Spectroscopy of Orbitally Excited B Mesons in Z Decays at LEP

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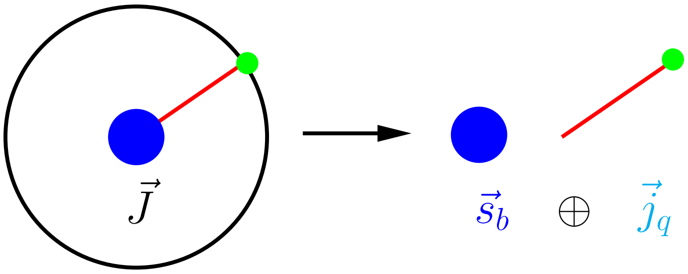
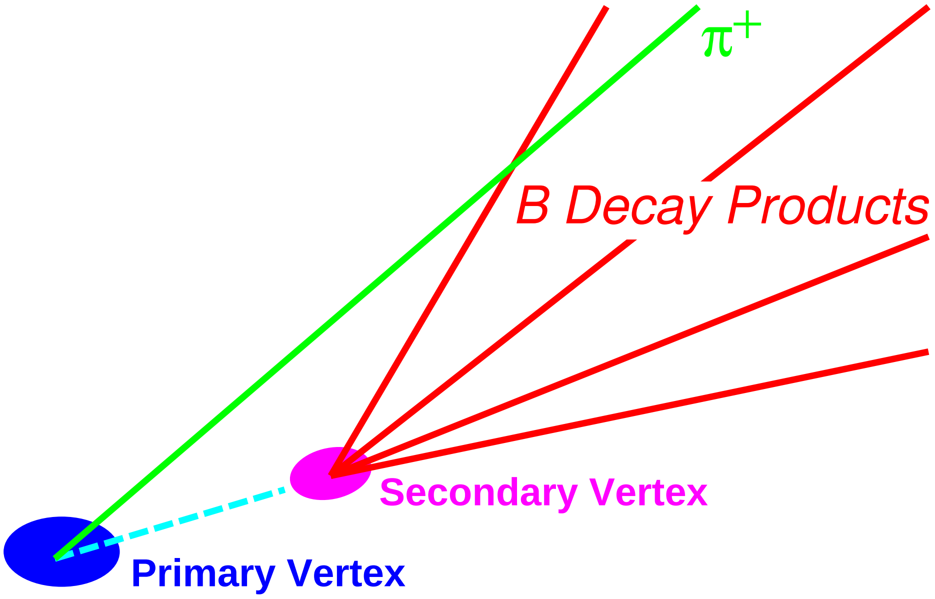


WHS99 - Workshop on Hadron Spectroscopy

Frascati, Italy – 10 March 1999



Selection of $\mathrm{Z} \rightarrow b\bar{b}$

- Lifetime-Based Event Tag

Selection of B

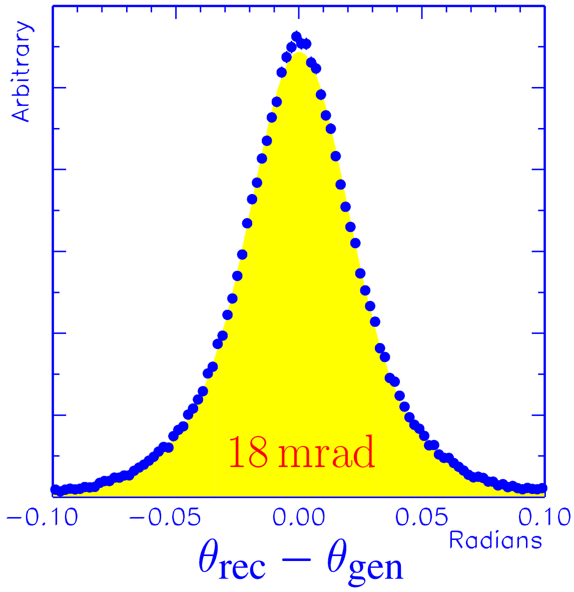
- Energetic Jet with Decay Vertex: DL $> 3\sigma$

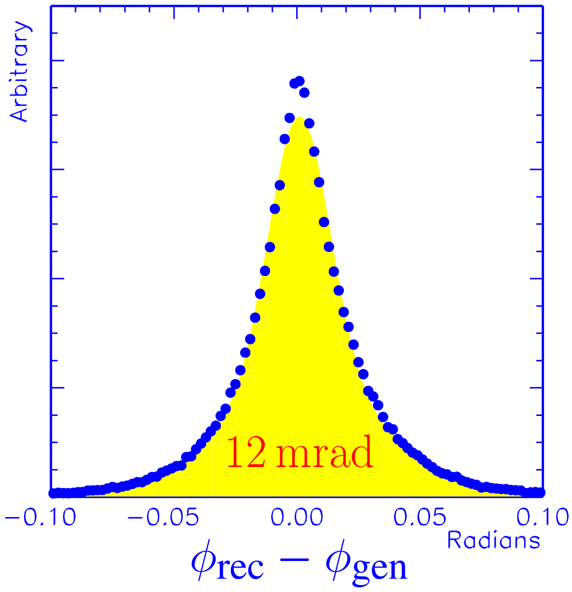
Selection of π

- Maximum p_l^{B} Primary Vertex Track

$$\boxed{\begin{array}{c} 48,022\ \mathrm{B}\pi \text{ candidates} \\ (\pi_{\mathrm{B}} = 0.942) \end{array}}$$

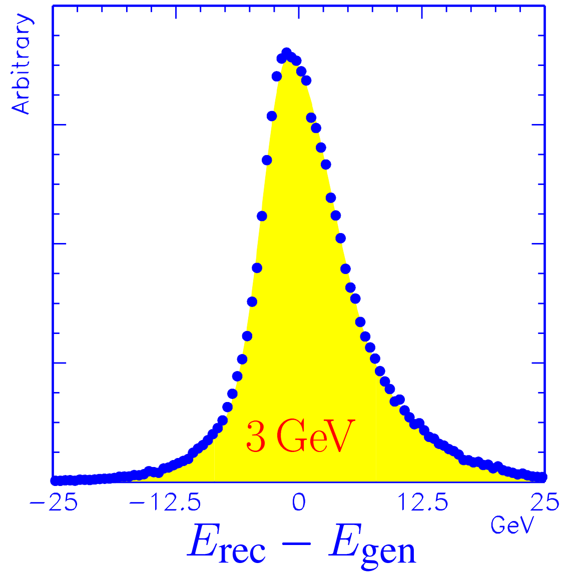
Direction: *Error-Weighted Average*

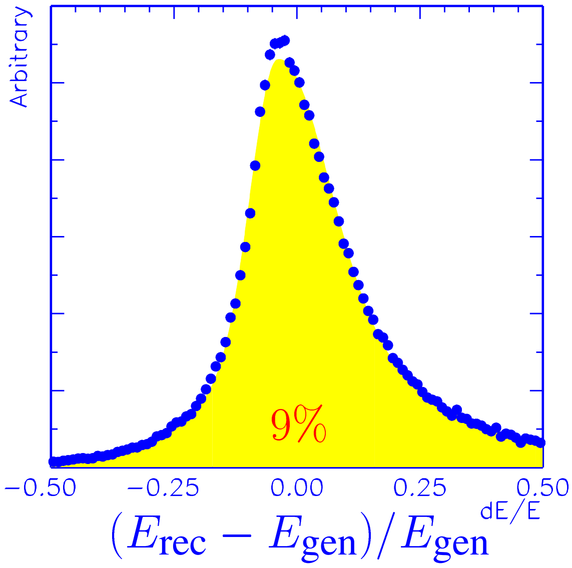




Energy: *Constrained by E_{CM}*

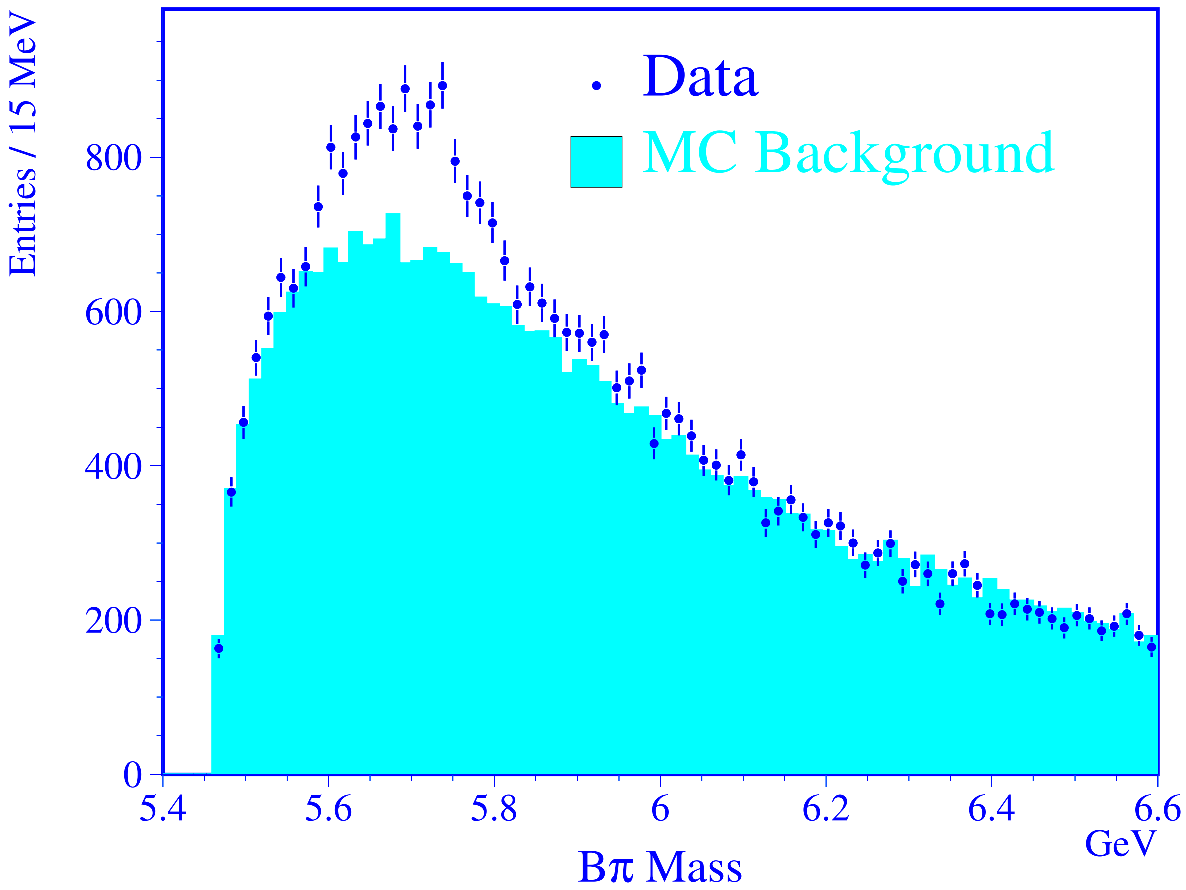
$$\boxed{E_B = \frac{M_Z^2 - M_{\rm recoil}^2 + M_B^2}{2M_Z}}$$





$B\pi$ Mass

Reconstructed $B\pi$ Mass Spectrum



$$M_{B\pi} = \sqrt{M_B^2 + m_\pi^2 + 2E_BE_\pi - 2p_Bp_\pi cos\alpha}$$

Fitting the Signal

HQET Predictions

j_q	J^P	Name	Mass	Width	Decay
$3/2$	2^+	B_2^*	5771 MeV[a] 5733 MeV[b]	25 MeV	$L=2$ (D-wave) $\rightarrow \mathrm{B}\pi, \mathrm{B}^*\pi$
$3/2$	1^+	B_1	5759 MeV 5719 MeV	21 MeV	$L=2$ (D-wave) $\rightarrow \mathrm{B}^*\pi$
$1/2$	1^+	B_1^*	5671 MeV 5757 MeV	$\sim$ 150 MeV	$L=0$ (S-wave) $\rightarrow \mathrm{B}^*\pi$
$1/2$	0^+	B_0^*	5659 MeV 5738 MeV	$\sim$ 150 MeV	$L=0$ (S-wave) $\rightarrow \mathrm{B}\pi$

(a) Quigg, *et al.* (b) Ebert, *et al.*.

Constrained Fit to Signal

- *Five Breit-Wigners Convoluted by Resolution*

  $\sigma(M)$ *unfolded from Monte Carlo*

- *Parameter Constraints:*

j_q	J^P	Name	Mass	Width	Production
$3/2$	2^+	B_2^*	free	free	$5/12$
$3/2$	1^+	B_1	$M_{\mathrm{B}_2^*} - 12$ MeV	$\Gamma_{\mathrm{B}_2^*}$	$3/12$
$1/2$	1^+	B_1^*	free	free	$3/12$
$1/2$	0^+	B_0^*	$M_{\mathrm{B}_1^*} - 12$ MeV	$\Gamma_{\mathrm{B}_1^*}$	$1/12$

- *Output from Fit:*

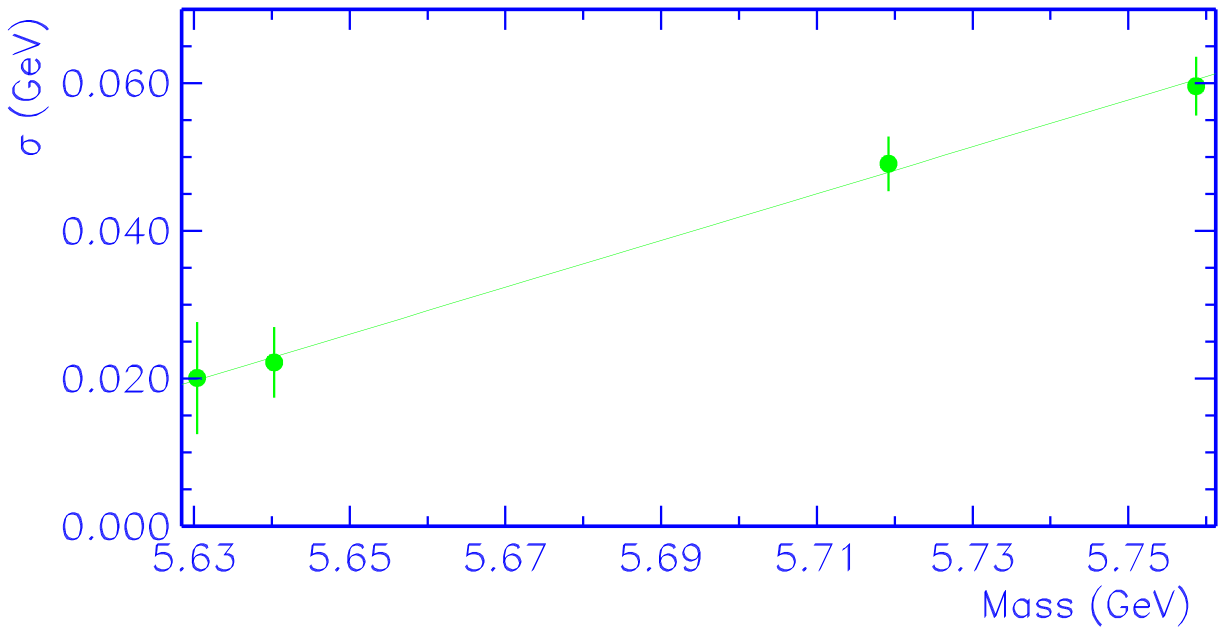
$$\Rightarrow \quad M_{\mathrm{B}_2^*}, \Gamma_{\mathrm{B}_2^*}, M_{\mathrm{B}_1^*}, \Gamma_{\mathrm{B}_1^*}$$

$$\Rightarrow \quad \mathrm{Br}(b \rightarrow \mathrm{B}_{u,d}^{**} \rightarrow \mathrm{B}^{(*)}\pi)$$

$B\pi$ Mass Fit

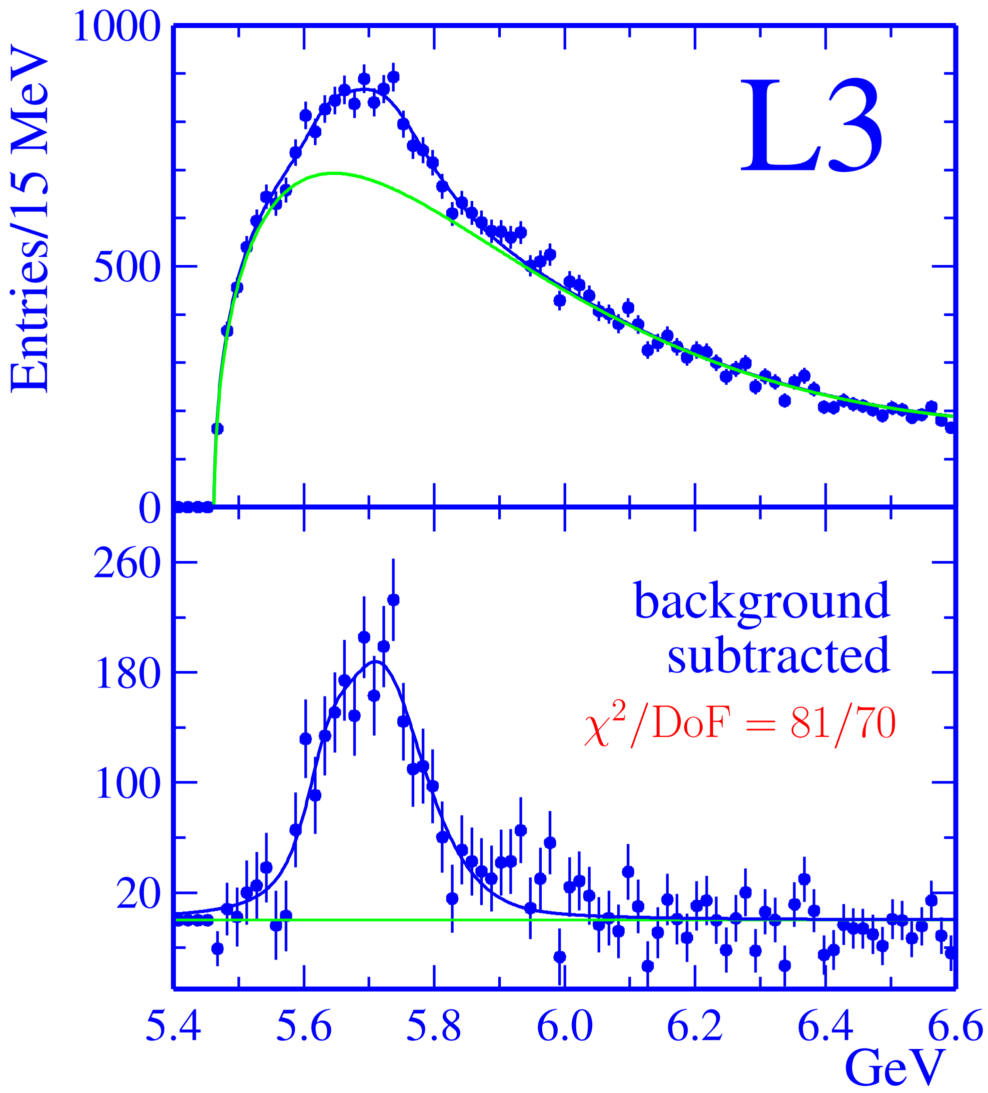
Resolution Function

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



$$\boxed{\sigma(M) \;=\; 0.448M - 2.500\,\mathrm{GeV}}$$

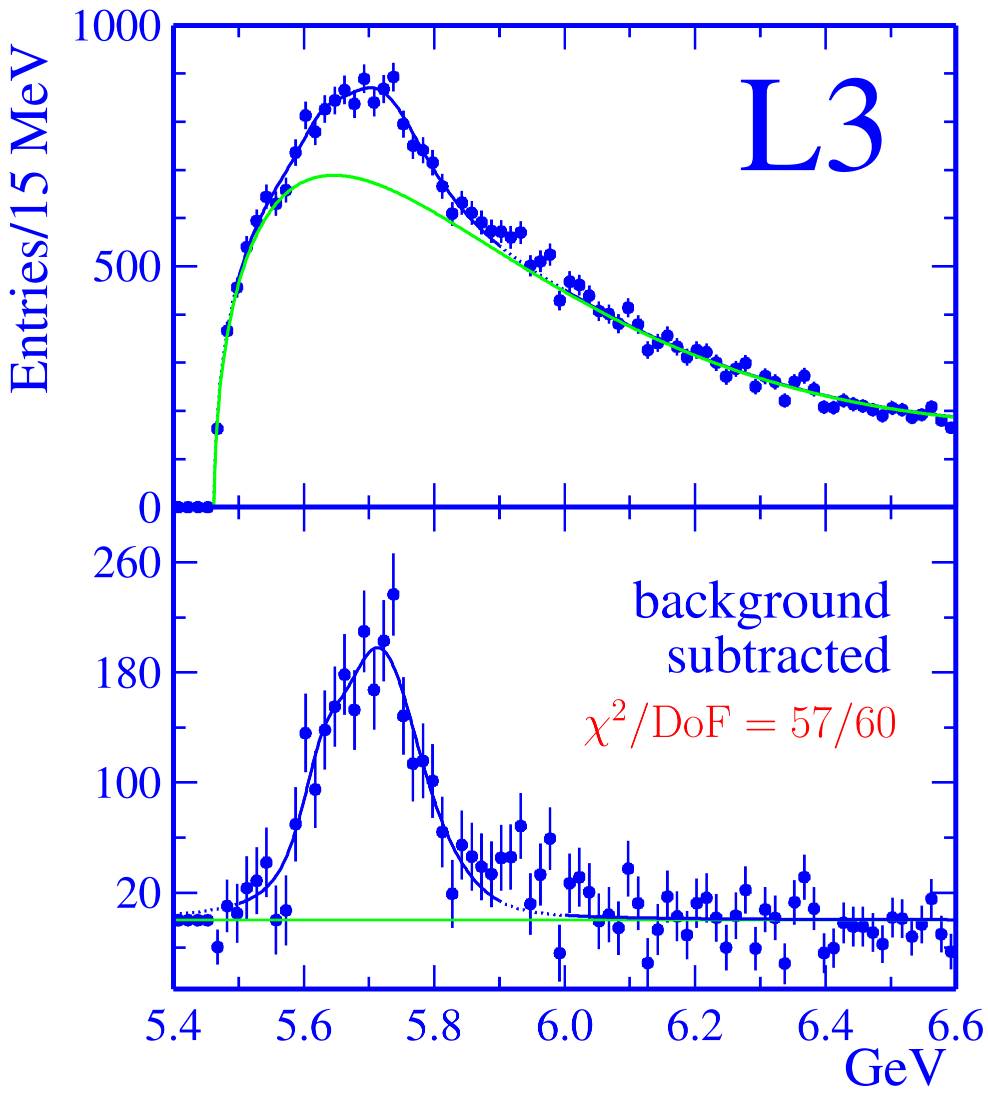
First Attempt



$$
\begin{aligned}
M_{\mathrm{B}_2^*} &= (5771 \pm 7)\ \mathrm{MeV} \\
\Gamma_{\mathrm{B}_2^*} &= (41 \pm 43)\ \mathrm{MeV} \\
M_{\mathrm{B}_1^*} &= (5682 \pm 23)\ \mathrm{MeV} \\
\Gamma_{\mathrm{B}_1^*} &= (73 \pm 44)\ \mathrm{MeV} \\
\mathrm{Br}(b \to \mathrm{B}_{u,d}^{**}) &= 0.32 \pm 0.05
\end{aligned}
$$

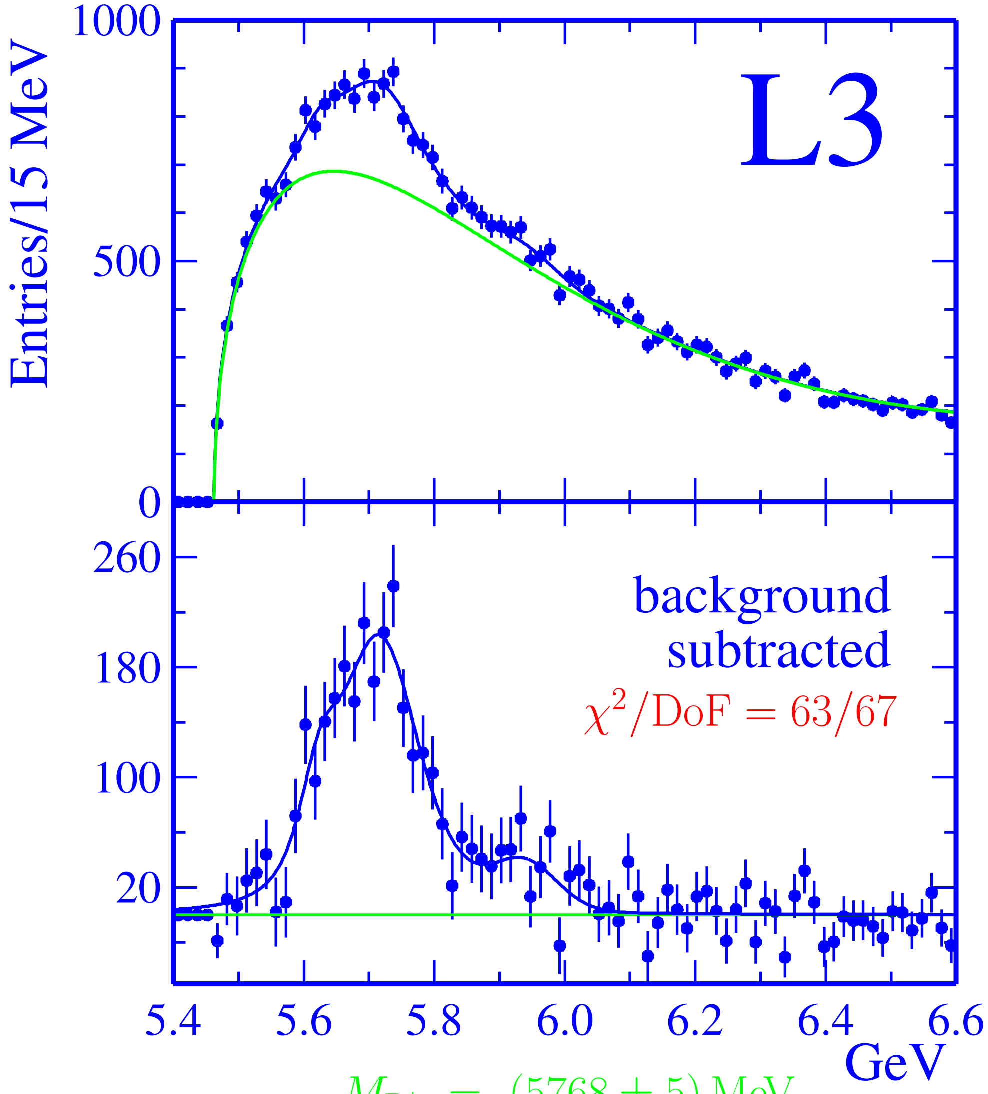
Bπ Mass Fit

Excluding $M_{B\pi} = 5.9 - 6.0$ GeV



$$
\begin{aligned}
M_{B_2^*} &= (5769 \pm 6)\ \mathrm{MeV} \\
\Gamma_{B_2^*} &= (31 \pm 27)\ \mathrm{MeV} \\
M_{B_1^*} &= (5673 \pm 12)\ \mathrm{MeV} \\
\Gamma_{B_1^*} &= (75 \pm 29)\ \mathrm{MeV} \\
\mathrm{Br}(b \to B_{u,d}^{**}) &= 0.32 \pm 0.04
\end{aligned}
$$

Including Gaussian for B′



$$M_{\mathrm{B}_2^*} = (5768 \pm 5)\ \mathrm{MeV}$$

$$\Gamma_{\mathrm{B}_2^*} = (24 \pm 19)\ \mathrm{MeV}$$

$$M_{\mathrm{B}_1^*} = (5670 \pm 10)\ \mathrm{MeV}$$

$$\Gamma_{\mathrm{B}_1^*} = (70 \pm 21)\ \mathrm{MeV}$$

$$\mathrm{Br}(b \rightarrow \mathrm{B}_{u,d}^{**}) = 0.32 \pm 0.03$$

$$M_{\mathrm{B}'} = (5937 \pm 21)\ \mathrm{MeV}$$

$$\sigma_{\mathrm{B}'} = (50 \pm 22)\ \mathrm{MeV}$$

$$\mathrm{Br}(b \rightarrow \mathrm{B}') = 0.034 \pm 0.011$$

Uncertainty Estimates

Systematic Uncertainty

Sources	$\delta M_{B_2^*}$	$\delta\Gamma_{B_2^*}$	$\delta M_{B_1^*}$	$\delta\Gamma_{B_1^*}$	$\delta \mathrm{Br}(B_{u,d}^{**})$	$\delta M_{B'}$	$\delta\sigma_{B'}$	$\delta \mathrm{Br}(B')$
b purity	—	—	—	—	± 0.01	—	—	± 0.007
background modelling	± 2	± 9	± 3	± 9	± 0.05	± 2	± 2	± 0.002
mass constraints	± 4	± 7	± 4	± 7	< 0.01	± 1	± 1	< 0.01
width constraints	< 1	± 2	< 1	± 2	< 0.01	< 1	± 2	< 0.01
signal resolution	± 2	± 9	± 1	± 9	± 0.01	< 1	< 1	< 0.01
signal efficiency	< 1	± 1	< 1	± 1	± 0.01	< 1	< 1	± 0.001
existence of B'	± 3	± 19	± 12	± 19	± 0.01	—	—	—
Total	± 6	± 24	± 13	± 24	± 0.05	± 2	± 3	± 0.007

Systematic Tests

- Background
  - variation of background function parameters
  - fits with other background functions
- Signal
  - variation of mass constraints
  - variation of width constraints
  - variation of slope/offset of resolution function
  - definition of efficiency function and subsequent variations
  - fits with and without B'
- Miscellaneous
  - removal of $j_q = 1/2$ mass difference constraint
  - forced spin-orbit conversion
  - studies of $B^{**} \to B\pi\pi$ and $B_s^{**} \to BK$ fakes

Results of This Measurement

$$
\begin{aligned}
M_{\mathrm{B}_2^*} &= (5768 \pm 5(\text{stat}) \pm 6(\text{syst}))\ \mathrm{MeV} \\
\Gamma_{\mathrm{B}_2^*} &= (24 \pm 19(\text{stat}) \pm 24(\text{syst}))\ \mathrm{MeV} \\
M_{\mathrm{B}_1^*} &= (5670 \pm 10(\text{stat}) \pm 13(\text{syst}))\ \mathrm{MeV} \\
\Gamma_{\mathrm{B}_1^*} &= (70 \pm 21(\text{stat}) \pm 24(\text{syst}))\ \mathrm{MeV} \\
\mathrm{Br}(b \to \mathrm{B}_{u,d}^{**}) &= 0.32 \pm 0.03(\text{stat}) \pm 0.05(\text{syst}) \\
M_{\mathrm{B}'} &= (5937 \pm 21(\text{stat}) \pm 2(\text{syst}))\ \mathrm{MeV} \\
\sigma_{\mathrm{B}'} &= (50 \pm 22(\text{stat}) \pm 3(\text{syst}))\ \mathrm{MeV} \\
\mathrm{Br}(b \to \mathrm{B}') &= 0.034 \pm 0.011(\text{stat}) \pm 0.007(\text{syst})
\end{aligned}
$$

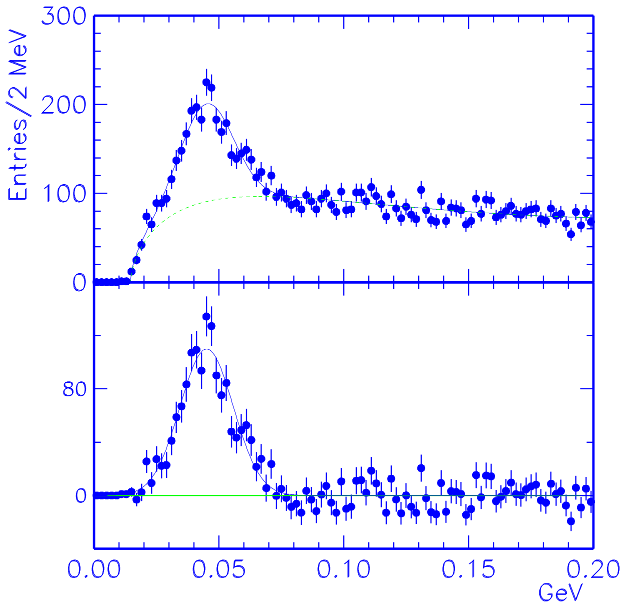
Other B^{**} Measurements from LEP

Analysis	Measurement
OPAL	$M(\mathrm{B}_{u,d}^{**}) = (5.60 - 5.85)\ \mathrm{GeV}$
Inclusive	$\mathrm{Br}(\bar{b} \to \mathrm{B}^{**0} \to \mathrm{B}^{(*)+}\pi^-)/\mathrm{Br}(\bar{b} \to \mathrm{B}^+)$
(Vertex Charge)	$= 0.18 \pm 0.01(\text{stat}) \pm 0.04(\text{syst})$
DELPHI	$M(\mathrm{B}_{u,d}^{**}) = (5734 \pm 5(\text{stat}) \pm 17(\text{syst}))\ \mathrm{MeV}$
Inclusive	$\sigma(\Delta M) = (72 \pm 5(\text{stat}) \pm 8(\text{syst}))\ \mathrm{MeV}$
(Rapidity)	$\mathrm{Br}(b \to \mathrm{B}_{u,d}^{**}) = 0.26 \pm 0.015(\text{stat}) \pm 0.05(\text{syst})$
ALEPH	$M(\mathrm{B}_{u,d}^{**}) = (5703 \pm 4(\text{stat}) \pm 10(\text{syst}))\ \mathrm{MeV}$
Inclusive	$\sigma(\Delta M) = (53 \pm 3(\text{stat}) \pm 9(\text{syst}))\ \mathrm{MeV}$
(Rapidity)	$\mathrm{Br}(b \to \mathrm{B}_{u,d}^{**}) = 0.279 \pm 0.016(\text{stat}) \pm 0.059(\text{syst})\ {}^{+3.9}_{-5.6}(\text{model})$
ALEPH	$M_{\mathrm{B}_2^*} = (5739\ {}^{+8}_{-11}(\text{stat})\ {}^{+6}_{-4}(\text{syst}))\ \mathrm{MeV}$
Reconstructed	$\mathrm{Br}(b \to \mathrm{B}_{u,d}^{**}) = 0.31 \pm 9(\text{stat})\ {}^{+6}_{-5}(\text{syst})$

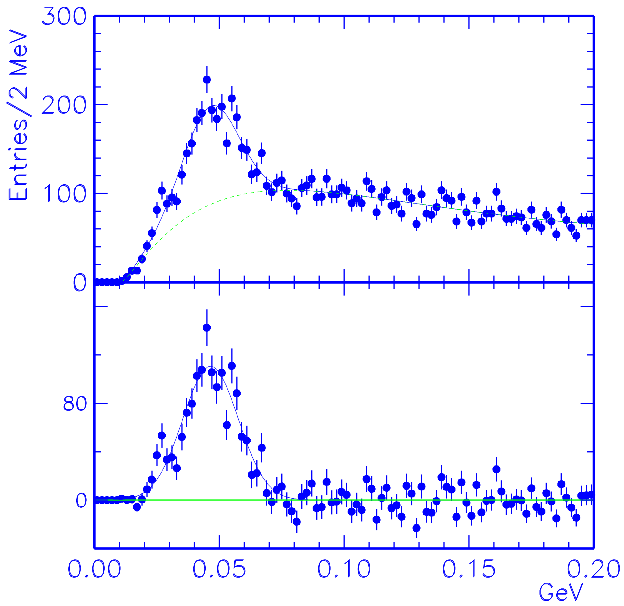
Mass Resolution

Confidence in Data/MC Agreement

- Largest Component Due to B Reconstruction
- Same as for B^* Uncertainty



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



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

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

All Measured Parameters

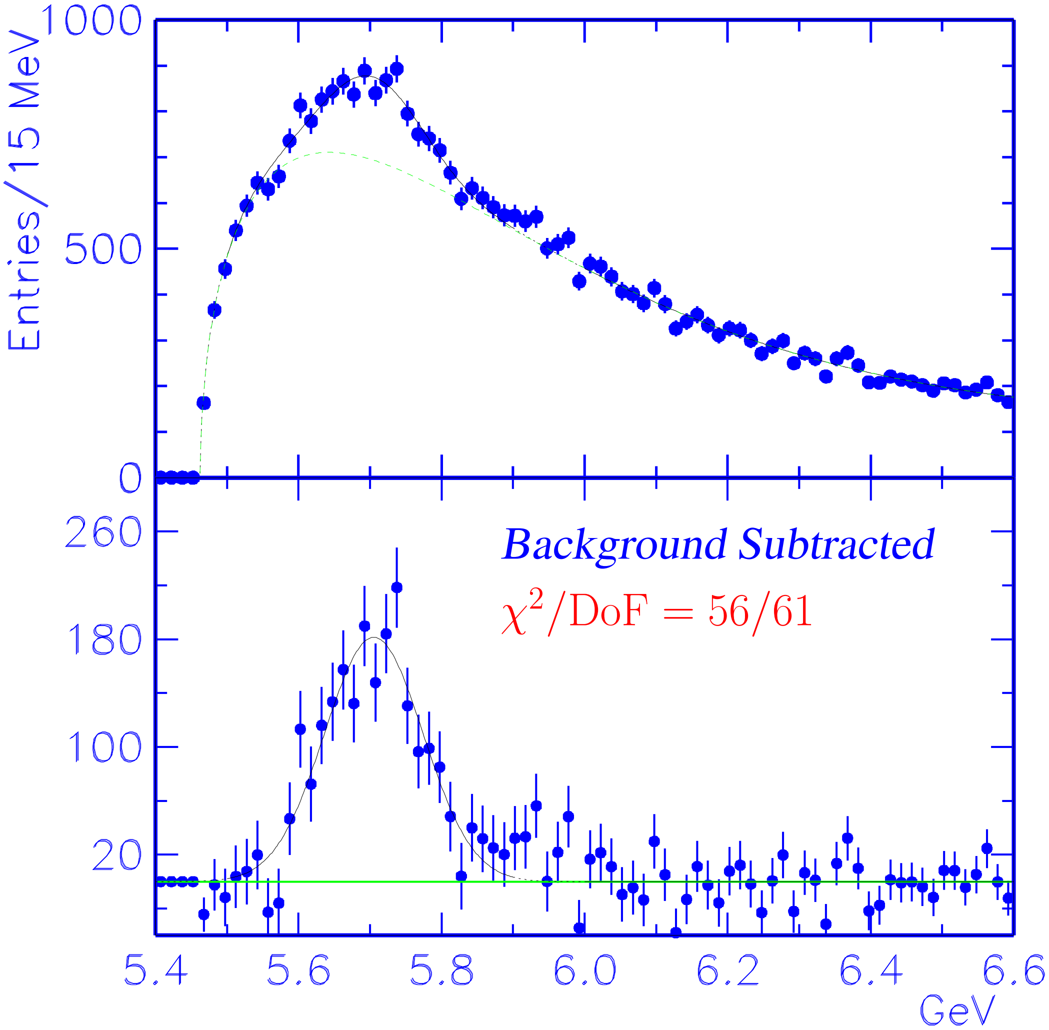
	Global	$N_{\rm bgd}$	$N_{\rm B_2^*}$	$M_{\rm B_2^*}$	$\Gamma_{\rm B_2^*}$	$M_{\rm B_1^*}$	$\Gamma_{\rm B_1^*}$	$N_{\rm B'}$	$M_{\rm B'}$	$\Gamma_{\rm B'}$
$N_{\rm bgd}$	0.82040	1.000	-0.579	0.100	-0.231	0.144	-0.140	-0.606	-0.157	-0.432
$N_{\rm B_2^*}$	0.82977	-0.579	1.000	0.133	0.607	0.004	0.468	0.050	0.289	-0.022
$M_{\rm B_2^*}$	0.59576	0.100	0.133	1.000	-0.041	0.276	-0.124	-0.355	0.247	-0.362
$\Gamma_{\rm B_2^*}$	0.73913	-0.231	0.607	-0.041	1.000	0.269	0.506	-0.127	0.192	-0.060
$M_{\rm B_1^*}$	0.47792	0.144	0.004	0.276	0.269	1.000	0.023	-0.244	0.090	-0.190
$\Gamma_{\rm B_1^*}$	0.59168	-0.140	0.468	-0.124	0.506	0.023	1.000	-0.115	0.120	-0.086
$N_{\rm B'}$	0.86046	-0.606	0.050	-0.355	-0.127	-0.244	-0.115	1.000	-0.024	0.773
$M_{\rm B'}$	0.40642	-0.157	0.289	0.247	0.192	0.090	0.120	-0.024	1.000	0.058
$\Gamma_{\rm B'}$	0.79260	-0.432	-0.022	-0.362	-0.060	-0.190	-0.086	0.773	0.058	1.000

$\rm B_2^*$ and $\rm B_1^*$ Parameters Only

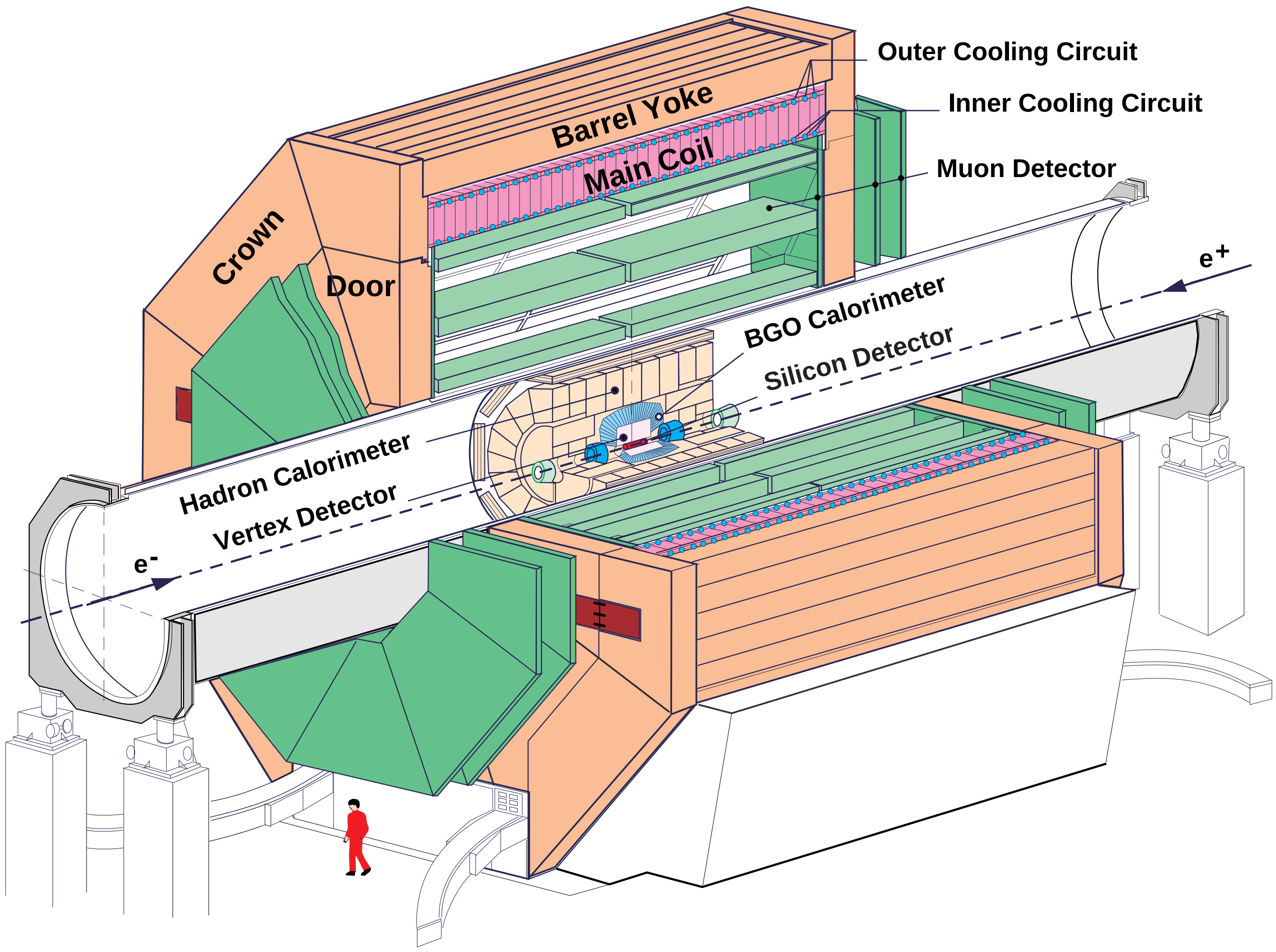
	Global	$N_{\rm bgd}$	$N_{\rm B_2^*}$	$M_{\rm B_2^*}$	$\Gamma_{\rm B_2^*}$	$M_{\rm B_1^*}$	$\Gamma_{\rm B_1^*}$
$N_{\rm bgd}$	0.75933	1.000	-0.754	-0.118	-0.546	-0.188	-0.388
$N_{\rm B_2^*}$	0.88642	-0.754	1.000	0.096	0.772	0.281	0.598
$M_{\rm B_2^*}$	0.45452	-0.118	0.096	1.000	-0.034	0.196	-0.213
$\Gamma_{\rm B_2^*}$	0.86402	-0.546	0.772	-0.034	1.000	0.525	0.646
$M_{\rm B_1^*}$	0.61593	-0.188	0.281	0.196	0.525	1.000	0.265
$\Gamma_{\rm B_1^*}$	0.70438	-0.388	0.598	-0.213	0.646	0.265	1.000

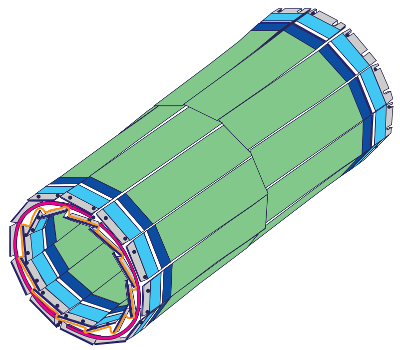
Bπ Mass Fit

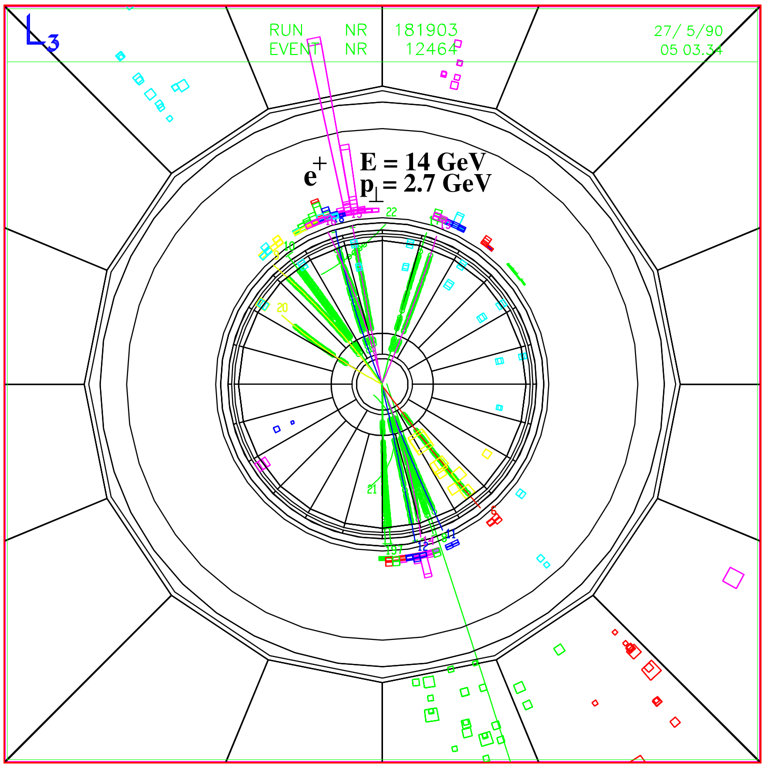
Gaussian + Background



$$\hat{M}_{\mathrm{B}^{**}} = (5705 \pm 5)\ \mathrm{MeV}$$
$$\hat{\sigma}_{\mathrm{B}^{**}} = (69 \pm 7)\ \mathrm{MeV}$$
$$\mathrm{Br}(b \rightarrow \mathrm{B}^{**}_{u,d}) = 0.28 \pm 0.03$$


Outer Cooling Circuit
Inner Cooling Circuit
Muon Detector
Barrel Yoke
Main Coil
Crown
Door
BGO Calorimeter
Silicon Detector
Hadron Calorimeter
Vertex Detector
e-
e+

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