Beauty and the Beast

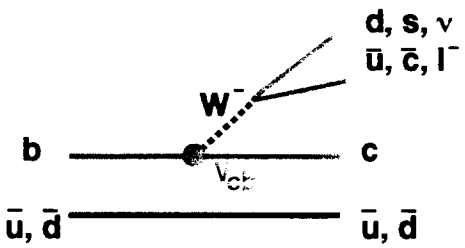
Klaus Honscheid
Ohio State University

... and the Beast

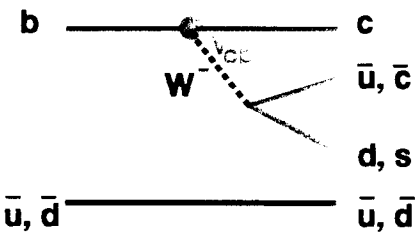
the strong interaction between quarks

B Decay Diagrams

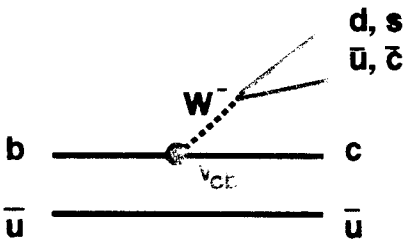
a) External Spectator

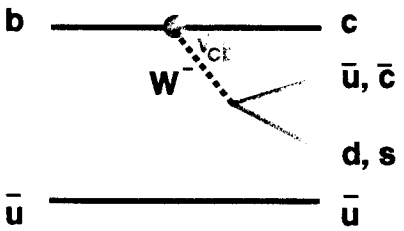


b) Internal Spectator

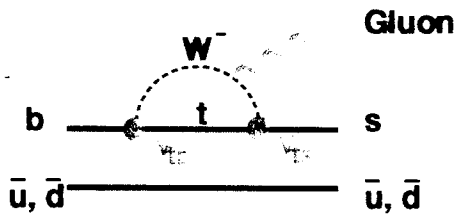


d) Charged B Decay

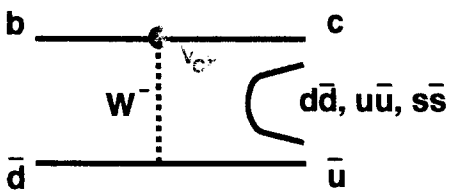




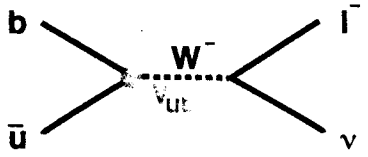
d) Gluonic Penguin



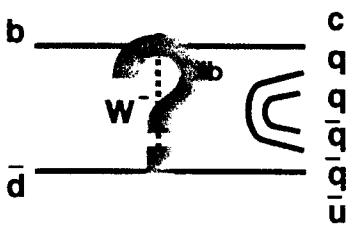
e) W - Exchange



f) Annihilation



e) Baryon Production



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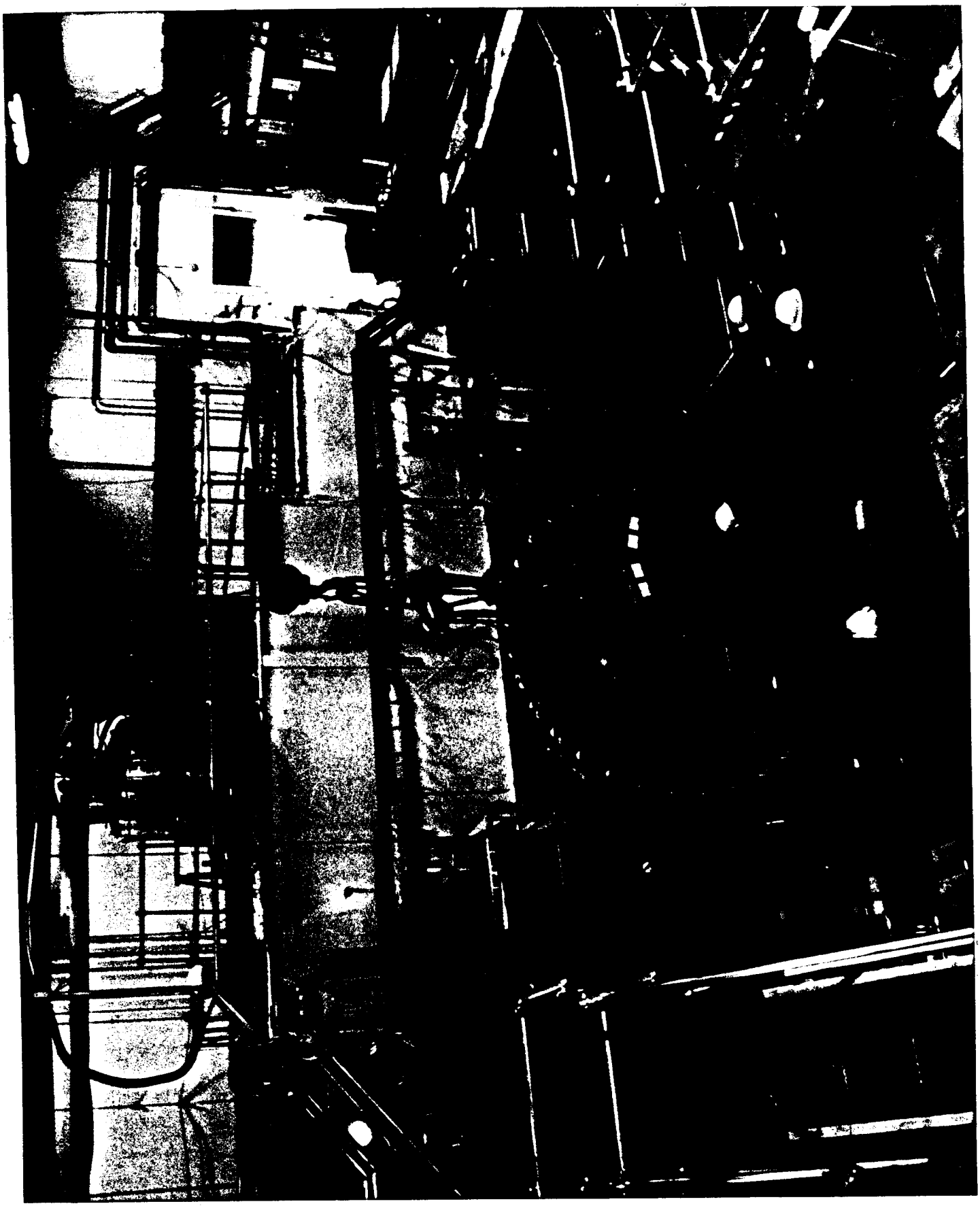
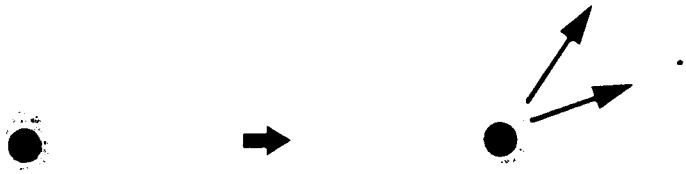


Heavy Quark Effective Theory

B meson → D meson



$m_Q \to \infty$ ➡ (Heavy) flavor symmetry, spin symmetry ➡ Universal Formfactor

➡ Absolute Normalization at zero recoil: $\xi(1) = 1$

$m_Q < \infty$

$$\xi(1) = \eta_A(1 + 0\ \Lambda_{QCD}/m_Q + c_2\ (\Lambda_{QCD}/m_Q)^2 \ldots) = \eta_A(1+\delta)$$

for B->D*lν (Luke)

$\xi(1) = 0.91 +/- 0.03$ (Neubert, Shifman ...)

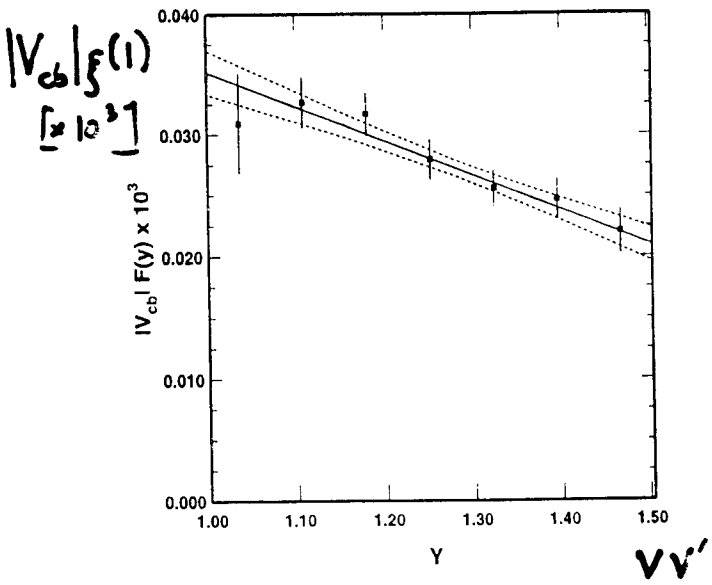
Experiments

Measure V_{cb} -- twice

(CLEO, Argus, Lep experiments)

I. Exclusive Semileptonic Decays, HQET

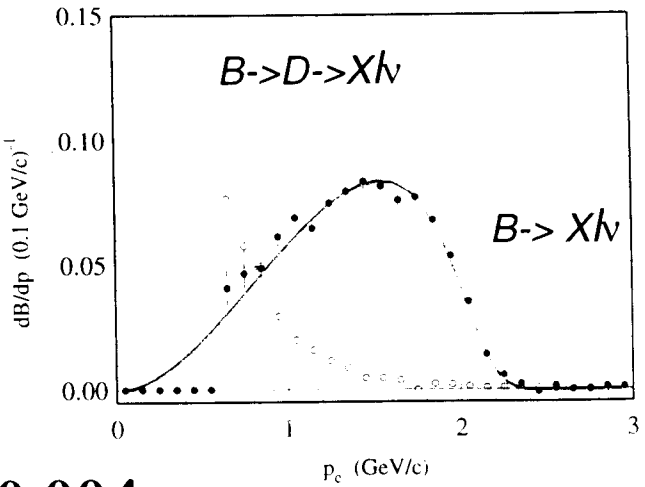
$BR(\bar{B}^{o} \to D^{*+} l^{-} \nu) = 4.87 +/- 0.26 +/- 0.19\ \%$



$|V_{cb}| =$
$0.038+/-0.002+/-0.002$

II. Inclusive Semileptonic Decays, Quark Models

$BR(B \to X l^{-} \nu) = 10.49 +/- 0.17\ 0.43\%$ (CLEO)



Models

using
$BR = \tau_B\ \gamma_c\ |V_{cb}|^2$

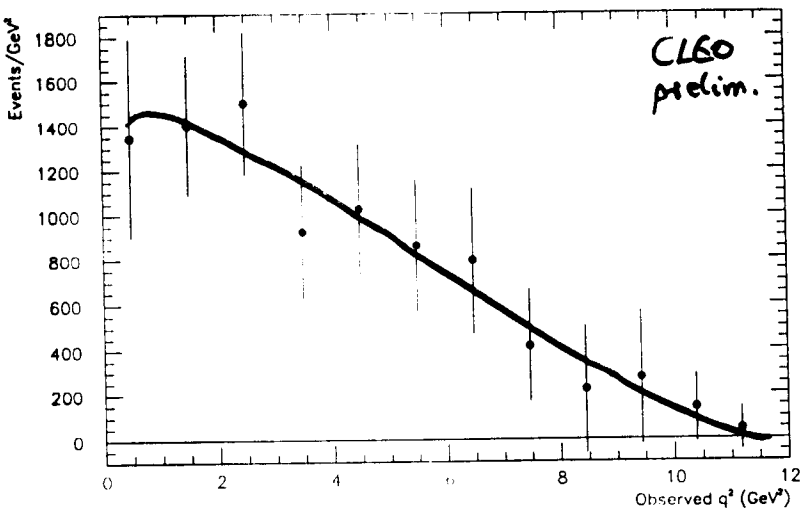
yields
$|V_{cb}| = 0.039+/-0.001+/-0.004$

$D^+ \ell\nu$ Form Factor + HQET

CLEO prelim

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{cb}|^2 p_D^3}{24\pi^3} |f_+(q^2)|^2$$

Problem: we don't measure q^2 ! MC: smearing small!



$\tilde{q}^2$

Ansatz: $f_+(q) = f_+(0)(1+aq^2)$

$\Rightarrow |V_{cb} f_+(0)| = 2.46 \times 10^{-2}$

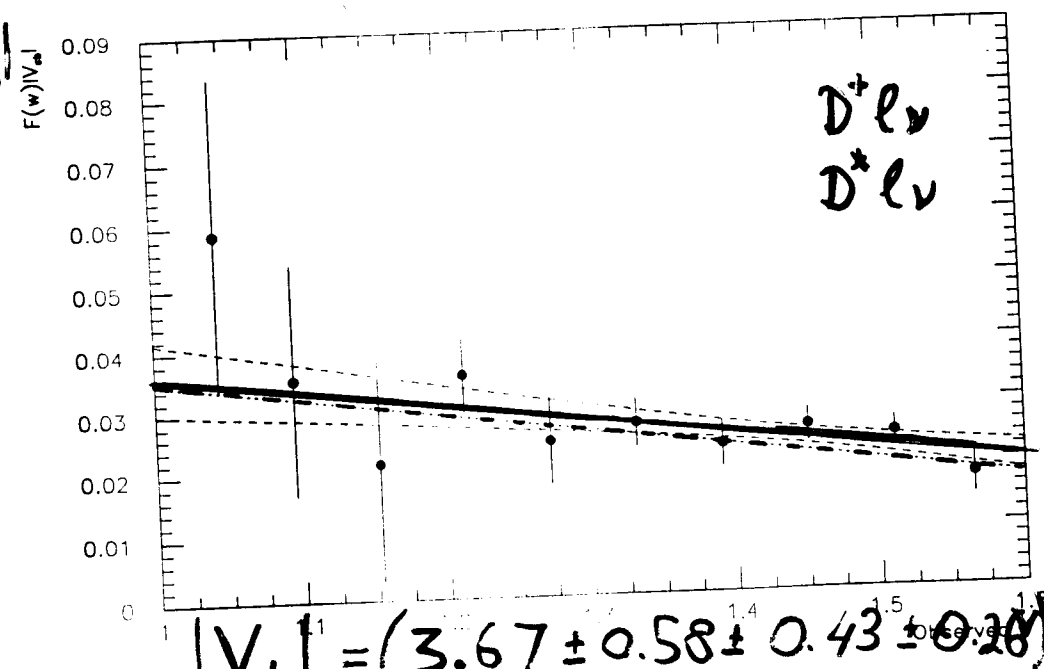
$a = 4.98 \cdot 10^{-2}$ GeV^{-2}

HQET $v \cdot v' = \frac{M^2 + m^2 - q^2}{2Mm}$

heavy quark limit: universal ff: $\boxed{\xi(w) = \mathcal{F}(1)\left(1 - \rho^2(w-1)\right)}$

$|\mathcal{F}(1) V_{cb}| = (3.60 \pm 0.57 \pm 0.42) \times 10^{-2}$; $\rho^2 = 0.73 \pm 0.24 \pm 0.10$

$|\mathcal{F} V_{cb}|$



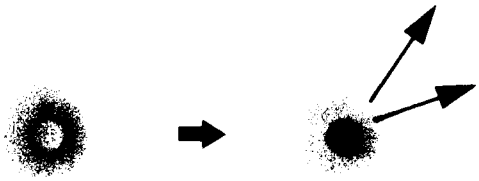
Caprini Neubert

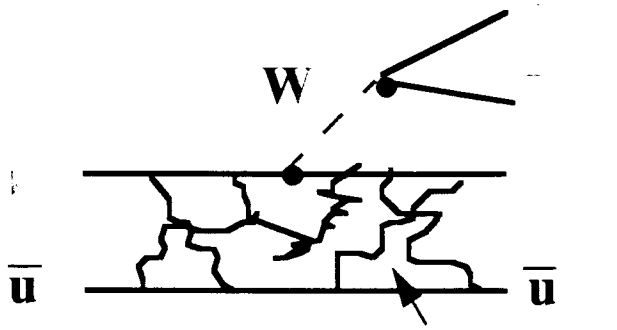
$\mathcal{F}(1) = 0.9$

$|V_{cb}| = (3.67 \pm 0.58 \pm 0.43 \pm 0.2) \times 10^{-2}$

Understanding Hadronic Decays

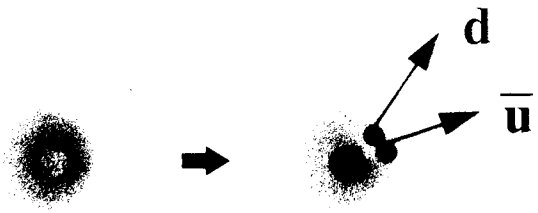
= Semileptonic

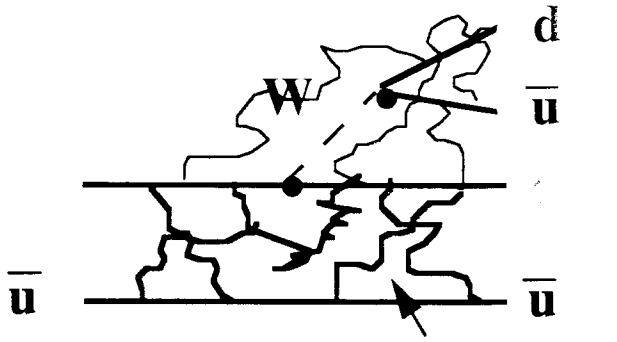




Strong Interaction

= Hadronic



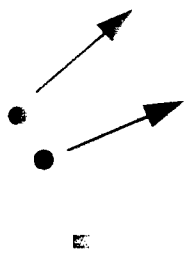


Strong Interaction

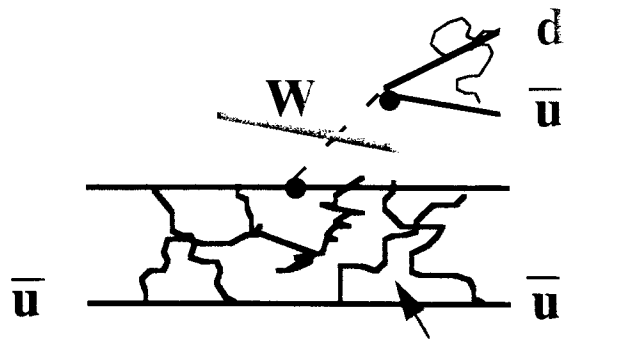
But it ...

W creates $\bar{u}d$ pointlike

- **color singlet**



if they get out fast enough ...



Strong Interaction

Hadronic Decays and Factorization

Semileptonic (e.g. $B \to D^{*+} l^- \nu$)

$$A = \frac{G_F}{\sqrt{2}} V_{cb} \langle \nu | \gamma_\mu (1-\gamma_5) | \ell \rangle \langle D^{*+} | (\bar{c}b) | \bar{B}^0 \rangle$$

Hadronic (+Factorization) (e.g. $B \to D^{*+}\pi$)

$$A = \frac{G_F}{\sqrt{2}} V_{cb} V_{ud}^* \langle \pi^- | (\bar{d}u) | 0 \rangle \langle D^{*+} | (\bar{c}b) | \bar{B}^0 \rangle$$

I. Branching Ratio Tests

Input: π decay constant ✓
semileptonic decay rate ✓

$$\frac{\Gamma(\bar{B}^0 \to D^{*+} \pi^-)}{\left.\frac{d\Gamma}{dq^2}(\bar{B}^0 \to D^{*+} \ell^- \bar{\nu})\right|_{q^2 = m_\pi^2}} = 6\pi^2 C_1^2 f_\pi^2 |V_{ud}|^2$$

$\Downarrow$ $\Downarrow$

	B->D*	B->D	"Theory"
$B^0 \to D^{(*)-}\pi^+$	1.18+/-0.21	0.94+/-0.30	1.22+/-0.15
$B^0 \to D^{(*)-}\rho^+$	2.92+/-0.70	2.63+/-0.88	3.26+/-0.42
$B^0 \to D^{(*)-}a_1^+$	3.8+/-1.0		3.0+/-0.5

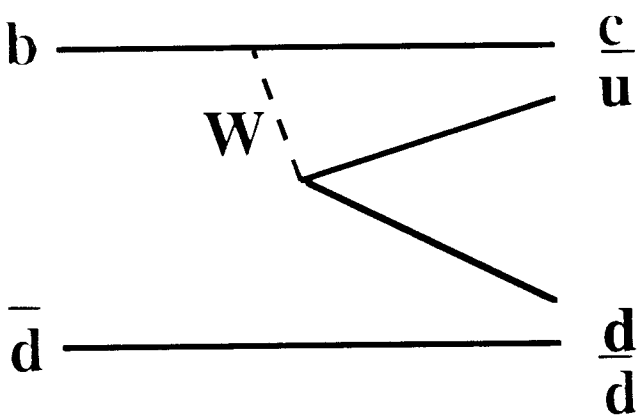
II. Polarization Tests

$\Gamma_L / \Gamma(B^0 \to D^* \rho^+) = 90 +/- 7 +/- 5\%$ $\quad$ $\Gamma_L / \Gamma(B^0 \to D^{*+} l^+ \nu) = 88\%$

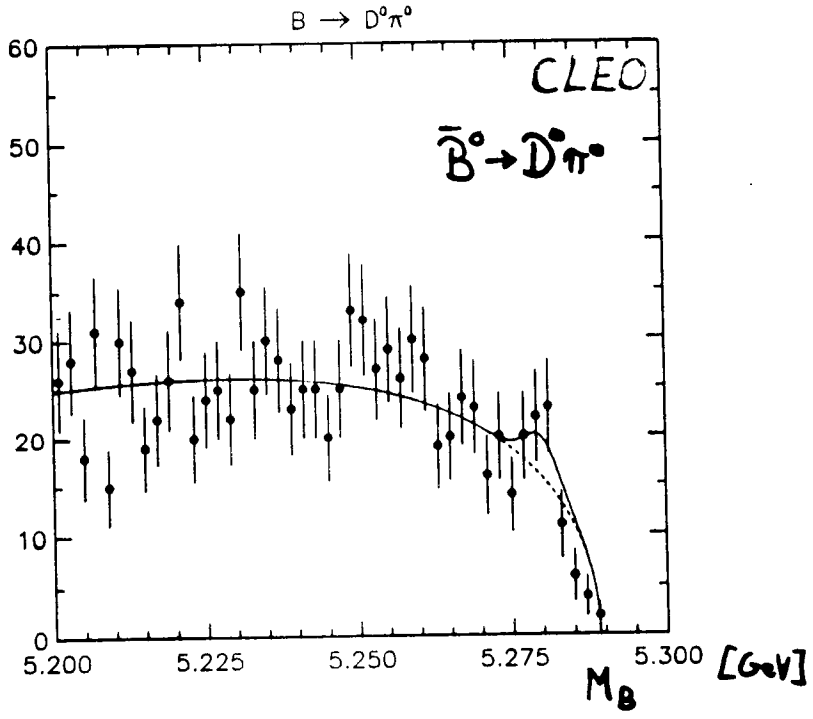
How can we learn more about Factorization?

- extend tests to higher values of q2
- study Final State Interaction
- Partial wave analysis, e.g. $B \to D^0\pi^-$, $D^0\pi^+$, $D^0\pi^0$

Color-suppressed B Decays



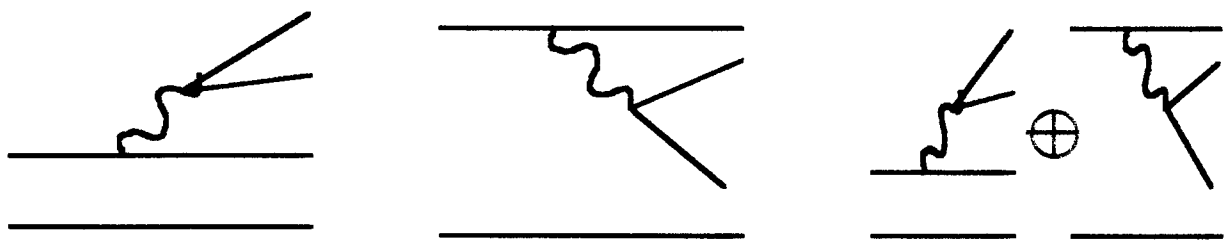
- color match required
- not at work in charm decay
- B decay?



BR(B-> $D^0\pi^0$)
< 0.03% (90% CL)

Color-suppression operative in hadronic B decay

Charge B Decay & Interference



Example	$\bar{B}^0 \to D^{*+}\pi^-$	$\bar{B}^0 \to D^{*0}\pi^0$	$B^- \to D^{*0}\pi^-$
BR:	0.27%	< 0.097 %	0.50 %
Model:	$0.254\ a_1^2$	$0.21\ a_2^2$	$0.255(a_1 + 1.29a_2)^2$

Extract a_1 and a_2:

BSW

$\boxed{a_1}$ $\bar{B}^0 \to D^{*+}\pi^-,\ D^{*+}\rho^-$ $\quad |a_1| = 1.07 \pm 0.04 \pm 0.06$

$D^{*+}\rho^-,\ D^{*+}\rho^-$

or $B^-, \bar{B}^0 \to D^{(*)} D_s^{(*)}$ $\quad |a_1| = 0.98 \pm 0.06 \pm 0.04$

$\boxed{a_2}$ $B^-, \bar{B}^0 \to \psi K, \psi K^*$ $\quad |a_2| = 0.2[illegible] \pm [illegible] \pm [illegible]$

$\boxed{a_2/a_1}$ $B^- \to D^{*0}\pi^-,\ D^{*0}\rho^-$ $\quad \frac{a_2}{a_1} = 0.1[illegible] \pm [illegible] \pm [illegible]$

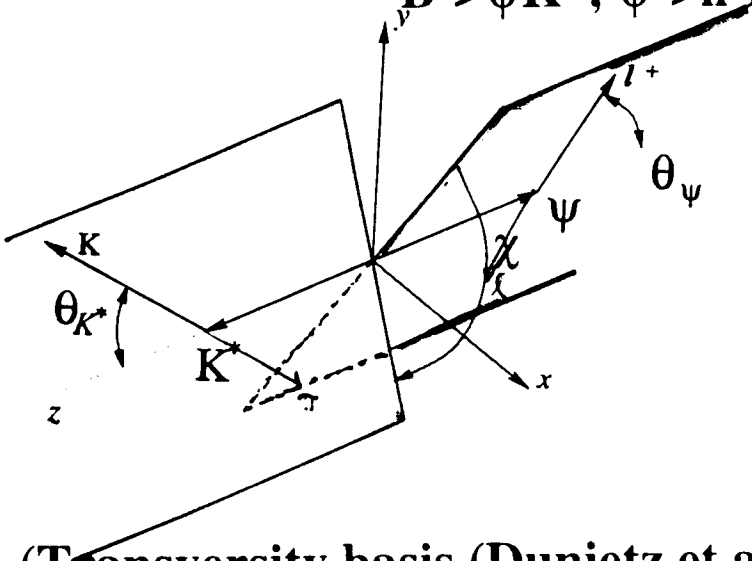
$D^0\pi^-,\ D^0\rho^-$ $\quad \hookrightarrow a_2 = 0.21 \pm 0.0[illegible]$

Compare: $a_1 = c_1(m_b) + \frac{1}{3} c_2(m_b) = [illegible]$; $a_2 = c_2 + \frac{1}{3} c_1 = [illegible]$

Full Angular Analysis of B->ψK*

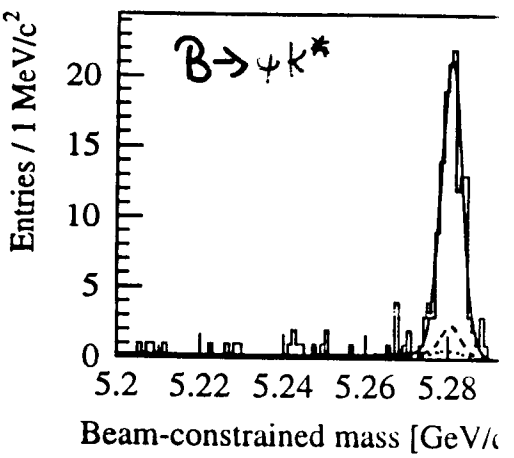
CLEO **3.36x10⁶ BB decays**

B->ψK*, ψ->ll⁺, K*->Kπ



(Transversity basis (Dunietz et al))

$$\frac{d^3\Gamma}{d\cos\theta_{tr}\, d\cos\theta_{K^*}\, d\phi_{tr}} = \frac{9}{32\pi}\{2\cos^2\theta_{K^*}(1-\sin^2\theta_{tr}\cos^2\phi_{tr})\,|A_0|^2$$
$$+ \sin^2\theta_{K^*}(1-\sin^2\theta_{tr}\sin^2\phi_{tr})\,|A_{\parallel}|^2$$
$$+ \sin^2\theta_{K^*}\sin^2\theta_{tr}\sin^2\phi_{tr}\,|A_{\perp}|^2$$
$$- \sin^2\theta_{K^*}\sin 2\theta_{tr}\sin\phi_{tr}\,\mathrm{Im}\,(A_{\parallel}^* A_{\perp})$$



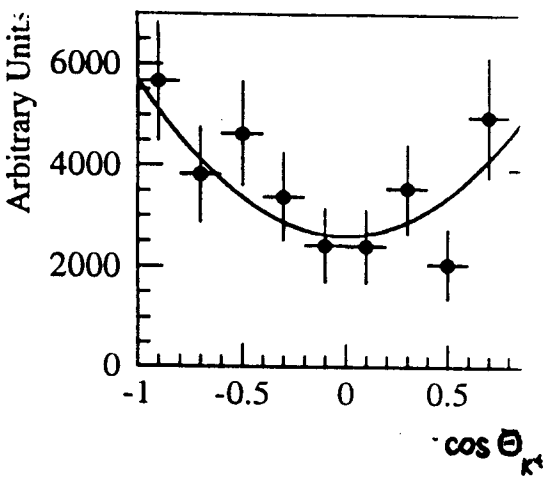
$|A_0|^2 = 0.52 \pm 0.07$

$|A_\perp|^2 = 0.16 \pm 0.08$

set $\phi(A_0) \equiv 0$

$\Rightarrow \quad \phi(A_\parallel) = 3.00 \pm 0.37 \pm 0.03$

$\phi(A_\perp) = -0.11 \pm 0.46 \pm 0.03$



consistent with 0 and 2π ➡ no evidence for FSI

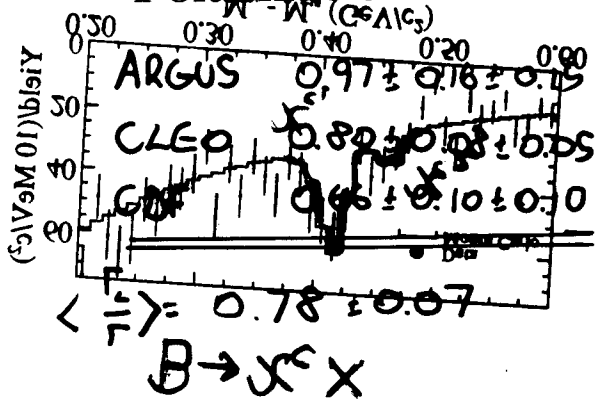
B to Charmonium Transitions

Experiment (pre-1996):

Production Ratio

$$\frac{BR(B \to \psi K^*)}{BR(B \to \psi K)} = 1.47 \pm 0.21$$

Polarization



Theory:

Models have difficulties to combine the measured production ratio and polarization

	Ratio	Γ_L/Γ
BSW	4.23	0.57
Neubert et al	1.61	0.36
ISGW	1.71	0.07
Aleksan et al	2.15	0.45
Cheng et al	1.81	0.56

$$A(B \to \psi K(K^*)) = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* a_2 \left[\langle \psi K(K^*) \mid (\bar{c}c)(\bar{s}b) \mid B \rangle + \kappa \left\langle \psi K(K^*) \mid H_w^{(8)} \mid B \right\rangle \right], \quad (5)$$

non-factorizable contributions?

reduce transverse amplitude

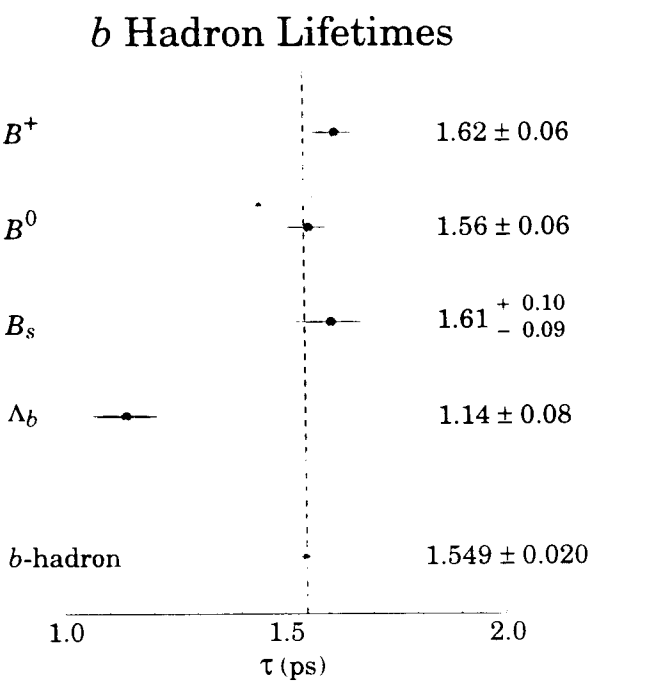
Ratio ~ 1.5 and Γ_L/Γ ~ 0.75

CLEO (1996)

R = 1.36+/-0.17+/-0.11, Γ_L/Γ = 0.52+/-0.07+/-0.04

something more inclusive?

PDG96



Theoretical Expectation (Bigi et al)

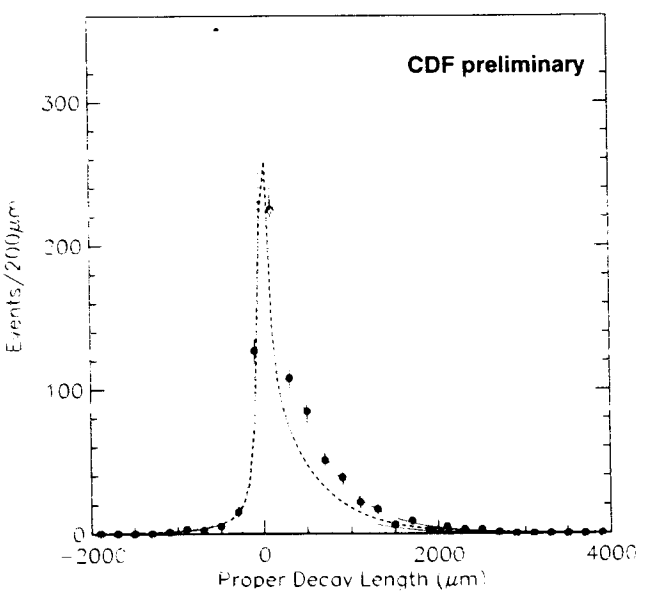
Observable	QCD Expectations ($1/m_b$ expansion)	Ref.	Data
$\tau(B^-)/\tau(B_d)$	$1 + 0.05(f_B/200\ \text{MeV})^2[1 \pm \mathcal{O}(30\%)] > 1$ (mainly due to *destructive* interference)	[16]	1.04 ± 0.04
$\bar{\tau}(B_s)/\tau(B_d)$	$1 \pm \mathcal{O}(0.01)$	[123]	0.97 ± 0.05
$\tau(\Lambda_b)/\tau(B_d)$	$\simeq$ **0.9**	[123]	0.77 ± 0.05

τ_{Λ_b}:

New CDF result:

$\tau(\Lambda_b) = 1.32 +/- 0.15 +/- 0.07$ ps

using 110 pb^{-1}
and $\Lambda^0_b \to \Lambda^+_c l\nu$



The Baffling Semileptonic BR

a problem(?) in review

Experiment

$$BR_{sl} = 10.49 \pm 0.17 \pm 0.43\ \%$$

(CLEO)

Theory

$$BR_{sl} = \frac{\Gamma_{sl}}{\Gamma_{Tot}} = \frac{\Gamma_{sl}}{\Sigma(\Gamma_{sl}) + \Gamma_{Hadronic}}$$

1. Naive, count W decay channels
   $BR_{sl} \approx 15\text{-}16\ \%$

2. Perturbative QCD
   $BR_{sl} \approx 13\text{-}14\ \%$

3. Non Perturbative Corrections (HQE)
   $BR_{sl} > \underline{12.5\ \%}$

Solution: increase $\Gamma_{Hadronic}$

⇨ constructive interference in charge B decays

⇨ additional modes, e.g. gluonic penguins

⇨ re-visit perturbative correction
(Ball, Bagan et al.)
(Neubert, Sachrajda)

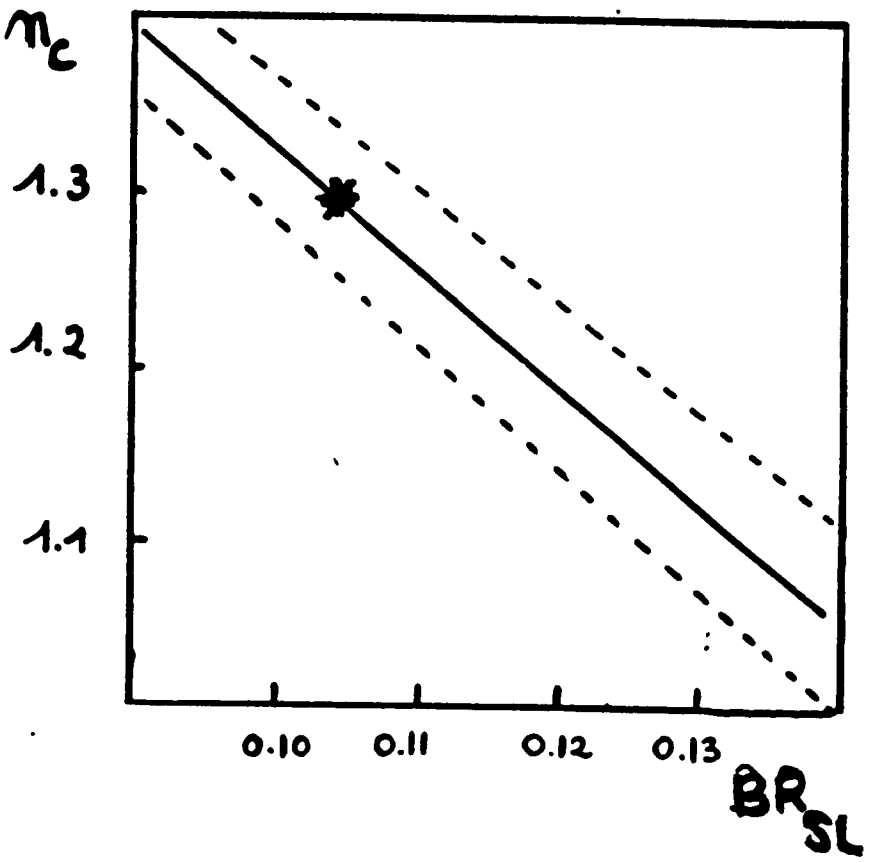
- o massive charm quark
- o renormalization scale

BR_{SL} = (12.1 +/- 0.7 $^{+0.9}_{-1.2}$) % (on shell)

(11.7 +/- 0.7 $^{+0.9}_{-1.3}$) % (MS)

BUT

... the b->ccs increases and so does N_c



Buchalla
Dunietz
Yamamoto
FNAL 95/167

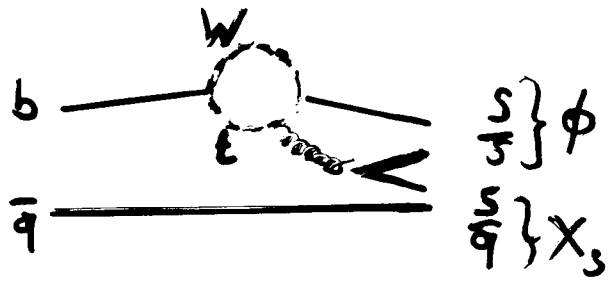
we create a new problem:

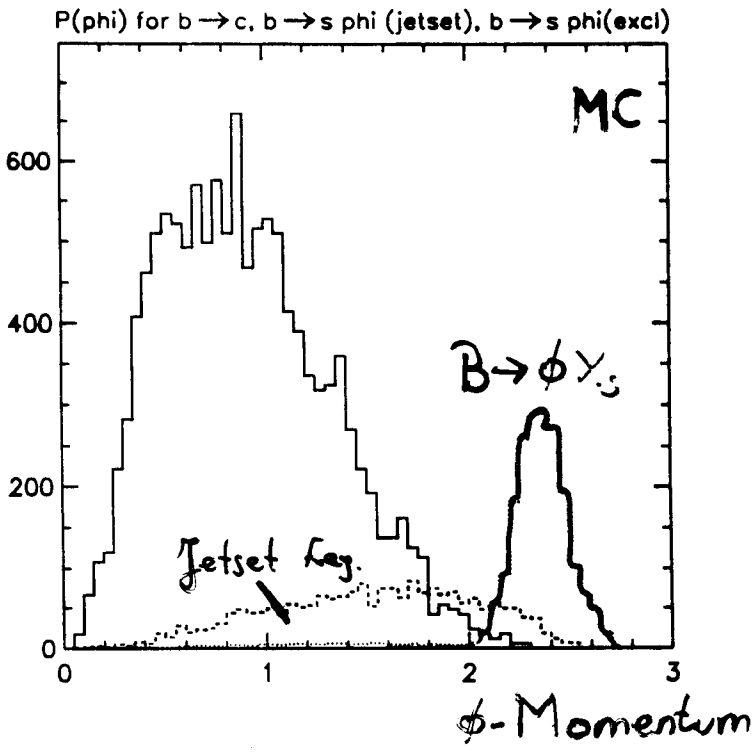
n_{charm} = 1.27+/- 0.07 (Buchalla et al)
n_{charm} = 1.21+/- 0.04+/-0.01 (N&S)

Charm Counting

Inclusive ϕ – Production
Search for gluonic penguins

Datasample
2.1 fb^{-1} ON
1.0 fb^{-1} OFF





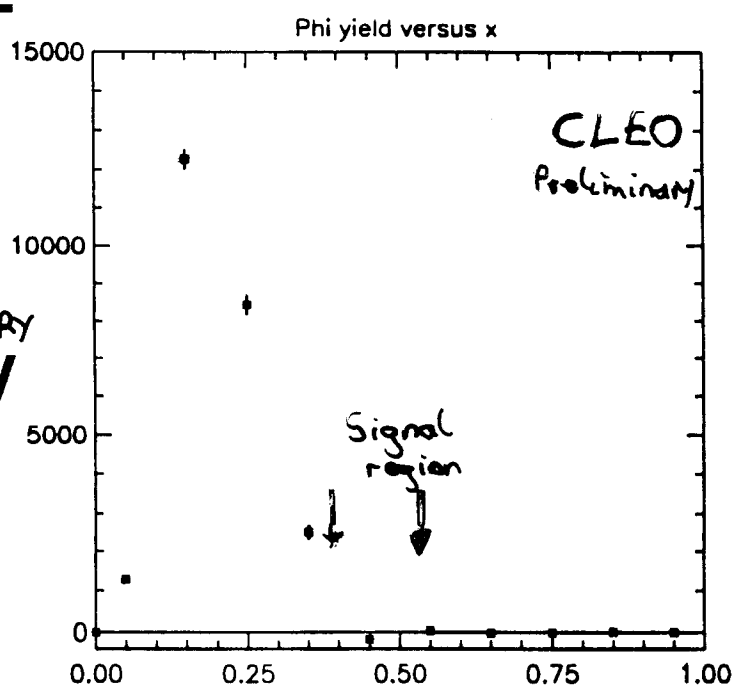
No evidence for 2-body component

$B \to \phi X_s$ [2-2.5 GeV] $\lesssim 1.1 \times 10^{-4}$ PRELIMINARY

Extrapolation very uncertain!

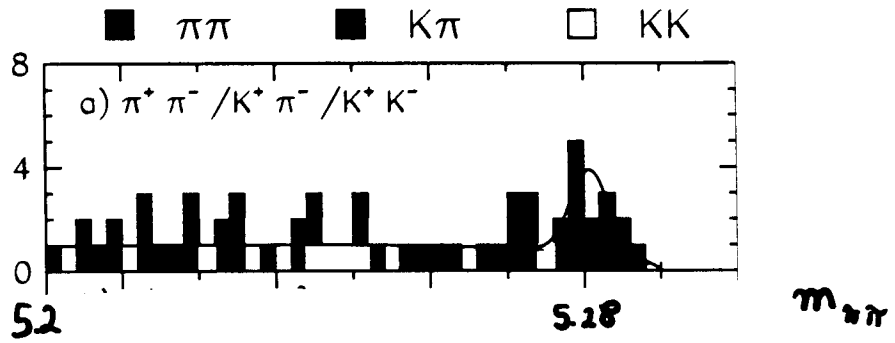
Similar $B \to \eta' X_s < 1.7 \times 10^{-3}$

$B \to K_S X < 7.5 \times 10^{-4}$



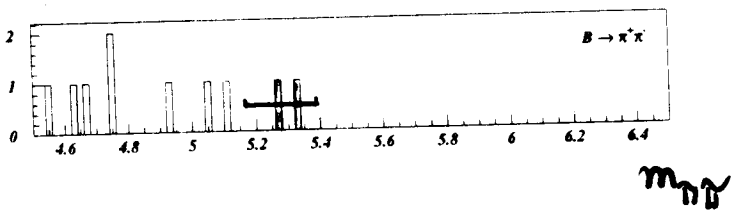
sin (2α): B-> ππ and B-> Kπ

CLEO (95)



$BR(B \to h^+h^-) = (1.8 \pm 0.6 \pm 0.3) \times 10^{-5}$

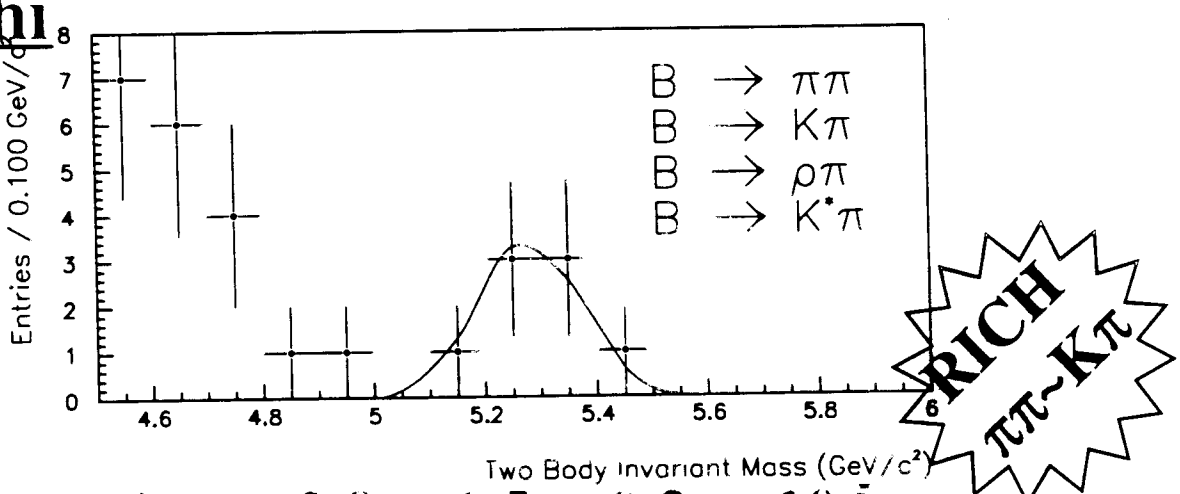
Aleph



$(1.7^{+1.0}_{-0.7} \pm 0.2)$

$BR(b \to h^+h^-) = (2 \pm 1) \times 10^{-5}$

Delphi



$BR(b \to h^+h^-) = (2.8 \pm 1.5 \pm 0.2) \times 10^{-5}$

	CLEO
N_{Charm} = BR(D^oX)	64.8+/-3.4
+ BR(D^+X)	24.2+/-2.3
+ BR(D_sX)	10.1+/-2.6
+ BR(Λ_cX)	6.3+/-1.6
+ BR(Ξ^o_cX)	2.4+/-1.3
+ BR(Ξ^+_cX)	1.5+/-0.7
+ 2xBR(ψX)	0.82+/-0.08
+ 2xBR($\psi'X$)	0.35+/-0.05
+ 2xBR($\chi_{c1}X$)	0.37+/-0.05
+ 2xBR($\chi_{c2}X$)	0.25+/-0.10
+ 2xBR(η_cX)	< 0.90

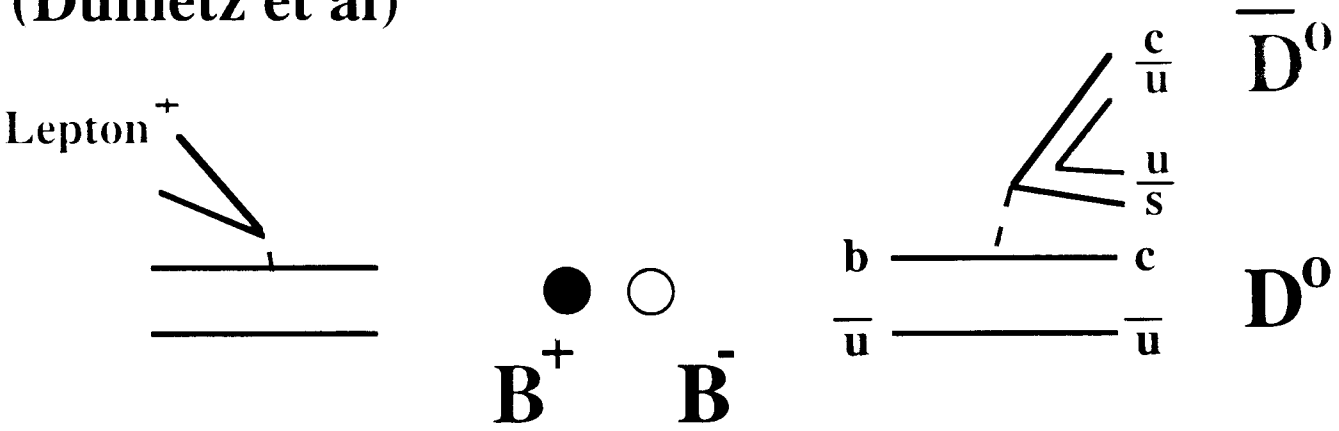
Charm Yield | **1.15 +/- 0.5**

N_{cc} = BR(D_sX) + BR(Ξ^o_cX)
+ BR(Ξ^+_cX) + BR(ψX) + BR($\psi'X$)
+ BR($\chi_{c1}X$) + BR($\chi_{c2}X$) + BR(η_cX)

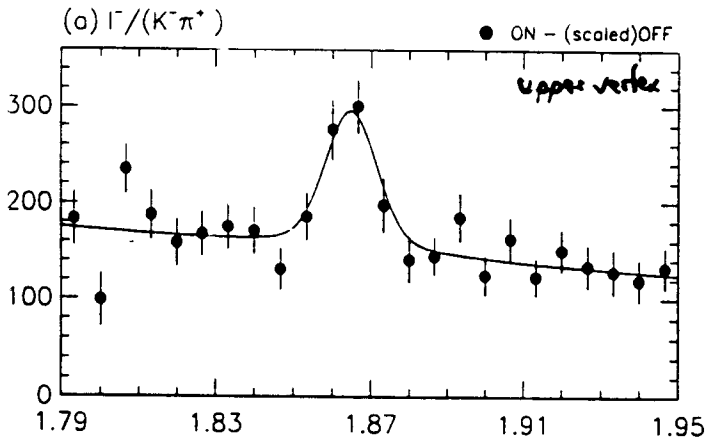
b-> $c\bar{c}s$ | **= 15.8 +/- 2.8**

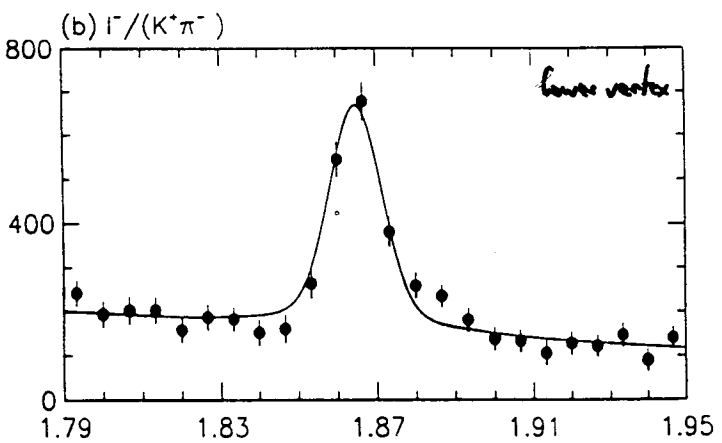
Search for b->ccs

what if W -> cs creates more than one particle ?
(Dunietz et al)



➡ search for D^0- Lepton Correlations





$BR\ (B->DX)_{upper\ vertex} = (8.1 +/- 2.6)\ \%$

Relief for $b->c\bar{c}s$ but what about N_c

Still baffled?

	Theory	CLEO	ALEPH
B_{sl}	~11.5	10.49+/-0.46	11.01+/-0.40
n_c	~1.27	1.15+/-0.05	1.20+/-0.07
n_{ccs}	~27	23.9+/- 3.8	30+/-5

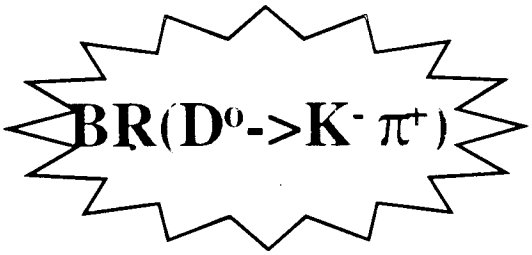
ALEPH: BR(DDX) = 12.8+/-2.7+/-2.6

n_c for Z-> bb (B_c, Λ_b effects)

Experimental systematics?

PDG96: 3.83+/-0.12%

Browder+KH: 3.76+/-0.15%



if D->Kπ is 10% smaller:

- n_c increases
- exclusive BR_{sl} = inclusive BR_{sl}
-
- (Dunietz, hep-ph/9606247)

But a new ALEPH result: 3.897+/-0.094+/-0.117%

Summary

B mesons provide a wonderful laboratory to study the strong interaction

The b quark appears to be heavy enough to apply HQET

Simple factorization works in hadronic B decay
Initial studies on Final State Interactions

Color suppression works in neutral B decay

Constructive interference in charged B decay remains a puzzle

Open questions in inclusive studies:

- Λ_b lifetime
- B_{sl} and charm counting