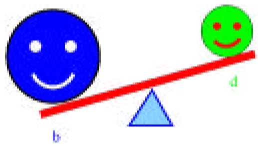
B^0 oscillations before the b-factories



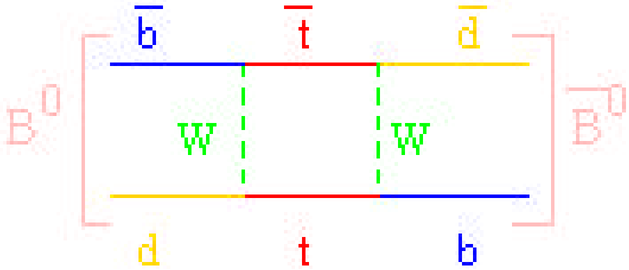
Richard Hawkings (CERN/OPAL)

CKM workshop, 12/2/02

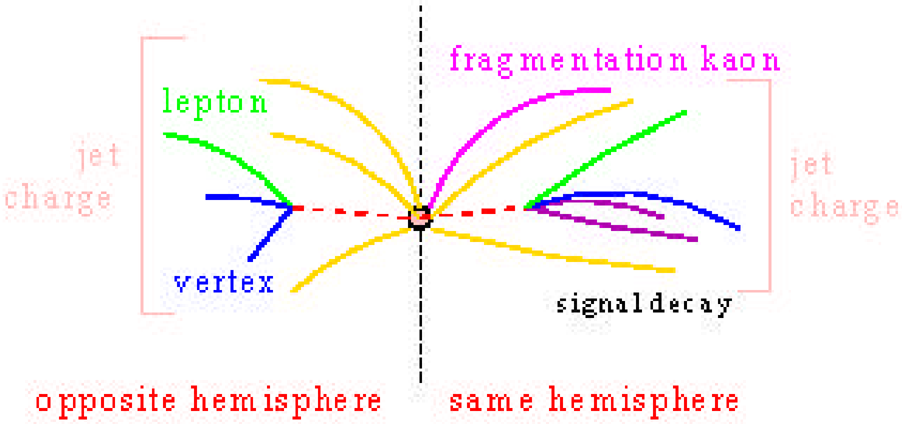
- A slightly historical overview of LEP / SLD / CDF run 1 Δm_d analyses.
  - Few new results from these expts in last year
  - Try to put them in a historical context:
    - → Progress in these analyses since the end of LEP1 data taking.
  - The various methods of measuring Δm_d
  - Techniques for getting more from the same data:
    - → New channels/analysis methods.
    - → Better production and decay tagging.
  - As we move to the b-factory era, what have we learned from the first-generation experiments ?

Introduction

- Neutral B mesons (B^0_d and B^0_s):
  - **Weak** eigenstates ≠ **mass** eigenstates
  - Transitions via box diagrams depending on $|V_{td}|$

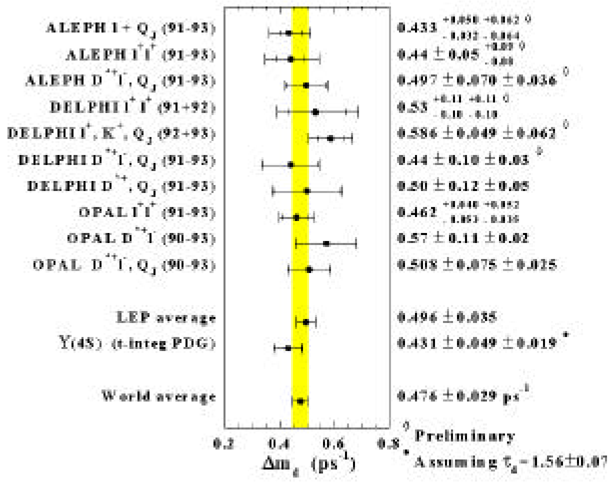


  - $P(B^0 \rightarrow B^0\text{-bar}) = ½(1-\cos \Delta m_d\, t)$
  - Extraction of $|V_{td}|$ from Δm_d is currently theoretically limited (±10%).
    - → Precise measurements more useful when Δm_s known.
- Measurement of Δm_d requires:
  - Tag b-flavour (B^0 or B^0-bar) at production/decay.
    - → Production from properties of rest of event.
  - Reconstruction of proper time of B^0-decay
    - → Large b boost at colliders -> resolution << τ_B.
  - Enhancement of B^0 purity
    - → Not strictly needed, only B^0 has oscillatory signature.



From then to now

- From spring 1995 - 1/2 LEP data sample:



$\Delta m_d = 0.496 \pm 0.035\ ps^{-1}$

(M. Jimack,Moriond 95)

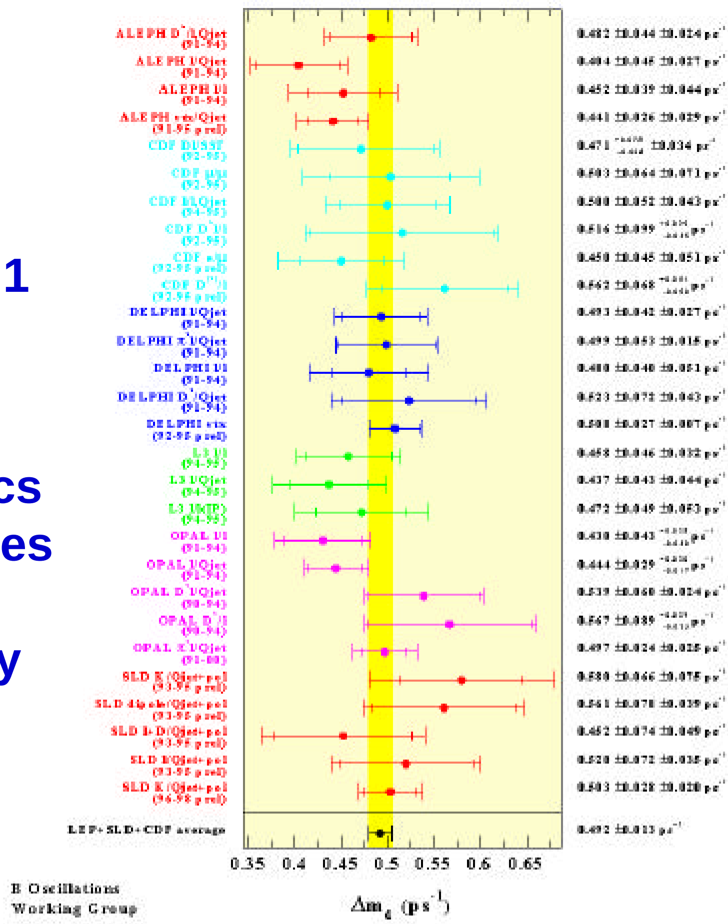
- To winter 2002:

+ Full LEP data sample
+ Add SLD and CDF run 1

+ $\Delta m_d = 0.492 \pm 0.013\ ps^{-1}$

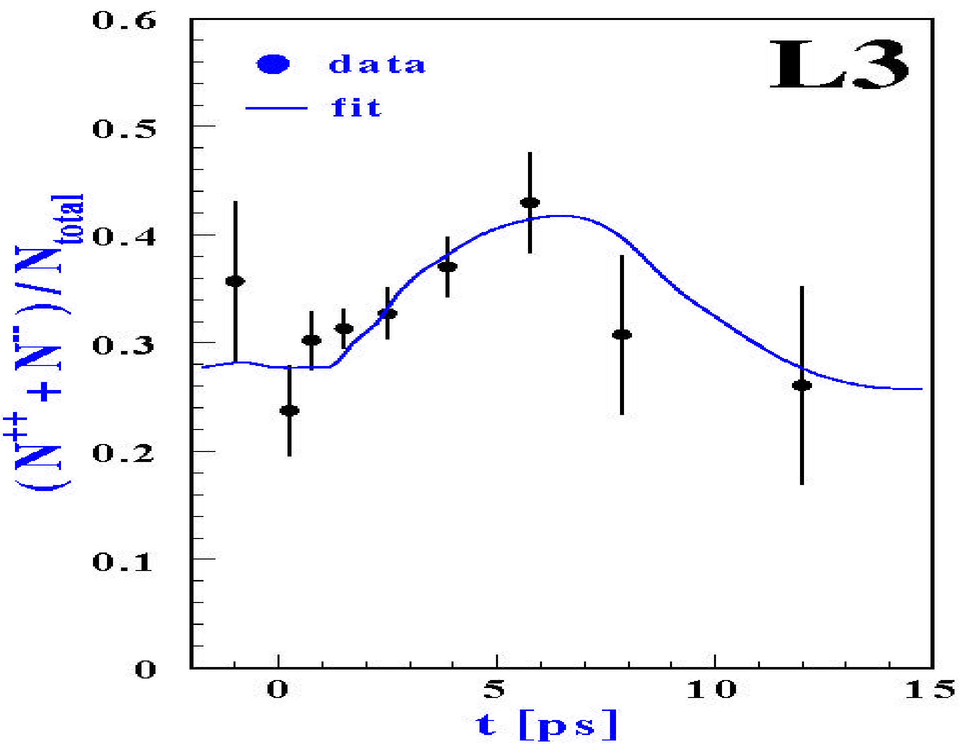
+ Increased data statistics
+ New analysis techniques

+ Now enter the b-factory era, but how did we get here ?



Dilepton measurements…
the discovery channel

- Select events with two high-p,pt leptons:
  - $Z \to bb$ event with both $b \to$ lepton.
    - → Same sign leptons signature of b-mixing
    - → Fraction of same sign leptons as function of reconstructed proper time measures Δm_d:



  - No selection of B^0_d decays - all b states present:
    - → B^+ and b-baryons dilute signal (no mixing)
    - → B^0_s oscillate too fast to be resolved
    - → Cascade decays ($b \to c \to l^+$) also dilutes: wrong-sign tag
  - Systematics: Amplitude depends on $f(B^0_d)$
    - → Measured from difference in time integrated mixing seen at LEP (χ-bar) and at Ψ(4S) (χ_d)
    - → χ-bar also meausred from dileptons - care needed

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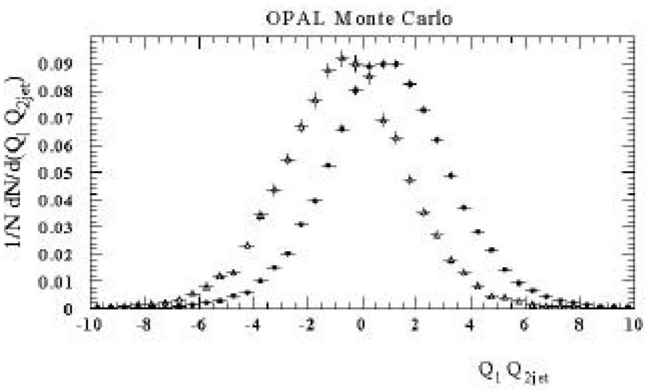
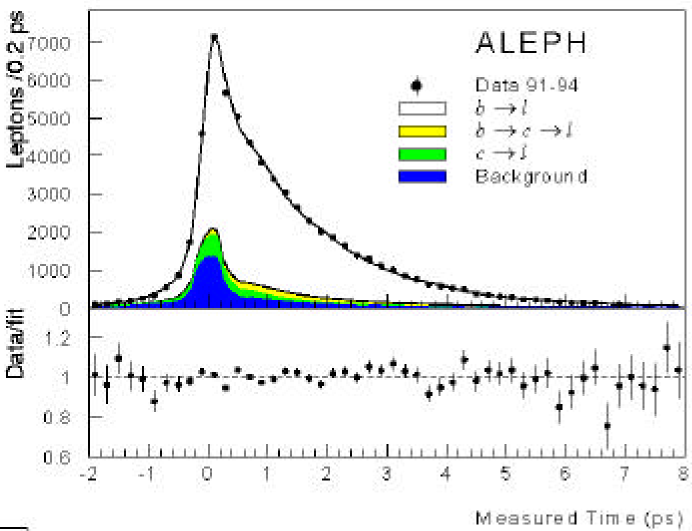
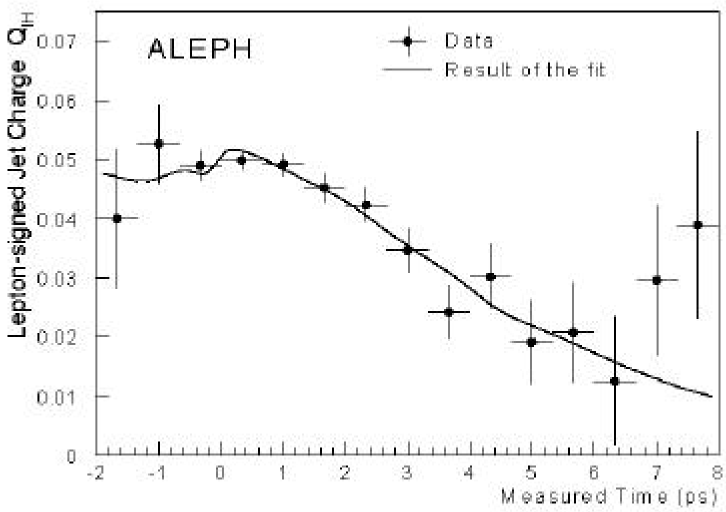
Going further - inclusive lepton measurements

- Second lepton only measures 'production flavour'
  - Replace it with 'jet charge'- momentum weighted sum of all track charges in jet/hemisphere
    - → Measures production flavour with 100% efficiency, but high mistag (35% events tagged wrongly)
  - Loss of second-lepton also gives more charm bkgd







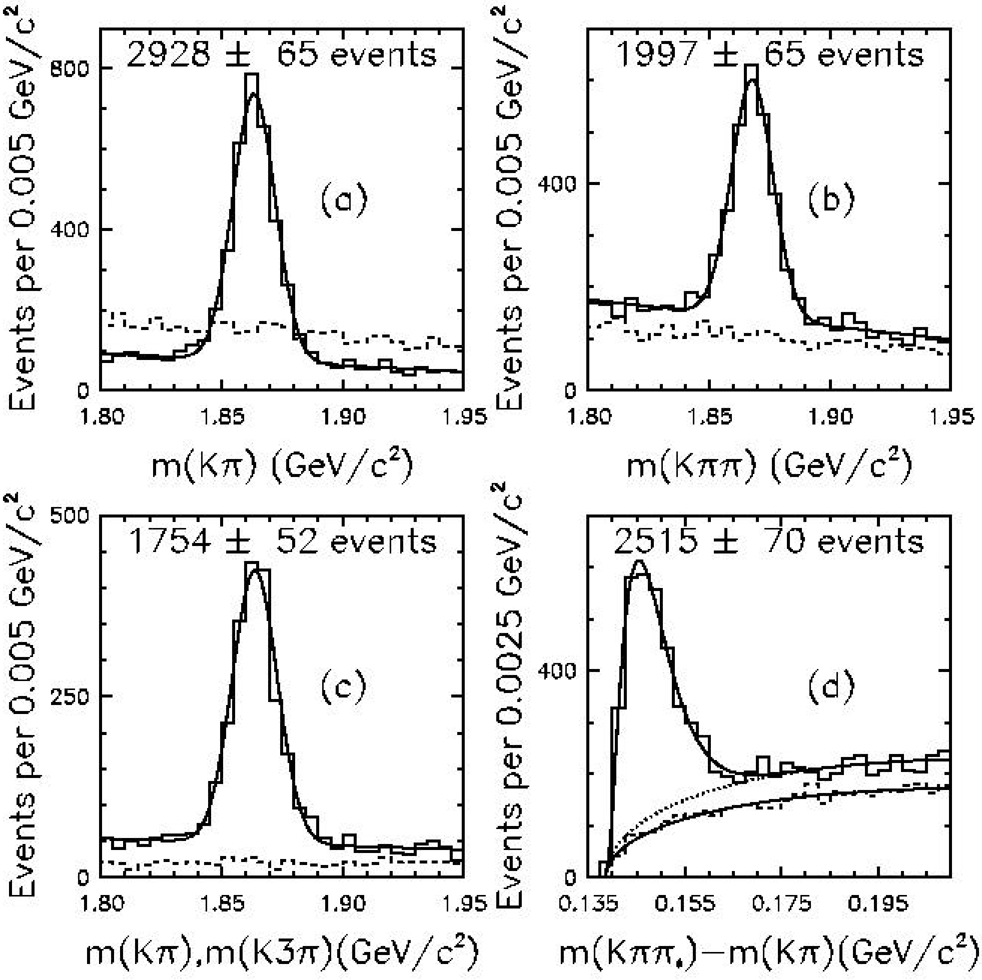
\+ Much higher statistics, more background

\+ Jet charge value correlated with tag purity - use in fit to weight events

\+ Results more precise than dilepton analyses

Exclusive measurements

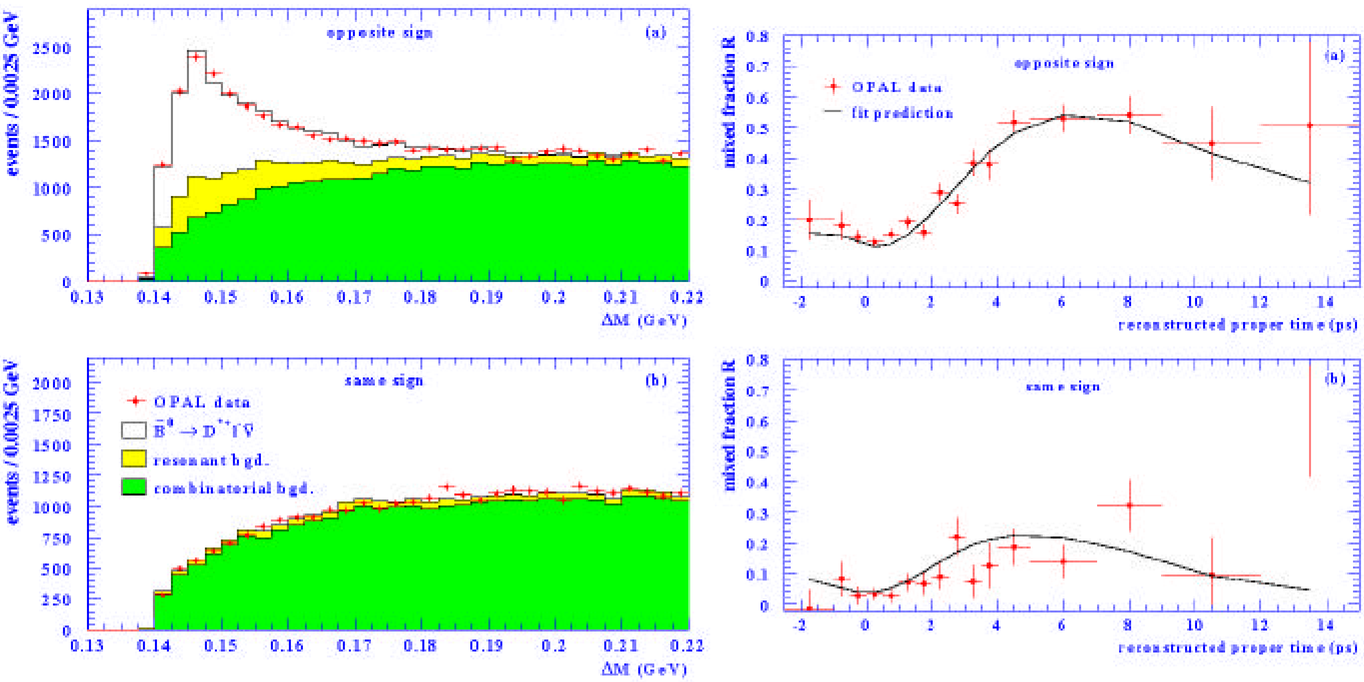
- Reconstruct specific B^0_d final state:
  - e.g. $B^0_d \to D^* l^- \nu$, $D^* \to D^0 \pi^+$ or $B^0_d \to D^+ l^- \nu$ with various D^0 and D^+ decay modes at CDF:



  - Relatively pure samples of a few 1000 events (10-100 times smaller than inclusive lepton samples).
  - Better time resolution in exclusive samples does not help Δm_d measurement
    - → Contribution of exclusive samples larger for Δm_s

The quest for more events

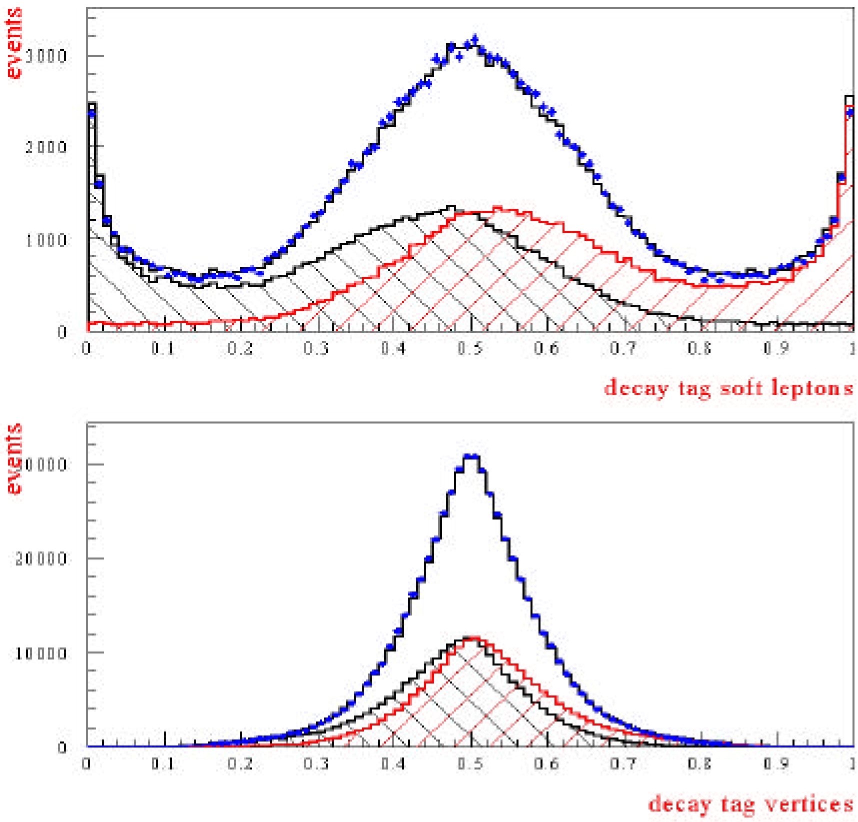
- Exploit kinematics of $D^{*+} \to D^0\pi^+$ decay - slow pion.
  - Peak in $\Delta m = m(D^*) - m(D^0)$ distribution can be identified using inclusive reconstruction of D^0.
  - Look for $l^-\pi^+$ combinations - sample of $B^0 \to D^{*+}l^-$
    - → Wrong sign $l^+\pi^-$ combinations and sidebands control background.



- Around 7000 signal decays in low Δm region.
  - → Non-combinatorial background from $B \to D^{**}l\nu$ decays has to be estimated (B^0, B^+ and B_s contributions)
  - → Combinatorial background also has oscillatory component.
- Most precise single LEP measurement.

Measurements without leptons I

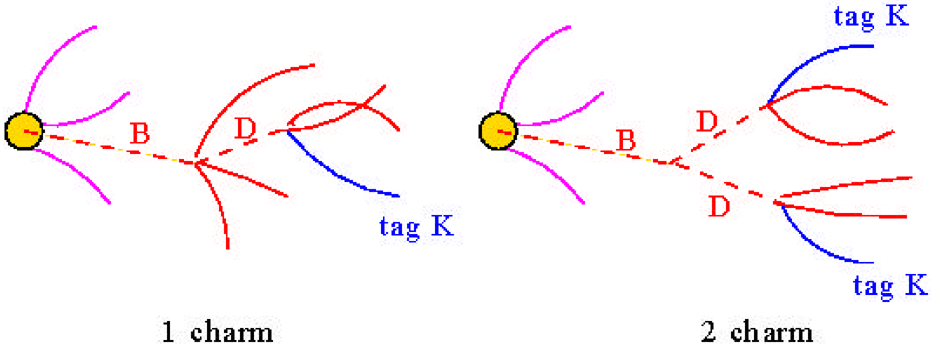
- Vertex-based b-tags→large samples of B mesons
  - To exploit them for B^0 oscillations, need decay flavour tag without using high-p/p_t leptons.
  - DELPHI uses 'soft lepton tag' - enough to give decay flavour, not enough for b-tag.
  - Try to separate direct B and cascade D products using kinematic information in B rest frame.
    - → $B^0 \rightarrow D^+x$ not D^-x, but also $B^0 \rightarrow D^{**}x$, $B^0 \rightarrow DD$ decays.



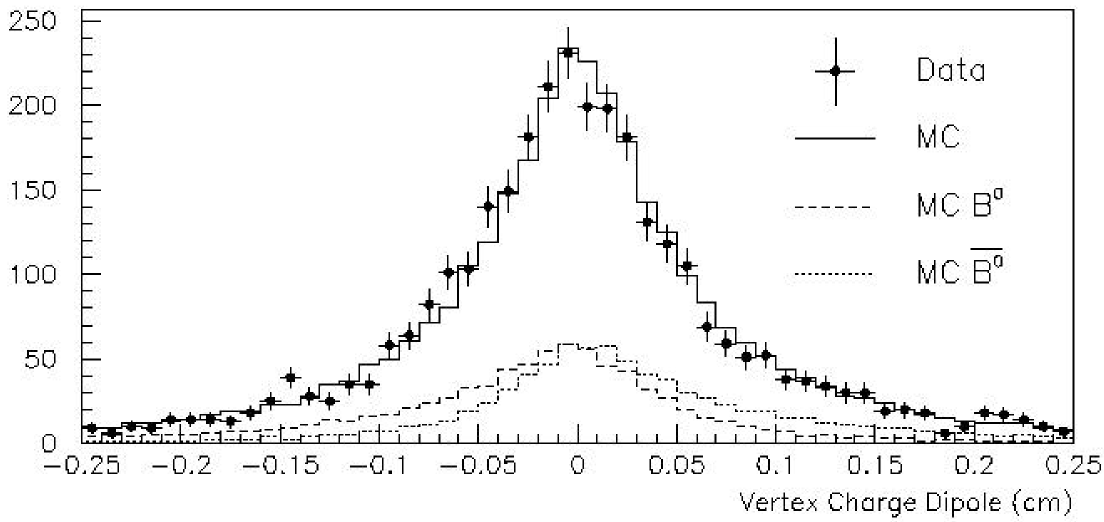
  - High statistics samples, but very poor tagging power (42% mistag) and difficult to calibrate.
  - ALEPH uses jet charge in B^0 decay hemisphere
    - → Sensitive to both production and decay flavour.

Measurements without leptons II

- SLD exploits high resolution vertex detector:
  - Reconstruct details of the B^0 decay:

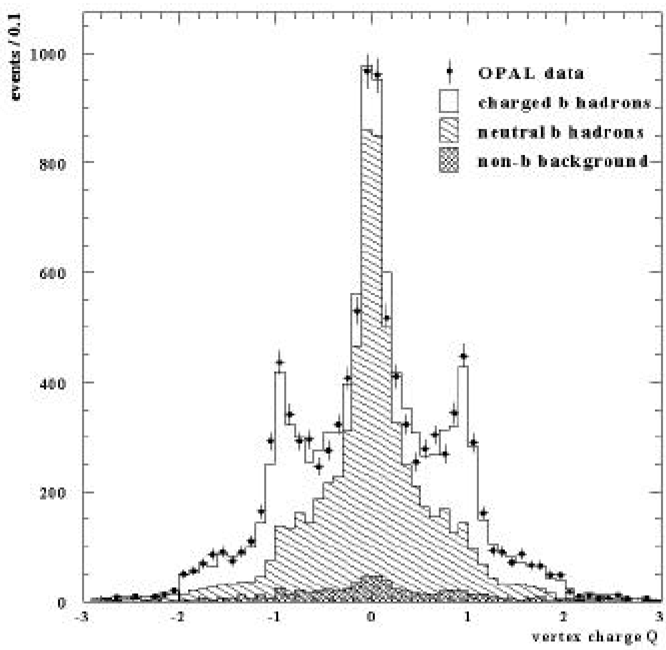


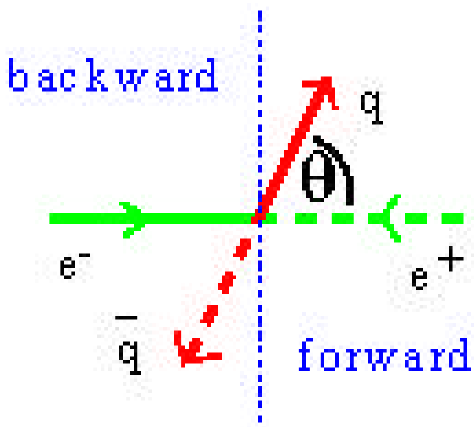
  - Kaons (identified with Cherenkov detector) tag B^0 decay flavour through $b \to c \to s$ decay chain.
    - → 1/3 of hadronic B^0 decays, ~23% mistag.
  - Some separation of B and D decay products in vertex topology - charge dipole tags $B^0 \to D^+$.
    - → Tagging power increases with D flight distance, smallest mistag of 32% in tails.
    - → Cross-check tagging power using data (beam polarisation).



Improving the production flavour tag

- First measurements used lepton or jet charge
  - Tag opposite side to infer b-production flavour
- Several other techniques can be used:
  - Kaons from B decay (gives production flavour in absense of B mixing)
  - Vertex charge - unambiguous B^+ or B^- vertex allows production flavour to be inferred.
  - Polarisation at SLD: from b asymmetry

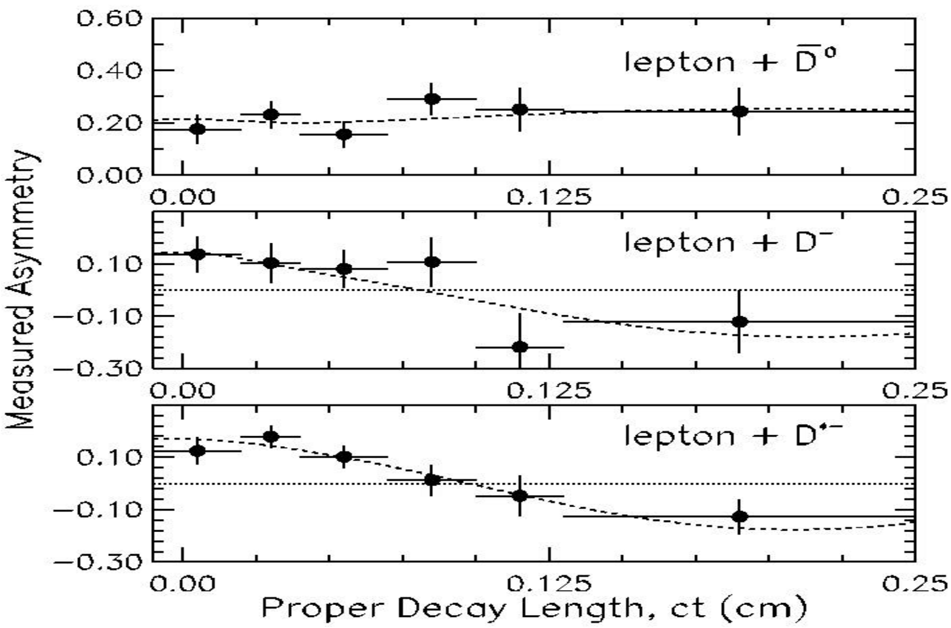




- Combine all estimates to single tag probability
  - Weight each tag with reliability estimate
  - Combination with likelihood or neural network
  - Event-by-event tag estimate for optimum statistical power.

Same side tagging

- At Z^0, both b decays in event always accessible
  - Infer production flavour from opposite hemisphere
  - At hadron colliders, this is often not true, and opposite side tag is diluted by underlying event
- Tag production flavour using same-side jet:
  - Correlations in fragmentation process
  - Decays of excited b-mesons: $B^{**\pm} \rightarrow B\pi^{\pm}$
  - Both lead to pion charge correlated with B production flavour (B^0-π^-, B^0-bar-π^+)
  - Select pions with kinematic criteria and consistency with primary vertex.



  - Clear signal for oscillations in B^0, none in B^+ sample
    - → At hadron colliders, this tagging is competitive with other methods.

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Putting it all together

- Very sophisticated fitting techniques
  - Use all available information
    - → Event-by-event tagging probabilities, resolutions and purities
  - Fit auxiliary parameters from data wherever possible to reduce systematics
    - → e.g. simultaneous fitting of Δm_d and B^0_d fraction
- Main sources of systematic errors:
  - Detector (proper time) resolution
  - Understanding of backgrounds (b/c physics)
  - b hadron lifetimes
  - Production/decay tagging uncertainties
- Current (winter 02) LEP+SLD+CDF run I result:
  - $\mathbf{\Delta m_d=0.492\pm0.013\ ps^{-1}}$ (0.009 stat, 0.009 syst)
  - A measurement with 2.6% precision.
  - No big improvements expected from LEP/SLD
    - → Nearly all data analysed, a few results still preliminary.
  - But b-factories have overtaken the older experiments with $\mathbf{\Delta m_d=0.495\pm0.007\ ps^{-1}}$
  - Cambining all Δm_d with time integrated mixing measurement χ_d=0.182±0.015 from CLEO/ARGUS: $\mathbf{\Delta m_d=0.494\pm0.007\ ps^{-1}}$.

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Conclusions

- LEP+SLD+CDF run 1 have made a great contribution to B^0 oscillations:
  - First measurement of time dependent mixing.
  - Many new techniques pioneered, e.g:
    - → Combined production tags from many sources.
    - → Same side tagging.
  - These are important for measurement of CP-violation in b decays, e.g. the first measurements of sin2b.
  - Achieved 2.6% precision measurement of Δm_d before the b-factory era.
  - Similar techniques used for B^0_s oscillation search.
- Now its time for the new experiments ...