Quark Asymmetries

Pippa Wells
CERN

28 February 2003

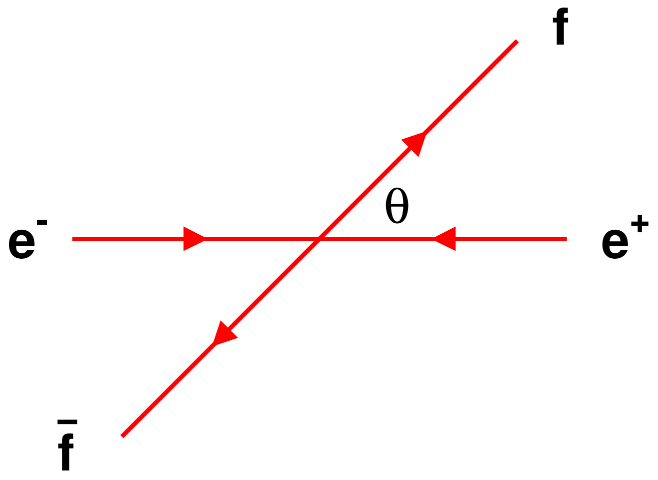
- Ingredients of the asymmetry method
- Flavour tagging
- Quark production charge determination
- Fitting techniques
- Corrections to derive pole asymmetries
- Results, implications for couplings
- Past, present and future...

To measure a forward-backward asymmetry...

- Identify Z to hadron events. Generally split event into 2 hemispheres by plane perpendicular to thrust axis. Tag heavy quark events.
  - Leptons (p, p_T) and reconstructed hadrons (notably D for charm)
  - Lifetime, mass of vertex
  - Other jet properties.
- Identify quark direction, including charge. Outgoing electron is in forward hemisphere.
  - Thrust axis $\cos\theta$
  - Lepton charge, vertex/jet charge...
  - Account for B^0 mixing, charge tag purity
- Fit to differential cross section

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

- Maybe simultaneous fit for $A_{FB}^{b\bar{b}}$, $A_{FB}^{c\bar{c}}$
- Corrections to get to pole asymmetry



Heavy flavour tags – leptons

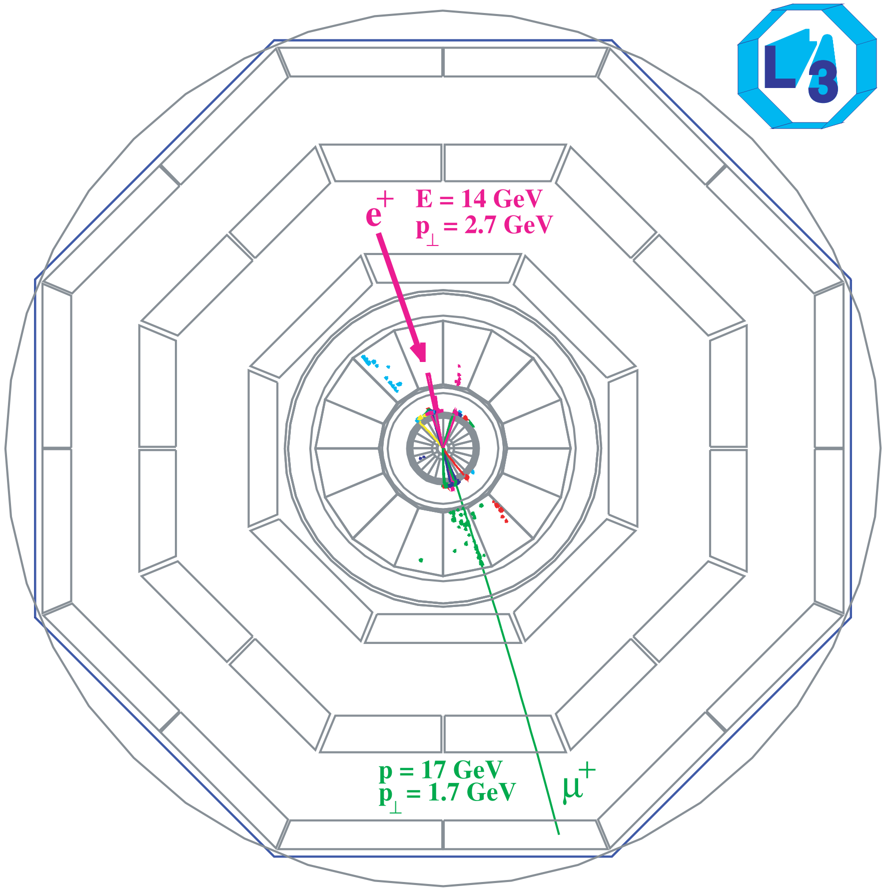
Semileptonic BR of b and c hadrons ≈ 20%

Electrons: ionisation in tracking chambers dE/dx, E/p, shower shape

Muons: Match between central track and muon chambers

Leptons also give charge of the decaying hadron

Lepton p and p_T plus jet properties and lifetime information used for flavour separation.



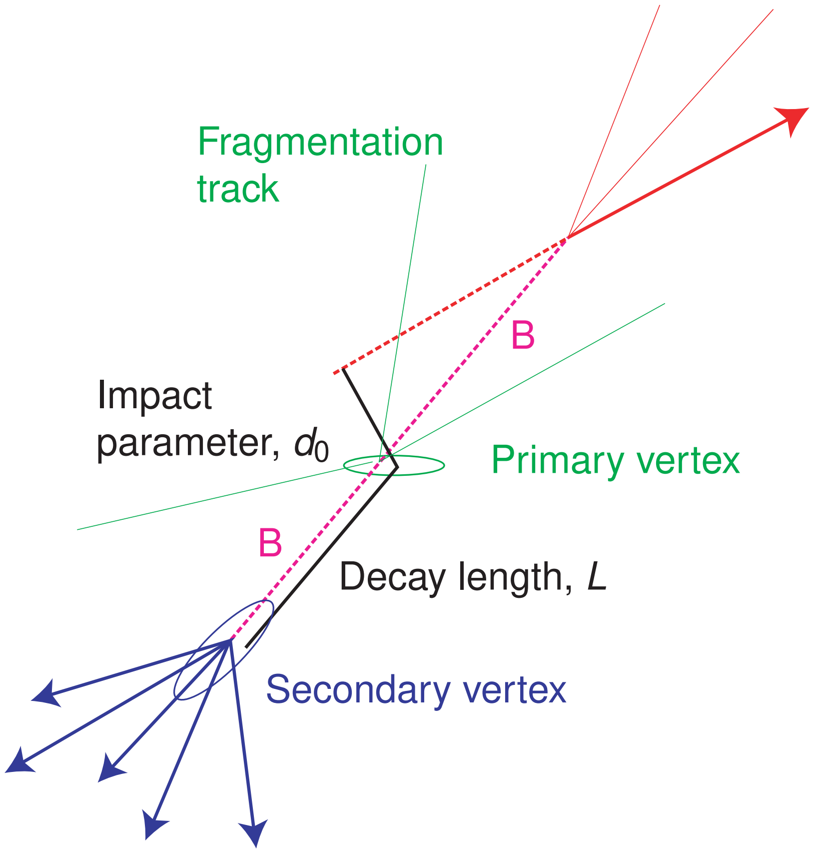
Heavy flavour tags – lifetimes

Event/detector characteristics:

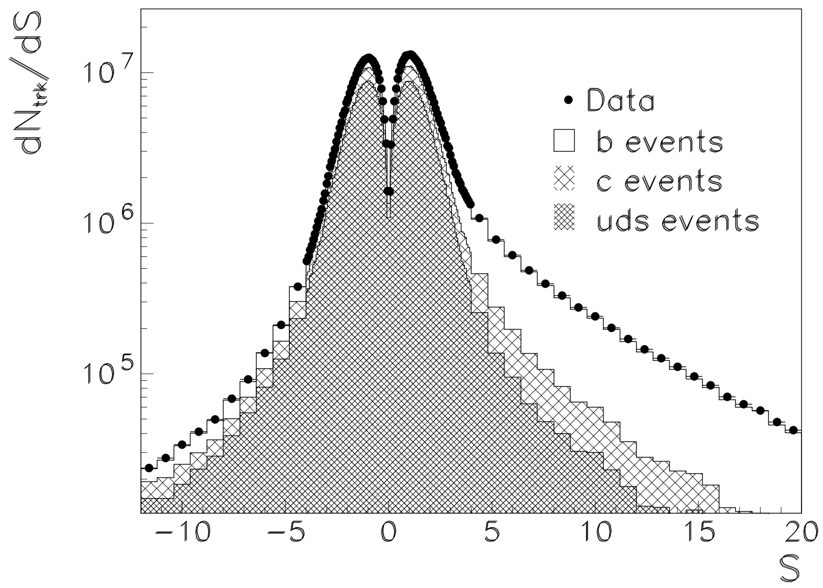
- B lifetime 1.5ps, energy 30 GeV decay length 3mm, charged multiplicity 5
- vertex detector radius 6-10cm
- impact parameter resolution 20μm

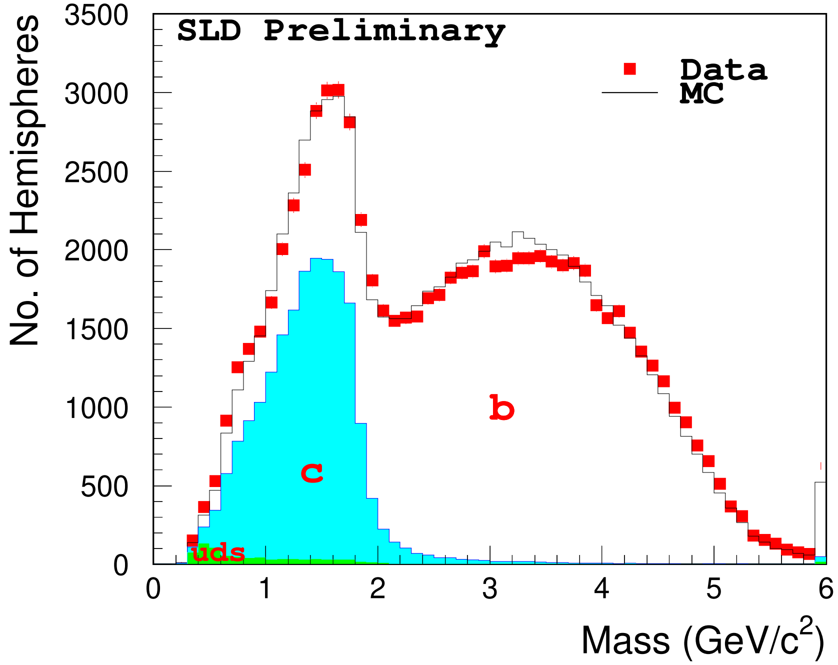
Useful variables include:

- probabilities/weights for tracks to be associated to primary/secondary vertex
- χ^2 of fits assuming primary or primary+secondary vertex
- decay length of secondary vertex and its error
- mass of secondary vertex



Heavy flavour tags – lifetimes





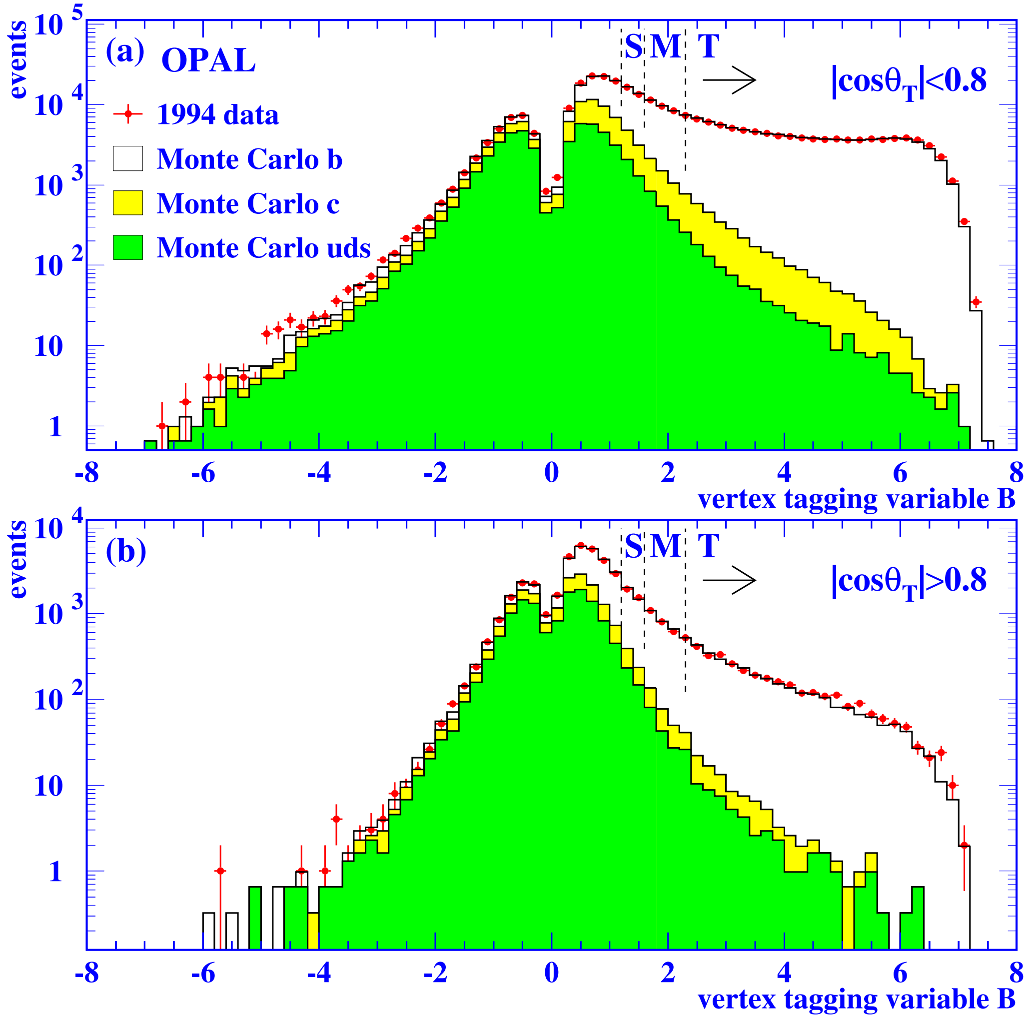
Distribution of impact parameter divided by its error for all tracks

Use negative i.p. tracks to control resolution

Mass of secondary vertex

Heavy flavour tags – multivariate

- Combine several variables into one hemisphere tag
- Leptons may also be included in an overal tagging variable, or used as a separate category
- Different ranges of the tagging variable have different purities. Can achieve very high b-purity (80-95%) with dominant background from charm



Lepton analyses

Leptons (and reconstructed hadrons, used for charm tagging) give flavour (b, c vs. $\overline{\mathrm{b}}, \overline{\mathrm{c}}$) of decaying hadron directly.

Complications from $\mathrm{B}^0\overline{\mathrm{B}^0}$ mixing and *cascade* decays: $\mathrm{b} \to \ell^-$, $\mathrm{b} \to \mathrm{c} \to \ell^+$, $\mathrm{b} \to \overline{\mathrm{c}} \to \ell^-$,

$$A_{\mathrm{FB}}^{\mathrm{obs}} = f_{\mathrm{b}\ell} A_{\mathrm{FB}}^{\mathrm{b\overline{b}}}(1 - 2\overline{\chi}) - f_{\mathrm{c}\ell} A_{\mathrm{FB}}^{\mathrm{c\overline{c}}} - f_{\mathrm{bc}\ell} A_{\mathrm{FB}}^{\mathrm{b\overline{b}}}(1 - 2\overline{\chi}) + f_{\mathrm{bkg}} A_{\mathrm{FB}}^{\mathrm{bkg}}$$

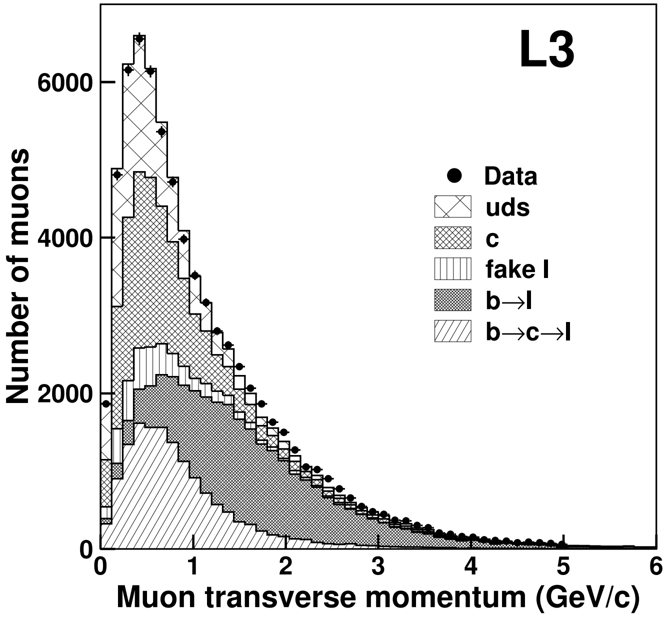
In addition to lepton p and p_T, use additional jet shape and lifetime variables to separate b, c, cascade decays and light quark background

Fit to single and dilepton samples to determine $A_{\mathrm{FB}}^{\mathrm{b\overline{b}}}$, $A_{\mathrm{FB}}^{\mathrm{c\overline{c}}}$ and $\overline{\chi}$.
Effective mixing parameter biased by

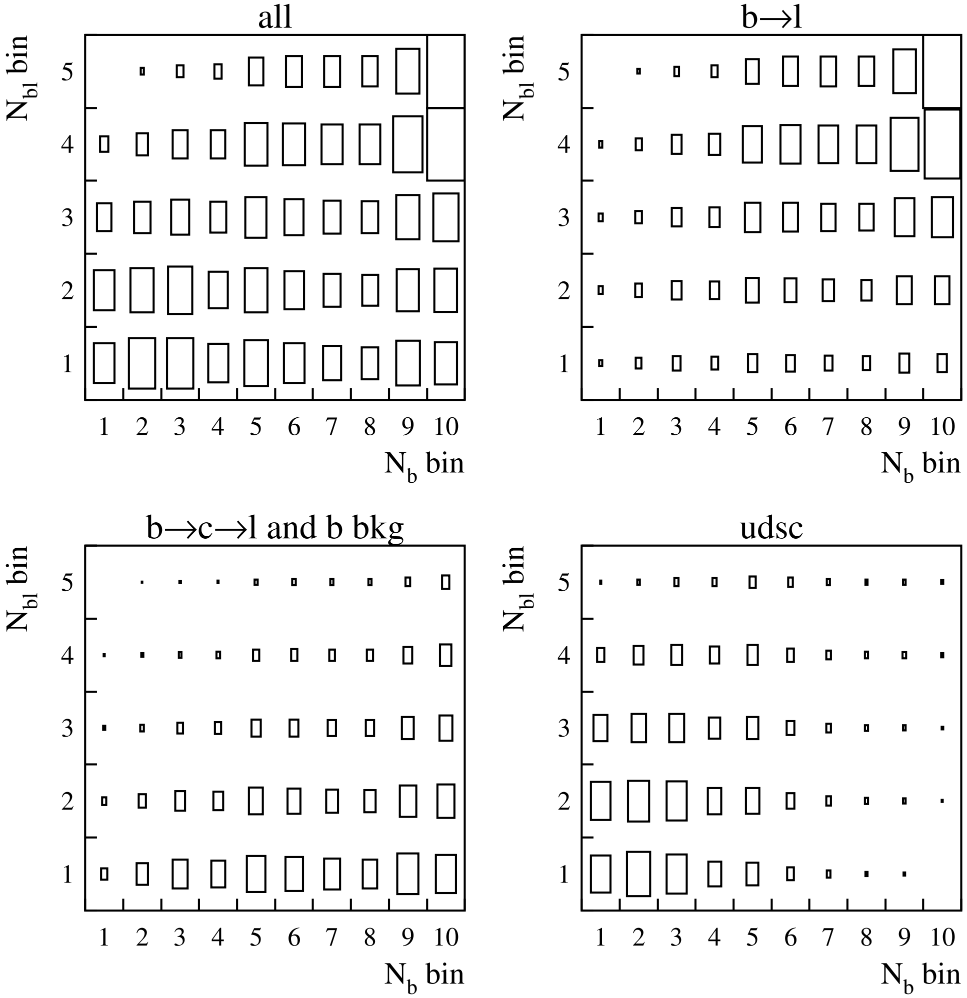
- lifetime variables used for flavour separation
- cascade decays, since B^0 decays more often to D^+, which has a larger semileptonic decay branching ratio than D^0.

Aside: DELPHI include information from *jet charge* in opposite hemisphere to improve the production charge tagging

Lepton analyses



Muon p_T spectrum



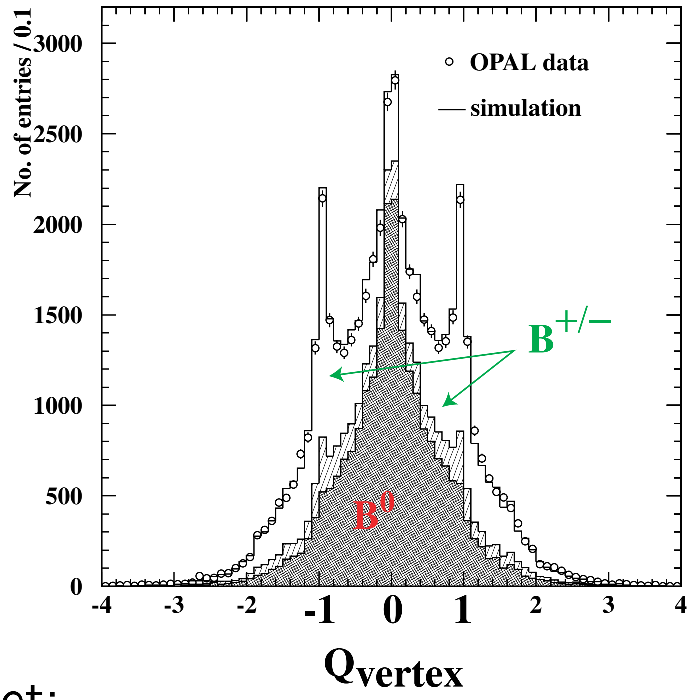
Distribution in bins of Nb and Nbl (b and cascade networks) for events with low value of Nuds (ALEPH MC)

Inclusive charge determination

$$Q_{\text{jet}} = \frac{\sum_{\text{tracks},i} p^{\kappa}_{\parallel,i} q_i}{\sum_{\text{tracks},i} p^{\kappa}_{\parallel,i}}$$

Different values of κ appropriate for B^0 ($\kappa \approx 0$) or B^+ ($\kappa \approx 1$)

$$Q_{\text{vertex}} = \sum_{\text{tracks},i} w_i^{\text{sec/prim}} q_i$$



Several variables in production charge NNet:

- One or more jet charges, vertex charge and its error
- Charge of an identified kaon $b \to c \to s \to K$
- DELPHI include relative probability of B^0, B^+, B_s, b-baryon
- Variables on which performance depends eg. $\cos\theta$, decay length
- DELPHI include charge of identified leptons; ALEPH and OPAL treat leptons as ordinary tracks to reduce correlation with lepton fits.

Fit method – inclusives

- In general, the experiments perform fits in many bins of b-tag purity and $\cos\theta$.
- The flavour fractions in each bin are calibrated from the data, usually by a double tag method.
- Performance of production charge determination is also calibrated from data
  - ALEPH, L3 and OPAL use the variable $\langle Q_{\mathrm{F}} - Q_{\mathrm{B}} \rangle$ as a measure of the forward backward asymmetry
  - DELPHI use a double tag method to calibrate the charge mis-tag rate from the relative rates of like-sign and unlike-sign events
- Systematic uncertainties enter via the residual model dependence. In particular, correlations between tag rates and charge determination between the hemispheres are taken from the MC, and must be controlled.

Double tag method for purities

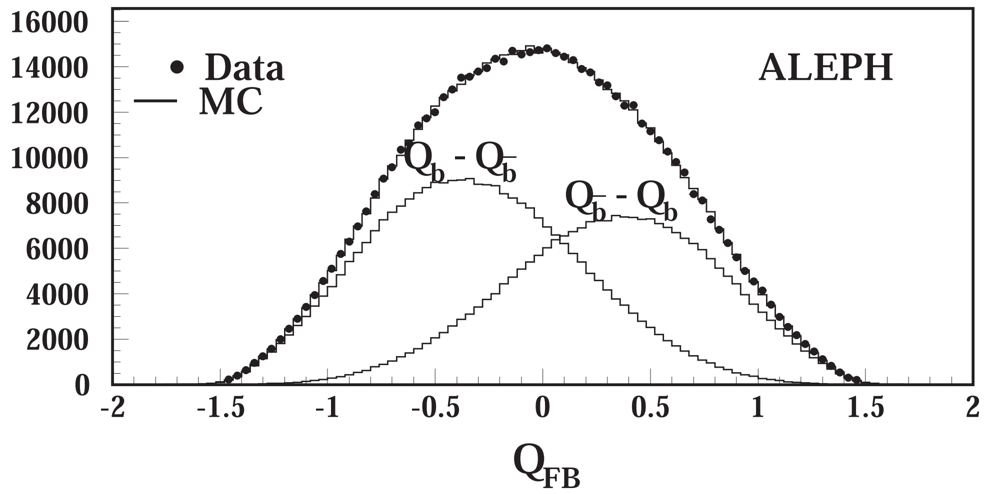
- Count fraction of hemispheres with a tag, f_s, and fraction of events with a double tag, f_d, for tagging variables i, l, k (eg. different bins of lifetime tag, or lepton vs. vertex tags...)

$$
\begin{aligned}
f_s^i &= \varepsilon_{\mathrm{b}}^i R_{\mathrm{b}} + \varepsilon_{\mathrm{c}}^i R_{\mathrm{c}} + \varepsilon_{\mathrm{uds}}^i (1 - R_{\mathrm{b}} - R_{\mathrm{c}}) \,, \\
f_d^{kl} &= \varepsilon_{\mathrm{b}}^k \varepsilon_{\mathrm{b}}^l D_{\mathrm{b}}^{kl} R_{\mathrm{b}} + \varepsilon_{\mathrm{c}}^k \varepsilon_{\mathrm{c}}^l D_{\mathrm{c}}^{kl} R_{\mathrm{c}} + \varepsilon_{\mathrm{uds}}^k \varepsilon_{\mathrm{uds}}^l (1 - R_{\mathrm{b}} - R_{\mathrm{c}}) \ .
\end{aligned}
$$

- Correlations of tagging probability between hemispheres:
  $D_f^{kl} = \varepsilon_f^{kl} / (\varepsilon_f^k \varepsilon_f^l)$
  - Detector geometry
  - Primary vertex common to both hemispheres (correlation much reduced by finding primary vertex separately in each hemisphere)
  - B-hadron momenta correlated, gluon radiation....
- To solve system of equations for data, take minimum input from MC: correlations and the lowest efficiencies.

$\langle Q_F - Q_B \rangle$ *method*

Example: b-rich sample from multivariate flavour tag: vertex, jet and kaon charges combined in a Q neural net



Consider only b quarks. Observable (in bins of $\cos\theta$) is:

$$\langle Q^b_{FB} \rangle \equiv \langle Q^b_F - Q^b_B \rangle = \frac{1}{n^b_{tot}} \left(n^b_F \langle Q_b - Q_{\bar{b}} \rangle + n^b_B \langle Q_{\bar{b}} - Q_b \rangle \right)$$

$$= \delta_b A^{b\bar{b}}_{FB} \frac{8}{3} \frac{\cos\theta}{1+\cos^2\theta}$$

Asymmetry diluted by charge separation $\delta_b = \langle Q_b - Q_{\bar{b}} \rangle$

With all flavours, writing $s_f = \pm 1$ for down/up-type quark, P_f fraction of flavour f:

$$\langle Q_{FB} \rangle = \sum_f s_f P_f \delta_f A^{f\bar{f}}_{FB} \frac{8}{3} \frac{\cos\theta}{1+\cos^2\theta}$$

$\langle Q_{\mathrm{F}} - Q_{\mathrm{B}} \rangle$ *method*

To derive $A_{\mathrm{FB}}^{\mathrm{b\bar{b}}}$, fit in bins of flavour tagging variables and $\cos\theta$. Use double-tag method to find fractions P_f.

Average charge separation $\delta = \sum_f s_f P_f \delta_f$ can be derived from data, noting that $\langle Q_f Q_{\bar{f}} \rangle \equiv \langle Q_{\mathrm{F}} Q_{\mathrm{B}} \rangle$

$$\frac{\delta^2}{4} = \frac{-\langle Q_{\mathrm{F}} \cdot Q_{\mathrm{B}} \rangle + \rho \cdot \sigma^2 + \mu^2}{1+\rho} \,,$$

μ and σ^2 mean and variance of hemisphere charge

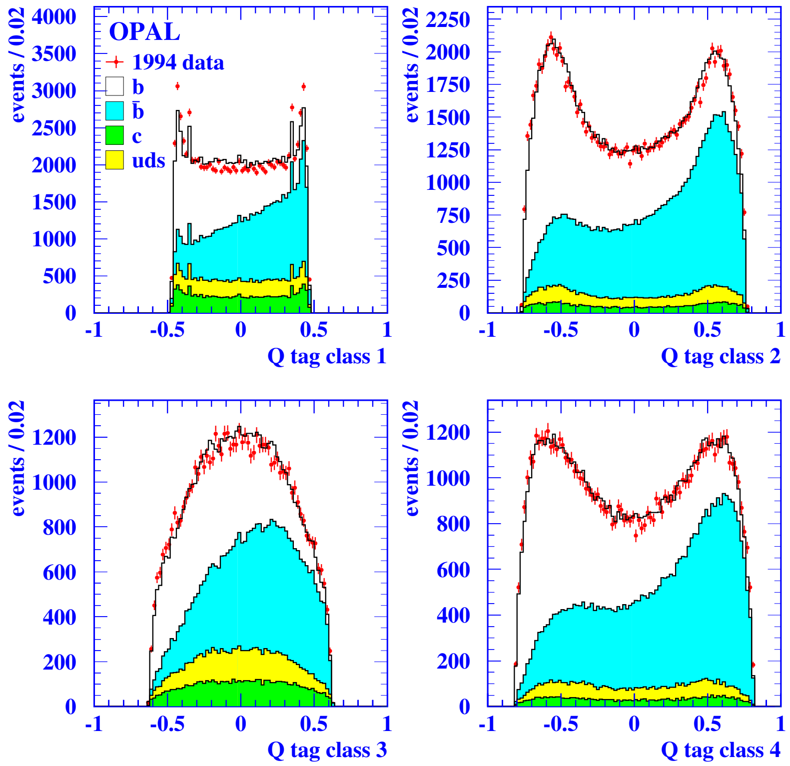
ρ is the correlation between Q_f and $Q_{\bar{f}}$, evaluated in MC.

$$\rho = \frac{\langle Q_{\bar{f}} \cdot Q_f \rangle - \langle Q_{\bar{f}} \rangle \cdot \langle Q_f \rangle}{\sigma_{Q_{\bar{f}}} \sigma_{Q_f}} \,,$$

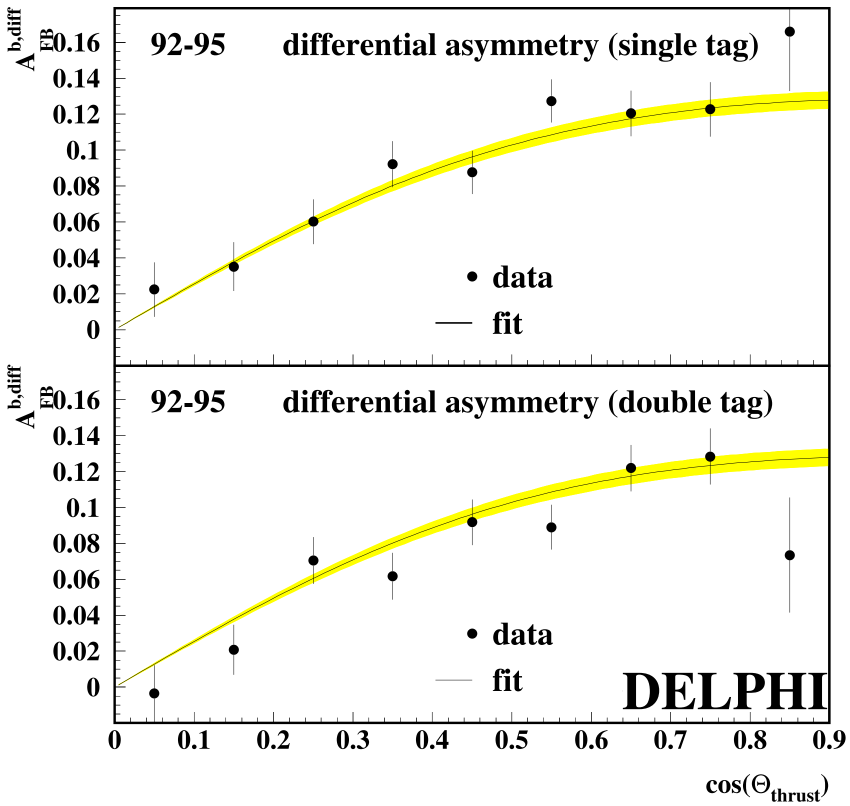
Either take values of δ_f for c and uds from MC, then δ_b is from data (OPAL) or fit in different tag purity regions to derive all δ's, taking all correlations from MC (ALEPH).

δ_b from data *i.e.* charge separation calibrated from data.

Data quality of inclusive analyses



Q variables for four event classes. (These are then rescaled to give a smooth variable between -1 and $+1$)



Result of the asymmetry fit

Systematic uncertainties

- In general, as much as possible is measured from data. Measurements are designed to be statistics limited
- Uncertainties in MC modelling feed into analysis via quantities taken from MC, eg. hemisphere correlations. Errors include:
  - b,c fragmentation, knowledge of hadron properties, decays...
  - detector resolution effects on c/uds backgrounds
  - material asymmetries and/or magnetic field effects causing asymmetries in positive/negative tracks
- Uncertainty in QCD correction
- Most difficult (to do and to explain!) is to control hemisphere correlations in flavour and charge tagging. General ideas:
  - Identify the variables that contribute to the correlation in MC
  - Identify closely related observables that allow the modelling of these variables to be studied in data and compared with MC. Assess the range of correlation that is consistent with the data.

QCD Corrections

- $A_{FB}^{b\bar{b},meas} = (1 - s_{bias}\, C_{QCD}^{b}) A_{FB}^{b\bar{b},noQCD}$
- Quark direction estimated by event thrust axis
- QCD corrections to final state calculated to 1st order with mass corrections, 2nd order for massless quarks, using parton thrust axis. Need to correct to hadron level.
- $C_{QCD}^{b} = C_{analytic}^{parton-thrust} + \langle C_{MC}^{hadron-thrust} - C_{MC}^{parton-thrust} \rangle$
  Full MC parton to hadron shift also taken as an error
- Several effects in the analyses reduce impact of QCD correction, for example
  - event selection requiring high value of thrust,
  - high lepton p leaves less energy for gluons
  - charge tagging calibrated on data
- Estimate s_{bias} due detector effects, fitting technique etc. for each analysis using full MC simulation:
  $A_{FB}^{b\bar{b},MCmeas} = (1 - s_{bias}\, C_{MC}^{hadron-thrust}) A_{FB}^{b\bar{b},MCnoQCD}$

QCD Corrections – theory error

Value of C_{QCD}	$b\bar{b}$	$c\bar{c}$
	0.0354	0.0413
Error on C_{QCD}	**$b\bar{b}$**	**$c\bar{c}$**
Higher orders	0.0025	0.0046
Error on quark mass	0.0015	0.0008
Higher order mass effects	0.005	0.002
$\alpha_S = 0.0119 \pm 0.003$	0.0012	0.0015
MC parton to hadron	0.0023	0.0035
Total error	0.0063	0.0063

For further discussion of higher order errors, S. Catani and M. H. Seymour, JHEP 9907 (1999) 023

- Total error in C_{QCD} taken as fully correlated between experiments.
- Error scaled by $A_{FB}^{b\bar{b}}$ and further reduced by $\approx 50\%$ on average by s_{bias}. Inconsistent approach by experiments, eg. DELPHI scales theory error by full s_{bias}, OPAL only scales by $A_{FB}^{b\bar{b}}$, and ALEPH assess applicable fraction from dependence of correction on thrust.

Energy dependence

Energy dependence follows SM expectation.

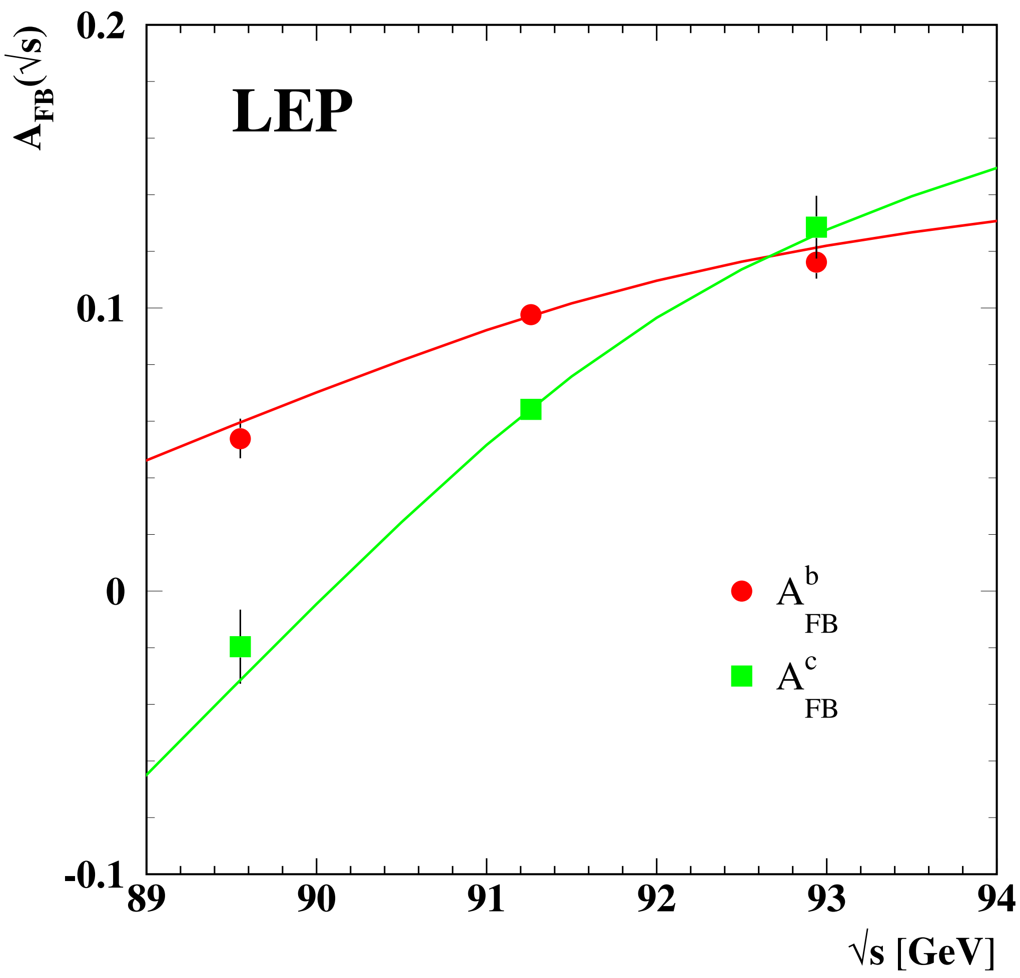
Correct off-peak asymmetries to $\sqrt{s} = m_Z$ using ZFITTER v.6.35 with:

$$\begin{aligned} m_Z &= 91.1875\,\text{GeV}, \\ m_t &= 175\,\text{GeV}, \\ m_H &= 100\,\text{GeV}, \\ \alpha_S &= 0.12. \end{aligned}$$

Also use ZFITTER to calculate shifts in $A_{FB}^{b\bar{b}}$ due to

ISR: $+0.0041$

γ, γ-Z interf. & m_b: -0.0003

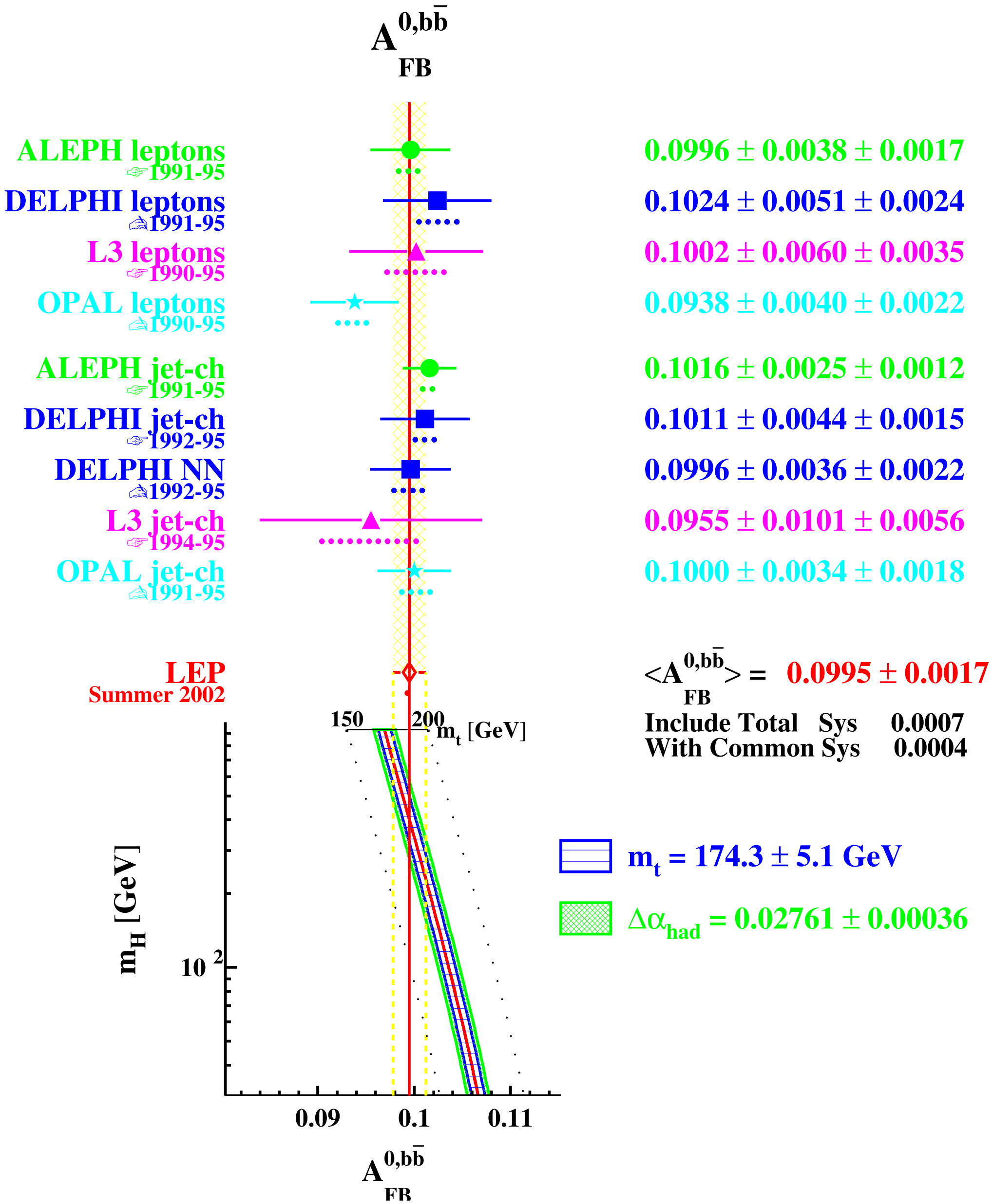


Heavy Flavour Averaging Procedure

- χ^2 minimisation
- Build full covariance matrix between measurements.
  - Include statistical correlations
  - Assume that each source of systematic error is 0% or 100% correlated with other measurements
  - Account for dependences on other SM parameters (R_b, R_c...), and on some additional quantities that are included in the fits such as semileptonic branching ratios, charm meson production rates.
- Make one fit with on and off-peak asymmetries separately, and a second fit for pole asymmetries
- Low $\chi^2 = 47.6$ for (105-14) dof, prob. 0.99995. Suggests errors are over estimated.
- Using statistical errors only, $\chi^2 = 85.2$ for (105-14) dof.
- Low χ^2 "shared" between asymmetries and widths.

$A_{FB}^{0,b}$ *results*

- LEP Average $A_{FB}^{0,b} = 0.0995 \pm 0.0017$
- Statistics dominated
- Total syst 0.00068
- Common syst 0.00040
- QCD corr 0.00035
- Maybe concern about statistical correlations

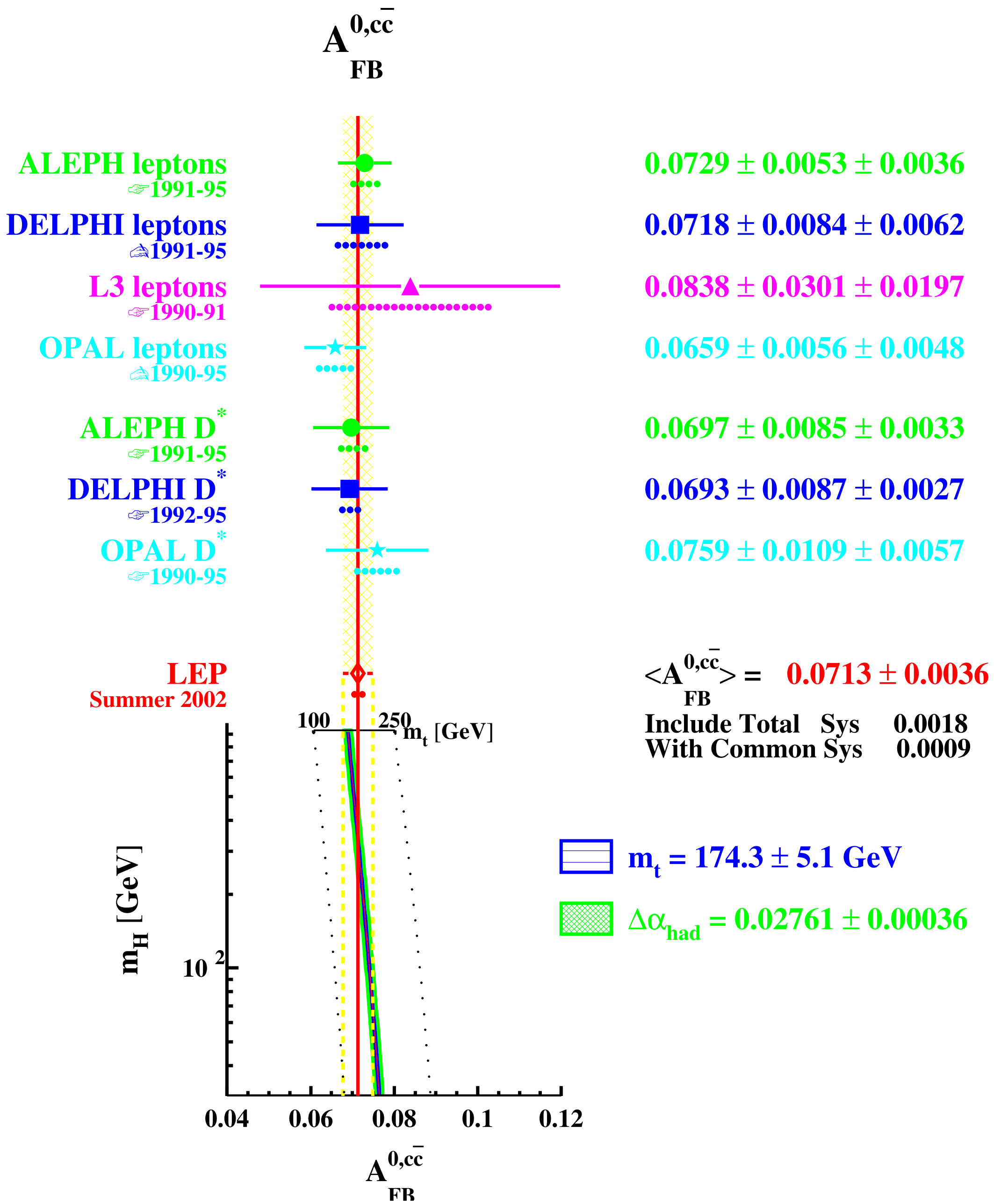


Statistical Correlations

- ALEPH inclusive–lepton correlation 0.264 ± 0.039 estimated from repeating the fit on 600 data subsamples
- DELPHI correlation of 0.49 between new inclusive and old jet charge analyses. Correlation of only 0.30 between new inclusive and lepton analyses, despite
  - Use of jet charge in opposite hemisphere to lepton
  - Use of lepton id in inclusive charge tag
- L3 correlation of only 0.06 - only lepton p and p_T are used in the lepton analysis. No lepton id in jetcharge analysis
- OPAL preliminary estimate of 0.35 for correlation between (final) inclusive and (preliminary) lepton analyses

$A_{FB}^{0,c}$ *results*

- LEP Average $A_{FB}^{0,c}$ = 0.0713 ± 0.0036
- Again statistics limited -
  total syst 0.0018
- Less precise than $A_{FB}^{0,b}$ and in addition less sensitive to $\sin^2\theta_{eff}^{lept}$

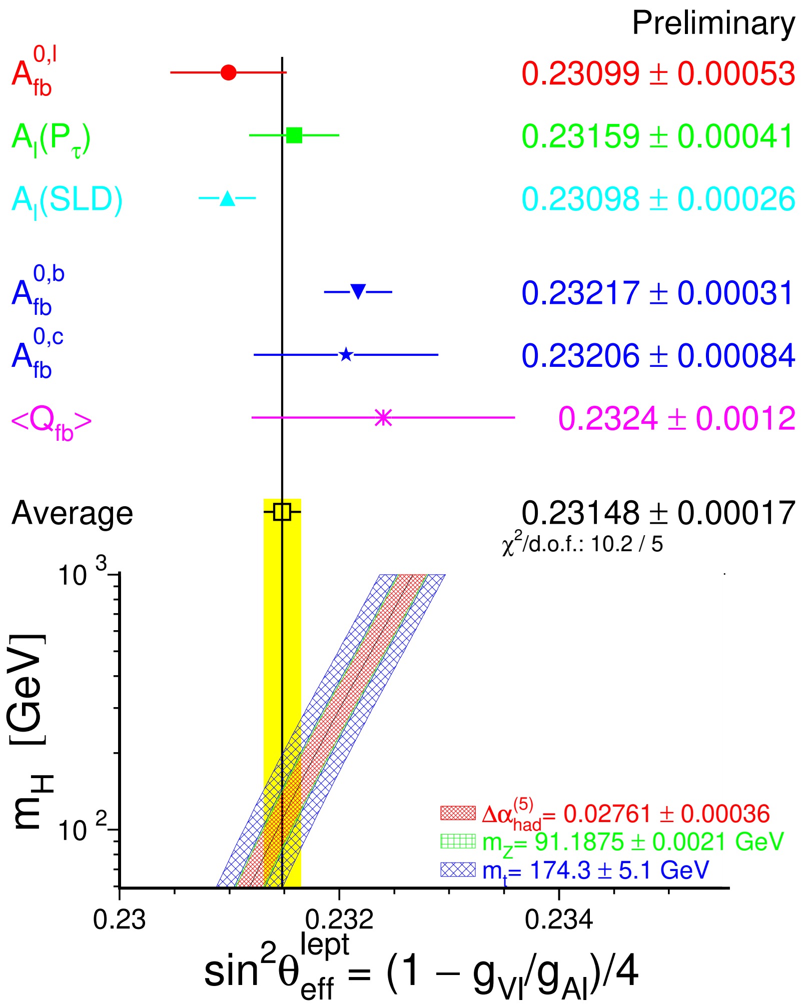


Interpret as $\sin^2 \theta_{\mathrm{eff}}^{\mathrm{lept}}$

Assuming lepton universality :

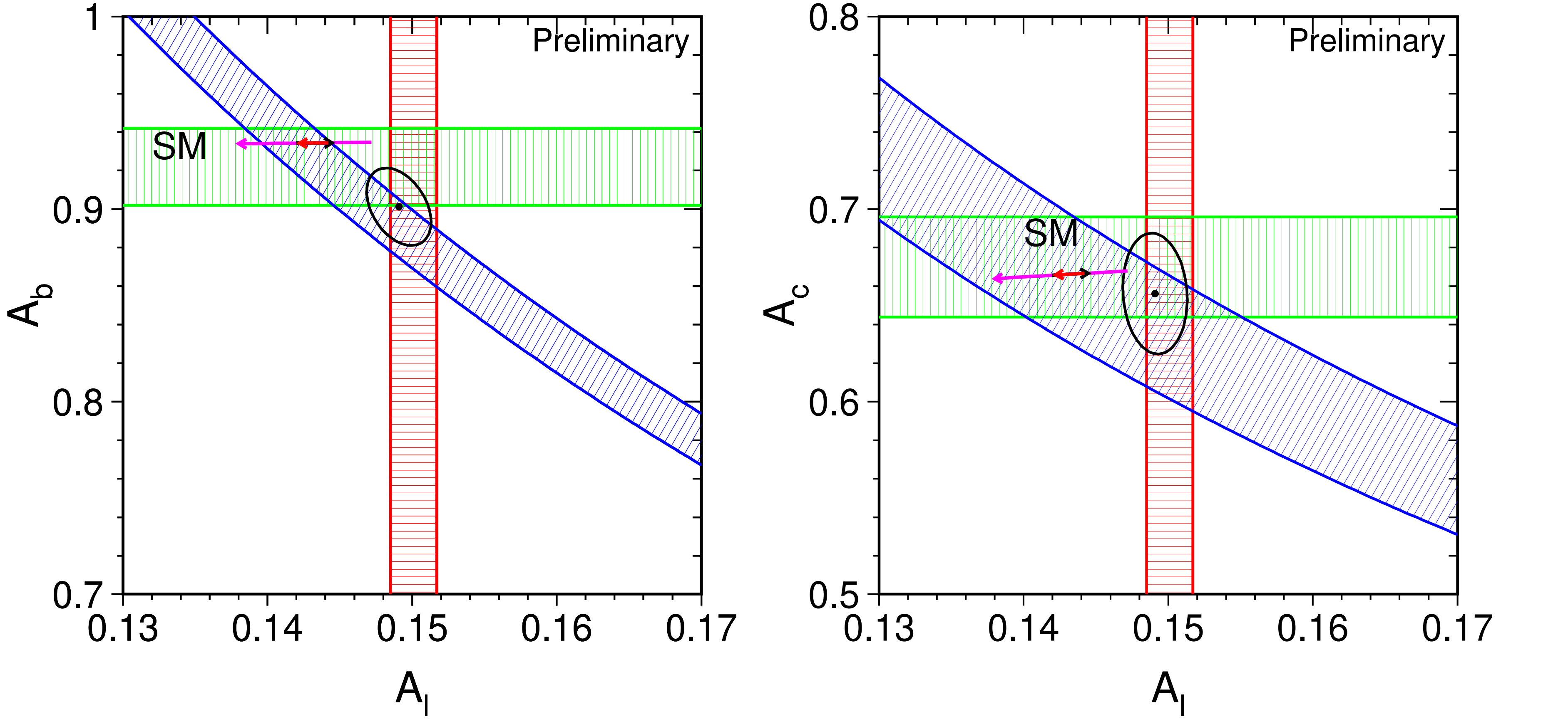
$$
\begin{aligned}
\chi^2/\mathrm{dof(lept.)} &= 1.6/2\ (P = 45\%) \\
\chi^2/\mathrm{dof(hadr.)} &= 0.05/2\ (P = 98\%) \\
\chi^2/\mathrm{dof(tot.)} &= 10.2/5\ (P = 7\%)
\end{aligned}
$$

hadrons-leptons $\simeq 3\sigma$



Comparison of $\mathcal{A}_{\mathrm{b}}$, $\mathcal{A}_{\mathrm{c}}$ and $\mathcal{A}_{\ell}$

horizontal band: $\mathcal{A}_{\mathrm{b}}$,$\mathcal{A}_{\mathrm{c}}$(SLD); vertical band: $\mathcal{A}_{\ell}$(LEP+SLD);
diagonal band : $A_{\mathrm{FB}}^{0,\,\mathrm{b}}$, $A_{\mathrm{FB}}^{0,\,\mathrm{c}}$(LEP); arrow $m_{\mathrm{H}} \in [114, 1000]$



Direct $\mathcal{A}_{\mathrm{b}}$, $\mathcal{A}_{\mathrm{c}}$ agree with SM; $A_{\mathrm{FB}}^{0,\,\mathrm{b}}$ prefers high m_{H}; $\mathcal{A}_{\ell}$ prefers low m_{H}

Effective couplings

Reminder:

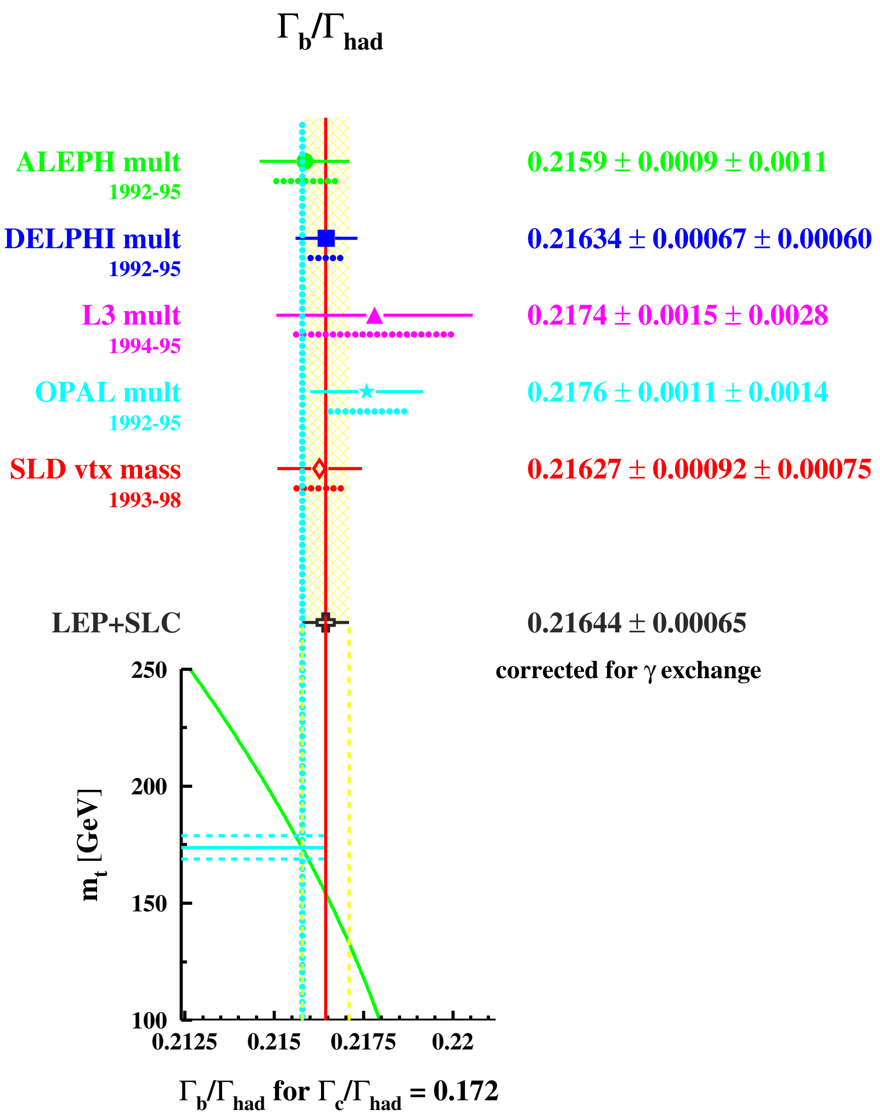
$$
\begin{aligned}
A_{FB}^{0,f} &= \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \\
\mathcal{A}_f &= 2\frac{g_{Vf}\,g_{Af}}{g_{Vf}^2+g_{Af}^2}
\end{aligned}
\qquad
\begin{aligned}
g_V &= \sqrt{\rho}\left(T^{(3)}-2Q\sin^2\theta_{eff}\right) \\
g_A &= \sqrt{\rho}\;T^{(3)}
\end{aligned}
$$

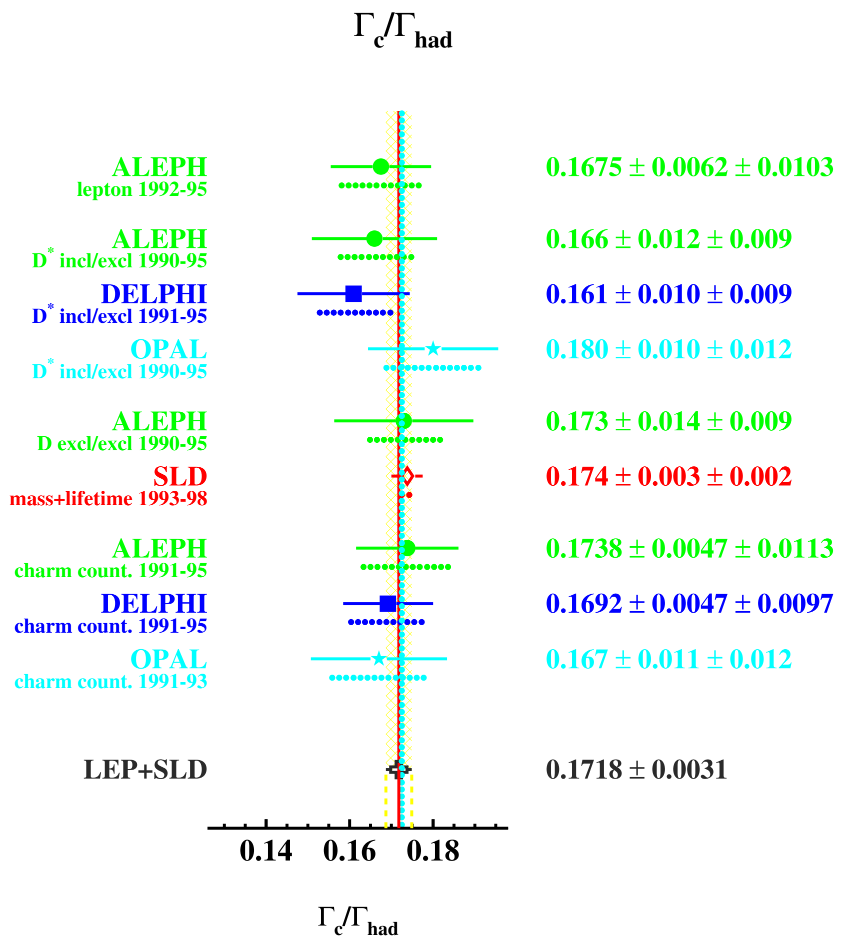
Link to experimental measurements:

- $A_{FB}^{0,f} \Rightarrow \mathcal{A}_e\mathcal{A}_f$
- SLD (polarised electron beam) $A_{LRFB}^{f} \Rightarrow \mathcal{A}_b$, $\mathcal{A}_c$ directly

- Asymmetries $\Rightarrow g_V/g_A$
- Partial widths $\Rightarrow g_V^2+g_A^2$

Partial width results

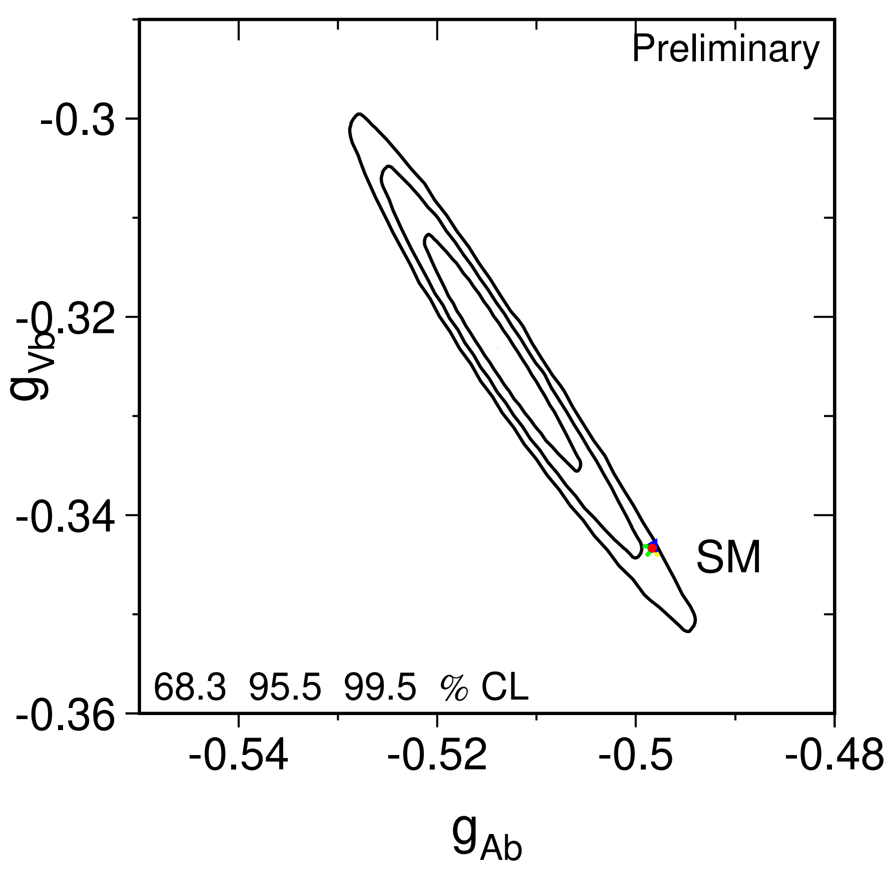


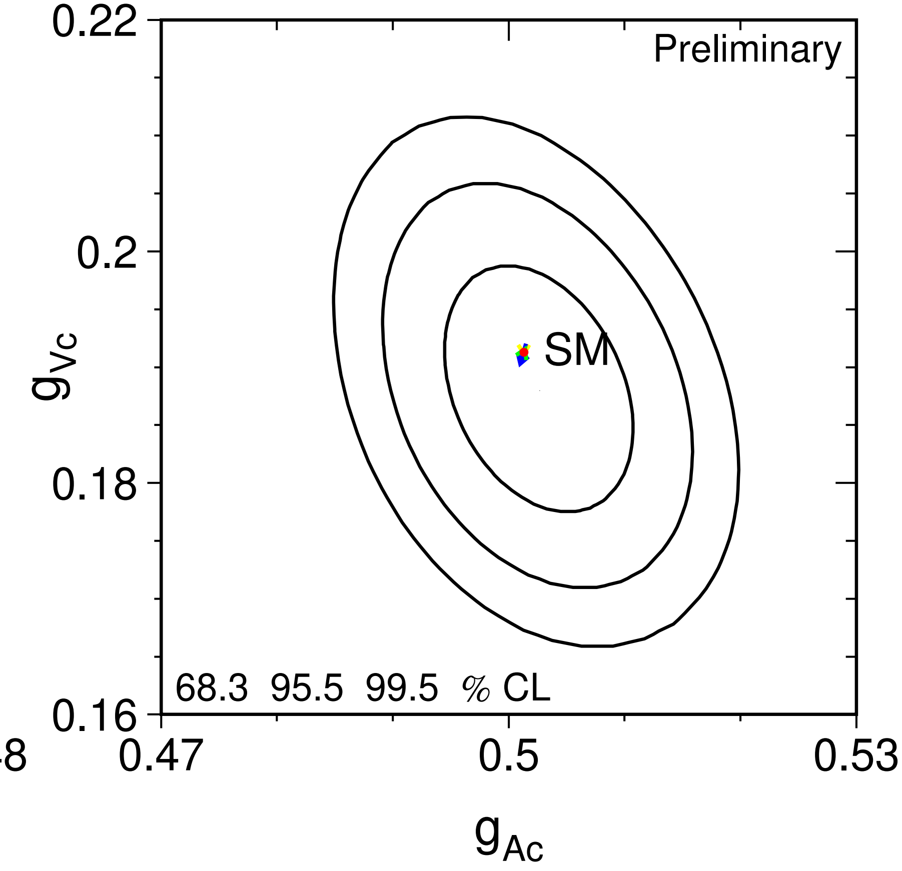


R_b and R_c consistent with SM expectation

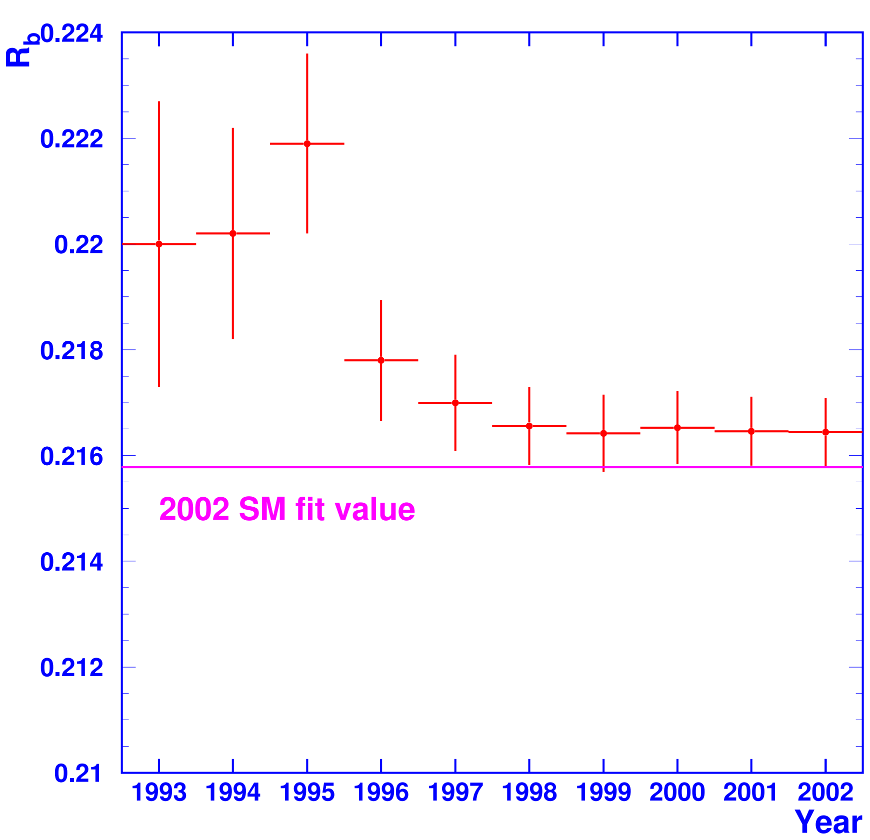
Derived couplings: $g_{Ab}, g_{Vb}, g_{Ac}, g_{Vc}$

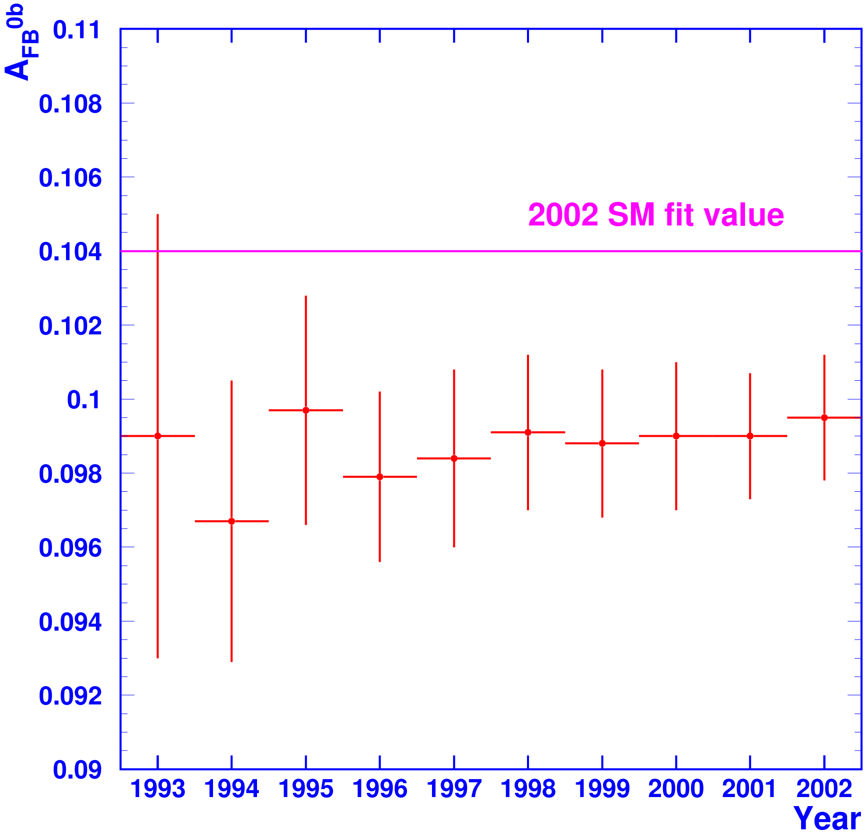
LEP+SLD, assuming lepton universality





History...





R_b SLD results still preliminary.

$A_{FB}^{0,b}$ DELPHI, OPAL partly prelim.

Future...

- ALEPH and L3 results final.
- DELPHI expect improved precision of inclusive tag measurement. Will maybe drop jet charge measurement from average (50% correlated with new inclusive tag). Lepton result also to be finalised.
- OPAL expect some improvement in precision of lepton result.
- Results are statistics limited. Maybe marginal changes to ensure uniform treatment of QCD correction and uncertainty in statistical correlations.
- Little chance of running SLD/SLC again, and in any case $\mathcal{A}_{\mathrm{b}}$ agrees with SM and $A_{\mathrm{FB}}^{0,\mathrm{b}}$.
- Future linear collider???!!!!