HEAVY QUARK ASYMMETRIES

with the

SLD

Oct 5 2001

St Francis Yacht Club

SLD Swan Song Collaboration Meeting

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UC Santa Cruz / SCIPP

Parity Violation in the Standard Model

$$SU(2)_L \otimes U(1)$$

maximal P.V. ($SU(2)_L$) — mixed P.V. ($U(1)$)

Neutral Sector

(photon) $A_\mu = W^3_\mu \sin\theta_W + B_\mu \cos\theta_W$

(Z°) $Z_\mu = W^3_\mu \cos\theta_W - B_\mu \sin\theta_W$

$\Rightarrow$ Parity violation in weak neutral sector is telling test of S.M.

Parity Violation and Chiral Couplings

Parity Violation $\Leftrightarrow$ L, R handed couplings differ

Define "parity violation parameters"

$$A_f = \frac{(g_L^f)^2 - (g_R^f)^2}{(g_L^f)^2 + (g_R^f)^2}$$

where g_L^f, g_R^f are couplings of fermion f to the Z^0.

$\Rightarrow$ Quantitative measure of extent of PV in coupling of Z^0 to fermion f.

$m_J = -1$

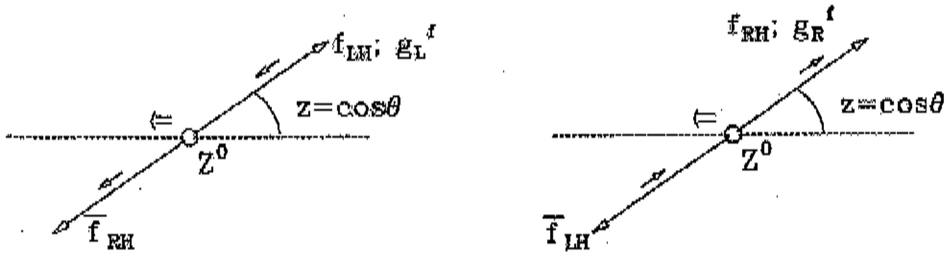


Figure 1. Decay of an $m_J = -1$ Z^0 boson into left- and right- handed fermions.

But how to MEASURE!? ($e^+e^- \to Z^0 \to f\bar{f}$)

Use angular momentum arguments:

Polar angle distribution sensitive to A_f's (participating f's)

No Electron Polarization ($P_e = 0$) (LEP)

$$\frac{d\sigma^f}{dz} \propto 1 + z^2 + 2 A_f A_e z$$

⇒ Sensitive to combination $A_e A_f$

With Electron Polarization ($P_e = \pm|P_e|$) (SLC)

$$\frac{d\sigma^f}{dz} \propto (1 - A_e P_e)(1 + z^2) + 2 A_f (A_e - P_e) z$$

⇒ sensitive to A_f in isolation

Table 1. Standard Model Couplings and Parity Violation (assuming $\sin^2\theta_W = 0.231$)

Fermion	t_3^f	Q^f	g_L^f	g_R^f	A_f	$dA_f/d\sin^2\theta_W$
e, μ, τ	-1/2	-1	-0.269	0.231	0.151	-7.8
ν	+1/2	0	0.500	0.000	1.000	-0.0
d, s, b	-1/2	-1/3	-0.423	0.077	0.935	-0.6
u, c, t	+1/2	+2/3	0.346	-0.154	0.669	-3.5

For the couplings of the Z^0 to fermion f:

$$g_L^f = t_3^f - Q^f \sin^2\theta_W$$
$$g_R^f = -Q^f \sin^2\theta_W$$

t_3 = 3rd component of weak isospin

Q = electric charge

⇒ A_{lept} very sensitive to $\sin^2\theta_W$ (A_{LR}, etc).

⇒ $A_{d,s,b}$ very insensitive to $\sin^2\theta_W$ (complementary)

⇒ $A_{c,t,u}$ is somewhere in between.

N.B.: masses in SM not yet understood; b couples strongly to generation mechanism ⇒ A_b interesting!

Measuring A_f : Practical Note

One needs to:

- Isolate sample of $Z \to f\bar{f}$ decays for 'f' of interest
- Discriminate f from $\bar{f}$
- Estimate $z = \cos\theta$ of parton
- Monitor polarization appropriately

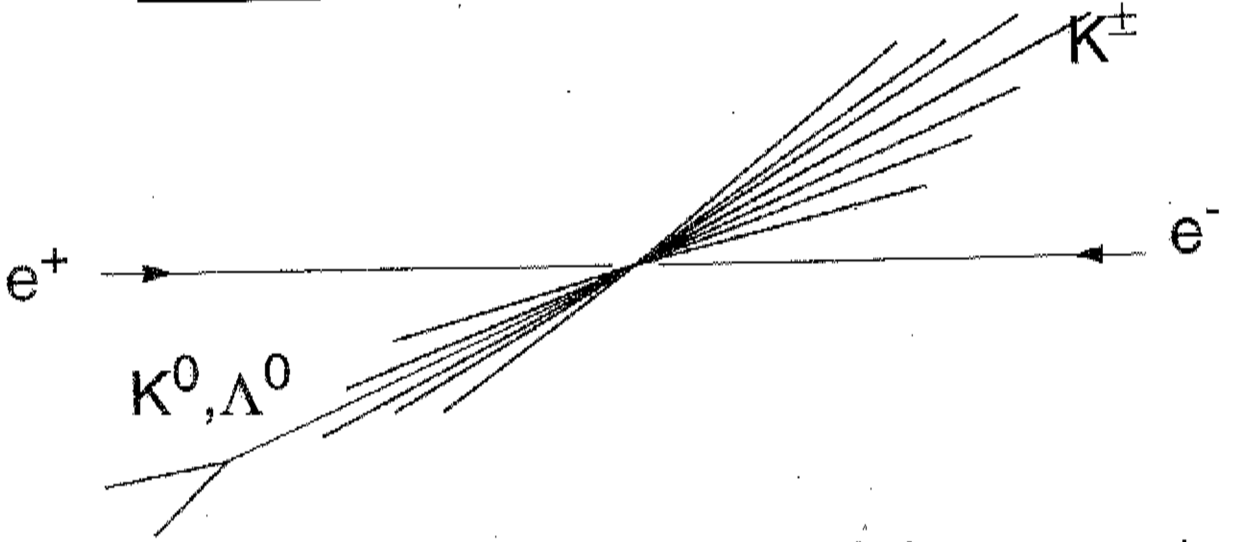
⇒ Exploits <u>full</u> capabilities of detector

- Tracking (VTX, mass reconstruction)
- Cal (electron ID)
- CRID (K, e, μ ID)
- Muon system (μ ID, tracking)
- Polarimetry

SLD A_q THESES

1)	Kenji Abe	A_b kaons	JAPAN
2)	Giulia Bellodi	A_b, A_c muons	ITALY
3)	Jorge Fernandez	A_b electrons	USA
4)	Mike Hildreth	A_c D^*'s	USA
5)	Tom Junk	A_b jet charge	USA
6)	Giampiero Mancinelli	A_b, A_c muons	ITALY
7)	Shinya Narita	A_s	JAPAN
8)	Hermann Stoengle	A_s	GERMANY
9)	David Williams	A_b muons	USA
10)	Tom Wright	A_b, A_c vtx charge	IOWA

Structure of $e^+e^- \rightarrow s\bar{s}$ Events



- An s-jet often includes a high-momentum particle with strangeness -1, such as

K^-	'stable'	
K^0_S	~50 cm flight dist.	68% → 2 tracks
K^0_L	'stable'	
Λ^0	~80 cm flight dist.	64% → 2 tracks

- However: exact rate unknown
  large bkg. from B, D decays
  bkg. from leading K,L in u,d jets
  bkg. from fragmentation
  analyzing power unknown

→ A measurement of R_s or A_s using strange particle tags could be highly model-dependent

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- We know that:
    - there is a signal in s jets
    - the a.p. is high (prl 78,3442)
    - $0.4 < (u+d):s < 0.8$
    - a leading K^+ in a u or d jet is accompanied by a <u>fast</u> K^-, K^0, Λ^0, ...
    - a fast K^+ in an s jet is accompanied by <u>two</u> <u>fast</u> K^-, K^0, Λ^0, ...
    - the heavy flavor background can be suppressed independently using vertexing
- Strategy: take advantage of these features
  use data to constrain rates

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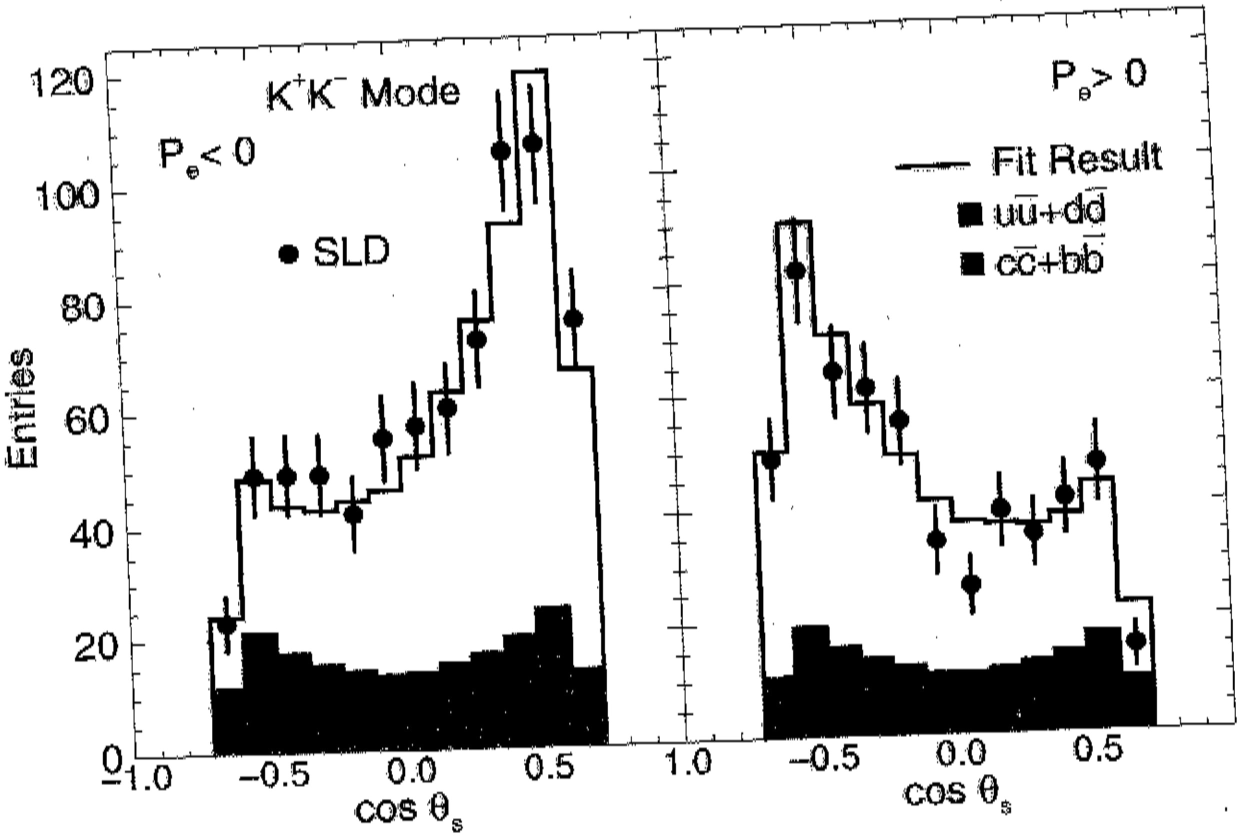
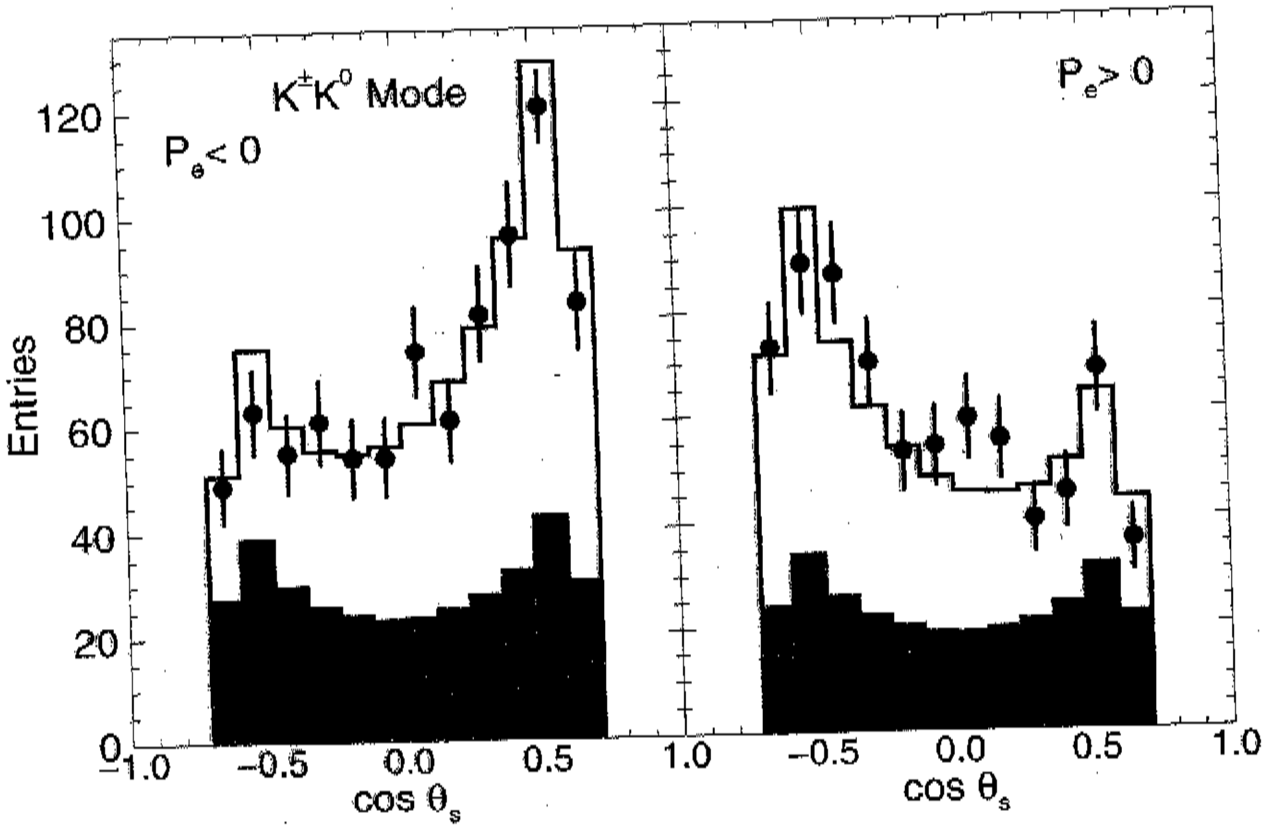


K+K- Mode
Pe< 0
Pe> 0
SLD
Fit Result
uū+dd̄
cc̄+bb̄
Entries
cos θs



K±K0 Mode
Pe< 0
Pe> 0
Entries
cos θs

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- Difficult to measure any of the unknowns cleanly from the data...
- ...but there are several checks/constraints available, given that the simulation contains the above qualitative features of the data.

  For example:

  1) Compare the number of jets with 3 ID'd $K^{\pm}$, K^0 with the prediction of the simulation

     → 33% 'measurement' of the wrong-sign fraction

  2) Compare the number of jets with an ID'd K^+K^- or $K^{\pm}K^0$ pair with the prediction

     → 13% 'measurement' of (u+d):s

  3) Compare the number of events with an ID'd K^+ (or K^-) in both jets with the prediction

     → 57% 'measurement' of the a.p. for u,d

Result: $A_s = 0.85 \pm 0.17$ (stat.) ± 0.10 (syst.)

Expect: $A_s = 0....$ $\pm$ <u>0.08</u> (stat.) $\pm$ <u>0.07</u> (syst.)

OLD, but...

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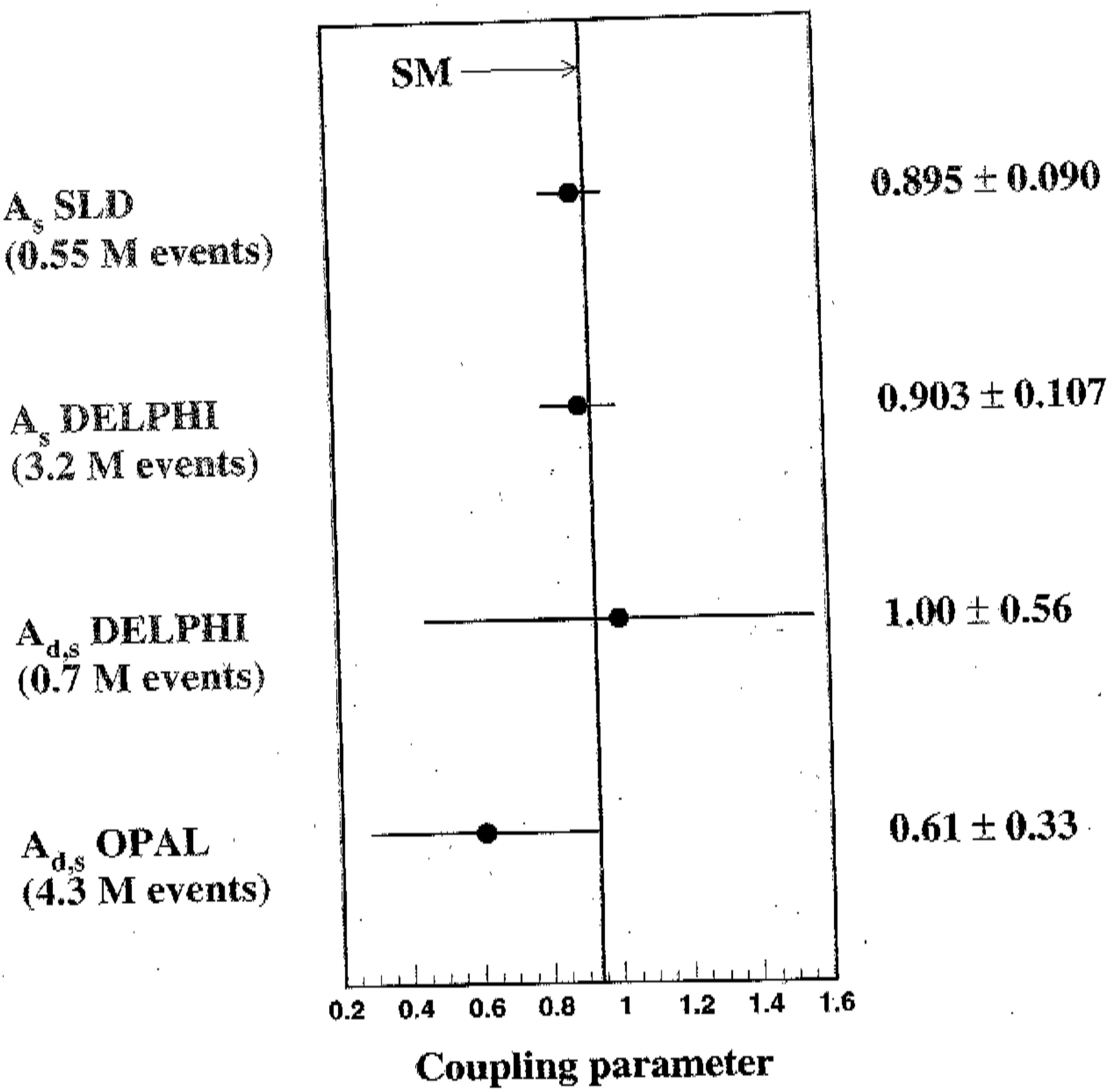


SM
A_s SLD
(0.55 M events)
A_s DELPHI
(3.2 M events)
$A_{d,s}$ DELPHI
(0.7 M events)
$A_{d,s}$ OPAL
(4.3 M events)
0.895 ± 0.090
0.903 ± 0.107
1.00 ± 0.56
0.61 ± 0.33
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Coupling parameter

Measuring A_c

1) Exclusive Reconstruction

$D^{*+} \to D^0 \pi_s^+$; $D^0 \to K^- \pi^+$
$\hookrightarrow K^- \pi^+ \pi^0$
$\hookrightarrow K^- \pi^+ \pi^+ \pi^-$
$\hookrightarrow K^- \ell^+ \nu_\ell$

$D^0 \to K^- \pi^+$

$D^+ \to K^- \pi^+ \pi^+$

Charge determined by slow pion π_s^+ or π_s^-

Precise, but not so efficient!

$$A_c = 0.590 \pm 0.042 \pm 0.021$$

(cut on D momentum 'x_D' selects against $B \to D$)

Dominant systematic:

Backgrounds $\pm .018$

Mixing $\pm .009$

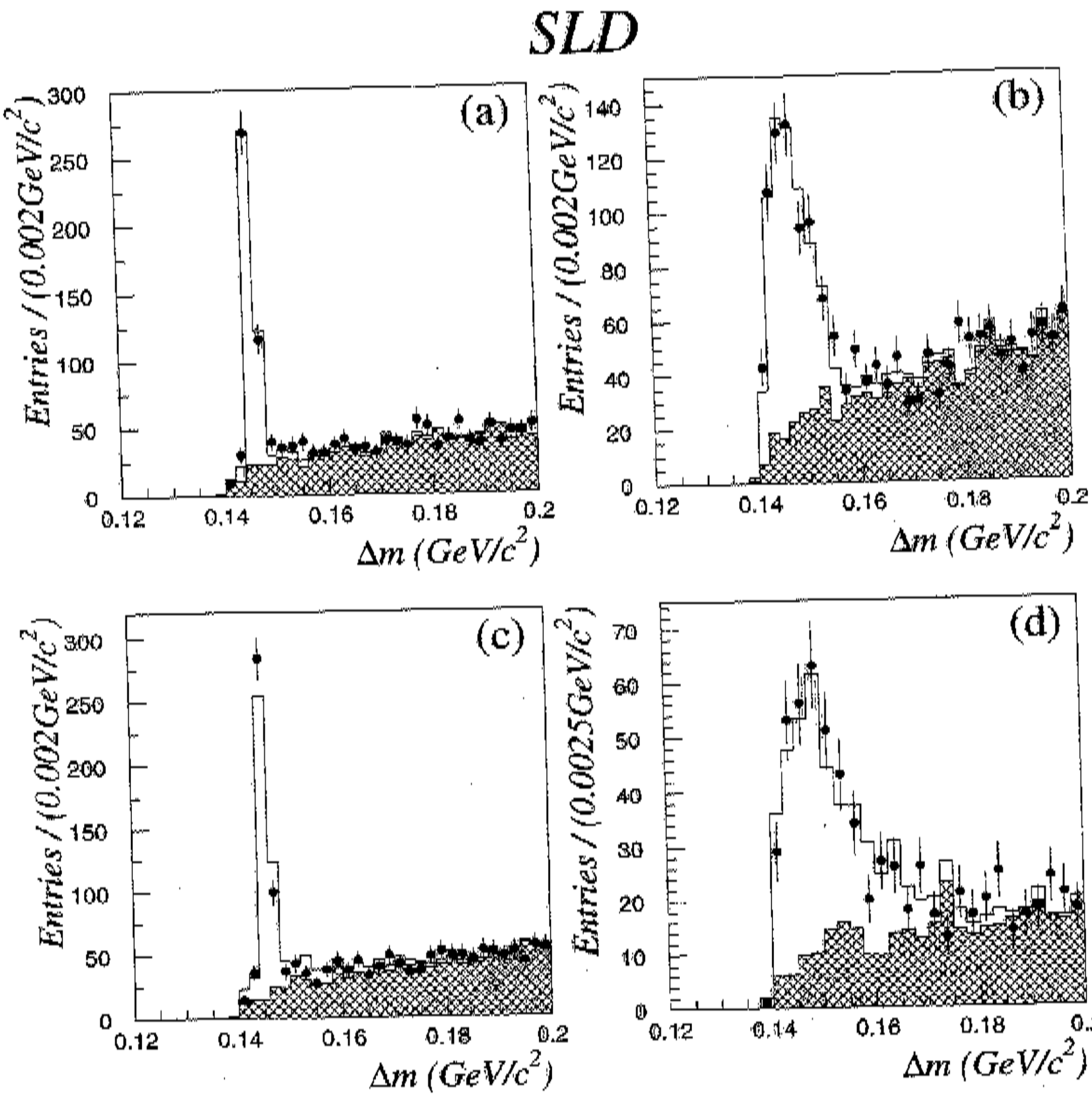


FIG. 2. The mass-difference distributions for the decay of (a)$D^{*+} \to D^0\pi_s^+$, $D^0 \to K^-\pi^+$, (b)$D^0 \to K^-\pi^+\pi^0$, (c)$D^0 \to K^-\pi^+\pi^+\pi^-$, and (d)$D^0 \to K^-l^+\nu_l$ (l =e or μ). The solid circles indicate the experimental data, and histograms are MC of signal (open) and RCBG (double hatched).

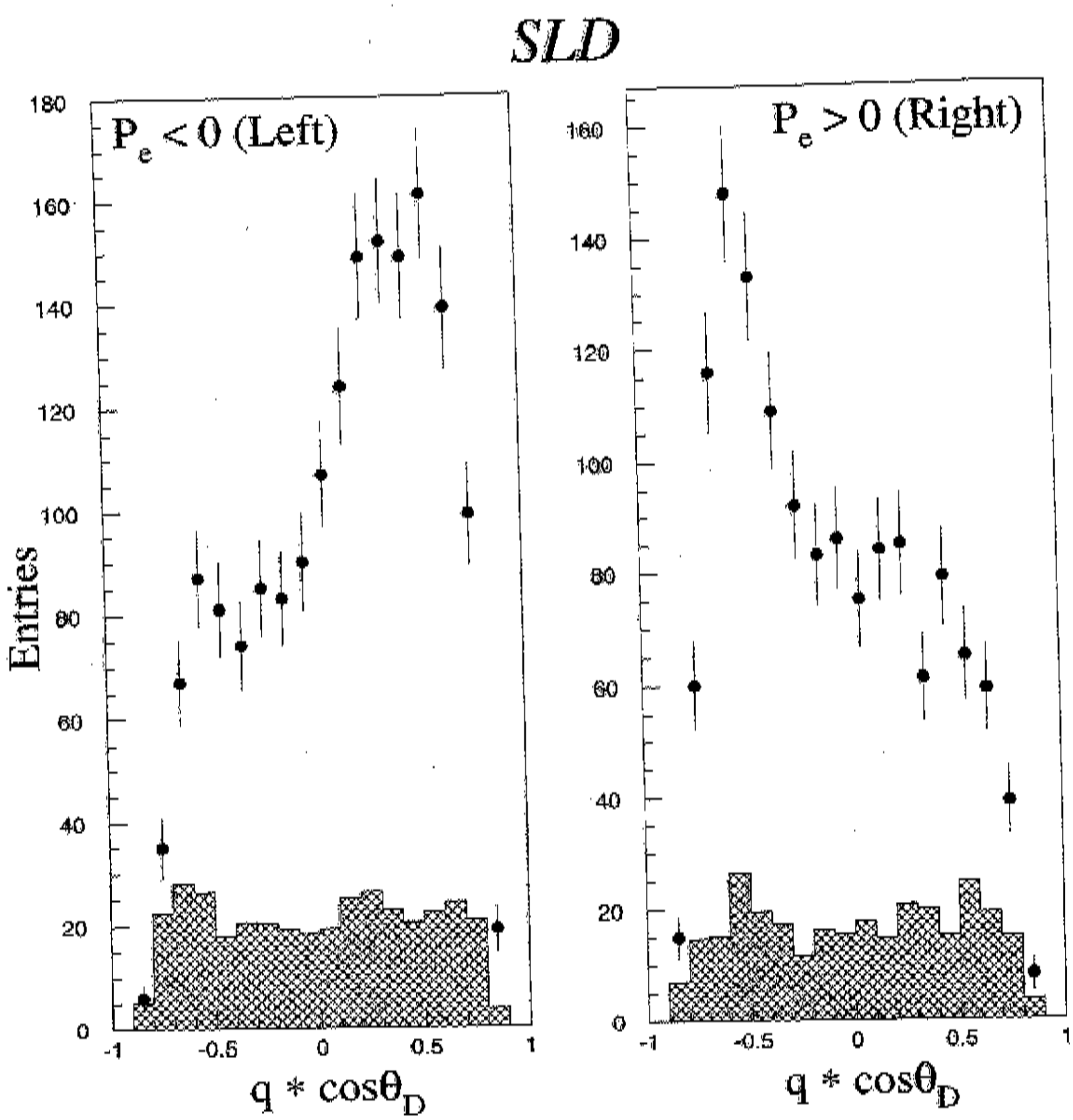
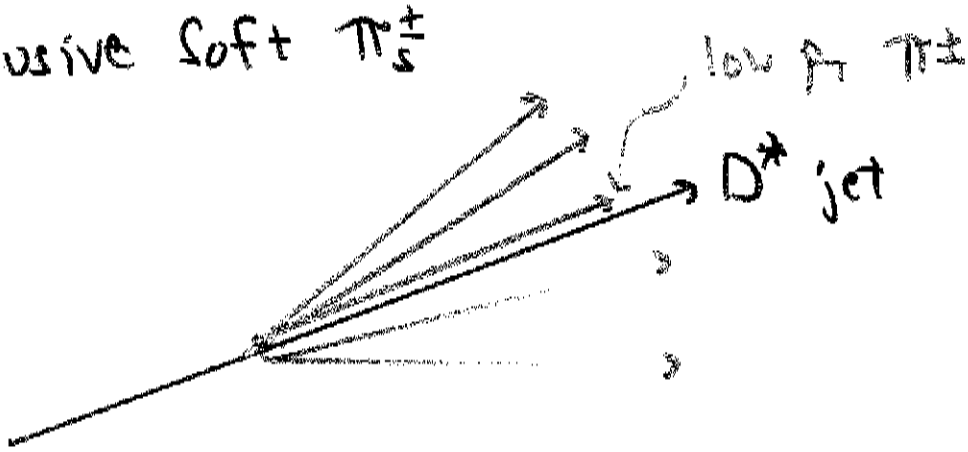


FIG. 4. The distributions of $q \cdot \cos\theta_D$ for the selected D meson sample for (a) left- and (b) right-handed electron beams. The solid circles are experimental data, and double hatched histograms are RCBG estimated from side-band regions.

2) Inclusive Soft $\pi_s^{\pm}$



- Look for $p_\perp$ relative to nearest jet
- Jets must have vertex, significant impact parameters, but not be b-tagged.
- Sign with π_s charge

⇒ Efficient, somewhat sloppy

$$A_c = 0.685 \pm 0.052 \pm 0.038$$

Dominant systematic:

Backgrounds	± .036
Mixing	± .012

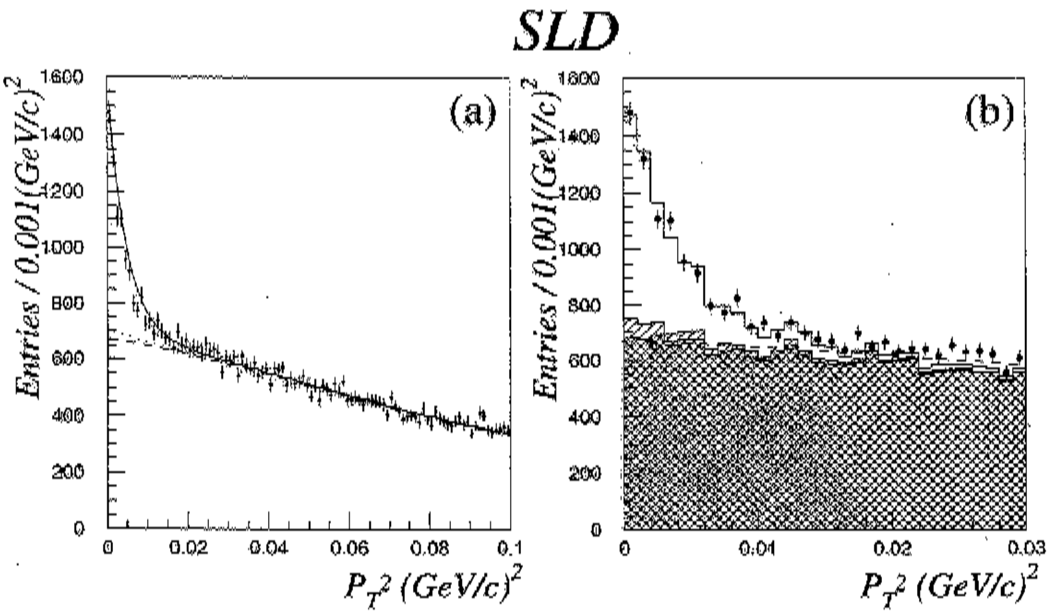


FIG. 6. The P_T^2 distributions for soft-pion candidate tracks. (a) The solid circles indicate the experimental data. The curves are the result of the a fit $S(P_T^2) + F_1(P_T^2)$ performed for $P_T^2 < 0.1$ GeV/c (solid line), and the extrapolations of $F_1(P_T^2)$ (dashed line) and $F_2(P_T^2)$ (dotted line). The definition of the functions are described in the text. (b) The solid circles are the experimental data, and histograms are MC predictions for D mesons from c-decay (open), D mesons from b-decay (single hatched), and background (double hatched). The extrapolation of $F_1(P_T^2)$ is also shown as a dashed line.

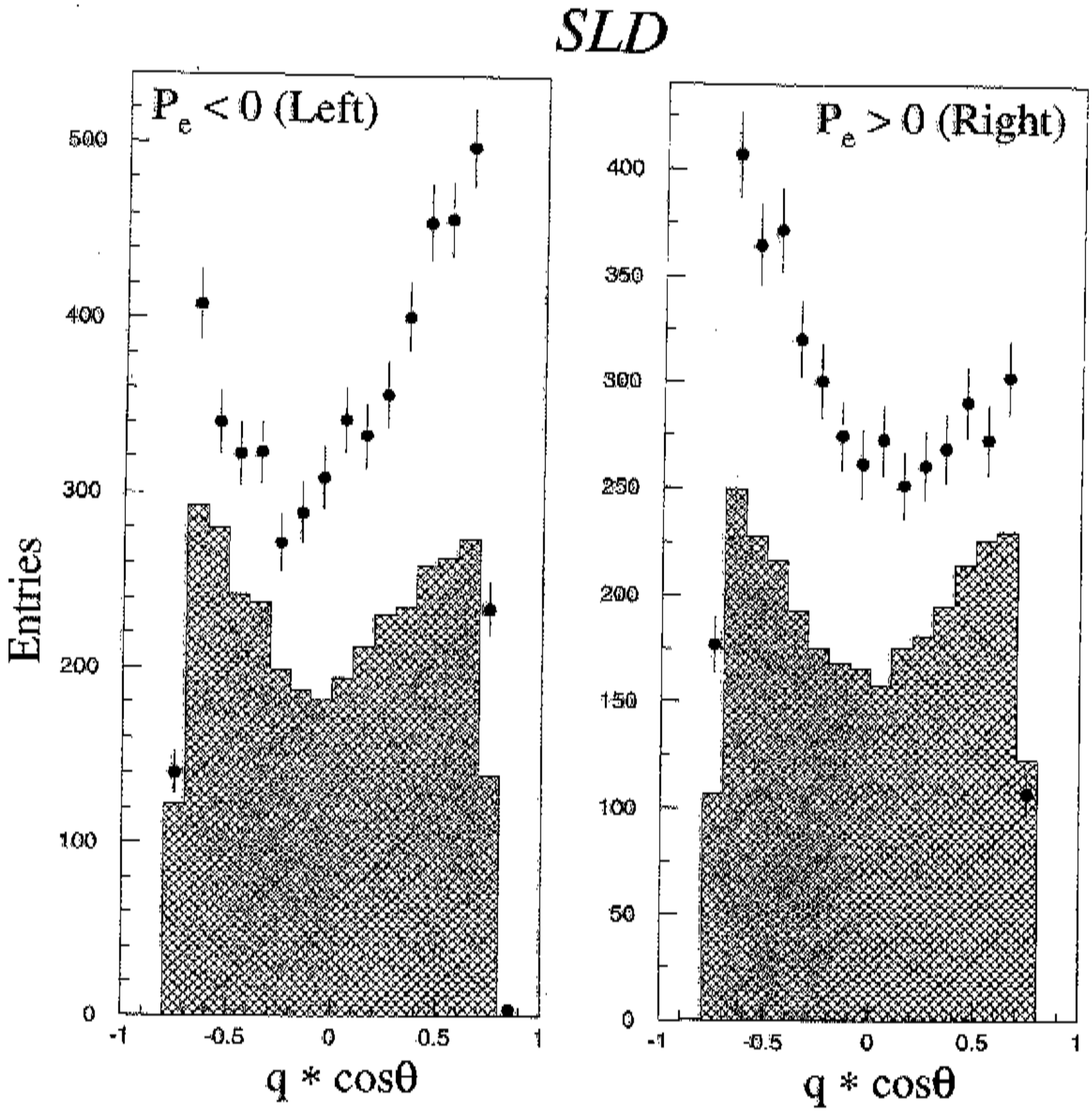


FIG. 7. The distributions of $q \cdot \cos\theta_D$ for the selected D^{*+} meson sample for (a) left- and (b) right- handed electron beams. The solid circles are experimental data, and hatched histograms are RCBG estimated from side-band regions.

(3) Inclusive leptons from SL decays (μ only!)

To be described later

$$A_c = 0.583 \pm 0.055 \pm 0.055$$

Dominant systematic:

Sample purity $\pm .053$

(4) VTX and Kaon Charge

To be described later

$$A_c = 0.673 \pm 0.029 \pm 0.023$$

Dominant systematic:

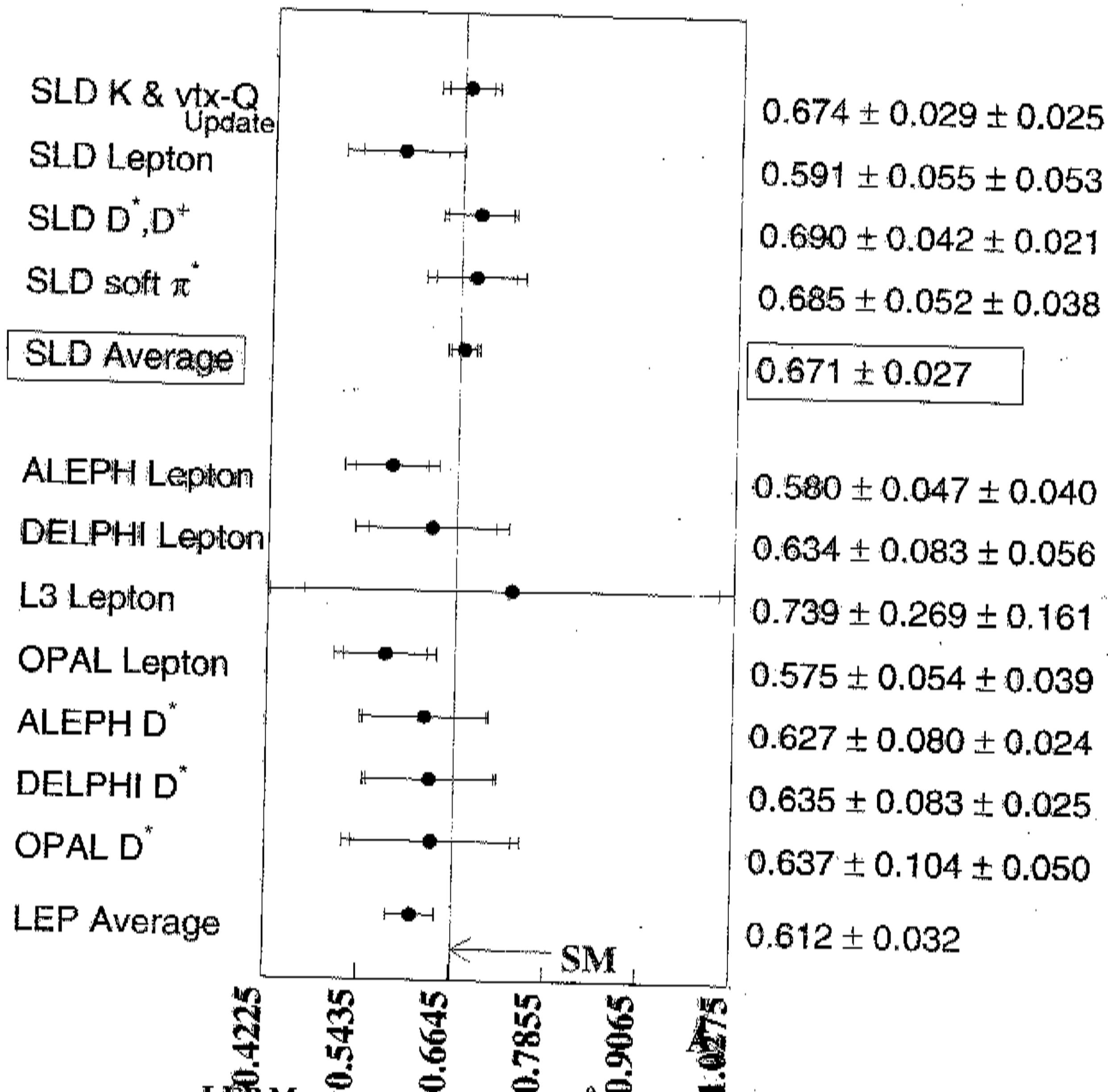
Self-calibration statistics $\pm .020$

Combined

$$\boxed{A_c = 0.671 \pm 0.027}$$

A_c Summary

A_c Measurements (Winter-01)



LEP Measurements: $A_c = 4 A^{0,c}_{FB} / 3 A_e$

Using A_e=0.1500±0.0016 (Combine SLD A_{LR} and LEP A_l)

Semileptonic Decays

In recent years, analyses have benefitted from:

- Neural-net particle identification, including CRID information (e/π and $\mu/K,\pi$ separation)

- Multivariate separation of sources:

  $b \to \ell$ $\quad b \to c \to \ell$ $\quad c \to \ell$ $\quad$ background

Lepton p	* VTX significance
Lepton p_t	Opposite VTX mass
Associated VTX mass	* B meson boost
* Associated VTX momentum	L/D

* electrons only

NOTE: VTX requirement for e sample $\Rightarrow$ no A_c from electrons.

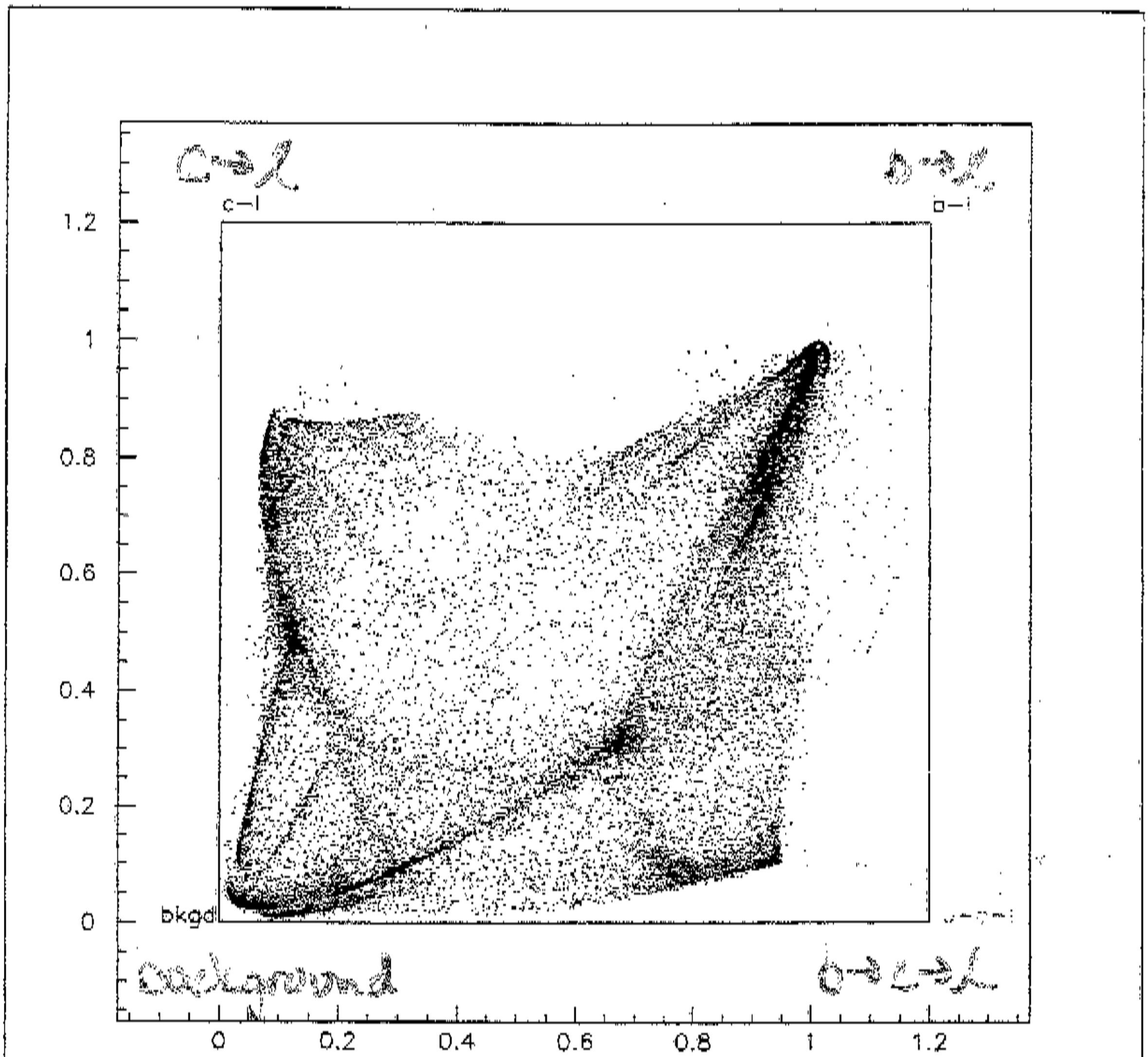


Figure 5.17: Reduced space for event classifications in the 1998 Monte Carlo. This distribution is used to calculate the weights as a function of NN outputs for each data candidate. In this space, the axes are defined as: $x = \mathrm{NN}_{bc} + \mathrm{NN}_b$ and $y = \mathrm{NN}_c + NN_b$, where NN_b = b-direct, NN_{bc} = b-cascade and NN_c = c-direct output nodes from the NN. By explicit omission, the miss-ID's fall to the origin.

With source determined, lepton provides charge and direction of underlying quark.

$$A_b = 0.919 \pm 0.030 \pm 0.024$$

Dominant systematic:

Sample purity	$\pm .013$
B mixing	$\pm .010$
$B(B \to D\bar{D} \to \ell)$	$\pm .009$

Inclusive Jet Charge (b-tagged events)

- In each hemisphere, form weighted sum

$$Q_{hem} = \sum_{tracks} q_i \left| \vec{p}_i \cdot \hat{T} \right|^{0.5}$$

- $Q_{hem} < 0 \Rightarrow$ b quark

- Self-calibration: compare

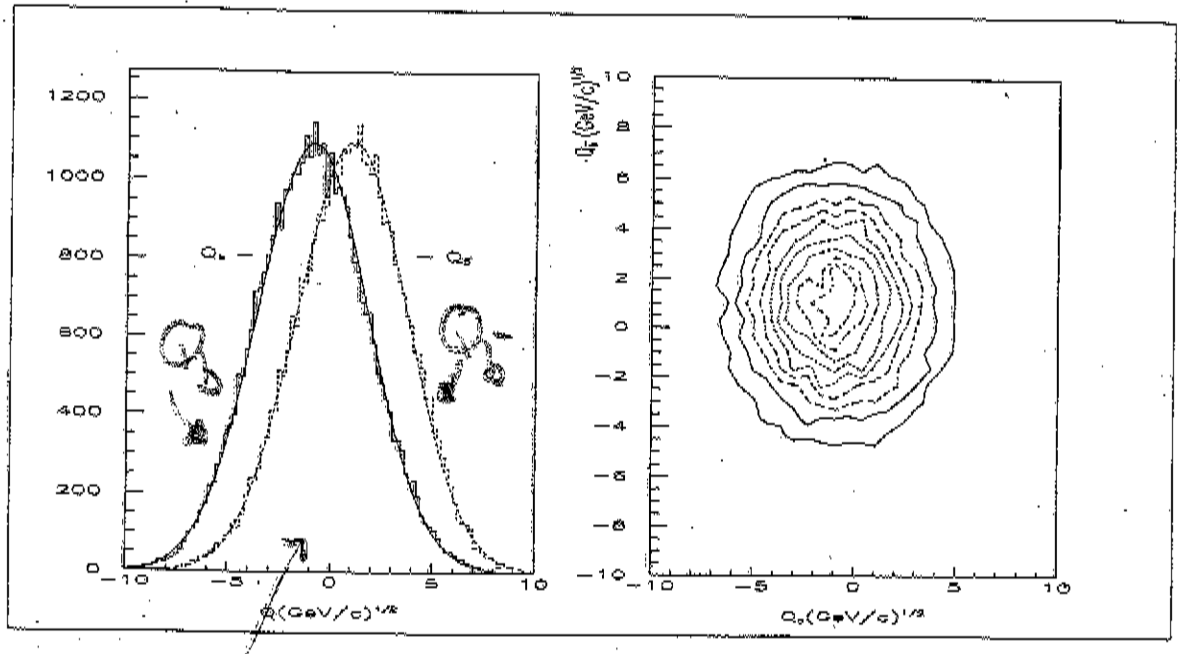
  $|Q_{dif}| = |Q_{(1)} - Q_{(2)}|$ to

  $Q_{sum} = Q_{(1)} + Q_{(2)}$

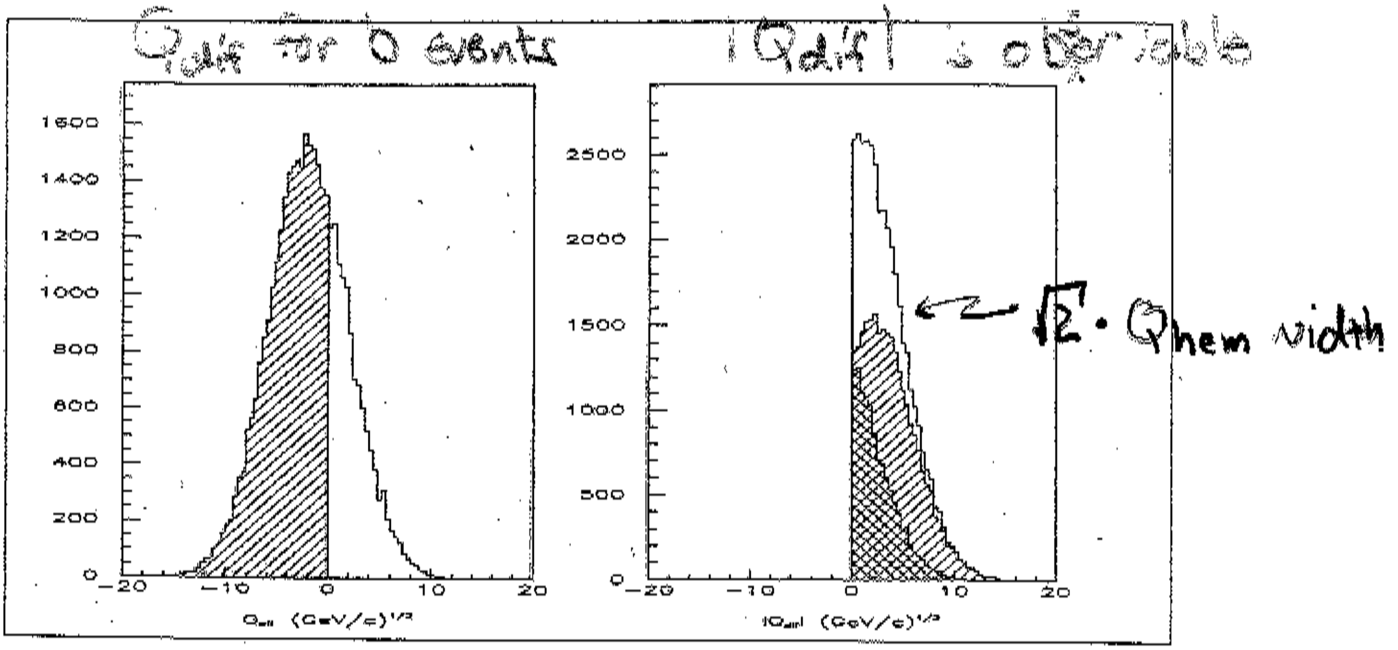
- Dominant systematic:

  Hemisphere correlations (fragmentation)

- $A_b = 0.907 \pm 0.020 \pm 0.024$



$Q_b + Q_{\bar{b}}$ wider than Q_{dif}; comparison gives analyzing power of $Q_{sum} = Q_b + Q_{\bar{b}}$



Vertex / Kaon Charge

- Net charge of secondary VTX signs heavy quark (also incorporate high-b K for $Z \to c\bar{c}$)
- NN charm/bottom separation
- Exhaustive + exacting study of correlations
- Multi-faceted calibration

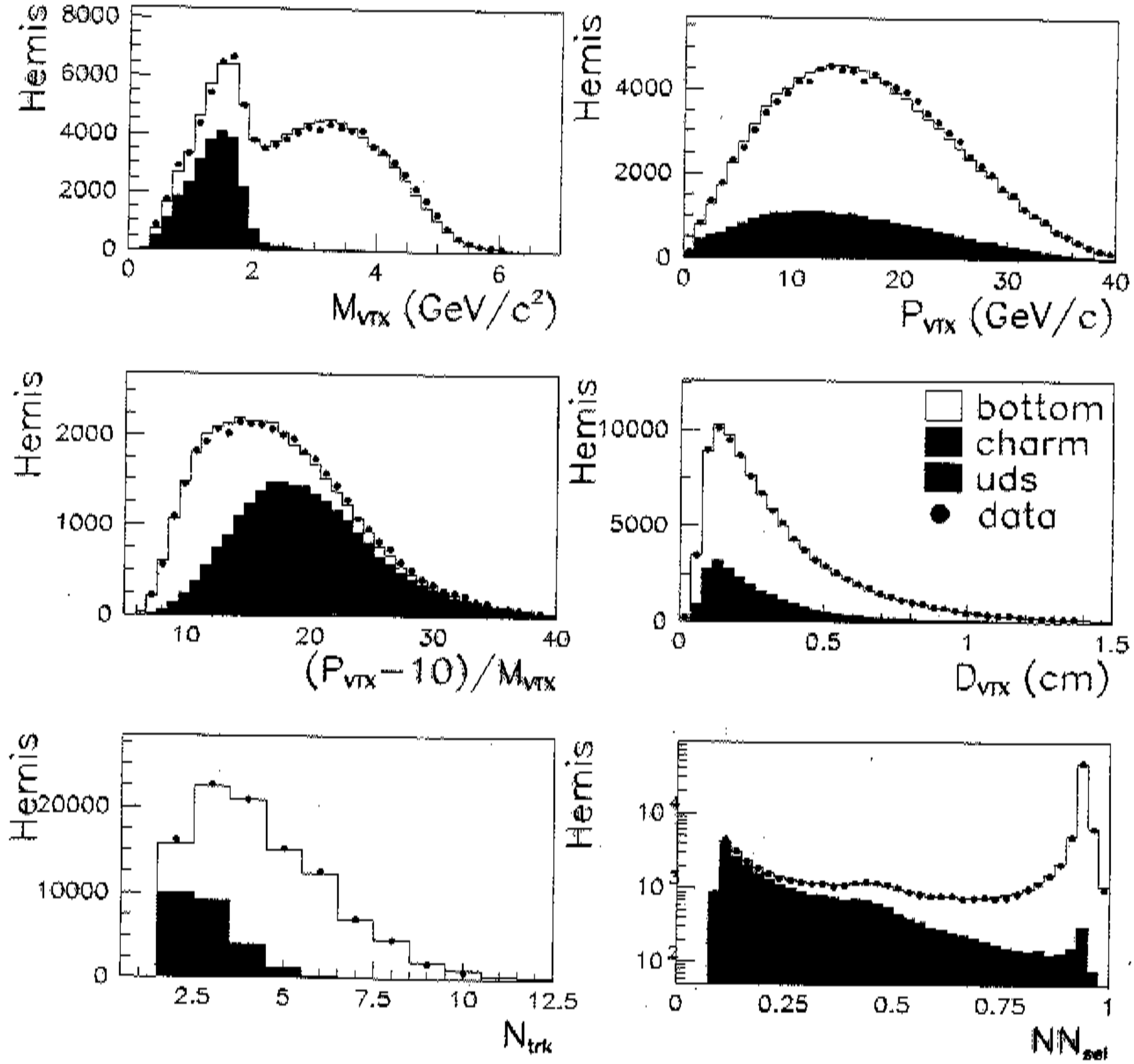
$$A_b = 0.919 \pm 0.018 \pm 0.017$$

Dominant systematic:

Calibration stats	± .014
Charm background	± .005
Polarization	± .005
QCD correction	± .004

Charm/Bottom Separation

Uses (4:5:1) neural network



Require

→ $NN_{sel} < 0.4, P_{VTX} > 5$ for charm tag

→ $NN_{sel} > 0.9, M_{VTX} < 7$ for bottom tag

Efficiency Definitions

Only interested in charged tags
→ if $Q_{VTX} = Q_K = 0$, consider hemisphere untagged
→ if Q_{VTX} and Q_K disagree, untag hemisphere

Each tag has an associated efficiency ω_f^q, with:

$\omega = (X, \eta, \epsilon)$ for (untagged, c-tagged, b-tagged)

$q = (r, w, 0)$ for (right-sign, wrong-sign, unsigned)
→ only 0 possible for untagged hemispheres
→ only r, w possible for HF-tagged hemispheres
→ right-sign means signed $\vec{T}$ points along primary quark

$f = (uds, c, b)$ for (light-flavor, charm, bottom) event flavor

There are $(1\,X + 2\,\eta + 2\,\epsilon) \times (3\text{ flavors}) = 15$ total efficiencies

Assign charges so that $Q_{hemi} > 0$ means right-sign
→ for η tags, $Q_{hemi} = +Q_{VTX}$ or $-Q_K$
→ for ϵ tags, $Q_{hemi} = -Q_{VTX}$ or $-Q_K$

Calibrate these tags by counting event rates in data
straightforward extension of R_b technique

Efficiency Calibration

Can express expected number of tagged events as:

$$N_{tags} = N_{tot} \sum_f \left(\sum \omega_{f,1}^{q_1} \omega_{f,2}^{q_2} \right) R_f$$

$\rightarrow$ sum over ω^q combs. which can produce an event type

$\rightarrow$ R_f is hadronic partial width to flavor f

tags	Q_1Q_2	N_{tags}	$\sum \omega_1^{q_1} \omega_2^{q_2}$	gives
$X - X$	00	189575	$X_f^0 X_f^0$	X_f^0
$X - \eta$	$0\pm$	9440	$X_f^0(\eta_f^r + \eta_f^w)$	η_c
$X - \epsilon$	$0\pm$	22070	$X_f^0(\epsilon_f^r + \epsilon_f^w)$	ϵ_c
$\eta - \eta$	$\pm\mp$	465	$\eta_f^r\eta_f^r + \eta_f^w\eta_f^w$	η_c^r, η_c^w
$\eta - \eta$	$\pm\pm$	92	$\eta_f^r\eta_f^w$	η_c^r, η_c^w
$\eta - \epsilon$	$\pm\mp$	421	$\eta_f^r\epsilon_f^r + \eta_f^w\epsilon_f^w$	η_b^r, η_b^w
$\eta - \epsilon$	$\pm\pm$	389	$\eta_f^r\epsilon_f^w + \eta_f^w\epsilon_f^r$	η_b^r, η_b^w
$\epsilon - \epsilon$	$\pm\mp$	4231	$\epsilon_f^r\epsilon_f^r + \epsilon_f^w\epsilon_f^w$	$\epsilon_b^r, \epsilon_b^w$
$\epsilon - \epsilon$	$\pm\pm$	2029	$\epsilon_f^r\epsilon_f^w$	$\epsilon_b^r, \epsilon_b^w$

Nine independent Poisson-distributed variables - measure these N_{tags} and fit for the efficiencies?

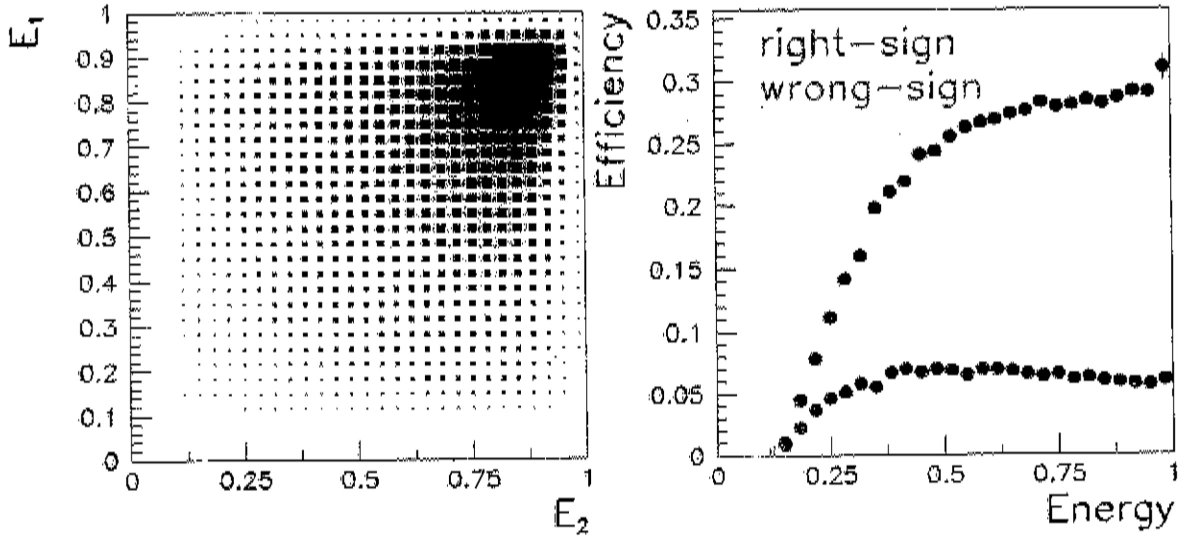
$\rightarrow$ life is not quite so easy...

Correlations

Two hemispheres are not independent

→ if $x_1 = x_1(x_2)$ and $\omega = \omega(x)$, then $\omega_{12} \neq \omega_1\omega_2$

Example: B-hadron energies



Define correlation parameter γ as:

$$\gamma_{12}^{q_1 q_2} = \frac{\omega_{12}^{q_1 q_2}}{\omega_1^{q_1}\omega_2^{q_2}}$$

where $\omega_{12}^{q_1 q_2}$ is the efficiency to tag an *event* of that type.

For each flavor and tag combination, get a γ from MC

→ enumerate sources, do they saturate total correlation?

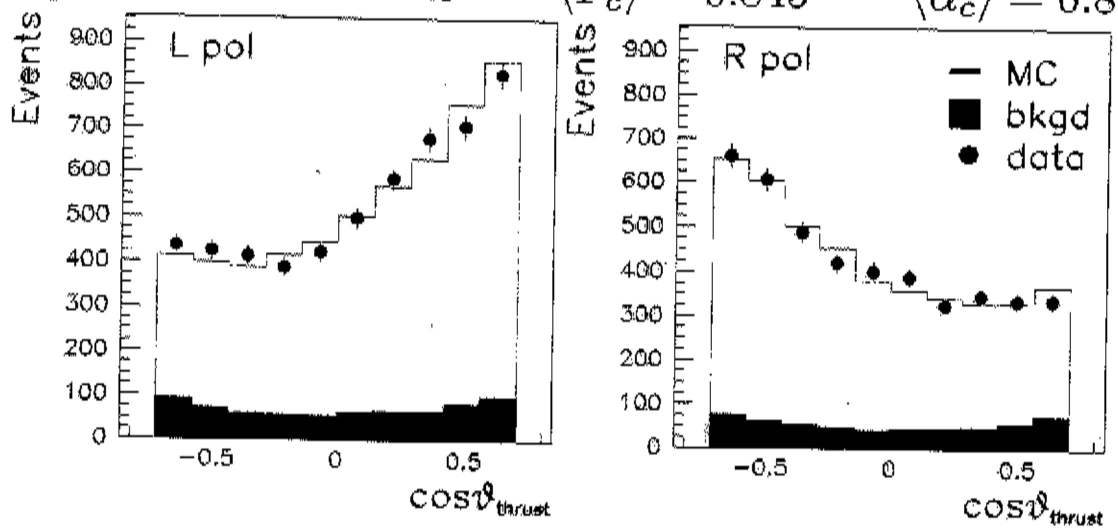
For a source characterized by x, find $\omega(x)$ and calculate:

$$\gamma_x = \frac{\langle \omega_1^{q_1}(x)\omega_2^{q_2}(x)\rangle}{\langle \omega_1^{q_1}(x)\rangle \langle \omega_2^{q_2}(x)\rangle}$$

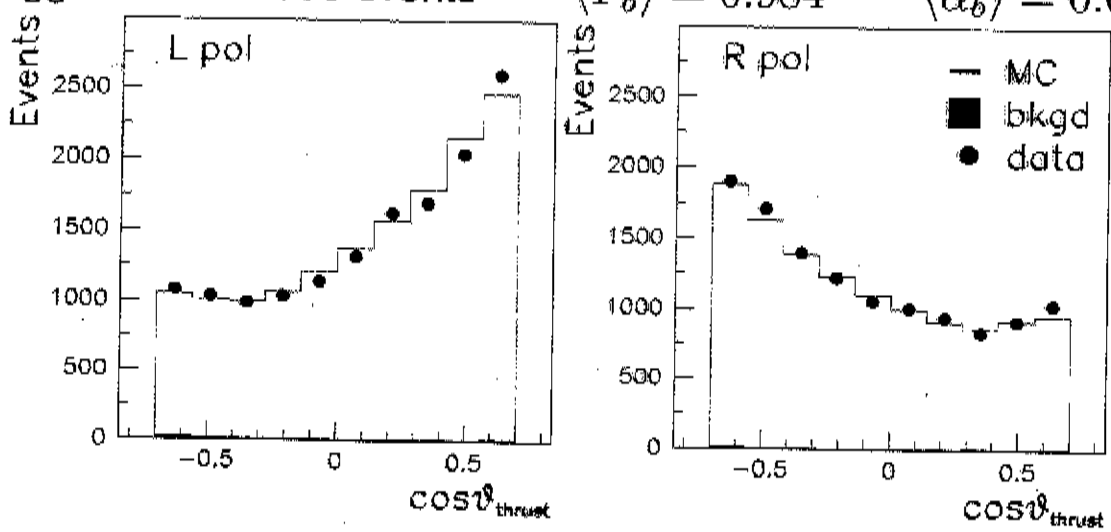
then compare $\prod \gamma_x$ to the total γ

Results

c-tagged: 9727 events $\langle F_c \rangle = 0.845$ $\langle \alpha_c \rangle = 0.838$



b-tagged: 26595 events $\langle F_b \rangle = 0.984$ $\langle \alpha_b \rangle = 0.635$

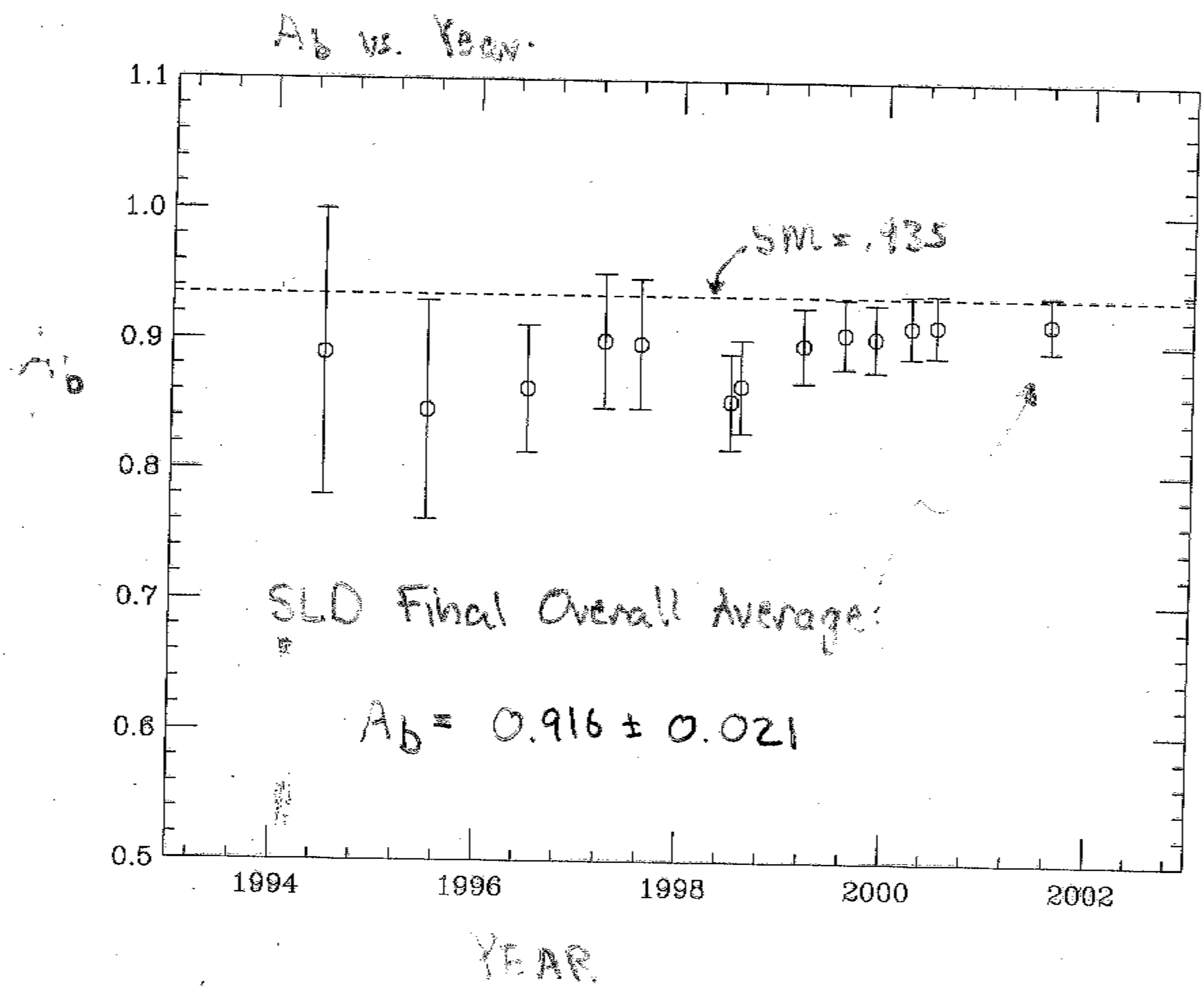


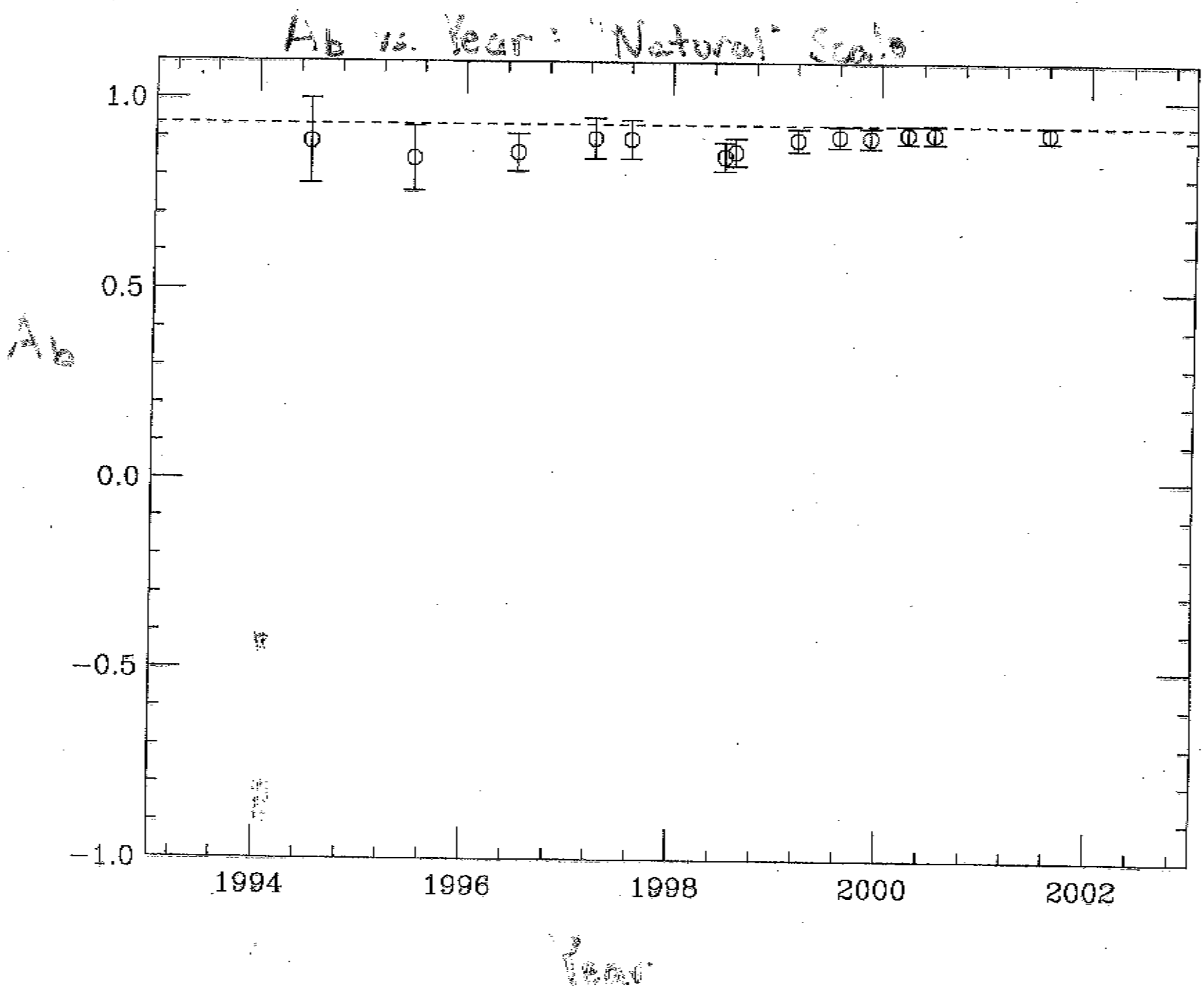
SLD preliminary results

$A_c = 0.674 \pm 0.029$

$A_b = 0.913 \pm 0.019$

Errors are statistical only


Ab vs. Year.
1.1
1.0
0.9
0.8
0.7
0.6
0.5
Ab
SM = .935
SLD Final Overall Average:
Ab = 0.916 ± 0.021
1994
1996
1998
2000
2002
YEAR

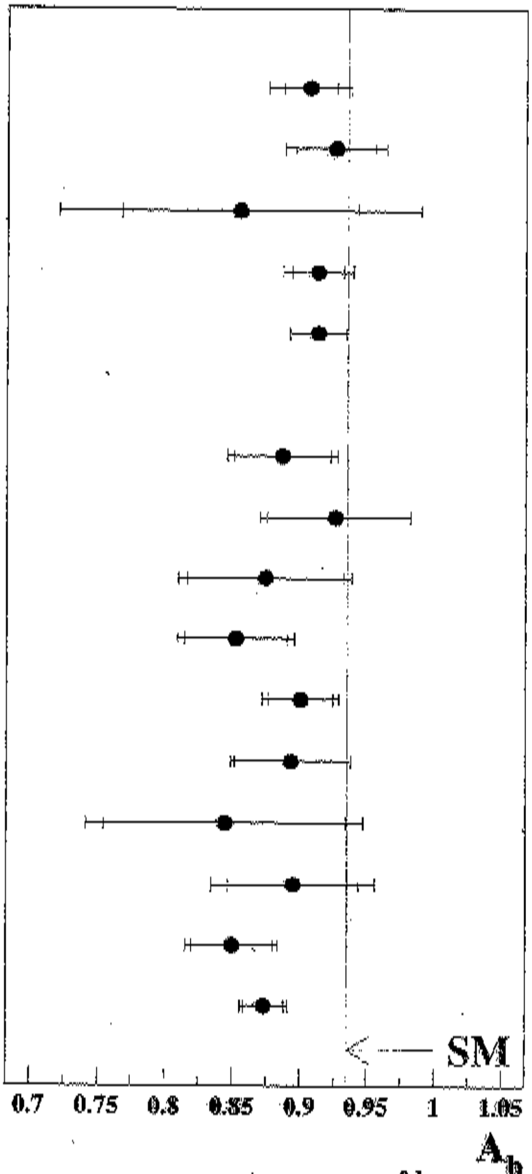


Ab vs. Year : "Natural" Scale
1.0
0.5
0.0
−0.5
−1.0
Ab
1994
1996
1998
2000
2002
Year

A_b Summary

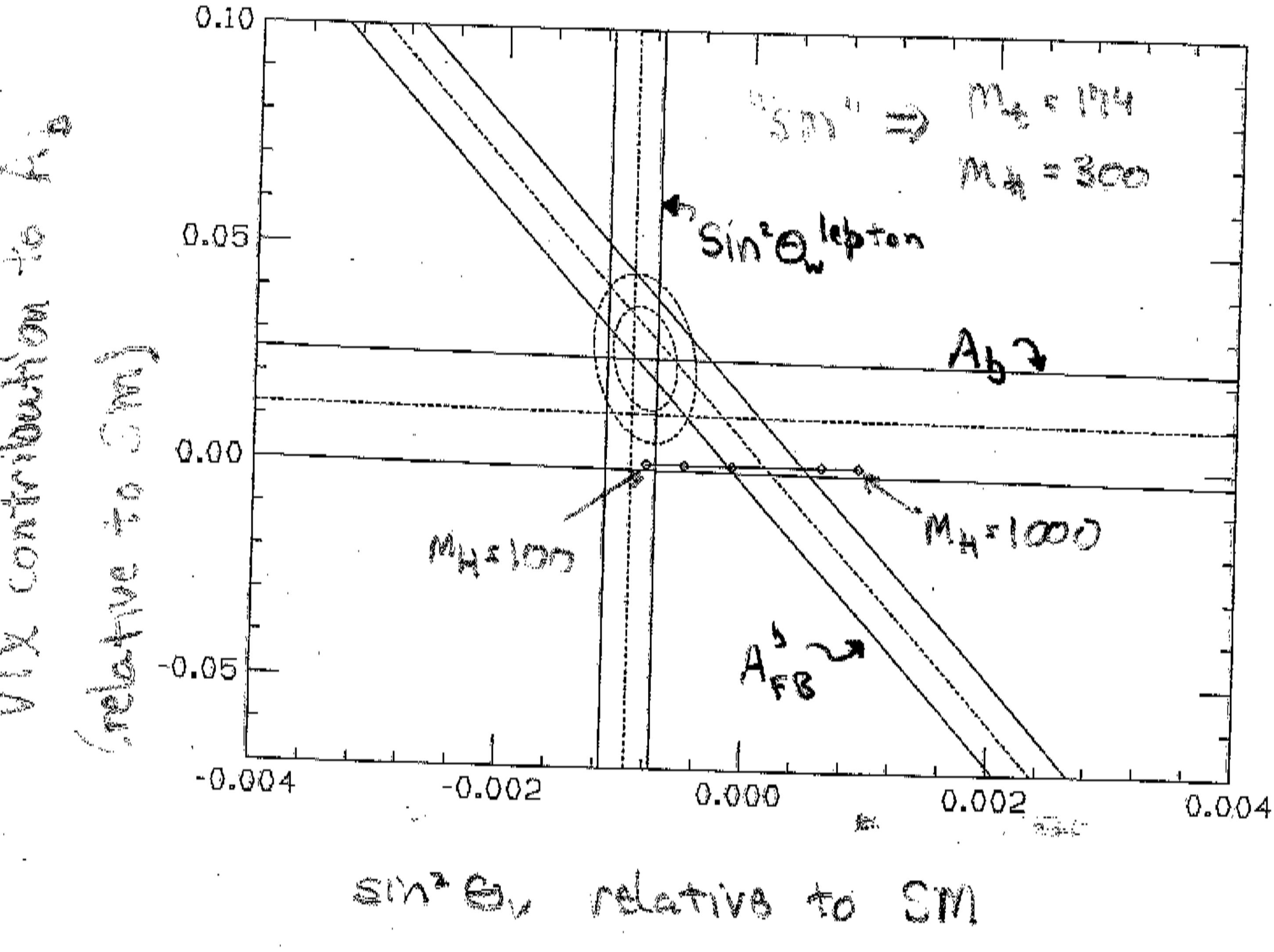
A_b Measurements (Winter-2001)

Measurement	A_b
SLD JetC (Update)	$0.907 \pm 0.020 \pm 0.024$
SLD Lepton	$0.926 \pm 0.030 \pm 0.024$
SLD $K^{\pm}$ tag	$0.855 \pm 0.088 \pm 0.102$
SLD VtxQ+K (Update)	$0.913 \pm 0.019 \pm 0.018$
SLD Average	**0.913 ± 0.021**
ALEPH Lept	$0.886 \pm 0.035 \pm 0.020$
DELPHI Lept	$0.926 \pm 0.051 \pm 0.024$
L3 Lept	$0.874 \pm 0.058 \pm 0.026$
OPAL Lept	$0.852 \pm 0.038 \pm 0.021$
ALEPH JetC (Update)	$0.900 \pm 0.024 \pm 0.015$
DELPHI JetC	$0.893 \pm 0.042 \pm 0.015$
L3 JetC	$0.844 \pm 0.090 \pm 0.050$
OPAL JetC	$0.895 \pm 0.049 \pm 0.036$
DELPHI NN (New)	$0.849 \pm 0.030 \pm 0.016$
LEP Average	0.873 ± 0.018



LEP Measurements: $A_b = 4\,A^{0,b}_{FB} / 3\,A_e$
Using A_e=0.1500±0.0016 (Combine SLD A_{LR} and LEP A_l)

"TGR" Fits



0.10
0.05
0.00
-0.05
-0.004
-0.002
0.000
0.002
0.004
"SM" ⇒ $m_t = 174$
$m_H = 300$
$\sin^2\theta_W^{lepton}$
A_b
$m_H = 100$
$m_H = 1000$
A_{FB}^b
VTX contribution to R_b
(relative to SM)
$\sin^2\theta_W$ relative to SM

TGR Results

Some numbers from simultaneous fit for $\delta \sin^2\Theta_w$, δR_b, δA_b : ($M_H = 300$)

	$\delta \sin^2\Theta_w$:	-0.00085 ± 0.00019
Insensitive to M_H	δR_b :	-0.00060 ± 0.00072
	δA_b :	0.0245 ± 0.0087 (2.8σ)

W/OUT SLD A_b

$\delta \sin^2\Theta_w$:	-0.00095 ± 0.00020
δR_b :	-0.00058 ± 0.00072
δA_b :	0.0353 ± 0.0116 (3.0σ)

Publication Status (Final Results)

- A_s (Muller)

  Phys. Rev. Lett. **85**, 5059 (2000)

- A_c from D^* (Iwasaki)

  Phys. Rev. D **63**, 032005 (2001)

- A_b, A_c from leptons (Schumm)

  Final comments in, ready for submission to PRL

- A_b from jet charge (Schumm)

  Draft exists, awaiting final plots, numbers from Victor

- A_b, A_c from VTX, Kaon Charge (Wright)

  As soon as Tom's thesis is done

A_b WRAP-UP

- Very successful component of SLD program
  - $\delta A_b \cong$ all LEP
  - $\delta A_c, \delta A_s$ dominate WA
  - Unique direct measurement
- SLD msmt of A_b has saved a lot of theorists from needless speculation
- Future? Giga-Z proposals speculate
  - $\delta A_b \cong 0.003$

(now, $A_b = 0.916 \pm 0.021$)