

Semileptonic b-decays

[V_{cb} and V_{ub} extraction]

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Semileptonic b decays

- **Exclusive rates:**

- $b \rightarrow D^{**} l \nu \Rightarrow \text{HQET}$
- $b \rightarrow D^* l \nu \Rightarrow V_{cb}$
- $b \rightarrow D^+ l \nu \Rightarrow V_{cb}$ (no news)
- $\Lambda_b \rightarrow l \nu X \Rightarrow \text{HQET}$ (no news)

- **Inclusive rate:**

- $b \rightarrow l \nu X_c \Rightarrow V_{cb}$
- $b \rightarrow l \nu X_u \Rightarrow V_{ub}$

CKM mixing matrix

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- In the Standard Model the elements of CKM are fundamental parameters: their values must be determined experimentally

Using the Wolfenstein parameterisation

$$\begin{pmatrix} V_{ud} & V_{us} & \color{red}{V_{ub}} \\ V_{cd} & V_{cs} & \color{red}{V_{cb}} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & \color{red}{A\lambda^3(\rho - i\eta)} \\ -\lambda & 1 - \frac{\lambda^2}{2} & \color{red}{A\lambda^2} \\ \color{red}{A\lambda^3(1 - \rho - i\eta)} & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- $\color{red}{V_{cb}}$ \implies third best measured CKM matrix element after V_{us} , V_{ud}
- $\color{red}{V_{ub}}$ \implies improved a lot with the LEP measurements

$V_{us} = \lambda$ and $\color{red}{V_{cb}}$ gives A

$\color{red}{V_{ub}}$ information on ρ and η

QCD: $\Lambda_{QCD} \ll m_{c,b}$

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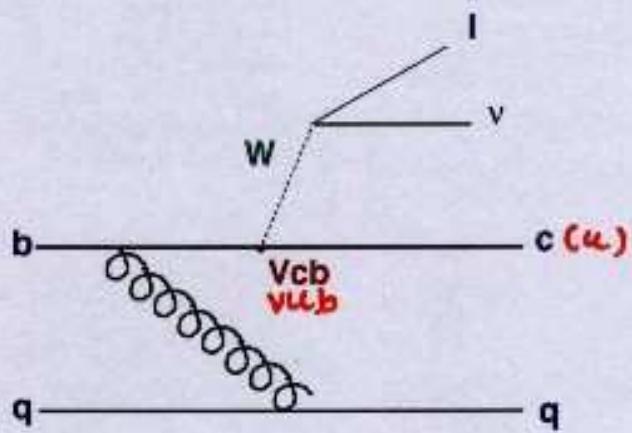
b → c transition is governed by V_{cb}

b → u transition is governed by V_{ub}

- Quarks are inside hadrons bound by soft gluons \Rightarrow non-perturbative QCD
- Asymptotic freedom
 - Energy of soft gluon $\sim \Lambda_{QCD} \sim 250\text{MeV} \ll m_{c,b} \Rightarrow$ heavy quark
 - Range of interactions $\sim 1/\Lambda_{QCD} >> \lambda_{b,c}^{\text{compton}} \Rightarrow$ perturbative QCD
 - Heavy quark properties are **not** resolved by soft gluon
 \Rightarrow Heavy quark properties are preserved
- Heavy Quark Effective Theory (HQET) \Rightarrow simplified description of processes involving heavy quark to heavy quark transitions i.e. form factor in $m_Q \rightarrow \infty$ limit

HQET: QCD in the $m_{c,b} \rightarrow \infty$ limit

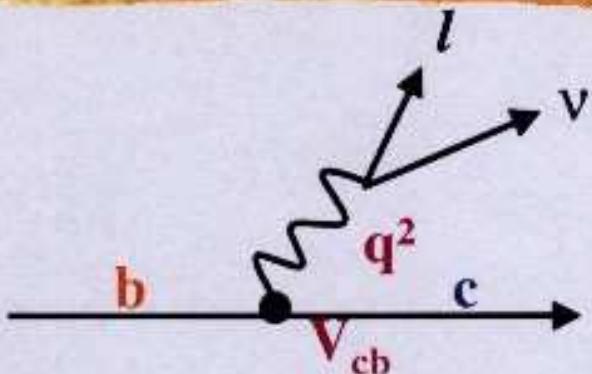
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- HQET \implies determination of V_{cb} and V_{ub} from semileptonic b hadron decays
- Semileptonic **B** decays \implies non-perturbative QCD effects can be described by invariant form factors, depending on the momentum transfer between hadrons
- Non leptonic decays \implies no quantitative understanding of QCD effects

V_{cb}

Two methods



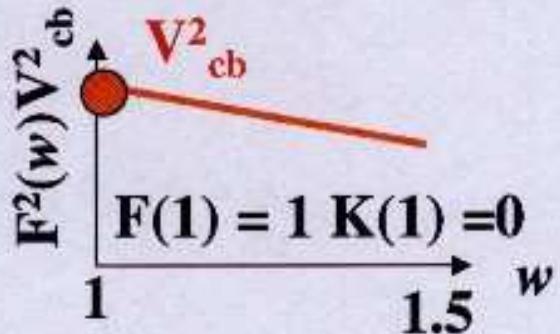
- **Inclusive** $\tau_b + \text{Br}(b \rightarrow l)$

$$|V_{cb}|^2 = \frac{\text{Br}(B \rightarrow X_c l \bar{\nu})}{\gamma_c \tau_B}$$

- **Exclusive** $\text{Br}(B \rightarrow D^* l \bar{\nu}) + \text{HQET}$

$$\frac{1}{\tau_b} \frac{d\text{Br}(B^0 \rightarrow D^* l \bar{\nu})}{dw} = K(w) F^2(w) |V_{cb}|^2$$

$$w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}}$$



V_{cb} inclusive

$$|V_{cb}| = K \times \Gamma(B \rightarrow X_c l \bar{\nu})^{1/5} \left(1 - 0.24(\mu_\pi^2 - 0.5) \right) \times \\ (1 \pm 0.030_{pert} \pm 0.020_{mb} \pm 0.024_{1/m_b^3})$$

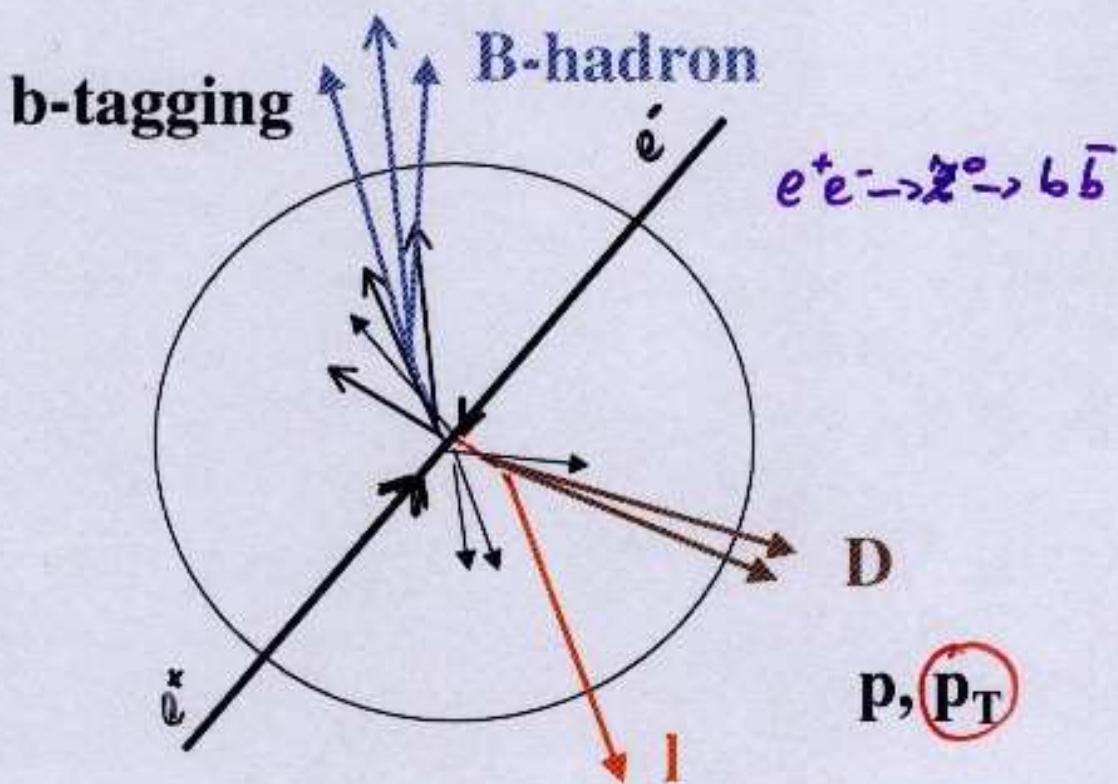
**X_c any state containing charm
(b → ulν contribution subtracted)**

μ_π²=0.5±0.1 is assumed (HFWG)

$$\Gamma(b \rightarrow \chi l^+ \bar{\nu}) = \frac{Br(b \rightarrow \chi l^+ \bar{\nu})}{\tau_b}$$

$$\text{Br}(b \rightarrow l \nu X_c)$$

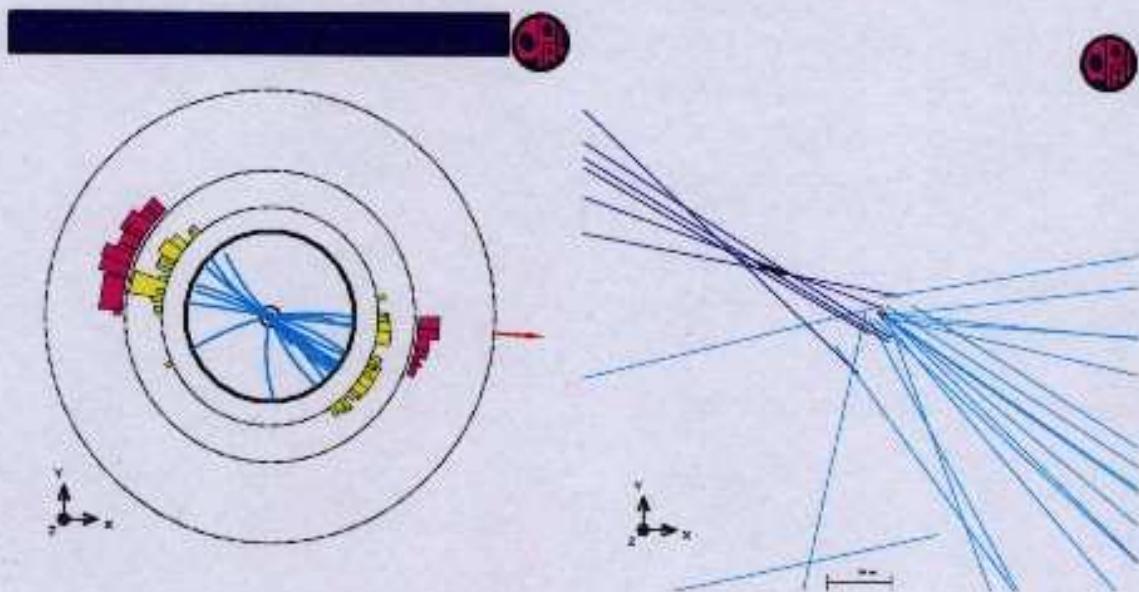
● selection



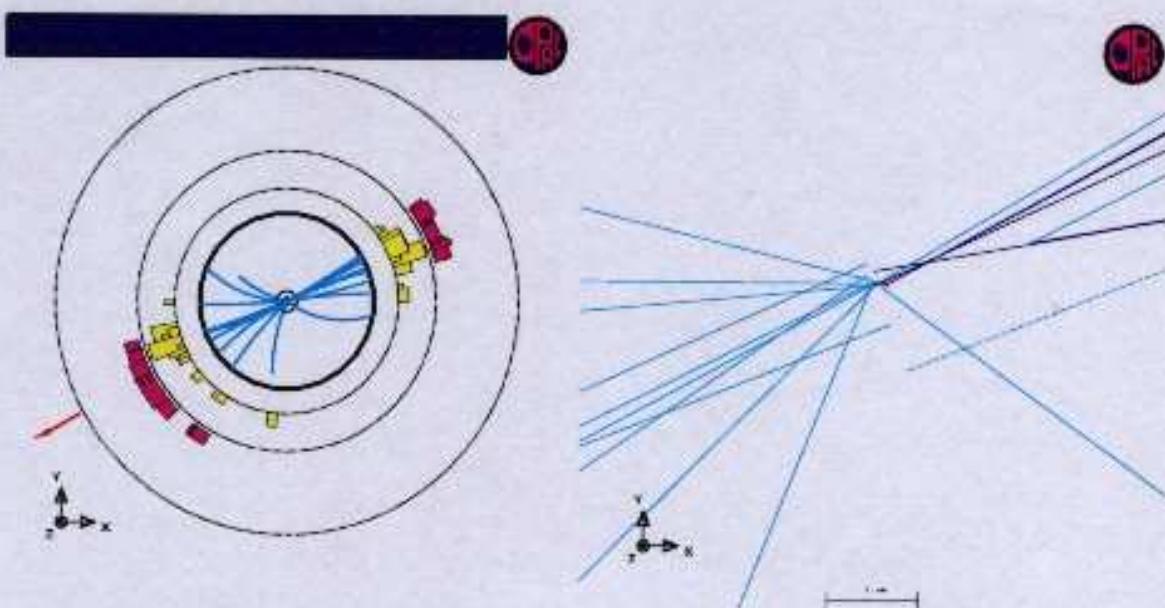
main background: $b \rightarrow c \rightarrow l$

Separating $(b \rightarrow \ell)$ from $(b \rightarrow c \rightarrow \ell)$

Typical $(b \rightarrow \mu)$ MC event in OPAL



Typical $(b \rightarrow c \rightarrow \mu)$ MC event in OPAL



$P_T; \ell^+ Q_{\text{jet}}^{\text{same}}$ to reduce $b \rightarrow c \rightarrow e$
 $b \rightarrow e \Rightarrow \ell^+ Q_b > 0$
 $b \rightarrow c \rightarrow e \Rightarrow \ell^+ Q_b < 0$

V_{cb} Inclusive

- **Experimentally**

$$\Gamma(b \rightarrow X l^+ \nu) = \frac{Br(b \rightarrow X l^+ \nu)}{\tau_b}$$

where

$$Br(b \rightarrow X l^+ \nu) = (1040 \pm 0.24)\% \text{ (LEPEW)}$$

$$\tau_b = (1.56 \pm 0.01) \text{ ps (LEPWG)}$$

using LEPHF estimation

$$V_{cb} = (40.75 \pm 0.41_{\text{exp}} \pm 2.04_{\text{theo}}) 10^{-3}$$

- $\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}$:

largest branching fraction of B meson decay modes

- HQET lowest order \implies one form factor ξ (Isgur-Wise function) as a function of the Lorentz invariant

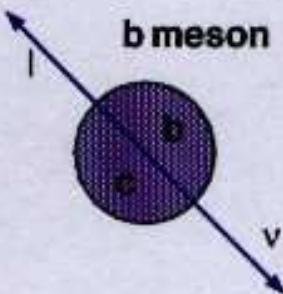
$\omega = \mathbf{v}_B \times \mathbf{v}_{D^*} = D^*$ boost in B rest frame

\mathbf{v}_B : B four velocity

\mathbf{v}_{D^*} : D^* four velocity

$\omega = 1$ for D^* produced at rest in the B rest frame (**recoil**)

- c at rest in B rest frame \implies hadronic system is not perturbed



- HQET predicts:

$$\xi(1) = 1$$

- maximum recoil $\omega = 1.5$

$B^0 \rightarrow D^{*+} \ell^- \bar{\nu}$ in HQET

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- HQET $\implies V_{cb}$ from $\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}$ at $\omega \sim 1$ with little model dependence
- Measure

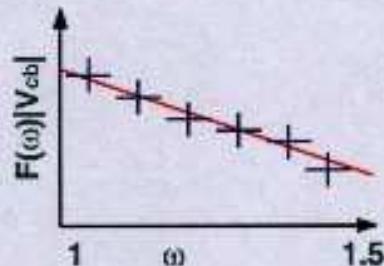
$$\frac{d\Gamma}{d\omega} = \frac{1}{\tau_{B^0}} \frac{d\text{Br}(\bar{B}^0 \rightarrow D^{*+} \ell^- \bar{\nu}_\ell)}{d\omega}$$

at $\omega = 1$

- Differential decay rate:

$$\frac{d\Gamma}{d\omega} = \mathcal{K}(\omega) \mathcal{F}^2(\omega) |V_{cb}|^2$$

- $\mathcal{K}(\omega)$ = Known function of ω
- $\mathcal{K}(1) = 0 \implies$ phase space 0 at $\omega = 1$
- $\mathcal{F}(\omega)$ = Form factor



- Extrapolate $\frac{d\Gamma}{d\omega}$ to $\omega = 1$ from $\frac{d\Gamma}{d\omega}$ measured in $1 < \omega < 1.5$
 \implies Form factor shape is important

V_{cb} exclusive



- ARGUS - CLEO (Y(4S))
 - B⁰ produced at rest:
 - Good resolution: $\omega \sim E_{D^*}/m_{D^*}$
 - poor efficiency at $\omega \sim 1$
- LEP (Z⁰)
 - B⁰ produced with large boost (~30 GeV):
 - poor resolution
 - good efficiency at $\omega \sim 1$

Extrapolation of $\frac{d\Gamma}{d\omega}$ at $w = 1$

7

- Differential decay rate:

$$\frac{d\Gamma}{d\omega} = \mathcal{K}(\omega) \mathcal{F}^2(\omega) |V_{cb}|^2$$

- the phase space is 0 at $\omega = 1$
- extrapolate from $\frac{d\Gamma}{d\omega}$ distribution ($1 < \omega < 1.5$)
- $\mathcal{F}(\omega) = \mathcal{F}(1) \times g(\omega)$
- Fit for $\mathcal{F}(1) |V_{cb}|^2$

Form Factor

- New form factor:

$$F(w) = F(1) \times [1 - f(\rho^2)z + f_1(\rho^2)z^2 - f_2(\rho^2)z^3]$$

where

$$z = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

theoretical predictions:

$$0.14 < \rho^2 < 1.54$$

$$F(1) = 0.88 \pm 0.05$$

Experimental Channels

$$B^0 \rightarrow D^{*+} l \bar{\nu}$$

$$\downarrow D^0 \pi^+$$



$$\overline{K^-\pi^+ \quad K^-3\pi \quad K_s^0\pi^-\pi^+ \quad K^-\pi^+(\pi^0) \quad \text{incl}}$$

Cleo x**Argus** x x**Aleph** x x x**Delphi** x x x**Opal** x x x

$$B^- \rightarrow D^{*0} l \bar{\nu}$$

$$\downarrow D^0 \pi^0 \rightarrow K^-\pi^+$$

Cleo x

D^{**} background treatment

- Vertex charge to have different date samples:
enhanced and depleted in B^+
(information on the B^+ amount)
- Predicted amount of D^{**} allowed to vary under Gaussian constraint:
 $Br(b \rightarrow D^{**} h \bar{\nu}) = (0.76 \pm 0.16)\%$
- D^{**} w-spectrum from digeti et al.

Systematic error: 0.6% rate
 4.1% models

(total systematic error 6.8%)

b → **D^{**}** lν

(LEP HF note)

- **Total rate:**

- $\text{Br}(\text{B}_d^0 \rightarrow \text{D}^{**+} l\nu) = (3.04 \pm 0.44)\%$

- **decays involving D^{*}:**

- $\text{Br}(\text{B}_d^0 \rightarrow \text{D}^{*+} \pi^0 l\nu) = (0.58 \pm 0.08)\%$
 - $\text{Br}(\text{B}_d^0 \rightarrow \text{D}^{*+} K^0 l\nu) = (0.61 \pm 0.22)\%$

- **Narrow states:**

- $\text{Br}(\text{B}_d^0 \rightarrow \text{D}_{-1}^{*+} l\nu) = (0.63 \pm 0.11)\%$
 - $\text{Br}(\text{B}_d^0 \rightarrow \text{D}_{-2}^{*+} l\nu) = (0.23 \pm 0.09)\%$

- **R^{**} = 0.37 ± 0.16 < 0.6 @ 95%CL**
 - from HQET naïve expectations 1.6
⇒ 1/m_c corrections

D** model

- Old model overestimate the D** rate @ $w=1$
- New model $\Rightarrow (w^2-1)$ suppression @ $w=1$
 - different form factors:
3-parameter dependence
1 parameter very sensitive to R^{**}
- systematics $\Rightarrow 0.5$ of the difference of the most extreme case
(one parameter varied at a time)

Vcb Exclusive

- Main experimental limitation:
 $B \rightarrow D^{**} l \bar{\nu}$ background
- new decay models (Ligeti et al)
⇒ larger systematics ($R^{**} < 1$ @ 95% CL)

BUT

new R^{} value ⇒ constraints on decay models**

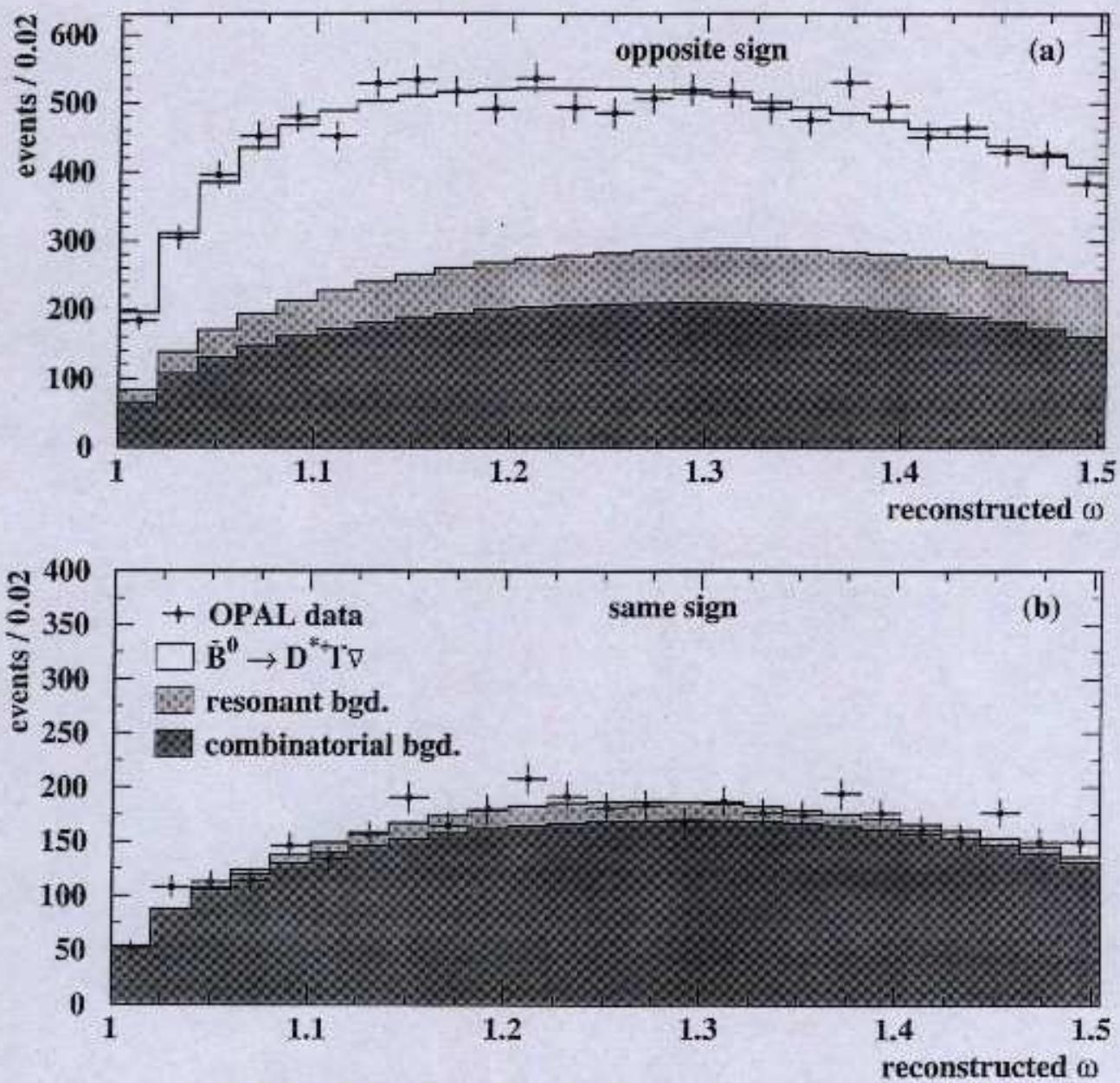
6% (OPAL 95) ⇒ 2% (OPAL 00)*

***(same analysis)**

CLEO will try to fit the model

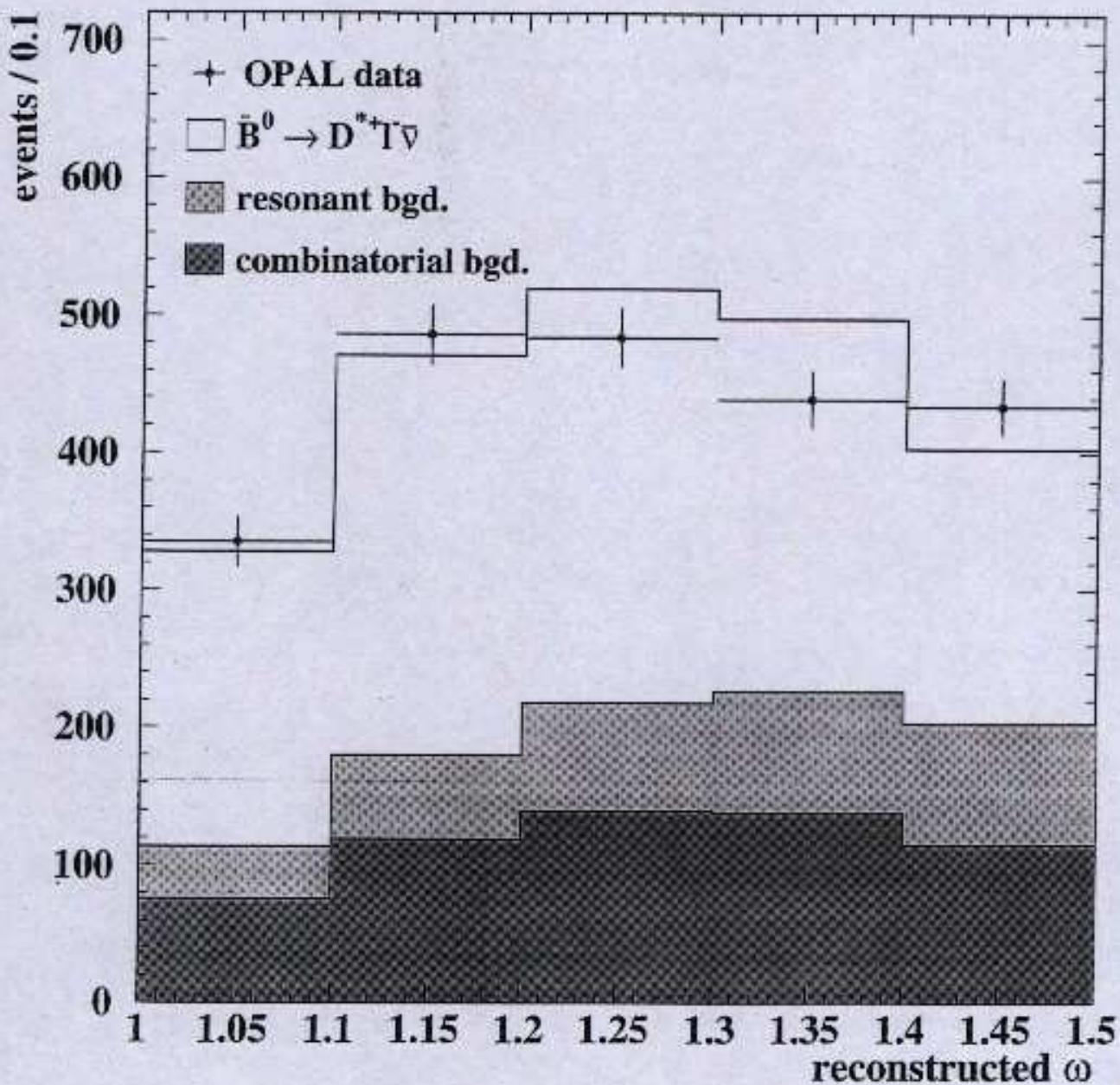
- wide D^{**} resonances?
- future ⇒ average with CLEO

$B \rightarrow \bar{\nu} \ell \nu X$



$$F(1)|V_{cb}| = (37.5 \pm 1.2 \pm 2.5) \cdot 10^{-3}$$

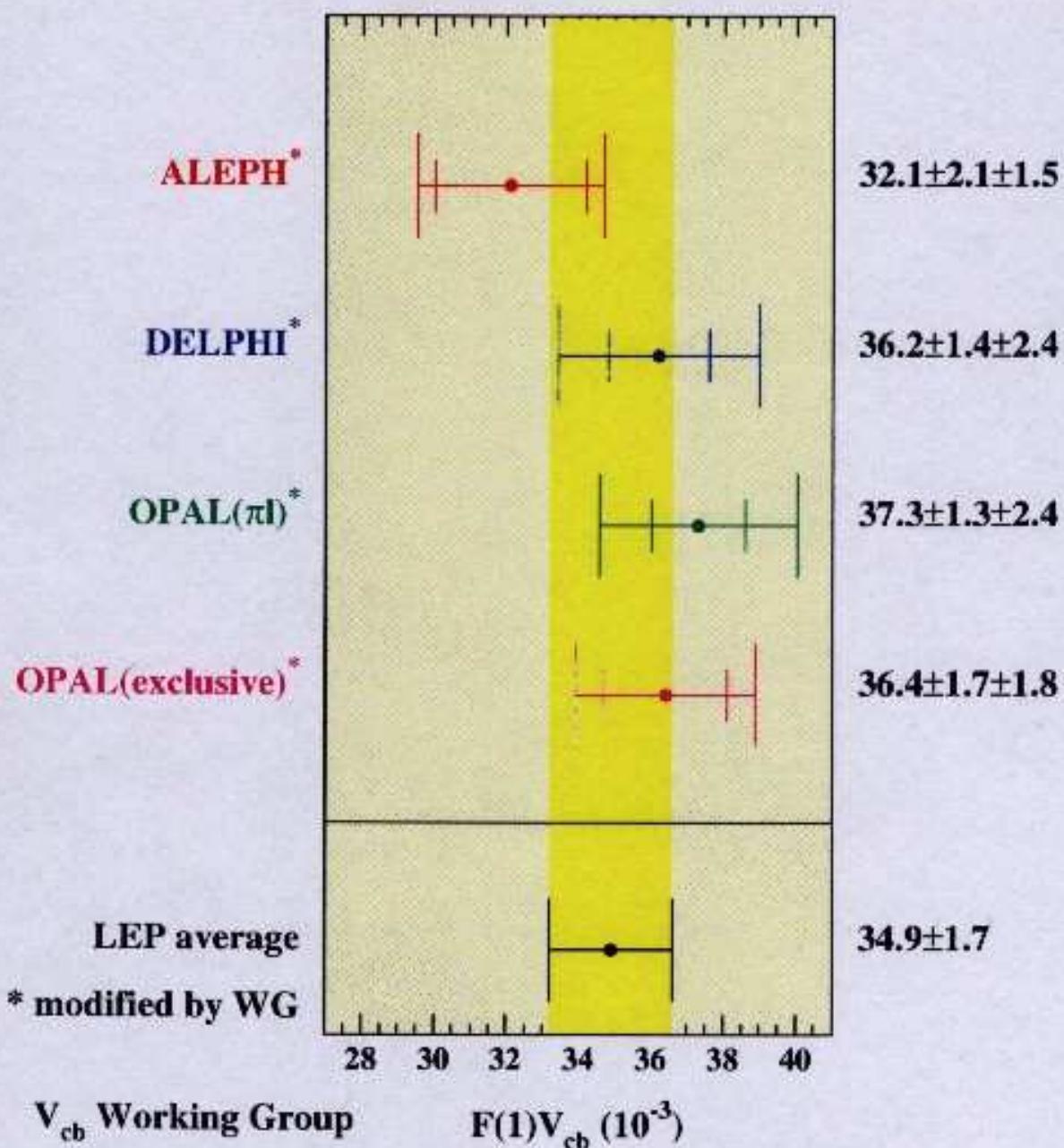
$$f^2 = 1.12 \pm 0.14 \pm 0.29$$



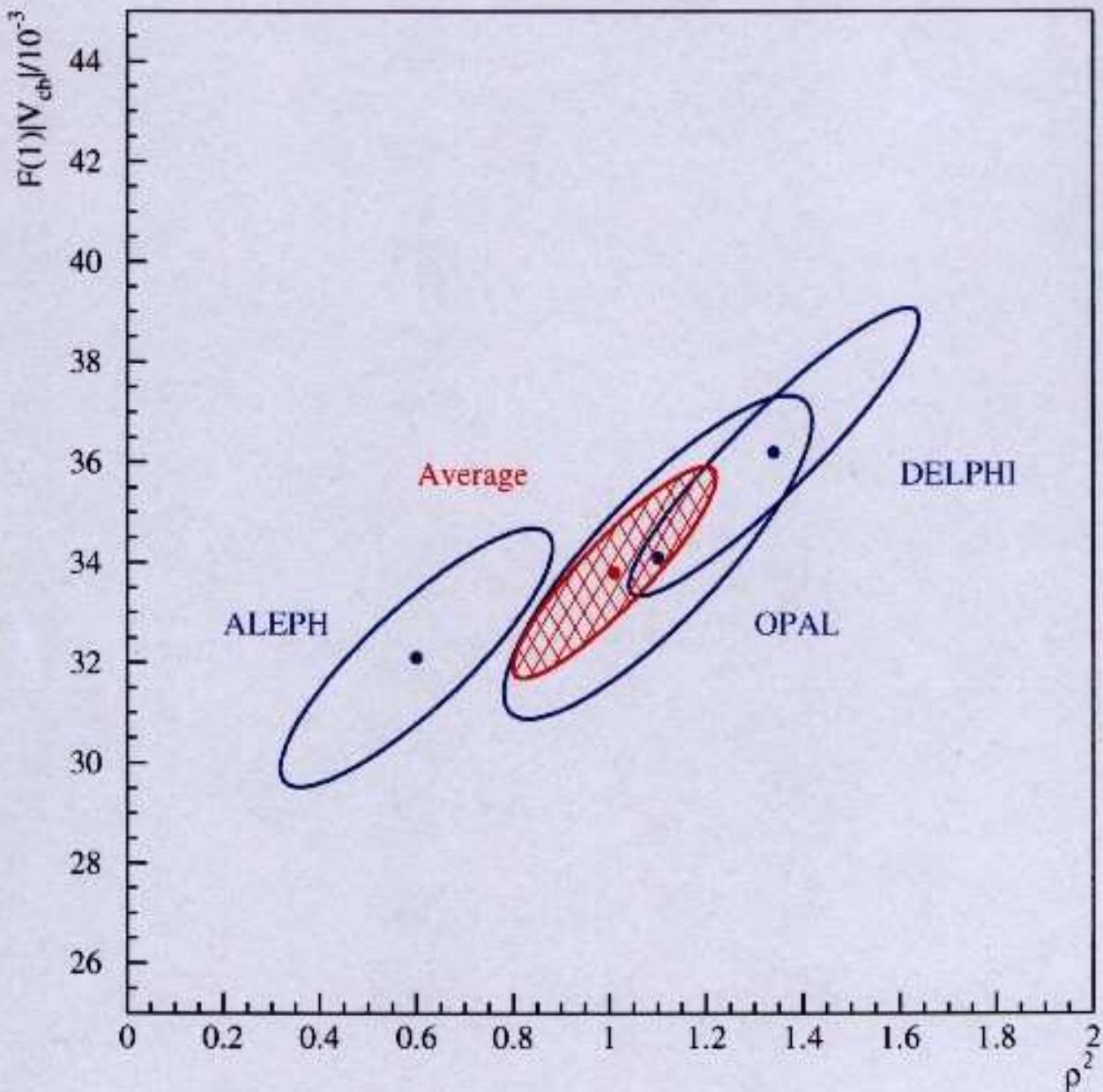
$$F(1)|V_{cb}| = (36.8 \pm 1.6 \pm 2.0) \cdot 10^{-3}$$

$$g^2 = 1.31 \pm 0.21 \pm 0.18$$

V_{cb} exclusive



V_{cb} exclusive



Opal result

Average between the two measurements
(18% correlated - stat)

$$F(1) |V_{cb}| = (37.1 \pm 1.0 \pm 2.0) 10^{-3}$$

$$\rho = 1.21 \pm 0.12 \pm 0.20$$

$F(1) |V_{cb}| - \rho$ correlations:

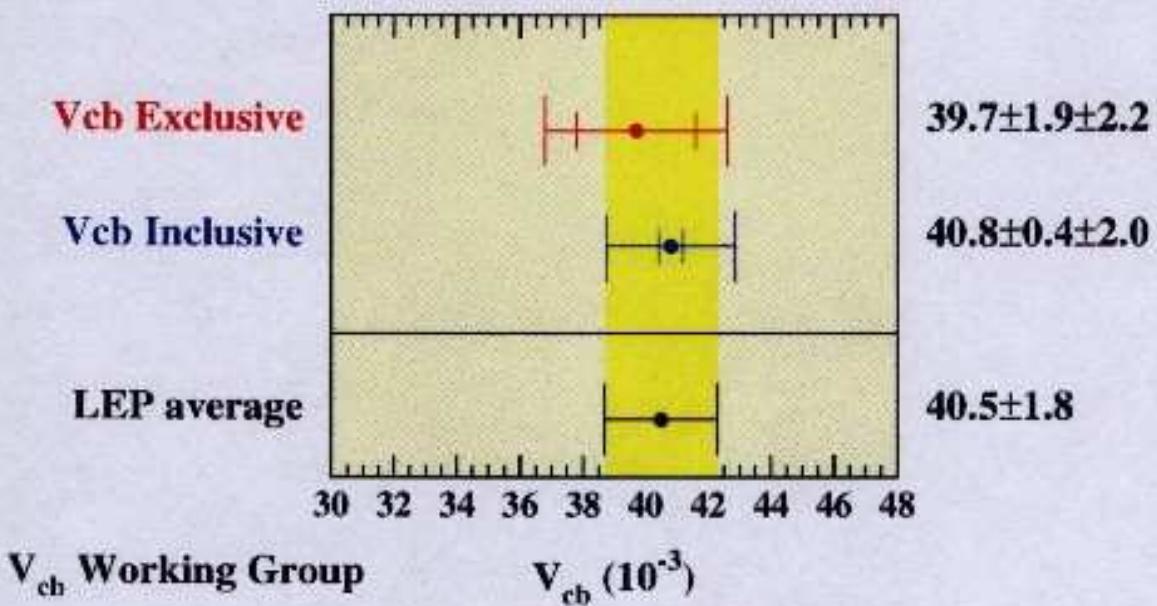
statistical : 0.90

systematics : 0.54

Most precise measurement up to date

Vcb

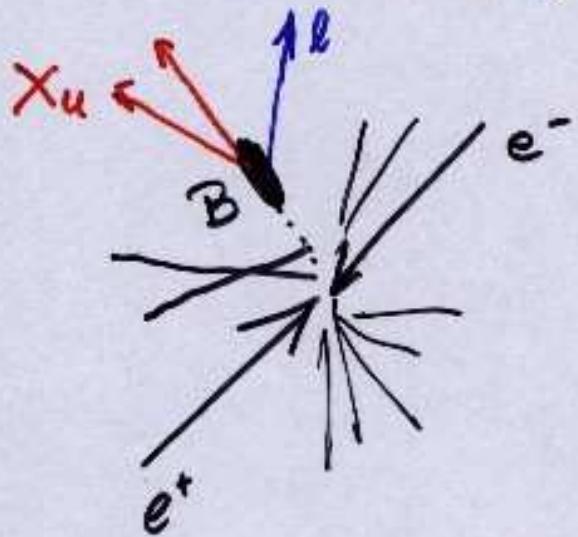
LEP



$$\underline{\text{Br}(b \rightarrow X_u l \bar{\nu})}$$

Unique to LEP

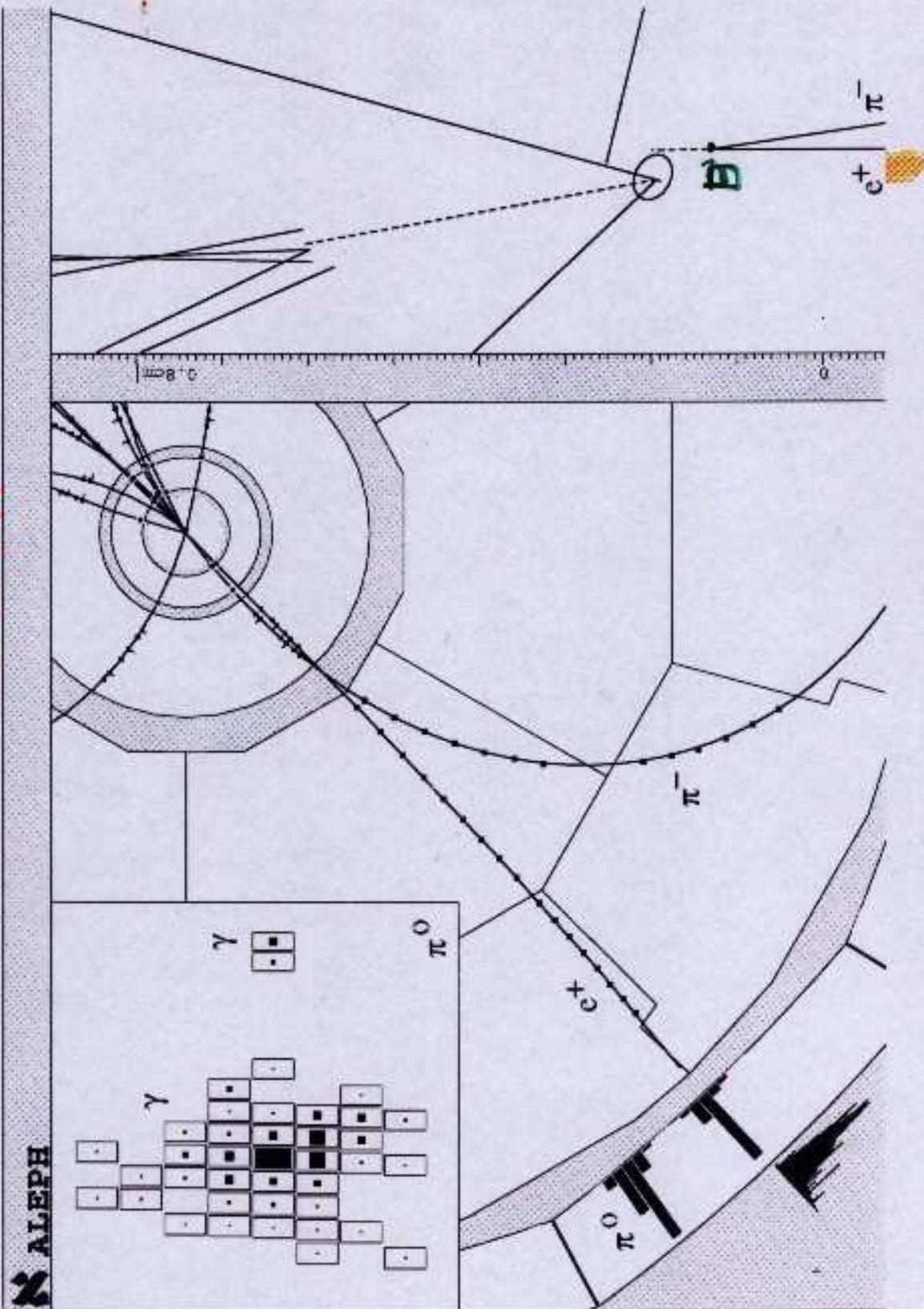
- ① B boosted \Rightarrow B decay products well separated



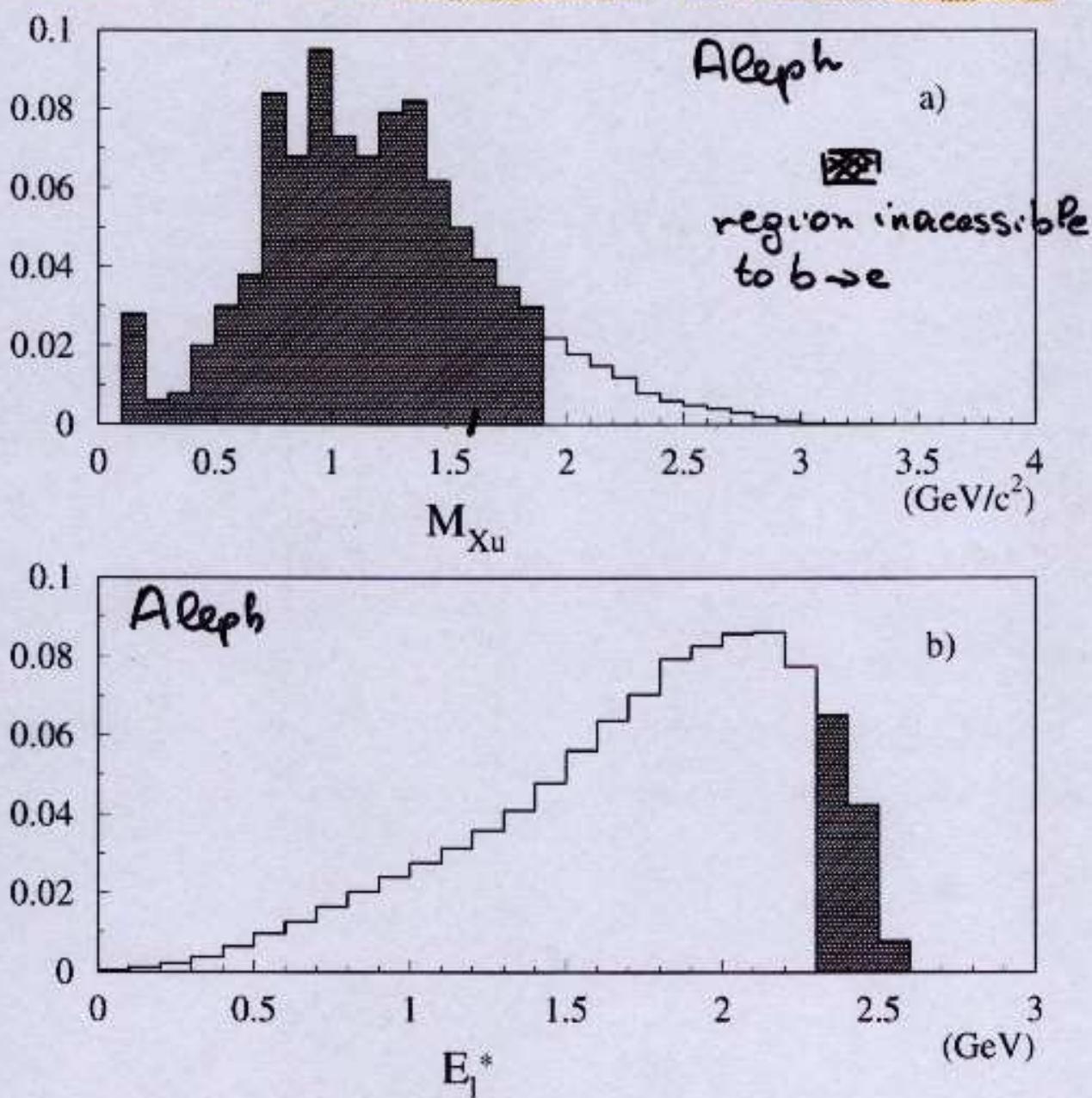
- ② low mass of the hadronic system ($< \sim 4.6 \text{ GeV}$)

higher E_e

$B^0 \rightarrow \ell^- \bar{\nu} \pi^+ \pi^- \gamma \gamma$

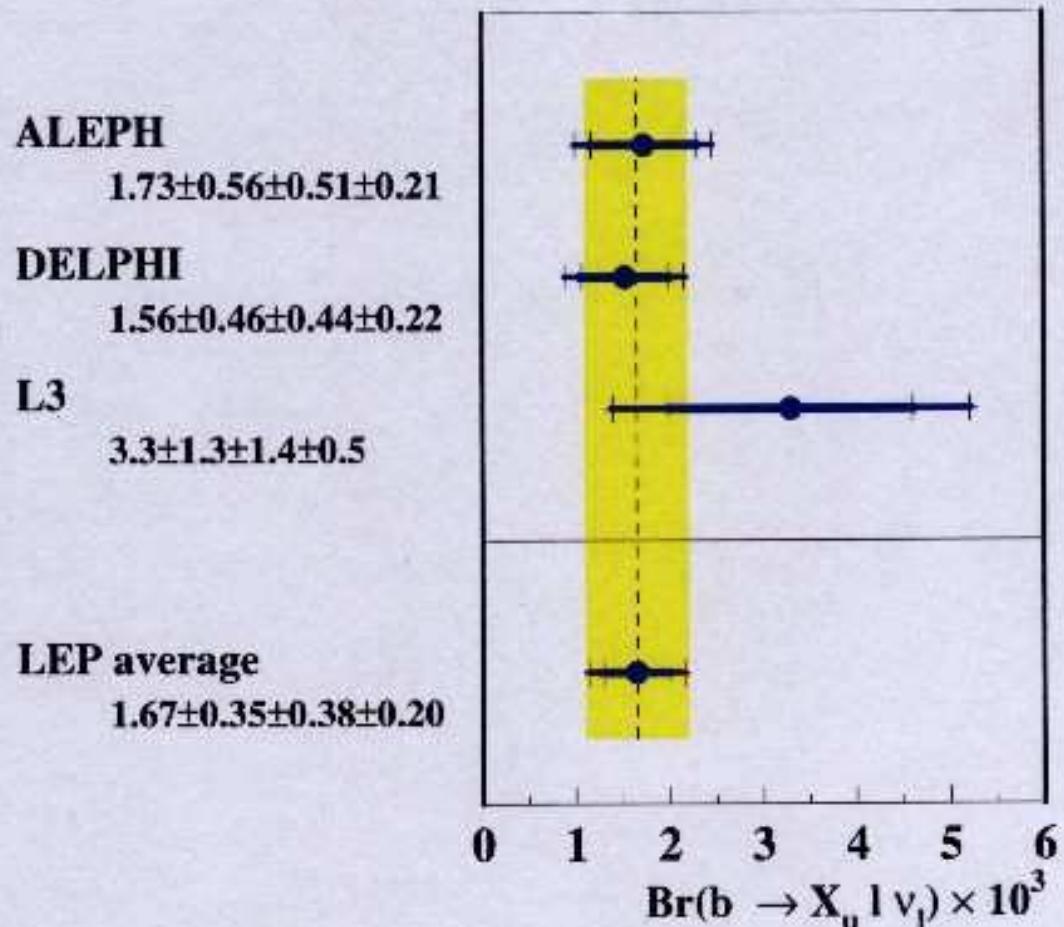


Hadronic mass



$\text{Br}(\mathbf{b} \rightarrow X_u l \nu)$

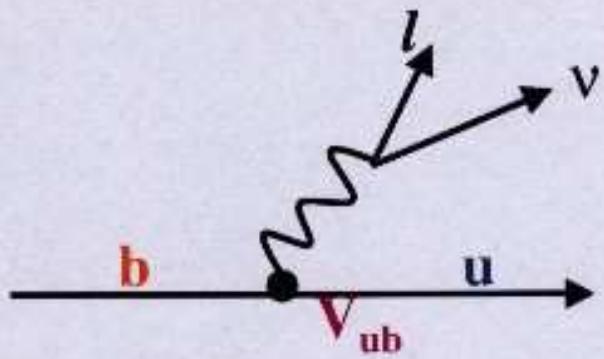
— statistical + detector error
— $b \rightarrow c$ error
— $b \rightarrow u$ modelling error



V_{ub}

LEP \Rightarrow inclusive

τ_b and $\text{Br}(b \rightarrow ulv)$



$$|V_{ub}|^2 = \frac{\text{Br}(B \rightarrow X_u l v)}{\gamma_c \tau_B}$$

$$|V_{ub}| = (4.04^{+1.17}_{-1.71}) \times 10^{-3}$$

CLEO $\Rightarrow B \rightarrow \rho l v$

V_{ub} inclusive \Rightarrow theoretical error more under control

Future \Rightarrow do a global average with CLEO

Conclusions

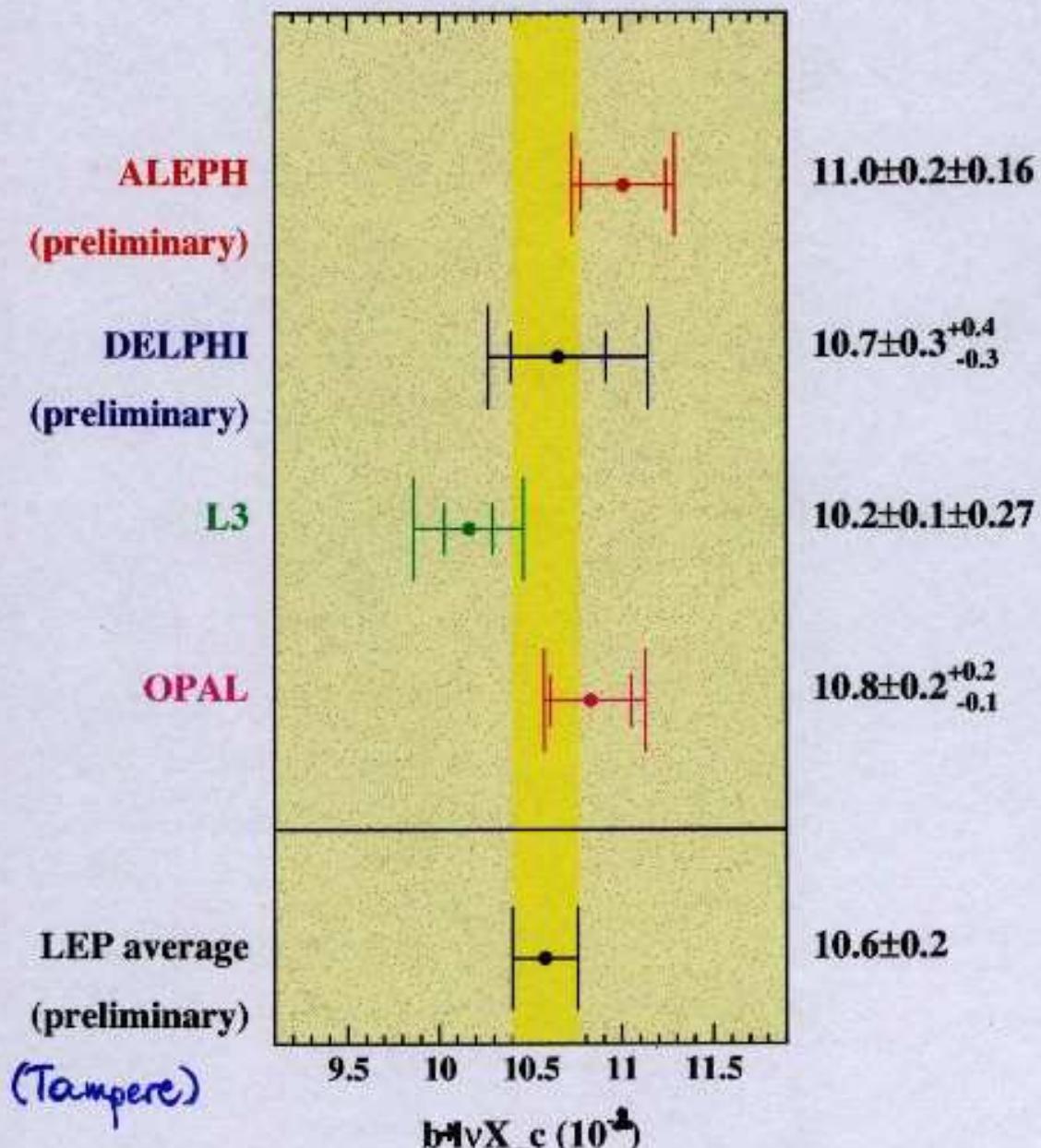
- $b \rightarrow l$ almost final

Aeo promised $b \rightarrow l$ model for
the summer.

- V_{cb} exclusive : Delphi finalize the publ.
understand the D^{**} sys.
 $J(1)$?
average with Aeo

- $b \rightarrow X_u b \bar{v}$: Opal is still missing
 $b \rightarrow c$ systematics
average with Aeo

Final LEP results for middle/end 2001
(big review paper)

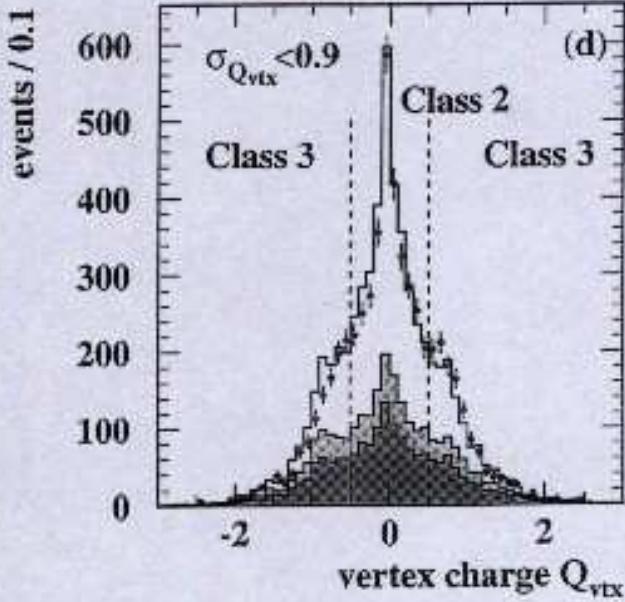
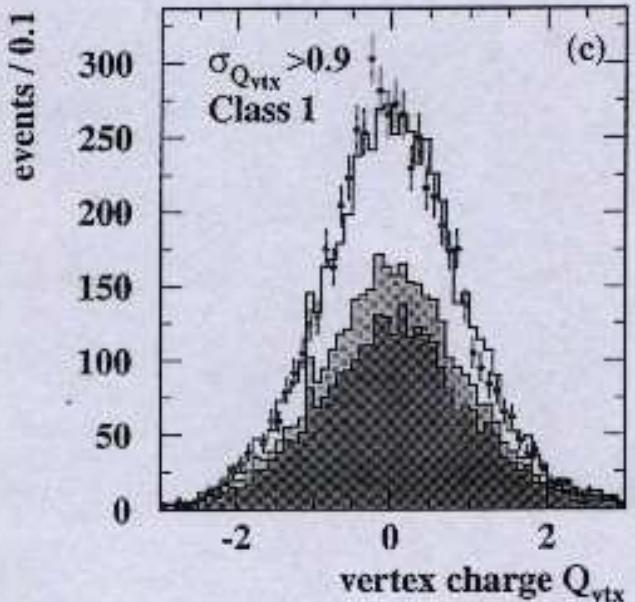
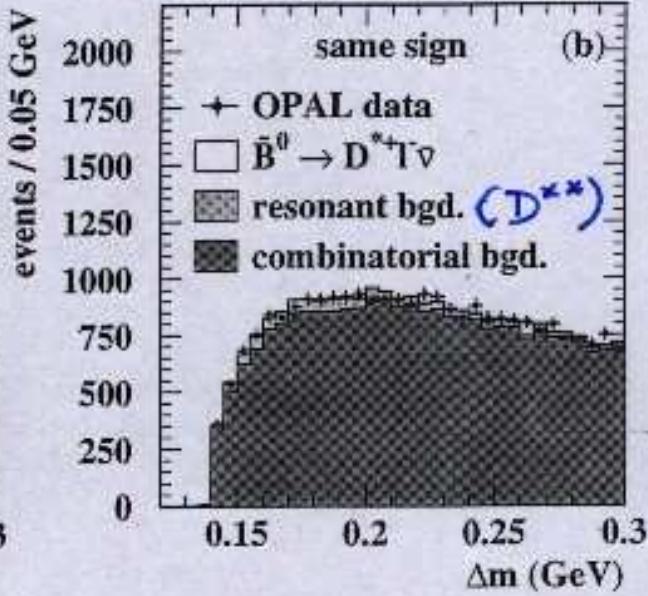
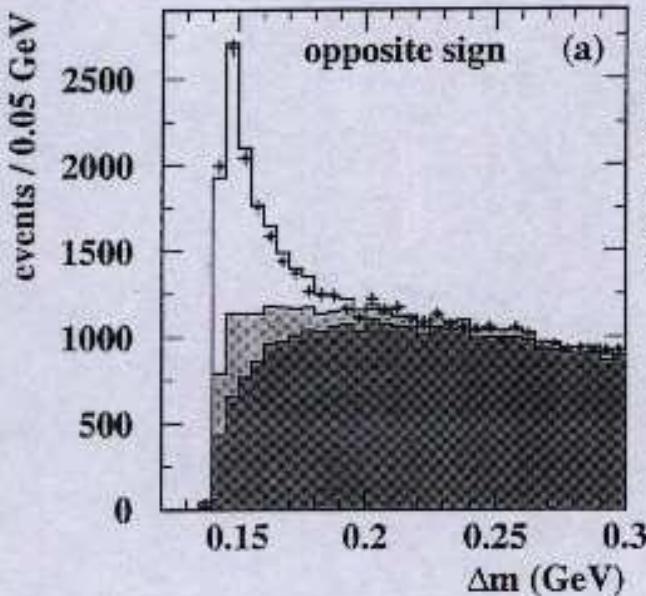
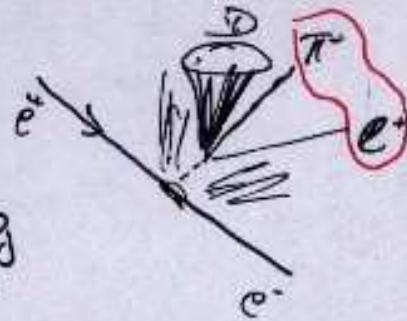


$B^0 \rightarrow D^{*+} l^+ \bar{\nu}$

$\hookrightarrow D^{*+} h^-$

anything

$$\Delta m = m_{D^{*+}} - m_{B^0} \sim m_{\pi^0}$$



Main background

$B \rightarrow D^{*+} l^+ \bar{\nu}$

$\hookrightarrow D^{*+} h^-$ \Rightarrow Vertex charge to have enriched/depleted B^+ samples