CLEO

CLEO I.5

CLEO II

CLEO II.V

CLEO III

Recent Results on Hadronic B Decay

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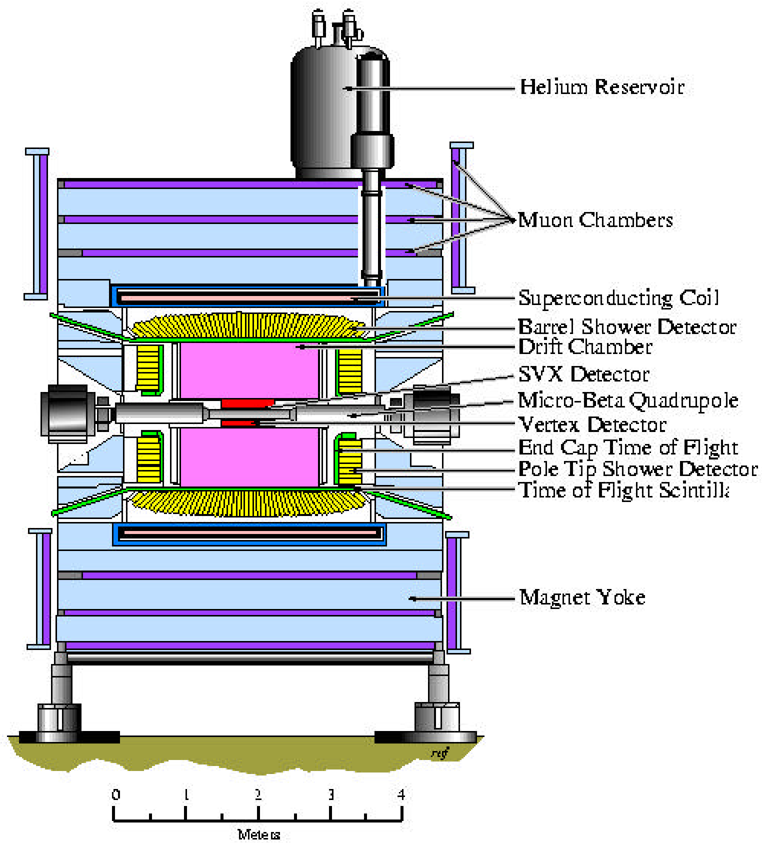
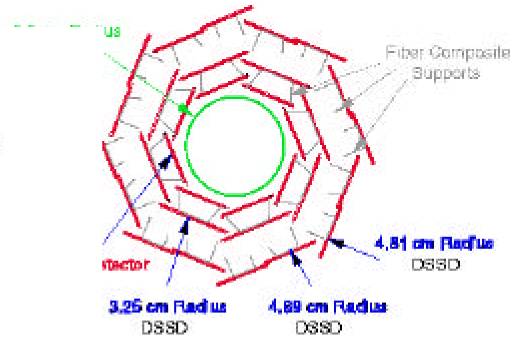
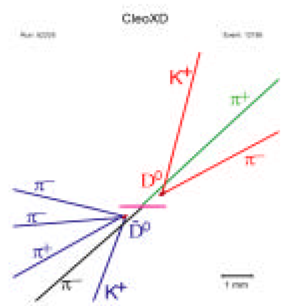
Ohio State University
HF9, Pasadena 2001

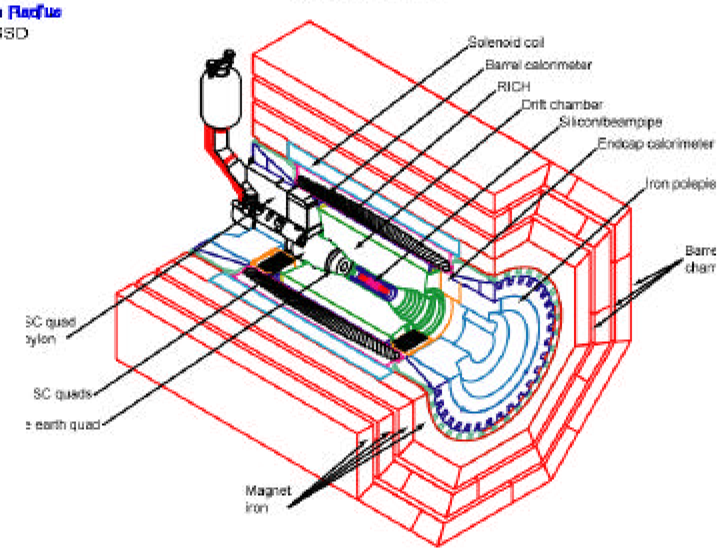
CLEO II (90 – 95), CLEO II.V (95-99) and CLEO III (00-01)







CLEO III



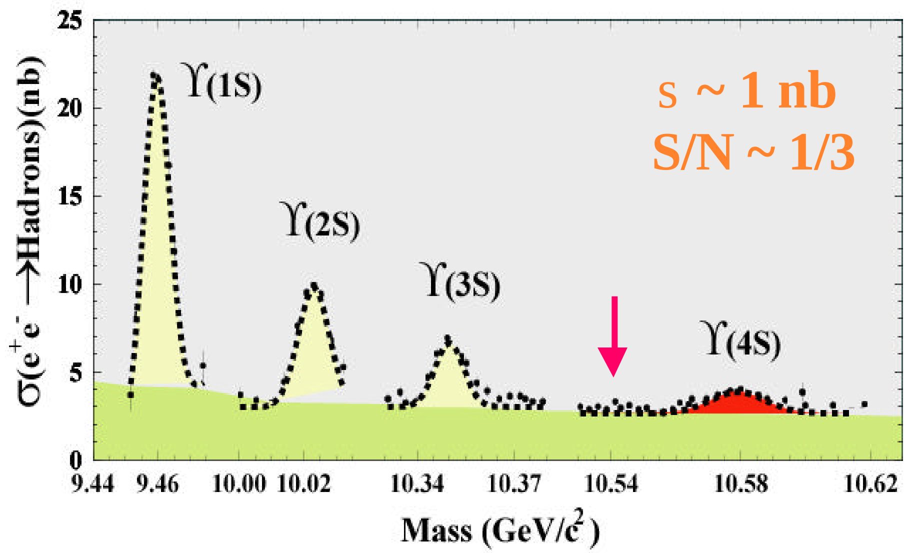
CLEO Data Set

- CESR - symmetric e^+e^- storage ring
  - operates on Υ(4S)
  - BB produced near threshold
- B decay kinematics
  - Energy difference

$$\Delta E = E_B - E_{beam}$$

  - Beam-constrained mass

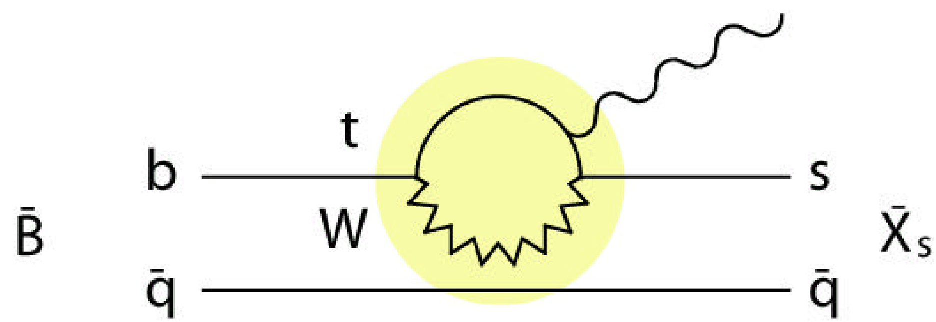
$$M_{bc} = \sqrt{E_{beam}^2 - p_B^2}$$



- Data sets
  - CLEO II, II.V
    - ~ 9.1 fb^{-1} on Υ(4S) => 9.7 x 10^6 BB Events
    - ~ 4.4 fb^{-1} off Υ(4S)
  - CLEO III
    - ~ 6.9 fb^{-1} on Υ(4S) => 7.4 x 10^6 BB Events
    - ~ 2.3 fb^{-1} off Υ(4S)

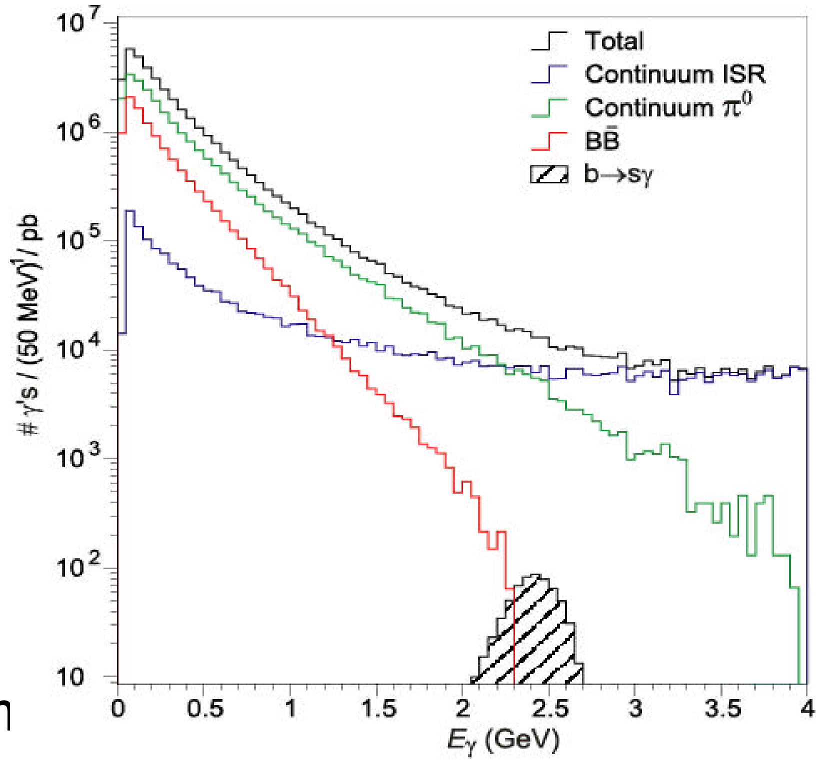
Inclusive Radiative Penguin Decays

- Inclusive B(b->sγ) is sensitive to New Physics beyond the Standard Model
  - Charged Higgs
  - Anomalous WWγ couplings
  - Charginos
- Photon Spectrum (HQET/OPE, V_{cb}, V_{ub})
- Next-to-Leading order calculation
- Improve original CLEO result PRL 74, 2885 (1995)

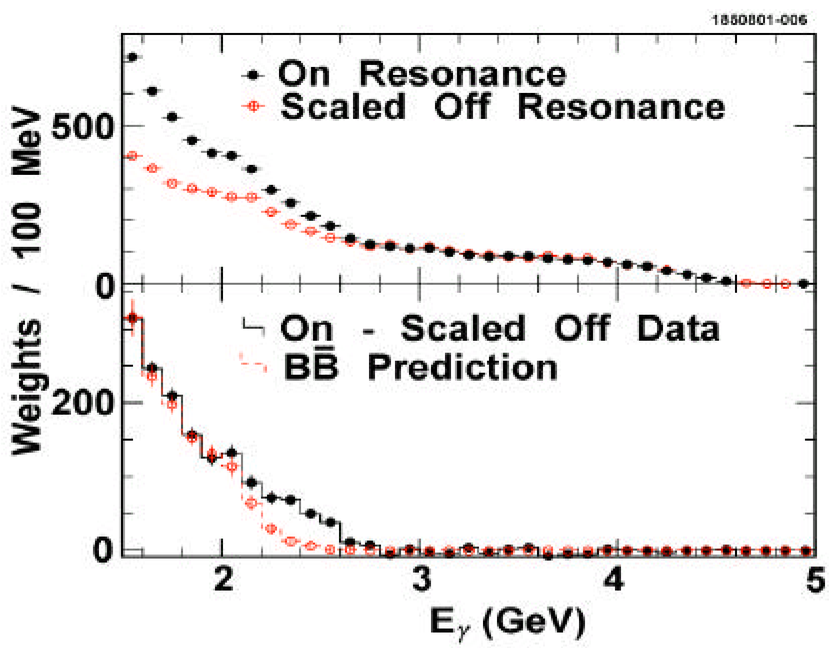


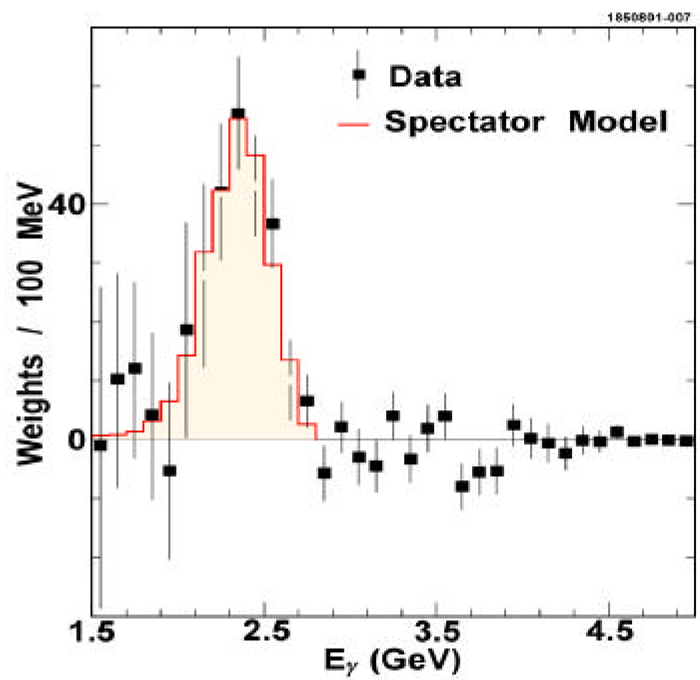
b -> sγ Decays

- 19.4 x 10^6 B decays
- Extended signal region $2.0<E_\gamma<2.7$
  - Includes essentially entire γ spectrum
  - Much less model dependence
- Huge # of γ's from continuum
  - π^0, η decay, ISR
  - Reduce using event shape and X_s pseudo-reconstruction
  - Subtract remaining background using off-Υ(4S) data
- Combine all information into a single weight between 0.0 (continuum and 1.0 (b-> sγ)



b -> sγ Decays (CLNS 01/1751, subm. to PRL)





Result (CLEO II, II.V)

$$B\,(b \to s\gamma) = (3.21 \pm 0.43 \pm 0.27^{+0.18}_{-0.10}) \times 10^{-4}$$

Theory (Chetyrkin, Misiak, Munz and Kagan, Neubert)

$$B(b \to s\gamma) = (3.29 \pm 0.33) \times 10^{-4}$$

Conclusion: The window for New Physics is closing

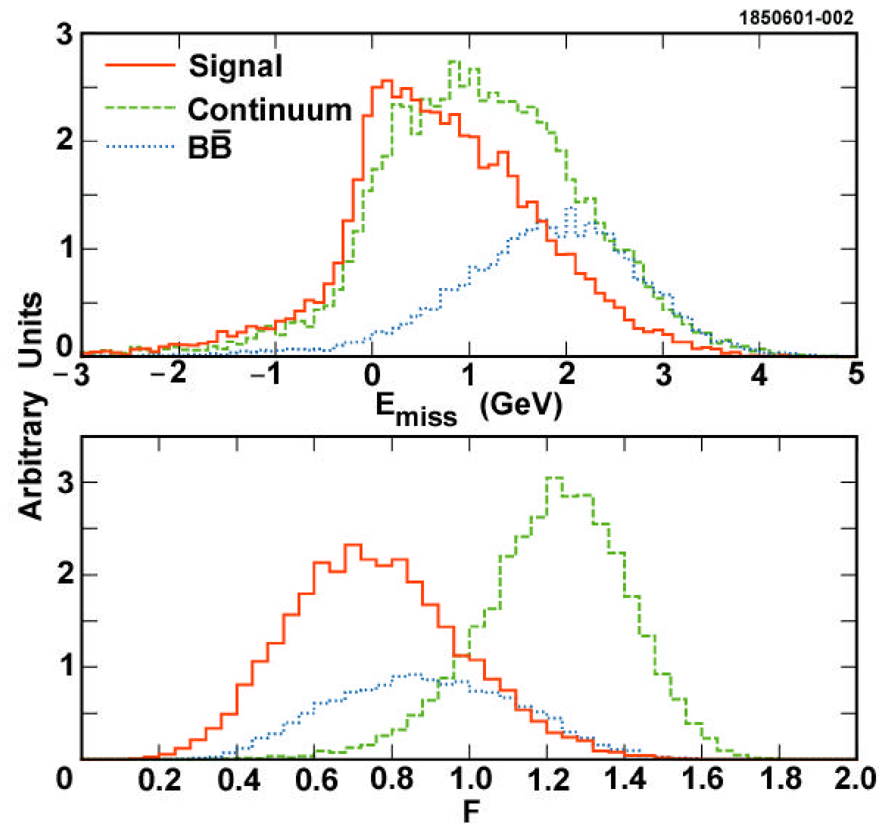
Search for B-> $K^{(*)}$ l^+l^- Decays

Motivation

- Sensitive to New Physics
  - Different Wilson coefficients (C_7, C_9, C_{10})
  - Reduce C_7 dependence ($\gamma_{virtual}$ pole) by requiring m_{ll}>0.5 GeV in B->$K^*l^+l^-$ analysis

Analysis

- Tight e, μ identification
- BG from semileptonic B decay
  - Require small missing energy
- ψ veto
- Fisher Discriminant to suppress continuum BG
- Count events in M_{bc}-ΔE signal box



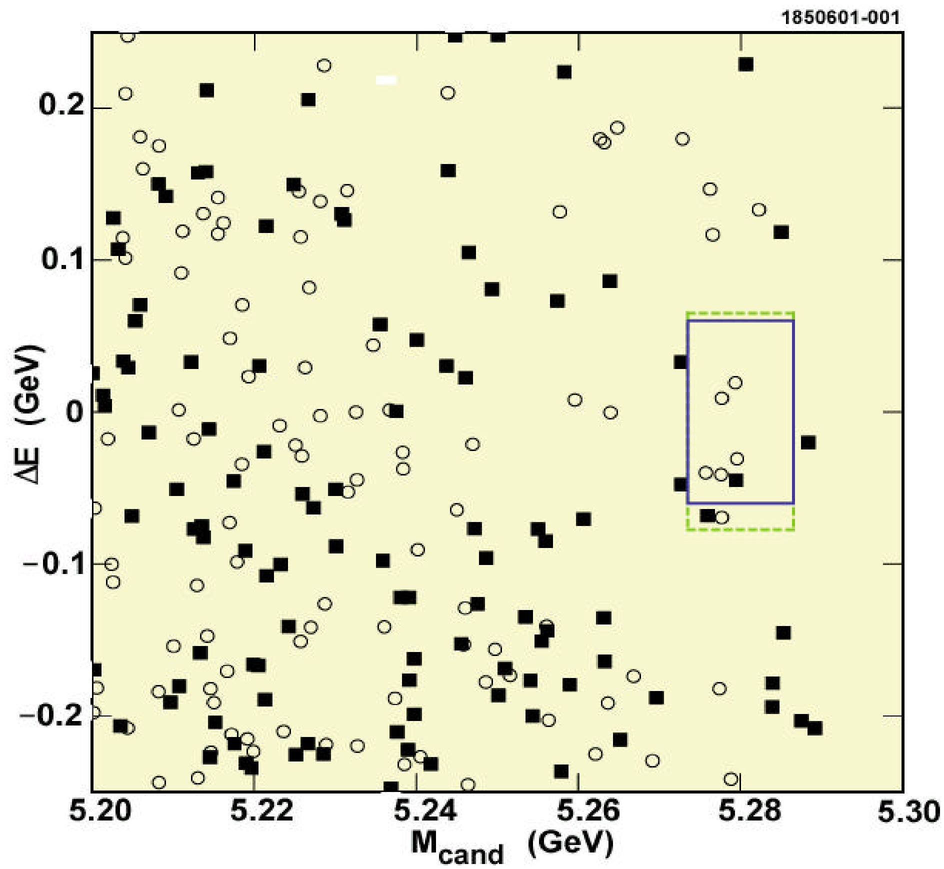
Search for B-> $K^{(*)}\ l^+l^-$ Decays

Results (90% C.L.)

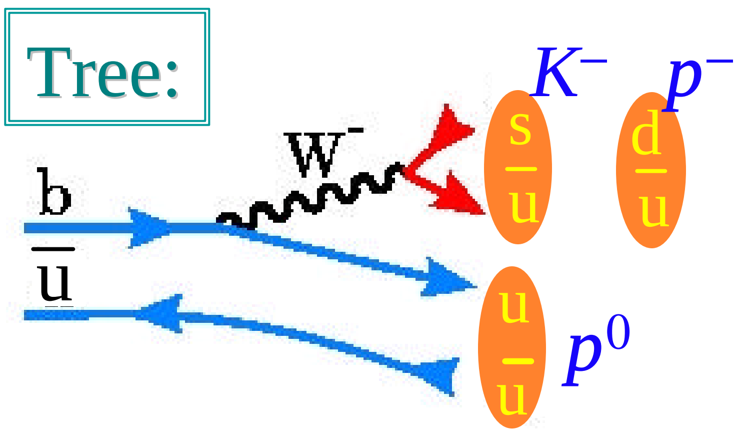
- $B(B \to K l^+ l^-) < 1.5 \times 10^{-6}$
- $B(B \to K^* l^+ l^-)_{mll>0.5} < 3.3 \times 10^{-6}$
- Weighted average (65% B→K, 35% B→K*)

  $B(B \to K^{(*)} l^+ l^-) < 1.7 \times 10^{-6}$

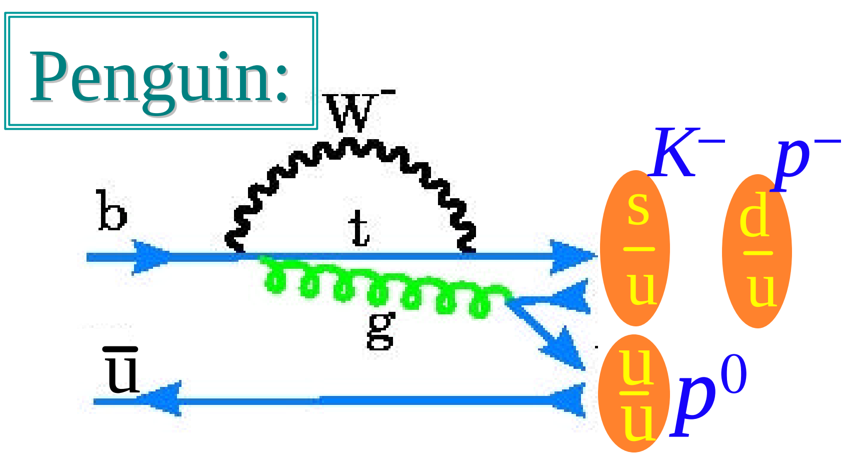
- Consistent with SM but only slightly above prediction
- hep-ex/0106060 (subm. To PRL)



Rare B Decay

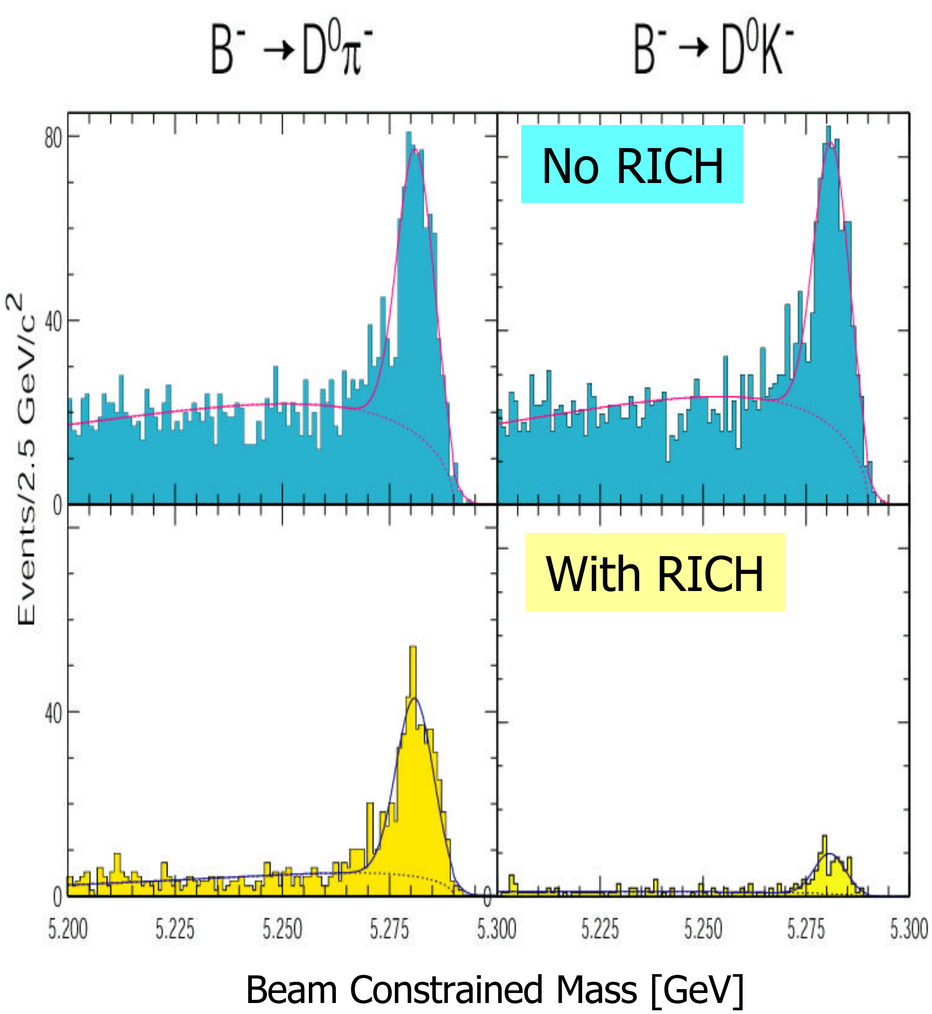


- Tree decays $b\to u$ vs. $b\to c$ suppressed by $|V_{ub}|^2/|V_{cb}|^2 \sim 0.01$
- Additional $|V_{us}|^2/|V_{ud}|^2 \sim 0.04$ for K^-
- Expect tree dominantly $b\to u\bar{u}d$.



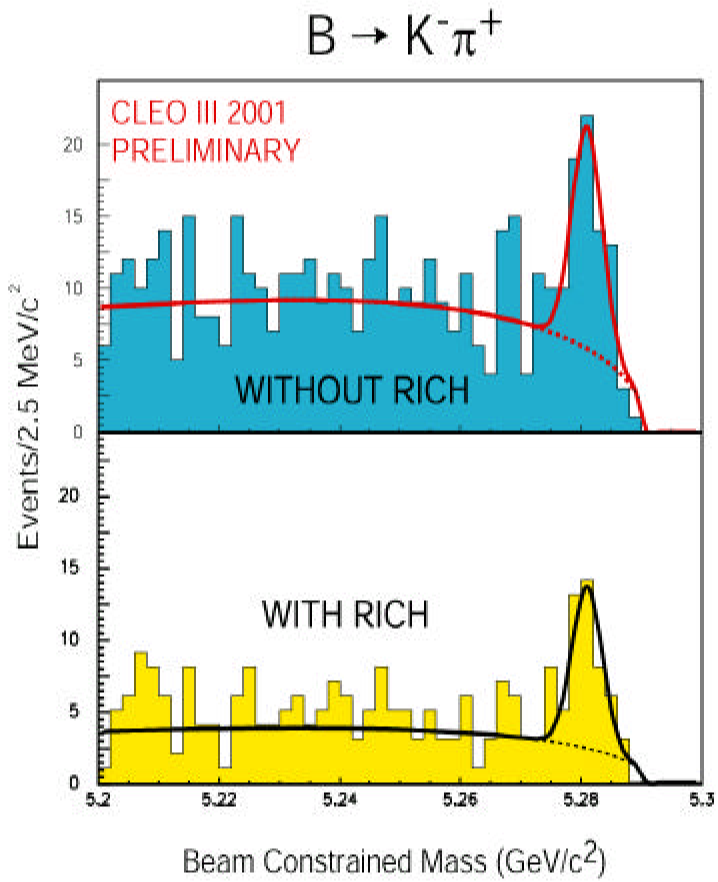
- Decays $b\to s,d$ GIM-suppressed
- Loop diagram $\propto (m_t/m_W)^2$.
- $|V_{td}|^2/|V_{ts}|^2 \sim 0.01$
- Expect penguins dominantly $b\to u\bar{u}s$.

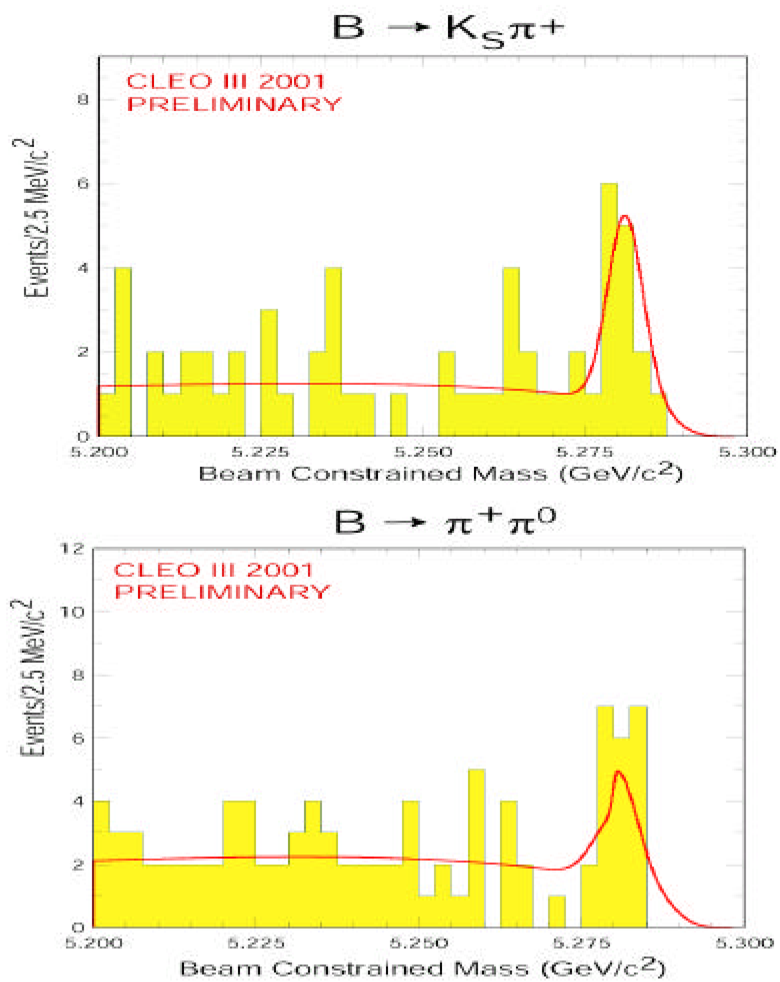
$B \to K\pi$ and $B \to \pi\pi$ from CLEO III



- Preliminary results using 1/2 of the CLEO III data
- RICH provides clean K/π separation at 2.2 GeV
  - K efficiency 85%
  - π fake rate 7%
- Standard CLEO rare B reconstruction technique

$B \to K\pi$ and $B \to \pi\pi$ from CLEO III





B $\rightarrow$ Kπ and B $\rightarrow$ $\pi\pi$ from CLEO III

CLEO III – 2001 Preliminary

(CLEO 1999 published results)

Mode	Eff (%)	Yield	Signif	B (10^{-6})	U L (10^{-6})
$K^+\pi^-$	46	$29.2^{+7.1}_{-6.4}$	5.4σ	$18.6^{-4.5\ -3.0}_{-4.1\ -3.4}$	
	45	$80.2^{+11.8}_{-11.0}$	11.7σ	$18.8^{+2.8}_{-2.6} \pm 1.3$	
$K^\pm\pi^0$	32	$12.9^{+6.5}_{-5.5}$	3.8σ	$13.1^{+5.8+2.8}_{-4.9-2.9}$	
	38	$44.9^{+11.3}_{-10.3}$	6.1σ	$12.1^{+3.0+2.1}_{-2.8-1.4}$	
$K^0\pi^\pm$	12	$14.8^{+4.9}_{-4.1}$	6.2σ	$35.7^{+12\ +5.4}_{-9.9\ -6.2}$	
	14	$25.2^{+6.4}_{-5.6}$	7.6σ	$18.2^{+4.6}_{-4.0} \pm 1.6$	
$K^0\pi^0$	8.5	$3.0^{+2.9}_{-2.5}$	1.6σ	$10.4^{+10\ +2.9}_{-8.3\ -2.9}$	72
	11	$15.5^{+5.9}_{-5.0}$	4.7σ	$14.8^{+5.9+2.4}_{-5.1\ -3.3}$	

$B \to K\pi$ and $B \to \pi\pi$ from CLEO III

CLEO III – 2001 Preliminary

(CLEO 1999 published results)

Mode	Eff (%)	Yield	Signif	B (10^{-6})	UL (10^{-6})
$\pi^0\pi^0$	29	$2.7^{+2.4}_{-1.6}$	2.9 σ		11
	29	$6.2^{+4.8}_{-3.7}$	2.0 σ		5.7
K^+K^-	36	$1.0^{+2.4}_{-1.7}$	0.6 σ		4.5
	45	$0.0^{+3.4}_{-0.0}$	0.0 σ		2
$K^0K^\pm$	12	$0.5^{+1.9}_{-1.1}$	0.8 σ		18
	14	$1.4^{+2.4}_{-1.3}$	1.1 σ		5.1
$K^0\bar{K}^0$	13	$0.0^{+0.5}_{-0.5}$			13
	19	$1.0^{+1.9}_{-1.0}$			6.1

$B \to K\pi$ and $B \to \pi\pi$ from CLEO III

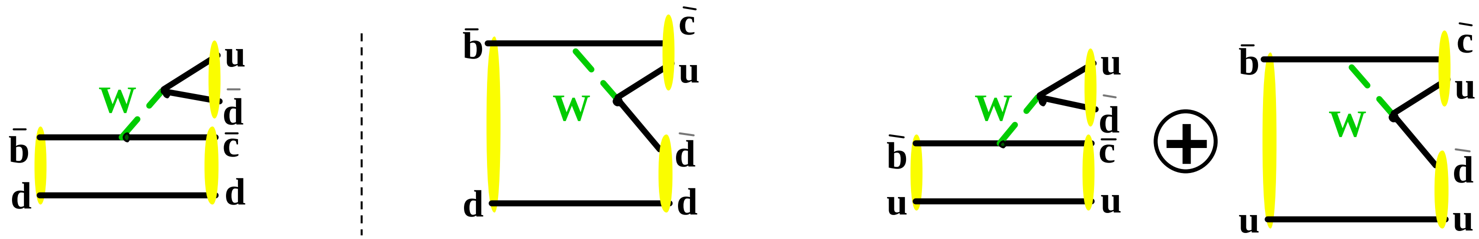
CLEO III – 2001 Preliminary

(CLEO 1999 published results)

Mode	Eff (%)	Yield	Signif	B (10^{-6})	UL (10^{-6})
$\pi^+ \pi^-$	35	$3.9^{+1.5}_{-1.2}$	2.2	$3.2^{+3.3+1.0}_{-2.5-1.0}$	11
	45	$20.0^{+7.6}_{-6.5}$	4.2	$4.7^{+1.8}_{-1.5} \pm 0.6$	
$\pi^\pm \pi^0$	29	$11.5^{+5.6}_{-4.5}$	3.4	$11.7^{+5.7+2.2}_{-4.6-2.4}$	25
	41	$23.1^{+9.1}_{-8.7}$	3.2	$5.6^{+2.6+1.7}_{-2.3-1.7}$	12

Understanding Hadronic B Decay

B^0 Decay | B^+ Decay



B^0 ->$D^- p^+$ | **B^0 ->$D^0 p^0$** | **B^+ ->$D^0 p^+$**

BSW: class-1 (a_1) | class-2 (a_2) | class-3 (a_1+ z a_2)

- Experimental and theoretical justification for factorization?
- Are the phenomenological constants a_1, a_2 universal?
- Quite successful in charm decay:
  - destructive interference
  - smaller $G_{Hadronic}$ for D^+
  - $t_{D+} >> t_{D0}$

Mode	B^0 (x10^{-3})	B^+ (x10^{-3})
Dπ	3.0+/-0.4	5.3+/-0.5
Dρ	7.9+/-1.4	13.4+/1.8
Da_1	6.0+/-3.3	
Dρ’	2.8+/-0.6	4.1+/-0.8
D*π	2.8+/-0.2	4.6+/-0.4
D*ρ	6.8+/-3.4	15.5+/-3.1
D^*a_1	13+/-2.7	19+/-5
D*ρ’	2.9+/-0.5	4.1+/-0.8

Factorization

Color transparency

(lots of recent theoretical activity, see afternoon session)

- Semileptonic Decay

$$A = \frac{G_F}{\sqrt{2}} V_{cb} V_{ub}^{*} < \nu | \gamma_\mu (1 - \gamma_5) | l > < D^{*-} | (cb) | B^0 >$$

- Hadronic + Factorization

$$A = \frac{G_F}{\sqrt{2}} V_{cb} V_{ub}^{*} < \pi | (du) | 0 > < D^{*-} | (cb) | B^0 >$$

Factorization Tests

- Branching Ratios

$$\frac{\Gamma(B \to D^{*+} h^-)}{\frac{d\Gamma}{dq^2}(B \to D^{*+} l\nu)|_{q^2 = m_h^2}} = 6\pi^2 c_1^2 f_h^2 |V_{ud}|^2$$

- Polarization

$$\Gamma_L / \Gamma(B \to D^{*+} h^-) = \Gamma_L / \Gamma(B \to D^{*+} l\nu)|_{q^2 = m_h^2}$$

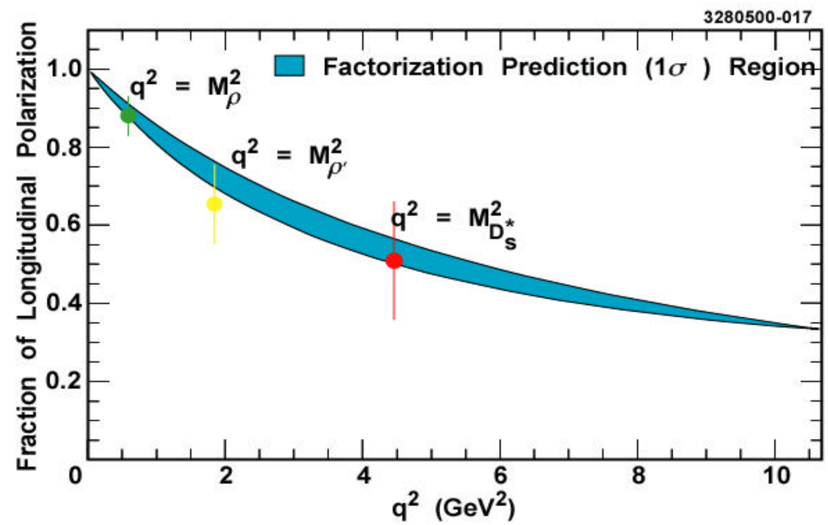
Testing Factorization (Class-1 Decays)

- **Branching Ratios (CLEO data, fit to dG/dq$_2$(B ® D$^{(*)}$ln))**

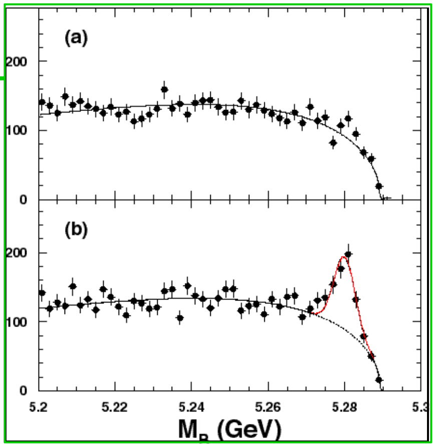
	B ® D*	B ® D	Factorization
B^0® D$^{(*)}$p$^+$	1.18+/-0.21	0.94+/-0.30	1.22+/-0.15
B^0® D$^{(*)}$r$^+$	2.92+/-0.70	2.63+/-0.88	3.26+/-0.42
B^0® D$^{(*)}$a$_1^+$	3.8+/-1.0		3.0+/-0.5

- **Polarization**

D^{*+} +	Γ_L/Γ (%)
ρ^-	**87.8±5.3**
ρ'^-	**63 ± 9**
D_s^-	**50.6±13.9±3.6**



More factorization tests

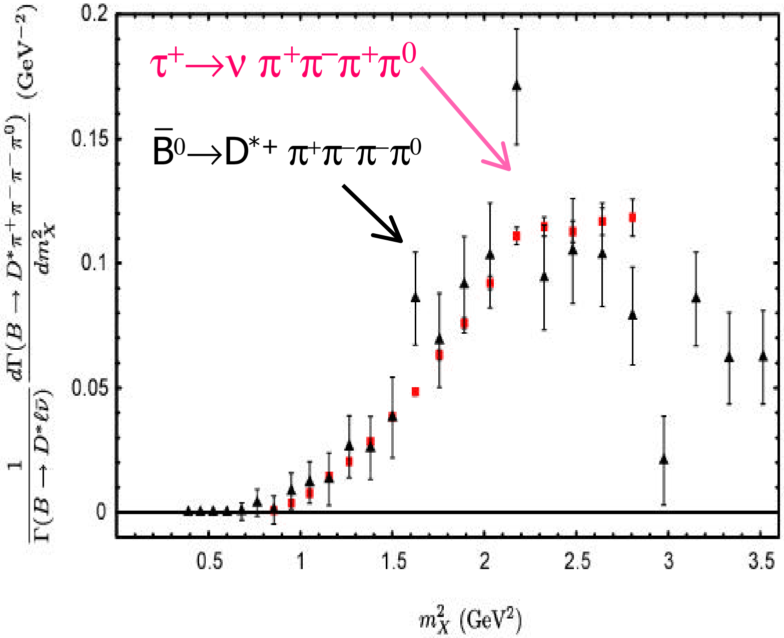


- CLEO found (hep-ex/0103021)
  $B(\bar{B}^0 \to D^{*+} \pi^+\pi^-\pi^-\pi^0) = (1.72 +/- 0.14 +/- 0.24)\%$

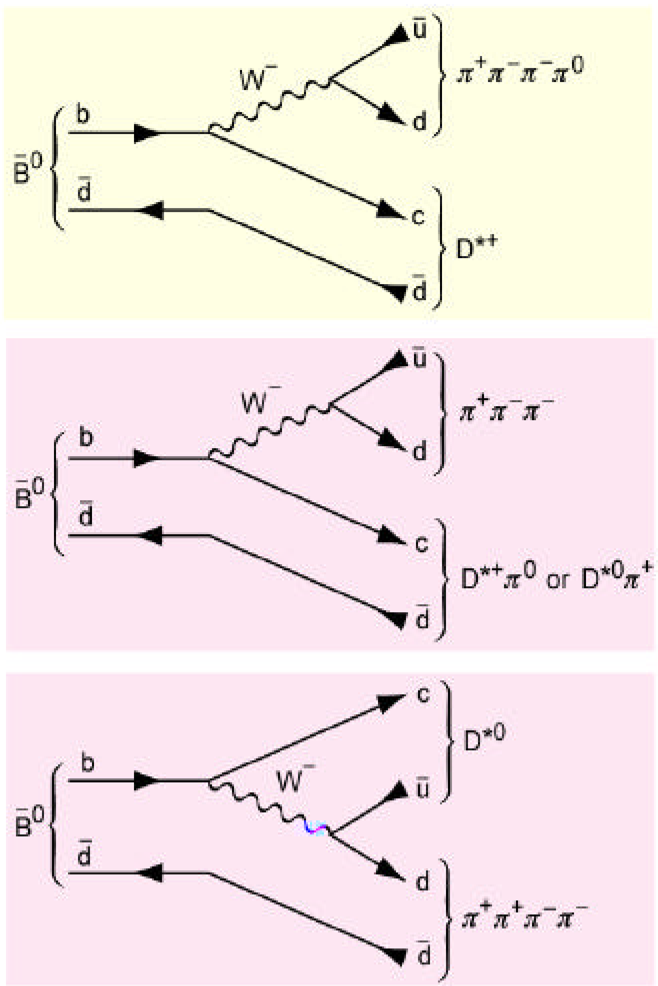
- Ligeti, Luke, Wise (PL B507 142 2001) compare invariant 4π mass spectrum to $\tau^- \to \nu\, \pi^+\pi^-\pi^-\pi^0$ data

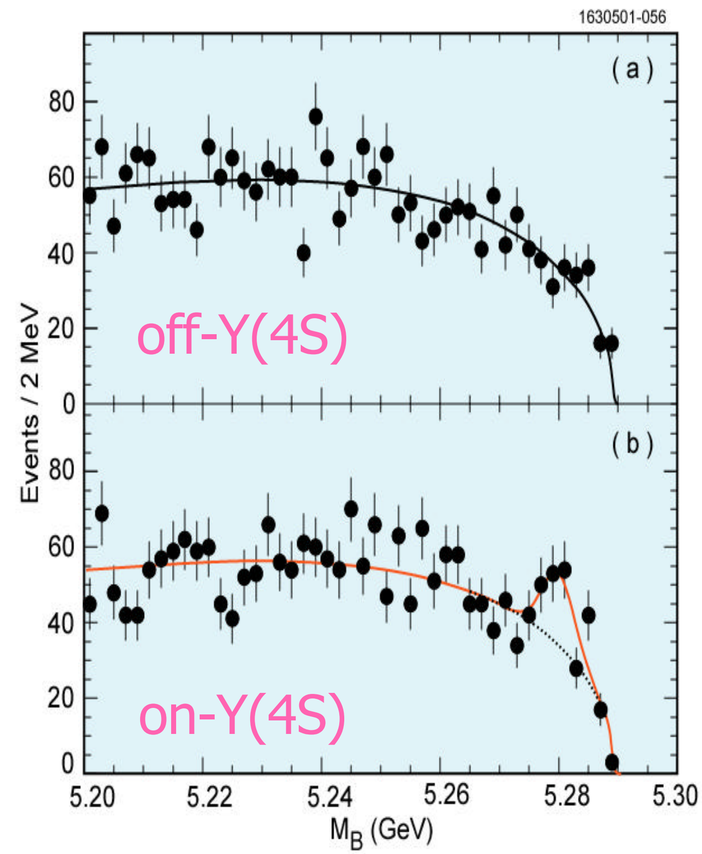
- Using factorization they find good agreement up to $m_{4\pi}^2 < 2.9$ GeV^2

- Good factorization test if decay is dominated by class-1 B->D* transition



Is the LLW factorization test valid?





$\mathcal{B}(B^0 \rightarrow D^{*0}\, \pi^+\pi^-\pi^+\pi^-) = (0.30 +/- 0.07 +/- 0.06)\%$

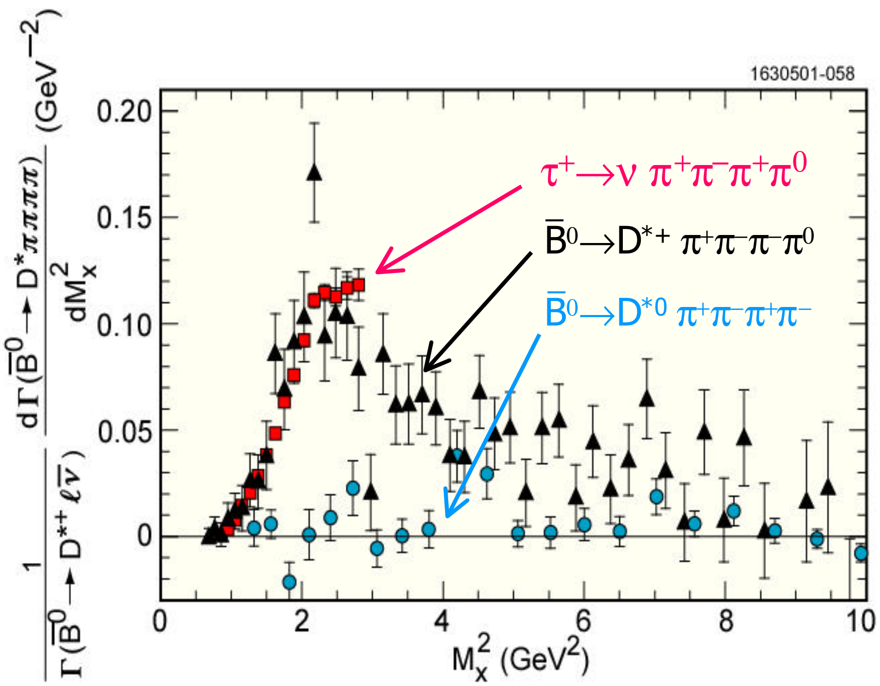
Large $D^{**+} \rightarrow D^{*0}\, \pi^+$ component

More factorization tests

- Contributions from different decay diagrams

- But for $m_{4\pi}^2 < 2.9\ \mathrm{GeV}^2$:

$$\frac{G(B^0 \circledR D^{*0}\ p^+p^-p^+p^-)}{G(B^0 \circledR D^{*0}\ p^+p^-p^+p^-)} < 0.13 \text{ at 90\% CL}$$



➡ LLW factorization test still valid

What is known about a_1 and a_2?

- Using class-1 decays $\bar{B}^0 \to D^{(*)+}X^-$ and a model by Neubert et al we find:

  $|a_1|_\pi \approx |a_1|_\rho \approx |a_1|_{a1} \approx |a_1|_{Ds} \approx |a_1|_{Ds*} \approx 1.0 - 1.2$

- Using class-2 decays $B \to \Psi^{(')}K^{(*)}$ and a model by Neubert et al we find:

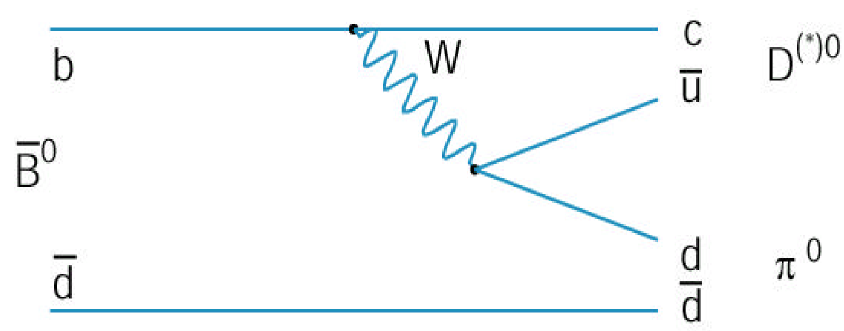
  $|a_2|_\Psi \approx 0.2 - 0.3$

- Using class-3 decays $B^- \to D^{(*)0}X^-$ and a model by Neubert et al we find:

  $a_2/a_1 \approx 0.22 +/- 0.04 +/- 0.06$

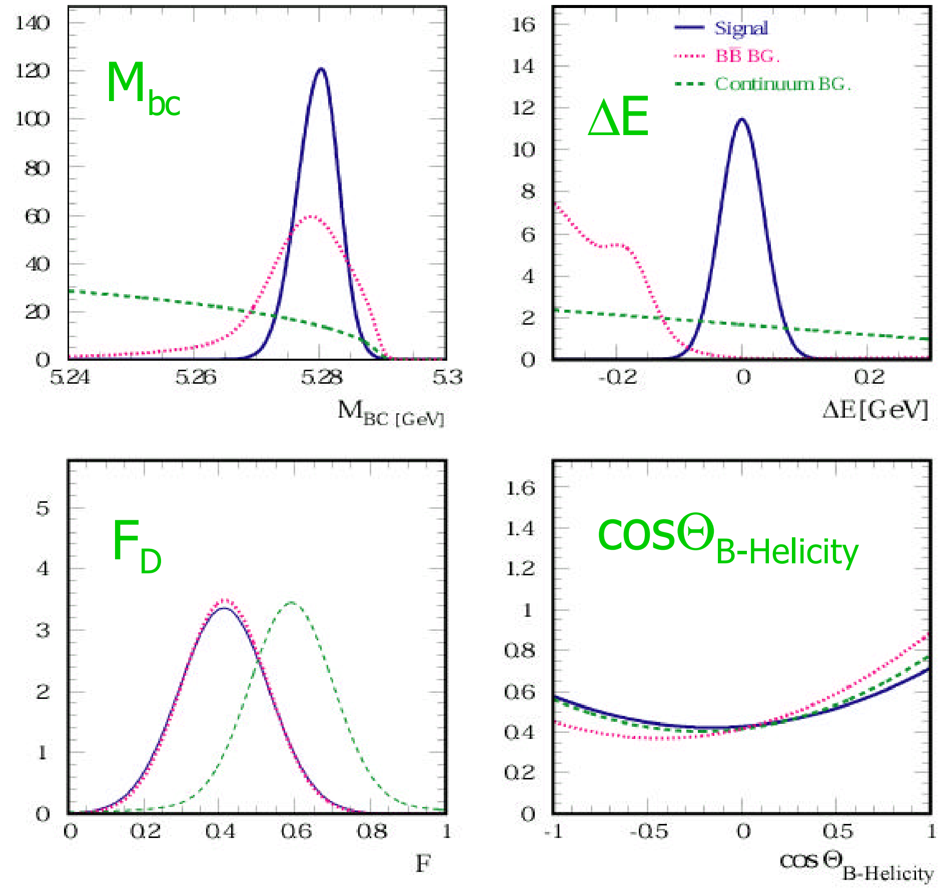
- Search for the missing piece:

  Color-suppressed $B \to D$ decays



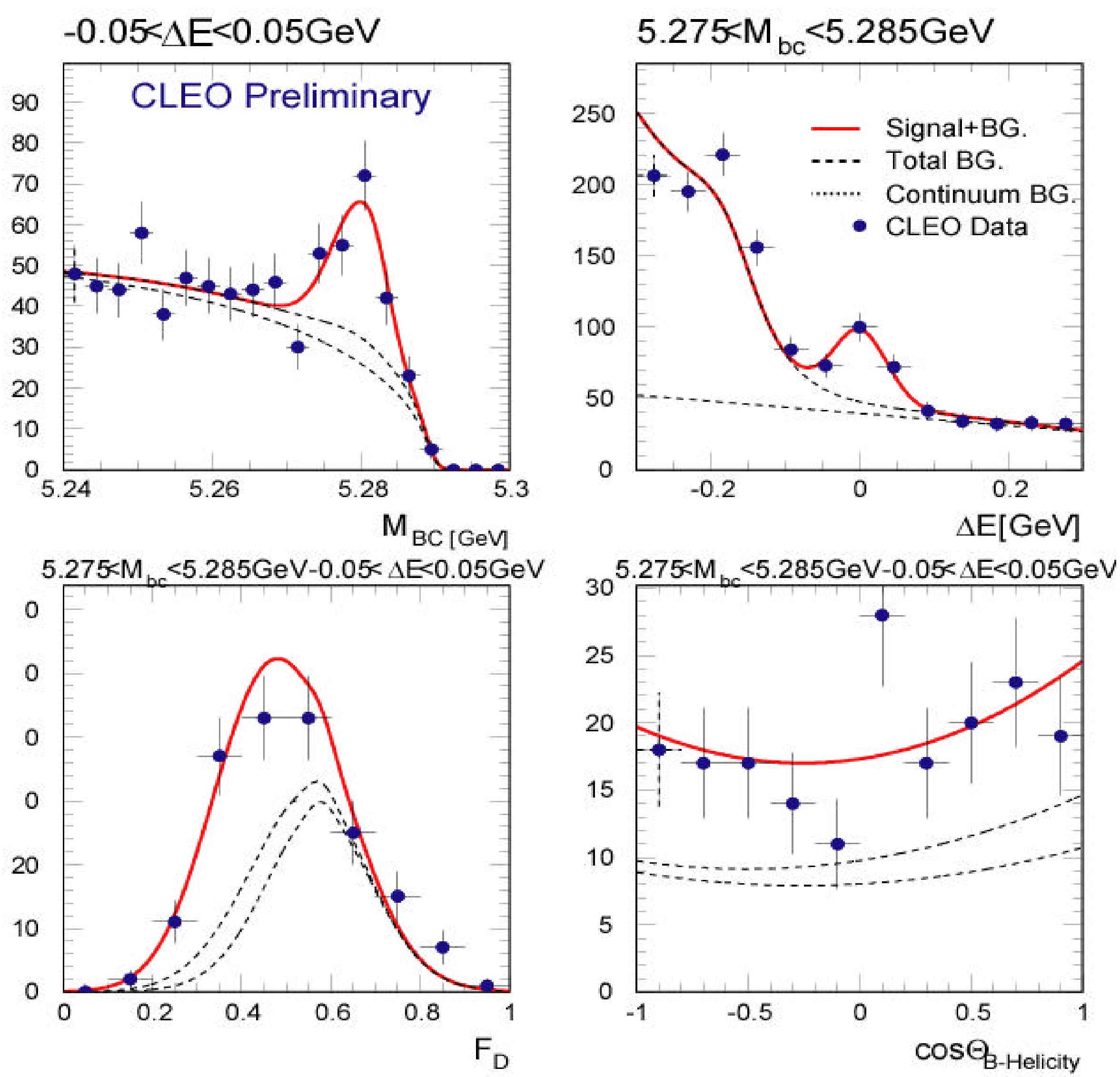
Color Suppressed B Decays

- Full CLEO II, II.5 data sample
  9.7 x 10^6 $B\bar{B}$ Events
- Select high momentum π^0, $D^{(*)0}$
  p > 1.8 GeV
- Suppress (jet-like) continuum background
- Unbinned ML fit in 4 variables:
  - Beam constrained mass
  - Engery difference
  - Event shape (Fisher Disc.)
  - Helicity angle of B



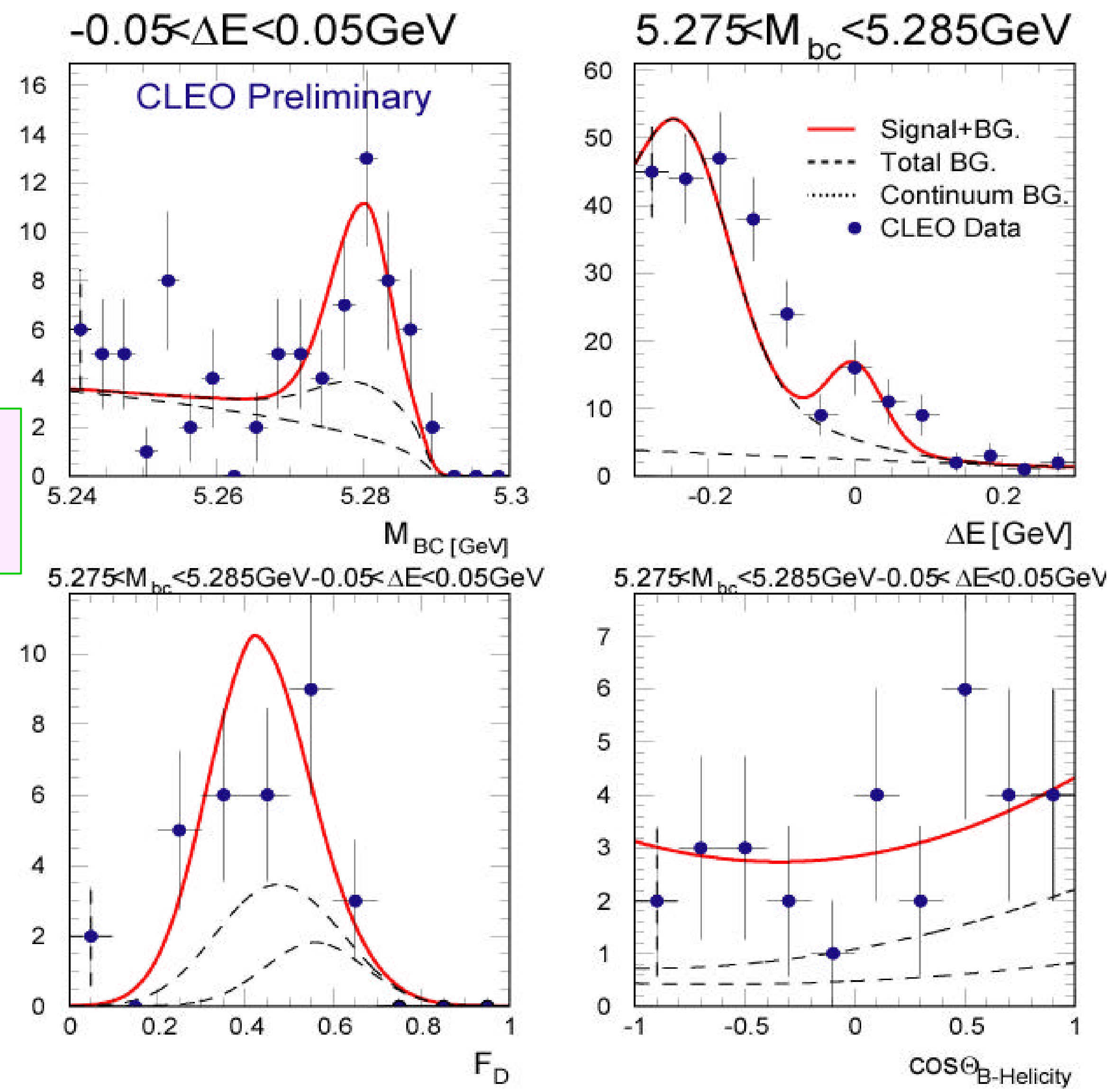
Color Suppressed B Decays II

Fit projections for signal region: $\bar{B}^0$ ® $D^0\pi^0$



Color Suppressed B Decays III

Fit projections for signal region: $\bar{B}^0$ ® $D^{*0}\pi^0$



Color Suppressed B Decays IV

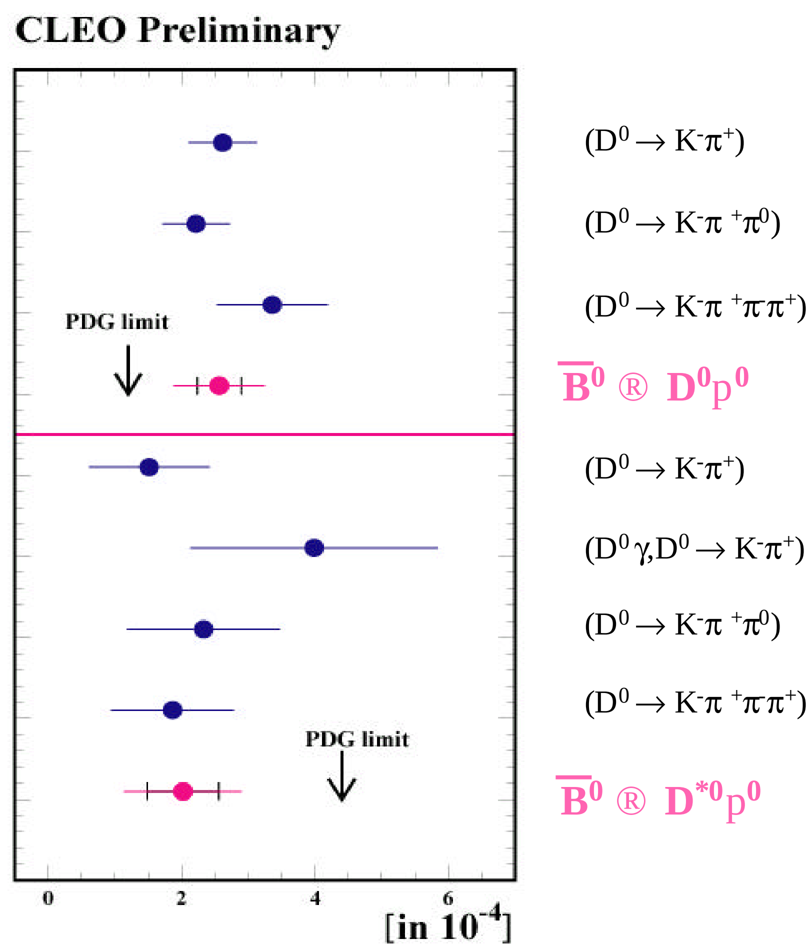
Results:

B($\bar{B}^0$ ® D^0p^0) = (2.6+/-0.3+/-0.6)x10^{-4}

B($\bar{B}^0$ ® $D^{*0}p^0$) = (2.0+/-0.5+/-0.7)x10^{-4}

Larger than expected ➡ $|a_2|$ shows process dependency

$|a_2|_{D(*)0p0} \sim 0.4 \neq |a_2|_{\psi} = |a_2|_{Class\ 3} \sim 0.2$



Isospin Amplitudes and Strong Phases

- B → Dπ and B → D*π isospin multiplets are now complete.

- Determine phase difference between $A_{1/2}$ and $A_{3/2}$ amplitudes (e.g. Rosner hep-ph/9903543)

$$|\mathbf{A}_{3/2}|^2 = \Gamma\left(\mathbf{B}^+ \to \overline{\mathbf{D}}^0 \pi^+\right) \qquad |\mathbf{A}_{1/2}|^2 = \frac{3}{2}\left[\Gamma\left(\mathbf{B}^0 \to \mathbf{D}^- \pi^+\right) + \Gamma\left(\mathbf{B}^0 \to \overline{\mathbf{D}}^0 \pi^0\right)\right] - \frac{1}{2}\Gamma\left(\mathbf{B}^+ \to \overline{\mathbf{D}}^0 \pi^+\right)$$

- Relative phase between isospin amplitudes

$$\cos\delta_I = \frac{3\Gamma\left(\mathbf{B}^0 \to \mathbf{D}^- \pi^+\right) + \Gamma\left(\mathbf{B}^+ \to \overline{\mathbf{D}}^0 \pi^+\right) - 6\Gamma\left(\mathbf{B}^0 \to \overline{\mathbf{D}}^0 \pi^0\right)}{4|\mathbf{A}_{1/2}\mathbf{A}_{3/2}|}$$

- $\cos\delta_I(D\pi) = 0.90+/-0.09$, $\cos\delta_I(D^*\pi)$ 0.91+/-0.08

- Phases around 25° but still consistent with 0 (c.f ~90° in charm)

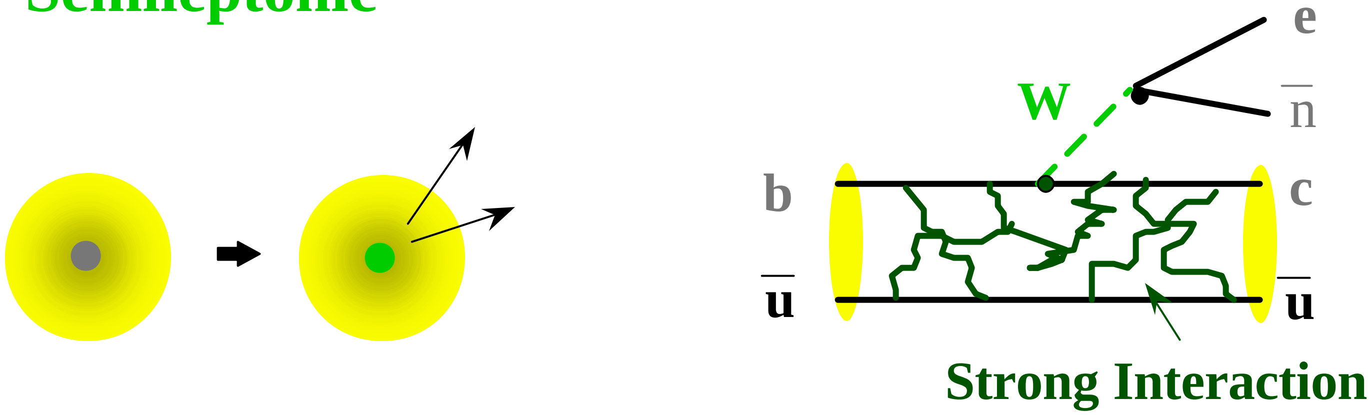
Conclusions

- Inclusive radiative penguins
  - $B(b \to s\gamma) = (3.21 +/- 0.43 +/- 0.27\ ^{+0.18}_{-0.10}) \times 10^{-4}$
  - CP Asymmetry $-0.27 < A_{cp} < 0.10$ (90% CL) [PRL 86 (2001) 5661]
- First CLEO III results, many more to come
- Hadronic B Decays still interesting
  - Extended Factorization tests
    - $B(\bar{B}^0 \to D^{*0} \pi^+\pi^-\pi^+\pi^-) = (0.30 +/- 0.07 +/- 0.06)\%$
  - First observation (with BELLE) of color-suppressed B®D decays
    - $B(\bar{B}^0$ ® $D^0 p^0) = (2.6 +/- 0.3 +/- 0.6) \times 10^{-4}$
    - $B(\bar{B}^0$ ® $D^{*0} p^0) = (2.0 +/- 0.5 +/- 0.7) \times 10^{-4}$
    - $|a_2|$ process dependence begins to show
    - Strong phases (still) consistent with 0

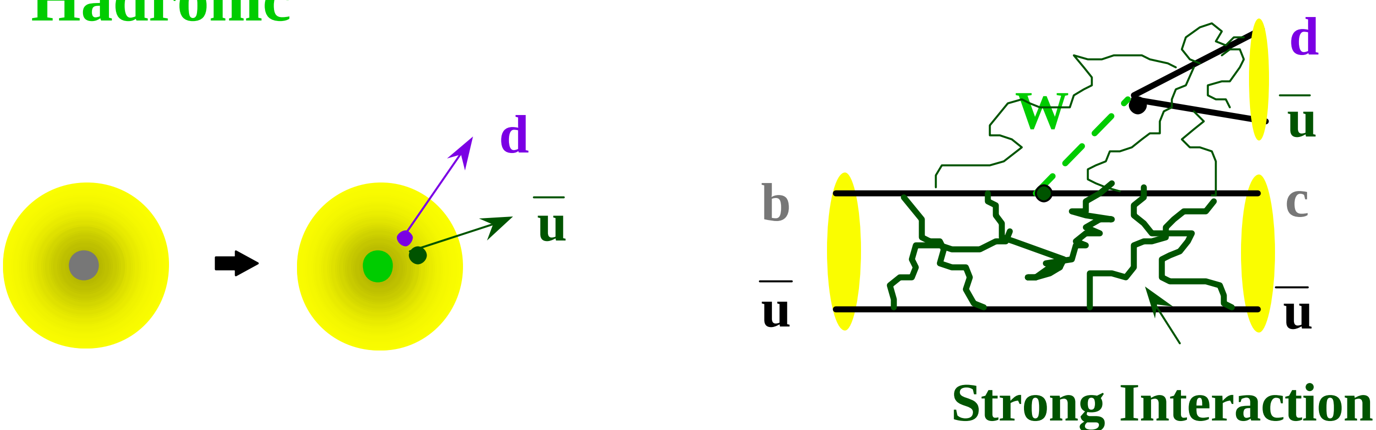
Additional Transparencies

Understanding Hadronic Decays

Semileptonic



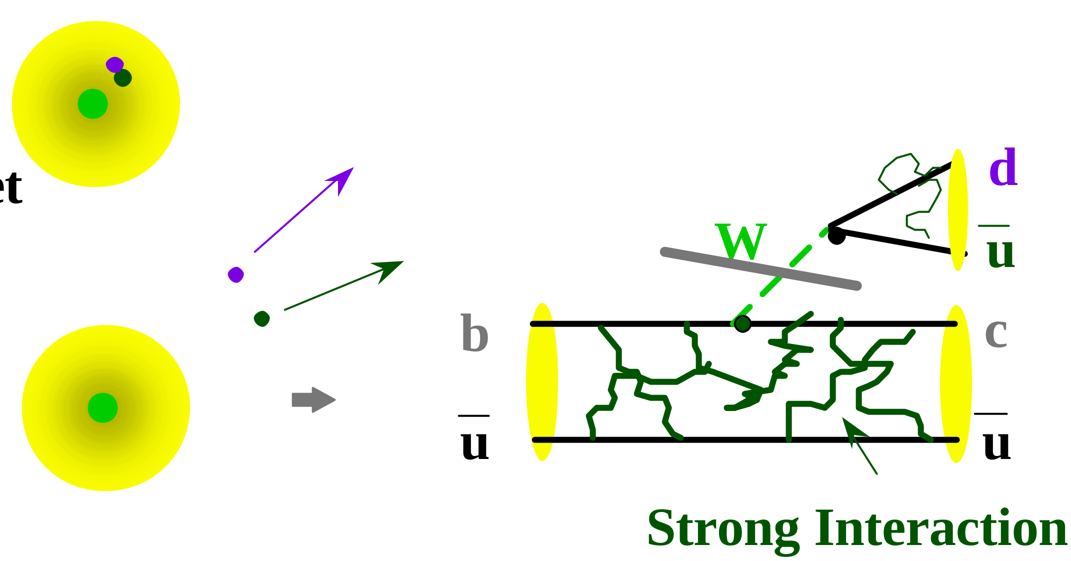
Hadronic



But if ...

W creates $\bar{u}d$
pointlike
➡ color singlet

if they get out
fast enough ...



Hadronic Decays and Factorization

(1997)

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

$$A = G_F/1.4\, V_{cb} \langle \nu | \gamma_\mu (1-\gamma_5) | l \rangle \langle D^{*-} | (cb) | B^0 \rangle$$

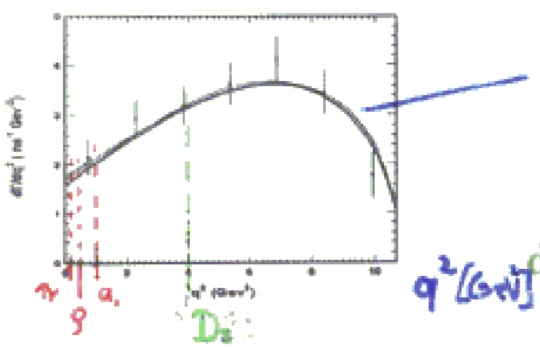
Hadronic (+Factorization) (e.g. $B \to D^{*-} \pi^+$)

$$A = G_F/1.4\, V_{cb} \langle \pi | (du) | 0 \rangle \langle D^{*-} | (cb) | B^0 \rangle$$

I. Branching Ratio Tests

Input: π decay constant ✓

semileptonic decay rate ✓



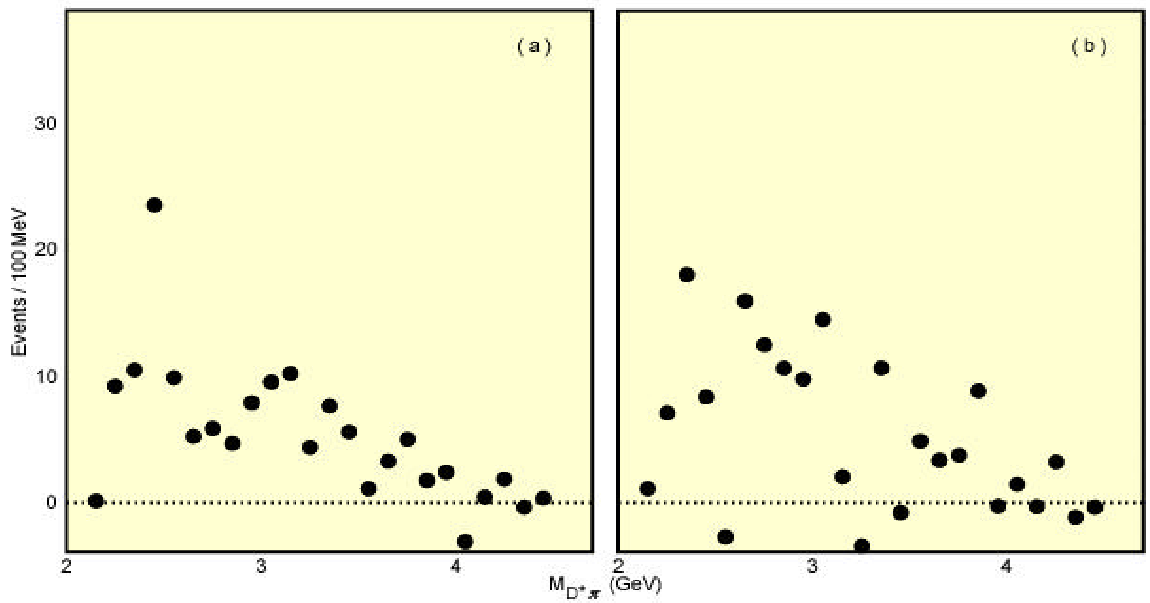
$$\frac{\Gamma(B^0 \to D^{*-} \pi^+)}{d\Gamma/dq^2 (B^0 \to D^{*-} l^+ \nu)} = 6\, \pi^2 c_1^{\,2} f_\pi^{\,2} |V_{ud}|^2$$

	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

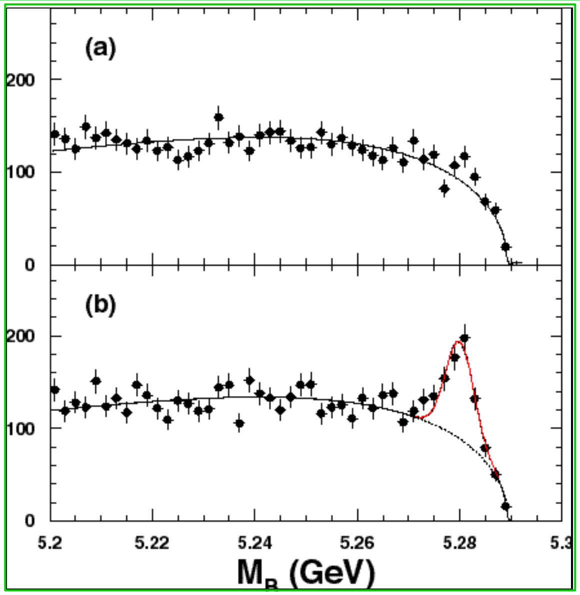
$\Gamma_L / \Gamma(B^0 \to D^{*-} \rho^+) = 90 \pm 7 \pm 5\%$ ⇨ $\Gamma_L / \Gamma(B^0 \to D^{*-} l^+ \nu) = 88\%$

More factorization tests



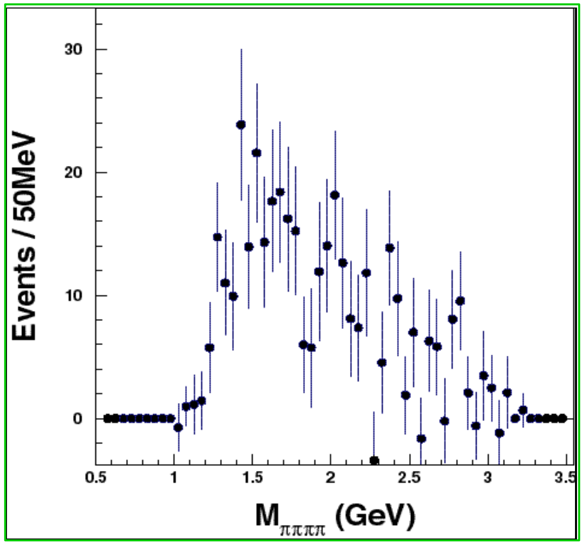
The $D^{*+}\pi^+\pi^-\pi^-\pi^o$ Final State

- (a) ΔE sidebands $|3.0 – 5.0\ \sigma|$
- (b) ΔE around 0 $\pm 2.0\sigma$ fit with sideband shape fixed & norm allowed to float
- Also signals in $D^o \rightarrow K^-\pi^+\pi^o$ and $D^o \rightarrow K^-\pi^+\pi^+\pi^-$ (not shown)
- Fit B yield in bins of $M(4\pi)$



($D^o \rightarrow K^-\pi^+$)

358±29



Summary & Discussion of Rates

Mode	Br (%)	# of events
$\bar{B}^\circ \to D^{*+}\pi^\circ\pi^+\pi^-\pi^-$	1.72±0.14±0.24	1230±70
$\bar{B}^\circ \to D^{*+}\omega\pi^-$	0.29±0.03±0.04	136±15
$\bar{B}^\circ \to D^{+}\omega\pi^-$	0.28±0.05±0.03	91±18
$B^- \to D^{*\circ}\pi^\circ\pi^+\pi^-\pi^-$	1.80±0.24±0.25	195±26
$B^- \to D^{*\circ}\omega\pi^-$	0.45±0.10±0.07	26± 6
$B^- \to D^{\circ}\omega\pi^-$	0.41±0.07±0.04	88±14

- ρ' dominates the $\omega\pi^-$ final state
- $\Gamma(\bar{B}^\circ \to D^{*+}\rho'^-) / \Gamma(B^\circ \to D^+\rho'^-)$ = 1.04±0.21±0.06

  $\Gamma(B^- \to D^{*\circ}\rho'^-) / \Gamma(B^- \to D^\circ\rho'^-)$ = 1.10±0.31±0.06

  $\Gamma(B \to D^*\rho'^-) / \Gamma(B \to D\rho'^-)$ = 1.06±0.17±0.04
- Consistent with Heavy Quark Symmetry prediction (ratio = 1)
- With B $(\rho'^- \to \omega\pi^-)$=39%, $\Gamma(B \to D^{(*)}\rho'^-) \sim \Gamma(B \to D^{(*)}\rho^-)$