Rare Hadronic B Decays and the Determination of CKM Parameters

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Based on collaborations with M. Beneke, G. Buchalla, C. Sachrajda

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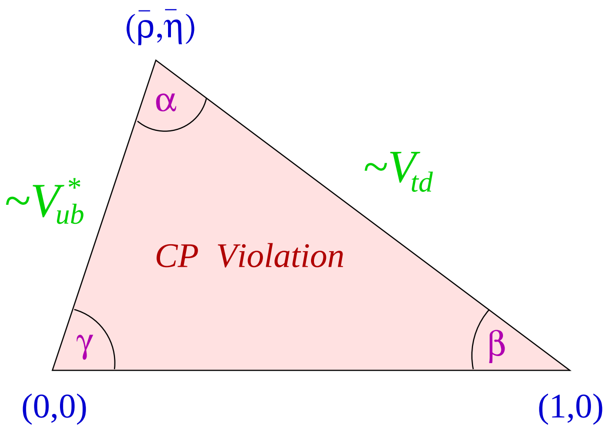
Introduction

* rare hadronic B decays play a crucial role in studies of the unitarity triangle and CP violation

* tree–penguin interference gives sensitivity to the CP-violating weak phase $\gamma = \arg(V_{ub}^*)$



* combining measurements of semileptonic B decays, B–$\bar{B}$ mixing and K–$\bar{K}$ mixing, the unitarity triangle has already been determined with great accuracy

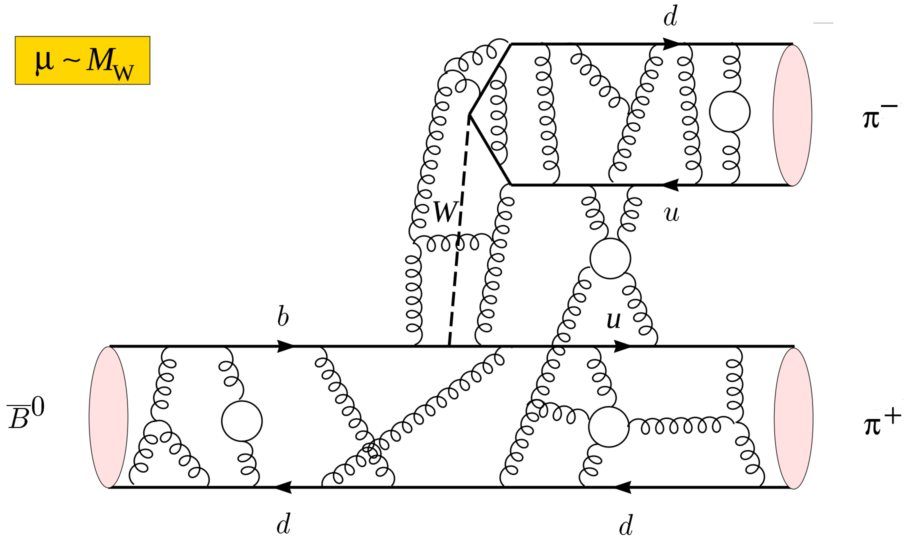
  $\rightarrow$ probes complex phase in top sector (V_{td})

* however, precise determination of $\bar\rho$ and $\bar\eta$ in itself is now only one of many goals; focus has shifted to testing the consistency of the CKM picture

  $\rightarrow$ probe complex phase in bottom sector (V_{ub})!

QCD Factorization Formula

* theoretical description of hadronic weak decays is difficult due to nonperturbative hadronic dynamics
* the problem:



* relevant mass scales:

M_W

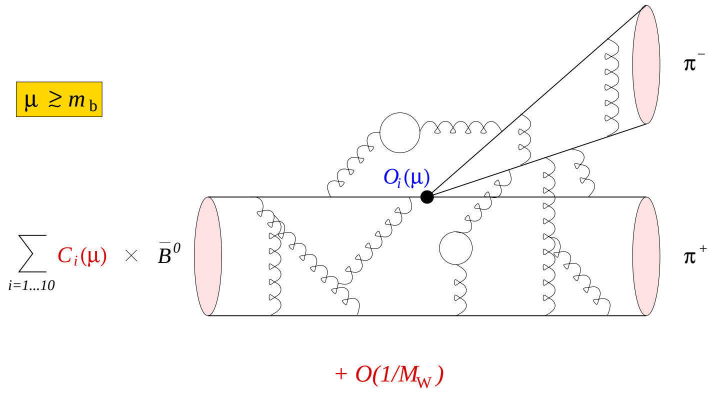
↓ local OPE:
soft gluon effects are power suppressed in $1/M_W$

m_b

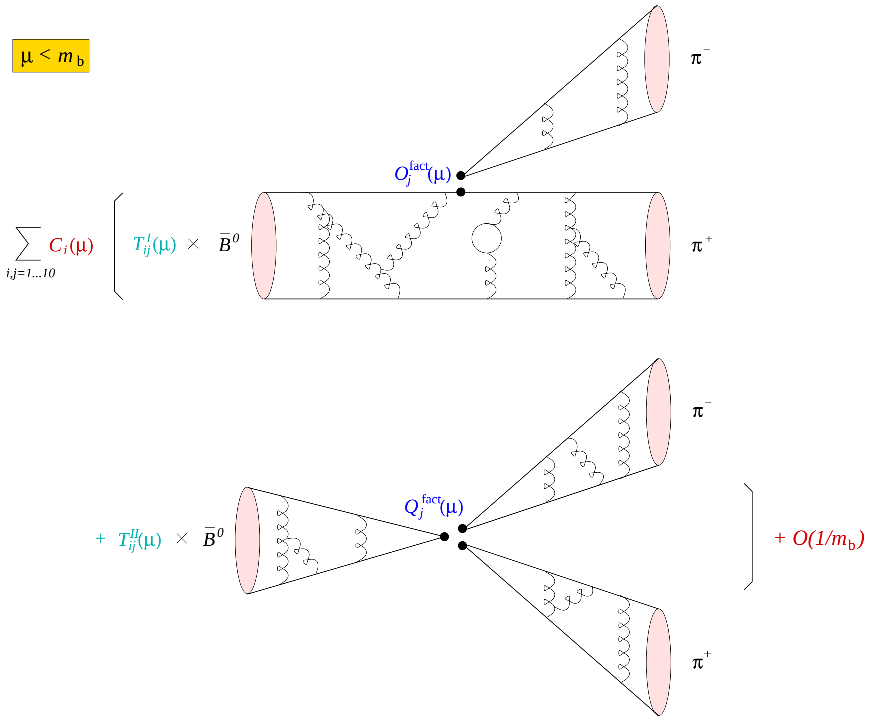
↓ QCD factorization: color transparency!
soft gluon effects are power suppressed in $1/m_b$

Λ_{QCD}

* hard gluon effects with $\mu \gg m_b$ can be calculated and factorized into the Wilson coefficients $C_i(\mu)$ of an effective weak Hamiltonian:



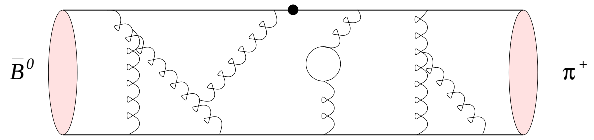
* hard gluon effects with $\mu \sim m_b$ can be calculated and factorized into hard-scattering kernels $T_{ij}(\mu)$:

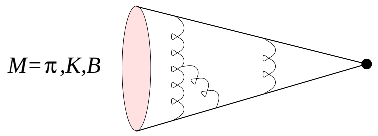


* soft (and collinear) nonfactorizable gluons decouple because of color transparency!

Nonperturbative input:

* semileptonic $B \to \pi, K$ form factors, meson decay constants and light-cone distribution amplitudes





$\to$ extract these quantities from experimental data on semileptonic $B \to M\, l\, \nu$ decay, leptonic $M \to l\, \nu$ decay, other hard exclusive processes, and theoretical calculations (lattice, QCD sum rules, ...)

QCD Factorization Formula:

* allows for a systematic, model-independent calculation of corrections to "naive" factorization, which emerges as leading term in heavy-quark limit

* strong FSI and rescattering phases are calculable and are perturbative or power suppressed (soft rescattering vanishes in the heavy-quark limit)

Power Corrections

* factorization formula gives model-independent predictions for decay amplitudes and their phases in heavy-quark limit

  → valid to all orders of perturbation theory; corrections suppressed by powers of $\Lambda_{\rm QCD}/m_b$

* naive dimensional analysis suggest power corrections $< 10\%$, but they could be enhanced in some cases due to presence of small parameters other than $\Lambda_{\rm QCD}/m_b$ (CKM elements, Wilson coefficients,...)

"Chirally-enhanced" power corrections:

* some power corrections scale like:

$$\frac{1}{m_b} \times \frac{2m_K^2}{m_u + m_s} \approx \frac{1}{m_b} \times \frac{2m_\pi^2}{m_u + m_d} \approx 0.8$$

  → this happens, e.g., for some matrix elements of penguin operators (important for $B \to \pi K$)

* all such terms can be identified and related to twist-3 light-cone distribution amplitudes

* these twist-3 penguin amplitudes factorize and can

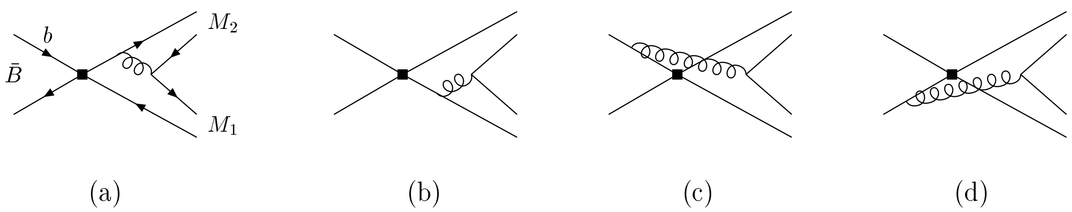
be consistently calculated!

* related twist-3 corrections to twist-2 hard spectator contributions exist, which spoil factorization (logarithmic endpoint divergences)

  → for phenomenology, calculate divergent integrals using a cutoff (e.g., transverse momentum), and assign a 100% (complex) theoretical uncertainty

Weak annihilation contributions:

* Keum, Li, Sanda have argued that annihilation topologies may be largely enhanced:



* these effects are power suppressed and violate factorization

  → estimate "annihilation kernels" using a cutoff, and assign a conservative (complex) error

  → find moderate corrections ($\sim 10\%$), but with large uncertainty

Tests of QCD factorization

* important to test QCD factorization in decays of $B \to 2\,\text{light mesons}$ in a way that is insensitive to γ
* $B^\pm \to \pi^\pm\pi^0$ ($\simeq$ pure tree) and $B^\pm \to \pi^\pm K^0$ ($\simeq$ pure penguin) are best suited for this purpose, because they have negligible amplitude interference

Absolute predictions for branching ratios:

$$\text{Br}(B^\pm \to \pi^\pm\pi^0) = \left[5.3\,^{+0.8}_{-0.4}\,(\text{pars.}) \pm 0.3\,(\text{power})\right] \cdot 10^{-6} \times \left[\frac{|V_{ub}|}{0.0035}\,\frac{F_0^{B\to\pi}(0)}{0.28}\right]^2$$

$$\text{Exp.} = (5.6 \pm 1.5) \cdot 10^{-6}$$

$$\text{Br}(B^\pm \to \pi^\pm K^0) = \left[14.1\,^{+6.4}_{-4.0}\,(m_s)\,^{+8.1}_{-3.6}\,(\text{power})\right] \cdot 10^{-6} \times \left[\frac{F_0^{B\to\pi}(0)}{0.28}\right]^2$$

$$\text{Exp.} = (17.2 \pm 2.5) \cdot 10^{-6}$$

* sensitivity to semileptonic form factors can be eliminated by taking ratios

First test of factorization:

$$\frac{\Gamma(B^\pm \to \pi^\pm \pi^0)}{d\Gamma(\bar{B}^0 \to \pi^+ l^- \bar{\nu})/dq^2|_{q^2=0}} = 3\pi^2 f_\pi^2 \underbrace{|a_1^{(\pi\pi)} + a_2^{(\pi\pi)}|^2}_{1.33\,^{+0.20}_{-0.11}\,(\text{pars.})\pm 0.07\,(\text{power})}$$

$$= (0.68\,^{+0.11}_{-0.06})\ \text{GeV}^2$$

$\to$ independent of weak annihilation and $|V_{ub}|$!

- probes factorization in $B \to \pi\pi$, including the sizeable ($\sim 25\%$) contribution of the hard scattering term in the factorization formula
- verification must await precise experimental data

Second test of factorization:

$$\varepsilon_{\text{exp}} = \left|\frac{T}{P}\right| = \tan\theta_C \, \frac{f_K}{f_\pi} \left[\frac{2\text{Br}(B^\pm \to \pi^\pm \pi^0)}{\text{Br}(B^\pm \to \pi^\pm K^0)}\right]^{\frac{1}{2}} = 0.223 \pm 0.034$$

$\to$ independent of form factors, but $\propto |V_{ub}/V_{cb}|$

- probes tree-to-penguin ratio and is sensitive to (penguin) annihilation contribution
- theoretical prediction agrees well with data:

$$\boxed{\varepsilon = 0.24 \pm 0.04(\text{pars.}) \pm 0.04(\text{power}) \pm 0.05(V_{ub})}$$

Probing γ in $B \to \pi K, \pi\pi$ decays

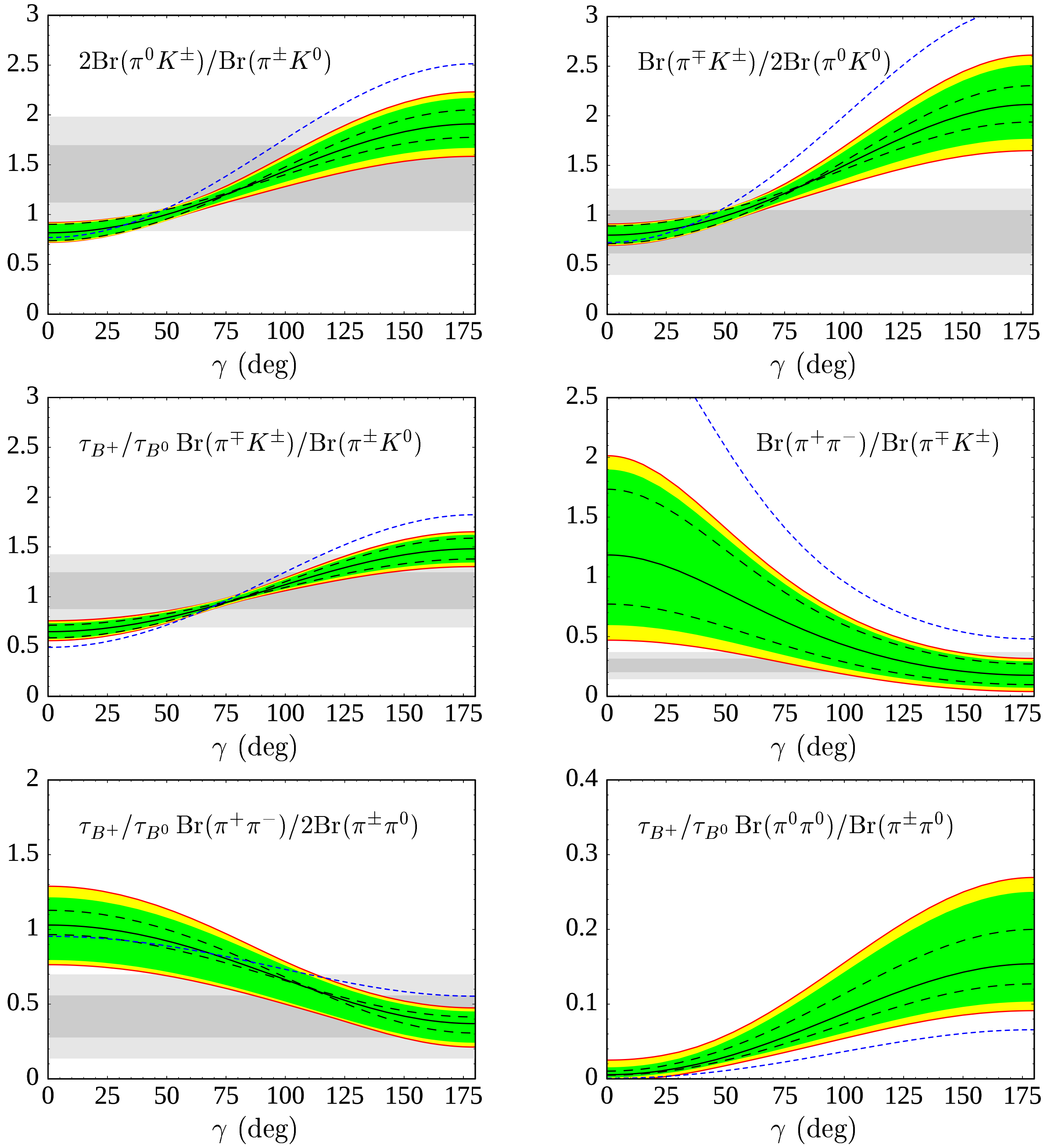
* factorization formula makes large class of rare, hadronic B decay modes accessible to a systematic, theoretical description

* basis for analysis of recent experimental data on CP-averaged branching ratios (in units of 10^{-6}):

Decay Mode	CLEO (PRL 2000)	BaBar (March 2001)	Belle (Feb. 2001)	Average
$B^0 \to \pi^+\pi^-$	$4.3^{+1.6}_{-1.4} \pm 0.5$	$4.1 \pm 1.0 \pm 0.7$	$5.9^{+2.4}_{-2.1} \pm 0.5$	4.4 ± 0.9
$B^\pm \to \pi^\pm\pi^0$	$5.6^{+2.6}_{-2.3} \pm 1.7$	$5.1^{+2.0}_{-1.8} \pm 0.8$	$7.1^{+3.6}_{-3.0}{}^{+0.9}_{-1.2}$	5.6 ± 1.5
	< 12.7 (90% C.L.)	< 9.0 (90% C.L.)	< 12.6 (90% C.L.)	
$B^0 \to \pi^\mp K^\pm$	$17.2^{+2.5}_{-2.4} \pm 1.2$	$16.7 \pm 1.6^{+1.2}_{-1.7}$	$18.7^{+3.3}_{-3.0} \pm 1.6$	17.2 ± 1.5
$B^\pm \to \pi^0 K^\pm$	$11.6^{+3.0}_{-2.7}{}^{+1.4}_{-1.3}$	$10.8^{+2.1}_{-1.9}{}^{+1.0}_{-1.2}$	$17.0^{+3.7}_{-3.3}{}^{+2.0}_{-2.2}$	12.1 ± 1.7
$B^\pm \to \pi^\pm K^0$	$18.2^{+4.6}_{-4.0} \pm 1.6$	$18.2^{+3.3}_{-3.0}{}^{+1.6}_{-2.0}$	$13.1^{+5.5}_{-4.6} \pm 2.6$	17.2 ± 2.5
$B^0 \to \pi^0 K^0$	$14.6^{+5.9}_{-5.1}{}^{+2.4}_{-3.3}$	$8.2^{+3.1}_{-2.7}{}^{+1.1}_{-1.2}$	$14.6^{+6.1}_{-5.1} \pm 2.7$	10.3 ± 2.5

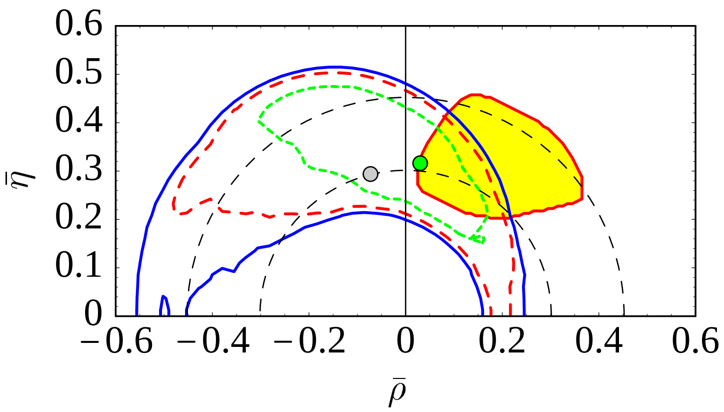
* experimental errors of order 10–20%, which will be reduced further by summer of 2001

* to match this precision theoretically, focus on ratios of decay rates, which are less sensitive to theory input parameters (e.g., semileptonic form factors)



* present error on $|V_{ub}/V_{cb}| = 0.085 \pm 0.017$ is often a dominant contribution to the theoretical uncertainty (dashed lines)

* unfold this dependence and combine information from all $B \to \pi K, \pi\pi$ measurements into a global fit in the $(\bar\rho, \bar\eta)$ plane:



95%, 90% and 68% confidence level contours in the $(\bar\rho, \bar\eta)$ plane obtained from rare hadronic B decays (green dot = overall best fit; gray dot = best fit for default parameter set). The yellow region shows the standard CKM fit.

* results are compatible with the standard fit using semileptonic decays ($|V_{ub}|$, $|V_{cb}|$), K–$\bar K$ mixing (Im$(V_{td})^2$), and B–$\bar B$ mixing ($|V_{td}|$, $\sin 2\beta$)

* best fit prefers larger γ and/or smaller $|V_{ub}|$, as well as $\mu \approx 3\,\text{GeV}$ and $m_s(2\,\text{GeV}) \approx 90\,\text{MeV}$

* combination of results from rare hadronic B decays with $|V_{ub}|$ from semileptonic decays excludes $\bar\eta = 0$ at 95% C.L., thus establishing the existence of a CP-violating phase in the bottom sector!

Outlook

* B physics has entered a new, exciting phase, where we will test the consistency of the CKM model, explore CP violation in the B system, and search for hints of flavor physics beyond the Standard Model
* rare decays play a central role in this program
  - systematic analysis possible due to recent theoretical developments:

    QCD factorization formula
  - heavy-quark expansion for nonleptonic decays
* expect many important results (and surprises?) in the very near future!