New Results on Flavor Physics

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EPS HEP 2001, Budapest, July 17

- Introduction

  ... Goal: precision tests of the Standard Model flavor structure
- Semileptonic and rare decays

  ... Determination of $|V_{ub}|$ and $|V_{cb}|$; $B \to K^{(*)}\ell^+\ell^-$ and $B \to K^*\gamma$
- Nonleptonic decays

  ... Factorization in $b \to c$ decay; b lifetimes; $D^0 - \bar{D}^0$ mixing
- Conclusions

Thanks to: A. Falk, M. Luke, H. Quinn, M. Wise

Three talks on flavor physics & CP violation

ZL

- Semileptonic decays
  $|V_{ub}|$ and $|V_{cb}|$
- Exclusive rare decays:
  $B \to K^{(*)}\ell^+\ell^-$,
  $B \to K^*\gamma$
- Nonleptonic decays
  and factorization tests
  in $b \to c$ decay
- (b hadron lifetimes)
- $D^0 - \bar{D}^0$ mixing

Hamel de Monchenault

- B factories
- CPV in mixing
- CPV in interference:
  $\sin 2\beta$ measurement
  B_d mixing & lifetime
- CPV in decay: direct
  CPV measurements
  $K\pi$, $\pi\pi$; $\psi K^{\pm}$; $K^*\gamma$
- Expt. prospects for
  CPV in B system

Beneke

- CPV in kaon decays
- Unitarity triangle
  determination
- Interpretation of $\sin 2\beta$
  measurement
- CPV in B decays:
  strategies for angles,
    bounds on γ
  QCD factorization
    results for $\pi\pi/K\pi$
- CPV in extensions of
  the standard model

Introduction

(Full refs if published starting Y2K, Speakers somewhat larger fonts)

Dictionary: CPV $= CP$ violation

SM $=$ standard model

NP $=$ new physics

Central questions about SM

1. Origin of electroweak symmetry breaking:

   spontaneous breaking of a gauge symmetry by $v \sim 250\,$GeV VEV

   $W_L W_L \to W_L W_L$ breaks unitarity ~TeV ... we know where to look

2. Origin of flavor symmetry breaking:

   global symmetries broken by renormalizable interactions

   ... we do not know what scale to look

Flavor and electroweak symmetry breaking may or may not be connected

However, flavor physics depends on both — the Yukawa couplings determine quark masses, mixing, and CP violation

The flavor sector is a major constraint / problem for model building

Why flavor physics?

Bits of history: $K\bar{K}$ mixing $\Rightarrow$ GIM & charm
CP violation $\Rightarrow$ three generations, CKM
$B\bar{B}$ mixing $\Rightarrow$ heavy top

The B meson system:

- Intermediate top quark in loop diagrams is neither GIM nor CKM suppressed
- Large CP violating effects possible, some of which have clean interpretation
- Some of the hadronic physics understood model independently ($m_b \gg \Lambda_{\rm QCD}$)

Best sensitivity to some particles predicted in the MSSM comes from (crudely...)

experiment	energy scale	best sensitivity to
Tevatron	~ 2 TeV	squarks, gluinos
LEP	~ 200 GeV	sleptons, charginos
$B \to X_s\gamma$	~ 5 GeV	charged Higgs

B factories

- Goal: precision tests of the flavor sector via redundant measurements which in the SM determine CKM elements, but sensitive to different short distance physics

Number of B meson pairs whose decays are accessible to experimental studies:

Summer ’99: ~ 10 million
Summer ’00: ~ 30 million
Summer ’01: ~ 90 million

Beginning of exciting era

During this talk, Babar / Belle would produce close to 10000 B meson pairs each (if all goes well...)

In the next 4–5 years, B samples expected to increase another factor of 10–20

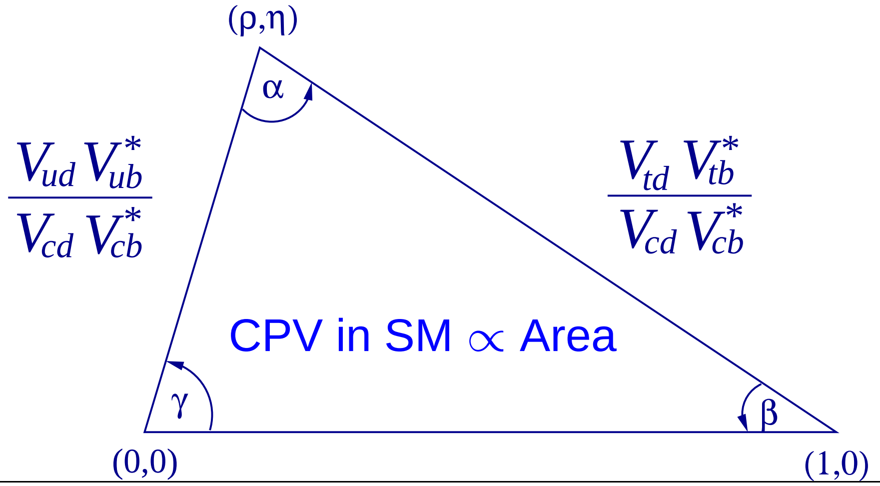
Unitarity triangle

- Charged current weak interactions:

$$(u,\, c,\, t) \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \qquad \begin{array}{c} \sim 1 \\ \sim \lambda \\ \sim \lambda^2 \\ \sim \lambda^3 \end{array} \qquad \lambda \sim 0.22$$

  - $\mathbf{V}_{\mathrm{CKM}}$ is the only source of CPV in the SM
  - Elements depend on 4 real parameters in the SM (3 angles $+$ 1 CPV phase)

- The unitarity triangle provides a simple way to visualize the SM constraints



$$V_{ud}\,V_{ub}^* + V_{cd}\,V_{cb}^* + V_{td}\,V_{tb}^* = 0$$

The angles and sides are directly measurable — want to overconstrain this picture

Hadronic uncertainties

- To believe discrepancy $=$ new physics, need model independent predictions:

$$\text{Quantity of interest} = (\text{calculable prefactor}) \times \Big[\, 1 + \sum_k (\text{small parameters})^k \Big]$$

Theoretical uncertainty is parametrically suppressed by $\sim$ $(\text{small parameter})^N$, but models may be used to estimate the uncertainty

Most of the recent progress comes from expanding in powers of Λ/m_Q, $\alpha_s(m_Q)$
... a priori not known whether $\Lambda \sim 200\text{MeV}$ or $\sim 2\text{GeV}$ $(f_\pi, m_\rho, m_K^2/m_s)$
... need experimental guidance to see which cases work how well

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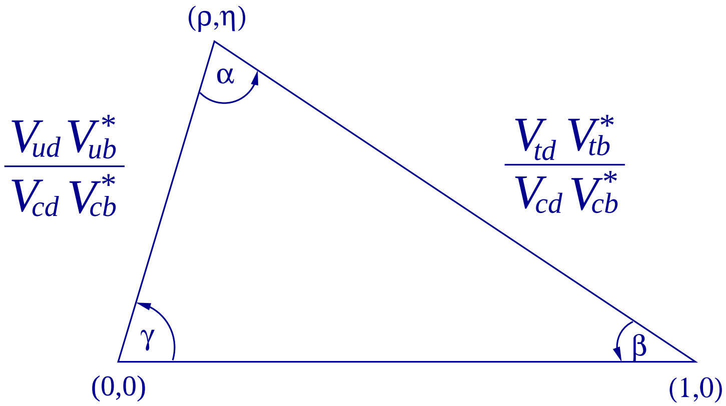
$|V_{cb}|$, $\sin 2\beta$, $|V_{td}/V_{ts}|$ are “easy” — both theory and experiment are tractable

$|V_{ub}|$, α, γ are “hard” — our ability to test CKM depends on the precision with which these can be measured



Status of CKM

- >11 days ago we knew that CKM was consistent at $\sim 30\%$ level ($|V_{ub}|$, ϵ_K, Δm_B)

  Used to ask whether preliminary $\sin 2\beta$ measurements were compatible with this

- As $\sin 2\beta$ is becoming the most precisely known ingredient of the unitarity triangle

  Questions: Is the SM the *only* source of CPV?

  Does the SM *fully* explain flavor physics?

- Heading towards $\sim 10\%$ test of CKM: Our ability to overconstrain CKM in B decays depends on a third measurement besides $\sin 2\beta$ and $|V_{td}/V_{ts}|$

  Central themes: 1) How to determine $|V_{ub}|$ model independently

  2) Reliability of factorization to determine α / γ from rates or "simple" time dependent asymmetries

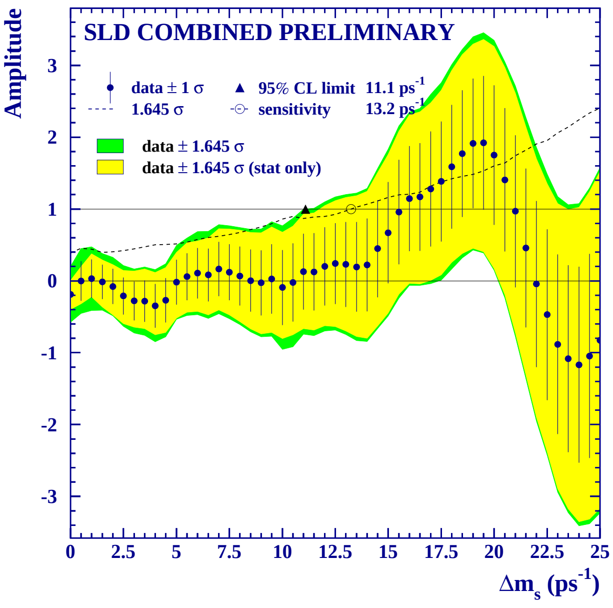
  3) "Zero prediction" observables: $a_{CP}(B_s \to \psi\phi)$, $a_{dir}(B \to s\gamma)$

  For both 1) and 2), it is crucial to understand hadronic physics from first principles

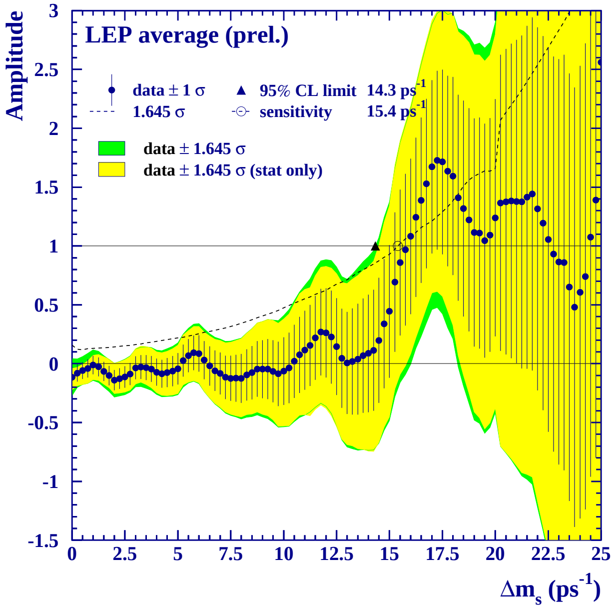
$B_{d,s}$ mixing: $|V_{td}|$ and $|V_{ts}|$

- Need from lattice QCD: $\Delta m_{d,s} = (\text{known factors}) \times f^2_{B_{d,s}} B_{B_{d,s}}$ — ratio is cleaner

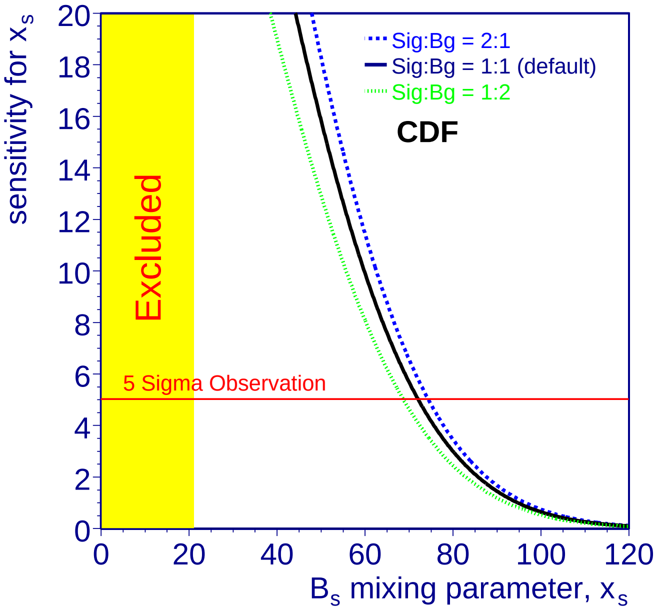
$$\frac{f^2_{B_s} B_{B_s}}{f^2_{B_d} B_{B_d}} = 1 \text{ in } SU(3) \text{ limit} \quad \begin{cases} \text{Lattice:} & \sim [1.17(6)]^2, \quad \text{need unquenched} \\ \text{[Chiral logs:} & \sim 1.3 \qquad \text{(Grinstein } et\ al., \text{'92)]} \end{cases}$$



SLD limits (Thom)



LEP limits (Weiser)



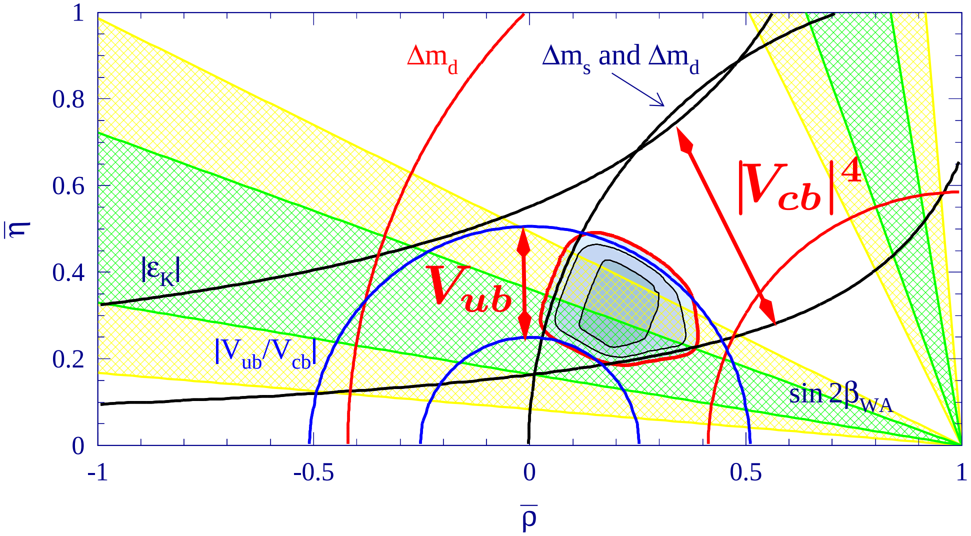
CDF Run II reach (Wicklund)

Present LEP / SLD / CDF combined limit: $\Delta m_s > 14.6\,\text{ps}^{-1}$ (95% CL)

Semileptonic and rare B decays

Theory error of $|V_{ub}|$ dominates SM allowed range of $\sin 2\beta$

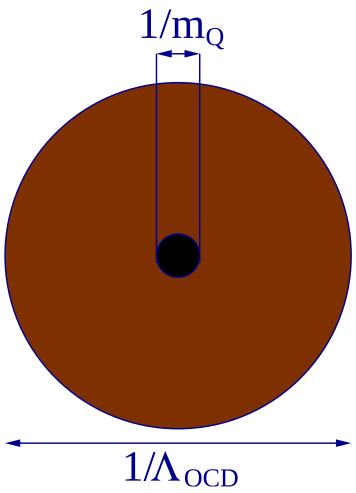
Error of $|V_{cb}|$ is a large part of the uncertainty of the ϵ_K constraint



(Hocker, Lacker, Laplace, Le Diberder, hep-ph/0104062)

Rare decays mediated by $b \to s\gamma$ and $b \to s\,\ell^+\ell^-$ transitions are sensitive probes of the Standard Model

Exclusive semileptonic $B \to D^{(*)}$ decay



In $Q\,\bar{q}$ mesons, in the $m_Q \to \infty$ limit, the heavy quark acts as a static color source with fixed four-velocity v^μ

Light degrees of freedom become insensitive to spin and flavor of heavy quark

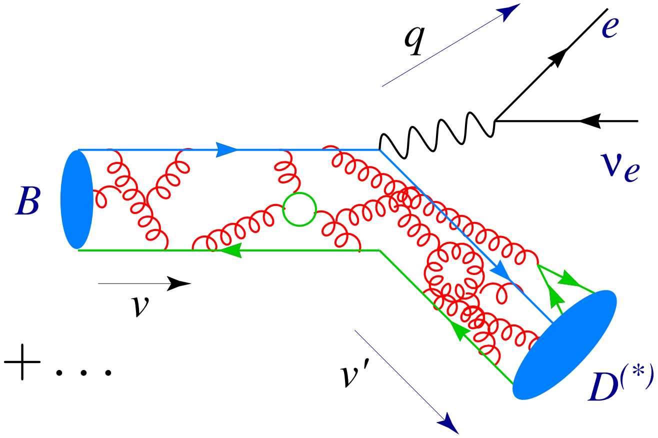
$\Rightarrow SU(2n)$ heavy quark spin-flavor symmetry at fixed v^μ

- Extract $|V_{cb}|$ from $B \to D^* \ell \bar{\nu}$ rate at $w \equiv \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D} = 1$ (theory most restrictive)

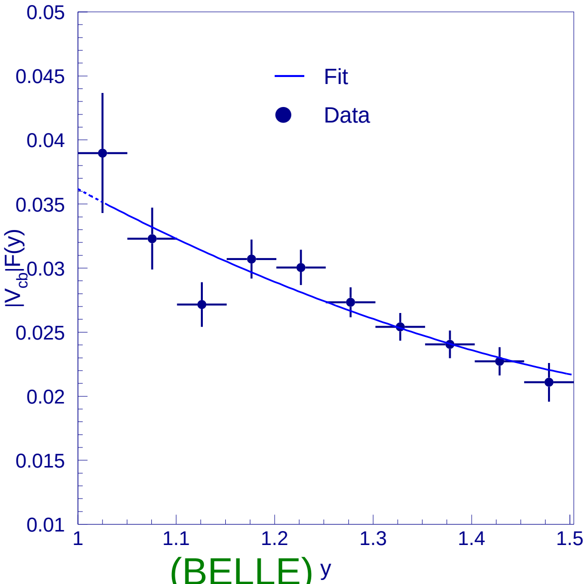
$$\frac{\mathrm{d}\Gamma(B \to D^* \ell \bar{\nu})}{\mathrm{d}w} = \text{(known factors)}\ |V_{cb}|^2\, \mathcal{F}_*^2(w)$$

$$\mathcal{F}_{(*)}(w) = \text{Isgur-Wise function} + O(\alpha_s, \Lambda_{\mathrm{QCD}}/m_{c,b})$$

$$\mathcal{F}_*(1) = 1 - 0.04_{\alpha_s, \alpha_s^2} + \frac{0}{m_{c,b}} + \frac{\text{(lattice or model dept.)}}{m_{c,b}^2} + \ldots$$



Experimental status of $|V_{cb}|_{\text{exclusive}}$

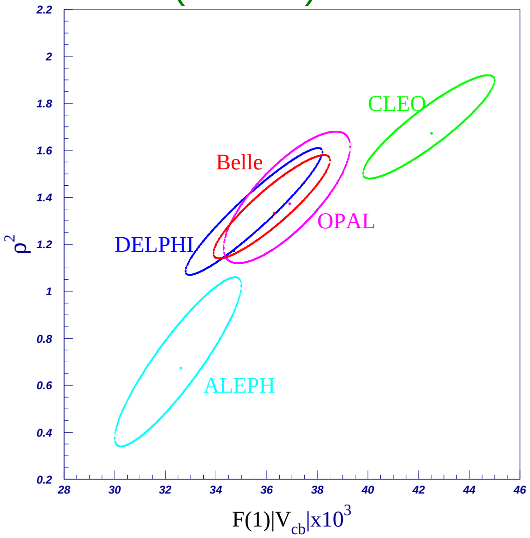


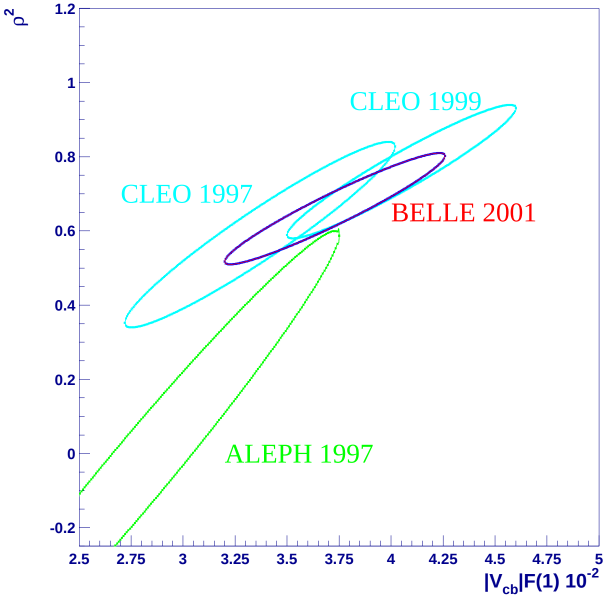
(BELLE)

$$|V_{cb}|\,\mathcal{F}_*(1) = 10^{-3} \times \begin{cases} 35.6 \pm 1.7 & \text{(LEP, Palla)} \\ 42.2 \pm 2.2 & \text{(CLEO, Miller)} \\ 36.2 \pm 2.3 & \text{(BELLE, Won)} \end{cases}$$

$$\mathcal{F}_*(1) = 0.91 \pm 0.04 \qquad \text{(my estimate)}$$

$B \to D\ell\bar{\nu}$ may be important for future improvements:





Uncertainties in $|V_{cb}|_{\text{exclusive}}$

- Nonperturbative correction at zero recoil
  - Models or bounds from sum rules
  - Lattice QCD: Calculate $\mathcal{F}_{(*)} - 1$ from a double ratio of correlation functions

    (D easier than D^*) $\mathcal{F}(1) = 1.06 \pm 0.02\,,\ \mathcal{F}_*(1) = 0.935 \pm 0.03$ (FNAL quenched)

Checks: consistency between $B \to D^*$ and D, and form factor ratios

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- Extrapolation to zero recoil
  - Constrain $\rho^2 \equiv -\mathcal{F}_*'(1)$ by studying excited D states' contributions near $w = 1$

    Important to understand $B \to D^{**}\ell\bar\nu$ better

    (Uraltsev, PLB 501 86; Le Yaouanc, Oliver, Pene, Raynal, Morenas, hep-ph/0105247)
  - Unitarity constraints: strong correlation between slope and curvature of $\mathcal{F}_*(w)$

    (Boyd, Grinstein, Lebed; Caprini, Lellouch, Neubert)

... might become less crucial with much higher statistics

Inclusive semileptonic B decay

- Operator Product Expansion (OPE): expand decay rates in $\Lambda_{\rm QCD}/m_b$ and $\alpha_s(m_b)$

$\Rightarrow$ model independent results for "sufficiently inclusive" observables

$$d\Gamma = \begin{pmatrix} b \text{ quark} \\ \text{decay} \end{pmatrix} \times \left\{ 1 + \frac{0}{m_b} + \frac{f(\lambda_1, \lambda_2)}{m_b^2} + \ldots + \alpha_s(\ldots) + \alpha_s^2(\ldots) + \ldots \right\}$$

Interesting quantities computed to order α_s, $\alpha_s^2\beta_0$, and $1/m^2$
($1/m^3$ used to estimate uncertainties)

- Good news: Total rates known at few ($\lesssim 5$) percent level (duality...) $\Rightarrow$ $|V_{cb}|$

Improvements: better m_b from Υ sum rules / moments of B decay spectra / Lattice

- Bad news: In certain restricted regions of phase space the OPE breaks down

To determine $|V_{ub}|$, stringent cuts required to eliminate ~ 100 times larger $b \to c$ background... and the troubles begin...

Inclusive $|V_{cb}|$ determination

Upsilon expansion: (Hoang, ZL, Manohar)

$$|V_{cb}| = \left(41.9 \pm 0.8_{(\mathrm{pert})} \pm 0.5_{(m_b)} \pm 0.7_{(\lambda_1)}\right) \times 10^{-3} \left(\frac{\mathcal{B}(B \to X_c \ell \bar\nu)}{0.105} \, \frac{1.6\,\mathrm{ps}}{\tau_B}\right)^{1/2}$$

(Central value is 40.5 $[40.8]$ in (Bigi, Shifman, Uraltsev))

$$\mathcal{B}(B \to X \ell \bar\nu) = \begin{cases} 10.65 \pm 0.23\% & \text{(LEP, Palla)} \\ 10.86 \pm 0.49\% & \text{(BELLE, Won)} \end{cases} \qquad \Rightarrow |V_{cb}| \sim (41 \pm 2.4_{\mathrm{th}}) \times 10^{-3}$$

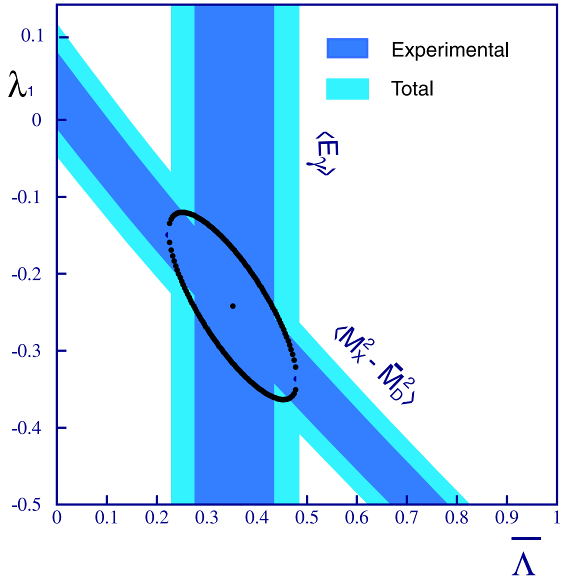
Future improvements likely to come from combined analyses using inclusive spectra to determine m_b and λ_1 (CLEO, Miller)

$$\bar\Lambda = 0.35 \pm 0.13\,\mathrm{GeV}$$

$$\lambda_1 = -0.24 \pm 0.11\,\mathrm{GeV}^2$$

$$\Downarrow$$

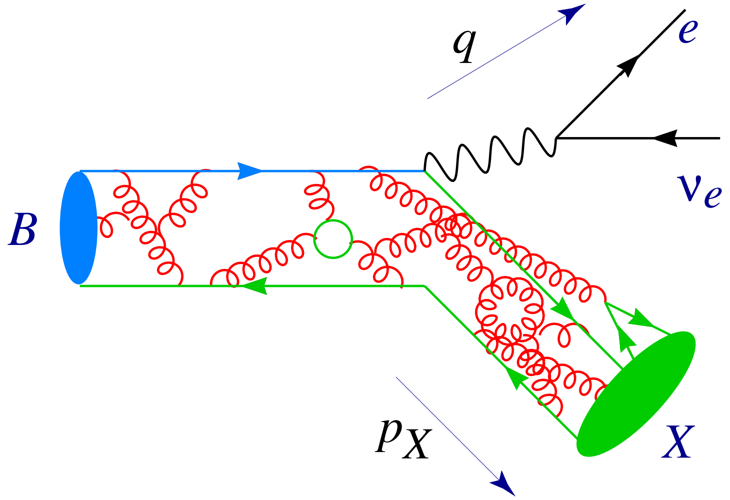
$$|V_{cb}| \sim (40.4 \pm 1.6) \times 10^{-3}$$



Also allows tests of quark-hadron duality

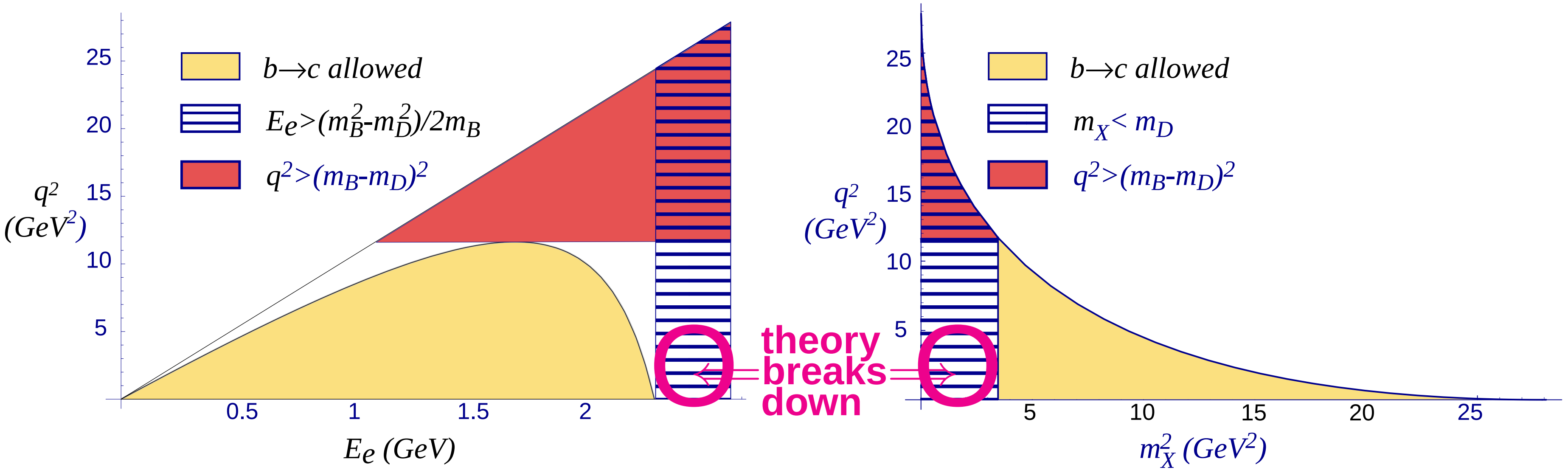
⇒ May get $\sigma(V_{cb}) \sim 2 - 3\%$ in future

Inclusive $B \to X_u \ell \bar{\nu}$ decay and $|V_{ub}|$



Proposals to measure $|V_{ub}|$:

- Lepton spectrum: $E_\ell < (m_B^2 - m_D^2)/2m_B$
- Hadronic mass spectrum: $m_X < m_D$
- Dilepton mass spectrum: $q^2 < (m_B - m_D)^2$



$B \to X_u \ell \bar{\nu}$ spectra

- Three qualitatively different regions of phase space:

1) $m_X^2 \gg E_X \Lambda_{\rm QCD} \gg \Lambda_{\rm QCD}^2$: the OPE converges, first few terms can be trusted

2) $m_X^2 \sim E_X \Lambda_{\rm QCD} \gg \Lambda_{\rm QCD}^2$: infinite set of terms equally important, the OPE becomes a twist expansion

3) $m_X \sim \Lambda_{\rm QCD}$: resonance region — cannot compute reliably

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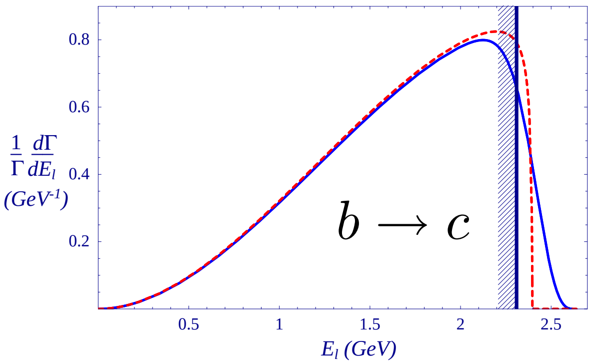
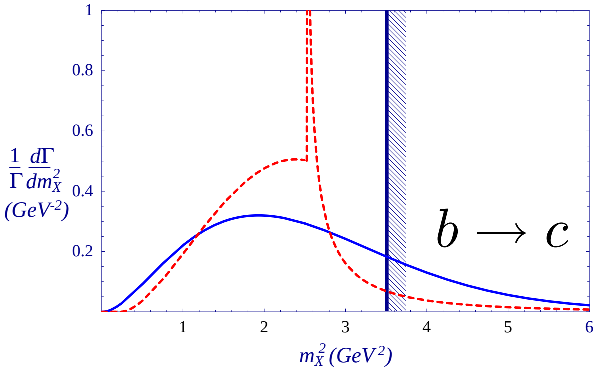
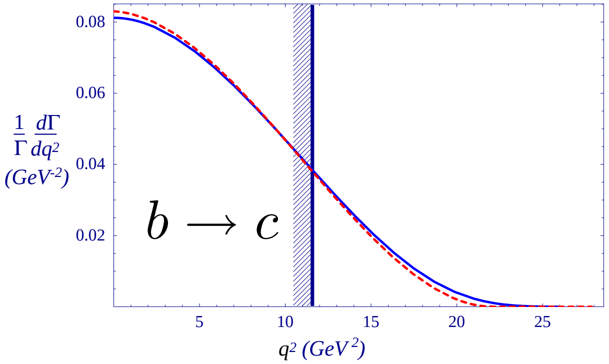
- Both $E_\ell > (m_B^2 - m_D^2)/2m_B$ and $m_X < m_D$ are in (2) since $m_B \Lambda_{\rm QCD} \sim m_D^2$







— b quark decay to $O(\alpha_s)$
— incl. "Fermi-motion" (model)


Theory happy
Experiment happy

V_{ub}: lepton endpoint region

- Need to resum infinite set of equally important terms in the OPE into a nonperturbative "shape function", which can be related to $B \to X_s\gamma$ photon spectrum

(early 90's: Neubert; Bigi, Shifman, Uraltsev, Vainshtein)

Recently: Relations worked out including resummed NLO corrections

(Leibovich, Low, Rothstein, PRD 61 053006; 074006; PLB 486 86)

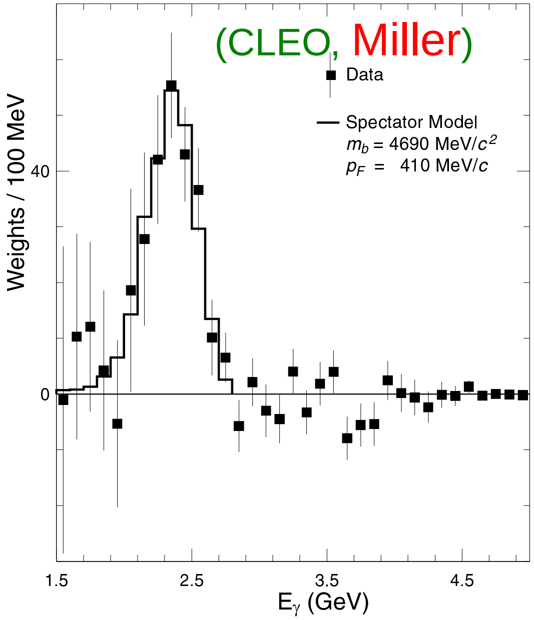
Operators other than O_7 make large correction (Neubert, hep-ph/0104280)

The goal is to use the $B \to X_s\gamma$ photon spectrum as an input to determine $|V_{ub}|$

... measures the "Fermi-motion" of the b quark

CLEO results coming soon

Limiting uncertainties: unknown $O(1/m_b)$ correction
weak annihilation (see later)


(CLEO, Miller)

V_{ub}: q^2 spectrum

- In large q^2 region, first few terms in OPE can be trusted (Bauer, ZL, Luke, PLB 479 395)

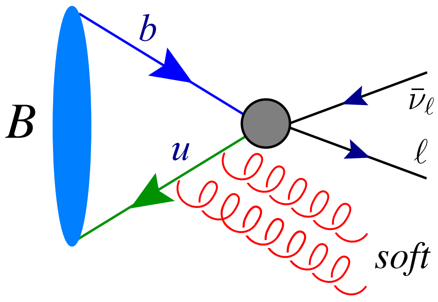
  Reason: $q^2 > (m_B - m_D)^2$ cut implies $E_X < m_D$ [$\Rightarrow m_X^2 \gg E_X \Lambda_{\text{QCD}}$]

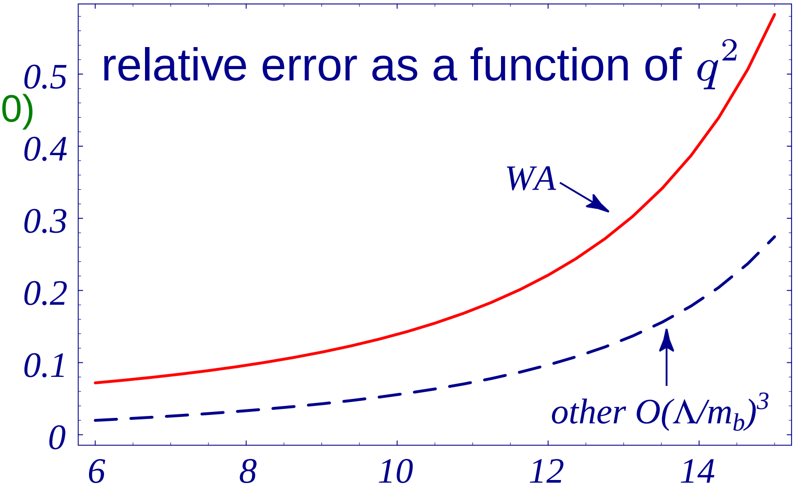
  Leading and subleading logs of $x = m_b/(m_b - \sqrt{q^2})$ were summed ($\alpha_s^{n+1} \ln^n x$, $x\, \alpha_s^n \ln^n x$); results consistent within 1σ (Becher, Neubert, hep-ph/0105217)

Unknown corrections are $\sim O(\Lambda_{\text{QCD}}/m_b)^3$

Weak annihilation dominates (Voloshin, hep-ph/0106040)

Guesstimate: $\sim$ 2–3% of $b \to u$ semileptonic rate; delta-function at maximal q^2 and maximal E_ℓ





Lattice gives a 2–4 times larger estimate [$B_1 - B_2 \sim 0.2$–0.4] (Becirevic)

$\Rightarrow$ Constrain WA by comparing D^0 vs. D_s SL widths, or V_{ub} from $B^\pm$ vs. B^0 decay

V_{ub}: combine q^2 & m_X cuts

- Can get $|V_{ub}|$ with theoretical uncertainty at the 5–10% level, from up to $\sim 45\%$ of the events (Bauer, ZL, Luke, hep-ph/0107074)

Such precision can be achieved even with cuts away from the $b \to c$ threshold

Cuts on (q^2, m_X^2)	included fraction of $b \to u\ell\bar{\nu}$ rate	error of $\lvert V_{ub}\rvert$ $\delta m_b = 80/30\,\mathrm{MeV}$
$6\,\mathrm{GeV}^2,\ m_D$	46%	$8\%/5\%$
$8\,\mathrm{GeV}^2,\ 1.7\,\mathrm{GeV}$	33%	$9\%/6\%$
$(m_B - m_D)^2, m_D$	17%	$15\%/12\%$

Strategy: (i) reconstruct q^2 and m_X; make cut on m_X as large as possible
(ii) for a given m_X cut, reduce q^2 cut to minimize overall uncertainty

...Would reduce SM allowed range of $\sin 2\beta$ very significantly

Rare B decays

- Important probes of new physics — measurements of CKM elements
  - $B \to K^*\gamma$ or $X_s\gamma$: Best $m_{H^\pm}$ limits in 2HDM — in SUSY many param's
  - $B \to K^{(*)}\ell^+\ell^-$ or $X_s\ell^+\ell^-$: bsZ penguins, SUSY, right handed couplings

A crude guide... ($\ell = e$ or μ)

Decay	∼SM rate	physics examples
$B \to s\gamma$	3×10^{-4}	$\lvert V_{ts}\rvert$, $H^\pm$, SUSY
$B \to s\nu\nu$	4×10^{-5}	new physics
$B \to \tau\nu$	4×10^{-5}	$f_B\lvert V_{ub}\rvert$, $H^\pm$
$B \to s\ell^+\ell^-$	7×10^{-6}	new physics
$B_s \to \tau^+\tau^-$	1×10^{-6}	
$B \to s\tau^+\tau^-$	5×10^{-7}	$\vdots$
$B \to \mu\nu$	3×10^{-7}	
$B_s \to \mu^+\mu^-$	4×10^{-9}	
$B \to \mu^+\mu^-$	1×10^{-10}	

Replacing $b \to s$ by $b \to d$ costs factor ~ 20 (in SM)

In $B \to q\, l_1\, l_2$ decays expect ~ 10–20% K^*/ρ, and ~ 5–10% K/π (model dependent)

Best upper limits (90% CL):

$$\mathcal{B}(B \to K\ell^+\ell^-) < 0.6 \times 10^{-6}$$
$$\mathcal{B}(B \to K^*\ell^+\ell^-) < 2.5 \times 10^{-6}$$

(BaBar, Mancinelli)

... very near the SM expectations

Exclusive rare decays

Inclusive: Theoretically cleaner: calculable in OPE $+$ precise multi-loop results

New calculation of two-loop virtual corrections to $b \to s\ell^+\ell^-$ (Greub)

Exclusive: Experimentally easier — need to understand form factors

Lattice / symmetries between semileptonic and rare decay form factors

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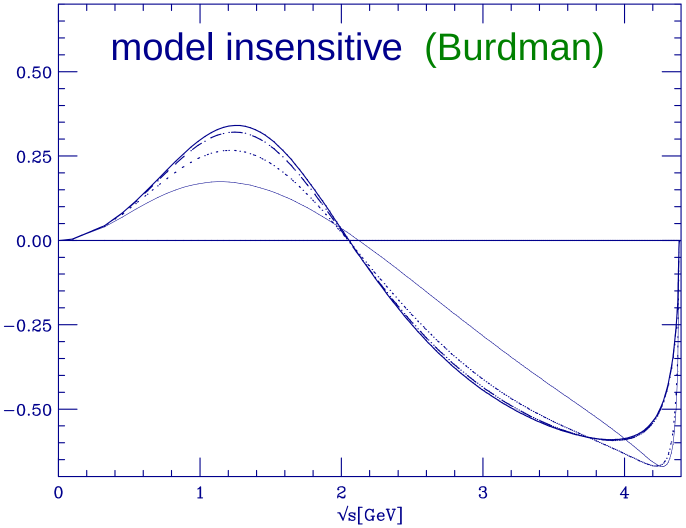
There is an observable insensitive to the precise values of the form factors:



Forward-backward asymmetry in $B \to K^*\ell^+\ell^-$ changes sign:

$$C_9^{\rm eff}(s_0) = -\frac{2m_B m_b}{s_0}\,C_7^{\rm eff} \times [\,1 + O(\alpha_s, \Lambda_{\rm QCD}/m_b)\,]$$

Nonfactorizable corrections computed recently

(Beneke, Feldmann, Seidel, hep-ph/0106067)

$\Rightarrow$ Clean measurement of C_9 (sensitive to NP)

Exclusive $B \to$ light form factors

HQS relates form factors in large q^2 region ($B \to \rho\ell\bar{\nu}, K^*\ell^+\ell^-, K^*\gamma$, etc.)

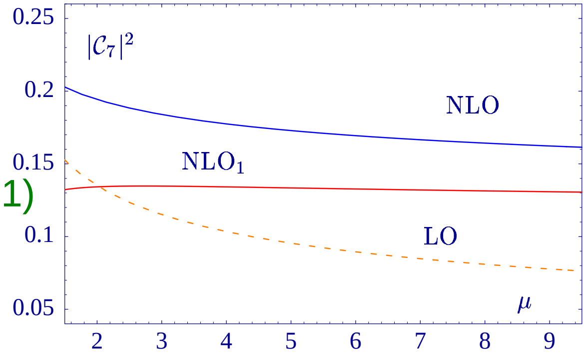
Recently: shown for $q^2 \ll m_B^2$, with some assumptions, that 7 vector meson form factors related to $\xi_\perp(E)$, $\xi_{||}(E)$; and 3 pseudoscalar form factors related to $\xi_P(E)$

Charles *et al*, PRD 60 014001

- Computation of α_s corrections (Beneke, Feldmann, NPB 592 3)
- Constraints from $B \to K^*\gamma$ (Burdman, Hiller, PRD 63 113008)
- Attempt to formulate as an effective theory (Bauer, Fleming, Pirjol, Stewart, PRD 63 114020)

Find $\sim 80\%$ enhancement of $B \to K^*\gamma$ rate at NLO $\Rightarrow$ $1/m$ correction large or/and form factors significantly different from model predictions

(Beneke, Feldmann, Seidel, hep-ph/0106067; Bosch, Buchalla, hep-ph/0106081)



How well these predictions work may give insights to some aspects of factorization in the future

Semileptonic & rare decays — Summary

- $|V_{cb}|$ is known at the $\sim 5\%$ level; error may become half of this in the next few years using both inclusive and exclusive determinations (latter will rely on lattice)
- Situation for $|V_{ub}|$ may become similar to present $|V_{cb}|$; for precise inclusive determination the neutrino reconstruction seems crucial; the exclusive will use lattice.
- Lot of progress in understanding exclusive rare decays in the small q^2 regime, $B \to K^{(*)}\gamma$ and $B \to K^{(*)}\ell^+\ell^-$ below the ψ $\Rightarrow$ increase sensitivity to new physics

  Also tests some assumptions entering factorization in charmless decays

Nonleptonic decays

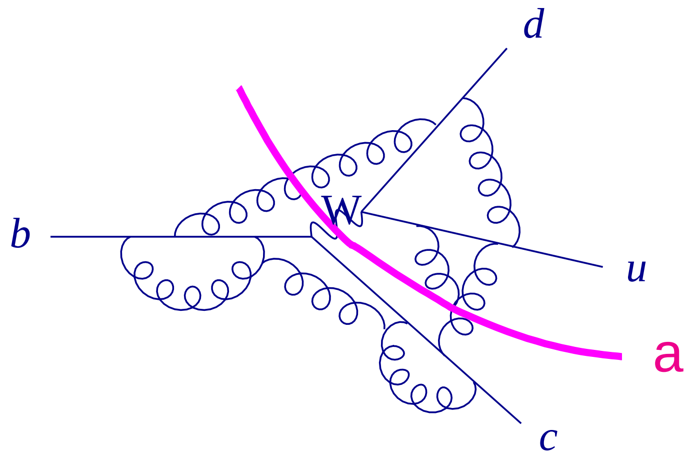
Exclusive: Until recently little was known model independently — there has been significant progress towards justifying factorization in certain cases

Especially charmless decays are important for study of CP violation

Inclusive: Lifetimes calculable in OPE; interesting testing ground for theoretical tools also used elsewhere

D mixing: Last year there were two 2σ signals; understanding hadronic physics may limit its sensitivity to new physics

Factorization in $b \to c$ exclusive decays



Start from OPE; estimate matrix elements of four-quark operators by grouping the quark fields into two that mediate $B \to M_1$, and two that can describe vacuum $\to M_2$

assume that effect of gluons across W is calculable

- If M_1 is heavy ($D^{(*)}$) and M_2 is light (π) then "color transparency" provides a physical picture how factorization may work (early 90's: Bjorken; Politzer, Wise; Dugan, Grinstein)

  Recently shown to be consistent to 2-loops (Beneke, Buchalla, Neubert, Sachrajda, NPB 591 313)
  and suggested to hold to all orders (BBNS; Bauer, Pirjol, Stewart, hep-ph/0107002)

- No OPE $\Rightarrow$ corrections unknown [order $(\Lambda/m_b)^n$?]
  renormalon analysis (Burrell, Williamson PRD 64 034009; Becher, Neubert, Pecjak, hep-ph/0102219)

Factorization tests

- Factorization has been observed to work in $B^0 \to D^{(*)\pm}\pi^\mp/\rho^\mp$ decays at the $\lesssim 10\%$ level (in amplitudes) ...it gets really interesting just below this ($\sim 1/N_c^2$)

Want to understand quantitatively accuracy of factorization in different processes

E.g., Spectator in B going into π should be power suppressed, therefore:

$$\frac{\mathcal{B}(B\to D^{(*)0}\pi^-)}{\mathcal{B}(B\to D^{(*)+}\pi^-)} = 1 + O(\alpha_s, 1/m_b)\,,$$ however $\sim 1.8 \pm 0.3$ (PDG) (BBNS)

$1/m$ suppression may not be effective, ratios consistent with $(1+1/N_c)^2$

Can learn more from new data on color suppressed rates

$\mathcal{B}(B \to D^0\pi^0)$	$\mathcal{B}(B \to D^{*0}\pi^0)$	$[\times 10^{-4}]$
$2.9^{+0.4}_{-0.3} \pm 0.6$	$1.5^{+0.6+0.3}_{-0.5-0.4}$	(Belle, Lu)
$2.6 \pm 0.3 \pm 0.6$	$2.0 \pm 0.5 \pm 0.7$	(CLEO, von Toerne)

For the first time, we can determine strong phase between $I = \frac{3}{2}$ and $\frac{1}{2}$ amplitudes from the rates for $D^+\pi^-, D^0\pi^-, D^0\pi^0$ — I get: $\delta \simeq 24^\circ \pm 6^\circ$(asymmetric)

Origin of factorization?

- The color transparency argument relies on M_2 being fast ($m/E \ll 1$); the large-N_c argument is independent of this — Does factorization become a worse approximation in a pattern consistent with the expectations?

- At the level of existing data (crude), factorization also works in $B \to D_s^{(*)} D^{(*)}$ when both particles are heavy (Luo, Rosner, hep-ph/0101089)
- See if factorization is worse in $B_d \to D_s^{(*)\pm}\, \pi^{\mp}$ than in $B_d \to D^{(*)\pm}\, \pi^{\mp}$? Should be $|V_{ub}/V_{cb}|^2 \times$ power suppressed — spectator in B & u from $b \to u$ must form the π (only upper limits on rates yet; needs $B \to \pi$ form factor)
- Study decays to mesons with small decay constants or spin ≥ 2 so that factorizable pieces are suppressed and α_s & $1/m$ corrections are very important, e.g, $B^0 \to D^{(*)+} a_0/b_1/\pi_2$, etc. Rates at 10^{-6} level — soon accessible?
(Diehl, Hiller, JHEP 0106 067; also: Laplace, Shelkov, hep-ph/0105252)

  Similar charmless decays ($a_0\, \pi$) may be first seen (BaBar, Bona)

Factorization in $B \to D^{(*)} X$

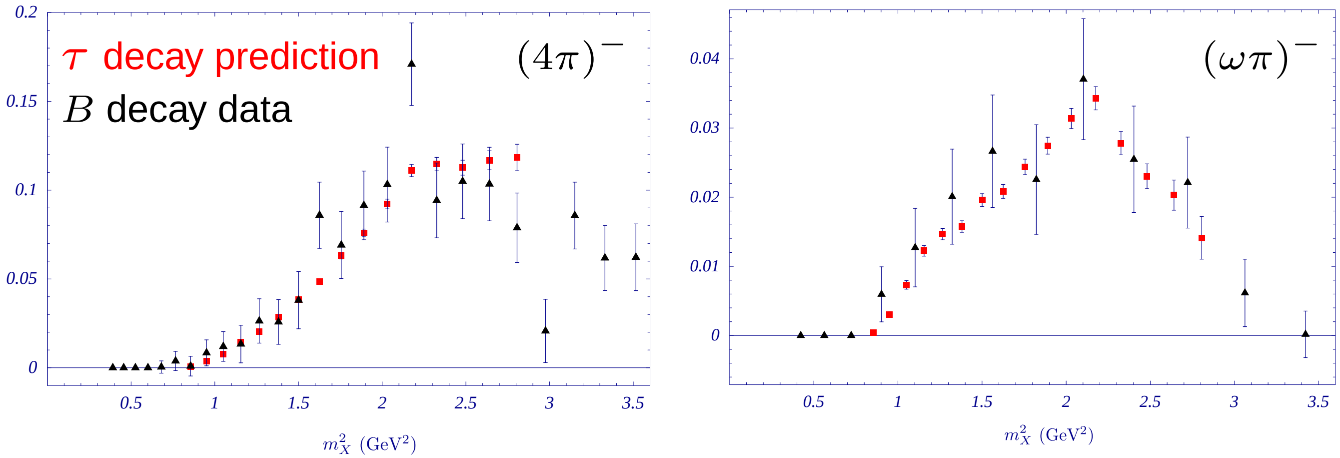
- Study accuracy as a function of the kinematics, with fixed final states

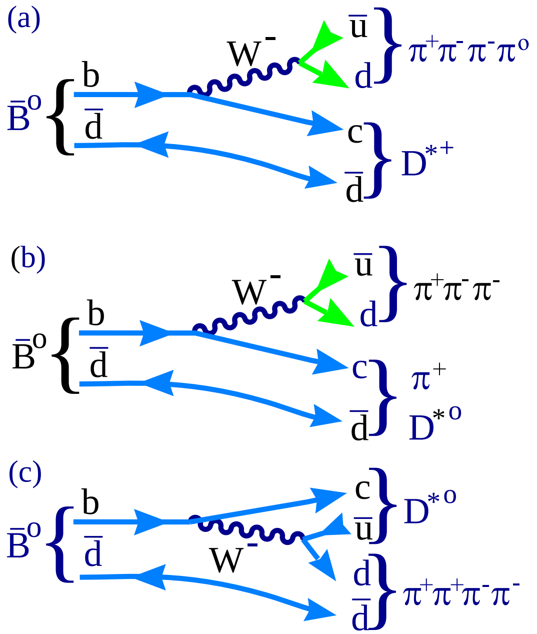
Expect some nonperturbative corrections to grow as invariant mass of X increases — compare $B \to D^* 4\pi$ with $\tau \to 4\pi$ (allows $0.4 \lesssim m_X/E_X \lesssim 0.7$)

(ZL, Luke, Wise, PLB 507 142)

Different charge modes can disentangle backgrounds from D^{**}, etc.

(CLEO, von Toerne, hep-ex/0103021; hep-ex/0105071; PRD 61 072003)





Observing deviations that grow with m_X would be evidence that perturbative QCD is an important part of the success of factorization in $B \to D^* X$

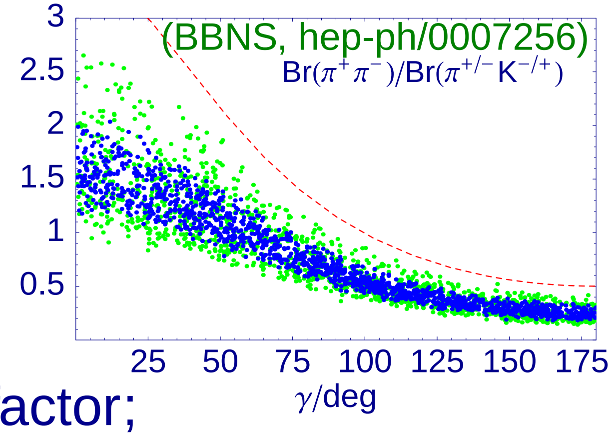
Factorization in charmless B decays

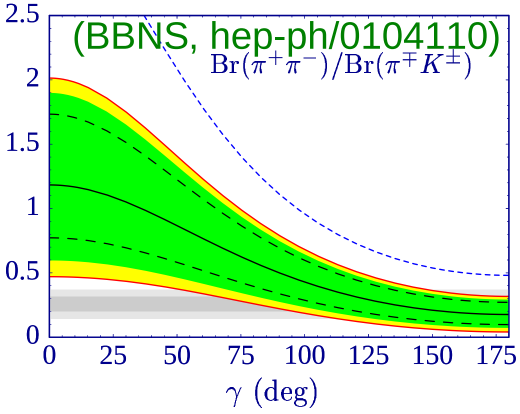
- Especially important for CP violation — several new issues arise:
  - Power counting depends on treatment of Sudakovs

    In "perturbative QCD approach" larger strong phases, annihilation & penguin contributions more important (Keum, Li, Sanda, PLB 504 6; PRD 63 054008; PRD63 074006)

    Use $B \to \phi K,\ \psi K^{(*)}$ to try to discriminate between two approaches (Cheng)
  - Chirally enhanced terms $2m_K^2/m_b m_s \sim 1$, although formally $O(\Lambda_{\rm QCD}/m_b)$

    Weak annihilation is sizable





  - Other issues raised: π form factor;

    Charming penguins (Ciuchini *et al.*, hep-ph/0104126); Intrinsic charm (Brodsky, BCP4)

It is unfortunately a lot harder to test the assumptions than to use the predictions

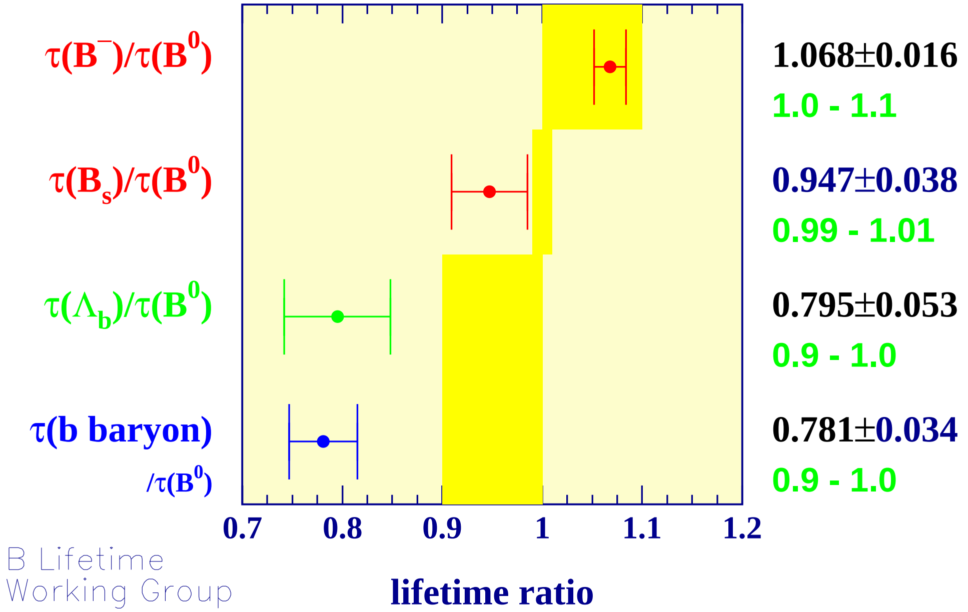
... possible tests include direct CPV, for which the predictions also differ

Inclusive nonleptonic decays, b hadron lifetimes

Good news: Inclusive nonleptonic decays can be calculated in the OPE, like inclusive semileptonic decays

Bad news: The OPE has to be performed in the physical region (local duality); it is less clear whether predictions are reliable at the scale m_b

Experimental status (Osterberg)



Lifetime differences arise in the OPE at order $(\Lambda_{\rm QCD}/m_b)^3$ from matrix elements of four-quark operators

The Λ_b lifetime remains hard to explain; this need not be relevant for semileptonic decay though, since $\mathcal{B}(\Lambda_b \to X\ell\bar\nu)/\tau(\Lambda_b) \simeq \mathcal{B}(B \to X\ell\bar\nu)/\tau(B)$ (Palla)

Recent developments

- In the ´t Hooft Model: large local deviations between heavy meson and heavy quark widths — need to average over "m_b" to obtain $1/m^2$ difference in qualitative agreement with OPE (Grinstein, hep-ph/0106205)

- New lattice calculation of matrix elements of four-quark operators relevant for meson lifetimes (Becirevic)

  These matrix elements (and their error) also determine the uncertainty in width differences $\Delta\Gamma_{s,d}$, and therefore control whether:

  - $\Delta\Gamma_s$ may be useful to look for NP (Dunietz, Fleischer, Nierste, PRD 63 114015)
  - $\Delta\Gamma_d$ at NLO may be close to 1% — relevant for $\sin 2\beta$ at percent level (Hurth)

$D^0 - \bar{D}^0$ mixing

The only meson system where mixing is generated by the down type quarks

It is expected to be small in the SM, i.e., $\Delta M, \Delta\Gamma \lesssim 10^{-3} \times \Gamma$

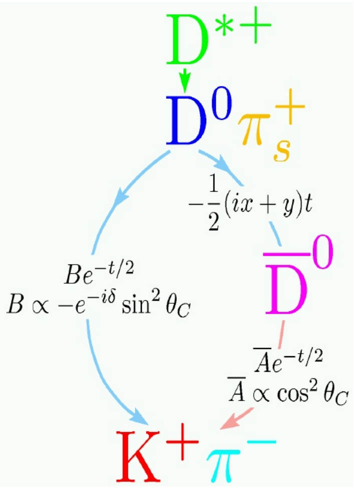
New physics can easily enhance ΔM but would not affect $\Delta\Gamma$ $\Rightarrow$ sensitive to NP

Definitions: $x \equiv \dfrac{\Delta M}{\Gamma}$ $\qquad y \equiv \dfrac{\Delta\Gamma}{2\Gamma}$

Two different measurements:

Measure D lifetime in decays to a CP eigenstate, e.g., K^+K^- and a flavor eigenstate, e.g., π^+K^-

Measure time dependence of “wrong sign” decays, e.g., $D^0 \to K^+\pi^-$ and $\bar{D}^0 \to K^-\pi^+$



Theoretical status of D mixing

It is very hard to estimate x and y in the SM

Was argued to be long distance dominated (still DCS and vanishes in $SU(3)$ limit): $x, y \sim \sin^2\theta_C\, \epsilon^2_{SU(3)}$

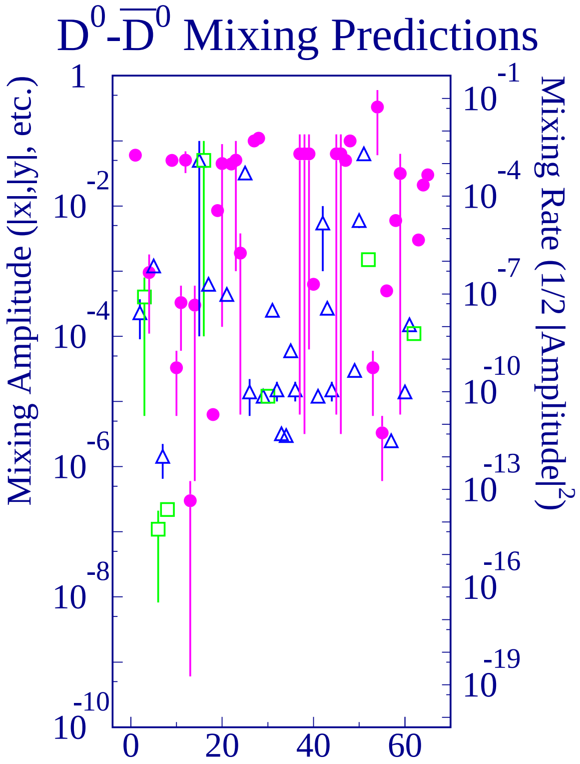
Short distance box diagram: $x \propto \dfrac{m_s^2}{m_W^2} \times \dfrac{m_s^2}{m_c^2} \to 10^{-5}$

OPE: higher order terms are suppressed by fewer powers of m_s

	dim-6	dim-9	dim-12
$\dfrac{\Delta M}{\Delta M_{\rm box}}$	1	$\dfrac{\Lambda^2}{m_s m_c}$	$\dfrac{\Lambda^4}{m_s^2 m_c^2}\,\dfrac{\alpha_s}{4\pi}$
$\dfrac{\Delta\Gamma}{\Delta M}$	$\dfrac{m_s^2}{m_c^2}$	$\dfrac{\alpha_s}{4\pi}$	$\dfrac{\alpha_s}{4\pi}\,\beta_0$

With large uncertainties, and some assumptions about the matrix elements: $x, y \lesssim 10^{-3}$

(Georgi; Bergmann *et al.*, PLB 486 418; Bigi, Uraltsev, NPB 592 92)



(H. Nelson, hep-ex/9908021)

△ — SM predictions for x

□ — SM predictions for y

○ — NP predictions for x

Experimental status of D mixing

- Measure D lifetime in decays to K^+K^- & π^+K^-, fitting exp. time-dependences:

$$y_{CP} = y\cos\phi - x\sin\phi\, A_m/2 = \frac{\hat\tau(D\to K^+K^-)}{\hat\tau(D\to\pi^+K^-)} - 1$$

$A_m = |q/p|^2 - 1$; ϕ is the CPV phase in the mixing — very small in the SM

- Time dependence of "wrong sign" decays $D \to K^+\pi^-$ & $\bar D \to K^-\pi^+$ measures:

$$x' = x\cos\delta + y\sin\delta \qquad\qquad y' = y\cos\delta - x\sin\delta$$

δ is the strong phase between the CA and DCS amplitudes

$$y_{CP} = \begin{cases} 3.42 \pm 1.57\% & \text{(FOCUS, Ratti)} \\ 0.5 \pm 1 \pm 1\% & \text{(BELLE, Yabsley)} \\ -1.1 \pm 2.9\% & \text{(CLEO, Kagan)} \end{cases}$$

$$x' = 0.0 \pm 1.5\%$$

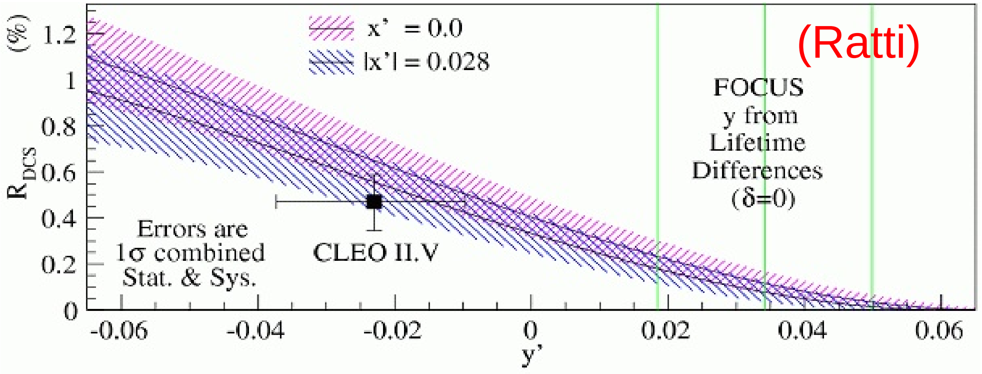
$$y'\cos\phi = -2.5^{+1.4}_{-1.6}\,\% \quad \text{(CLEO, Savinov)}$$

Large y_{CP} could be explained by
large y or large x, A_m, and ϕ

Large y' could be explained by $y \sim 10^{-2}$
and $\delta \ll 1$ or large $x \sim 10^{-2}$ and $\delta \sim 1$

Implications for sensitivity to new physics

- The central values of FOCUS' large y_{CP} and CLEO's large negative y' would imply together that δ has to be large independent of x and y [in $SU(3)$ limit $\delta = 0$]


(Ratti)

- If $y \gtrsim x$ then we would loose sensitivity to new physics in the mixing amplitude even if NP dominates x

Important to improve measurements of both $\Delta\Gamma_D$ and Δm_D to be able to interpret the latter as a signal for new physics

Nonleptonic decays — Summary

- New tools to investigate exclusive nonleptonic decays
  factorization in $B \to D^{(*)\pm} \pi^{\mp}/\rho^{\mp}$ well established theoretically

- Flood of new and more precise data will allow many tests of factorization and tell us about significance of unknown power suppressed terms in various processes

- Δm_D can only be an unambiguous signal for new physics if $\Delta\Gamma_D$ is smaller
  $\Rightarrow$ important to measure both

Summary

Final remarks

- To overconstrain CKM, all possible clean measurements are very important, both CP violating and conserving, even if redundant in SM (correlations important)
- The key processes are those which give clean information on short distance parameters ...one theoretically clean measurement is worth ten dirty ones
- It changes with time what is theoretically clean — significant recent progress for:
  - Determination of $|V_{ub}|$ from inclusive B decay
  - Rare decay form factors at small q^2
  - Factorization in certain nonleptonic decays
- Studying CKM/CPV and hadronic physics is complementary; except for a few very clean cases several measurements needed to minimize theoretical uncertainties — data will help to get rid of nasty things hard to constrain otherwise

Conclusions

- There is important progress towards understanding the hadronic physics crucial both for standard model measurements and for searches for new physics
- The point is not simply to measure (ρ, η), or (α, β, γ), or look for CP violation in the B system, but to probe the flavor sector of the standard model until it breaks

  ...the program as a whole is a lot more interesting than any single measurement
- First precise test of CKM, in my opinion, will come from:

  $$\sin 2\beta, \quad |V_{ub}/V_{cb}|, \quad |V_{td}/V_{ts}|$$

  (both) (e^+e^-) (Tevatron)

  ...e^+e^- and hadronic B factories are complementary
- Vibrant theoretical and experimental program — hope to find unexpected physics!

> “This is not the end. It is not even the beginning of the end.
> But it is, perhaps, the end of the beginning.”
>
> — W. Churchill (Nov. 10, 1942)