

# Heavy Quark Decays

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LEPTON-PHOTON 99

XIX INTERNATIONAL SYMPOSIUM ON  
LEPTON AND PHOTON INTERACTIONS AT HIGH ENERGIES

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[http://www.umn.edu/~poling/HQD\\_LP99.html](http://www.umn.edu/~poling/HQD_LP99.html)

# Outline of this Talk

- The Framework of Heavy Quark Decay
- Semileptonic Decays:  $V_{cb}$  and  $V_{ub}$
- Rare  $B$  Decays
- Interpretation - CKM
- A Bit of Charm
- Summary and Outlook

Not Covered Here:

Production, quarkonia, charmed baryons

Lifetimes, mixing (Blaylock, next)

# Quark Mixing in the Standard Model

- Quark mass eigenstates  $\neq$  weak eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Unitarity, etc.  $\rightarrow$  four fundamental parameters
- These **must** be determined experimentally
- Many observables allow redundant tests, but there are obstacles: strong-interaction effects!

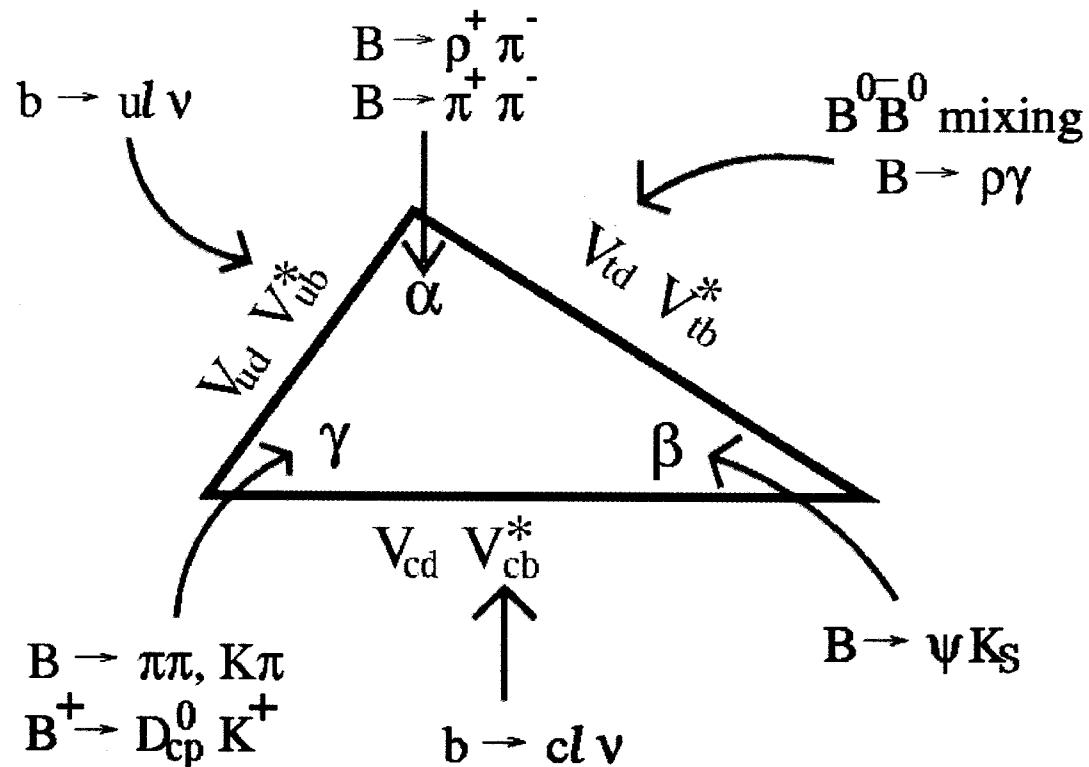
# Wolfenstein's parameterization:

$$V \approx \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

What we know for sure:

$$\lambda = 0.22 \quad A \approx 0.8 \quad \eta \neq 0 \text{ for CP}$$

# The Roadmap



- $\alpha = \arg \left[ -\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right]$
- $\beta = \arg \left[ -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right]$
- $\gamma = \arg \left[ -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right]$

# The Players and their Data

- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ 
  - CLEO II  $3.3 \times 10^6 B\bar{B}$
  - CLEO II.V  $6.4 \times 10^6 B\bar{B}$
  - CESR:  $\mathcal{L} \sim 0.8 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$
- $e^+e^- \rightarrow Z^0$ 
  - LEP:  
ALEPH, DELPHI, L3, OPAL  
each with  $\sim 4M e^+e^- \rightarrow Z^0$ ,  
 $\sim 0.9M b\bar{b}$
  - SLC:  
 $550K Z^0$ ,  $\sim 100K b\bar{b}$
- $e^+e^- \rightarrow c\bar{c}$  at  $\sim 4 \text{ GeV}$ 
  - BEPC & BES
- Tevatron Run I
  - CDF
  - D0

}

$\sim 100 \text{ pb}^{-1} p\bar{p}$
- Fast  $B$ 's, huge cross section but lots of background - lepton triggers and lifetime tags
- FNAL Fixed-Target Charm
  - FOCUS - wide-band  $\gamma$  beam
  - SELEX - 600 GeV  $\Sigma^-$ ,  $\pi^-$ ,  $p$
  - E789 - 800 GeV  $p$
  - E791 - 500 GeV  $\pi^-$

# Semileptonic $B$ Decay

- Still the best (only!) way to determine  $V_{ub}$  and  $V_{cb}$ .

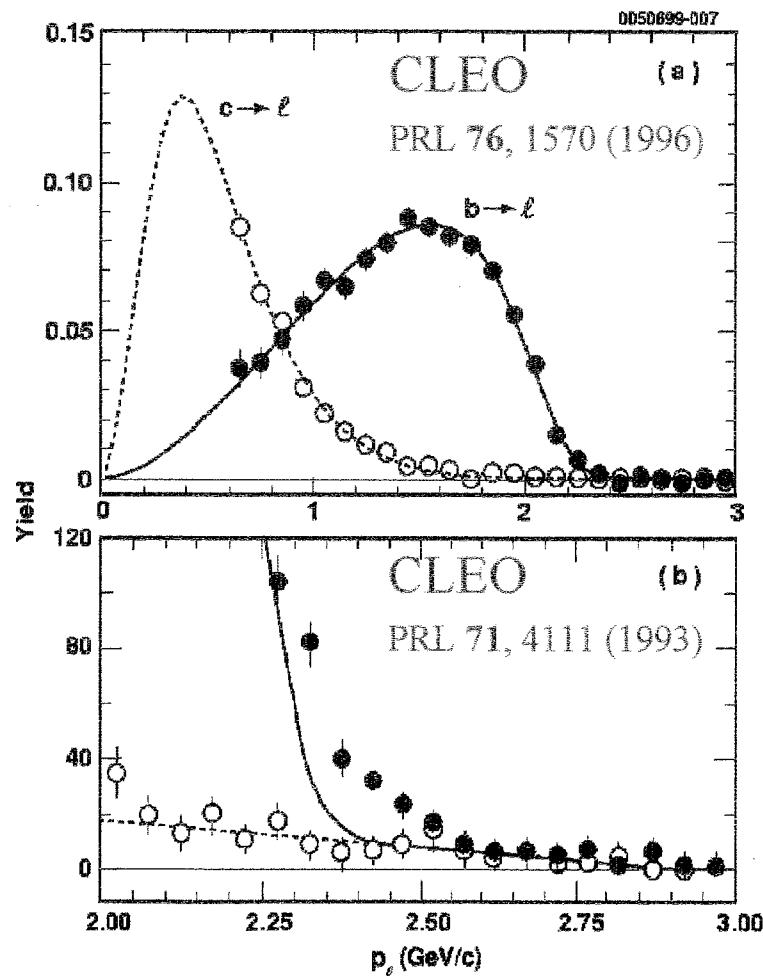
- $b \rightarrow cl\nu$

- Inclusive and exclusive
- Interpretable with HQET
- $|V_{cb}|$  known to  $\sim 6\%$

- $b \rightarrow ul\nu$

- Inclusive is hard to see, hard to interpret
- Exclusive somewhat easier to interpret, experimentally tough
- $|V_{cb}|$  known to  $\sim 15\%$

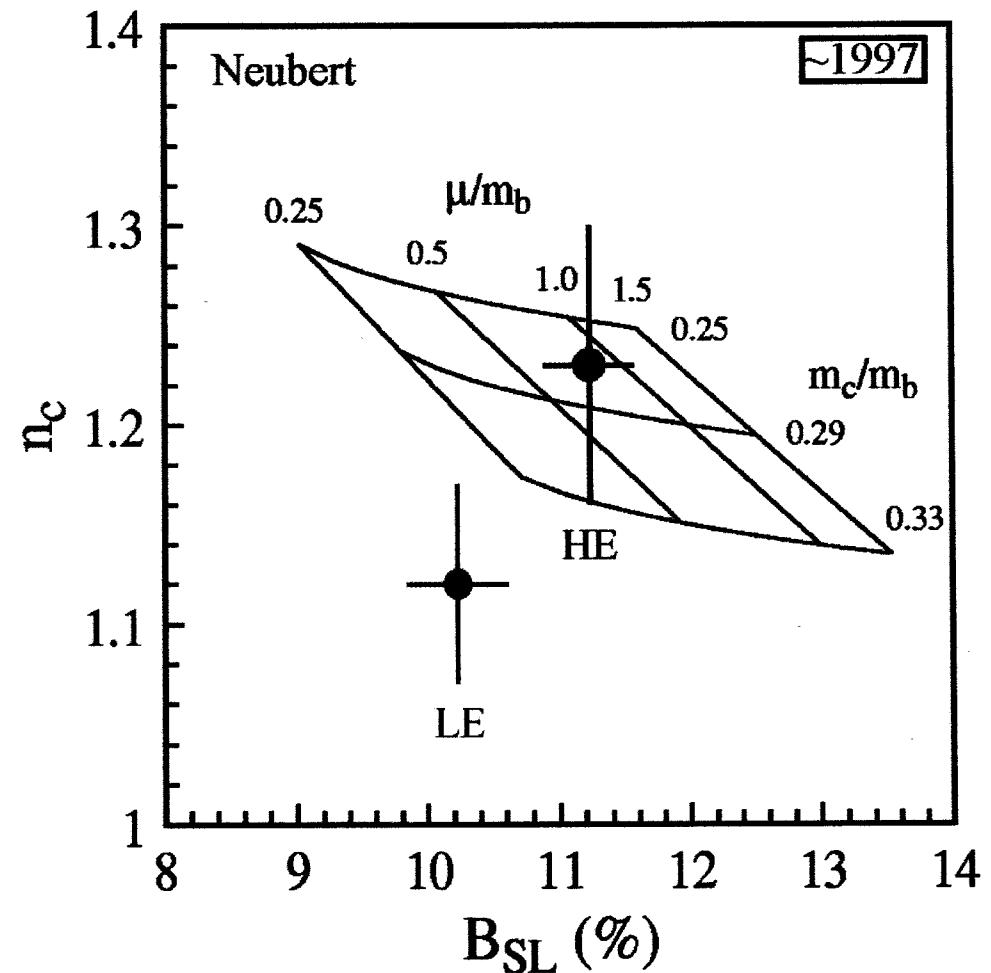
August 19, 1999 15% or so



Ron Poling - Lepton-Photon '99

# So simple, yet so troublesome ...

- Why is the  $B$  semileptonic branching fraction so small?
- Why is the  $B$  semileptonic branching fraction at the  $Z^0$  larger than that at the  $\Upsilon(4S)$ ?

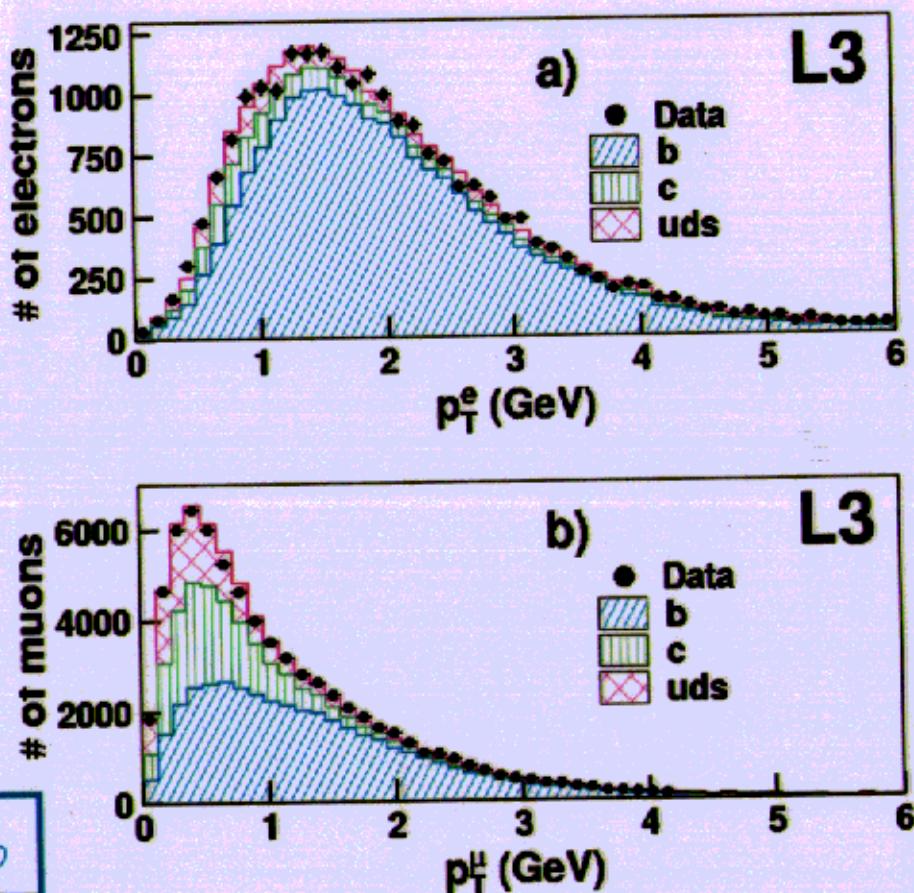


# Measurement of... $\text{Br}(b \rightarrow l\nu X)$ at LEP using Double-Tag Methods

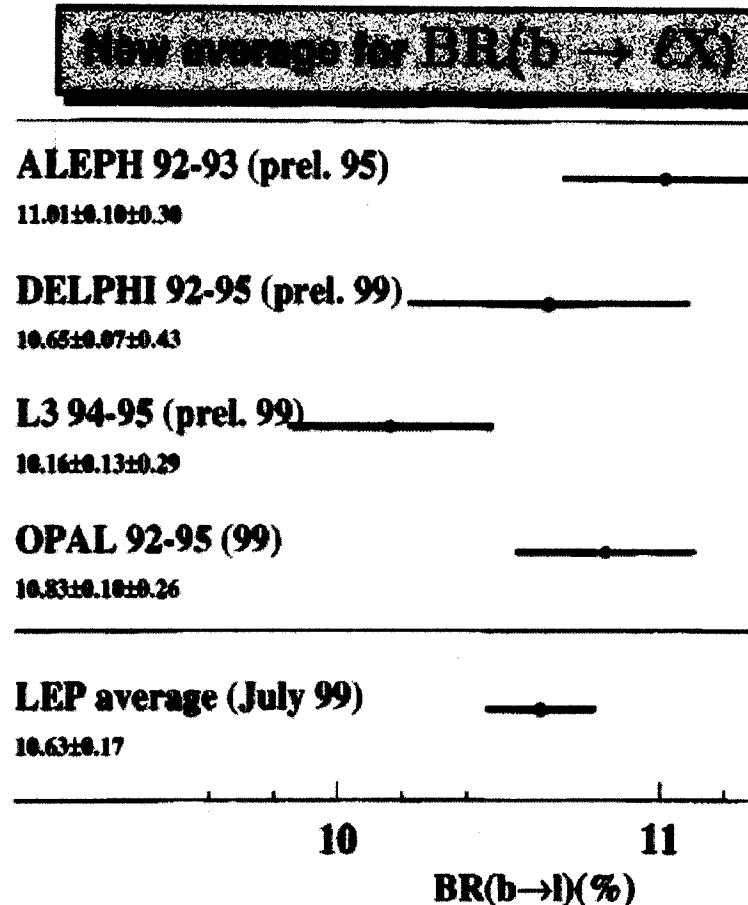
L3 - 1M  $Z^0$   
L3 Note 2420  
EPS Paper 5-282

- Tag hemispheres by
  - big impact parameter
  - high- $p_T$ , lepton
- Determine efficiency in data:
  - fit to five ratios among numbers of single tags, double tags and hadronic events
- Results:  
 $R_b = 0.2174 \pm 0.0015 \pm 0.0028$

$$\mathcal{B}(b \rightarrow Xl\nu) = (10.16 \pm 0.13 \pm 0.27)\%$$



# Pauline Gagnon at EPS/Tampere:



- New EW fit does not include old lepton fits  
 $\rightarrow N_{\text{lepton}} = (\text{BR}(b \rightarrow \ell X) \cdot R_b) / \epsilon_\ell$   
 $\rightarrow -0.95$  correlation between  $\text{BR}(b \rightarrow \ell X)$  and  $R_b$
- Include only b-tagged measurements in global EW fit
- Constraint from  $A_{fb}$  reduces modelling error  
 $\rightarrow \pm 0.09 \rightarrow \pm 0.11$  without  $A_{fb}$  in fit

New LEP-SLD average:  $\text{BR}(b \rightarrow X\ell) = (10.63 \pm 0.17)\%$

# Measurement of... Multiplicity of Charm Quarks per $b$ Decay

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

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

$D_s \rightarrow \phi(1020)\pi^+, \bar{K}^*(892)K^+$

$\Lambda_c \rightarrow pK\pi^+$

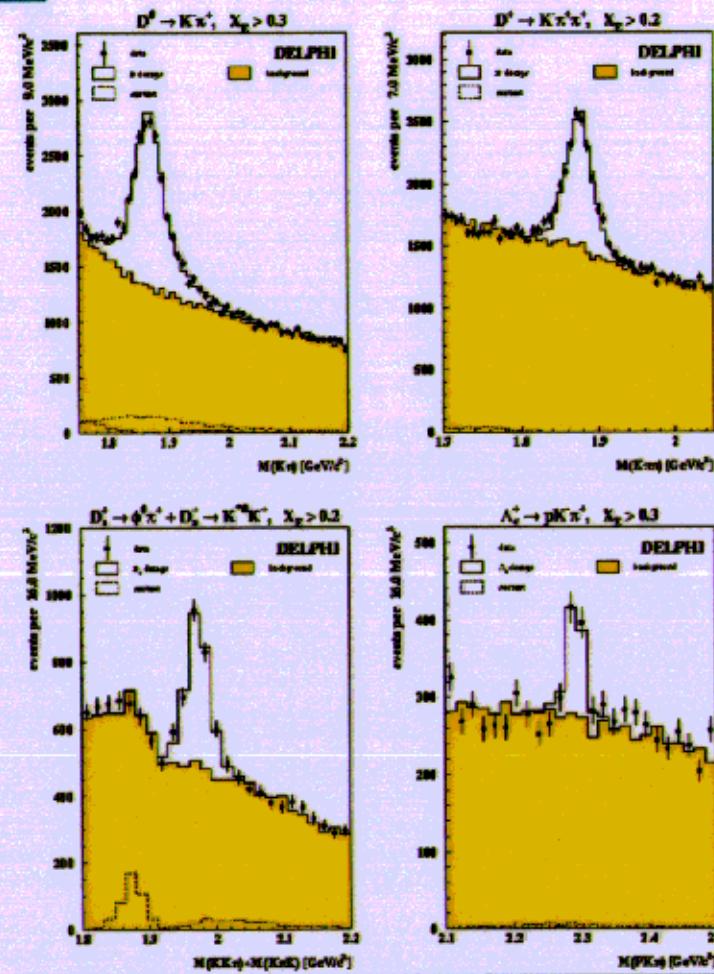
Separate  $b/c$  contributions and obtain yields by fitting scaled energy, impact parameter, resonance mass, PID.

$c \rightarrow D$ : big energy, short flight

$b \rightarrow D$ : small energy, long flight

DELPHI

CERN-EP/99-66

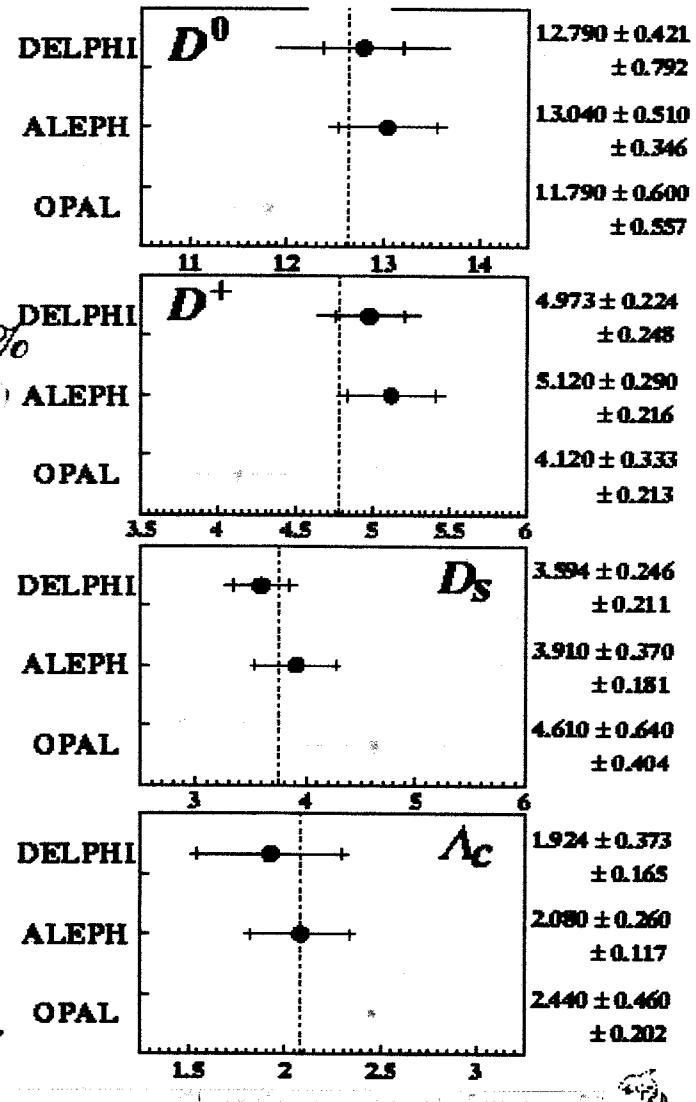


# Markus Elsing at EPS/Tampere:

## Charm counting in $b$ decays

- measured  $R_b^* P(b \rightarrow D)^* \text{BR}(D \rightarrow X)$
- divide by  $R_b^* \text{BR}(b \rightarrow D)^*$  (PDG)
- add 2x measured charmonia  $\sim 4.0 \pm 1.3\%$   
charmonium yields at  $100 \text{ GeV}$ :  $\psi(3770) = 8.7 \pm 1.2\%$ ;  $J/\psi = 3.1 \pm 0.3\%$  (Kubis et al.)
- correct for  $E_c \sim 4.0 \pm 1.6\%$   
use CLEO BR and correct for  $P_X$  and  $\lambda_{gg}$ )
- updated DELPHI result :  
 $n_c = 1.166 \pm 0.031 \pm 0.059 \pm 0.054$  (BR)  
old ALEPH yields :  $n_c = 1.190 \pm 0.034 \pm 0.065$   
old OPAL yields :  $n_c = 1.137 \pm 0.048 \pm 0.084$
- correlated average :  
 $n_c = 1.151 \pm 0.022 \pm 0.022 \pm 0.051$  (BR)

( $\text{CBR}$  not included in plots)  $R_b^* P(b \rightarrow X) [\%]$  →



# Is the $B$ SLBR still *baffling*?

$Z^0$

$$\mathcal{B}(B \rightarrow Xl\nu) = 10.63 \pm 0.17$$

(correct for  $\tau_B/\tau_b$ )

$$n_c = 1.15 \pm 0.04$$

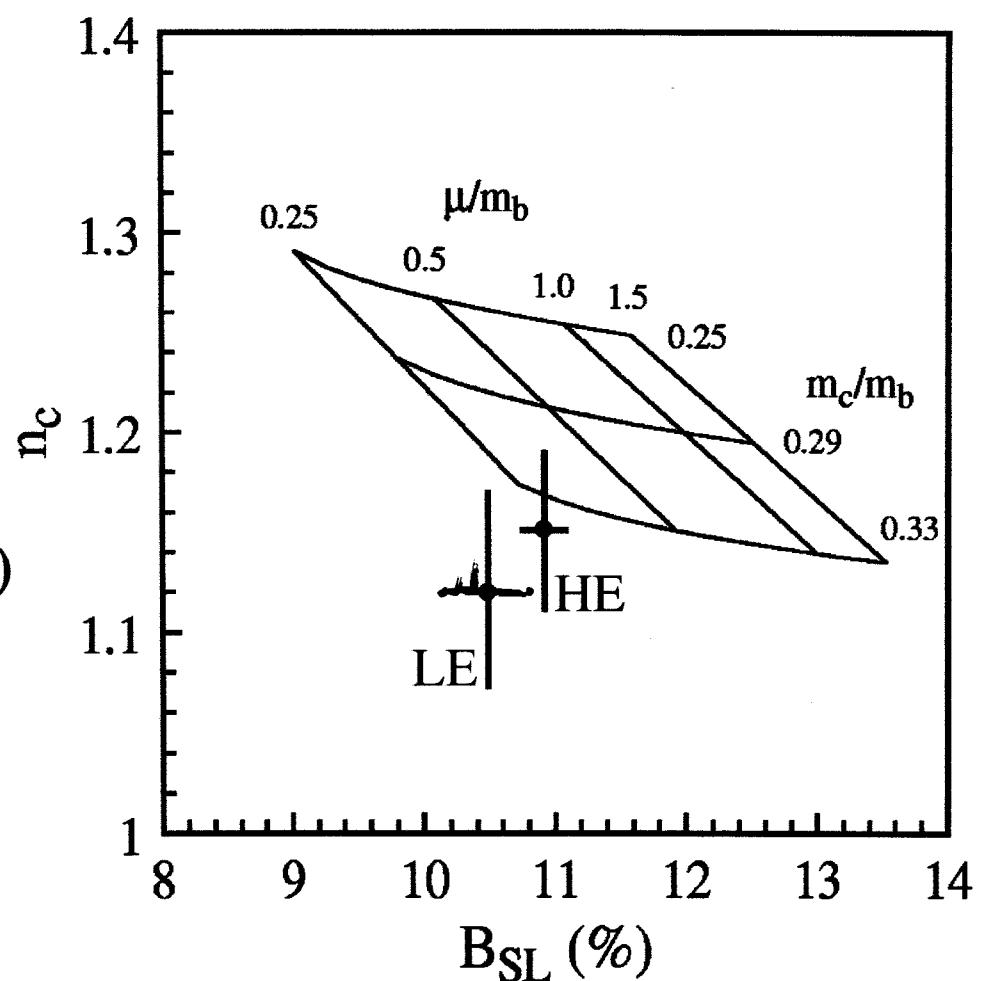
$\Upsilon(4S)$

$$\mathcal{B}(B \rightarrow Xl\nu) = 10.45 \pm 0.21 \text{ (PDG)}$$

$$\mathcal{B}(B \rightarrow Xl\nu) = 10.49 \pm 0.46 \text{ (Tag)}$$

$$n_c = 1.10 \pm 0.05 \rightarrow 1.12 \pm 0.05$$

(with consistent BR's)



$$|V_{cb}| \text{ from } B \rightarrow X_c l \nu$$

$$\mathcal{B}(B \rightarrow X_c l \nu) = \tau \Gamma(B \rightarrow X_c l \nu)$$

HQET + OPE gives  $\Gamma(B \rightarrow X_c l \nu)$ :

$$\Gamma_{SL}(B) = \frac{G_F^2 m_b^5 |V(cb)|^2}{192\pi^3} \left[ z_0 \left( 1 - \frac{\mu_\pi^2 - \mu_G^2}{2m_b^2} \right) - 2 \left( 1 - \frac{m_c^2}{m_b^2} \right)^4 \frac{\mu_G^2}{m_b^2} - \frac{2\alpha_S}{3\pi} z_0^{(1)} + \dots \right]$$

Don't fuss over which SLBR to use!

$$|V_{cb}| = (40. \pm 0.4 \pm 2.0) \times 10^{-3}$$

The fit gives...

$$R_c P_{c \rightarrow X(c)} BR$$

$$R_b Pb_{c \rightarrow X(c)} BR$$

Background normalization ]

$$X_c = D, \Lambda_c$$

Use  $BR$ 's:

| Mode   | branching fraction  |
|--|---------------------|
| $D^0 \rightarrow K^- \pi^+$  | $0.0385 \pm 0.0009$ |
| $D^+ \rightarrow K^- \pi^+ \pi^+$  | $0.090 \pm 0.006$   |
| $D_s^+ \rightarrow \phi(1020) \pi^+$   | $0.036 \pm 0.009$   |
| $\frac{BR(D_s^+ \rightarrow \bar{K}^* K^+)}{BR(D_s^+ \rightarrow \phi \pi^+)}$ | $0.95 \pm 0.10$     |
| $\Lambda_c^+ \rightarrow p K^- \pi^+$  | $0.050 \pm 0.013$   |

and  $R_b = 0.21626 \pm 0.0074$

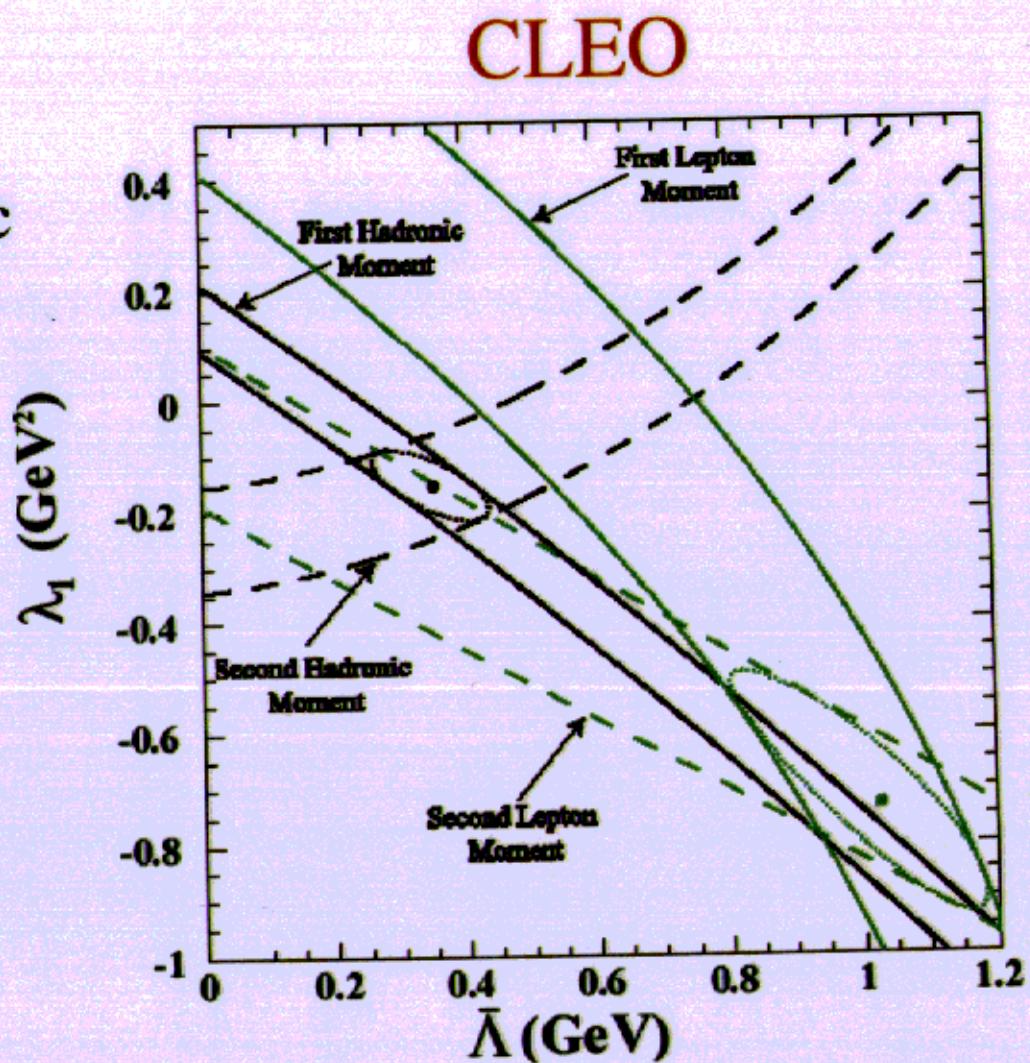
(CLEO info on  $\Xi_c$ )

Result:  $n_c = 1.166 \pm 0.031 \pm 0.059 \pm 0.054$

## Caveat emptor ...

- CLEO fits moments of the lepton energy and hadronic mass spectra.
- Discrepancy between parameter values from the two fits is significant.
- Experimental screwup?  
Need for higher-order treatment? Theory in trouble?

Update (~5 times more data)  
in progress.



$$|V_{cb}| \text{ from } B \rightarrow D^* l \nu$$

HQET tells us that a heavy-light meson decaying at rest really isn't changing at all.

$$\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^3} |V_{cb}|^2 m_{D^*} (m_B - m_{D^*})^2 \mathcal{F}^2(w) \mathcal{G}(w)$$

$$w = (m_B^2 + m_{D^*}^2 - q^2)/(2m_B m_{D^*})$$

Extrapolation to zero-recoil gives

$$\mathcal{F}(1)V_{cb}$$

Add  $\mathcal{F}(1)$  from theory and we're done.

# New precise measurement of $V_{cb}$

DELPHI  
*Preliminary*

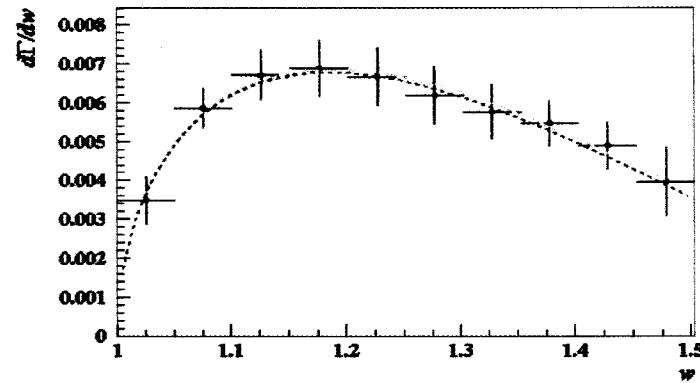
DELPHI 99-107 CONF 294 - Updated by K. Österberg at EPS.

“Inclusive Analysis” -  $B \rightarrow D^* l \nu$  with  $D^{*+}$  identified by soft-pion tag.

~5500 tagged decays

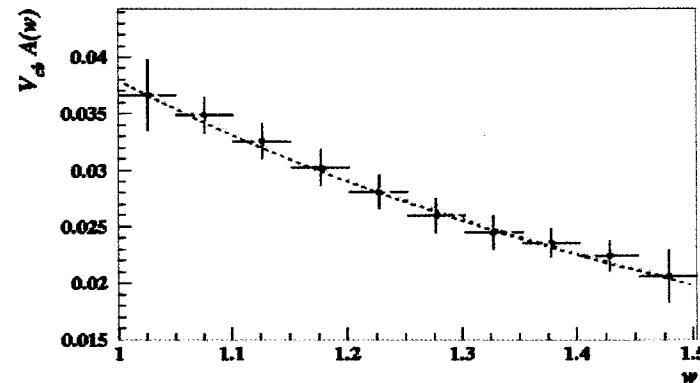
$$F(1) \cdot |V_{cb}| = (36.3 \pm 1.4 \pm 2.5) \times 10^{-3}$$

$$\rho_A^2 = 1.4 \pm 0.1 \pm 0.3$$



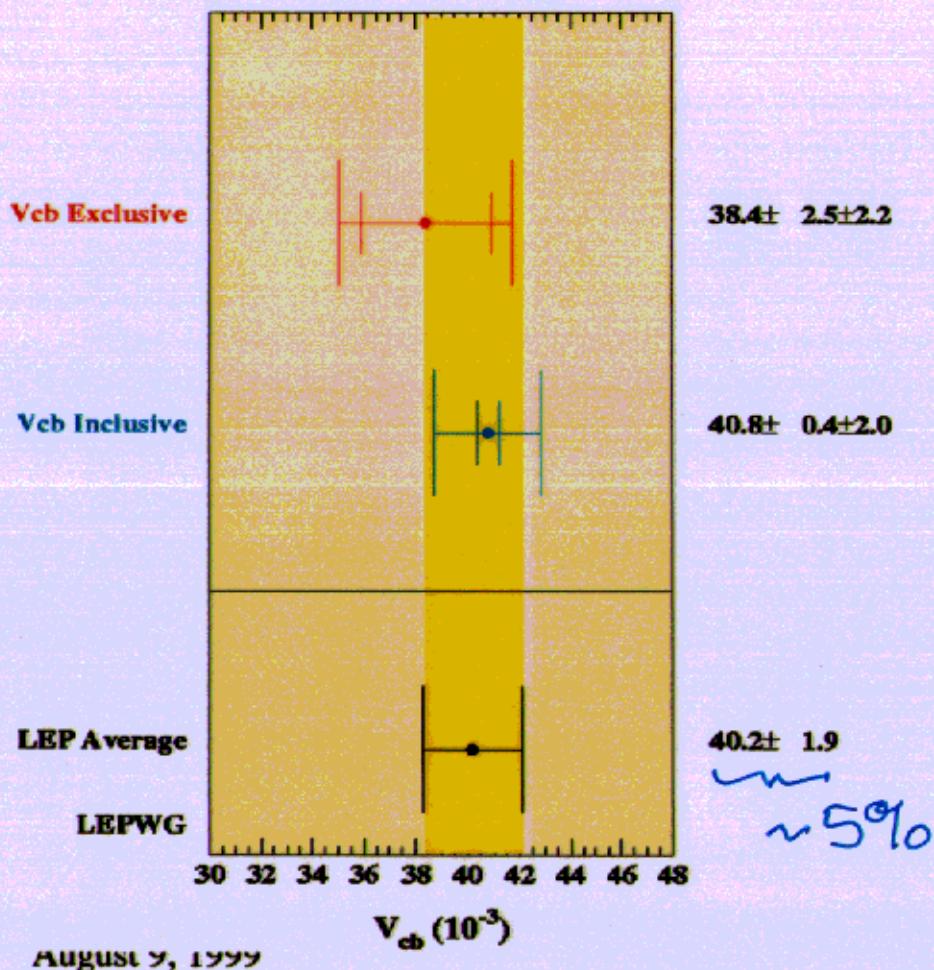
Using  $F(1) = 0.88 \pm 0.08$  (Bigi) gives

$$|V_{cb}| = (41.2 \pm 1.6 \pm 2.8 \pm 2.3) \times 10^{-3}$$



# Summarizing $V_{cb}$

New DELPHI + Updated ALEPH/OPAL  
→ LEP Average



## CLEO Exclusives

$$|V_{cb}| = (40.4 \pm 3.4) \times 10^{-3}$$

(Based on first ~sixth of full CLEO II/II.V data sample)

Deep thinking under way.

⇒ theory errors  
in flux

# Measurement of $B \rightarrow \rho l \nu$ decay and $|V_{ub}|$

CLEO CONF 99-02  
 $3.3 \times 10^6 B\bar{B}$

Exclusive  $b \rightarrow ul\nu$  discovery  
(full reconstruction): PRL 77,  
5000 (1996)

Fit  $E_l$ ,  $\Delta E$ ,  $M(\text{cand})$  to...  
five signal modes +  
other  $b \rightarrow ul\nu$  +  
 $b \rightarrow cl\nu$

This analysis:

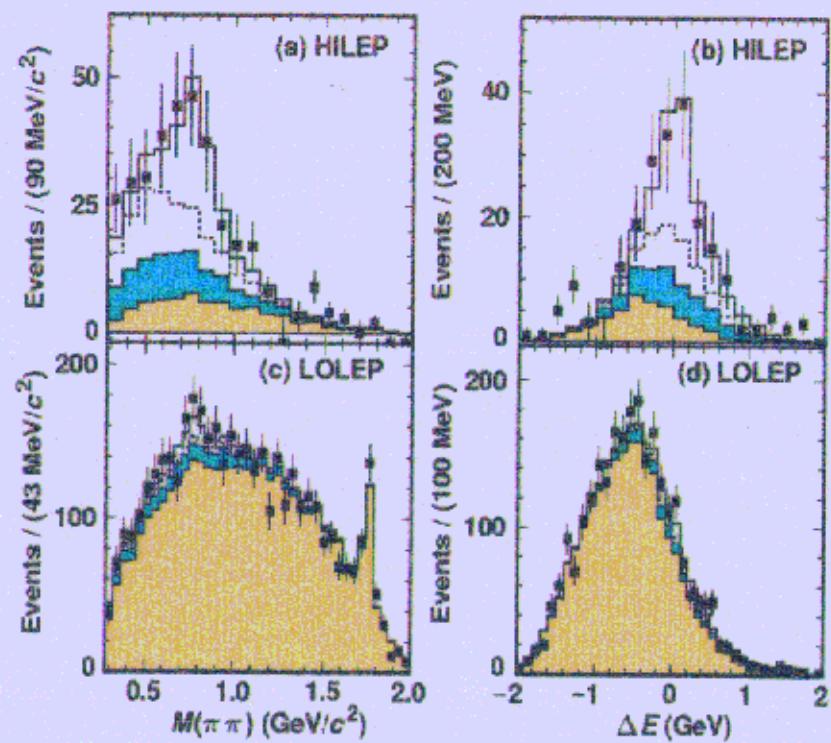
$\pi^+ \pi^0$  ( $\rho^+$ ),  $\pi^+ \pi^-$  ( $\rho^+$ )  
 $\pi^+ \pi^0 \pi^+$  ( $\omega$ )  
 $\pi^+, \pi^0$

+ Leptons  
HILEP: 2.3-2.7 GeV  
LOLEP: 2.0-2.3 GeV

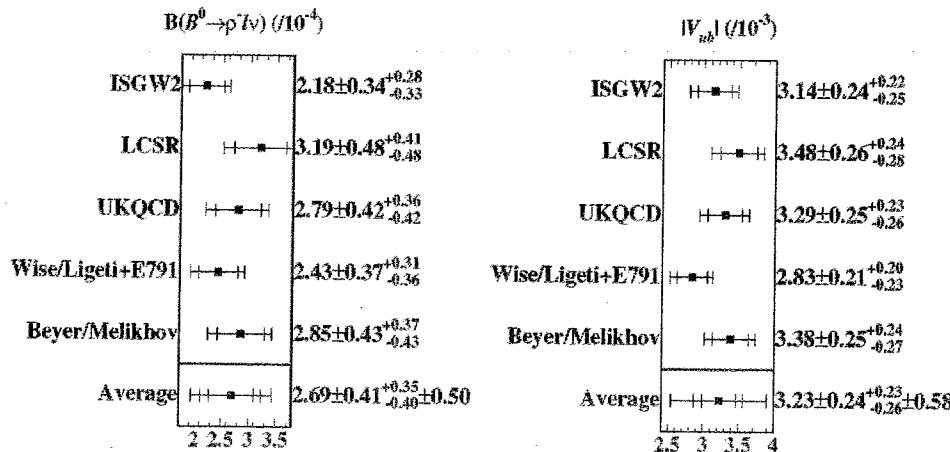
Suppress continuum.

Demand kinematic consistency.

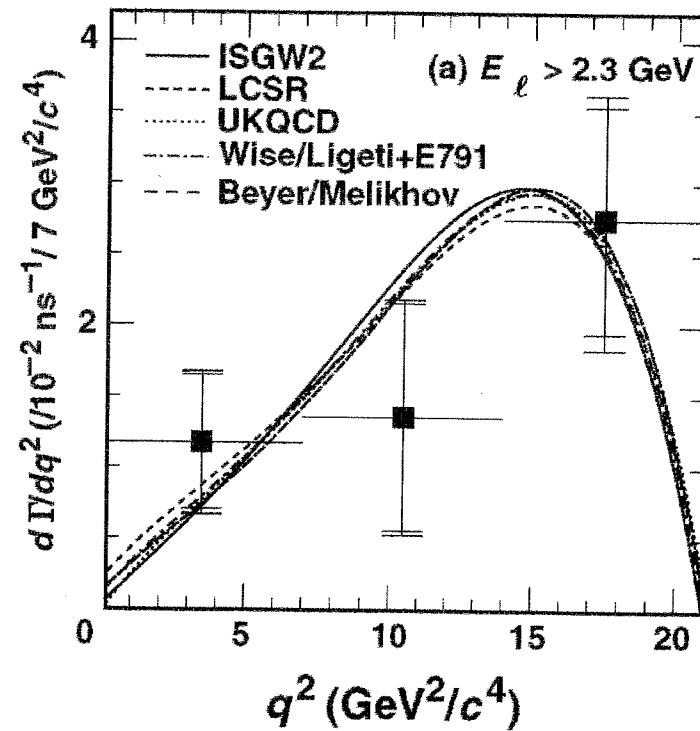
Fit to obtain yields.



# Results



## Measurement of the $q^2$ Distribution for $B \rightarrow \rho l \nu$



Statistically independent of previous measurement, so average:

$$\text{BR}(B^0 \rightarrow \rho^- l^+ \nu) = (2.57 \pm 0.29^{+0.33}_{-0.46} \pm 0.41) \times 10^{-4}$$

$$|V_{ub}| = (3.25 \pm 0.14^{+0.21}_{-0.29} \pm 0.55) \times 10^{-3}$$

$$\text{CLEO Inclusive: } |V_{ub}| = (3.2 \pm 0.8) \times 10^{-3}$$

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# LEP Measurements of $b \rightarrow ulv$

ALEPH

Eur. Phys. J. **C6**, 55 (1999)

DELPHI

EPS HEP '99 Paper 4\_521

(DELPHI 99-10 CONF 297)

L3

PL **B436**, 174 (1998)

## General Approach:

Boost  $\Rightarrow$

End-point not well defined in lab

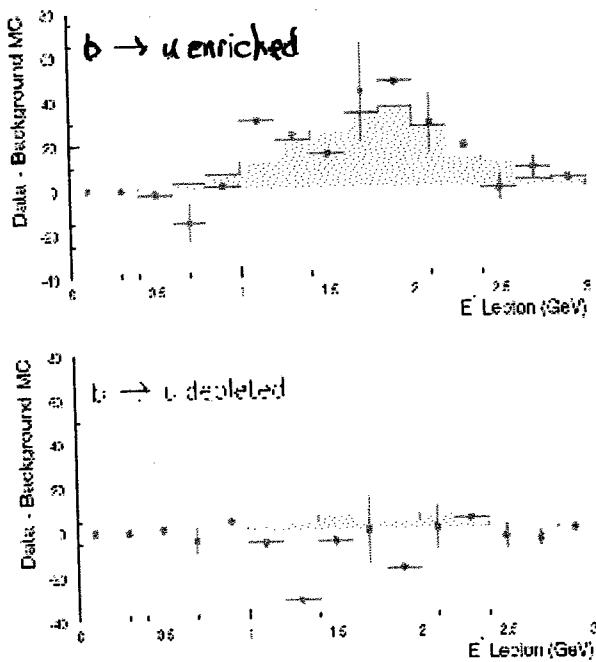
Decay products fast-moving and well separated.

Reconstruct (charmless) hadronic mass  $m_X$  in  $b \rightarrow Xlv$ .

Make sample enriched in  $b \rightarrow u$  by demanding  $m_X < \sim 1.6 \text{ GeV}/c^2$ .

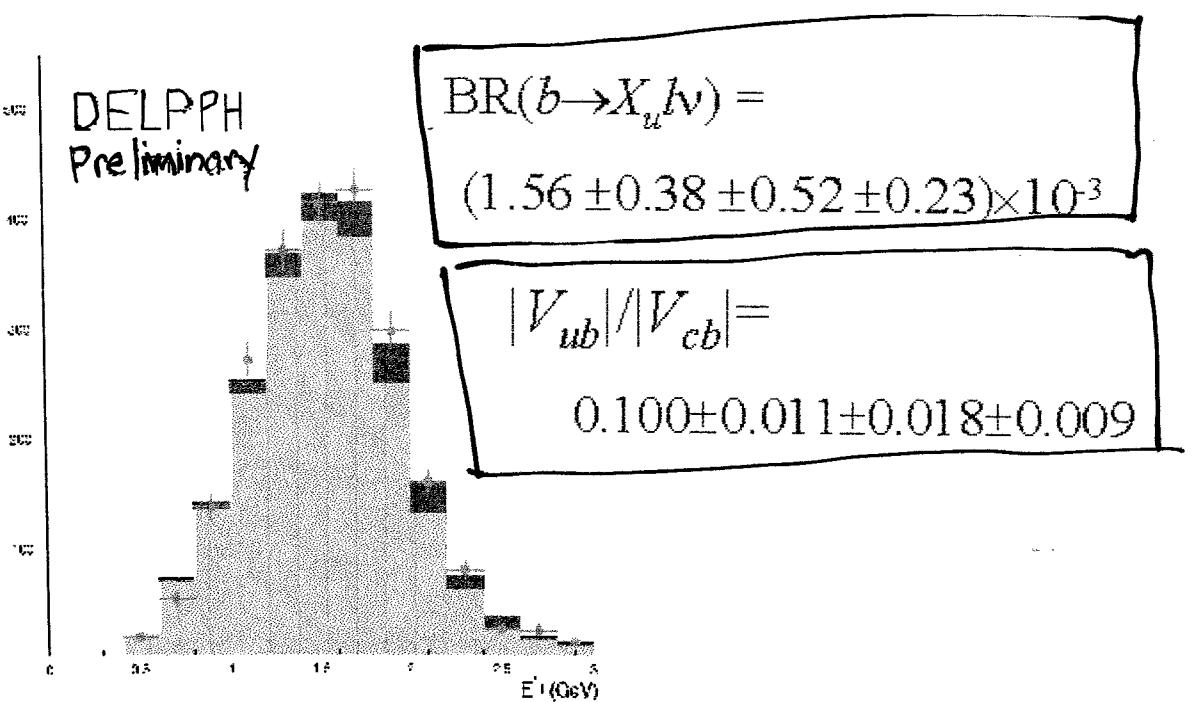
# Measurement of $\text{BR}(b \rightarrow X_u l \nu)$ and Determination of $|V_{ub}|/|V_{cb}|$ with DELPHI at LEP

EPS HEP '99  
Paper 4\_521  
*Preliminary*



Select  $b \rightarrow u$ -enriched sample with cut on  $m_x$ .

Fit  $E_l^*$  distribution of  $b \rightarrow u$ -enriched sample to get yields.



# LEP $|V_{ub}|$ Summary

M. Battaglia  
K. Österberg (EPS)  
LEP  $|V_{ub}|$  Working Group

Combine the three measurements with weights chosen to optimize the overall precision, accounting for correlations.

$$\text{BR}(b \rightarrow X_u l \bar{\nu}) = (1.67 \pm 0.35 \pm 0.38 \pm 0.20) \times 10^{-3}$$

From this result  $|V_{ub}|$  is extracted, with theoretical guidance (Bigi; Uraltsev *et al.*; Hoang, Ligeti and Manohar):

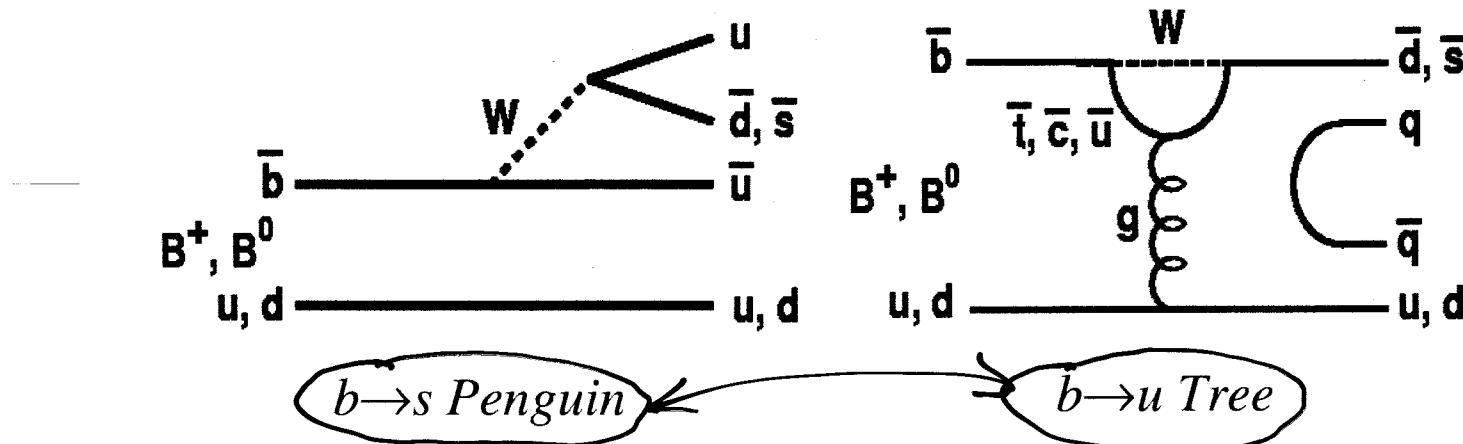
$$|V_{ub}| = (4.05 \pm 0.62) \times 10^{-3} \text{ (1-}\sigma\text{ conf. interval)}$$

*or*

$$|V_{ub}| = (4.05 \pm 1.17) \times 10^{-3} \text{ (2-}\sigma\text{ conf. interval)}$$

# Charmless Hadronic $B$ Decays

Principal processes:



- Modes relevant to  $\mathcal{CP}$  searches ( $\pi\pi, \pi\rho$ )
- Potential for direct  $\mathcal{CP}$  in penguin/tree interference
- The unexpected
- New searches /measurements from ...
  - CLEO
  - ALEPH
  - CDF

# Overview of CLEO Charmless Hadronic *B* Decay Measurements

- Updates to full data sample:  $9.7 \times 10^6 B\bar{B}$  for many modes
- Tools of the trade:
  - Beam-constrained mass:  $M_B = \sqrt{E_{beam}^2 - \vec{p}_B^2}$   $\sigma(M_B) \approx 2.5 \text{ MeV}/c^2$
  - Candidate energy:  $\Delta E = E_1 + E_2 - E_{beam}$   $\sigma(\Delta E) \sim 15\text{-}25 \text{ MeV}$
  - Continuum suppression:  $e^+e^- \rightarrow q\bar{q}, q \neq b$ 
    - Event-shape cuts, “linear multivariate discriminant”
  - Signal-specific cuts: resonance mass, particle ID, helicity angle

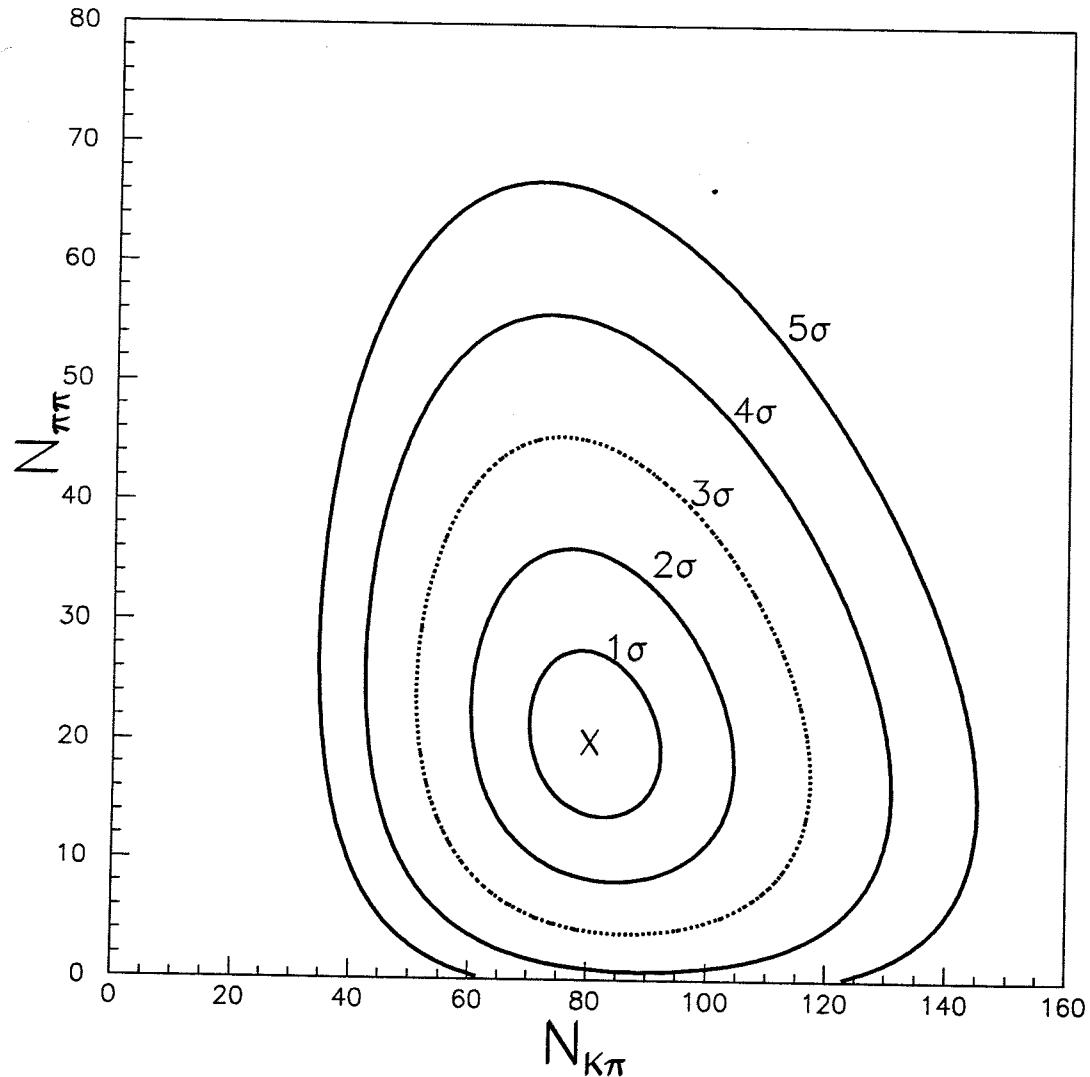
# Extraction of Signals

- $|\Delta E| < 200 \text{ MeV}$  or  $300 \text{ MeV}$
  - $5.2 < M_B < 5.3 \text{ GeV}$
  - $|\cos \theta_{\text{spher}}| < 0.8$  or  $0.9$
  - Loose resonance mass, PID cuts
- ] Loose cuts -  
include sidebands

Yields are obtained from unbinned ML fits to  $\sim 7$  variables.  
Include all relevant signal components, and background if  
nonnegligible. Shapes from MC or data.

Also do cut-and-count analyses for confirmation.

$\bar{B}^0 \rightarrow K^+ \pi^-$ ,  $\pi^+ \pi^-$ ,  $K^+ K^-$   $\times$   
 { { {  
 11.7 $\sigma$  4.2 $\sigma$  no evidence



# Confidence checks . . .

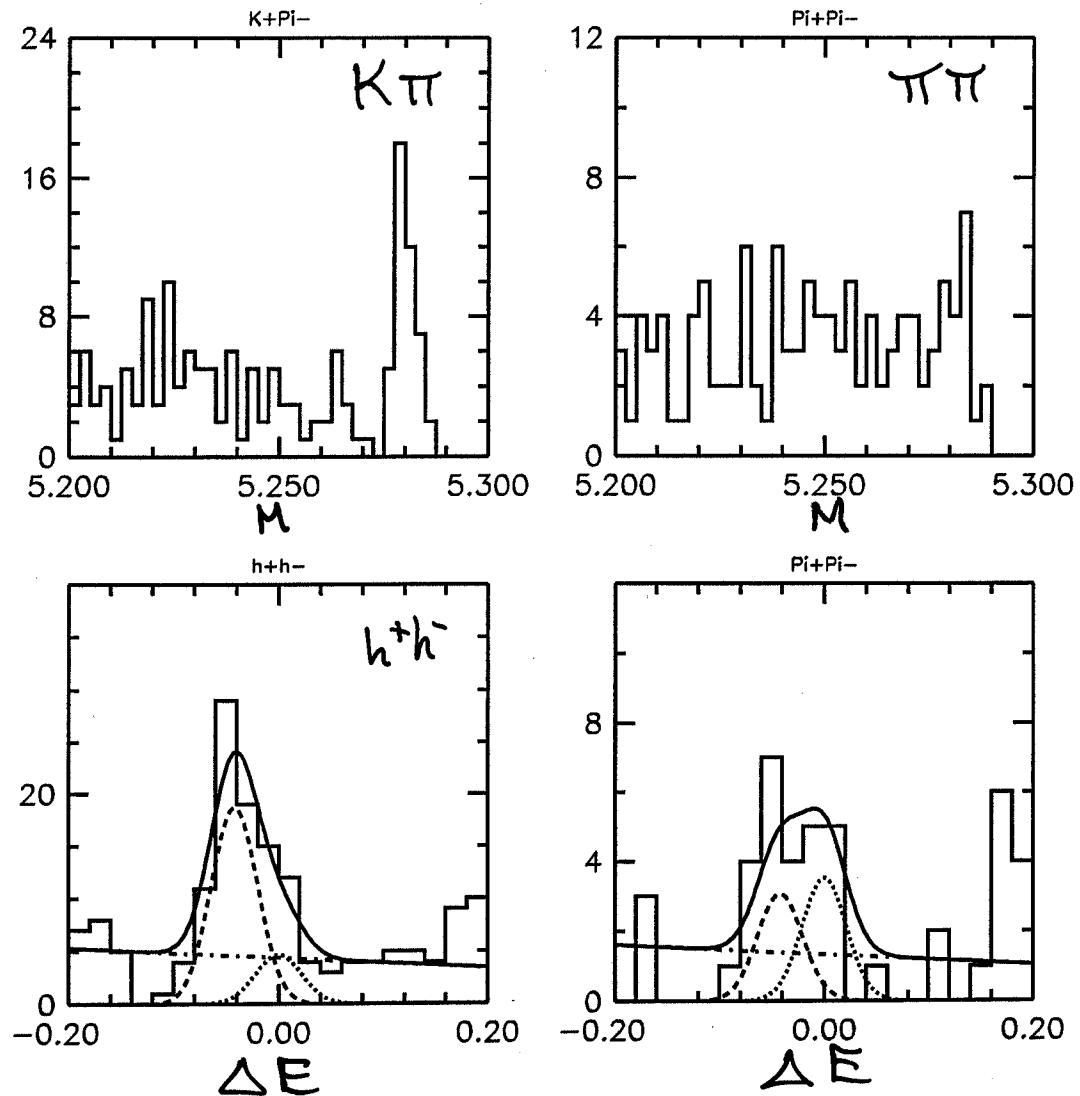


FIG. 3. Projections of  $K\pi$  and  $\pi\pi$  events onto  $M$  and  $\Delta E$  with cuts. Upper left:  $M$  distribution of  $K\pi$ -like events; upper right:  $M$  distribution of  $\pi\pi$ -like events. Lower left:  $\Delta E$  distribution of events prior to  $\pi\pi$  vs  $K\pi$  vs  $KK$  selection according to  $dE/dx$ ; Lower right:  $\Delta E$  distribution of events that are more likely to be  $\pi\pi$  than  $K\pi$  or  $KK$  based on  $dE/dx$ . Overlays in the lower plots are the results of the likelihood fit scaled by the efficiency of the cuts used to project into these plots. Solid line: total fit; dashed:  $K\pi$ ; dotted:  $\pi\pi$ ; dot-dash: continuum background.

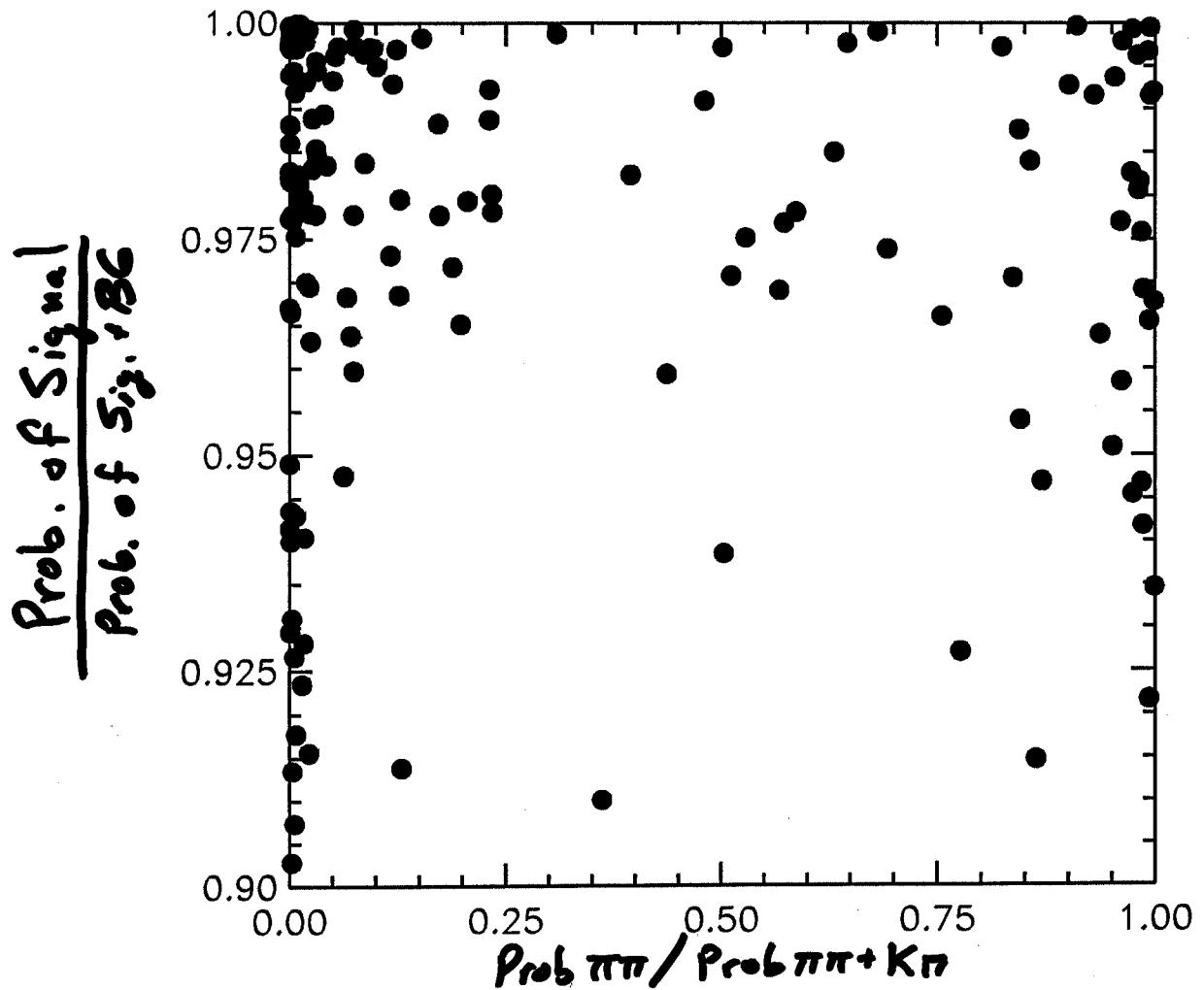


FIG. 4. The horizontal axis shows  $P_{\pi\pi}^s / (P_{\pi\pi}^s + P_{K\pi}^s)$  while the vertical axis depicts  $(P_{\pi\pi}^s + P_{K\pi}^s) / (P_{\pi\pi}^s + P_{K\pi}^s + P_{\pi\pi}^c + P_{K\pi}^c + P_{KK}^c)$ . Superscript *s* and *c* stand for signal and continuum background, respectively. Signal events cluster near the top of the figure, and separate into  $K\pi$ -like events on the left and  $\pi\pi$ -like events on the right.

# Summary of $B \rightarrow \pi\pi/K\pi/KK$

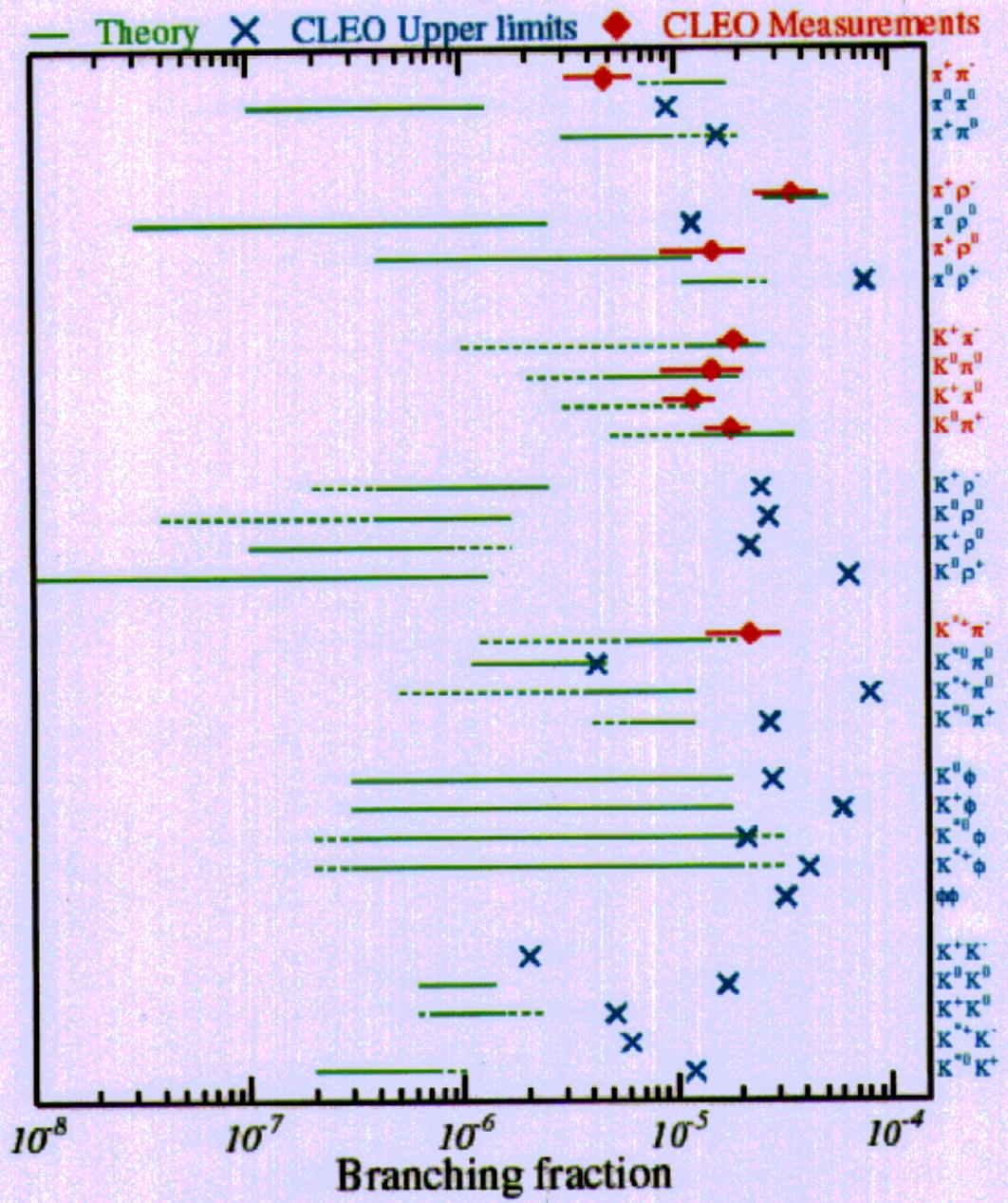
Full CLEO II + II.V Sample

TABLE I. Experimental results. Branching fractions ( $\mathcal{B}$ ) and 90% C.L. upper limits are given in units of  $10^{-6}$ . The errors on  $\mathcal{B}$  are statistical and systematics respectively. Reconstruction efficiency  $\mathcal{E}$  includes branching fractions of  $K^0 \rightarrow K_S^0 \rightarrow \pi^+\pi^-$  and  $\pi^0 \rightarrow \gamma\gamma$ . We quote the central value branching fraction in  $\pi^\pm\pi^0$  for convenience only. The statistical significance of the excess above background in this final state is insufficient for a first observation of this decay mode.

| Mode                   | $\mathcal{E}(\%)$ | $\mathcal{B}_{fit}(10^{-6})$ | Signif.(std.dev.) | $\mathcal{B}(10^{-6})$       |
|------------------------|-------------------|------------------------------|-------------------|------------------------------|
| $\pi^+\pi^-$           | 45                | $4.7^{+1.8}_{-1.5}$          | 4.2               | $4.7^{+1.8}_{-1.5} \pm 0.6$  |
| $\pi^+\pi^0$           | 41                | $5.4^{+2.1}_{-2.0} \pm 1.5$  | 3.2               | < 12                         |
| $K^+\pi^-$             | 45                | $18.8^{+2.8}_{-2.6}$         | 11.7              | $18.8^{+2.8}_{-2.6} \pm 1.3$ |
| $K^+\pi^0$             | 38                | $12.1^{+3.0}_{-2.8}$         | 6.1               | $12.1^{+3.0+2.1}_{-2.8-1.4}$ |
| $K^0\pi^+$             | 14                | $18.2^{+4.6}_{-4.0}$         | 7.6               | $18.2^{+4.6}_{-4.0} \pm 1.6$ |
| $\rightarrow K^0\pi^0$ | 11                | $14.8^{+5.9}_{-5.1}$         | 4.7               | $14.8^{+5.9+2.4}_{-5.1-3.3}$ |
| $K^+K^-$               | 45                |                              | 0.                | < 2.0                        |
| $K^+\bar{K}^0$         | 14                |                              | 1.1               | < 5.1                        |

August 9, 1999

## $K\pi$ Summary

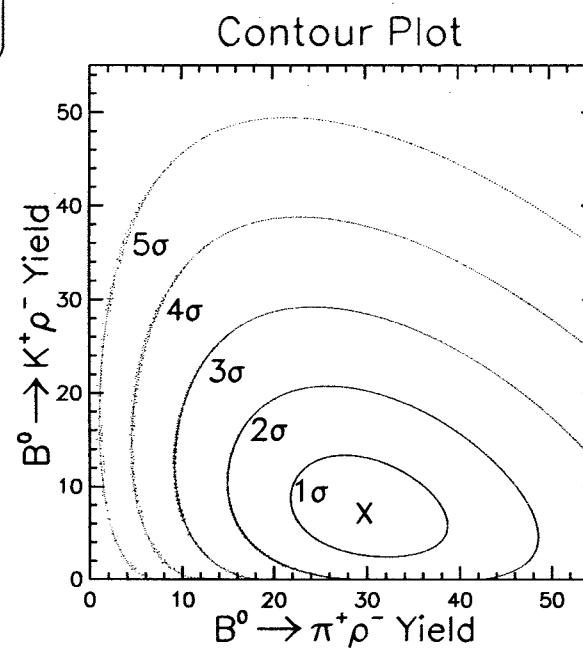


$B^0 \rightarrow \rho^\pm \pi^\mp, \rho^\pm K^\mp$

$7.0 \times 10^6 B\bar{B}$

$$N(\rho^\pm \pi^\mp) = 29.7^{+8.9}_{-7.9}$$

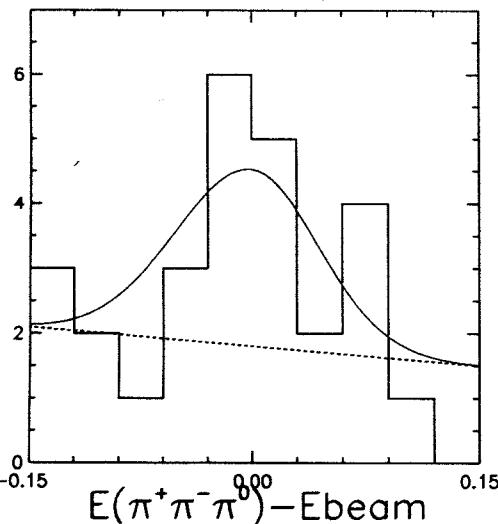
$$N(\rho^\pm K^\mp) = 7.2^{+6.2}_{-4.7}$$



$$\mathcal{B}(B^0 \rightarrow \rho^\pm \pi^\mp) = (3.5^{+1.1}_{-1.0} \pm 0.5) \times 10^{-5}$$

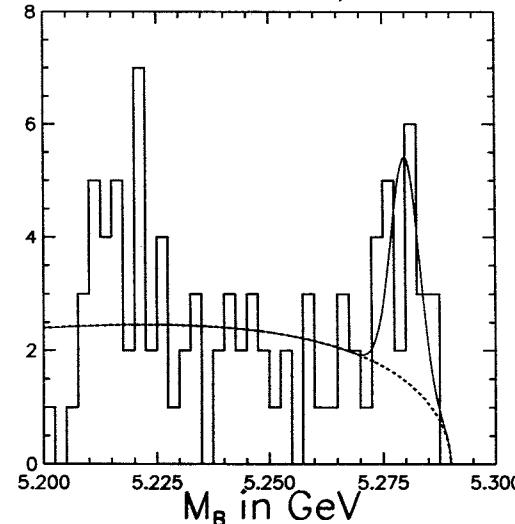
$$\mathcal{B}(B^0 \rightarrow \rho^\pm K^\mp) < 2.5 \times 10^{-5} \text{ @ 90% CL}$$

$B^0 \rightarrow h^+ \rho^-$



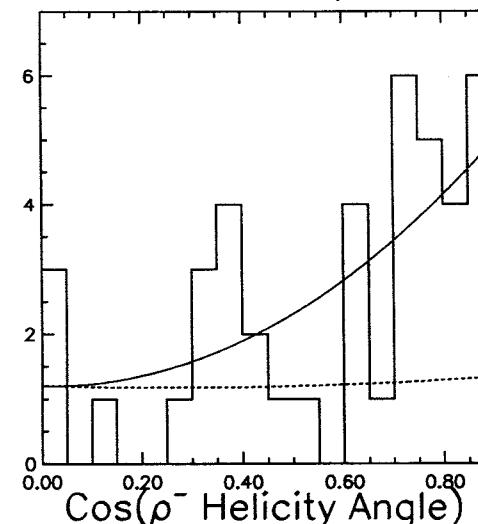
$E(\pi\pi\pi) - E(\text{beam})$

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



$M(B)$

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



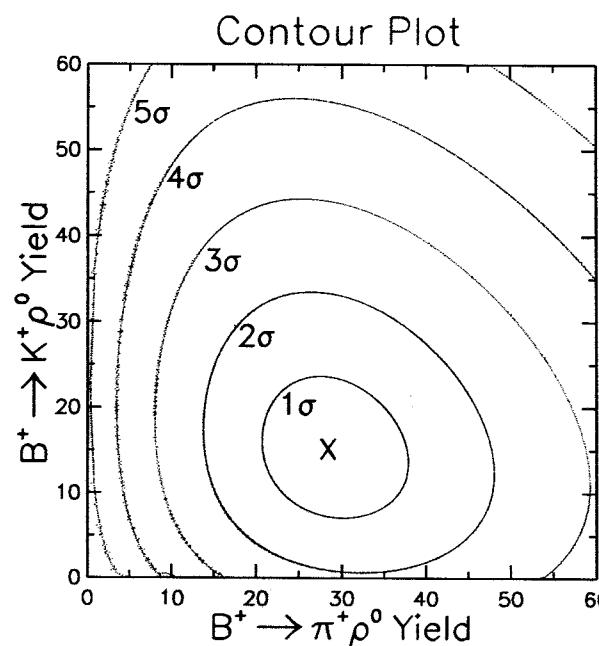
$\cos \theta_{\text{helicity}}$

$$B^+ \rightarrow \rho^0 \pi^+, \rho^0 K^+$$

$$5.8 \times 10^6 B\bar{B}$$

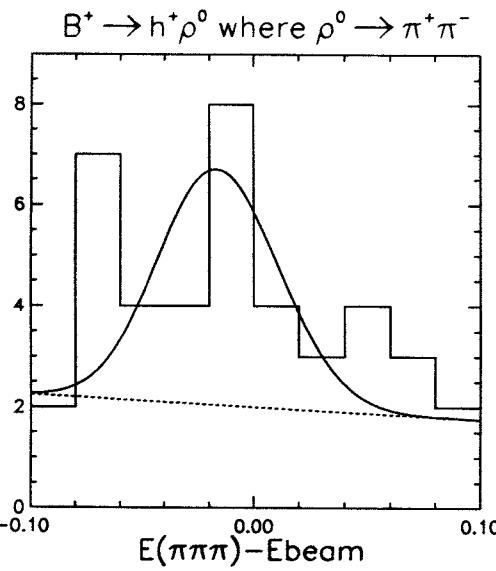
$$N(\rho^0 \pi^+) = 26.1^{+9.1}_{-8.0}$$

$$N(\rho^0 K^+) = 14.8^{+8.8}_{-7.7}$$

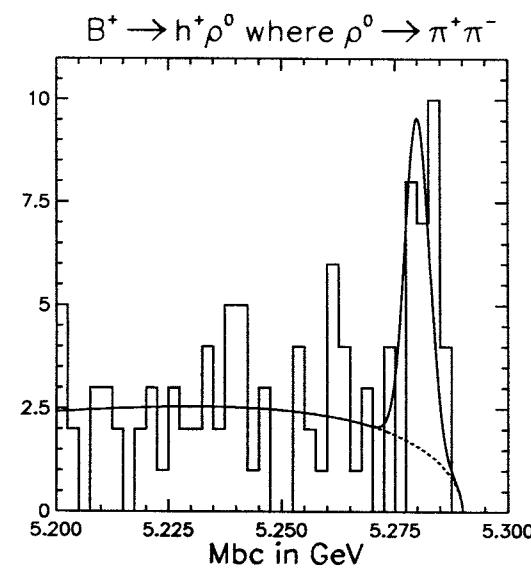


$$\mathcal{B}(B^+ \rightarrow \rho^0 \pi^+) = (1.5 \pm 0.5 \pm 0.4) \times 10^{-5}$$

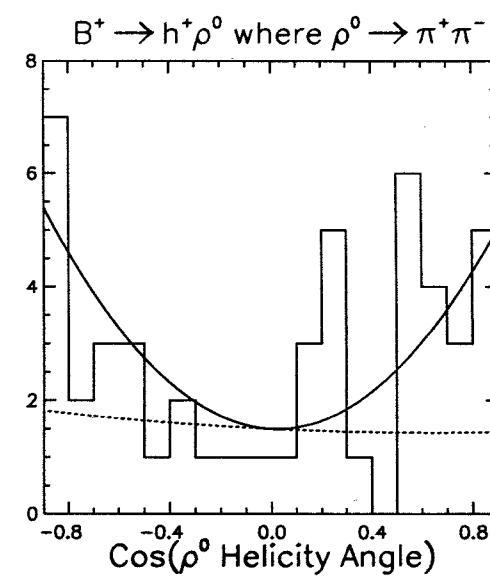
$$\mathcal{B}(B^+ \rightarrow \rho^0 K^+) < 2.2 \times 10^{-5} \text{ @ 90% CL}$$



$$E(\pi\pi\pi) - E(\text{beam})$$



$$M(B)$$



$$\cos \theta_{\text{helicity}}$$

$B^+ \rightarrow \omega K^+, \omega \pi^+$

Previously... PRL 81,272 (1998)       $3.3 \times 10^6 B\bar{B}$

$$\mathcal{B}(B^+ \rightarrow \omega K^+) = (1.5 \pm 0.2) \times 10^{-5}$$

$$\mathcal{B}(B^+ \rightarrow \omega \pi^+) < 2.3 \times 10^{-5} \text{ (90% C.L.)}$$

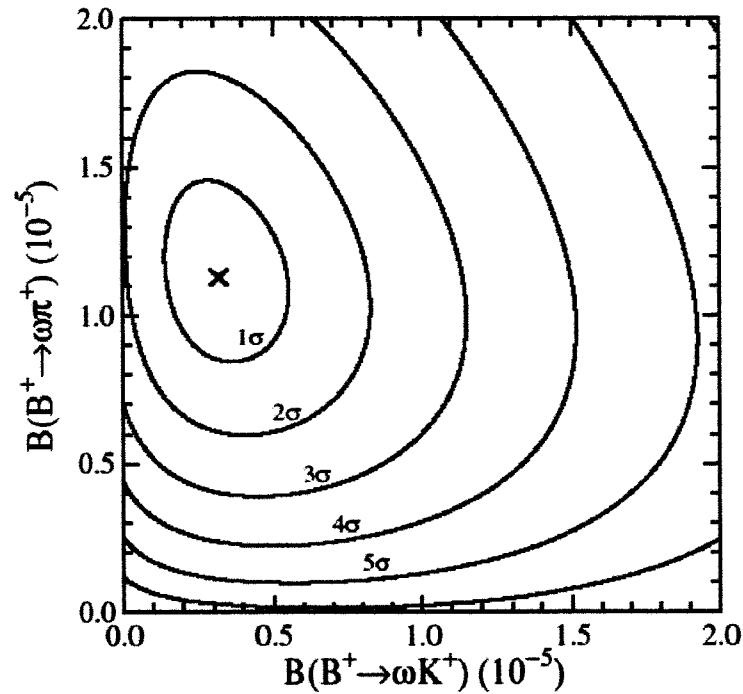
The plan:

Get more data.

Reanalyze previous data sample.

***Sometimes more can be less!***

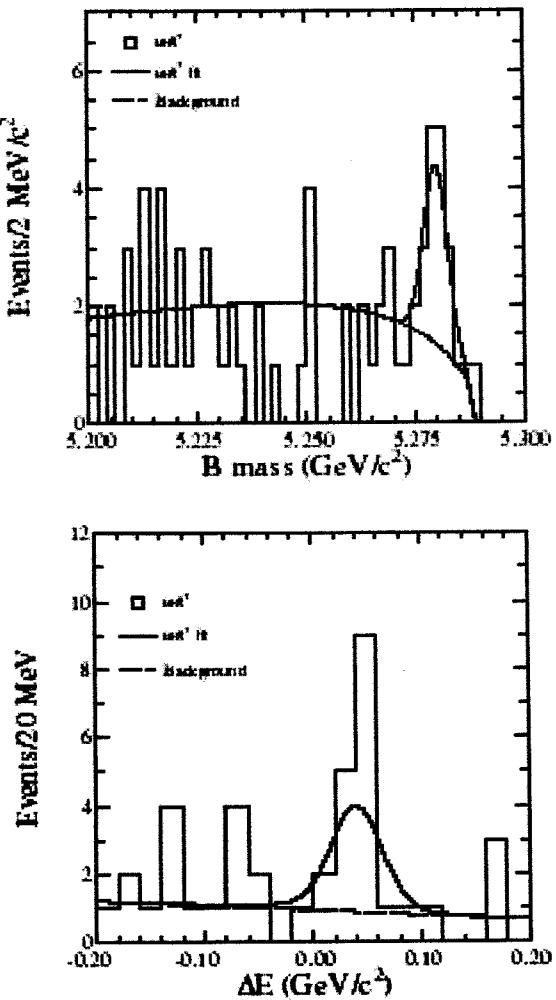
$B^+ \rightarrow \omega K^+, \omega \pi^+$



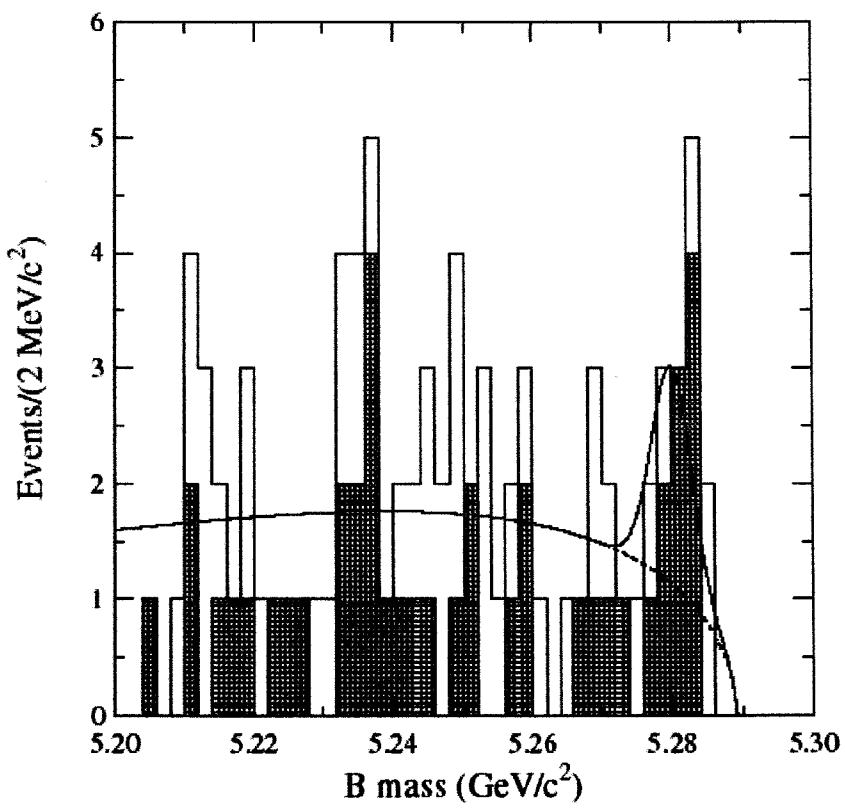
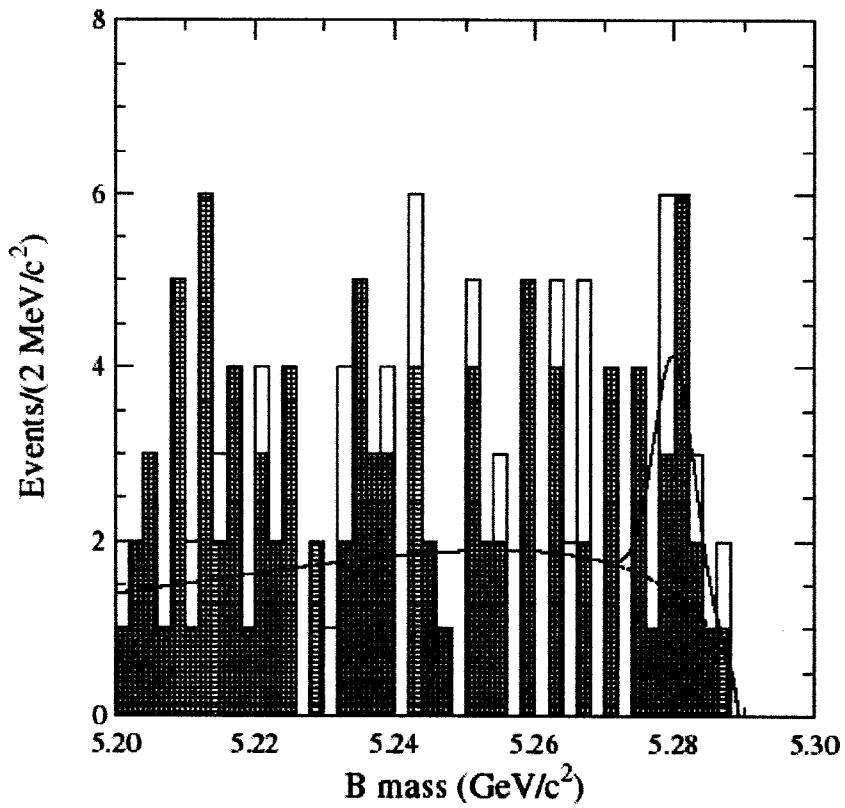
$$\mathcal{B}(B^0 \rightarrow \omega \pi^+) = (1.1 \pm 0.3 \pm 0.1) \times 10^{-5}$$

$$\mathcal{B}(B^0 \rightarrow \omega K^+) < 0.8 \times 10^{-5} \text{ (90\% C.L.)}$$

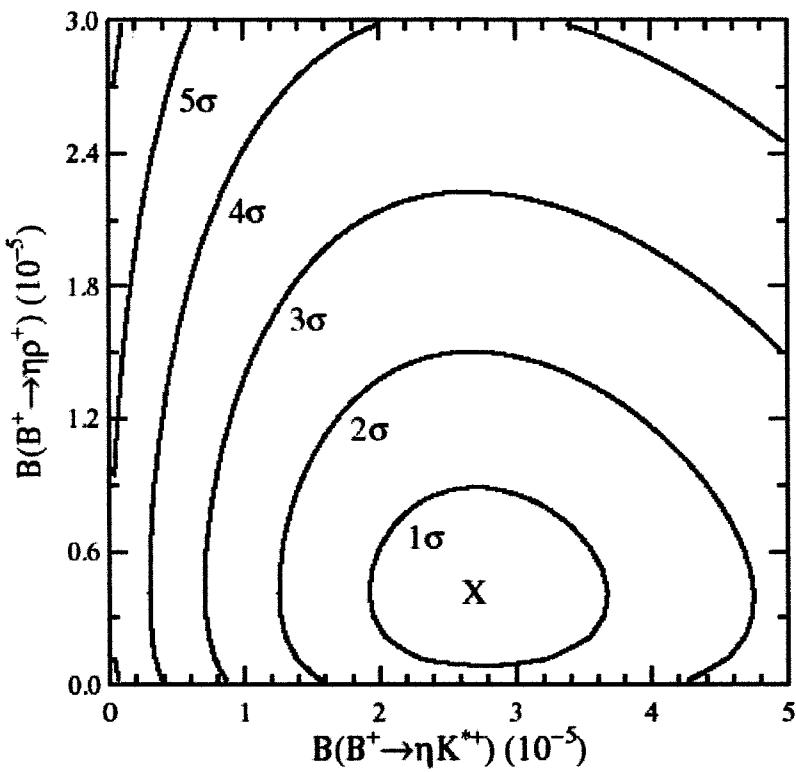
CLEO, CONF 99-13  
*Preliminary*  $9.7 \times 10^6 BB$



# Projections onto $m_B$



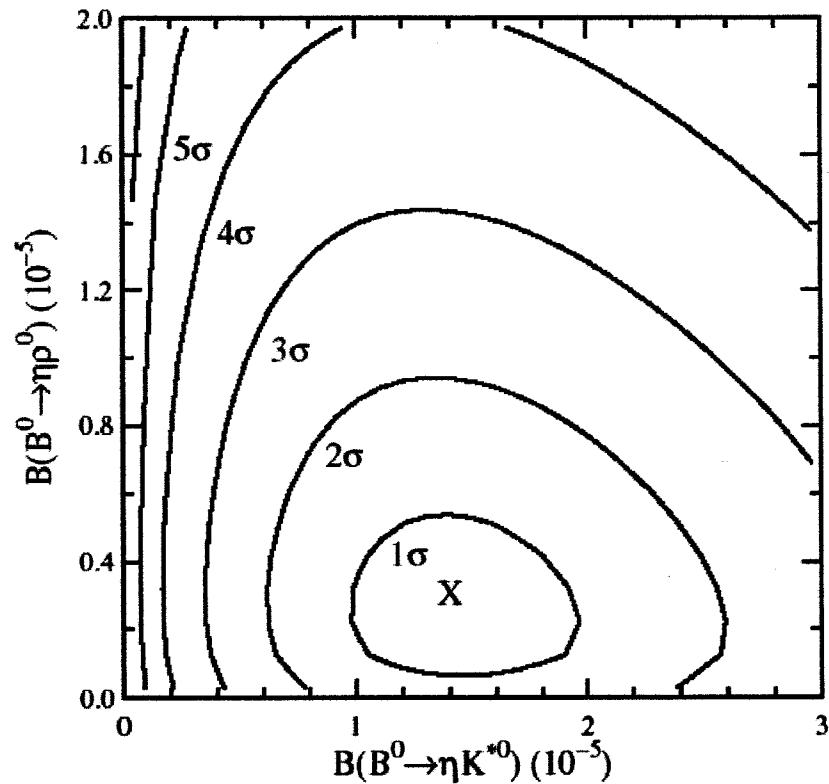
# First Observation of $B \rightarrow \eta K^*$



$$\mathcal{B}(B^+ \rightarrow \eta K^{*+}) =$$

$$(27.3_{-8.2}^{+9.6} \pm 5.0) \times 10^{-6}$$

August 9, 1999



$$\mathcal{B}(B^0 \rightarrow \eta K^{*0}) =$$

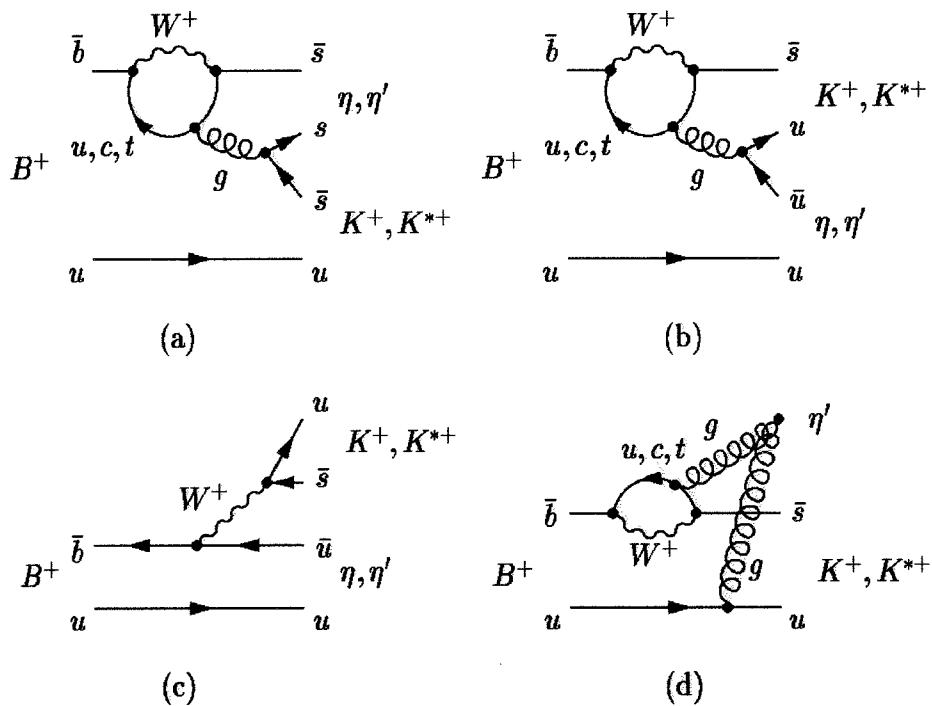
$$(13.8_{-4.4}^{+5.5} \pm 1.7) \times 10^{-6}$$

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# Summary $B \rightarrow (\eta, \eta') X$

| Decay mode                     | $\mathcal{B}_{\text{fit}}(10^{-6})$ | Signif. ( $\sigma$ ) | $\mathcal{B}(10^{-6})$       | Source    | Theory $\mathcal{B}(10^{-6})$ |
|--------------------------------|-------------------------------------|----------------------|------------------------------|-----------|-------------------------------|
| $B^+ \rightarrow \eta' K^+$    | $80^{+10}_{-9} \pm 8$               | 16.8                 | $80^{+10}_{-9} \pm 8$        | This Exp. | 7 - 65 [17,19]                |
| $B^0 \rightarrow \eta' K^0$    | $88^{+18}_{-16} \pm 9$              | 11.7                 | $88^{+18}_{-16} \pm 9$       | This Exp. | 9 - 59 [17,19]                |
| $B^+ \rightarrow \eta' \pi^+$  | $1.0^{+5.3}_{-1.0} \pm 0.1$         | 0.2                  | < 11                         | This Exp. | 1 - 23 [17,19]                |
| $B^0 \rightarrow \eta' \pi^0$  |                                     |                      | < 11                         | [11]      | 0.1 - 14 [17,19]              |
| $B^+ \rightarrow \eta' K^{*+}$ |                                     | 1.2                  | < 87                         | [20]      | 0.1 - 3.7 [17,19]             |
| $B^0 \rightarrow \eta' K^{*0}$ |                                     | 1.0                  | < 20                         | [20]      | 0.1 - 8.0 [17,19]             |
| $B^+ \rightarrow \eta' \rho^+$ |                                     |                      | < 47                         | [11]      | 3 - 24 [17,19]                |
| $B^0 \rightarrow \eta' \rho^0$ |                                     |                      | < 23                         | [11]      | 0.1 - 11 [17,19]              |
| $B^+ \rightarrow \eta K^+$     | $2.2^{+2.6}_{-2.2}$                 | 1.0                  | < 7.1                        | This Exp. | 0.2 - 5.0 [17,19]             |
| $B^0 \rightarrow \eta K^0$     | $0.0^{+3.0}_{-0.0}$                 | 0.0                  | < 9.5                        | This Exp. | 0.1 - 3.0 [17-19]             |
| $B^+ \rightarrow \eta \pi^+$   | $1.2^{+2.6}_{-1.2}$                 | 0.6                  | < 6.0                        | This Exp. | 1.9 - 7.4 [17-19]             |
| $B^0 \rightarrow \eta \pi^0$   | $0.0^{+0.7}_{-0.0}$                 | 0.0                  | < 3.1                        | This Exp. | 0.2 - 4.3 [17,19]             |
| $B^+ \rightarrow \eta K^{*+}$  | $27.3^{+9.6}_{-8.2} \pm 5.0$        | 4.8                  | $27.3^{+9.6}_{-8.2} \pm 5.0$ | This Exp. | 0.2 - 8.2 [17,19]             |
| $B^0 \rightarrow \eta K^{*0}$  | $13.8^{+5.5}_{-4.4} \pm 1.7$        | 5.1                  | $13.8^{+5.5}_{-4.4} \pm 1.7$ | This Exp. | 0.1 - 8.9 [17-19]             |
| $B^+ \rightarrow \eta \rho^+$  | $4.3^{+4.6}_{-3.4} \pm 0.7$         | 1.3                  | < 16                         | This Exp. | 4 - 17 [17-19]                |
| $B^0 \rightarrow \eta \rho^0$  | $2.6^{+3.0}_{-2.4} \pm 0.3$         | 1.3                  | < 11                         | This Exp. | 0.1 - 6.5 [17-19]             |

# Interpretation



Lipkin:

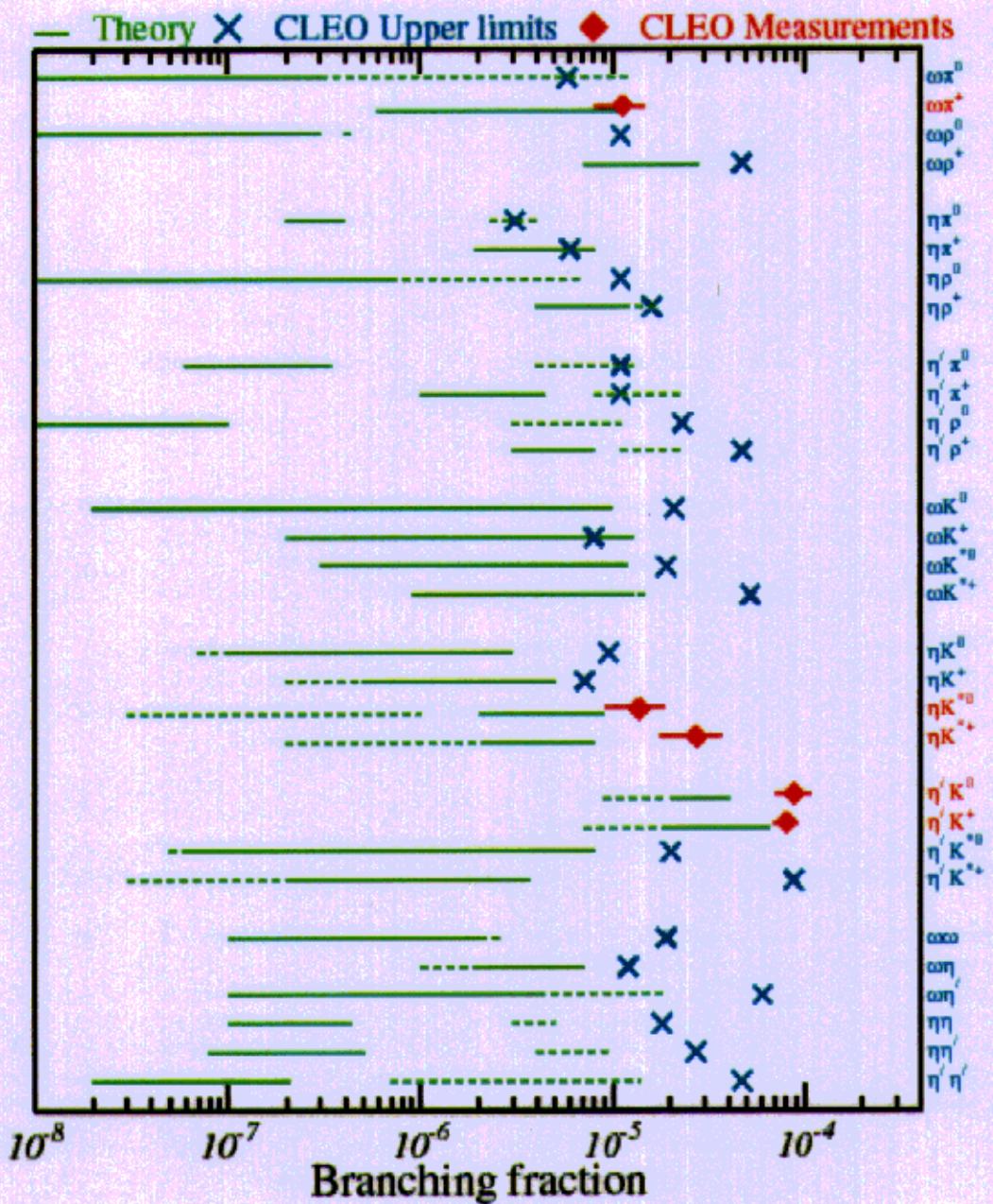
$$\frac{K\eta' + K^*\eta}{K\eta + K^*\eta'}$$

enhanced by interference.

Various:

Flavor-singlet penguin  
interferes with usual  
penguin, effects of gluon or  
 $c\bar{c}$  content of  $\eta'$ .

## Other Rare Decay - Summary



# CLEO Update $b \rightarrow s\gamma$

Neural Net  
Shape Variables  
+  
Pseudo-Reconstruction

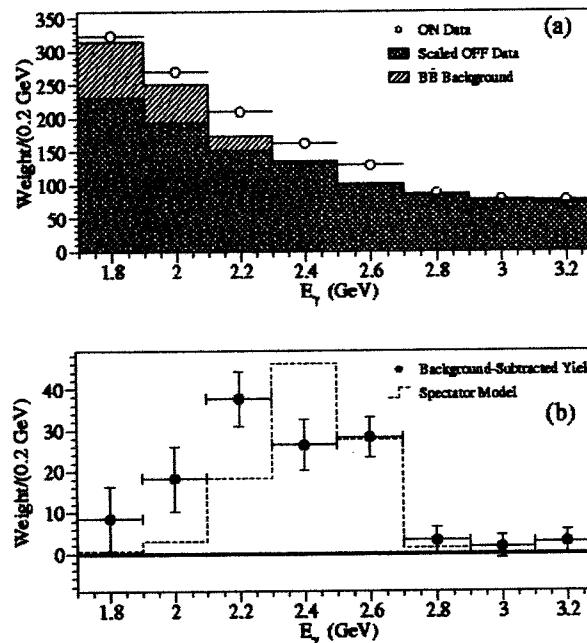
$$\mathcal{B}(b \rightarrow s\gamma) = (3.15 \pm 0.35 \pm 0.32 \pm 0.26) \times 10^{-4}$$

$$2.0 \times 10^{-4} < \mathcal{B}(b \rightarrow s\gamma) < 4.5 \times 10^{-4} \quad (95\% \text{ C.C.})$$

Next-to-leading-log calculation  $(3.28 \pm 0.33) \times 10^{-4}$

PRELIMINARY

$3.3 \times 10^6 B\bar{B}$



Chetyrkin *et al.*  
Kagan and Neubert

# Measurement of Charge Asymmetries in Charmless Semileptonic $B$ Decays

CLEO, CONF 99-16  
Preliminary  
 $9.7 \times 10^6 BB$

$$A_{CP} = \frac{\text{Br}(b \rightarrow f) - \text{Br}(\bar{b} \rightarrow \bar{f})}{\text{Br}(b \rightarrow f) + \text{Br}(\bar{b} \rightarrow \bar{f})}$$

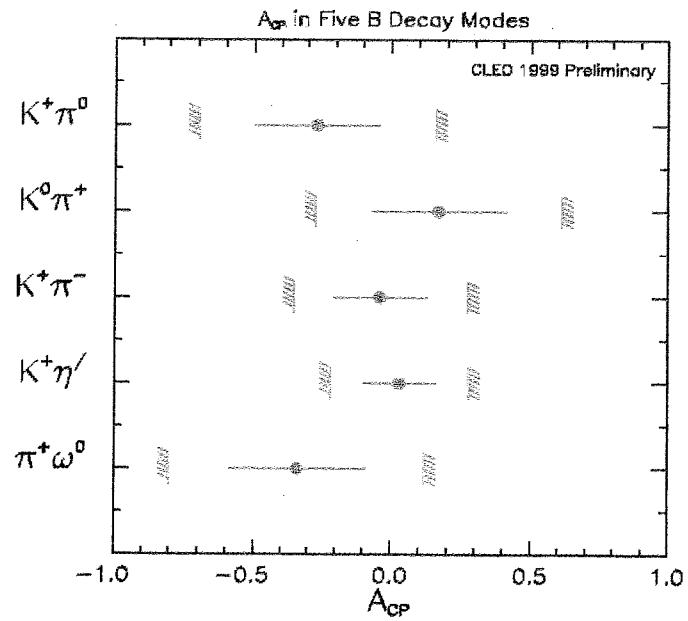
Direct CP violation - two or more contributing diagrams differ in weak and strong phases

Modes investigated:  $K\pi^+$ ,  $K\pi^0$ ,  $K_S^0\pi^+$ ,  $K\eta'$ ,  $\omega\pi^+$

Expectation (Ali *et al.*) up to  $\sim 0.10$  in  $K\pi$ .

Results:

| Mode        | $\mathcal{S}$        | $\bar{\mathcal{S}}$  | $A_{CP}$                  | 90% CL interval |
|-------------|----------------------|----------------------|---------------------------|-----------------|
| $K\pi^0$    | $16.8 \pm 7.5$       | $28.9 \pm 7.5$       | $-0.27 \pm 0.23 \pm 0.05$ | $[-0.70, 0.16]$ |
| $K_S^0\pi$  | $14.5 \pm 4.4$       | $10.2 \pm 4.0$       | $0.17 \pm 0.24 \pm 0.05$  | $[-0.27, 0.61]$ |
| $K\pi$      | $38.6^{+9.0}_{-8.1}$ | $41.6^{+8.9}_{-8.0}$ | $-0.04 \pm 0.16 \pm 0.05$ | $[-0.35, 0.27]$ |
| $\eta'K$    | $51.7 \pm 9.2$       | $48.7 \pm 8.9$       | $0.03 \pm 0.12 \pm 0.05$  | $[-0.22, 0.28]$ |
| $\omega\pi$ | $9.4^{+4.9}_{-4.0}$  | $19.1^{+6.8}_{-5.9}$ | $-0.34 \pm 0.25 \pm 0.05$ | $[-0.80, 0.12]$ |



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$b \rightarrow s\gamma$

## “Electroweak Penguins”

Exclusive: PRL **71**, 674 (1993)

Inclusive: PRL **74**, 2885 (1995)

$$\mathcal{B}(b \rightarrow s\gamma) = (2.32 \pm 0.57 \pm 0.35) \times 10^{-4}$$

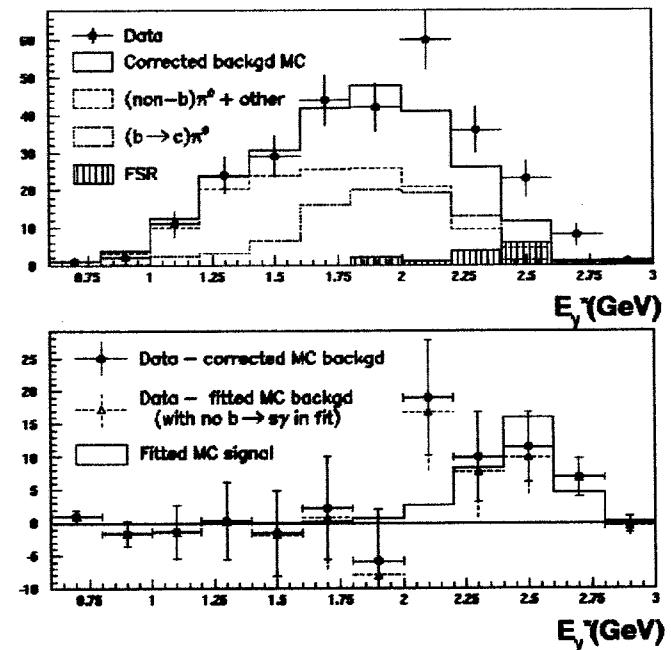
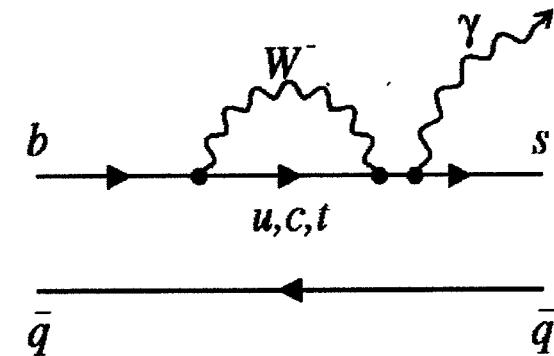
Confirmation: ALEPH

PL **B429**, 169 (1998)

Lifetime tag opposite hemisphere

Pseudo-reconstruction

$$\mathcal{B}(b \rightarrow s\gamma) = (3.11 \pm 0.80 \pm 0.72) \times 10^{-4}$$



# Search for $CP$ Asymmetry in $b \rightarrow s\gamma$

$3.3 \times 10^6 BB$

Standard Model predicts no asymmetry, but new physics...

Kagan and Neubert

Aoki, Cho, Oshimo

Want to measure the time asymmetry in the pseudo-reconstructed sample...

$$A = \frac{N(b \rightarrow s\gamma) - N(\bar{b} \rightarrow \bar{s}\gamma)}{N(b \rightarrow s\gamma) + N(\bar{b} \rightarrow \bar{s}\gamma)}$$

...but there are complications.

- Sometimes flavor can't be determined (but mistakes are possible).
- Sometimes flavor is determinable, but is wrong.

$$A \approx A^{\text{meas}} = (0.16 \pm 0.14 \pm 0.05) \times (1.000 \pm 0.041)$$

$$-0.09 < A < 0.42 \quad (90\% \text{ C.L.})$$

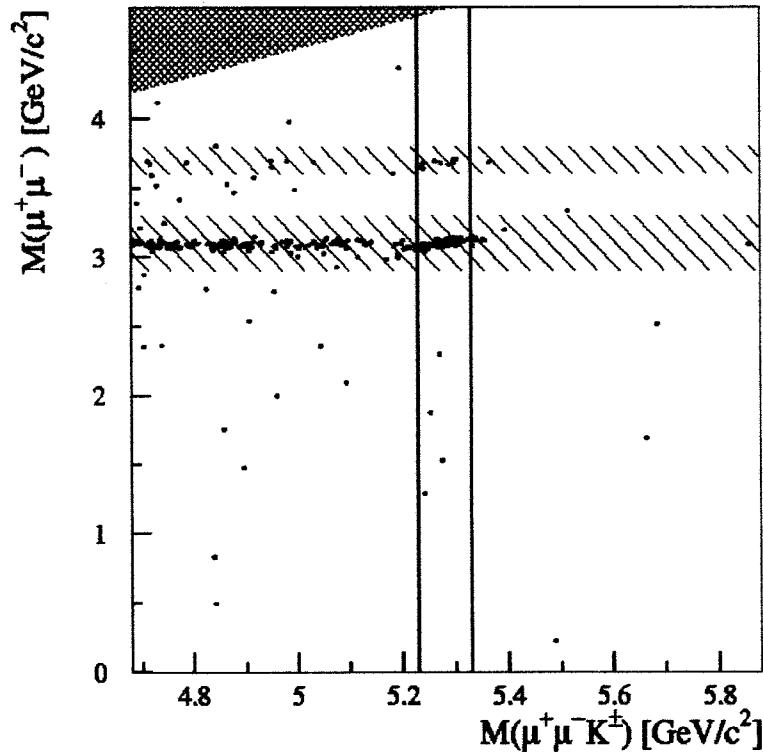
$B \rightarrow \mu^+ \mu^- K^+$

$B \rightarrow \mu^+ \mu^- K^{*0}$

from *CDF*

hep-ex/9905004

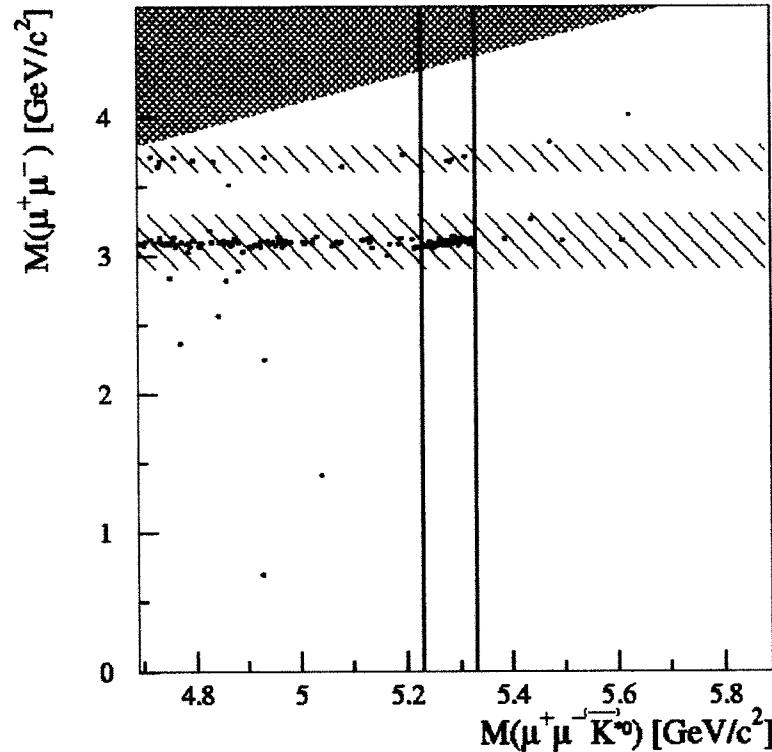
88 pb<sup>-1</sup> from 92-93  
and 94-95



$$\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-) < 5.2 \times 10^{-6} \text{ (90\% C.L.)}$$

Prediction:  $(0.3 - 0.7) \times 10^{-6}$

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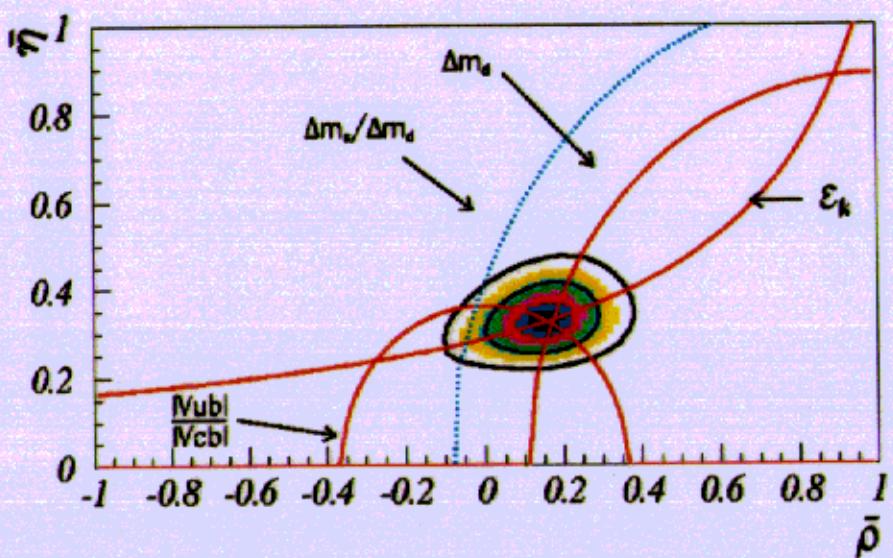


$$\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-) < 4.0 \times 10^{-6} \text{ (90\% C.L.)}$$

Prediction:  $(1 - 4) \times 10^{-6}$

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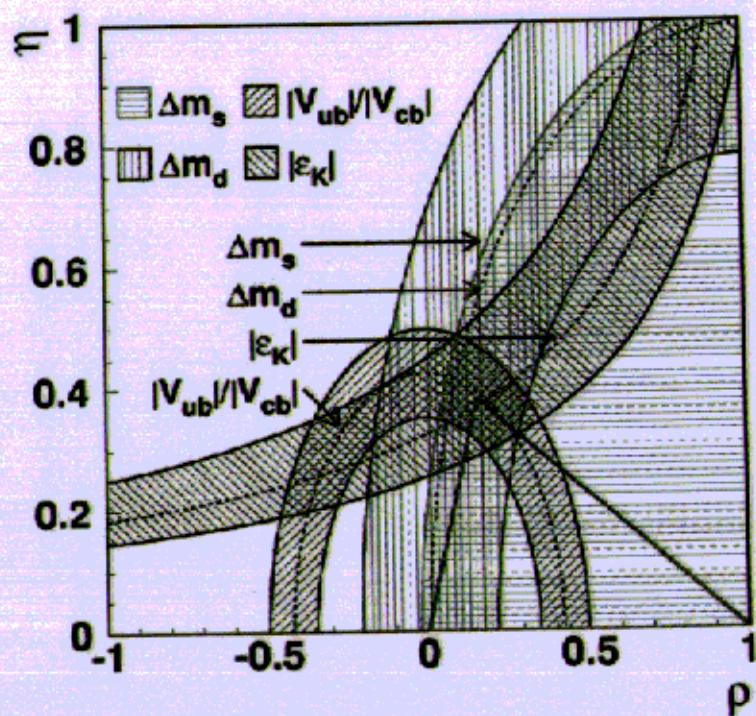
# CKM Fits



Parodi, Roudeau, Stocchi

hep-ph/9802289

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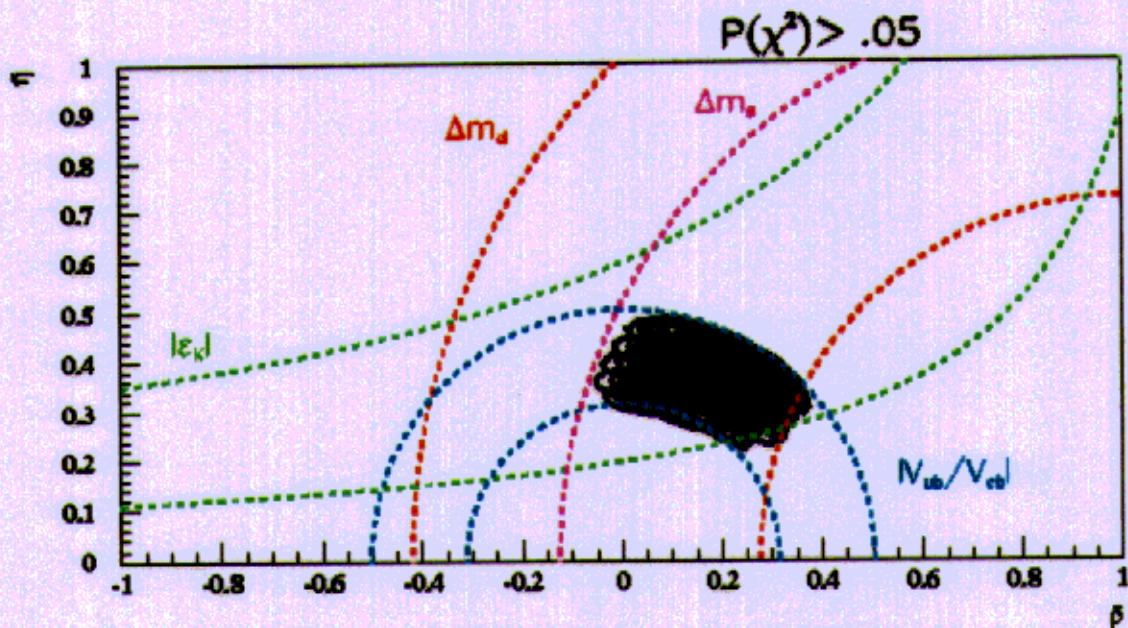


S. Mele

Phys. Rev. D59, 113011 (1999)

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## Unitarity Triangle in 1999



### Experimental inputs

$$\Delta m_4 = 0.471 \pm 0.016 \text{ ps}^{-1}$$

$$|f_B| = 0.002285 \pm 1.8E-05$$

$$N_u/N_d = N_u/N_{d\bar{d}} \pm 0.003$$

$$N_{d\bar{d}} = 0.04 \pm 0.002$$

$$\bar{m}_t = 165 \pm 6 \text{ GeV}$$

### Theoretical scan

$$0.16 < f_B \sqrt{B_\pi} < 0.24 \text{ GeV}$$

$$0.65 < B_\pi < 0.95$$

$$0.075 < N_u/N_{d\bar{d}} < 0.105$$

$$1.12 < \xi^2 < 1.48$$

$$-.05 < \bar{\rho} < .35 \text{ (95\% CL)}$$

$$.22 < \bar{\eta} < .48 \text{ (95\% CL)}$$

What can charmless hadronic B decays  
tell us about  $\gamma$ ?

Interference of tree and penguin diagrams  
brings in  $\gamma$ . Several methods have been  
proposed for extracting  $\gamma$  information.

Potentially lots of murky hadronic physics,  
but with factorization.

Have faith! (And see where it takes you.)

He, Hou, Yang : PRL 83, 1100 (1999)

Hou, Yang : hep-ph/9908202

CLEO charmless hadronic BR's suggest  
a preference for  $\cos \gamma < 0.0$ .

With more modes and better measurements  
this summer, try again.

Assuming factorization and B-decay amplitudes can be written in terms of a few parameters:

$$\gamma = \text{Arg}(V_{ub}^*)$$

$$|V_{ub}/V_{cb}|$$

$R_{SU}$  (quark masses)

$$F^{B\pi} \quad (B \rightarrow \pi \text{ FF})$$

$$A_0^{B\rho} \quad (B \rightarrow \rho \text{ FF})$$

Fit CP-averaged BR's for 14 modes.

Constrain  $|V_{ub}/V_{cb}| = 0.08 \pm 0.02$

The fit converges, giving us - - -

$$\gamma = 113^{+25}_{-23} \text{ degrees}$$

Best fit for other parameters come out close to theoretical expectations.

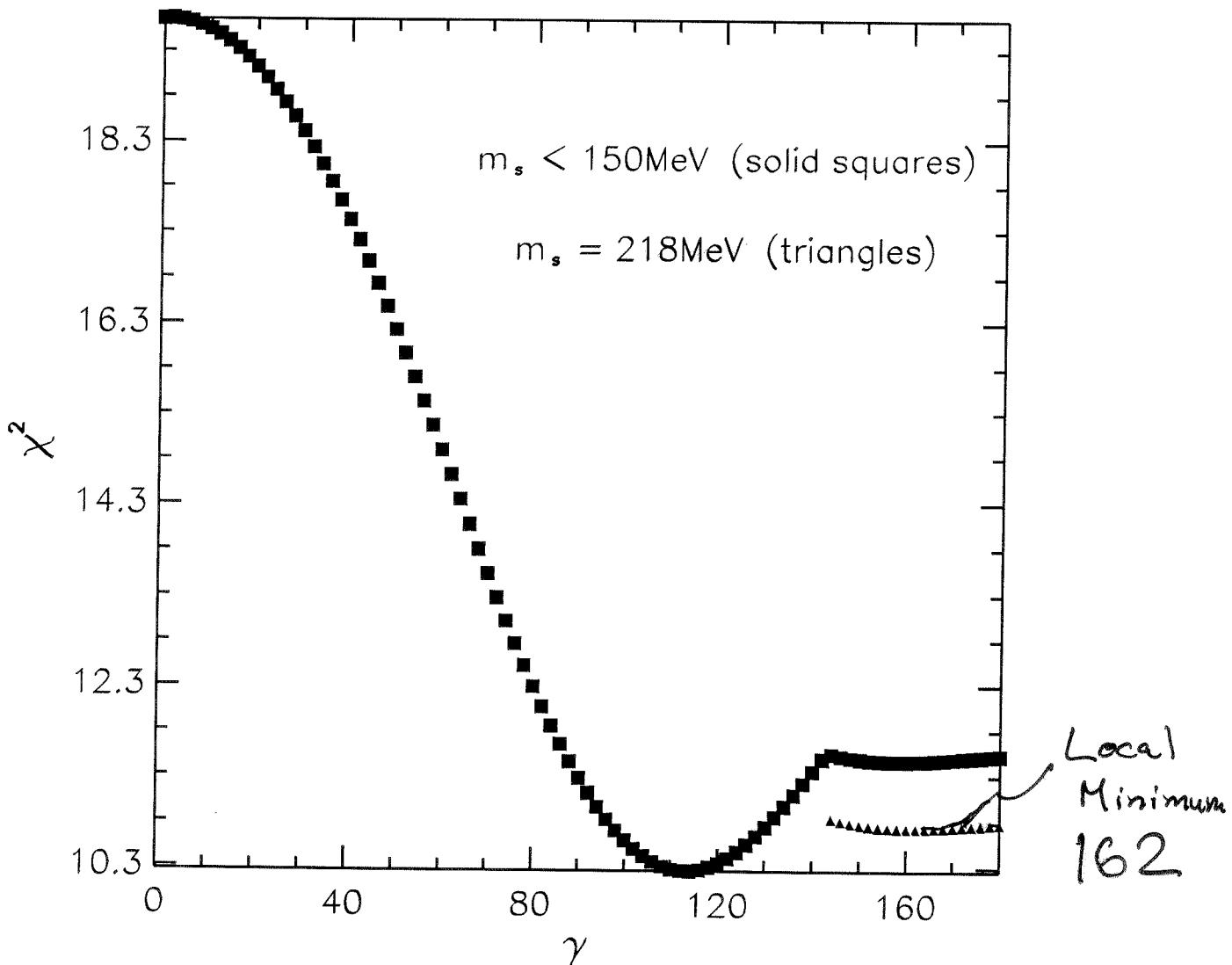
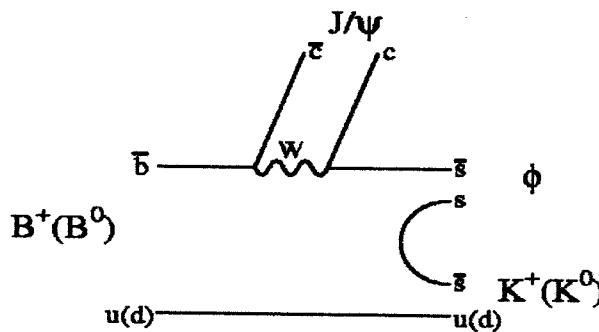


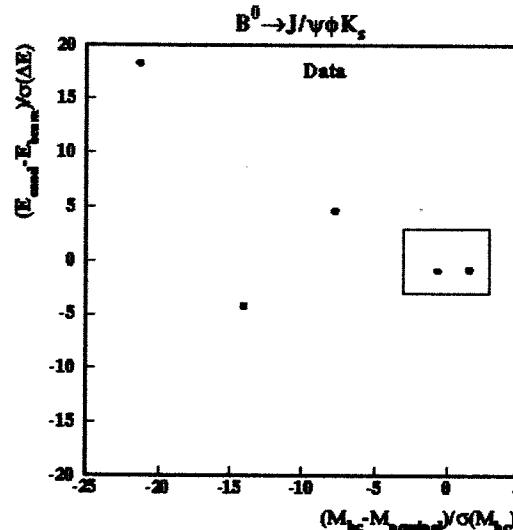
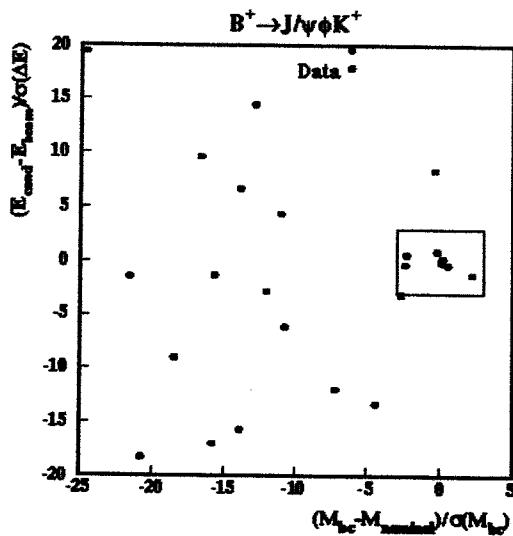
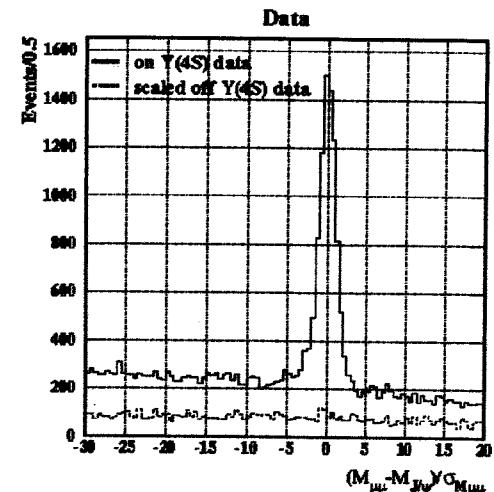
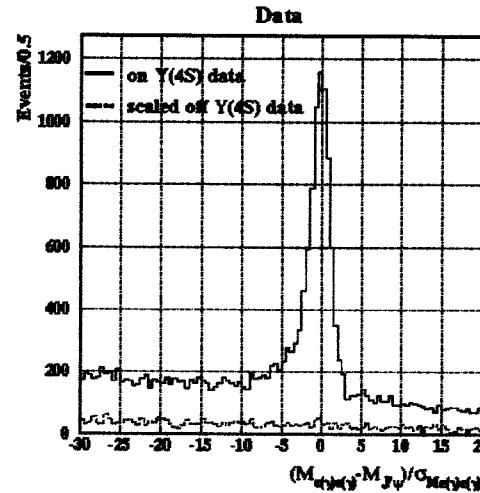
FIG. 10.  $\chi^2$  versus  $\gamma$  curve for global fit to CP-averaged charmless hadronic  $B$  decay branching fractions. The triangles depict a local minimum that has the feature of  $m_s = 218\text{MeV}$ . The squares depict the  $\chi^2$  curve with the additional constraint of  $m_s < 150\text{MeV}$ .

# First Observation of $B \rightarrow J/\psi \phi K$



$B$ -meson decay with  $s\bar{s}$  popping

CLEO CONF 99-15  
Preliminary  
 $9.6 \times 10^6 B\bar{B}$



10  $B \rightarrow J/\psi \phi K$  candidates  
estimated BG 0.5 events

$$\beta(B \rightarrow J/\psi \phi K) = (8.8^{+3.5}_{-3.0} \pm 1.3) \times 10^{-5}$$

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# PRELIMINARY $D^+ \rightarrow K^+ K^- K^+$ ~100% FOCUS

- $D_s^+ \rightarrow K^+ K^- K^+$  is a SCSD
- $D^+ \rightarrow K^+ K^- K^+$  is a  $\Delta C = -\Delta S$  DCSD which cannot occur via a spectator diagram.

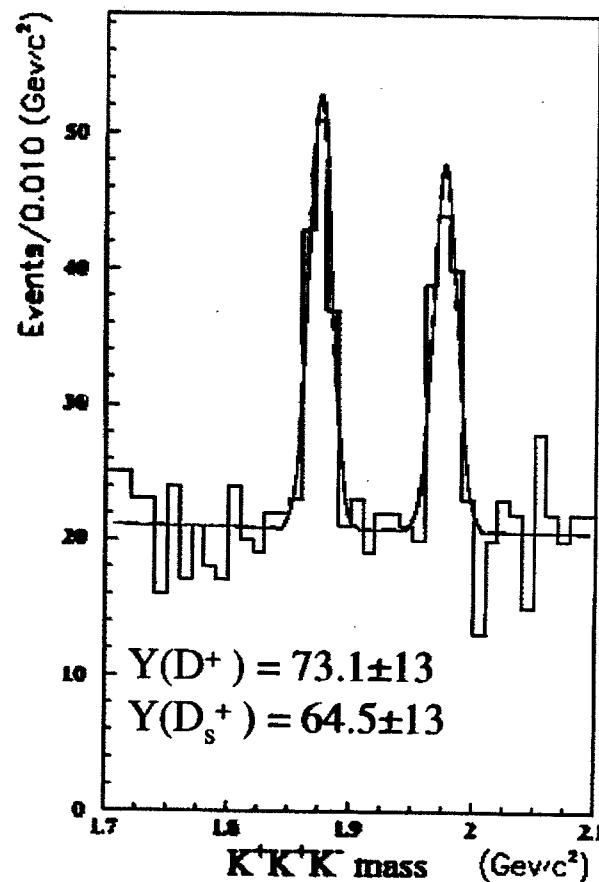
$$\Gamma(D^+ \rightarrow K^+ K^- K^+) / \Gamma(D^+) = (1.41 \pm 0.27) \times 10^{-4}$$

Just on PDG 98 limit from E687 of  
 $Br < 1.4 \times 10^{-4}$  CL=90%

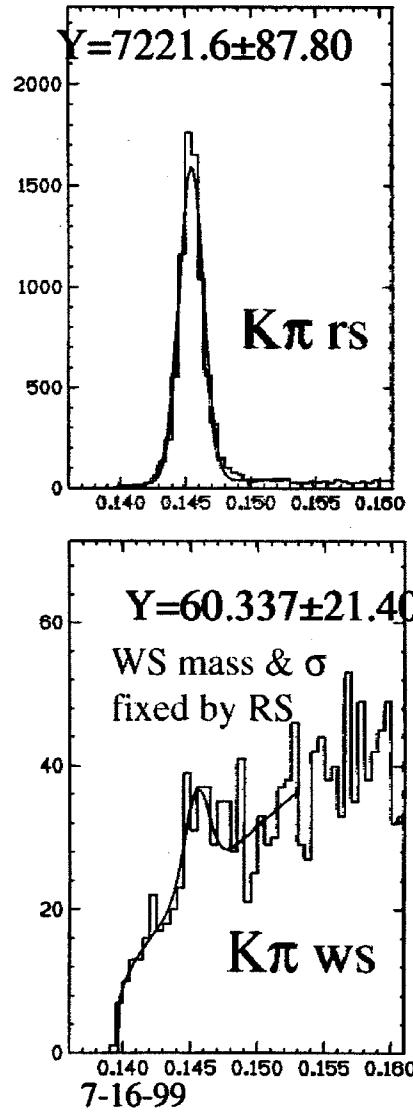
Our rarest DCSD BR yet :

$$\Gamma(D^+ \rightarrow K^+ K^- K^+) / \Gamma(K^- \pi^+ \pi^+) \approx \tan^4 \theta_C / 2$$

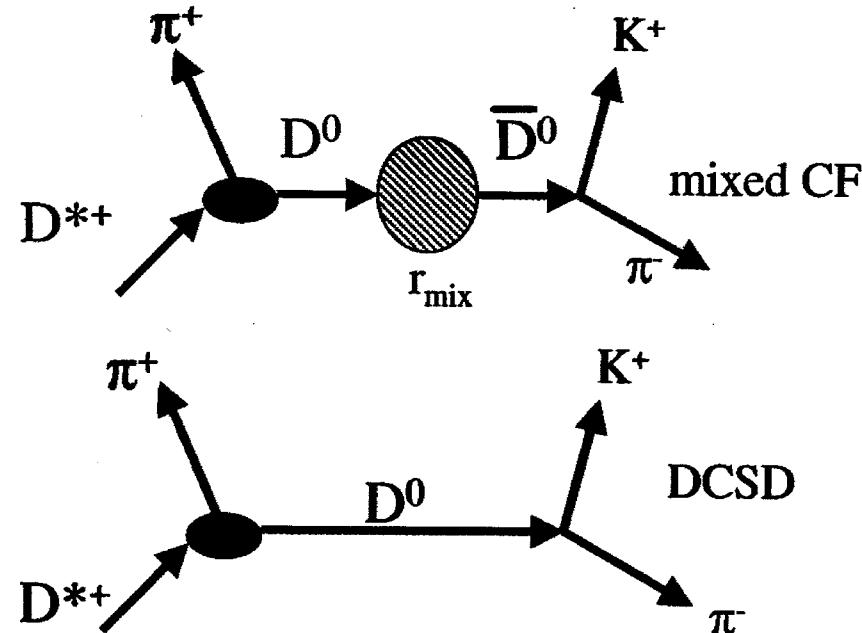
A KKK Dalitz analysis may shed light on the KKK decay mechanism.

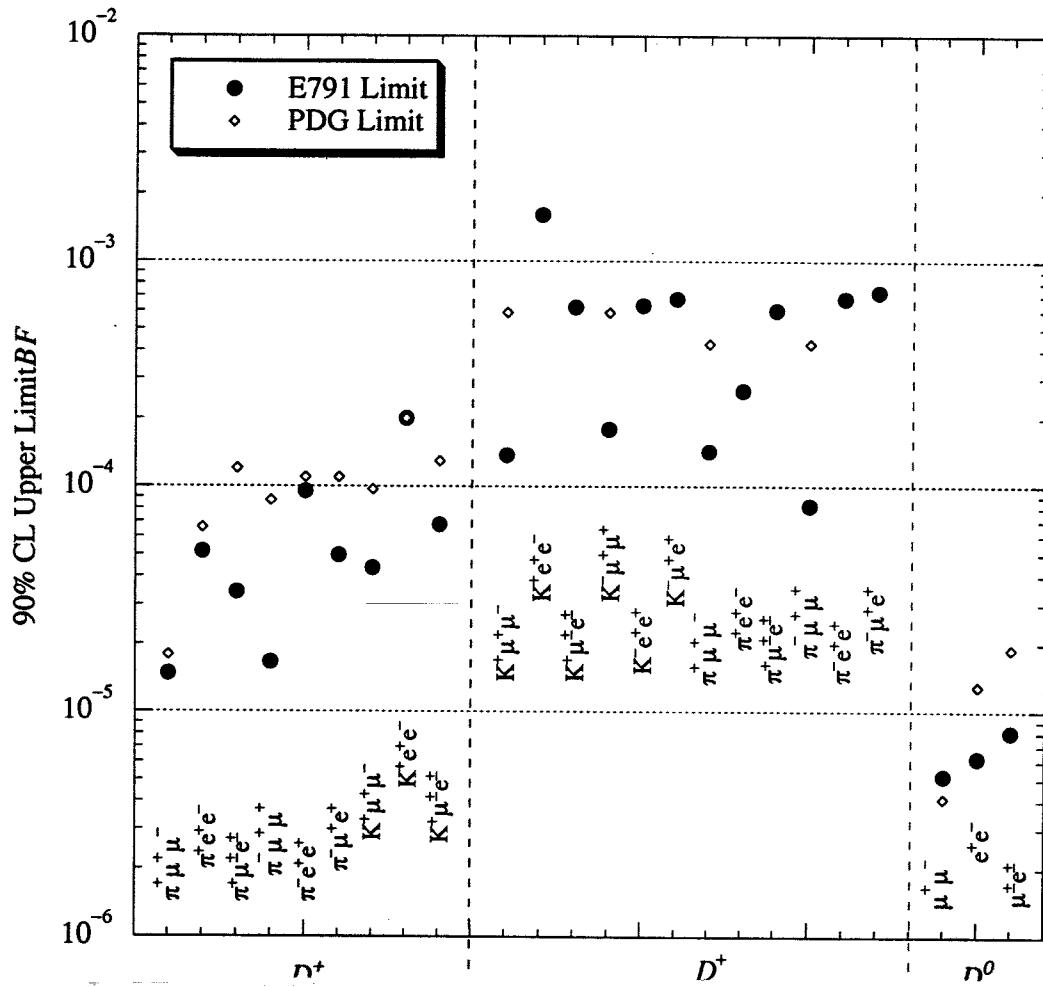


# PRELIMINARY (~40%) $D^0$ DCSD



Here we look for WS  $D^0$  decays where the kaon has the same sign as the  $D^{*+}$  decay pion. This is also a classic way to search for mixing and could interfere with mixing.  $BR(DCSD) \approx WS/RS$





Upper limits of the branching ratios, corrected for systematic errors, are shown along with the 1998 PDG values.

E789 results:  
 $\mu^+ \mu^- = 15.6 \times 10^{-6}$   
 $e^+ e^- = 8.19 \times 10^{-6}$   
 $\mu^\pm e^\pm = 17.2 \times 10^{-6}$

# Summary/Outlook

- Steady progress on a broad program of Standard Model tests.
- $B$  semileptonic decay is still puzzling, but  $Z^0/\Upsilon(4S)$  conflict looks less severe. Other hints of trouble?
- $V_{ub}$  and  $V_{cb}$  - still much to be done both on the experimental front and on interpretation. Intensive theory/experiment collaboration a big plus. Theoretical uncertainties are a main focus, growing larger as we become smarter.
- $B \rightarrow \pi\pi$  has likely been found. The rare charmless hadronic decay picture is filling in with more measurements and tighter limits.
- On the threshold of significant tests of the CKM triangle. Fits to usual experimental constraints show the SM to be holding up well. Do the hints from rare decays mean we are heading for trouble?
- Exciting years to come. CLEO II, LEP will continue to produce physics while new machines accumulate large data samples.
- Program to make definitive test of the Standard Model will be long term. Much will be done at the  $B$  factories, but much will remain afterwards.  $e^+e^-$  upgrades, LHC-b, BTeV will hopefully carry us well beyond the Standard Model.