^{**} \longrightarrow B^{*}\pi$ decays
- No specific use of HQET predictions in fitting the spectrum
- Method : 4 steps
  - Select B (B-tag,inclusive)
  - Select B^{*} via its $B\gamma$ decay
  - Get B^{**} via $B^{(*)}\pi$ selection
  - Select $B^{**} \longrightarrow B^{*}\pi$ via Probability function $W(B^{*})$

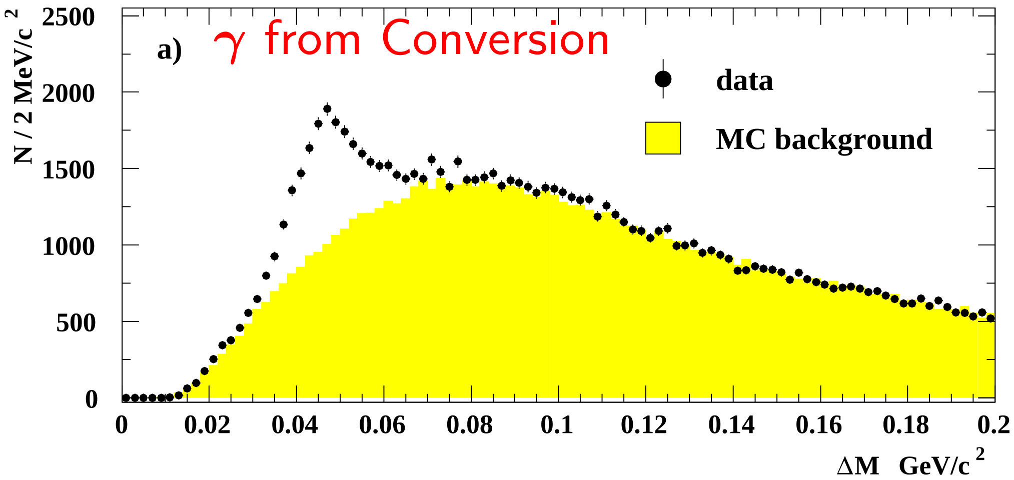
$\longrightarrow$ One B^{*} depleted sample
$\longrightarrow$ One B^{*} enriched sample

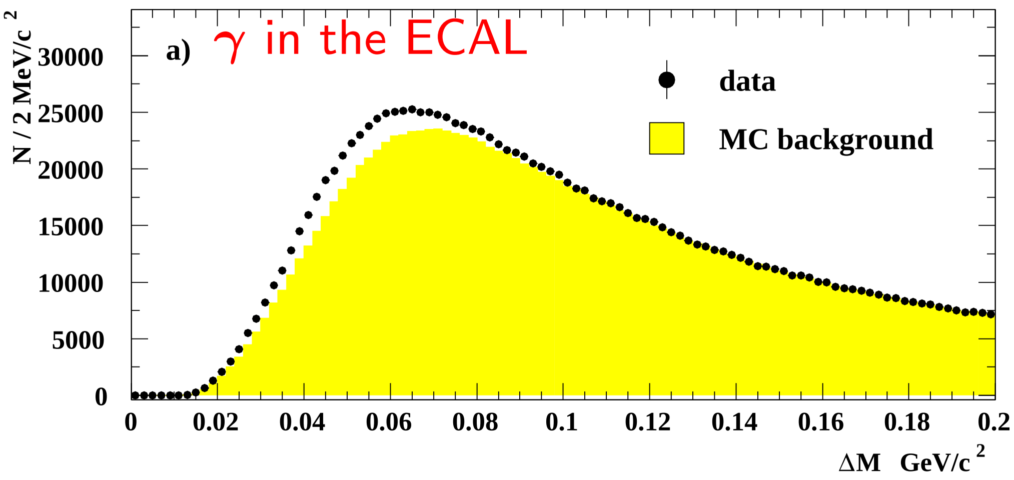
$$\Longrightarrow BR(B^{**} \rightarrow B^{*}\pi)$$

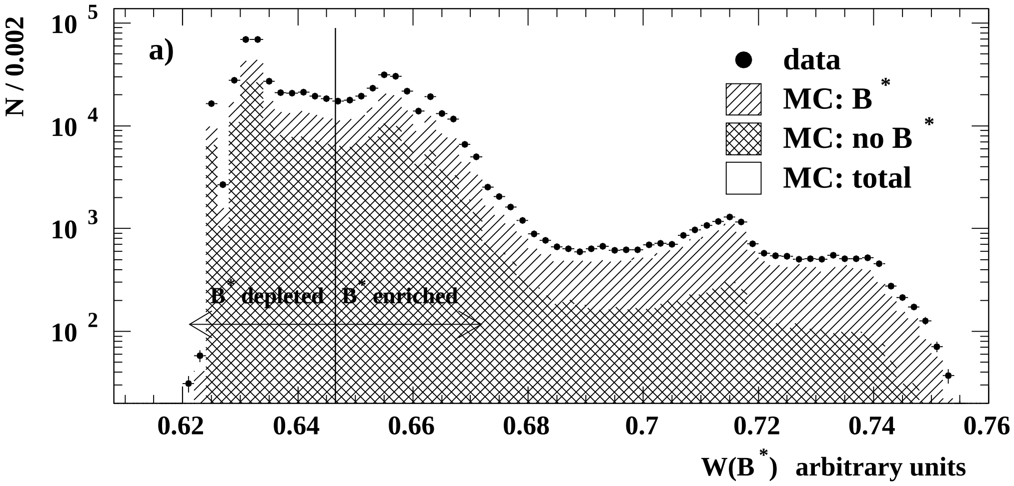
OPAL B**

$$\Delta M = M_{B\gamma} - M_B$$

OPAL preliminary

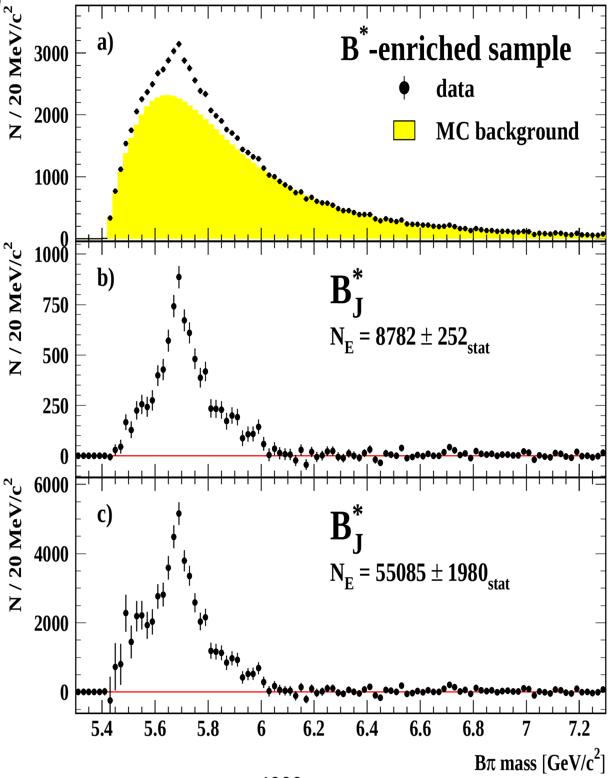


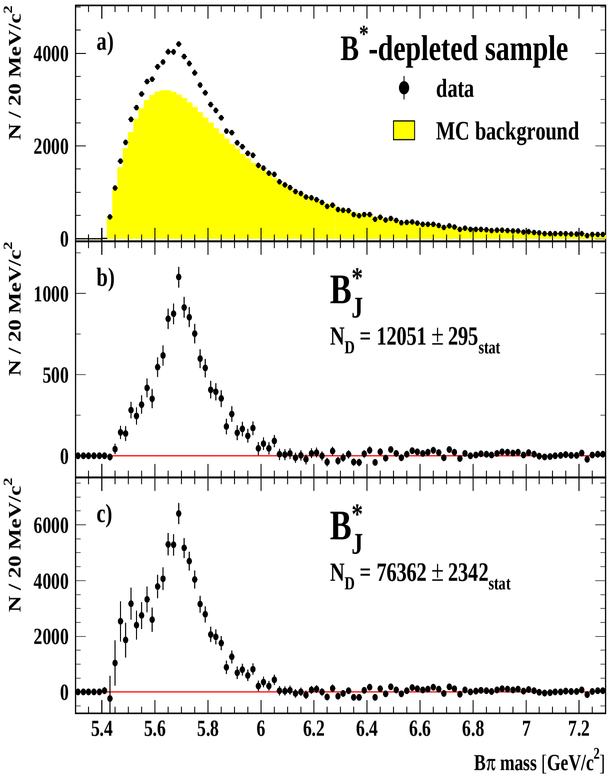


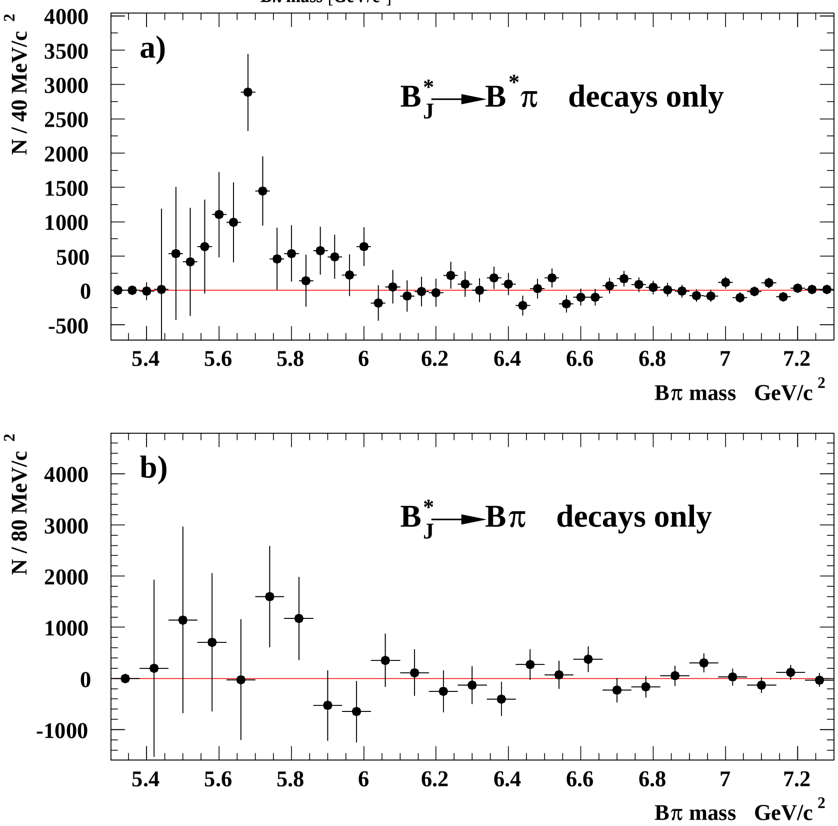


OPAL B^{**}

OPAL preliminary







$$\mathrm{Br}(B_J^*(5732) \to B^*\pi) = 0.85^{+0.26}_{-0.27} \pm 0.12$$

B^{**} Summary

- LEP (Single bump fit)

$M(B^{**}_{u,d})$	$=$	$5703 \pm 4 \pm 10\,\mathrm{MeV}$	ALEPH
f^{**}	$=$	$0.279 \pm 0.016 \pm 0.059\ ^{+0.039}_{-0.056}$	
$M(B^{**}_{u,d})$	$=$	$5734 \pm 5 \pm 17\,\mathrm{MeV}$	DELPHI
f^{**}	$=$	$0.32 \pm 0.018 \pm 0.06$	
$M(B^{**}_{u,d})$	$=$	$5681 \pm 11\,\mathrm{MeV}$	OPAL
f^{**}	$=$	0.270 ± 0.056	

- L3 new result :

$$\begin{aligned} M_{B_2^*} &= 5768 \pm 5 \pm 6\,\mathrm{MeV} \\ \Gamma_{B_2^*} &= 24 \pm 19 \pm 24\,\mathrm{MeV} \\ M_{B_1^*} &= 5670 \pm 10 \pm 13\,\mathrm{MeV} \\ \Gamma_{B_1^*} &= 70 \pm 21 \pm 25\,\mathrm{MeV} \\ f^{**} &= 0.32 \pm 0.03 \pm 0.06 \end{aligned}$$

- ALEPH (exclusive) :

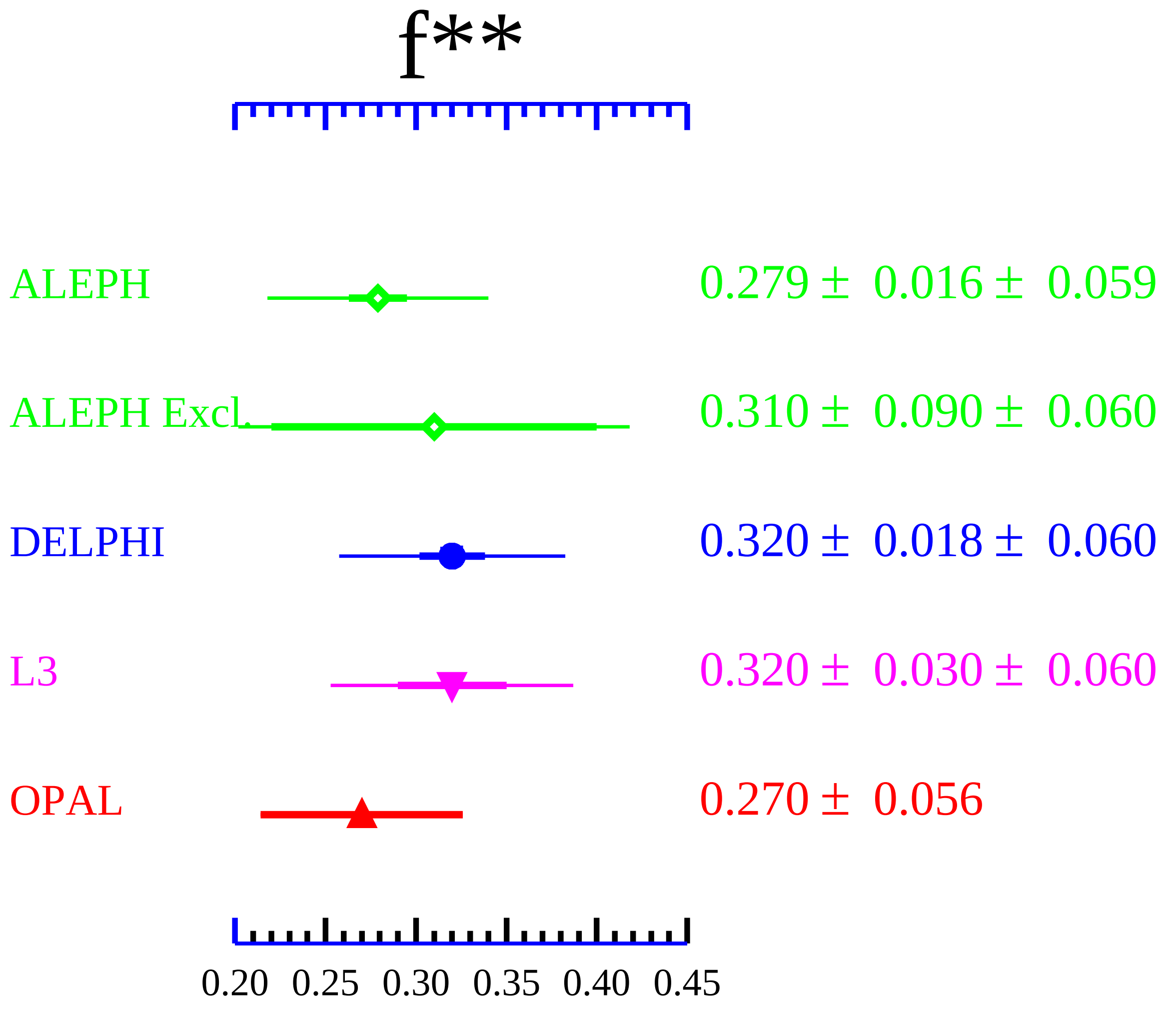
$$\begin{aligned} M_{B_2^*} &= 5739\ ^{+8}_{-11}\ ^{+6}_{-4}\,\mathrm{MeV} \\ f^{**} &= 0.31 \pm 0.09\ ^{+0.06}_{-0.05} \end{aligned}$$

- OPAL new result :

$$\mathrm{Br}(B_J^*(5732) \to B^*\pi) = 0.85^{+0.26}_{-0.27} \pm 0.12$$

f^{**} Comparison

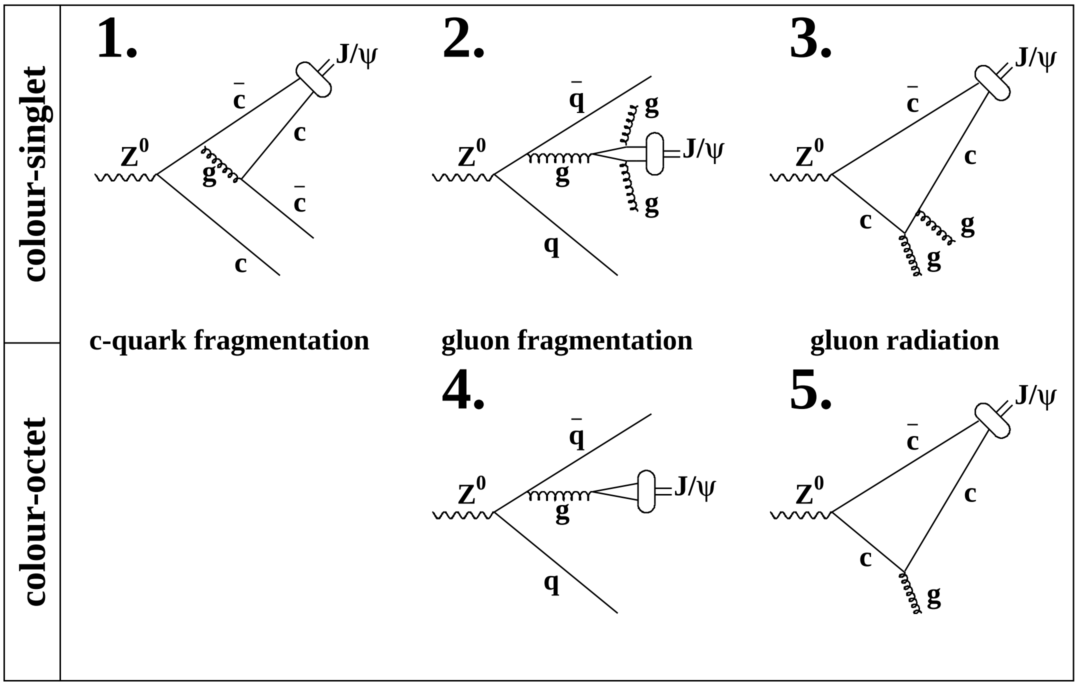
$$\mathbf{f_{B^{**}} = BR(b \rightarrow B^{**}_{u,d})/BR(b \rightarrow B_{u,d})}$$



Motivations

Quarkonium Production

- Important test of the relative contributions of the different models
- Check of TEVATRON measurement on high prompt quarkonium production rate (J/ψ)
- Test production via Color Octet Contribution (CO)?
  -$BR(Z \to J_p + X) = 0.9 \times 10^{-4}$ CS
  -$BR(Z \to J_p + X) = 2.8 \times 10^{-4}$ CO

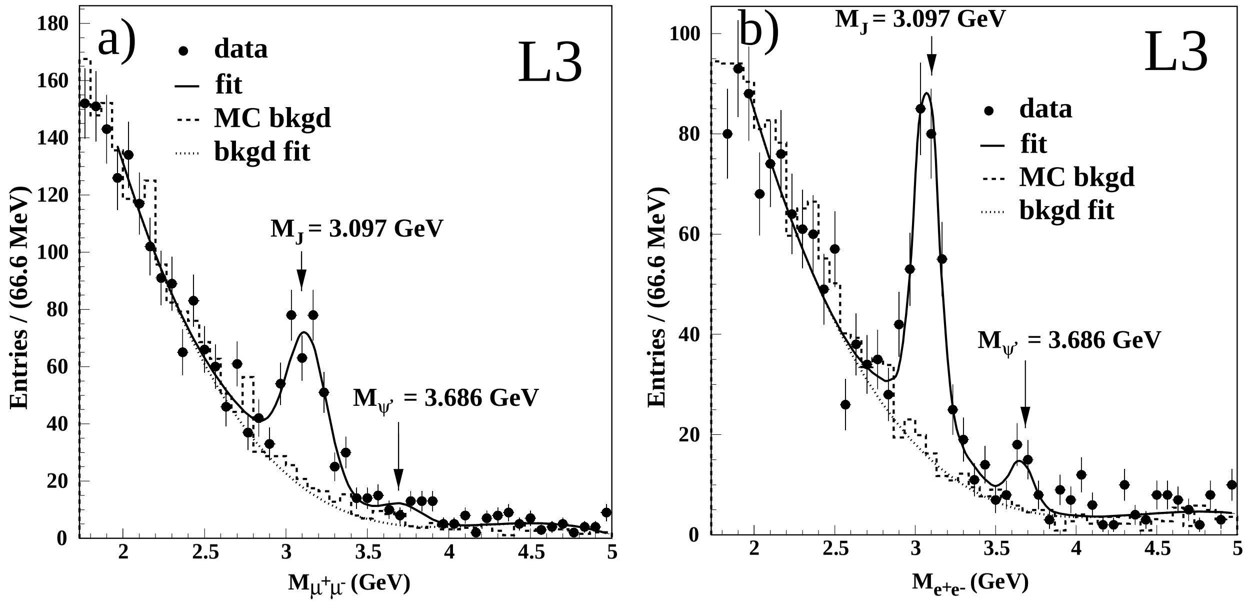


J/ψ Production

- At LEP, most of J/ψ produced by B decays.
- L3 new analysis: 91-95 (3.6M had.Z decays)
  -Look for $\mathbf{J}/\psi \to \mu^+\mu^-$ and $\mathbf{J}/\psi \to \mathbf{e^+e^-}$
  (12% of all J/ψ decay)
  -Lept.sel. $+ \theta(\mu^+\mu^- - e^+e^-) < 90^o$

	$J/\psi \to \mu\mu$	$J/\psi \to ee$
ϵ	31.1 %	24.7 %
N_{obs}	288 ± 29	265 ± 23

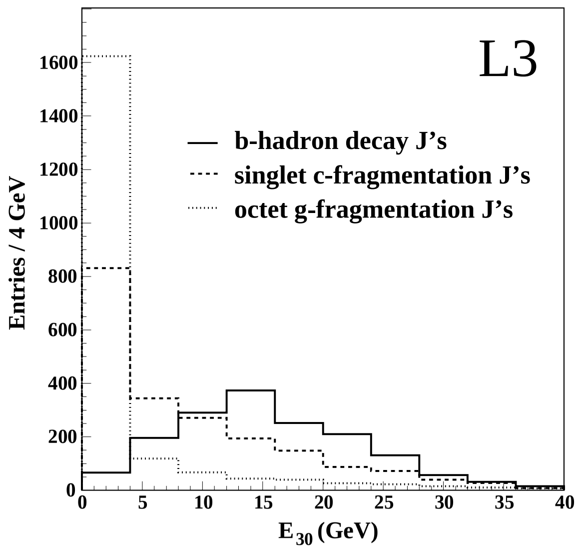
- Binned Fit : 3^{rd} ord. polyn. Backgnd
  2 Gaussians Signal

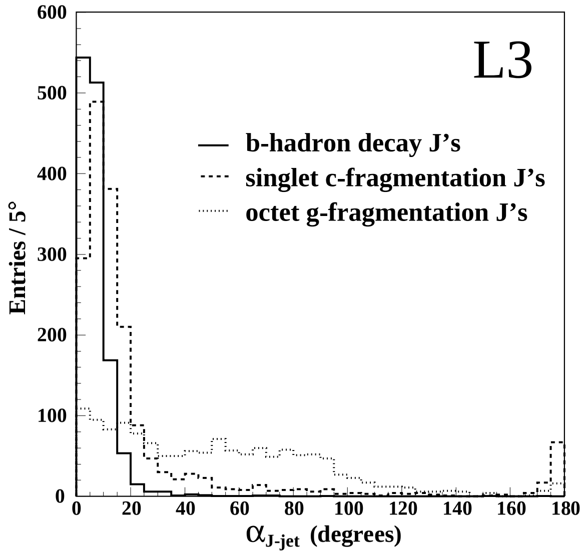


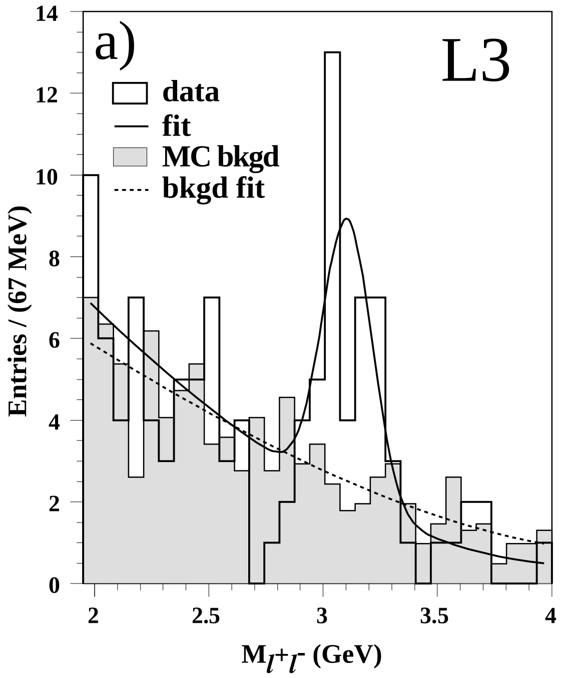
$$\mathbf{BR(Z \to J + X) = (3.21 \pm 0.21^{+0.19}_{-0.28}) \times 10^{-3}}$$

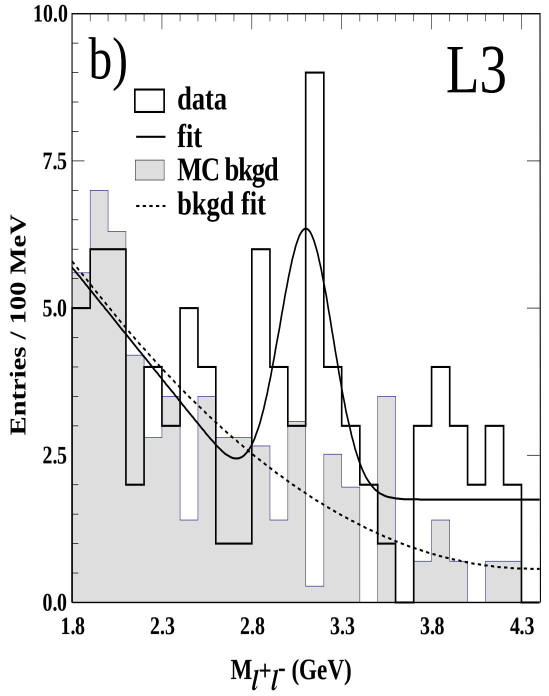
Prompt J/ψ

- Discrimination obtained using $\mathbf{E_{30}}$ and $\alpha_{J-\mathrm{jet}}$







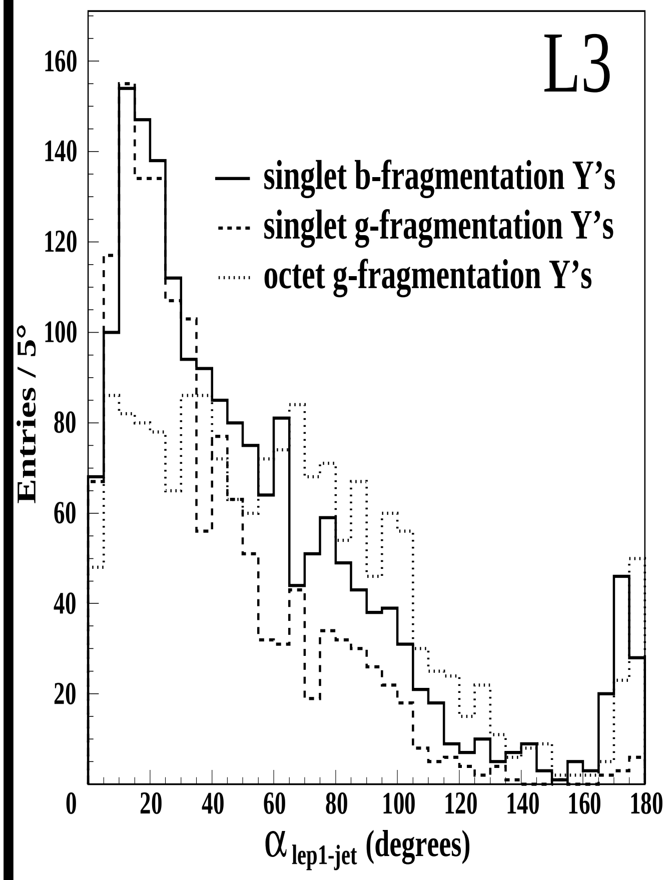


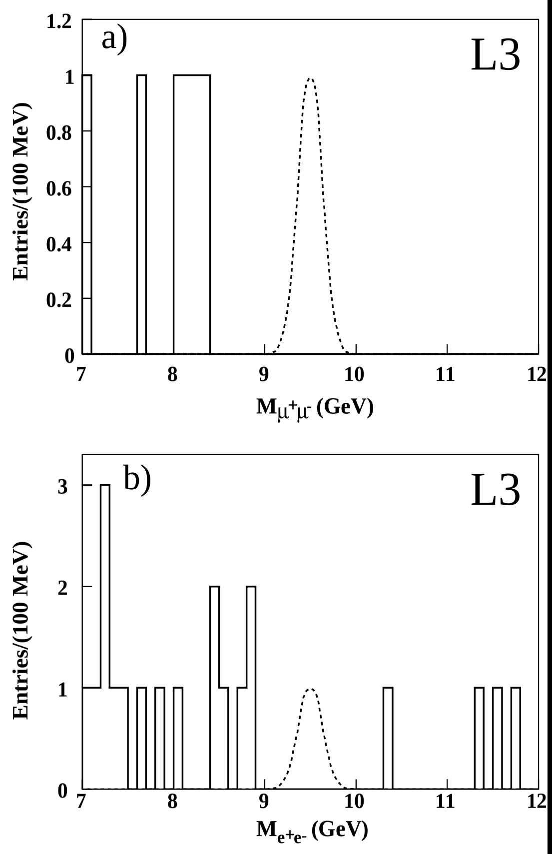
$$f_p = 7.1 \pm 2.1 \pm 1.2^{+1.5}_{-0.8}$$

$$BR(Z \to J_p + X) = (2.1 \pm 0.6 \pm 0.4^{+0.4}_{-0.2})10^{-4}$$

Prompt Υ Production

- Use $\Upsilon \to \mu^+\mu^-$ and $\Upsilon \to e^+e^-$ (5% of total Υ decays)
- Discrimination from $\alpha_{\mathrm{lep1-jet}}$
- Events seen in [7-9] GeV range consistent with expected background
- 1 event in Υ peak region, consistent with expected background





$$\mathrm{BR}(\mathrm{Z} \to \Upsilon(1s) + \mathrm{X}) < 4.4 \times 10^{-5}$$

LEP Results

Exp.	$BR(Z \to J + X)$ $\times 10^{-3}$	$BR(Z \to J_p + X)$ $\times 10^{-4}$
ALEPH	$3.9 \pm 0.2 \pm 0.3$	$3.00 \pm 0.78 \pm 0.30 \pm 0.15$
DELPHI	$3.7 \pm 0.4 \pm 0.2$	$< 7.9\ (90\%\ CL)$
L3	$3.21 \pm 0.21^{+0.19}_{-0.28}$	$2.1 \pm 0.6 \pm 0.4^{+0.4}_{-0.2}$
OPAL	$3.9 \pm 0.2 \pm 0.3$	$1.9 \pm 0.7 \pm 0.5 \pm 0.4$
Stat. Av.	3.69 ± 0.11	2.3 ± 0.4
Theory		$0.9(cs) - 2.8(co)$

Exp.	$BR(Z \to \Upsilon(1S) + X)$ $\times 10^{-5}$
ALEPH	$< 7.3\ (90\%\ CL)$
L3	$< 4.4\ (95\%\ CL)$
OPAL	$10 \pm 4 \pm 1 \pm 2$
Theory	$1.7(cs) - 5.9(co)$

Déborah Sciarrino
University of Geneva

Conclusion

- LEP Collaborations still produce new results on B

B Spectroscopy :

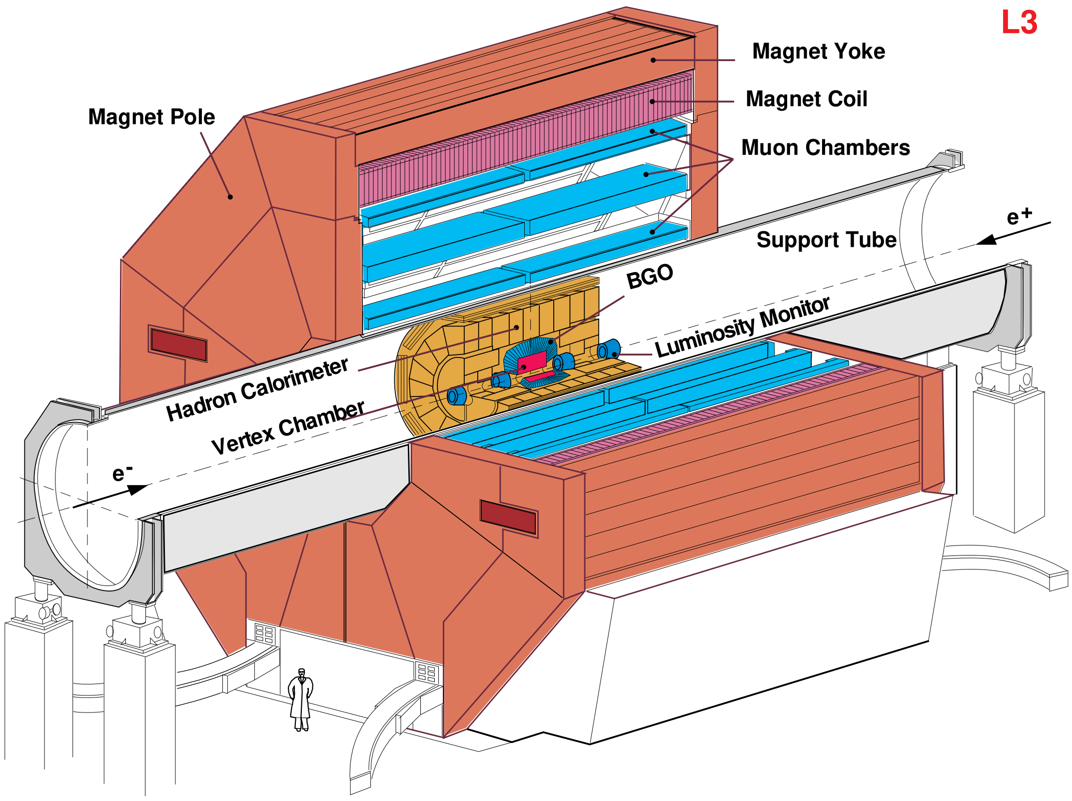
- Most results are consistent with HQET. No confirmation of spin-orbit inversion.

Heavy Quarkonium production :

- Excess over Color Singlet production. $\Longrightarrow$ Color Octet contribution

LEP Detectors

ALEPH, DELPHI, L3 and OPAL



Data Sample

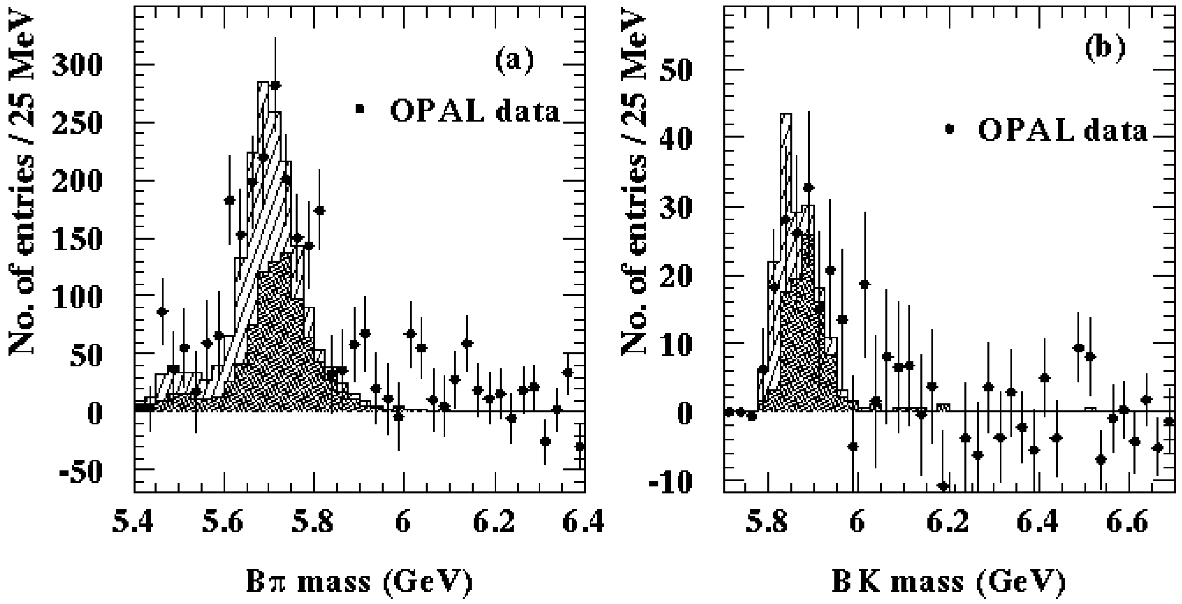
$$e^+e^- \rightarrow Z \rightarrow q\bar{q}$$
$$\rightarrow b\bar{b} \rightarrow B\bar{B}X$$

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

B** at LEP

Inclusive Measurements

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



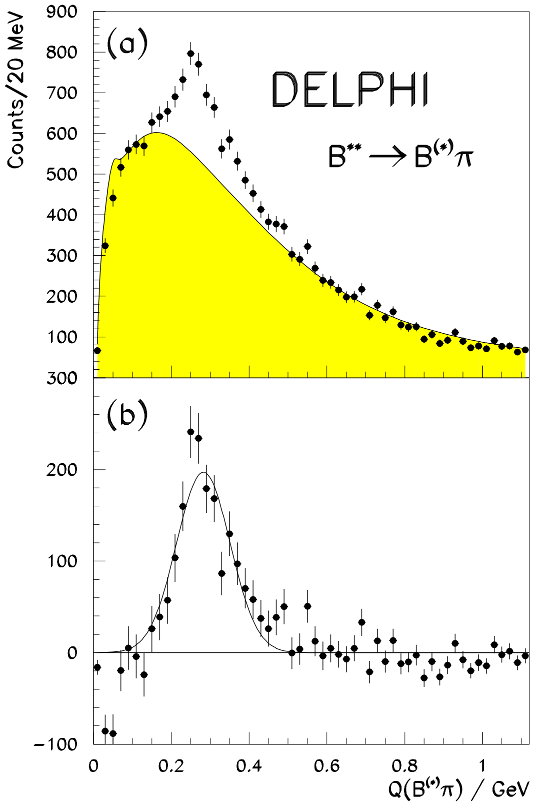
Background: wrong (like)-sign combinations

Signal: Single Breit-Wigner resonance
1738 ± 121 $\mathrm{B}^{(*)+}\pi^-$ and 149 ± 30 $\mathrm{B}^{(*)+}\mathrm{K}^-$

$$M(\mathrm{B}^{**}_{u,d}) = 5681 \pm 11\,\mathrm{MeV}$$
$$f^{**} = 0.270 \pm 0.056$$

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)

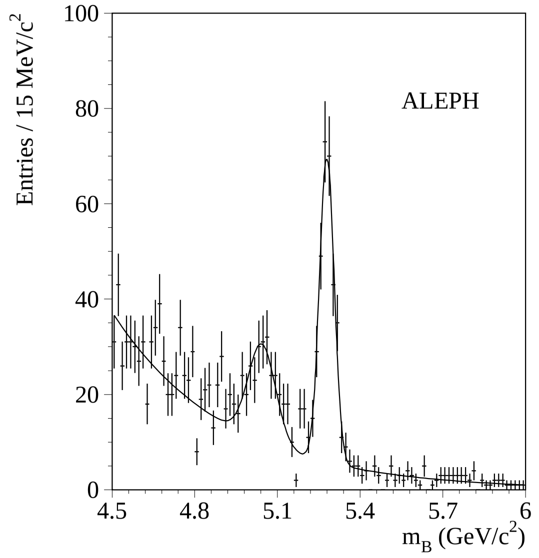
$$M(\mathrm{B}^{**}_{u,d}) = 5703 \pm 4 \pm 10\,\mathrm{MeV}$$
$$f^{**} = 0.279 \pm 0.016 \pm 0.059\ ^{+0.039}_{-0.056}$$

ALEPH B^{**}

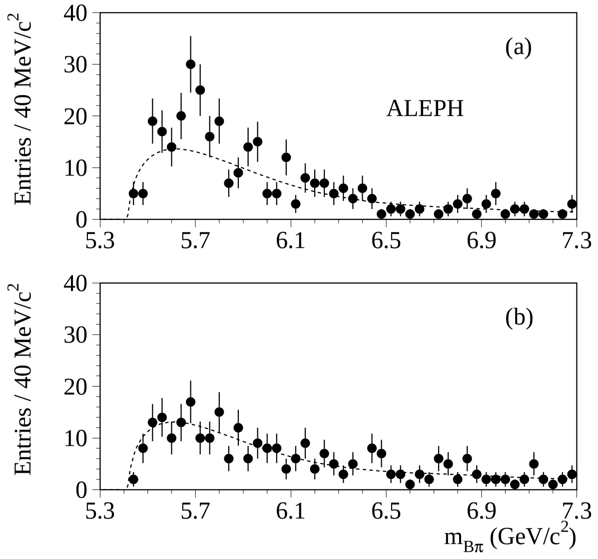
Exclusive Measurement

(PLB 425 (1998) 215)

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



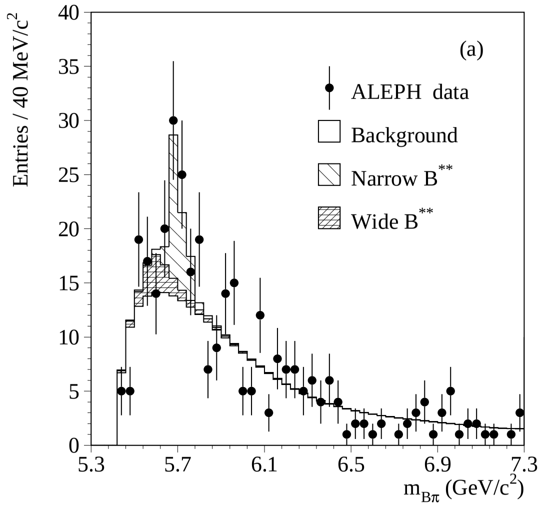
238 charged and 166 neutral B candidates (85 % purity)

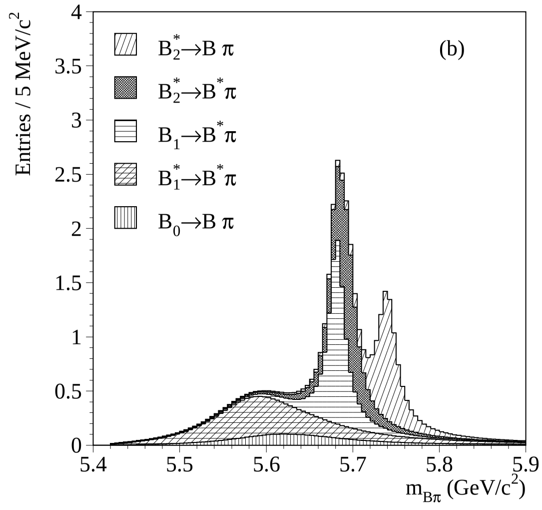


$\mathrm{B}\pi$ mass distributions:
a) right-sign
b) wrong-sign
Excess events:
45 ± 13

ALEPH B^{**}

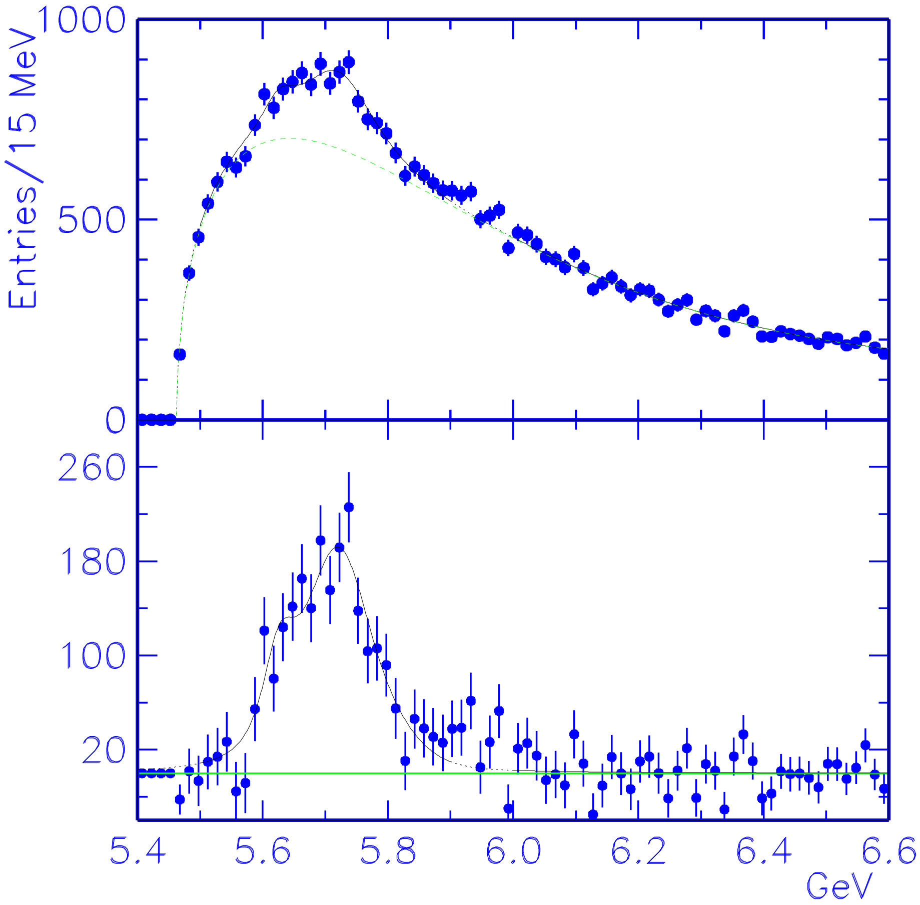
- Signal shape:
  5 Breit-Wigners assuming HQET predictions for masses, widths, and production
  $\Longrightarrow$ Fit for mass $M(B_2^*)$ and rate f^{**}
- Background:
  high B mass sideband, Monte Carlo normalized to data above 6 GeV





$$M_{B_2^*} = 5739\ ^{+8}_{-11}\ ^{+6}_{-4}\ \mathrm{MeV}$$
$$f^{**} = 0.31 \pm 0.09\ ^{+0.06}_{-0.05}$$

L3 B**



$$N_{B^{**}} = 2770 \pm 294$$
$$M_{B_2^*} = 5771 \pm 7\,\mathrm{MeV}$$
$$\Gamma_{B_2^*} = 41 \pm 43\,\mathrm{MeV}$$
$$M_{B_1^*} = 5682 \pm 23\,\mathrm{MeV}$$
$$\Gamma_{B_1^*} = 73 \pm 44\,\mathrm{MeV}$$

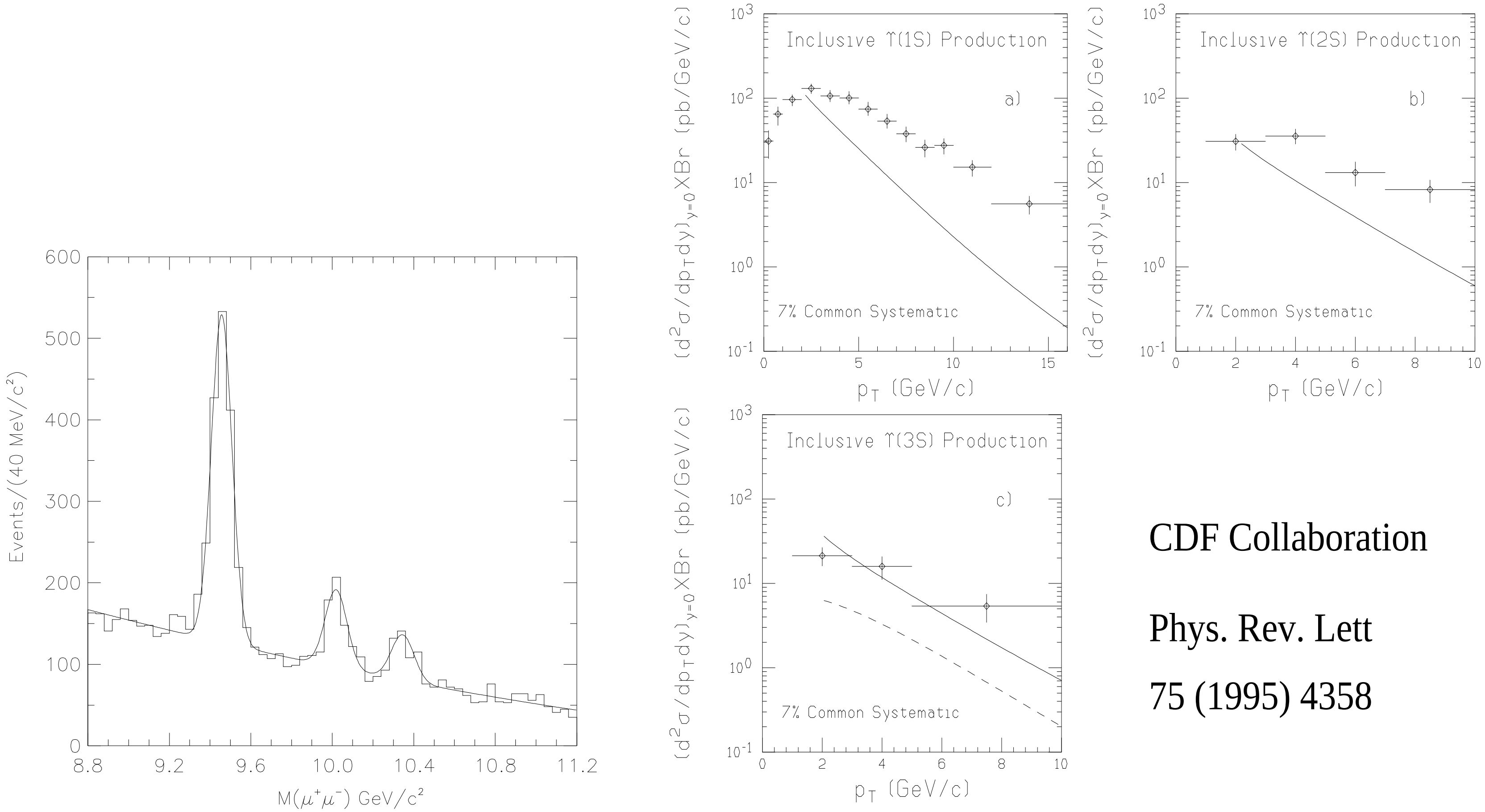
$$\chi^2/Dof = 81/70$$

L3 B^{**}

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	—	—	—	—	± 0.01
fraction $\mathrm{B}_2^* \to B, \mathrm{B}^*$	± 2	± 4	± 1	± 2	< 0.01
background modelling	± 2	± 12	± 3	± 19	± 0.06
signal resolution	± 2	± 9	± 1	± 9	± 0.01
signal efficiency	< 1	± 1	< 1	± 1	± 0.01
mass constraints	± 4	± 7	± 4	± 7	< 0.01
width constraints	< 1	± 2	< 1	± 2	< 0.01
inclusion of B'	± 3	± 17	± 12	± 12	± 1
Total	± 6	± 24	± 13	± 25	± 0.06

The CDF Anomaly



CDF Collaboration

Phys. Rev. Lett

75 (1995) 4358

Measured rates much higher (factor ∼50) than predictions for colour-singlet processes

Discrepancies were resolved by including colour-octet processes