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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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SMR.762 - 22

SUMMER SCHOOL IN HIGH ENERGY PHYSICS AND COSMOLOGY

13 June - 29 July 1994

B PHYSICS AT OPAL

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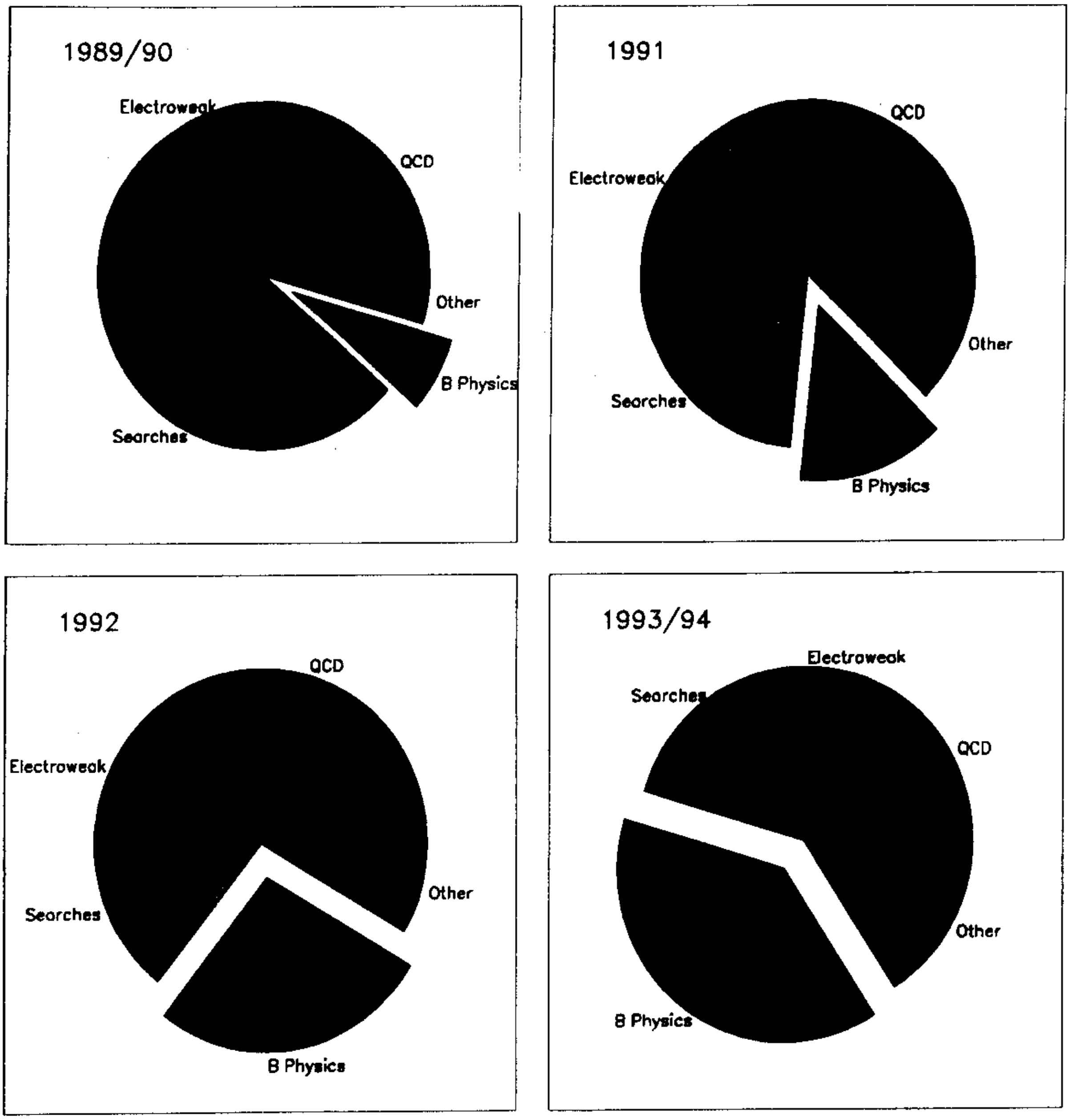
Please note: These are preliminary notes intended for internal distribution only.

S.L.Lloyd
ICTP Trieste
July 1994

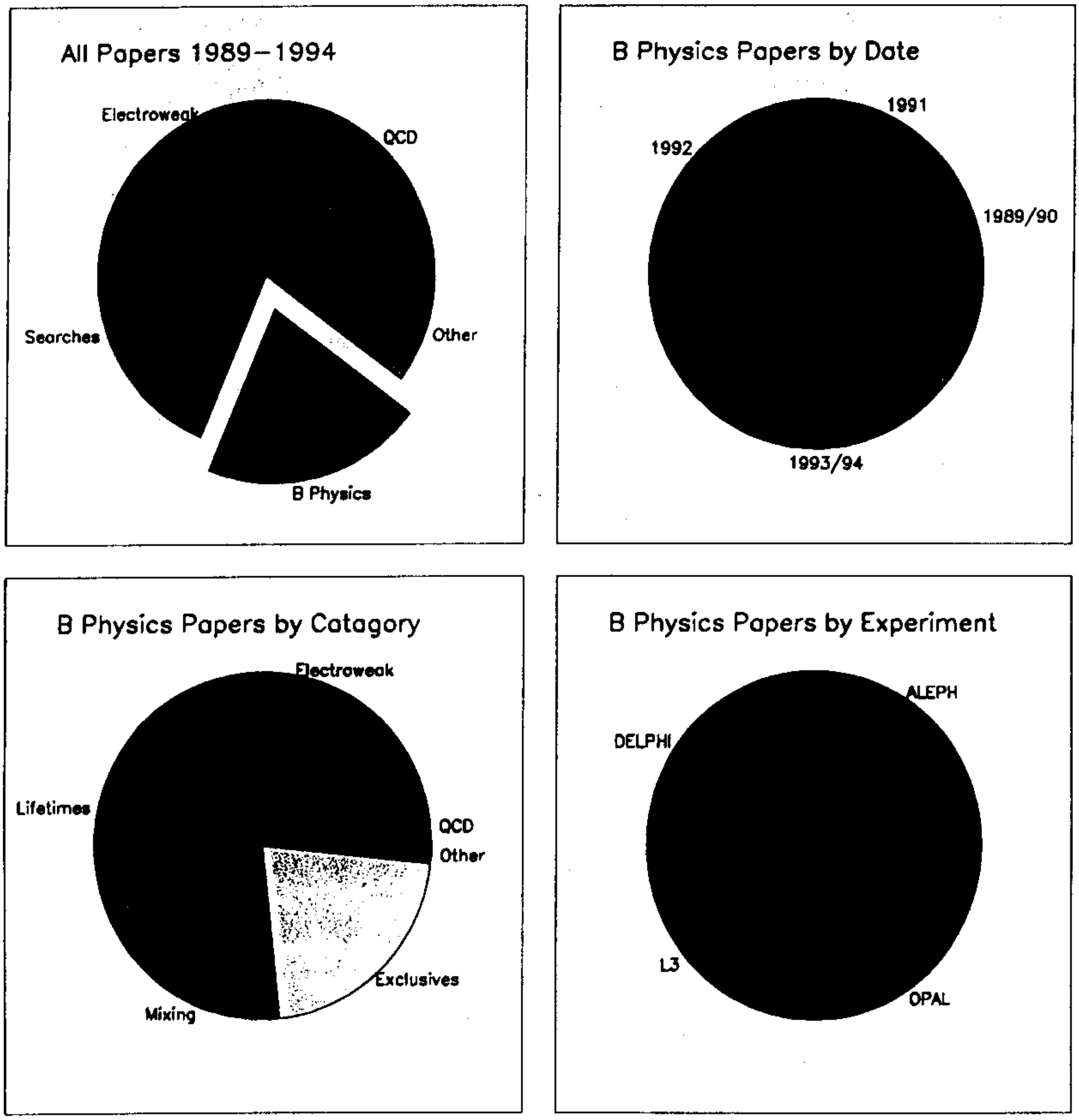
B Physics at OPAL

- Introduction
- Electroweak Measurements
- Lifetime Measurements
- Mixing
- Exclusive B Decays

LEP Physics Papers 1989–1994



LEP B Physics Papers 1989–1994



Why Study B's?

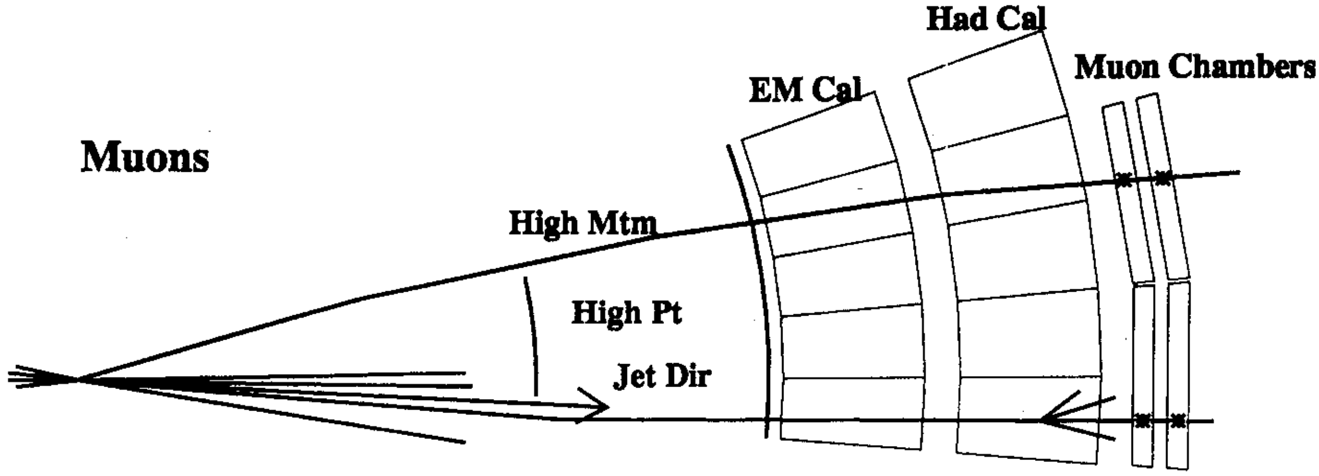
- Heaviest quark available
  At LEP, centre of mass energy $W \gg M_b \gg \Lambda_{QCD}$
- Intimately related to top quark (and Higgs)

Experimentally:

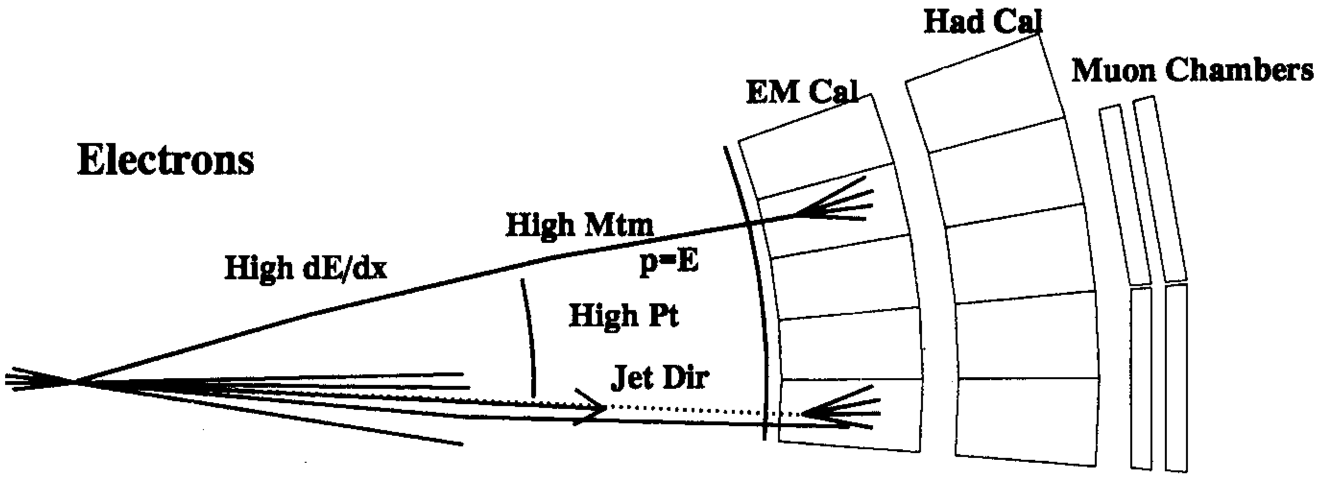
- Heavy mass
  $\Longrightarrow$ High momentum products
  (hard fragmentation)
  $\Longrightarrow$ High transverse momentum
  to initial quark direction
- Significant semi–leptonic branching ratios
  BR($b \rightarrow e$)$\sim$10%
  BR($b \rightarrow \mu$)$\sim$10%
  $\Longrightarrow$ Lepton tagging
- Long lived $\tau_b \sim 1.5$ps
  $\Longrightarrow$ Vertex tagging
- $Z^0 \rightarrow b\bar{b}$ is 22% of all hadronic Z^0 decays
- No target remnants

Each LEP experiment has $\sim$2 Million hadronic Z^0 decays
$\Longrightarrow \sim$ 500K $Z^0 \rightarrow b\bar{b}$ decays

B Identification using Leptons

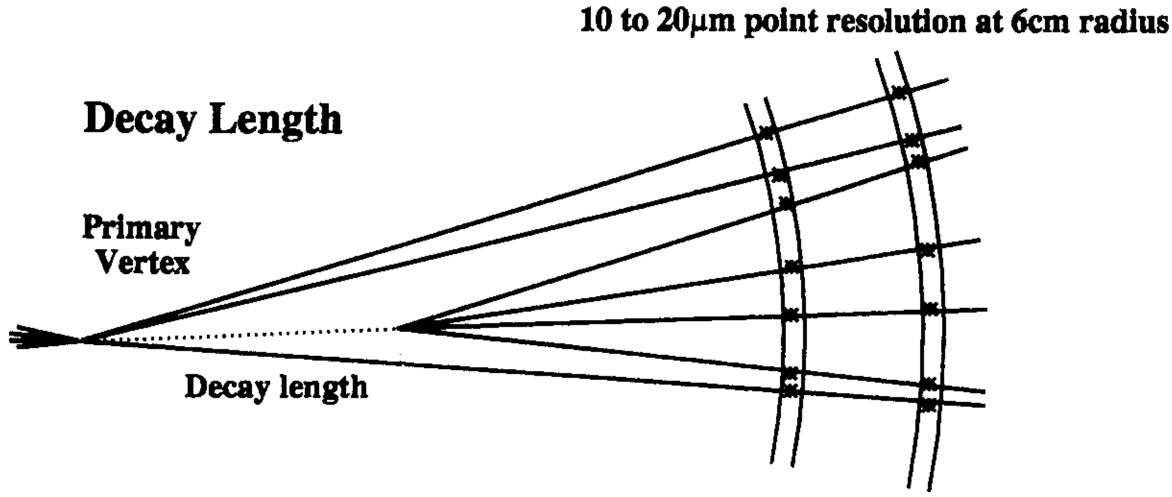


Background:
- Real muons from charm decays
- Muons from $K^{\pm}$ and $\pi^{\pm}$ decays
- Hadron interactions in calorimeters etc

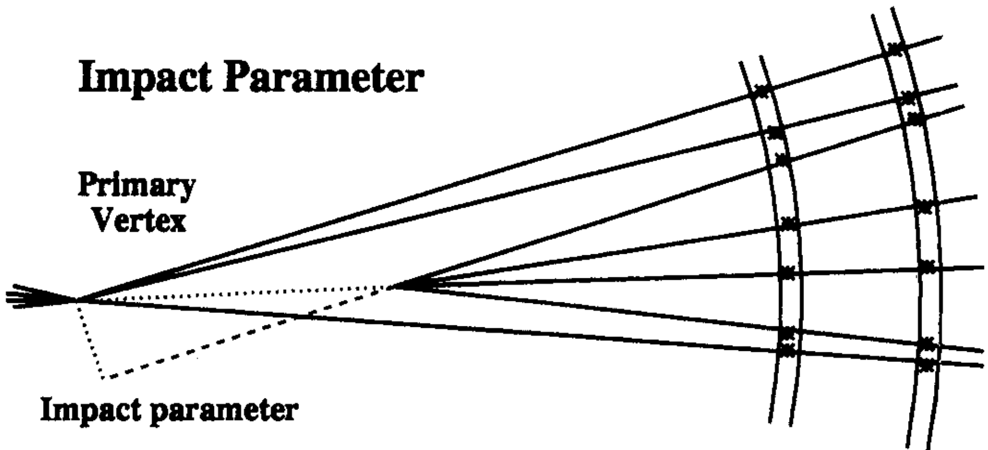


Background:
- Real electrons from charm decays
- Electrons from γ conversions
- Tracks overlapping with γs from π^0s

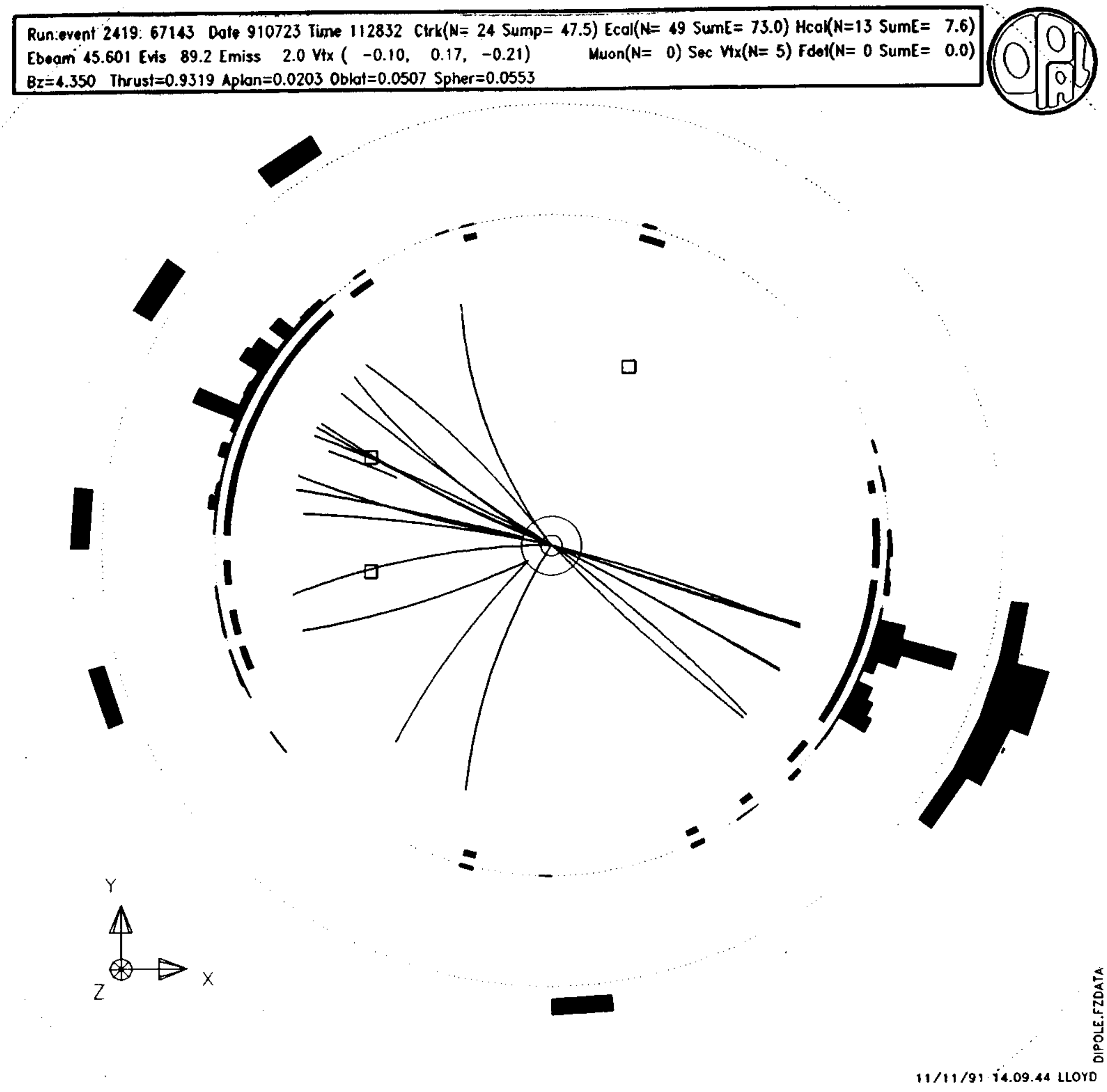
B Identification using Silicon Detectors

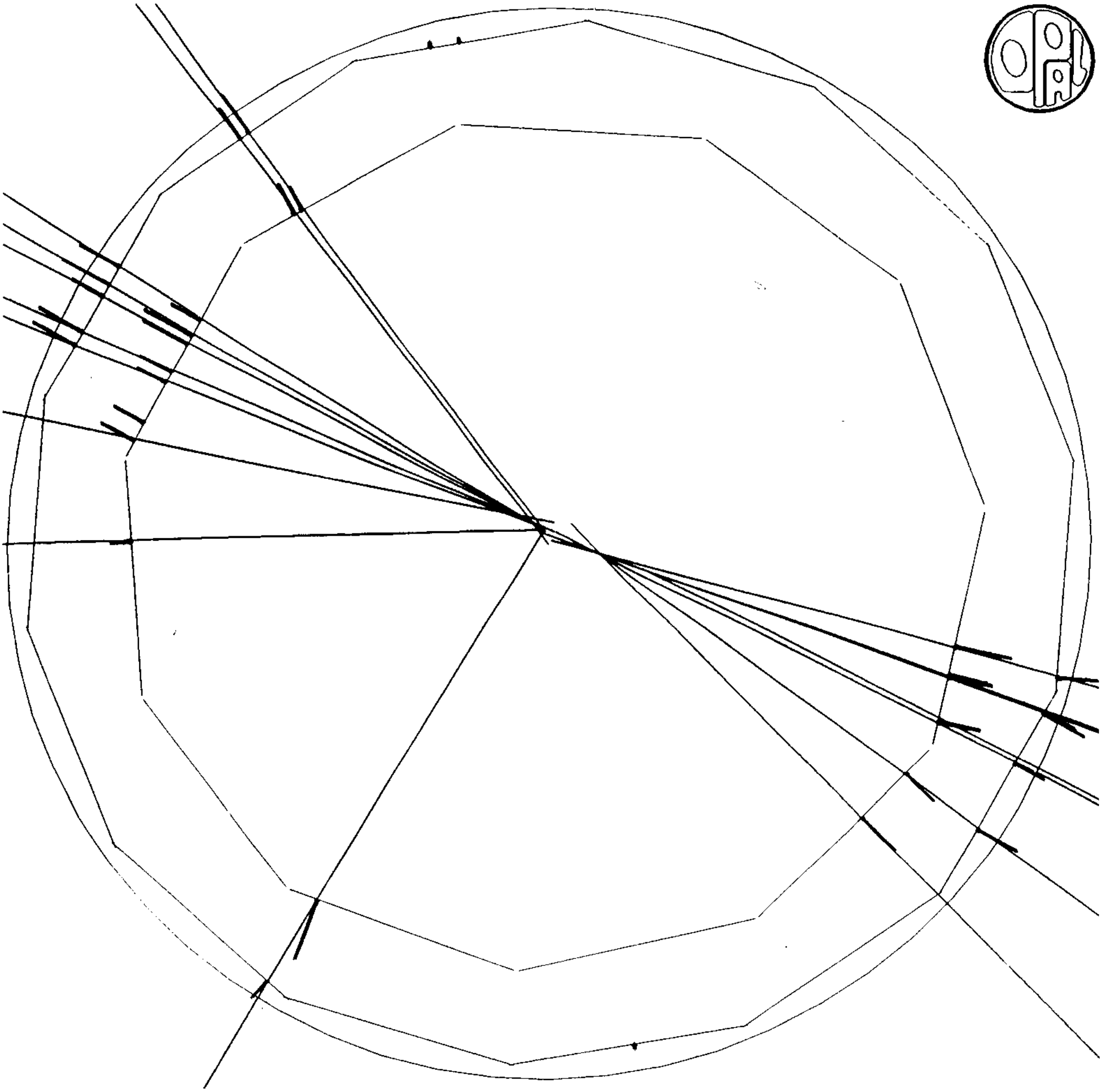


Typical decay length 2mm at LEP
Typical resolution 500μm

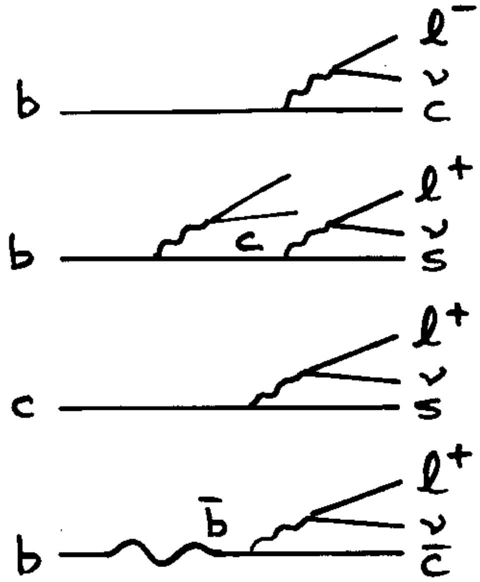


Typical resolution 20 to 50μm


Run:event 2419: 67143 Date 910723 Time 112832 Ctrk(N= 24 Sump= 47.5) Ecal(N= 49 SumE= 73.0) Hcal(N=13 SumE= 7.6)
Ebeam 45.601 Evis 89.2 Emiss 2.0 Vtx (-0.10, 0.17, -0.21) Muon(N= 0) Sec Vtx(N= 5) Fdet(N= 0 SumE= 0.0)
Bz=4.350 Thrust=0.9319 Aplan=0.0203 Oblat=0.0507 Spher=0.0553
Y
Z
X
DIPOLE.FZDATA
11/11/91 14.09.44 LLOYD



Sources of leptons



+ Background

Measurements

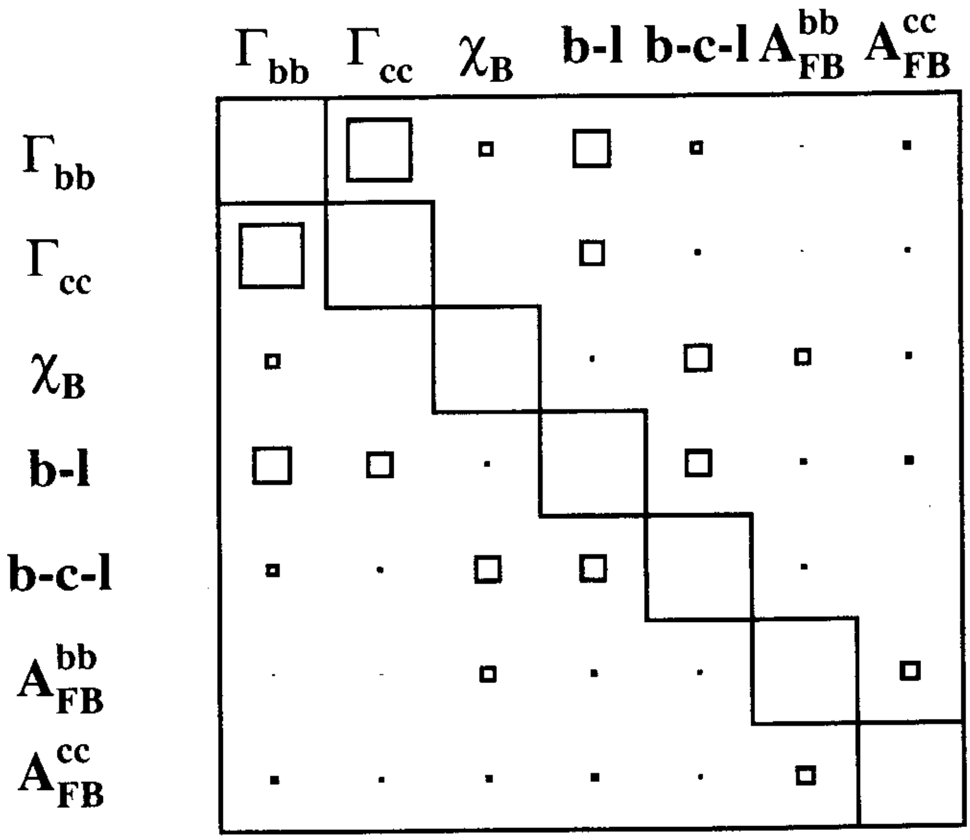
$\Gamma_{b\bar{b}}/\Gamma_{had}$	High p_t $\ell^\pm$
$\Gamma_{c\bar{c}}/\Gamma_{had}$	Low p_t $\ell^\pm$
Mixing χ_B	$\ell^+\ell^+$ or $\ell^-\ell^-$
A_{FB}^b , A_{FB}^c	Cos Θ distribution

+ Branching ratios

These are all correlated

Uncertainty in one

⇒ systematic error in others



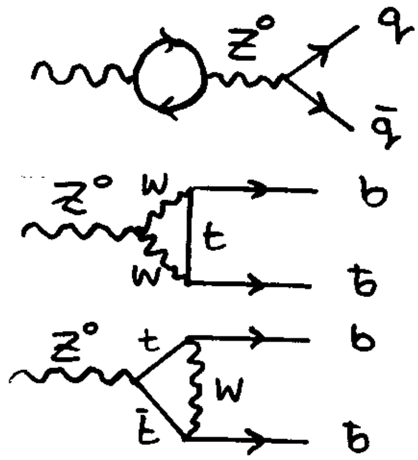
Solution ⇒ Global fits to all observables

p, p_t, charge, Cos Θ ....

⇒ Measure all quantities simultaneously

Measurement of Rb

$$R_b = \frac{\Gamma_{b\bar{b}}}{\Gamma_{had}} = \frac{\Gamma(Z^0 \to b\bar{b})}{\Gamma(Z^0 \to \text{hadrons})} \leftarrow \sum_{udscb} Z^0 \to q\bar{q}$$



- QCD effects largely cancel
- Higgs effects largely cancel
- $Zb\bar{b}$ vertex corrections cancel $t\bar{t}$ loops in $\Gamma_{b\bar{b}}$

$\Rightarrow$ Large M_t^2 dependence due to $t\bar{t}$ loops in Γ_{had}

In Principle:

Count number of 'b tags' 'tag' $= \begin{cases} \text{Lepton} \\ \text{Vertex} \\ \text{Event shape} \end{cases}$

$$N^{tag} = 2 \times N_{had} \times R_b \times \varepsilon_b + N^{tag}_{udsc}$$

Efficiency of tag from Monte Carlo
- dominates systematic error

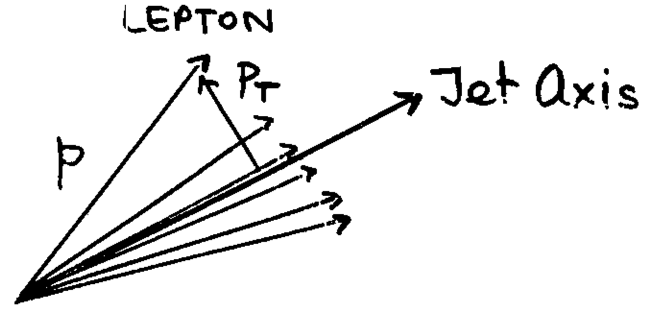
In Practice:

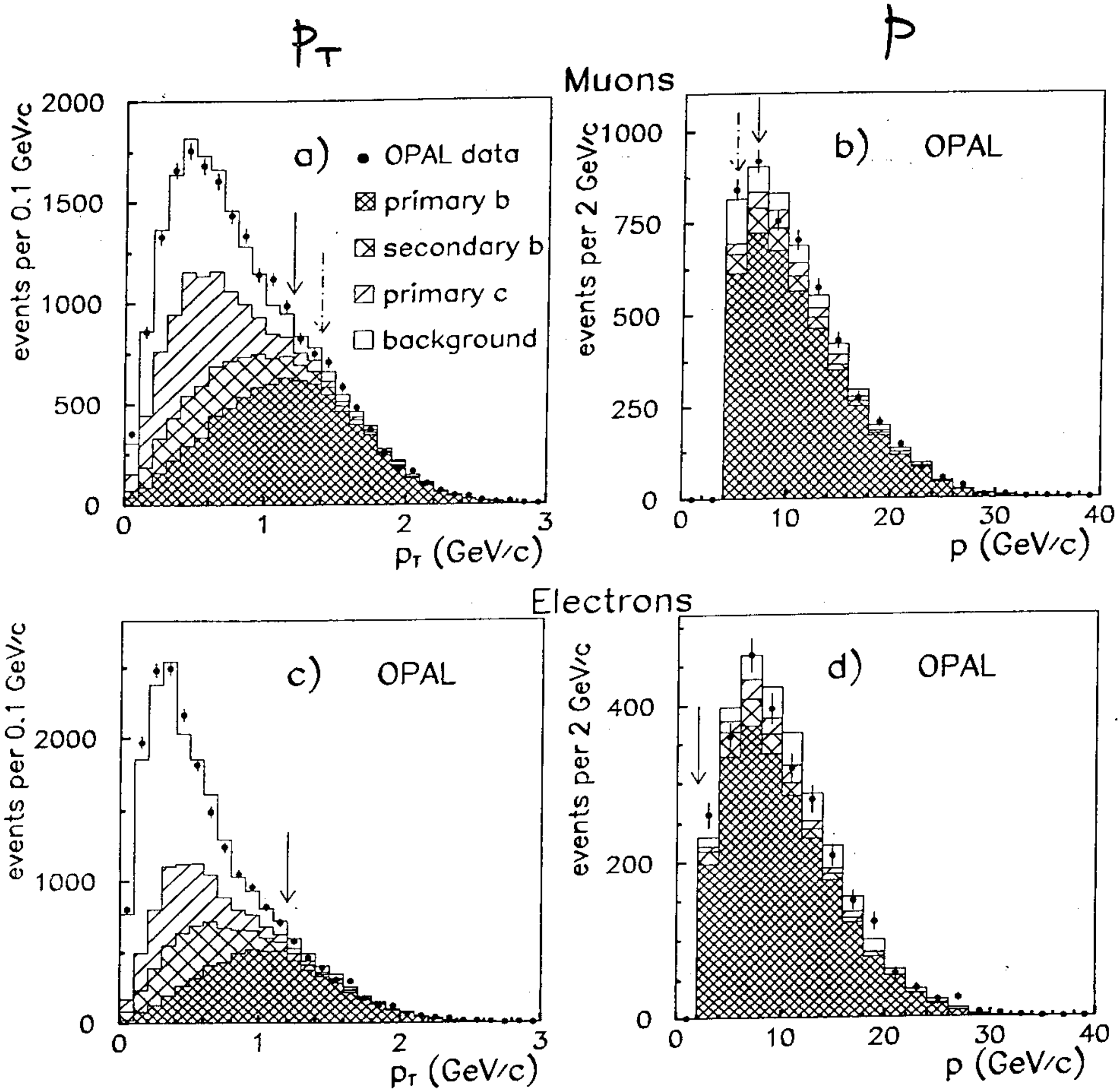
Count number of 'double tagged' events as well

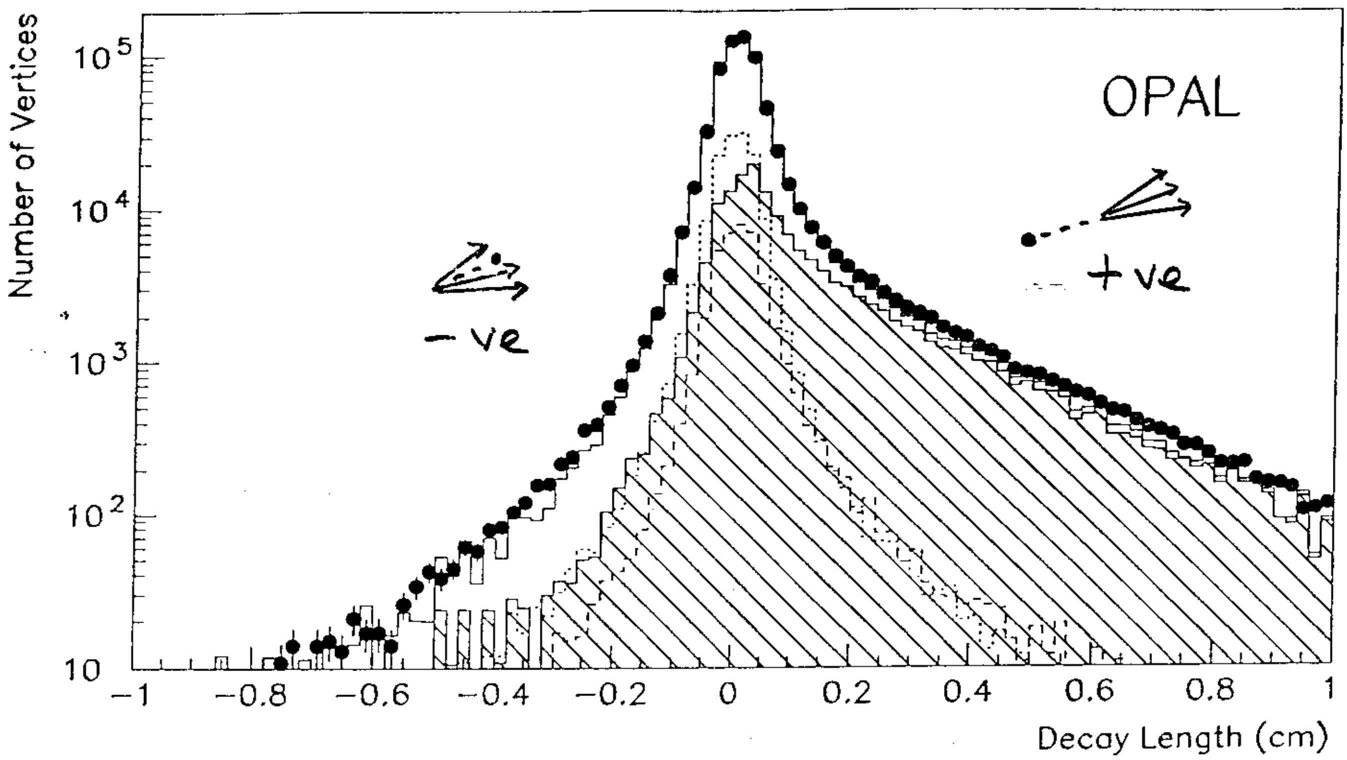
$$N^{double} = N_{had} \times R_b \times \varepsilon_b^2 + N^{double}_{udsc}$$

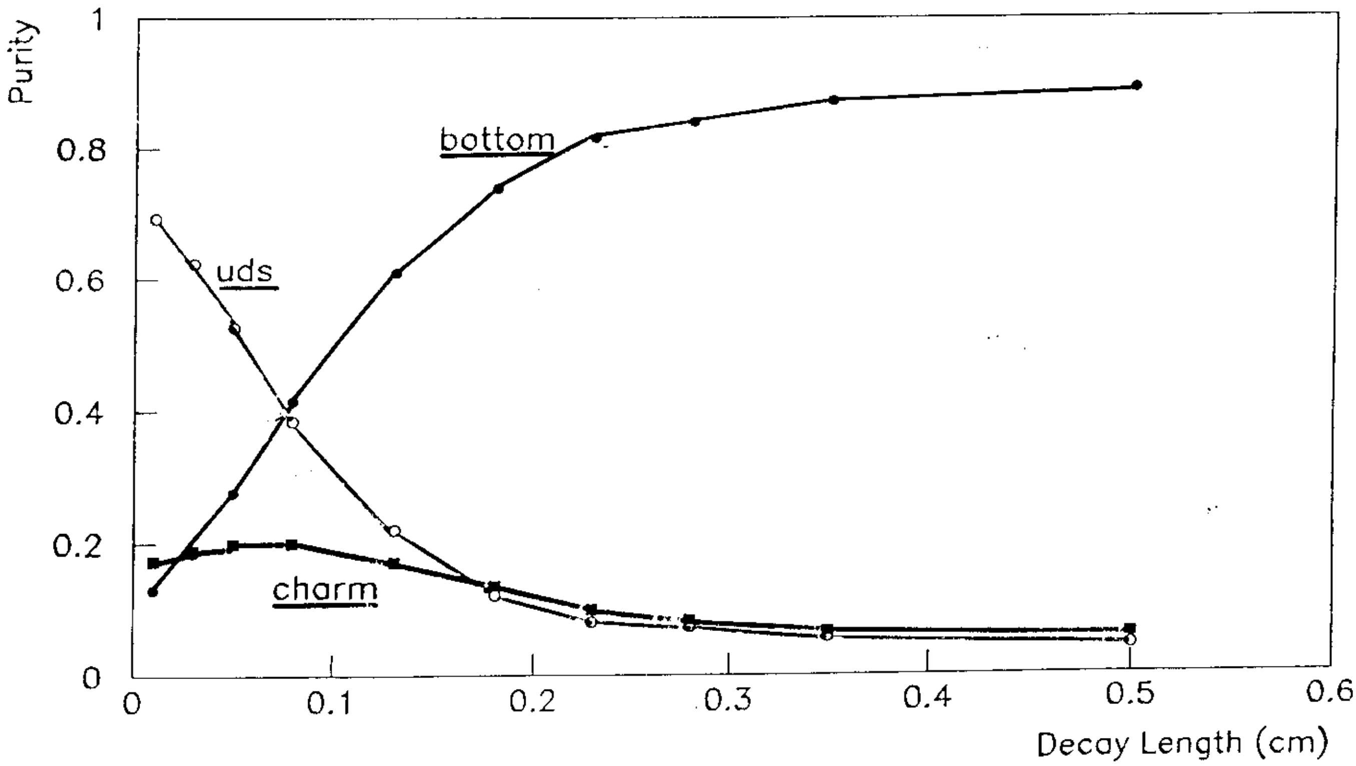
$$N^{single} = 2 \times N_{had} \times R_b \times \varepsilon_b(1-\varepsilon_b) + N^{single}_{udsc}$$

Solve for Rb and ε_b and hence reduce systematic errors (requires more data though)

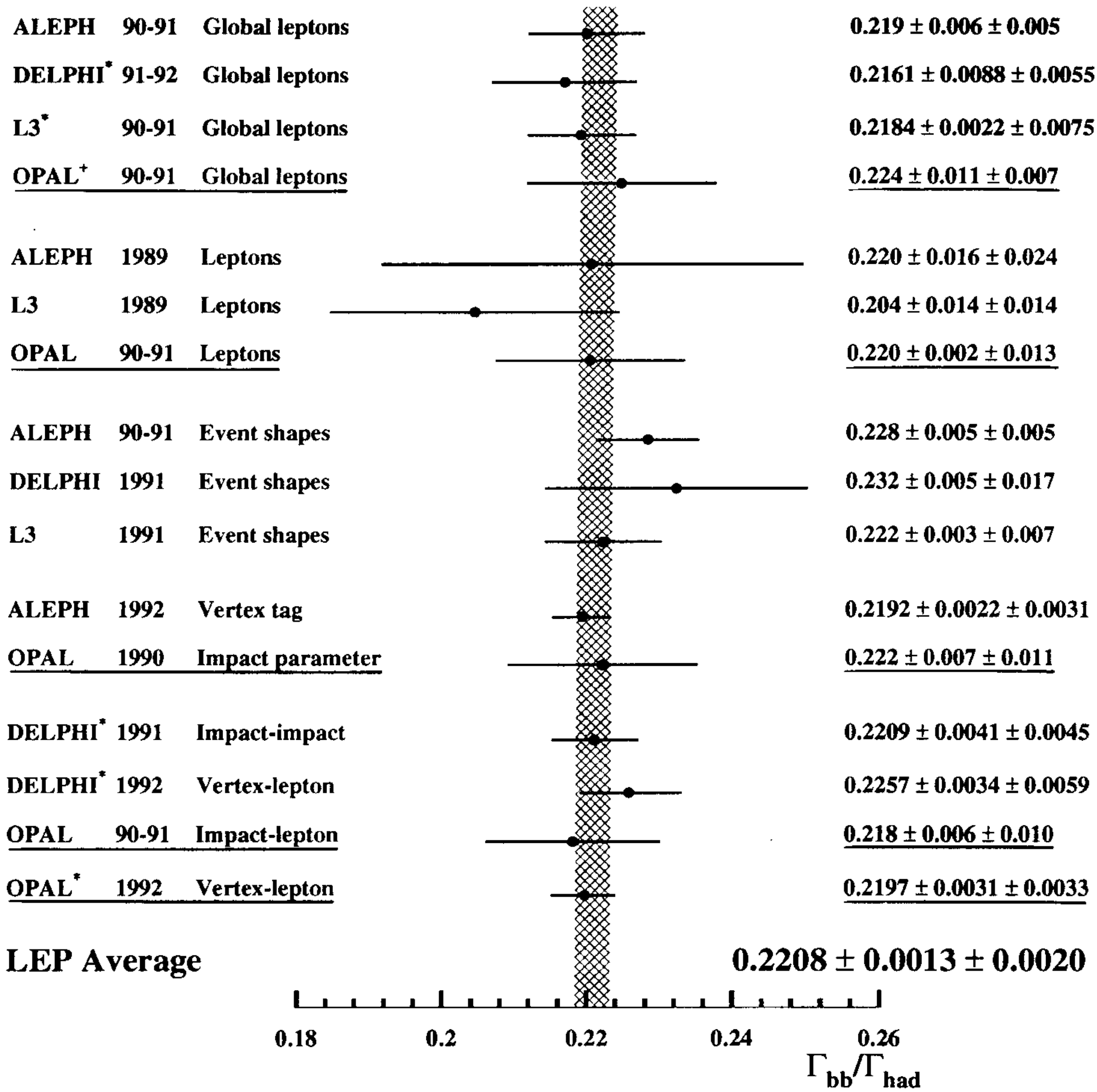

LEPTON
p_T
p
Jet Axis

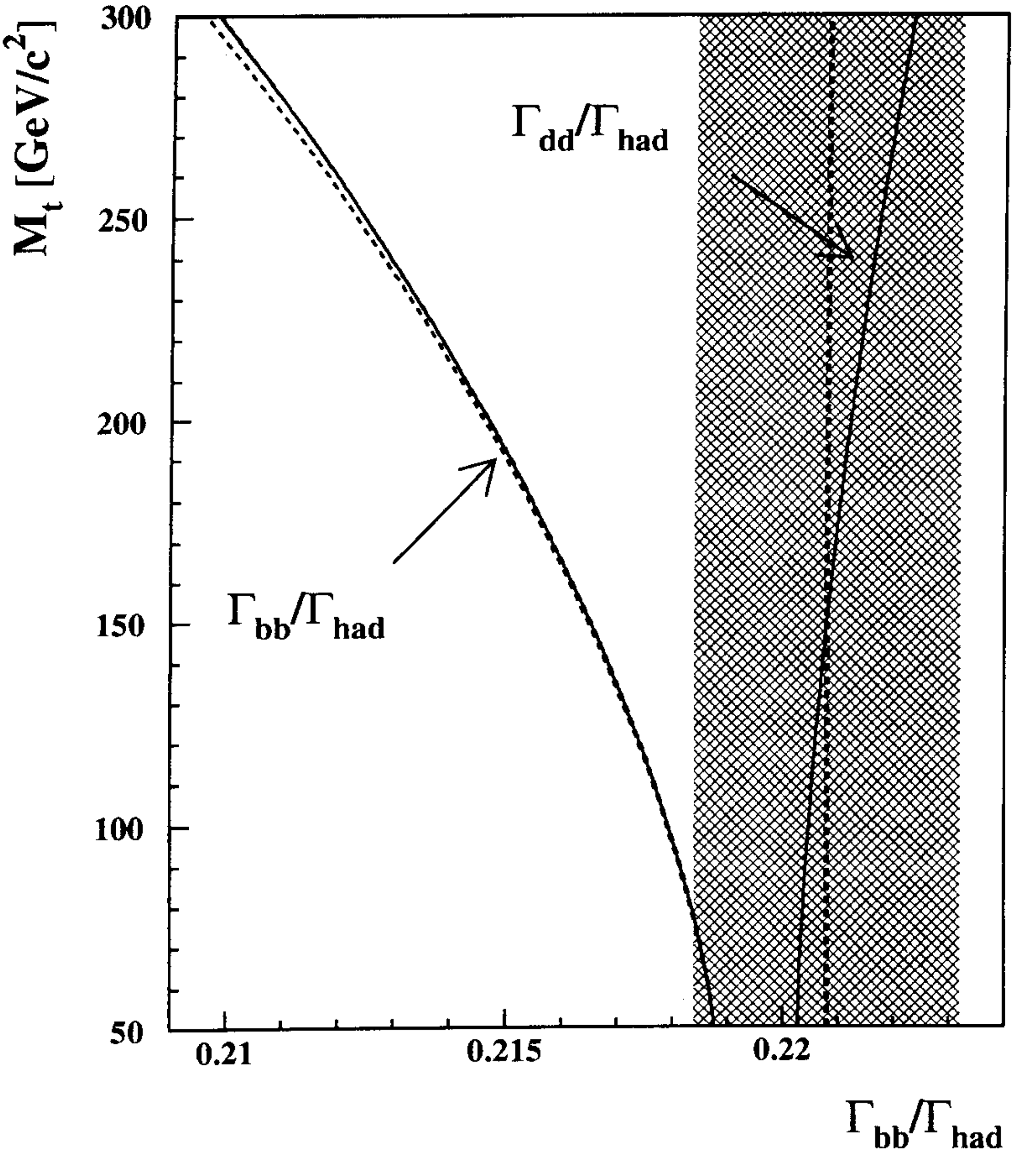

p_T
p
Muons
a)
OPAL data
primary b
secondary b
primary c
background
events per 0.1 GeV/c
p_T (GeV/c)
b) OPAL
events per 2 GeV/c
p (GeV/c)
Electrons
c) OPAL
events per 0.1 GeV/c
p_T (GeV/c)
d) OPAL
events per 2 GeV/c
p (GeV/c)


Number of Vertices
OPAL
-ve
+ve
Decay Length (cm)


Purity
bottom
uds
charm
Decay Length (cm)

$\Gamma_{b\bar{b}}/\Gamma_{had}$ Measurements from LEP





M_t [GeV/c^2]
300
250
200
150
100
50
0.21
0.215
0.22
Γ_{dd}/Γ_{had}
Γ_{bb}/Γ_{had}
Γ_{bb}/Γ_{had}

Forward Backward Asymmetry $A_{FB}^{b\bar{b}}$

$$\frac{d\sigma}{d(\cos\theta)} \propto (1+\cos^2\theta) + \frac{8}{3} A_{FB} \cos\theta$$

Cross section

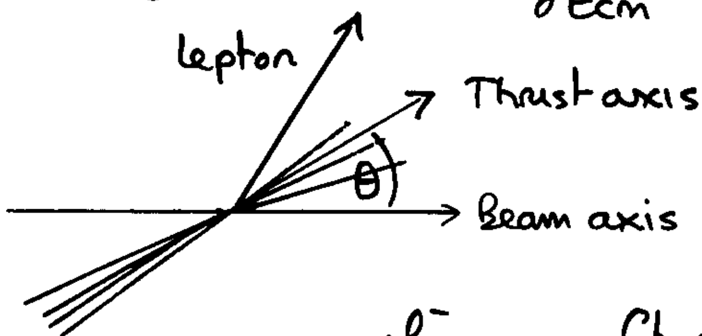
$\propto (a_e^2+v_e^2)(a_b^2+v_b^2)$

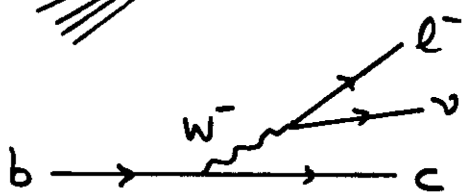
Forward Backward asymmetry

$$A_{FB} \propto \frac{a_e v_e a_b v_b}{(a_e^2+v_e^2)(a_b^2+v_b^2)}$$

- Since $\dfrac{\left(\frac{\partial A_{FB}^{b\bar{b}}}{\partial v_e}\right)}{\left(\frac{\partial A_{FB}^{b\bar{b}}}{\partial v_b}\right)} \sim \dfrac{v_b}{v_e} \sim 10$ $\quad A_{FB}^{b\bar{b}}$ mainly sensitive to v_e !!

Energy dependence $\dfrac{\partial A_{FB}^{b\bar{b}}}{\partial E_{cm}} \propto a_e a_b$



- 

Charge of lepton Q

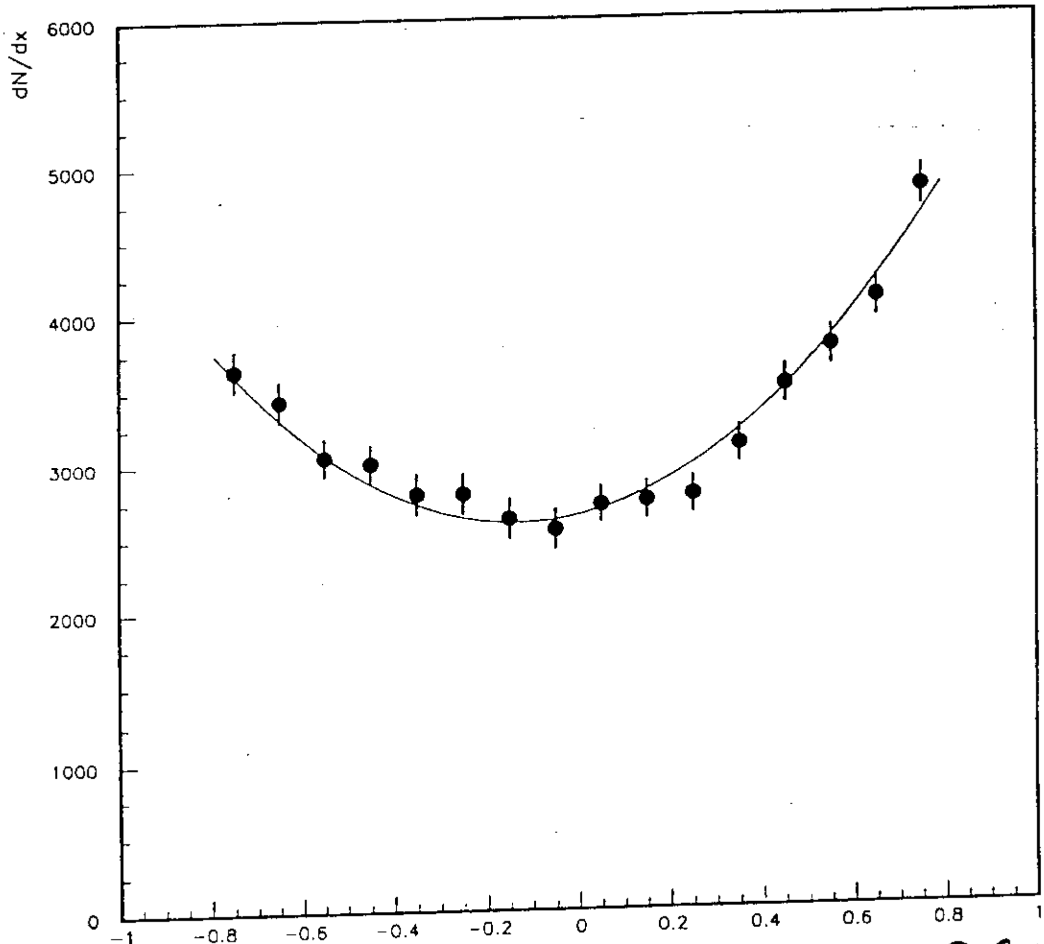
$\Rightarrow b$ or $\bar{b}$

Plot angular distribution of $-Q\cos\theta_{thrust}$

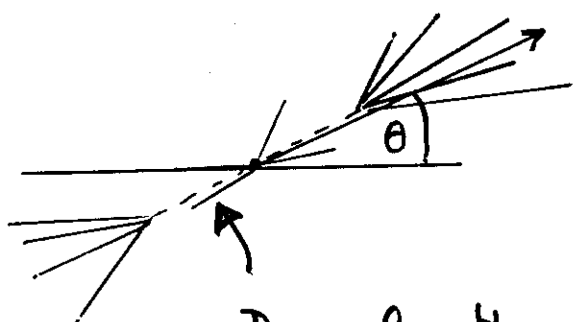
Problems:
- leptons from $b \to c \to \ell^+$
- leptons from $Z^0 \to c\bar{c} \to$ leptons
- Mixing $b \to \bar{b} \to \ell^+$
- Fake leptons

Corrections:
- Energy shift to Z^0
- QCD
- QED

Angular Distribution of $Z^0 \to b\bar{b}$ events using Jet Charge method.



$-Q \cos \theta$

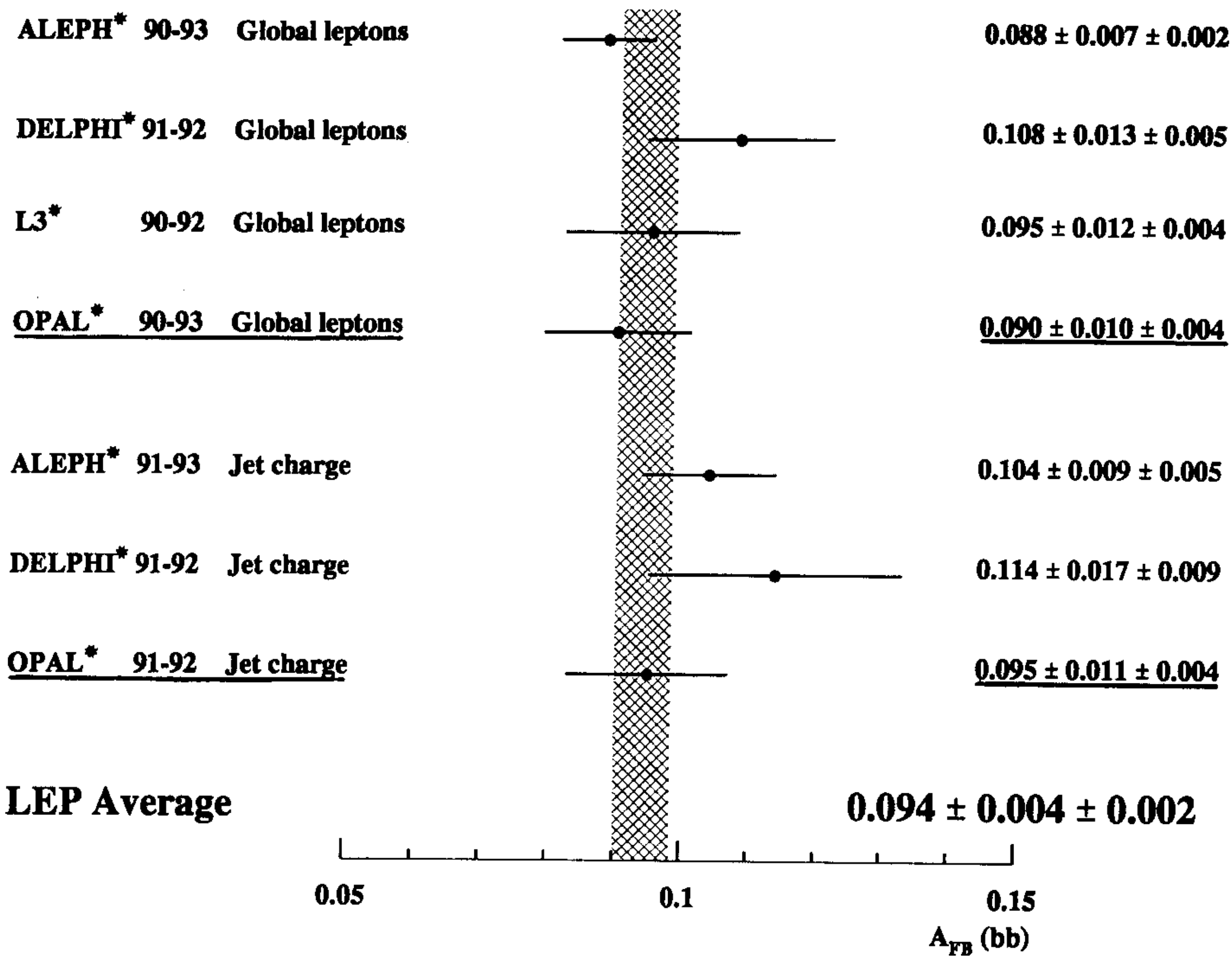


} Jet charge

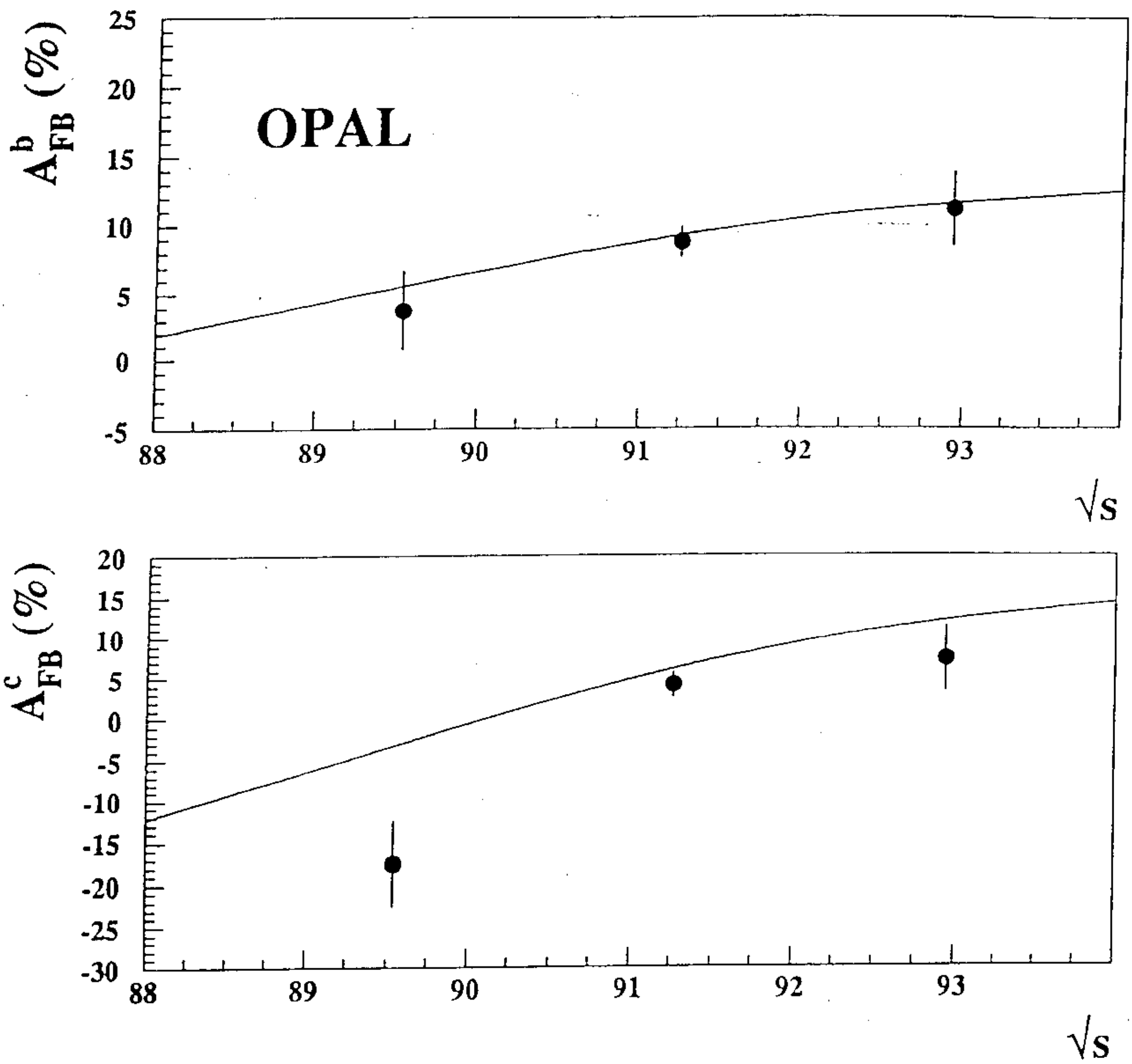
$$Q \doteq \frac{\sum^{jet} p_i^k q_i}{\sum p_i^k} \quad (k \sim 0.5)$$

Decay length
$\Rightarrow b\bar{b}$ event

$A_{FB}(b\bar{b})$ Measurements from LEP



Measurements of A_{FB}^{b} and A_{FB}^{c} compared to Standard Model predictions



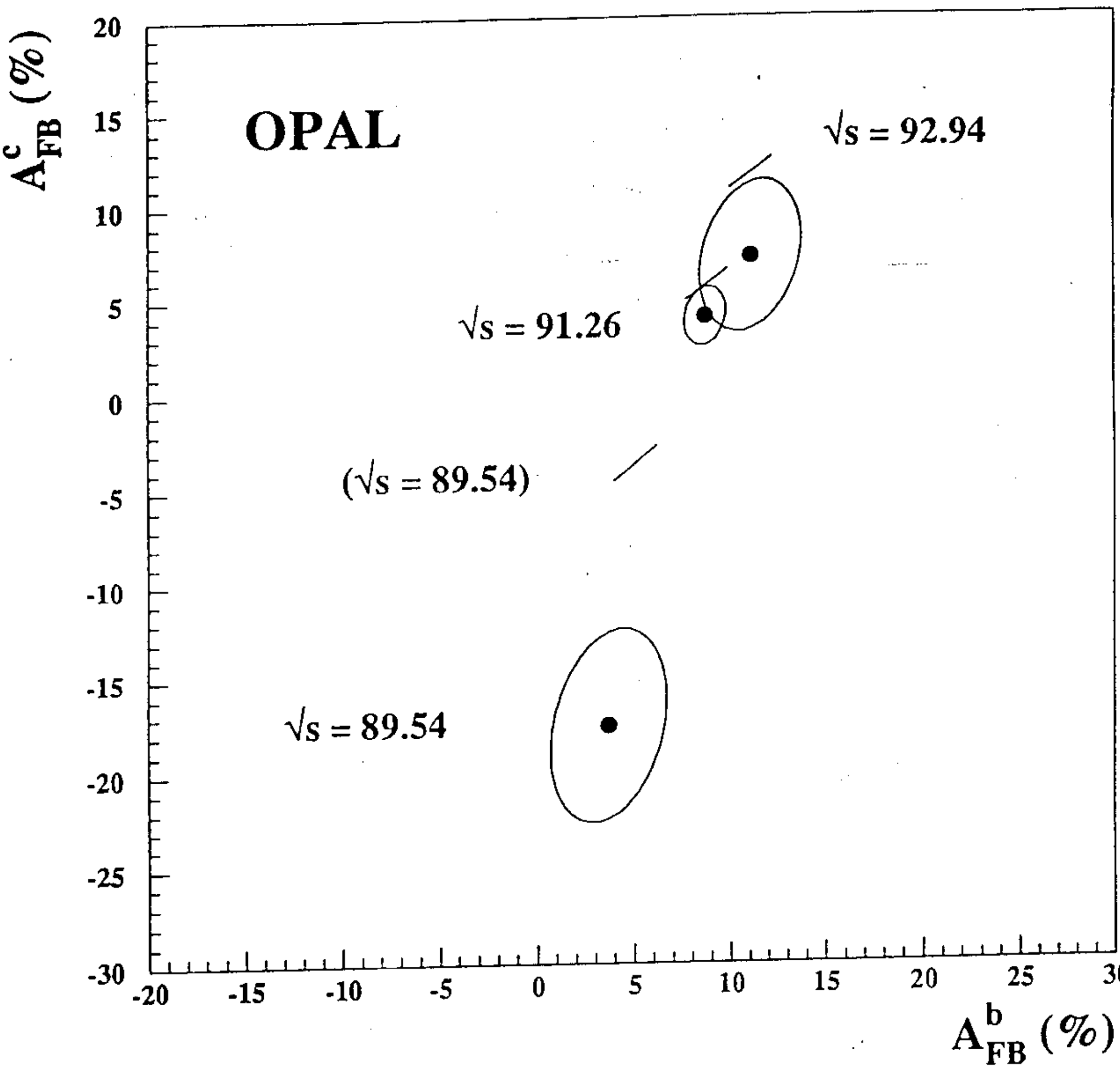
Centre of Mass Energy

Using $M_Z = 91.187\ GeV/c^2$

$M_H = 300\ GeV/c^2$

$\alpha_s = 0.12$

$M_{top} = 164\ GeV/c^2$

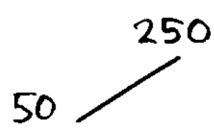


$M_Z = 91.187\ GeV/c^2$

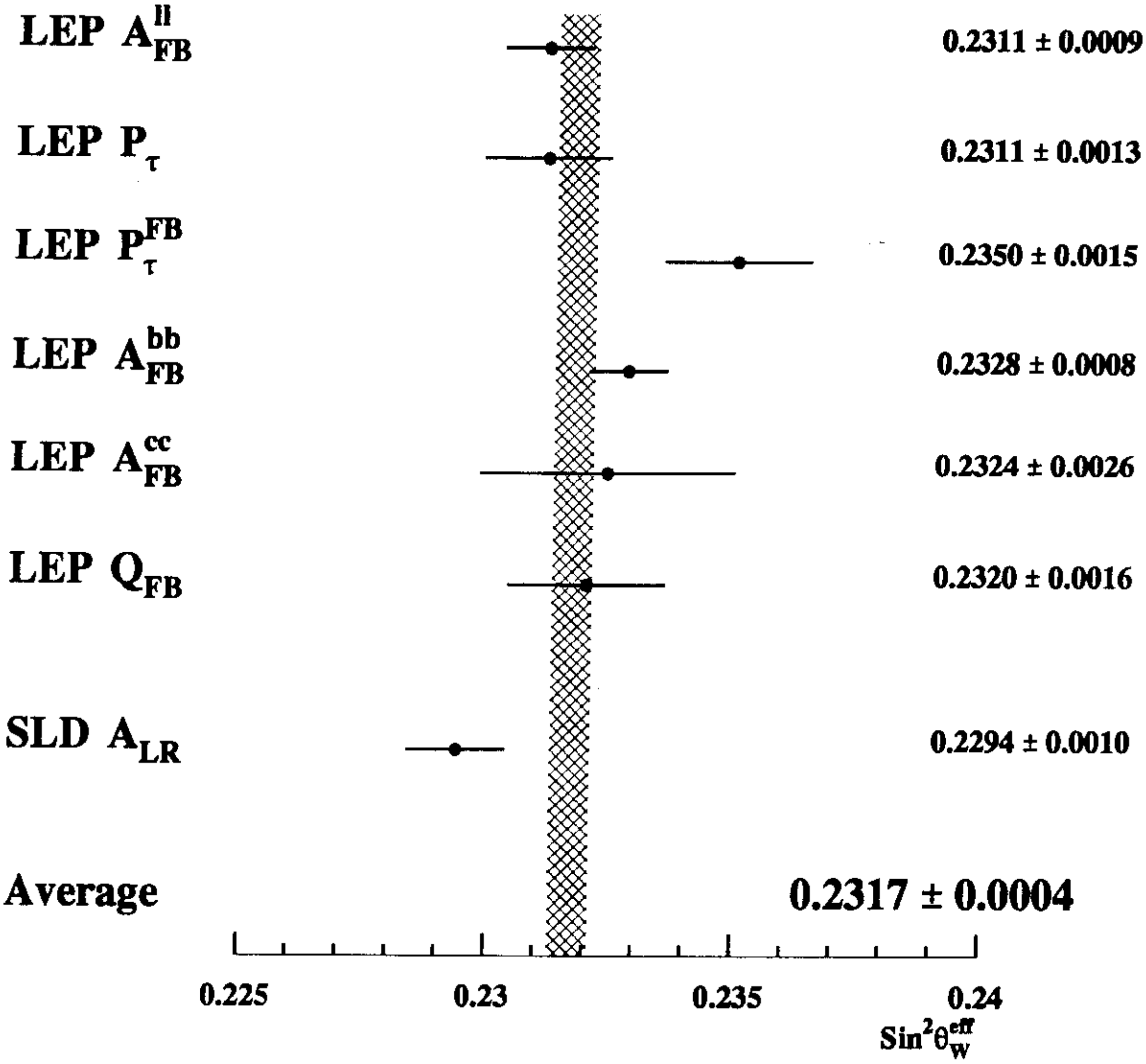
$M_H = 300\ GeV/c^2$

$\alpha_s = 0.12$

$M_{top} = 50$ to $250\ GeV/c^2$

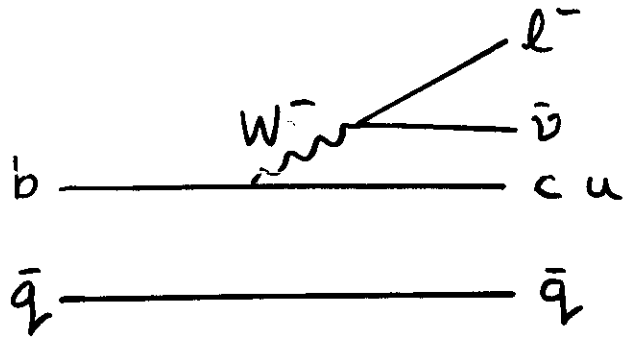


$\sin^2\theta_{\rm eff}^{\rm lept}$ Measurements from LEP/SLC



B lifetime

In Spectator Model



$$\Gamma(B \to X \ell \bar{\nu}) = \frac{Br(B \to X \ell \bar{\nu})}{\tau_b} = \frac{G_F^2 M_b^5}{192\pi^3}\left(K_c |V_{cb}|^2 + K_u |V_{ub}|^2\right)$$

$\frac{\Delta Br}{Br} \sim 3\%$ $\qquad\qquad$ $\frac{\Delta K}{K} \gtrsim 20\%$

- LEP Average $\tau_b = 1.533 \pm 0.022$ $\quad (\Sigma B^0, B^\pm, B_s, \Lambda_b)$

  $$\Rightarrow \frac{\Delta \tau_b}{\tau_b} \simeq 1.4\%$$

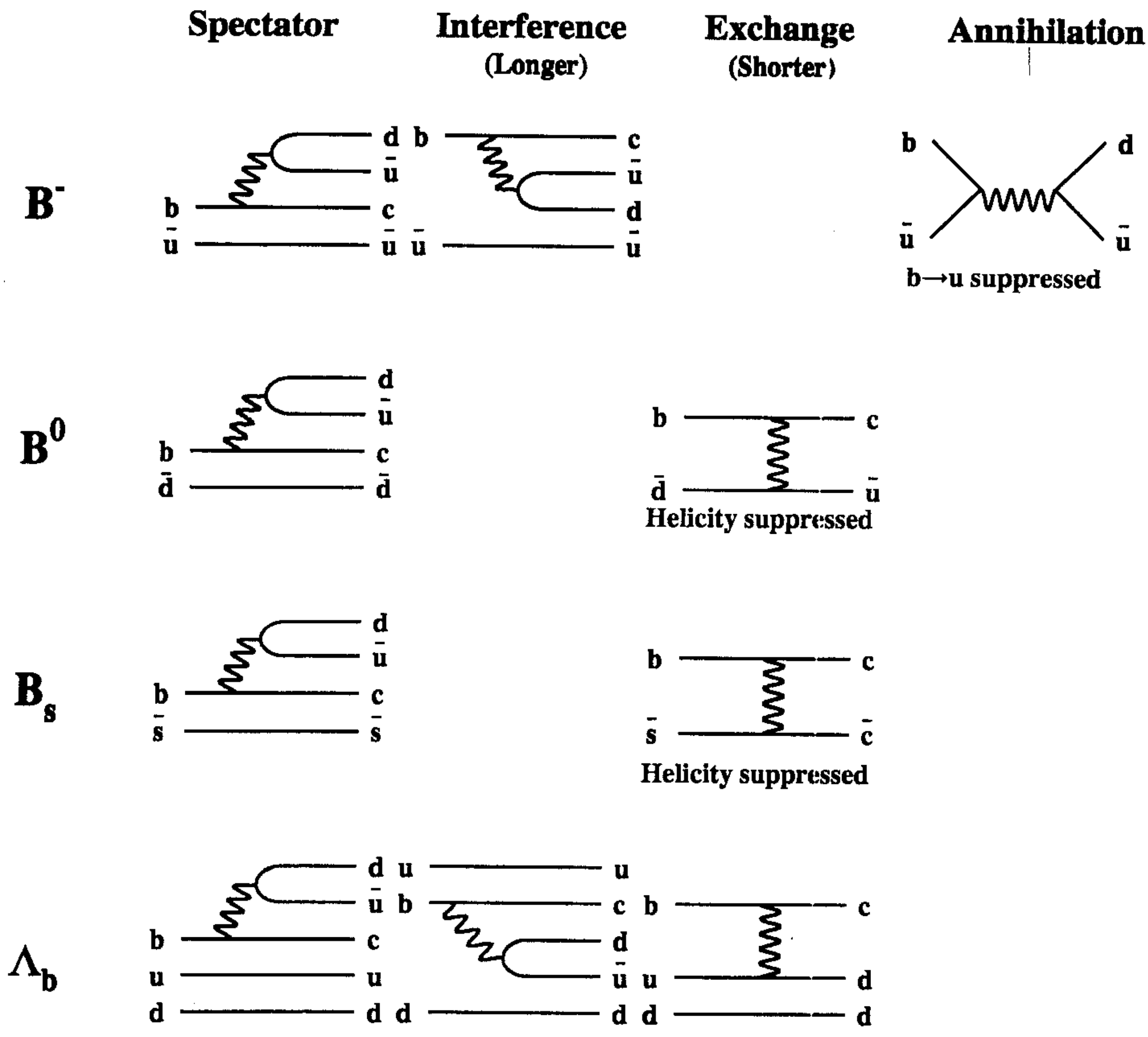
  No longer clear what the average b lifetime measures.

  $\Rightarrow$ Measure individual B lifetimes

- Expect differences, but smaller than for charm

  $$\tau(D^+) \sim 2.5\, \tau(D^0) \sim 5\, \tau(\Lambda_c)$$

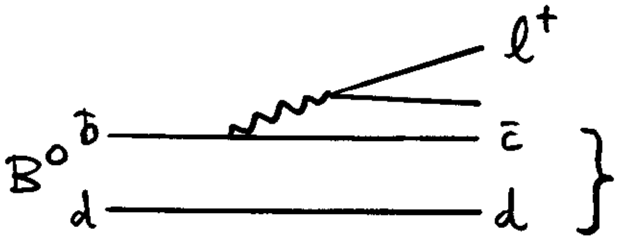
Contributions to B Lifetimes



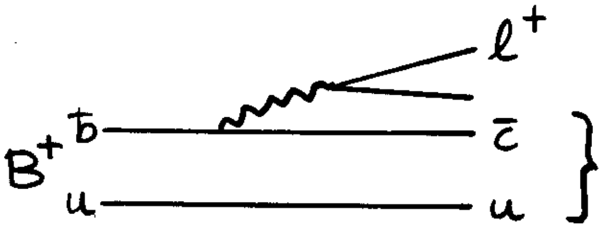
Expect $\tau(B^-) > \tau(B^0) \geq \tau(B_s) > \tau(\Lambda_b)$

B^0 and $B^\pm$ Lifetimes

Use D+lepton events



D^- or $D^{*-} \rightarrow 55\%\ \bar{D}^0,\ 45\%\ D^-$



$\bar{D}^0$ or $\bar{D}^{*0} \rightarrow 100\%\ \bar{D}^0$

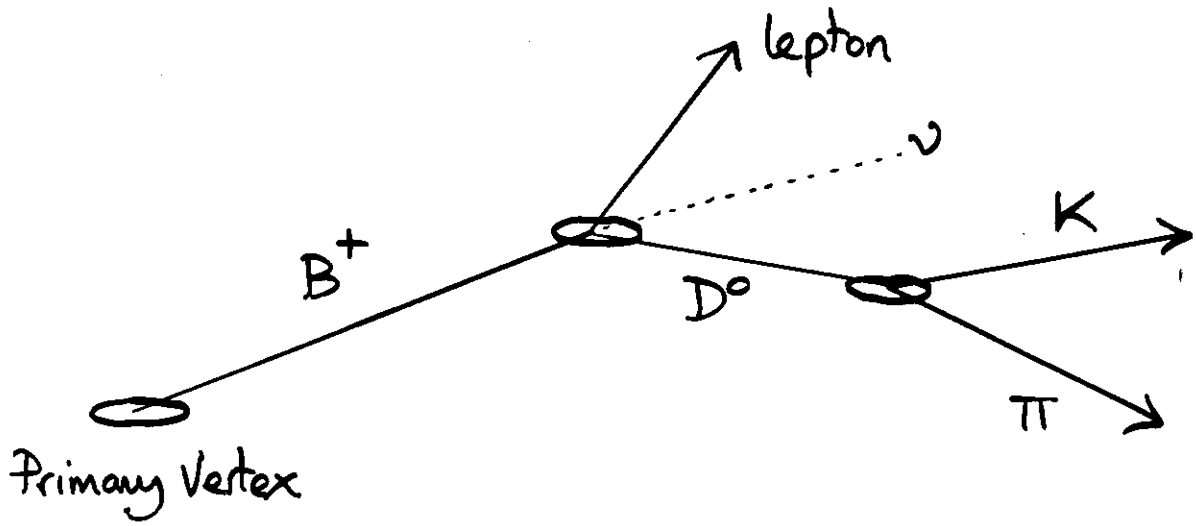
$\Rightarrow$ $D^-\ell^+$ all B^0 ($D^+\ell^+$ wrong sign)

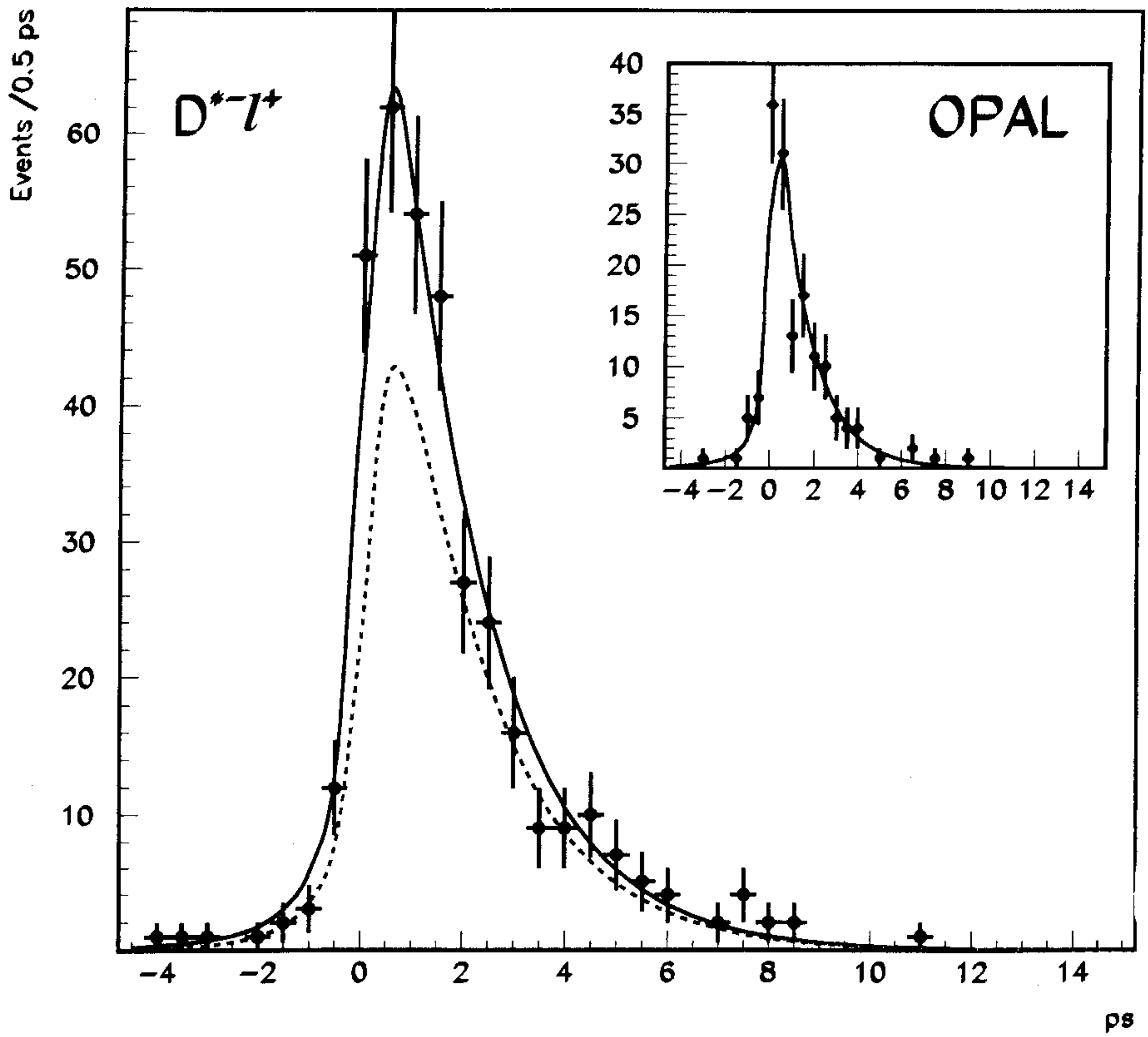
$\bar{D}^0\ell^+$ largely B^+

Complicated by $B^+ \rightarrow D^{**}\ell^+\nu \rightarrow D^-\pi^+\ell^+\nu$ etc

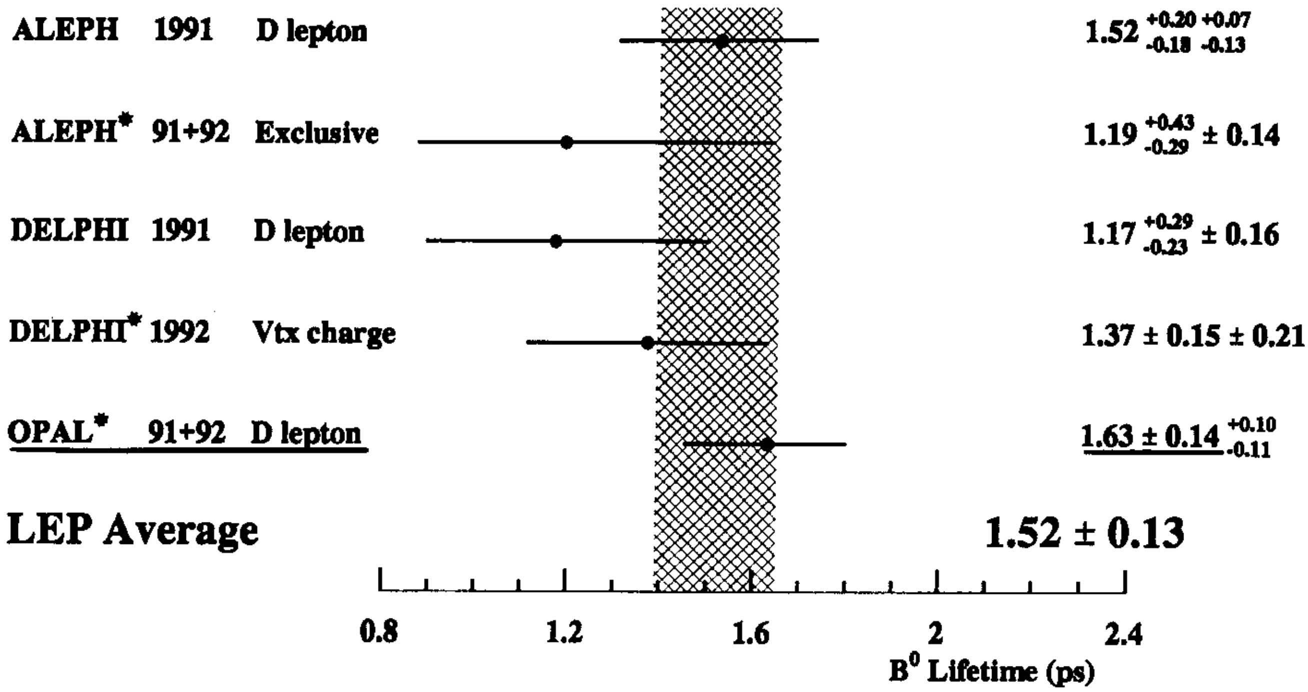
Reconstruct $D^0 \rightarrow K^-\pi^+,\ K^-\pi^+\pi^+\pi^-$

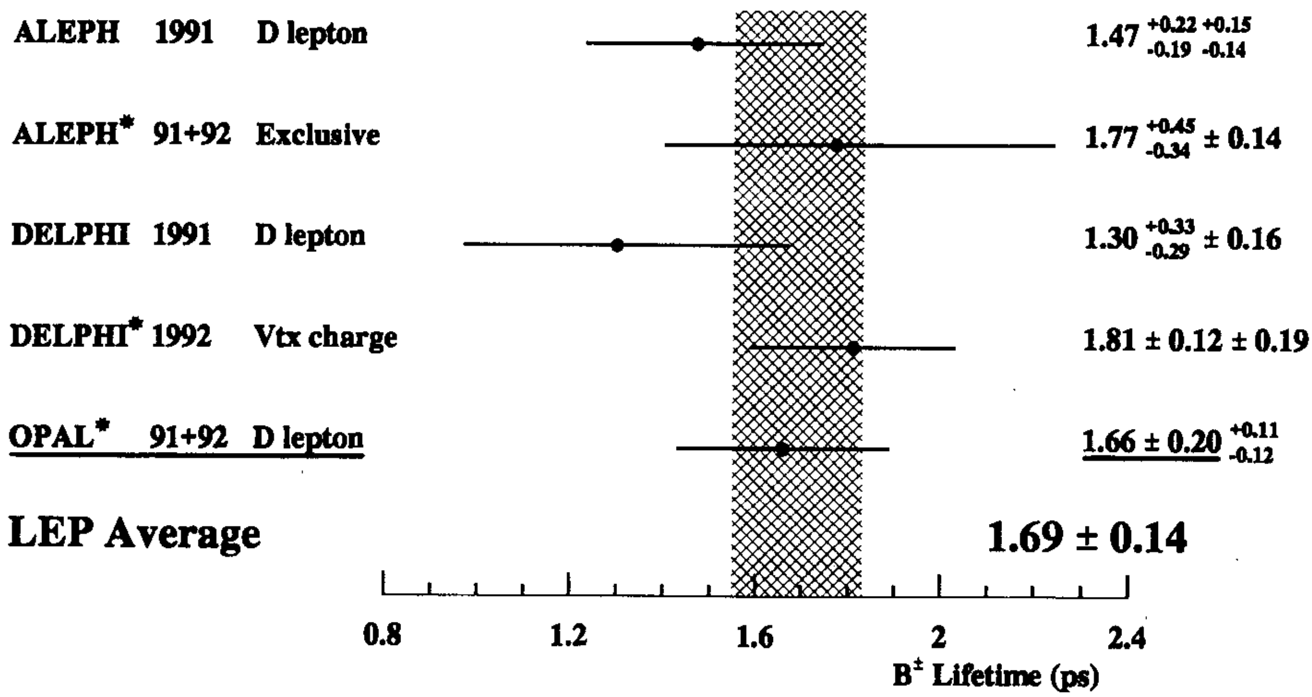
$D^+ \rightarrow K^-\pi^+\pi^+$ etc.




Events /0.5 ps
D*⁻l⁺
OPAL
ps
-4
-2
0
2
4
6
8
10
12
14
10
20
30
40
50
60
5
15
25
35

B^0 and $B^{\pm}$ Lifetimes from LEP

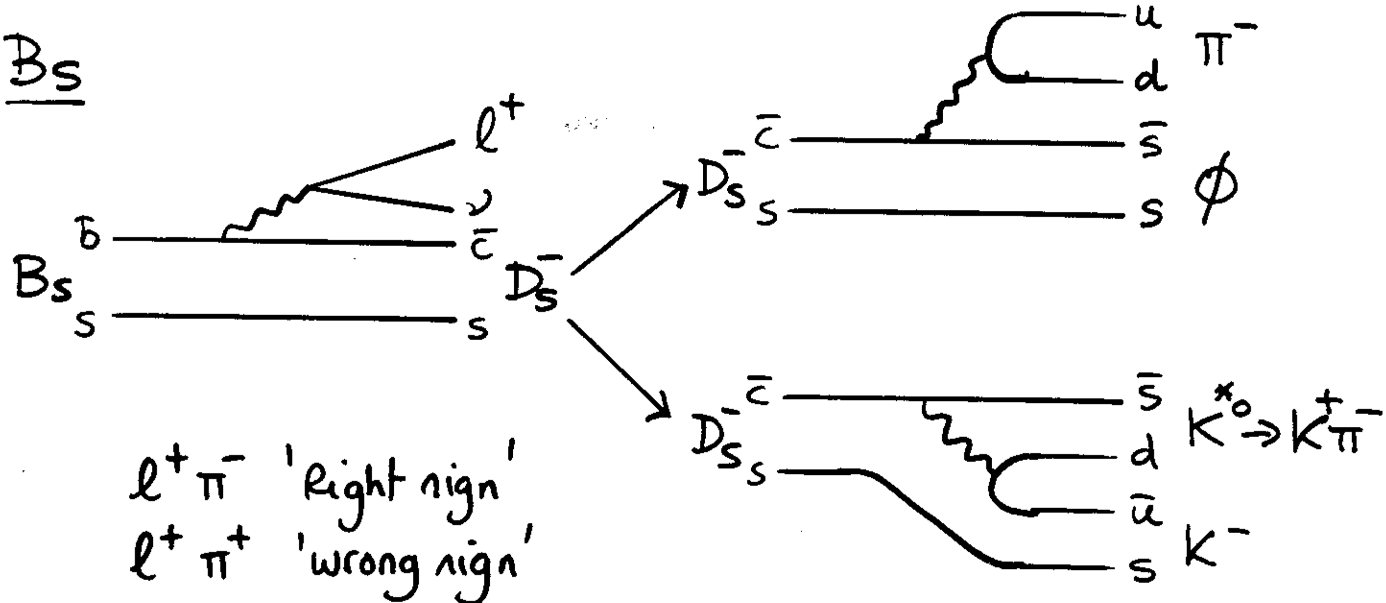




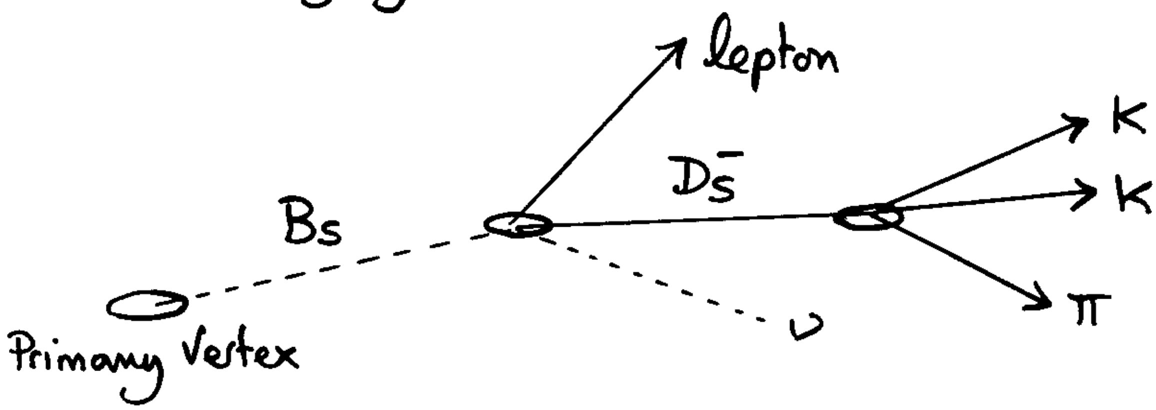
LEP Average $B^{\pm}$ Lifetime/B^0 Lifetime $= 1.14 \pm 0.15$

B_s and Λ_b Lifetimes

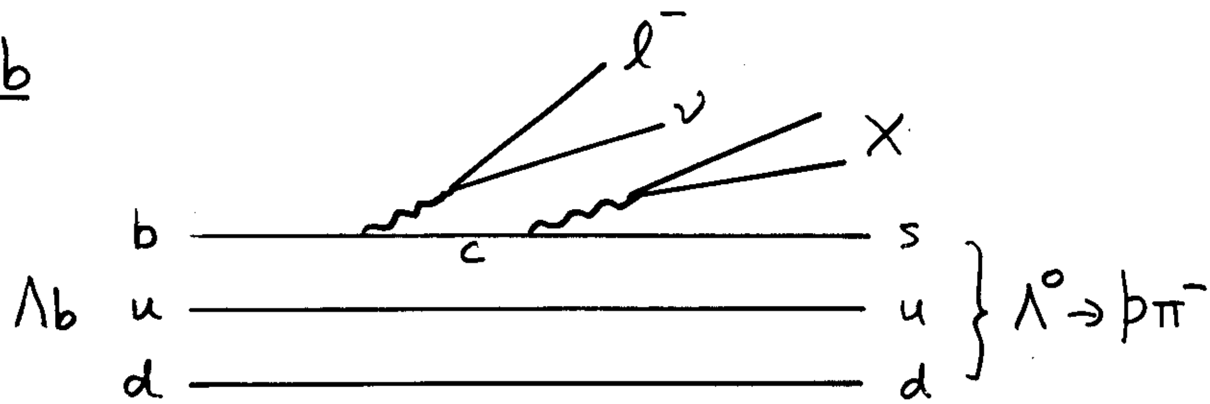
B_s



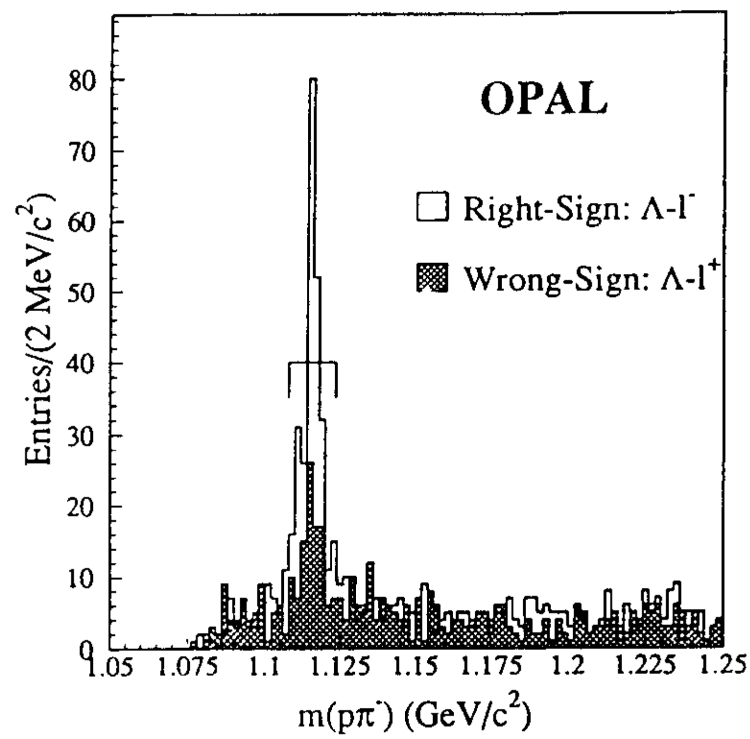
$\ell^+\pi^-$ 'Right sign'
$\ell^+\pi^+$ 'wrong sign'



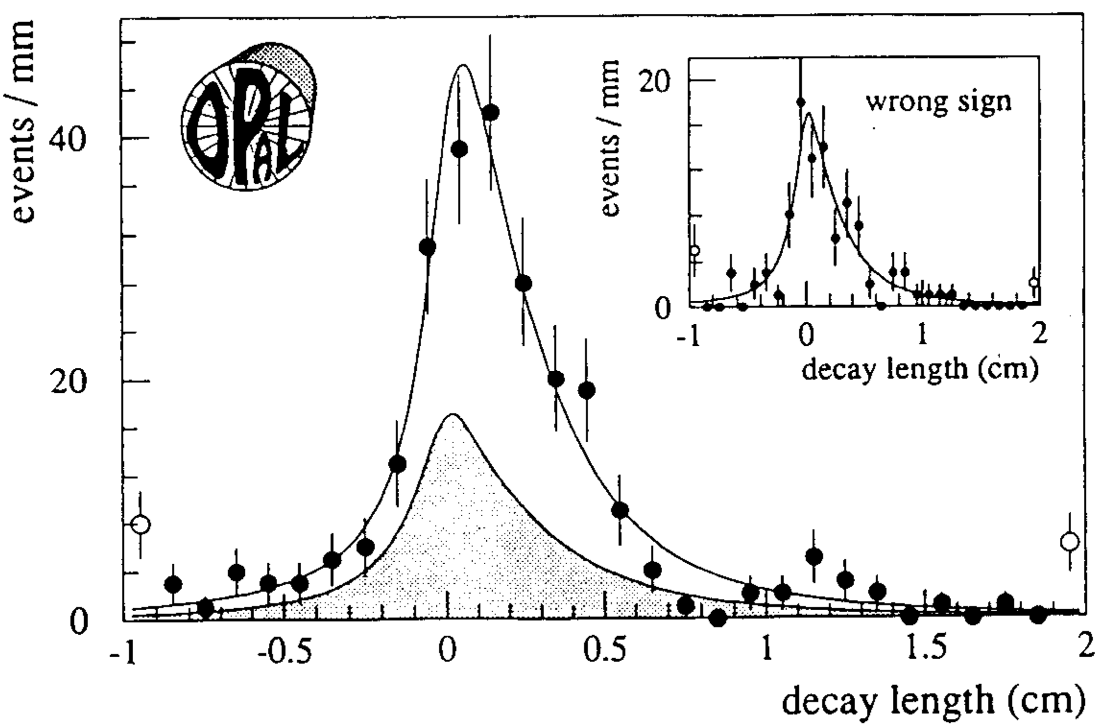
Λ_b



$\Lambda \ell^-$ and $\bar{\Lambda} \ell^+$ 'Right sign'
$\Lambda \ell^+$ and $\bar{\Lambda} \ell^-$ 'wrong sign'

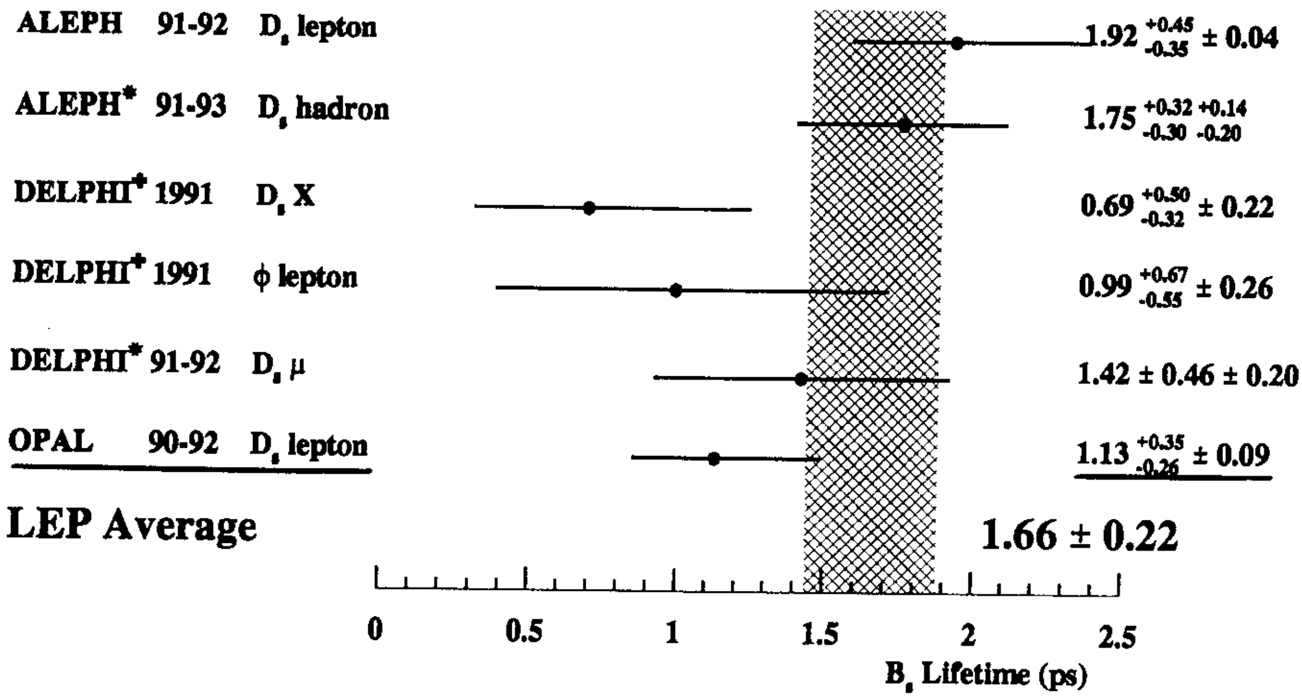


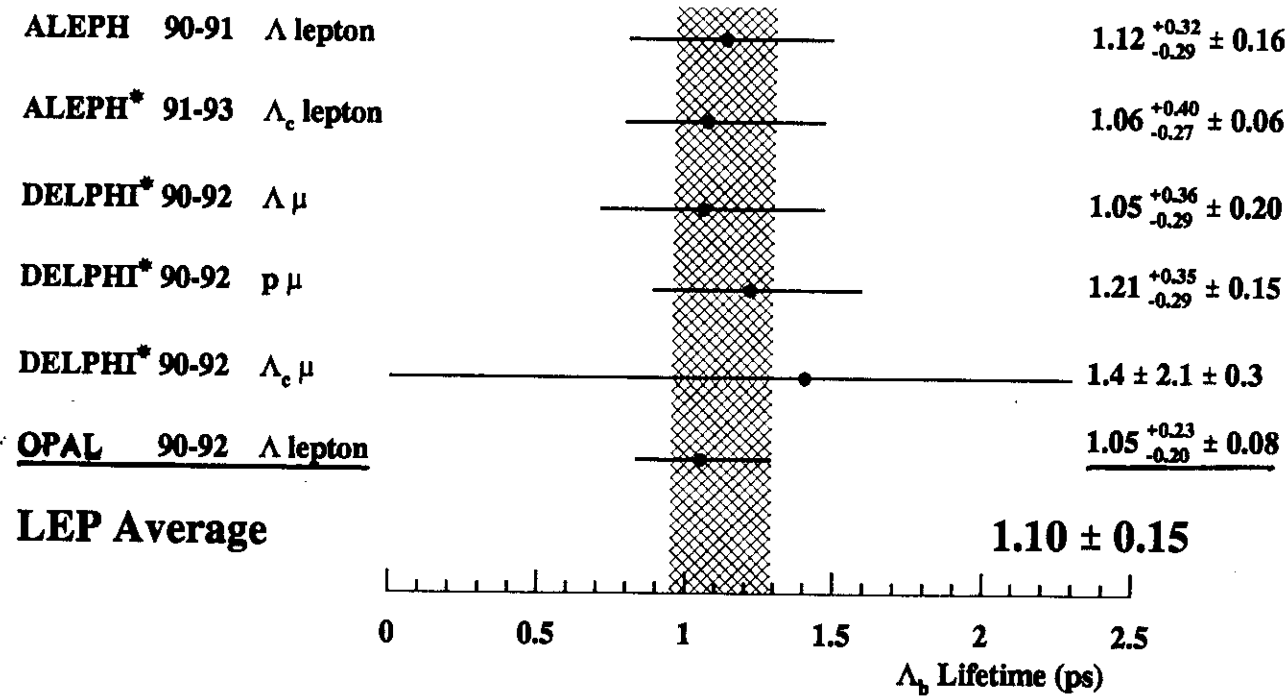
OPAL
Right-Sign: Λ-l⁻
Wrong-Sign: Λ-l⁺
Entries/(2 MeV/c²)
m(pπ⁻) (GeV/c²)



events / mm
decay length (cm)
wrong sign
events / mm
decay length (cm)

B_s and Λ_b Lifetimes from LEP

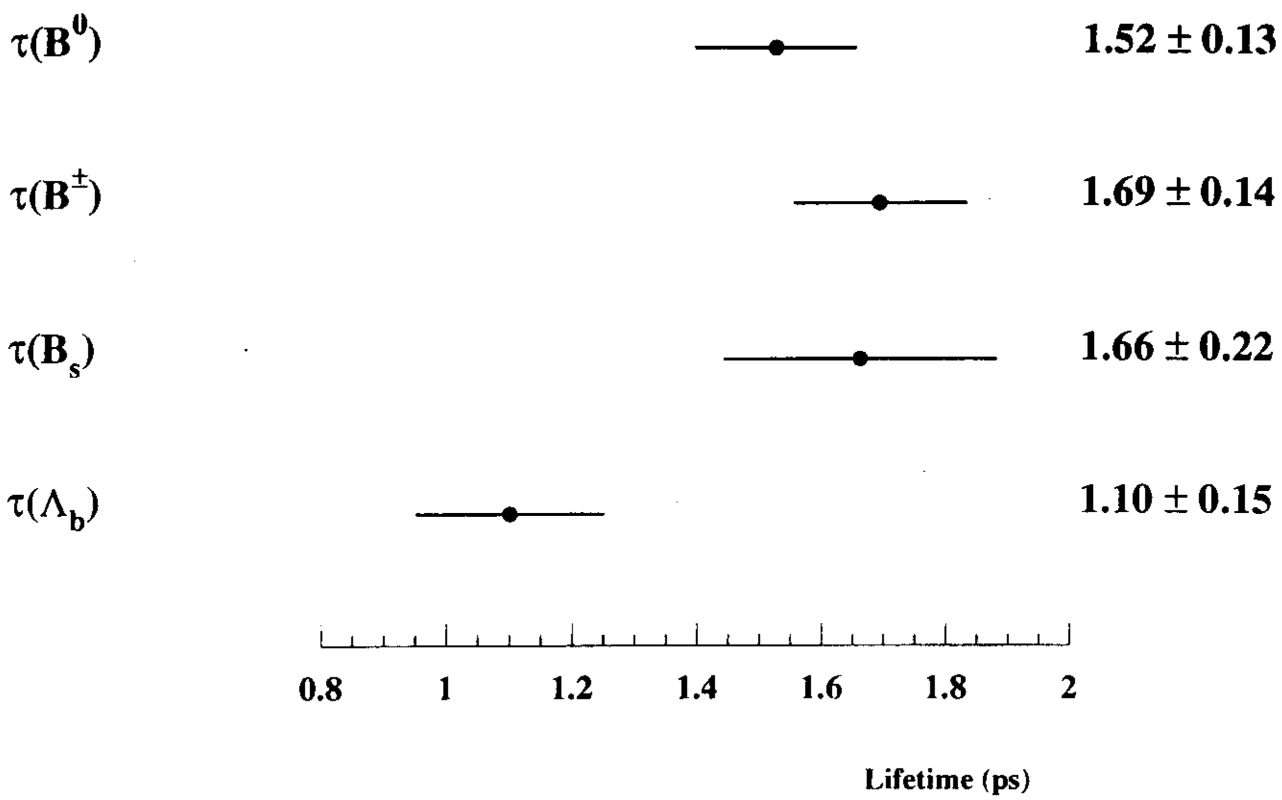




LEP Average B_s Lifetime/B^0 Lifetime $= 1.11 \pm 0.18$

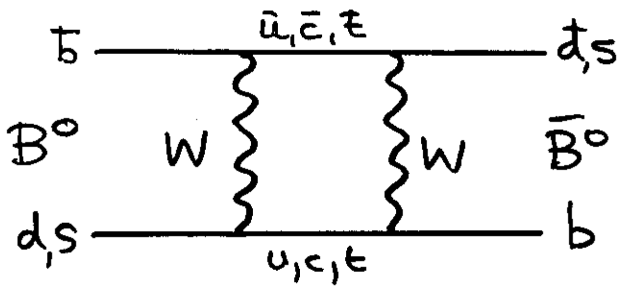
LEP Average Λ_b Lifetime/B^0 Lifetime $= 0.75 \pm 0.12$

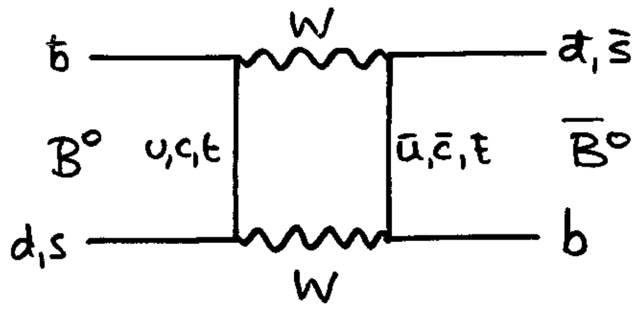
B Lifetime Summary



$\tau(B^{\pm})/\tau(B^0)$	1.14 ± 0.15	Theory 1.05
$\tau(B_s)/\tau(B^0)$	1.11 ± 0.18	Theory 1.00
$\tau(\Lambda_b)/\tau(B^0)$	0.75 ± 0.12	Theory 0.90

B Mixing





$$B^0 = \frac{1}{\sqrt{2}}(B_1 + B_2) \qquad \bar{B}^0 = \frac{1}{\sqrt{2}}(B_1 - B_2)$$

Flavour Eigenstate

Mass Eigenstate

- $$\Delta M = M_1 - M_2 \qquad \Gamma \simeq \Gamma_1 \simeq \Gamma_2$$

  If at $t=0$ B^0 state

  $$P_{B^0}(t) = \frac{1}{\tau} e^{-t/\tau} \cos^2 \frac{\Delta M t}{2}$$

  $$P_{\bar{B}^0}(t) = \frac{1}{\tau} e^{-t/\tau} \sin^2 \frac{\Delta M t}{2}$$

  Quantified by $x = \frac{\Delta M}{\Gamma} = \frac{\text{Lifetime}}{\text{Oscillation time}}$

- If no time measurement, integrated value

  $$\chi = \frac{N_{B^0B^0} + N_{\bar{B}^0\bar{B}^0}}{N_{b\bar{b}}} = \frac{x^2}{2+2x^2}$$

  At $\Upsilon(4s)$ only B^0_d $\chi_d = 0.167 \pm 0.037$ CLEO ARGUS

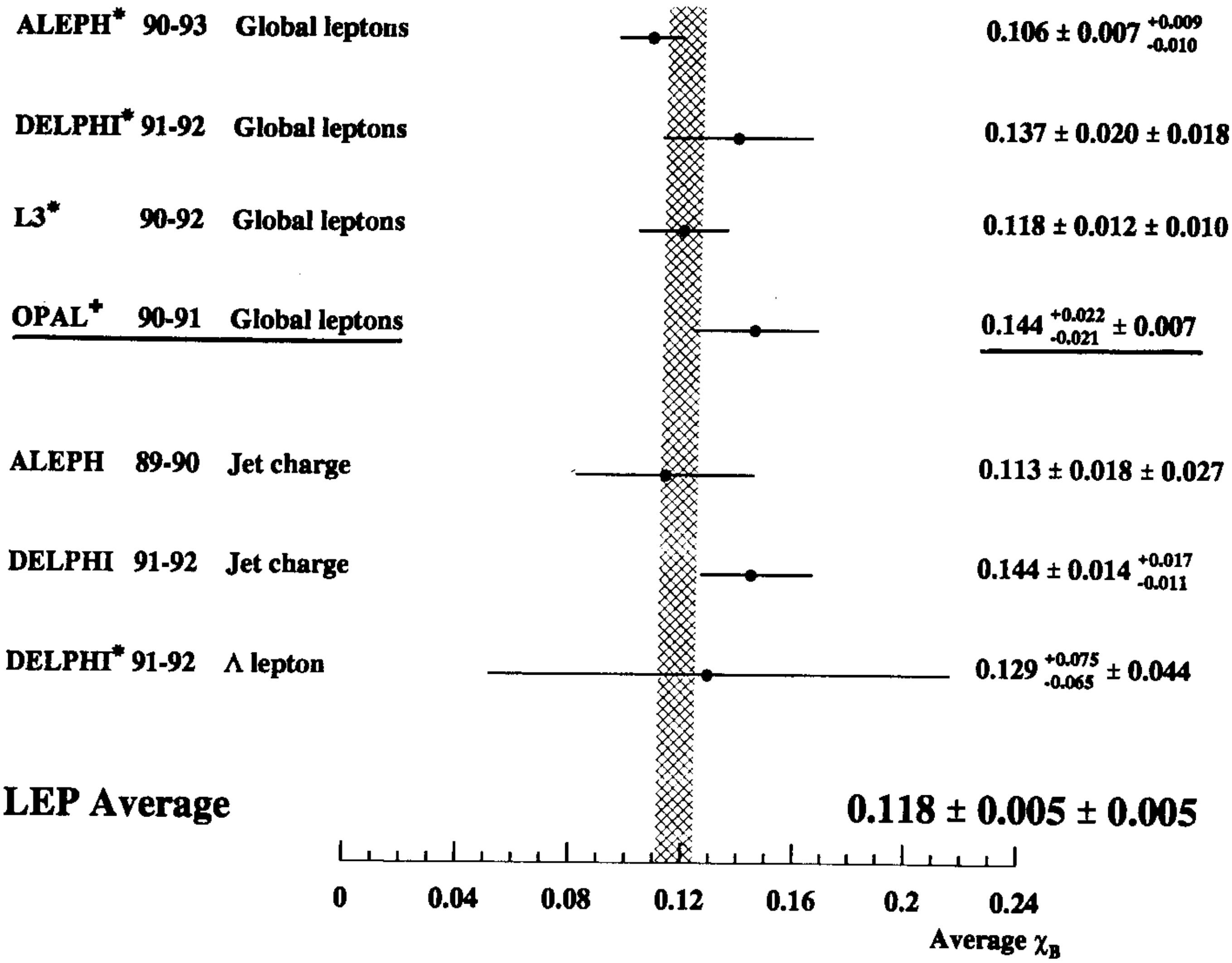
  $$\Rightarrow x_d \simeq 0.71 \pm 0.09$$

  Expect $\frac{x_s}{x_d} \sim \frac{|V_{ts}|^2}{|V_{td}|^2} \Rightarrow \quad 8 \lesssim x_s \lesssim 24$

  Maximal mixing

  $$\chi_s \to 0.5$$

χ_B Measurements from LEP



$$\chi_{LEP} = f_d \chi_d + f_s \chi_s = 0.118 \pm 0.007$$

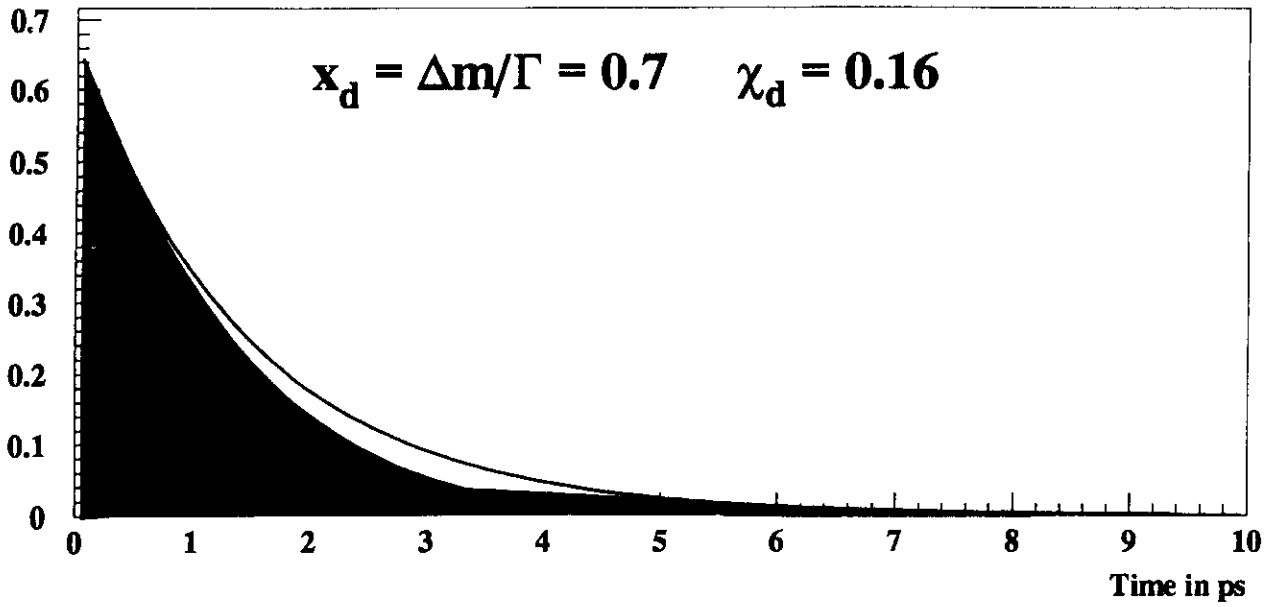
Using $f_u = f_d = 0.4$, $f_s = 0.12$

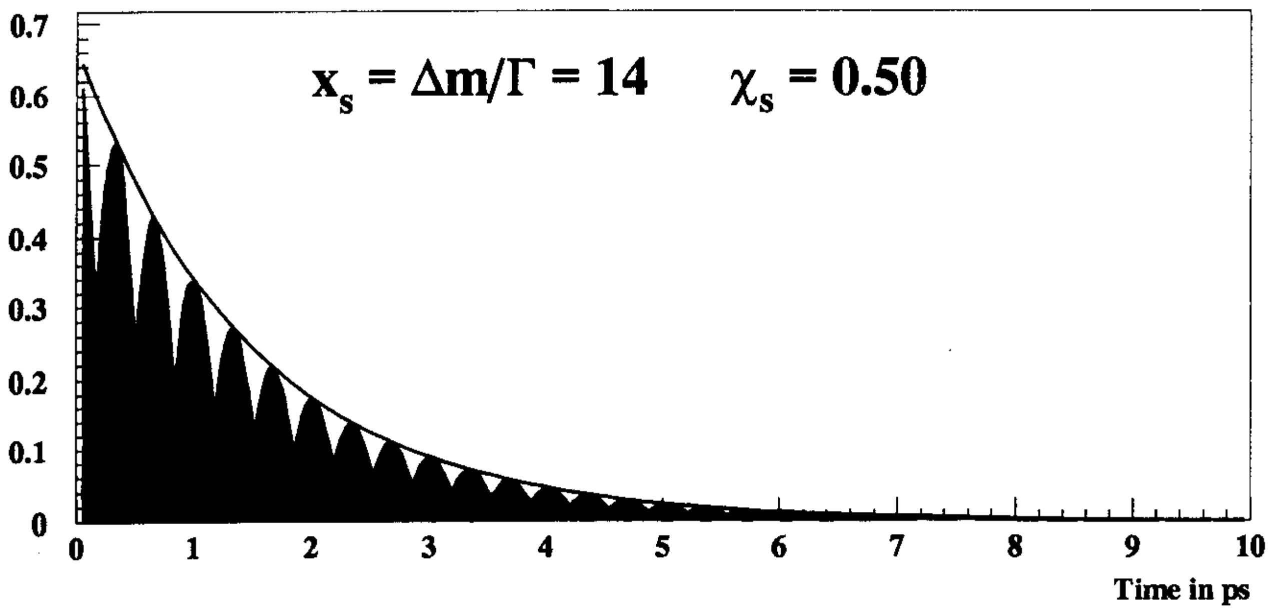
and $\chi_d = 0.167 \pm 0.037$

$$\Rightarrow \chi_s = 0.43 \pm 0.14$$

$$\Rightarrow x_s \gtrsim 0.7$$

Time Dependent B Mixing



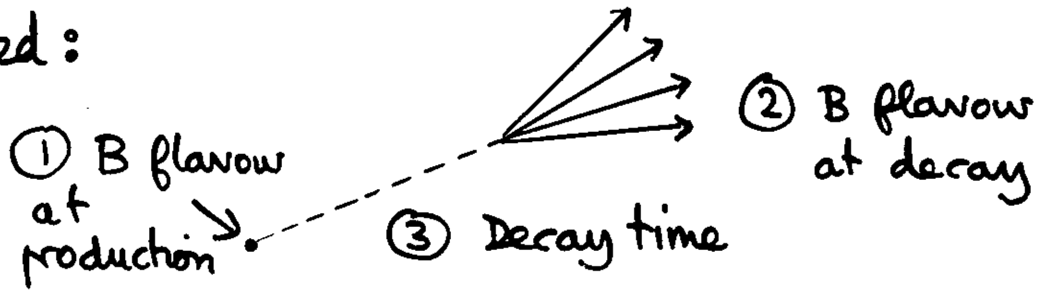


B Oscillations

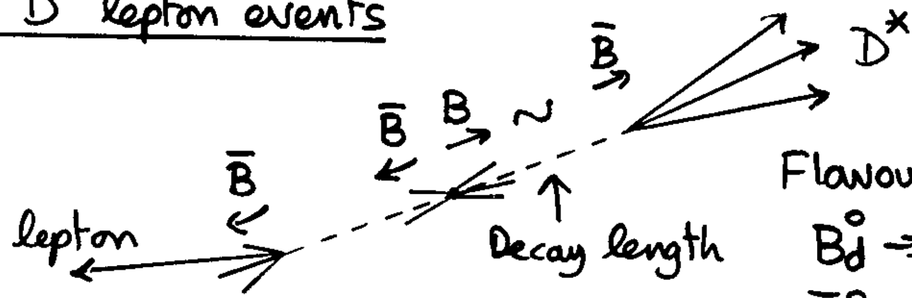
For B_d^0 with $\chi_d \sim 0.16$ $\quad x_d \sim 0.7$

One oscillation takes ~ 9 lifetimes

Need:



1. D^* lepton events



Flavour at Decay

$B_d^0 \rightarrow D^{*-} X$

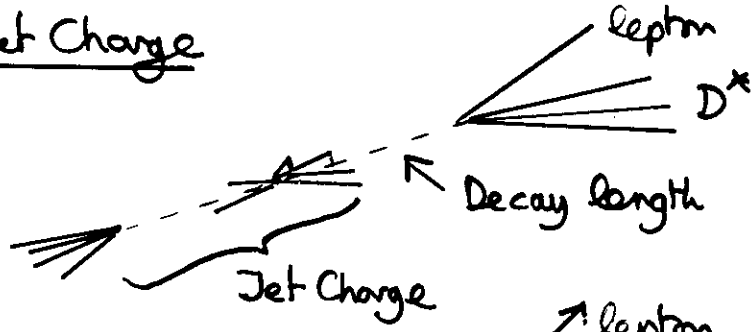
$\bar{B}_d^0 \rightarrow D^{*+} X$

Flavour at production

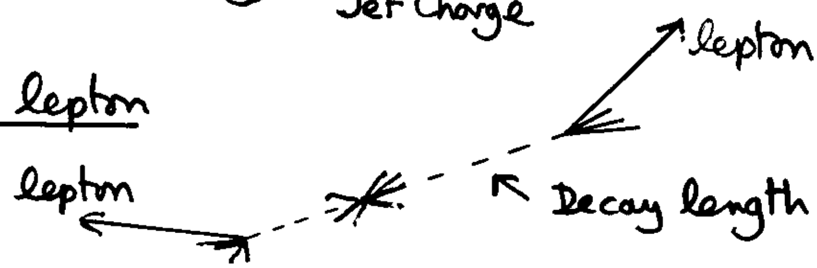
$B \rightarrow \ell^+ \Rightarrow \bar{B}^0$ at production $\quad$ 'Mixed' $= \ell^+ D^{*-}$

$\bar{B} \rightarrow \ell^- \Rightarrow B^0$ at production $\quad$ 'Unmixed' $= \ell^- D^{*-}$

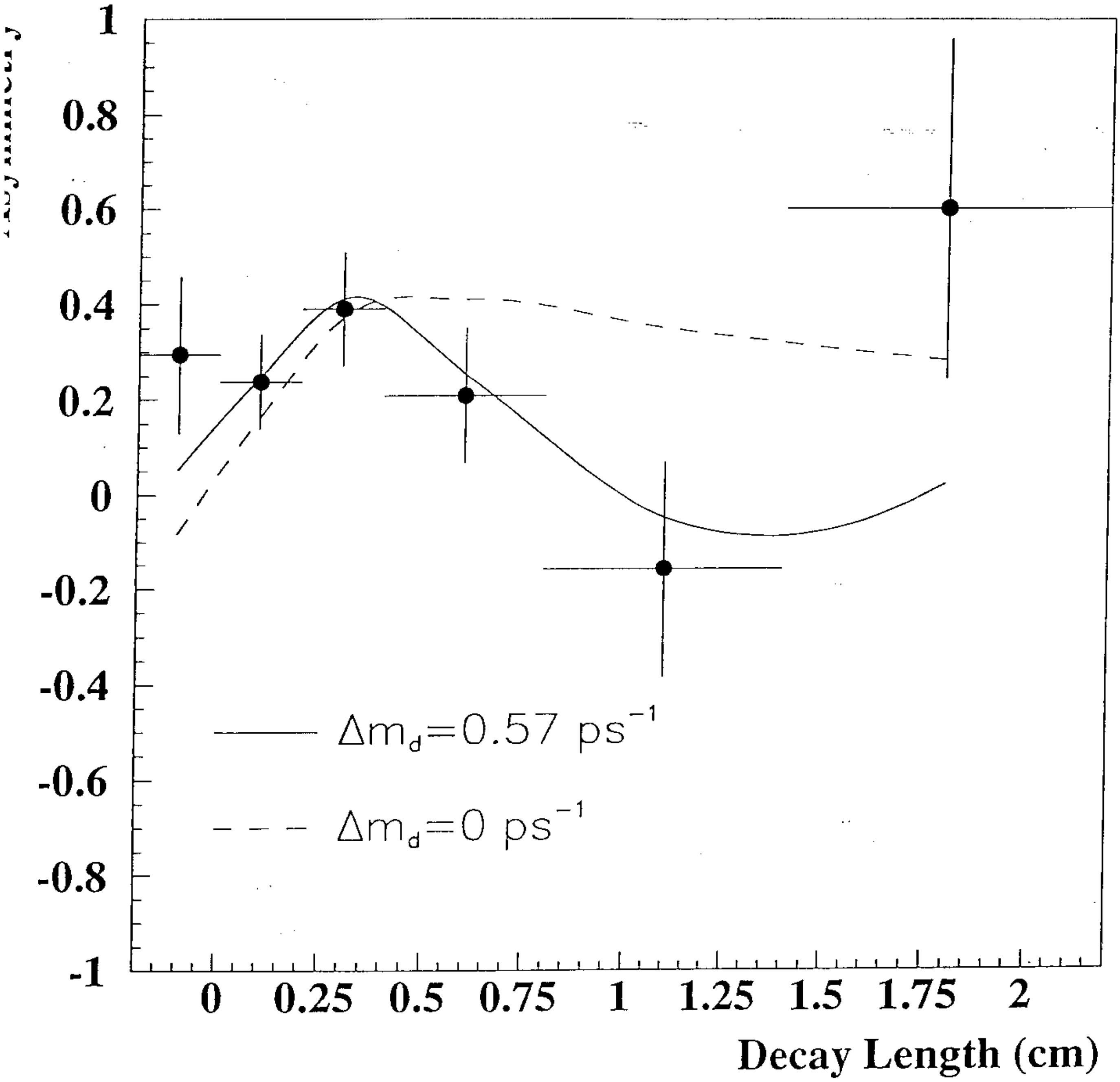
2. D^* lepton Jet Charge



3. lepton lepton



In all cases plot $\dfrac{\text{Mixed} - \text{Unmixed}}{\text{Mixed} + \text{Unmixed}}$ as function of decay time



1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
Decay Length (cm)
Δm_d=0.57 ps^{-1}
Δm_d=0 ps^{-1}

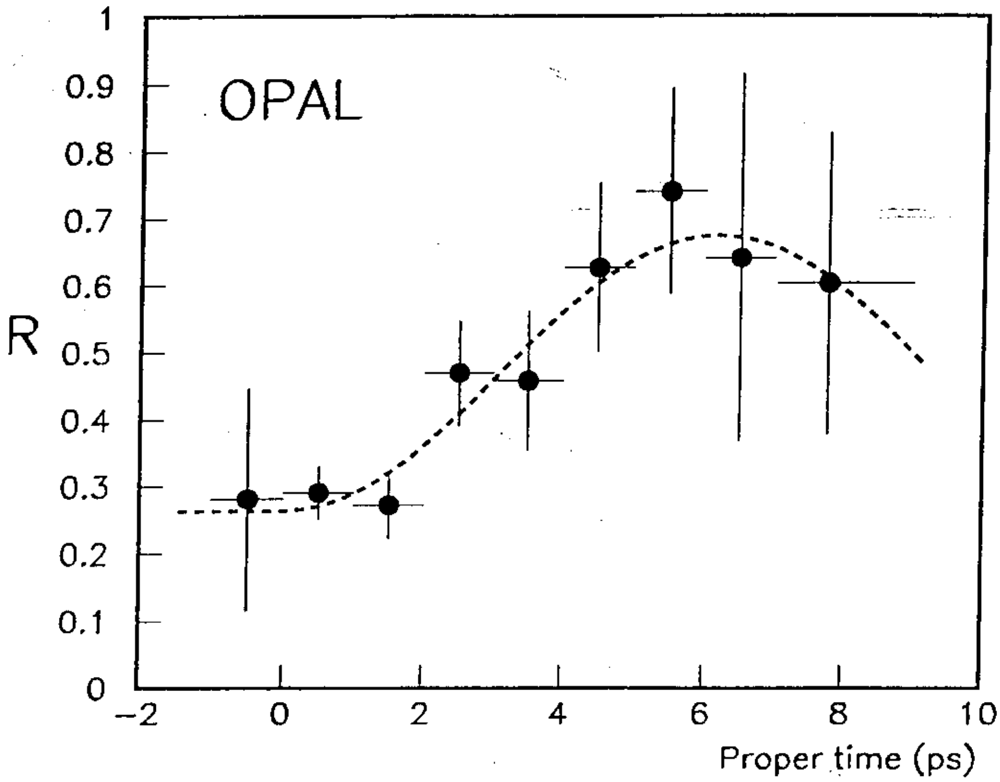
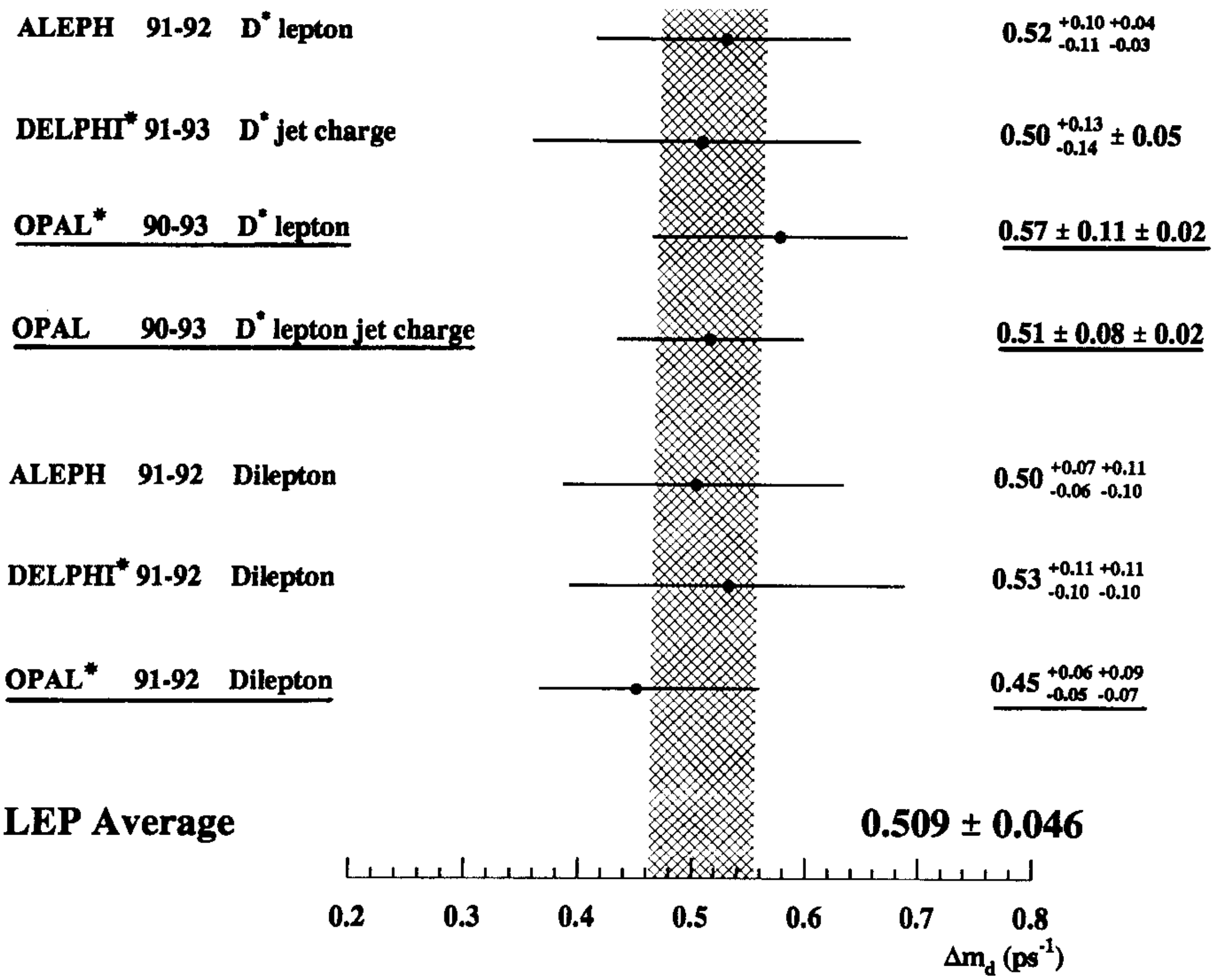


Figure 5

Δm_d Measurements from LEP



$$\Delta m_d = 0.509 \pm 0.046 \text{ ps}^{-1}$$
$$\equiv (3.35 \pm 0.30) \times 10^{-4} \text{ eV}/c^2$$

For $\tau_B = 1.5$ ps $\Rightarrow x_d = 0.764 \pm 0.069$

(CLEO/ARGUS 0.71 ± 0.09)

Exclusive B Decays

Say 2M $Z^\circ \to$ hadrons / experiment

$\times$ 22% BR ($Z^\circ \to b\bar{b}$)

$\times$ 2 $\Rightarrow$ 880,000 B hadrons

$\times$ 40%

$\Rightarrow$ 352,000 B°

BR($B^\circ \to D^- \pi^+$) $(3.2 \pm 0.7)\,10^{-3}$

BR($B^+ \to D^\circ \pi^+$) $(3.8 \pm 1.1)\,10^{-3}$

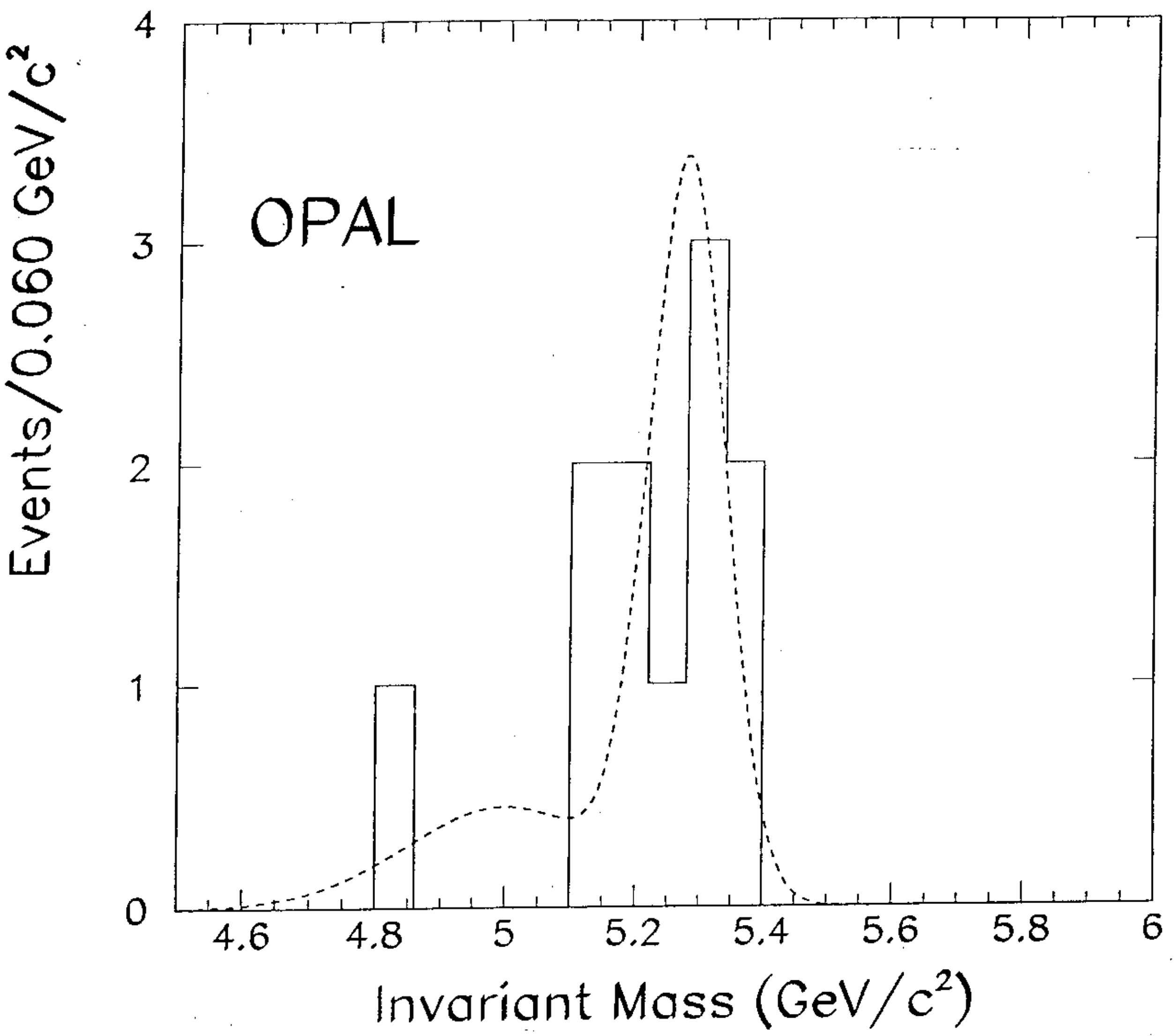
BR($D^- \to K^- \pi^+ \pi^+$) 8%

BR($D^\circ \to K^- \pi^+$) 3.65%

$\Rightarrow$ 50 events before any cuts

B_s, Λ_b worse

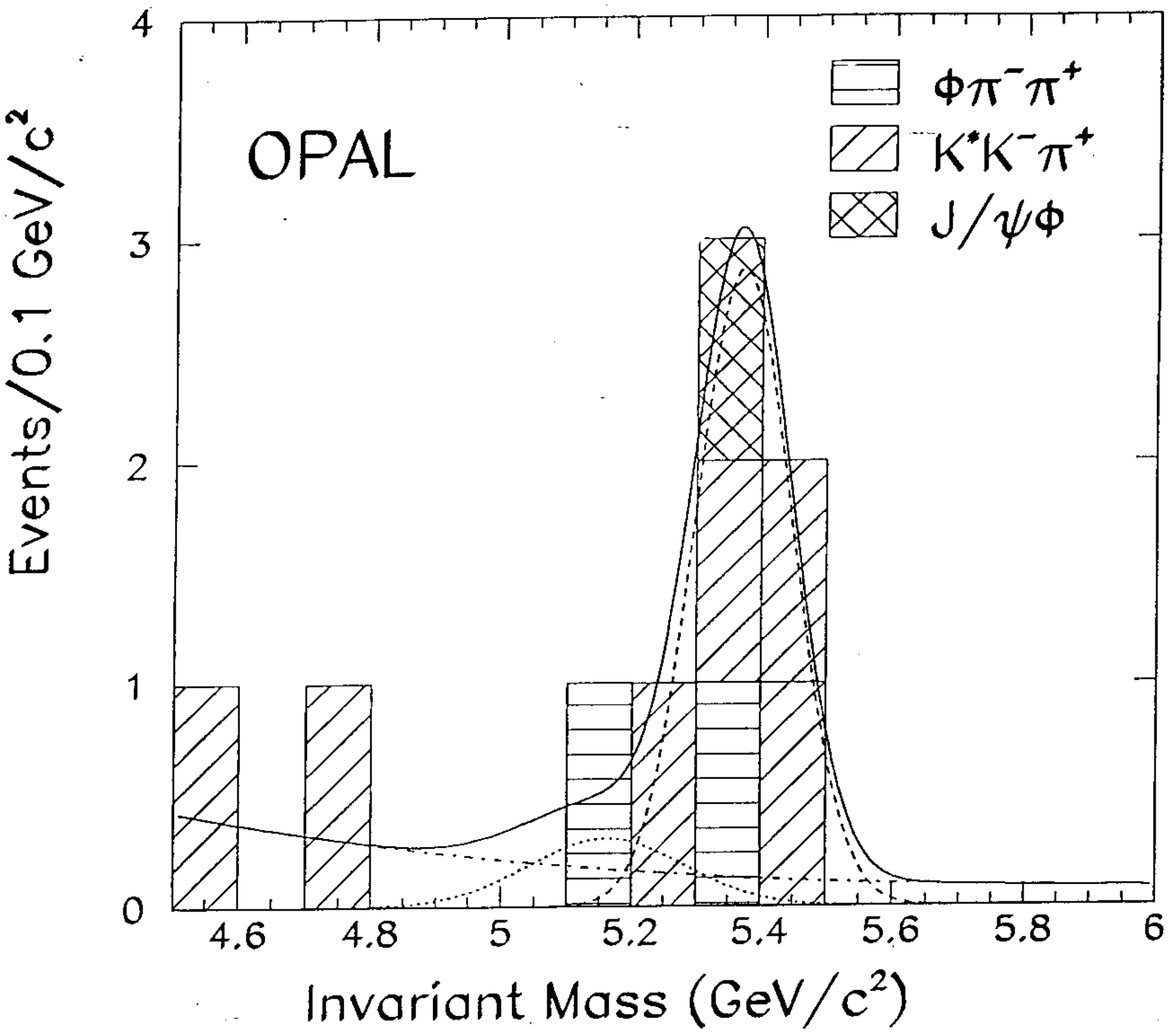
$B_d^0 \to D^{*-}\pi^+$ and $B_d^0 \to D^{*-}\rho^+$

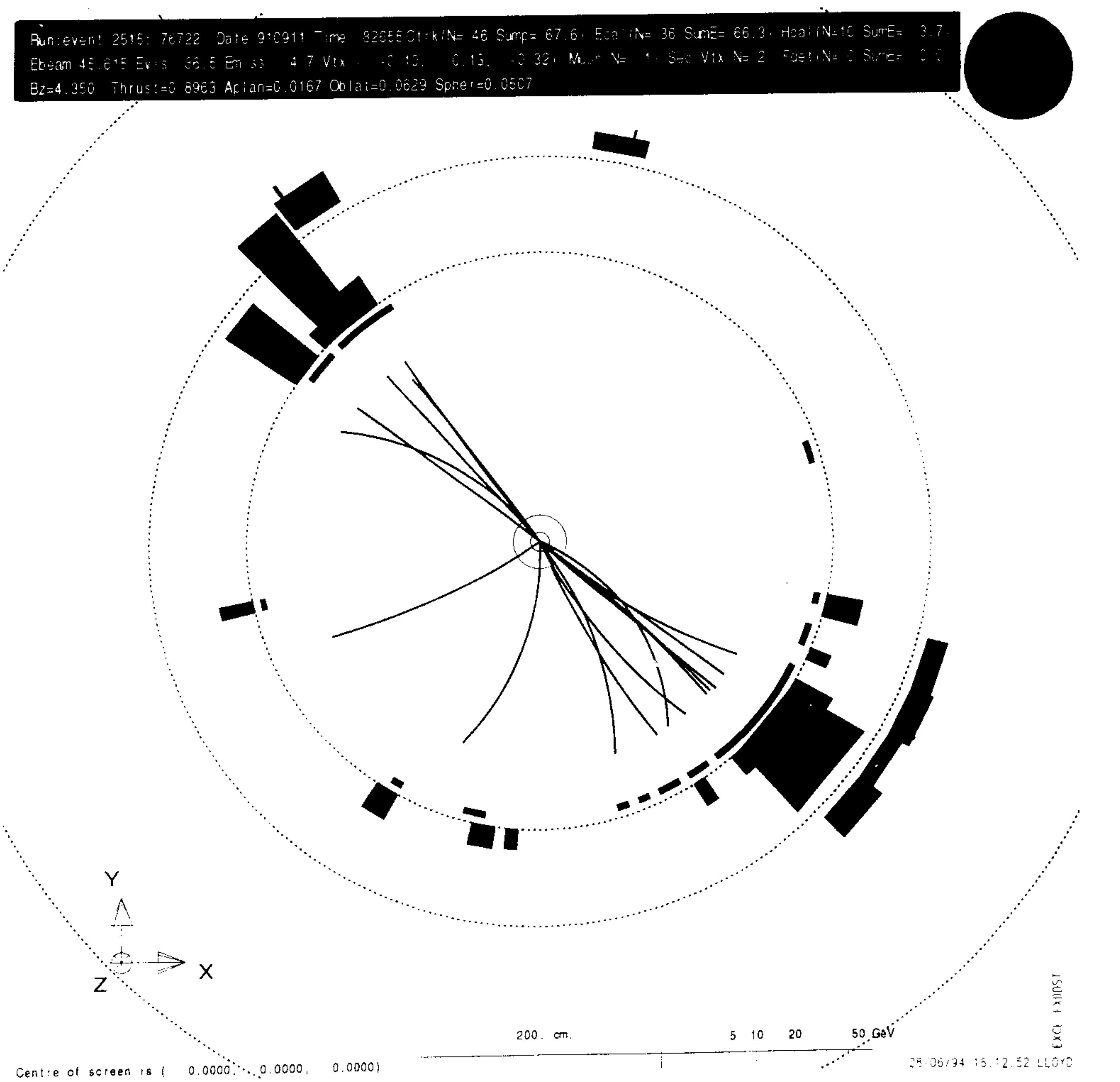


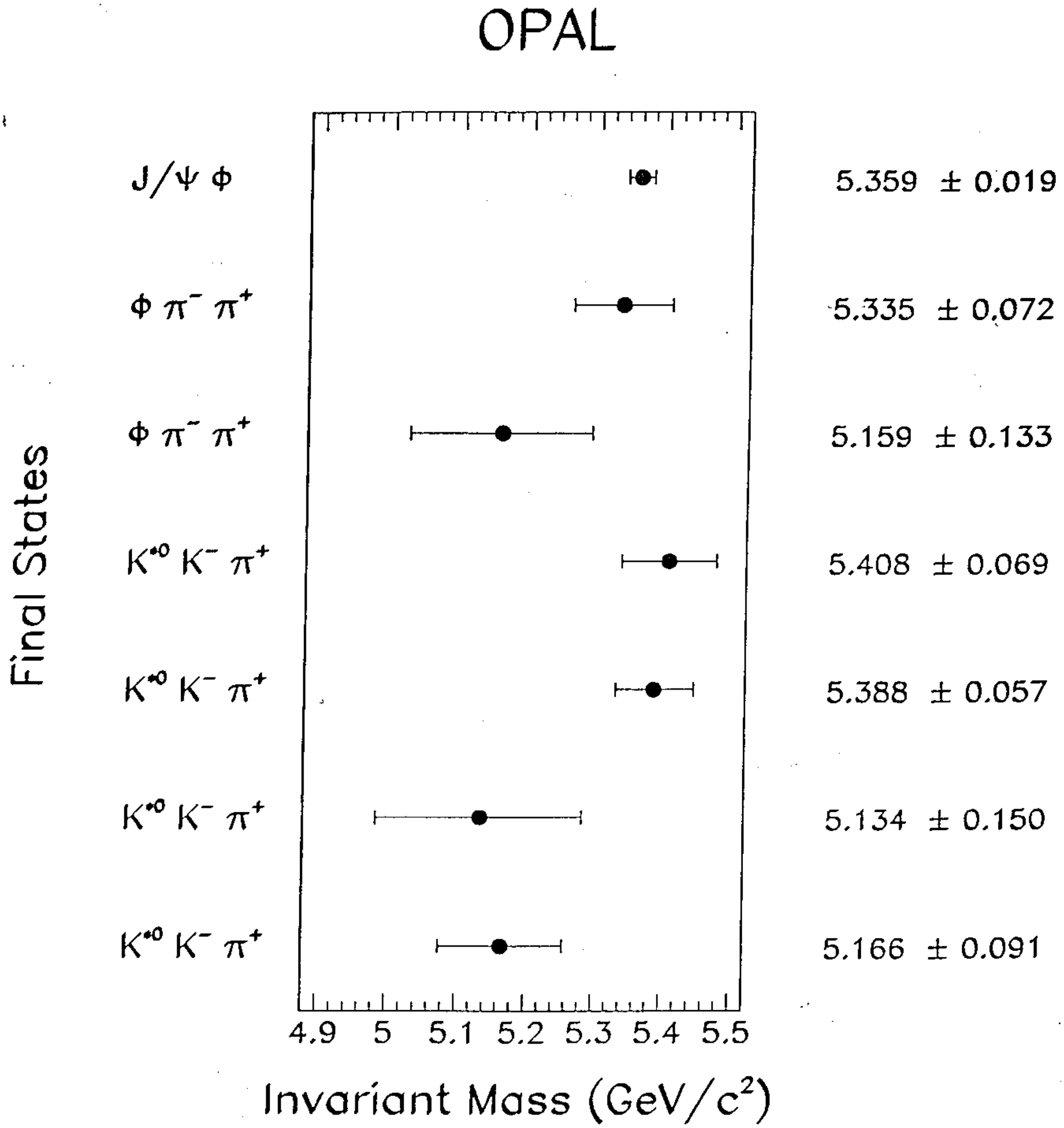
$B_s \to D_s^- \pi^+ \to \phi \pi^- \pi^+$

$B_s \to D_s^- \pi^+ \to K^{*0} K^- \pi^+$

$B_s \to \psi \phi$

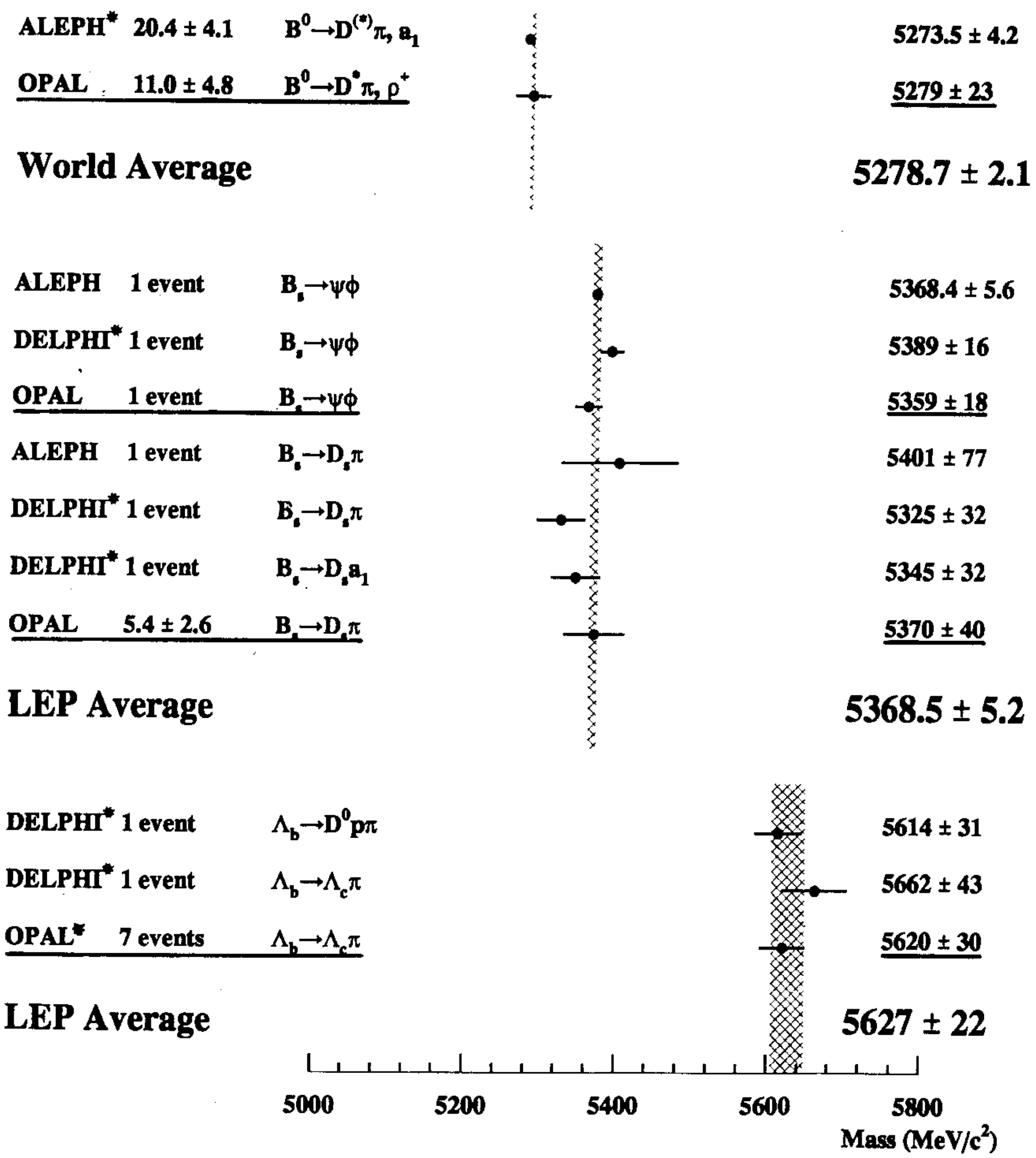



Bz=4.350 Thrust=0 8963 Aplan=0.0167 Oblat=0.0629 Spher=0.0507
Y
X
Z
200. cm.
5 10 20 50 GeV
Centre of screen is (0.0000, 0.0000, 0.0000)
28/06/94 15.12.52 LLOYD


OPAL
Final States
J/ψ φ
φ π⁻ π⁺
φ π⁻ π⁺
K*⁰ K⁻ π⁺
K*⁰ K⁻ π⁺
K*⁰ K⁻ π⁺
K*⁰ K⁻ π⁺
5.359 ± 0.019
5.335 ± 0.072
5.159 ± 0.133
5.408 ± 0.069
5.388 ± 0.057
5.134 ± 0.150
5.166 ± 0.091
4.9
5
5.1
5.2
5.3
5.4
5.5
Invariant Mass (GeV/c²)

B_s Mass

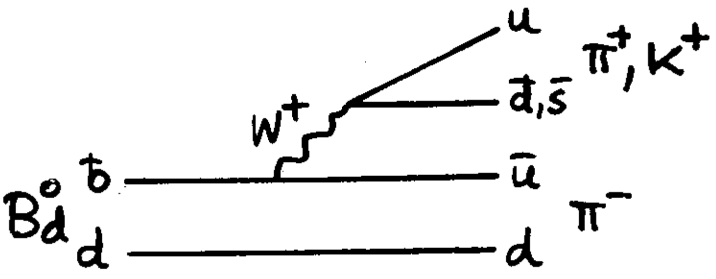
Exclusive B Measurements from LEP

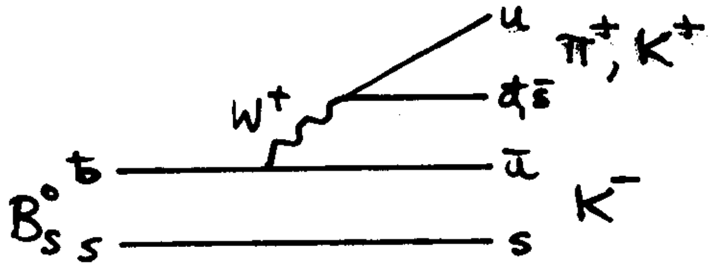


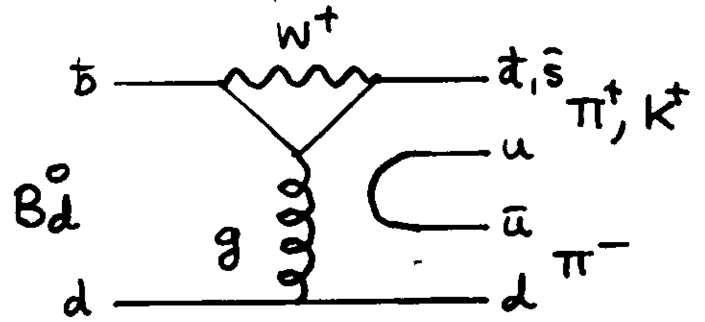
Rare B Decays

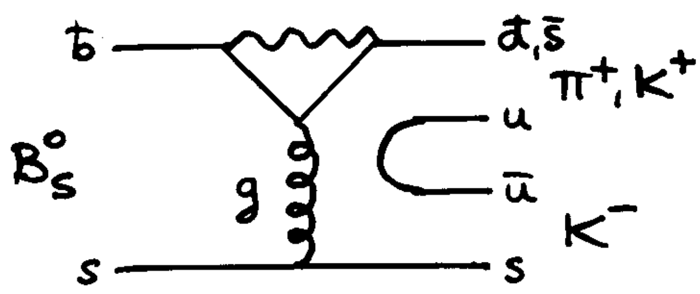
$B_d^0 \to \pi^+\pi^-$ $\qquad$ $B_s^0 \to \pi^+K^-$

$B_d^0 \to K^+\pi^-$ $\qquad$ $B_s^0 \to K^+K^-$









No significant excess of events seen:

$$Br\,(B_d^0 \to \pi^+\pi^-) < 4.7\ 10^{-5}$$

$$Br\,(B_d^0 \to K^+\pi^-) < 8.1\ 10^{-5}$$

$$Br\,(B_s^0 \to \pi^+K^-) < 2.6\ 10^{-4}$$

$$Br\,(B_s^0 \to K^+K^-) < 1.4\ 10^{-4}$$

Conclusions

B Physics is a very fruitful field at LEP

- Will provide (eventually) the most precise tests of the Electroweak Standard Model
- Individual B lifetimes starting to show interesting differences
- Time dependent $B^0 - \overline{B}^0$ mixing observed and more precise measurements will follow
- Some exclusive B decays seen – more detailed studies with higher statistics
- Better measurements of B production and decay in near future due to improved tagging techniques