Inclusive b-hadron semileptonic decays at LEP and extraction of $|V_{cb}|$

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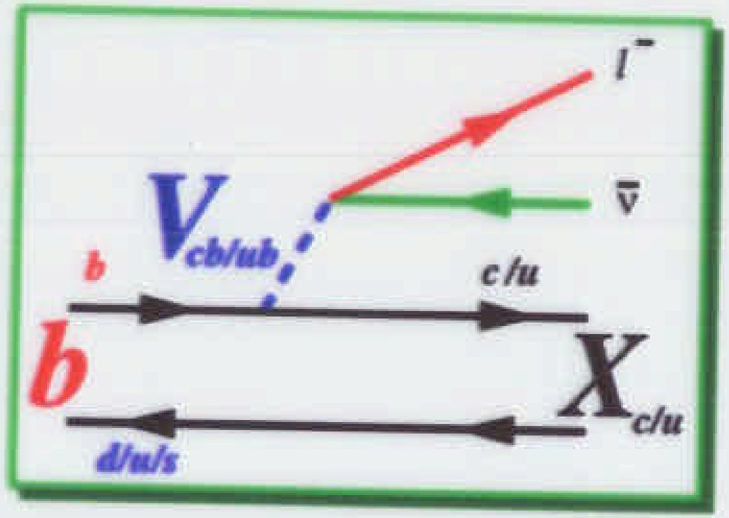
Conference submissions: 93,182,391,840

- Motivation for measuring semileptonic BR's
- ALEPH new measurement
- DELPHI,L3,OPAL
- $b \to \ell^- \bar{\nu}_\ell X$ lepton spectra modelling
- L3,ALEPH & OPAL modelling studies
- LEP global fits
- Comparisons with $\Upsilon(4S)$
- Extraction of $|V_{cb}|$

Why measure inclusive semileptonic BR's ?

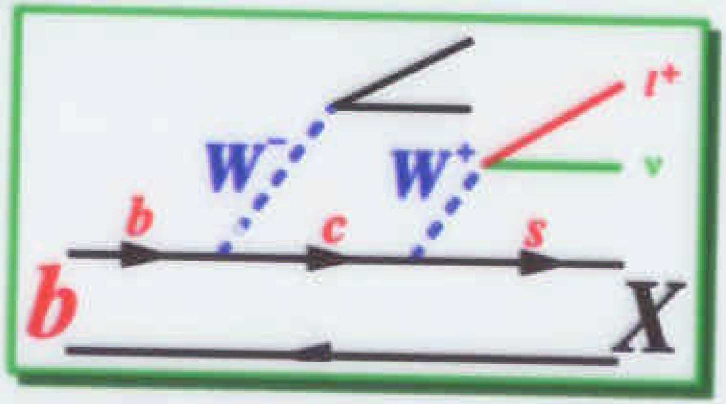
$\mathrm{BR}(b \to \ell^- \bar{\nu}_\ell X)$

- Most direct route to $|V_{cb}|$
- Inclusive quantities place lesser demands on both theory and experiment → more significant tests
- Longstanding differences between Z^0 and $\Upsilon(4S)$ measurements
- Measurements have been lower than expectations
- Probe of strong-interaction effects

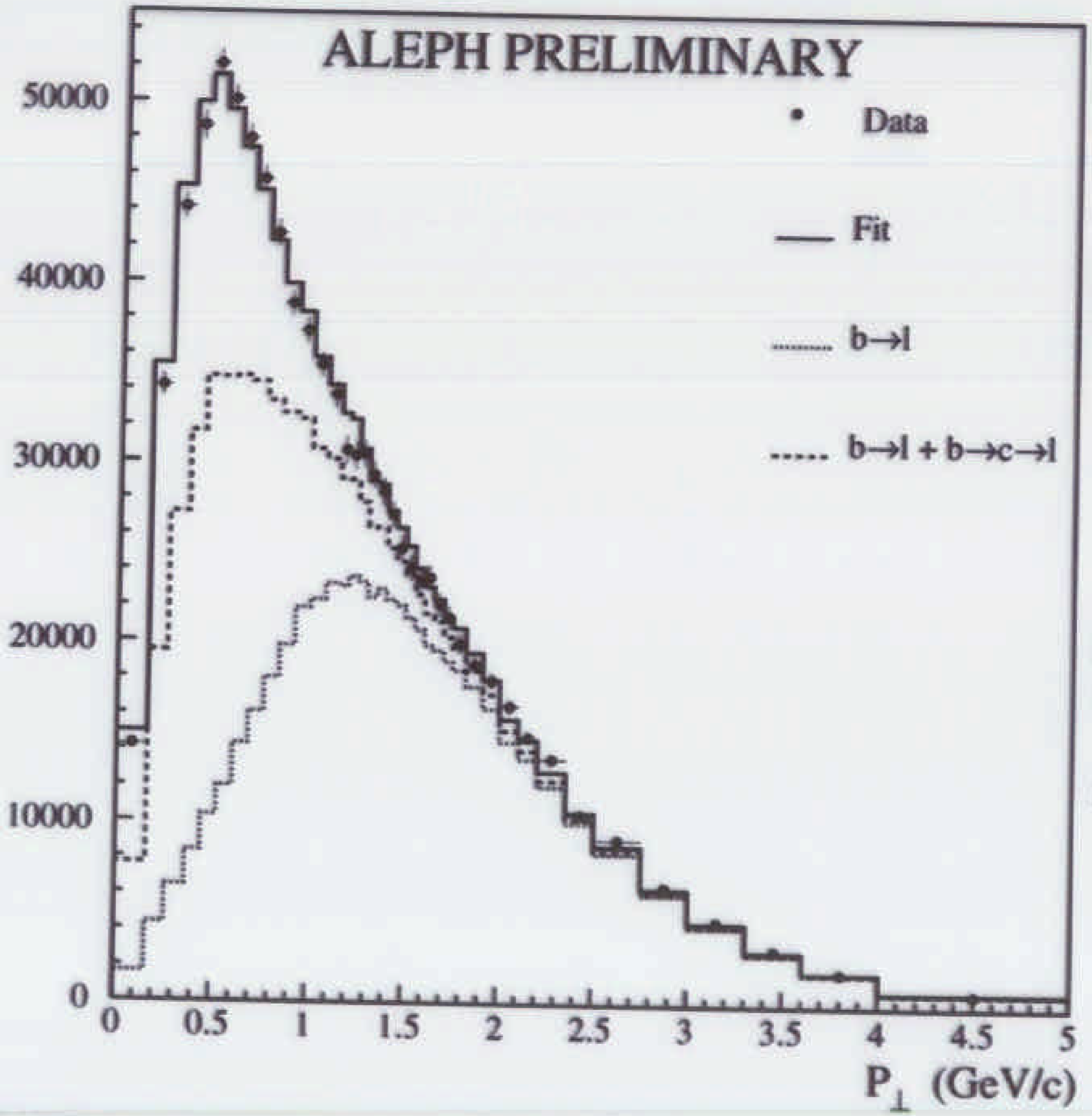


$\mathrm{BR}(b \to c \to \ell^+ \nu_\ell X)$

- Main background to the direct decays
- Important input to HF measurements, eg asymmetries, oscillations



ALEPH Lepton p_t



p_t **spectra** likelihood fit on ℓ opposite to tight b-tag ($\mathcal{B}$):

$$\mathcal{L} = \underbrace{\frac{e^{-\mu}\mu^N}{N!}}_{\text{counting}} \times \underbrace{\prod_{j=1}^{N_\ell} \frac{\mu_i(p_t^j)}{\mu}}_{p_t \text{ spectrum}}$$

<u>Sensitivities of the 2 factors:</u>

counting: weighted sum of direct & cascade BRs

p_t **spectrum:** relative contributions of direct & cascade

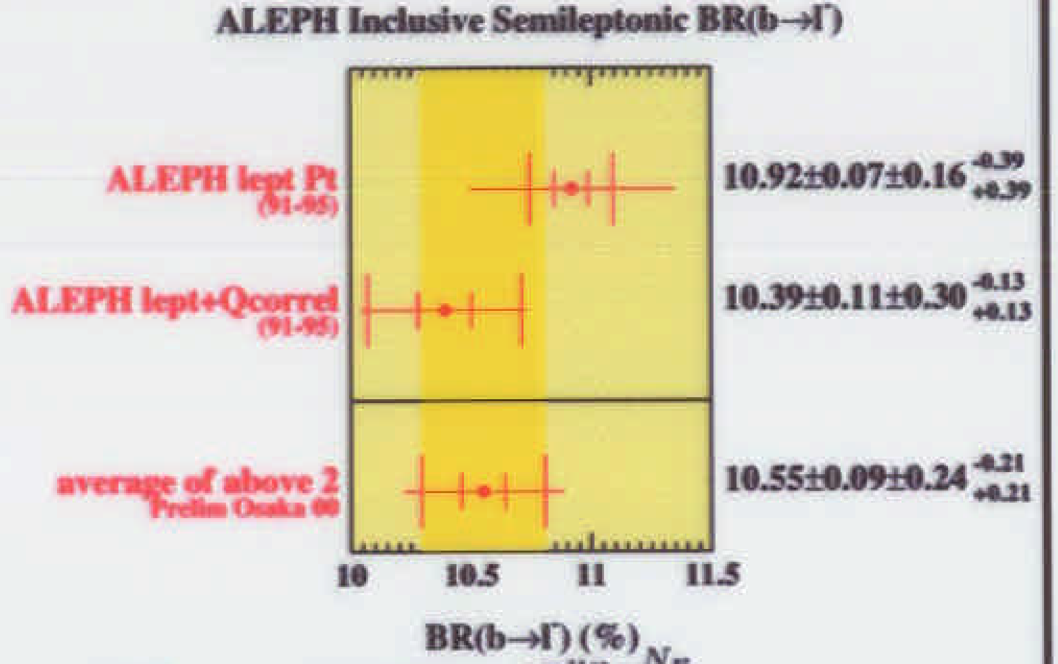
ALEPH Charge correlation

Look for ℓ opposite to hemispheres tagged in 3 ways:

		"Q_b"	P_b
$\mathcal{P}$	random hemisphere with $p_t^\ell > 1.25$GeV	Q_ℓ	0.81
$\mathcal{J}$	loosely b-tagged & $\lvert Q_{\text{hemi}}\rvert > 0.2$ (indep. of $\mathcal{P}$)	Q_{hemi}	0.73
$\mathcal{B}$	tightly b-tagged hemisphere	-	-

Q_{hemi} from weighted charges:

- $\Sigma q_i p_\parallel^{0.5} / \Sigma p_\parallel^{0.5}$, momentum $\parallel$ to thrust
- $\Sigma q_i s^{0.3} / \Sigma s^{0.3}$, i.p. significance



P_b: probability of correct "Q_b" - from data by double-tag method

Likelihood fit using $\mathcal{P}, \mathcal{J}, \mathcal{B}$:

$$\mathcal{L} = \underbrace{\mathcal{F}_{\mathcal{P}}^{op\,N_{\mathcal{P}}^{op}} (1-\mathcal{F}_{\mathcal{P}}^{op})^{N_{\mathcal{P}}^{sm}}}_{\text{charge }(\mathcal{P})} \times \underbrace{\mathcal{F}_{\mathcal{J}}^{op\,N_{\mathcal{J}}^{op}} (1-\mathcal{F}_{\mathcal{J}}^{op})^{N_{\mathcal{J}}^{sm}}}_{\text{charge }(\mathcal{J})} \times \underbrace{\frac{e^{-\mu_{\mathcal{B}}} \mu_{\mathcal{B}}^{N_{\mathcal{B}}}}{N_{\mathcal{B}}!}}_{\text{counting }(\mathcal{B})}$$

Fit numbers of opposite(same)-charge events $N_{\mathcal{P},\mathcal{J}}^{op(sm)}$ to expected fractions $\mathcal{F}_{\mathcal{P},\mathcal{J}}^{op}$ & $(1-\mathcal{F}_{\mathcal{P},\mathcal{J}}^{op})$, expressed with P_b (from data) and sample compositions.

Compositions estimated from R_b,R_c, $\underbrace{\epsilon_c \text{ and } \epsilon_{uds}}_{\text{from simulation}}$ and data fractions of hemispheres tagged.

DELPHI $BR(b \to \ell^- \bar{\nu}_\ell X)$, four methods

single lepton + di-lepton fit:

single-lepton: (p, p_t)

di-lepton: like & unlike-sign (p_c^{min}, p_c^{max})

single lepton + charge correlation fit:

k^* : p^{lept} in b-hadron rest frame

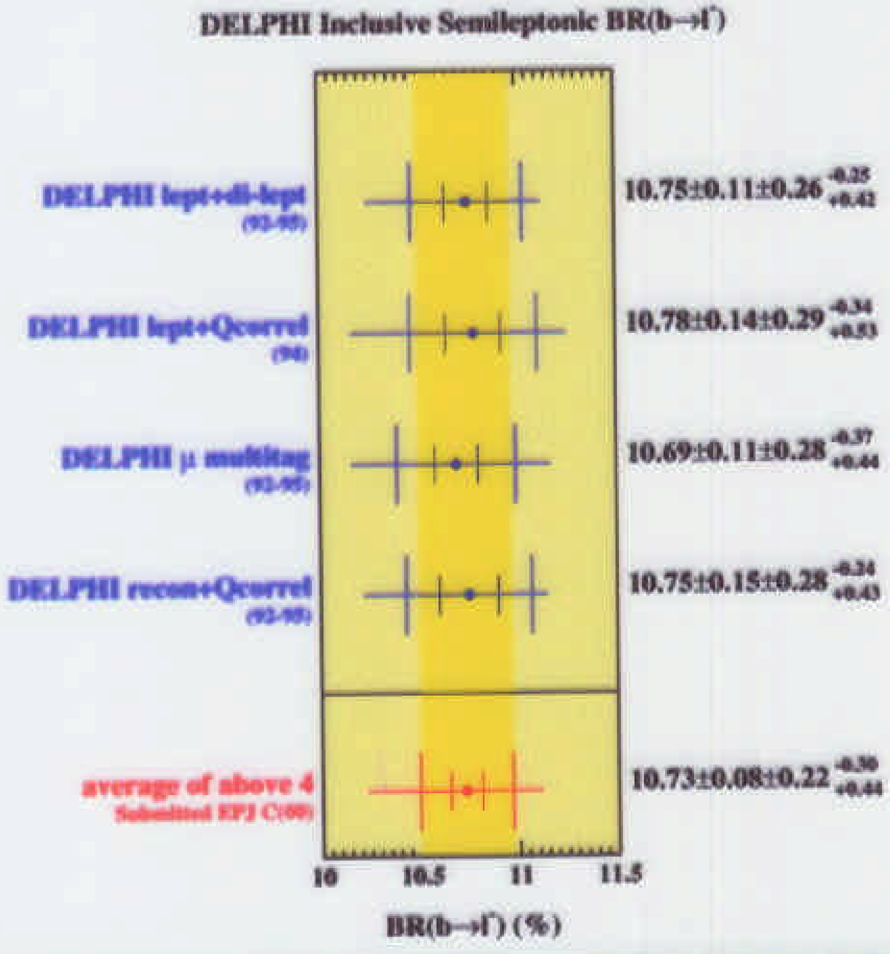
$\lambda_Q = Q_l \cdot Q_b$: correlation between opposite hemispheres

muon multitag fit:

(p, p_t^{in}, p_t^{out}) : deconvoluted μ spectra

inclusive reconstructed b + charge correlation

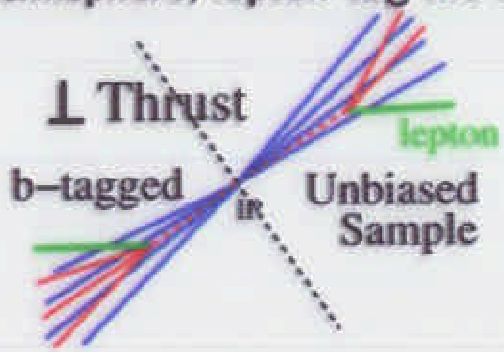
Same jet fits of like & unlike sign k^*



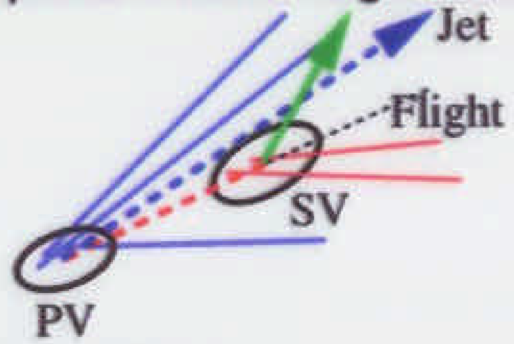
- Consistent results for all methods
- Correlated modelling systematics prevent large gains

DELPHI Single-lepton + Di-lepton spectra

b-tag one hemisphere, lepton tag the other:



PV→SV improves *b*-hadron flight reconstruction:

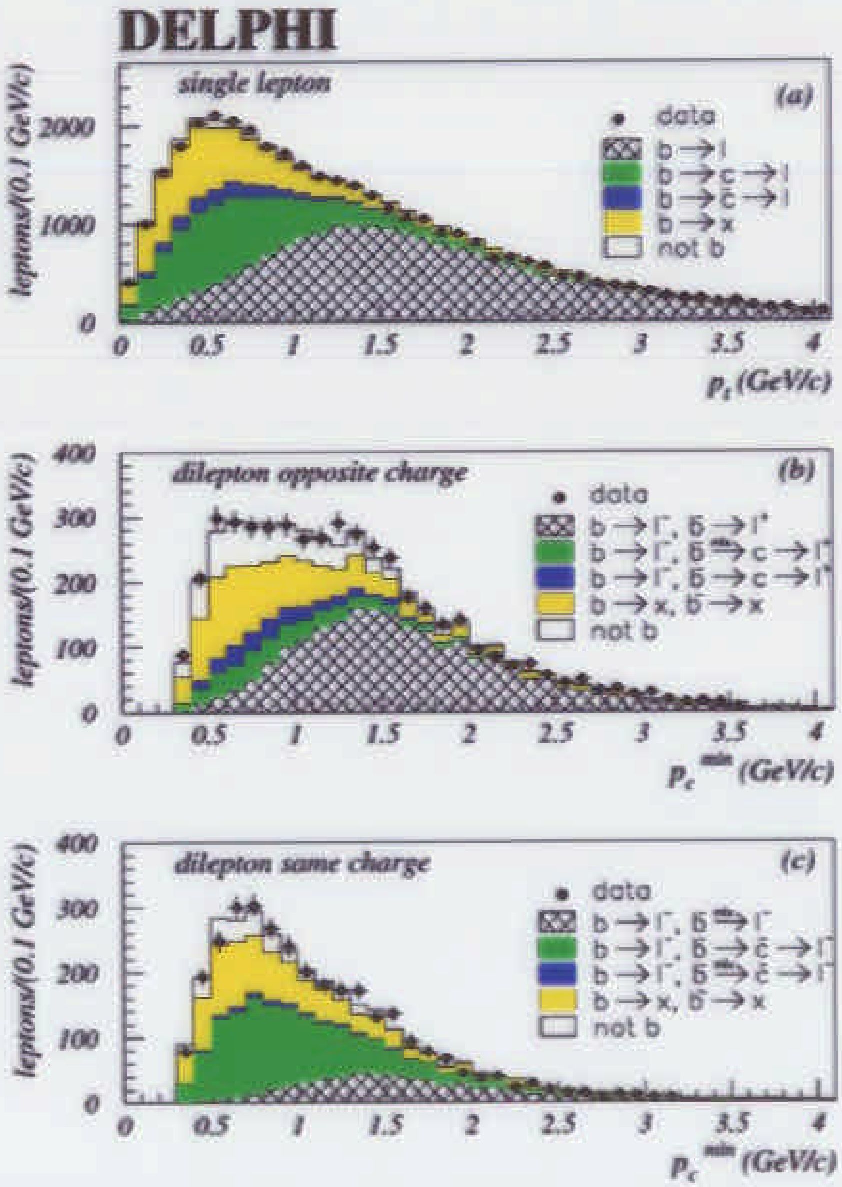


Binned likelihood fit to:

- ✦ single-lepton: p and p_t
- ✦ di-lepton: p_c^{min},p_c^{max},charge correlations

$[p_c = \sqrt{p_t^2 + p^2/100}]$

Yields: $\bar{X}$, $BR(b \to \ell^- \bar{\nu}_\ell X)$, $BR(b \to c \to \ell^+ \nu_\ell X)$, $BR(b \to \bar{c} \to \ell^- \bar{\nu}_\ell X)$



Simulation spectra re-weighted to fit results.

L3 Double tag determination of $BR(b \to \ell^- \bar{\nu}_\ell X)$ and R_b

Hemisphere impact parameter & lepton ($p_T^{lept} > 1$ GeV, $p^{lept} > 3$ GeV) tags t,t':

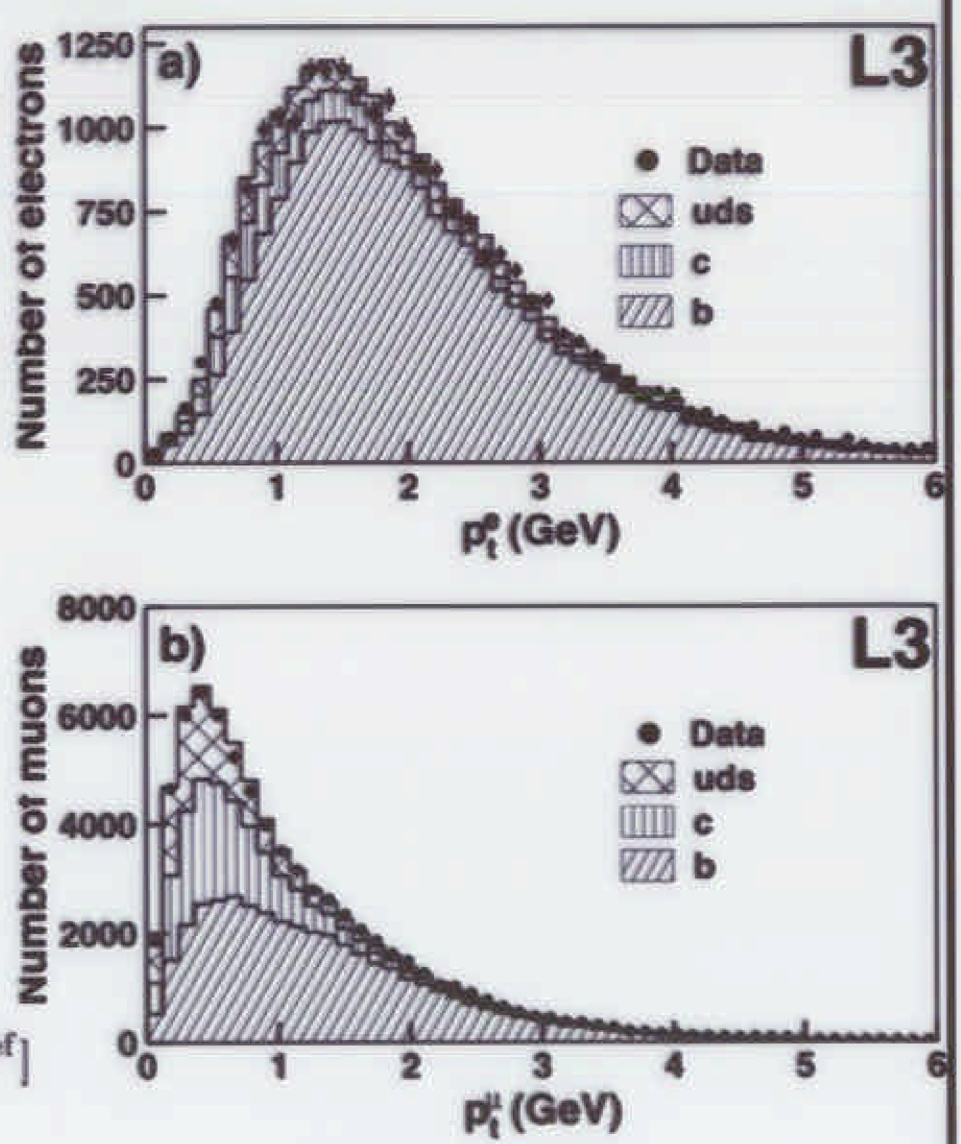
$$\frac{N_t}{2N_{had}} = R_b\epsilon_b + R_c\epsilon_c + R_{uds}\epsilon_{uds}$$
$$\frac{N_{tt}}{N_{had}} = c_b R_b \epsilon_b{}^2 + c_c R_c \epsilon_c^2 + c_{uds} R_{uds} \epsilon_{uds}^2$$
$$\frac{N_{t'}}{2N_{had}} = R_b\epsilon'_b + R_c\epsilon'_c + R_{uds}\epsilon'_{uds}$$
$$\frac{N_{t't'}}{N_{had}} = c'_b R_b \epsilon'_b{}^2 + R_c \epsilon'_c{}^2 + R_{uds}\epsilon'^2_{uds}$$
$$\frac{N_{tt'}}{2N_{had}} = c''_b R_b \epsilon_b \epsilon'_b + R_c\epsilon_c\epsilon'_c + R_{uds}\epsilon_{uds}\epsilon'_{uds}$$
$$R_{uds} = (1 - R_c - R_b)$$

Global fit to five observables yields $(R_b, \epsilon_b, \epsilon'_b)$

Linear dependence of ϵ'_b on $BR(b \to \ell)$:

$$\epsilon'_b = \epsilon'_b{}^{ref} + 0.5444\,[BR(b \to \ell) - BR(b \to \ell)^{ref}]$$

- lepton efficiency ϵ'_b obtained from data
- R_b & ϵ'_b stat. correlation -0.72



e and μ p_T spectra

OPAL $b \to \ell^- \bar{\nu}_\ell X$ modelling studies

Perform (NN_{bl},NN_{bcl}) fits to: ACCMM | ISGW | ISGW** | ISGW2 | ISGW2** | ACCMM*

for 3 fragmentation functions:

Peterson | Collins & Spiller | Kartvelishvili

Using parameters:

$BR(b \to \ell^- \bar{\nu}_\ell X)$ | $BR(b \to c \to \ell^+ \nu_\ell X)$ | $\langle x_E \rangle$

and:

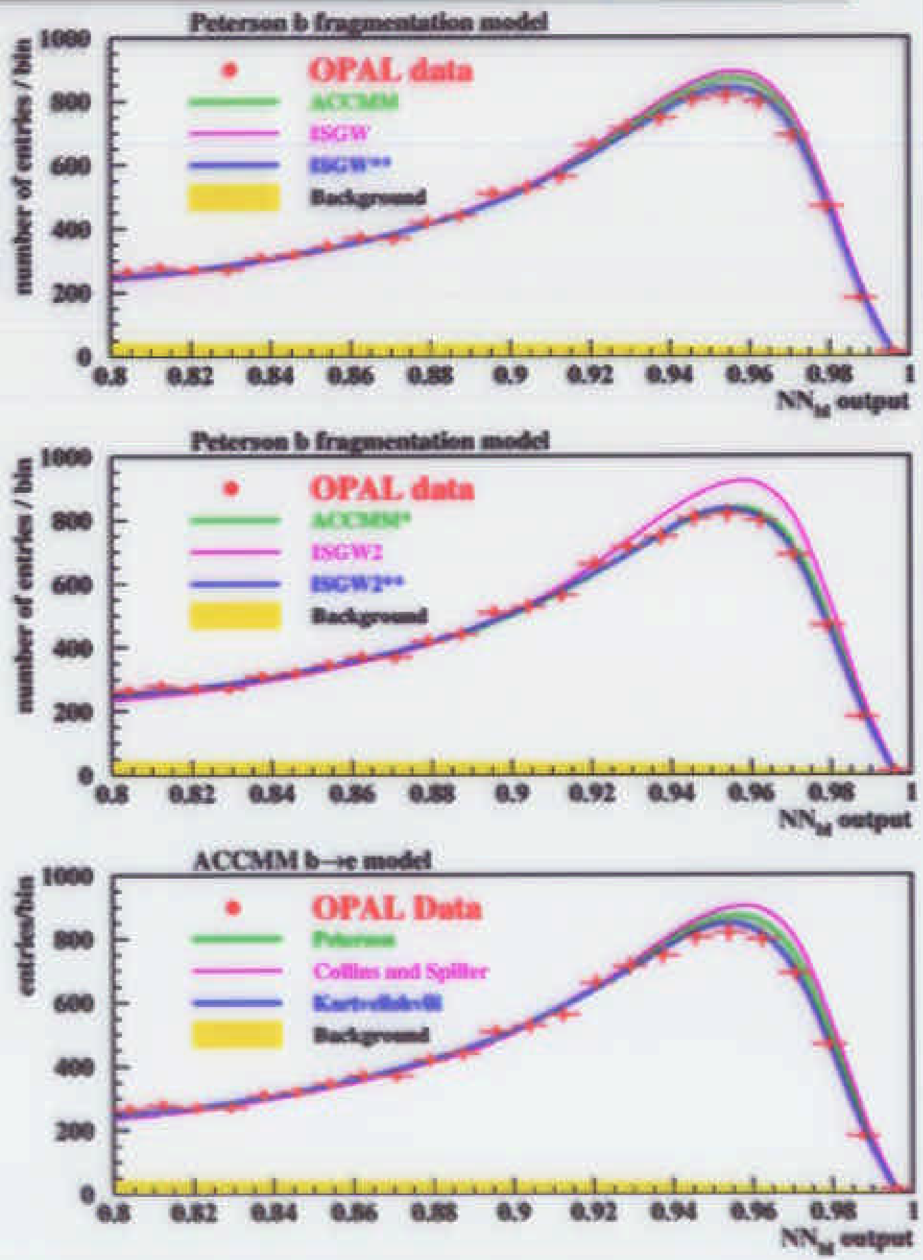
f_{D**}	for ISGW2**
(p_f, m_c)	for ACCMM*

For $NN_{bl} > 0.8$, purity of $b \to \ell^- \bar{\nu}_\ell X \approx 93$ %

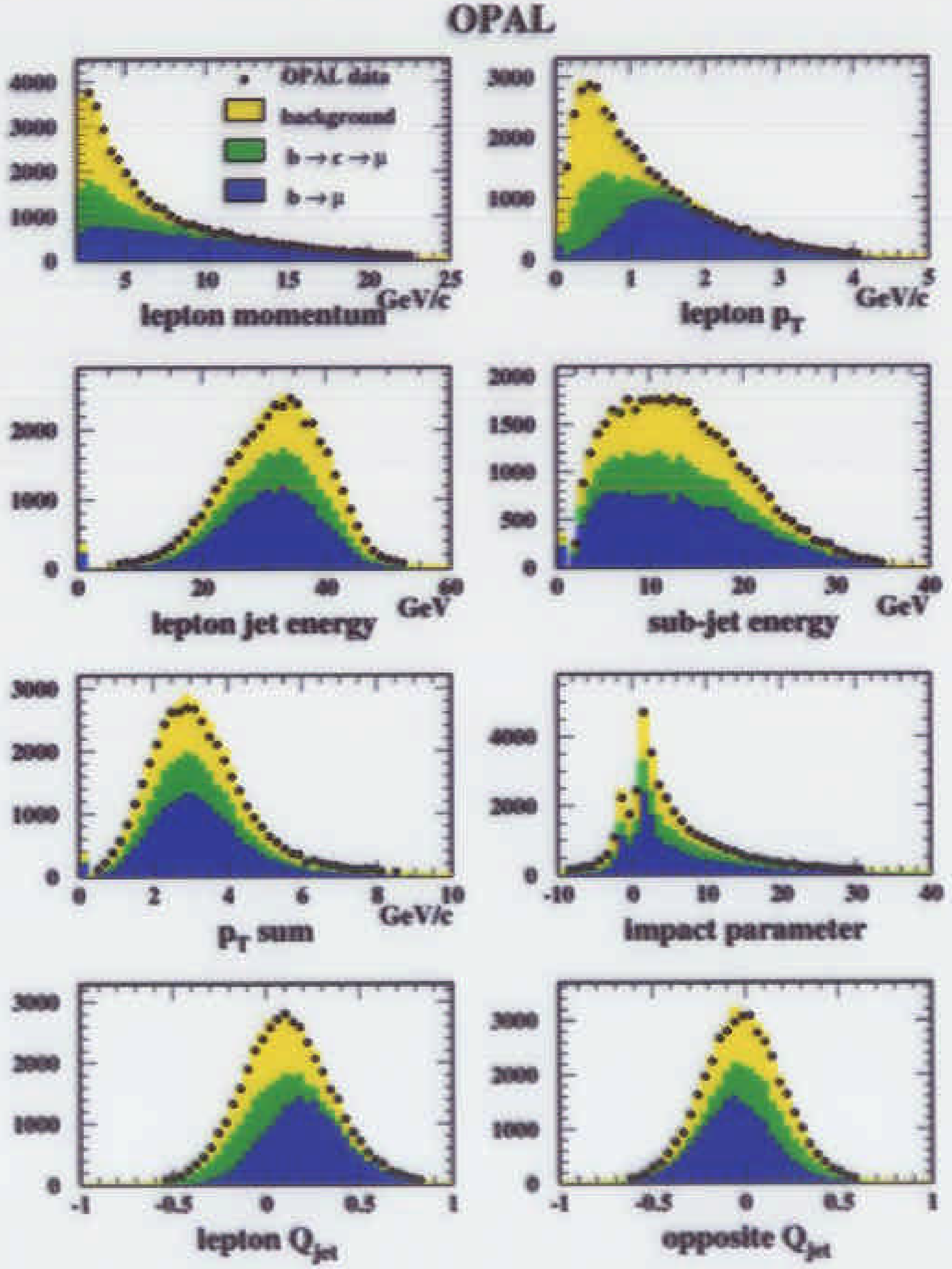
Unable to exclude models, but:

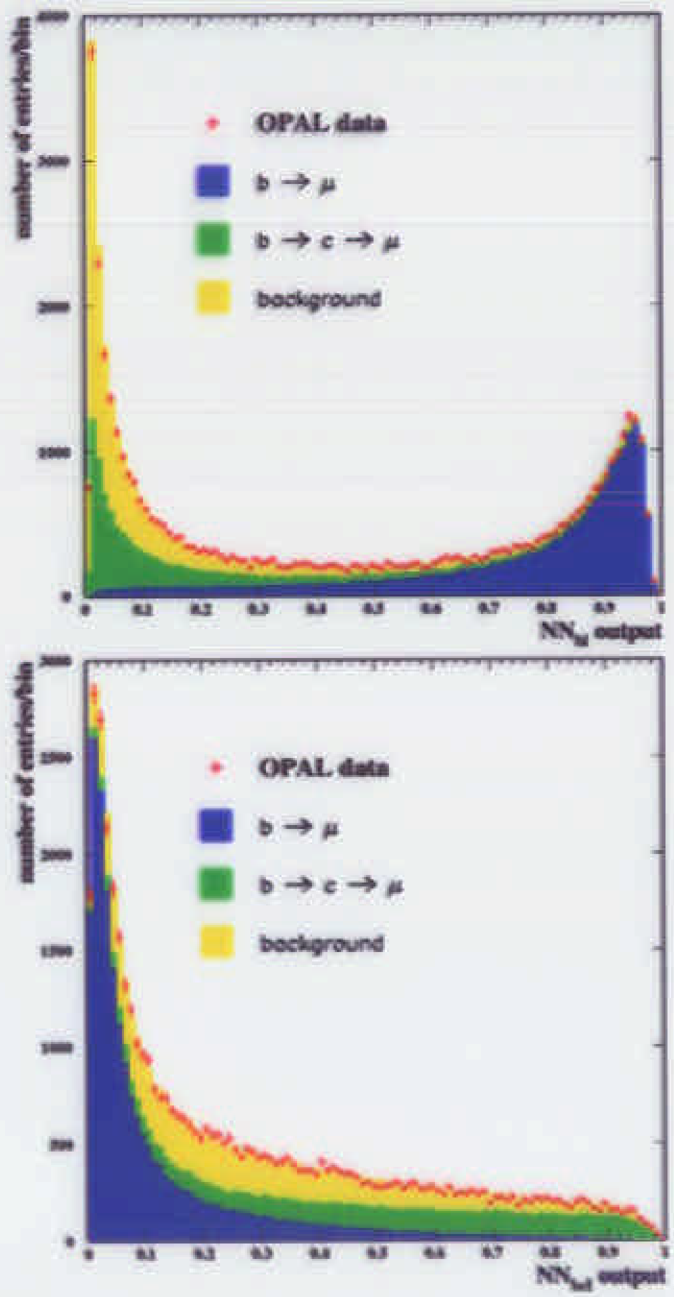
- Best agreement with ISGW**, ISGW2**
- ISGW preferred over ISGW2
- Collins & Spiller fragmentation disfavoured
- ACCMM* (p_f, m_c) fit yields:

$$p_f = 837 \pm 143 \pm 132^{+234}_{-186} MeV/c$$
$$m_c = 1287 \pm 100 \pm 87^{+112}_{-136} MeV/c^2$$



OPAL distinguish $b \to \ell^- \bar{\nu}_\ell X$ & $b \to c \to \ell^+ \nu_\ell X$ from backgrounds with 2 NNs





2D fit to NN($b \to \ell^- \bar{\nu}_\ell X$) and NN($b \to c \to \ell^+ \nu_\ell X$) yields e & μ sample compositions and $\langle x_E \rangle$

$b \to \ell^- \bar{\nu}_\ell X$ lepton spectra modelling

- Reweight to various models according to p^{lept} in rest frame of B.

Convenient benchmark models used for combination (not an endorsement):

$+1\sigma$	ISGW	model prediction 11% D^{**} [$L = 1$ charm meson]	harder
central	ACCMM	p_f=298 MeV/c, m_c=1673 MeV/c^2 [tuned to CLEO data]	
-1σ	ISGW**	empirical modification of ISGW to 32% D^{**}	softer

Other models investigated:

ACCMM*	p_f and m_c as free parameters
ISGW2	ISGW revision with HQS constraints+... (predicts 9.3% D^{**})
ISGW2**	ISGW2 with free D^{**} fraction

L3 modelling studies

ACCMM*(p,p_t;p_f,m_c) fits to (p,p_t) yield:

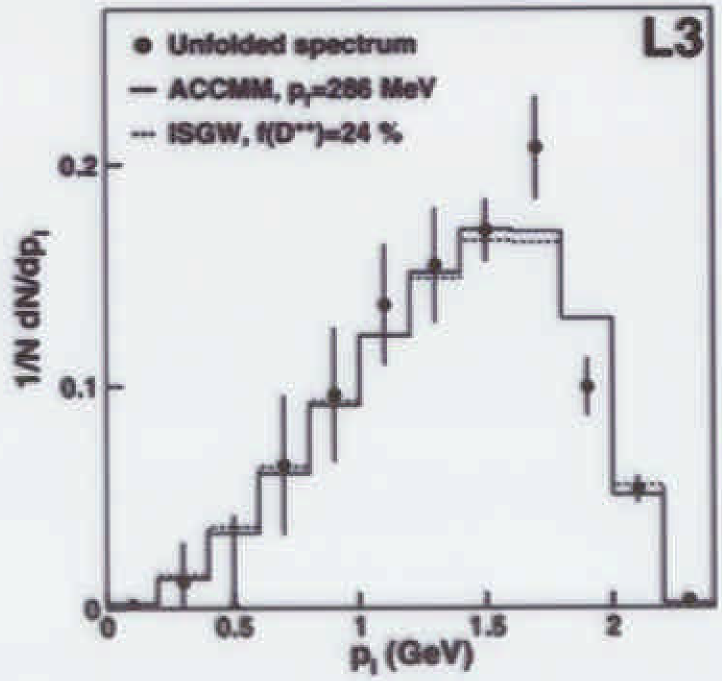
$p_f = 286 \pm 18$ fixed $m_c = 1673$MeV/c
$p_f = 273 \pm 17$ no p_t cut
$p_f = 288 \pm 20$ with $p > 4$ GeV
$p_f = 272 \pm 13$ without lifetime tag

$p_f = 286 \pm 18 \pm 30$ MeV

ISGW**(p,p_t;f_{D**}) fit yields:

$f_{D**} = (24 \pm 4 \pm 6)$ %

Good agreement of unfolded spectrum with fit result:



p^{lept} in b-hadron rest frame

ALEPH $b \to \ell^- \bar{\nu}_\ell X$ modelling studies

Expected inclusive spectra from:

$(f_{D^{**}} \approx 28\%)$	BR [%]
$B \to D\ell\nu$	1.95 ± 0.27
$B \to D^*\ell\nu$	5.05 ± 0.25
$B \to D^{**}\ell\nu$	2.7 ± 0.7
$B \to D_1\ell\nu$	0.63 ± 0.11
$B \to D_2^*\ell\nu$	0.23 ± 0.09
$B \to D^{(*)}\pi\ell\nu$	"1.84"

and predicted exclusive spectra.

Spectra uncertainty from:

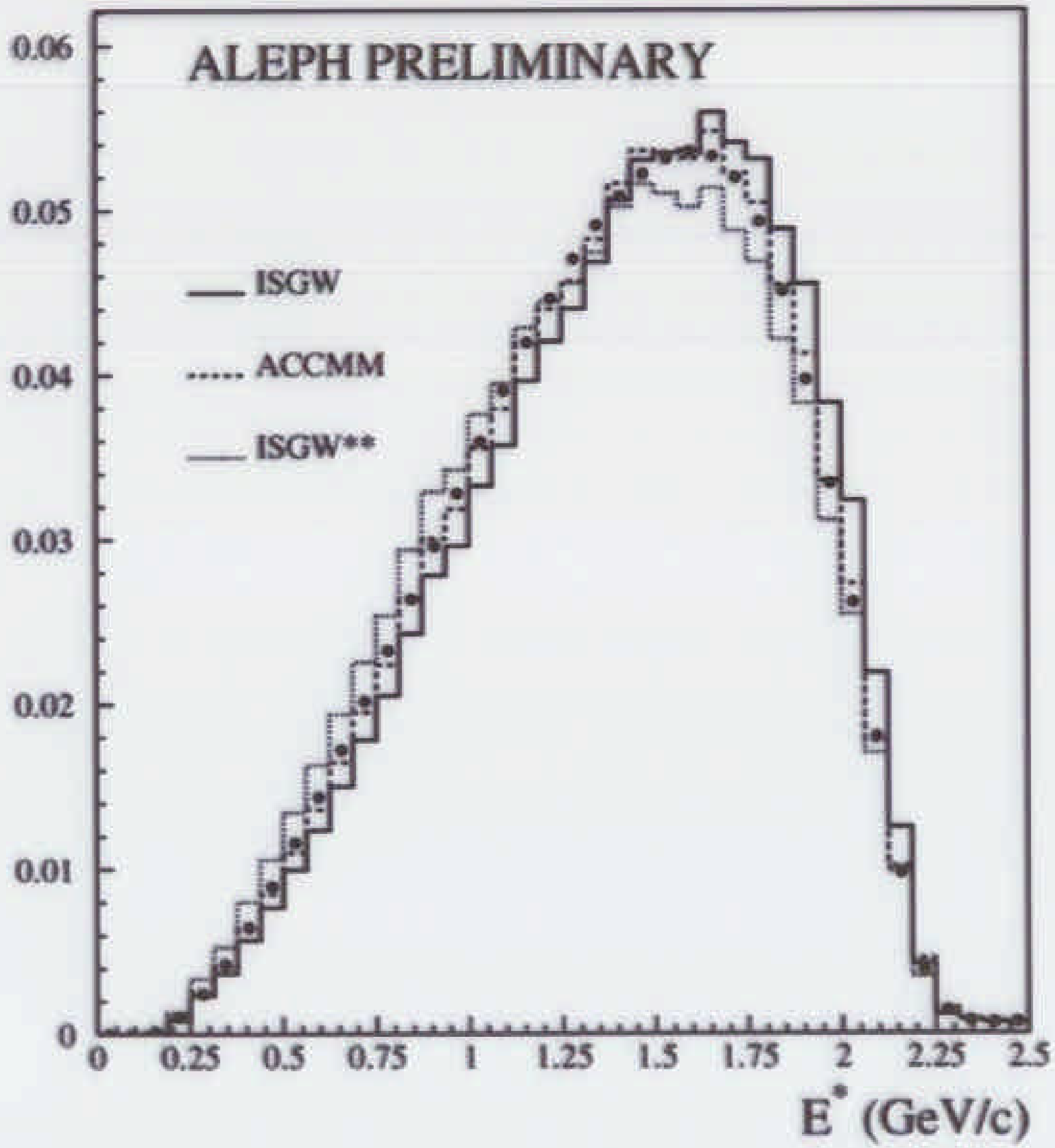
- measured BR uncertainties
- $D^{**} \Leftrightarrow D^{(*)}\pi$

Inflate by 25% for B_s^0, Λ_b

Uncertainties cf. prescription:

- p_t - slightly reduced
- Q-correl - larger

Spectrum reweighting compared to fraction reweighting.



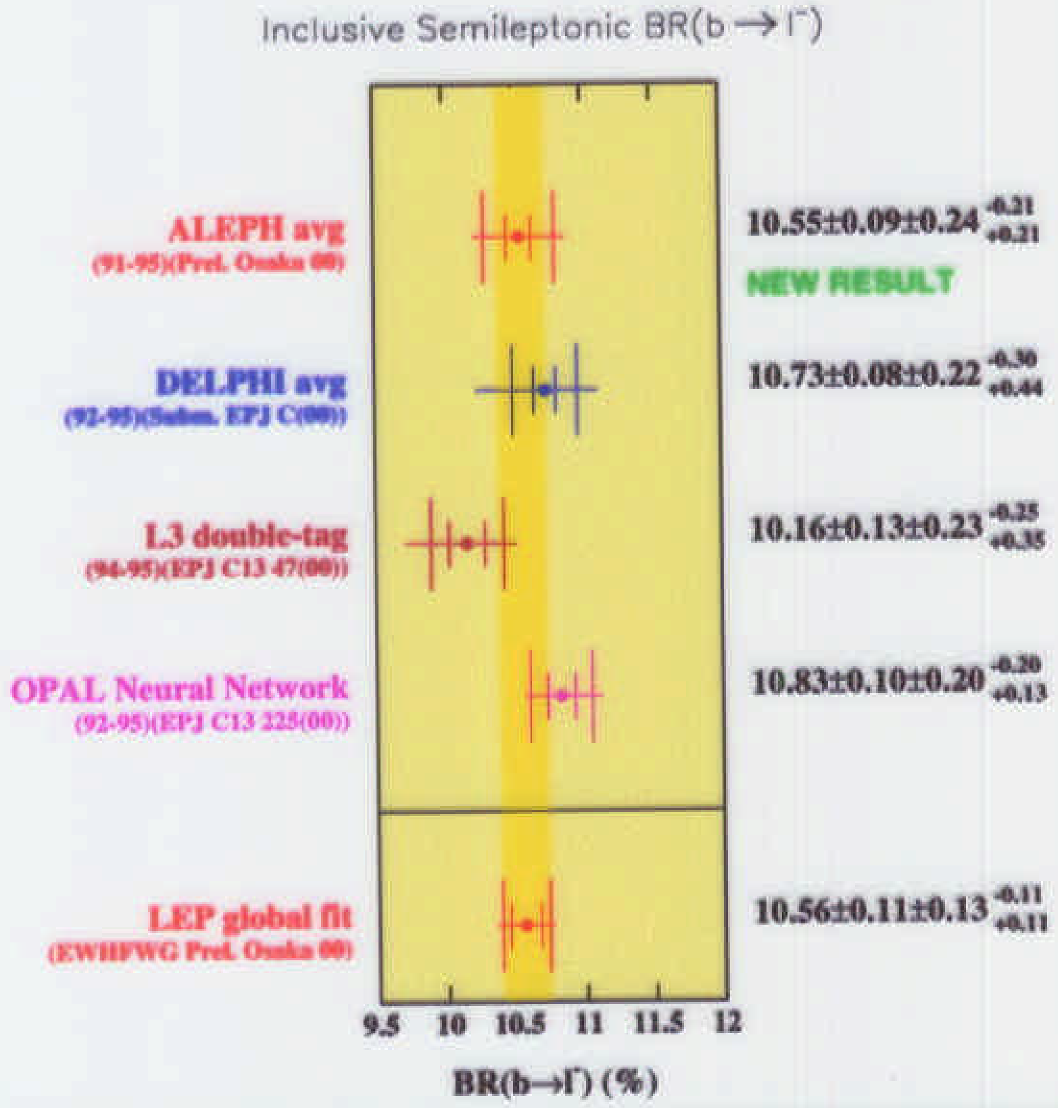
Lepton energy spectrum in b-hadron rest frame

LEP $BR(b \to \ell^- \bar{\nu}_\ell X)$ results and global fit

Global fit to Z^0 HF results performed by LEP+SLD EW-HFWG:

R_b	$BR(b \to \ell^-)$	$BR(b \to c \to \ell^+)$	$BR(c \to \ell^+)$	$\bar{\chi}$

- **Common** input parameter values and systematic **defns** used by all measurements (or small corrections made to achieve consistency)
- Well established B.L.U.E. combination accounts for interdependences and correlations between measurements

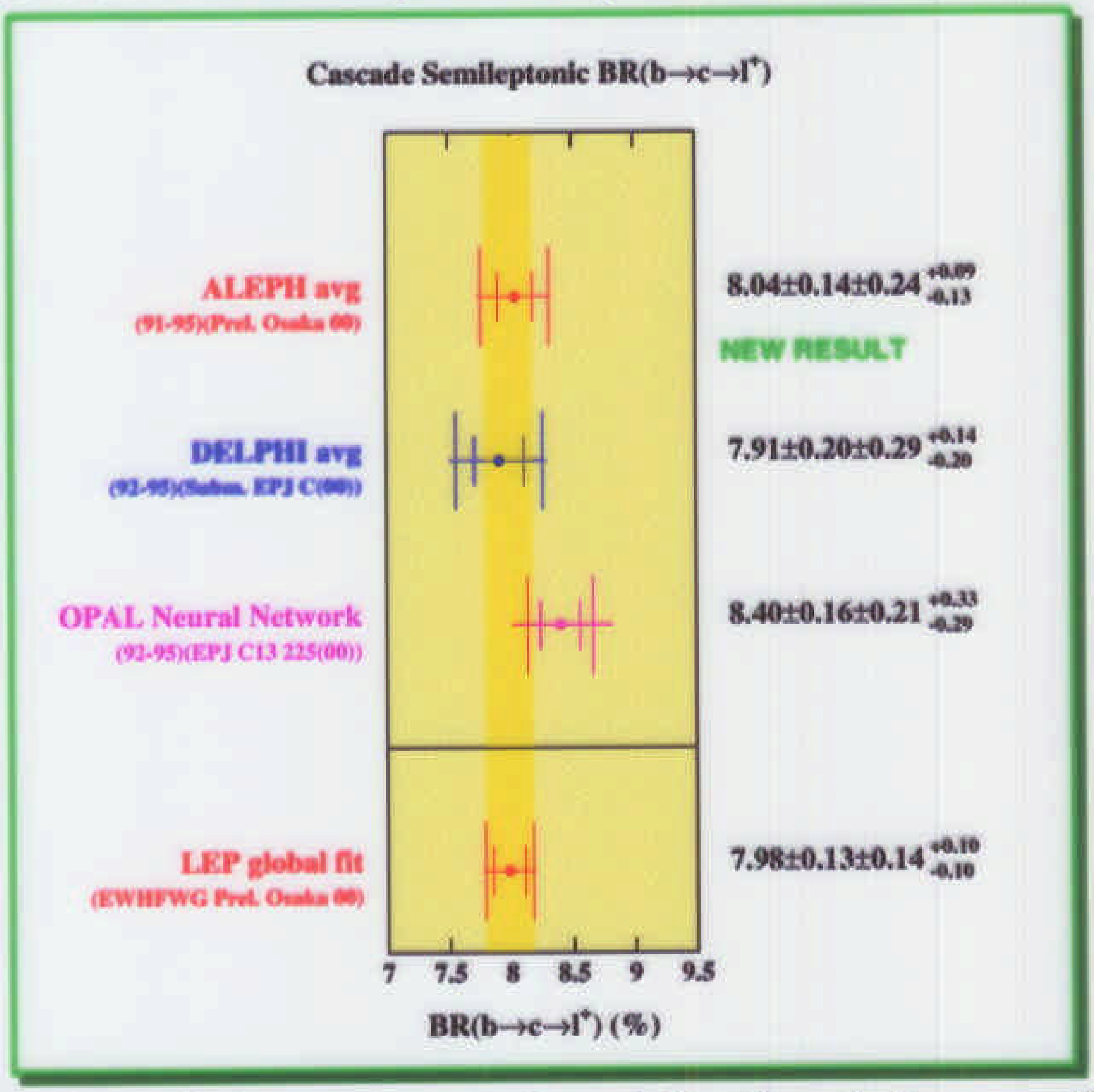


Uncertainty split into: stat., syst. & modelling ($b \to \ell^-, b \to c \to \ell^+$)

- $b \to \ell^-$ modelling uncertainty **dominates** for all measurements

LEP $BR(b \to c \to \ell^+ \nu_\ell X)$ results and global fit

Global fit to Z^0 HF results performed by LEPEW-HFWG:



Uncertainty split into: stat., syst. & modelling ($b \to \ell^-, b \to c \to \ell^+$)

- $b \to \ell^-$ modelling uncertainty dominates, but significant addition from $b \to c \to \ell^+$

DELCO+MARK III ACCMM fit results used for $c \to \ell$ modelling :

$+1\sigma$	ACCMM2	p_f=353 MeV/c, m_s=0.001 GeV/c^2
central	ACCMM1	p_f=467 MeV/c, m_s=0.001 GeV/c^2
-1σ	ACCMM3	p_f=467 MeV/c, m_s=0.153 GeV/c^2

For $b \to c \to \ell^+$ the CLEO $b \to D$ spectrum (modelled with Peterson $\epsilon = 0.42 \pm 0.07$) is used with the three $c \to \ell$ models.

Differences between Z^0 and $\Upsilon(4S)$ measurements of $BR(b \to \ell^- \bar{\nu}_\ell X)$?

Assuming $\Gamma_{SL}(\Lambda_b^0) = \Gamma_{SL}(b - \text{meson}) = \Gamma_{SL}(b - \text{hadron})$:

B Oscillations WG - Osaka 00	
f_{B^0}, f_{B^-}	0.400 ± 0.010
f_{B_s}	0.097 ± 0.012
f_{Λ_b}	0.104 ± 0.017
B Lifetimes WG - Osaka 00	
τ_b	1.564 ± 0.014 ps
τ_{B^0}	1.647 ± 0.021 ps
τ_{B^-}	1.548 ± 0.021 ps

$$\mathrm{BR}_{\mathrm{SL}}^{Z^0} \approx (f_{B^0}\tau_{B^0} + f_{B^-}\tau_{B^-} + f_{B_s}\tau_{B_s} + f_{\Lambda_b}\tau_{\Lambda_b})\Gamma_{\mathrm{SL}} \approx \tau_b\Gamma_{\mathrm{SL}}$$

$$\mathrm{BR}_{\mathrm{SL}}^{\Upsilon(4S)} = (f_{B^0}\tau_{B^0} + f_{B^-}\tau_{B^-})\Gamma_{\mathrm{SL}} = \tau_B\Gamma_{\mathrm{SL}}$$

$$f_\tau = \frac{\frac{1}{2}(\tau_{B^0} + \tau_{B^-})}{\tau_b} = 1.021 \pm 0.013 \ (1)$$

	Λ_b(*b*-baryons)	*b*-hadrons B^0, B^-, B_s, Λ_b	Λ_b/b (4)
BR_{SL} [%]	8.0 ± 1.2 (2)	10.56 ± 0.21 (3)	0.76 ± 0.11
τ [ps]	1.208 ± 0.051 (3)	1.564 ± 0.014 (3)	0.77 ± 0.03

- Agreement between τ and BR_{SL} ratios supports Γ_{SL} equality.
- A 15% deviation from width equality, propagates to $\approx 1\%$ effect on BR_{SL} :

$$\mathrm{BR}_{\mathrm{SL}}^{Z^0} \approx \tau_b\Gamma_{\mathrm{SL}}\left[1 + f_{\Lambda_b}\frac{\tau_{\Lambda_b}}{\tau_b}\left(\frac{\Gamma_{\mathrm{SL}}(\Lambda_b^0)}{\Gamma_{\mathrm{SL}}(b - \text{meson})} - 1\right)\right]$$

(1) Private uncorrelated combination of WG results
(2) P. Gagnon, Tampere99 avg of OPAL & ALEPH
(3) EWHF and Lifetime WGs Osaka updates
(4) Private uncorrelated ratios of WG results

$N_c(\approx 1 + N_{cc} - N_{no-c})$ vs BR_{sl} theory comparison

Related by: $$\mathrm{BR_{sl}} = \frac{\Gamma_{sl(\ell)}}{2\Gamma_{sl(\ell)}+\Gamma_{sl(\tau)}+\underbrace{\Gamma(c\bar{c}s) + \Gamma(c\bar{u}d) + \Gamma(sg)}_{\Gamma_{had}}}$$

M. Neubert, C.T. Sachrajda, NPB483(1997) 339.

Consistency of $\Upsilon(4S)$ & Z^0 results

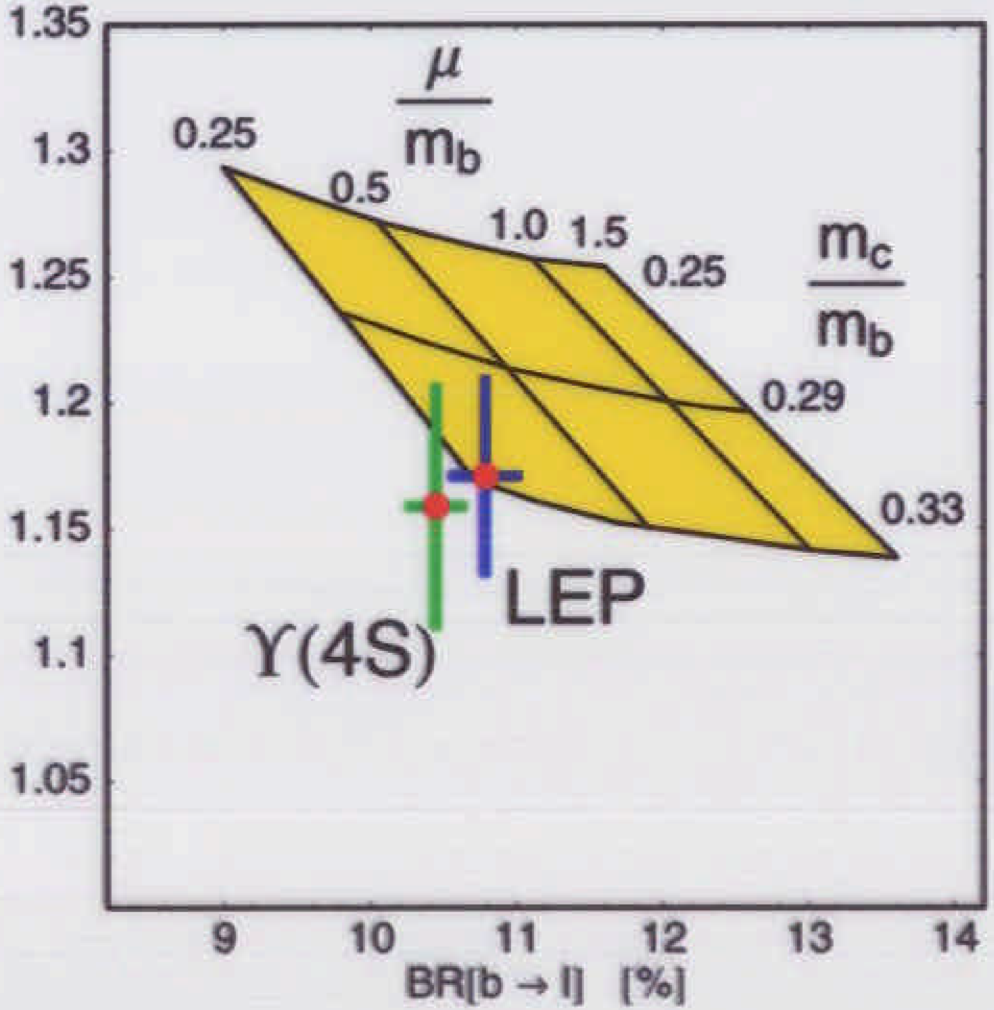
Δ BR$_{SL} \approx 1.4 - 1.6\sigma$:

BR$_{SL}^{Z^0}$ [%]	10.56 ± 0.21 (1)
f_τ BR$_{SL}^{Z^0}$ [%]	10.79 ± 0.25 (2)
BR$_{SL}^{\Upsilon(4S)}$ [%]	10.45 ± 0.21 (3)

$\Delta N_c < 0.3\sigma$

$N_c^{\Upsilon(4S)}$	1.159 ± 0.049 (4)
$N_c^{Z^0}$	1.171 ± 0.040 (5)

(see talk by Gary Barker)



Depends on mass ratio m_c/m_b & renormalisation scale μ

(1) EWHF WG Osaka update
(2) Private uncorrelated f_τ correction
(3) PDG98 - ARGUS & CLEO
(4) P.Roudeau, private Osaka avg of CLEO incl. & excl.
(5) P.Roudeau, private Osaka avg of ALEPH,DELPHI

Extraction of $|V_{cb}|$ from $BR(b \to \ell^- \bar{\nu}_\ell X)$-$BR(b \to \ell^- \bar{\nu}_\ell X_u)$ and τ_b

Heavy quark theory ($m_b >> \Lambda_{QCD}$) implemented through operator product expansion (OPE) provides $\Gamma(b \to \ell^- \bar{\nu}_\ell X_c)$ in powers of Λ_{QCD}/m_b, giving:

$$|V_{cb}| = 0.0411\sqrt{\frac{BR(b \to \ell^- \bar{\nu}_\ell X_c)}{0.105} \cdot \frac{1.55\ ps}{\tau_b}} \times \left(1 - 0.024\left[\frac{\mu_\pi^2 - 0.5\ GeV^2}{0.2\ GeV^2}\right]\right) \times$$

$$\underbrace{(1 \pm 0.030(pert.) \pm 0.020(m_b) \pm 0.024(m_b^{-3}))}_{\text{inflated } \times 2} \qquad [\mu_\pi^2 = \langle p_b^2 \rangle]$$

I.I.Bigi, M.Shifman, N.Uraltsev, Annu. Rev. Nucl. Part. Sci. 47(1997) 591.

$BR(b \to \ell^- \bar{\nu}_\ell X)$ (%)	$10.56 \pm 0.11 \pm 0.13 \mp 0.11$	Global fit, LEP+SLD EWHF WG
$BR(b \to \ell^- \bar{\nu}_\ell X_u)$ (%)	0.174 ± 0.057	Charmless BR, LEP $\lvert V_{ub}\rvert$ WG
Average b-hadron, τ_b (ps)	1.564 ± 0.014	LEP+SLD b Lifetimes WG

$$|V_{cb}|^{incl.} = (40.70 \pm 0.41(br) \pm 0.18(\tau) \pm 2.03(th)) \times 10^{-3}$$

- Most precise measurement - 5 % theory error dominates - consistent with exclusive result
- Outcome of theory workshops instigated by $|V_{cb}|$ & $|V_{ub}|$ WG's was improved confidence in these theoretical uncertainties (I.I. Bigi, UND-HEP-BIG-99-05)

See HF Steering group summer '99 combination - CERN-EP-2000-096/SLAC-PUB-8492 and forthcoming summer '00 update

Conclusions

$$\mathrm{BR}(b \to \ell^- \bar{\nu}_\ell X) = 0.1056 \pm 0.0021$$

- Includes preliminary ALEPH results - DELPHI,L3,OPAL published
- Differences between Z^0 and $\Upsilon(4S)$ at 1.5σ
- Recent progress on lepton spectra modelling

$$|V_{cb}|^{incl.} = (40.7 \pm 0.4 \pm 2.0) \times 10^{-3}$$

- Most precise measurement
- Theoretical improvements would be welcome !