

# B physics at DELPHI/LEP



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DIS 2004, Štrbské Pleso



# Outline

## ➤ Introduction

## ➤ b-physics results from DELPHI/LEP

### ↳ b-hadron production/fragmentation properties

- ➔ production fractions
- ➔ b-fragmentation function
- ➔ spectroscopy

### ↳ CKM related measurements

- ➔  $V_{cb}$  in exclusive decays
- ➔ hadronic and leptonic moments in semileptonic decays

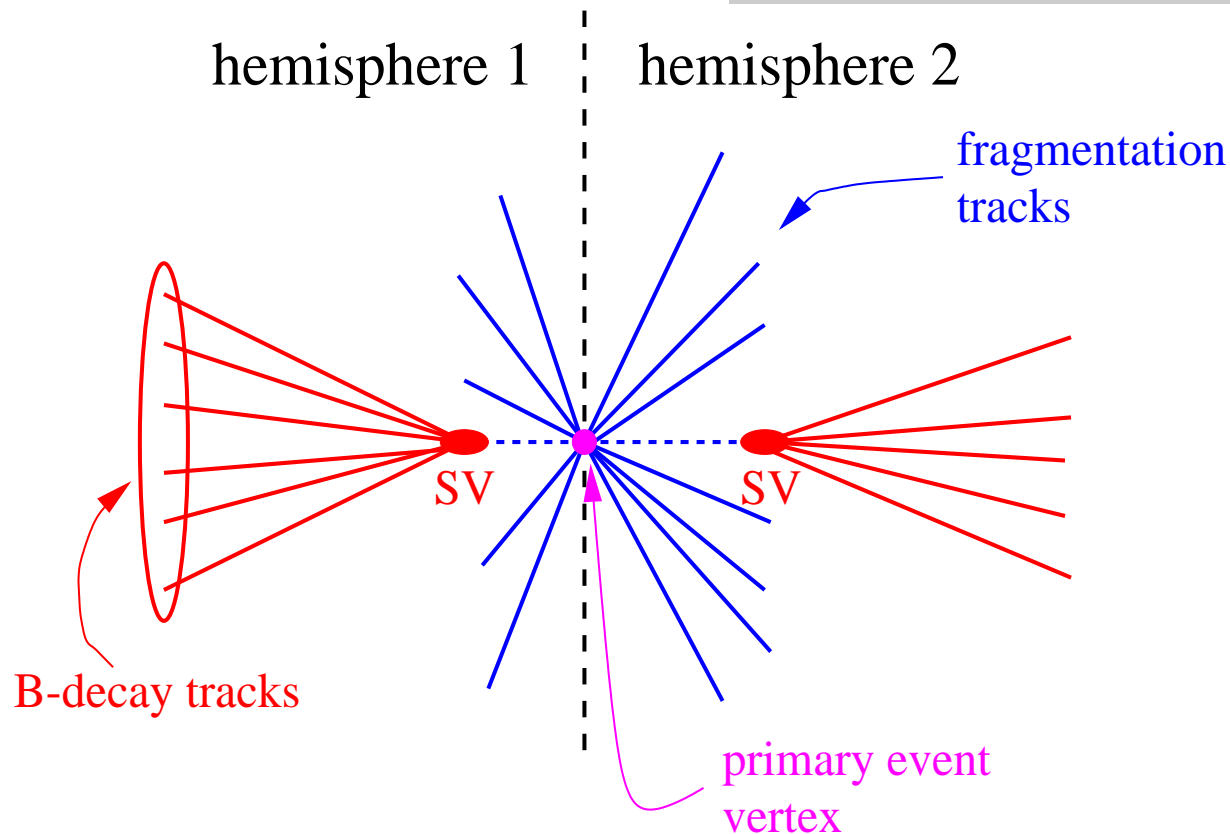
↳ The focus will be on recent measurements and measurements which will still have significant weight in combined results even compared to results from the b-factories and/or the TEVATRON  
(some other results will be briefly summarised)

↳ No electroweak physics covered in this talk (e.g. asymmetries)

**LEP 1 data taking ended 1995, but because of improved reprocessed data sets and analysis techniques many final results are published now!**

# Topology of b events at LEP

$$e^+ e^- \rightarrow Z^0 \rightarrow b \bar{b} \quad BR(Z^0 \rightarrow b \bar{b}) \approx 0.15$$



- Almost 'monochromatic' b-hadrons
- uncorrelated production in two opposite hemispheres
- measurable flight distance  
➔ Vertex-detectors
- $\sqrt{s} \gg m_b$ :  
Production of mesons and baryons in ground- and excited states

- + Particles from b-decay well separated in two hemispheres
  - additional particles from fragmentation spoil B-reconstruction
- ➔ similar to hadron colliders, but contrary to  $\Upsilon(4s)$ -decays

**LEP I  $\approx$  1.6 million b-hadrons per experiment**

# b-hadron production

- 'Branching ratio' of the b-quark into different b-hadrons?  
→ b-hadron production rates
- Energy Spectrum of the b-hadrons?  
→ b-fragmentation function
- Which states? rate? Properties?  
→ b-spectroscopy
- Very important for physics at hadron-colliders where many measurements can not be done with similar precision!
- Important systematics for many measurements in the heavy flavour sector (e.g. oscillations, CKM elements, lifetimes)
- Universality?  
Compare b-hadron production properties for different environments (  $e^+ e^-$ ,  $p \bar{p}$ ,  $ep$  )
- Some measurements easier for bottom than for charm because of large uncertainties on exclusive BR

# b hadron production fractions

$\bar{b}$

$$f_{B_i}^{(')} = BR(\bar{b} \rightarrow B_i)$$

*b* primary quark!

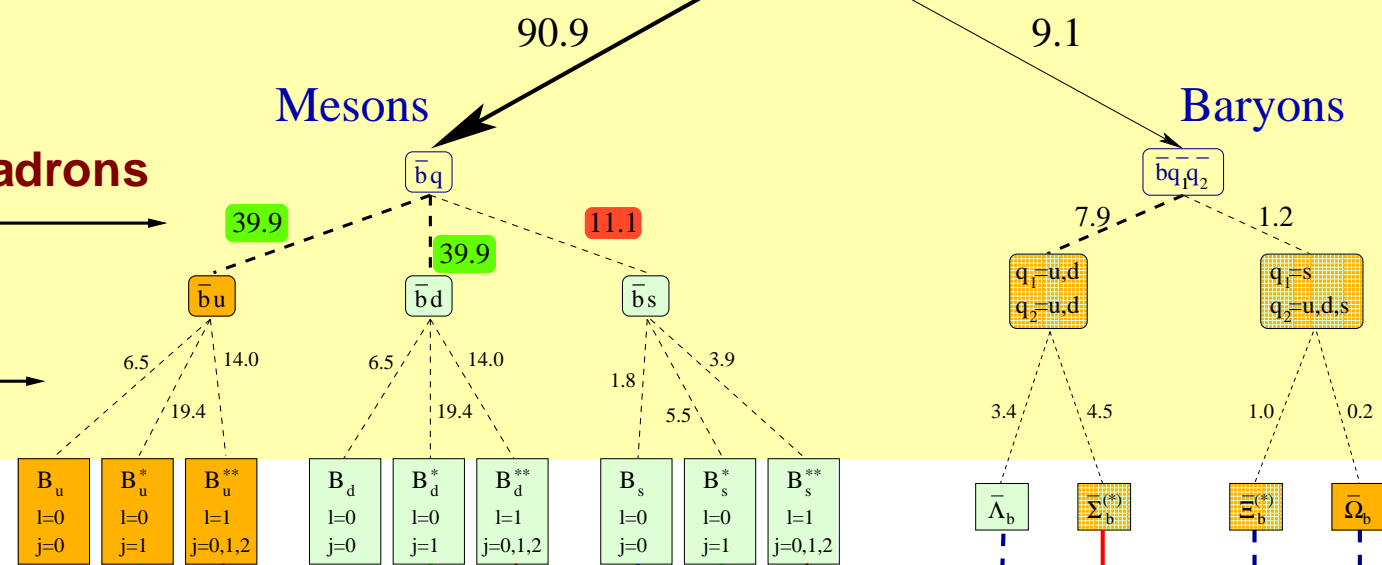
primary b-hadrons

$f_i'$

Mesons

Baryons

Fragmentation (QCD)



weakly decaying b-hadrons

$f_i$

b-Hadron Decays

$\pi, K$  (QCD)  
 $\gamma$  (QED)

may change  $f_i' \rightarrow f_i$

(numbers from simulation)

Important input for other HF measurements



# The fraction of charged b hadrons: $f_+$

First (and only) direct measurements of  $f^+ = BR(\bar{b} \rightarrow X_B^+) = BR(b \rightarrow X_B^-)$

→  $f_{B_u}$  can be extracted with small additional uncertainties from  $f^+$

**Basic Idea: Reconstruct charge of weakly decaying b-hadron**

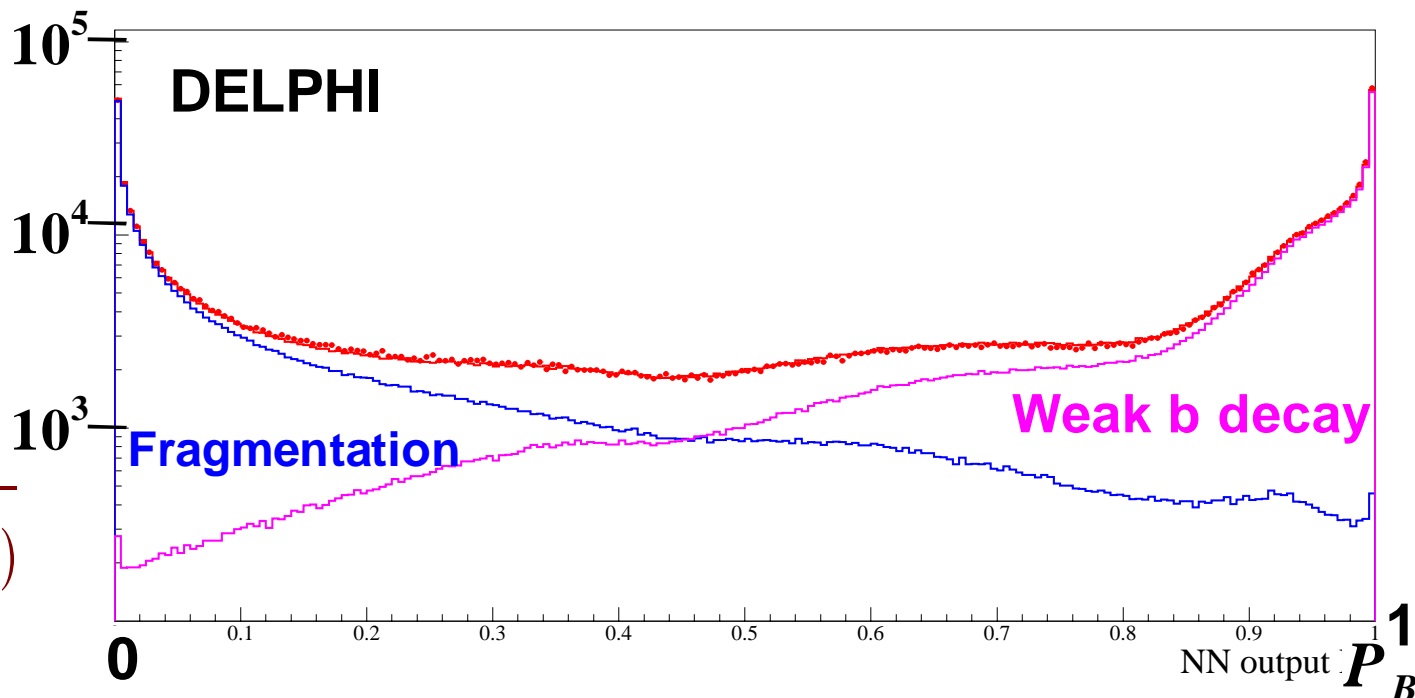
Neural Network to define probability  $P_B$  that a charged particle stems from a weak B-decay

Define Vertex Charge

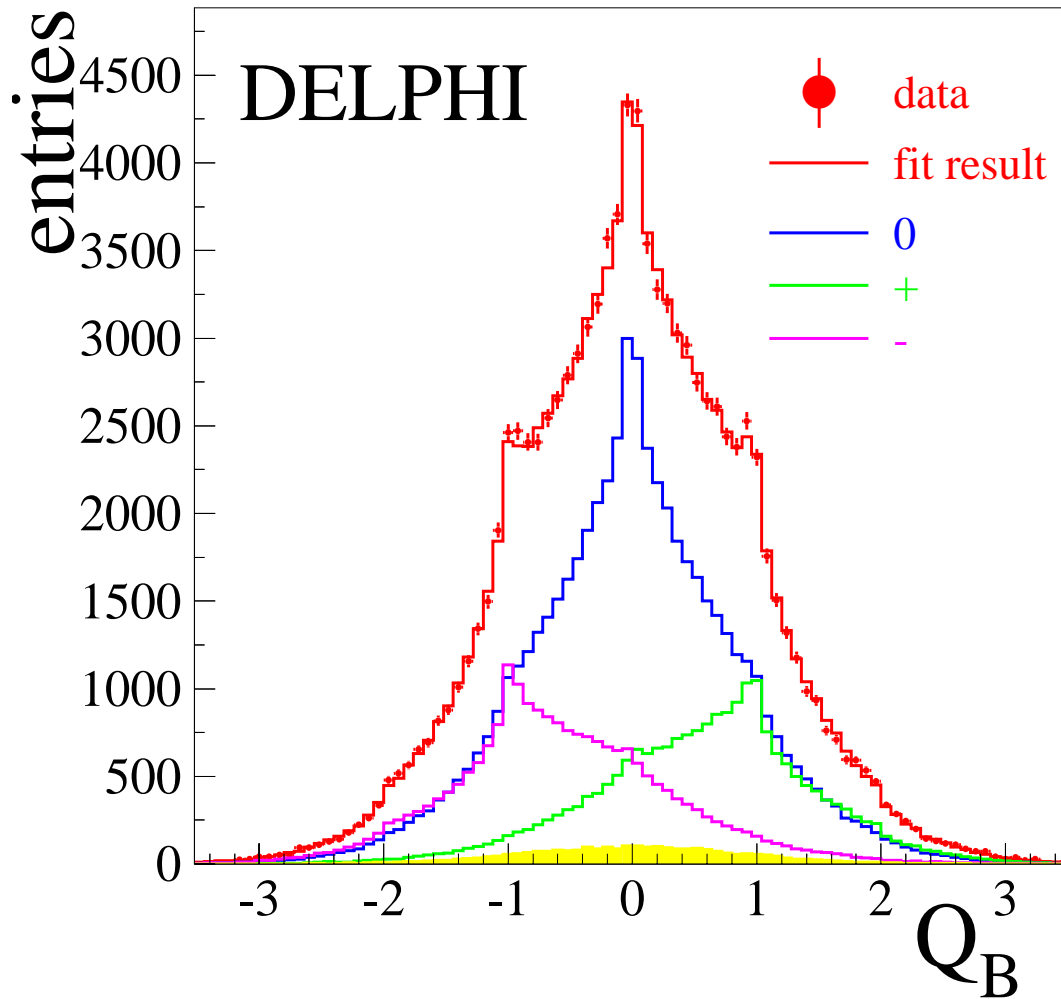
$$Q_B = \sum_{i=1}^{N_{hem}} Q_i \cdot P_{B,i}$$

and 'error'

$$\sigma_{Q_B} = \sqrt{\sum_{i=1}^{N_{hem}} P_{B,i} \cdot (1 - P_{B,i})}$$



# Results



$$f^+ = (42.09 \pm 0.82(\text{stat.}) \pm 0.89(\text{syst.}))\%$$

Subtract charged  $\Xi_b^-$  baryons:

$$f_{B_u} = (40.99 \pm 0.82(\text{stat.}) \pm 1.11(\text{syst.}))\%$$

Combination of b-fractions data (direct and indirect) from LEP and CDF:

Assumptions:

➤  $f(\text{Z-decays}) = f(\text{TEVATRON})$

➤  $\sum_i f_i = 1$

➤  $f_{B_u} = f_{B_d}$

HFAG Winter 2004:

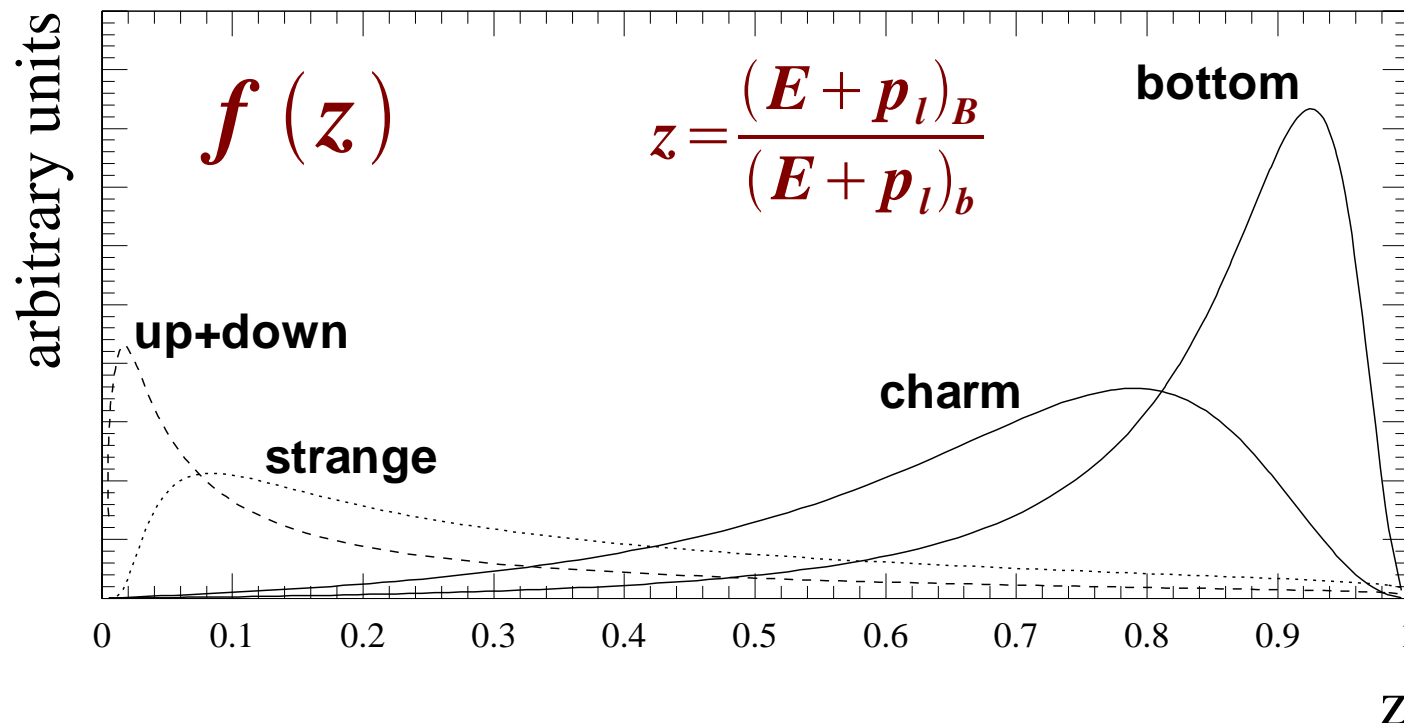
$$f_{B_s} = (10.5 \pm 1.5)\%$$

$$f_{b\text{-baryon}} = (9.9 \pm 1.7)\%$$

$$f_{B_u} = f_{B_d} = (39.8 \pm 1.0)\%$$

# b fragmentation function

- testing perturbative and non-perturbative QCD
- precise measurements at LEP and SLD sensitive to the shape of the fragmentation function
- improved NLL calculations + soft gluon resummation for perturbative part
- significant uncertainty for many measurements in the heavy flavour sector
- important input for hadron colliders (e.g. total b cross-section)



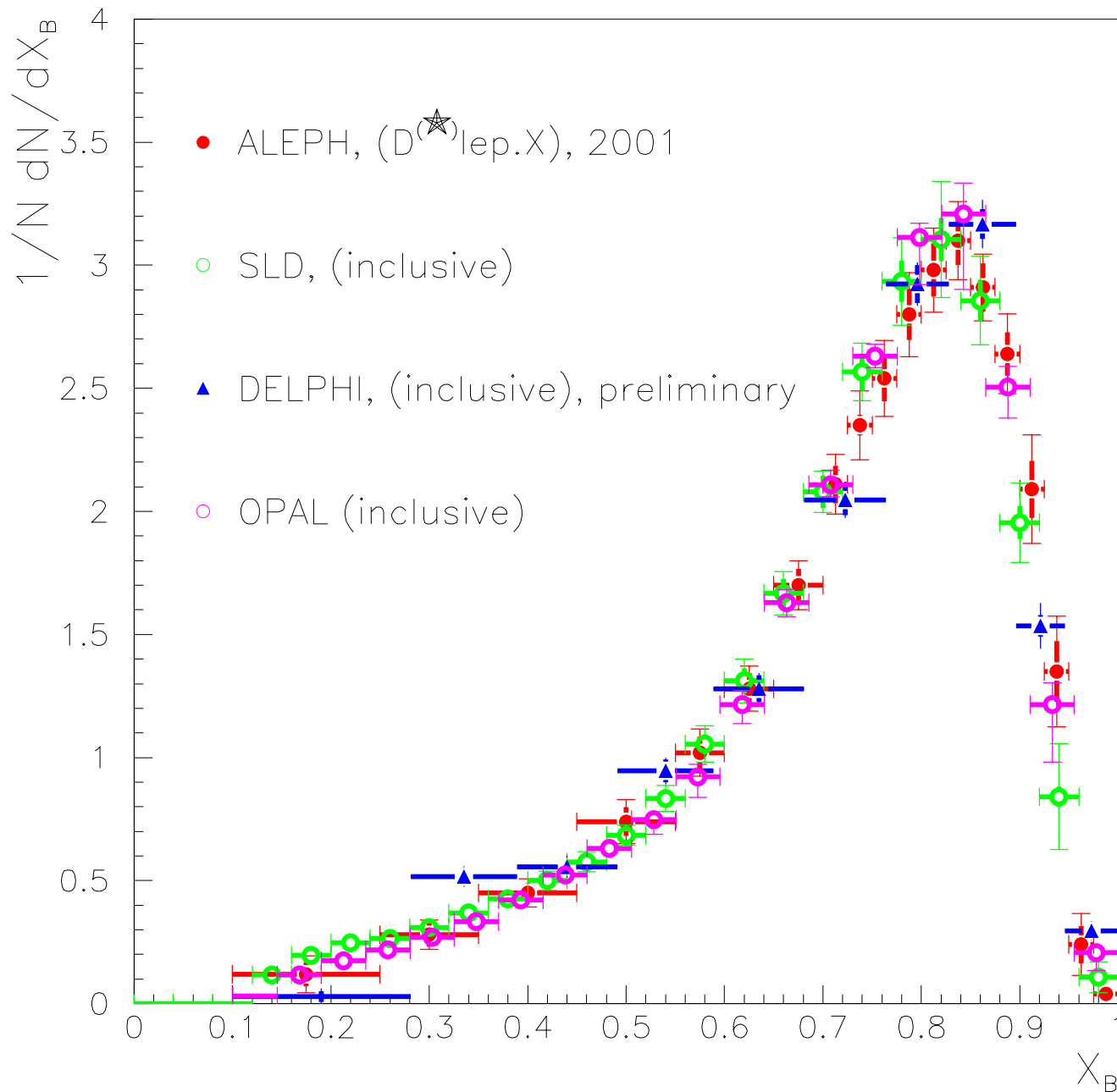
# Experimental methods

Experiments measure  $x_B = \frac{2 \cdot E_B}{\sqrt{S}}$  where  $x_B$  can refer either to the primary or weakly decaying b-hadron ( $x_B^{prim}, x_B^{weak}$ ).

## Several analysis methods:

- **inclusive leptons from semileptonic decay:**  
large statistics, but limited by model uncertainties; poor sensitivity to shape  
→ **obsolete; not used anymore!**
- **semi-exclusive decays  $B \rightarrow D^{(*)} l \nu$  (ALEPH):**  
low statistics but better energy estimate; but: uncertainties from final state!  
only sensitive to B-mesons for these final states!
- **inclusive analyses (DELPHI, OPAL, SLD):**  
OPAL, DELPHI: huge statistics, worse resolution → systematics dominates  
SLD: lower statistics but excellent vertexing possible  
→ better resolution, stat.  $\approx$  syst.

# Results



**ALEPH:**

$$\langle x_B^{weak} \rangle = 0.716 \pm 0.006 \pm 0.006$$

**DELPHI: (preliminary)**

$$\langle x_B^{weak} \rangle = 0.7153 \pm 0.0007^{+0.0049}_{-0.0052}$$

**OPAL:**

$$\langle x_B^{weak} \rangle = 0.7193 \pm 0.0016^{+0.0036}_{-0.0031}$$

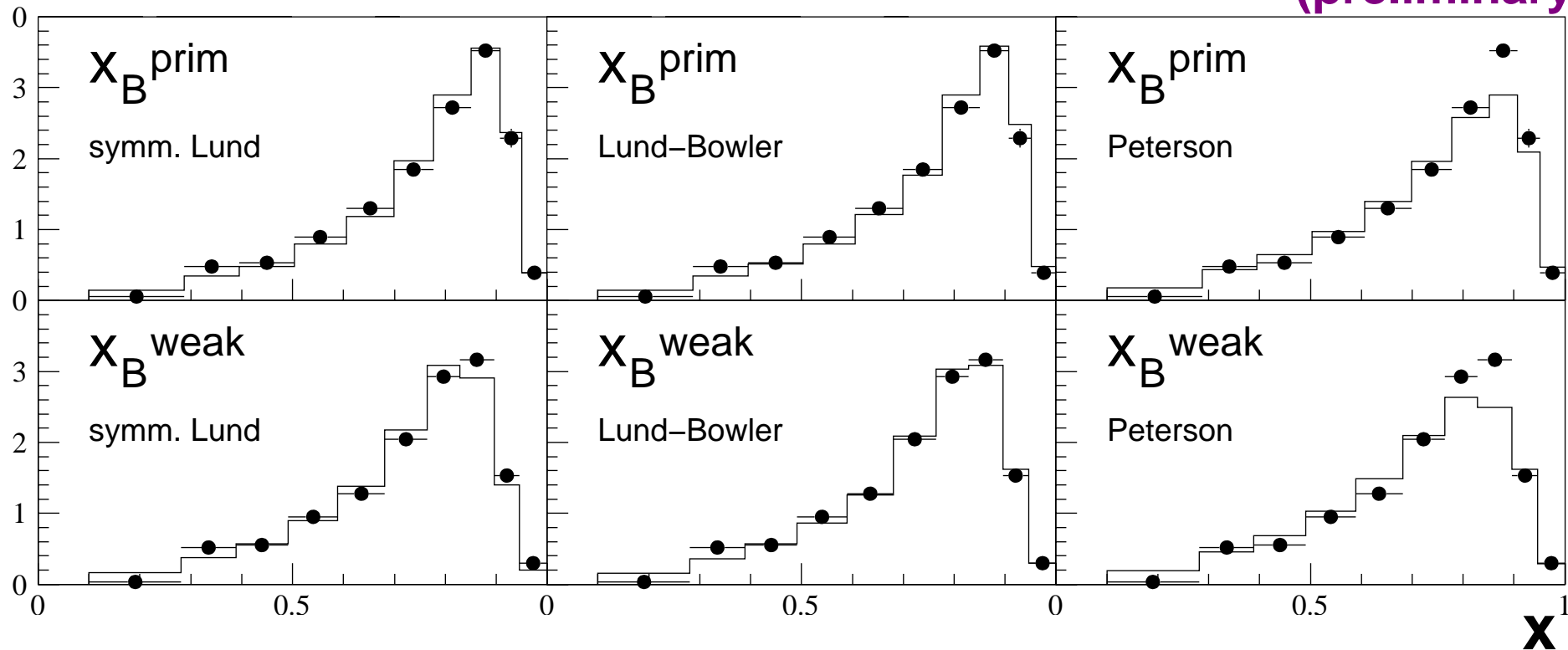
**SLD:**

$$\langle x_B^{weak} \rangle = 0.709 \pm 0.003 \pm 0.004$$

# Model tests

**DELPHI: fit model parameters to unfolded distributions**

(preliminary)



- **LUND and Bowler give best description of the data, better than e.g. the Peterson model, which has been invented for heavy quarks!**
- **similar ranking seen by all experiments**
- **but: strictly speaking only valid for the generator (pert. model!) used; (however: using a different perturbative model does not change the picture)**
- **possible to extract non-perturbative component in moments space**

# B hadron spectroscopy

**HQET:** Heavy Quark as static colour source; light degrees of freedom decoupled from spin of heavy quark

$$\vec{s}_q \oplus \vec{l} \rightarrow \vec{j}_q; \quad \vec{s}_Q \oplus \vec{j}_q \rightarrow \vec{J}$$

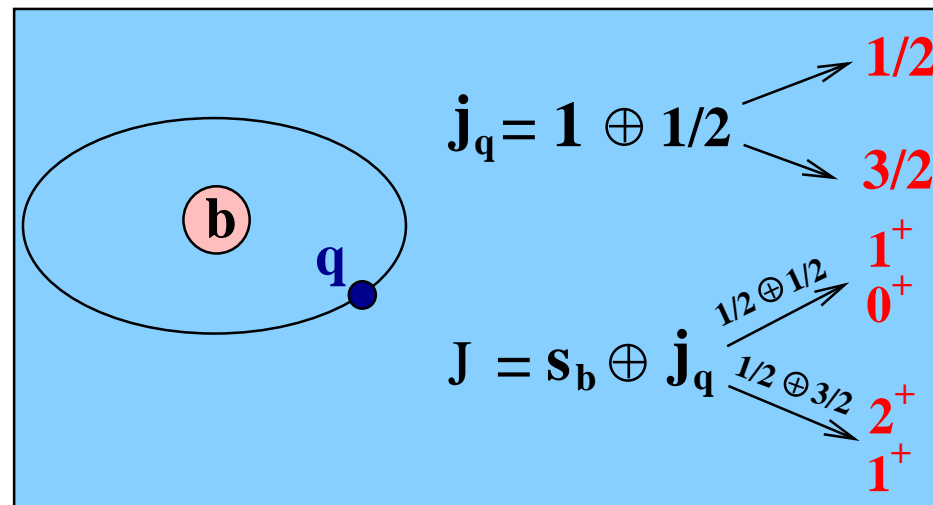
→  $\vec{s}_Q$  and  $\vec{j}_q$  separately conserved

→ Grouping in Doublets with same  $j_q$  (degenerate for  $m_Q \rightarrow \infty$ )

$l$	$j_q$	$J^P$	state	dom. decay mode
0	$\frac{1}{2}$	$0^-$	B	
		$1^-$	B*	B $\gamma$
1	$\frac{1}{2}$	$0^+$	B <sub>0</sub> *	B $\pi$ (s-wave) <b>broad</b>
		$1^+$	B <sub>1</sub> *	B* $\pi$ (s-wave)
1	$\frac{3}{2}$	$1^+$	B <sub>1</sub>	B* $\pi$ (d-wave) <b>narrow</b>
		$2^+$	B <sub>2</sub> *	B <sup>(*)</sup> $\pi$ (d-wave)

$B^{**} (B_J^*)$

Orbital excitation  $l=1$ :  $B^{**}$



$\approx$  similar for D-mesons

➤ similar for  $B_s^{**}$ , but  $B_s^{**} \rightarrow B_s^{(*)} \pi$  forbidden (Isospin!)

→  $B_s^{**} \rightarrow B^{(*)} K$  dominant (if above threshold)

# Experimental Status

- Inclusive analyses from all LEP Collaborations
- Exclusive analysis from ALEPH
- Semi-exclusive analysis from CDF ( $B \rightarrow D^{(*)} l X$ )

Different assumptions to estimate masses and rates!

	$M(B^{**}) [MeV]$	$\sigma_{B_{u,d}^{**}} / \sigma_b$
OPAL incl.	$5712 \pm 11$	$0.22 \pm 0.05$
DELPHI incl.	$5734 \pm 5 \pm 17$	$0.26 \pm 0.02 \pm 0.05$
ALEPH incl.	$5734 \pm 3 \pm 16$	$0.14 \pm 0.01 \pm 0.03$
L3 incl.	$B_2^* : 5768 \pm 5 \pm 6$	$0.32 \pm 0.03 \pm 0.06$
CDF semi-excl.	$B_1 : 5710 \pm 20$	$0.22 \pm 0.05 \pm 0.02$
ALEPH excl.	$B_2^* : 5739^{+8}_{-11} \text{ } ^{+6}_{-4}$	$0.25 \pm 0.07^{+0.05}_{-0.04}$

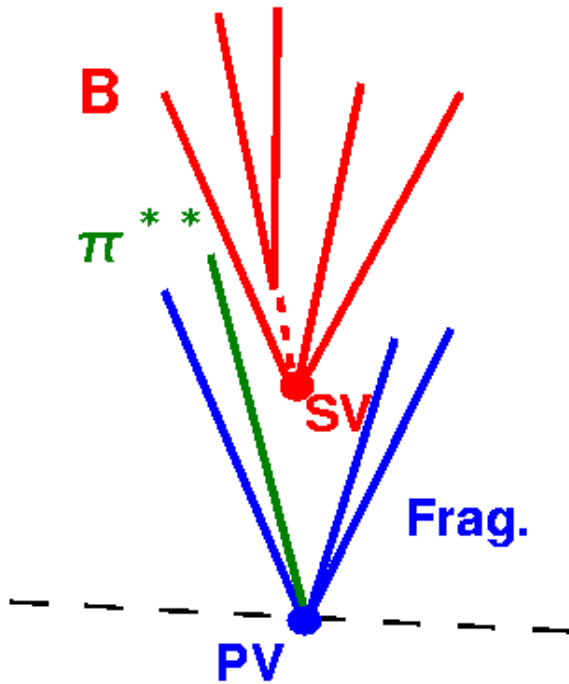
**Some numbers recomputed (adjusted inputs etc.)**

- Masses in reasonable agreement
- Rates not very well consistent (Interpretation?)  
(Systematics from background-modelling dominates inclusive analyses)

## Open Questions:

- Composition of signals? Isolating the narrow doublet?
- Broad states?
- Mass-hierarchy ('Spin-Orbit Inversion')?

# Principles of the measurements

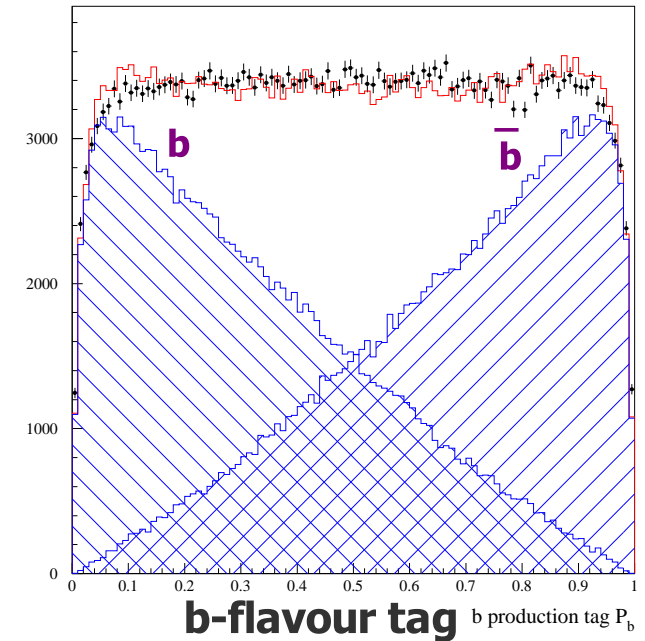


$$B_d^{**}(\bar{b}d) \rightarrow B^+ \pi^-$$

$$\rightarrow B^0 \pi^0$$

$$B_u^{**}(\bar{b}u) \rightarrow B^0 \pi^+$$

$$\rightarrow B^+ \pi^0$$



➤ inclusive reconstruction of weakly decaying B-meson

➤ add pion (kaon) from primary vertex (strong decay!)

➤ analyse Q-value:  $Q = m(B^{(*)} \pi / K) - m(B^{(*)}) - m(\pi / K)$

➤ exploit correlations  $Q_{\pi/K} \Leftrightarrow \mathbf{b\text{-flavour}}$   
 $Q_{\pi/K} \Leftrightarrow Q_B$

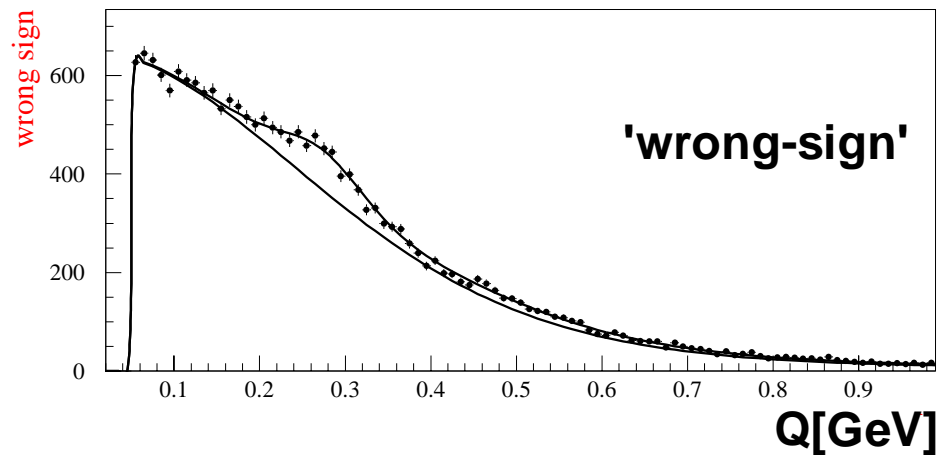
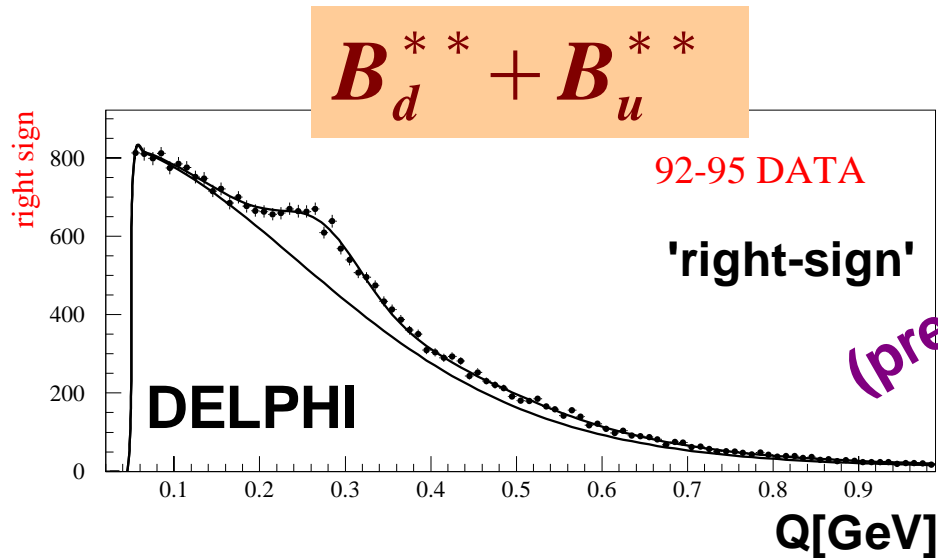
to define 1)  $B_d^{**} / B_u^{**}$  enriched samples

2) signal enhanced/depleted samples

# Analyses

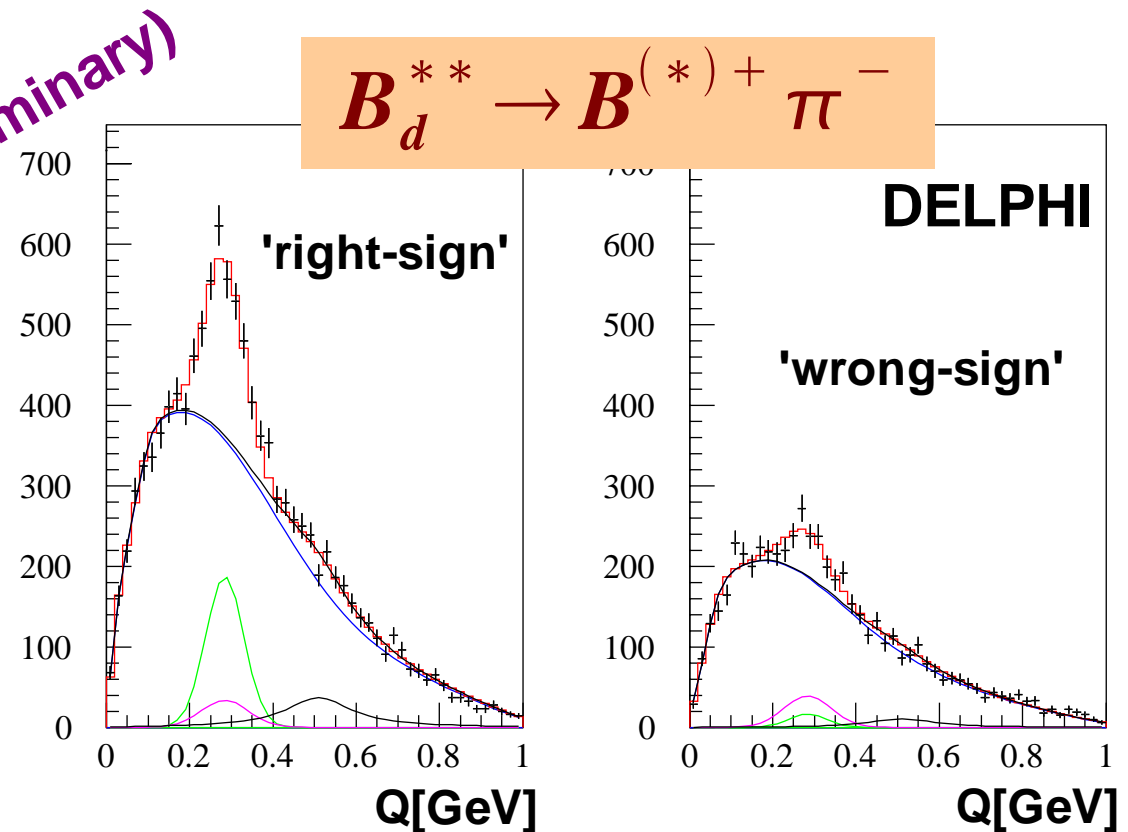
## 'High Efficiency' Analysis:

- aim for optimal background control
- fit background on data
- only very limited input from simulation



## 'High Purity' Analysis:

- aim for optimal background suppression
- use of Neural Networks
- background from simulation + correction



# Results and Interpretation

For a Gaussian component:

'High-Efficiency'

$$Q = 292 \pm 3 \text{ (stat.)} \pm 12 \text{ (syst.) MeV/c}^2$$

$$\sigma = 45 \pm 4 \text{ (stat.)} \pm 4 \text{ (syst.) MeV/c}^2$$

'High-Purity'

$$Q = 286 \pm 3 \text{ (stat.)} \pm 3 \text{ (syst.) MeV/c}^2$$

$$\sigma_d = 46 \pm 5 \text{ (stat.)} \pm 3 \text{ (syst.) MeV/c}^2$$

$$\sigma_u = 57 \pm 6 \text{ (stat.)} \pm 4 \text{ (syst.) MeV/c}^2$$

$$\frac{\sigma(B_d^{**}) + \sigma(B_u^{**})}{\sigma_b} = 0.122 \pm 0.014 \pm 0.018$$

$$\frac{\sigma(B_d^{**}) + \sigma(B_u^{**})}{\sigma_b} = 0.143 \pm 0.014 \pm 0.018$$

**PRELIMINARY!**

➤ narrow resonances → 3 narrow peaks

$B_2^* \rightarrow B\pi, B^*\pi$  leads to shift  $\Delta Q \approx 46 \text{ MeV}$

hyperfine splitting within  $j=3/2$  doublet  $\approx \frac{m_c}{m_b} \Delta m(D_2^* - D_1) \approx 12 \text{ MeV}$

↪ can't be resolved with the experimental resolution!

➤ parameter for narrow resonance compatible with experimental resolution

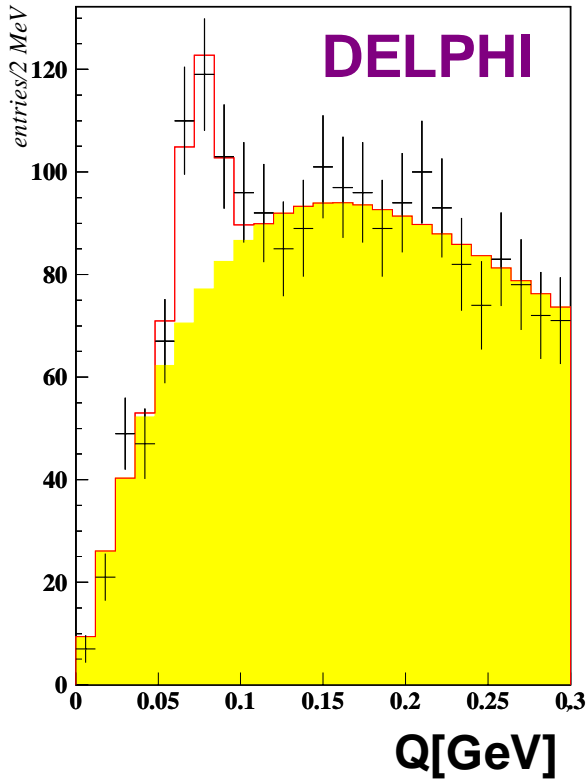
→ suggests interpretation as narrow states

→ small mass splitting within doublet and small contribution from

$B_2 \rightarrow B\pi$  favoured

# $B_s^{**}$

- replace pion by kaon
  - low production rate, kaon-identification
  - ✚ charge and flavour correlations work better



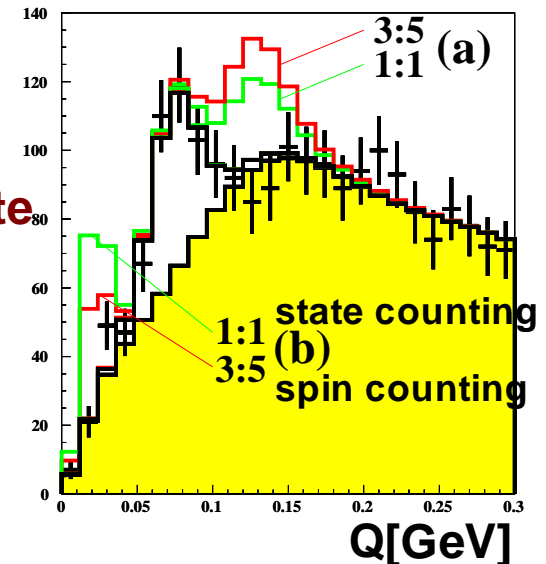
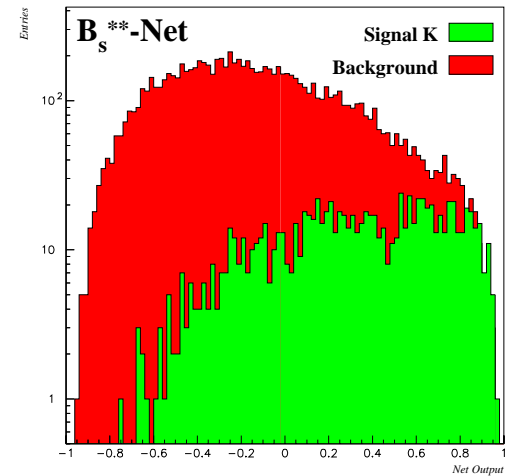
$$\langle Q \rangle = 76.3 \pm 3.2 \pm 4.7 \text{ MeV} / c^2$$

$$\frac{\sigma(B_s^{**}) BR(B_s^{**} \rightarrow B^{(*)} K)}{\sigma_b} = 0.010 \pm 0.002 \pm 0.003$$

**PRELIMINARY!**

- parameter for observed resonance compatible with experimental resolution
  - ➔ suggests interpretation as narrow state
- no sensitivity to broad states
- what is seen?

- a)  $B_{s1}, B_{s2}^* \rightarrow B^* K$
- b)  $B_{s2}^* \rightarrow B K$

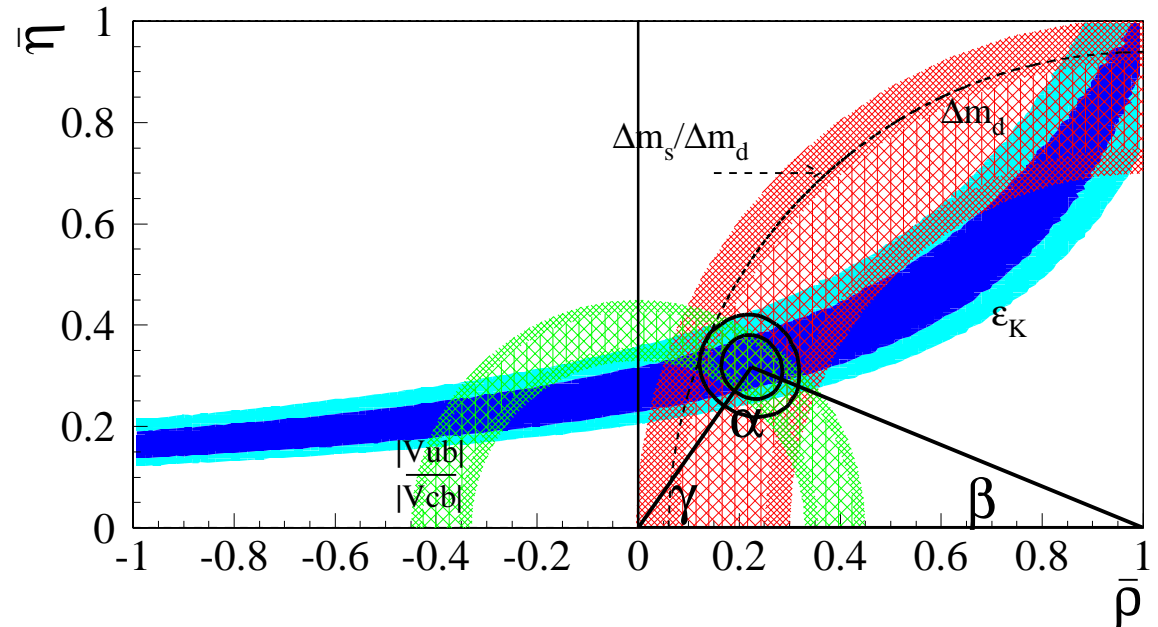


**The final word from DELPHI on b spectroscopy is expected this summer!**

# The CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

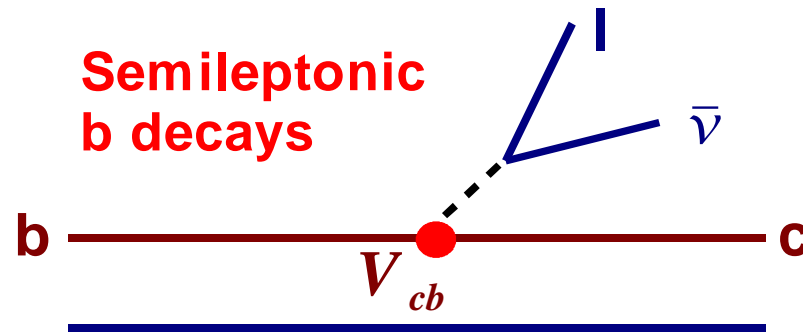
$$\sim \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



## Contributions from LEP helping to constrain the unitarity triangle:

- $V_{ub}$  in semileptonic b decays (hadronic mass)
- $V_{cb}$  in inclusive and exclusive semileptonic b decays
- $\Delta m_d$  from time dependent  $B^0$  oscillations
- limits on  $\Delta m_s$

# $V_{cb}$



1) inclusive:  $\Gamma_{sl}(b \rightarrow c l^- \bar{\nu}) = \frac{BR(b \rightarrow c l^- \bar{\nu})}{\tau_b} = |V_{cb}|^2 \cdot f_{theory}$

→ precise measurements of lifetime and semileptonic branching ratio needed

→ uncertainties from  $f_{theory}$  can be reduced through dedicated analyses

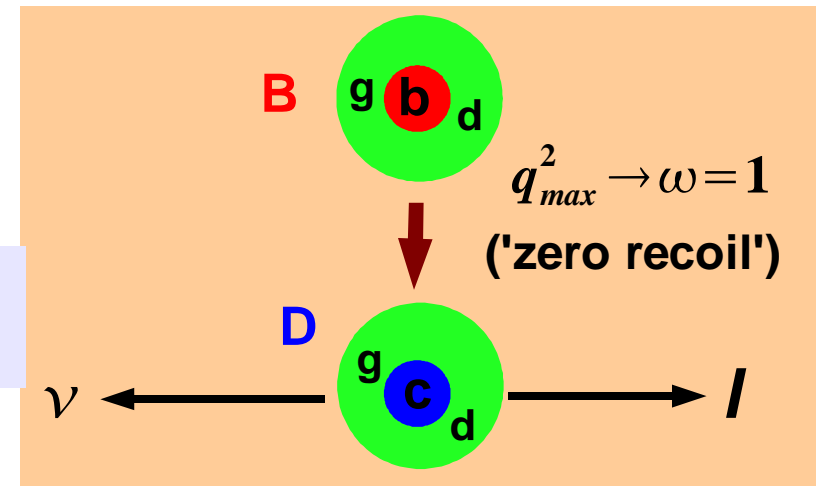
2) exclusive decays:  $\bar{B}_d^0 \rightarrow D^{*+} l^- \bar{\nu}$

$$\frac{d\Gamma(\bar{B} \rightarrow D^* l^- \bar{\nu})}{d\omega} = \frac{G_F^2}{48\pi^3} \cdot |V_{cb}|^2 \cdot F^2(\omega) \cdot K(\omega)$$

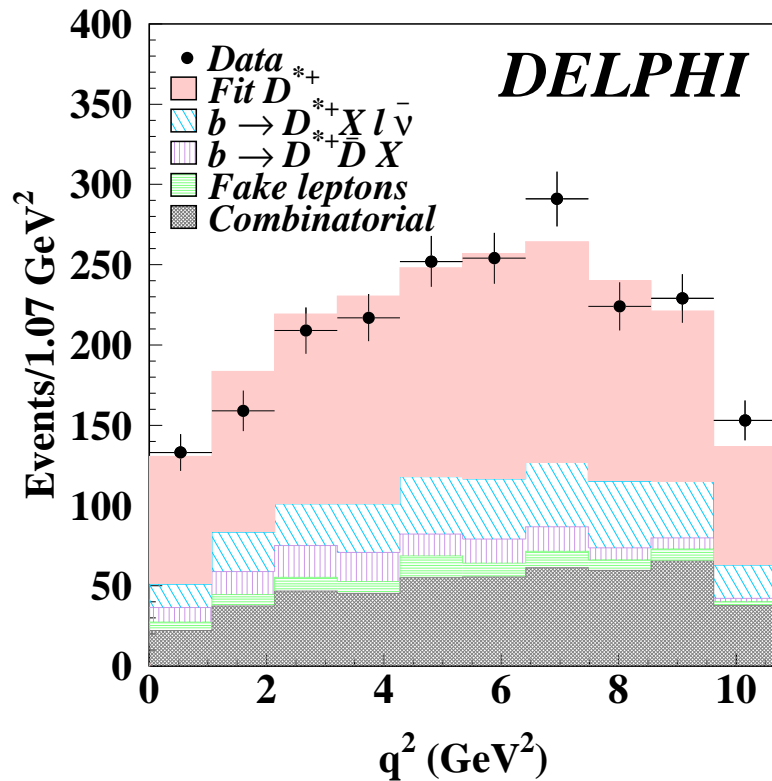
$m_Q \rightarrow \infty$ :  $F(\omega=1) = 1$

$$\omega = v_B \cdot v_D = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 \cdot m_B \cdot m_{D^*}}$$

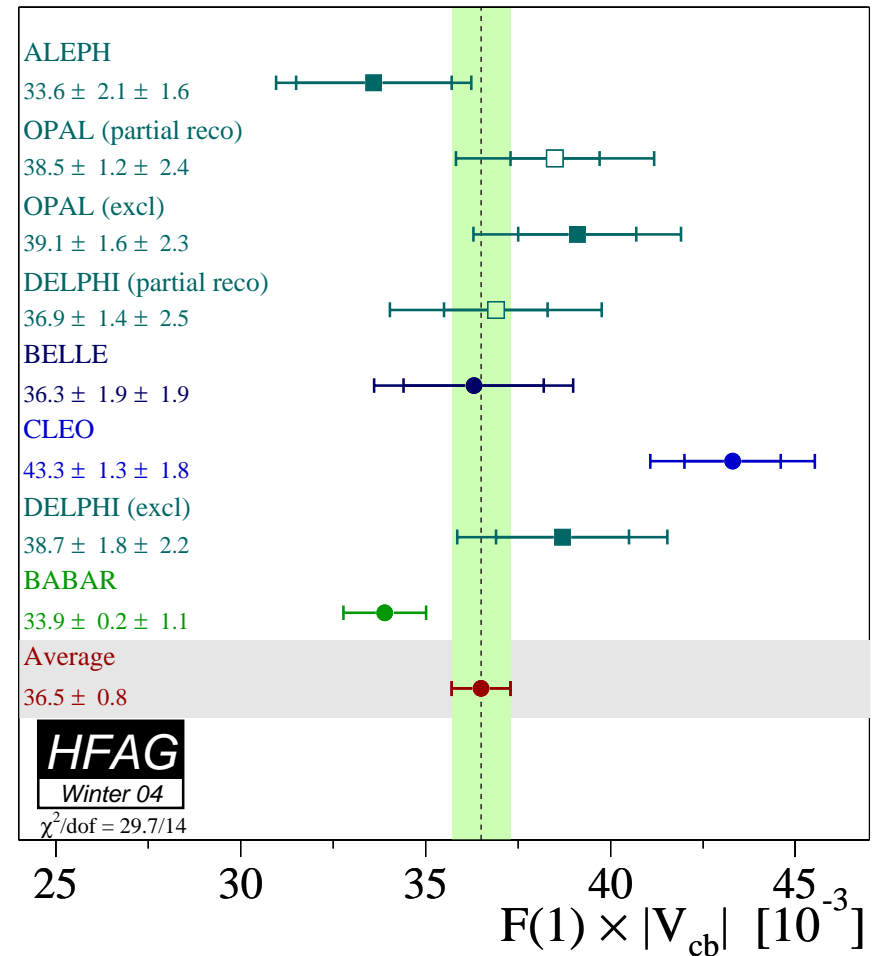
corrections:  $F(\omega=1) = 0.91 \pm 0.04$



# $V_{cb}$ exclusive



## Combination:



Combined with 'soft pion' analysis:

$$F(1) \cdot |V_{cb}| = (37.7 \pm 1.1 \pm 1.9) \cdot 10^{-3}$$

$$\text{Slope at zero recoil: } \rho^2 = 1.39 \pm 0.10 \pm 0.33$$

$$BR(\bar{B}_d^0 \rightarrow D^{*+} l^- \bar{\nu}) = (5.39 \pm 0.11 \pm 0.34) \%$$

$$\rightarrow |V_{cb}| = (41.4 \pm 1.2 \pm 2.1 \pm 1.8) \cdot 10^{-3} \quad F(1) : 4\% \text{ relative error}$$

# Leptonic and hadronic moments

$V_{cb}$  from inclusive semileptonic decays: O.P.E.:

$$\Gamma_{sl}(b \rightarrow c l^- \bar{\nu}) = |V_{cb}|^2 \cdot \frac{G_F^2 m_b^5}{192 \pi^3} \cdot [c_3 \langle B | O_3 | B \rangle + c_5 \frac{\langle B | O_5 | B \rangle}{m_b^2} + c_6 \frac{\langle B | O_6 | B \rangle}{m_b^3} + O\left(\frac{1}{m_b^4}\right)]$$

$\mu_\pi^2, \mu_G^2$

$\rho_{LS}^3, \rho_D^3$

non-perturbative parameters ('kinetic mass scheme'):

$m_b, m_c$

$\mu_\pi^2$  : Kinetic energy of the b-quark inside the meson

$\mu_G^2$  : chromo-magnetic coupling ( $B^* - B$  mass splitting)

$\rho_{LS}^3$  : spin-orbit interaction

$\rho_D^3$  : Darwin term

'pole mass scheme':

Parameters

$\bar{\Lambda}, \lambda_1, \lambda_2, \rho_1, \rho_2$

relations e.g.

$\bar{\Lambda} \Leftrightarrow m_b$

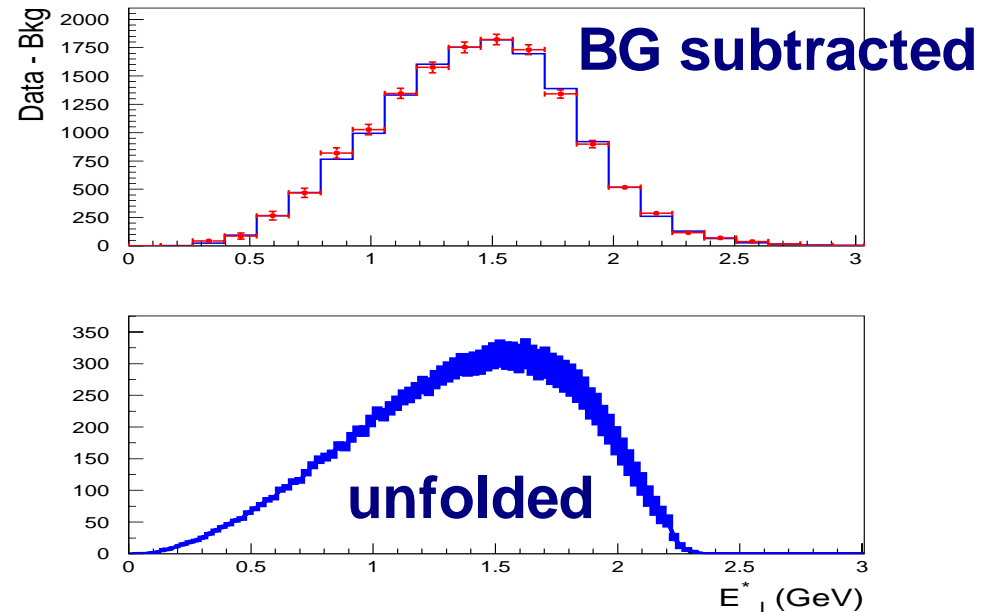
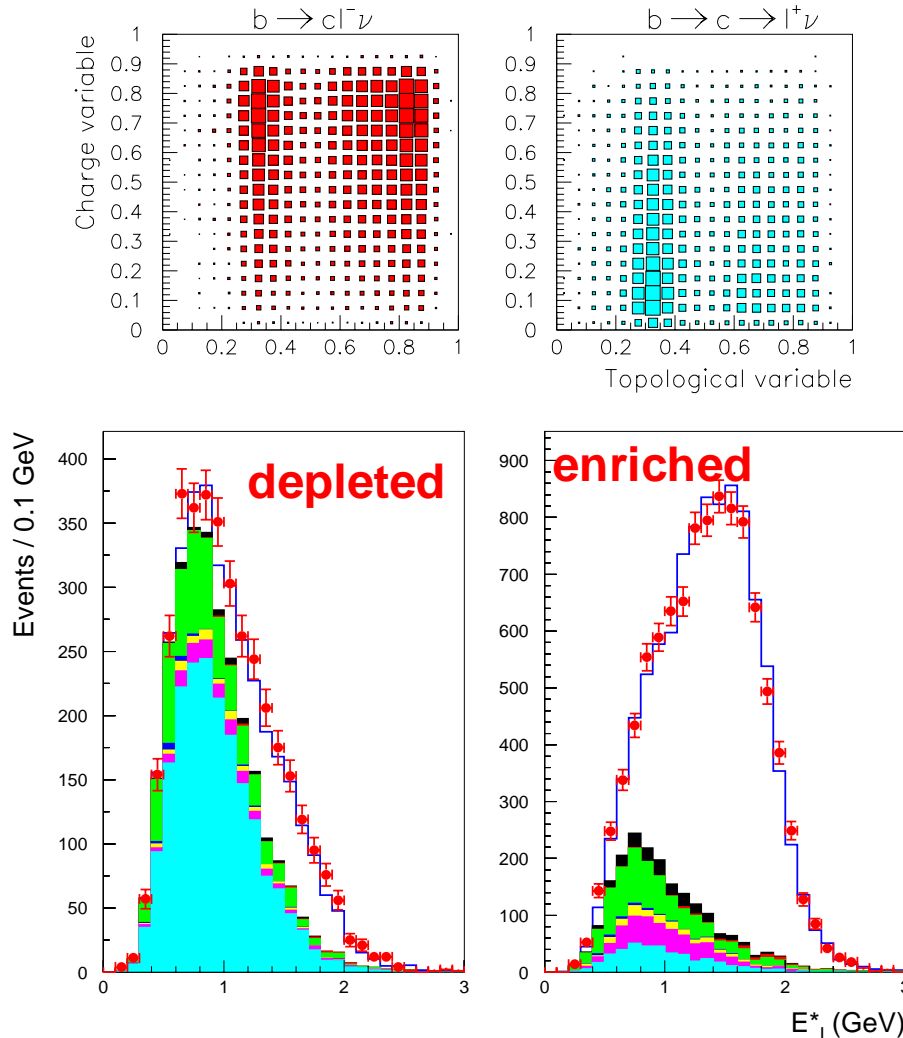
$\lambda_1 \Leftrightarrow \mu_\pi^2$

Moments of the lepton energy spectrum and hadronic mass spectrum are sensitive to these parameters → reduce uncertainties using experimental input

# Lepton Moments

at LEP: sensitivity to the full spectrum; no momentum cutoff!

- inclusive reconstruction of the accompanying hadronic system
- discriminate against background from cascade decays



➔ first three moments: **PRELIMINARY!**

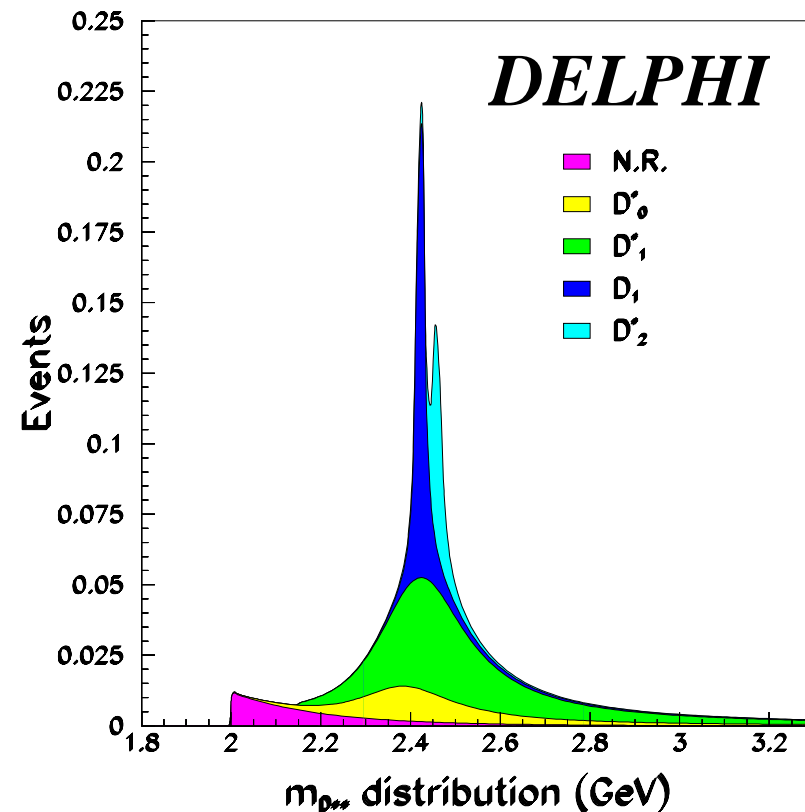
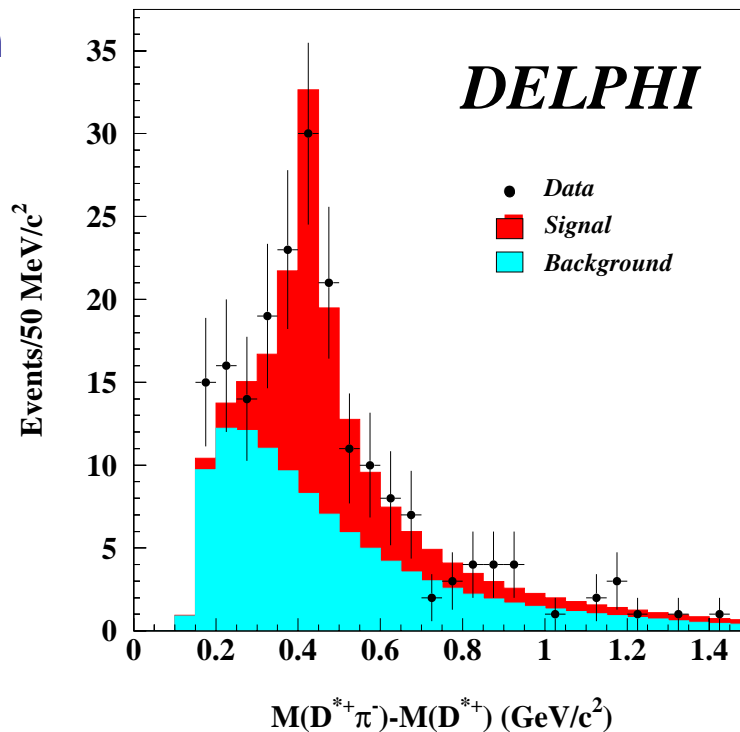
$$\langle E_l^* \rangle = 1.383 \pm 0.012 \pm 0.009 \text{ GeV}$$

$$\langle (E_l^* - \langle E_l^* \rangle)^2 \rangle = 0.192 \pm 0.005 \pm 0.008 \text{ GeV}^2$$

$$\langle (E_l^* - \langle E_l^* \rangle)^3 \rangle = -0.029 \pm 0.005 \pm 0.006 \text{ GeV}^3$$

# Hadronic Moments

Mass spectrum of hadronic  $D^{**}$  system (resonant + non-resonant) using exclusively reconstructed  $D^{(*)}$  decays



Fit for composition of the hadronic mass spectrum, e.g. for the broad  $D_1^{*+}$  state:

$$BR(\bar{B}_d^0 \rightarrow D_1^{*+} l^- \bar{\nu}) = (1.24 \pm 0.25 \pm 0.27) \%$$

Consistent with CLEO and BELLE!

$$m_{D_1^{*+}} = (2445 \pm 34 \pm 10) \text{ MeV} / c^2$$

$$\Gamma_{D_1^{*+}} = (234 \pm 74 \pm 25) \text{ MeV} / c^2$$

Moments:

**PRELIMINARY!**

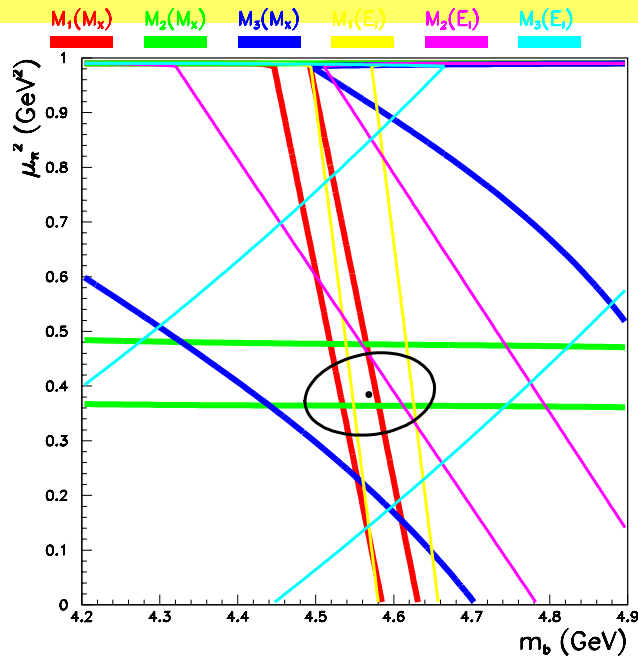
$$M_1 = \langle m_H^2 - \bar{m}_D^2 \rangle = 0.647 \pm 0.046 \pm 0.093 (\text{GeV} / c^2)^2$$

$$M_2 = \langle (m_H^2 - \bar{m}_D^2)^2 \rangle = 1.98 \pm 0.23 \pm 0.29 (\text{GeV} / c^2)^4$$

$$M_2' = \langle (m_H^2 - \langle m_H^2 \rangle)^2 \rangle = 1.56 \pm 0.18 \pm 0.17 (\text{GeV} / c^2)^4$$

$$M_3' = \langle (m_H^2 - \langle m_H^2 \rangle)^3 \rangle = 4.05 \pm 0.74 \pm 0.31 (\text{GeV} / c^2)^6$$

# Parameter Fit



Fit 3 lepton moments and 3 hadronic moments ( $M_1, M_2', M_3'$ )

$m_b, \mu_\pi^2$  scheme

Fit moments theory

$$m_b(1\text{ GeV}) = 4.570 \pm 0.082 \pm 0.010 \pm 0.005 \text{ GeV}$$

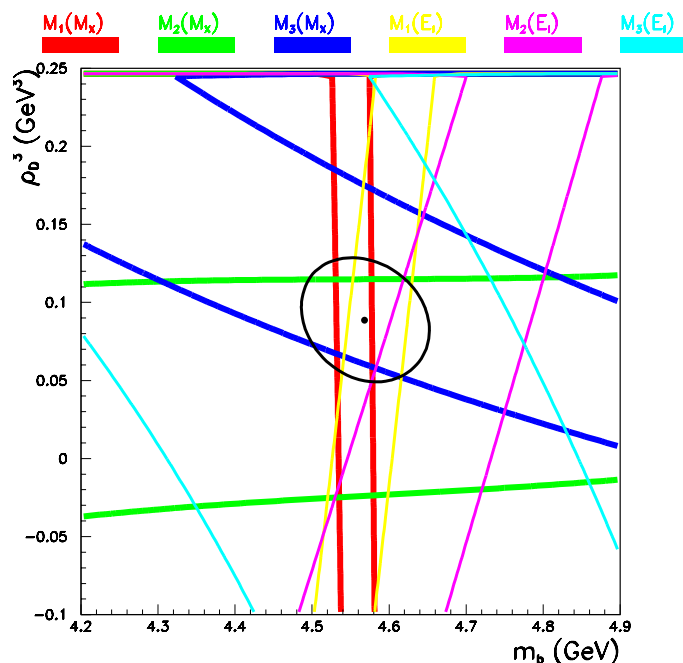
$$m_c(1\text{ GeV}) = 1.133 \pm 0.134 \pm 0.019 \pm 0.020 \text{ GeV}$$

$$\mu_\pi^2(1\text{ GeV}) = 0.382 \pm 0.070 \pm 0.031 \pm 0.020 \text{ GeV}^2$$

$$\rho_D^3(1\text{ GeV}) = 0.089 \pm 0.039 \pm 0.004 \pm 0.010 \text{ GeV}^3$$

( $\mu_G^2, \rho_{LS}^3$  constrained)

**PRELIMINARY!**



Implications for  $V_{cb}$  :

$$|V_{cb}| = 42.4 \cdot (1 \pm 0.015 \pm 0.014 \pm 0.015) \cdot 10^{-3}$$

Expt: lifetime, BR  
from LEP  
( $\approx 0.010$  for  
all data)

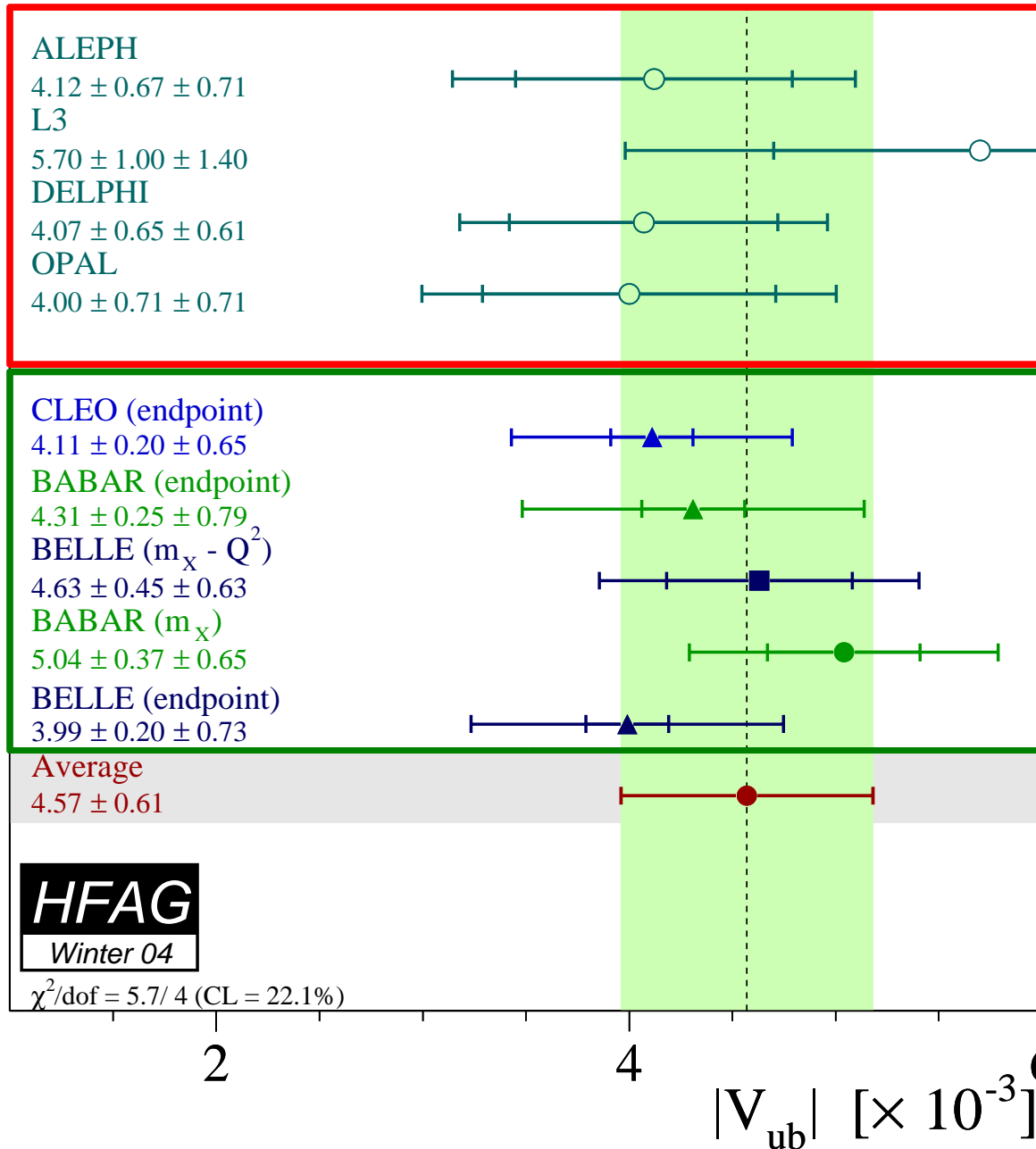
Moments fit

Theory

In good agreement with B-factories!

Compare hadronic moments wrt. lepton energy cut!

# $V_{ub}$ Results



# Bs-oscillation results

- all LEP results now published
- LEP and SLD have roughly equal weight at high  $\Delta m_s$

World average:

$$\Delta m_s > 14.5 \text{ ps}^{-1}$$

sensitivity:  $18.3 \text{ ps}^{-1}$

LEP only:

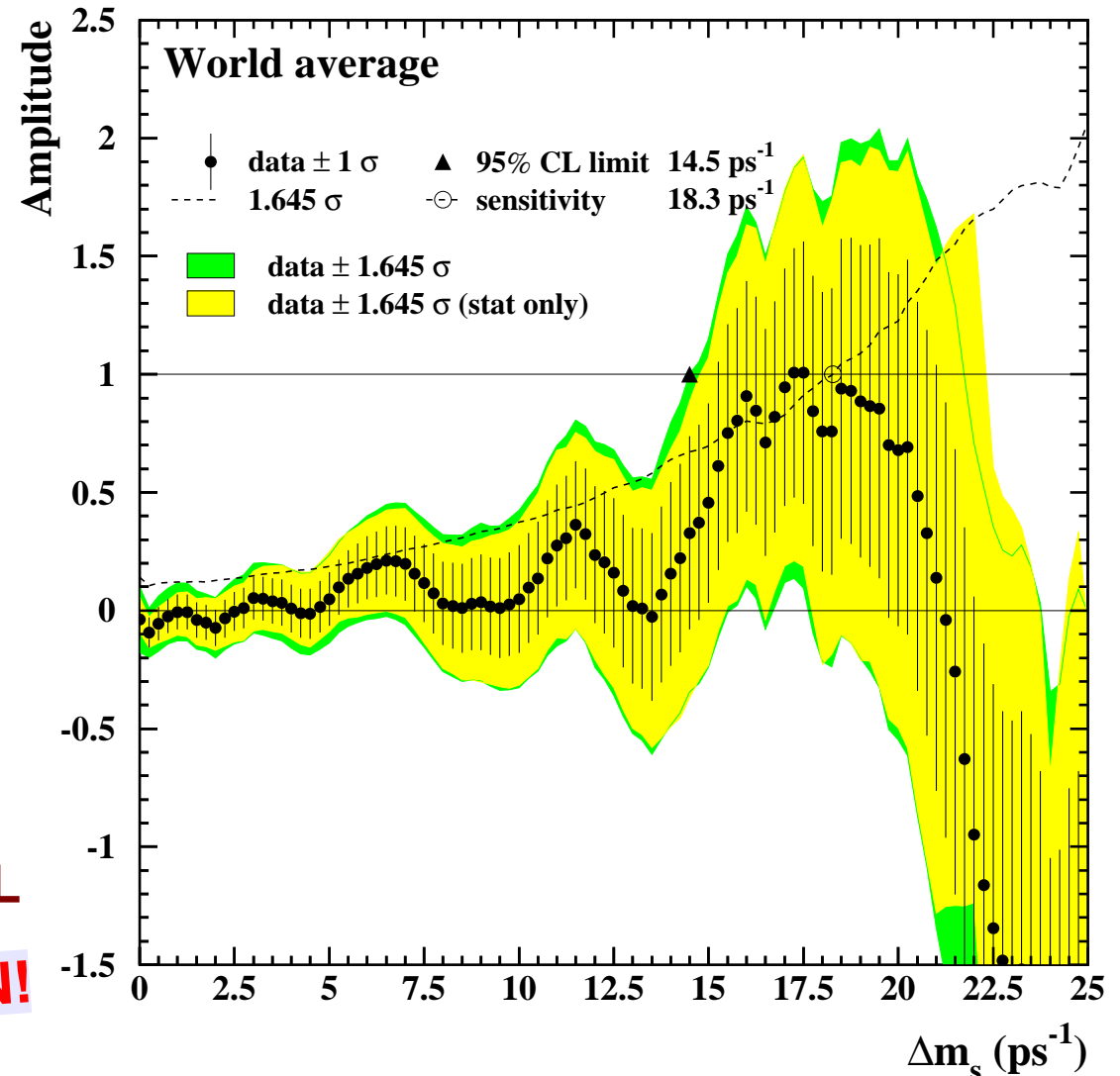
$$\Delta m_s > 11.5 \text{ ps}^{-1}$$

sensitivity:  $16.9 \text{ ps}^{-1}$

From UTfit:

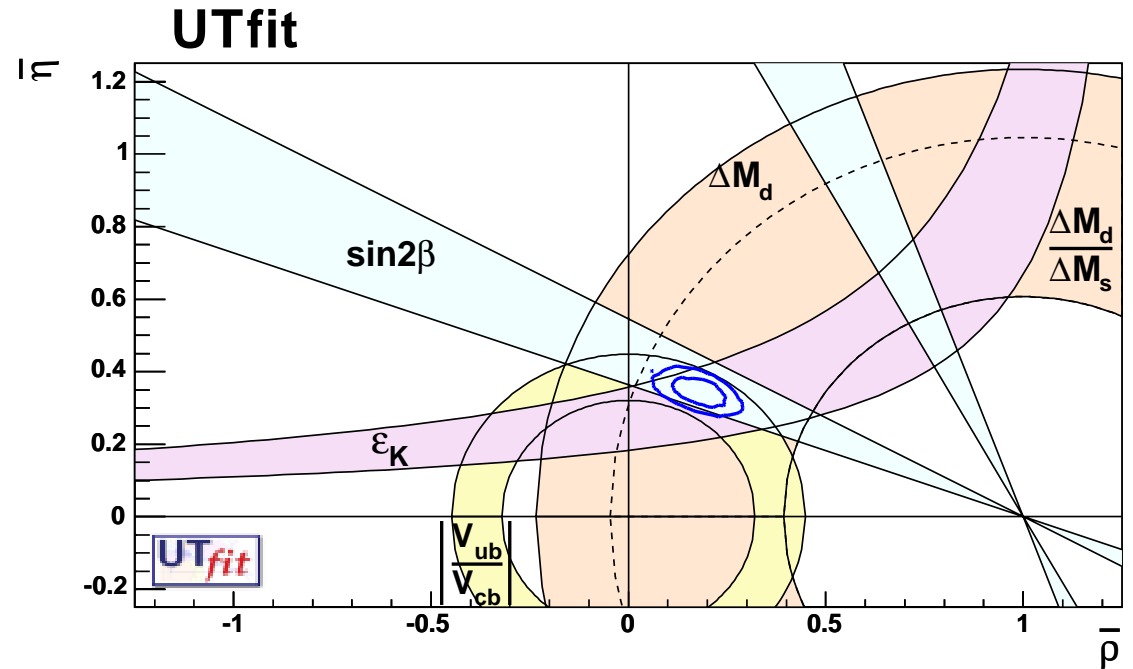
$$\Delta m_s \in [15.2, 21.2] \text{ ps}^{-1} @ 95\% \text{ CL}$$

To be measured at the TEVATRON!

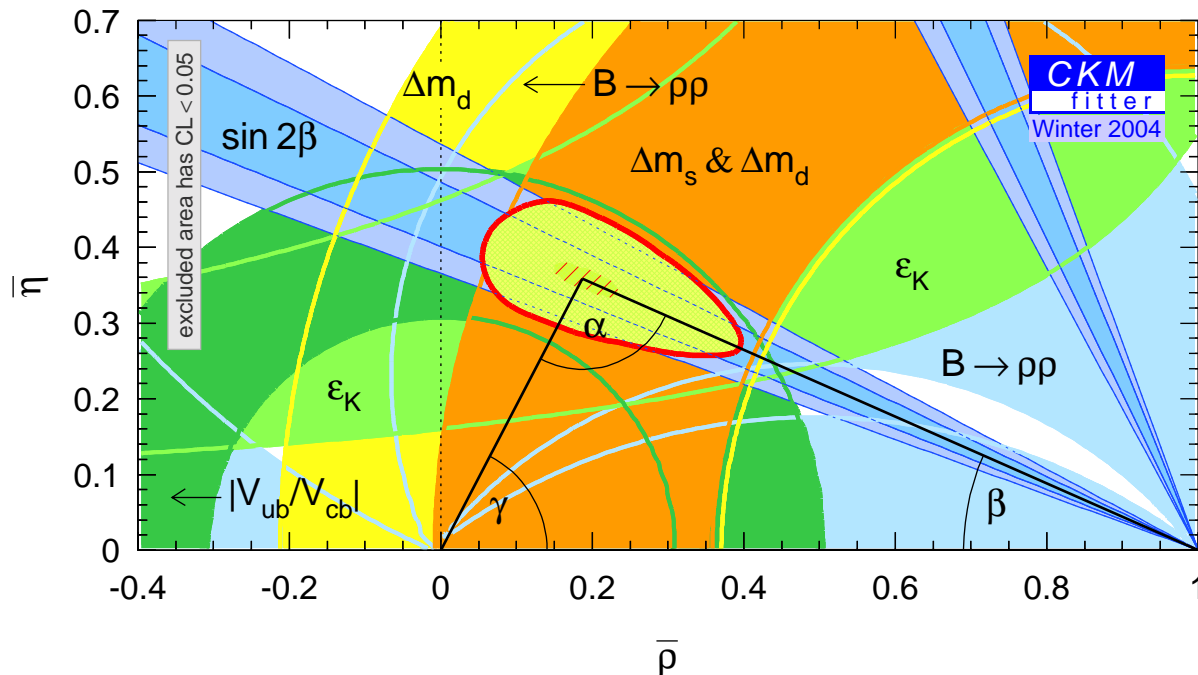


# CKM Fit

Performed by several groups



CKMfitter



$$\sin(2\beta) = 0.715 \pm 0.030$$

$$\in [0.65, 0.78] \text{ @ 95\% CL}$$

Good agreement for  $\sin(2\beta)$  comparing direct and indirect measurements!

# Summary and Conclusions

➤ LEP has contributed to many fields of b-physics, e.g.:

↪ **b-production:**    **b-hadron fractions**  
                          **b-fragmentation function**  
                          **b-spectroscopy**

**these results are important input for hadron colliders!**

↪ **b-decays:**        **lifetimes**  
                          **charm counting**  
                          **semileptonic branching ratio**

↪ **CKM matrix:**    **oscillations**  
                           **$V_{cb}$ ,  $V_{ub}$**

↪ **and many more not mentioned here!**

➤ Last b physics results to be published this year

➤ Many results will still have significant impact in the future