# Measurement of $A_{FB}^{q}$ in $Z^0$ decays

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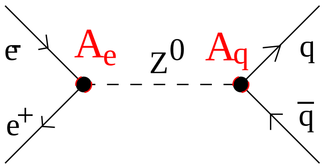
(OPAL collaboration)

- Introduction—what is the asymmetry and how to measure it.
- Measurements with leptons, D-mesons and jet charge.
- Corrections to the measurements.
- Results from LEP and SLD on $\mathrm{b}$ and $\mathrm{c}$ quark asymmetries.
- Light quark (uds) asymmetries.
- Comparison of results with Standard Model predictions.

Many thanks to the LEP Electroweak Working Group for Winter 97 averages, plots etc.

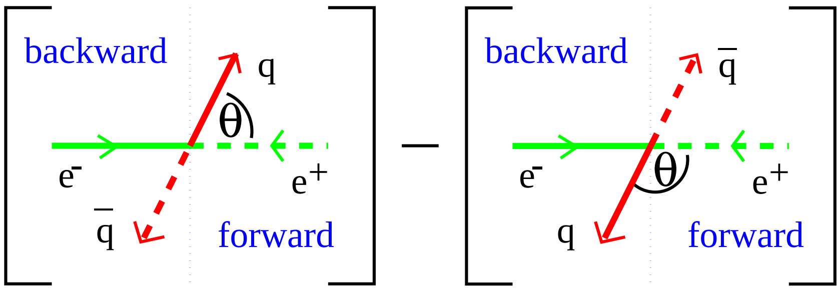
(see http://www.cern.ch/LEPEWWG/ for full story)

# What is the asymmetry?




$$\mathcal{A}_q = \frac{2 g_{V_q} g_{A_q}}{g_{V_q}^2 + g_{A_q}^2}$$

At LEP, with unpolarised beams ($4 \times 4$ million $Z^0 \rightarrow \mathrm{q\bar{q}}$ in 1990–1995):



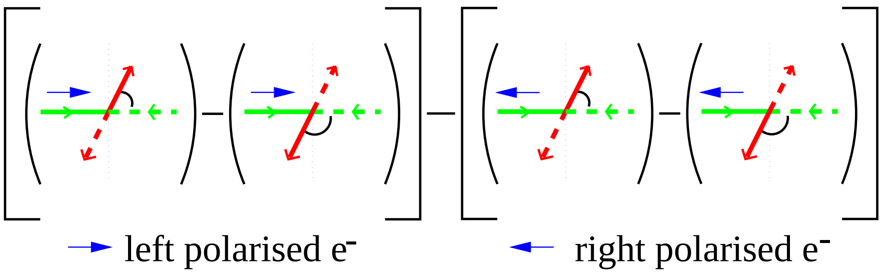

$$\neq 0 \rightarrow A_{\mathrm{FB}}^{\mathrm{q}}$$

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

From measured $A_{\mathrm{FB}}^{\mathrm{q}}$, obtain corrected pole asymmetry $A_{\mathrm{FB}}^{0,\mathrm{q}} = \frac{3}{4}\mathcal{A}_{\mathrm{e}}\mathcal{A}_q$.

At SLC, with polarised beams ($150,000$ $Z^0 \rightarrow \mathrm{q\bar{q}}$ in 1993–1995):

$$\frac{d\sigma}{d\cos\theta} \propto (1 - \mathcal{A}_{\mathrm{e}} P_e)(1 + \cos^2\theta) + 2\mathcal{A}_q(\mathcal{A}_{\mathrm{e}} - P_e)\cos\theta$$




$$\neq 0 \rightarrow A_{\mathrm{LRFB}}^{\mathrm{q}}$$

The 'left-right forward-backward' asymmetry $A_{\mathrm{LRFB}}^{\mathrm{q}}$ gives $\mathcal{A}_q$ directly.

# Ingredients of a measurement

To measure a heavy quark asymmetry:

- Tag events of the desired quark flavour.
- Measure the quark/anti-quark axis direction $(\cos\theta)$.
- Identify which hemisphere contained the quark and which the anti-quark.

Analyses proceed by:

- Fitting $\cos\theta$ distribution of tagged events, usually with log-likelihood technique (binned or unbinned). Events with high $\cos\theta$ have highest sensitivity, but are hardest to measure.
- Good control of background level and asymmetry is essential.
- Raw results must be corrected for biases due to event selection, detector charge asymmetry and QCD effects.

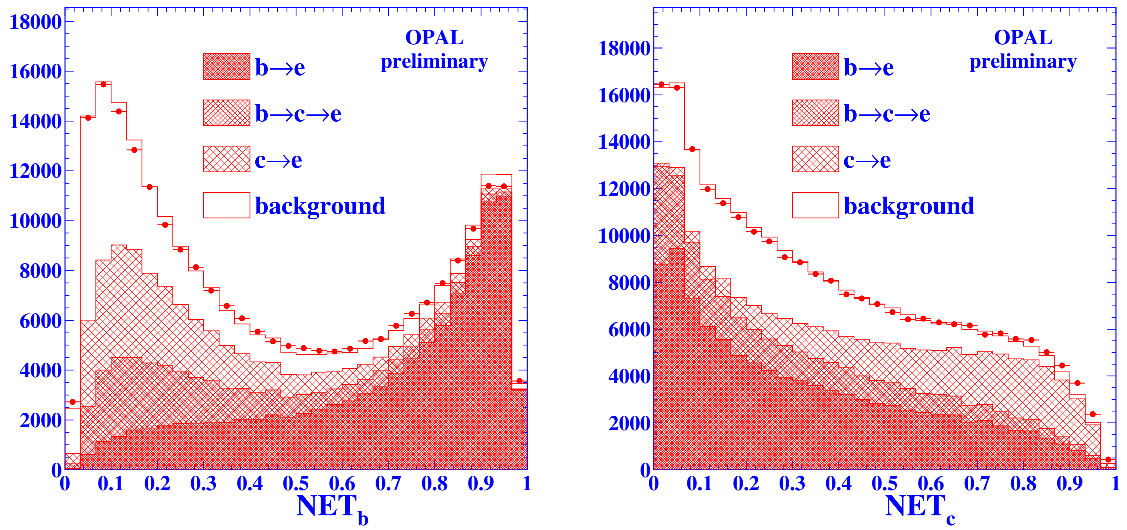
Many results on asymmetries of $\mathrm{b\bar{b}}$ and $\mathrm{c\bar{c}}$ events, a few also on light quark asymmetries.

# Measurements using leptons

All collaborations have used leptons ($e$, $\mu$) for b and c asymmetries.

- Leptons classified as from $b \to l$, $b \to c \to l$, $c \to l$ or background using momentum $p$, $p_t$ with respect to jet axis and other variables.
- Lepton sign tags primary quark/anti-quark (but effects of $B^0$ mixing, cascade $b \to c \to l$).
- Primary quark polar angle $\theta$ taken from nearest jet or thrust axis.

OPAL uses neural networks to select $b \to l$ and $c \to l$:

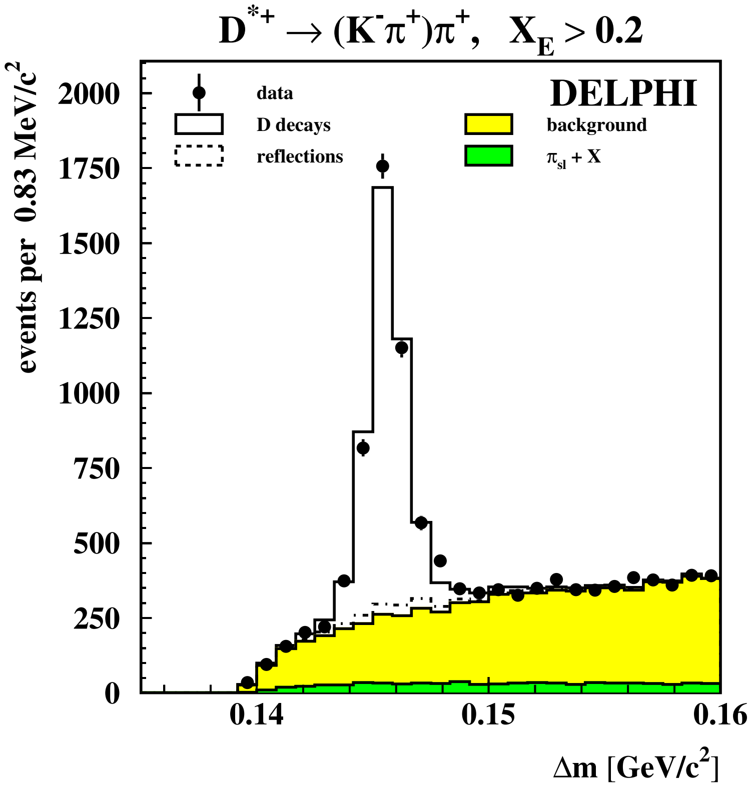



Separation variables: $p$, $p_t$, jet and subjet energies and momenta, vertex decay length and lepton impact parameter significances.

# $D^{(*)}$ measurements

ALEPH, DELPHI and OPAL use reconstructed $D^{(*)}$ mesons to measure $A_{\mathrm{FB}}^{\mathrm{c}}$ (and also $A_{\mathrm{FB}}^{\mathrm{b}}$).

- D-mesons reconstructed in various channels:
  $D^0 \rightarrow K^-\pi^+$; $D^+ \rightarrow K^-\pi^+\pi^+$; $D^{*+} \rightarrow D^0\pi$
  $D^0 \rightarrow K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-, K^-e^+\nu, K^-\mu^+\nu.$
- Charge of $D^{(*)}$ gives $\mathrm{q}$ or $\overline{\mathrm{q}}$, polar angle or thrust axis gives $\cos\theta$.
- Large combinatorial backgrounds controlled with mass side bands, 'reflected' pions from opposite hemisphere.




Separation between $\mathrm{b\overline{b}}$ and $\mathrm{c\overline{c}}$ events can be performed using lifetime information (b-tagging), $D^{(*)}$ momentum ($x_{D^{(*)}}$), and jet shape variables.

# Inclusive measurements

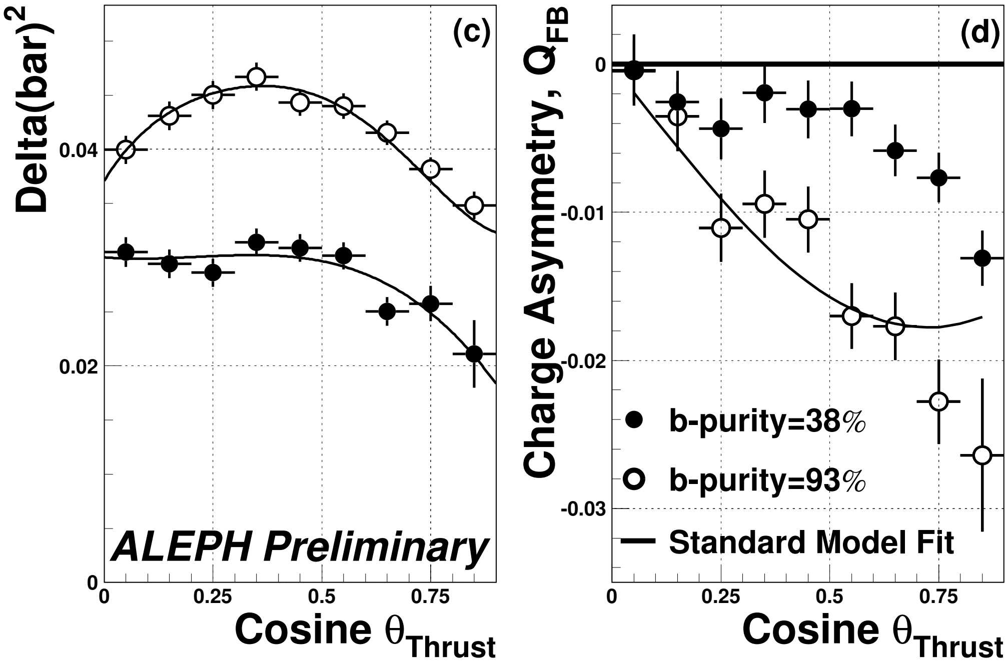
Measurements of $A_{\rm FB}^{\rm b}$ using leptons and $D^{(*)}$ are statistics limited. More inclusive techniques can be used:

- Lifetime tag to select $\rm b\overline{b}$ events, thrust axis gives $\cos\theta$.
- Primary quark hemisphere determined using jet or hemisphere charge:

$$Q_{jet} = \frac{\Sigma(\mid p_{l,i} \mid)^{\kappa} q_i}{\Sigma(\mid p_{l,i} \mid)^{\kappa}}, \kappa \sim 0.5$$

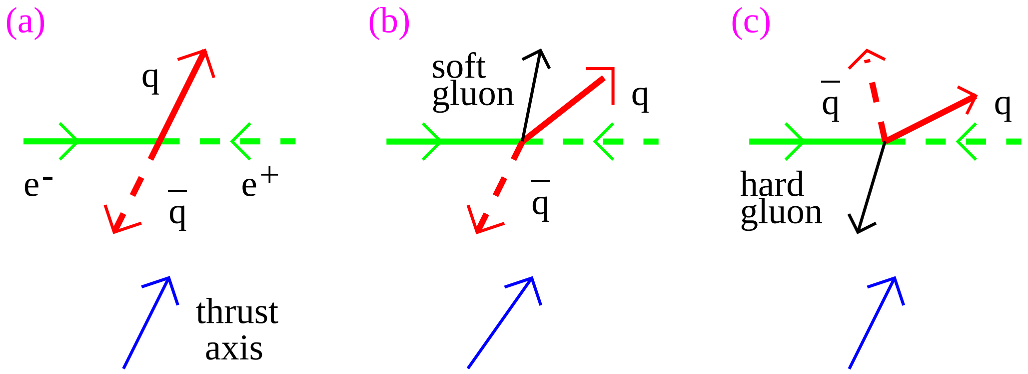
- Charge asymmetry $< Q_F - Q_B > \approx \delta \cdot A_{\rm FB}^{\rm b}$ sensitive to quark asymmetry.
- Charge separation measured by $\delta^2 = -4 < Q_F Q_B >$

ALEPH analysis fits for $\delta^2$ and $< Q_F - Q_B >$ as function of $\cos\theta$ and b-purity to get $A_{\rm FB}^{\rm b}$.



# Correcting the results

To relate the measured ‘raw’ asymmetry to theory, corrections are required for detector acceptance, charge bias, QCD effects:




Asymmetry measurable in cases (a), (b), not in (c).

$$A_{\mathrm{FB}}^{\mathrm{q}} = (1 - \mathcal{B}\delta_{QCD})A_{\mathrm{FB}}^{0,\mathrm{q}}$$

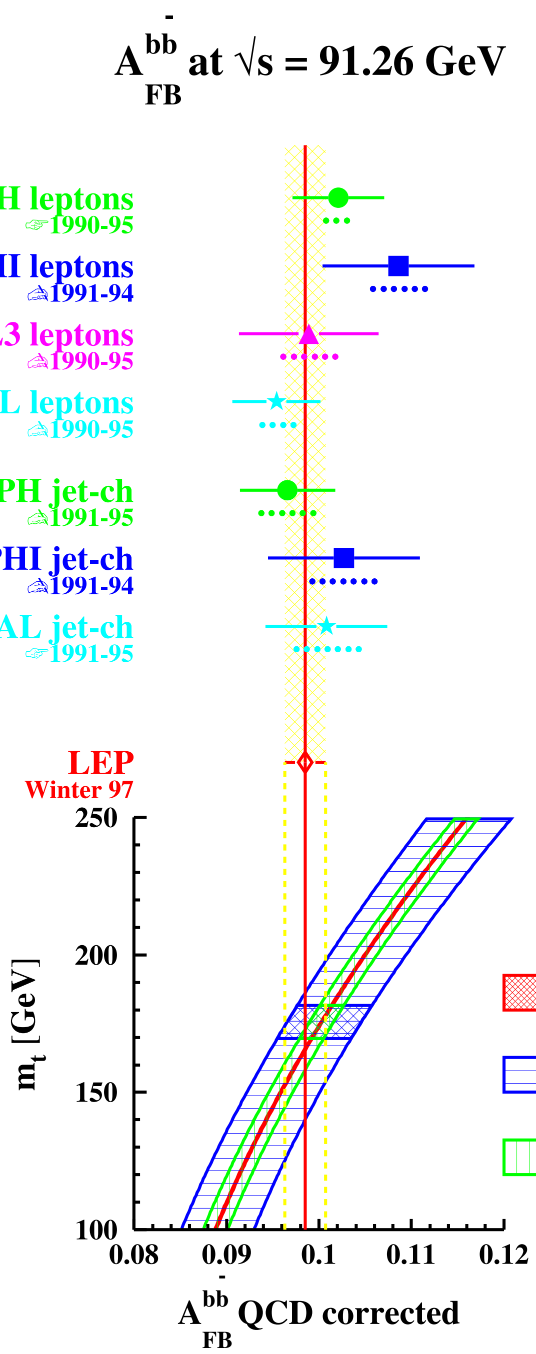
$\delta_{QCD}$ is ‘raw’ effect of gluon radiation, reduces $A_{\mathrm{FB}}^{\mathrm{q}}$ by $\sim 5\%$.

- $\delta_{QCD}$ is analytically calculable to ‘parton-thrust axis’ level (to order $\alpha_s$, some terms to order $\alpha_s^2$).
- Additional correction to ‘hadron-thrust axis’ level evaluated with Monte Carlo event generators (e.g. JETSET, HERWIG).
- $\mathcal{B}$ is experimental bias, e.g. $D^{(*)}$ and lepton analyses less likely to select topology (c) as quarks have reduced energy.

Also QED (initial state radiation), photon exchange and centre of mass energy corrections to finally derive $A_{\mathrm{FB}}^{0,\mathrm{q}}$.

# LEP $A_{FB}^{0,b}$ results

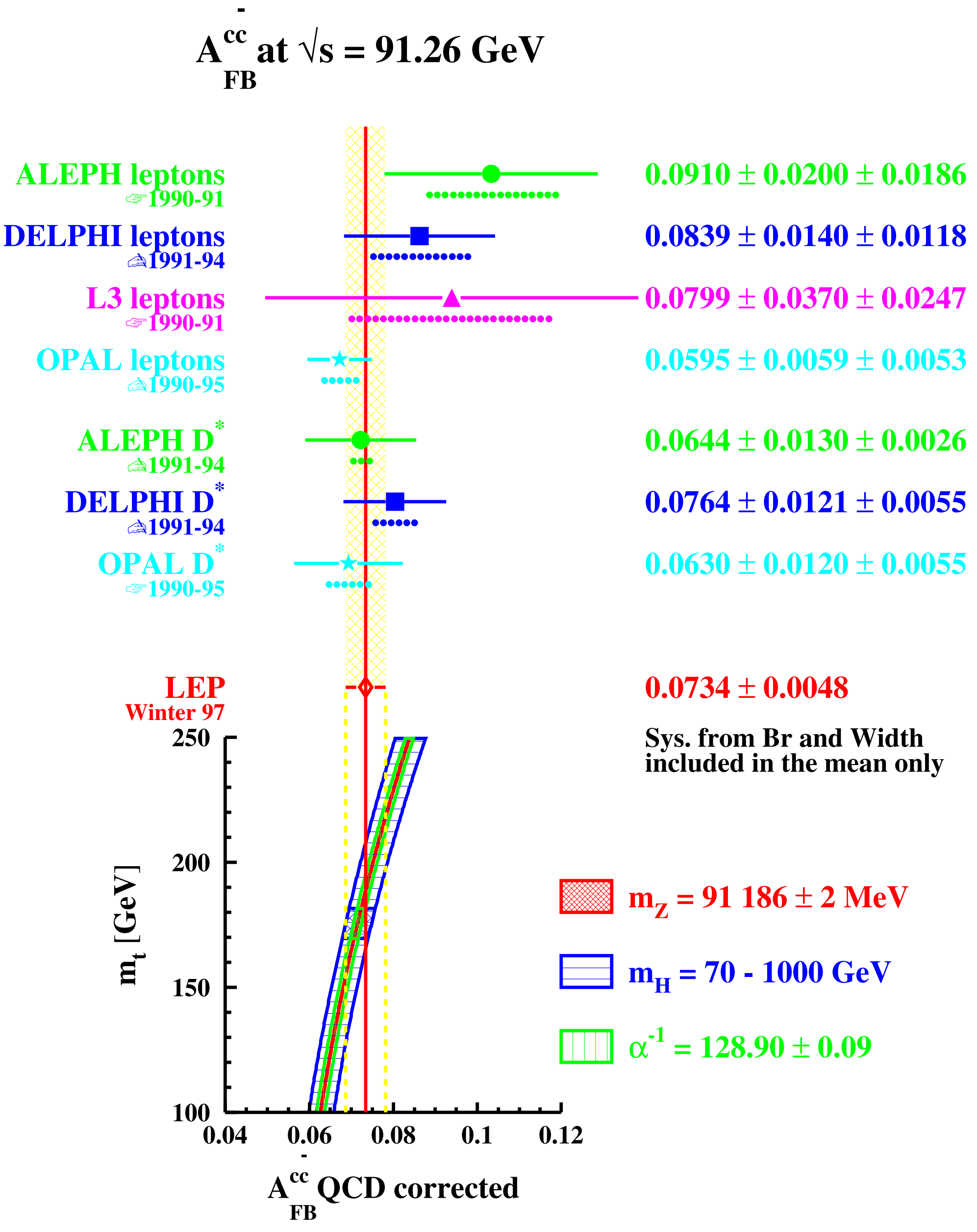
All LEP data, off peak data corrected to $Z^0$ pole ($D^{(*)}$ not shown).




Standard model prediction using $G_F, m_z, m_H, \alpha$.

# LEP $A_{FB}^{0,c}$ results

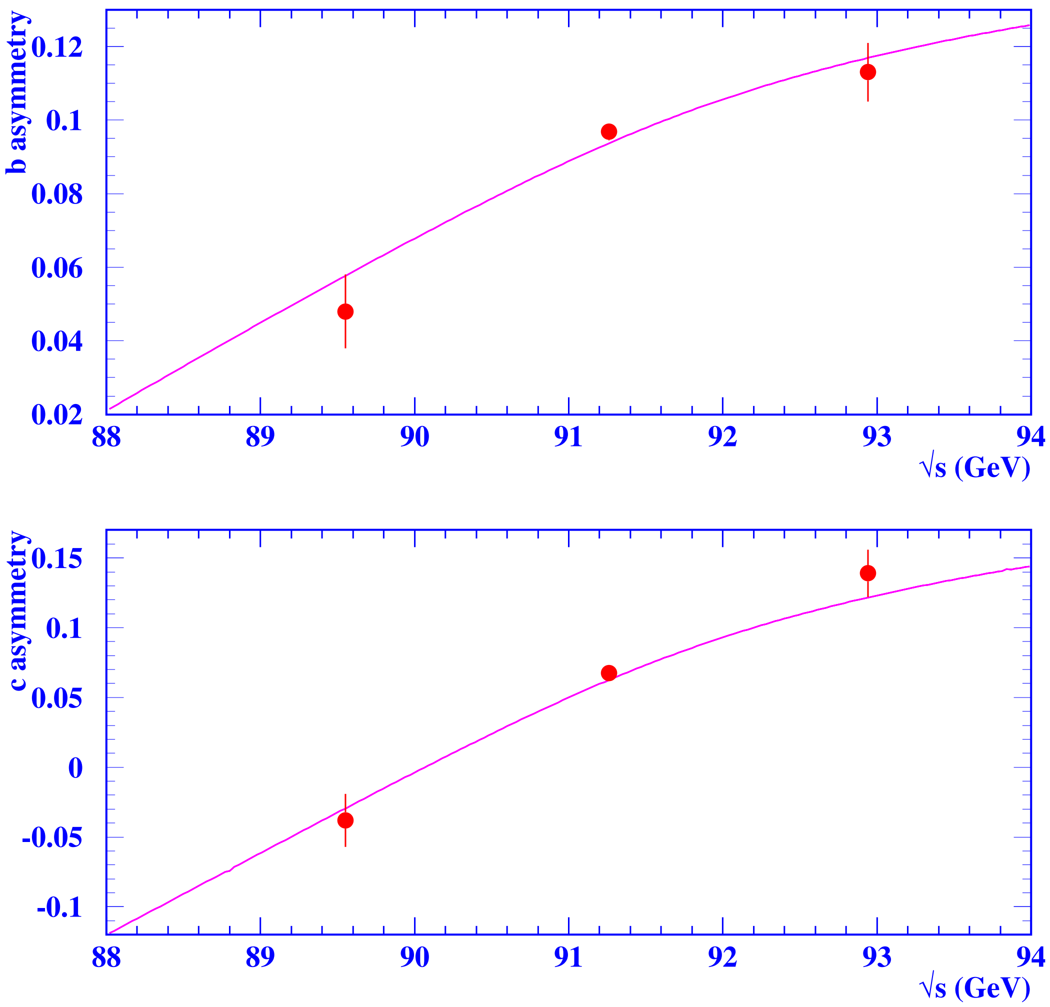
All LEP data, off peak data corrected to $Z^0$ pole.




Standard model prediction using $G_F, m_z, m_H, \alpha$.

# Off peak measurements

- The LEP experiments have taken some data $\sim 2\,\mathrm{GeV}$ above and below the $Z^0$ resonance—can measure asymmetry here too.
- Standard Model predicts centre of mass energy ($\sqrt{s}$) dependence of $A^{\mathrm{b}}_{\mathrm{FB}}$ and $A^{\mathrm{c}}_{\mathrm{FB}}$—no longer the 'pole' asymmetry.




Off peak measurements have lower statistics, but agree with prediction.

# Polarised measurements at SLD

$$\frac{d\sigma}{d\cos\theta} \propto (1-\mathcal{A}_{\mathrm{e}}P_e)(1+\cos^2\theta)+2\mathcal{A}_q(\mathcal{A}_{\mathrm{e}}-P_e)\cos\theta$$

- The observed 'left right forward backward asymmetry' $A^{\mathrm{q}}_{\mathrm{LRFB}}$ allows measurement of $\mathcal{A}_q$ directly, without knowing $\mathcal{A}_{\mathrm{e}}$.
- Observed asymmetry $A^{\mathrm{q}}_{\mathrm{LRFB}} \approx P_e\mathcal{A}_q$, where electron beam polarisation $P_e$ ≈0.6–0.8 and is measured to $\leq 1$% accuracy.
- Since at LEP $A^{0,\mathrm{q}}_{\mathrm{FB}} = \frac{3}{4}\mathcal{A}_{\mathrm{e}}\mathcal{A}_q$, and $\mathcal{A}_{\mathrm{e}} \approx 0.15$, large statistical advantage $(P_e/\mathcal{A}_{\mathrm{e}})^2 \sim 25$ of SLD over LEP experiments.

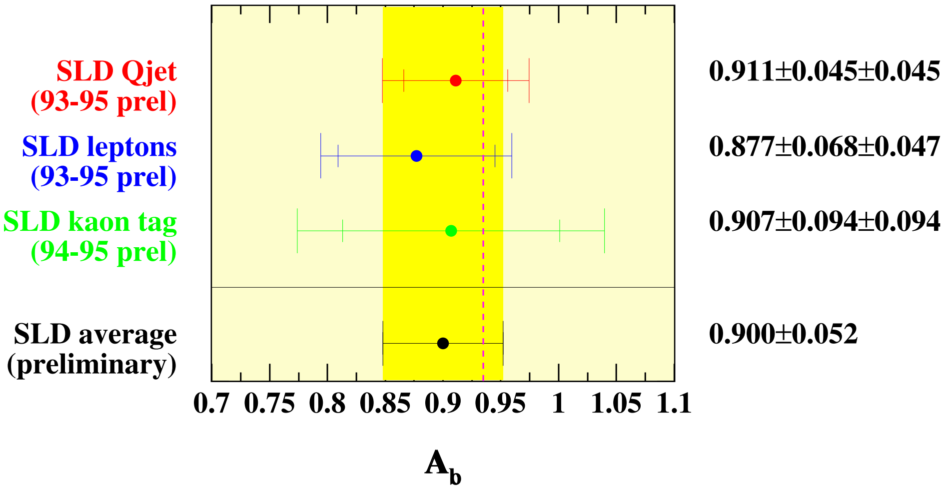
SLD uses vertex and lepton tags to measure $\mathcal{A}_b$, and lepton and $D^{(*)}$ tags to measure $\mathcal{A}_c$.

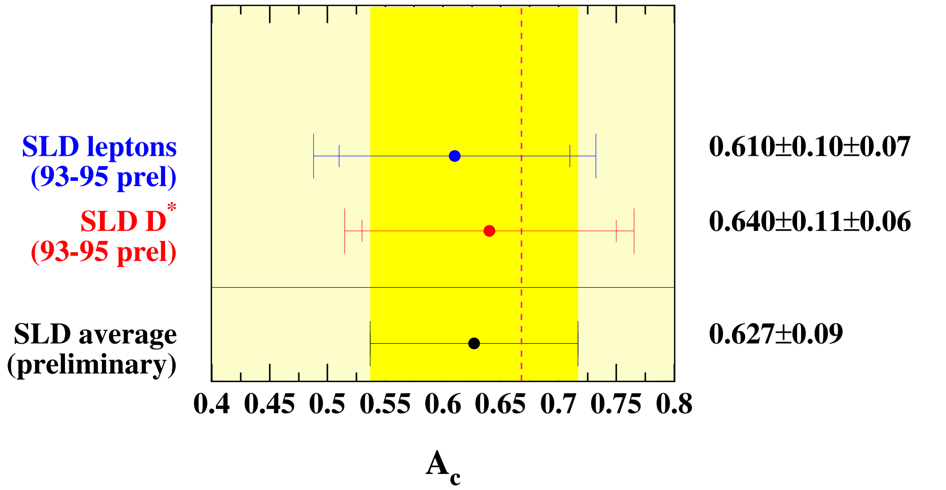
- Techniques similar to LEP experiments, but benefit from higher efficiency b-tagging due to high resolution vertex detector and small stable beam spot.
- Vertex tagged analysis also uses kaon charge to tag primary quark/anti-quark in dominant $b \rightarrow c \rightarrow s$ transition:
  $K^-$ tags $\mathrm{b}$ quark, $K^+$ tags $\overline{\mathrm{b}}$ anti-quark.

Results are preliminary and rapidly evolving (some new for Winter 97).

# SLD $\mathcal{A}_b$ and $\mathcal{A}_c$ results

SLD asymmetry measurements compared to Standard Model predictions of $\mathcal{A}_b = 0.935$, $\mathcal{A}_c = 0.668$:




Measurements agree with Standard Model prediction.

# What about the light quarks?

Impossible to tag high purity samples of $\mathrm{u\overline{u}}$, $\mathrm{d\overline{d}}$, $\mathrm{s\overline{s}}$ events, but high $x$ particles can be used to achieve moderate purities ($\sim$ 40% $\mathrm{s\overline{s}}$).

- DELPHI used high $x$ $K^{\pm}$ and $\Lambda^0$ to tag $\mathrm{s\overline{s}}$ events, and $K_L$ and neutron HCAL showers to tag $\mathrm{s\overline{s}}$ and $\mathrm{d\overline{d}}$ events:

$$A_{\mathrm{FB}}^{\mathrm{s}} = 0.121 \pm 0.024 \pm 0.014$$

$$A_{\mathrm{FB}}^{\mathrm{s,d}} = 0.131 \pm 0.035 \pm 0.013$$

  Result uses JETSET PS model to describe hadronisation (contributions from fragmentation, heavy quark cascade decays).

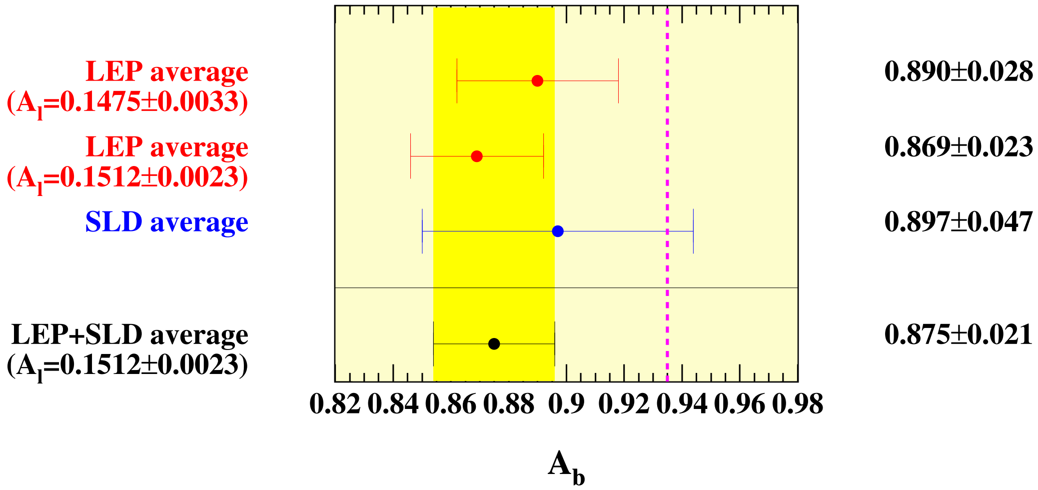
- OPAL used high $x$ $\pi^{\pm}$, protons, $K^{\pm}$, $K_S^0$ and $\Lambda^0$ to tag $\mathrm{u\overline{u}}$, $\mathrm{d\overline{d}}$, and $\mathrm{s\overline{s}}$ events.
  Double tagging used to estimate tagging efficiencies.
  Assuming isospin symmetry, flavour independence of QCD, $R_d = R_s$ and $A_{\mathrm{FB}}^{\mathrm{d}} = A_{\mathrm{FB}}^{\mathrm{s}}$, get:

$$A_{\mathrm{FB}}^{\mathrm{s,d}} = 0.067 \pm 0.034 \pm 0.011$$

  independent of hadronisation models.

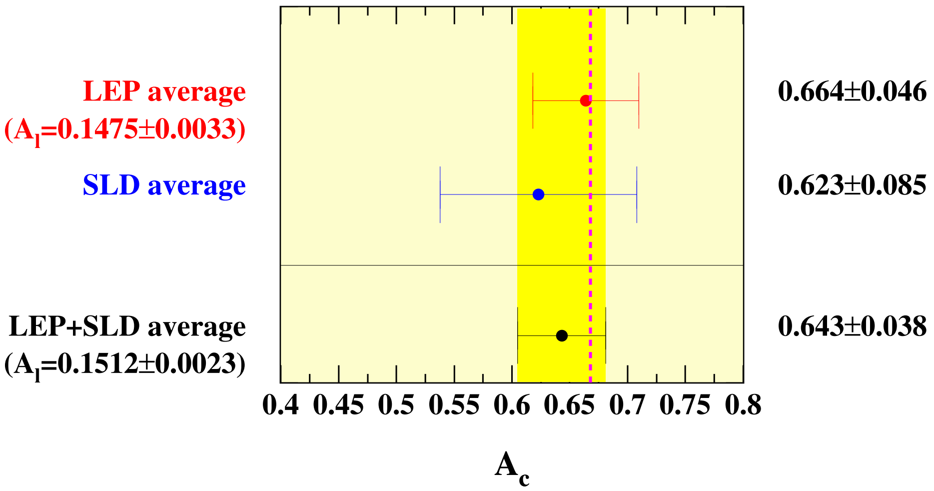
# Combining the LEP and SLD results

- LEP $A^{q}_{FB}$ can be converted to $\mathcal{A}_q$ using $\mathcal{A}_e$ from LEP $\mathcal{A}_l$
- A 'grand combination' can be made by using $\mathcal{A}_e$ from LEP $\mathcal{A}_l$ and SLD $A_{LR}$ (the inclusive left-right asymmetry).




LEP+SLD $\mathcal{A}_b$ combination is $3\sigma$ below Standard Model (0.935). However, this is due to a 'conspiracy' of several effects:

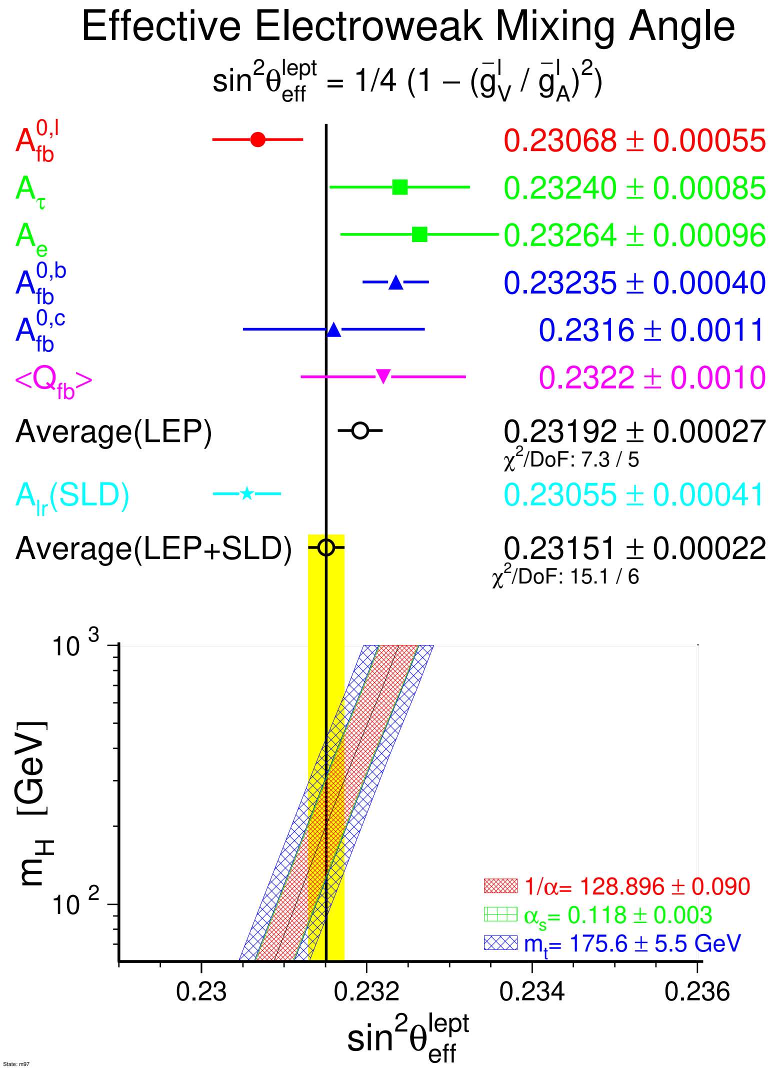
- $A^{b}_{FB}$ from LEP is 'low', $\mathcal{A}_b$ from SLD is slightly 'low',
- $A_{LR}$ from SLD is 'high' compared to the Standard Model.




LEP+SLD $\mathcal{A}_c$ combination is in good agreement with Standard Model.

# Measurements of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$

- Asymmetry measurements can be expressed in terms of effective electroweak mixing angle $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$.
- Lepton asymmetries and $A_{\mathrm{LR}}$ also measure $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$.




LEP+SLD average consistent with Standard Model, but $\chi^2$ is high, mainly because of $A_{\mathrm{LR}}$ and $A^{\mathrm{b}}_{\mathrm{FB}}$ (due to $\mathcal{A}_l$).

# Conclusions and outlook

- Heavy quark asymmetry measurements now reaching maturity at LEP.
- Some small improvements to come by using full data sample in all analyses, but no big changes likely.
- Measurements from SLD becoming competitive, and further big improvements likely in future (1996 data and beyond).
- Results from LEP and SLD on $\mathcal{A}_b$ and $\mathcal{A}_c$ are consistent, but slightly lower than Standard Model.
- Discrepancy gets worse when SLD $A_{\mathrm{LR}}$ results are included.

Watch for improved SLD results in the future…