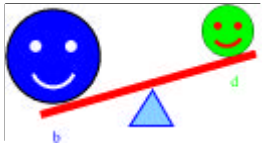
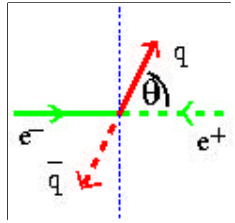


LEP/SLD heavy flavour electroweak physics



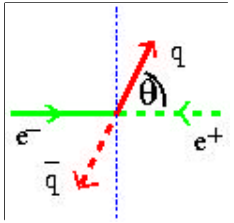
Richard Hawkings (CERN)

ICHEP Beijing, 17/8/04

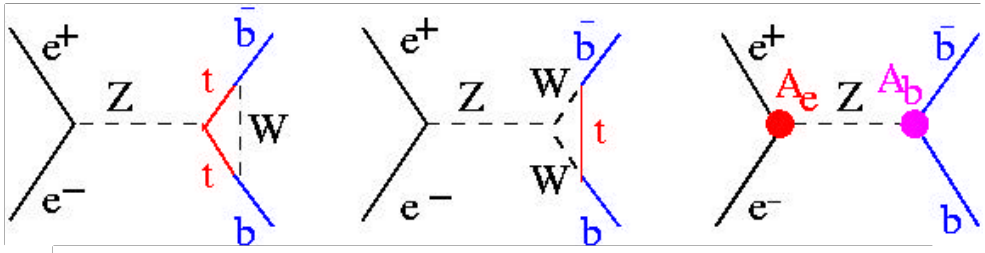
- Heavy flavour electroweak measurements at LEP and SLD:
  - Theoretical motivation and background
  - Experimental analyses at LEP1 and SLD (e^+e^- $\sqrt{s} \approx 91$ GeV)
  - Heavy flavour electroweak fit and (almost) final results
  - Going to high energies (LEP2: e^+e^- $\sqrt{s}$=130-209 GeV)
  - Summary and conclusions

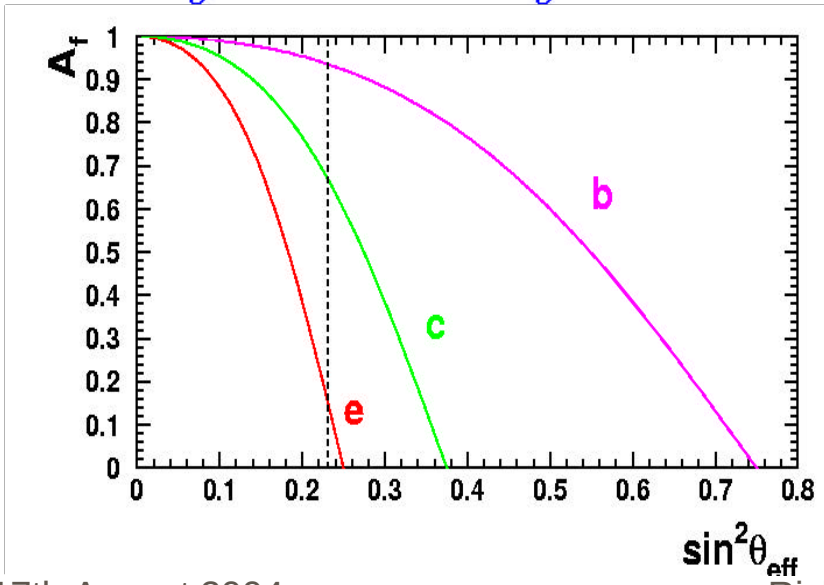
- Thanks to LEP electroweak working group
  - See http://lepewwg.web.cern.ch/LEPEWWG for numbers, plots…

Theoretical motivation

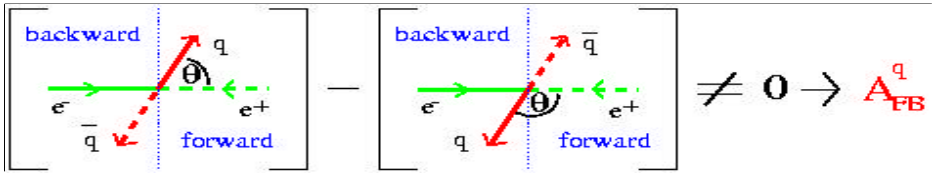


- Measurement Z^0 partial decay width:
  - $R_b \cong G(b\bar{b})/G(had)$
  - Vertex corrections involving top
    - New physics coupling to mass ?

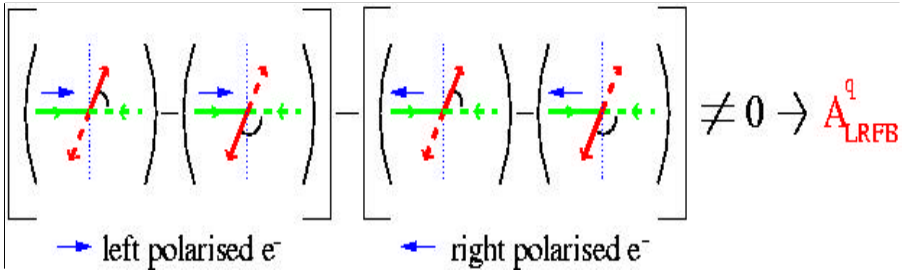


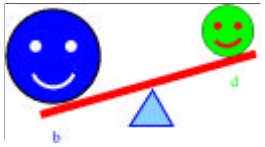


- Measurement of asymmetries:
  - At LEP $A_{FB}^{0,q} = \frac{3}{4} A_e A_q$

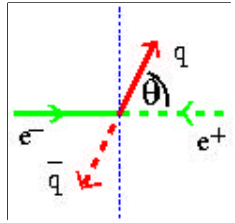


    - $A_f = 2 g_V g_A / (g_V^2 + g_A^2)$
    - Effective couplings $g_V/g_A \Rightarrow \sin^2\theta_{eff}$
  - Due to isospin structure for e,b, LEP A_{FB}^b mainly sensitive to A_e
  - SLD: e^- beam polarisation (~73%) allows direct measurement of A_b

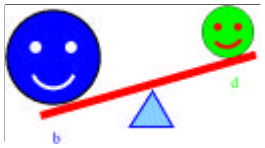




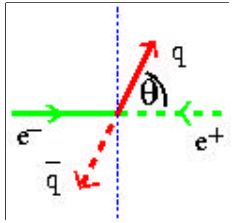
What's new ?



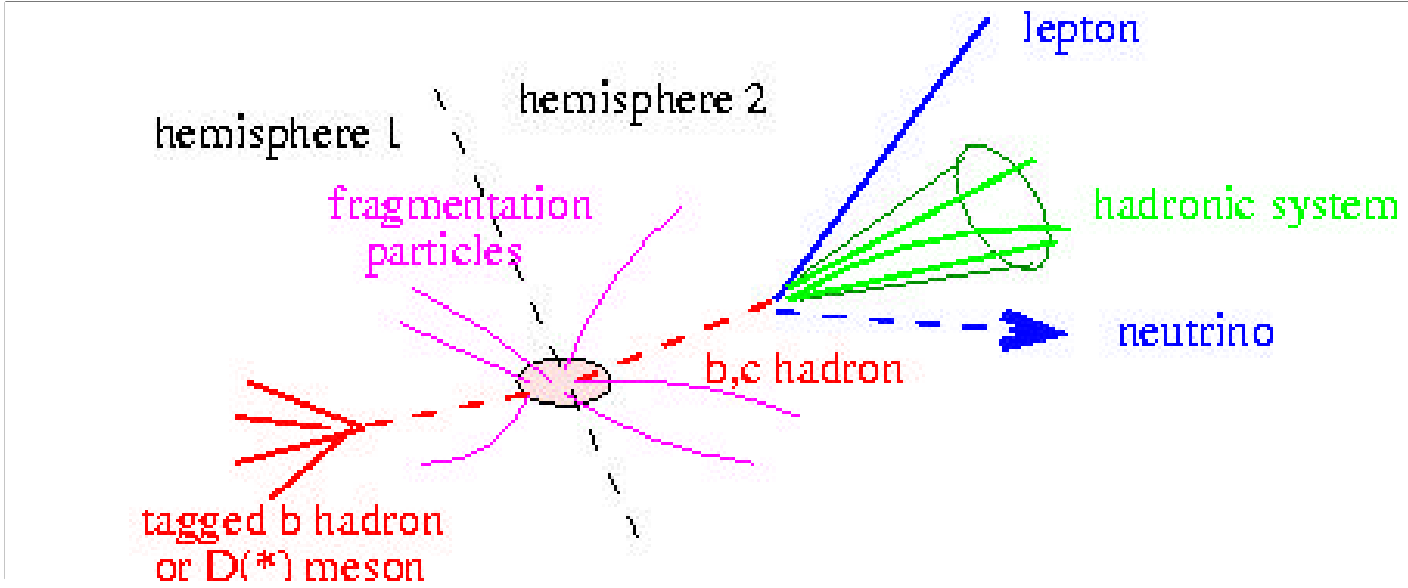
- LEP/SLD now 'part time' collaborations – things change slowly
  - Analyses very mature, publishing final results
- New since ICHEP02:
  - DELPHI and OPAL finalised all b and c quark asymmetries
  - SLD finalised R_b, R_c and asymmetries
  - All done - LEP1/SLD results are **final**
    - Sophisticated analyses used on complete final datasets
  - LEP2 results:
    - Analyses still preliminary in many cases, some with partial datasets
    - Work continues to publish final results
    - Available data and combinations unchanged since ICHEP02



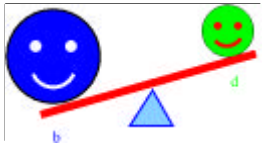
Experimental environment



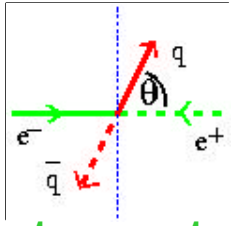
- Structure of of $Z \rightarrow b\bar{b}$ and $Z \rightarrow c\bar{c}$ events at LEP/SLD:



- 2-jet structure: initial $q/\bar{q}$ to largely independent hemispheres
- Apply flavour (b/c/uds) and charge ($q/\bar{q}$) tagging to each
  - Lifetime, lepton, $D^{(*)}$ meson tags, and combinations
  - Exploit consistency of tag results for tag calibration and systematics
  - Systematic issues: control of backgrounds from unwanted quark flavours, understanding of hemisphere correlations (e.g. 3-jet events)

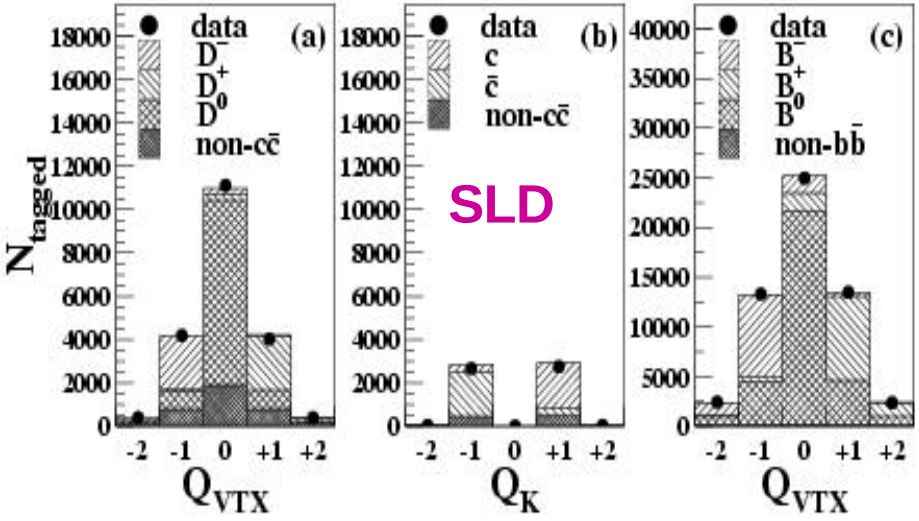


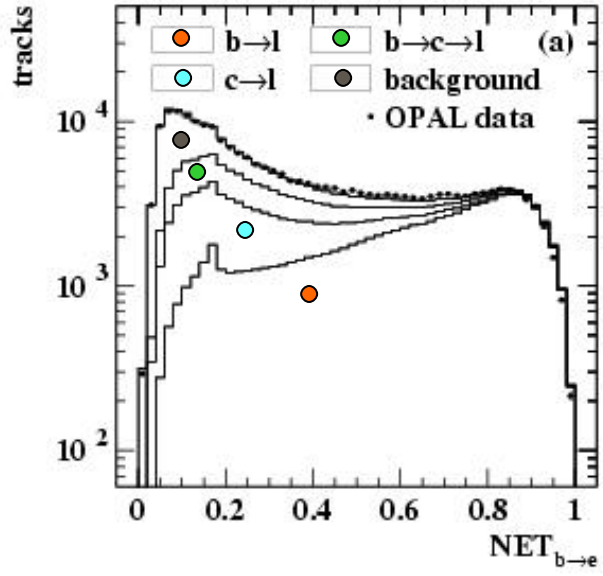
b and c flavour/charge tagging

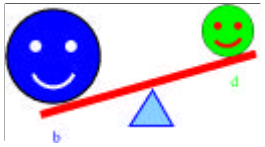


- b-tagging based on silicon vertex detectors
  - Impact parameters, secondary vertex reconstruction, vertex mass
    - b-flavour tag: e=25-50%, purity 95-99%
  - B secondary vertex charge: B^+ or B^-
    - Tags quark charge for long-lived decays
    - Can also reconstruct decay chain $(b\rightarrow)c\rightarrow s\rightarrow K^-$, tag kaon charge
    - Kaon ID with Cherenkov or dE/dx
- Lepton-based b/c-tagging (e or μ)
  - Limited by BR(b→l) and (c→l) to e ≈ 5%
    - Separate b→l, c→l and b→c→l
    - Lepton p, p_t and jet shape variables in likelihood or NN ⇒extract quark charge
- $D^{(*)}$ meson-based c-tagging
  - Small BRs, enrich with incl. $D^{*+}\rightarrow D^0\pi^+$

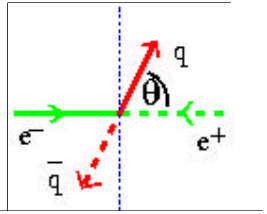
c-tag vertex **c-tag kaon** **b-tag vertex**







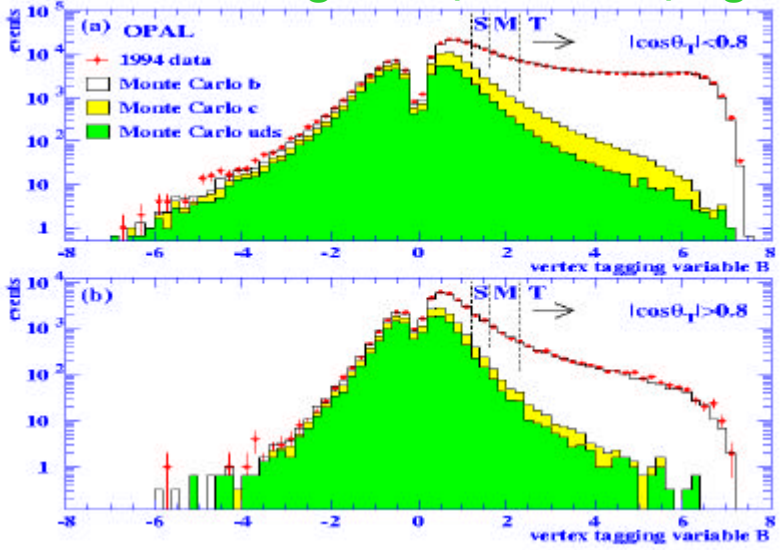
Reaching the ultimate precision

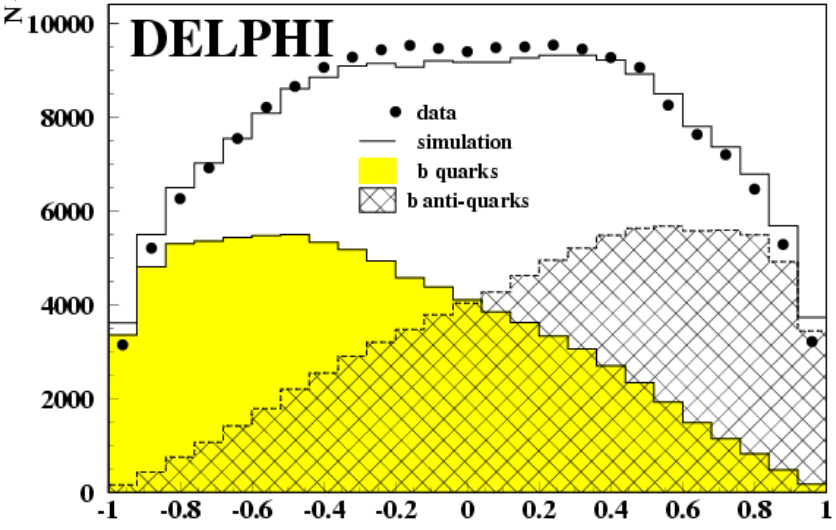


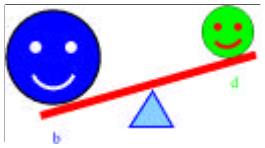
- Combine the basic techniques
  - Multiple b/c flavour tags with different purities and efficiencies
  - Double tags allow b and sometimes c efficiencies to be derived from data
    - Monte Carlo needed mainly for uds efficiencies and hemisphere correlations
  - Charge tagging – combine jet charge
    - $Q_{jet}=\Sigma q_i(p_i)^k$ with various k weights $0<k<1$

    … with other available estimators in each hemisphere (lepton, vertex, kaon)
    - Typical mistag rate 25-30% for b-hemis
- Sophisticated multi-dimensional fits
  - Extract the maximum from each event, depending on purity and tag confidence

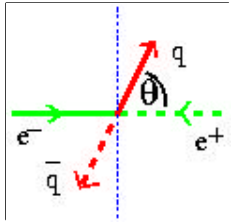
b-flavour tag: soft, medium, tight





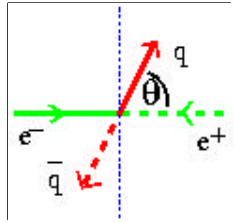


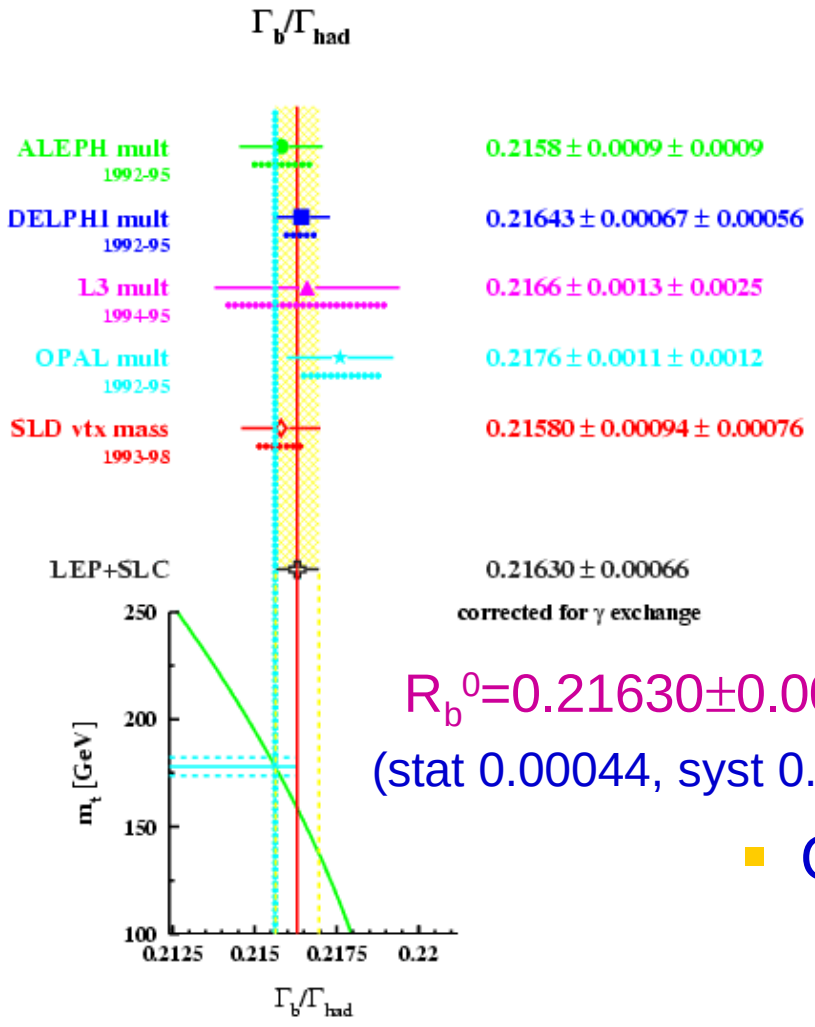
Heavy flavour electroweak fit



- Sophisticated combination procedure is used:
  - R_b, R_c and asymmetry measurements depend on each other, common systematics and external inputs (LEP+elsewhere)
  - Common fit to electroweak observables plus auxiliary params
    - Charm hadron production fractions, b/c semileptonic BRs and mixing $\bar{c}$
    - All measurements corrected to consistent set of external inputs
  - Fit LEP asymmetries $A_{FB}^{b,c}$ and SLD $A_{b,c}$ separately
    - Also fit LEP off-peak asymmetries separately to check energy dep. OK
- Final fit χ^2 with all LEP asym corrected to peak is 53/(105-14)
  - Very low – are errors overestimated? Combination of effects:
    - Statistical errors only: c^2=92/(105-14), but large contrib. from BR(b→l)
    - Without this, c^2_{stat}=65/(99-13)≡4%; low fluctuation..?
    - With systematics: c^2 reduced by 'extreme' semileptonic decay models; other systematics estimated from statistical data-MC comparisons

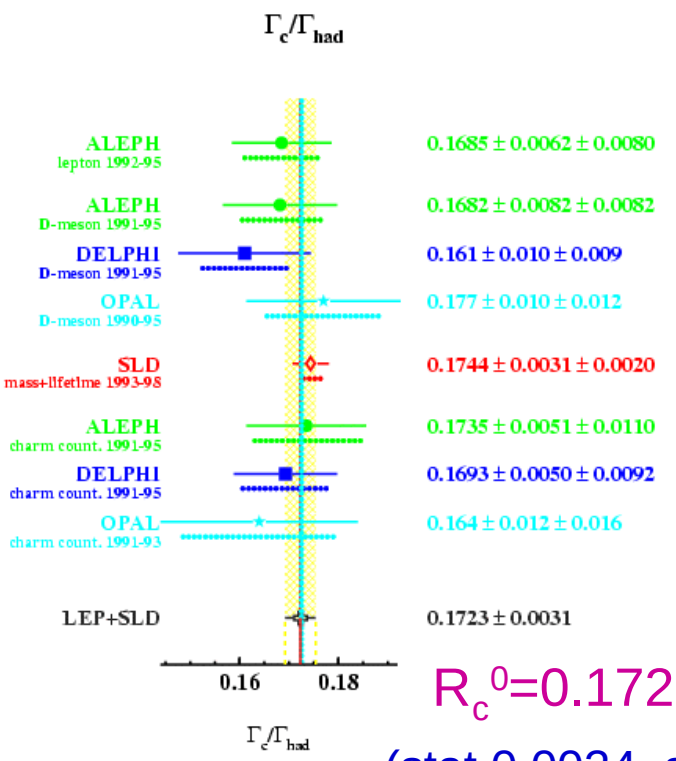
Results for R_b and R_c





$R_b^0 = 0.21630 \pm 0.00066$

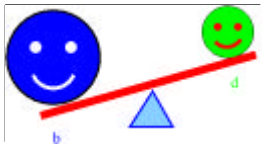
(stat 0.00044, syst 0.00050)



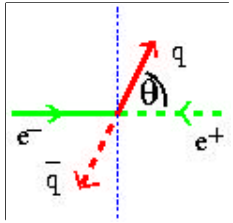
$R_c^0 = 0.1723 \pm 0.0031$

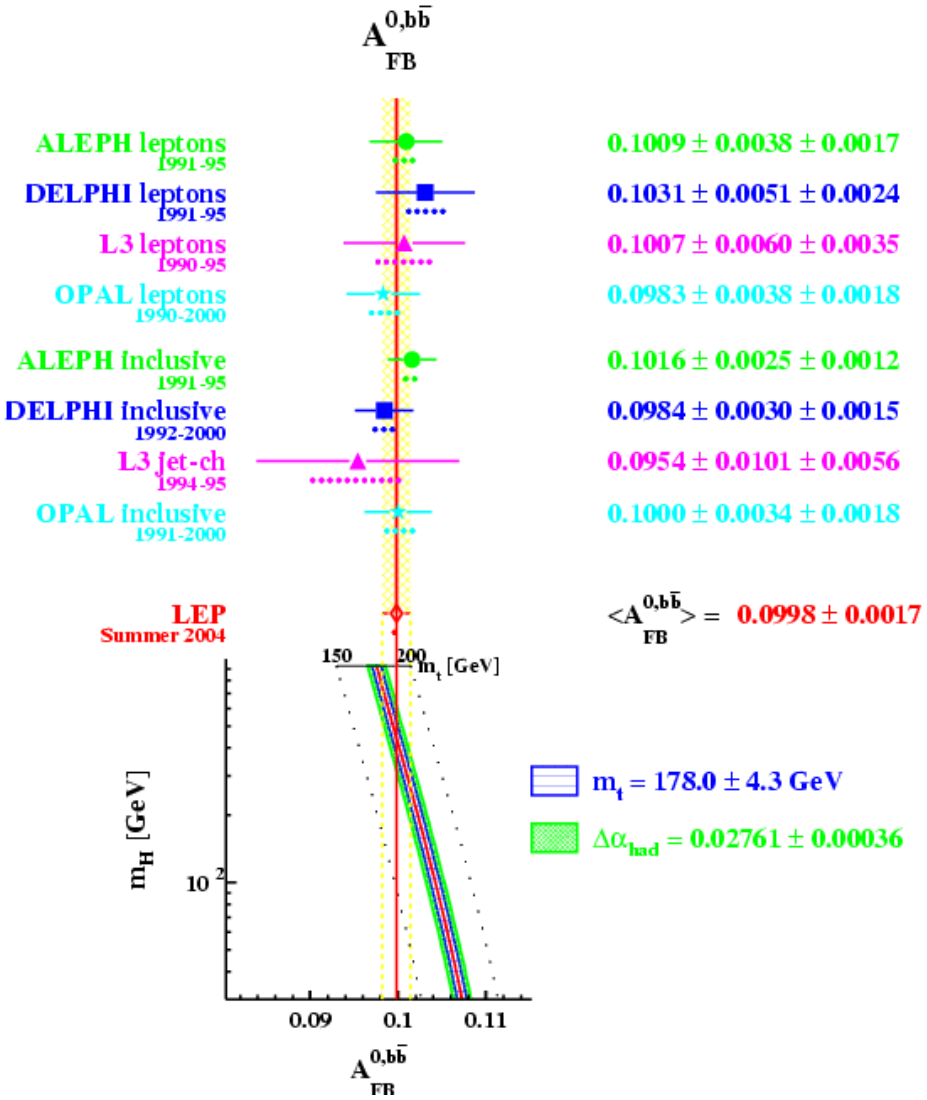
(stat 0.0024, syst 0.0019)

- Good agreement with SM expectations
  - R_b sensitive to m_{top} and in good agreement with direct Tevatron measurement



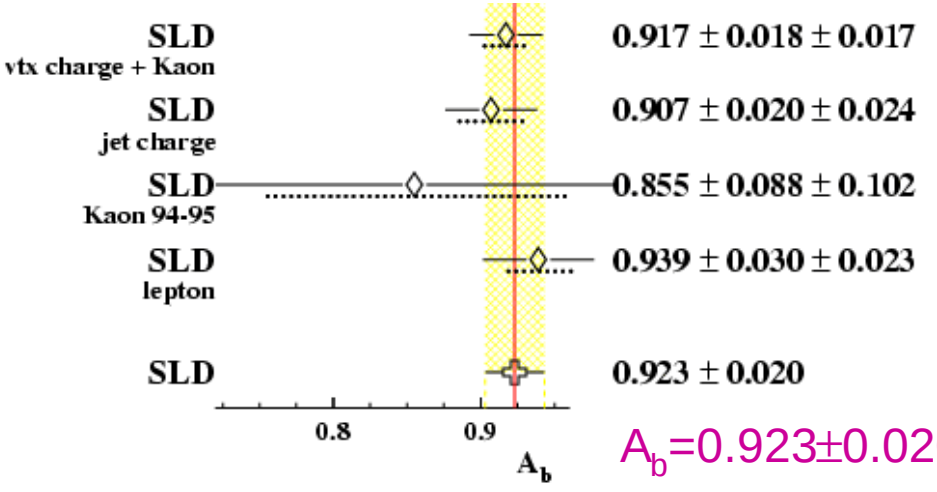
b-asymmetry at Z pole





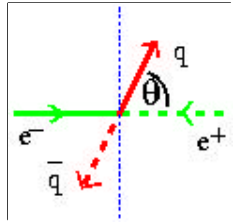
- LEP analyses using leptons (also give A_{FB}^{c}) and inclusive (jet charge++)
  - (Too) good consistency between them

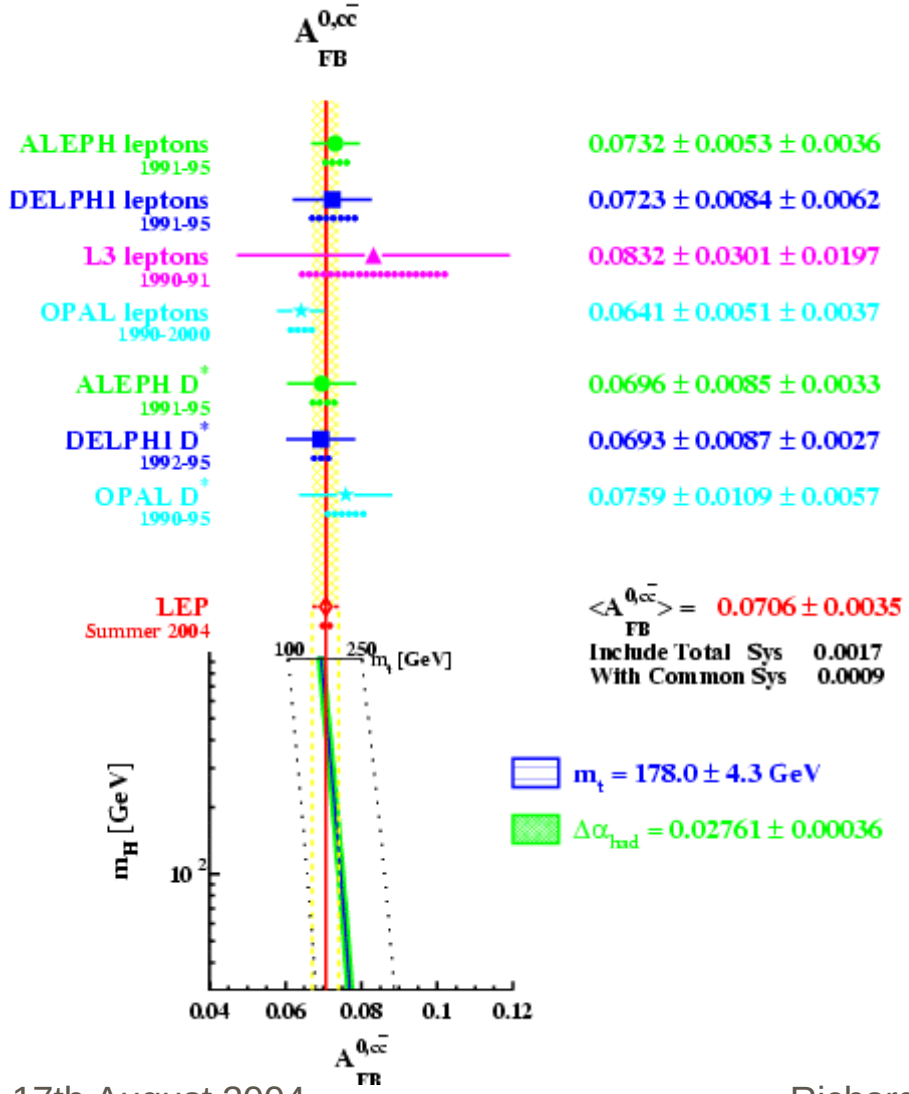
  $A_{FB}^{b}=0.0998\pm0.0015\pm0.0006\pm0.0005$
- Uncertainty is statistics dominated
- Common expt. systematic is 0.0004
  - Mainly from QCD effects – ¼ total error
  - Additional theory uncertainty of 0.0005 from comparison of ZFITTER versions



$A_b=0.923\pm0.020$

c-asymmetry at Z pole

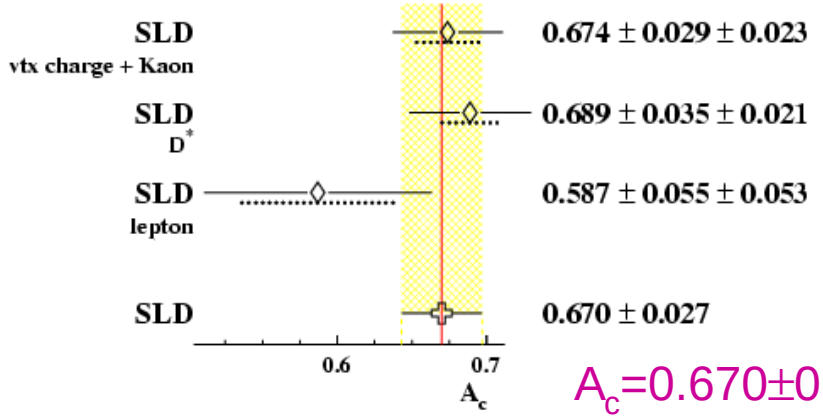




- LEP analyses using leptons (also measure $A_{FB}^{b)}$ and $D^{(*)}$ mesons
  - Good agreement provides confidence that b/c separation in leptonic events is understood

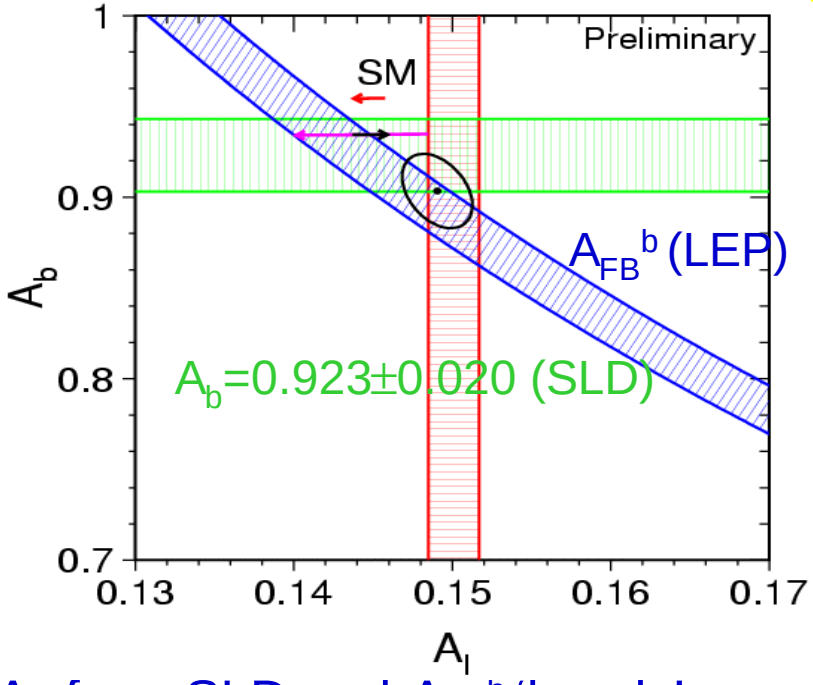
A_{FB}^{c}=0.0706±0.0030±0.0017

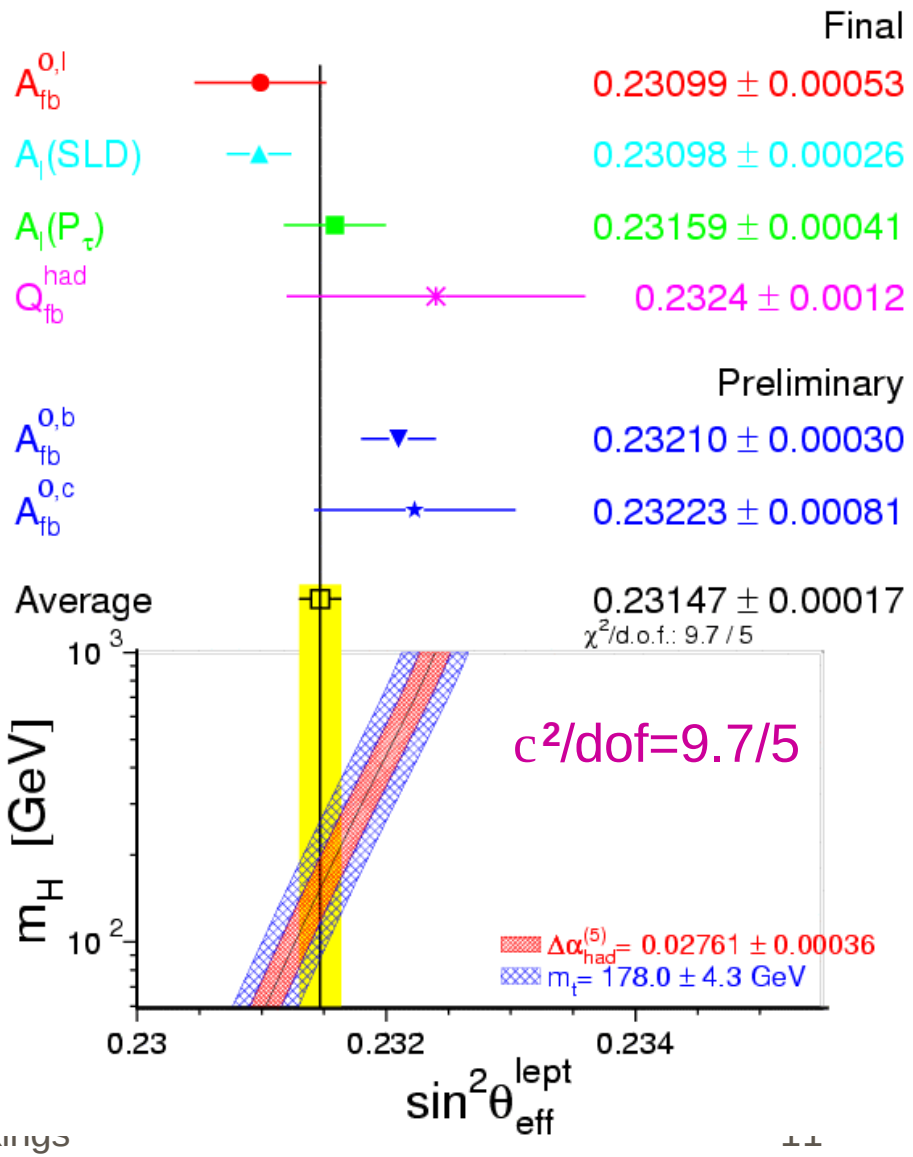
- Result is also statistics dominated, common systematic 0.0009
  - Additional theory uncertainty is negligible for A_{FB}^{c}



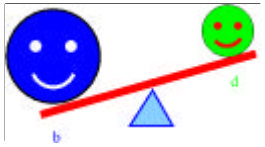
A_c=0.670±0.027

Tensions in the Standard Model

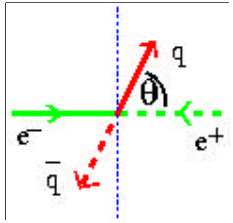




- A_b from SLD and A_{FB}^{b} 'bands' consistent with Standard Model
  - A_l (from A_{LR}, lepton asym and τ_{pol} is 'high'
  - … giving a 'low' A_b from LEP A_{FB}^{b} results
- Also seen when measurements are interpreted as $\sin^2\theta$ in Standard Model
  - ~3σ discrepancy between A_{LR} and A_{FB}^{b}

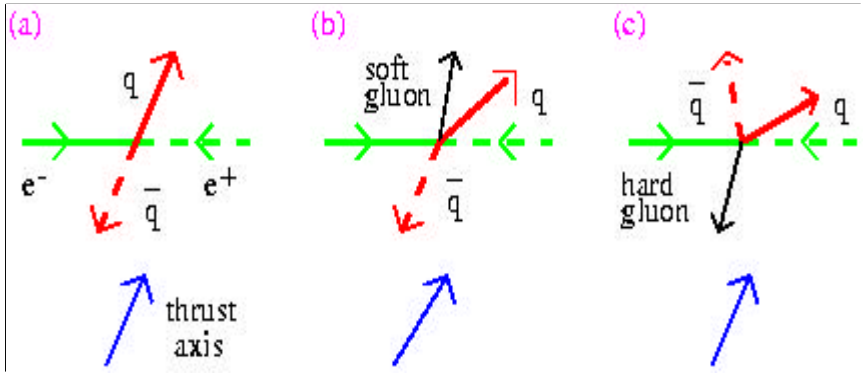


What could be wrong with the b-asymmetry?



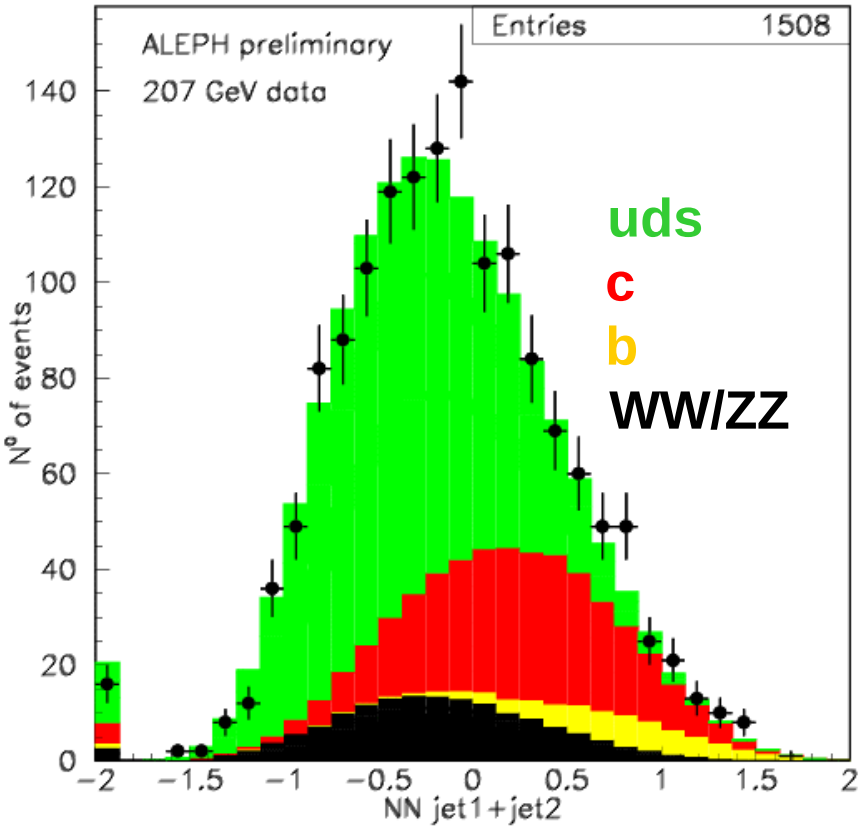
- Could A_{FB}^{b} from LEP be wrong?
  - Total error is completely dominated by statistical uncertainty
    - 7 measurements from 4 collaborations, leptons and inclusive/jet-charge
  - QCD correlated systematics including hemisphere correlations
    - Gluon radiation dilutes asym by ~4%
    - Effects calculable up to $O(\alpha_s^2)$ and partially removed by tag calibration
  - New QED theoretical uncertainty from γ/Z interference in ZFITTER
    - Some inconsistencies in option settings, expect this to be resolved
  - Any of these uncertainties would have to be underestimated by $O(10\sigma)$ to 'explain' A_{FB}^{b}-A_{LR} discrepancy!

Source	$\sigma(A_{FB}^{b})$
Statistics	0.0014
Internal systematics	0.0004
QCD effects (corl^n)	0.0004
QED theoretical	0.0005
b/c physics	0.0002
Total	0.0017



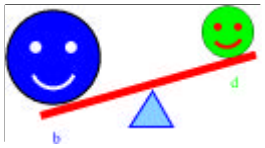
Going to high energies

- $q\bar{q}$ cross section only O(10^{-3}) of LEP1
  - Relatively low statistics – use single tag measurements (or event tags)
    - Increase in systematics not significant
- New features
  - Reject radiative return to Z
    - Kinematic fits for γ along beampipe or in detector acceptance
  - Reject WW and ZZ background
    - Standard WW/ZZ selections as vetos
- Tag b and c with lifetime/leptons/D^*
  - Asymmetry from leptons, D^*, jet charge
- Data from 130-209 GeV (~700 pb^{-1}/expt)
  - Currently results from subset of data
    - Lower energies final, higher preliminary

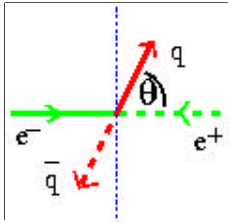


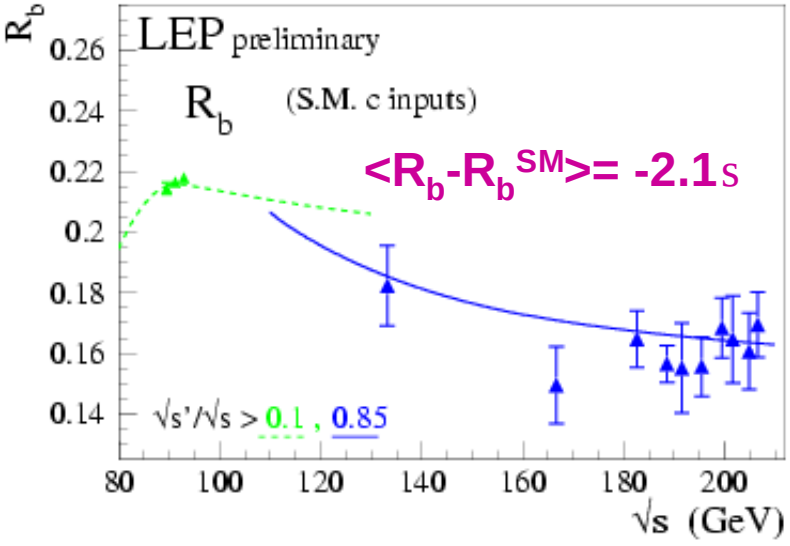
Charm tag for high energy data

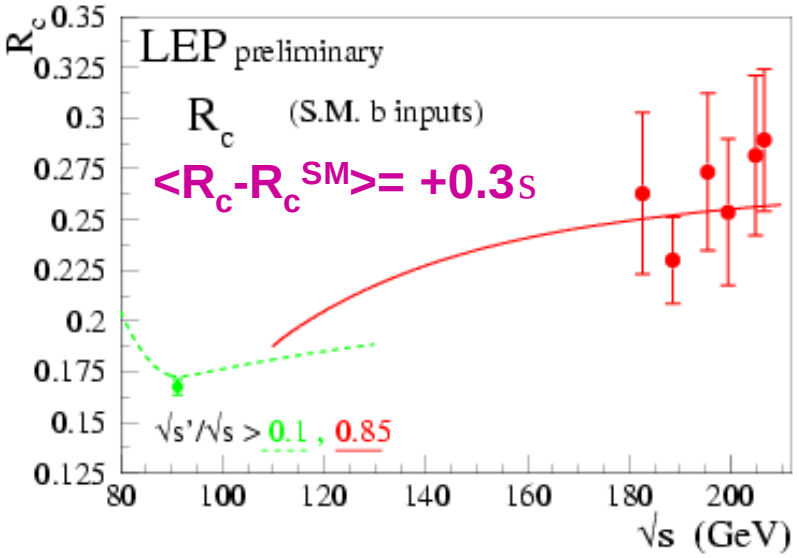
- Reject b-events using lifetime tag
- Separate charm from uds with NN
  - Event shapes, lifetime, particle ID

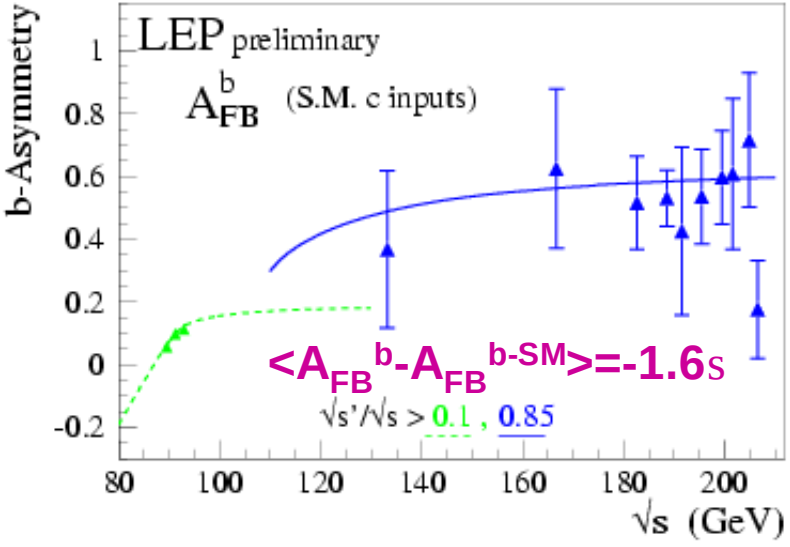


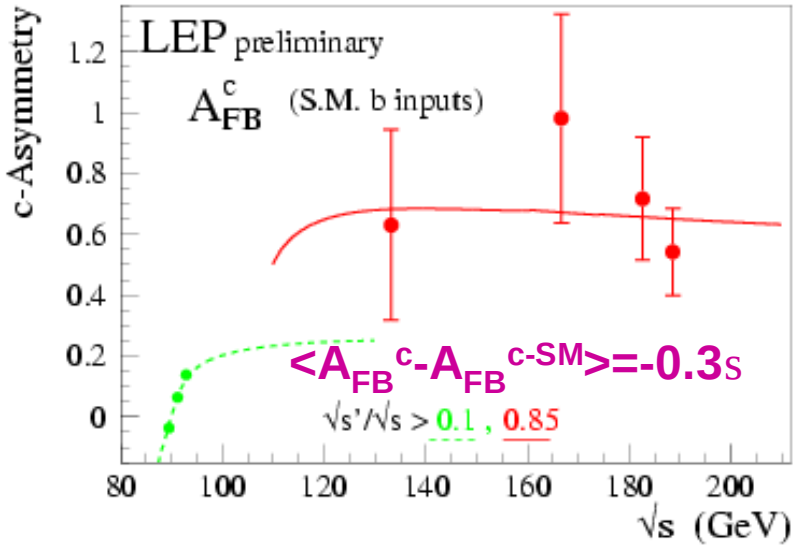
LEP2 b/c-quark results



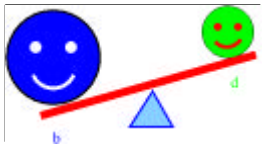




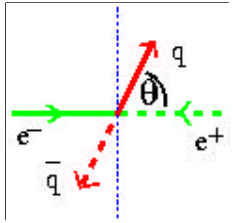




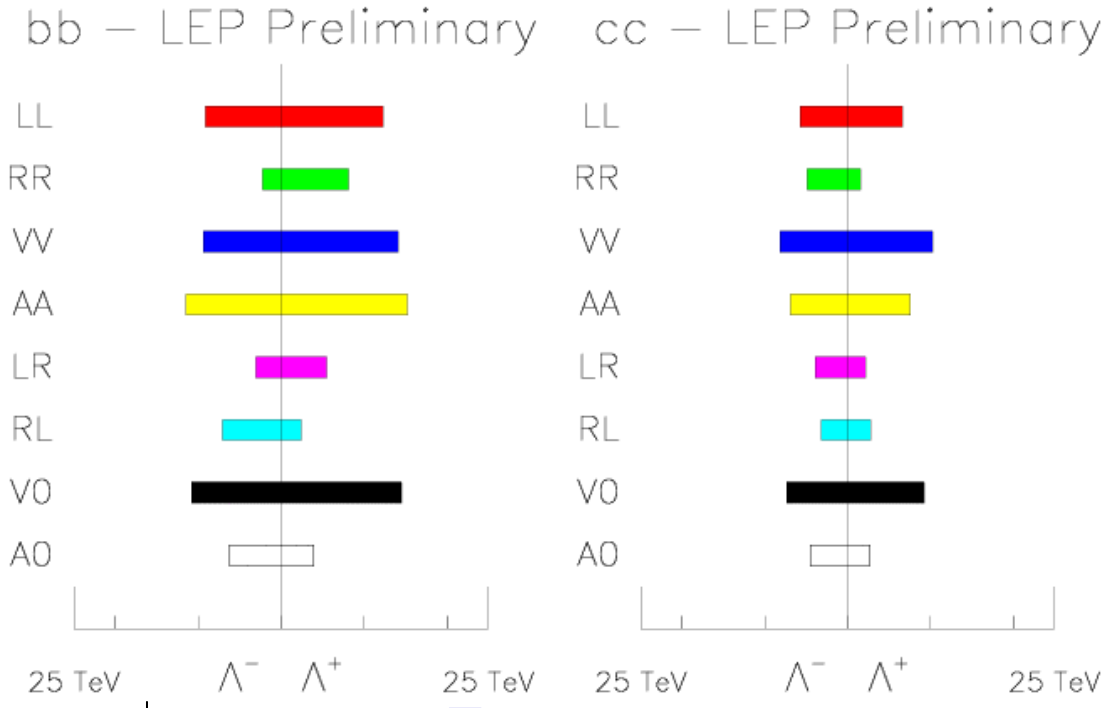
Good agreement with SM predictions



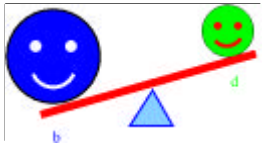
Constraints from high energy results



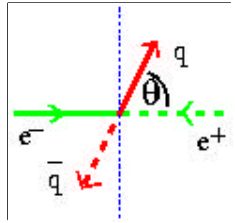
- Set limits on non-SM physics:
  - Contact interactions: limits on models with various couplings with energy scale Λ; $\epsilon=1/\Lambda^2$
  - Affects both cross-section and asymmetries
    - Heavy flavour results test eebb and eecc couplings directly
- Leptoquark exchange:
  - Again, modify cross-section and asymmetries
    - Heavy flavour results test 2nd (c) and 3rd (b) generation LQ couplings
  - Limits are complementary to those from HERA + Tevatron



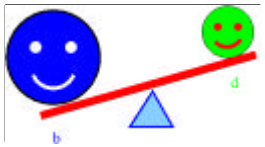
	X_0L	X_0R	$\overline{X}_0R$	$X_{½}L$	$X_{½}R$	$\overline{X}_{½}L$	X_1R
S-2nd	539	430	285	269	309		478
S-3rd			465		389	107	1050
V-2nd	692	183	630	357	256	187	873
V-3rd	829	170		451	183		829



Summary and conclusion



- LEP1/SLD heavy flavour electroweak results are final
  - (Small theoretical QED issue still to be resolved)
  - Huge amount of work by many people over many years
  - Sophisticated analyses to squeeze maximum out of the data
  - Standard Model is impressively verified
    - Prediction of m_{top}, m_w, m_H,…
  - ~3σ discrepancy between $A_{FB}{}^b$ from LEP and A_{LR} from SLD
    - No evidence of systematic problems with $A_{FB}{}^b$ on level needed to explain this effect … a statistical fluctuation or new physics?
    - An intriguing puzzle left from the LEP/SLD era for the next generation
- LEP2 heavy flavour electroweak results still being finalised
  - Publishing of final results on complete datasets ongoing
    - No surprises so far – good agreement with Standard Model predictions



LEP asymmetries vs energy