The Discovery and Study of *B* Mesons in the CLEO Experiment

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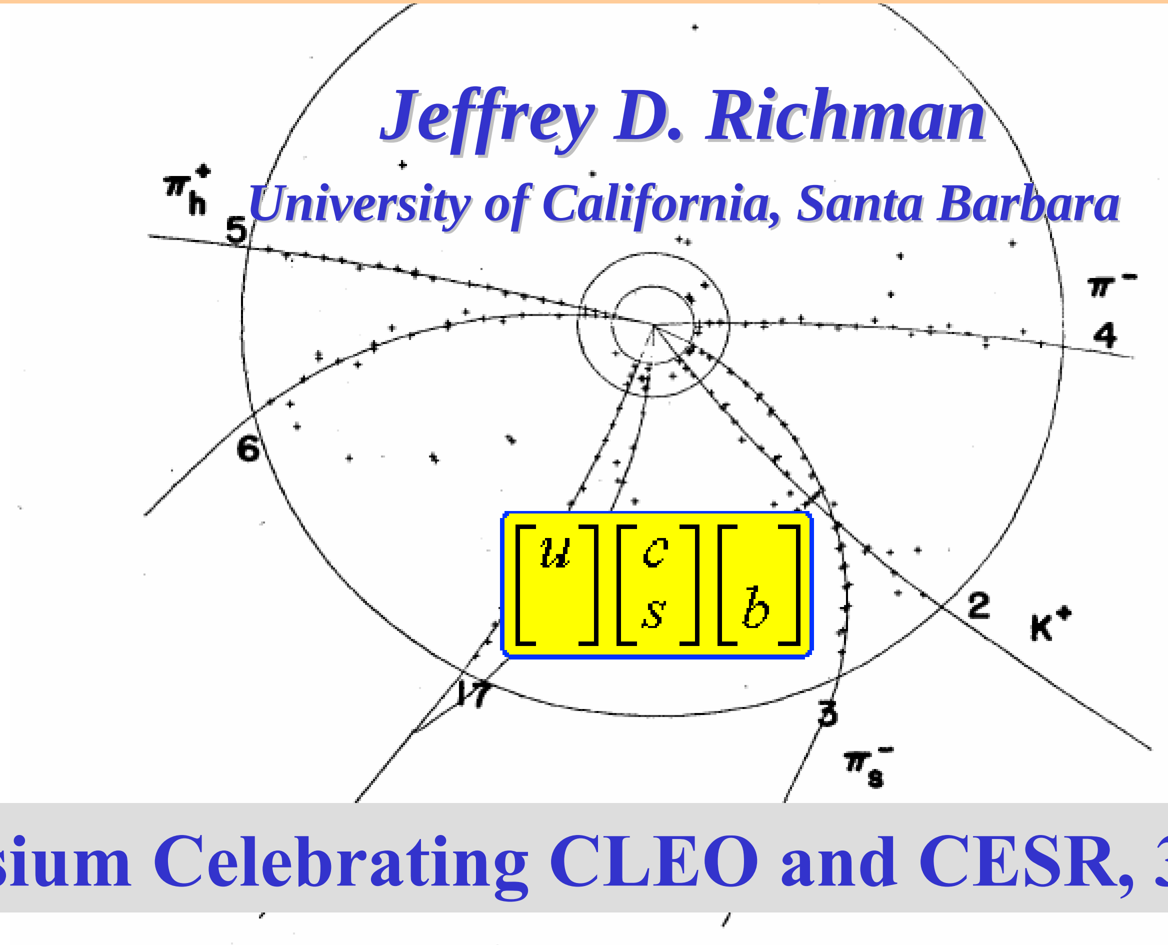


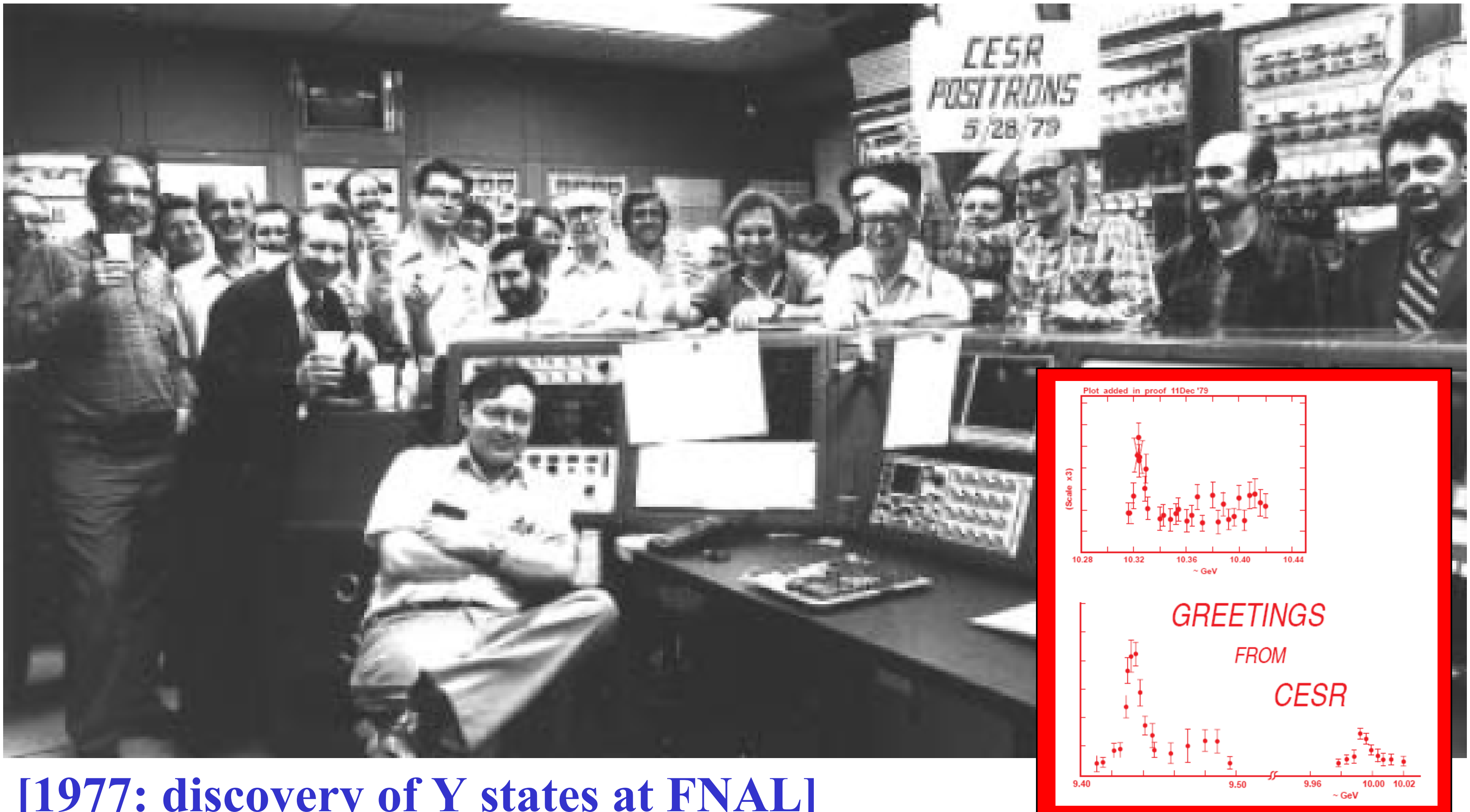
Symposium Celebrating CLEO and CESR, 31 May 2008

Outline

- **Terra incognita: Mapping the unknown territory of B physics in the CLEO I era**
- **CLEO II & CLEO II.V: the right stuff**
  - **The march of the penguins**
  - **The elegant simplicity of semileptonic decays**
  - **The triumph of hadronic decays**
- **The success of the CLEO program as a scientific enterprise**

My apologies for not covering all the important measurements and papers. I had to leave out a lot of them!

Terra Incognita: Mapping the New Territory of B Physics in the CLEO I Era



[1977: discovery of Υ states at FNAL]

courtesy Karl Berkelman

Physics themes of the early CLEO I era

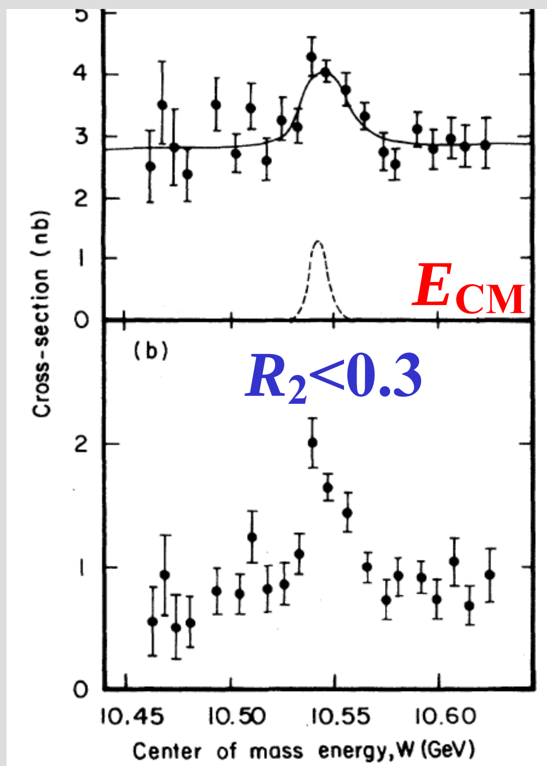
- Υ(1S), Υ(2S), Υ(3S), and... discovery of the Υ(4S)! (1980)
  - large decay width
  - $\sigma(\Upsilon(4S))$ vs. $\sigma(\text{continuum})$
- "Evidence for New Flavor Production at the Υ(4S)" (1981)
  - Υ(4S) as a fountain of $B\bar{B}$ pairs → can study weak decays!
  - Inclusive single-lepton final state as signature of weak decay; issues of continuum background & event shape variables; off-resonance running
- Inclusive properties of B Decay
- Critical milestone: observation of fully reconstructed hadronic decays (1983)

VOLUME 45, NUMBER 4 PHYSICAL REVIEW LETTERS 28 JULY 1980

Observation of a Fourth Upsilon State in e^+e^- Annihilations 1.09 pb^{-1} (scan)

A fourth state in the upsilon energy region has been seen in e^+e^- collisions at the Cornell Electron Storage Ring. A resonance is observed with a mass 1112 ± 5 MeV above the lowest upsilon state. The 9.6-MeV rms width is greater than the 4.6-MeV energy resolution of the e^+e^- beams. The observed characteristics of the new state make it a likely candidate for the 4^3S state of the $b\bar{b}$ system, lying above the threshold for the production of B mesons.

σ (nb) vs. E_{CM} (GeV)



Scan 10.46—10.64 GeV

- Mass: M(1S)+(1112 +/- 5) MeV

  ➔ M(4S) = (10572 +/- 5 MeV)

  PDG: M(4S) = (10579.4 +/ 1.2 MeV)
- Width: Γ = (19.9 +/- 5.5 +/- 5) MeV
- σ(res)/σ(non-res) = 1/3
- Event shape: more spherical than jet-like; R_2 used from the beginning!

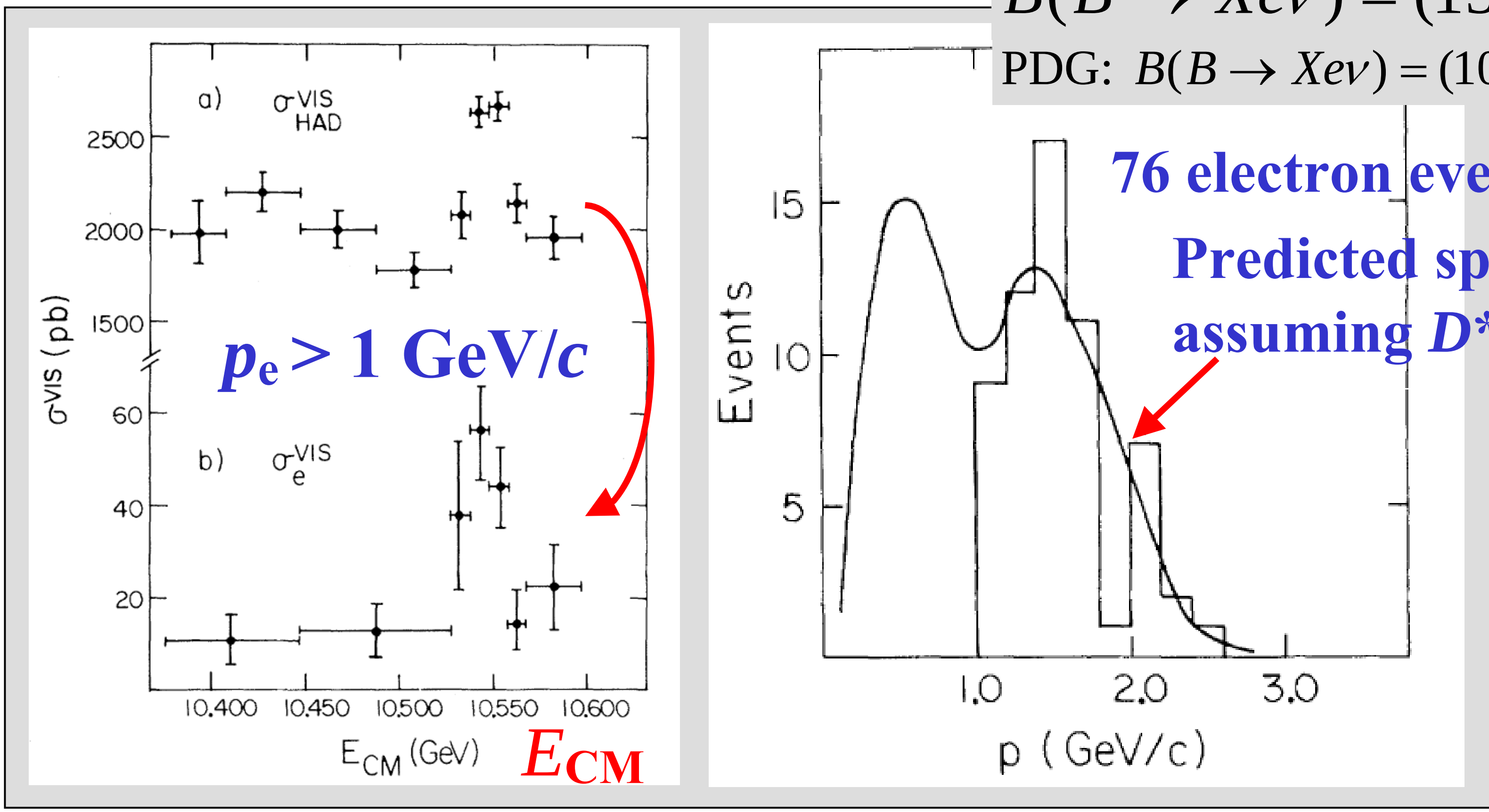
VOLUME 46, NUMBER 2 PHYSICAL REVIEW LETTERS 12 JANUARY 1981

Evidence for New-Flavor Production at the $\Upsilon(4S)$ 2.5 pb^{-1} (scan)

An enhancement has been observed in the inclusive cross section for direct single electrons produced in e^+e^- annihilations at the $\Upsilon(4S)$. This is interpreted as evidence for a new weakly decaying particle, the B meson. A branching ratio for $B \to Xe\nu$ of $[13 \pm 3\ (\pm 3)]\%$ is inferred, where the first set of errors is statistical and the estimated systematic error is enclosed in parentheses.

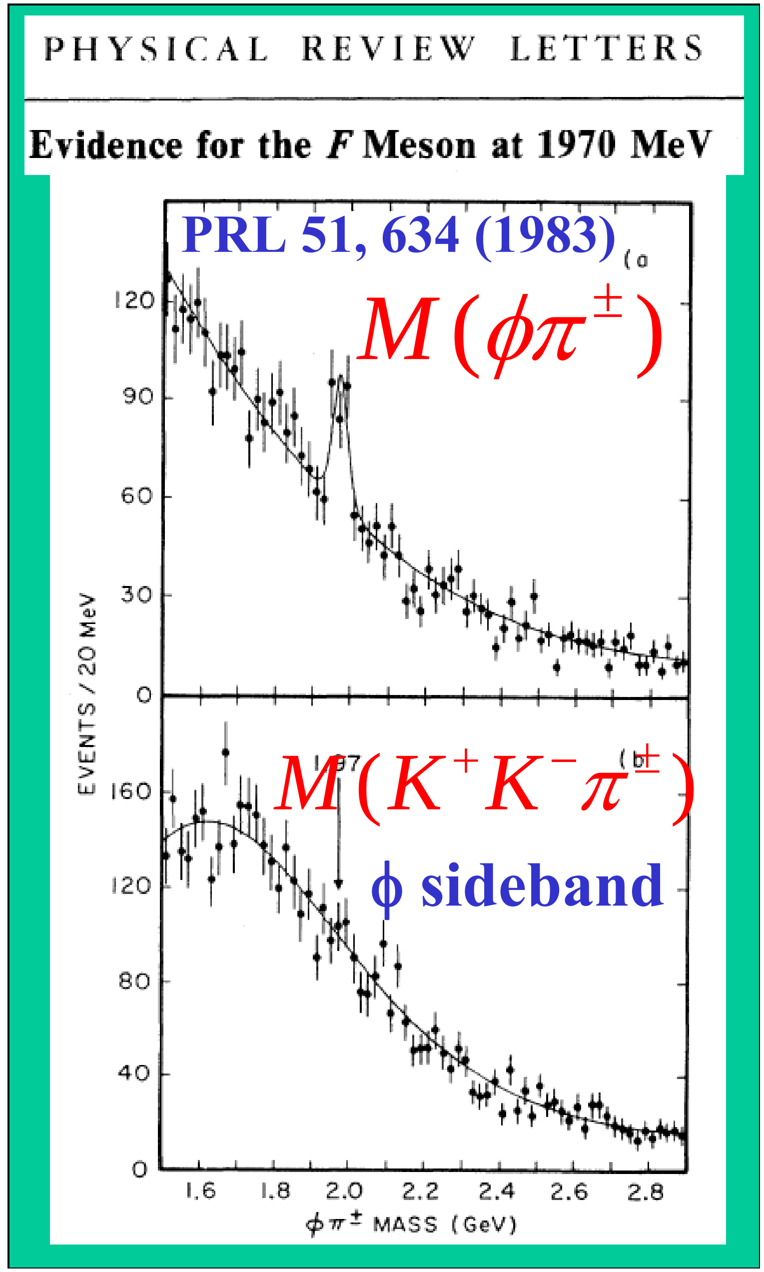
$$B(B \to Xe\nu) = (13 \pm 3 \pm 3)\%$$

PDG: $B(B \to Xe\nu) = (10.78 \pm 0.18)\%$



Inclusive properties of B decays (1981-1983)

- Decay of b-flavored Hadrons to Single-Muon and Dimuon Final States (1981)
- Decay of B mesons into Charged and Neutral Kaons (1982)
- Charged-Particle Multiplicities in B-Meson Decay (1982)
- Semileptonic Decay of B Mesons (1983)
- Ruling out Exotic Models of b Quark Decay (1983)
- Observation of Exclusive Decay Modes of b-flavored Mesons (1983)
- D^0 spectrum from B-Meson Decay (1983)
- Observation of Baryons in B-Meson Decay (1983)

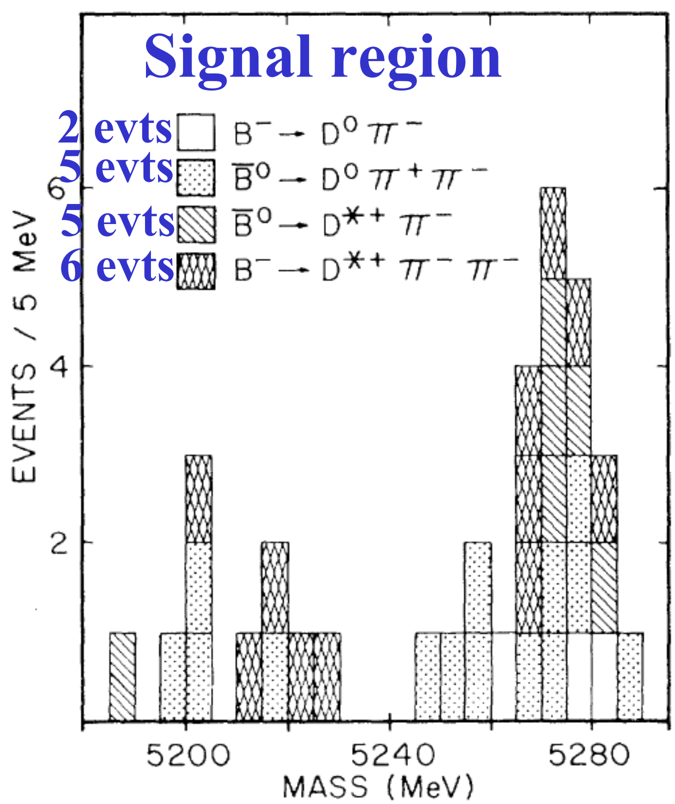


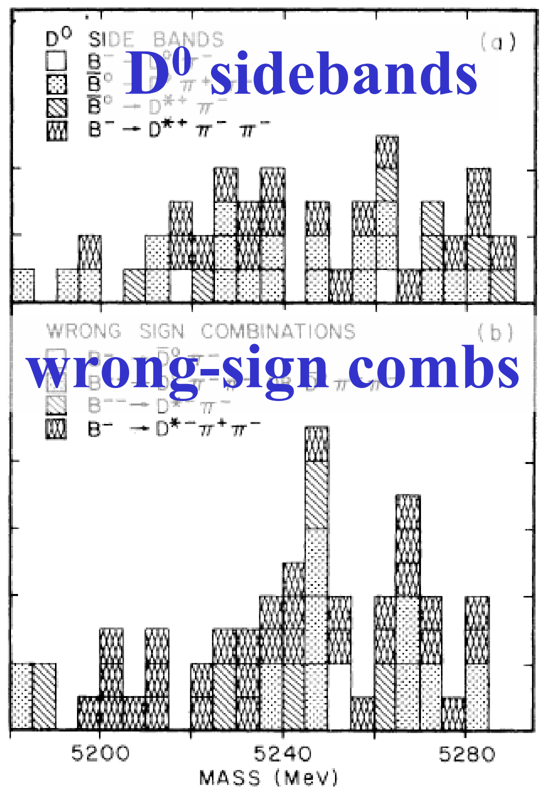
VOLUME 50, NUMBER 12 PHYSICAL REVIEW LETTERS 21 MARCH 1983

Observation of Exclusive Decay Modes of *b*-Flavored Mesons **40.7 pb^{-1}**

B-meson decays to final states consisting of a D^0 or $D^{*\pm}$ and one or two charged pions have been observed. The charged-B mass is $5270.8 \pm 2.3 \pm 2.0$ MeV and the neutral-B mass is $5274.2 \pm 1.9 \pm 2.0$ MeV.

"Until now, the b-flavored mesons themselves had not been found. Here we report that discovery."





M(B^0)
5274.2+/-1.9+/-2.0 MeV
5279.3+/-0.7 MeV PDG '06

M(B$^-$)
5270.8+/-2.3+/-2.0 MeV
5279.1+/-0.5 MeV PDG '06

Branching fractions a little high.

VOLUME 45, NUMBER 12 PHYSICAL REVIEW LETTERS 22 SEPTEMBER 1980

CP Nonconservation in Cascade Decays of *B* Mesons

Ashton B. Carter and A. I. Sanda
Rockefeller University, New York, New York 10021
(Received 2 June 1980)

General techniques are introduced to expose new *CP*-nonconserving effects in cascade decays of *B* mesons. These effects are computed in the Kobayashi-Maskawa model. The *CP* asymmetries so obtained range from 2% to 20% if the parameters are in the favorable range $s_3 < s_2 \lesssim 0.1$. Effects of this size should be observable in upcoming experiments.

Nuclear Physics B193 (1981) 85–108

NOTES ON THE OBSERVABILITY OF *CP* VIOLATIONS IN B DECAYS

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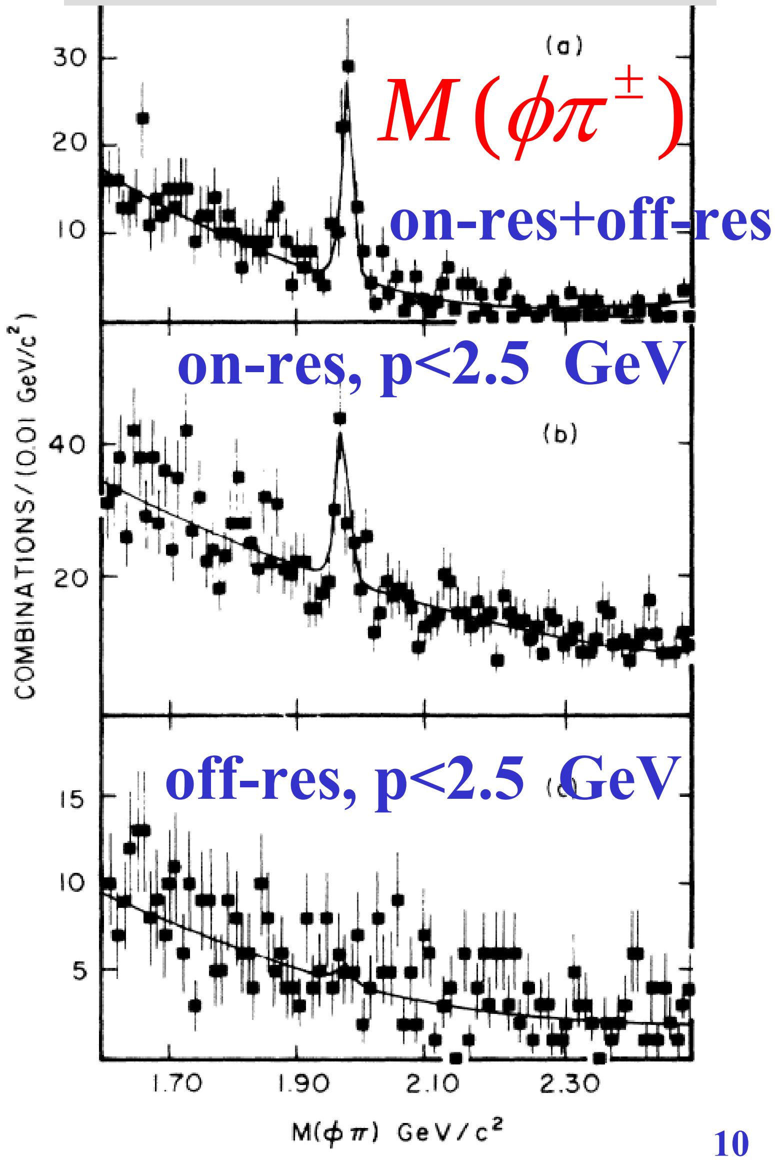
Received 16 June 1981

We describe a general method of exposing *CP* violations in on-shell transitions of B mesons. Such *CP* asymmetries can reach values of the order of up to 10% within the Kobayashi–Maskawa model for plausible values of the model parameters. Our discussion focuses on those (mainly non-leptonic) decay modes which carry the promise of exhibiting clean and relatively large *CP* asymmetries at the expense of a reduction in counting rates. Accordingly we address the complexities encountered when performing *CP* tests with a high statistics B meson factory like the Z^0 (and a toponium) resonance.

Beyond the basics

- Limit on the b→u coupling from Semileptonic B Decay (1984)
- Upper Limit on Flavor-Changing Neutral-Current Decays of the b Quark (1984)
- Two-Body Decays of B Mesons (1984)
- Inclusive Decay of B Mesons into Charged D* (1985)
- Observation of the Decay $B^0 \rightarrow D^{*+}\rho^-$ (1985)
- Decay B→ψ X (1985)
- Inclusive φ production in B-Meson Decay (1986)
- Observation of the Decay B→FX (1986)
- Inclusive B-Meson Decay to Charm (1987)
- Limits on Rare Exclusive Decays of B Mesons (1987)

Observation of B→FX
PRL 56, 2781 (1986)

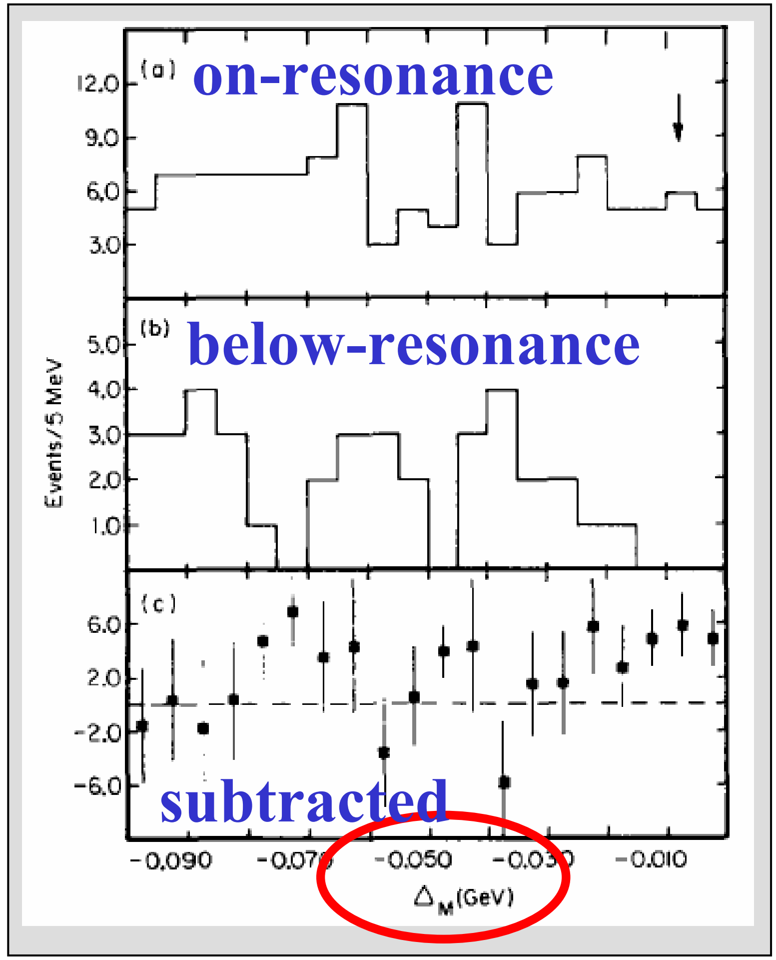


LIMITS ON RARE EXCLUSIVE DECAYS OF B MESONS

$117\ \mathrm{pb}^{-1}$

Mode	Number of events 90% CL limits	Detection efficiency	Branching fraction 90% CL limits
$K^+\pi^-$	15.3	0.46	3.2×10^{-4}
$K^0\pi^+$	5.3	0.05	6.8×10^{-4}
$K^{*0}\pi^+$	6.8	0.17	2.6×10^{-4}
$K^{*+}\pi^-$	2.3	0.03	7.0×10^{-4}
ρ^0K^+	10.1	0.25	2.6×10^{-4}
ρ^0K^0	3.4	0.04	8.0×10^{-4}
ϕK^+	3.9	0.12	2.1×10^{-4}
ϕK^0	3.9	0.03	13.0×10^{-4}
ϕK^{*0}	3.9	0.08	4.7×10^{-4}
ρ^0K^{*0}	19.1	0.16	11.5×10^{-4}
$K^{*0}\gamma$	22.0	0.11	20.5×10^{-4}
$K^{*+}\gamma$	3.2	0.014	18.4×10^{-4}
$K^+\mu^+\mu^-$	11.8	0.24	3.2×10^{-4}
$K^+e^+e^-$	5.8	0.18	2.1×10^{-4}
$K^0\mu^+\mu^-$	2.3	0.05	4.5×10^{-4}
$K^0e^+e^-$	5.3	0.03	6.5×10^{-4}
e^+e^-	2.3	0.29	0.8×10^{-4}
$\mu^+\mu^-$	3.9	0.40	0.9×10^{-4}
$\mu^\pm e^\mp$			

Very relevant selection of modes!

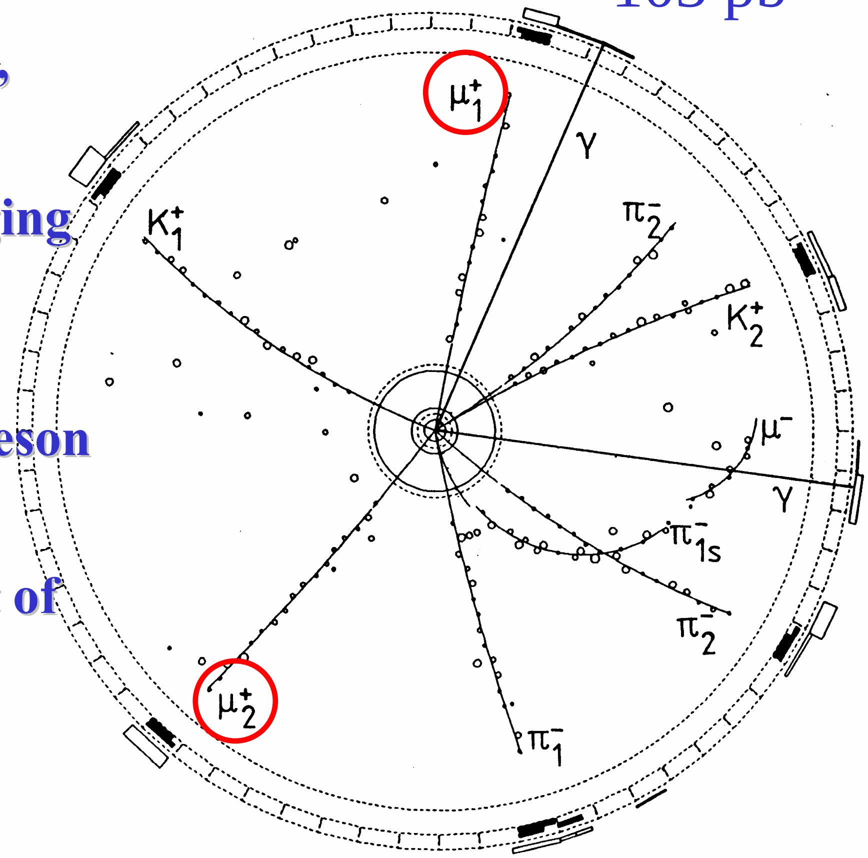


$$\Delta_m = (E_{\mathrm{beam}}^2 - p_{\mathrm{total}}^2)^{1/2} - E_{\mathrm{beam}} .$$

Into the era of $B^0 - \bar{B}^0$ mixing

- Limits on B^0-$\bar{B}^0$ Mixing and $\tau B^0/\tau B^+$ (1987) ← 79.5 pb^{-1}
- Branching Ratios of B Mesons to K^+, K^-, and K^0/K^0 (1987)
- Improved Upper limit on Flavor-Changing Neutral-Current Decays of the b Quark (1987)
- Evidence for Charmed Baryons in B-Meson Decay ((1987)
- $\Gamma(b\rightarrow u l \nu)/\Gamma(b\rightarrow c l \nu)$ from the End Point of the Lepton Momentum Spectrum in Semileptonic B Decay (1987)
- Exclusive Decays and Masses of the B Mesons (1987)
- B^0-$\bar{B}^0$ mixing at the Y(4S) (1989) ← 212 pb^{-1}

ARGUS
103 pb^{-1}



ARGUS, Phys. Lett. B **192**, 245 (1987)

$$\chi_d = 0.17 \pm 0.05$$

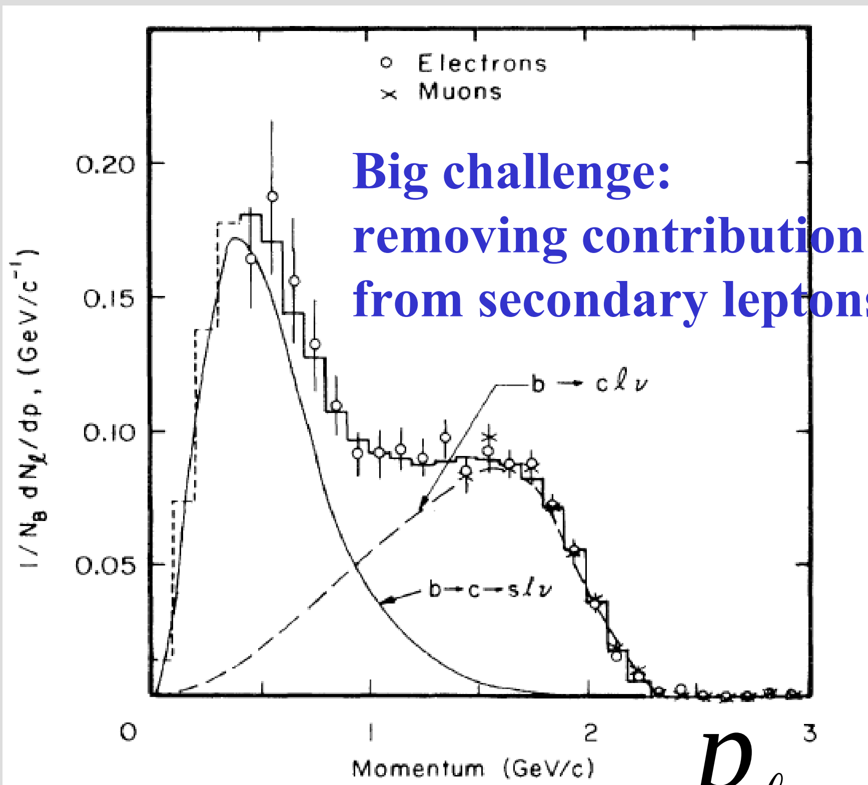
Time-integrated mixing rate: 21%

VOLUME 62, NUMBER 19 PHYSICAL REVIEW LETTERS 8 MAY 1989

$B^0\bar{B}^0$ Mixing at the $\Upsilon(4S)$

212 pb^{-1}; 240 K BB

We have measured $B^0\bar{B}^0$ mixing by observing like-sign dilepton events in $\Upsilon(4S)$ decay. Assuming that the semileptonic branching fraction of the charged and neutral B mesons are equal and that the $\Upsilon(4S)$ decays to B^+B^- 55% of the time and to $B^0\bar{B}^0$ 45% of the time, we measure the mixing parameter r to be $0.19 \pm 0.06 \pm 0.06$, where the first error is statistical and the second is systematic.



Big challenge: removing contribution from secondary leptons.

p_ℓ

$$r = \frac{N(mix)}{N(nomix)}$$

$$= \frac{N(B^0B^0) + N(\bar{B}^0\bar{B}^0)}{N(B^0\bar{B}^0)}$$

$$= (0.19 \pm 0.06 \pm 0.06)$$

$$\frac{\Delta M}{\Gamma} = 0.69 \pm 0.12 \pm 0.12$$

PDG: 0.776 ± 0.008

Observation of B^0-$\bar{B}^0$ Mixing in CLEO using Dileptons

TABLE I. Numbers of dilepton events.

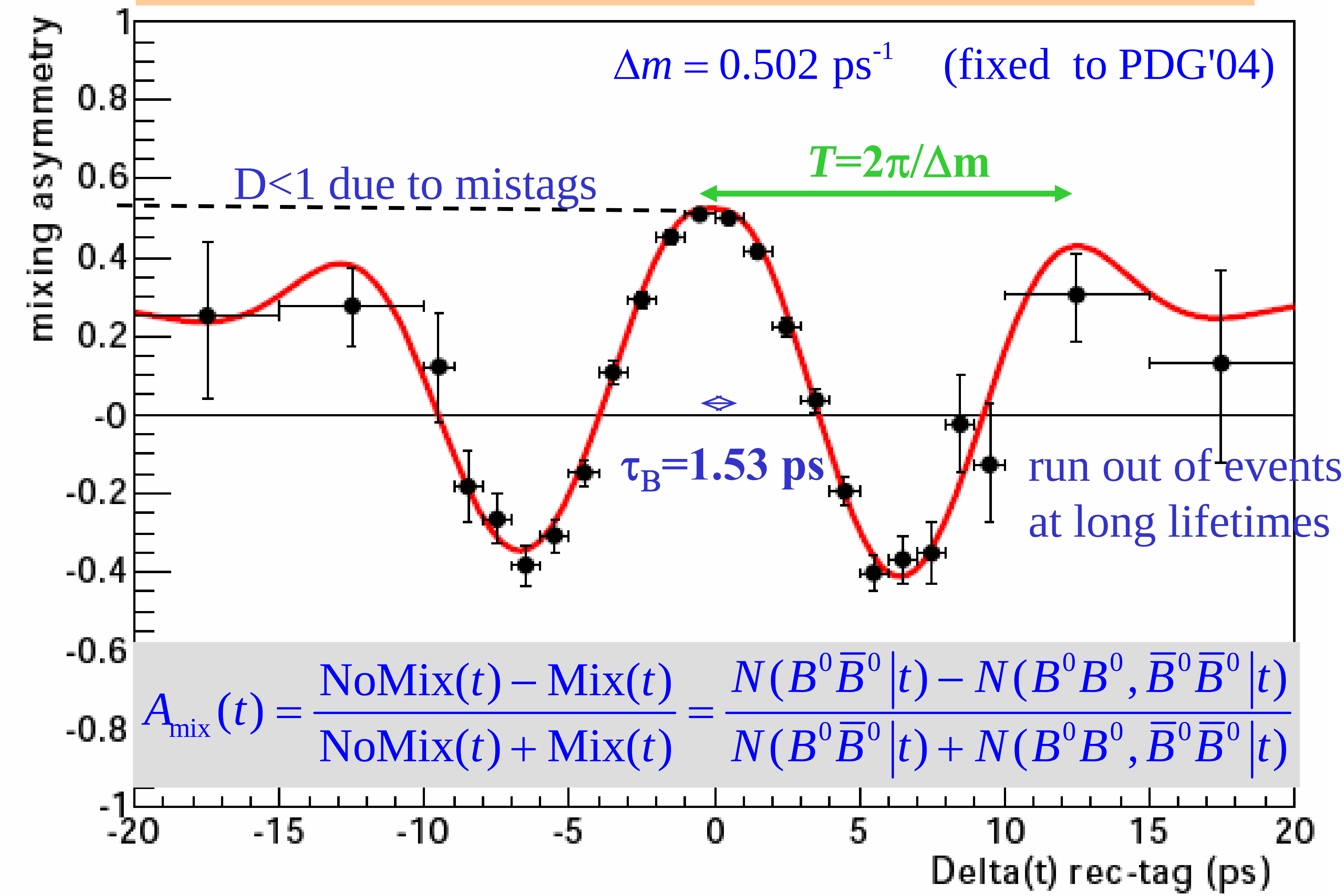
Type	Unlike sign e^+e^-	Unlike sign $\mu^+\mu^-$	Unlike sign $e^\pm\mu^\mp$	Like sign $e^\pm e^\pm$	Like sign $\mu^\pm\mu^\pm$	Like sign $e^\pm\mu^\pm$
On $\Upsilon(4S)$	186	66	218	26	6	39
Fakes	9.4 $\pm$2.7	6.3 $\pm$2.1	17.2 $\pm$5.2	3.8 $\pm$1.1	2.2 $\pm$0.7	6.7 $\pm$2.2
Cascades	2.0 $\pm$0.8	0.5 $\pm$0.2	1.9 $\pm$0.8	10.7 $\pm$3.2	2.6 $\pm$0.8	10.5 $\pm$3.2
ψ+primary lepton	0.7 $\pm$0.3	0.3 $\pm$0.2	1.0 $\pm$0.5	0.7 $\pm$0.3	0.3 $\pm$0.2	1.0 $\pm$0.5
Continuum background	6.5 $\pm$4.2	2.4 $\pm$3.0	−3.7 $\pm$1.3		None (see text)	
Signal statistical systematic	167 $\pm$14 $\pm$2.8	57 $\pm$8 $\pm$2.1	202 $\pm$15 $\pm$5.3	10.8 $\pm$5.1 $\pm$3.4	0.9 $\pm$2.4 $\pm$1.1	20.8 $\pm$6.2 $\pm$3.9

Unlike-sign dileptons

Like-sign dileptons

(For unlike sign, need to subtract contribution from B^+B^- events.)

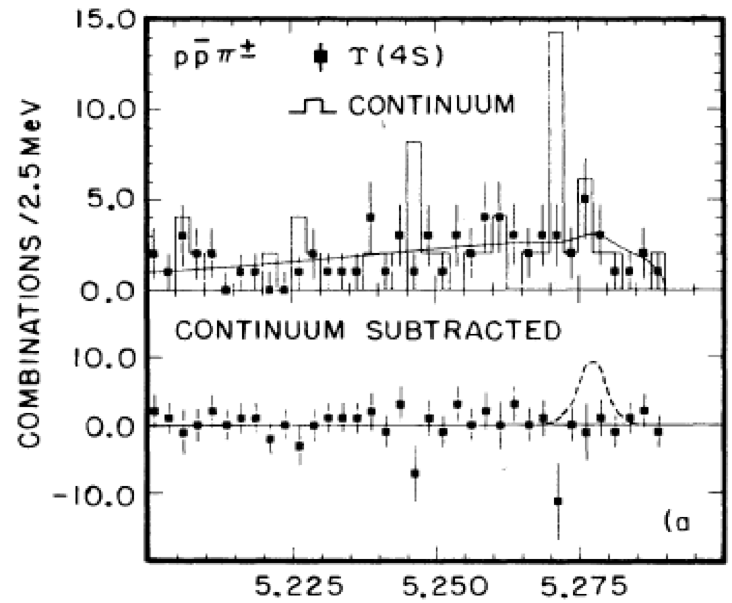
BABAR Mixing asymmetry data (raw)

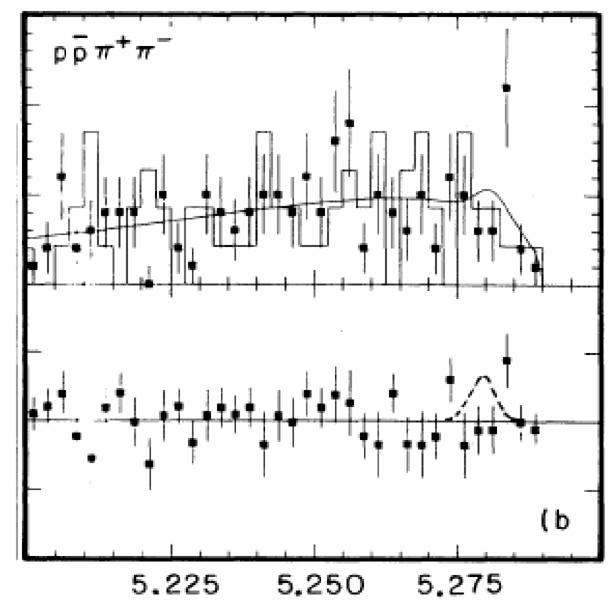


$$A_{\mathrm{mix}}(t) = \frac{\mathrm{NoMix}(t) - \mathrm{Mix}(t)}{\mathrm{NoMix}(t) + \mathrm{Mix}(t)} = \frac{N(B^0\overline{B}^0 \mid t) - N(B^0B^0, \overline{B}^0\overline{B}^0 \mid t)}{N(B^0\overline{B}^0 \mid t) + N(B^0B^0, \overline{B}^0\overline{B}^0 \mid t)}$$

Searching for b→u...and finding it!

- Search for Charmless Decays B→p$\bar{p}$ π and B→p$\bar{p}$ π π (1989)
- Search for b→u Transitions in Exclusive Hadronic B-Meson Decays (1989)
- A Search for Exclusive Penguin Decays of B Mesons (1989)
- Study of the decay B→D^{*+} l ν (1989)
- Observation of B-Meson Semileptonic Decays to Noncharmed Final States (1990)
- Exclusive and Inclusive Decays of B Mesons into D_s Mesons (1990)
- Exclusive and Inclusive Semileptonic Decays of B Mesons to D Mesons (1991)
- Inclusive and Exclusive Decays of B Mesons to Final States Including Charm and Charmonium Mesons (1992)

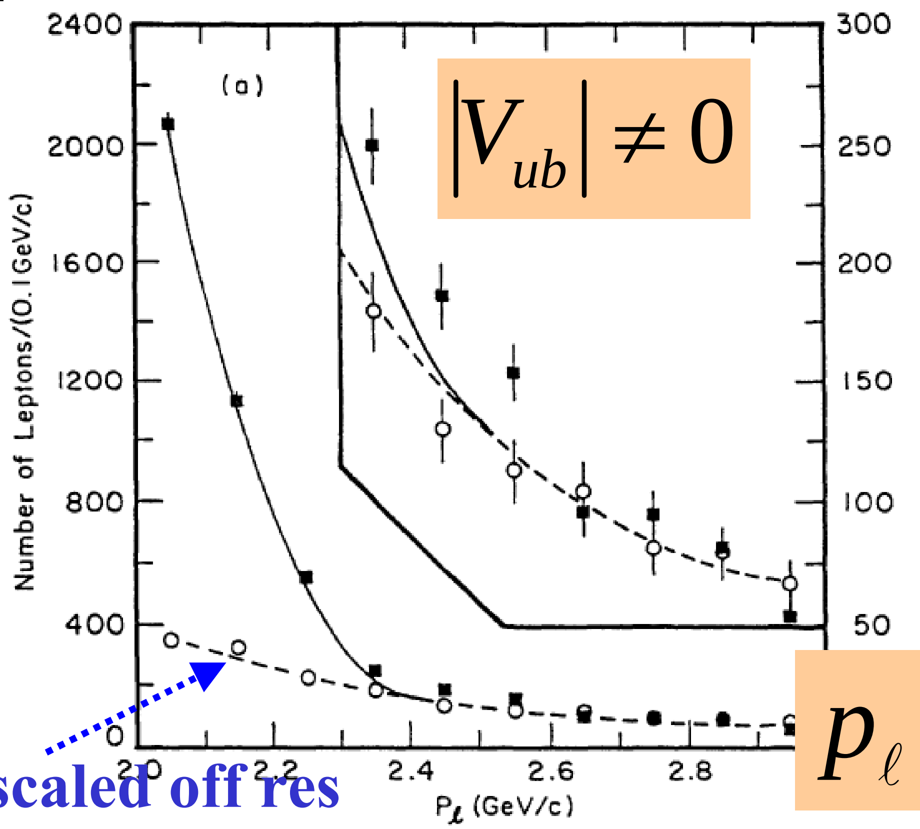




VOLUME 64, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JANUARY 1990

Observation of *B*-Meson Semileptonic Decays to Noncharmed Final States 212 pb^{-1}

We report the first evidence of charmless semileptonic decays of B mesons. In the momentum interval 2.4–2.6 GeV/c where the background from $b \to c l \nu$ is negligible, the average of the measured $b \to u e \nu$ and $b \to u \mu \nu$ partial branching ratios is $\Delta B_{ub}(2.4,2.6) = (1.8 \pm 0.4 \pm 0.3) \times 10^{-4}$. Inclusion of data from the interval 2.2–2.4 GeV/c, where the lepton yield is dominated by $b \to c l \nu$, gives $\Delta B_{ub}(2.2,2.6) = (3.3 \pm 0.8 \pm 0.8) \times 10^{-4}$. $|V_{ub}/V_{cb}|$ depends on the theoretical model of $b \to u l \nu$ decay and is approximately 0.1.



$|V_{ub}| \neq 0$

p_ℓ

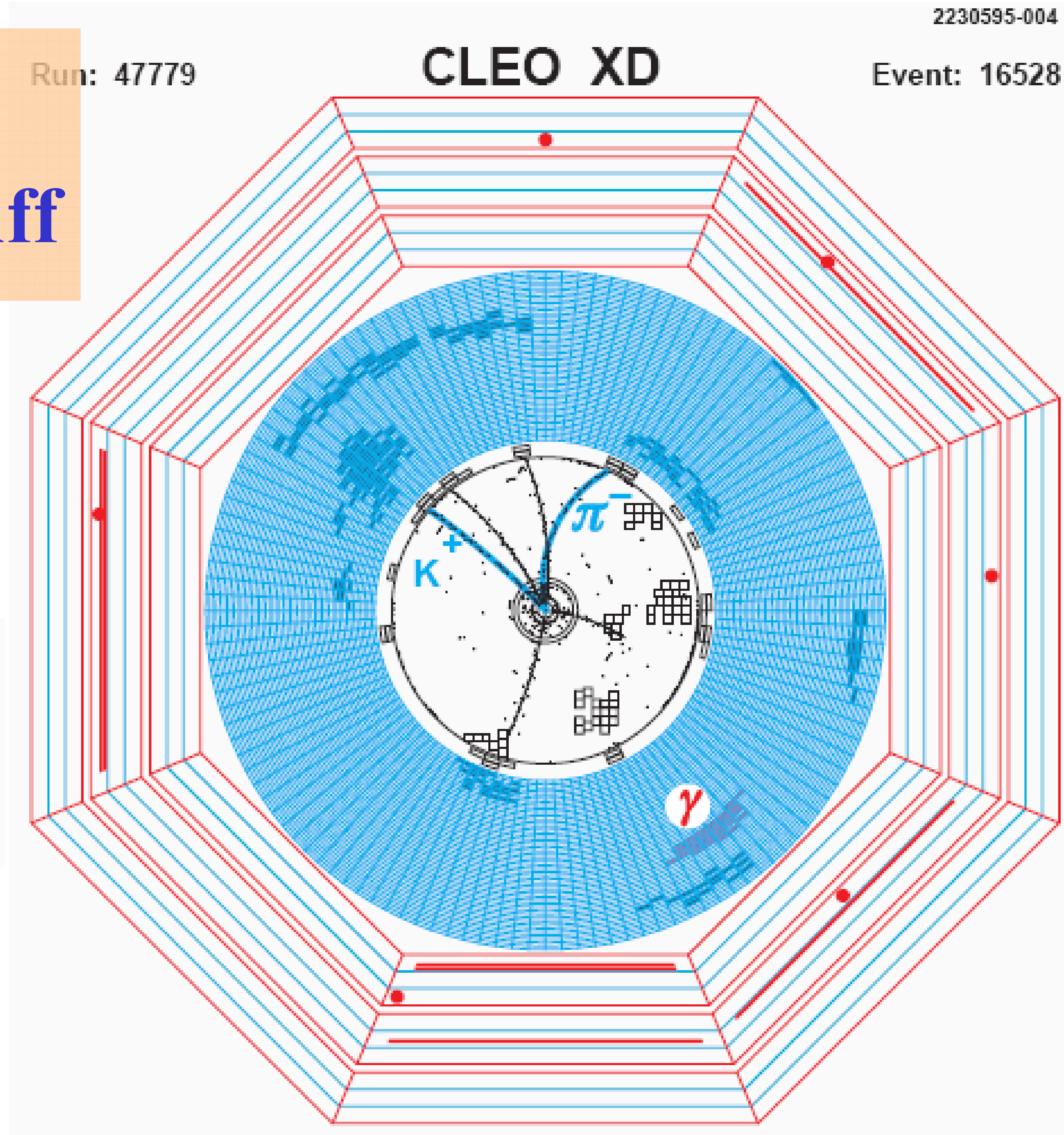
scaled off res

- **Major 1st step in the long struggle to measure $|V_{ub}|$.**
- **Inclusive measurement…in very limited region of phase space.**
- **Continuum background suppression & determination crucial**
- **If $|V_{ub}|=0$, SM would predict no CP violation.**

CLEO II:
The Right Stuff

$$B^0 \to K^{*0}\gamma$$
$$\quad \hookrightarrow K^+\pi^-$$

$$\bar{B}^0 \to D^+\rho^-$$
$$\quad \rho^- \hookrightarrow \pi^-\pi^0$$
$$\quad D^+ \hookrightarrow K^-\pi^+\pi^+$$



How long to run below resonance?

CBX 90– 59
7 November, 1990
E. H. Thorndike

ON4S vs. OFF4S Running

I. Introduction

At the November CLEO meeting we will discuss the running schedule for the next several months, and in particular reconsider whether our long–established pattern of 2–ON, 1–below is optimum for physics with CLEO–II. There are both objective and subjective elements in determining the optimum ON/OFF distribution. We run ON4S to study

II. A Simple Situation

As a warmup, consider a world in which we are interested in three classes of experiments:

(i) Continuum production over the full momentum range.

(ii) Small–signal b physics with background coming entirely from the continuum.

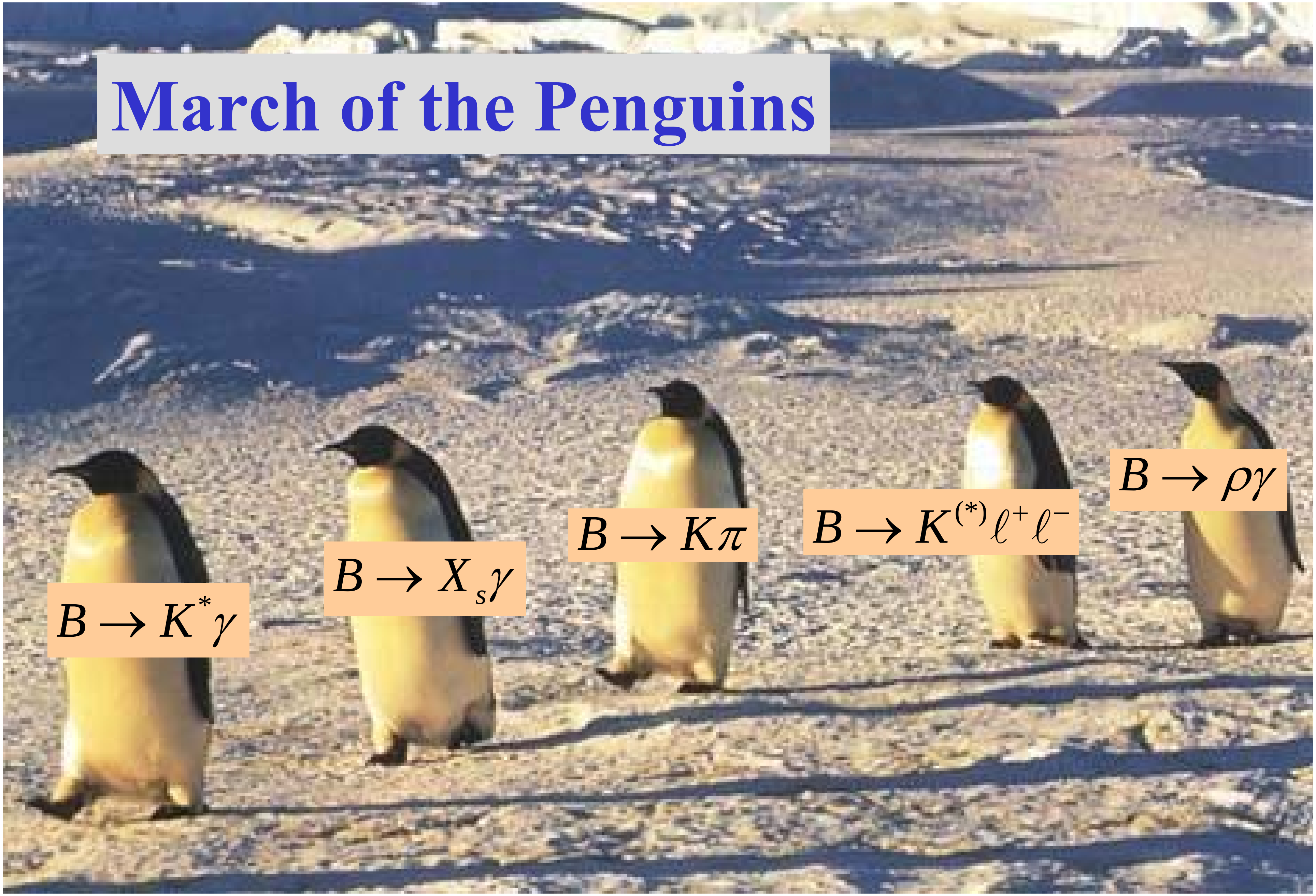
(iii) B physics for which the continuum background is known to be negligible.

Having determined the optimum value of f for three separate classes of experiments, we must now grapple with determining the optimum value of f for a PHYSICS PROGRAM. As a first try, suppose we assign to each of the three classes of experiments a weighting (W_i, W_{ii}, W_{iii}) depending on their relative importance. This of course is highly subjective, but can be done somehow. One's first guess would be that the optimum value of f would be found by maximizing the effective luminosity summed over the components of the program, each with its importance weighting, i.e., by maximizing $W_i(1-f)+W_{ii}4f(1-f)+W_{iii}f$. Suppose for example we take $W_{ii}=0$, $W_i=W_{iii}$. Then we are led to the conclusion that any value of f is equally good – what one gains or loses on experiments of class i one loses or gains on experiments of class iii. If $W_i=0.51$ and $W_{iii}=0.49$, then we should do all running OFF, while if $W_i=0.49$ and $W_{iii}=0.51$, we should do all running ON. This does not feel right.

As a second attempt, consider minimizing the weighted sum of the square of the errors, i.e. minimize $W_i/(1-f) + W_{ii}/[4f(1-f)] + W_{iii}/f$. This behaves much better, in that it varies smoothly as the W's are varied, and doesn't wipe out any project unless that project has zero weight. This feels like CLEO – preference to the most important, but don't kill the little guy. The optimum value for f is found by solving the quadratic equation

$$(W_1 - W_3)\, f^2 + 2\left(W_3 + \frac{W_2}{4}\right) f - \left(W_3 + \frac{W_2}{4}\right) = 0$$

My personal conclusion is that we should stick with $f = 2/3$. It looks best for bottom physics. Charm physics would push it up, (gently, because the gain is small). Continuum physics would push it down (gently, because continuum physics carries little weight). Tau and two-photon physics push it negligibly down.


March of the Penguins
$B \to K^* \gamma$
$B \to X_s \gamma$
$B \to K\pi$
$B \to K^{(*)} \ell^+ \ell^-$
$B \to \rho\gamma$

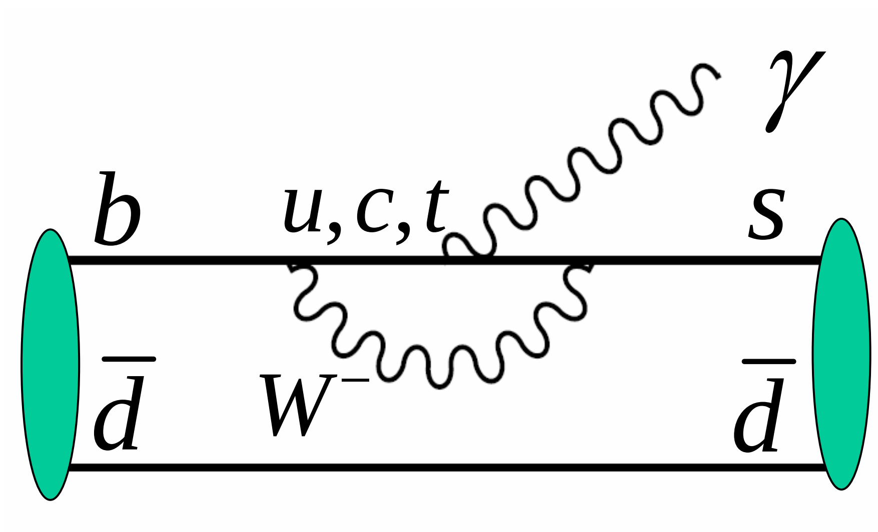
Loops in B decays: probe high mass scales!

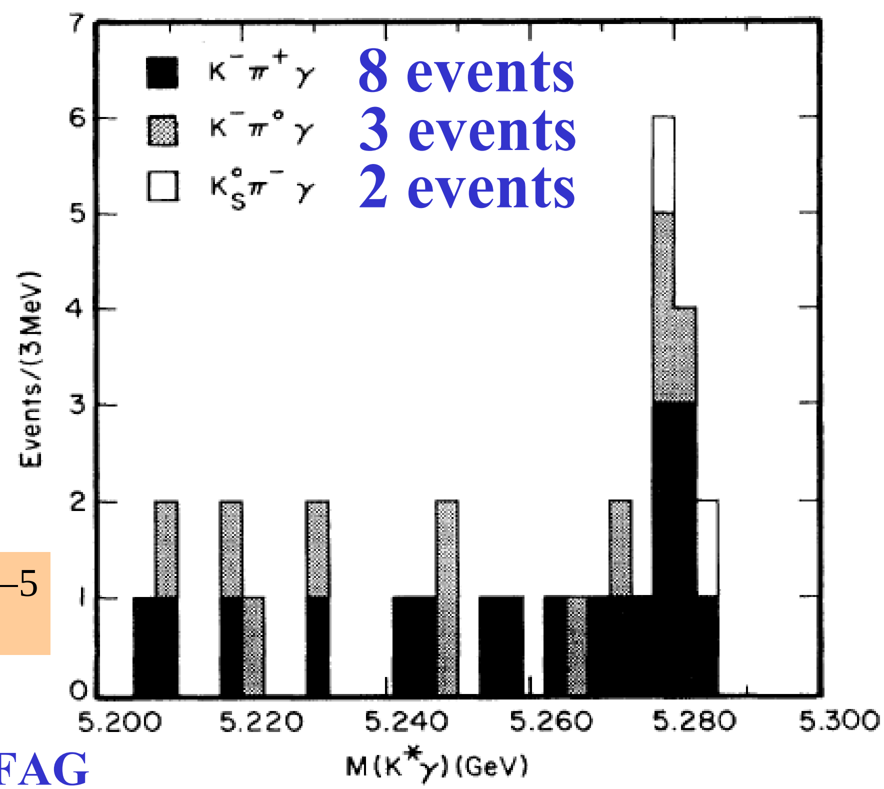
cited 560 times **1.377 fb^{-1}**

VOLUME 71, NUMBER 5 PHYSICAL REVIEW LETTERS 2 AUGUST 1993

Evidence for Penguin-Diagram Decays: First Observation of $B \to K^*(892)\gamma$

We have observed the decays $B^0 \to K^*(892)^0\gamma$ and $B^- \to K^*(892)^-\gamma$, which are evidence for the quark-level process $b \to s\gamma$. The average branching fraction is $(4.5 \pm 1.5 \pm 0.9) \times 10^{-5}$. This value is consistent with standard model predictions from electromagnetic penguin diagrams.





$$B(B \to K^*\gamma) = (4.5 \pm 1.5 \pm 0.9) \times 10^{-5}$$

$$B(\bar{B}^0 \to K^{*0}\gamma) = (4.01 \pm 0.2) \times 10^{-5}$$ **HFAG**

VOLUME 74, NUMBER 15 PHYSICAL REVIEW LETTERS 10 APRIL 1995

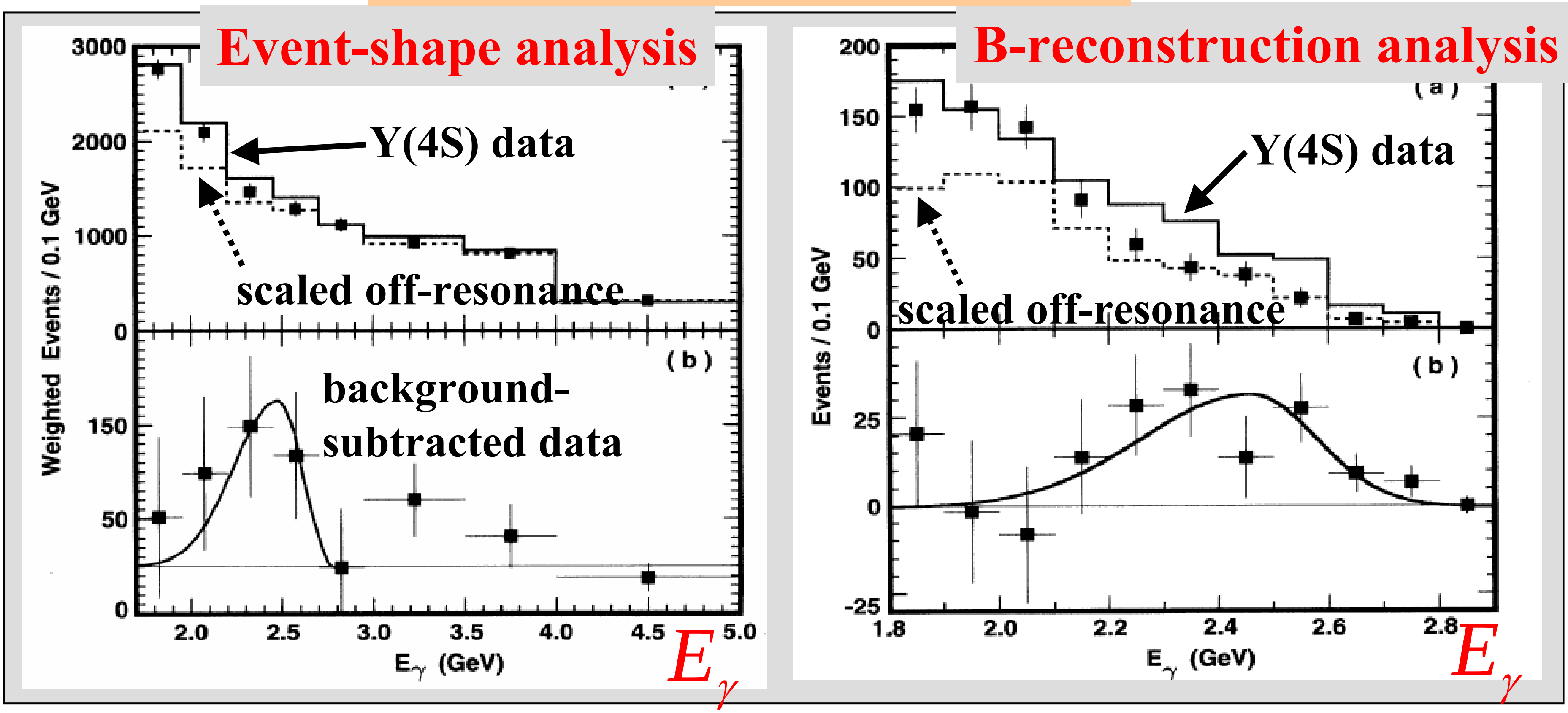
cited 768 times **2.01 fb^{-1}**

First Measurement of the Rate for the Inclusive Radiative Penguin Decay $b \to s\gamma$

We have measured the inclusive $b \to s\gamma$ branching ratio to be $(2.32 \pm 0.57 \pm 0.35) \times 10^{-4}$, where the first error is statistical and the second is systematic. Upper and lower limits on the branching ratio, each at 95% C.L., are $\mathcal{B}(b \to s\gamma) < 4.2 \times 10^{-4}$ and $\mathcal{B}(b \to s\gamma) > 1.0 \times 10^{-4}$. These limits restrict the parameters of extensions of the standard model.

$$B(B \to X_s\gamma) = (2.32 \pm 0.57 \pm 0.35) \times 10^{-4}$$

not all that rare!

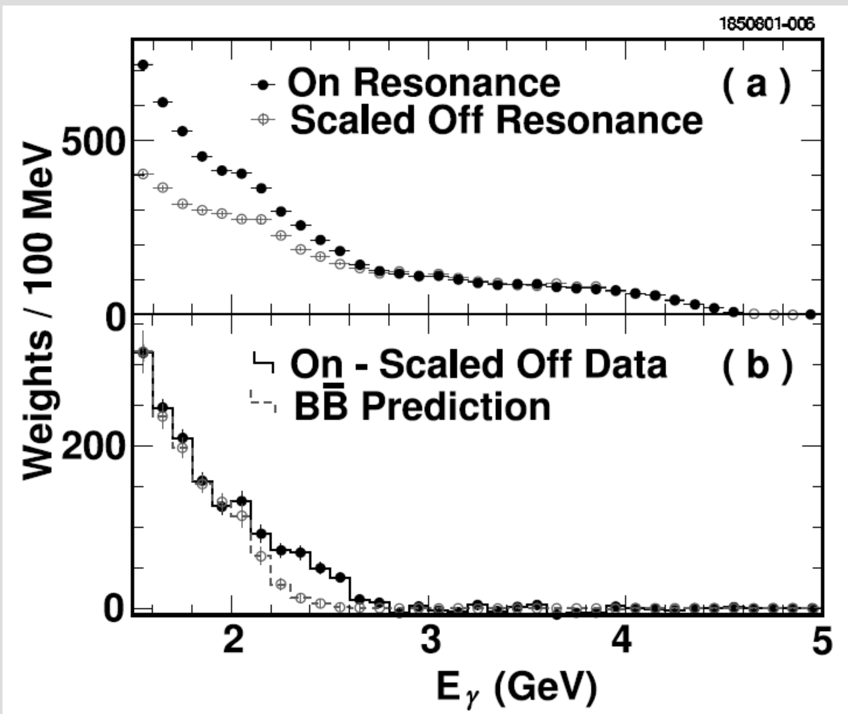


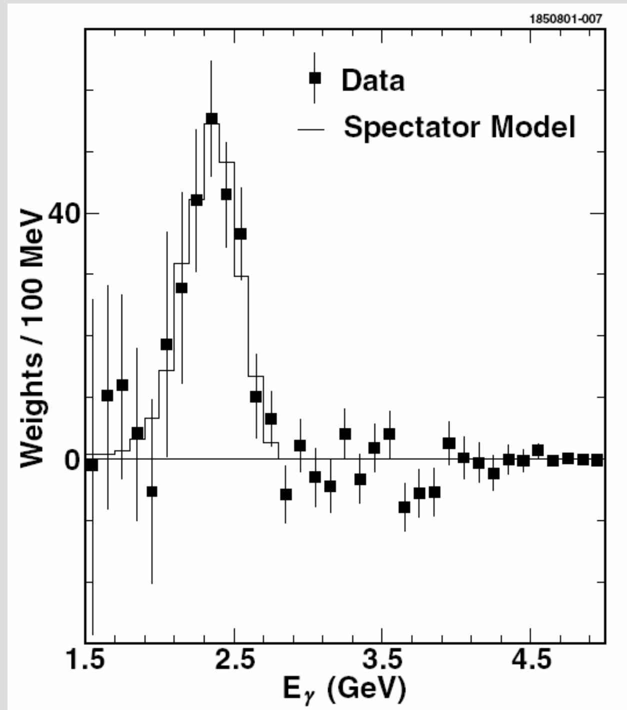
VOLUME 87, NUMBER 25 PHYSICAL REVIEW LETTERS 17 DECEMBER 2001

Branching Fraction and Photon Energy Spectrum for $b \to s\gamma$

9.1 fb^{-1}

We have measured the branching fraction and photon energy spectrum for the radiative penguin process $b \to s\gamma$. We find $\mathcal{B}(b \to s\gamma) = (3.21 \pm 0.43 \pm 0.27^{+0.18}_{-0.10}) \times 10^{-4}$, where the errors are statistical, systematic, and from theory corrections. We obtain first and second moments of the photon energy spectrum above 2.0 GeV, $\langle E_\gamma \rangle = 2.346 \pm 0.032 \pm 0.011$ GeV, and $\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2 = 0.0226 \pm 0.0066 \pm 0.0020$ GeV^2, where the errors are statistical and systematic. From the first moment, we obtain (in the modified minimal subtraction renormalization scheme, to order $1/M_B^3$ and $\beta_0 \alpha_s^2$) the heavy quark effective theory parameter $\bar{\Lambda} = 0.35 \pm 0.08 \pm 0.10$ GeV.





Summary of B($B \rightarrow X_s\gamma$)

Thanks to Henning Flaecher!

CLEO Phys.Rev.Lett.87,251807(2001)
BR($B \rightarrow X_s\gamma$) = (3.29± 0.53) 10^{-4} (9.1 fb^{-1})

Belle Semi Phys.Lett.B511:151(2001)
BR($B \rightarrow X_s\gamma$) = (3.29± 0.53) 10^{-4} (5.8 fb^{-1})

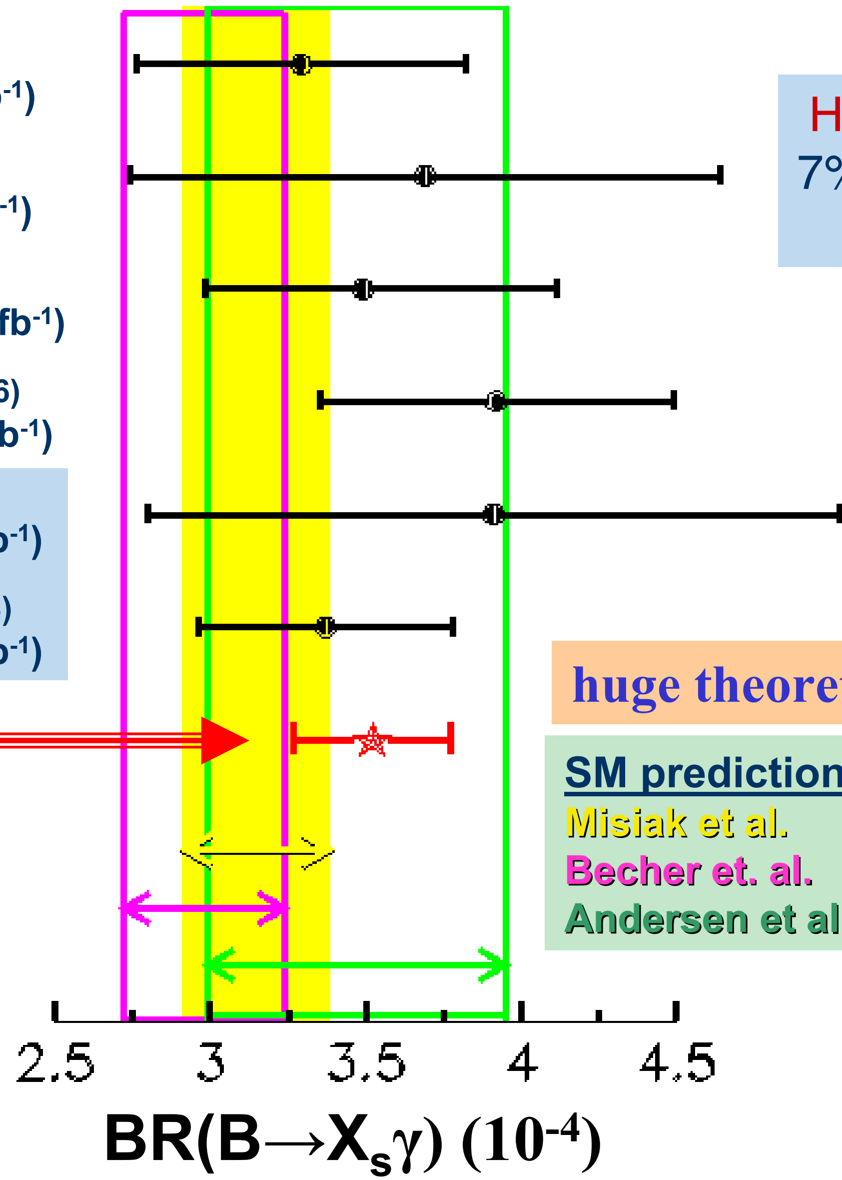
BaBar Semi Phys.Rev.D72:052004(2005)
BR($B \rightarrow X_s\gamma$) = ($3.29^{+0.62}_{-0.50}$) 10^{-4} (81.5 fb^{-1})

BaBar Incl Phys.Rev.Lett.97:171803(2006)
BR($B \rightarrow X_s\gamma$) = (3.92± 0.56) 10^{-4} (81.5 fb^{-1})

BaBar Full Phys.Rev.D77:051103(2008)
BR($B \rightarrow X_s\gamma$) = (3.91± 1.11) 10^{-4} (210 fb^{-1})

BELLE Incl (A. Limosani, Moriond EW08)
BR($B \rightarrow X_s\gamma$) = (3.37± 0.41) 10^{-4} (605 fb^{-1})

HFAG Average 08 (preliminary)
BR($B \rightarrow X_s\gamma$) = (3.52± 0.25) 10^{-4}



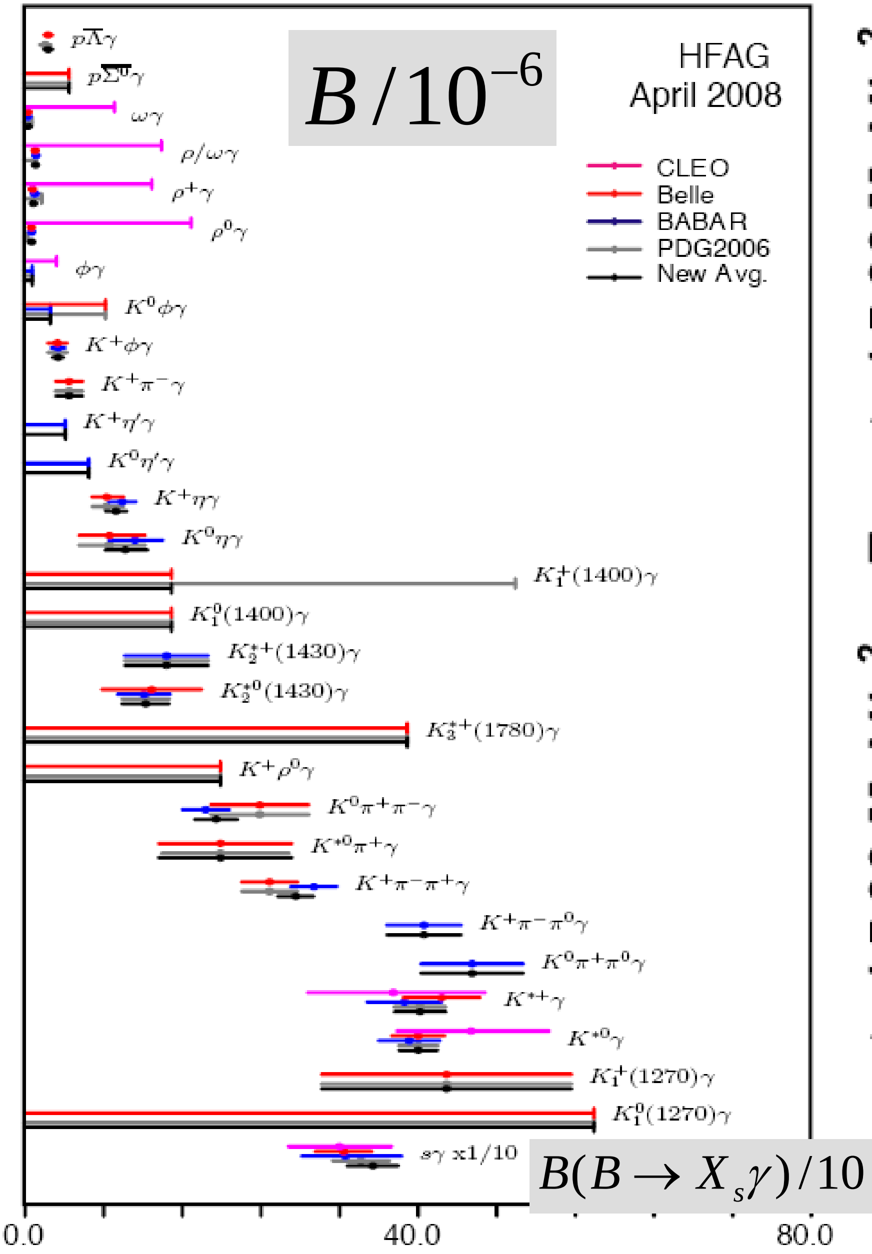
HFAG average:
7% experimental uncertainty

huge theoretical effort:

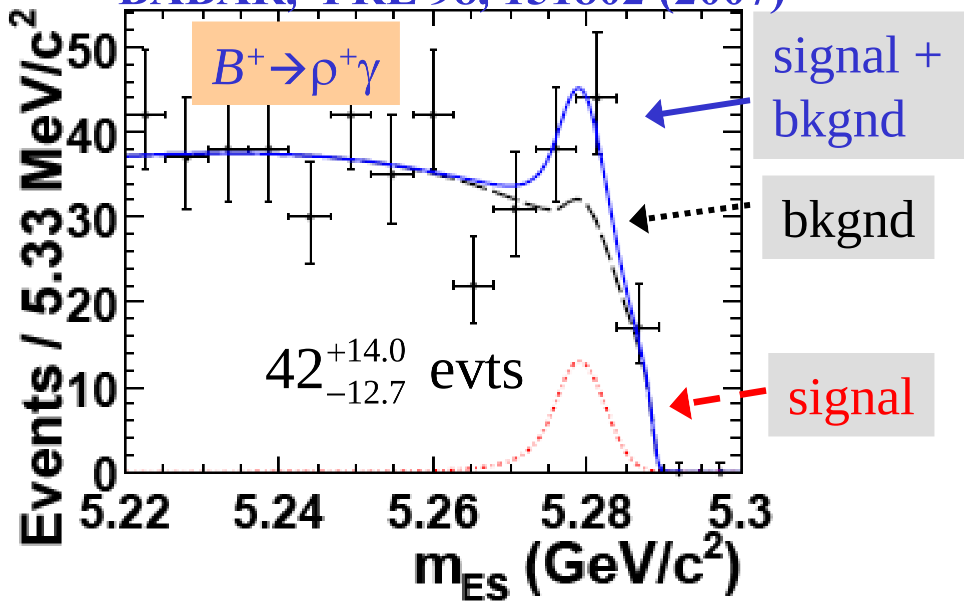
SM predictions:
Misiak et al. (hep-ph/0609232)
Becher et. al. (hep-ph/0610067)
Andersen et al. (hep-ph/0609250)

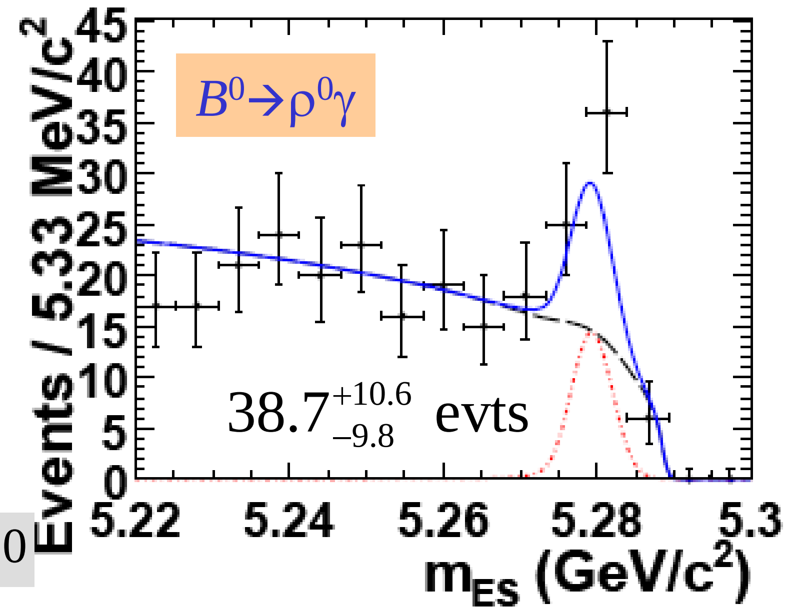
Very good agreement between experiments and analysis methods!

Radiative penguins: The Next Generation!



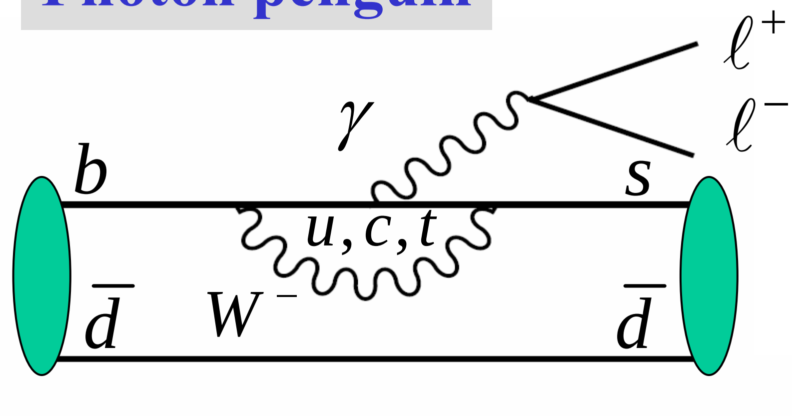
BABAR, PRL 98, 151802 (2007)



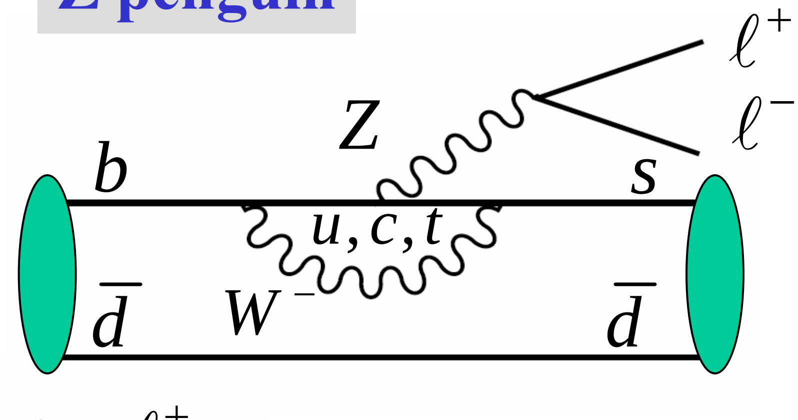


Yet another generation: electroweak penguins!

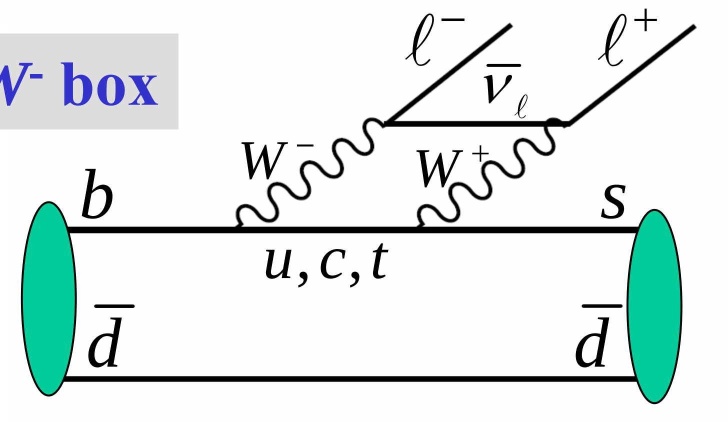
Photon penguin



Z penguin

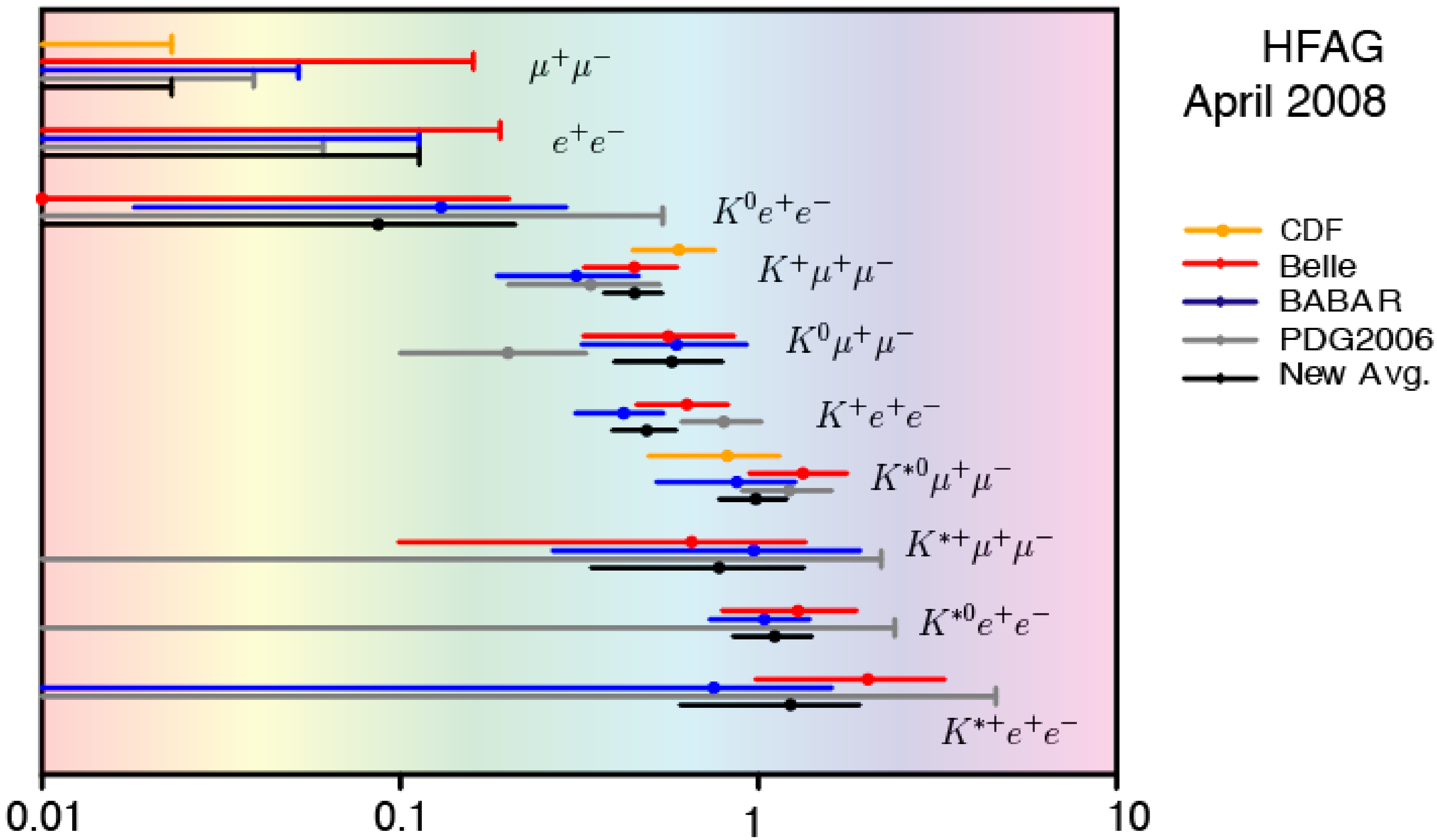


W^+W^- box



- BaBar, Belle, CDF have observed $B \rightarrow K l^+ l^-$ and $B \rightarrow K^* l^+ l^-$
- Rarest observed B decay: $\mathcal{B}(B \rightarrow K \ell^+ \ell^-) = (3.9 \pm 0.6) \times 10^{-7}$
- Kinematic distributions sensitive to new physics (A_{FB} vs. q^2)

$$B \to \ell^+\ell^-, B \to K\ell^+\ell^-, B \to K^*\ell^+\ell^-$$



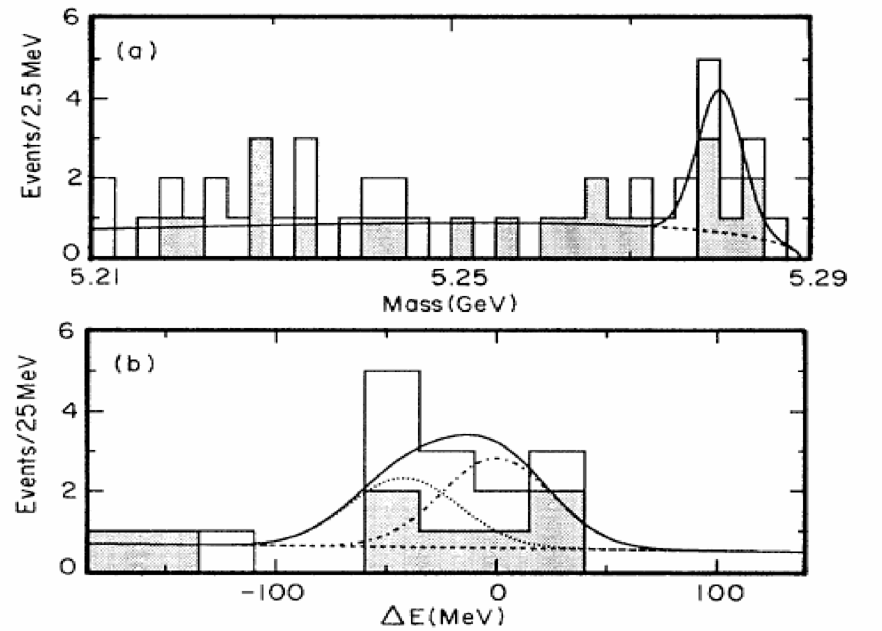
Branching Fraction/10^{-6}

VOLUME 71, NUMBER 24 PHYSICAL REVIEW LETTERS 13 DECEMBER 1993

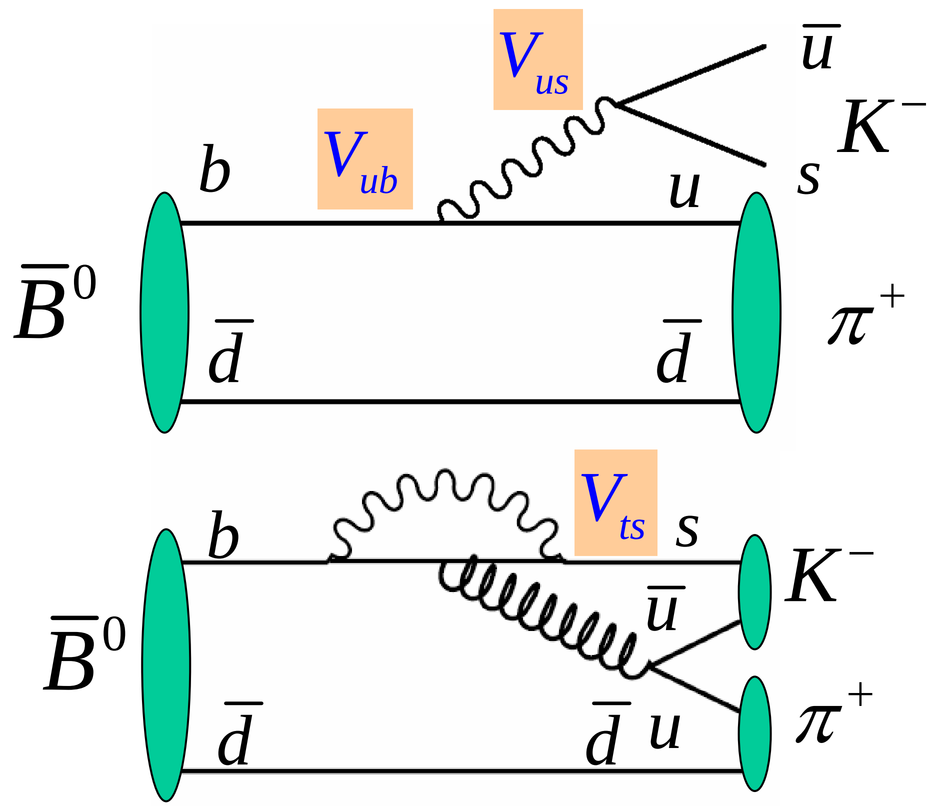
Observation of B^0 Decay to Two Charmless Mesons

1.37 fb^{-1}

We report results from a search for the decays $B^0 \to \pi^+\pi^-$, $B^0 \to K^+\pi^-$, and $B^0 \to K^+K^-$. We find 90% confidence level upper limits on the branching fractions, $B_{\pi\pi} < 2.9 \times 10^{-5}$, $B_{K\pi} < 2.6 \times 10^{-5}$, and $B_{KK} < 0.7 \times 10^{-5}$. While there is no statistically significant signal in the individual modes, the sum of $B_{\pi\pi}$ and $B_{K\pi}$ exceeds zero with a significance of more than 4 standard deviations, indicating that we have observed charmless hadronic B decays.



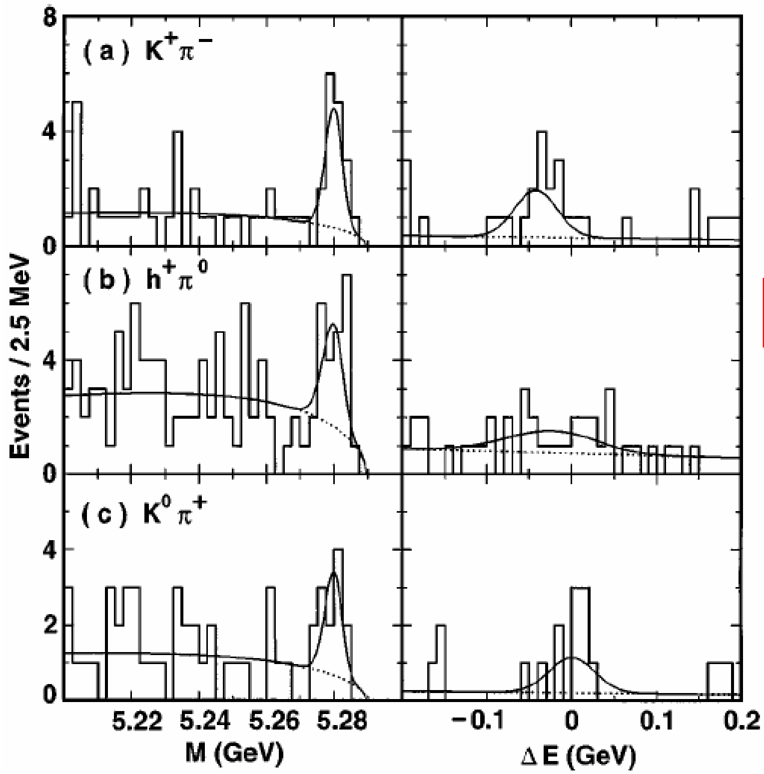
Mode	N_{fit}	$B\ (10^{-5})$
$\pi^+\pi^-$	$7.2^{+4.3}_{-3.5}$	$1.3^{+0.8}_{-0.6} \pm 0.2$
$K^+\pi^-$	$6.4^{+3.9}_{-3.1}$	$1.1^{+0.7}_{-0.6} \pm 0.2$
K^+K^-	$0.0^{+0.8}_{-0.0}$	$0.0^{+0.2}_{-0.0}$
$\pi^+\pi^-$ or $K^+\pi^-$	$13.6^{+4.7}_{-3.9}$	$2.4^{+0.8}_{-0.7} \pm 0.2$



VOLUME 80, NUMBER 16 PHYSICAL REVIEW LETTERS 20 APRIL 1998

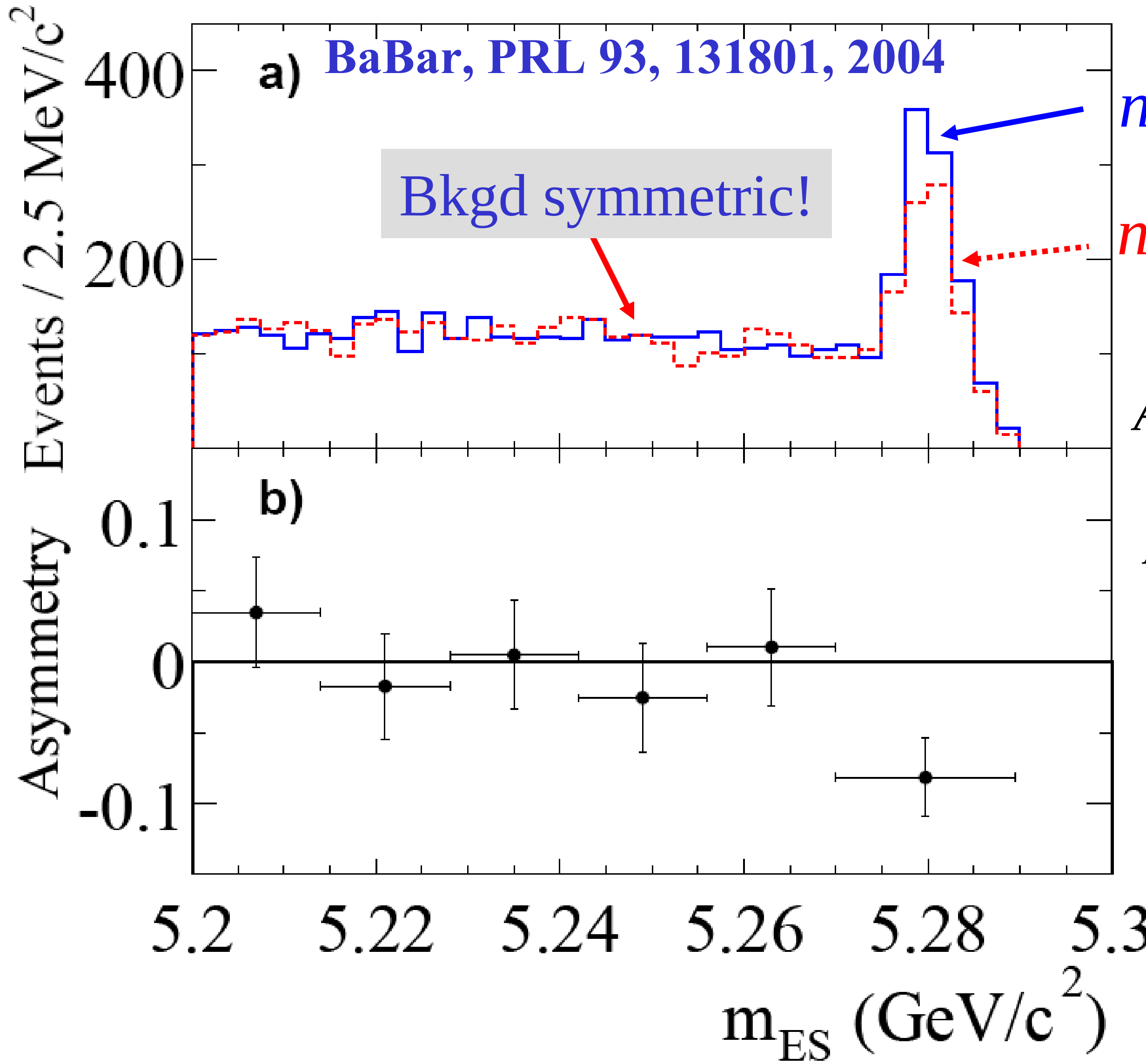
Observation of Exclusive Two-Body B Decays to Kaons and Pions 3.14 fb^{-1}

We have studied two-body charmless hadronic decays of B mesons into the final states $\pi\pi$, $K\pi$, and KK. Using 3.3×10^6 $B\overline{B}$ pairs collected with the CLEO-II detector, we have made the first observation of the decay $B^0 \to K^+\pi^-$, the sum of $B^+ \to \pi^+\pi^0$ and $B^+ \to K^+\pi^0$ decays, and see strong evidence for the decay $B^+ \to K^0\pi^+$ (an average over charge-conjugate states is always implied). We place upper limits on branching fractions for the remaining decay modes. [S0031-9007(98)05799-8]



Mode	N_S	Sig.	$\mathcal{B}/10^{-5}$
$\pi^+\pi^-$	$9.9^{+6.0}_{-5.1}$	2.2σ	$<1.5(1.3)$
$\pi^+\pi^0$	$11.3^{+6.3}_{-5.2}$	2.8σ	$<2.0(1.6)$
$\pi^0\pi^0$	$2.7^{+2.7}_{-1.7}$	2.4σ	$<0.93(0.74)$
$K^+\pi^-$	$21.6^{+6.8}_{-6.0}$	5.6σ	$1.5^{+0.5}_{-0.4} \pm 0.1 \pm 0.1$
$K^+\pi^0$	$8.7^{+5.3}_{-4.2}$	2.7σ	$<1.6(1.3)$
$K^0\pi^+$	$9.2^{+4.3}_{-3.8}$	3.2σ	$2.3^{+1.1}_{-1.0} \pm 0.3 \pm 0.2$
$K^0\pi^0$	$4.1^{+3.1}_{-2.4}$	2.2σ	$<4.1(3.3)$
K^+K^-	$0.0^{+1.3}_{-0.0}$	0.0σ	$<0.43(0.35)$
$K^+\overline{K}^0$	$0.6^{+3.8}_{-0.6}$	0.2σ	$<2.1(1.7)$
$K^0\overline{K}^0$	0	$\cdots$	$<1.7(1.5)$
$h^+\pi^0$	$20.0^{+6.8}_{-5.9}$	5.5σ	$1.6^{+0.6}_{-0.5} \pm 0.3 \pm 0.2$

B→K π: Direct CP Violation from Interference between Penguin and Tree Diagrams



$$n\left(B^0 \to K^+\pi^-\right) = 910$$

$$n\left(\bar{B}^0 \to K^-\pi^+\right) = 696$$

$$A_{K\pi} = \frac{696-910}{696+910} = -0.133$$

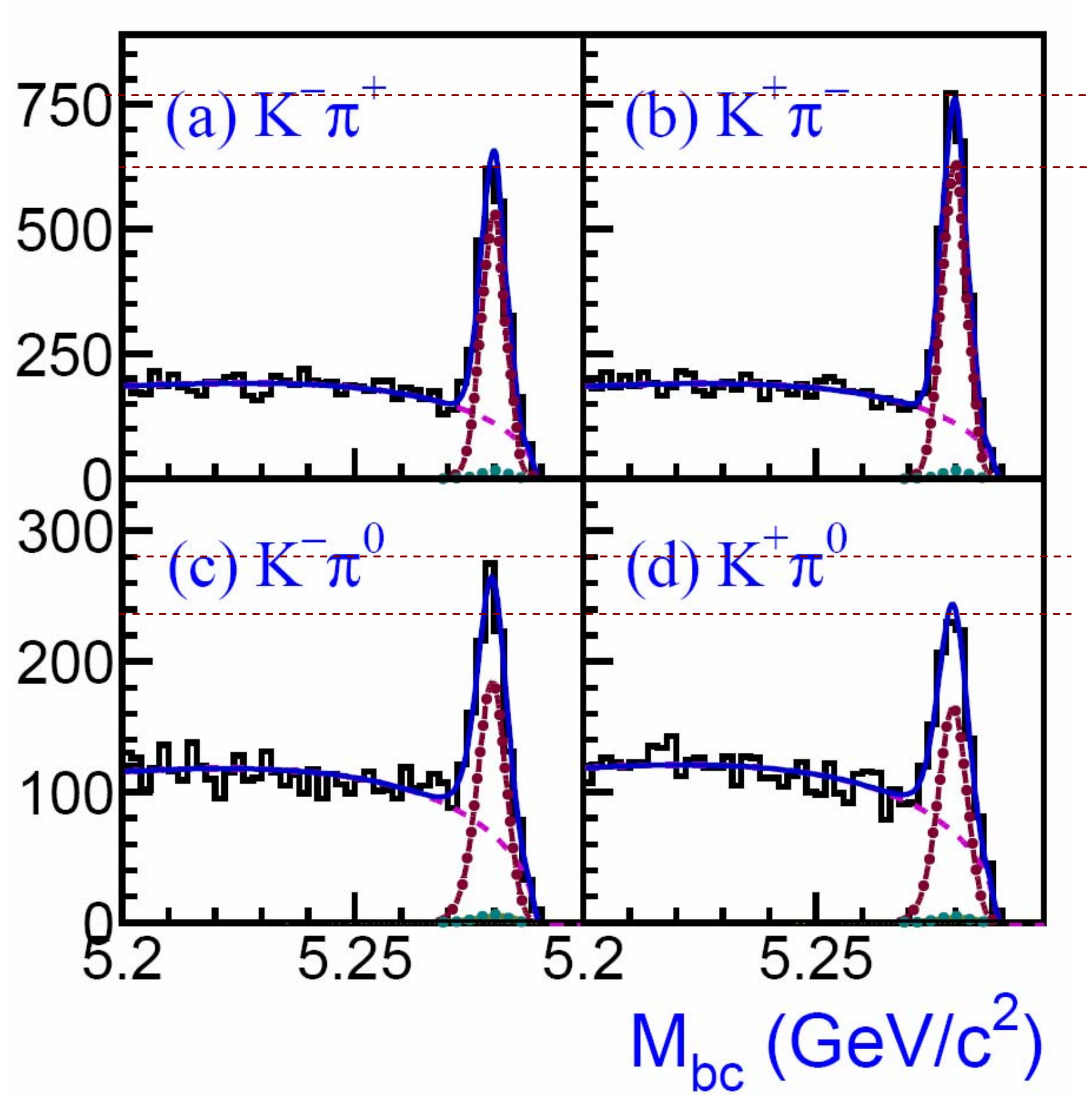
$$A_{K\pi} = -0.133 \pm 0.030 \pm 0.009$$

$$N(B\bar{B}) = 227 \times 10^6$$

penguin "pollution" in $B \to \pi^+\pi^-$

from Steve Olsen's talk at Aspen Winter Conf., 2008

Direct CPV in $B \rightarrow K\pi$ decays



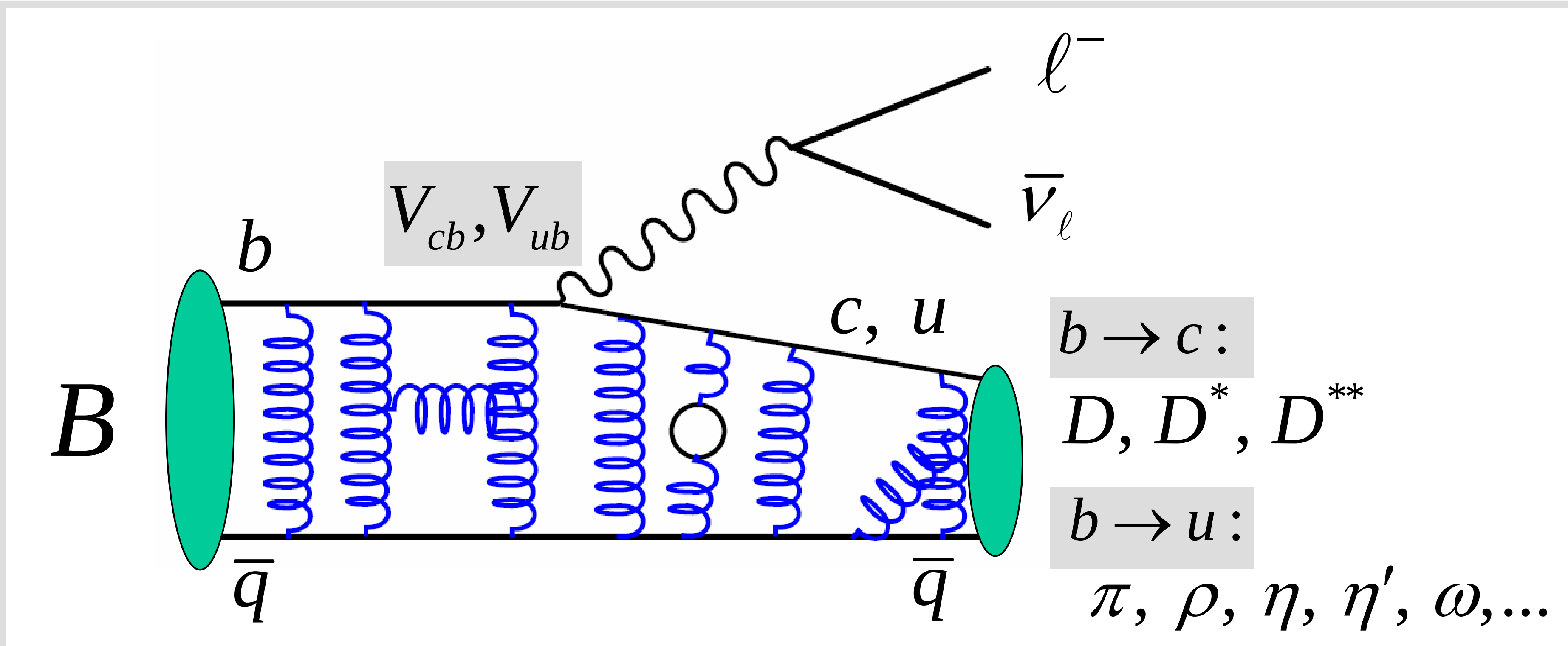
World Averages:

$A_{cp}(K^+\pi^-)$ = - 0.097 ± 0.012

5σ difference!

$A_{cp}(K^+\pi^0)$ = +0.047 ± 0.026

Simple is beautiful: semileptonic B decays



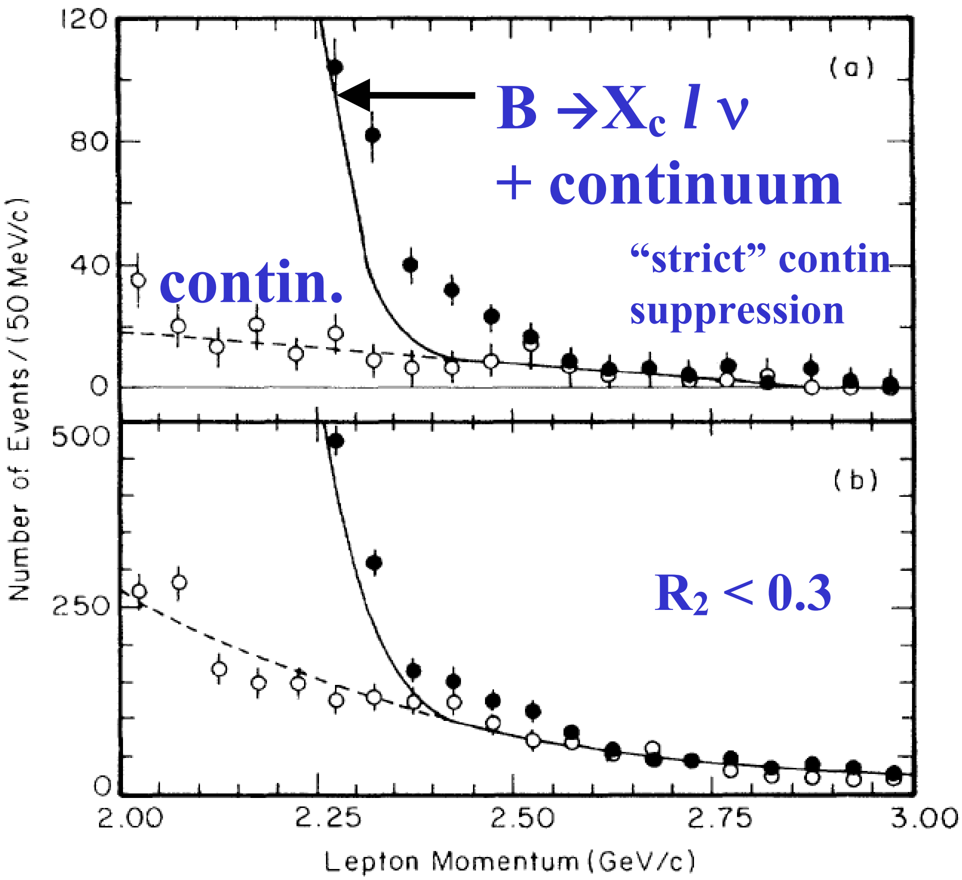
CKM matrix elements $\longleftrightarrow$ **Understanding dynamics: form factors, HQE params, quark masses**

VOLUME 71, NUMBER 25 PHYSICAL REVIEW LETTERS 20 DECEMBER 1993

Measurement of Charmless Semileptonic Decays of B Mesons

924 pb^{-1}

Using the CLEO II detector and a sample of 955 000 $\Upsilon(4S)$ decays we have confirmed charmless semileptonic decays of B mesons. In the momentum interval 2.3–2.6 GeV/c we observe an excess of $107 \pm 15 \pm 11$ leptons, which we attribute to $b \to u\ell\nu$. This result yields a model-dependent range of values for $|V_{ub}/V_{cb}|$ that is lower than has been obtained in previous studies. For the inclusive spectator model of Altarelli *et al.* we find $|V_{ub}/V_{cb}| = 0.076 \pm 0.008$. Models that describe $b \to u\ell\nu$ with a limited set of exclusive final states give $|V_{ub}/V_{cb}| = 0.06 - 0.10$.



- **Quantitative statement about size of $|V_{ub}|$**

$$\left|\frac{V_{ub}}{V_{cb}}\right| = 0.076 \pm 0.008$$

Altarelli model

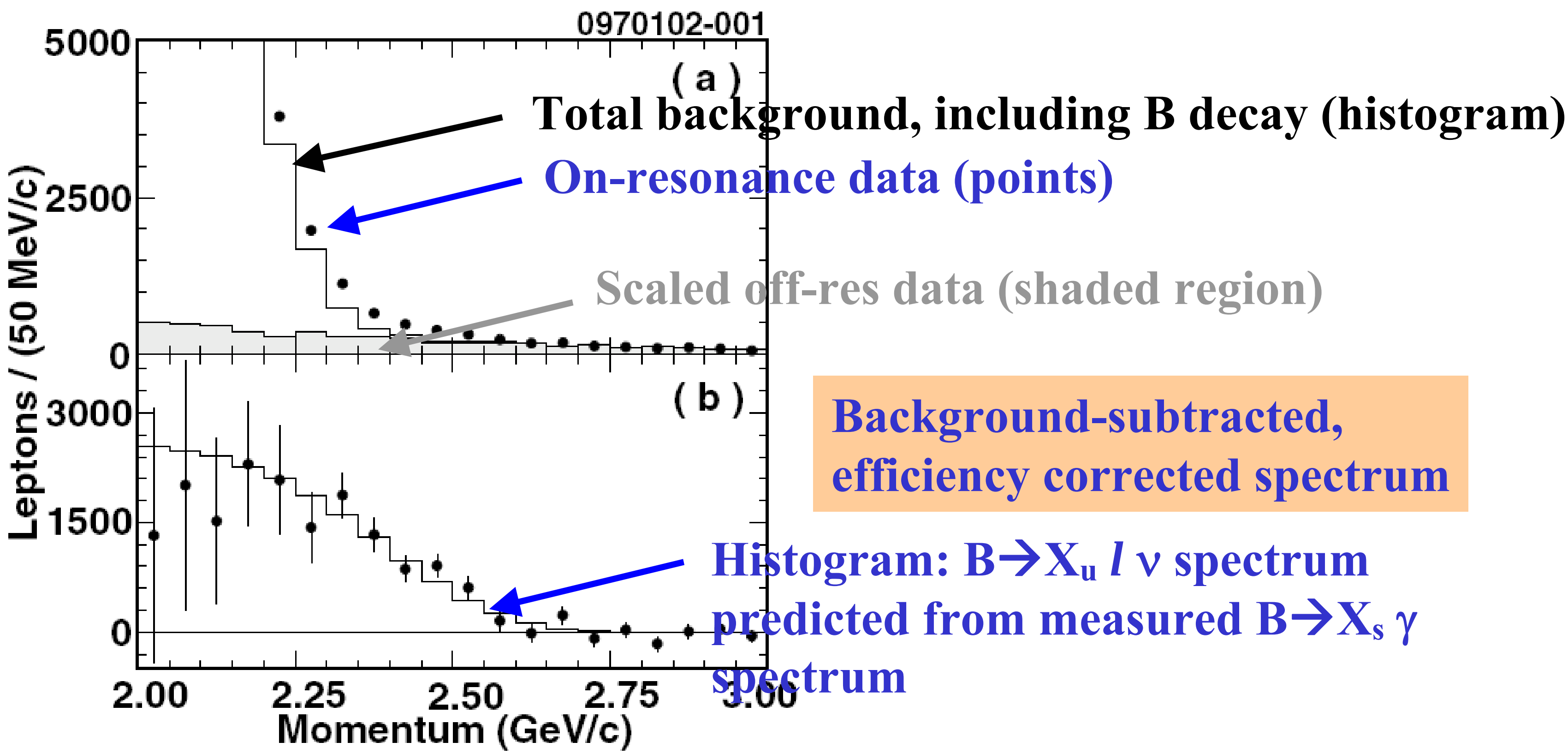
- **Model dependence studied; part of long, long struggle.**

VOLUME 88, NUMBER 23 PHYSICAL REVIEW LETTERS 10 JUNE 2002

...and with a factor of 10 more data

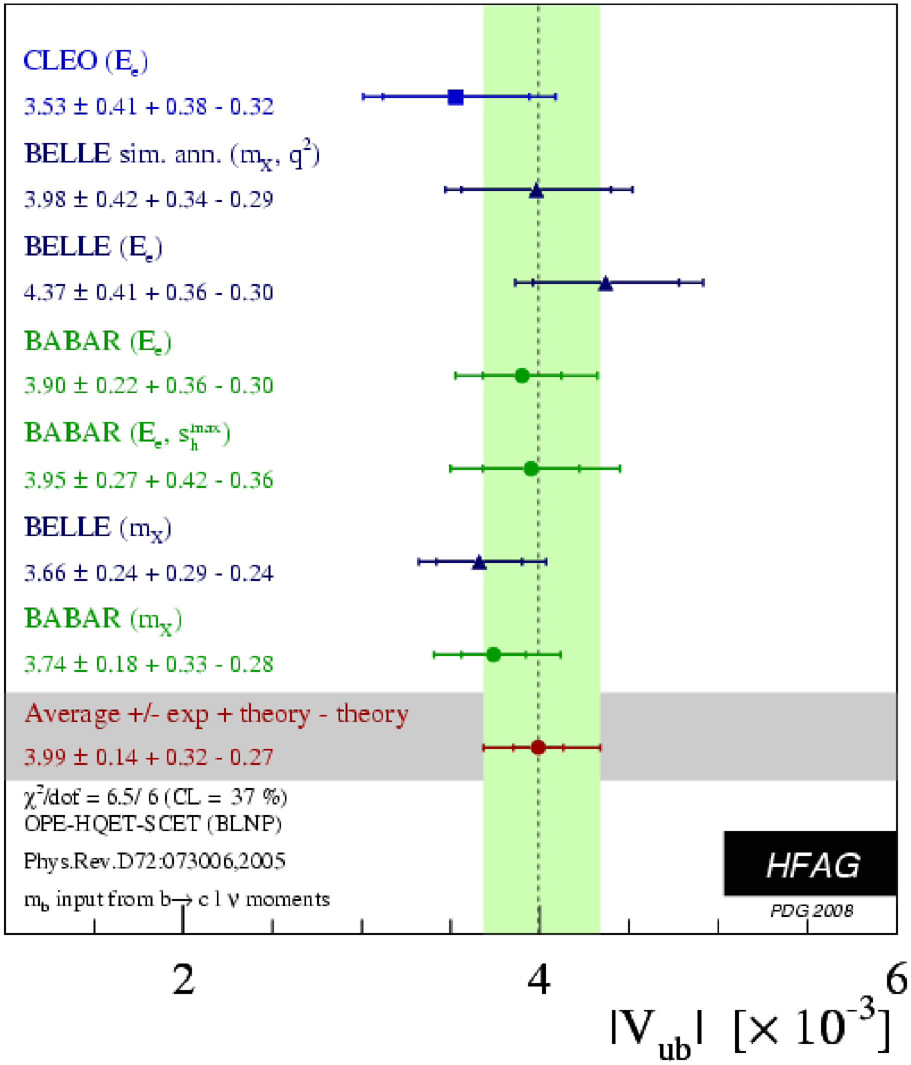
Improved Measurement of $|V_{ub}|$ with Inclusive Semileptonic B Decays 9.13 fb^{-1}

We report a new measurement of the Cabibbo-Kobayashi-Maskawa parameter $|V_{ub}|$ made with a sample of 9.7×10^6 $B\bar{B}$ events collected with the CLEO II detector. Using heavy quark theory, we combine the observed yield of leptons from semileptonic B decay in the end-point momentum interval $2.2-2.6$ GeV$/c$ with recent CLEO II data on $B \to X_s\gamma$ to find $|V_{ub}| = (4.08 \pm 0.34 \pm 0.44 \pm 0.16 \pm 0.24) \times 10^{-3}$, where the first two uncertainties are experimental and the last two are from theory.



Background-subtracted, efficiency corrected spectrum

$|V_{ub}|$ Inclusive Measurements: HFAG Averages



Theory framework:

BLNP - B.O. Lange, M. Neubert and G. Paz, Phys. Rev. D72:073006 (2005)

$$\left|V_{ub}\right| = (3.99 \pm 0.14^{+0.32}_{-0.27}) \times 10^{-3}$$

Good or Bad?

The full breakdown of the uncertainties on the average $|V_{ub}|$ above is (all errors quoted in percent):

positive errors: $+2.0_{\text{stat}}$ $+2.3_{\text{exp}}$ $+1.3_{\text{b2c model}}$ $+1.4_{\text{b2u model}}$ $+7.0_{\text{HQE param}}$ $+0.5_{\text{SF func}}$ $+0.7_{\text{sub SF}}$ $+3.6_{\text{matching}}$ $+1.3_{\text{WA}}$ $= +8.8_{\text{tot}}$

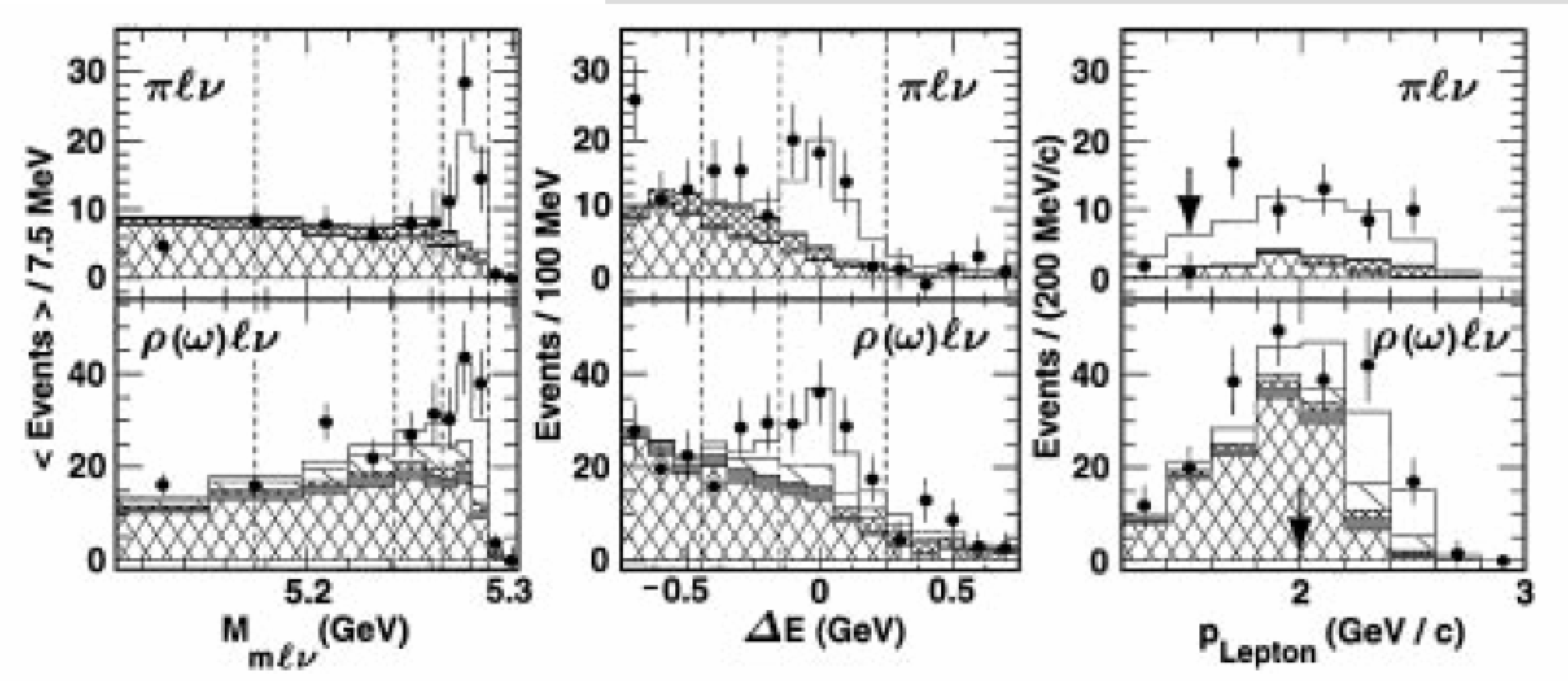
negative errors: -2.0_{stat} -2.2_{exp} $-1.2_{\text{b2c model}}$ $-1.4_{\text{b2u model}}$ $-5.8_{\text{HQE param}}$ $-0.5_{\text{SF func}}$ $-0.7_{\text{sub SF}}$ -3.3_{matching} -1.3_{WA} $= -7.7_{\text{tot}}$

VOLUME 77, NUMBER 25 PHYSICAL REVIEW LETTERS 16 DECEMBER 1996

First Measurement of the $B \to \pi \ell \nu$ and $B \to \rho(\omega) \ell \nu$ Branching Fractions

CLEO has studied B decays to $\pi \ell \nu$, $\rho \ell \nu$, and $\omega \ell \nu$, where $\ell = e$ or μ, by incorporating the missing momentum into full B reconstruction. With the B^0 and B^+ modes combined according to isospin predictions for the relative partial widths, we obtain $\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) = (1.8 \pm 0.4 \pm 0.3 \pm 0.2) \times 10^{-4}$ and $\mathcal{B}(B^0 \to \rho^- \ell^+ \nu) = (2.5 \pm 0.4^{+0.5}_{-0.7} \pm 0.5) \times 10^{-4}$, where the errors are statistical, systematic, and the estimated model dependence. We also estimate $|V_{ub}| = (3.3 \pm 0.2^{+0.3}_{-0.4} \pm 0.7) \times 10^{-3}$. [S0031-9007(96)01807-8]

Lattice QCD input is essential to fully exploit...



The Heavy Quark Effective Theory Revolution

Volume 232, number 1 PHYSICS LETTERS B 23 November 1989

WEAK DECAYS OF HEAVY MESONS IN THE STATIC QUARK APPROXIMATION ☆

TopCite 1000+ (cited 1576 times)

Nathan ISGUR

Department of Physics, University of Toronto, Toronto, Canada M5S 1A7

and

Mark B. WISE

California Institute of Technology, Pasadena, CA 91125, USA

Received 8 October 1989

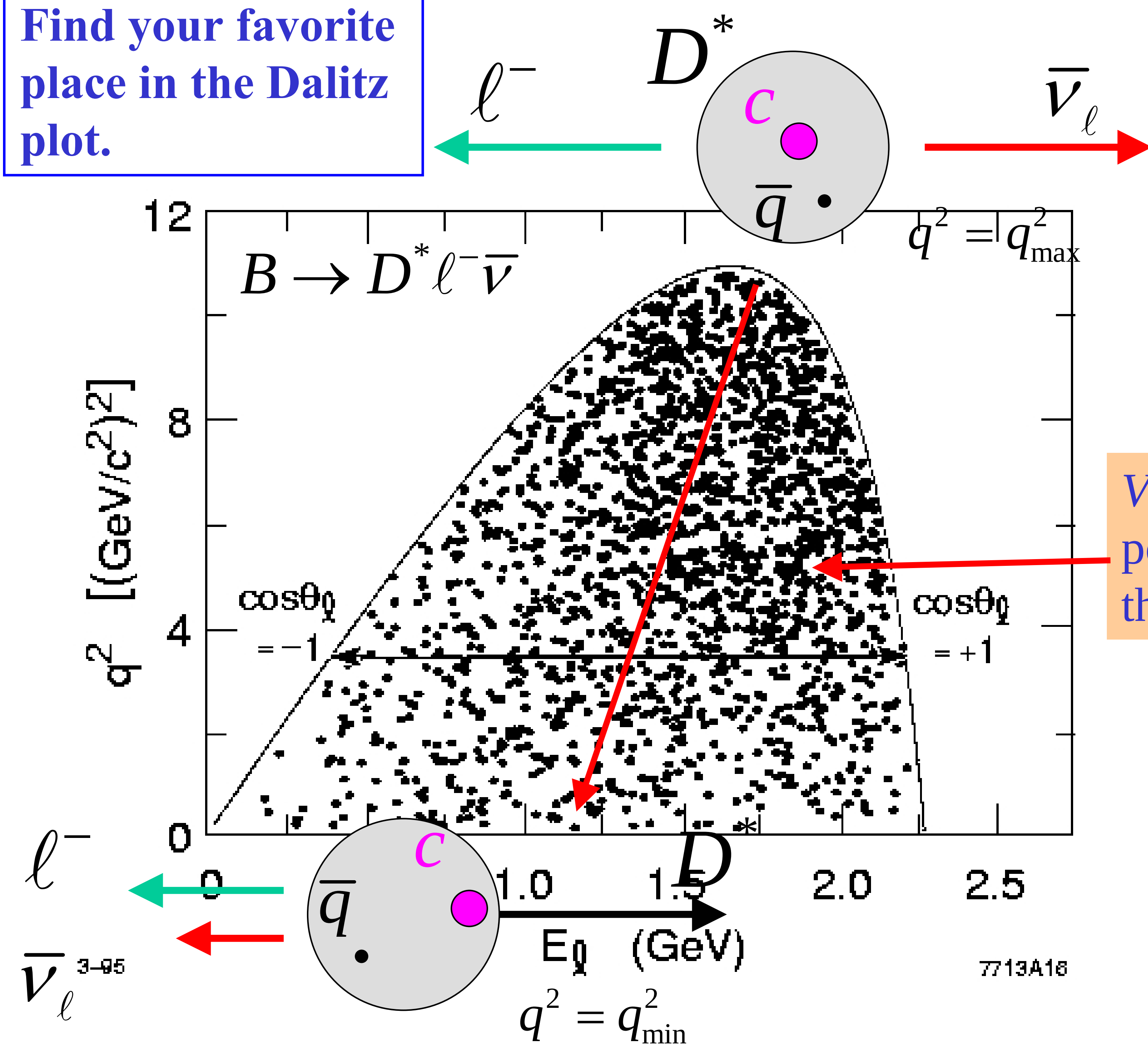
When one or more quarks are heavy compared to hadronic scales, some new symmetries appear in the low energy effective lagrangian for QCD. We exploit these static quark symmetries to derive model-independent normalizations of some weak hadronic matrix elements involving heavy quarks, as well as many relationships between such matrix elements. We briefly discuss how some of these conditions can be used to improve determinations of Kobayashi–Maskawa angles.

- **Weak Transition Form-Factors Between Heavy Mesons, N. Isgur and M.B. Wise, Phys. Lett. B237, 527 (1990). Cited 1458 times.**
- **Semileptonic B and D Decays in the Quark Model, N. Isgur, D. Scora, G. Grinstein, and M. Wise, Phys. Rev. D39, 799, 1989. Cited 1114 times.**

3 papers: 4000 citations

Find your favorite place in the Dalitz plot.

final-state D* at rest

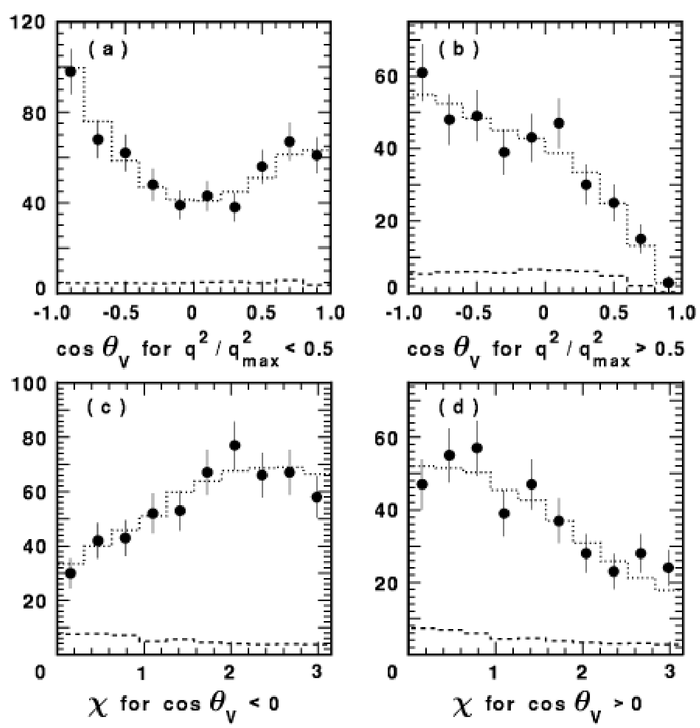


V-A: more points on R-than L-side

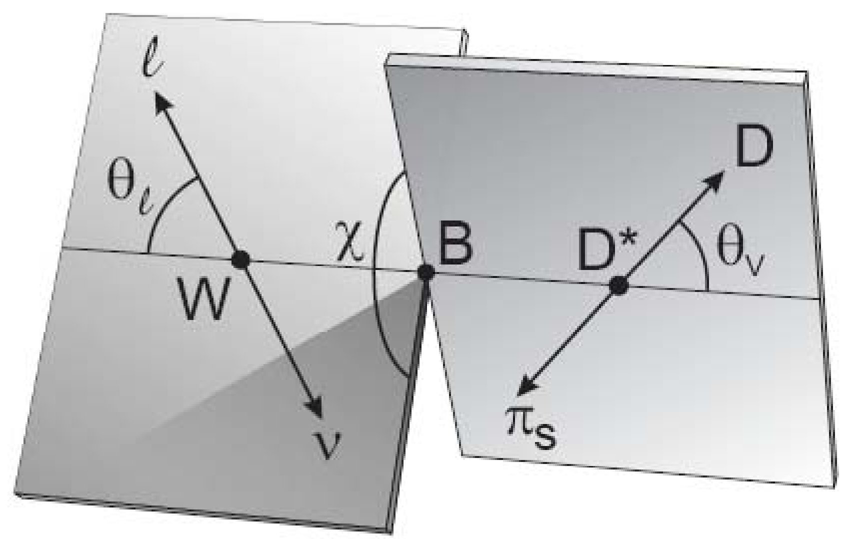
VOLUME 76, NUMBER 21 PHYSICAL REVIEW LETTERS 20 MAY 1996

Measurement of the Form Factors for $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$ **2.4 fb^{-1}**

Using a sample of 2.6×10^6 $\Upsilon(4S) \to B\overline{B}$ events collected with the CLEO II detector at the Cornell Electron Storage Ring, we have measured the form factors for $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}$. We perform a three-parameter fit with the joint distribution of four kinematic variables to obtain the form-factor ratios $R_1 = 1.18 \pm 0.30 \pm 0.12$ and $R_2 = 0.71 \pm 0.22 \pm 0.07$, and the form-factor slope $\rho^2_{A_1} = 0.91 \pm 0.15 \pm 0.06$, which is closely related to the slope of the Isgur-Wise function. The form-factor ratios are consistent with predicted corrections to the heavy-quark symmetry limit $R_1 = R_2 = 1$. [S0031-9007(96)00254-2]



Confirmed by BaBar, PRD 74, 692004 (2006)

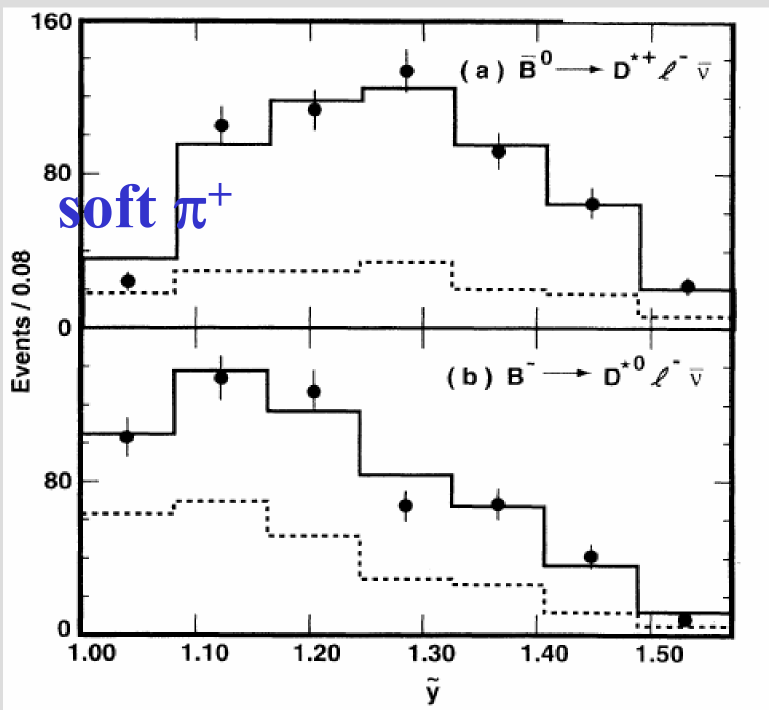


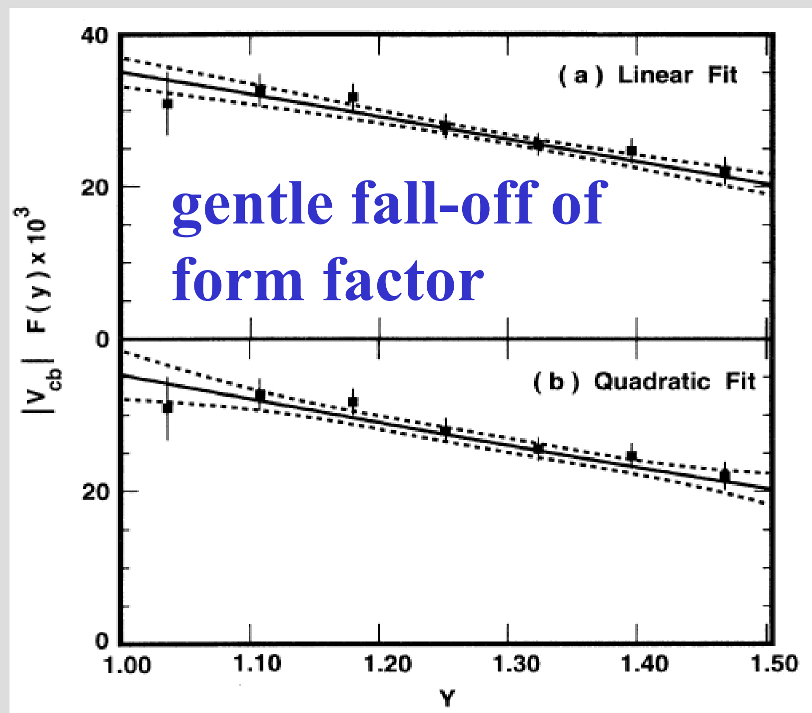
PHYSICAL REVIEW D VOLUME 51, NUMBER 3 1 FEBRUARY 1995

Measurement of the $\bar{B} \to D^* \ell \bar{\nu}$ branching fractions and $|V_{cb}|$

We study the exclusive semileptonic B meson decays $B^- \to D^{*0} \ell^- \bar{\nu}$ and $\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}$ using data collected with the CLEO II detector at the Cornell Electron-positron Storage Ring (CESR). We present measurements of the branching fractions $\mathcal{B}(\bar{B}^0 \to D^{*+} \ell^- \bar{\nu}) = (0.5/f_{00})[4.49 \pm 0.32(\text{stat}) \pm 0.39(\text{syst})]\%$ and $\mathcal{B}(B^- \to D^{*0} \ell^- \bar{\nu}) = (0.5/f_{+-})[5.13 \pm 0.54(\text{stat}) \pm 0.64(\text{syst})]\%$, where

the individual B lifetimes, but only on the charged to neutral B lifetime ratio. The product of the CKM matrix element $|V_{cb}|$ times the normalization of the decay form factor at the point of no recoil of the D^* meson, $\mathcal{F}(y=1)$, is determined from a linear fit to the combined differential decay rate of the exclusive $\bar{B} \to D^* \ell \bar{\nu}$ decays: $|V_{cb}|\mathcal{F}(1) = 0.0351 \pm 0.0019(\text{stat}) \pm 0.0018(\text{syst}) \pm 0.0008(\text{lifetime})$. The value for $|V_{cb}|$ is extracted using theoretical calculations of the form factor normalization.

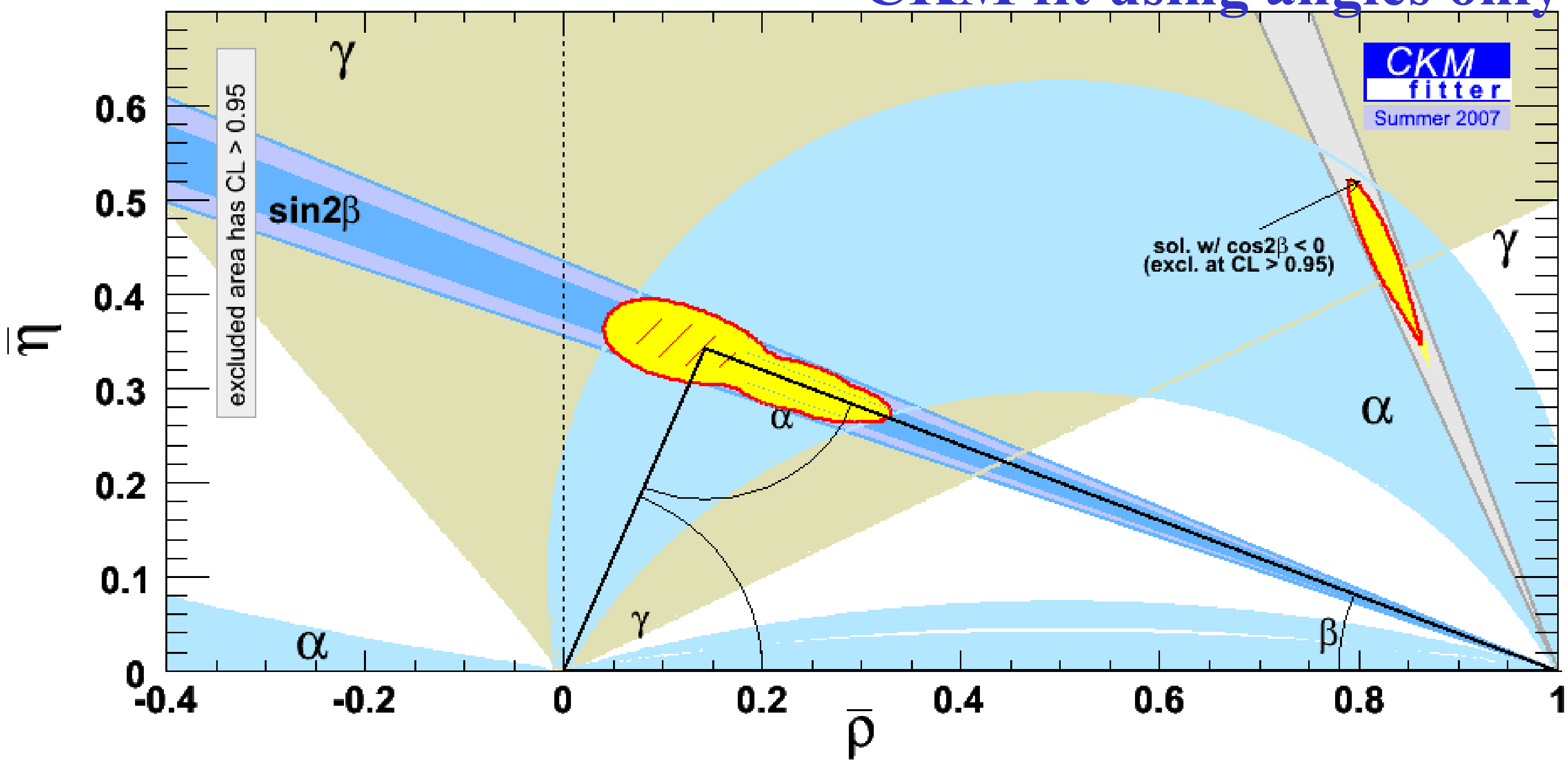




The Triumph of Hadronic Decays

Hadronic B decays have ultimately provided the most compelling test of the CKM framework through CP-violating effects. We need *interfering amplitudes* to do this.
CLEO laid much of the foundation for this work.

CKM fit using angles only



PHYSICAL REVIEW D VOLUME 50, NUMBER 1 1 JULY 1994

The "Big B Paper"

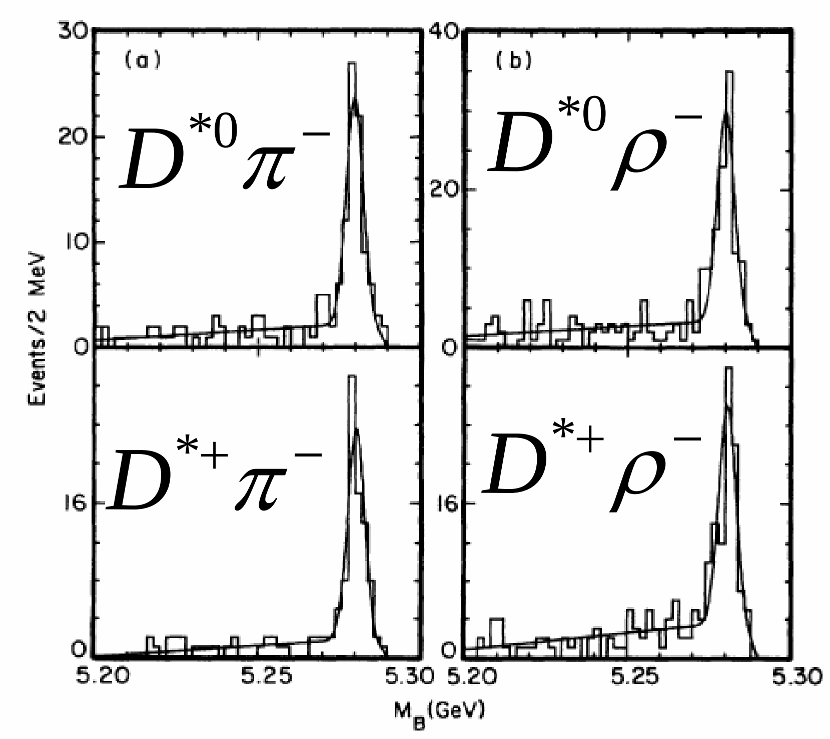
203 cites

ARTICLES

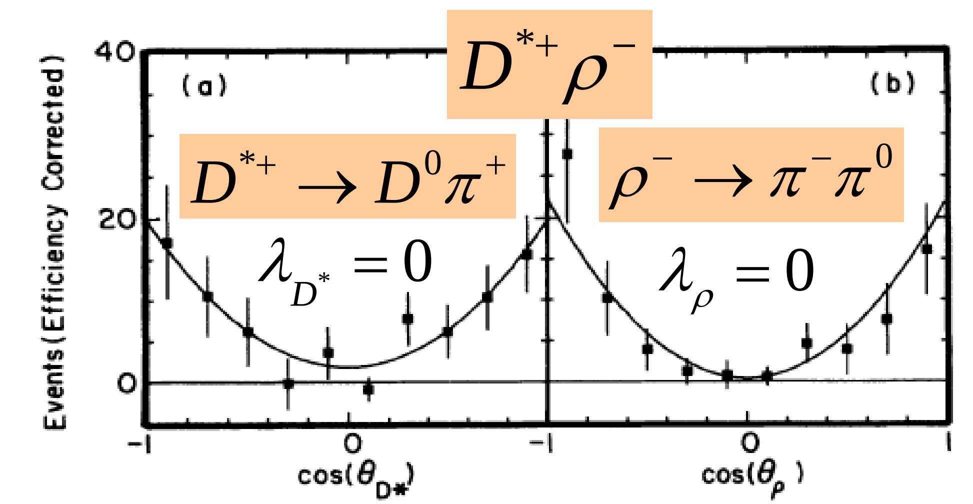
0.89 fb^{-1}

Exclusive hadronic B decays to charm and charmonium final states

We have fully reconstructed decays of both $\bar{B}^0$ and B^- mesons into final states containing either D, D^*, D^{**}, ψ, ψ', or χ_{c1} mesons. This allows us to obtain new results on many physics topics including branching ratios, tests of the factorization hypothesis, color suppression, resonant substructure, and the B^--$\bar{B}^0$ mass difference.



- **Huge number of branching fractions**
- **Color-suppressed decays**
- **Polarization & factorization studies**
- **Resonant substructure**



B decays involving charmonium

DECAYS TO CH

golden mode for sin2β

TABLE IX. Exclusive $B \to c\bar{c}$ branching ratios and 90% confidence level upper limits (%).

B mode	$\sigma(\Delta E)$	No. of events	ϵ [a]	$\mathcal{B}$ (%)
$B^- \to \psi K^-$	13	58.7 ± 7.9	0.47	$0.110 \pm 0.015 \pm 0.009$
$B^0 \to \psi K^0$	13	10.0 ± 3.2	0.34	$0.075 \pm 0.024 \pm 0.008$
$B^0 \to \psi K^{*0}$	12	29.0 ± 5.4	0.23	$0.169 \pm 0.031 \pm 0.018$
$B^- \to \psi K^{*-}$, $K^{*-} \to K^- \pi^0$	21	6.0 ± 2.4	0.07	$0.218 \pm 0.089 \pm 0.026$
$B^- \to \psi K^{*-}$, $K^{*-} \to K^0_S \pi^-$	11	6.6 ± 2.7	0.17	$0.130 \pm 0.058 \pm 0.018$
$B^- \to \psi K^{*-}$ (combined)		12.6 ± 3.6		$0.178 \pm 0.051 \pm 0.023$
$B^- \to \psi' K^-$	$9.8, 11$	7.0 ± 2.6	$0.36, 0.15$	$0.061 \pm 0.023 \pm 0.009$
$B^0 \to \psi' K^0$	$8.4, 10$	0	$0.28, 0.11$	< 0.08
$B^0 \to \psi' K^{*0}$	$9.7, 10$	4.2 ± 2.3	$0.24, 0.091$	< 0.19
$B^- \to \psi' K^{*-}$, $K^{*-} \to K^- \pi^0$	$18, 17$	1 ± 1	$0.077, 0.023$	< 0.56
$B^- \to \psi' K^{*-}$, $K^{*-} \to K^0_S \pi^-$	$7.9, 9.8$	1 ± 1	$0.16, 0.057$	< 0.36
$B^- \to \psi' K^{*-}$ (combined)		2 ± 1.4		< 0.30
$B^- \to \chi_{c1} K^-$	18	6 ± 2.4	0.20	$0.097 \pm 0.040 \pm 0.009$
$B^0 \to \chi_{c1} K^0$	16	1 ± 1	0.14	< 0.27
$B^0 \to \chi_{c1} K^{*0}$	15	1.2 ± 1.5	0.13	< 0.21
$B^- \to \chi_{c1} K^{*-}$, $K^{*-} \to K^- \pi^0$	15	0	0.033	< 0.67
$B^- \to \chi_{c1} K^{*-}$, $K^{*-} \to K_s \pi^-$	17	0	0.11	< 0.30
$B^- \to \chi_{c1} K^{*-}$ (combined)		0		< 0.21

[a] This efficiency does not include the ψ, ψ', χ_{c1}, K^0, K^*, or K^0_S branching ratios. The two sets of values given for the ψ' channels correspond to the two ψ' decay modes $\psi' \to l^+ l^-$ and $\psi' \to \psi \pi^+ \pi^-$.

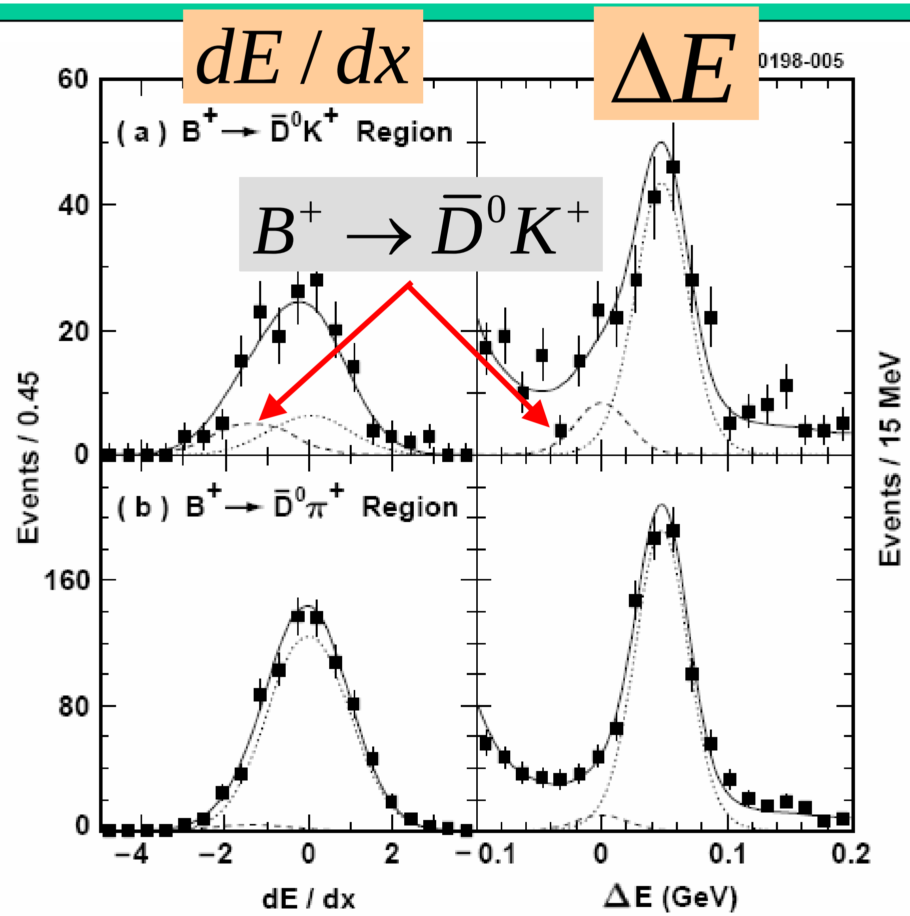
VOLUME 80, NUMBER 25 PHYSICAL REVIEW LETTERS 22 JUNE 1998

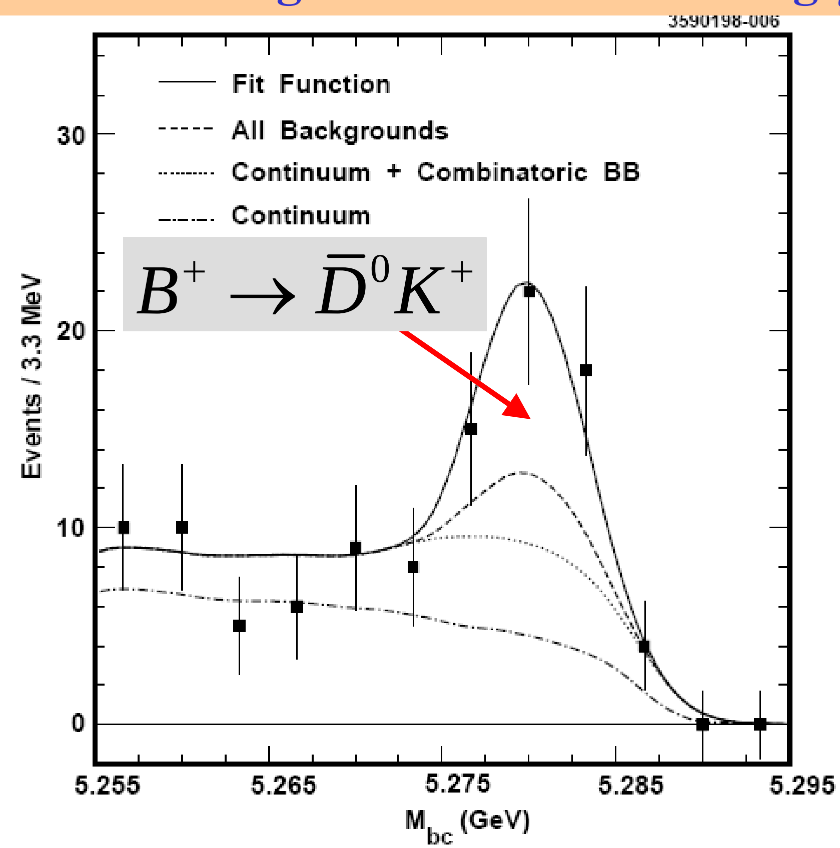
First Observation of the Cabibbo Suppressed Decay $B^+ \to \bar{D}^0 K^+$

3.1 fb^{-1}

We have observed the decay $B^+ \to \bar{D}^0 K^+$, using 3.3×10^6 $B\bar{B}$ pairs collected with the CLEO II detector at the Cornell Electron Storage Ring. We find the ratio of branching fractions $R \equiv \mathcal{B}(B^+ \to \bar{D}^0 K^+)/\mathcal{B}(B^+ \to \bar{D}^0 \pi^+) = 0.055 \pm 0.014 \pm 0.005$. [S0031-9007(98)06422-9]

contributing mode for constraining γ

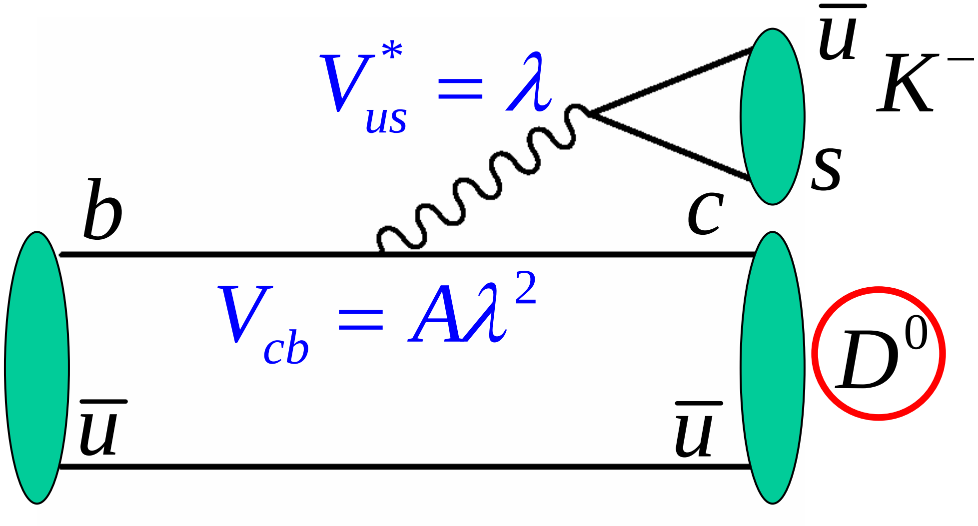




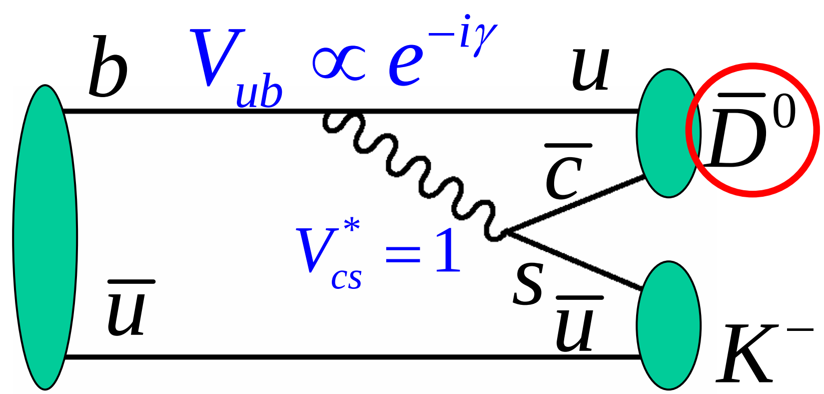
A path to γ

$A(B^- \to D^0 K^-) = A_B$

$A(B^- \to \bar{D}^0 K^-) = A_B r_B e^{i(\delta-\gamma)}$



color suppressed



How can we get interference? Need $D^0 \to f$ and $\bar{D}^0 \to f$. (For example, f $=K_S^0\pi^+\pi^-$.) Some observations:

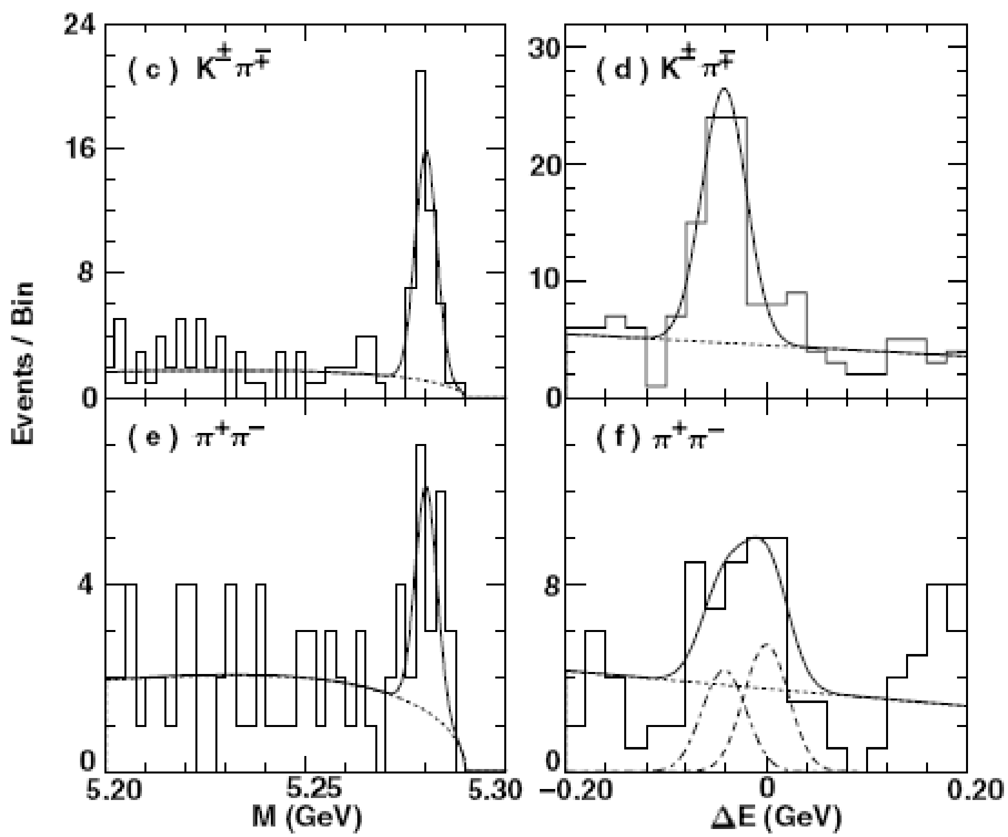
1. <u>*Uses charged B decays*</u>; method is based on a direct CP asymmetry. Issues: strong phase δ, $r_B = |A(b \to u)/A(b \to c)| = 0.1\text{-}0.2$
2. <u>*Uses tree diagrams*</u>: no loops/mixing diagrams, no penguin/new physics issues. Together with $|V_{ub}|$, gives CKM test with trees only.

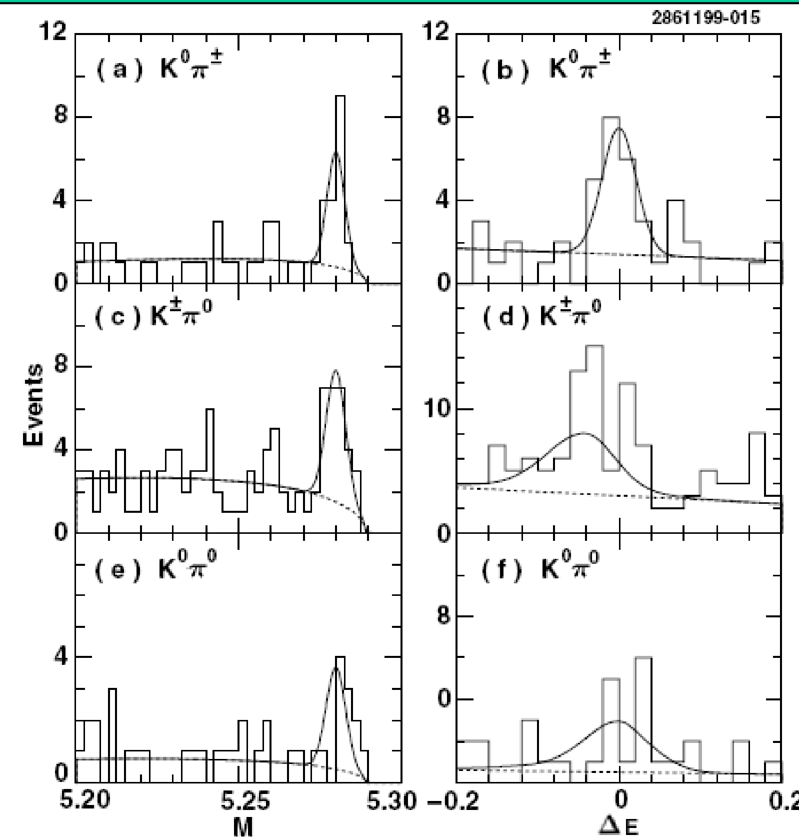
VOLUME 85, NUMBER 3 PHYSICAL REVIEW LETTERS 17 JULY 2000

Observation of $B \to K^{\pm}\pi^{0}$ and $B \to K^{0}\pi^{0}$, and Evidence for $B \to \pi^{+}\pi^{-}$ 9.13 fb^{-1}

We have studied charmless hadronic decays of B mesons into two-body final states with kaons and pions and observe three new processes with the following branching fractions: $\mathcal{B}(B \to \pi^{+}\pi^{-}) = (4.3^{+1.6}_{-1.4} \pm 0.5) \times 10^{-6}$, $\mathcal{B}(B \to K^{0}\pi^{0}) = (14.6^{+5.9+2.4}_{-5.1-3.3}) \times 10^{-6}$, and $\mathcal{B}(B \to K^{\pm}\pi^{0}) = (11.6^{+3.0+1.4}_{-2.7-1.3}) \times 10^{-6}$. We also update our previous measurements for the decays $B \to K^{\pm}\pi^{\mp}$ and $B^{\pm} \to K^{0}\pi^{\pm}$.

contributing mode for constraint on CKM angle α

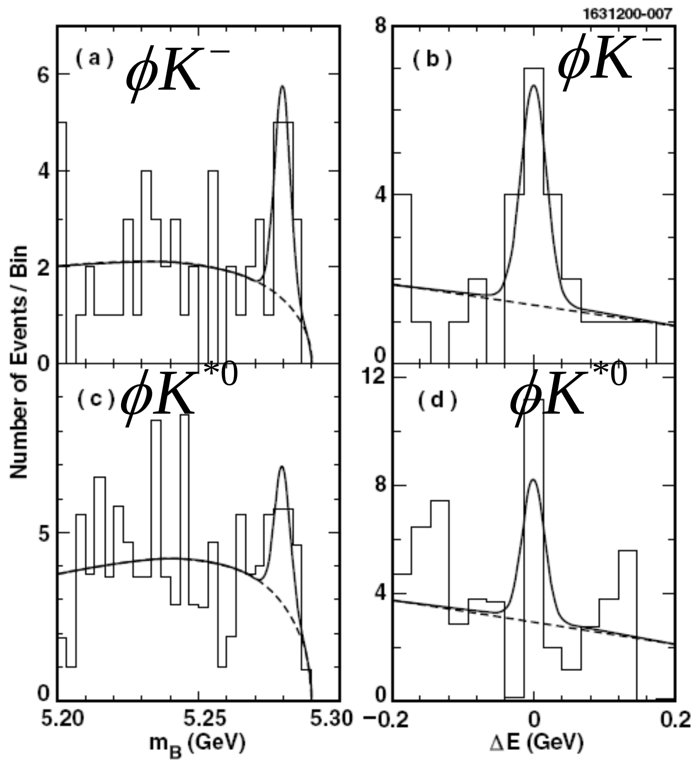




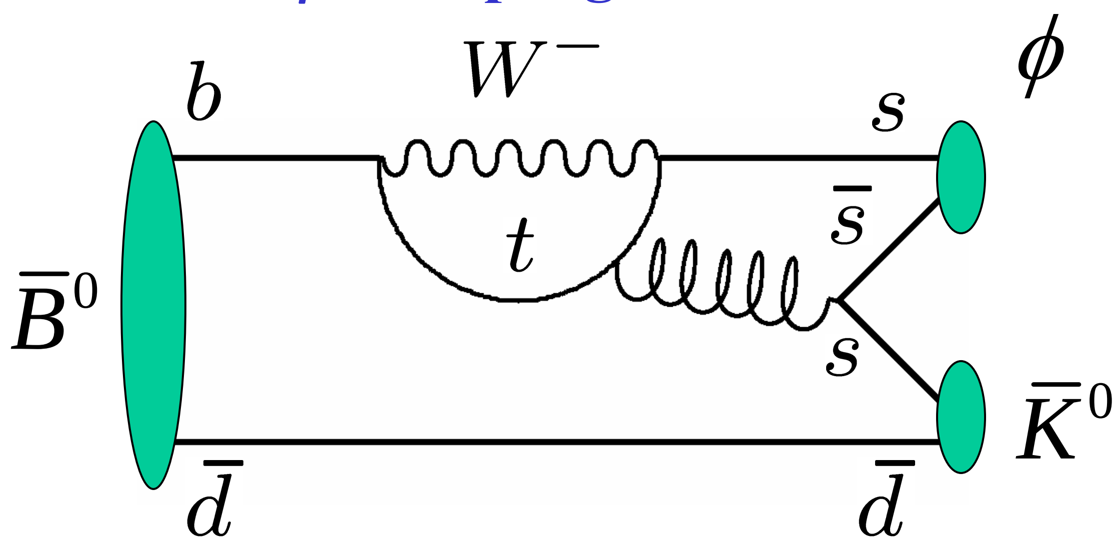
VOLUME 86, NUMBER 17 PHYSICAL REVIEW LETTERS 23 APRIL 2001

Observation of $B \to \phi K$ and $B \to \phi K^*$ **9.13 fb^{-1}**

We have studied two-body charmless hadronic decays of B mesons into the final states ϕK and ϕK^*. Using 9.7 million $B\bar{B}$ pairs collected with the CLEO II detector, we observe the decays $B^- \to \phi K^-$ and $B^0 \to \phi K^{*0}$ with the following branching fractions: $\mathcal{B}(B^- \to \phi K^-) = (5.5^{+2.1}_{-1.8} \pm 0.6) \times 10^{-6}$ and $\mathcal{B}(B^0 \to \phi K^{*0}) = (11.5^{+4.5+1.8}_{-3.7-1.7}) \times 10^{-6}$. We also see evidence for the decays $B^0 \to \phi K^0$ and $B^- \to \phi K^{*-}$. However, since the statistical significance is not overwhelming for these modes, we determine upper limits of $<12.3 \times 10^{-6}$ and $<22.5 \times 10^{-6}$ (90% confidence level), respectively.



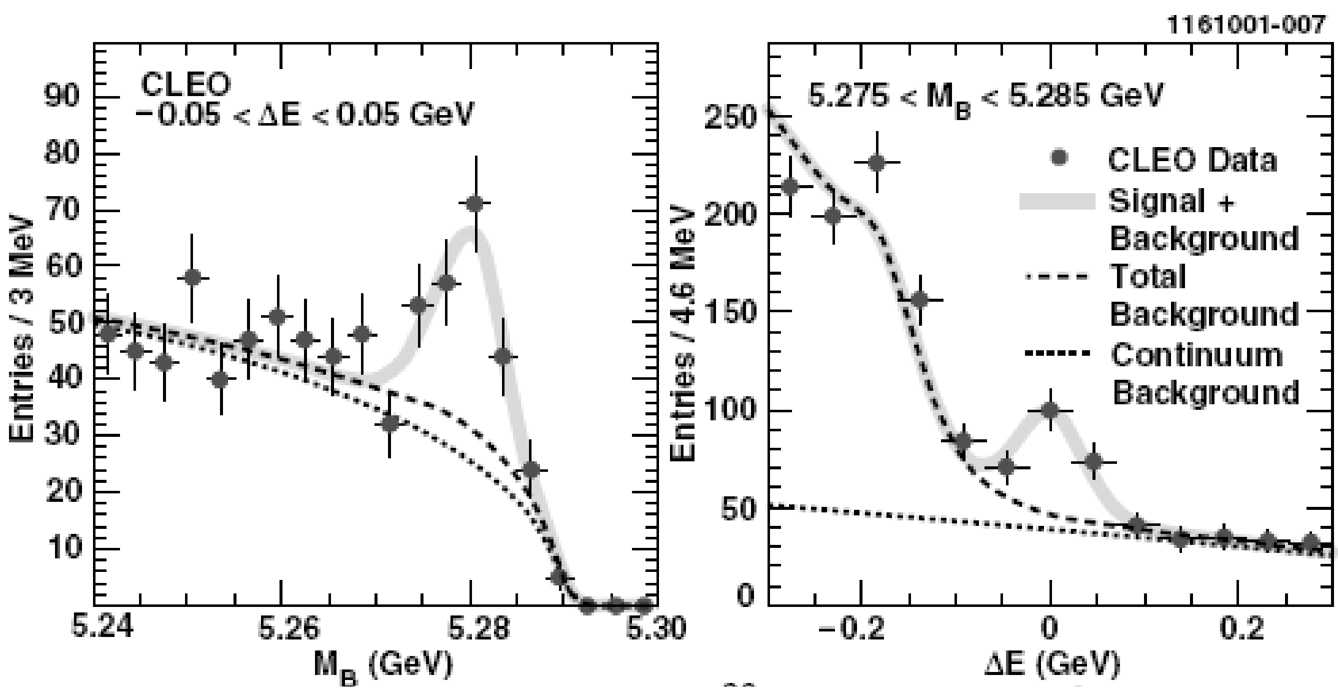
sin2β with penguins!



VOLUME 88, NUMBER 6 PHYSICAL REVIEW LETTERS 11 FEBRUARY 2002

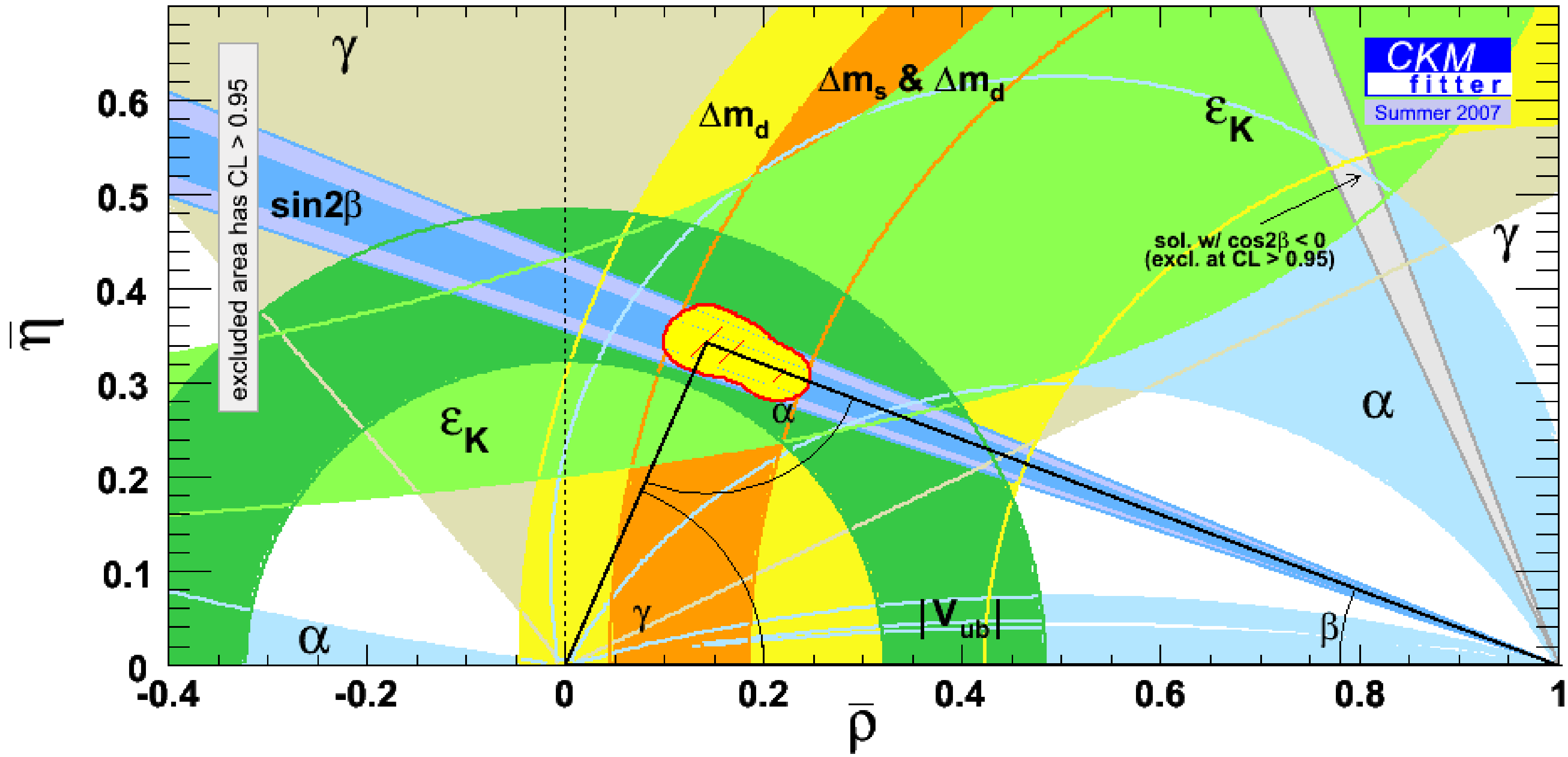
Observation of $\overline{B}^0 \to D^0\pi^0$ and $\overline{B}^0 \to D^{*0}\pi^0$ **9.15 fb^{-1}**

We have studied the color-suppressed hadronic decays of neutral B mesons into the final states $D^{(*)0}\pi^0$. Using 9.67×10^6 $B\overline{B}$ pairs collected with the CLEO detector, we observe the decays $\overline{B}^0 \to D^0\pi^0$ and $\overline{B}^0 \to D^{*0}\pi^0$ with the branching fractions $\mathcal{B}(\overline{B}^0 \to D^0\pi^0) = (2.74^{+0.36}_{-0.32} \pm 0.55) \times 10^{-4}$ and $\mathcal{B}(\overline{B}^0 \to D^{*0}\pi^0) = (2.20^{+0.59}_{-0.52} \pm 0.79) \times 10^{-4}$. The first error is statistical and the second systematic. The statistical significance of the $D^0\pi^0$ signal is 12.1σ (5.9σ for $D^{*0}\pi^0$). Utilizing the $\overline{B}^0 \to D^{(*)0}\pi^0$ branching fractions we determine the strong phases $\delta_{I,D(*)}$ between isospin 1/2 and 3/2 amplitudes in the $D\pi$ and $D^*\pi$ final states to be $\cos\delta_{I,D} = 0.89 \pm 0.08$ and $\cos\delta_{I,D*} = 0.89 \pm 0.08$, respectively.



The full glory of the Cabibbo-Kobayashi-Maskawa framework

We need to see if it <u>all</u> fits: B, B_s, K, penguins, box, trees:



The Success of the CLEO Program as a Scientific Enterprise

- Many experiments have contributed to the huge project of understanding B physics.
  - ALEPH, ARGUS, BaBar, Belle, CDF, CLEO, D0, DELPHI, L3, OPAL, ...
- ARGUS contributed enormously, far more than the relative size of their data sample suggests.
- Still, I believe that CLEO, more than any other experiment, set the standard and created the foundation of this field.
- I would like to express my deep appreciation to Wilson Laboratory and to all the members of the collaboration for making CLEO such a great project to work on!

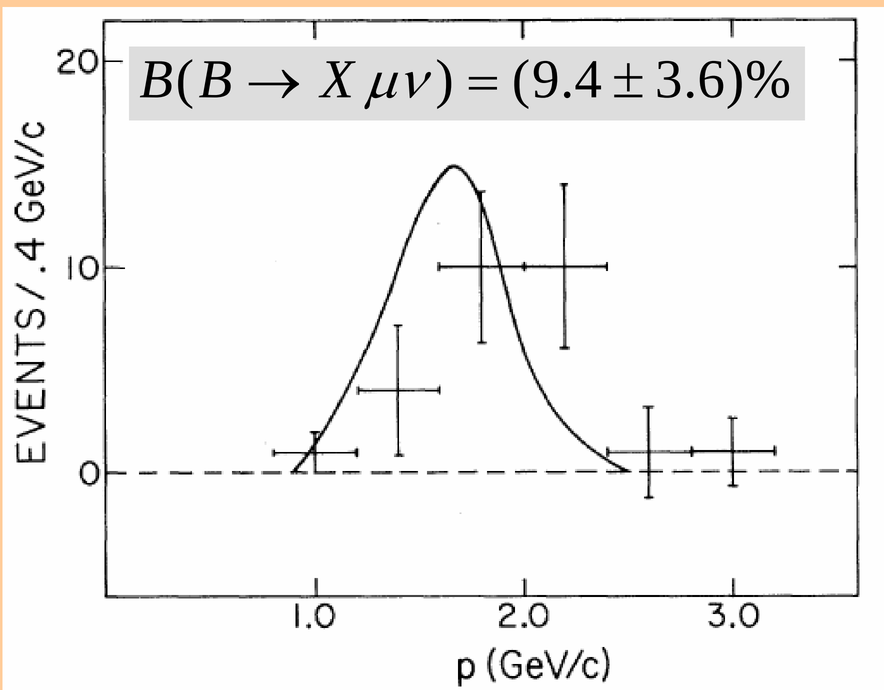
Backup Slides

VOLUME 46, NUMBER 2 PHYSICAL REVIEW LETTERS 12 JANUARY 1981

Decay of *b*-Flavored Hadrons to Single-Muon and Dimuon Final States

An enhancement in the inclusive cross section for single muons produced in e^+e^- annihilation at the $\Upsilon(4S)$ is observed, confirming the interpretation that a new bare flavor (B mesons) is produced at the $\Upsilon(4S)$. A branching ratio for $B \to X\mu\nu$ of $(9.4 \pm 3.6)\%$ is obtained. The two-muon decay, $B \to X\mu^+\mu^-$ is not observed, providing a 90%-confidence-level upper limit for the branching ratio for that decay of 1.7%. Combining this with our previously reported limit of 5% for $B \to Xe^+e^-$, we obtain 1.3% as an upper limit for $B \to Xl^+l^-$.

720 $B\bar{B}$ events



"The nonobservation of *t* quarks has led to the introduction of several models in which the *t* quark does not appear. Some of these models require flavor-changing neutral weak currents..."

Dilepton search:

No $\mu\mu$, including $J/\psi \to \mu^+ \mu^-$

1 μ e , 2 $e^+ e^-$ (1 $J/\psi \to e^+ e^-$)

$B(B \to X\, l^+ l^-) < 1.3\%$ (90% C.L.)

VOLUME 51, NUMBER 5 PHYSICAL REVIEW LETTERS 1 AUGUST 1983

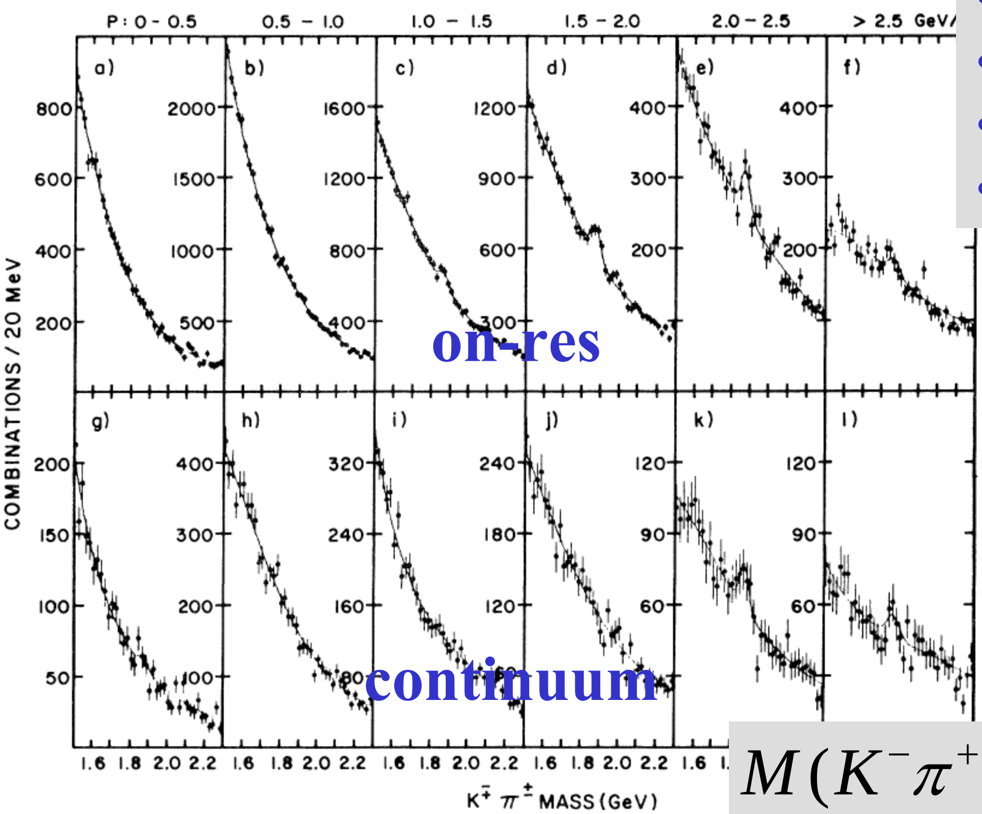
D^0 Spectrum from B-Meson Decay

40.8 pb^{-1} (on res)

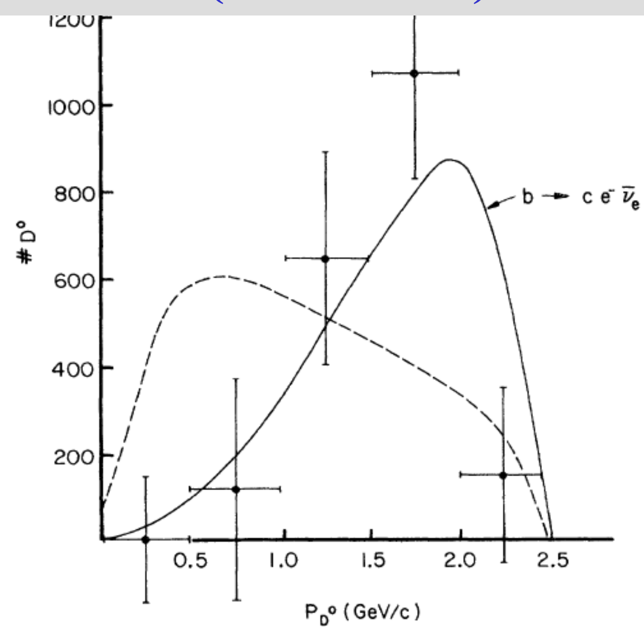
The inclusive branching fraction for B-meson decay into D^0 mesons and the momentum spectrum of the D^0's have been measured. $0.8 \pm 0.2 \pm 0.2$ D^0 per B decay was found. The shape of the spectrum suggests an interesting picture of B-meson decay.

M(K$^-\pi^+$) vs. p

- B(B→D^0*X*) = (0.8+/-0.2 +/- 0.2)
- used B(D^0 →K$^-\pi^+$)=(3.0 +/- 0.6)%
- update to B(D^0→ K$^-\pi^+$)=(3.8+/-0.07)%
- B(B→D^{0}X)=(0.63+/-0.2+/-0.2)
- PDG'06 → (0.64+/-0.03)



$M(K^-\pi^+)$



p_{D^0}

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

yes!

Two-body decays of B mesons

40.6 pb^{-1}

Various exclusive and inclusive decays of B mesons have been studied using data taken with the CLEO detector at the Cornell Electron Storage Ring. The exclusive modes examined are mostly decays into two hadrons. The branching ratio for a B meson to decay into a charmed meson and a charged pion is found to be about 2%. Upper limits are quoted for other final states ψK^-, $\pi^+\pi^-$, $\rho^0\pi^-$, $\mu^+\mu^-$, e^+e^-, and $\mu^\pm e^\mp$. We also give an upper limit on inclusive ψ production and improved charged multiplicity measurements.

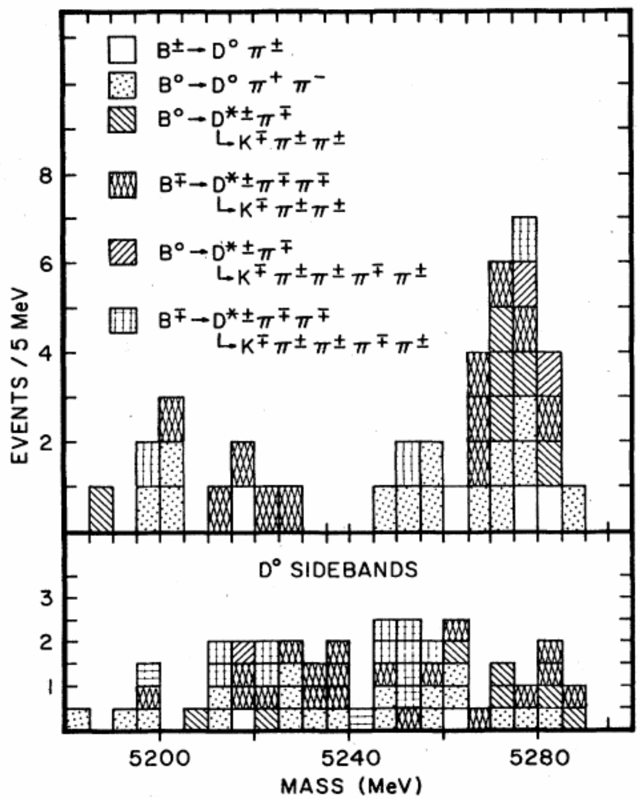


TABLE III. Branching fractions of reconstructed-B-meson channels.

Reaction	Branching fraction (%)
$B^- \to D^0\pi^-$	4.2 ± 4.2[a]
$\bar{B}^0 \to D^0\pi^+\pi^-$	13.0 ± 9.0[b]
$\bar{B}^0 \to D^{*+}\pi^-$	2.6 ± 1.9
$B^- \to D^{*+}\pi^-\pi^-$	4.8 ± 3.0

[a]Includes contribution from $D^{*0}\pi^-$ and $D^{*+}\pi^-$.
[b]Includes contribution from $D^{*0}\pi^+\pi^-$.

TABLE II. B-mesons masses.

Particle	Mass (MeV)
$\langle B \rangle$	$5273.0\pm1.3\pm2.0$
B^-	$5271.2\pm2.2\pm2.0$
$\bar{B}^0$	$5275.2\pm1.9\pm2.0$
$\bar{B}^0 - B^-$	$4.0\pm2.7\pm2.0$

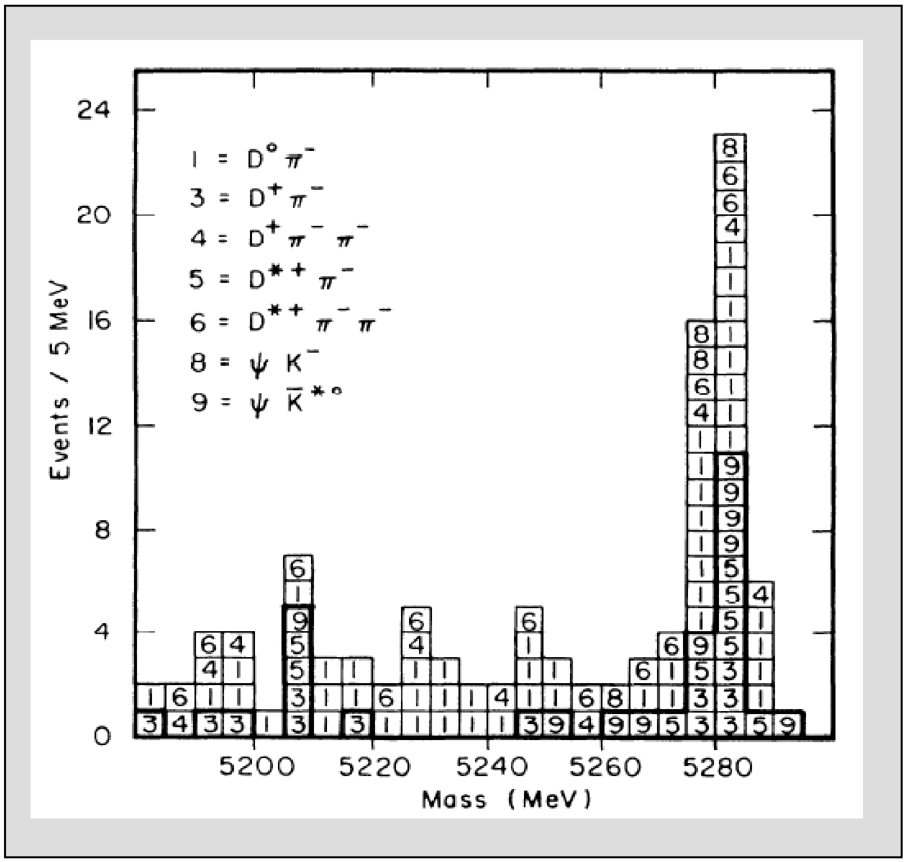
PHYSICAL REVIEW D

PARTICLES AND FIELDS

THIRD SERIES, VOLUME 36, NUMBER 5 — 1 SEPTEMBER 1987

Exclusive decays and masses of the B mesons

78 pb^{-1} (doubled)



$$M(\Upsilon(4S)) - 2M_{\bar{B}^0} = 18.8 \pm 1.7 \pm 2.0 \text{ MeV}$$

and

$$M(\Upsilon(4S)) - 2M_{B^-} = 22.8 \pm 1.7 \pm 2.0 \text{ MeV} .$$

Although the difference between the $\bar{B}^0$ and B^- meson masses is in agreement with our published value,[4] the previous B-mass values are about 6 MeV lower than the present results. Besides the statistical uncertainty, there are two explanations: (1) the CESR single-beam energy calibration used in the run 1 analysis is now known to have been wrong by 2.3 MeV, and (2) the average masses may have been lowered if there was feed-down background included in the earlier analysis. To give credence to this hypothesis, we note that the higher-mass candidates from our previous publications are retained to a greater extent than the lower-mass candidates [especially in mode (6)] by our new analysis procedure, which includes the ΔE requirement and im-

TABLE I. Number of events observed (and the statistical error) or 90%-confidence-level upper limits for various B-decay reactions. B-meson branching fractions (with statistical and systematic errors, respectively) or 90%-confidence-level upper limits. Charge-conjugate modes are assumed to have the same branching fractions.

Reaction	Number of events	Branching fraction (%)
$B^- \to D^0\pi^-$	$14.0^{+4.6}_{-3.9}$	$0.47^{+0.16+0.11}_{-0.13-0.08}$
$\bar{B}^0 \to D^0\pi^+\pi^-$	<10	<3.9[a]
$\bar{B}^0 \to D^+\pi^-$	$4.3^{+2.4}_{-2.1}$	$0.59^{+0.33+0.15}_{-0.29-0.14}$
$B^- \to D^+\pi^-\pi^-$	$1.2^{+2.0}_{-1.1}$	$0.25^{+0.41+0.24}_{-0.23-0.08}$
$\bar{B}^0 \to D^{*+}\pi^-$	$5.3^{+2.8}_{-2.2}$	$0.31^{+0.17+0.11}_{-0.13-0.07}$
$B^- \to D^{*+}\pi^-\pi^-$	$2.7^{+1.9}_{-1.7}$	$0.20^{+0.14+0.08}_{-0.13-0.05}$
$\bar{B}^0 \to D^{*+}\pi^+\pi^-\pi^-$	<15	<4.6[a]
$B^- \to D^{*0}\pi^-$	See text	0.27 ± 0.44[b]
$B^- \to \psi K^-$	3.0 ± 1.7	$0.09\pm0.06\pm0.02$
$\bar{B}^0 \to \psi \bar{K}^{*0}$	5.0 ± 2.2	$0.41\pm0.19\pm0.03$
$B^- \to \pi^0\pi^-$	<188	<0.23[c]
$\bar{B}^0 \to \rho^\pm\pi^\mp$	<376	<0.61[c,d]
$\bar{B}^0 \to \pi^+\pi^-$	<8	<0.03
$B^- \to \rho^0\pi^-$	<2	<0.02
$\bar{B}^0 \to \rho^0\rho^0$	<9	<0.05
$\bar{B}^0 \to \pi^\pm a_1(1270)^\mp$	<7	<0.12[d]
$\bar{B}^0 \to \pi^\pm a_2(1320)^\mp$	<4	<0.16[d]
$B^- \to \rho^0 a_1(1270)^-$	<52	<0.32
$B^- \to \rho^0 a_2(1320)^-$	<21	<0.23
$\bar{B}^0 \to p\bar{p}$	<6	<0.02

still < 15 events in each mode

[a]The 90%-confidence-level upper limits on the number of events and branching ratio for this mode are calculated (conservatively) without subtracting any background.
[b]This branching ratio is inferred in Sec. V.
[c]The upper limit for this decay mode is obtained from analysis of the charged-particle momentum spectrum (Sec. V).
[d]The notation $\bar{B}^0 \to x^\pm y^\mp$ means that the limit quoted is for the sum of the branching ratios for $\bar{B}^0 \to x^+y^-$ and $\bar{B}^0 \to x^-y^+$.

Time-integrated mixing probabilities

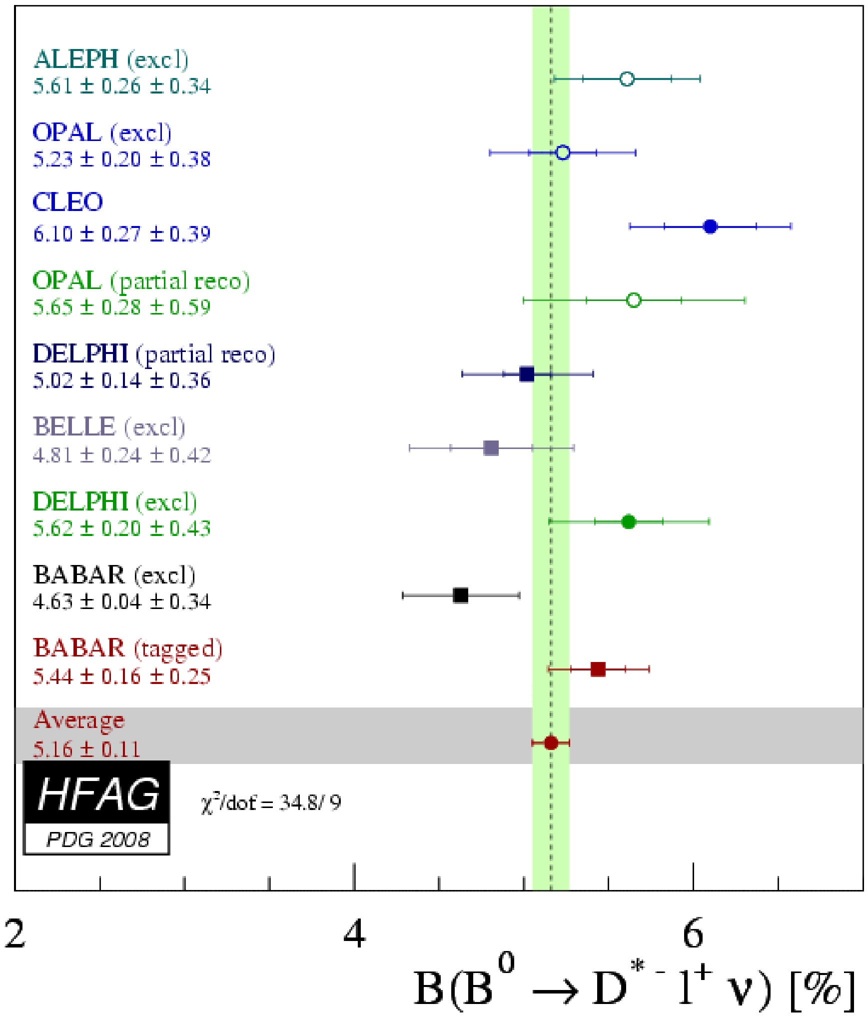
$B^0\bar{B}^0$ oscillations were measured without explicitly measuring the time dependence. How was the mixing rate inferred?

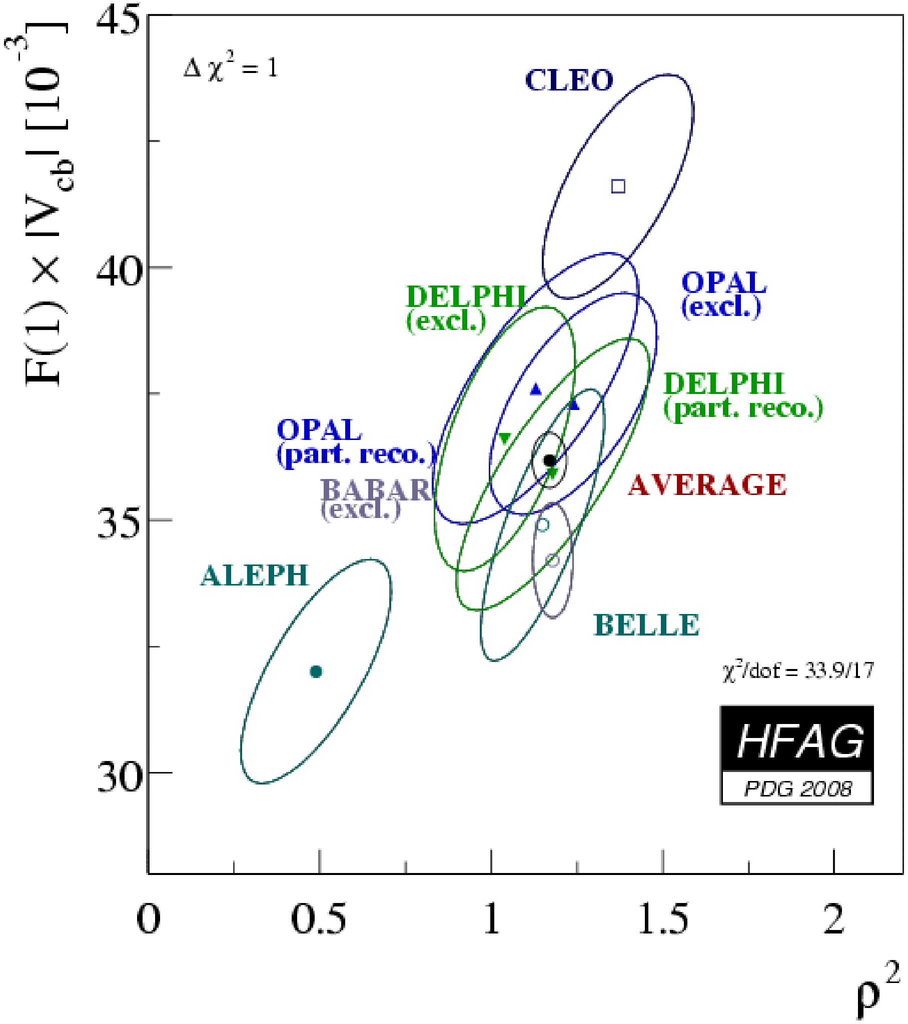
$$\chi = \frac{\int_0^\infty P_{B^0\to\bar{B}^0}(t)dt}{\int_0^\infty P_{B^0\to\bar{B}^0}(t)dt + \int_0^\infty P_{B^0\to B^0}(t)dt} = \frac{\left(\frac{\Delta M}{\Gamma}\right)^2}{2\left[1+\left(\frac{\Delta M}{\Gamma}\right)^2\right]}$$

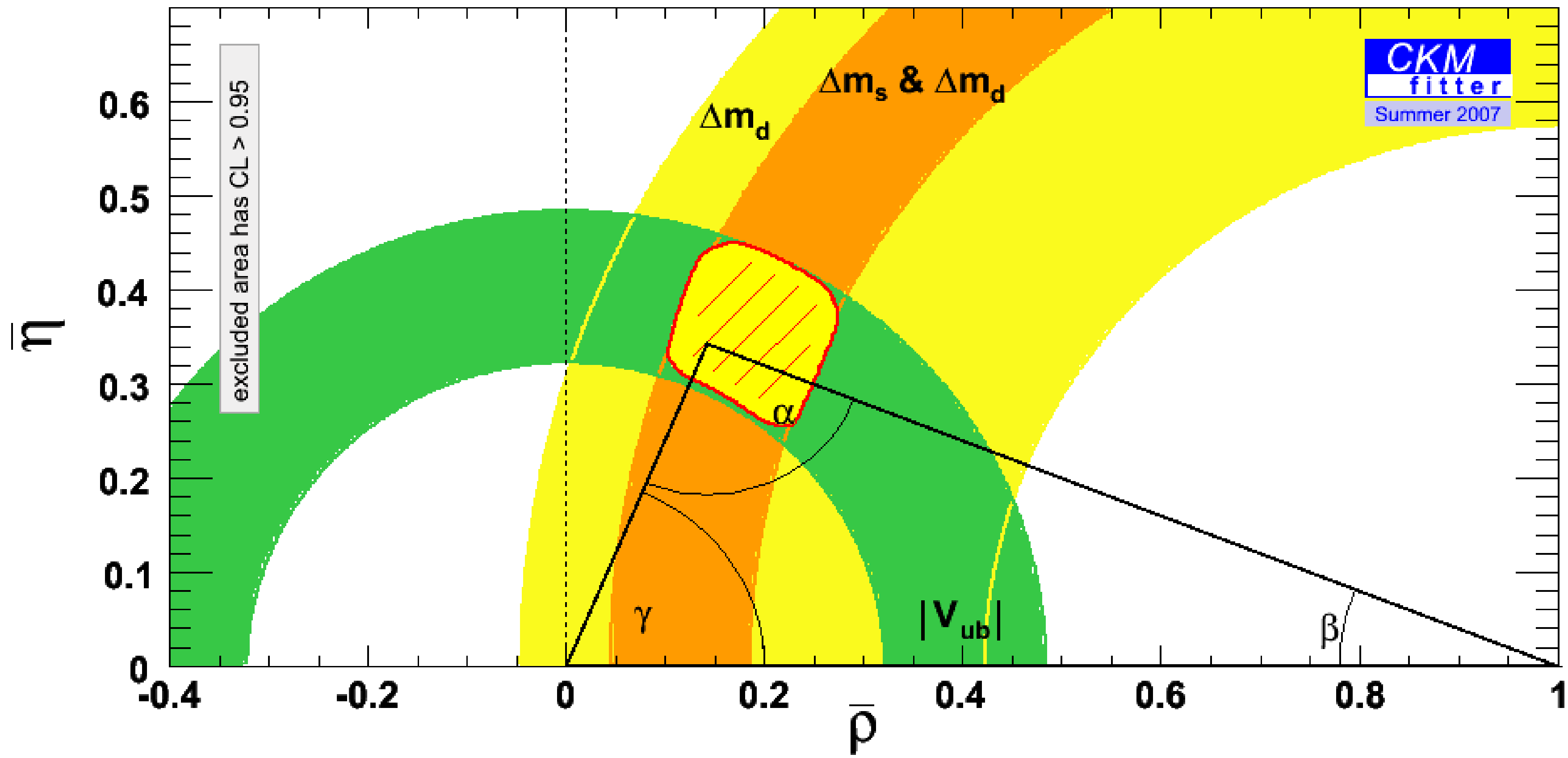
B_d system: $\frac{\Delta M_d}{\Gamma_d} = \left(0.51\ \text{ps}^{-1}\right)\left(1.53\ \text{ps}\right) \simeq 0.8 \quad \Leftrightarrow \quad \chi_d \simeq 0.2$

B_s system: $\frac{\Delta M_s}{\Gamma_s} > \left(14.5\ \text{ps}^{-1}\right)\left(1.48\ \text{ps}\right) \simeq 21.5 \quad \Leftrightarrow \quad \chi_s \simeq 0.5$

Measurements from $B \rightarrow D^{*+} l \nu$: HFAG Averages







CKM fitter
Summer 2007
excluded area has CL > 0.95
Δm_s & Δm_d
Δm_d
|V_ub|
α
β
γ
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

γ (Dalitz plot): $B^- \to [\, D^0 \to K_s\, \pi^+ \pi^- ;\ \bar{D}^0 \to K_s\, \pi^+ \pi^- \,] K^-$,

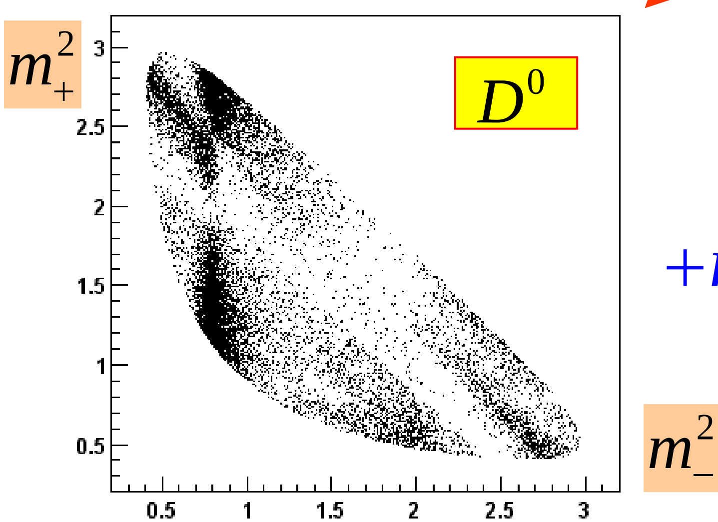
$m_\pm^2 \equiv m^2(K_S^0 \pi^\pm)^2$

Giri, Grossman, Soffer, & Zupan, PRD 68, 054018 (2003),
Bondar (Belle), PRD 70, 072003 (2004)

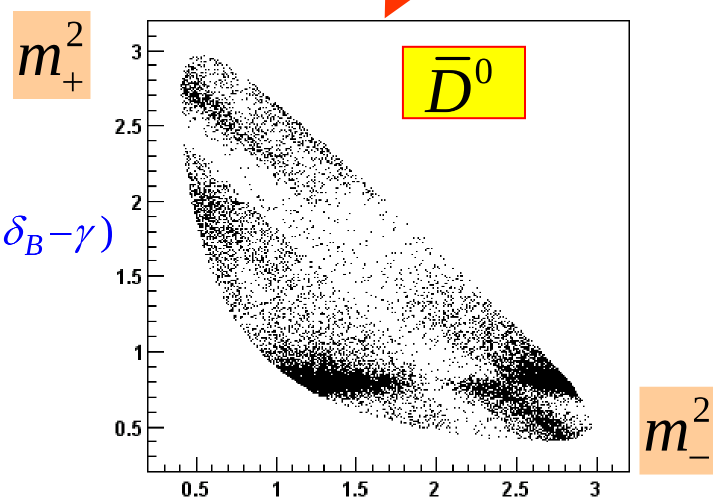
$$B^- \qquad M_-(m_-^2, m_+^2) = \left| A(B^- \to D^0 K^-) \right| \left[f(m_-^2, m_+^2) + r_B e^{i\delta_B} e^{-i\gamma} f(m_+^2, m_-^2) \right]$$

$$B^+ \qquad M_+(m_-^2, m_+^2) = \left| A(B^+ \to \bar{D}^0 K^+) \right| \left[f(m_+^2, m_-^2) + r_B e^{i\delta_B} e^{+i\gamma} f(m_-^2, m_+^2) \right]$$

$|M_-|^2 = \Bigg|$



$+ r_B e^{i(\delta_B - \gamma)}$



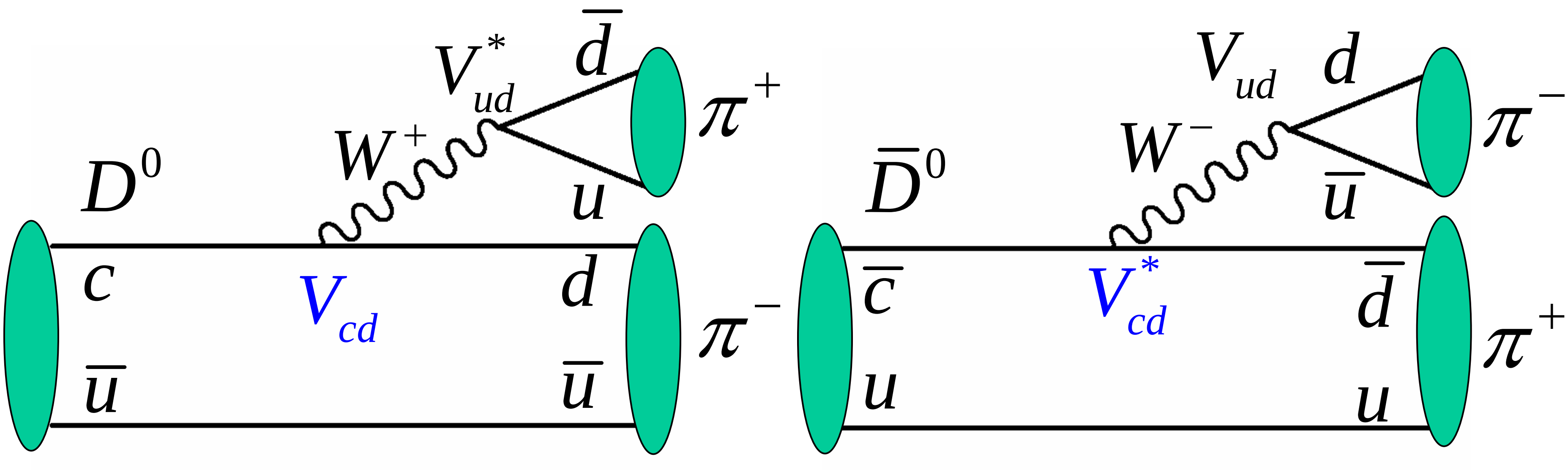
$\Bigg|^2$

Relatively large BFs; all charged tracks; only 2-fold γ ambiguity.

Interference depends on Dalitz region: $f = K_S^0 \rho^0$ (CP), $f = K^{*-} \pi^+$ (DCSD)

γ (GLW method): $B^- \to D_{CP} K^-$, $D_{CP} \to f_{CP}$

D^0 ($\bar{D}^0$) $\to f_{CP}$ = CP eigenstate from singly-Cabibbo-suppressed decay.
[Gronau & London, PLB 253, 483 (1991), Gronau & Wyler, PLB 265, 172 (1991)].



$CP = +1 \quad \pi^+\pi^-, K^+K^-$

$CP = -1 \quad K_S^0\pi^0, K_S^0\phi, K_S^0\omega, K_S^0\eta, K_S^0\eta'$

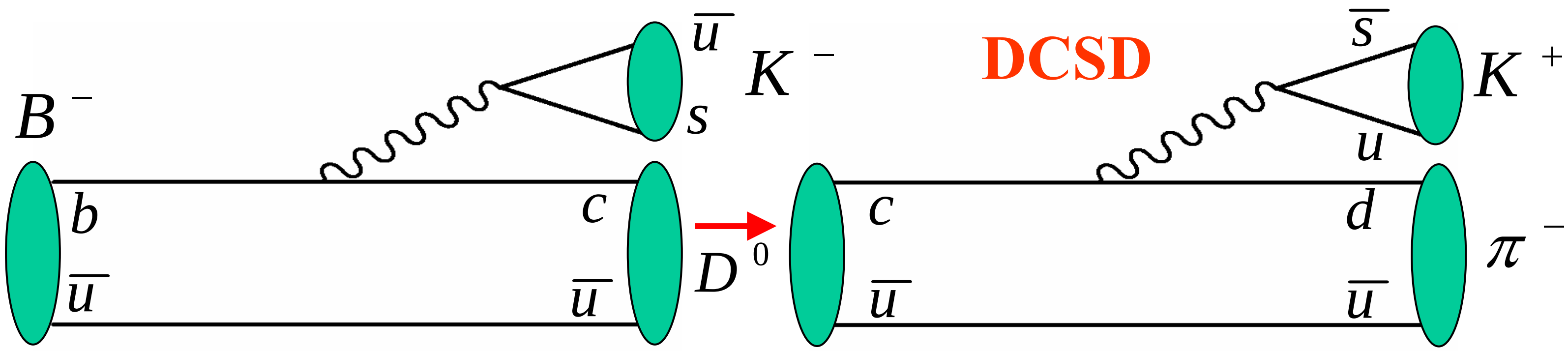
$$Amp\left(B^\pm, CP_{D^0} = \eta_D\right) \propto A_B\left[1 + \eta_D r_B e^{i(\delta_B \pm \gamma)}\right]$$

Large rate, but <u>interference is small</u>: $r_B << 1$

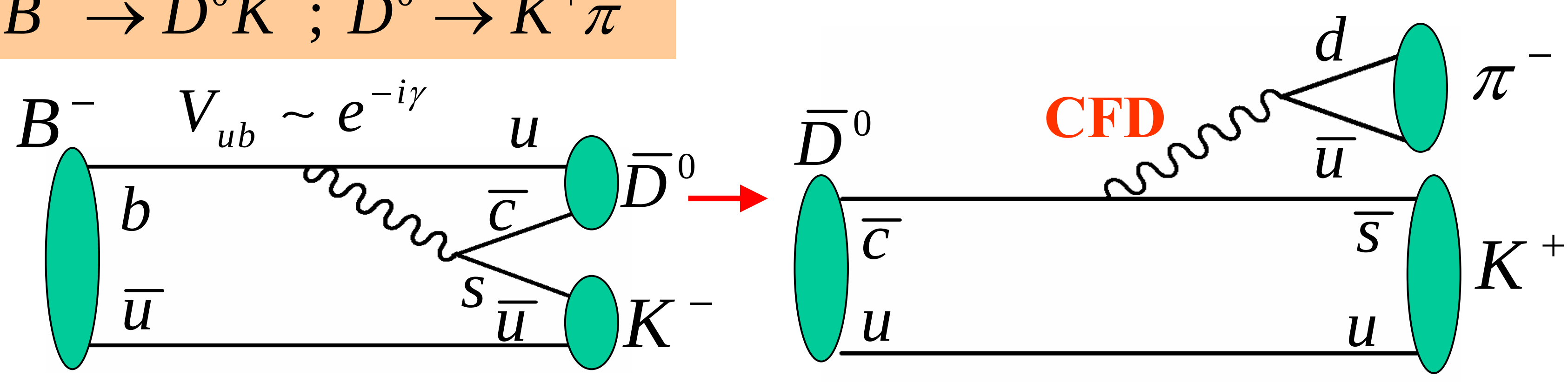
γ (ADS method): $B^- \rightarrow [\, D^0 \rightarrow K^+\pi^-;\ \bar{D}^0 \rightarrow K^+\pi^-]K^-$

Atwood, Dunietz, & Soni, PRL 78, 3257 (1997), PRD 63, 036005 (2001)

$$B^- \rightarrow D^0 K^-;\ D^0 \rightarrow K^+\pi^-$$



$$B^- \rightarrow \bar{D}^0 K^-;\ \bar{D}^0 \rightarrow K^+\pi^-$$



$$A\left(B^\pm, D \rightarrow K^\pm\pi^\mp\right) = A_B A_D \left[r_D e^{i\delta_D} + r_B e^{i(\delta_B \pm \gamma)} \right]$$

Interference is large: r_B, r_D comparable, but overall rate is small!

Extracting $|V_{td}/V_{ts}|$ from $b \rightarrow d\,\gamma$ Decays

Belle, PRL 96, 221601 (2006).

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.199^{+0.026}_{-0.025}{}^{+0.018}_{-0.015}$$

expt thy

BABAR, hep-ex/0607099 (preliminary)

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.171^{+0.018}_{-0.021}{}^{+0.017}_{-0.014}$$

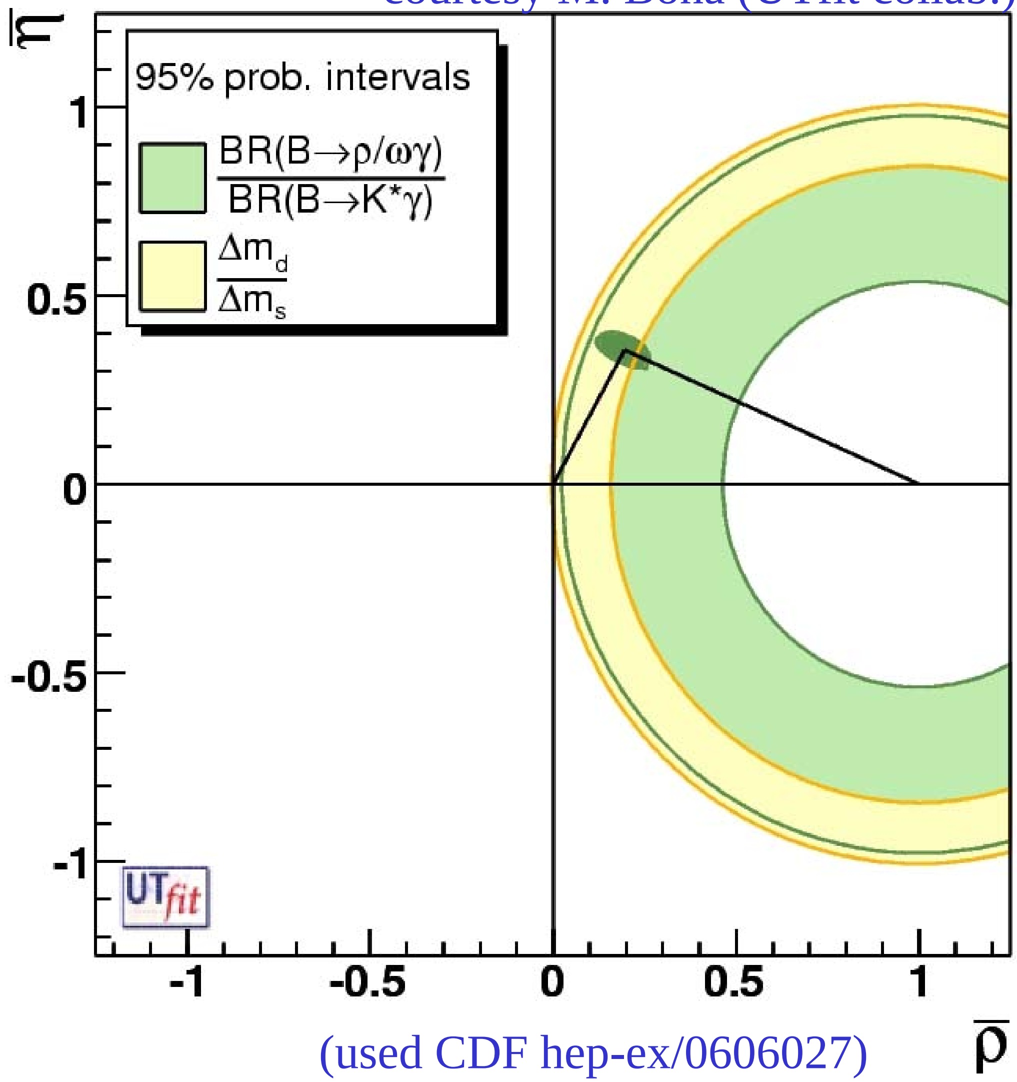
expt thy

CDF, hep-ex/0609040 (preliminary)

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2060 \pm 0.0007^{+0.0081}_{-0.0060}$$

expt thy

courtesy M. Bona (UTfit collab.)



(used CDF hep-ex/0606027)

Consistent within errors!

Theoretical uncertainties already or soon limiting both approaches.

Amplitude for $B \rightarrow K^* l^+ l^-$

$$M(B \to K^* \ell^+ \ell^-) = \frac{G_F \alpha_{EM}}{\sqrt{2\pi}} V_{ts}^* V_{tb} \left\{ \left[C_9^{eff} \left\langle K^* \middle| \bar{s}\gamma_\mu P_L b \middle| B \right\rangle \right. \right.$$

photon penguin dom. at v. low q^2

$$\left. -2\frac{m_b}{q^2} C_7^{eff} \left\langle K^* \middle| \bar{s} i \sigma_{\mu\nu} q^\nu P_R b \middle| B \right\rangle \right] \left(\bar{\ell} \gamma^\mu \ell \right)$$

mix of Z-penguin, W^+W^- box

$$\left. + C_{10} \left\langle K^* \middle| \bar{s}\gamma_\mu P_L b \middle| B \right\rangle \left(\bar{\ell} \gamma^\mu \gamma_5 \ell \right) \right\}$$

Kruger and Matias; PRD 71, 094009 (2005)

Short-distance physics encoded in C_i's (Wilson coefficients); calculated at NNLO in SM:

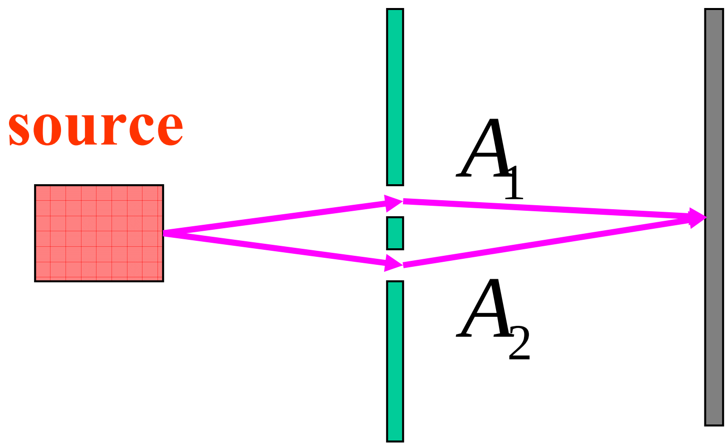
$$C_7^{eff} \simeq -0.3 \quad C_9 \simeq +4.3 \quad C_{10} \simeq -4.7$$

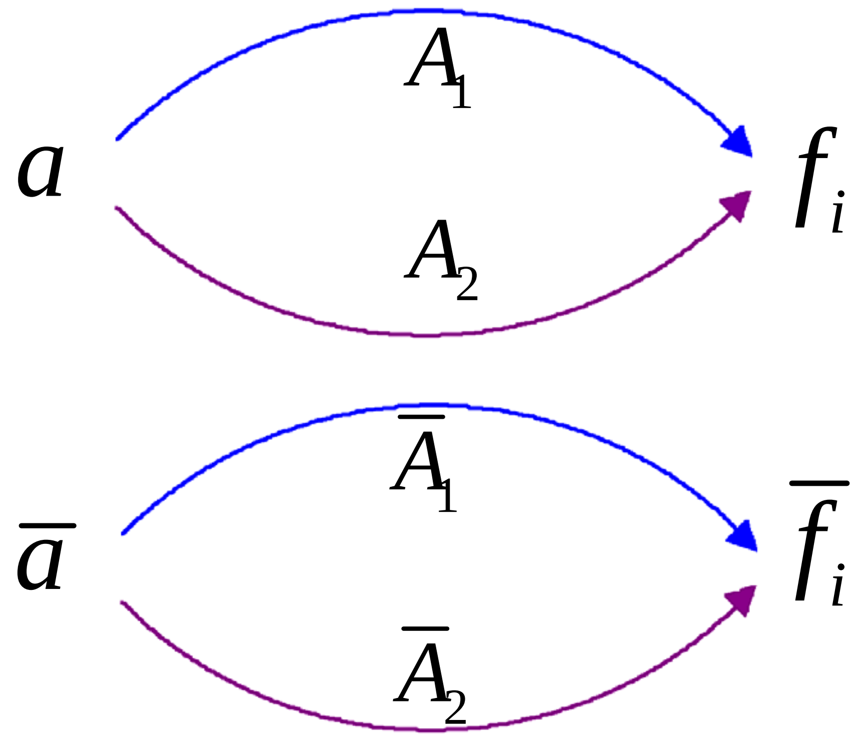
Ali *et al.*, PRD 61, 074024 (2000)

- Interference terms generate asymmetries in lepton angular distribution over most of q^2 range.
- C_i's can be affected by new physics; enters at same order as SM amp.

How are CP violating asymmetries produced?

The Standard Model predicts that, if CP violation occurs, it must occur through specific kinds of <u>quantum interference effects</u>..





Double-slit experiment: if the final state does not distinguish between the paths, then the amplitudes A_1 and A_2 interfere!

Three Kinds of *CP* Violation

We have seen that CP violation arises as an <u>interference effect</u>.

- Need at least two interfering amplitudes
- Need relative CP-violating phase
- Need relative CP-conserving phase

A single CP-violating amplitude will not produce observable CP violation!

<u>**Classification of CP-violating effects in particle transitions**</u>

(based on the sources of amplitudes that are present).

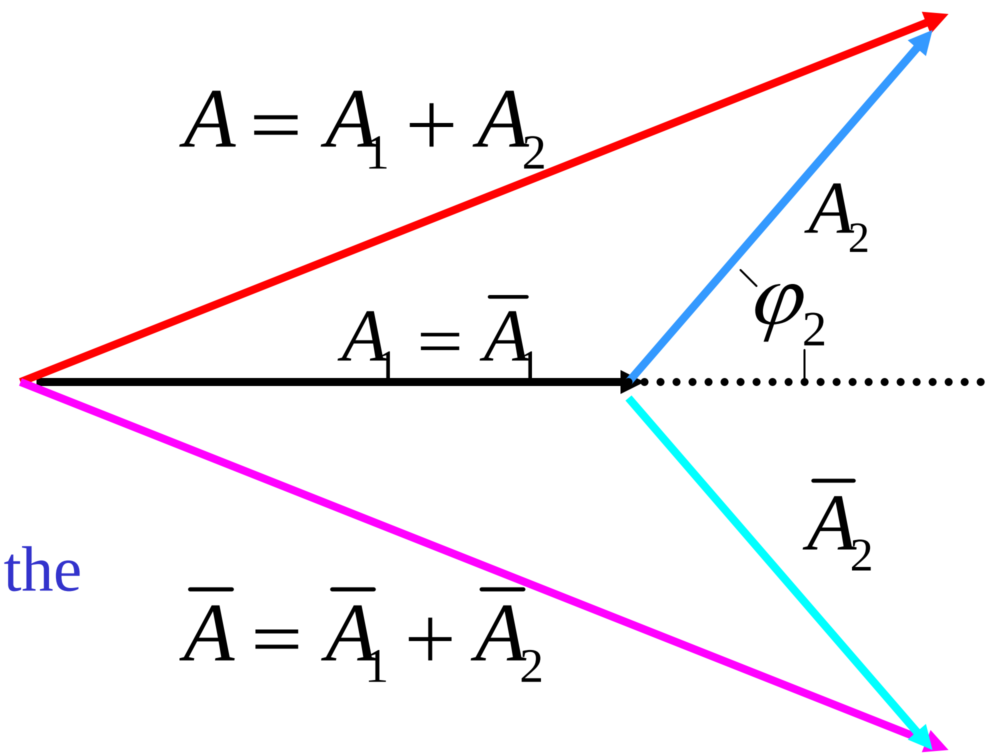
1. CP violation in oscillations (“indirect CP violation”)
2. CP violation in decay   (“direct CP violation”)
3. CP violation in the interference between mixing and decay

Two amplitudes with a CP-violating relative phase

- Suppose a decay can occur through two processes, with amplitudes A_1 and A_2. Let A_2 have a CP-violating phase ϕ_2.

$$A = A_1 + a_2 e^{i\varphi_2}$$

$$\bar{A} = A_1 + a_2 e^{-i\varphi_2}$$



No CP asymmetry!
(But the decay rate is different from what it would be without the phase.)

Two amplitudes with CP-conserving & CP-violating phases

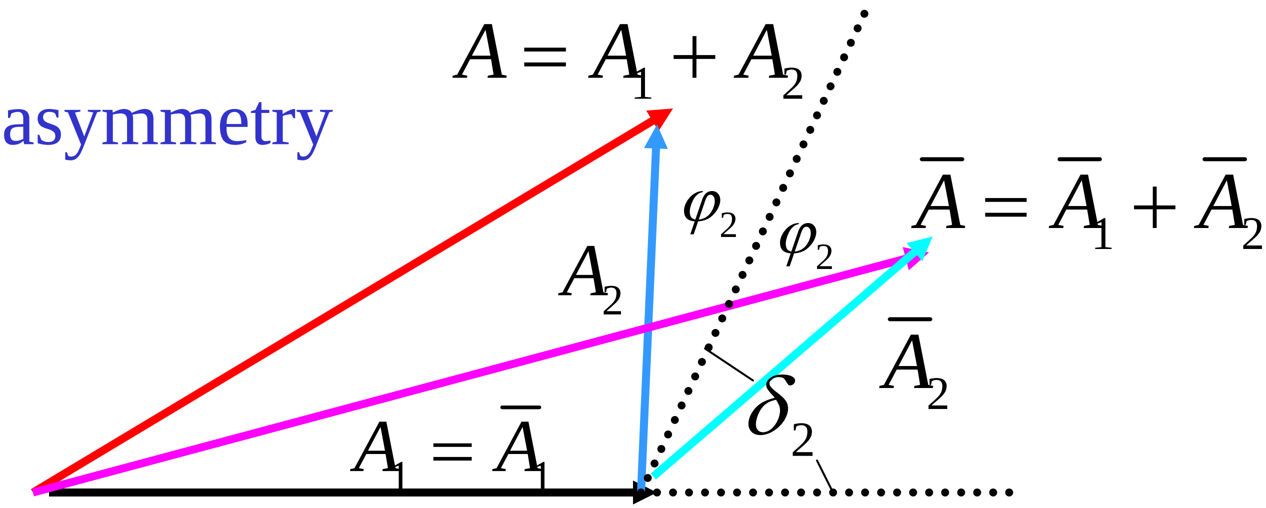
- Next, introduce a *CP-conserving* phase in addition to the *CP-violating* phase.

$$A = A_1 + a_2 e^{i(\varphi_2 + \delta_2)}$$

$$\bar{A} = A_1 + a_2 e^{i(-\varphi_2 + \delta_2)}$$

- Now have a CP asymmetry

$$|A| \neq |\bar{A}|$$



Amplitude analysis for direct CP violation

$$A = |A_1| e^{i(\varphi_1 + \delta_1)} + |A_2| e^{i(\varphi_2 + \delta_2)}$$

$$\bar{A} = (|A_1| e^{i(-\varphi_1 + \delta_1)} + |A_2| e^{i(-\varphi_2 + \delta_2)}) e^{-i[\theta(P) - \theta(f)]}$$

$$\text{Asymmetry} = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{2\sin(\varphi_1 - \varphi_2)\sin(\delta_1 - \delta_2)}{\left|\frac{A_2}{A_1}\right|^2 + \left|\frac{A_2}{A_1}\right|^2 + 2\cos(\varphi_1 - \varphi_2)\cos(\delta_1 - \delta_2)}$$

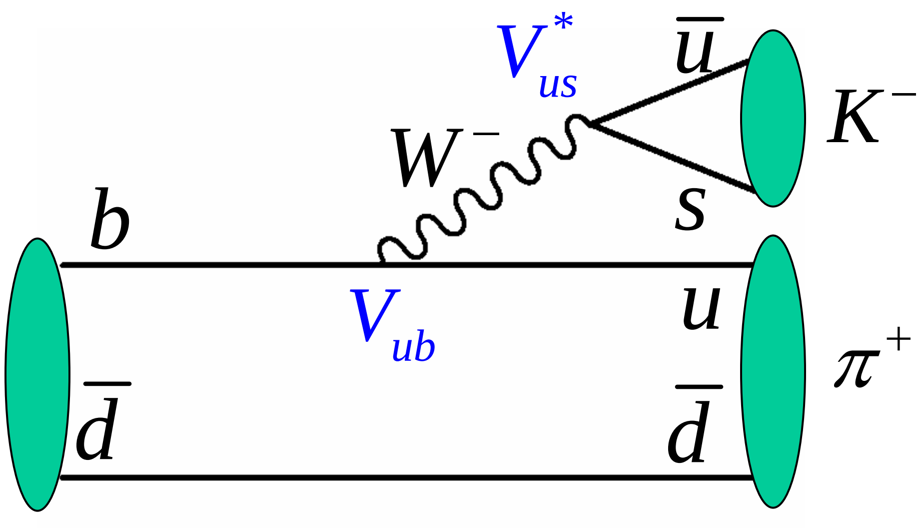
Problems with interpreting measurements of direct CP asymmetries:

1. we often don't know the difference δ_1-δ_2 , so we cannot extract ϕ_1-ϕ_2 from the asymmetry.
2. we often don't know the relative magnitude of the interfering amps.

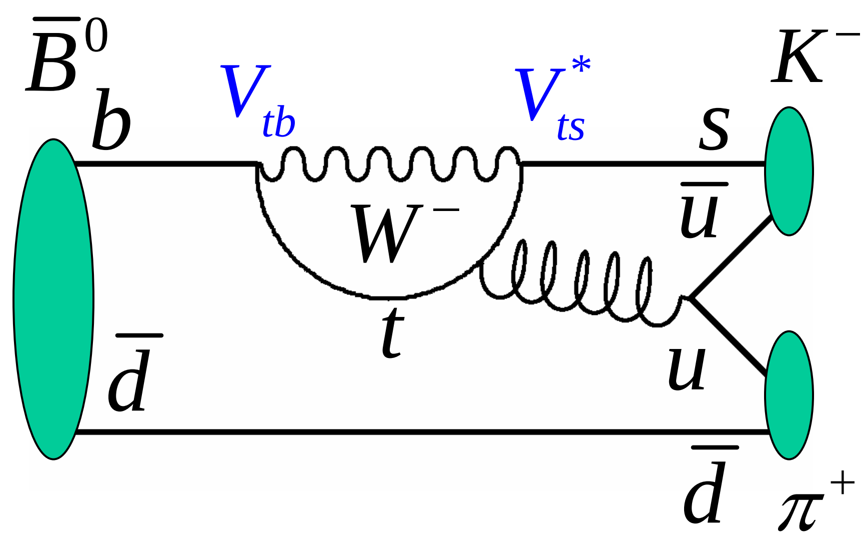
Direct CP violation in $B \rightarrow K^{-}\pi^{+}$

Interference between tree and penguin amplitudes produces a CP asymmetry in $B \rightarrow K^{-}\pi^{+}$. Both processes are suppressed!

External spectator



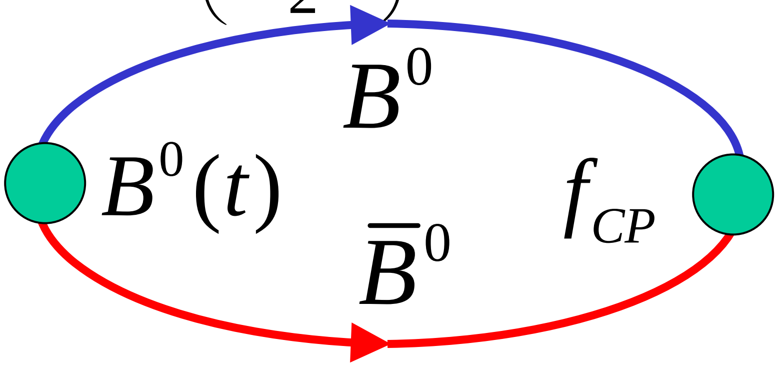
Gluonic penguin



In our Wolfenstein convention, the CP-violating phase factor comes from $V_{ub} \propto e^{-i\gamma}$.

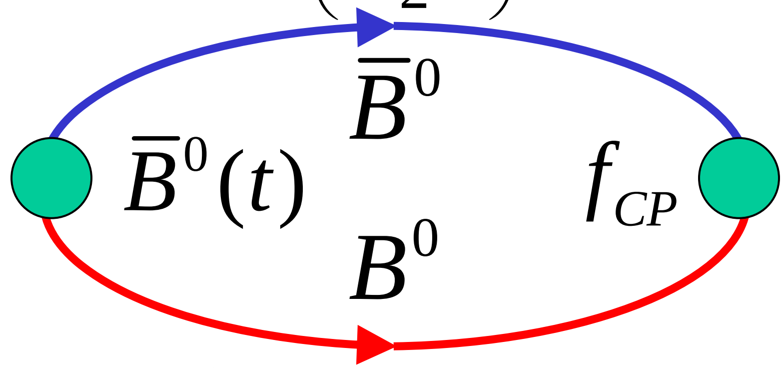
How the magic works

$$\cos\left(\frac{\Delta m\cdot t}{2}\right)\cdot|a|e^{i(\delta+\phi_D)}$$



$$-i\cdot\eta_{CP}(f)\sin\left(\frac{\Delta m\cdot t}{2}\right)\cdot|a|e^{i(\delta-\phi_D)}e^{2i\phi_M}$$

$$\eta_{CP}(f)\cdot\cos\left(\frac{\Delta m\cdot t}{2}\right)\cdot|a|e^{i(\delta-\phi_D)}$$



$$-i\cdot\sin\left(\frac{\Delta m\cdot t}{2}\right)\cdot|a|e^{i(\delta+\phi_D)}e^{-2i\phi_M}$$

$$\mathrm{Amp}(B^0\to f_{CP})$$

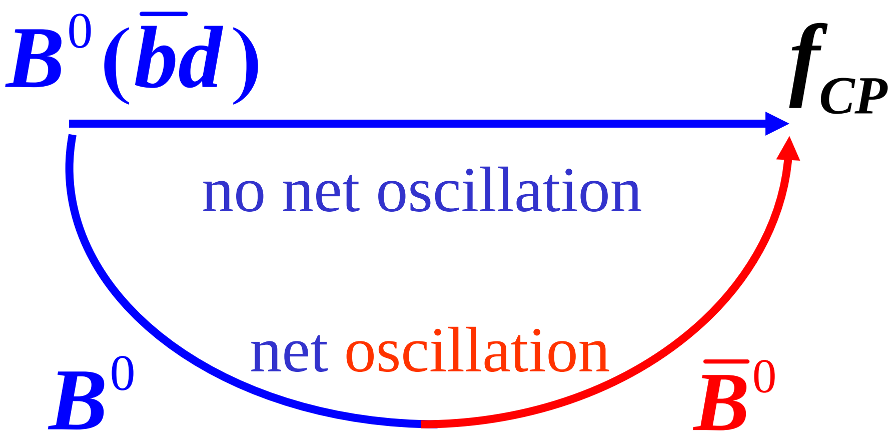
$$\mathrm{Amp}(\overline{B}^0(t)\to f_{CP})$$

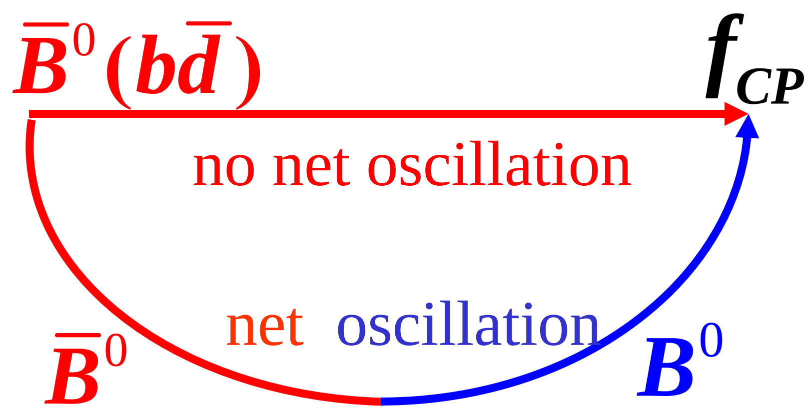
In each case, the two interfering amplitudes have the same CP conserving phase from strong interactions, so it is irrelevant.

$$A(t)=\mathrm{Im}(\lambda)\cdot\sin(\Delta m\cdot t)$$

Time-dependent CP asymmetries from the interference between mixing and decay amplitudes

By modifying the mixing measurement, we can observe whole new class of CP-violating phenomena: pick final states that both B^0 and $\bar{B}^0$ can decay into. (Often a CP eigenstate, but doesn't have to be.)



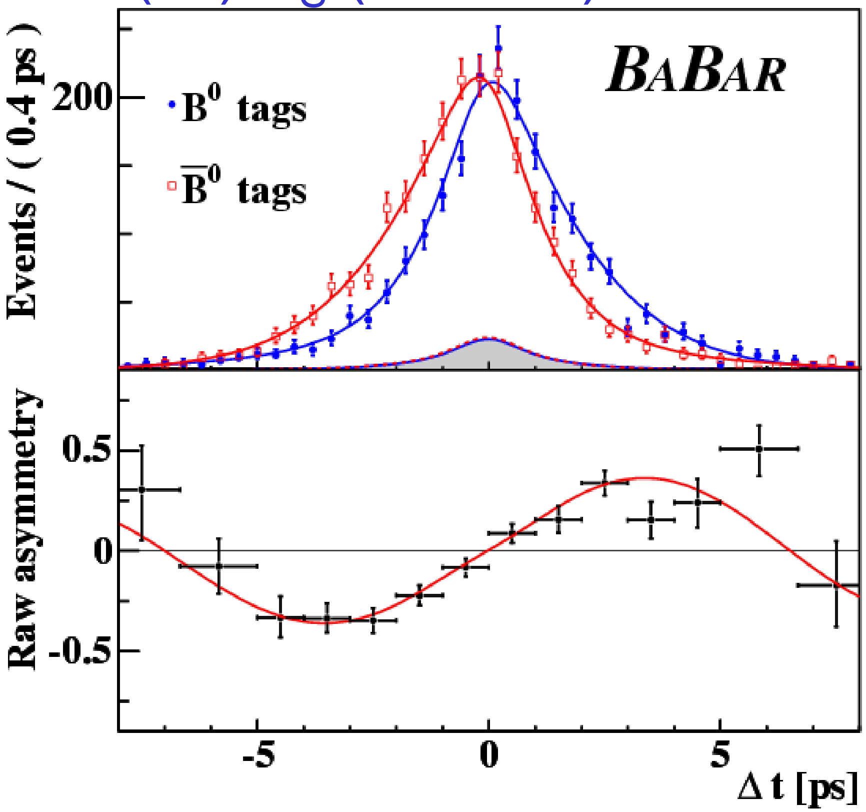


$$\Gamma(B^0_{phys}(t) \to f_{CP})$$

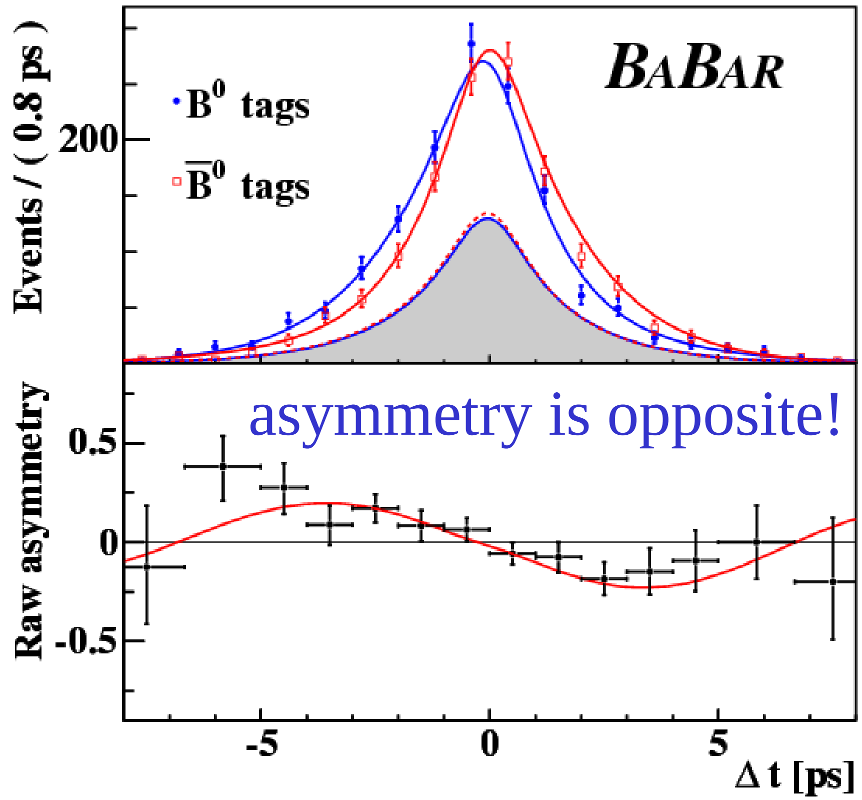
$$\Gamma(\bar{B}^0_{phys}(t) \to f_{CP})$$

Results on sin2β from charmonium modes

$(c\bar{c})\ K_S$ (CP odd) modes



$J/\psi\ K_L$ (CP even) mode



$\sin 2\beta = 0.722 \pm 0.040\ (\text{stat}) \pm 0.023\ (\text{sys})$

$|\lambda| = 0.950$ +/- 0.031 (stat) +/- 0.013 (sys)

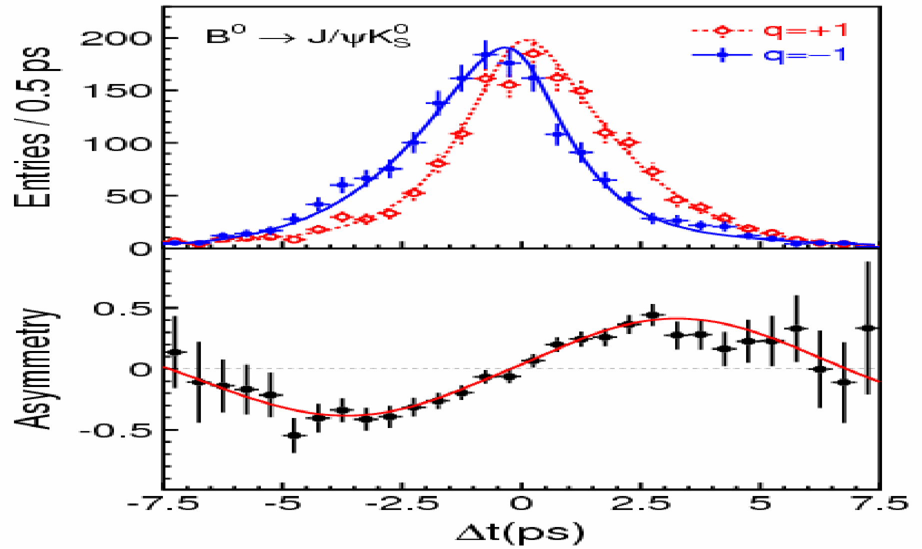
227 M $B\bar{B}$ events

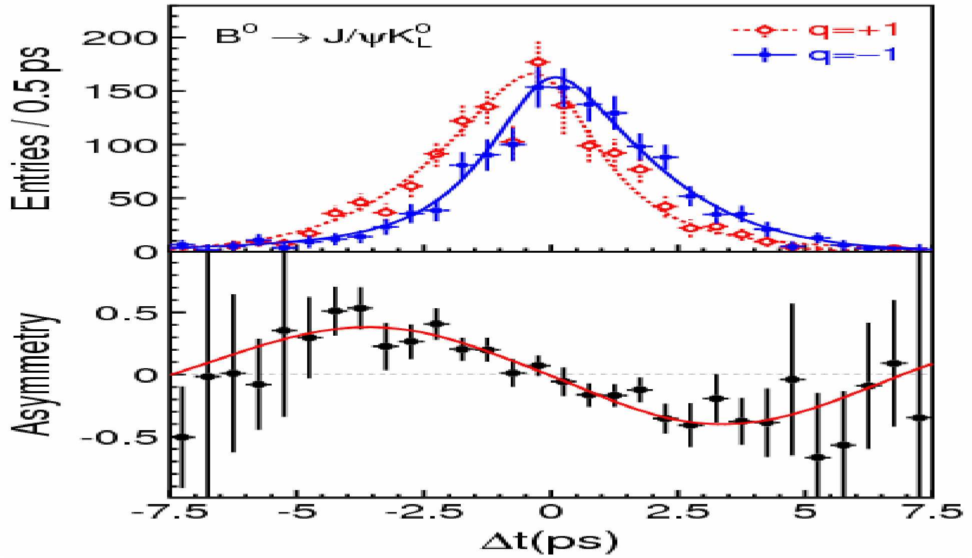
(raw asymmetry shown above must be corrected for the dilution) from Steve Olsen talk at Aspen Winter Conference, 2008

ϕ_1 from the "golden" b→cc̄s mode

$535 M B\overline{B}$

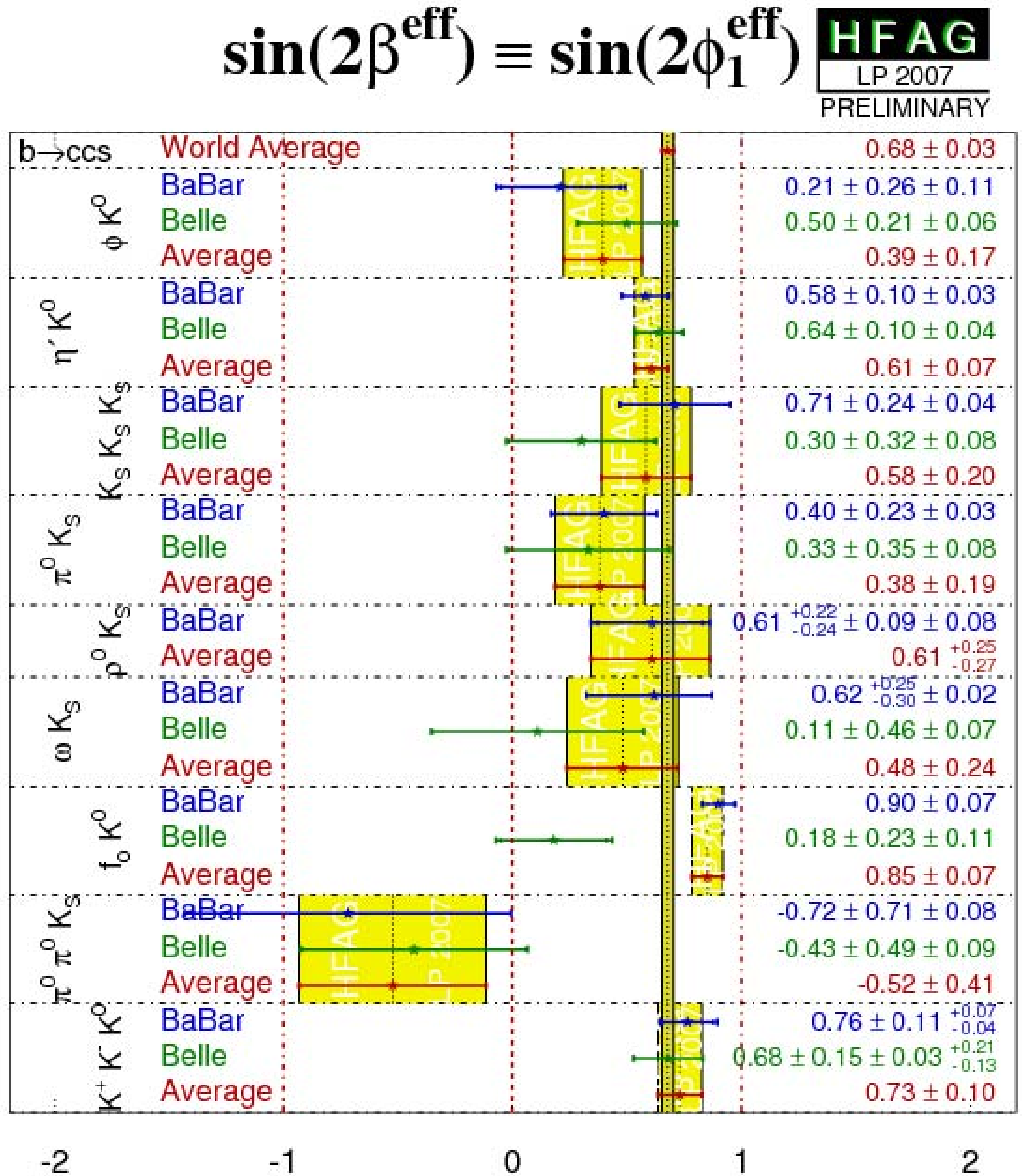
PRL 98, 031802 (2007)





$$S = 0.642 \pm 0.031 \pm 0.017$$

$$C = 0.018 \pm 0.021 \pm 0.014$$


sin(2β^eff) ≡ sin(2φ1^eff)
HFAG
LP 2007
PRELIMINARY
b→ccs World Average 0.68 ± 0.03
φ K0
BaBar 0.21 ± 0.26 ± 0.11
Belle 0.50 ± 0.21 ± 0.06
Average 0.39 ± 0.17
η′ K0
BaBar 0.58 ± 0.10 ± 0.03
Belle 0.64 ± 0.10 ± 0.04
Average 0.61 ± 0.07
KS KS KS
BaBar 0.71 ± 0.24 ± 0.04
Belle 0.30 ± 0.32 ± 0.08
Average 0.58 ± 0.20
π0 KS
BaBar 0.40 ± 0.23 ± 0.03
Belle 0.33 ± 0.35 ± 0.08
Average 0.38 ± 0.19
ρ0 KS
BaBar 0.61 +0.22 -0.24 ± 0.09 ± 0.08
Average 0.61 +0.25 -0.27
ω KS
BaBar 0.62 +0.25 -0.30 ± 0.02
Belle 0.11 ± 0.46 ± 0.07
Average 0.48 ± 0.24
f0 K0
BaBar 0.90 ± 0.07
Belle 0.18 ± 0.23 ± 0.11
Average 0.85 ± 0.07
π0 π0 KS
BaBar -0.72 ± 0.71 ± 0.08
Belle -0.43 ± 0.49 ± 0.09
Average -0.52 ± 0.41
K+ K- K0
BaBar 0.76 ± 0.11 +0.07 -0.04
Belle 0.68 ± 0.15 ± 0.03 +0.21 -0.13
Average 0.73 ± 0.10
-2
-1
0
1
2